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# Evaluating the Effects of Tidal Turbines on Water-Mass Transport with the Lagrangian Barycentric Method

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**Abstract:** Characterising circulation pathways in tidal stream energy sites is fundamental to evaluate the effects of turbines power extraction on long-term water-mass transport. The Lagrangian residual currents are commonly used to assess the displacement of water particles over the tidal period. The associated circulation is, however, characterised by a strong dispersion as water particles may follow different trajectories depending on the release time during a tidal cycle. In order to obtain a synthetic cartography of the Lagrangian circulation, Salomon et al. (1988) proposed an original method that allocates the residual currents at the barycentre of particle trajectories. This Lagrangian barycentric method was here applied to the Fromveur Strait (western Brittany) – a region with strong potential for turbine farm implementation along the coast of France. A high-resolution depth-averaged numerical model computed the tidal circulation driven by the principal lunar semi-diurnal constituent  $M_2$ . The initial particle positions were taken at the 14,026 nodes of the unstructured computational grid surrounding the area of interest with a spatial resolution below 50 m. In the strait, the residual Lagrangian circulation was characterised by a strong asymmetry between (i) a prominent north-eastern pathway with residual currents up to  $0.45 \text{ ms}^{-1}$  and (ii) a southward circulation. Both upstream and downstream the strait, we exhibited prominent cyclonic and anti-cyclonic recirculations. A close correlation was found between the north eddy and a prominent sand bank. We simulated the forces induced by a series of horizontal-axis turbines as an additional bed friction sink term at the scale of the tidal farm. The extraction of tidal stream energy modified the amplitude and direction of the Lagrangian circulation along the current stream emerging from the strait with (i) a tendency for surrounding eddies to get closer to the tidal stream energy site and (ii) possible effects on the evolution of surrounding seabed features.

**Key words:** Tidal Flow Asymmetry; Water Particles; Drifters; Numerical Modelling; Telemac; Fromveur Strait.

## 1. Introduction

The evaluation of water-mass transport in tidal stream energy sites is of great ecological interest in assessing water-quality changes induced by turbines power extraction. This includes effects on trapping and dispersion of fish eggs, larvae, nutrients, and suspended sediments (Edwards *et al.*, 2006). But it may also serve specific objectives like transport predictions of (i) drifters potentially harmful to structures' blades or (ii) polluting substances accidentally released by devices (Sanderson and Redden, 2015). Transport studies in stream energy sites were, however, primarily dedicated to changes induced by turbines on sediment transport (*e.g.*, Neill *et al.*, 2012; Fairley *et al.*, 2015; Thiébot *et al.*, 2015). Shapiro (2011) conducted a preliminary numerical evaluation of turbines' effects on passive tracer pathways in the Celtic Sea, north of Cornwall (the United-Kingdom). Nevertheless,

simulations operated a single release of floats disregarding the influence of the initial drop time on particle trajectories.

In this study, we investigated the impacts of tidal stream power extraction on the long-term displacement of water particles by exhibiting changes induced on the Lagrangian Residual Circulation (LRC). As water particles may follow different trajectories depending on the release time during a tidal cycle, residual currents are characterised by a strong dispersion and are difficult to define in a single synoptic view. We thus relied on an original method, proposed by Salomon *et al.* (1988), to map the LRC in the English Channel and western Brittany. This technique, denominated Lagrangian barycentric, applies for a tidal circulation driven by a single tidal harmonic, such as the principal lunar semi-diurnal component  $M_2$  along the Atlantic coast of Europe. It provided furthermore a first overview of long-term transport pathways in north-western European shelf seas while significantly reducing the

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computational time (Orbi and Salomon, 1988; Salomon and Breton, 1993; Breton and Salomon, 1995).

The method was applied to the Fromveur Strait, off western Brittany, which separates the island of Ushant from the Molène archipelago through a 2 km wide and 50 m deep strait (Fig. 1). This location was identified, with the Alderney Race in the English Channel, as one of the largest tidal stream energy resources along the coast of France (Guillou *et al.*, 2018). The French government thus identified a restricted area of 4 km<sup>2</sup> within the strait for the implementation of tidal stream arrays. A series of numerical investigations were conducted in this site to refine the predictions of available tidal kinetic energy and evaluate the short-term hydrodynamic effects induced by tidal stream power extraction (Guillou *et al.*, 2016; Guillou and Thiébot, 2016; Guillou, 2017). Nevertheless, no modelling study was dedicated to capture of, at high-spatial resolutions (~50-100 m), (i) the tide-induced circulation pathways in this strait and (ii) the changes associated with tidal stream power extraction.

An original approach was adopted to couple the Lagrangian barycentric method (Section 2.1) with numerical predictions of particle tracking obtained at high-spatial resolution in the strait (Section 2.2). Predictions were assessed against available measurements of current amplitude and direction at two locations in the area of interest (Section 3.1). LRC patterns were interpreted in relation to the tidal-current asymmetry and recirculations in the area of interest (Section 3.2). This investigation was completed by an analysis of long-term particle trajectories (Section 3.3). Changes induced by a series of horizontal-axis turbines, varying in numbers, were finally evaluated (Section 3.4).

