

Wind-induced cross-strait sea level variability in the Strait of Gibraltar from coastal altimetry and in-situ measurements

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Abstract

Coastal altimetry products are available and are being extensively validated. Their accuracy has been assessed in many coastal zones around the world and they are ready for exploitation near the shore. This opens a variety of applications of the sea level data obtained from the specific reprocessing of radar altimeter signals in the coastal strip. In this work, we retracked altimeter waveforms of the European Space Agency satellites: ERS-2 RA and Envisat RA-2 from descending track (#0360) over the eastern side of the Strait of Gibraltar using the Adaptive Leading Edge Sub-waveform (ALES) retracker. We estimated along-track Sea Level Anomaly (AT_SLA) profiles (RA-2) at high posting rate (18 Hz) using improved range and geophysical corrections. Tides were removed with a global model (DTU10) that displays a good performance in the study area: the mean root square sum (*RSS*) of the main constituents obtained with *DTU10* and 11 tide gauge stations was 4.3 cm in agreement with the *RSS* using a high-resolution local hydrodynamic model (*UCA2.5D*) (4.2 cm). We also estimated a local mean sea surface by reprocessing ERS-2/Envisat waveforms (track #0360) with ALES. The use of this local model gave more realistic AT_SLA than the values obtained with the global model DTU15MSS. Finally, the along-track Absolute Dynamic Topography (AT_ADT) was estimated using a local Mean Dynamic Topography obtained with the local hydrodynamic model UCA2.5D. We analysed the cross-strait variability of the sea level difference between the African / Spanish coasts along the selected track segment. This was compared to the sea level cross-strait difference from the records of two tide gauges located in the African (Ceuta) and Spanish (Tarifa) coasts. The sea level differences from altimetry and tide gauges were linked to the zonal component of the wind. We found a positive and significant (>95% c.l.) correlation between easterlies / westerlies and positive / negative cross-strait sea level differences between the southern and northern coasts of the Strait in both datasets (altimetry: $r = 0.54$ and in-situ: $r = 0.82$).

Keywords: Strait of Gibraltar, cross-strait sea level, satellite altimetry, tide gauge, wind-induced.

2 **1. Introduction**

3 Sea level is one of the Essential Climate Variables (ECV) listed in the Global
4 Climate Observing System inventory (GCOS, 2016). The European Space Agency
5 (ESA) launched in 2010 the Climate Change Initiative (CCI), aiming at providing the
6 most accurate and homogeneous time series of some ECVs for climate studies,
7 including altimeter-derived sea level records, such as gridded monthly maps of Sea
8 Level Anomaly (SLA) (Quartly et al., 2017; Legeais et al., 2018) ([http://www.esa-](http://www.esa-sealevel-cci.org/)
9 [sealevel-cci.org/](http://www.esa-sealevel-cci.org/)). Despite all the benefits of using gridded altimetry products in many
10 applications (e.g., scientific, social, commercial), their use is more problematic in
11 coastal zones due to poor spatio-temporal resolution of the products and processing
12 difficulties (Vignudelli et al., 2011). These difficulties have been mitigated thanks to the
13 efforts made in the last decade by the coastal altimetry community
14 (<http://www.coastalt.eu/community>). Basically, the success is based on the generation
15 of accurate along-track altimetry products near the shore (see Vignudelli et al. (2011);
16 Cipollini et al. (2017); and references therein).

17
18 In recent years, many works are found in the literature focused on the generation
19 and validation of improved along-track ‘coastal’ datasets from past to present altimetry
20 missions. All of them are based on the analysis of improved geophysical corrections to
21 the altimeter *Range* (Brown, 2010; Carrère and Lyard, 2003; Handoko et al., 2017;
22 among others), and/or more dedicated retracking processing which take into account the
23 shape of the radar waveforms near the coast (basically, due to land or calm water
24 contamination) (Gommenginger et al., 2011; Passaro et al. 2014; Peng and Deng, 2018;
25 Röscher et al., 2017). A summary table with all the datasets available to date for coastal
26 altimetry can be found in Cipollini et al. (2017). There is no operational coastal

27 altimetry product available yet, however, the experimental data sets that are already
28 validated can now support the investigation of specific ocean processes occurring in
29 regions close to land. The available experimental datasets offering retracked Ranges are
30 the Adaptive Leading Edge Sub-waveform ALES (from the Physical Oceanography
31 Distributed Active Archive Center-PODAAC and from the Open Altimeter Database-
32 OpenADB (https://openadb.dgfi.tum.de/en/data_access/; Passaro et al., 2014) and
33 Prototype Innovant de Systèm de Traitement pour les Applications Côtieres et
34 l'Hydrologie-PISTACH (CNES) ([https://www.aviso.altimetry.fr/en/data/products/sea-](https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/coastal-and-hydrological-products.html)
35 [surface-height-products/global/coastal-and-hydrological-products.html](https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/coastal-and-hydrological-products.html)); Mercier et al.,
36 2010). In a recent work, Xi-Yu et al. (2018) used a parameter available in the Jason-2
37 Geophysical Data Record and considered a coastal band of up to 70 km in their analysis
38 offshore Hong Kong. Notably, the work was an independent study that compared ALES
39 data against data from the PISTACH coastal retracker and rated the first as the one
40 giving the best results, while pointing out that a careful outlier analysis was needed.

41

42 Despite all these efforts, little is still done in the use of along-track high-
43 resolution products (from 18 Hz to 80 Hz, corresponding to along-track distance
44 between two consecutive measurements from ~350 m to ~85 m) for oceanographic
45 applications in the coastal strip. Exploitation of such products is crucial for many
46 applications (infrastructure designs, coastal zone protection, and improvements in ship
47 route security, among others) and to characterise the different processes (coastal sea
48 level change, storm surges, coastal currents and fronts, etc.) observed in the coast.
49 Improved reprocessing of along-track coastal altimetry data is important for coastal
50 observing systems (monitoring) and to re-analyse previous datasets. Recently, Dong et
51 al. (2018) identified tidal mixing fronts using Jason-2 20-Hz along-track SLA data over

52 Georges Bank (Northwestern Atlantic Ocean). Han et al. (2012) analysed 20-Hz and 1-
53 Hz Jason-2 data to study Hurricane Igor storm surge off Newfoundland (Canada). At
54 seasonal time scales, Passaro et al. (2015) determined the annual cycle of the sea level
55 in the Baltic Sea/North Sea transition zone and Passaro et al. (2016) observed the
56 seasonalities and trends of internal seas in the Indonesian Archipelago, using the ALES
57 18-Hz data set from Envisat RA-2. Here we propose to exploit the information in along-
58 track altimetry in our study area, the Strait of Gibraltar. The product could be used to
59 better understand and monitor the local oceanographic processes taking place in such a
60 complex environment and to estimate transports, and therefore water exchange,
61 contributing to 1) closing the water balance over the Mediterranean basin; 2) monitoring
62 changes in the Mediterranean outflow under climate change conditions; and 3)
63 monitoring the wind-induced changes in the sea level of the Mediterranean and Black
64 seas.

65

66 The questions addressed here are of large scientific and societal impact. The
67 Mediterranean Water outflowing the Strait of Gibraltar contributes to maintain the high
68 salinity of the Norwegian Sea (e.g. Reid, 1979), a key area for deep water formation in
69 the North Atlantic and, on the other side, the net flow through the Strait of Gibraltar
70 must close the water budget over the Mediterranean basin (Candela, 2001). This is why
71 monitoring exchange flows through the Strait of Gibraltar has been proposed as a key
72 action for climate studies of the Mediterranean and the Global Circulation (Candela,
73 2001). The sea level in the Strait of Gibraltar will react to changes in the flow.
74 Therefore, monitoring the sea level signal will provide us information on exchange
75 flows through the Strait of Gibraltar (Hughes et al., 2015). At the same time, local wind
76 forcing in the Strait of Gibraltar has a far reaching impact in terms of spatial and time

77 scales. Garcia Lafuente et al. (2002) estimated that the wind forcing contribution to
78 exchange flows through the Strait of Gibraltar is of 0.3 Sv, and Fukumori et al. (2007)
79 suggested that altimetry observed basin-wide sea-level interannual variability in the
80 Mediterranean Sea was linked to winds in the Strait of Gibraltar area. The driving
81 mechanism, according to Menemenlis et al. (2007), is the Atlantic Ocean to
82 Mediterranean Sea sea-level difference reaction to the along-strait wind set up. Calafat
83 et al. (2012) showed that the observed tide gauge decadal variability in the
84 Mediterranean Sea is mostly driven by mass exchange through the Strait of Gibraltar,
85 which is also affected by local winds. The hypothesis that local wind in the Strait of
86 Gibraltar area drives basin-wide sea-level changes in the Mediterranean Sea is further
87 supported by sea-level altimetry and ocean mass GRACE data analysis (Landerer and
88 Volkov, 2013). More recently Volkov and Landerer (2015) and Volkov et al. (2016)
89 highlighted that local winds in the Strait of Gibraltar also affect the Black Sea sea level
90 variability.

