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Accuracy of high resolution coastal flow speed simulations during and outside of wind, wave and stratification events (Gulf of Lion, NW Mediterranean)

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Abstract

Accurately predicting the flow speed is crucial for applications of coastal ocean circulation simulations such as sediment, larval or contaminant dispersal. This study aims to assess the accuracy of simulated flow speed in a coastal circulation model in comparison with field observations. Deviation between simulated and observed flow speed was assessed in four shallow, coastal locations and four deep, offshore locations in the Gulf of Lion (NW Mediterranean Sea) using six indicators (bias, relative bias, root mean square error, Hanna & Heinold index, correlation and scatter index). Statistical dis-

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tributions of indicators were calculated during reference periods with low wind, no waves and no stratification. During these periods, relative bias indicated the model displayed a higher performance in predicting transport at shallow stations than at deep stations probably due to grid refinement at these stations. However, there was a low correlation between simulated and observed flow speed, indicating short term time/space mismatches, at all stations during reference periods. Indicators were then calculated during three types of events (wind, waves and stratification) when model assumptions were expected to be violated and their corresponding probability during reference periods indicated that neither wind, wave nor stratification events worsens model's performance.

Keywords: Coastal circulation, modelling, flow speed, uncertainty quantification, Mediterranean, Gulf of Lion

1 **1. Introduction**

2 Ocean currents are the key drivers of dissolved and particulate compound
3 transport. At the global scale, the thermohaline circulation regulates the
4 earth's climate (McCarthy et al., 2015; Clark et al., 2019). Wind-driven,
5 upwelling currents arrange nutrient transport and mixing and regulate pri-
6 mary production at the regional scale (Falkowski et al., 1998). From regional
7 to coastal scales, ocean currents play an imperative role in sediment trans-
8 port and pollution diffusion (James, 2002; Dufois et al., 2008; Warner et al.,
9 2008; Mansui et al., 2020). At all spatial scales, vessel navigation and marine
10 population connectivity (from large mammal migration to benthic species'
11 larval dispersal) are affected by ocean currents (Cowen et al., 2000; Briton

12 et al., 2018; Putman, 2018; Mannarini and Carelli, 2019). These applica-
13 tions are currently simulated with Lagrangian dispersal models which, in
14 contrast to Eulerian models, disregard mixing processes and only account
15 for transport processes. Unfortunately, ocean velocity observations, which
16 are necessary to describe these transport processes, are often limited in
17 either time or space. Satellite-mounted altimeters and radars, land-based
18 radars and Lagrangian drifters can measure the currents over a wide area,
19 but only near the ocean’s surface (Dohan et al., 2010; Mader et al., 2016).
20 Some in situ current meters do provide flow measurement time series along
21 vertical profiles (e.g. Acoustic Doppler Current Profiler, ADCP), but sin-
22 gular point measurements are still common (Schroeder et al., 2013; Durrieu
23 De Madron et al., 2019). ADCPs which were previously only deployed at
24 fixed moorings (Guizien et al., 1999) are now being mounted on the hulls of
25 ships (Système Acquisition Validation Exploitation de Données des Navires
26 de l’INSU - Projet SAVED [https://sextant.ifremer.fr/record/6f6e95e9-8e97-
27 48d6-b536-b40f2ad87402/](https://sextant.ifremer.fr/record/6f6e95e9-8e97-48d6-b536-b40f2ad87402/), accessed 04/06/2021) or on autonomous under-
28 water vehicles (Dohan et al., 2010; Bourrin et al., 2015; Gentil et al., 2020).
29 Ultimately, ocean current measuring devices are either deployed on the hor-
30 izontal or on the vertical plane, which strongly limits their applicability to
31 study transport processes. For this reason, transport processes are mainly
32 studied using current simulations over the entire ocean. Ocean circulation
33 models vary according to the different scales and processes they aim to simu-
34 late. Tide models are bidimensional models, predicting sea surface elevation
35 and depth-integrated horizontal flow transport, whose main application is
36 navigation (Le Provost and Lyard, 2000). Global ocean circulation mod-

37 els (OGCMs) are three-dimensional models resolving the ocean dynamics at
38 coarse spatial scales everywhere on earth ($1/12^\circ$). They either rely on at-
39 mospheric coupling for climate predictions (Siedler et al., 2001; Chassignet
40 et al., 2007; Somot et al., 2008) or on one-way atmospheric forcing for mod-
41 elling ocean energy, fishery management and ship routing (Dréville et al.,
42 2018). Coastal circulation models are three-dimensional models forced by
43 atmospheric models, most of the time without air-sea interaction, simulating
44 the ocean flow dynamics and hydrology on a limited area. These models
45 aim to simulate meso-scale to sub-meso-scale ocean processes, like eddies
46 (Hu et al., 2009, 2011), dense water cascading (Ulses et al., 2008) and river
47 plumes (Marsaleix et al., 1998). They use a spatial resolution that reaches
48 about 100 m in the horizontal and 1 m in the vertical (Dumas and Langlois,
49 2009; Briton et al., 2018). Such models are considered capable of describing
50 the processes controlling the transport of dissolved and/or particulate matter
51 in a variety of applications (oil spills, land-sea transfer, ecosystem modelling,
52 population connectivity). Regional circulation models have also been coupled
53 to wave models for sediment transport and beach erosion prediction (Ulses
54 et al., 2008; Dufois et al., 2008; Warner et al., 2008). Examples of these
55 models are the Model for Applications at Regional Scale (MARS 3D, Lazure
56 and Dumas, 2008; Dumas and Langlois, 2009), the COupled Hydrodynami-
57 cal Ecological model for REgionNal Shelf seas (COHERENS, Dréville et al.,
58 2018), the Regional Ocean Modelling System (ROMS, Moore et al., 2011)
59 and SYMPHONIE (Marsaleix et al., 2008, 2009a).

60 However, circulation simulations are subject to various sources of un-
61 certainties, either linked to the model's implementation or to the model's

62 intrinsic assumptions. The model’s implementation includes the spatial and
63 temporal resolution of the baroclinic modes and the precision of the forcing
64 data (atmospheric forcing, river runoff, bathymetry and open-boundary forc-
65 ing). The sensitivity to the grid’s spatial resolution (Kirtman et al., 2012;
66 Kvile et al., 2018; Cai et al., 2020) and to atmospheric and open bound-
67 ary forcing (Kourafalou et al., 2009) has been thoroughly illustrated. In
68 addition to uncertainties coming from model implementations, uncertainties
69 can come from the model’s intrinsic assumptions, such as hydrostaticity, the
70 Boussinesq approximation, the turbulent closure scheme and air-sea interac-
71 tion. The hydrostatic assumption that the vertical variation of the pressure
72 is dominated by gravity acceleration (resulting in negligible vertical velocities
73 compared to horizontal ones) is not met during wave events (Marshall et al.,
74 1997; Zhang et al., 2014). The Boussinesq approximation (density variations
75 can be neglected except in the terms associated with buoyancy forcing) may
76 not be met in the upper stratified ocean, since water density can vary up
77 to 5%, particularly in coastal areas under riverine influence. Therefore, the
78 Boussinesq approximation can cause inaccuracies in the Eulerian simulated
79 velocity of the same magnitude as the water density variation (McDougall
80 et al., 2002). Turbulence closure is also a vital part of any flow dynamics
81 model as it distributes the total flow energy between the turbulent energy
82 resulting from all velocity fluctuations at the subgrid scale and the mean
83 flow (Boussinesq, 1903; Prandtl, 1925). This splitting of the flow energy is
84 essential to describe transport and mixing processes in the numerical simu-
85 lations. Turbulence closure is expected to play a more prominent role when
86 energetic transfer happens at scales smaller than the spatio-temporal grid,

87 such as during wind-wave (Fisher et al., 2018) or river flooding events (Ref-
88 fray et al., 2004). Evaluating model accuracy during selected events when
89 the classical assumptions of ocean models aren't met has been frequent prac-
90 tice in the coastal modelling community over the last two decades (Marsaleix
91 et al., 1998; Estournel et al., 2001; Reffray et al., 2004; Petrenko et al., 2005;
92 Ulses et al., 2008; Estournel et al., 2016, in the Gulf of Lion). Nevertheless,
93 to disentangle uncertainties due to model assumption violation from those
94 related to implementation, it is necessary to quantify the uncertainty of the
95 model when the assumptions are valid. To our knowledge, this has never
96 been done together and actually, implementation uncertainties on predicted
97 flow speed have been assessed qualitatively only (André et al., 2005; Petrenko
98 et al., 2005; Schaeffer et al., 2011, in the Gulf of Lion).