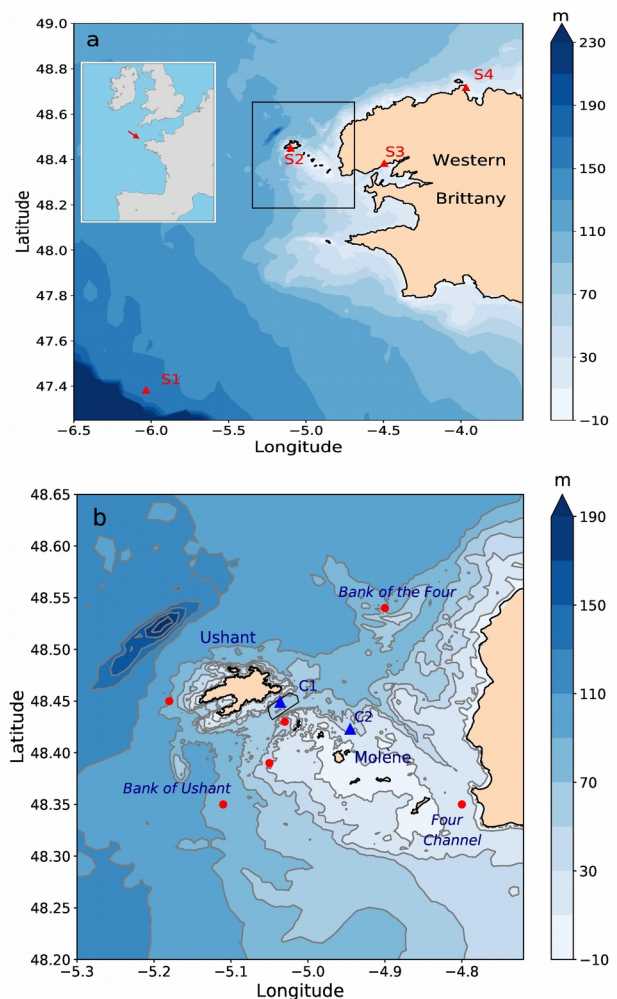
## 2. Materials and Methods

### 2.1. Lagrangian Barycentric Method

The different steps of the Lagrangian barycentric method are briefly detailed hereafter. Further information can be found in Salomon *et al.* (1988), Orbi and Salomon (1988), and Salomon and Breton (1993).

The first step is to compute, based on a particle-tracking numerical method, the trajectories of drifters released at hourly intervals during a tidal cycle. The circulation model is driven by a mono-frequency tide to emphasise the single period that characterises the long-term displacements of water particles. The dominant semi-diurnal constituent  $M_2$  is usually retained along the European Atlantic coast. The initial particle positions have to be spread over the area of interest while covering, with a refined spatial resolution, shoals and coastal irregularities that may impact the tidal circulation.

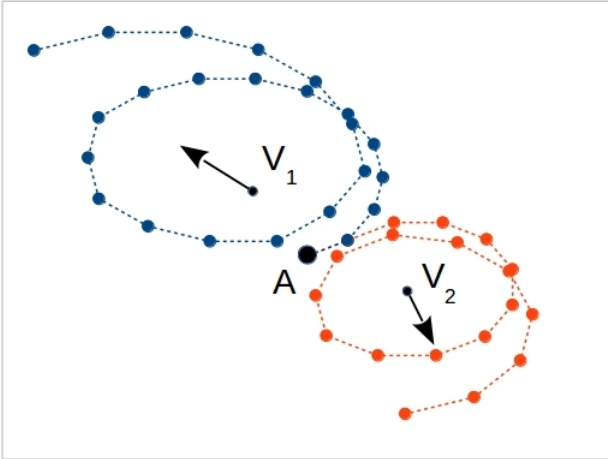
The second step is to compute the Lagrangian residual currents defined as the displacements of water particles over the tidal period considered (Zimmerman, 1979). For a



**Figure 1. Bathymetry of the Ushant-Molène archipelago with locations of available tidal gauges S1-S4 (red triangles), current meters C1 and C2 (blue triangles) and initial positions of floats for assessing long-term particles trajectories (red circles). The black line delimits the area of interest for turbine implementation in the Fromveur Strait. Water depth is relative to mean sea level.**

given initial position, a series of Lagrangian residual currents is thus obtained, the total number matching with the number of particles released during a tidal cycle. The computed vector field presents, however, a strong dispersion that exhibits the influence of the release time on particle trajectories (Fig. 2). At a given position, this is characterised by a beam of Lagrangian velocities that is very difficult to analyse and interpret. In order to reduce the dispersion of the vector field, residual currents are allocated at the barycentre of computed trajectories, considered to be more representative of particle displacements.