91

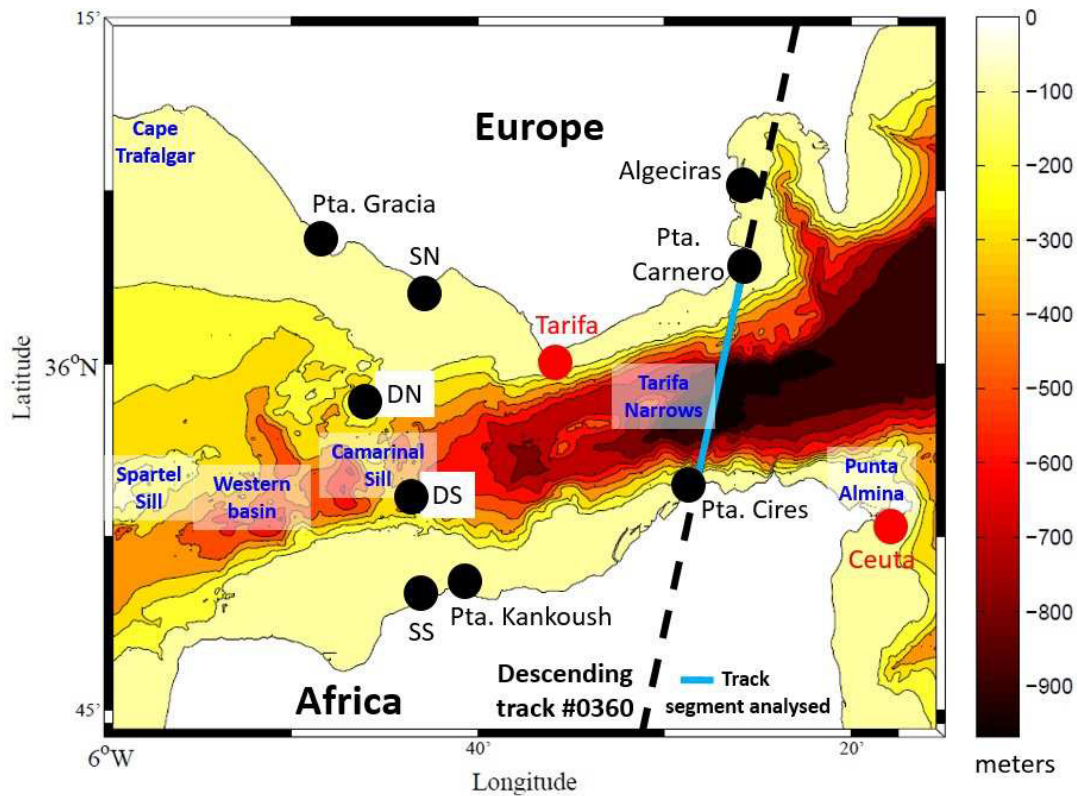
92 The main contribution of this work is twofold: (1) analysis of the oceanographic
93 content of coastal altimetry products at high-spatial resolution along track (~350 m
94 between two consecutive 18-Hz sea level measurements) in the Strait of Gibraltar; and
95 (2) exploitation of these products for a better understanding of the oceanographic
96 processes in the study area. To do this, we estimated along-track Absolute Dynamic
97 Topography (ADT) profiles obtained from the European Space Agency (ESA) Envisat
98 RA-2 descending track #0360 (Figure 1) using the coastal-dedicated ALES retracker
99 and accurate range and geophysical corrections. We analysed their spatio-temporal
100 variability by estimating the sea level difference between the southern and northern
101 sectors of the track segment and its relationship with the wind regime. The present

102 paper is a step forward in the use of accurate altimeter products to extract relevant
 103 information of oceanographic processes close to coastal zones, such as the Strait of
 104 Gibraltar.

105

106 The paper is organised with Section 2 describing the study area (Strait of
 107 Gibraltar). Section 3 gives details of the datasets and method used to estimate the
 108 Absolute Dynamic Topography. The results are presented in Section 4 and discussed in
 109 Section 5. The paper ends with the concluding remarks in Section 6.

110



111

112 Figure 1. Study area: The Strait of Gibraltar between Europe and Africa. Colour scale indicates
 113 the bathymetry (in meters). Also shown the location of ERS-2 / Envisat descending track #0360
 114 (the track segment analysed is highlighted in blue), the main topographic features mentioned in
 115 the text, and the location of the tide gauge and bottom pressure measurement sites used for
 116 validation of the tidal constituents. Red circles indicate the tide gauges used in the analysis of
 117 the cross-strait variability.

118 **2. Study area: The Strait of Gibraltar**

119 The Strait of Gibraltar is the choke point connecting the Atlantic Ocean and the
120 Mediterranean Sea. Its bathymetry is shallower in the western part featuring the Spartel
121 sill (depth 300 m) and the Camarinal sill (depth 280 m) separated by the Western basin.
122 The Strait then deepens to 1100 m to the East in the Tarifa Narrows (Figure 1).

123

124 Due to the presence of less-salty, warmer Atlantic waters in the upper water
125 masses, and saltier, cooler Mediterranean waters underneath, there is a strong density-
126 stratification in the water column within the Strait. This leads to an inverse estuarine
127 circulation with a two-layer exchange with a net resulting eastward flow needed to close
128 the Mediterranean Sea water and salt balance. Lacombe and Richez (1982)
129 characterised the hydrodynamic regime of the Strait distinguishing three main scales of
130 variability:

131

132 (i) long period: related to seasonal, interannual, and longer period fluctuations
133 (e.g. Garrett et al., 1990; Candela et al., 1989; Brandt et al., 2004);

134 (ii) subinertial: ranging from few days to few months, it is related to the
135 exchange flows modulation caused by meteorological forcing (Candela et al., 1989).
136 Winds are the most important meteorological forcing. Their regime is zonal with
137 alternating easterlies-westerlies, reaching mean speeds up to 20 m s^{-1} . The alternated
138 winds affect the along and cross-strait dynamics (Stanichny et al., 2005);

139 (iii) tidal, which represents the most energetic process in the Strait shows a
140 predominant semidiurnal character but with a significant diurnal contribution. Tidal
141 current velocities are strong enough to periodically reverse the flow in both layers near
142 Camarinal Sill (Candela et al., 1990).

143

144 **3. Datasets and methods**

145 In this work we used accurate coastal altimetry products from the European
146 Space Agency Satellites ERS-2 RA and Envisat RA-2 (subsection 3.1) combined with a
147 global tidal model, a local hydrodynamic model and mean sea surface models presented
148 in subsections 3.2 and 3.3, respectively. The experimental data (tide gauge, bathymetry
149 and wind velocity) are described in subsection 3.4. Finally, the methodology used to
150 estimate the along-track Absolute Dynamic Topography is explained in subsection 3.5.

151

152 **3.1 ERS-2 RA and Envisat RA-2**

153 Along-track sea surface heights and sea level anomalies (*AT_SLA*, henceforth) 18
154 Hz were retrieved from the track #0360 of ERS-2 RA (cycle 1 to cycle 85, from May
155 1995 to June 2003) and Envisat RA-2 Phase E2 (cycle 6 to cycle 93, from May 2002 to
156 September 2010) during the 35-day repetitive orbit of the missions. ERS-2 / Envisat
157 RA-2 track crossed the eastern side of the Strait at 11:15 / 10:46 UTC times,
158 respectively (Figure 1). Along-track measurements for each cycle were linearly
159 interpolated to the 18-Hz nominal locations. We followed the methods explained in
160 Gómez-Enri et al. (2016) to obtain *AT_SLA* (Envisat RA-2) using different sources of
161 information and fields:

162

- 163 • Sensor Geophysical Data Records (SGDR) official product: *orbit, ionospheric,*
164 *dry / wet tropospheric, solid earth tide and pole tide* corrections (ESA, 2007).
- 165 • Adaptive Leading Edge Subwaveform (ALES) retracker: *range, sigma0* and
166 *significant wave height (SWH)* (Passaro et al., 2014).