99 In the present study, we assessed the uncertainties of regional circulation
100 speed simulations performed in the NW Mediterranean Sea with the hy-
101 drostatic Boussinesq model SYMPHONIE (S26 version, [https://sirocco.obs-
103 mip.fr/ocean-models/s-model/download/](https://sirocco.obs-
102 mip.fr/ocean-models/s-model/download/)), implemented at one of the finest
104 spatio-temporal resolution to date for bathymetry, atmospheric data and
105 river data. The simulations, which were performed from January 2010 to
106 June 2013, were compared to hydrodynamic observations available in the
107 area during this period. Uncertainties in flow speed in different locations
108 and periods were assessed when the model's assumptions were valid (reference
109 period in absence of wind, waves and stratification) and when assumptions
110 were violated (strong wind events, wave events and stratification events).
111 Model performance was systematically assessed by comparing six indicators
calculated during each event type and observation station to their statistical

112 distribution outside of these events.

113 **2. Material and methods**

114 *2.1. Study area*

115 The Gulf of Lion is located in the northwestern part of the microtidal
116 Mediterranean Sea and has a wide continental shelf with a mean depth of 70
117 m (Aloisi et al., 1973). It is delineated by a steep shelf break, incised by a
118 dense network of submarine canyons (Figure 1). Its coastal circulation mainly
119 results from the interaction between the thermohaline Northern Current,
120 which flows along the shelf break from the northeast to the southwest and
121 the frequent continental winds blowing from the north and northwest (Mistral
122 and Tramontane resp.), which induce winter convection (Millot, 1990). The
123 south-easterly and southerly winds, which blow less frequently, occur mainly
124 from autumn to spring and can cause large swells (Guizien, 2009). The
125 Gulf of Lion’s coastal circulation is also influenced by the outflow of one
126 of the largest Mediterranean rivers, the Rhône River, and a series of smaller
127 rivers with typical Mediterranean flash-flooding regimes (Guizien et al., 2007;
128 Ludwig et al., 2009). The size of the freshwater plume from the Rhône River
129 depends on the atmospheric conditions, the strength of the river flow and
130 the sea water circulation (Millot, 1990; Many et al., 2016, 2018). The surface
131 layers in the Gulf of Lion can stratify thermally between spring and autumn
132 and are recurrently destabilised nearshore by coastal upwelling (Millot, 1990;
133 Petrenko et al., 2005).

134 *2.2. Water current observations*

135 Horizontal velocity measurements were gathered from eight locations in
136 the Gulf of Lion between January 2010 and June 2013 (Figure 1). Observa-
137 tions included the shallow coastal ADCP moorings BeSete, Mesurho, POEM,
138 and SOLA and the deep moorings Planier, Cap de Creus (Creus), Lacaze-
139 Duthiers (LD) and Lion with one or more single point, acoustic Doppler cur-
140 rent meters (SP-ADCMs). The time periods for which flow speed data was
141 acquired are given in Table 1. Additional information on the observations,
142 such as equipment specifications, can be found in the appendix Table A.1.

143 The observations were filtered to remove erroneous data. For the deep
144 stations, if the velocity measurements presented abnormal values (defined as
145 spikes of intensity with respect to the daily average greater than three times
146 the standard deviation), they were replaced by the average of the previous
147 and the following valid value. For the shallow stations, the upper three meters
148 of the water column were not taken into account, to avoid measuring air speed
149 amid sea surface fluctuations. Moreover, all observations were filtered over
150 time to detect unrealistically fast changes in water speed. The maximum
151 change in water speed tolerated was 30 cm/s over one hour. Another filter
152 was applied on the vertical level and the maximum change in water speed
153 tolerated was 10 cm/s over one meter.

154 *2.3. Ocean circulation simulations*

155 The free surface ocean model SYMPHONIE (Marsaleix et al., 2009a,b,
156 2012, SIROCCO, <https://sirocco.obs-mip.fr/ocean-models/s-model/>, accessed
157 17/05/2021) was set up to perform regional ocean circulation simulations at a
158 very high resolution in the Gulf of Lion (Briton et al., 2018). The model solves

159 hydrostatic primitive equations with a finite-difference method on a C curvi-
160 linear grid under Boussinesq approximation and with an energy conserving
161 numerical scheme (Marsaleix et al., 2008). Wave-coupling was not activated
162 and turbulent closure scheme was set to two-equation $K-\epsilon$ (Michaud et al.,
163 2012). A bipolar, curvilinear, 680x710 horizontal grid was used to mesh the
164 Gulf of Lion yielding a resolution of 80 m at the coast and 2.7 km in the open
165 ocean (Figure 1, Bentsen et al., 1999). Generalized σ -coordinates were used
166 for vertical meshing, with 29 vertical levels (Briton et al., 2018). Simulations
167 were carried out over the period January 2010- June 2013 and were forced
168 by sea-surface dynamical downscaling of the ERA-Interim atmospheric re-
169 analysis by the regional climate model ALADIN-Climate (ALDERA, 12 km
170 horizontal and 3 h temporal resolutions) and by open-sea boundary condi-
171 tions from the hindcast downscaled simulation NM12-FREE (~ 7 km hor-
172 izontal resolution, Hamon et al., 2016). Observed daily discharge of nine
173 rivers (Var, Grand Rhône, Petit Rhône, Hérault, Orb, Aude, Agly, Têt,
174 Tech; <http://www.hydro.eaufrance.fr/>, accessed 17/05/2021) were included
175 as well. The model’s internal and external timesteps were 25.48s and 1.59s,
176 respectively. The simulated velocities were extracted four times per hour on
177 minute 0, 20, 30 and 40 to correspond with the times the observations were
178 measured. On the horizontal, the simulated flow speeds were extracted at
179 the grid point closest to the observations’ location (less than 132 m apart).
180 On the vertical, since the simulation’s vertical levels did not match the obser-
181 vations’ depths, the simulated speeds were interpolated at the same depth as
182 the observations. If the actual water depth was larger than the water depth
183 in the simulation (bathymetric discrepancy), the simulated speeds were in-

184 interpolated at the depth with the same distance from the bottom as the
 185 observation.

186 2.4. Statistical indicators

187 The deviation between observed O_{ij} and simulated M_{ij} current speed at
 188 depth i and time j was described by six time- and depth-averaged statistical
 189 indicators, calculated as follows:

$$Bias = \frac{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} (M_{ij} - O_{ij})}{N_d N_t} \quad (1)$$

$$RelativeBias = \frac{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} (M_{ij} - O_{ij})}{\sqrt{N_d N_t \sum_{i=1}^{N_d} \sum_{j=1}^{N_t} M_{ij} O_{ij}}} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} (M_{ij} - O_{ij})^2}{N_d N_t}} \quad (3)$$

$$HH = \sqrt{\frac{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} [(M_{ij} - O_{ij})^2]}{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} M_{ij} O_{ij}}} \quad (4)$$

$$SI = \sqrt{\frac{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} [(M_{ij} - \bar{M}) - (O_{ij} - \bar{O})]^2}{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} M_{ij} O_{ij}}} \quad (5)$$

$$Correlation = \frac{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} [(M_{ij} - \bar{M}) \cdot (O_{ij} - \bar{O})]^2}{\sqrt{\sum_{i=1}^{N_d} \sum_{j=1}^{N_t} (M_{ij} - \bar{M})^2 \cdot \sum_{i=1}^{N_d} \sum_{j=1}^{N_t} (O_{ij} - \bar{O})^2}} \quad (6)$$

190 with \bar{O} the observed current speed averaged over depth and time and \bar{M}
 191 the simulated current speed averaged over depth and time.