The non-divergence of the velocity field is finally evaluated. The result is a single Lagrangian residual



**Figure 2. Schematic representation of the barycentric system.**

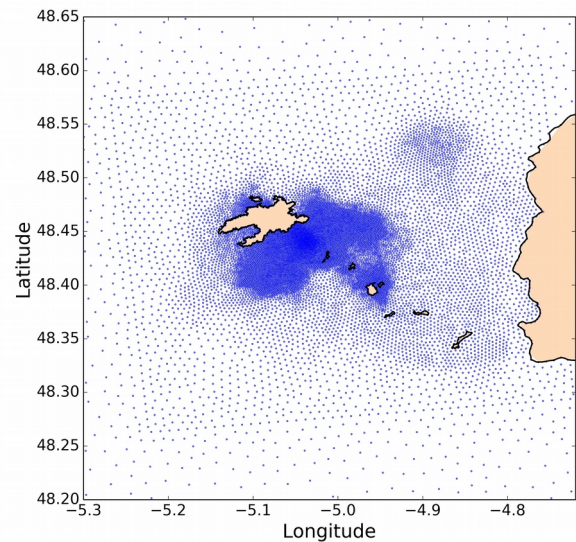
velocity field that can be exploited to identify and depict the major patterns of tide-induced particle transport.

### 2.2. Numerical Modelling

The application of the Lagrangian barycentric method in the Fromveur Strait relied on numerical simulations of tidal currents conducted by Guillou and Thiébot (2016). The depth-averaged model Telemac 2D (version v6p3; Hervouet, 2007) was implemented on an unstructured computational grid covering the western extend of Brittany with a spatial resolution of 10 km at offshore sea boundaries to less than 50 m in the strait. Whereas the area of interest may be subjected to storm wave conditions liable to impact tidal currents (*e.g.*, Guillou and Chapalain, 2015; Guillou *et al.*, 2016), these effects were disregarded driving simulations with the dominant  $M_2$  component and its quarter-diurnal generated harmonic  $M_4$ . Integrating the  $M_4$  forcings was found to improve its generation from  $M_2$  in the numerical model, in particular at open boundaries close to landmass (Pingree and Maddock, 1978; Guillou and Chapalain, 2010). A series of major harmonic components was furthermore considered to assess model's performances with respect to in-situ currents measurements. The harmonic components were extracted from the TPX07-atlas 2011 database that covers the area of interest with a spatial resolution of  $1/12^\circ$  (Egbert and Erofeeva, 2002).

Particle trajectories were computed with the transport module of Telemac 2D (EDF R&D, 2013; Joly *et al.*, 2014). The initial particle positions were taken at the 14,026 nodes of the computational grid surrounding the Ushant-Molène archipelago (Fig. 3). Particles were released at a hourly interval during a  $M_2$  tidal cycle, resulting in a field of 182,338 ( $=13 \times 14,026$ ) Lagrangian residual vectors. The velocity field was allocated at the barycentre of particle trajectories and finally, its non-divergence was finally evaluated.

In the numerical model, the effect of tidal stream power extraction on the tidal circulation was integrated as an additional bed friction sink term in the momentum equations. This sink term was computed by averaging the turbines' thrust and structural drag forces over the  $4 \text{ km}^2$  area covered by the proposed array (Plew and Stevens, 2013). Further details about this numerical approach are available in Guillou and Thiébot (2016). The investigation considered horizontal-axis turbines with a blade diameter of 18.6 m and maximum power output of 1 MW (Plew and Stevens, 2013; Guillou and Thiébot, 2016). Finally, simulations integrated five tidal farm configurations varying in the number of turbines: 10, 50, 100, 150, and 207 devices. The number of 207 turbines was obtained by retaining a density of 50 machines per  $\text{km}^2$  over the area identified for the implementation of tidal stream arrays in the Fromveur Strait (Thiébot *et al.*, 2015).



**Figure 3. Spatial distribution of computational nodes around the Ushant-Molène archipelago. This distribution displays the initial particle positions.**

## 3. Results and Discussion

### 3.1. Evaluation of Model Predictions

Attention was first directed to the evaluation of model's ability to reproduce tidal harmonic components. This was then followed by a comparison of predicted currents against observed currents.