167 • Danmarks Tekniske Universitet (DTU): *mean sea surface (DTU15MSS,*
168 *Andersen et al., 2016)* and *tidal model (DTU10, Cheng and Andersen, 2011).*

169

170 Some of the corrections available in the SGDR were at a 1-Hz along-track
171 spatial resolution, so they had to be linearly interpolated to 18 Hz prior to application to
172 the high-rate data. *sigma0* and *SWH* from ALES were used to re-compute the *Sea State*
173 *Bias (SSB)* correction. Gómez-Enri et al. (2016) validated time series of *AT_SLA* for the
174 same track segment within the Strait using the same products (with the exception of the
175 mean sea surface as they used an older version) against *in-situ* tide gauge data. They
176 found about a 20% of improvement with respect to the *AT_SLA* computed with the
177 *range* and *SSB* available in the SGDR official product. This was a promising result in
178 terms of accuracy of altimetry data in the study area.

179

180 *AT_SLA* profiles (18 Hz) were estimated following Eq. (1):

181

$$182 \quad AT_SLA = Orbit - Range - Range\ Corrections - Geophysical\ Corrections - MSS$$

183 (1)

184

185 where *Orbit*, is the distance between the satellite's orbit and the WGS84
186 reference ellipsoid. *Range*, is the retracked range from ALES. *Range Corrections* are:
187 *ionospheric, dry / wet tropospheric, SSB*. The set of *Geophysical Corrections* are: *solid*
188 *earth, geocentric pole* and *total geocentric ocean tides*.

189

190

191

192 **3.2 Global tidal model and local hydrodynamic model**

193 As mentioned, coastal altimetry products with a good level of accuracy and high
194 spatial resolution along track (~350 m) are becoming available thanks to a number of
195 free datasets (see Introduction section). Efforts are now needed in order to extract,
196 assess and exploit the oceanographic content of the coastal altimetry products,
197 especially in challenging zones such as the Strait of Gibraltar. The use of global tidal
198 models in coastal zones to de-tide the satellite-derived sea level oscillations might be
199 one of the main sources of noise in the sea level estimates and as such should be
200 verified with care. In this paper, we assessed the constituents of a global tidal model:
201 *DTU10* (Cheng and Andersen, 2011) and the ones obtained from a local hydrodynamic
202 model: *UCA2.5D* (Izquierdo et al., 2001), using in-situ measurements.

203

204 *3.2.1 Global tidal model DTU10*

205 The model *DTU10* is an updated version of *FES2004* (Lyard and Lefèvre, 2006)
206 ocean tide. Its resolution is $0.125^\circ \times 0.125^\circ$ worldwide. The tidal elevations (as the sum
207 of two terms: *Ocean Tide* and *Loading Tide*) were extracted from the Danmarks
208 Tekniske Universitet ftp server: (<ftp://ftp.space.dtu.dk/pub/DTU10/>). *DTU10* was
209 interpolated to the along-track positions of the track segment analysed.

210

211 *3.2.2 Local hydrodynamic model: UCA2.5D*

212 The two-dimensional (depth-averaged), two-layer, finite-difference,
213 hydrodynamic model *UCA2.5D* (Izquierdo et al., 2001; Brandt et al., 2004) was
214 developed specifically to reproduce the two-layer dynamics in the highly density-
215 stratified environment of the Strait of Gibraltar. The model outputs are the depth-
216 averaged horizontal currents in the upper and lower layers, as well as their respective

217 top-limit heights (i.e., free-surface and interface depth). The curvilinear model grid
218 extends from the easternmost area of the Gulf of Cadiz to the western half of the
219 Alboran Sea, with a variable horizontal spatial resolution ranging from ~1 km in the
220 eastern and western boundaries of the domain to ~125 m within the Strait of Gibraltar.
221 The model currently runs in pre-operational mode and is forced at the open boundaries
222 by the main semidiurnal (M_2 , S_2) and diurnal (K_1 , O_1) tidal constituents, as well as by
223 surface wind and Mean Sea Level Pressure (MSLP) fields (Izquierdo et al., 2016)
224 provided by the meteorological model MM5 (www2.mmm.ucar.edu). *UCA2.5D* has
225 been extensively applied and validated in the Strait of Gibraltar, showing in general a
226 good agreement with the observed hydrodynamics, including the mean interface depth
227 and its tidal oscillations (Sein et al., 1998; Izquierdo et al., 2001; Brandt et al., 2004;
228 Izquierdo et al., 2016).

229

230 **3.3 Mean Sea Surface models**

231 A mean sea surface (MSS) profile is subtracted to the along-track corrected sea
232 surface height in order to get the anomalies (SLA). We used two sources of along-track
233 MSS: (i) Global Mean Sea Surface: *DTU15MSS*; and (ii) Along-track Local Mean Sea
234 Surface: *AT_Local_MSS*.

235

236 *3.3.1 Global Mean Sea Surface: DTU15MSS*

237 This mean sea surface model is an updated version of the previous *DTU10MSS*
238 (Andersen and Knudsen, 2009; Andersen, 2010). The new version includes, globally, 4
239 years of CryoSat-2 data from its three modes of operation: Low Rate Mode (LRM),
240 Synthetic Aperture Radar (SAR) and SAR-Interferometric (SAR-Int). Data were
241 extracted from the Danmarks Tekniske Universitet ftp server:

242 ftp://ftp.space.dtu.dk/pub/DTU15/1_MIN/ at 1-minute resolution grid. *DTU15MSS* was
243 interpolated to the along-track positions of the track segment analysed.

244

245 *3.3.2 Along-track Local Mean Sea Surface: AT_Local_MSS*

246 An along-track Mean Sea Surface (*AT_Local_MSS*) based on ALES data was
247 computed by interpolating the along-track Sea Surface Height (SSH) onto nominal
248 tracks following the procedure explained in Passaro et al. (2014). We used the
249 descending orbit #0360 combining all the overpasses from both the ERS-2 and Envisat
250 missions with the same set of corrections. This approach brings several beneficial
251 effects:

252

- 253 - Using two missions allows the computation of the anomalies in the study
254 area, where the variability is higher, with a local mean sea level measured at
255 the same track locations over a longer time span than from the Envisat
256 mission alone;
- 257 - Using the same algorithm (ALES) and the same corrections as noted by
258 Andersen and Scharroo (2011), the use of a MSS computed using altimetry
259 data that are retracked with different algorithms and could therefore suffer
260 from biases w.r.t. ALES data even in the open ocean prevents biases or
261 differences that might otherwise show up as dynamic topography.

262

263 **3.4 Experimental data sets**

264 *3.4.1 Tide gauge and bottom pressure data*

265 The validation of the constituents of the global tidal model (*DTU10*) and of the
266 local hydrodynamic model (*UCA2.5D*) was made using information available in the

267 literature (García-Lafuente, 1986; Candela et al., 1990). We used the amplitude and
268 phase of the main tidal constituents obtained from 11 *in-situ* instruments (tide gauges
269 and bottom pressure sensors): Tarifa, SN, DN, DS, SS, Pta. Gracia, Pta. Kankoush, Pta.
270 Carnero, Pta. Cires, Algeciras, and Ceuta (Figure 1).

271

272 The cross-strait sea level variability in the study area was also analysed using the
273 measurements from two pressure tide gauges deployed at Ceuta and Tarifa by Puertos
274 del Estado (<http://www.puertos.es>) (Figure 1). The recorded 5-minute resolution time
275 series of water column height from 2002 to 2010 were smoothed and decimated to
276 standard hourly values (Godin, 1972), and the resulting hourly series were subjected to
277 harmonic analysis (Foreman and Henry, 1989), in order to obtain the amplitude and
278 phase harmonic constants for the resolvable tidal constituents, as well as the mean sea
279 level relative to the instrument. The difference between the original time series and the
280 corresponding tidal prediction computed from the obtained tidal harmonics, usually
281 known as ‘residual height’, is assumed to be free of any tidal contribution, and the
282 resulting residual series from the two locations were used to obtain the sea level
283 differences between them, in order to analyse their relationship with the wind
284 conditions.

285

286 *3.4.2 Bathymetry*

287 Bathymetry has a high spatial resolution of 50 m, provided by the Spanish Navy
288 Hydrographic Institute. It is available by request to the EMODNET Project web page:
289 <http://www.emodnet-bathymetry.eu>.

290

291

292 3.4.3 Wind velocity

293 The zonal component of the wind velocity (u) used in the study was extracted
294 from the hourly time series of 10-m height wind speed and direction from October 2002
295 to October 2010, recorded by the weather station deployed by the Spanish
296 Meteorological Agency (AEMET) at Tarifa (Figure 1).

