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Turbulence characterization at a tidal energy site using large-eddy simulations: case of the Alderney Race

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Sites suitable for the deployment of tidal turbines generally show a combination of complex seabed morphologies and extreme current magnitudes. Such configurations favour the formation of vortices, which can be very powerful. Anticipating the vortex effect on the turbine performance and/or lifespan requires refined description of the turbulence. Thanks to increased calculation resources, large-eddy simulation (LES) can now be applied to natural flow. An LES approach developed within the TELEMAC-3D open-source software is presented here. After validating the model with *in-situ* measurements, the model is applied to characterize the flow statistics of the Alderney Race.

This article is part of the theme issue ‘New insights on tidal dynamics and tidal energy harvesting in the Alderney Race’.

1. Introduction

In the context of the development of renewable energies, marine energies are viewed with great interest. Not yet mature, the tidal energy extraction sector has great potential, through the deployment of submerged turbine farms. The installation of devices requires a detailed knowledge of tidal currents, in order to be able to anticipate both their performance and their fatigue [1,2]. The turbulence produces vibrations of the turbine elements and induces fatigue. According

to Clark [1], small vortices (length smaller than the blade string) induce a local modification of the flow, and affect the blade surface boundary layer properties, altering mean drag and lift of blades. Medium-sized vortices cause unsteadiness of the mean flow by exerting snap loading. Finally, large-size vortices induce a significant variability of the mean flow.

The influence of turbulence on the power and the thrust of tidal turbines, as well as their wake, have been examined experimentally in [2,3]. These measurements were obtained by installing a turbine model in a flume tank and a towing tank, respectively, and varying the turbulent intensity in the flume. According to the measurements of [2], increasing turbulence intensity reduces the power and the thrust by over 10% in extreme cases. The turbulent effects have also been studied numerically in [4], where a horizontal axis tidal turbine operating over an irregular bathymetry has been simulated [5]. Those investigations confirmed that bedform-induced turbulence enhances wake deficit recovery. It also induces sudden drops in the turbines' instantaneous performance as well as large fluctuations in the hydrodynamic loadings on the blades (up to 20% as observed in [6,7]), the latter being a potential risk of fatigue failure of the blades. Field measurements have been conducted at sites favourable to the installation of tidal turbines [8,9]. Those field surveys have shown that flows are highly turbulent, but also site-specific [8,9] and highly dependent on the seabed morphology. Each tidal site of interest for the turbines' implantation should thus be characterized carefully. The Alderney Race (Raz Blanchard in French) situated between the Cap de la Hague (France) and the Alderney island is a highly energetic tidal site that was studied during the THYMOTE project [10].

The hydrodynamic characterization of tidal energy sites is generally carried out with numerical simulations [11–13], in which turbulence is modelled with Reynolds-Averaged Navier–Stokes (RANS) approaches [13–15]. In those studies, turbulence is not resolved and all turbulent statistics are not computed (the turbulence is assumed to be isotropic). The RANS approach is the main method used in environmental softwares (Delft3D, Mike3, TELEMAC-3D, MARS-3D) in which the effect of mean flow turbulence is simulated via turbulence models such as the $k - \varepsilon$ [16]. However, turbulent statistics are often incomplete and underestimated with RANS approaches [17,19,20], and thus cannot lead to a thorough turbulence description. Due to the rise of calculation resources, large-eddy simulation (LES) approaches are now envisaged for such applications.

The objective of this paper is to present a characterization of the turbulence in the Alderney Race by numerical simulation with the TELEMAC system [21]. The code TELEMAC-3D is a RANS finite-element free surface solver. It was modified to simulate environmental flow by LES [17,19]. The modelling strategy consisted in embedding an LES within a larger RANS simulation. Section 2 presents the turbulence modelling strategy, and §3 presents the Alderney Race and the numerical study of this site.

2. Numerical methods

Turbulence modelling in tidal flows is a highly multi-scale problem. Spatially, it requires to resolve scales ranging from the sizes of the coastal area (to simulate the tide propagation) to the sizes of the largest turbulent structures (to obtain reliable estimates of turbulent motion). We thus opted for an embedded LES technique.