Predicted amplitudes and phases of the  $M_2$  and  $M_4$  harmonic components were computed with a simple Fourier analyses of predicted sea-surface elevations. The results were compared to values derived from tidal-gauge observations at four locations in western Brittany, corresponding to stations (i) S1 in offshore waters ( $\lambda=6.033^\circ\text{W}$ ,  $\varphi=47.383^\circ\text{N}$ ), (ii) S2 near Ushant island ( $\lambda=5.100^\circ\text{W}$ ,  $\varphi=48.450^\circ\text{N}$ ), (iii) S3 in the harbor of Brest ( $\lambda=4.495^\circ\text{W}$ ,  $\varphi=48.383^\circ\text{N}$ ), and (iv) S4 in the harbor of

Roscoff ( $\lambda=3.967^\circ\text{W}$ ,  $\varphi=48.717^\circ\text{N}$ ) (Fig. 1a, Tables 1 and 2). The observations were extracted from the compilations established by Sinha and Pingree (1997) and Pouvreau (2008). The numerical results reproduced the amplitudes and phases of the harmonic components, and the northwards increase of the  $M_2$  amplitude with differences restricted to 1%. Greater differences were obtained for  $M_4$  at point S4. These results were, however, consistent with the numerical estimations of Sinha and Pingree (1997), both models integrating lower spatial resolution around the islands and shoals of north-eastern Brittany. Finally, the predicted spatial distributions of the amplitudes and phases of  $M_2$  and  $M_4$  were consistent with maps published by Sinha and Pingree (1997) and Pineau-Guillou (2013) at the scale of the European shelf seas. These comparisons confirm the model's ability to assess tide-induced vertical variations of the water surface within the area of interest.

**Table 1. Observed and predicted amplitudes  $A$  and phases  $G$  (relative to Greenwich) for  $M_2$  harmonic constituent at four locations in western Brittany.**

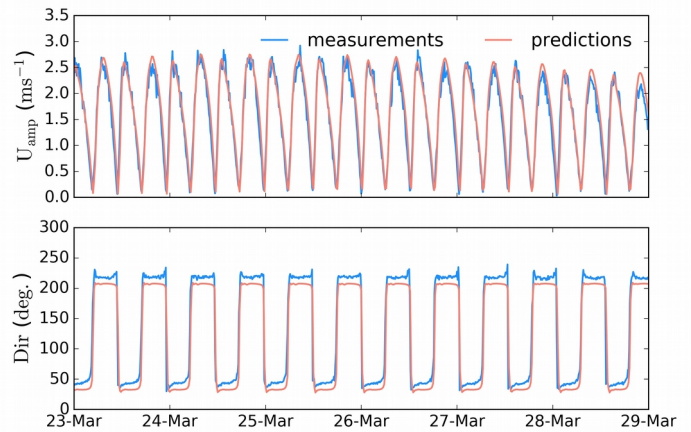
Station number	Observed		Modelled	
	A (m)	G (deg.)	A (m)	G (deg.)
S1 (offshore)	1.36	99.7	1.35	90.9
S2 (Ushant)	2.07	111.0	2.09	99.9
S3 (Brest)	2.05	-	2.06	-
S4 (Roscoff)	2.70	142.8	2.69	133.1

**Table 2. Observed and predicted amplitudes  $A$  and phases  $G$  (relative to Greenwich) for  $M_4$  harmonic constituent at four locations in western Brittany.**

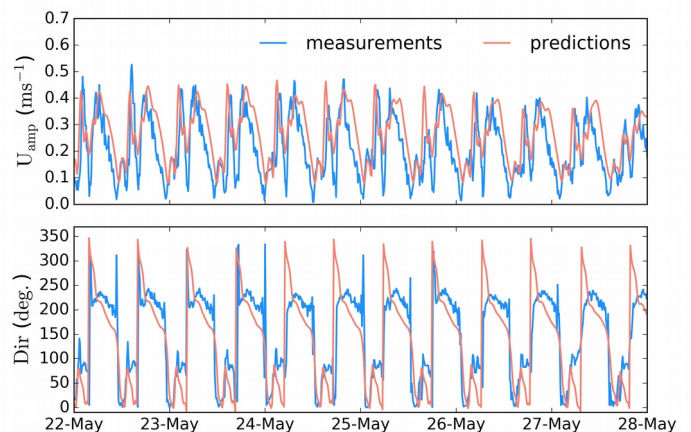
Station number	Observed		Modelled	
	A (m)	G (deg.)	A (m)	G (deg.)
S1 (offshore)	$1.2 \times 10^{-2}$	296.5	$1.2 \times 10^{-2}$	290.3
S2 (Ushant)	-	-	-	-
S3 (Brest)	$5.4 \times 10^{-2}$	-	$6.8 \times 10^{-2}$	-
S4 (Roscoff)	$5.4 \times 10^{-2}$	143.4	$9.1 \times 10^{-2}$	120.0

Evaluation of model's performances was completed by a comparison of predictions with measurements of current amplitude and direction, performed by the French navy SHOM, at two locations, in the Fromveur Strait (point C1,  $\lambda=5.036^\circ\text{W}$ ,  $\varphi=48.449^\circ\text{N}$ ) and north of Molène island (point C2,  $\lambda=4.945^\circ\text{W}$ ,  $\varphi=48.423^\circ\text{N}$ ) (Figs. 1b, 4, and 5). Measurements periods covered spring to neap tidal conditions between (i) 19 March and 2 April 1993 at point C1 and (ii) 14 May and 11 June 1993 at point C2.