297

298 **3.5 Absolute Dynamic Topography (ADT)**

299 The sea level above geoid is commonly known as Absolute Dynamic
300 Topography and can be obtained from the sum of two terms: along-track Sea Level
301 Anomaly (AT_SLA) and along-track Mean Dynamic Topography (AT_MDT):

302

$$303 \quad AT_ADT = AT_SLA + AT_MDT \quad (2)$$

304

305 AT_SLA was obtained using the corrections presented in subsection 3.1 (Eq. 1).

306 AT_MDT was obtained from two sources of Mean Dynamic Topography: *Global /*
307 *Local MDT*.

308

309 3.5.1 Global MDT

310 We used the most updated version available of the DTU Mean Dynamic
311 Topography. $DTU15MDT$ (Knudsen et al., 2016) were extracted from the ftp server:
312 ftp://ftp.space.dtu.dk/pub/DTU15/1_MIN/ at 1-minute resolution grid. In this model the
313 newer version of the gravity field (EIGEN-6C4) has been combined with $DTU15MSS$ to
314 obtain the global Mean Dynamic Topography.

315

316

317 3.5.2 Local MDT

318 The local MDT was obtained as the time mean of 1-year long sea surface height
319 hourly output from the local hydrodynamic model: *UCA2.5D* (Izquierdo et al., 2001).
320 Brandt et al. (2004) validated this numerical model in the study area in terms of current
321 velocity (current-meter moorings and the inverse tidal model of Baschek et al. 2001),
322 and sea surface elevation (bottom pressure tide gauges). In general, the authors found a
323 good level of agreement between the numerical model, the observations and the inverse
324 tidal model of Baschek et al. (2001).

325

326 4. Results

327 4.1 Assessment of the models used for altimeter corrections

328 4.1.1 *DTU10* vs. local hydrodynamic model

329 The performance of the global / local models in the Strait is analysed in detail.
330 The global tidal model *DTU10* was already assessed in a previous work (Gómez-Enri et
331 al., 2016). The authors compared the main constituents derived from a tide gauge
332 located at Tarifa harbour with the constituents provided by *DTU10* (at the tide gauge
333 location) estimating a root square sum (*RSS*) of 4.6 cm, following Oreiro et al. (2014).
334 We extended this analysis by assessing the constituents of the models (*DTU10* and
335 *UCA2.5D*) estimating the *RMS* of the differences and the *RSS* of the main constituents:
336 M_2 and S_2 (semidiurnals), K_1 and O_1 (diurnals) using information from a few tide
337 gauges and bottom pressure instruments located within the Strait of Gibraltar (Figure 1).
338 The results are summarized in Table 1. Overall, both models show similar results, in
339 terms of *Total_RSS* (4.3 / 4.2 cm for *DTU10* / *UCA2.5D*, respectively); we observe the
340 lowest *RSS* (below 2.0 cm) in a few stations: DN and Algeciras (*DTU10*), SS and Ceuta
341 (*UCA2.5D*). In the case of *DTU10* this might be due to the fact that these stations are

342 likely assimilated in the model. The comparison with the closest stations to the satellite
343 track (Pta. Carnero and Pta. Cires) gives similar *RSS* in Pta. Cires for both models and
344 slightly better results for *DTU10* in Pta. Carnero.

345

346 The analysis of the models in the study area indicates that *DTU10* (globally and
347 freely available) shows a similar level of accuracy as the local hydrodynamic model.
348 For this reason, we used the global model to de-tide the sea level signals to estimate the
349 *AT_SLA*.

350

351 *4.1.2 Spatial variability of AT_SLA*

352 Not all the overpasses of the satellite yield usable data – some cycles are missing
353 due to acquisition problems or other platform issues and in a few cases the data were
354 collected with a lower radar pulse bandwidth (20 MHz or 80 MHz instead of the usual
355 320 MHz over ocean), which makes them not accurate enough for oceanographic
356 investigation. The number of overpasses with valid 320-MHz data is 78. The removal of
357 outliers was made in two steps: (i) Only the *SLA* values between [-2.5 2.5] (m) were
358 retained; and (ii) All the absolute *SLA* values greater than 3 times the standard deviation
359 of the mean along-track profile were considered as outliers. Finally, a five-elements
360 running mean was applied to the valid *AT_SLA* to remove high frequency noise
361 (equivalent to 1.75 km).

362

363

364 Table. 1. *RMS* of the differences of the main constituents from the global model DTU10 and
 365 local hydrodynamic model UCA2.5D with some tide gauge and bottom pressure instruments in
 366 the study area. The *RSS* and *Total_RSS* are also shown.
 367

	<i>RMS differences (cm)</i>				<i>RSS (cm)</i>
	M_2	S_2	K_1	O_1	
Station/Tide Gauge	DTU10 / UCA2.5D				DTU10 / UCA2.5D
Tarifa	4.9 / 5.6	1.9 / 2.0	0.6 / 1.2	1.3 / 1.7	5.5 / 6.3
SN	4.9 / 5.6	2.1 / 1.9	0.4 / 1.0	0.6 / 1.1	5.4 / 6.1
DN	0.8 / 4.8	1.0 / 2.4	0.3 / 0.9	1.0 / 0.7	1.7 / 5.5
DS	4.0 / 2.4	0.2 / 0.9	0.9 / 1.0	0.9 / 1.2	4.2 / 3.0
SS	5.5 / 1.3	2.0 / 0.3	1.7 / 1.0	1.6 / 0.8	6.3 / 1.9
Pta. Gracia	3.6 / 6.3	2.2 / 2.2	1.1 / 1.5	0.7 / 1.5	4.4 / 7.0
Pta. Kankoush	7.0 / 3.4	1.5 / 1.3	0.8 / 1.7	1.2 / 1.8	7.3 / 4.5
Pta. Carnero	1.0 / 2.4	0.9 / 0.03	0.5 / 0.5	1.3 / 0.7	2.0 / 2.6
Pta. Cires	4.6 / 4.6	1.2 / 1.3	0.5 / 0.8	1.1 / 0.6	4.9 / 4.9
Algeciras	0.6 / 2.8	0.4 / 0.2	0.7 / 0.3	0.6 / 0.7	1.2 / 2.9
Ceuta	3.6 / 0.8	1.8 / 0.4	0.1 / 0.4	0.2 / 0.3	4.0 / 1.0
					<i>Total_RSS</i>
					4.3 / 4.2

368
 369 As shown from the results in Table 1 the accuracy of the global tidal model
 370 *DTU10* needs to be assessed with care in the Strait of Gibraltar. This model does not
 371 include tidal constituents of longer periods than semidiurnal and diurnals (Cheng and
 372 Andersen, 2011). Two of the most important constituents of longer periods in the Strait
 373 are: M_{sf} (lunisolar synodic fortnightly) and M_m (lunar monthly). The harmonic analysis
 374 made to de-tide the in-situ time series at Ceuta and Tarifa stations (Figure 1), included
 375 these and others constituents. We analysed their magnitude in the vicinity of the satellite

376 track segment. To do this, we obtained their amplitude and phase from the literature
 377 (Garcia-Lafuente et al., 1990) at the closest in-situ stations to the satellite pass: Pta.
 378 Carnero and Pta. Cires (Figure 1). The values are summarised in Table 2. The
 379 fortnightly constituent (M_{sf}) has a small and similar amplitude at both sides of the Strait
 380 showing a similar phase. The amplitude of the lunar monthly (M_m) is of the same order
 381 of magnitude at both stations, but they are in phase opposition. This comparison might
 382 indicate a small impact of not using longer period constituents to de-tide the sea level
 383 with the global model DTU10 in the Strait.