The TELEMAC-3D solver relies on a sigma transform [22,23]. Two-dimensional unstructured meshes are extruded over the vertical axis (z) into σ -layers and planes to form prismatic 3D elements, as shown in figure 1. This transformation is classically used in environmental software [21,24]. At the surface both dynamic (atmospheric pressure) and kinematic conditions are imposed. Horizontally, the domain Ω is decomposed into a domain Ω_{LES} in which an LES is performed and a domain Ω_{RANS} defined as $\Omega - \Omega_{\text{LES}}$ in which a RANS model is solved. The coupling method is described in the following. Figure 2 shows an embedded LES sketch for a two-dimensional computational domain. The 3D approach consists of applying this process for every mesh plane.

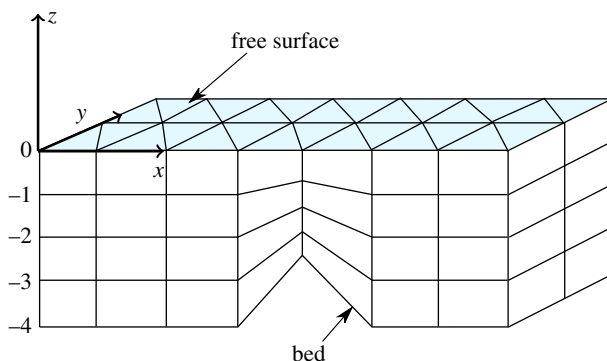


Figure 1. Schematic of a grid used in TELEMAC-3D. Source: *TELEMAC-3D theory guide*. See http://wiki.opentelemac.org/doku.php?id=documentation_v8p1r1. (Online version in colour.)

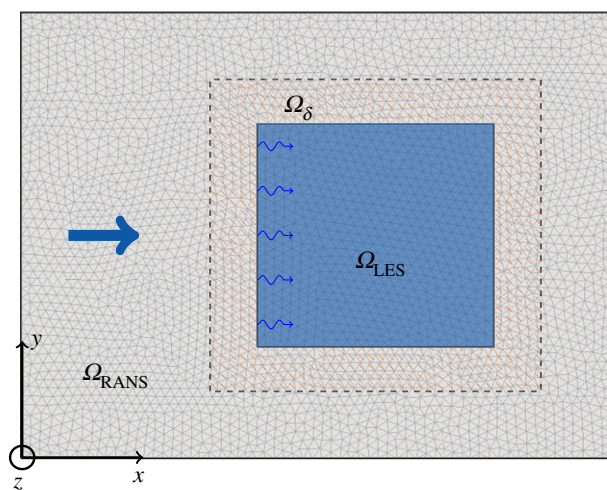


Figure 2. Schematic representations of the LES and RANS domains (in a horizontal plane). (Online version in colour.)

(a) Inner domain: LES model

LES is capable to resolve all the scales except the smallest eddies of turbulence [25]. By meaning operation, it permits the computation of the nine components of the Reynolds stress tensor (which corresponds to six degrees of freedom as the Reynold tensor is symmetric). The principle is to divide the energy spectrum [26] of the flow into two parts to separate the smallest turbulent length scales from the others. These two parts are treated differently. As the smaller turbulent structures have a more universal behaviour and are almost independent of initial conditions, they can be modelled; these are called ‘subgrid’ scales. Conversely, larger structures are directly solved by the governing equations, reproducing the unsteady flow behaviour. Applying a filtering operator to the Navier–Stokes equations involves introducing a new unknown tensor τ_{ij} , called the subgrid tensor. The filtered Navier–Stokes equations for an incompressible fluid then read:

$$\begin{cases} \frac{\partial \tilde{u}_i}{\partial x_i} = 0 \\ \frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \nu \frac{\partial}{\partial x_j} \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) - \frac{\partial \tau_{ij}}{\partial x_j}. \end{cases} \quad (2.1)$$

LES approaches assume that the interactions between the largest scales and the subgrid scales are governed by a dissipative process. In most cases, it is achieved by introducing an equivalent dissipative term, based on a subgrid viscosity ν_t [25]. The subgrid tensor can be written according to this new quantity and the filtered velocity gradients with the following formulation:

$$\tau_{ij} = \frac{2}{3} \tau_{kk} \delta_{ij} - 2\nu_t \tilde{S}_{ij}, \quad (2.2)$$

where

$$\tilde{S}_{ij} = \frac{1}{2} \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \quad (2.3)$$

is the strain rate tensor and δ_{ij} is the Kronecker operator.

