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## Toward science-oriented validations of coastal altimetry: Application to the Ligurian Sea

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**Abstract:**

This study is a preliminary contribution to the European Space Agency's efforts aimed at establishing reference in situ networks specifically targeted to validate coastal altimetry. For this purpose, we processed and cross-compared conjointly improved altimetry data and in situ measurements acquired over the Ligurian Sea – a coastal region of the Mediterranean characterised by complex, fine-scale and rapidly evolving oceanic features. We made use of several kinds of multi-sensor in situ observations located along SARAL and Jason-2 tracks. The main objectives of the study were to assess improved coastal oriented validation strategies, including the usage of a new in situ platform (Moving Vessel Profiler), while better understanding potential differences owing to physical content inconsistency and instrumental or data processing limitations. The results show remarkable agreements over spatial scales of few tens of kilometres, paving the way for the deployment of future in situ networks and the definition of science-oriented diagnostics targeted to assess the capability of present and future high-resolution altimetric missions in resolving small-scale physical features.

**Keywords:**

Coastal altimetry; Mesoscale; Validation and verification; Northern current

1       **Toward science-oriented validations of coastal altimetry: Application to the**  
2       **Ligurian Sea**

3

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15

16       **Abstract**

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18       aimed at establishing reference *in situ* networks specifically targeted to validate  
19       coastal altimetry. For this purpose, we processed and cross-compared conjointly  
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27 processing limitations. The results show remarkable agreements over spatial scales of  
28 few tens of kilometres, paving the way for the deployment of future *in situ* networks  
29 and the definition of science-oriented diagnostics targeted to assess the capability of  
30 present and future high-resolution altimetric missions in resolving small-scale  
31 physical features.

32

### 33 **1 Introduction**

34 Even if coastal zones cover only 8% of the entire ocean surface of the earth (Stanev et  
35 al., 2002), they play a crucial role for global ocean circulation, as it provides  
36 dynamical boundary layers for physical, chemical and biological processes. Coastal  
37 regions are characterised by complex ocean dynamics; they are often dominated by  
38 small and rapidly evolving mesoscale/sub-mesoscale structures (hereafter “(sub-  
39 )mesoscale”), which play a major role in the transport of heat, salt and  
40 biogeochemical tracers (McGillicuddy et al., 1998; Levy and Martin, 2013;  
41 Mahadevan, 2016) and significantly influence water-mass mixing and exchanges  
42 between the continental shelf and the open ocean (Huthnance, 1995; Muller-Karger et  
43 al., 2005). Despite their importance, the high spatial/temporal variability and  
44 complexity associated with (sub-)mesoscale dynamics make them difficult to study  
45 with sparse *in situ* observations (Nencioli et al., 2013), requiring the development of  
46 modelling at kilometric (Thomas et al., 2008) and sub-kilometric horizontal space  
47 grids (Gula et al., 2014; Shcherbina et al., 2013) as well as the use of high-resolution  
48 satellite observations (Lehahn et al., 2007; Fu and Ferrari, 2008; Bouffard et al.,  
49 2014; Hu et al., 2011). The issue of characterising (sub-)mesoscale processes is  
50 particularly critical over the coastal domain, where the local Rossby radius is smaller  
51 than in the open-ocean (Hallberg, 2013).

52 Over the last three decades, progress in satellite altimetry has contributed to  
53 revolutionising physical oceanography, enabling the global characterization of open-  
54 ocean large scale and mesoscale processes (Pascual et al., 2010, 2013; Fu et al.,  
55 2001). Satellite altimeters are particularly well adapted for observing open-ocean  
56 structures (Fu et al., 2010) and represent an invaluable source of data, providing  
57 repetitive views of phenomena unachievable by other means (Fu and Chelton, 2001).  
58 One of the main challenges for the next decade is the characterisation of fine-scale  
59 processes in the coastal domain (Cipollini et al., 2009). Achieving this goal requires  
60 not only the innovation of space-born instruments and processing techniques but also  
61 establishing *ad-hoc* validation approaches, allowing better assessment of potential  
62 improvements regarding the precision and accuracy of retrieved geophysical  
63 parameters. Increasingly more multi-disciplinary *in situ* data acquired by marine  
64 observatories and oceanographic campaigns are now being made available (Palacz et  
65 al., 2017) and can be used to derive quality indicators for coastal altimetry based on  
66 the assessment of along-track sea surface gradients complementary to the assessment  
67 of sea surface time series from tide gauges (Bonfond et al., 2018). Here, we  
68 propose exploiting such *in situ* data resources to quantify the potential benefit of  
69 innovative coastal altimetry processing techniques for the characterization of small-  
70 scale ocean geostrophic currents.

71 Several previous studies have evaluated the capabilities of conventional pulse-limited  
72 Ku-Band altimetry to observe mesoscale dynamics in semi-enclosed seas, such as the  
73 Mediterranean Sea (Vignudelli et al., 2005; Bouffard et al., 2008a, 2008b, 2011; Birol  
74 and Delebecque, 2014; Birol and Niño, 2015; Jebri et al., 2017). Despite significant  
75 advances, new coastal-oriented processing techniques require continuous  
76 optimisation and refinement by being systematically cross-compared with collocated

77 multi-platform measurements. Over the last decade, several cruise campaigns using  
78 ship and glider measurements along with altimeter tracks have been carried out in the  
79 Western Mediterranean Sea (Ruiz et al., 2012). For example, in Ruiz et al.'s (2009)  
80 study, glider- and ship-based measurements were performed under an ENVISAT  
81 track in order to provide a mesoscale description of the Balearic Front. Coastal and  
82 mesoscale dynamics analysis using conventional altimetry and gliders have also been  
83 described by Bouffard et al. (2010, 2012) and Aulicino et al. (2018) over the Balearic  
84 Sea and the Algerian Basin respectively. More recently, significant improvements  
85 have been obtained as a result of the advent of new technologies, such as Ka-band  
86 measurements from SARAL (Verron et al., 2015; Troupin et al. 2015; Pascual et al.,  
87 2015) and SAR altimetry measurements from the CryoSat-2 and Sentinel-3 missions  
88 (Bonnefond et al., 2018; Pascual et al., 2017; Morrow et al., 2017; Dinardo et al.,  
89 2017; Heslop et al., 2017; Bouffard et al., 2017; Calafat et al., 2016).

90 The goal of the present paper is to go one step further in the fine cross-analysis of  
91 coastal altimetry data and *in situ* measurements by determining the potential source of  
92 disagreements due to measurement errors and data processing limitations with respect  
93 to expected differences arising from physical content inhomogeneity and *in situ*  
94 reference level issues. Here, we utilise both Moving Vessel Profiler (MVP) and  
95 Acoustic Doppler Current Profiler (ADCP) acquired during the OSCAHR (Observing  
96 Submesoscale Coupling at High Resolution, Doglioli, 2015) Campaign along  
97 SARAL and Jason-2 altimetric tracks. We focus our analysis on the impact  
98 assessment of coastal-oriented altimetry processing strategies specifically developed  
99 and tested with experimental high frequency PEACHI products (Valladeau et al.,  
100 2015). The obtained improvements are discussed with respect to regional 1Hz  
101 AVISO Sea Level Anomaly products (<http://aviso.altimetry.fr/>). Two kinds of Mean

102 Dynamic Topographies (MTDs) have been also used and analysed in order to  
103 reconstruct Absolute Dynamic Topography (ADT).

104 After describing the study area and the characteristics of the *in situ* and space-based  
105 datasets used, the derived absolute geostrophic currents are compared to both ADCP  
106 and MVP measurements, which, in our knowledge, are used conjointly for the first  
107 time to evaluate coastal altimetry strategies. The paper then focuses on the  
108 quantitative and qualitative analysis of depicted ocean features, providing a critical  
109 discussion on the limitations and uncertainty associated with each observing system.

110

## 111 **2 Study Areas**

112 Although the issues addressed in this paper are of global relevance, its primary focus  
113 is on the North-Western Mediterranean (NWMed) Sea with particular emphasis on  
114 the Ligurian Sea area. Figure 1 shows the bathymetry of the selected area along with  
115 altimetry tracks (black lines), *in situ* measurements and the general circulation  
116 patterns.

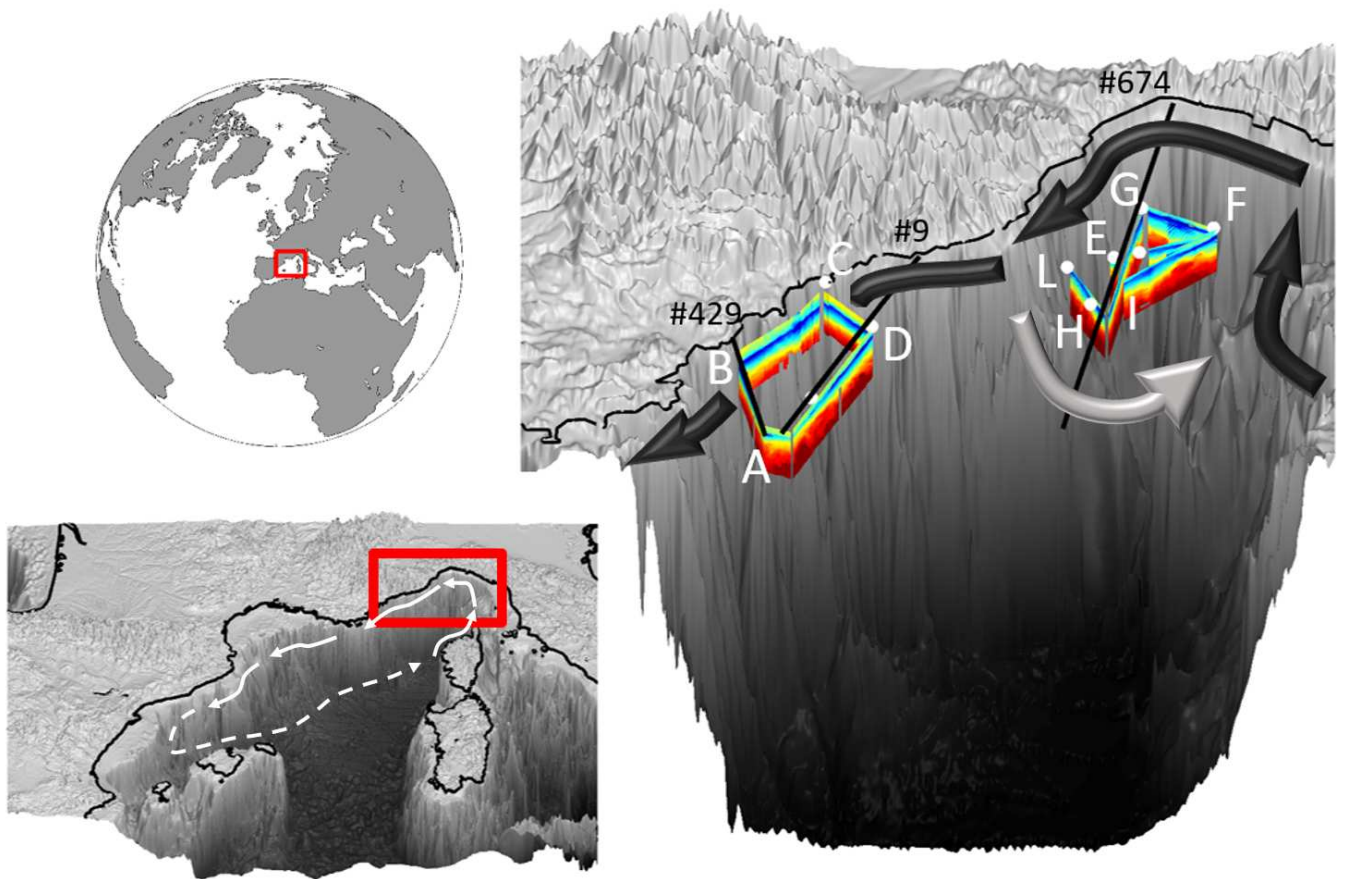
117 The regional dynamics of the area is dominated by a cyclonic gyre circulation, the  
118 northern part of which is known as the “Liguro-Provençal Current” (Millot, 1991,  
119 1999) or the “Northern Current” (NC) (Millot and Taupier Letage, 2005). This slope  
120 current arises from the merging of the eastern and western Corsica currents in the  
121 Ligurian Basin. It then flows to the southwest along the continental slope until it  
122 reaches the Balearic Sea. The NC exhibits a permanent surface density front between  
123 the lighter coastal waters and the denser waters found offshore, generating a sea  
124 surface high gradient in the across-shore direction.