384

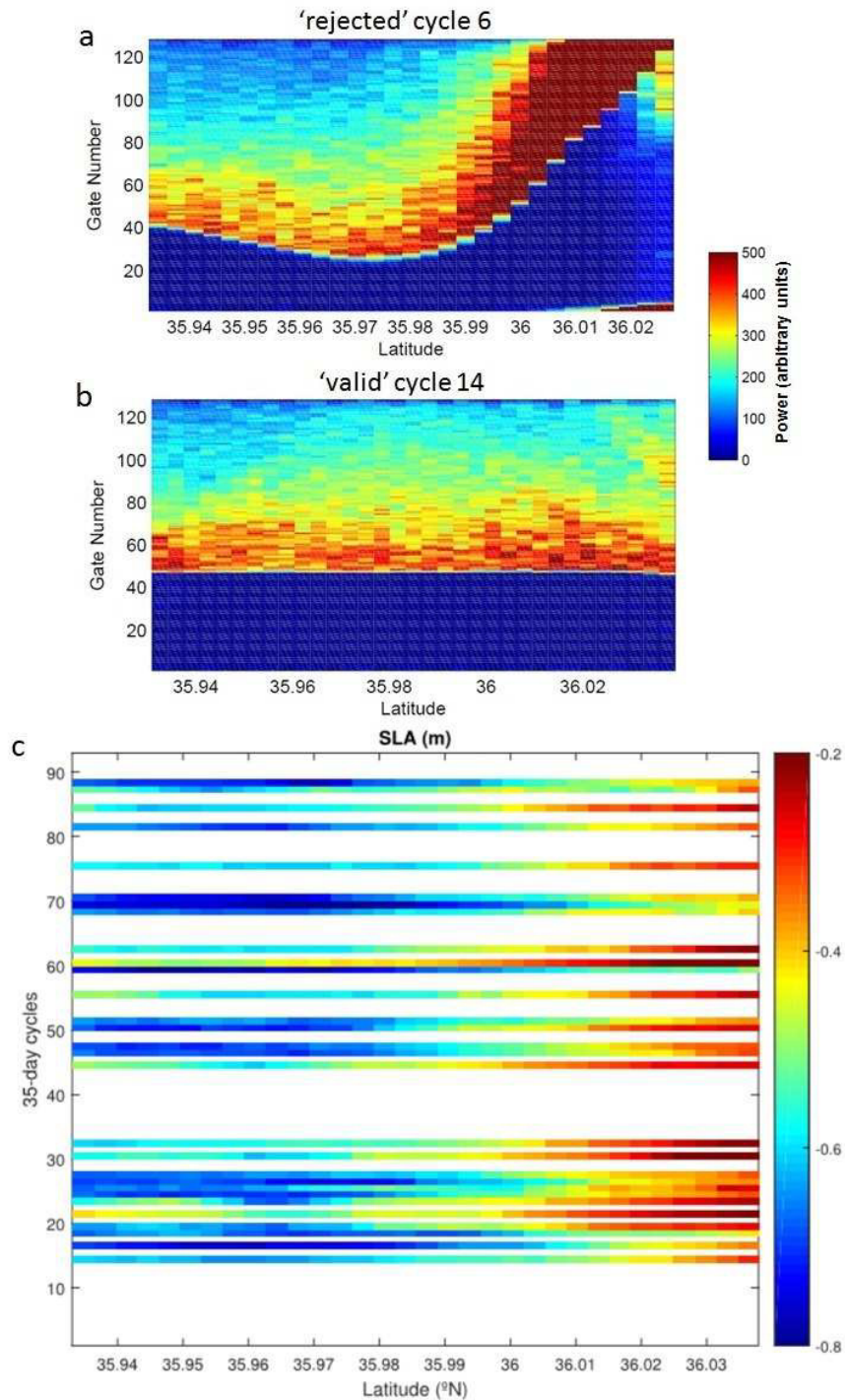
385 Table 2. Amplitude and phase of M_{sf} and M_m constituents for Pta. Carnero and Pta. Cires tide
 386 gauge stations
 387

	Pta. Carnero		Pta. Cires	
	<i>Amplitude (cm)</i>	<i>Phase (°)</i>	<i>Amplitude (cm)</i>	<i>Phase (°)</i>
M_{sf}	2.5	92	1.4	40
M_m	1.1	153	1.9	302

388

389 A visual inspection of the radargrams of the waveforms gave two main patterns
 390 in the leading edge area of the returned echoes: (i) ‘stable’ leading edge around the
 391 nominal tracking point; this was found in 30 out of 78 cycles; (ii) ‘non-stable’ undulated
 392 leading edge in the northern sector of the track segment; this was observed in 42 cycles.
 393 In 3 cycles we noted a strange behaviour in the leading edge and thermal noise areas.
 394 Finally, 3 cycles showed a short track segment. Thus, only 40% of cycles (30) were
 395 considered valid for further analysis. The radargrams of the waveform power of a
 396 rejected cycle (no. 6) and a valid cycle (no. 14) is presented in Fig. 2a and Fig. 2b,
 397 respectively. The undulated radargram is due to the known problems of the on-board
 398 tracker in keeping the signal within the analysis window in proximity of land
 399 (Gommenginger et al. 2011).

400



401

402 Figure 2. Radargram of the RA-2 radar waveform power for a rejected (Fig. 2.a) and a valid

403 (Fig. 2.b) cycle. The cycle-by-cycle *AT_SLA* for valid cycles is shown in Fig. 2.c.

404

405 The cycle-by-cycle *AT_SLA* profiles after the data screening and the removal of

406 invalid cycles due to unstable leading edges in the waveforms are shown in Fig. 2c. The

407 sea level oscillates in the range: [-0.8 -0.2] m with a marked difference between the

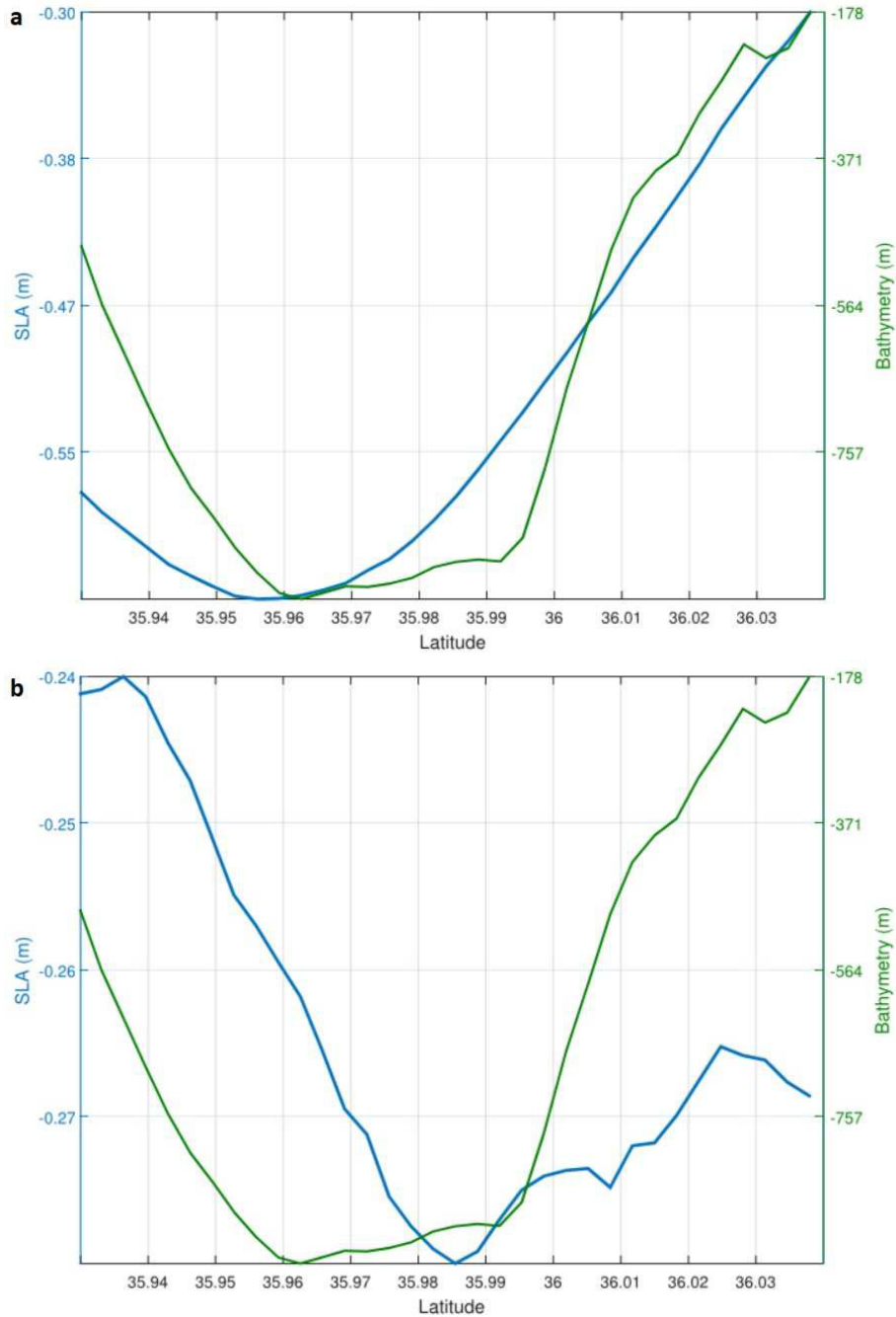
408 African (lower sea level) and the Spanish (higher sea level) coasts. This behaviour is not
409 in agreement with previous works made in the study area. Ross et al. (2000) indicated
410 higher sea level on the southern side of the Strait. They used data from two tide gauges
411 located in Ceuta (African coast) and Algeciras (Spanish coast) (Figure 1). The
412 magnitude of this difference seems to range between 20 cm and 10 cm between
413 maximal and submaximal exchange (Bormans and Garrett, 1989). A similar result was
414 also reported by Stanichny et al. (2005).