192 The bias (equation 1) is the difference between the simulated and observed
193 mean. It indicates systematic under- (negative value) or overestimation (pos-
194 itive value) of the simulated flow speed. The relative bias (equation 2) is the
195 absolute bias normalized by the square root of the mean of the product of
196 observed and simulated flow speed. The root mean square error (RMSE,
197 equation 3) is the square root of the quadratic mean of differences between
198 simulated and observed velocities. It adds to the bias as a measure of random
199 deviation and indicates the accuracy of simulations. The Hanna & Heinold
200 index (HH, equation 4, Hanna and D., 1985) normalized the RMSE by the
201 mean of the product of the observed and simulated flow speed. It indicates
202 the relative uncertainty from the mean flow and avoids biasing when the
203 model underestimates the currents (negative bias, Mentaschi et al., 2013).
204 The scatter index (SI, equation 5) is the quadratic mean of the difference
205 between simulated and observed flow speed fluctuations around the mean,
206 normalized by the mean of the product of observed and simulated flow speed.
207 It indicates if the simulated flow speed fluctuates more or less around the
208 mean than the observed flow speed. The correlation index (equation 6) is
209 the product of simulated and observed fluctuations around the mean flow
210 speed, normalized by the product of the standard deviation of the simulated
211 and observed flow speed. It varies between -1 and +1. Values close to 1
212 indicate co-variation (-1 indicates opposed variation) in the dynamics of sim-
213 ulated and observed flow speed, while values close to 0 indicate the dynamics
214 of simulated and observed flow are different.

215 *2.5. Definition of the reference period and the three types of specific events*

216 In order to separate uncertainties due to model implementation and hy-
217 pothesis violation, the six indicators were assessed separately during reference
218 periods defined by low wind conditions, no swell and absence of significant
219 stratification, and during events with either strong wind conditions (turbu-
220 lence closure or atmospheric forcing reliability), swell (hydrostatic hypothesis
221 violation), or in stratified conditions (Boussinesq approximation violation).
222 Importantly, the indicators were integrated over a same duration during ref-
223 erence periods as the event duration.

224 Wind conditions over the entire Gulf of Lion were estimated using the
225 wind stress used to force the ocean circulation simulations at the closest
226 atmospheric model grid point from the Planier and POEM stations (Fig-
227 ure 1). Low and strong wind conditions correspond to wind speed lower
228 than 40 km/hr and larger than 50 km/hr, respectively, separating negligible
229 effects from significant impacts in Beaufort scale. Wind speed thresholds
230 were converted into wind stress values to be detected in the atmospheric
231 forcings (using $\tau = C_D \rho U^2$ with τ the wind stress in Pa, U the wind speed
232 in m.s^{-1} , C_D a drag coefficient of 0.00171 and ρ the air density of 1.225
233 kg/m^3 , according to Smith, 1988). Practically, during the reference period,
234 wind stress values should not exceed 0.2586 Pa at both Planier and POEM
235 stations, while wind events were defined by wind stress values larger than
236 0.4041 Pa during more than 12 hr at both stations. Numerous northerly
237 wind events (37, Figure 2) were detected with wind stresses between 0.6903
238 Pa and 2.4939 Pa, as expected in the Gulf of Lion (Guénard et al., 2005).
239 These events were grouped according to their duration into four different

240 classes (12-24 hr, 24-36 hr, 36-48 hr, 48-60 hr, appendix Figure A.1).

241 Wave conditions over the entire Gulf of Lion were assessed using obser-
242 vations over the period January 2010- June 2013 at four stations (Banyuls,
243 Espiguette, Leucate, Sète, Figure 1) of the In Situ National Data Archiving
244 Center of Waves (Centre d'Archivage National des Données de Houle In Situ,
245 <http://candhis.cetmef.developpement-durable.gouv.fr>, accessed 01/06/2021).
246 Wave events were defined as the occurrence of swell with a peak period larger
247 than 8 s, a significant period larger than 5 s and a zeroth order moment wave
248 height larger than 3 m at any of four stations during at least 12 hours. The
249 four stations were necessary to detect the southerly to easterly swell impact-
250 ing the Gulf of Lion (Guizien, 2009). Such swell with wave length larger than
251 the resolution of the flow model at the coast (~ 100 m) exhibit wave steep-
252 ness (wave heighth to wave length ratio) larger than 1%, which corresponded
253 to vertical to horizontal velocity ruling out the hydrostatic assumption of the
254 flow model. These criteria resulted in the selection of five swell events with
255 different durations: 12 hr (max.: $T_p=12.5$ s, $T_z=8.0$ s, $H_{m0}=4.2$ m), 15 hr
256 (max.: $T_p=11.8$ s, $T_z=8.0$ s, $H_{m0}=5.5$ m), 21 hr (max.: $T_p=10.5$ s, $T_z=8.3$
257 s, $H_{m0}=4.1$ m), 40 hr (max.: $T_p=10.5$ s, $T_z=7.8$ s, $H_{m0}= 5.6$ m) and 86 hr
258 (max.: $T_p=10.5$ s, $T_z=7.7$ s, $H_{m0}=4.4$ m) (Figure 2). On the contrary, the
259 reference period was defined by the absence of swell with the above mention
260 characteristics at the four stations.

261 Stratification was estimated at each station after computing the Brunt-
262 Väisälä frequency $N^2(z) = -g/\rho_0 d\rho_0/dz$ with g the gravitational acceler-
263 ation, ρ_0 the density of sea water and z the depth in the sea water using
264 simulated salinity and temperature profiles to calculate sea water density

265 (Fofonoff and Millard, 1983). The threshold to separate stratified and un-
266 stratified periods was the maximum value of the Brunt-Väisälä frequency
267 over the entire water column of 0.005 s^{-2} for at least 12 hours. This value
268 was defined according to Gill (1982). This allowed us to assess the stratifica-
269 tion events at each station separately. No stratification events were detected
270 at the stations SOLA, LD, Lion and Planier, while at Mesurho, which was
271 closest to the Rhône river, the water column was almost always stratified.
272 Since at the aforementioned stations, there was either an absence of stratifica-
273 tion events or of reference conditions, there could be no comparison between
274 the two. Therefore, none of these stations were used for testing the effect of
275 the Boussinesq hypothesis violation on the model's performance. The only
276 stations that were considered were BeSete and POEM (shallow stations)
277 with four stratification events of 249 hr (max. $N^2=0.0150 \text{ s}^{-2}$), 81 hr (max.
278 $N^2=0.0084 \text{ s}^{-2}$), 194 hr (max. $N^2= 0.0202 \text{ s}^{-2}$) and 143 hr (max. $N^2=0.0124$
279 s^{-2}) at BeSete and three stratification events of 74 hr (max. $N^2=0.0953 \text{ s}^{-2}$),
280 79 hr (max. $N^2=0.0310 \text{ s}^{-2}$) and 103 hr (max. $N^2=0.0211 \text{ s}^{-2}$) at POEM
281 (Figure 2).

282 The three types of events were decorrelated and wind events could hap-
283 pen any time in the year (Figure 2). Therefore, reference periods were not
284 separated according to the season.

285 *2.6. Assessment of model performance during specific events*

286 Each of the aforementioned indicators is expected to vary with the du-
287 ration, the moment and the location on which they were calculated, either
288 randomly or systematically. Systematic variation indicates a worse model
289 performance. To test the model's performance under specific conditions (such

290 as strong wind, waves or density stratification), the value of each of these in-
291 dicators was computed during and in absence of such conditions over a same
292 duration. To compare the events to the reference period, reference cumula-
293 tive frequency distributions (CFDs) were established for each indicator and
294 each station for the same duration as the event to test. To do so, a set of
295 200 time periods with an equal event duration as the event to test was ran-
296 domly selected out of the reference period and used to build this reference
297 CFD for the indicator. These 200 time periods each had unique starting
298 moments, but in the case of stations with a short observation period, overlap
299 is possible. A bootstrap procedure was applied to produce 250 repeats of
300 the reference CFD. Those repeats were used to estimate the most probable
301 reference frequency distribution and a confidence interval around it. The
302 most probable reference CFD for the indicator was thus defined by the 50%
303 quartile (median) of the 250 repeats. For the wave and stratification events,
304 the reference CFDs were calculated using the same duration as the event to
305 test. For the wind events, the reference CFD was calculated over a duration
306 equal to the duration of the middle of the class this event belonged to (e.g A
307 wind event of 14 hr would belong to the class of 12-24hr and be compared to
308 the CFD calculated over 18 hr, as this is the middle of the class, see appendix
309 Figure A.2 for more information. Reference CFDs were used to determine
310 the corresponding cumulative frequencies of each indicator/station/event by
311 assessing the event's indicator value compared to the reference CFD (Fig-
312 ure 3, additional schematic in appendix Figure A.2). Those corresponding
313 cumulative frequencies were used to assess the model's performance, by com-
314 paring its value to a threshold value. For RMSE, HH and SI and relative

315 bias, if the corresponding cumulative frequency of the indicator value during
316 the event was larger than 75%, it was considered to have a higher uncer-
317 tainty during the event. For the correlation, the uncertainty of the model is
318 the lowest when the correlation is closer to 1. Therefore, there was a bad
319 model performance when the corresponding cumulative frequency was less
320 than 25%. For the bias, the uncertainty is the lowest when bias is close to
321 zero. Therefore, bad model performance was determined by a corresponding
322 cumulative frequency below 12.5% or above 87.5%. The proportion of events
323 during which the model performed worse than during the reference period
324 was calculated per station, per indicator and per event type. Those propor-
325 tions were averaged across all indicators and stations to assess whether there
326 was a difference in model performance per station, indicator or event type.