Evaluating subgrid viscosity requires a more or less complex formulation, depending on the selected subgrid model. A recent approach in subgrid modelling uses minimum dissipation models [27,28], which provides the minimum eddy dissipation required to dissipate the energy of the subgrid scales. It was first introduced for isotropic grids [27] by using the invariants of the strain rate tensor, and extended into an Anisotropic Minimum Dissipation model (AMD) [29]. These models show good behaviour for simulating atmospheric boundary layers [28,30]. The AMD subgrid viscosity reads:

$$\nu_t = C \frac{\max[-(\delta x_k (\partial \tilde{u}_i / \partial x_k)) (\delta x_k (\partial \tilde{u}_j / \partial x_k)) \tilde{S}_{ij}, 0]}{(\partial \tilde{u}_m / \partial x_l) (\partial \tilde{u}_m / \partial x_l)}, \quad (2.4)$$

where δx_k is the grid spacing in the k th direction.

Several features have been introduced in the environmental software TELEMACH-3D in order to allow LESs [17,19]. The resolution of the Navier–Stokes equations is based on the second-order Adams–Bashforth time integration scheme for the convection term and a Crank–Nicholson scheme for the diffusion term [31]. The spatial derivative operators are discretized with a central second order scheme in space. The velocity–pressure coupling is solved with a projection step relying on a Chorin–Temam method [32,33]. Boundary conditions have been modified in order to introduce turbulent inlet velocities following the Synthetic Eddy Method (SEM) [34].

(b) Larger domain: RANS model

The RANS method consists in averaging temporally the motion equations. Turbulent fluctuations in a flow are not resolved. Each quantity f of the flow is decomposed into an average component $\bar{f}$ and a fluctuating one f' , such as $f = \bar{f} + f'$. The values inherent to the resolution are then:

$$\bar{u}_i = \frac{1}{T} \int_0^T u_i \, dt, \quad \bar{p} = \frac{1}{T} \int_0^T p \, dt. \quad (2.5)$$

Then the Navier–Stokes equations are averaged and become the Reynolds equations:

$$\begin{cases} \frac{\partial \bar{u}_i}{\partial x_i} = 0 \\ \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i}{\partial x_j} \bar{u}_j = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial R_{ij}}{\partial x_j}. \end{cases} \quad (2.6)$$

This operation introduces a new term, called the Reynolds tensor $R_{ij} = \overline{u'_i u'_j}$, which characterizes the interactions between velocity fluctuations. In a similar way to the LES methods, it must be modelled. Several methods have been developed for this, but the most common is to assume that Reynolds tensions behave similarly to Boltzmann constraints. Using the Boussinesq

approximation [35], we can directly link the Reynolds tensor components to the S_{ij} strain rate tensor with the expression:

$$R_{ij} = \frac{2}{3}k\delta_{ij} - 2\nu_T S_{ij}, \quad (2.7)$$

where k is the turbulent kinetic energy, $S_{ij} = \frac{1}{2}((\partial \tilde{u}_i / \partial x_j) + (\partial \tilde{u}_j / \partial x_i))$ is the strain rate tensor and ν_T is the turbulent viscosity, which must then be estimated by a turbulent model.

For the present application, the RANS model of Spalart-Allmaras [36] has been selected and implemented in TELEMAC-3D [17,18]. Between scalar zero-equation models and two-equation models, this one-equation model is a good compromise between the computational time and the variety of turbulent processes (production, destruction, transport and diffusion).