415

416 One of the reasons that could explain this disagreement might be in the use of a
417 global mean sea level (*DTU15MSS*) to estimate *AT_SLA*. The model, as the other global
418 MSS models in the literature, is derived by merging several years of data from repeated
419 tracks with nonrepeating data from geodetic missions using sophisticated interpolation
420 techniques. The accuracy of these models is known to be degraded close to the coast
421 (Andersen et al., 1999; Vignudelli et al., 2006), since the quality and the amount of the
422 altimeter data used in the models is notably lower in the last ~25 km from the coast
423 (Passaro et al. 2014; 2015), which means that the MSS values in the coastal zone are
424 generally extrapolated (Andersen et al., 1999). This might be particularly relevant in our
425 study area due to the lack of accurate along track high-resolution altimeter data in the
426 past (Gómez-Enri et al., 2016). We investigated this by comparing the *AT_SLA* profiles
427 obtained using the global (*DTU15MSS*) and the local (*AT_MSS*) mean sea levels. Figure
428 3 shows the average of *AT_SLA* over all valid cycles. Fig. 3a (*DTU15MSS*) gives a
429 lower sea level in the African coasts (5-elements running mean applied). The ERS2 /
430 Envisat derived mean sea surface gives an *AT_SLA* (Fig. 3b) with a marked positive
431 cross-strait sea level difference between the African and Spanish coasts, which is in
432 agreement with previous studies (Bormans and Garrett, 1989; Ross et al., 2000;

433 Stanichny et al., 2005). Thus, the ‘local’ mean sea level (*AT_MSS*) was selected in order
434 to estimate the along-track Absolute Dynamic Topography (*AT_ADT*).

435



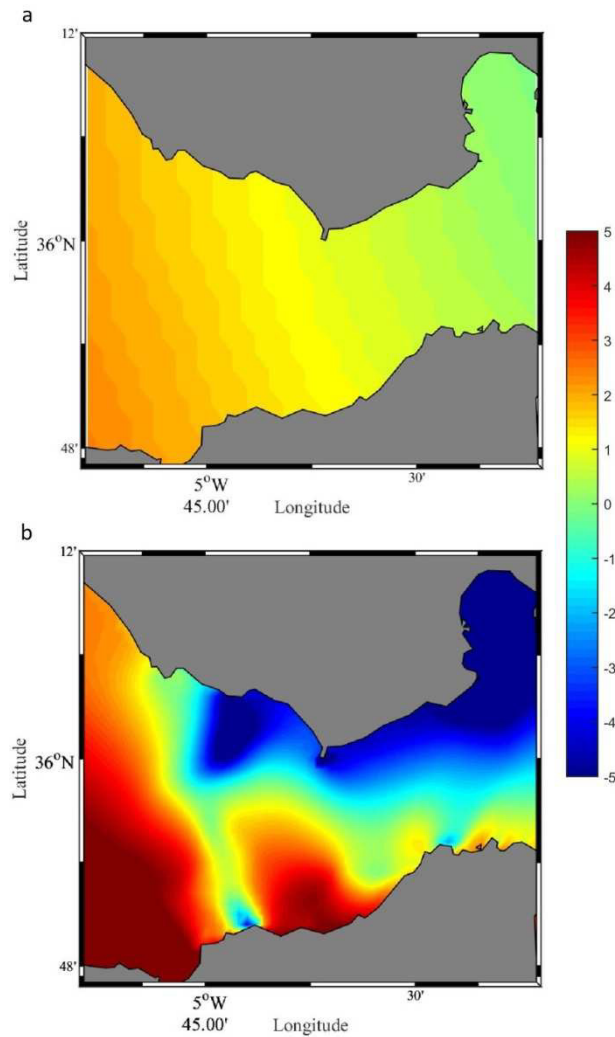
436
437 Figure 3. *AT_SLA* (5-elements running mean applied) for valid cycles using the global
438 *DT15MSS* (Fig. 3.a) and the local *AT_MSS* (Fig. 3.b). The green line gives the bathymetry
439 profile.

440

441 **4.2 Cross-strait variability in the Strait of Gibraltar**

442 *4.2.1 Along-track ADT*

443 As mentioned, we used two sources of *MDT* to compute the *AT_ADT* (Eq. 1).
444 Figure 4 shows the *MDT_DTU15* (Fig. 4a) and *MDT_Local* (Fig. 4b) obtained from the
445 local numerical model *UCA2.5D*. The magnitude of *MDT_DTU15* ranges between 4.5 -
446 7.5 cm, smaller than *MDT_Local*: -5 – 5 cm. The zonal variation of *MDT* (sea level
447 decrease toward east) along the strait can be observed in both models but the local *MDT*
448 shows a remarkable meridional cross-strait gradient. We also observe a difference in the
449 magnitude of the mean along-strait sea level difference between the two entrances of the
450 Strait. Thus, this difference is smaller than 2 cm for the global *MDT* but up to 6 cm for
451 the local model. Also, the strong change in sea level pattern around Camarinal Sill
452 shown in *MDT_Local* is not observed in *MDT_DTU15*. A possible explanation might
453 lie in the fact that this global model does not resolve properly the baroclinic coupling
454 between upper and lower layer flows (Brandt et al., 2004).



455

456 Figure 4. Mean Dynamic Topography (in cm) in the Strait of Gibraltar from the global model

457 *MDT_DTU15* (5.a) and the local model *MDT_UCA2D* (5.b).

458

459 We recalculated along-track *ADT* (*AT_ADT*) following Eq. (2) using the

460 *Local_MDT* (only for cycles with a ‘stable’ leading edge around the nominal tracking

461 point). It can be seen a clear cross-strait sea level difference with higher sea level on the

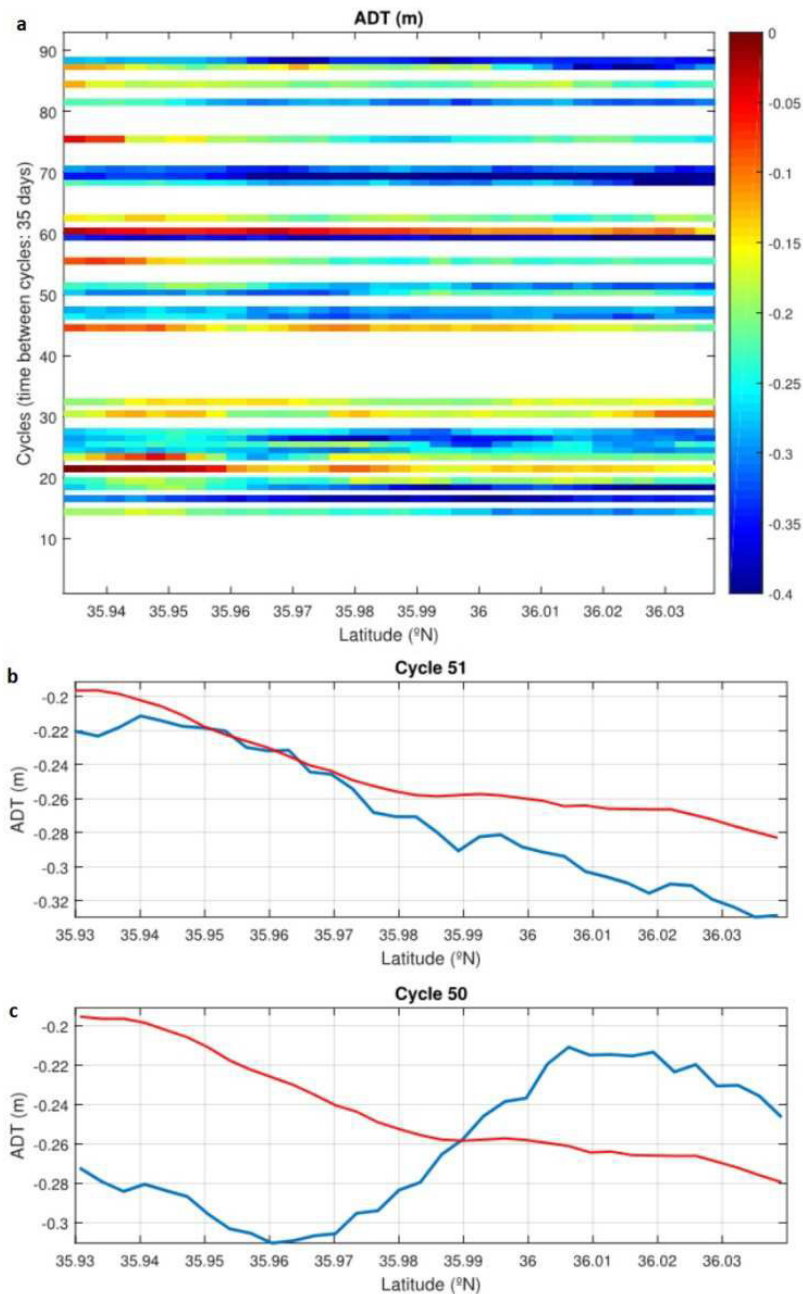
462 African side in most of the cycles (Fig. 5.a). Fig. 5.b gives the *AT_ADT* for a cycle (no.