125 Several numerical studies (Barrier et al., 2016; Zakardjan and Prieur, 1998) and  
126 observations along the path of the NC, such as hydrographic measurements from R/V

127 cruises and HF radar (Forget et al., 2006; Marmain et al., 2014) describe this current  
128 as a complex dynamical feature marked by a large spectrum of spatial and temporal  
129 scales of variability. The NC is relatively narrow (~30–75 km) and its mean position  
130 lies within 60 km off the coast (Petrenko, 2003). The core of the NC is stronger and  
131 located about 10–40 km away from the coast in winter, while it is less defined and  
132 further offshore in late summer and early fall (Birol et al., 2010; Piterbarg et al.,  
133 2014; Declerck et al., 2016).

134 Glider transects across the NC have been performed in the Ligurian Sea, such as in  
135 Cyr et al. (2017) and during the MOOSE project (Quentin et al., 2013). Two different  
136 parts constitute the main cyclonic circulation over this area: a small recirculation  
137 centred on the grey arrow in Figure 1 and a second one in the southwest separated by  
138 a local minimum in current intensity (Marrec et al., 2018). The ADT signature  
139 associated with this fine-scale circulation can be potentially observed using satellite  
140 altimetry measurements (Bouffard, 2010). However, monitoring coastal dynamics  
141 from space is still challenging because of the numerous instrumental and geophysical  
142 limitations in addition to the fact that the altimeter footprints may encounter the  
143 coastline, corrupting the raw along-track remote-sensed signal (Anzenhofer et al.,  
144 1999; Strub, 2001).





146            **Figure 1** OSCAHR cruise transects (in letters) showing MVP vertical salinity profiles (coloured  
 147            rectangles), geo-located with altimetric tracks #9 from Jason-2 and tracks #429 and #674 from  
 148            SARAL. The main flow of the NC is shown with black arrows, the recirculation with a grey arrow  
 149            and the Ligurian Sea area is highlighted by the red box.

150

### 151    **3    Data and Methods**

#### 152    **3.1    *In situ* observations**

153    The *in situ* observations used in our study were acquired during the OSCAHR  
 154    campaign (Doglioli, 2015), whose scientific objectives included the characterisation  
 155    of a sub-mesoscale dynamical structure and study of its influence on the distribution  
 156    of biogenic elements and the structure and dynamics of the first trophic levels  
 157    (Marrec et al., 2018). The cruise strategy utilises an adaptive approach based on the

158 near real-time analysis of both satellite data and numerical modelling in order to  
159 identify the dynamical features of interest and track their evolution. Apart from its  
160 main scientific objectives regarding (sub-)mesoscale physical/biochemistry coupling  
161 the OSCAHR campaign also aims to validate new remote-sensing retrieval  
162 techniques (altimetry, ocean colour, planktonic assemblage reconstruction) and high-  
163 resolution numerical modelling. In particular, we performed *in situ* measurements  
164 along three altimetric tracks shown in Figure 1 in the present study. The satellite and  
165 vessel passages are summarised in Table 1.

166 The R/V *Téthys II* is equipped with a hull-mounted ADCP RDI Ocean Sentinel 75  
167 kHz; however, the methodology considered in this paper includes the usage of novel  
168 platforms of observation for sampling the ocean sub-surface layer at a high spatial  
169 and temporal frequency. In particular, we use a MVP200 equipped with a MSFFF I  
170 (Multi-Sensor Free Fall Fish type I). A total of 448 casts were performed along a 366-  
171 km route (55 hours of effective work). During the free fall, for each cast,  
172 measurements of temperature, salinity and pressure were performed with a temporal  
173 resolution of 8–10 min, corresponding to a spatial horizontal resolution of ~ 1 km.  
174 The CTD (Conductivity Temperature and Depth) sensor mounted in the MVP towed  
175 fish has the following precisions:  $\pm 0.005$  [°C] for temperature and  $\pm 0.01$  [mS cm<sup>-1</sup>]  
176 for conductivity. The density is estimated using the TEOS-10 (Thermodynamic  
177 Equation of Seawater) equation of state of seawater. Thereafter, temperature, salinity  
178 and density fields were used to estimate the Dynamic Height (DH) with respect to an  
179 arbitrary, no-motion reference level. This reference level is generally chosen to be at  
180 the maximum depth reached by the probe. Following Pond et al., (1986):

181

$$182 \quad \text{DH} = \int \delta(T, S, p) dp \quad (1)$$

183

184 where:

$$185 \quad \delta(T, S, p) = \rho(T, S, p)^{-1} - \rho(0, 35, p)^{-1} \quad (2)$$

186

187  $\delta$  is the specific volume anomaly, i.e., the difference in volume between a unit mass  
188 of water at temperature  $T$ , salinity  $S$  and pressure  $p$  and a unit mass at the temperature  
189  $T = 0^\circ\text{C}$ , salinity  $S = 35.0$  and pressure  $p$ .

190 In a local Cartesian coordinate with  $x$  axis pointing East,  $y$  axis pointing North, the  
191 geostrophic approximation is then applied to compute the MVP-derived current:

$$192 \quad V = \frac{f}{g} \cdot \frac{dh}{dx} \quad (3)$$

193 where  $f$  is the Coriolis parameter,  $g$  is gravity ( $9.8 \text{ m s}^{-2}$ ) and  $h$  is the DH.

194 MVP-derived relative DH and geostrophic current (with respect to reference depth)  
195 were compared with the geo-located SARAL and Jason-2 altimetry-derived absolute  
196 ADT and currents (with respect to the geoid). As compared to ocean gliders, using  
197 MVP has three main advantages: i) the probe performs free fall vertical profiles; ii)  
198 the sampling rate is higher and iii) the planned route (e.g., the altimetric track) is  
199 better followed, being the exact probe wed by the vessel. On the other hand, the main  
200 limit is a lower maximum operating depth. Subsequently, to understand the impacts  
201 of the reference depth and ageostrophic motions in the altimetry versus MVP  
202 comparisons, ADCP measurements were also considered in this study. The ADCP  
203 configuration used during the whole cruise included 60 cells, 8 m depth bins, an  
204 ensemble average of 1' and bottom tracking when possible (although most of the  
205 cruise took place out of reach of the bottom). The depth range extends from 18.5 m to  
206 562.5 m with a vertically averaged error of 3.6 cm/s.

207

Table 1 Satellite *in situ* (MVP + ADCP) synchronization

Trace	Satellite Passage	Beginning waypoint	MVP Start	Ending Waypoint	MVP end	Time Diff.
Jason-2 #9	31/10/15 16:56	D	30/10/15 15:30	A	30/10/15 23:30	-21 h
SARAL #429	30/10/15 05:02	A	31/10/15 01:30	B	01/11/15 06:30	+35 h
SARAL #674	07/11/15 18:02	G	03/11/15 23:00	I	04/11/15 03:00	-89 h
SARAL #674	07/11/15 18:02	H	04/11/15 23:30	G	05/11/15 06:00	-63 h

209

## 210 3.2 Coastal altimetry

211 In this paper, we used regional Mediterranean 1 Hz Jason-2 and SARAL Sea Level  
 212 Anomaly (SLA), defined as the difference between the observed sea surface height  
 213 and the mean sea level available and distributed by AVISO (User Handbook  
 214 Ssalto/DUACS, 2016) as well as the experimental high frequency PEACHI  
 215 (Prototype for Expertise on SARAL for Coastal, Hydrology and Ice) products  
 216 (Valladeau et al., 2015.). Some specific retracking algorithms, corrections, editing  
 217 procedures and MDT have been applied to these products and have been described  
 218 below.

### 219 3.2.1 Retracking

220 One of the largest sources of errors in coastal altimetry is the inaccurate processing of  
 221 the return waveforms. A significant number of ocean return waveforms near the coast  
 222 indeed do not conform to the standard Brown model (Brown, 1997)), as they are

223 affected by the noisier radar echoes from the land and/or calmer water contamination  
224 (Vignudelli et al., 2011). Several studies addressed this issue in the coastal domain.  
225 For example, Brooks et al. (1998) analysed the TOPEX waveforms obtained when  
226 the altimeter transited from water to land and from land to water. They showed that  
227 waveform retracking can be used to extend the altimeter-derived sea surface  
228 topography several kilometres shoreward. Deng et al. (2002) investigated the  
229 behaviour of ERS-2 and POSEIDON altimeter waveform data in the Australian  
230 coastal region and mapped a boundary, located approximately 22 km from the coast  
231 of Australia, within which the altimeter range may be poorly estimated. Deng and  
232 Featherstone (2006) developed a retracking system that includes least-squares fitting  
233 of a five-parameter model and a threshold method applied to altimeter waveforms  
234 around Australia. In addition to the previously mentioned studies, Gomez-Enri et al.  
235 (2009) developed an experimental mixed Brown-specular retracker for the specular  
236 peak embedded within a Brown-type ocean waveform. More recently, new coastal  
237 retracking strategies have been developed and successfully applied, such as the ALES  
238 (Adaptive Leading Edge Subwaveform) (Passaro et al., 2014) and ALES+ (Passaro et  
239 al., 2018), potentially applicable to all pulse-limited altimetry missions over both  
240 open and coastal ocean with the same accuracy.

241 In this study, three types of retracking algorithms have been applied to PEACHI  
242 products. Their main characteristics are described below:

- 243 i. Red3 PISTACH (Prototype Innovant de Système de Traitement pour les  
244 Applications Côtières et l'Hydrologie) (Coastal and Hydrology Altimetry  
245 product handbook, 2010): This algorithm selects an analysis window  
246 centred on the main leading edge of the waveform and retracking  
247 parameters in this reduced window [-10; +20 samples] with a Maximum

248 Likelihood Estimator solving for 3 parameters (range, amplitude and  
249 Sigma composite).

250 ii. MLE4 (Maximum Likelihood Estimator) (Amarouche et al., 2004): This  
251 algorithm is an evolution of the Red3 retracker but is optimised for  
252 coastal applications with the estimator that solves for 4 parameters,  
253 adding the slope of the waveform trailing edge with respect to the Red3.