The associated turbulent eddy viscosity ν_T is defined as:

$$\nu_T = \tilde{\nu} f_{v1}, \quad f_{v1} = \frac{\chi^3}{\chi^3 + C_{v1}^3}, \quad (2.8)$$

where $\chi = \tilde{\nu} / \nu$. The viscosity-like variable $\tilde{\nu}$ is computed by the resolution of the following equation:

$$\begin{aligned} \frac{\partial \tilde{\nu}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\nu}}{\partial x_j} = & C_{b1}(1 - f_{t2})\tilde{\omega}'\tilde{\nu} - (C_{w1}f_{tw} - \frac{C_{b1}}{\kappa^2}f_{t2})\left(\frac{\tilde{\nu}}{d}\right)^2 \\ & + \frac{1}{\sigma} \left[\frac{\partial}{\partial x_j} \left((\nu + \tilde{\nu}) \frac{\partial \tilde{\nu}}{\partial x_j} \right) + C_{b2} \frac{\partial \tilde{\nu}}{\partial x_i} \frac{\partial \tilde{\nu}}{\partial x_i} \right], \end{aligned} \quad (2.9)$$

where $\tilde{\omega}$ is a modification of the vorticity ω such that:

$$\tilde{\omega}' = \tilde{\omega} + \frac{\tilde{\nu}}{\kappa^2 d^2} f_{v2}, \quad \tilde{\omega} = \sqrt{2\bar{\Omega}_{ij}\bar{\Omega}_{ij}} \quad \text{and} \quad \bar{\Omega}_{ij} = \frac{1}{2} \left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i} \right), \quad (2.10)$$

in which d is the distance to the nearest solid wall. $f_{v1}(\tilde{\nu})$, $f_{v2}(\tilde{\nu})$, $f_{t2}(\tilde{\nu})$, $f_{\omega}(\tilde{\nu}, \tilde{\omega})$ are functions introduced in [36]. Moreover, the model uses several constants such as the Von Karman constant $\kappa = 0.41$, the Prandtl constant $\sigma = 2/3$ and other constants originally defined in [36]: C_{b1} , C_{b2} , $C_{v1} = 7.1$, C_{w1} .

Finally, the turbulent kinetic energy k and the turbulent dissipation rate ε are rebuilt with the Bradshaw formula [37] as:

$$\left. \begin{aligned} k &= f_{v1}^{1/3} \tilde{\nu} \frac{\bar{S}}{\sqrt{C_{\mu}}} \\ \varepsilon &= f_{v1}^{1/2} \frac{(\sqrt{C_{\mu}}k)^2}{\tilde{\nu} + \nu} \end{aligned} \right\} \quad (2.11)$$

and

where C_{μ} is constant from the $k - \varepsilon$ model [16] and $\bar{S}$ is the strain rate tensor norm in the RANS formulation framework.

(c) Coupling between LES and RANS

The coupling between LES and RANS varies depending on the interfaces. From the LES to the RANS domain, the LES velocity field is filtered to remove the frequencies corresponding to turbulence and to approximate $\tilde{u}_i$. Then, the RANS turbulent viscosity is evaluated from the filtered velocity components, noted with $\hat{u}_i$.

A buffer area (noted as Ω_{δ} in figure 2) surrounding the LES subdomain has been added to smooth the transition between the models. The RANS equations are solved in all domains (Ω_{RANS} , Ω_{LES} , Ω_{δ}). The RANS viscosity ν_T , and solved with equation (2.8), received a special treatment depending on the domain.

- In Ω_{RANS} , the velocity used in this relation is the RANS velocity obtained with equation (2.6).

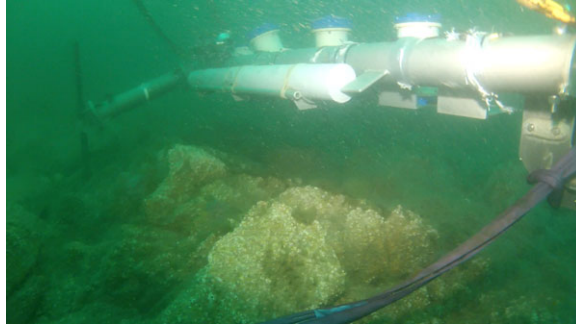


Figure 3. Seabed of the Alderney Race, photographed during the removal of ADCP devices, THYMOTE project. (Online version in colour.)