463 51) with a positive cross-strait sea level difference. Also, inversions of the sea level

464 differences between south and north sides are observed in some cycles. Fig. 5.c shows

465 *AT_ADT* for cycle 50. We investigated this further by analysing its relationship with the

466 wind regime.



467
 468 Figure 5. Cycle-by-cycle AT_ADT for valid cycles (Fig. 5.a). AT_ADT for cycle 51 (Fig. 5.b)
 469 and 50 (Fig. 5.c). The average of AT_ADT over all valid cycles is also shown in Fig. 5.b and 6.c
 470 (red line).

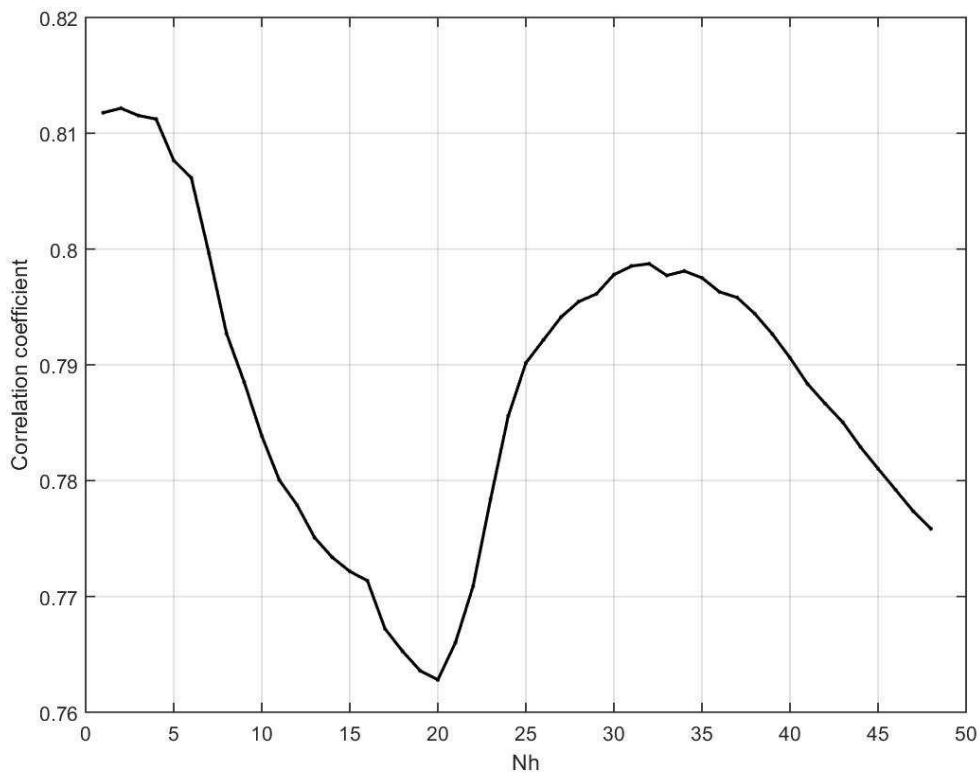
471

472 4.2.2 Inversion of the cross-strait sea level difference due to wind regime

473 We analysed the variability of the cross-strait sea level in the Strait of Gibraltar
 474 and its dependence on the wind regime. We first determine the response time of sea
 475 level to wind forcing following an empirical approach: the wind mean zonal component

476 (\hat{u}) was calculated as the average u value from a time interval (N_h) starting immediately
 477 before the pass of the satellite (about 10:46 UTC time). N_h was ranging from 1 to 48
 478 hours before that time. The time response selected was that corresponding to the
 479 averaging interval giving the maximum correlation coefficient between the calculated
 480 zonal component (\hat{u}) and the sea level difference between the two tide gauge stations.
 481 Figure 6 gives the correlation coefficients (p_value < 0.05) between \hat{u} and the sea level
 482 gradient for increasing N_h . The best correlation ($r = 0.812$) was found for $N_h = 2$.
 483 Easterly/westerly winds (the so-called Levante/Poniente winds, respectively) give
 484 negative/positive \hat{u} component.

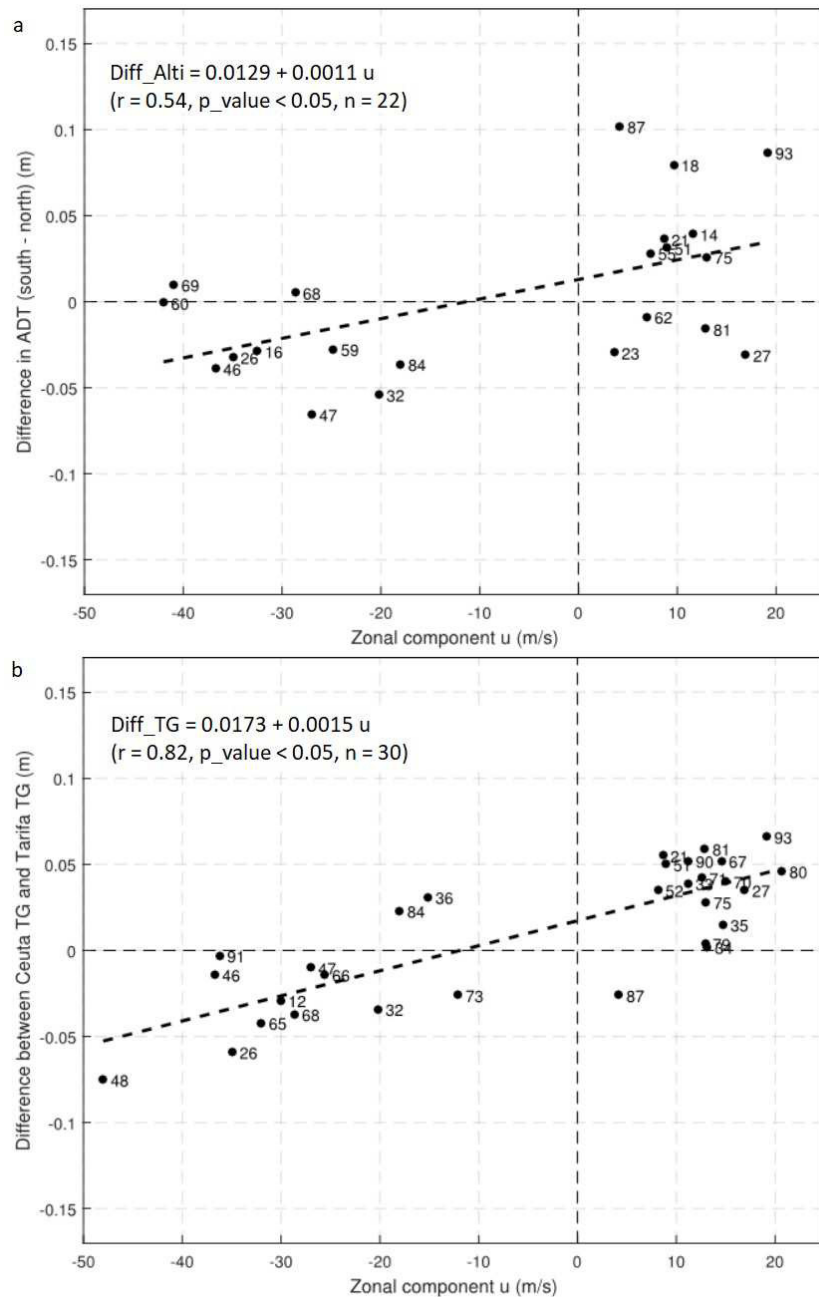
485



486 Figure 6. Correlation coefficient between the calculated zonal component (\hat{u}) and the sea level
 487 gradient between the two tide gauge stations (Ceuta and Tarifa) for increasing time intervals
 488 (N_h).