Assuming vertical logarithmic velocity profiles, the comparison was conducted 10 m above the bed, matching the operating height of horizontal-axis turbines in the strait (Guillou *et al.*, 2016). The agreement between predictions and observations was particularly noticeable in the Fromveur Strait. Numerical results approached the evolution of current amplitude seen in the observations, with a mean relative difference of  $0.06 \text{ m s}^{-1}$ , and Pearson's correlation coefficient of 0.96. Greater differences were seen to the north of Molène, a region characterised by complex hydrodynamics recirculations, impacted by shoals and islands. The numerical results reproduced the pronounced observed asymmetry of spring tidal currents with (i) strong and short north-eastern components and (ii) reduced, long-lasting south-western velocities. In both cases, the model simulated the abrupt changes observed between south-west and north-east directions.



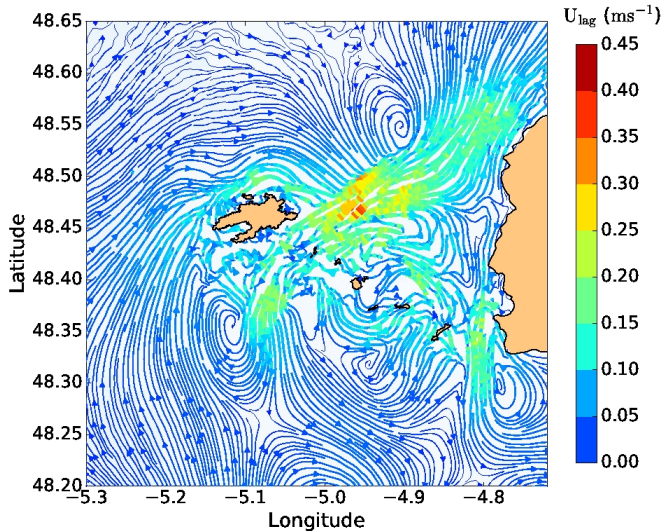
**Figure 4. Measured and computed time series of the amplitude and direction (anticlockwise convention from the East) of the current, 10 m above the bed, at point C1 (Fig. 1) in March 1993.**



**Figure 5. Measured and computed time series of the amplitude and direction (anticlockwise convention from the East) of the current, 10 m above the bed, at point C2 (Fig. 1) in May-June 1993.**

### 3.2. Lagrangian Circulation Pathways

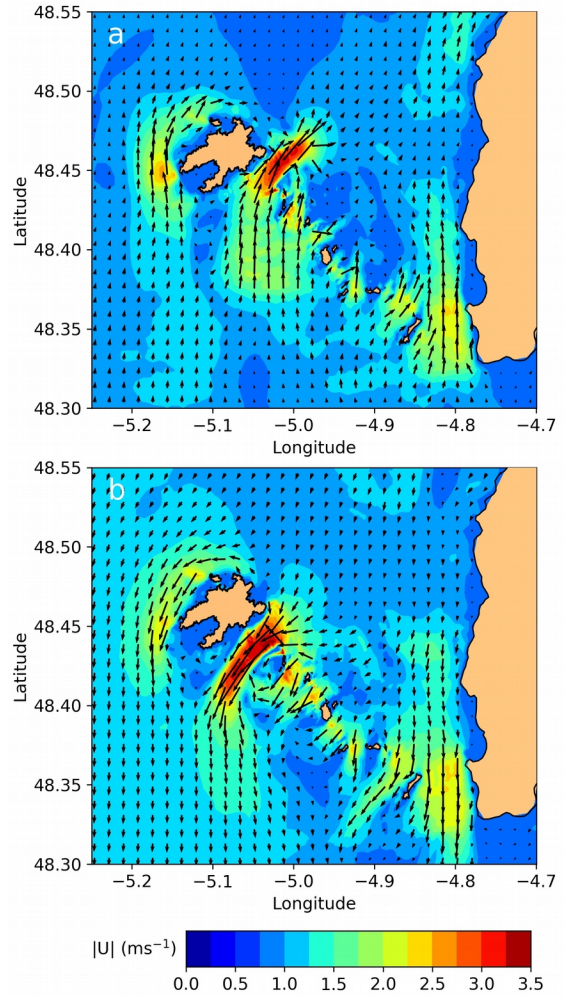
In the Fromveur Strait, the predicted LRC exhibited a central divergence area between (i) a prominent north-eastern pathway with residual currents up to  $0.45 \text{ m s}^{-1}$ , and (ii) a southward circulation with Lagrangian currents restricted to  $0.20 \text{ m s}^{-1}$  (Fig. 6). This Lagrangian pattern was partly associated with the asymmetry of tidal currents in the strait, characterised by (i) a north-eastern flood-dominated sector in the north, and (ii) a south-western ebb-dominated region in the south (Guillou and Thiébot, 2016; Fig. 7). As revealed by a series of numerical investigations (Neill *et al.*, 2014; Guillou and Chapalain, 2017; Guillou *et al.*, 2018), such asymmetry is typical of tidal strait dynamics and arises from the phase relationship between  $M_2$  and  $M_4$ . The central divergence area of tidal straits is thus primarily targeted for the development of tidal farm projects as it is characterised by reduced current asymmetry allowing thus balanced energy production between flood and ebb.