- In Ω_{LES} , we use the filtered velocity field obtained from the LES simulations (filtering based on multiple mass-lumping operations and temporal averages) ($\bar{u}_i \approx \hat{u}_i$).
- In the buffer area, it is evaluated using a weighted function involving the RANS velocity field $\bar{u}_i$ and its filtered counterpart: $\bar{u}_i \approx (1 - \theta)\hat{u}_i + \theta\bar{u}_i$, where θ is the weighting parameter evaluated from the distance to the LES subdomain. In this way, the RANS data ($\bar{u}_i, \bar{p}, v_T$) are computed in the whole computational domain Ω , which avoids introducing discontinuity problems.

The LES model is only solved in the subdomain Ω_{LES} with equation (2.4). Since the RANS model does not evaluate velocity fluctuations, a synthetic turbulence was added to the mean flow at the interfaces RANS to LES. Here, an artificial turbulence based on the isotropic Divergence Free Synthetic Eddy Method (DFSEMiso) [38] is introduced. It involves generating velocity fluctuations over the input velocity field from a prescribed Reynolds tensor, the latter being estimated from the RANS quantities (turbulent kinetic energy, turbulent dissipation rate).

3. Modelling the Alderney Race turbulence

The Alderney Race is the passage in the English Channel where one of the most powerful tidal currents in the World occurs. With an estimated maximum average power potential of 5.1 GW [39], the Alderney Race is a promising site for installing Tidal Energy Converters (TECs) farms [11,40,41]. The nature of the seabed in the Alderney Race was recently described by Furgerot *et al.* [42]. It is mainly composed of pebbles (north part) and rocky outcrops (south part), as shown in figure 3.

(a) Acoustic Doppler Current Profiler measurements

An Acoustic Doppler Current Profiler (ADCP) measurements campaign performed in the framework of the THYMOTE project was realized from 25 September 2017 to 4 November 2017 [43,44]. The measurement station is composed of two ADCPs (Teledyne RDI Workhorse Sentinel 600 kHz) coupled in master and slave. The location of the ADCP is given in table 1.

The ADCP was deployed almost transversely to the predominant tidal current. Defining (x_n, x_t, z) as the local ADCP frame, the angle between x_n and the North (y -axis) is 109° . In the following, (u_n, u_t, z) denotes the velocity components in this frame.

Reynolds stresses have been computed using either five or eight beams of the ADCP. The first method [45] enables the evaluation of five of six Reynolds stresses, which are $\overline{u'_n w'}$, $\overline{u'_t w'}$ and the three diagonal stresses $\overline{u'^2_n}$, $\overline{u'^2_t}$ and $\overline{w'^2}$. The eight-beam method permits the evaluation of the entire Reynolds tensor [46]. This method involves the use of two four-beam ADCPs, i.e. eight

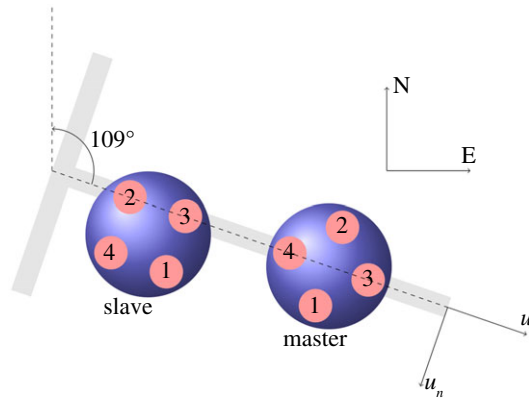


Figure 4. Sketch of ADCP cells positioning. (Online version in colour.)

Table 1. Locations of the ADCP [43].

GPS coordinates (WGS84)			
station	location		mean depth
	latitude	longitude	
ADCP	49°42, 8026' N	2°0, 1929' W	31 m

radial velocity components, which allows an overdetermined system of equations, but leads to a few under/over estimations according to [43,44,47]. A sketch of the device is presented in figure 4.