254 iii. Adaptive (Poisson et al., 2018): This approach is based on a physical  
255 retracking model accounting for the mean square slope of the surface. It  
256 grants the model the capability to adapt from a diffuse waveform to a  
257 pure specular waveform. The model accounts for instrumental  
258 characteristics (point target response, Antenna Gain Pattern, etc.) and a  
259 numerical solution can be used. The fitting criterion used is a pure least  
260 square only if the waveform classification performed before the fitting  
261 identifies a peaky waveform.

262 For AVISO products, the performance of MLE3 retracking (Amarouche et al., 2004)  
263 has been assessed. This retracking is similar to that for MLE4 but fits three unknown  
264 parameters (amplitude, arrival time and rise time) while the fourth, the trailing edge  
265 decay, is held fixed.

266

### 267 **3.2.2 Geophysical Corrections**

268 In addition to waveform retracking, other sources of uncertainties arise from the  
269 application of geophysical corrections to the altimetric sea surface height (SSH),  
270 defined as the height measured with respect to an arbitrary reference level, called the  
271 reference ellipsoid, which is not always optimised for the coastal domain. The main

272 corrections used in this paper are listed in Table 2 and described in the following  
273 sections.

274 One of the most critical corrections is the wet tropospheric path delay, showing a  
275 standard error of +/- 3 cm in the coastal domain (Smith et al., 2008). Approaching the  
276 coast, wet tropospheric signals have a smaller space-temporal scale of variability,  
277 which are poorly resolved by numerical models or are less precisely estimated by on-  
278 board radiometer, the radiometric footprint being potentially corrupted by land  
279 contaminations. Until recently, most altimeter data in a 10–30 km coastal band of the  
280 NWMed were flagged as invalid and discarded from standard regional products  
281 (Bouffard, 2007; Bouffard et al., 2008a, 2008b). The regional AVISO products used  
282 in this study contain an enhanced wet tropospheric correction near the coast (more  
283 details in Brown, 2010). The same approach has been applied to Jason-2 PEACHI  
284 products (Valladeau et al., 2015). For SARAL PEACHI products, the method  
285 described in Valladeau et al. (2015) has been applied, whereby the last valid  
286 brightness temperature (BT) is extrapolated and considered in place of the  
287 contaminated BT as input to the computation of the WTC – an approach that is less  
288 accurate than the Brown (2010) method but much simpler to configure and  
289 implement.

290 Although several algorithms for improving the wet path delay near the coast have  
291 been developed recently (Cipollini et al., 2017; Desportes et al., 2010; Fernandes et  
292 al., 2015; Fernandes and Lázaro, 2016), the detailed evaluation of related  
293 improvements do not lie within the scope of the present paper, which mainly focuses  
294 on the impact assessment of applying coastal-oriented retracking, editing and high-  
295 resolution MDT.

296 Both AVISO and PEACHI products use the Dry Tropospheric correction computed  
297 from 6-hour span outputs from the ECMWF (European Centre for Medium-Range  
298 Weather Forecasts) model. The dry tropospheric correction has a maximum standard  
299 error of +/- 1–2 cm in the coastal domain (Smith et al., 2008).

300 For AVISO, the GOT4.8 (Ray, 2013) ocean tide solutions were applied, while the  
301 FES2012 was used for PEACHI (Carrere et al., 2012), despite the tide signals (and  
302 associated error) in the considered region being particularly low (Alberola et al.,  
303 1995).

304 With regard to the SSB, a 2D wind speed model as a function of backscatter and  
305 Significant Wave Height (SWH) was developed in the framework of the PEACHI  
306 project (Valladeau et al., 2015), while an empirical solution fitted on six months of  
307 SARAL GDR\_C data (from NOAA Laboratory for Satellite Altimetry) was used in  
308 AVISO products (User Handbook Ssalto/DUACS, 2016). Alternative sea state bias  
309 (SSB) solutions are available in literature (Tran et al., 2010; Pires et al., 2016), aimed  
310 at developing a finer modelling of this effect, but have not been assessed in this  
311 study. The accuracy of SSB is about 2 cm (Smith et al., 2008).

312 In addition to the previously mentioned correction, the Global Ionospheric Map  
313 (GIM) from JPL (Jet Propulsion Laboratory) has been considered for the ionosphere  
314 correction for both AVISO and PEACHI products. Although the most accurate way  
315 to model the ionospheric effect is by using dual-frequency measurements (like in  
316 Imel, 1994), this approach is not applicable to SARAL, as it is a monoband radar  
317 altimeter. Thus, the JPL GIM model has been adopted in this study, as it is applicable  
318 to both Jason-2 and SARAL. The ionospheric correction has an error budget of +/- 3  
319 cm on derived SSH (Callahan, 1984). Both PEACHI and AVISO products are



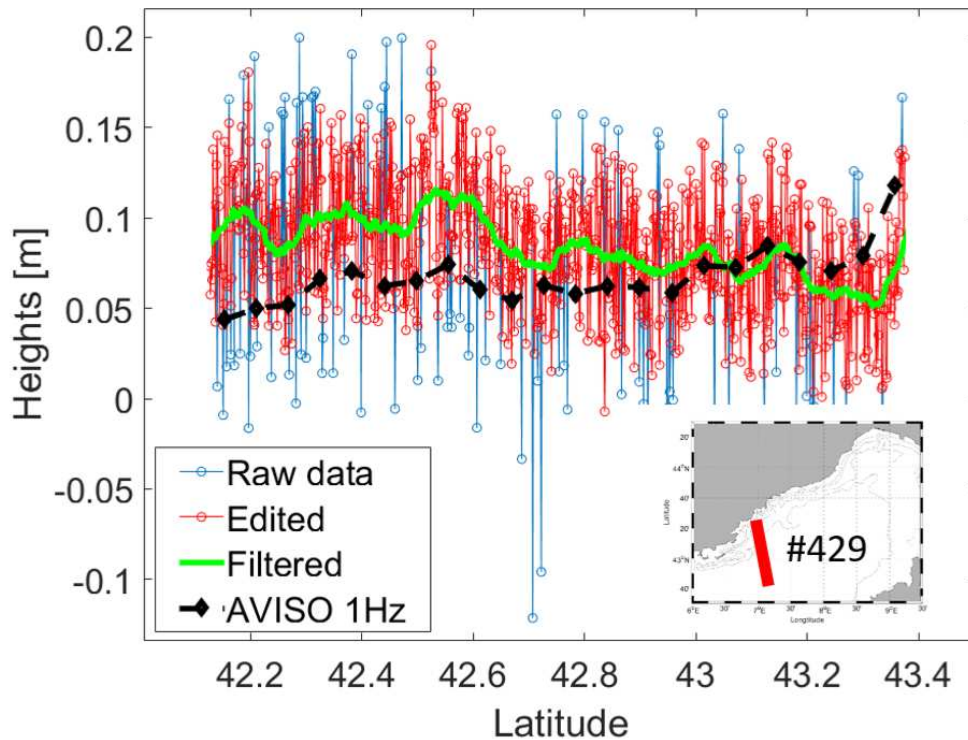
320 provided including a so-called Dynamic Atmospheric Correction (DAC) (Carrère and  
321 Lyard, 2003).

322

### 323 **3.2.3 Coastal Editing Strategy**

324 As the PEACHI experimental products have a high rate sampling of 40Hz for  
325 SARAL and 20Hz for Jason-2, specific editing and filtering procedures have been  
326 developed, following methods described in Bouffard et al. (2010). Figure 2 depicts an  
327 example of this procedure applied on AltiKa track #429 in deriving the edited (red  
328 curve) and filtered (green curve) heights from the raw data (blue curve).

329 First, a ten-step recurrent  $2 \times \text{std}$  editing algorithm was developed and applied to  
330 corrected high-rate along-track PEACHI SLA in order to remove residual spikes (see  
331 red curve on Figure 2). For each iteration, first, the difference between the altimetry  
332 raw and smoothed data was computed and then spikes higher than two standard  
333 deviations are flagged, removed and replaced by linearly interpolated values. The  
334 next iteration begins from this result by performing the spikes filtering and smoothing  
335 again. This recurrent procedure is repeated ten times in order to obtain the final edited  
336 and filtered SLA. At the end of these editing steps, 4% of spikes were eliminated  
337 from SARAL track #429 and 12% from SARAL track #674, while 7% spikes were  
338 filtered out from Jason-2 track #9. Thereafter, the edited high rate altimetric SLA was  
339 low-pass filtered (using a moving average filter) with a window of 2.5 km for  
340 SARAL (see green curve on Figure 2) and 8.5 km for Jason-2 in order to reduce  
341 residual noise, as in Bouffard et al. (2010). The MVP derived currents and ADCP  
342 currents were also smoothed from the raw signal with the same filter. Figure 2 also  
343 shows (in black) the 1 Hz AVISO product, highlighting the differences with respect  
344 to high-rate PEACHI products in terms of SLA-observed features.



345

346 **Figure 2 PEACHI high rate altimetry SLA editing and filtering for SARAL track #429. The black line**  
 347 **corresponds to the AVISO 1 Hz track.**