**Figure 6. Streamlines from tidal residual Lagrangian currents without effects of stream power extraction.**

Away from the strait, computed streamlines were consistent with the regional investigation conducted, in western Brittany, by Salomon *et al.* (1988) and based on the Lagrangian barycentric method. The residual currents thus exhibited a prominent northward pathway, which deflects towards the east around Ushant and connects to the circulation emerging from the Fromveur Strait.

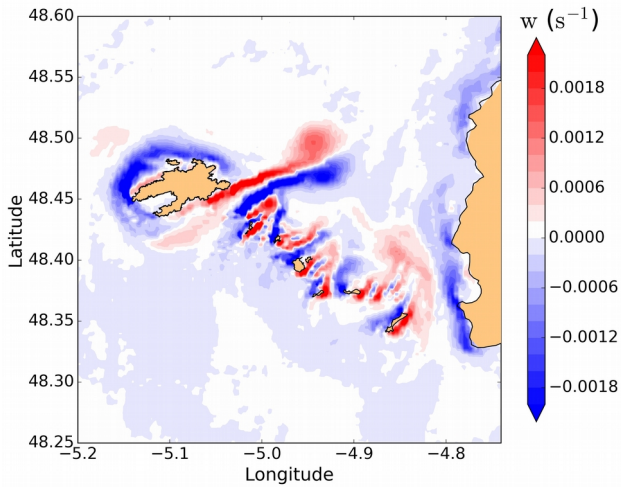
Both upstream and downstream the strait, prominent cyclonic and anti-cyclonic recirculations, with diameters of around 8 km, were seen. The LRC placed these eddies to the south and north-east of Ushant, respectively. The location of the northern eddy differed, however, from previous regional investigations conducted at the scale of western Brittany. Salomon *et al.* (1988) located this Lagrangian structure to the north of Ushant island by applying the Lagrangian barycentric method to regional tidal predictions. Muller *et al.* (2009) positioned it further



**Figure 7. Depth-averaged currents without tidal stream array at times of (a) flood and (b) ebb peaks of a  $M_2$  tidal cycle in the Fromveur Strait.**

west by relying on High-Frequency Radar (HFR) observations of the surface circulation in calm weather conditions. Nevertheless, the eddy, identified to the north-east of Ushant island, was closely correlated with the Bank of the Four, which confirms its position (Figs. 1 and 6). It was thus centred at the edge of the corner formed by the bank while extending to its southern and eastern limits. Following Neill and Scourse (2009) and Guillou and Chapalain (2011), a possible relationship may exist between this prominent sandbank and the tide-induced Lagrangian structure.

Further simulations showed that this residual eddy resulted from recirculations that appeared on the western edge of the flow emerging from the Fromveur Strait (Fig. 8). The residual Lagrangian structure was thus still present if the sandbank was removed from the bathymetry. It seems therefore that a refined spatial resolution is required to resolve the residual circulation emerging from the strait and