(b) Domain description and physical parameters

The Ω_{RANS} domain covers a surface of $150 \times 120 \text{ km}^2$, whereas the Ω_{LES} domain is restricted to a horizontal rectangle of $1.8 \times 2.5 \text{ km}^2$. The domains are shown in figure 5, showing a map of the Alderney Race morphology in the Universal Transverse Mercator system, zone n°30 (UTM30). Bathymetric data come from two digital elevation models, a coarse and a finer one. A 1 m-resolution Digital Elevation Model (DEM) is used in the area of interest, a 100 m-resolution DEM is used elsewhere.

The Reynolds number is very high (greater than 10^8) in that area. The viscous effect close to the bottom, which causes the important constraints on the mesh size needed when using LES, cannot be simulated with realism without a huge computational cost. Wall functions allow overcoming of this limitation. In the studied area, the bottom morphology is rough and following [48], the flow is not driven any more by the viscous effect, and the thickness of the vertical grid mesh should not be so small in the use of LES. The wall functions then must account for the bottom roughness. Finally, the validity of the LES model must be made on the basis of a comparison of the simulations with field measurements [49]. Thus, a grid convergence has been made hereafter.

(i) Wall boundary condition

The bottom roughness has been evaluated from a sediment map [50] (figure 6), with a Nikuradse Law [51], in which the bottom shear stress is:

$$\mu \frac{\partial \mathbf{u}}{\partial n} = -\frac{1}{2} \rho C_f \|\mathbf{u}\| \mathbf{u}, \quad (3.1)$$

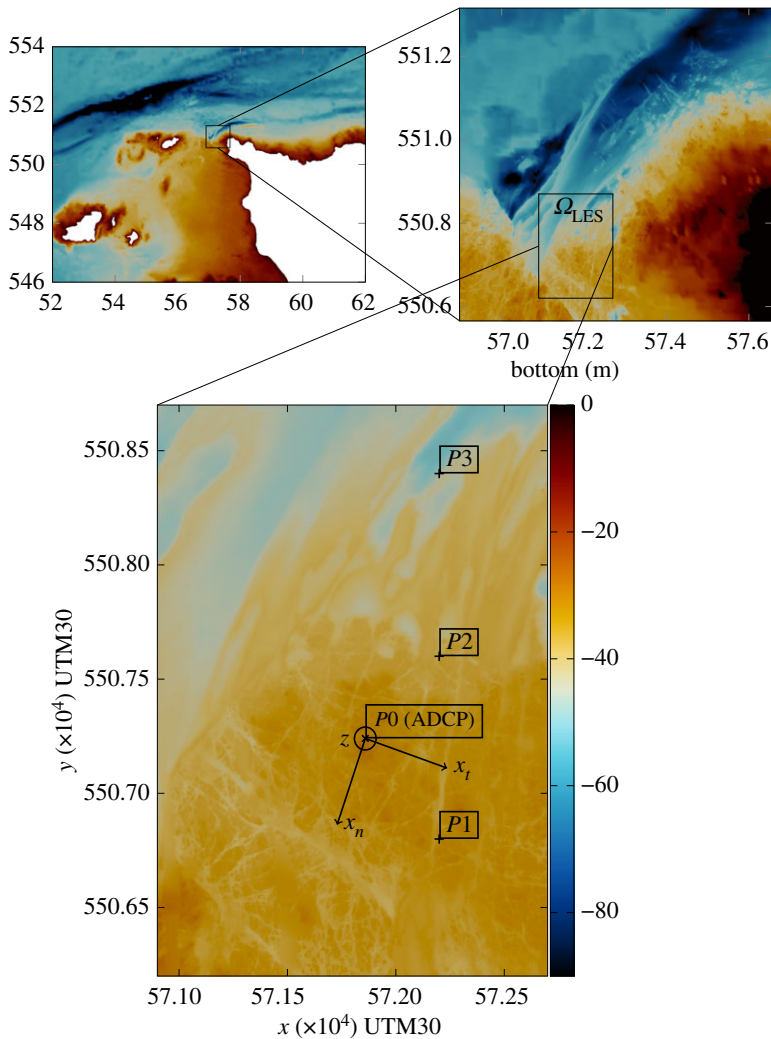


Figure 5. Elevation of the seabed with respect to the mean sea level in the Ω_{RANS} and Ω_{LES} domains in the (x -West-East, y -South-North) UTM30 coordinates system. Bathymetry detail in the Ω_{LES} with the locations of numerical probes. Point 0 corresponds to the location of the ADCP. The points $P1$, $P2$ and $P3$ correspond to virtual sensors. (Online version in colour.)