327 **3. Results**

328 The reference period CFD of each accuracy indicator in absence of wind,
329 waves and stratification was computed for durations ranging from 12 hr to 249
330 hr at each station (Figure 4 for a duration of 42 hr). Overall, the simulated
331 flow speed was underestimated at deep stations during the reference period,
332 with bias median values calculated over 42 hr ranging from -3 cm/s at Lion
333 to -1.2 cm/s in Creus and LD (Figure 4A). At the shallow stations, the flow
334 speed could be either underestimated (BeSete and SOLA, bias median values
335 of -1.2 cm/s and -0.6 cm/s resp.) or overestimated (Mesurho and POEM,
336 bias median values of 3.6 cm/s and 0.6 cm/s; Figure 4A). In both groups of
337 stations, bias values spread was large, with the first and third quartile being
338 -5.4 and 0 cm/s at deep stations and -4.2 and 6.6 cm/s at shallow stations.

339 After normalizing by the current magnitude in each station, the relative bias
340 was smaller at the shallow stations (with median values ranging from 30%
341 at BeSete and SOLA to 40% at POEM) than at the deep stations (with
342 median values ranging from 35% at Creus to 85% at Lion, Figure 4B). The
343 relative scatter index (SI) was variable amongst the stations, with a similar
344 variability among deep and shallow stations (median values ranging from 65%
345 at Lion to 93% at Mesurho; Figure 4C). As a result, the HH indicator, which
346 combines the relative scatter and relative bias was larger at deep stations
347 (median values ranging from 95% at LD and Creus to 110% at Lion) than
348 at shallow stations (median values ranging from 75% at SOLA and BeSete
349 to 83% at Mesurho, Figure 4E). Noteworthy, the median HH values were
350 larger than 70% at all stations. In absolute values, the median RMSE was
351 similar at deep and shallow stations, ranging from 2.5 cm/s at Planier and
352 BeSete to 5.6 cm/s at Creus and 5.3 cm/s at Mesurho (Figure 4D). However,
353 the RMSE's third quartile was less homogenous across deep stations, which
354 had values ranging from 3.2 cm/s to 12.6 cm/s, than across shallow stations,
355 with values ranging from 3.2 cm/s to 6.7 cm/s. Although the correlation was
356 low at all stations, it was higher at the shallow stations than at the deep
357 stations (Figure 4F). Median (third quartile) values ranged from 0.03 (0.14,
358 resp.) at BeSete to 0.13 (0.23, resp.) at POEM while median values in deep
359 stations had a median of -0.01 for LD and Lion and were always less than
360 0.01. Although the CFDs of the accuracy indicators clustered according to
361 the duration of the event, the deviation between the CFDs calculated over 12-
362 24 hr and those calculated over more than 72 hr remained limited (Appendix
363 Figure A.3). The median correlation at BeSete varied between 0.02 and 0.06

364 and the maximum between 0.33 and 0.63 for integration duration increasing
365 from 12-24 hr to more than 72 hr (Figure 5). While the correlation and bias
366 (relative and absolute) improved with increasing integration duration, the SI
367 worsened. With increasing integration duration, the deviation between the
368 first and third quartile of the RMSE and HH indicators decreased and the
369 median value increased (Figure 5 for the correlation, appendix Figure A.3
370 for the other indicators at BeSete). Despite the fact that the CFDs of the
371 accuracy indicators calculated during the reference period varied with the
372 event duration, the corresponding cumulative frequencies of the correlation
373 indicator calculated during wind, wave or stratification events were not tied
374 to the duration of the events, regardless of the station (Figure 6 for wind
375 events). Overall, the proportion of events where the model performed worse
376 during the events than during the reference period was low no matter the
377 event type. The average ratio worse ranged from 25% for the wind events
378 to 35% for the wave events (Table 2, Table 3). For the stratification events,
379 which were only studied at BeSete and POEM, the model performed worse
380 during the events than during the reference period for 25% and 33% of the
381 events on average, respectively (Table 4). However, the assessment of the
382 model's performance varied greatly depending on the indicator, with the HH
383 indicating a 13% ratio worse and the RMSE showing a 45% ratio worse in the
384 wind events for instance (Table 2, Figure 7B). When comparing the model's
385 performance across event types and stations, it was worse during wave events
386 than during wind events at shallow stations (except at the Mesurho station
387 in front of the Rhone River mouth), while no trend could be observed at
388 deep stations (Figure 7A). During the wave events, the model performed

389 similarly across all stations, with all stations indicating that the model was
390 worse than during the reference period less than 33% of the time on average,
391 except at the POEM station, where the ratio worse reached 67% (Table 3).
392 During the wind events, the model performed slightly better at the shallow
393 stations (ratio worse ranging from 11% to 31%) than at the deep stations
394 (ratio worse ranging from 26% to 37%, Table 2). For both event types,
395 absolute indicators (RMSE and bias) displayed worse model performance
396 than relative indicators (Figure 7B). All indicators except SI displayed worse
397 model performance during wave events than during wind events (Figure 7B).

398 **4. Discussion**

399 The present study quantified various indicators to describe the deviation
400 between observed and simulated flow speed across shallow and deep stations
401 within a highly dynamic region, during and outside short term events of three
402 types (wind, waves, stratification).

403 The assessment of ocean model accuracy has largely been implemented by
404 comparing simulated and observed hydrological variables (temperature and
405 salinity; e.g. Gustafsson et al., 1998; Reffray et al., 2004; André et al., 2005;
406 Kara et al., 2006; Chelton et al., 2007; Pairaud et al., 2011; Renault et al.,
407 2012; Marzocchi et al., 2015; Seyfried et al., 2017; Akhtar et al., 2018) as
408 their dynamics integrates transport (velocity) and mixing (turbulent kinetic
409 energy) in ocean circulation models. However, hydrological variables are little
410 informative about transport and mixing when well-mixed conditions prevail,
411 which is often the case in coastal areas (Gill, 1982; Holt et al., 2009).