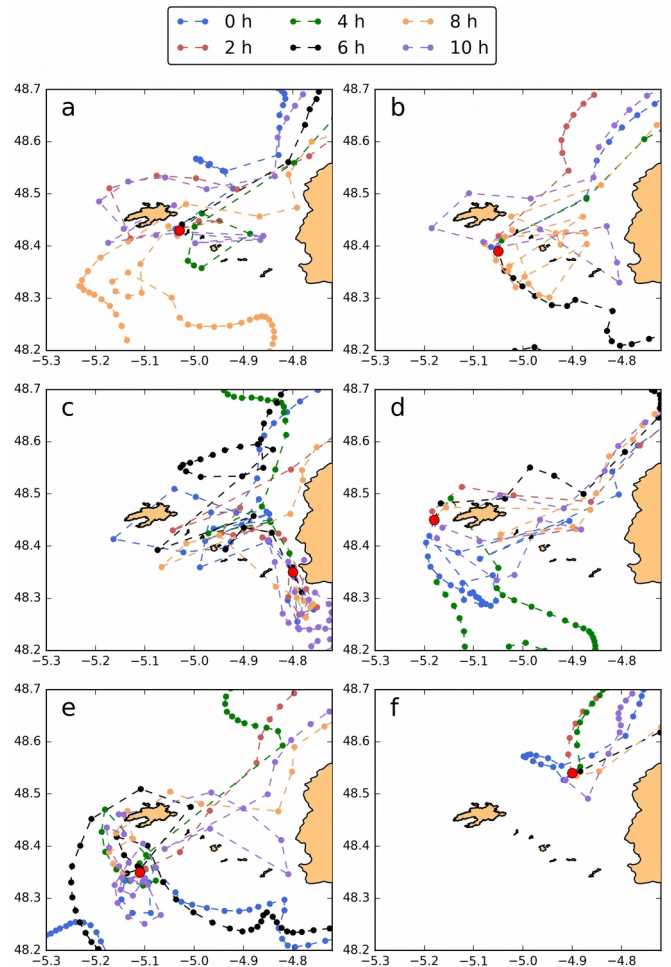


**Figure 8. Vorticity of depth-averaged tidal currents during the flood period in the Fromveur Strait.**

the associated recirculations. Previous studies in this area (Salomon *et al.*, 1988; Muller *et al.*, 2009) were conducted at spatial resolutions between 650 m and 1.5 km, whilst the numerical model adopted here used a mesh size of 50 m in the strait. This explains the differences in the reported LRC around the Ushant-Molène archipelago.

### 3.3. Particle Trajectories

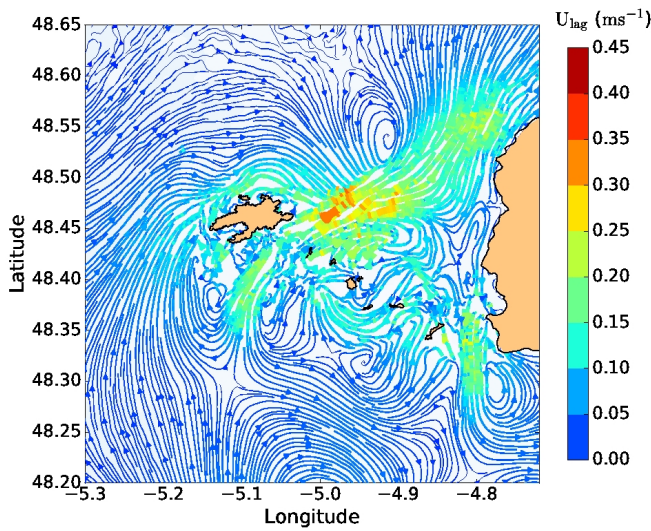
The investigation was completed with an analysis of float trajectories as validation of the Lagrangian barycentric method, and confirmation of the major features of the computed LRC. The initial particle positions were selected at six locations of interest in and around the Ushant-Molène archipelago, including the positions of surrounding sandbanks (Fig. 1). Predictions exhibited the dispersion of particle pathways with respect to the initial time of release during the tidal cycle (Fig. 9). Drifters released in the south-western part of the Fromveur Strait may thus (i) flow towards the English Channel following the prominent north-eastern circulation, (ii) flow around the western side of Ushant, another prominent pathway, or (iii) be driven towards the southern boundary (Fig. 9-b). The computed LRC (Fig. 6) was, however, consistent with these trajectories, reproducing the pathways' variability. Particle trajectories confirmed, in particular, (i) the asymmetry of residual currents in the strait and (ii) surrounding recirculations. The initial release in the Four Channel displayed the cyclonic recirculation identified above the Bank of the Four (Fig. 9-c). Finally, the area of interest was characterised by short residence times. Whereas localised trapping areas may be identified in the nearshore waters of the Molène archipelago, particles released in the vicinity of the Fromveur Strait were characterised by short residence times, being evacuated from the area of interest, on average, in less than three days.



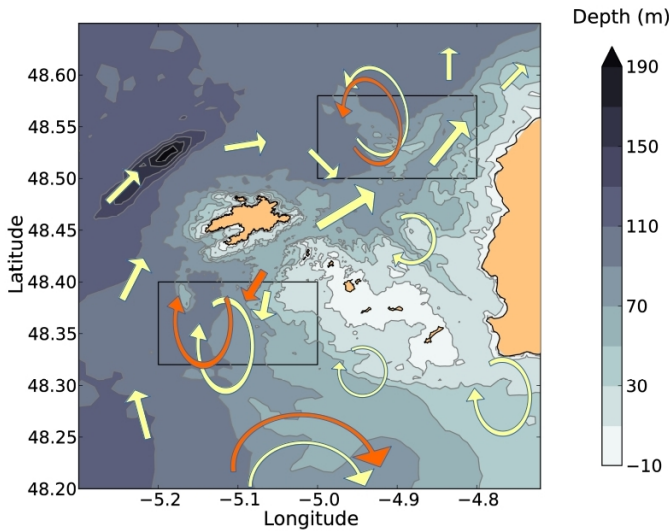
**Figure 9. Long-term trajectories resulting from the release of floats, with a time step of 2 hours, during a  $M_2$  tidal cycle. The initial positions of floats are indicated with red circles. Particles positions are displayed every 12 hours to facilitate the interpretation of trajectories.**