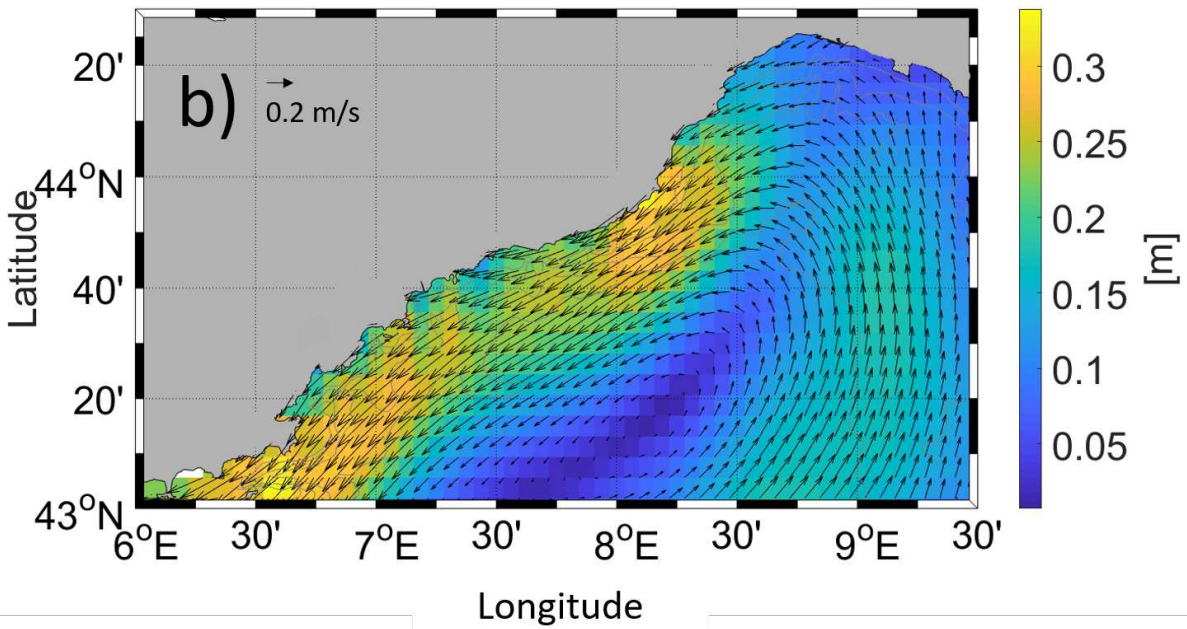
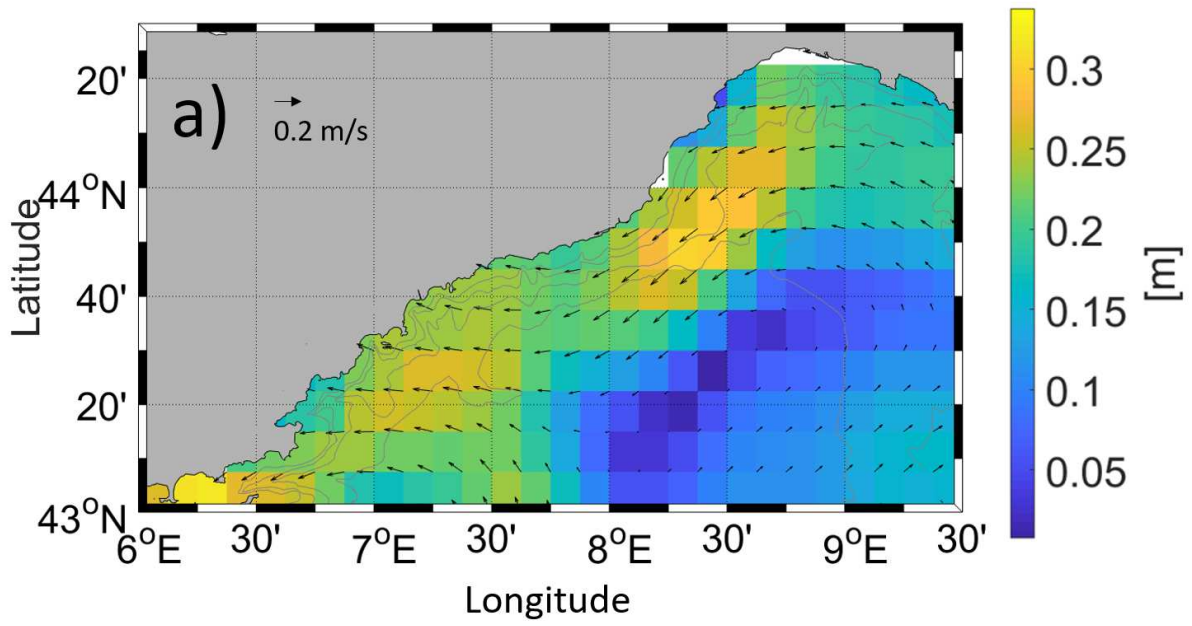
348

### 349 **3.2.4 Mean Dynamic Topography (MDT)**

350 The AVISO and PEACHI absolute geostrophic currents were then calculated from  
 351 the ADT, using the Powell and Leben (2004) filtering with a cut-off distance of 15  
 352 km, roughly corresponding to the local Rossby radius of deformation over the study  
 353 area (Grilli and Pinardi, 1998). Two Mean Dynamic Topography (MDT) have been  
 354 considered, spatially interpolated and added to the altimetric SLA in order to obtain  
 355 the along-track ADT: the Rio “old” MDT (after RIO07), resolution 1/8° (Rio et al.,  
 356 2007; see Figure 3a) and the Rio “new” MDT (RIO14) with resolution 1/16° (Rio et  
 357 al., 2014; see Figure 3b).

358 A linear interpolation was applied to both RIO07 and RIO14 gridded MDTs to obtain  
 359 an along-track MDT to be added to the altimetry SLA measurements.

360 The RIO14 benefits from the improvements enabled by the use of extended data sets  
361 and refined processing techniques. The updated data set spans the 1993–2012 period  
362 and consists of drifter velocities, altimetry data, hydrological profiles and model data.  
363 The methodology is similar to the previous RIO07, which did not use any  
364 hydrological profiles. As compared to the RIO07, the RIO14 therefore features  
365 shorter-scale structures owing to the use of more *in situ* and satellite-based  
366 observations.



367

368

Figure 3 RIO07 (a) and RIO14 (b) MDT overlapped by the derived mean current.

369

Table 2 Altimetry data characteristics

SLA	MDT	Retracker	Sampling	SLA Coastal Editing	Spatial Filtering	Corrections
AVISO Jason-2	RIO14 RIO07	MLE3	1 Hz	No	No	Wet tropo (Brown, 2010)
AVISO SARAL	RIO14 RIO07					Dry tropo (ECMWF Model)
PEACHI Jason-2	RIO14 RIO07	Red3 MLE4 Adaptive	20 Hz	10-step recurrent algorithm (Bouffard et al., 2010)	8.5 Km	Ionospheric (GIM from JPL)
PEACHI SARAL	RIO14 RIO07		40 Hz	10-step recurrent algorithm (Bouffard et al., 2010)	2.5 Km	Tides (FES2012 (Carrere et al., 2012))
						SSB (User Handbook Ssalto/DUACS, 2016)
						DAC (Carrère and Lyard, 2003)

371

372 **4 Results and discussions**373 **4.1 Impact of *in situ* MVP reference depth and sinopticity issue**

374 As reported in section 3.1, temperature, salinity and density fields retrieved by MVP  
375 can be used to estimate DH with respect to an arbitrary reference depth, which is  
376 supposed to be a no-motion level. As the reference depth issue does not affect  
377 altimetry, a sensitivity study has been performed to highlight effects on the  
378 computation of MVP-derived surface geostrophic current when compared to  
379 altimetry (shown in Figure 4). The latter shows the different MVP-derived

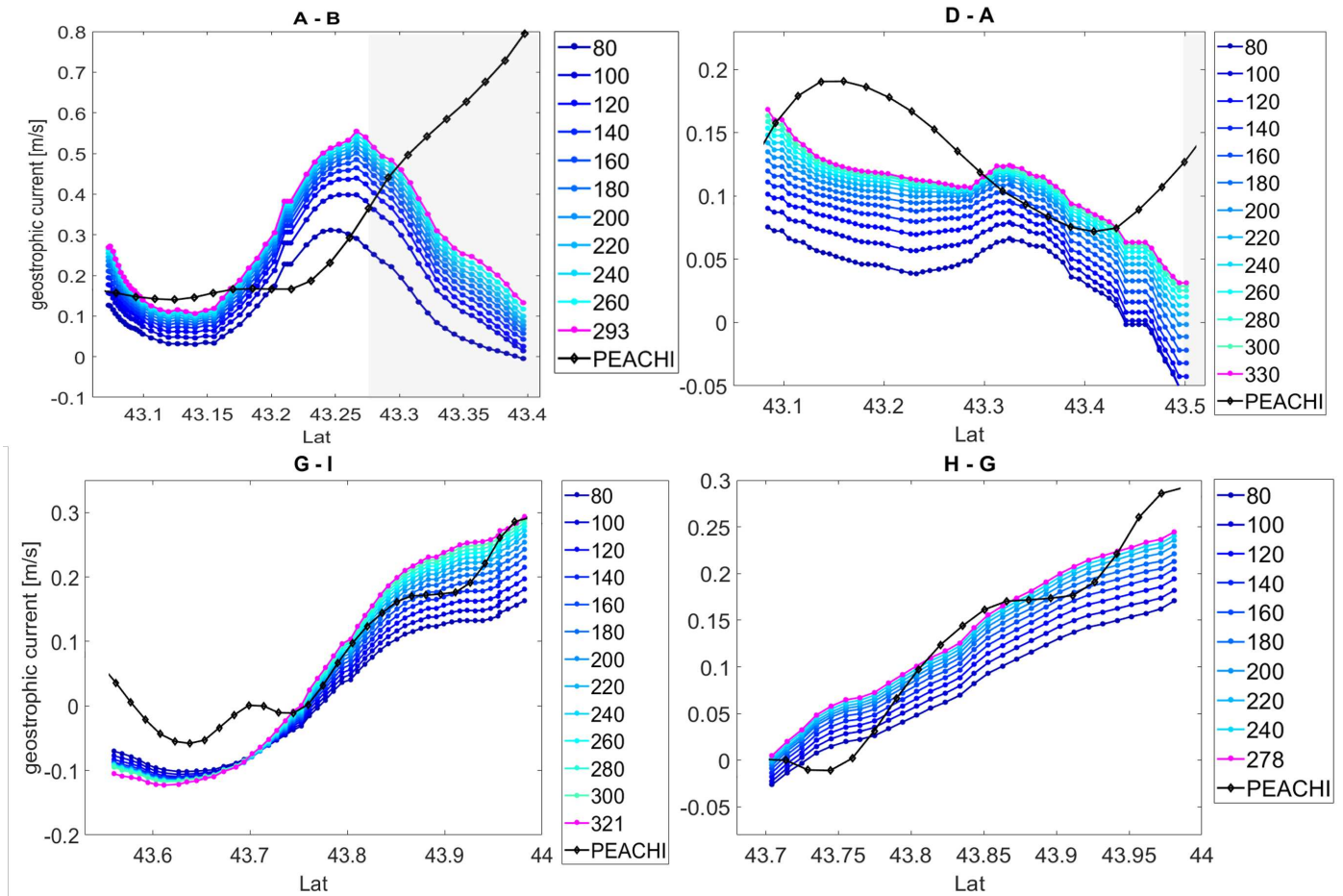
380 geostrophic currents computed by varying the reference depth, compared with  
381 PEACHI geostrophic currents using the MLE4 retracker. Each of the four transects  
382 has a different maximum depth for which valid measurements are available: 293 m  
383 for transect A – B, 330 m for transect D – A, 321 m for transect G – I and 278 m for  
384 transect H – G. Figure 5 reports the mean and standard deviation of the differences  
385 between PEACHI and MVP at different reference depths.

386 Examining the comparison statistics reported in Figure 5, it can be seen that the  
387 differences are reduced between altimetry and MVP datasets for transect D – A and H  
388 – G when considering a deeper reference level. For transect H – G, the difference  
389 between the two sensors is reduced from 0.052 m/s for a reference depth of 90 m to  
390 0.028 m/s for a reference depth of 278 m. The same conclusion is obtained for  
391 transect D – A and transect A – B with a mean reduction from 0.092 m/s to 0.041 m/s  
392 and from 0.210 m/s to 0.178 m/s, respectively. This is potentially caused by the deep  
393 flow of the NC along the Ligurian continental slope. The vertical temperature profile  
394 shows the NC signature with a stronger temperature up to a depth of 90 m for  
395 latitudes higher than 43.35° (see Figure 10 and associated discussions).

396 The results obtained for the MVP transects out of the NC are different. For transect G  
397 – I, the mean reduction of altimetry and MVP current difference is observed up to a  
398 140-m depth, whereas the differences go up for a higher depth (as for surface layers).  
399 This pattern could be potentially linked to the sub-surface currents associated with a  
400 strong and rapidly evolving mesoscale feature intercepted by this transect but not  
401 seen by transect H – G. Transects G – I and H – G are almost collocated but have a  
402 time separation of about one day (see Table 2) during which dynamical conditions  
403 may have changed with fine-scale surface features having moved in between the two  
404 MVP passes. This is confirmed by examining the vertical temperature profiles on

405 which changes are clearly observed along the water column (see Figure 10 and  
406 associated discussions). These high-frequency variations cannot be observed by  
407 instantaneous altimetry measurements, while they affect the MVP measurements all  
408 along the data sampling, emphasising potential impacts of synoptic issues in  
409 altimetric versus *in situ* comparisons.