412 The ability of the SYMPHONIE model to simulate flow speed and not

413 only hydrological parameters in the Gulf of Lion has been assessed before
414 but only qualitatively under a variety of coastal processes, such as thermally
415 stratified conditions (Petrenko et al., 2005), fresh water mixing in the Rhône
416 River prodelta (Estournel et al., 2001), wind driven Eckman flow (Davies
417 et al., 1998; Lapouyade and Durrieu De Madron, 2001; Molcard et al., 2002;
418 Schaeffer et al., 2011; Estournel et al., 2016), swell events (Michaud et al.,
419 2012; Mikolajczak et al., 2020) and dense water cascading (Ulses et al., 2008;
420 Estournel et al., 2016). Only one study assessed quantitatively the uncer-
421 tainty on simulated speeds in the Gulf of Lion. It compared another SYM-
422 PHONIE configuration than the one of the present study (horizontal resolu-
423 tion ranging from 300 m to 7 km, with and without wave coupling) to part
424 of the dataset used in our study that is a two month period which included
425 several wave events in (February to March, 2011, Mikolajczak, 2019). The
426 bias was 4 cm/s at the Mesurho station and -4 cm/s at the POEM station
427 whilst the RMSEs were 10 cm/s and 8 cm/s, respectively. The present study
428 compliments previous assessments of the SYMPHONIE model in the Gulf
429 of Lion, whilst extending them in space and time and using six quantitative
430 indicators. Using data from multiple years and stations, particularly shallow
431 versus deep ones enabled us to assess model implementation uncertainties
432 in the present study configuration. Focussing first on a reference period
433 (unstratified, with low wind conditions and no wave), when model assump-
434 tions are expected to be valid, bias and RMSE on simulated speeds during
435 the reference period were larger than the measuring device accuracy (about
436 1 cm/s Instruments, 2007). This is generally the the case among the few
437 studies that quantified uncertainties on simulated speeds, elsewhere. While

438 comparing Glazur60 simulations of the NEMO model (horizontal resolution
439 of $1/64^\circ$ hence 1.3 to 1.7 km) to the data of a fixed ADCP mooring located
440 at a hundred meters depth in the eastern part of the Gulf of Lion, a bias of
441 3.5 cm/s at 90 m and 7 cm/s at 20 m depth was found between simulations
442 and observations over an 11 month integration period (Barrier et al., 2016).
443 Similarly, while evaluating the effect of boundary conditions on simulations
444 using the SoFLA-HYCOM model configuration ($1/25^\circ$ hence 3.5 to 4 km
445 horizontal resolution) at shallow stations around the Strait of Florida, the
446 mean bias and the RMSE calculated between simulations and observations
447 over a one year period ranged from -3.5 cm/s to 8.2 cm/s for the bias and
448 from 5 to 13 cm/s for the RMSE, depending on the model's configuration
449 and the station (Kourafalou et al., 2009). Despite flow speed simulations not
450 being as precise as ADCP measurements, it is remarkable that the present
451 study's bias and RMSE values were smaller than the values reported in those
452 quantitative studies, despite these indicators were calculated over longer pe-
453 riods in the latter studies than in our study (weeks versus days). Indeed,
454 the systematic bias and the RMSE are expected to decrease with increasing
455 integration duration (Dekking, 2005). However, comparing bias and RMSE
456 values between simulations and observations in different environments can
457 be misleading regarding model performance and relative indicators should
458 be used.

459 In the present study, lower relative bias and HH were found at shal-
460 low stations compared to deep ones. The better model performance at the
461 shallow stations could be due to the refinement of the horizontal spatial res-
462 olution, thanks to the adaptive resolution of the curvilinear grid. Increasing

463 the resolution of model configurations have been tested to improve agree-
464 ment with other types of observations than flow speeds, sometimes showing
465 predictions improvements (Thoppil et al., 2011; Kirtman et al., 2012; Put-
466 man and He, 2013; Ringler et al., 2013; Akhtar et al., 2018; Kvile et al.,
467 2018; Ridenour et al., 2019). In addition to relative bias which indicates
468 goodness of transport predictions, the present study evaluated the corre-
469 lation between simulated and observed flow speed, an indicator generally
470 disregarded. At all stations, correlation indicated that the simulation failed
471 to reproduce the short term flow dynamics (hours to days). Short term flow
472 dynamics is expected to be driven by atmospherical forcings, especially in
473 the Gulf of Lion, where coastal circulation simulations have been shown to
474 dramatically change with the wind’s spatial gradient (Dumas and Langlois,
475 2009). Hence, the present study simulations were driven by atmospheric
476 field outputs from a reanalysis with assimilated observations and was up-
477 dated every three hours at the finest resolution available for the area at the
478 time of the simulations (Hamon et al., 2016). One way to improve the sim-
479 ulations’ accuracy is to use the bidirectional atmospheric coupling technique
480 (Gustafsson et al., 1998; Chelton et al., 2007; Schaeffer et al., 2011; Akhtar
481 et al., 2018). Two-ways air-sea coupling performed better than one-way at-
482 mospheric forcing during autumn storms, when the sea surface cools rapidly
483 (Seyfried et al., 2017). Nevertheless, in the Gulf of Lion, the added value
484 of coupling atmosphere-ocean simulations on modelled wind speed intensity
485 and sea surface temperature was not significant (Renault et al., 2012). Inter-
486 estingly, in the present study, the indicators did not display a worse model
487 performance during strong wind events when atmosphere-ocean interaction

488 increased, than outside those events. In any case, this limitation to repro-
489 duce the short term flow dynamics, including in low wind conditions, raises
490 the question of how short term (days) velocity dynamics' inaccuracies alter
491 particle tracking simulations (e.g. used in larval dispersal studies, Briton
492 et al., 2018).

493 Similarly, the model's performance was not systematically worse during
494 wave events, although it was slightly worse during wave than during wind
495 events. When comparing a hydrostatic, quasi-hydrostatic and nonhydrostatic
496 model, no difference between the three models was found at large scales with
497 coarse resolution (1° horizontal resolution, Marshall et al., 1997). However,
498 it is expected that quasi-hydrostatic and nonhydrostatic models should be
499 preferred when the spatial resolution increases as in the present study simu-
500 lations (Magaldi and Haine, 2015). Incorporating the effects of waves on the
501 coastal circulation simulations has been considered previously in the Gulf
502 of Lion and flow speed simulations in the surf zone (0-15m water depth)
503 were improved by using a fully nonhydrostatic coupled current-wave model
504 (Michaud et al., 2012). However, outside the surfzone, deviations between
505 observed and simulated flow speeds at POEM and Mesurho (same location
506 as in the present study but another time period) were similar regardless of
507 wave forcing.

508 Another model assumption which could have altered the model's perfor-
509 mance is the Boussinesq approximation, which can be violated in thermal
510 or fresh water stratification. In the Gulf of Lion, stratification effect was
511 only studied qualitatively. During summer, incorrect representation of the
512 stratification in the Gulf of Lion led to a misplacement of the NC in the

513 simulations compared to the field observations (Petrenko et al., 2005). In
514 contrast, simulations of the Rhône plume compared to radar observations
515 showed that the SYMPHONIE model can reproduce the spatial variation of
516 the current in front of the river mouth outside of strong wind events (Estour-
517 nel et al., 2001). Comparing with the rare quantitative studies from other
518 areas is equally unconvincing as only absolute indicators were computed (bias
519 (4-15cm/s) and RMSE (6-18cm/s) over two week period of salinity stratifica-
520 tion in an estuary in the USA Yang and Khangaonkar, 2009). In the present
521 study, testing model performance alteration due to stratification was limited
522 to few fresh water input events in two stations only as in other stations,
523 the water column was either never or always stratified. In these few events,
524 model performance was not significantly worse. However, outside specific
525 events, indicators were systematically larger at the continuously stratified
526 Mesurho station than at the other shallow stations, suggesting stratification
527 effect should be further tested.

528 In conclusion, a quantitative validation of simulated current speeds was
529 performed over a three-year period using in situ flow speed observations from
530 eight fixed moorings (four shallow and four deep). Multiple absolute, and
531 more importantly, relative indicators were calculated to evaluate the perfor-
532 mance of the model. In absence of wind, wave or stratification events, the
533 model performed better at shallow stations than at deep stations in predict-
534 ing the mean flow speed (lower relative bias). In contrast, scatter index was
535 equally large at all stations and correlation over short duration periods was
536 always low, indicating discrepancies between simulated and observed flow
537 speed dynamics. Overall, the model did not perform notably worse during

538 wind, wave or stratified events than outside of events. However, the model's
539 performance was lower during wave events than during wind events at shallow
540 stations.

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Table 1: Timetable of acquired flow speed data per observation station. X indicates there was data available during this month.