where C_f is a dimensionless friction coefficient, expressed from a roughness size k_s and h_0 is the elevation of the first sigma layer (with respect to the seabed) [51]:

$$C_f = \frac{1}{\kappa} \frac{1}{(\ln((30/e)(h_0/k_s)))^2}, \quad (3.2)$$

with κ being the Von Karman constant. This wall model was applied at both the bottom and the lateral walls.

(ii) Open sea boundary conditions

The open sea boundary conditions for the Ω domain are provided by the TPXO tidal database [52]. Only the horizontal velocities are prescribed with Dirichlet boundary conditions. A log profile is used to distribute the velocities along the vertical. The vertical velocity, the pressure and the water depth are free. In our simulation, we focus on a spring tide that occurred on 7 October 2017.

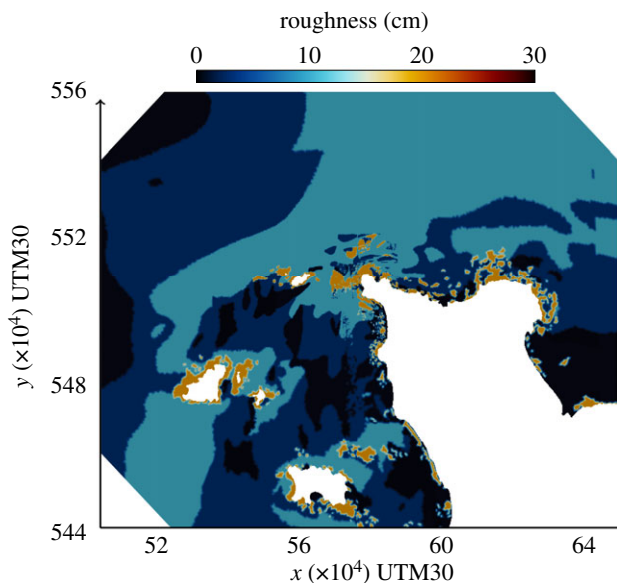


Figure 6. Roughness map used for the model of the Alderney Race. (Online version in colour.)

Table 2. Mesh characteristics used in the convergence analysis

	2D points (—)	N_v (—)	h_{LES} (m)	max cell size (m)	time step (s)
Grid 1	293591	10	8	500	1.0
Grid 2	353298	15	6	500	0.75
Grid 3	541668	20	4	500	0.5
Grid 4	818932	25	3	500	0.375

(c) Numerical settings

At the offshore boundaries, the horizontal (x, y) element size is approximately 500 m. It is gradually refined and reaches the horizontal grid size h_{LES} in the Alderney Race. As regards the vertical discretization (z axis), a sensitivity analysis has been performed to select the number of sigma layers N_v . A grid sensibility study has been carried out with four values of h_{LES} and N_v . Table 2 sums up each grid’s properties, as well as the time steps.

(d) Results processing

The flow statistics obtained with LES simulations are extracted along four vertical profiles every 5 min. The flow characteristics along the profile $P0$ (table 3) are compared with *in situ* measurements at the location presented in table 1 [43]. The sensors’ positions are shown in figure 5. Point $P1$ is located on the rocky plateau, whereas point $P3$ is in the smoother and deeper part of the domain. At least point $P2$ is sited close to the abrupt change of depth delimiting the southern area from the northern deeper area. Figure 7 shows the south–north bathymetric profile. It highlights two different zones: the southern part, shallow and very rough, and the northern area that is deeper and characterized by smoother variations of bathymetry.