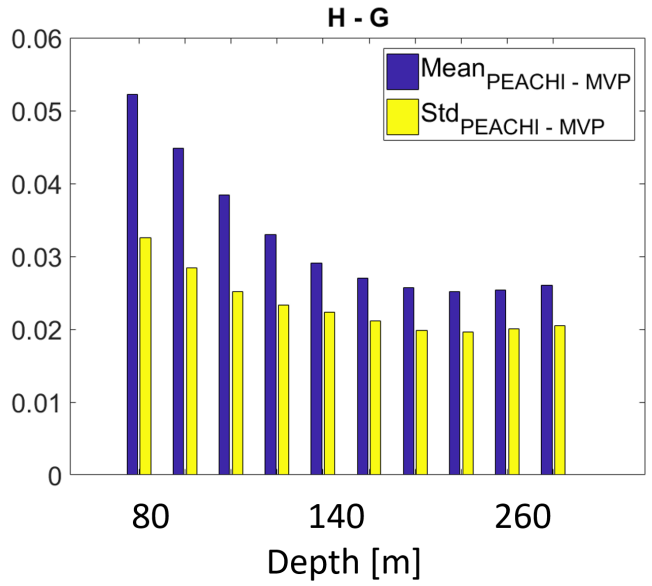
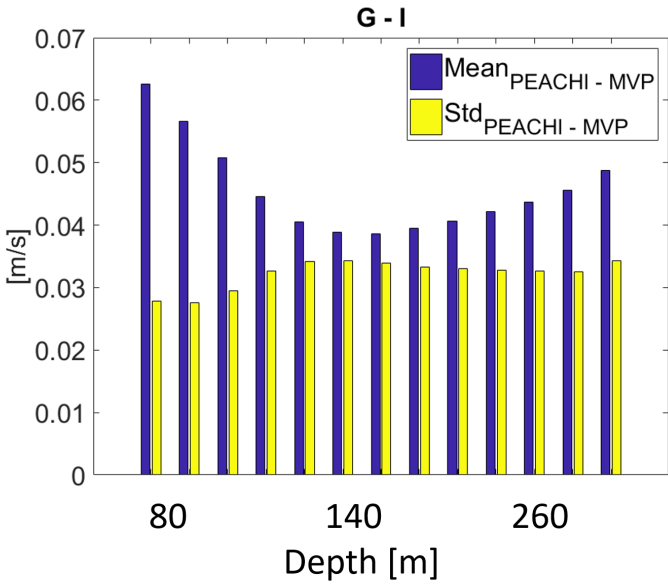
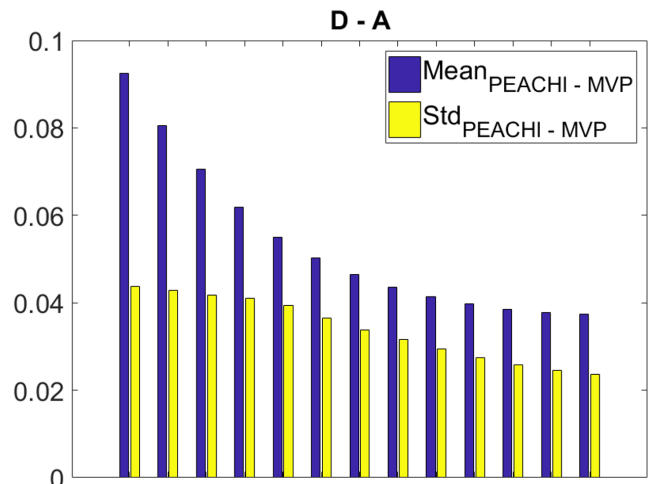
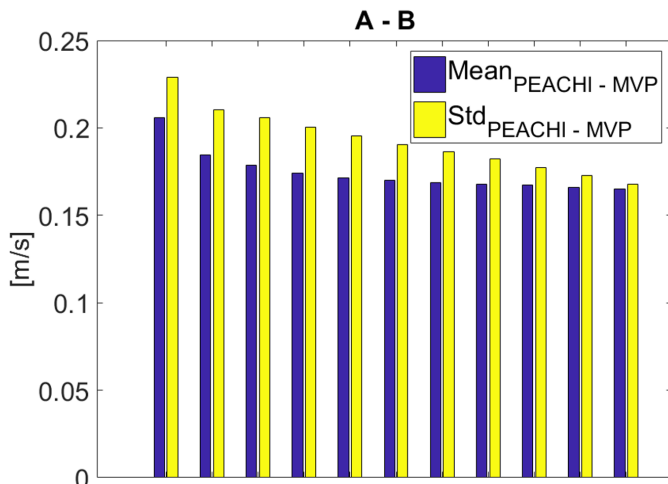
410 According to the above results (also confirmed by using Red3 or Adaptive retrackers  
411 in the sensitivity study) and despite the spotted sinopticity issue, the agreement  
412 between altimetry and MVP is generally satisfying when considering the deepest  
413 reference level (different for each of the four considered transect) as well as 20–30  
414 km offshore (the grey square on Figure 4). On one hand, the deepest reference level  
415 has been kept for the remaining analyses and is the one adopted in the results  
416 presented in section 4.3 On the other hand, two alternative retrackers (Red3,  
417 Adaptive) have been used and evaluated to highlight the potential improvement in the  
418 20–30 coastal bands.



420 **Figure 4 Reference depth sensitivity study for transects A – B, D – A, G – I and H – G. Different colours are**  
 421 **associated with different reference depths (in meters) considered in the vertical integration of MVP data**  
 422 **while the PEACHI altimetry data (MLE4 retracker) are shown in black. The magenta line represents the**  
 423 **MVP derived currents at the maximum operating depth. The shaded grey areas in transects A – B and D –**  
 424 **A correspond to 20 km from the coast.**

425





426

427

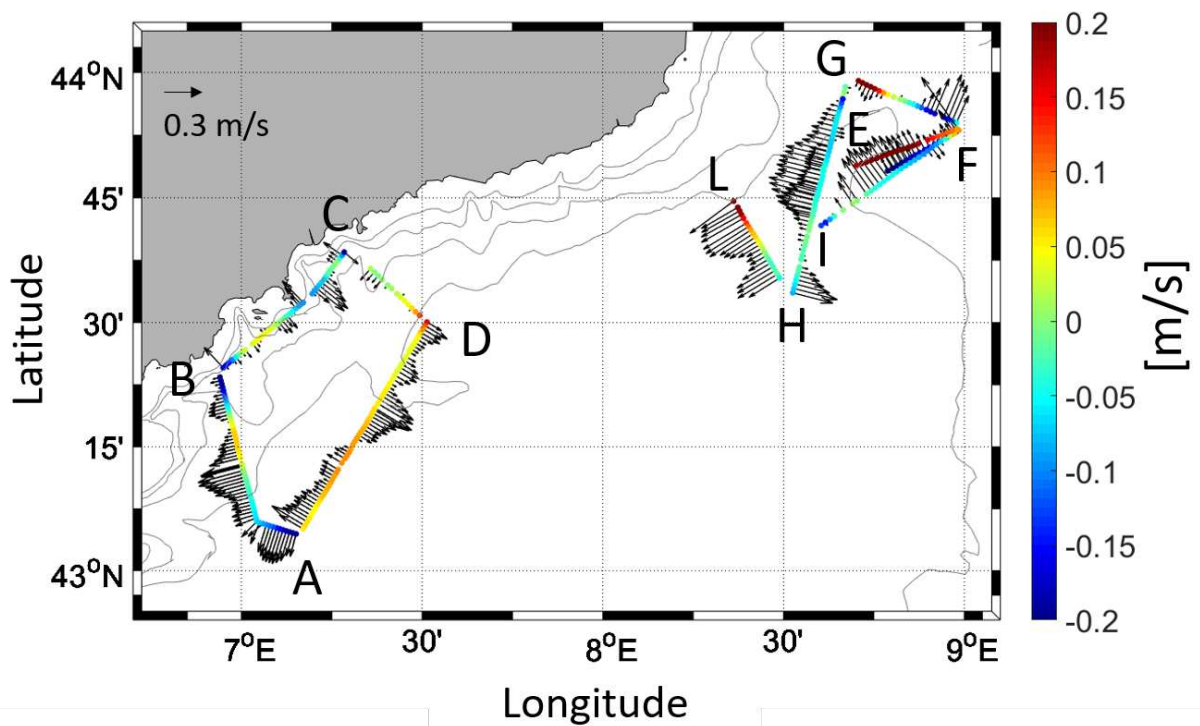
Figure 5 Mean (blue) and standard deviation (yellow) of the current differences between PEACHI and MVP.

428

429

430 **4.2 Impact of physical content and reference depth**

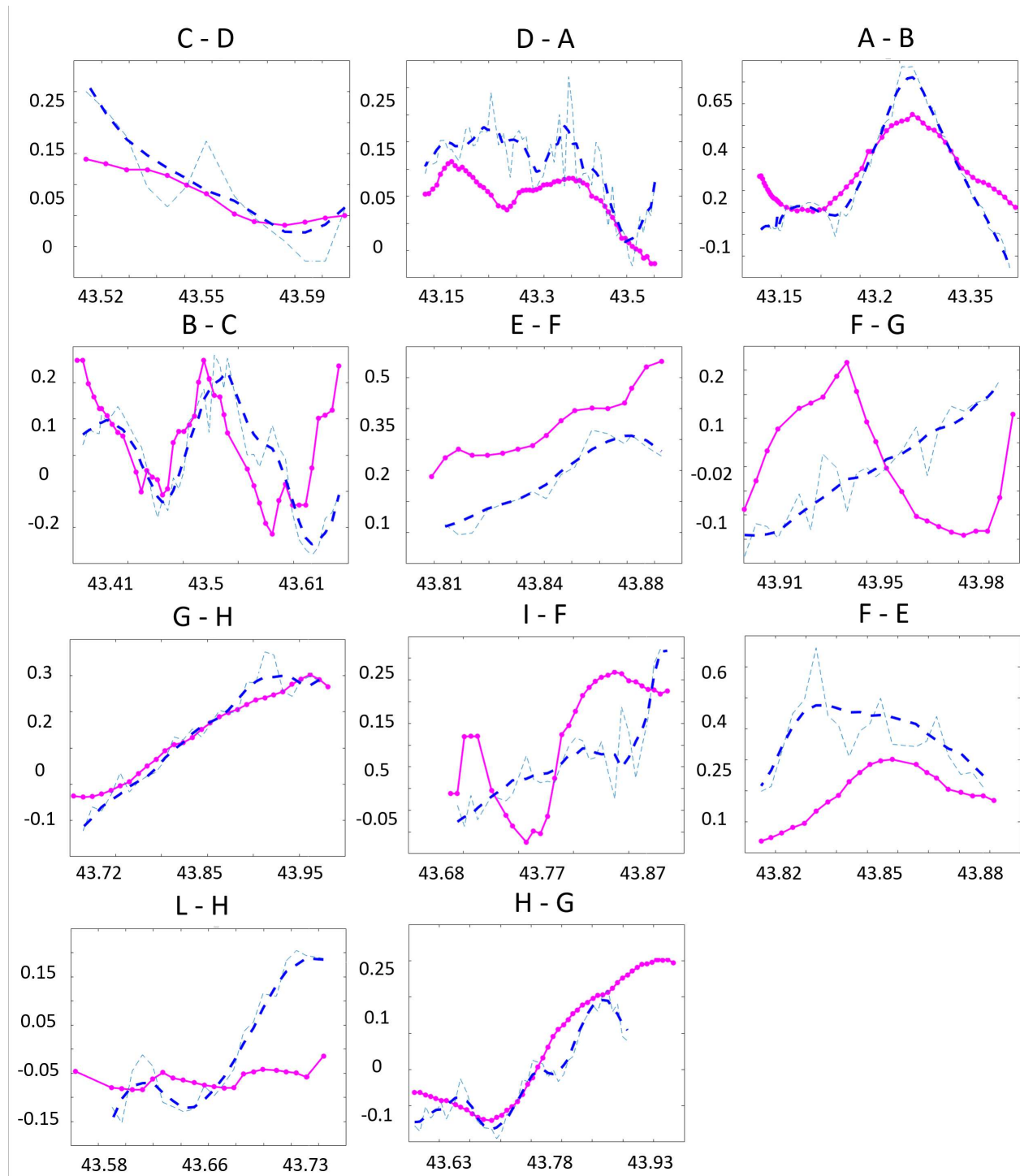
431 In order to assess the potential impact of the reference depth on the MVP retrieved  
432 current, geographical plots of the differences of the surface across-track current  
433 ADCP-MVP (coloured dots) have been computed (Figure 6), superposed to the cross-  
434 track component of the deep ADCP current, measured at 270 m depth. Comparison  
435 between surface across track MVP and ADCP derived currents are shown in Figure 7  
436 for each of the cruise transects.