Year	2010	2011	2012	2013
Month	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J
Creus	X X X X X X X X X	X X X X X X X X X X	X X X X X X X	
LD	X X X X X X X X X X X X	X X X X X X X X X X X X	X X X X X X X X X X X	
Lion	X X X X X X X X X X X X	X X X X X X X X X X X X	X X X X X X X X X X X X	X X X X X X
Planier	X X X X X X X X X X X X	X X X X X X X X X X X X	X X X X X X X X X X X	
Mesurho		X X X X X X	X X X X X X X X	X X X X
POEM		X X X		
SOLA	X X X			
BeSete	X X X X X X X X X X	X	X X X X X X	X X X X

Station / Indicator	Creus	LD	Lion	Planier	Mesurho	POEM	SOLA	BeSete	Mean per indicator
RMSE	50	56	58	25	59	50	33	25	45
Bias	50	41	28	42	32	0	0	42	29
HH	28	30	19	17	9	0	0	0	13
SI	33	33	25	21	27	50	33	0	28
Relative bias	28	22	17	24	21	0	0	23	17
Correlation	33	22	27	25	36	0	0	17	20
Mean per station	37	34	29	26	31	17	11	18	25
Nr of events	18	27	36	24	22	2	3	12	

Table 2: *Proportion of events worse during the event than during the reference period per indicator and per station for wind event type.*

Station / Indicator	Creus	LD	Lion	Planier	Mesurho	POEM	SOLA	BeSete	Mean per indicator
RMSE	67	40	40	20	67	100	0	100	54
Bias	67	40	40	60	33	100	0	0	43
HH	0	20	20	20	0	100	0	0	20
SI	0	20	0	40	0	0	100	0	20
Relative bias	0	20	20	20	33	100	100	0	37
Correlation	0	40	60	40	33	0	0	100	34
Mean per station	22	30	30	33	28	67	33	33	35
Nr of events	3	5	5	5	3	1	1	1	

Table 3: *Proportion of events worse during the event than during the reference period per indicator and per station for wave event type.*

Station / Indicator	POEM	BeSete	Mean per indicator
RMSE	33	25	29
Bias	33	50	42
HH	33	25	29
SI	67	25	46
Relative bias	0	0	0
Correlation	33	25	29
Mean per station	33	25	29
Nr of events	3	4	

Table 4: *Proportion of events worse during the event than during the reference period per indicator and per station for stratification event type.*

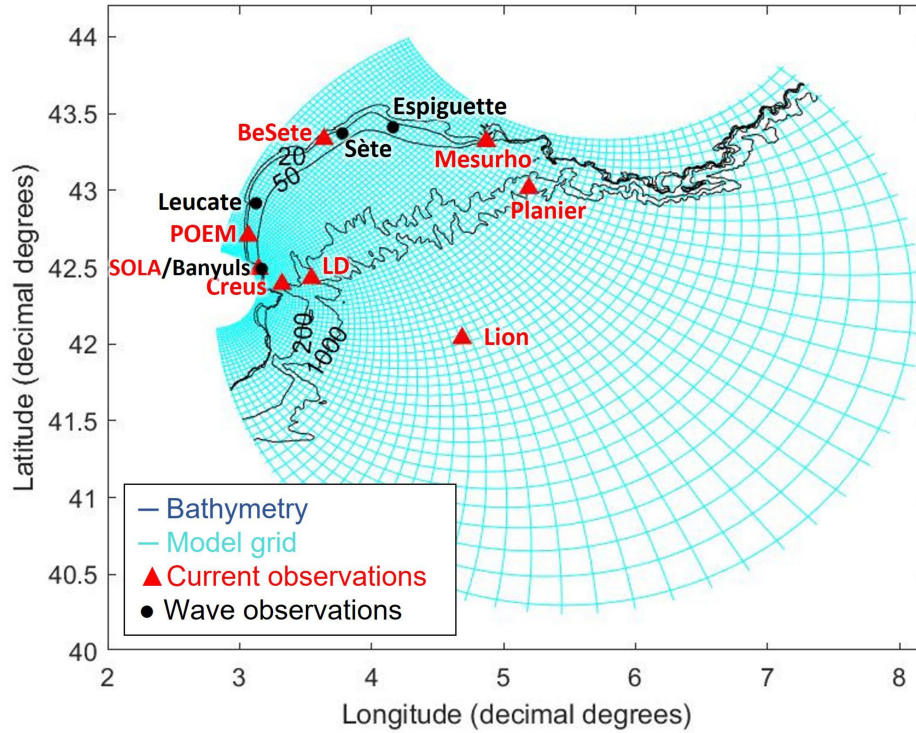


Figure 1: *The Gulf of Lion. Main bathymetrical contours (20, 50, 200, 1000 m) of the Gulf of Lion including the dipolar model grid (680 × 710; with one blue line every 10 cells; North pole (44.2°N, 5.3°E); South pole (42.37°N, 2.82°E); grid point (170; 710) corresponding to (47°N, 5°E); and the reference latitude for Mercator projection was 52° N). Further information on the grid can be found in Briton et al., (2018). The locations of the fixed moorings with current meters are in red: BeSete, Creus, LD (Lacaze-Duthiers), Lion, Mesurho (Measuring buoy at the mouth of the Rhône River), Planier, POEM (Observational Platform of the Mediterranean Environment/Plateforme d’Observation de l’Environnement Méditerranéen), SOLA (SOMLIT Observatory of the Arago Laboratory/SOMLIT Observatoire de Laboratoire Arago) and with wave buoy in black: Banyuls, Espiguette, Leucate, Sète.*

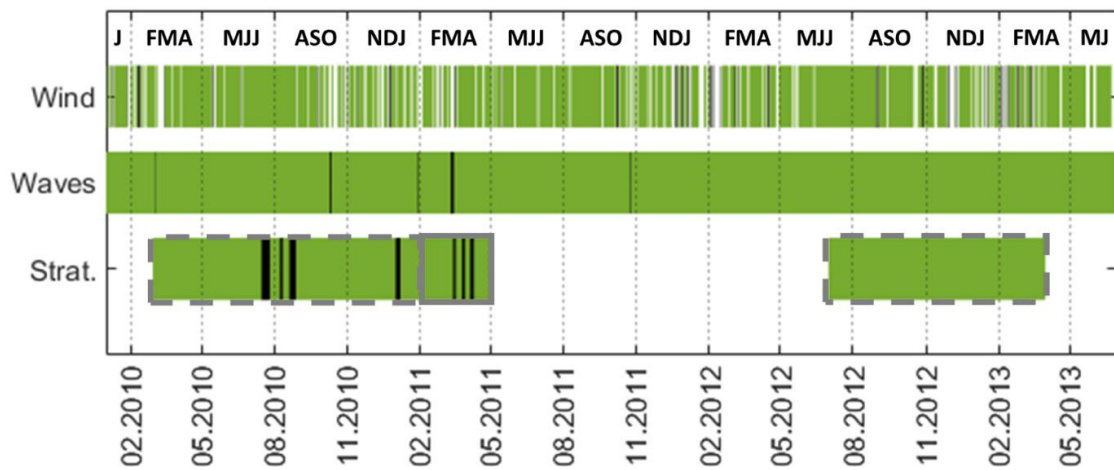


Figure 2: *Timetable with selected events (Black). Green is the reference period. For the wind events, the white zones are zones with intermediate wind. The wind and wave events are common to all stations. For the stratification event, striped line (- -) is the reference period for Besete and the full line (-) is the reference period for POEM. In the white zone, no observational data was available for these two stations. The dashed vertical lines (:) indicate the seasons and the letter triplets are the first letters of the months in that season.*

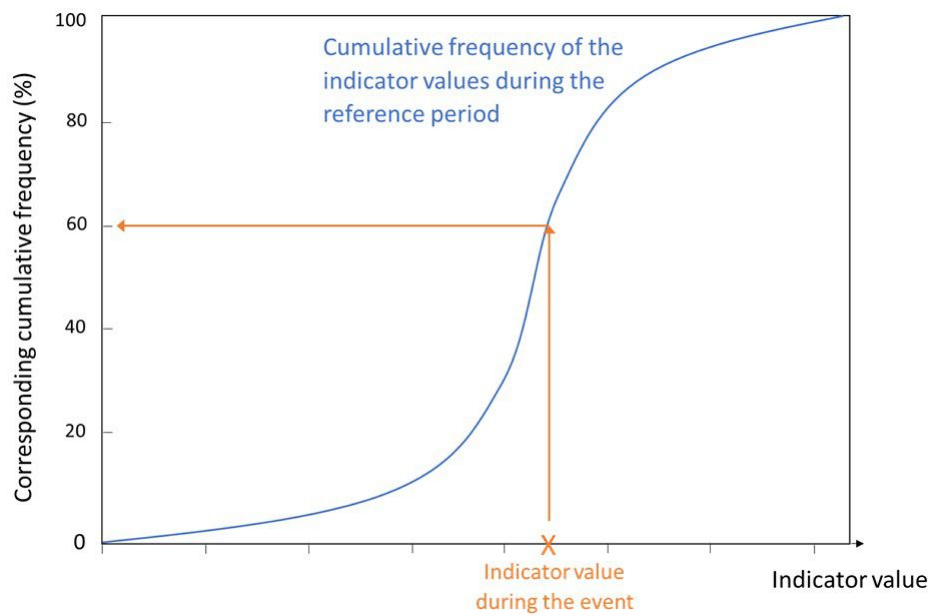


Figure 3: *Corresponding cumulative frequency example. The corresponding cumulative frequency of the indicator value during the event can be read on the y-axis of when placing the indicator value calculated during the event (orange X) on the cumulative frequency of the indicator values during the reference period (blue line).*