### 3.4. Effects of Tidal Stream Power Extraction

The extraction of tidal stream power impacted mainly (i) the amplitude and direction of the residual currents emerging from the Fromveur Strait and (ii) the locations of surrounding eddies (Figs. 10 and 11). The southward Lagrangian pathway was thus found to deviate westwards, modifying the anti-cyclonic recirculation identified in the vicinity of the Bank of Ushant. The north-eastern Lagrangian pathway, emerging from the strait, was characterised by a reduced amplitude, which displaced south-westwards the location of the cyclonic eddy to the northeast of Ushant. For the extreme array configuration that incorporated 207 turbines, the positions of the southern and northern eddies were modified by 3 and 1.7 km, respectively. These modifications may have possible implications on the evolutions of sandbanks. This may



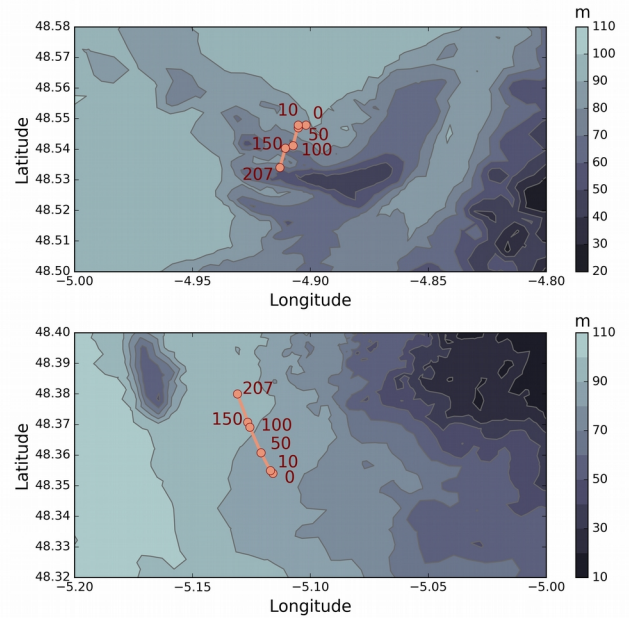
**Figure 10.** Streamlines from tidal residual Lagrangian currents with effects of stream power extraction from a series of 207 devices in the Fromveur Strait.



**Figure 11.** Interpretation of major features of residual Lagrangian currents patterns without (yellow lines) and with (orange lines) a tidal farm of 207 turbines in the Fromveur Strait. The spatial distribution of mean water depth is displayed in grey scale. The black lines delimit the areas displayed in Fig. 12.

impact mainly the Bank of the Four, whose location correlated strongly with the northern eddy (Section 3.2). As the southern eddy was closer to the strait than the northern eddy, changes induced by tidal stream power extraction were more noticeable for this recirculation. For the 50 device array configuration, the centre of the southern eddy moved by 820 m whilst the displacement of the northern recirculation was restricted to 220 m. Furthermore, the

induced modifications followed a non-linear evolution with respect to the number of turbines. The displacement of the eddy centres evolved in stages, as exhibited by the small differences seen between the 100 and 150 turbine configurations (Fig. 12).



**Figure 12.** Positions of the centres of the (top) northern and (bottom) southern Lagrangian residual recirculations identified on both part of the Fromveur Strait without turbines and for a series of devices in the tidal farm.

## 4. Conclusions

An original approach, coupling the Lagrangian barycentric method with predictions from a high-resolution depth-averaged circulation model, was applied to the tidal stream energy site of the Fromveur Strait in western Brittany (France). The main outcomes of the present investigation are as follows:

1. Predicted streamlines refined the definition of the LRC in the Ushant-Molène archipelago exhibiting prominent transport pathways and recirculations liable to trap water particles. The strait was characterised by a strong asymmetry between (i) a prominent north-eastern pathway with residual currents up to  $0.45 \text{ m s}^{-1}$  and (ii) a southward circulation. Both upstream and downstream of the strait, the computed LRC identified cyclonic and anti-cyclonic recirculations.

2. A close correlation was exhibited between the north cyclonic eddy and the Bank of the Four. The investigation of current vorticity highlighted that this residual eddy was generated from recirculations on the western edge of the flow emerging from the strait. Refined spatial resolutions are thus required to reproduce this recirculation, which



explains differences between this and previous regional investigations.

3. The extraction of tidal stream power modified the amplitude and direction of residual currents emerging from the strait, and the positions of the surrounding eddies. These recirculations moved closer to the tidal stream energy site as the number of turbines increased. For the extreme configurations that integrated 207 devices, the displacements of the eddy centres exceeded 1.5 km, with possible implications for the evolution of surrounding sand banks.

The Lagrangian barycentric method provided a synthetic overview of water particle trajectories exhibiting the major patterns of the complex circulation at the tidal stream energy site of the Fromveur Strait. However, further in situ observations of drifters trajectories are required to refine the assessment of the particle-tracking method retained here. Three-dimensional numerical modelling may furthermore be conducted to include the influences of meteorological forcings, in particular the wind-driven circulation.

### Acknowledgments

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