437

438 **Figure 6 Geographical plot of the differences (coloured dots) of the surface across track current ADCP-**

439 **MVP. The vectors are related to the cross-track component of the ADCP current at 270 m depth.**



441 **Figure 7 Comparison between MVP (magenta) and ADCP currents (m/s) vs. Latitude (raw data in thin**  
 442 **blue, filtered and smoothed data in dashed thick blue) for each transect.**

443 The principal differences between the two *in situ* observing systems highlighted in  
 444 Figure 7 should be mainly related to the fact that ADCP measures the total absolute  
 445 current and contains both geostrophic and ageostrophic motion, while the MVP

446 measurements are referenced to an unknown no-motion level and – as altimetry –  
447 capture the single geostrophic component.

448 Figure 6 shows that if a strong deep current is present at 270 m, the no-motion  
449 hypothesis is not verified, which consequently creates inconsistencies when  
450 comparing DH-derived MVP currents with the ones from ADCP (and hence with  
451 altimetry). This is evident from transect F – G, E – F and F – E, where the differences  
452 between the two observing systems are particularly high ( $> 0.16 \text{ ms}^{-1}$ ). This is also  
453 valid when examining transect A – B, where a strong deep current is visible in Figure  
454 6, generating a difference of  $0.10 \text{ ms}^{-1}$  between surface MVP and ADCP currents. On  
455 the other hand, transects G – H and H – G show small differences and high  
456 correlation ( $> 0.95$ ), although the ADCP measurements show finer-scale dynamics,  
457 perhaps due to ageostrophic variations that occurred during the time of route H – G  
458 and not during the same geographical transect G – H. During the period from October  
459 30 to November 2, 2015, a strong north-easterly wind event with velocity up to  $70$   
460  $\text{km h}^{-1}$  was recorded over the whole area (Marrec et al., 2018), reinforcing high-  
461 frequency and small-scale features

462 In addition, looking at *in situ* comparison statistics (Table 3), anticorrelated value was  
463 found for transect F – G as well as significant differences for transects E – F, F – E  
464 and F – G. Moreover, ADCP observations on Figure 7 show small-scale dynamics,  
465 not depicted by altimetry and MVP (for example along the transect D – A), but  
466 attesting the presence of high-frequency ageostrophic likely variations.

467

468

469

Transect	Mean(ADCP-MVP) [m]	Std(ADCP-MVP) [m]	Mean(MVP) [m]	Std(MVP) [m]	Mean(ADCP) [m]	Std(ADCP) [m]	Corr(ADCP, MVP)
C - D	0.03	0.04	0.08	0.04	0.11	0.08	0.94
D - A	0.06	0.03	0.10	0.05	0.16	0.06	0.81
A - B	0.10	0.08	0.27	0.14	0.23	0.24	0.93
B - C	0.13	0.13	0.03	0.10	0.00	0.13	0.44
E - F	0.18	0.05	0.34	0.11	0.18	0.11	0.89
F - G	0.18	0.07	0.01	0.12	0.00	0.10	-0.59
G - H	0.03	0.02	0.14	0.12	0.14	0.14	0.99
I - F	0.12	0.06	0.12	0.14	0.07	0.10	0.51
F - E	0.20	0.09	0.19	0.08	0.38	0.08	0.44
L - H	0.08	0.08	-0.06	0.02	-0.01	0.12	0.72
H - G	0.05	0.04	0.08	0.16	-0.02	0.12	0.95

471

472 After geostrophy, one of the major contributions to the ocean surface currents is the  
473 Ekman response of the ocean to high-frequency wind stress. Various studies have  
474 focused on understanding and modelling these currents in a more effective and  
475 comprehensive manner (Ralph and Niiler, 1999; Lagerloef et al., 1999; Elipot and  
476 Gille, 2009; Rio et al., 2003, 2011, 2012). The potential impacts of ageostrophy  
477 signatures from Ekman have been tentatively assessed in this study using  
478 GlobCurrent version 2 Ekman current at 0.25° resolution, 3-hourly, available from  
479 2002 to 2014 (accessed from <http://www.globcurrent.org/>). However, due to the  
480 coarse resolution of the GlobCurrent products and a lack of coverage over the coastal  
481 domain, it was not possible to assess precise Ekman impacts on the study area. A  
482 product with finer resolution should be processed in future GlobCurrent versions but  
483 was not available at the time of this study.

484 The following section reports the comparison between satellite altimetry and MVP  
485 with particular emphasis on the impacts of altimetry processing.

486

487

### 488 4.3 Impact of altimetry processing

489 SARAL tracks #429 and #674 together with Jason-2 track #9 SLA, ADT and derived  
490 currents were compared to MVP geo-located measurements (Figure 8). Tables 4 and  
491 5 report the mean statistical scores per mission. In total, combinations of 12  
492 comparisons per track have been performed between satellite altimetry measurements  
493 (considering different products, MDT and corrections) and *in situ* MVP/ADCP  
494 transects. The analysis has been performed up to 14.5 km from the coast for SARAL  
495 track #429, 37 km for SARAL track #674 and up to 13 km for Jason-2 track #9.

496 Examining the comparison plots between Jason-2 track #9 and MVP transect A-D  
497 (Figure 8a), it can be seen that the two bumps visible in currents at Latitude 43.2° and  
498 43.4° are related to the interception of the NC, which intersects the altimetric track  
499 twice due to its orientation with respect to the main flow. The NC signature is also  
500 evident when looking at SARAL track #429 from which the main current peak of  
501 0.55 m/s at Latitude 43.25° is captured by MVP and ADCP measurements (Figure  
502 8b). Along the SARAL track #674 and *in situ* transects G – I and H – G, a dipole-like  
503 mesoscale structure is observed in each altimetric dataset (see section 4.4; Figures 8c  
504 and 8d).

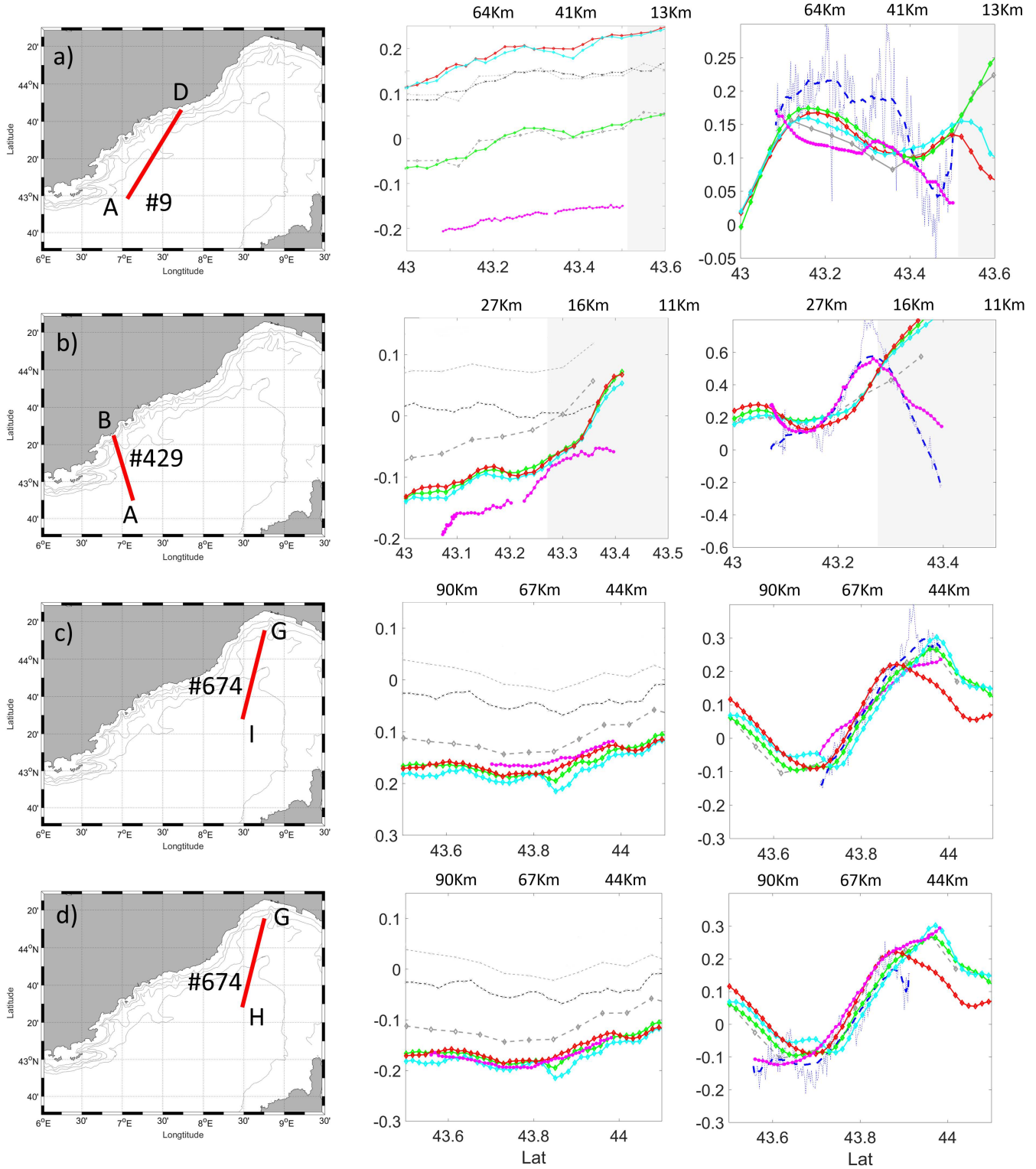
505 Despite good general agreement between altimetry and MVP, some important  
506 discrepancies were also observed. For track #429, the mean difference with respect to  
507 the MVP and ADCP current are 0.08 m/s and 0.20 m/s, respectively. These  
508 significant differences might potentially be due to land contamination affecting  
509 altimetry measurements approaching the coast and not processed with optimal  
510 retracking and/or local corrections. MVP and ADCP show some disagreements along  
511 the transect A – D, whereas ADCP – not affected by reference level issue – and

512 altimetry (track #9) show quite a similar pattern with an increasing velocity when  
513 approaching the coastline.