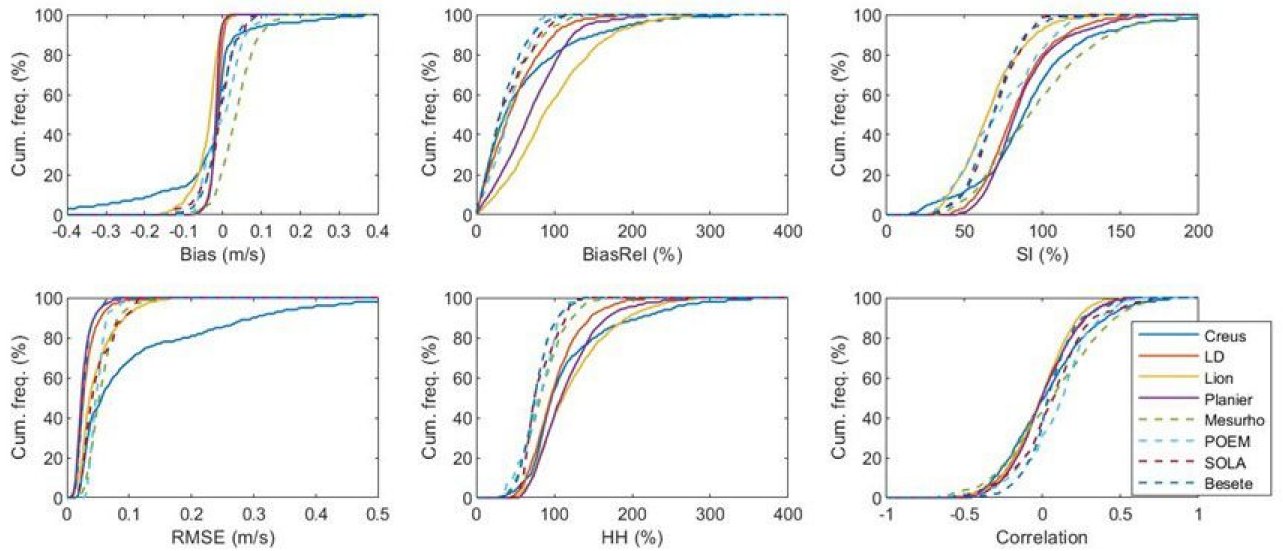


Figure 4: 42 hr reference period CFD. The indicators' cumulative frequencies integrated over 42 hr at all stations during the reference period. Shallow stations are depicted with a dashed line, deep stations with a solid line. A) Bias, B) Relative bias, C) SI, D) RMSE, E) HH, F) Correlation.

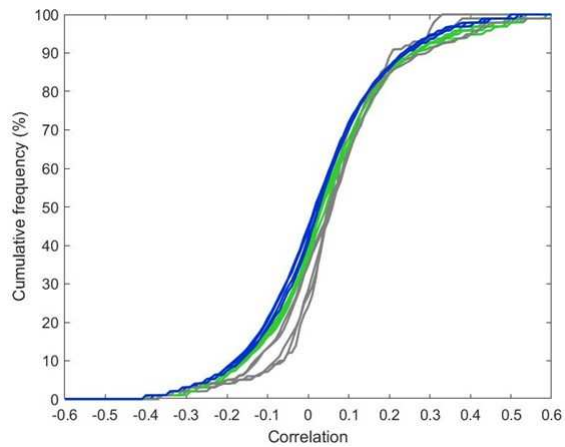


Figure 5: CFD of the correlation between modelled and observed flow speeds at BeSete during the reference period for different durations. Blue: 12-24hr, green: 24-72hr and grey: more than 72 hr.

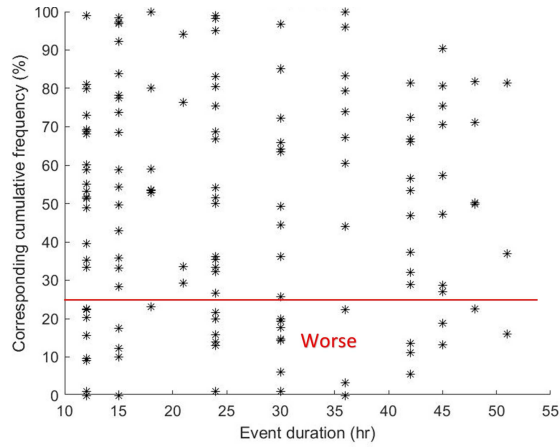


Figure 6: *Corresponding cumulative frequency of the wind's correlation. Scatter plot of the wind event duration in relation to the corresponding cumulative frequency of the correlation between modelled and observed current speed. Events with a corresponding cumulative frequency below 25% are considered worse during the event than during the reference period.*

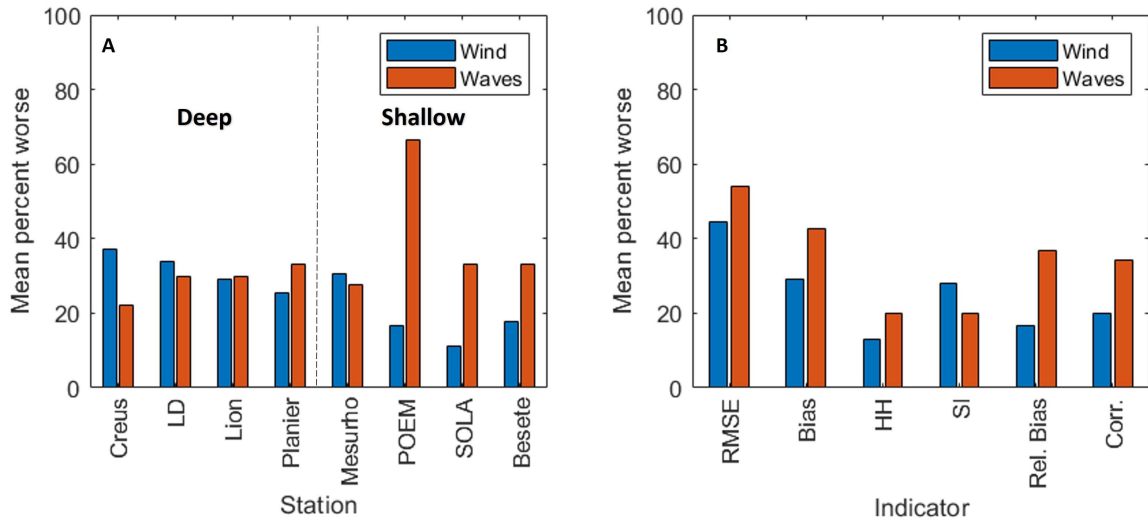


Figure 7: *Mean percent worse per station and indicator for wind and wave events. Histograms of the mean percent of wind/wave events worse during the events than during the reference period. A) Per station, B) Per indicator.*

Station name	Creus	LD	Lion	Planier	Mesurho	POEM	SOLA	BeSete (2010-2011)	BeSete (2012-2013)
Nr of bins	1	2	5	2	40	65	26	99	54
Bin size (m)	x	x	x	x	0.75	0.5	1.0	0.25	0.5
Depth (m)	295	505 975	152 246 501 1002 2330	505 975	18.7*	28.1*	24.9*	24.6*	24.4*
Time step (min)	30	60	30	60	10	60	20	20	20
Equipment (Frequency)	SP-ADCM (2MHz)				ADCP (600 KHz)				
Latitude	42.39	42.428050	42.037267	43.015083	43.32	42.704167	42.488333	43.333917	43.333917
Longitude	3.21667	3.544783	4.686133	5.192133	4.87	3.06667	3.145	3.639617	3.639617
Source	Schroeder et al. (2013)	Durrieu de Madron et al. (2019)	Testor et al. (2019) Houpert et al. (2016)	Durrieu de Madron et al. (2019)	Pairaud et al. (2016)	Bourin et al. (2015)	Unpublished Guizien	Unpublished Leredde	

Table A.1: Overview of all ocean current observation stations with the number of bins, the bin size, the depth, the time step, the type of equipment, the latitude, the longitude and the source. For the ADCPs, only the maximum depth is indicated (*).