490

491 We obtained the sea level difference between the south and north sides of the
492 Strait from altimetry and the two tide gauges located in Ceuta and Tarifa (Figure 1). The
493 sea level difference from altimetry was obtained by estimating the cross-strait sea level
494 slope using the starting and ending points of the linear fit made to the *AT_ADT* profiles.
495 We found 8 out of 30 cycles with a small confidence level and were rejected in the
496 analysis. The relationship between \hat{u} and the sea level differences are shown in Figure 7
497 for altimeter (Fig. 7.a) and tide gauge data (Fig. 7.b). Negative differences indicate the
498 inversion of the sea level difference between the southern and northern sectors of the
499 Strait. This is clearly seen during easterlies in the two datasets, more evident in the tide
500 gauge data, where the correlation coefficient is remarkably high (0.82). The inversion is
501 due to the Ekman transport during strong easterlies. As mentioned, this is in agreement
502 with previous observations in the study area. Stanichny et al. (2005) analysed
503 correlation between the sea level gradient among tide gauges located in Ceuta,
504 Algeciras and Tarifa and the zonal wind component of velocity. The authors found
505 negative cross-strait differences during severe easterlies and a notably similar
506 correlation coefficient (0.85). This effect of along-strait winds in the sea level difference
507 across the Strait is further supported by the results of a process-study simulation carried
508 out with UCA2.5D (Reyes, 2015). As compared to the no wind control solution, a
509 constant easterly wind of $10 \text{ m}\cdot\text{s}^{-1}$ originates a sea level rise between 2 and 5 cm from
510 Tarifa to Gibraltar, with a cross-strait sea-level difference of less than 7 cm at the
511 eastern entrance of the Strait. In the case of a constant westerly wind of equal
512 magnitude, this cross-strait sea-level difference is 12 cm.
513



514

515 Figure 7. Cross-strait sea level differences between the African and Spanish coasts as a function
 516 of the mean zonal \hat{u} component of the wind. Fig. 7.a gives the comparison using altimeter data
 517 and Fig. 7.b in-situ data. The numbers indicate the cycle number of the satellite pass.

518

519 **5. Discussion**

520 Our work was focused on the use of an accurate coastal sea level product from a
 521 pulse-limited altimeter (RA-2) in the Strait of Gibraltar. We have highlighted how the
 522 studies that look at spatial SLA profiles should take particular care of the MSS adopted.

523 We have shown (Figure 3) that even the use of a dedicated retracking procedure might
524 not be able to provide a realistic sea level profile if the MSS used to extract the anomaly
525 is based on standard products. There are at least two explanations for this. Firstly, the
526 standard products are severely flagged in the coastal zone to avoid the risk of erroneous
527 retrievals, which means that a global MSS model is probably characterised by strong
528 data interpolation in the absence of local sea level data in areas such as the Strait of
529 Gibraltar. Secondly, the use of different geophysical corrections in the computation of
530 the global MSS w.r.t. the corrections used in the reprocessed SSH might leave
531 unrealistic features when deriving the anomalies. This is for example the case of
532 corrections with different spatial resolutions: for example, the Wet Tropospheric
533 Correction from the radiometer rather than from an atmospheric model, or the Dynamic
534 Atmosphere Correction forced with the operational ECMWF atmospheric model rather
535 than with the ERA-Interim Reanalysis. These problems have been mentioned by
536 Andersen and Scharroo (2011), and more recently by Han et al. (2017), but the Coastal
537 Altimetry community has up to now overlooked the problem, which becomes of urgent
538 matter nowadays, when the discipline is mature for oceanographic exploitation.

539

540 A possible future extension of this work would be the use of SAR mode
541 altimetry from CryoSat-2 and Sentinel-3. The accuracy of current delay-Doppler
542 missions: CryoSat-2 SIRAL and Sentinel-3A SRAL (already joined by Sentinel-3B) in
543 terms of sea level has not been quantified in the study area. A thorough validation
544 exercise of CryoSat-2 SIRAL data was performed by Gómez-Enri et al. (2017) in the
545 eastern shelf of the Gulf of Cadiz (western end of the Strait). They concluded that the
546 quality of CryoSat-2 20-Hz SLA data was comparable to conventional altimetry (Saral
547 AltiKa 20-Hz data) in the coastal strip of the Gulf. However, the complexity of the

548 Strait of Gibraltar precludes the use of SAR altimetry missions for scientific
549 exploitation before performing their validation with in-situ tide gauge data. The unique
550 orbital configuration of the CryoSat-2 mission (369-days repeated cycle with a 30-days
551 sub-orbital cycle) would allow a geographically distributed assessment of the cross-
552 strait variability of the sea level in the Strait and its relationship with the wind regime.
553 In addition to this, the 27-days orbital cycle of Sentinel-3A gives two tracks (one
554 ascending and one descending) very close to the Envisat track analysed in this work
555 with the cross-over at Algeciras city, north of Punta Carnero (Figure 1). This convenient
556 sampling by Sentinel-3A combined with its SAR mode should allow a better knowledge
557 of the hydrodynamic processes in the eastern side of the Strait of Gibraltar. For both
558 CryoSat-2 and Sentinel-3, the use of a local mean sea surface to obtain the anomalies is
559 needed.

560

561 **6. Conclusions**

562 The cross-strait variability in the eastern side of the Strait of Gibraltar and its
563 relation to the wind regime has been analysed. We estimated the sea level differences
564 between the southern and northern sector of the Strait and analysed their variability as a
565 function of the zonal component of the wind. To do this, we estimated the absolute
566 dynamic topography from the sea level anomalies obtained using along-track SLA
567 (Envisat RA-2 descending track #0360) based on ALES reprocessing and improved
568 geophysical corrections. The sea level differences and its dependence with the wind
569 regime were compared with the outputs of two tide gauges located at both sides of the
570 Strait. The main conclusions are summarised as follows.

571

572 The global mean sea level *DTU15MSS* does not take into account some of the
573 particularities of such a complicated zone as the Strait of Gibraltar. Our results show
574 that its use to compute the sea level anomalies might hide some of the sea level
575 variability, and hence complicate their oceanographic interpretation. We have
576 demonstrated that a local mean sea level (*AT_Local_MSS*) based on ALES reprocessing
577 of ERS2/Envisat descending track #0360 along-track sea surface heights, gives a more
578 realistic cross-strait variability in the Strait improving the analysis of the hydrodynamic
579 processes in the area. The global tidal model *DTU10* shows a good performance in the
580 Strait of Gibraltar to de-tide altimetric records. The mean *RSS* of the main constituents
581 obtained with *DTU10* and 11 stations is 4.3 cm very similar to the *RSS* using a local
582 hydrodynamic model (*UCA2.5D*) (4.2 cm).

583

584 The cross-strait variability obtained between the southern (Pta. Cires) and
585 northern (Pta. Carnero) eastern zone of the Strait of Gibraltar is highly dependent on the
586 wind regime. The analysis of the along-track absolute dynamic topography showed a
587 positive correlation with the zonal component of the wind. The difference between the
588 sea level in the southern and northern segments of the altimeter track gives positive /
589 negative differences under westerlies / easterlies conditions. The inversion (negative) of
590 that difference is related to severe easterlies as a result of the Ekman transport. This
591 contributes to the modulation of the water exchange through the Strait of Gibraltar,
592 weakening the Atlantic water inflow toward the Mediterranean Sea.

593

594 Coastal altimeter data are ready for exploitation in the coastal zone. Data
595 accuracy needs to be continuously assessed near the shore, especially the products
596 obtained from present altimeter (conventional and delay-Doppler) missions. The Strait

597 of Gibraltar, the unique connection between the Mediterranean Sea and the Atlantic
598 Ocean, plays an important role in their water exchange and its complexity has been
599 thoroughly investigated for many years using ground-truth instruments and its
600 hydrodynamic processes have been modelled. We have demonstrated here that satellite
601 altimetry gives accurate sea level measurements in the Strait, and hence helps to a better
602 knowledge of its hydrodynamic processes. We have also shown that, at least regionally,
603 coastal altimetry can be used to significantly improve the knowledge of the MSS in the
604 coastal zone. There is therefore a strong need to perform an impact assessment looking
605 at the differences between current global MSS models and along-track MSS computed
606 using reprocessed dataset such as ALES in other regions. High quality satellite-based
607 altimeter with finer along-track spatial resolutions from SAR-mode missions such as
608 Sentinel-3A/B should be incorporated to the experimental datasets available in the area.

609

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891 **List of Figure Captions**

892

893 Figure 1. Study area: The Strait of Gibraltar between Europe and Africa. Colour scale
894 indicates the bathymetry (in meters). Also shown the location of ERS-2 / Envisat
895 descending track #0360 (the track segment analysed is highlighted in blue), the main
896 topographic features mentioned in the text, and the location of the tide gauge and
897 bottom pressure measurement sites used for validation of the tidal constituents. Red
898 circles indicate the tide gauges used in the analysis of the cross-strait variability.

899

900 Figure 2. Radargram of the RA-2 radar waveform power for a rejected (Fig. 2.a) and a
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907 Figure 4. Mean Dynamic Topography (in cm) in the Strait of Gibraltar from the global
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914 Figure 6. Correlation coefficient between the calculated zonal component (\hat{u}) and the
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917

918 Figure 7. Cross-strait sea level differences between the African and Spanish coasts as a
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921 the satellite pass.

922