514 When compared to ADCP and MVP-derived current, the benefit of adding MDT to  
515 the altimetric SLA is obviously confirmed for all considered tracks and missions; this  
516 is particularly evident for SARAL tracks, for which an improvement of 30% in  
517 correlation was observed. When compared to the RIO07 MDT, the use of the RIO14  
518 further improves the comparison scores in terms of correlation between altimetry data  
519 and MVP, with a mean increase of 10% for both AVISO and PEACHI products  
520 (Tables 4 and 5).

521 Using the PEACHI products, the mean and standard deviation differences between  
522 MVP and altimetry are still reduced: the overall mean difference goes from 0.04 m/s  
523 to 0.02 m/s for SARAL and from 0.35 m/s to 0.26 m/s for Jason-2 for 1 Hz AVISO  
524 and PEACHI products respectively. Comparison statistics (Table 4) show that for  
525 PEACHI products, the adaptive retracker provides better performances in coastal  
526 regions (correlation  $> 0.9$ ) for both 40 Hz SARAL and 20 Hz Jason-2 sensors when  
527 compared to standard 1 Hz regional AVISO.

528 With regard to previous studies (Birol et al., 2015; Verron et al., 2015; Troupin et al.,  
529 2015), considering AltiKa sensor on-board, SARAL provides better statistical  
530 agreement with *in situ* than the Ku-band mission, such as Jason-2 and, particularly in  
531 this study, using the combination with RIO14 and adaptive retracking, confirming  
532 that the Ka band is more reliable in resolving fine-scale coastal dynamics.



534 **Figure 8** PEACHI Altimetry (grey for SLA+RIO07 and red for adaptive retracking, cyan for Red3 retracking  
 535 and green for MLE4 retracking for SLA+RIO14) vs AVISO altimetry (light grey for SLA+RIO07 and grey for  
 536 SLA+RIO14) vs *in situ* (magenta for MVP, blue for ADCP). The different markers used for both AVISO and  
 537 PEACHI altimetry are related to elevations and currents computed with a different MDT (crosses for RIO07



538 and diamonds for RIO14). First column reports track geolocation, second column reports ADTs (m) vs Latitude  
 539 and third column reports satellite across track current (ms-1) derived from ADT computed only adding RIO14  
 540 to SLA vs Latitude together with in situ derived current vs Latitude. The distance to the coast is also reported in  
 541 kilometres.

542  
 543 **Table 4 PEACHI ADT and V vs MVP average comparison statistics (correlation) per retracking method**  
 544 **(the level of significance is 95%)**

Satellite	MDT	Parameter	Adaptive	MLE4	RED3	Total Average per MDT
SARAL	RIO14	ADT	0.93	0.90	0.78	0.87
		V	0.75	0.67	0.79	0.74
	RIO07	ADT	0.58	0.55	0.30	0.48
		V	0.76	0.51	0.71	0.66
	<b>Total Average per Retracking</b>	ADT	0.75	0.72	0.54	0.67
		V	0.76	0.59	0.75	0.70
Jason-2	RIO14	ADT	0.92	0.91	0.77	0.87
		V	0.71	0.74	0.73	0.73
	RIO07	ADT	0.83	0.81	0.71	0.79
		V	0.70	0.74	0.72	0.72
	<b>Total Average per Retracking</b>	ADT	0.88	0.86	0.74	0.83
		V	0.71	0.74	0.73	0.72

545

546  
 547 **Table 5 AVISO ADT and V vs MVP average comparison statistics (correlation) per retracking method (the**  
 548 **level of significance is 95%)**

Satellite	MDT	Parameter	MLE3
SARAL	RIO14	ADT	0.86
		V	0.82
	RIO07	ADT	0.60
		V	0.76
	<b>Total Average per Retracking</b>	ADT	0.73
		V	0.79
Jason-2	RIO14	ADT	0.87
		V	0.71
	RIO07	ADT	0.70
		V	0.68
	<b>Total Average per Retracking</b>	ADT	0.79
		V	0.70

549

550

551 From a general point of view, the comparison between altimetry and MVP over the  
552 study area is improved when considering experimental PEACHI high-rate altimetry  
553 data rather than the Mediterranean regional AVISO products. The NC signatures and  
554 small-scale oceanic features are, however, well captured by both datasets. Despite  
555 this encouraging result and as testified by cross-comparisons with collocated ADCP  
556 transects, the MVP measurements cannot be considered as a perfect reference dataset  
557 for validating coastal altimetry. This is due to its sensitivity to the reference level  
558 with regard to determining the DH along with the highlighted synopticity issues  
559 induced by high frequency and partially ageostrophic small-scale dynamics occurring  
560 during data acquisition.

561

#### 562 **4.4 Observed circulation patterns**

563 As shown on Figure 9, the combined use of surface altimetry and sub-surface *in situ*  
564 measurements (MVP and ADCP) allows the observation of small scale and coastal  
565 hydrodynamic features that are consistent with frontal structures depicted by  
566 PODAAC Sea Surface Temperature data (SST, L4 data, JPL OurOcean Project,  
567 2010).

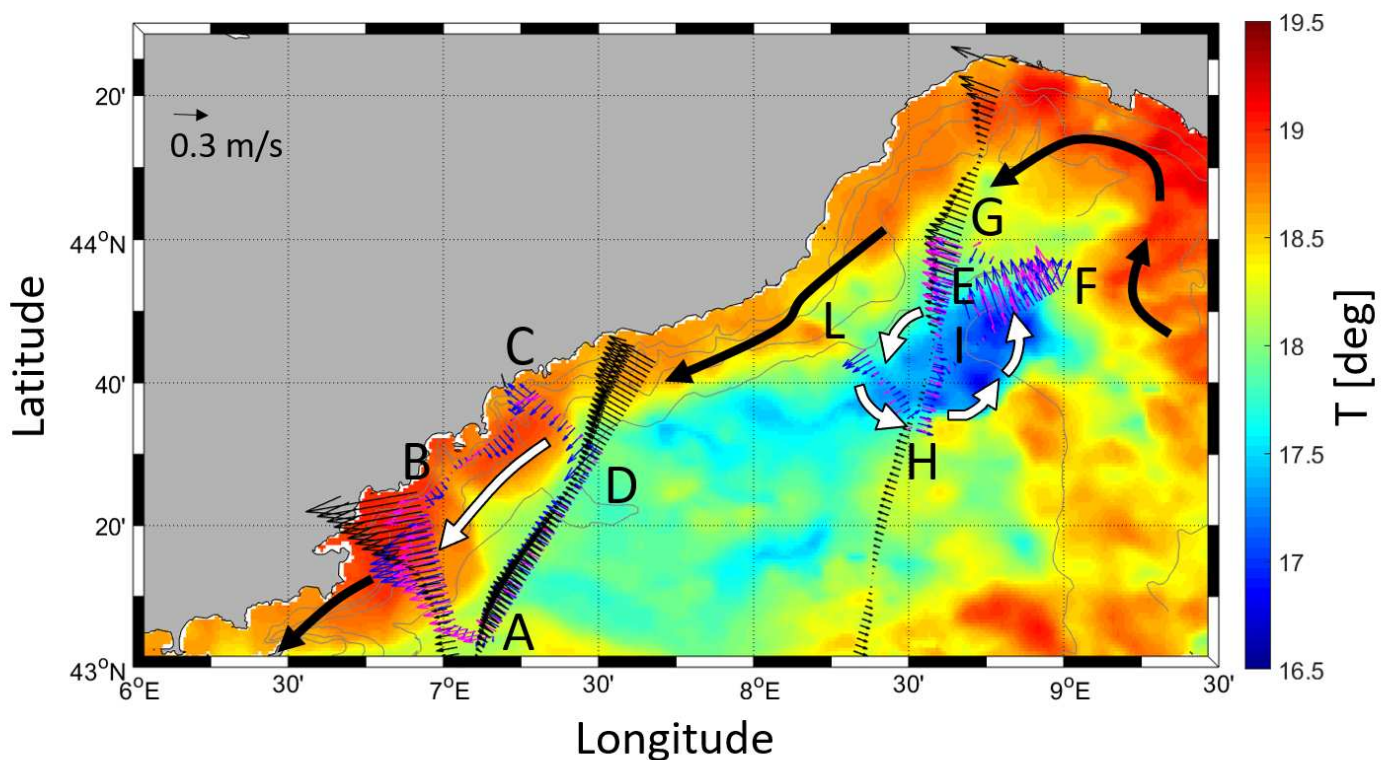
568 In Figure 9, looking at transect A – B, the NC main path, with high current velocity  
569 ( $> 0.3 \text{ ms}^{-1}$ ) is intercepted by altimetry around Latitude  $43.25^\circ$  and  $6.8^\circ$  Longitude.  
570 The associated surface frontal structure is also clearly captured by ADCP and MVP-  
571 derived current as well as from remote-sensing SST image. There, the vertical  
572 structure is characterised by the temperature profile of MVP, with higher temperature  
573  $> 18 \text{ }^\circ\text{C}$  (Figure 10) caused by the NC main flow and depicted up to its maximum  
574 depth (80 m).

575 More East and offshore, an eddy-like structure is instead depicted at the surface by  
576 altimetry, ADCP and MVP-derived currents along the transect G – I. Along the same  
577 transect, satellite SST also shows a zone of low temperature with values below 17 °C.  
578 This zone is surrounded by warmer boundary waters characterised by SST higher  
579 than 17 °C, suggesting ascendant vertical pumping of cold water in the central part of  
580 this small-scale dynamical feature.

581 Both *in situ* and satellite-derived surface current directions indicate that this  
582 mesoscale feature is linked to a cyclonic recirculation of the NC in the Ligurian sub-  
583 basin. Marrec et al. (2018) reported on this event, also attributing the important role  
584 of Ekman pumping, induced by a strong wind event just before the OSCAHR cruise,  
585 which has an impact on ocean biogeochemistry. Besides the strong wind event  
586 occurring during the first day of the cruise, the region has experienced several wind  
587 events two weeks before the cruise (Marrec et al., 2018), inducing a strong decline in  
588 SST. The low temperature patch described by satellite SST and MVP profile supports  
589 the Ekman pumping hypothesis. This process was also important in fertilizing the  
590 upper layer with nutrient-rich upwelled waters.

591 Figure 10 depicts the salinity and temperature vertical sections of MVP transects A –  
592 B, G – I, H – G and D – A. In transect G – I, the sea surface salinity (SSS) was lower  
593 (< 38.20) in the cold core than in the warm boundaries (> 38.20) and salinity at 300 m  
594 in depth was higher than 38.50. A subsurface layer of low-salinity waters (< 38.10) is  
595 present with a 40 to 80 m thickness. This subsurface layer was observed up to the  
596 surface in the centre of the cold core (between Latitude 43.7° and Latitude 43.8°),  
597 whereas in warm boundaries, saltier (> 35.20) surface waters overlaid it. Low-salinity  
598 waters (< 38.10) at the surface of the cold patch support the vertical Ekman pumping  
599 hypothesis, as suggested from multi-sensor surface observations reported in Figure 9.