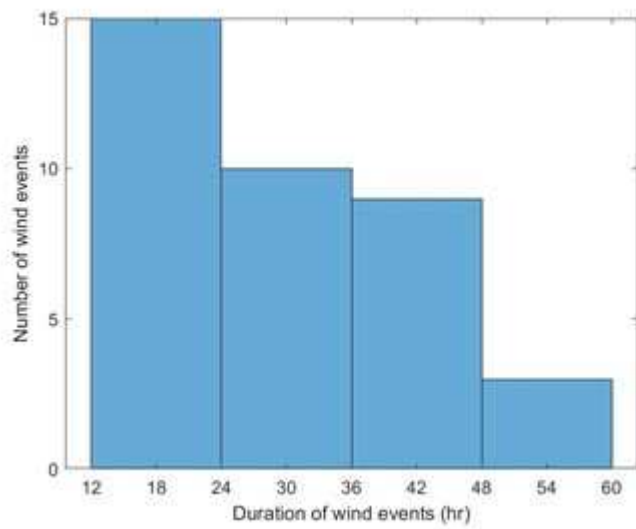


Figure A.1: *Frequency histogram of the durations of the wind events.*

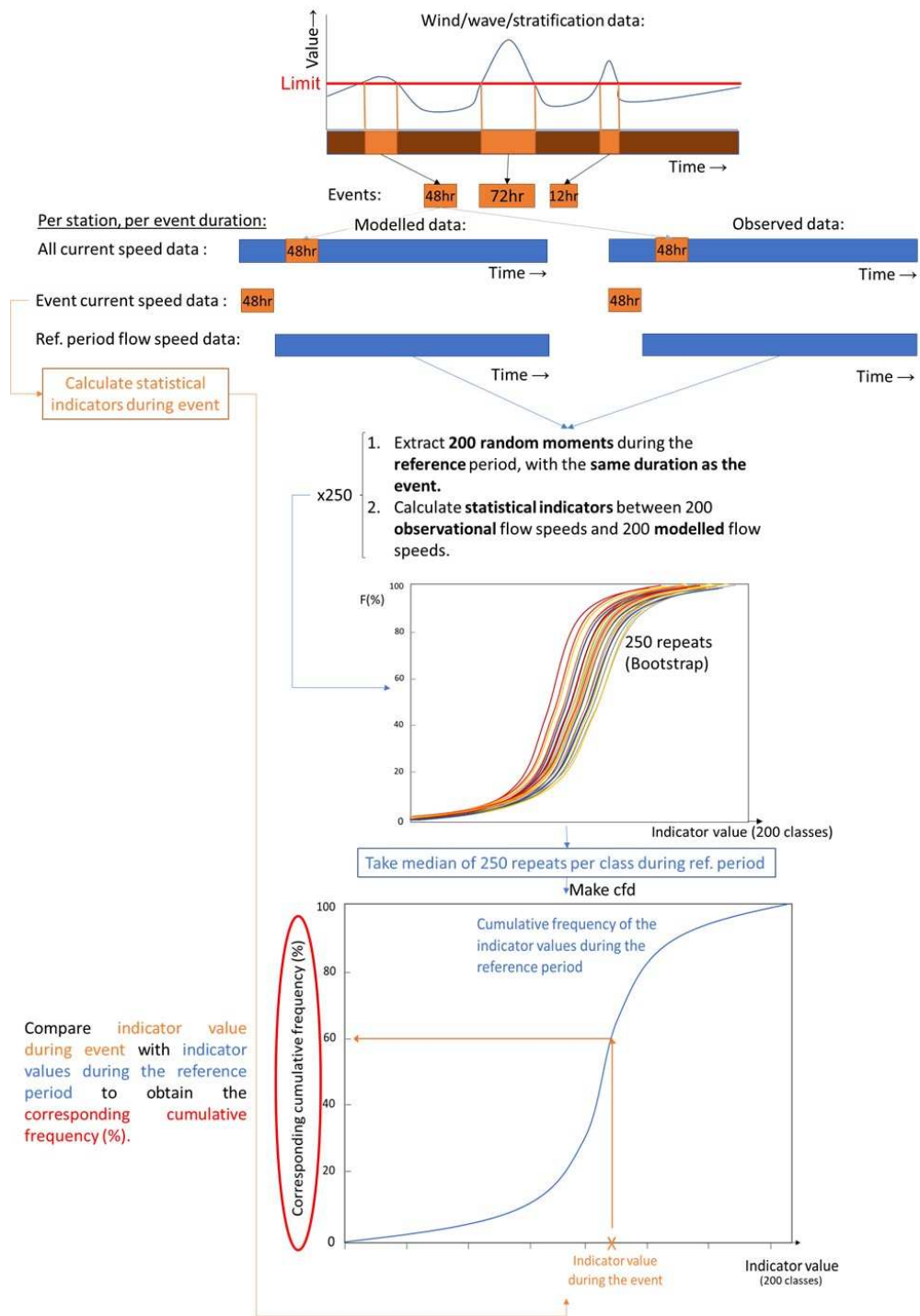


Figure A.2: Scheme on how to compare the uncertainty of the model during the event to the uncertainty of the model outside of the events.

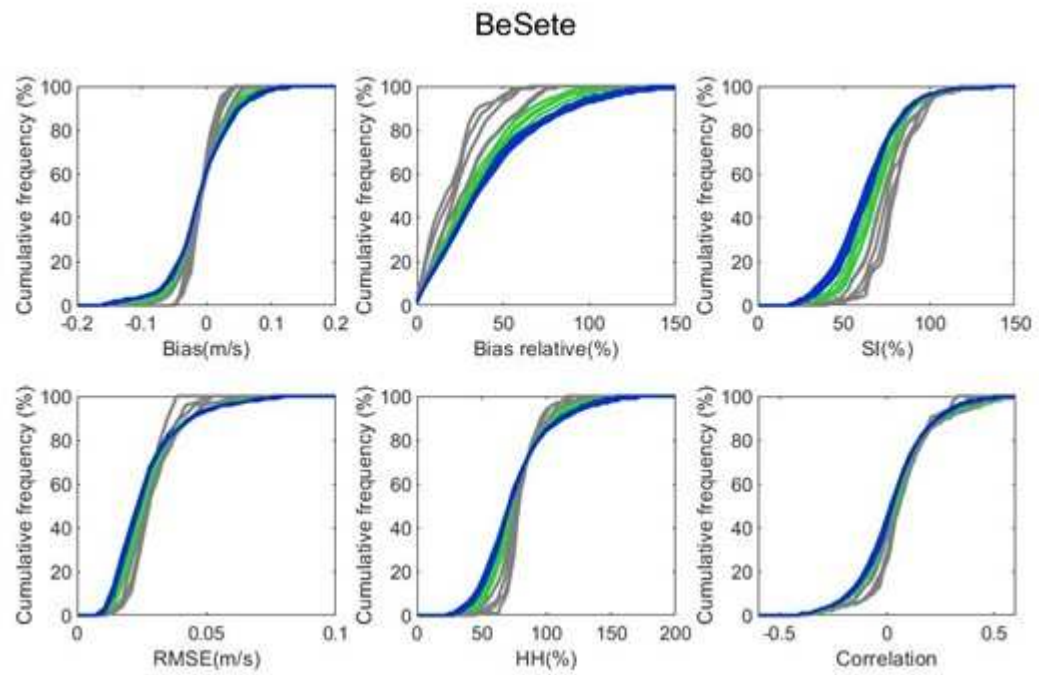


Figure A.3: Cumulative frequency distribution of the indicators calculated between modelled and observed flow speeds at BeSete during the reference period for different durations. Blue: 12-24hr, green: 24-72hr and grey: more than 72hr.