600 Transect H – G presents a lower salinity band (< 38.10) between 40 m to 80 m but  
 601 without reaching the surface, as for transect G – I. Higher values of depth salinity are  
 602 confirmed also for this transect. On transect A – B, where the signature of the NC is  
 603 clearly visible from the temperature profile (Figure 10) and altimetric-derived current  
 604 (Figure 9), the salinity values present lower values between 40 and 50 m depth in the  
 605 Latitude range between 43.1° and 43.2° to reach a thickness of 100 m (i.e. from 50 m  
 606 to 150 m) from Latitude 43.3° and Latitude 43.5°. The same features are observed in  
 607 transect D – A, but the lower values of salinity reach a depth of 100 m.

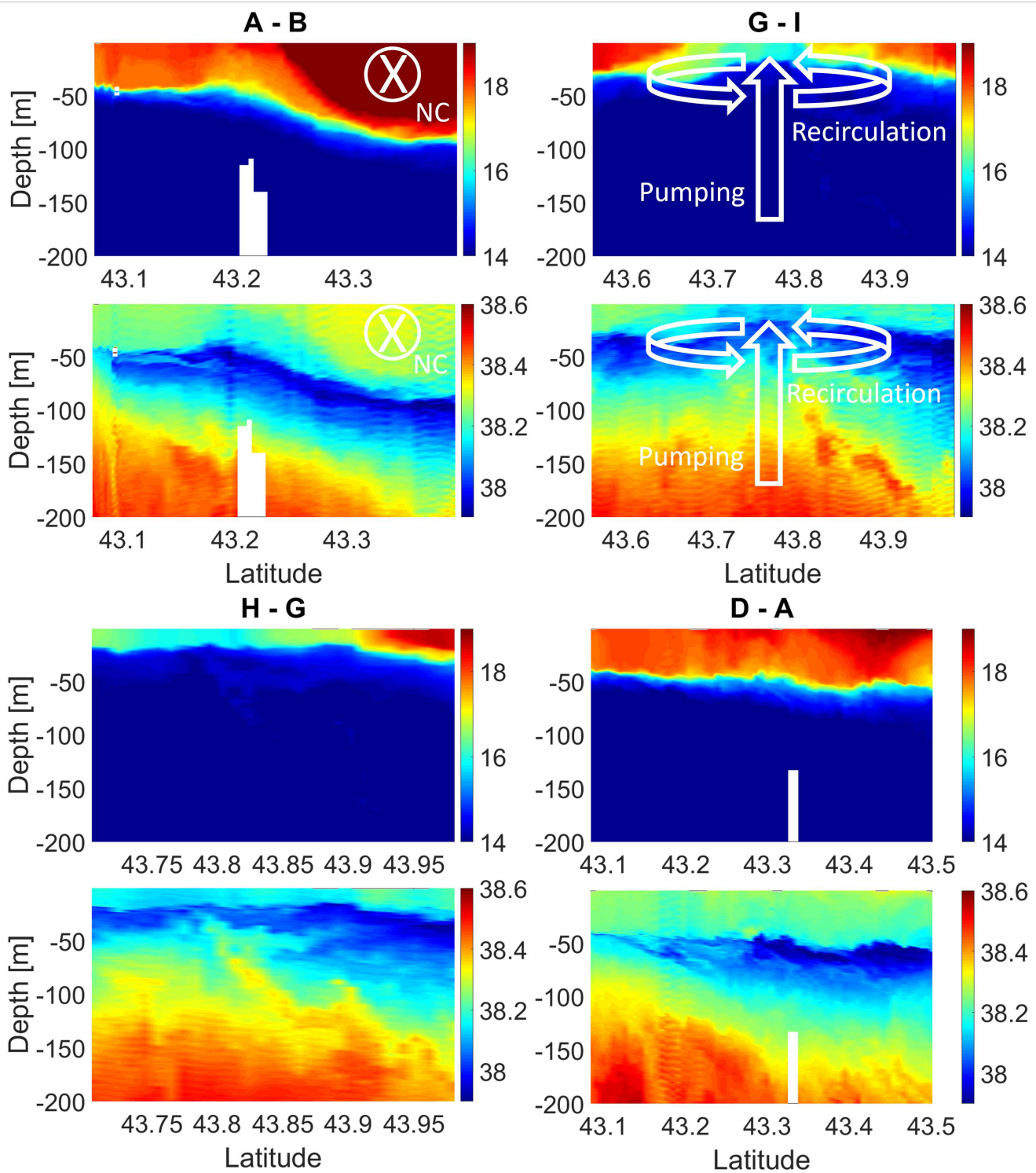


608

609 **Figure 9** Surface circulation pattern derived from *in situ* (magenta for MVP and blue for ADCP) and  
 610 PEACHI altimetry data (black). SST data is also shown with a Spatial Resolution of 0.062° (Latitude) x  
 611 0.062° (Longitude) and temporal resolution of 1 day. The SST maps is an average over the OSCAHR cruise  
 612 time period October 29, 2015 to November 06, 2015). White arrows depict the surface oceanographic  
 613 features reported also in Figure 10 vertical profiles.

614

615



617 **Figure 10 MVP Salinity and temperature vertical profiles. The oceanographic features have been depicted**  
 618 **with white arrows.**

619

620 **5 Conclusions**

621 The monitoring of small-scale processes in the coastal domain using satellite-based  
622 observations represents a key challenge in oceanography. In this paper, we discussed  
623 the issue of validating and optimising coastal altimetry data in areas characterised by  
624 fine-scale dynamics.

625 It has been discussed that regional 1 Hz altimetric data from AVISO are not always  
626 reliable close to the coast, and new experimental post processed and edited high rate  
627 PEACHI altimetric data have been considered to better resolve regional fine-scale  
628 features. Comparison statistics show that experimental high-rate PEACHI products  
629 using the adaptive retracker provide better performances in coastal regions for both  
630 40 Hz SARAL and 20 Hz Jason-2 missions. Moreover, the use of the new RIO14  
631 MDT instead of the RIO07 one increases the correlation scores with respect to *in situ*  
632 measurements.

633 The use of MVP platform has been assessed, as it was never used for validating  
634 coastal altimetry, highlighting the main challenges, advantages and limitations with  
635 respect to gliders. Further, regarding the MVP dataset, the importance of the  
636 reference level and sinopticity issues were discussed, and a sensitivity study was  
637 performed to highlight the effect on the derived geostrophic currents. It has been  
638 shown that, as for glider, measurements from the MVP are very promising for  
639 validating coastal altimetry techniques but cannot be considered as a perfect reference  
640 dataset by themselves. In this respect, the combined use of collocated MVP, altimetry  
641 and ADCP appears to be relevant, not only for validation purpose but also to better  
642 characterise the surface and sub-surface regional dynamics of the study area,  
643 including the North Current flow and the induced cyclonic recirculation in the eastern  
644 side of the Ligurian Sea. New benchmarking will also be performed, where the most

645 recent developments in geophysical corrections and new retracking methods in  
646 coastal domains will be taken into consideration.

647 From a more general point of view, this study illustrated the complexity of setting up  
648 adequate *in situ* validation networks for coastal altimetry in areas dominated by  
649 geostrophic and ageostrophic fine-scale oceanographic processes. It confirmed the  
650 key importance of developing *ad-hoc* validation approaches using multiple types of  
651 collocated instruments, which allow diagnosing and understanding the physical  
652 content and mechanisms of the observed oceanic features. Recent (Sentinel-3) and  
653 future high-resolution topographic missions, such as Jason-CS, Sentinel-6 and  
654 SWOT, will continue to provide improved ocean parameters that can significantly  
655 help in understanding climate changes, coastal and (sub-)mesoscale dynamics. Their  
656 full exploitation and integration into re-analysis and forecasting system will however  
657 depend on our capability to continuously develop science-oriented diagnostics and  
658 uncertainty estimation. This objective can only be achieved through the deployment  
659 and maintenance of long-term, independent, fully characterised and traceable multi-  
660 sensor *in situ* observations (so-called “Fiducial Reference Measurements”, FRM),  
661 collocated along altimetry tracks.

662

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1012

1013 **List of Figure Captions**

1014 Figure 11 OSCAHR cruise transects (in letters) showing MVP vertical salinity  
1015 profiles (coloured rectangles), geo-located with altimetric tracks #9 from Jason-2 and  
1016 tracks #429 and #674 from SARAL. The main flow of the NC is shown with black  
1017 arrows, the recirculation with the grey arrow and the Ligurian Sea area is highlighted  
1018 by the red box.

1019 Figure 12 PEACHI high rate altimetry SLA editing and filtering for SARAL track  
1020 #429. The black line corresponds to the AVISO 1 Hz track.

1021 Figure 13 RIO07 (a) and RIO14 (b) MDT overlapped by the derived mean current.

1022 Figure 14 Reference depth sensitivity study for transects A – B, D – A, G – I and H –  
1023 G. Different colours are associated with a different reference depths (in meters)  
1024 considered in the vertical integration of MVP data, while PEACHI altimetry data are  
1025 shown in black. The magenta line represents the MVP derived currents at the  
1026 maximum operating depth. The shaded grey areas in transects A – B and D – A  
1027 correspond to 20 km from the coast.

1028

1029 Figure 5 Mean (blue) and standard deviation (yellow) of the current differences  
1030 between PEACHI and MVP.

1031 Figure 6 Geographical plot of the differences (coloured dots) of the surface across  
1032 track current ADCP-MVP. The vectors are related to the cross-track component of  
1033 the ADCP current at 270 m depth.

1034 Figure 7 Comparison between MVP (magenta) and ADCP currents (raw data in thin  
1035 blue, filtered and smoothed data in dashed thick blue) for each transect.

1036 Figure 15 PEACHI Altimetry (grey for SLA+RIO07 and red for adaptive retracking,  
1037 cyan for Red3 retracking and green for MLE4 retracking for SLA+RIO14) vs AVISO  
1038 altimetry (light grey for SLA+RIO07 and grey for SLA+RIO14) vs *in situ* (magenta  
1039 for MVP, blue for ADCP). Different markers for both AVISO and PEACHI altimetry  
1040 are related to elevations and currents computed with a different MDT (crosses for  
1041 RIO07 and diamonds for RIO14). First column reports track geolocation, second  
1042 column reports ADT (m) vs Latitude and third column reports satellite across track  
1043 current (ms-1) derived from ADT computed adding RIO14 to SLA vs Latitude  
1044 together with *in situ* derived current vs Latitude. The distance to the coast is also  
1045 reported in Kilometres.

1046

1047 Figure 16 Surface circulation pattern derived from *in situ* (magenta for MVP and blue  
1048 for ADCP) and PEACHI altimetry data (black). SST data is also shown with a Spatial  
1049 Resolution of 0.062° (Latitude) x 0.062° (Longitude) and temporal resolution of 1  
1050 day. The SST maps is an average over the OSCAHR cruise time period (29<sup>th</sup> October  
1051 2015 to 6<sup>th</sup> November 2015). White arrows depict the surface oceanographic features  
1052 reported also in Figure 10 vertical profiles.

1053

1054 Figure 17 MVP Salinity and temperature vertical profiles. The oceanographic  
1055 features are reported with white arrows.