An average per block operator has been introduced to discriminate the turbulent fluctuations from the slower tidal motions. The computed Reynolds stresses have been rotated by $\theta = 109^\circ$ in

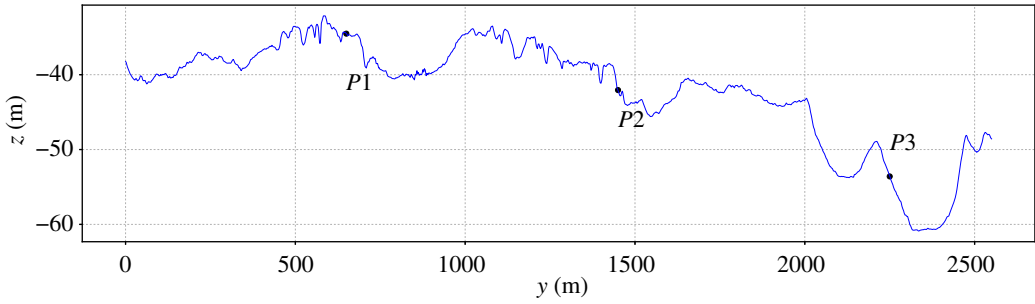


Figure 7. South–north bathymetric profile. (Online version in colour.)

Table 3. Locations and depths of the vertical profile probes in the UTM30 geographic system.

profiles	UTM30 coordinates		
	longitude	latitude	mean depth (m)
P0 (ADCP cage)	571859.88	5507240.25	31.41
P1	572200.00	5506800.00	34.28
P2	572200.00	5507600.00	42.58
P3	572200.00	5508400.00	52.99

order to be compared with the measured quantities (according to the orientation of the ADCP). The six obtained quantities are:

$$\begin{cases}
 \langle u'_n u'_n \rangle = \langle u' u' \rangle \cos^2(\theta) + \langle v' v' \rangle \sin^2(\theta) - 2 \langle u' v' \rangle \cos(\theta) \sin(\theta) \\
 \langle u'_n u'_t \rangle = (\langle u' u' \rangle - \langle v' v' \rangle) \cos(\theta) \sin(\theta) + \langle u' v' \rangle (\cos^2(\theta) - \sin^2(\theta)) \\
 \langle u'_n w' \rangle = \langle u' w' \rangle \cos(\theta) + \langle v' w' \rangle \sin(\theta) \\
 \langle u'_t u'_t \rangle = \langle u' u' \rangle \sin^2(\theta) + \langle v' v' \rangle \cos^2(\theta) + 2 \langle u' v' \rangle \cos(\theta) \sin(\theta) \\
 \langle u'_t w' \rangle = \langle u' w' \rangle \sin(\theta) + \langle v' w' \rangle \cos(\theta) \\
 \langle w' w' \rangle = \langle w' w' \rangle
 \end{cases} \quad (3.3)$$

4. Results

(a) Mesh convergence and validation

The flow statistics (averaged flow and Reynolds stresses) obtained with several discretizations are here compared with ADCP measurements at peak ebb flow (at 01.00 on 7 October 2017). Figure 8a shows the comparison of the three average velocity components. The horizontal ones (u_n and u_t) are in overall good agreement with the field data. However, there are significant discrepancies in vertical velocity magnitude despite an obvious numerical convergence. Figure 8b,c shows, respectively, the three diagonal Reynolds stress tensor components as well as the extra-diagonal Reynolds stresses. The stresses $\langle u'_t u'_t \rangle$, $\langle w' w' \rangle$ and $\langle u'_n w' \rangle$ are in satisfactory agreement with experimental results for all grids, and $\langle w' w' \rangle$ becomes more accurate as the grid becomes finer. The quantity $\langle u'_n u'_n \rangle$ is close to the field data but the peak located 10 m above the seabed is not predicted by the model. Some differences are observable for the $\langle u'_t w' \rangle$ component. Indeed, the field data do not follow a coherent behaviour whereas the numerical results converge towards a common profile. This analysis needs to be further developed. Lastly, $\langle u'_n u'_t \rangle$ has been represented even if it cannot be compared with the field data.

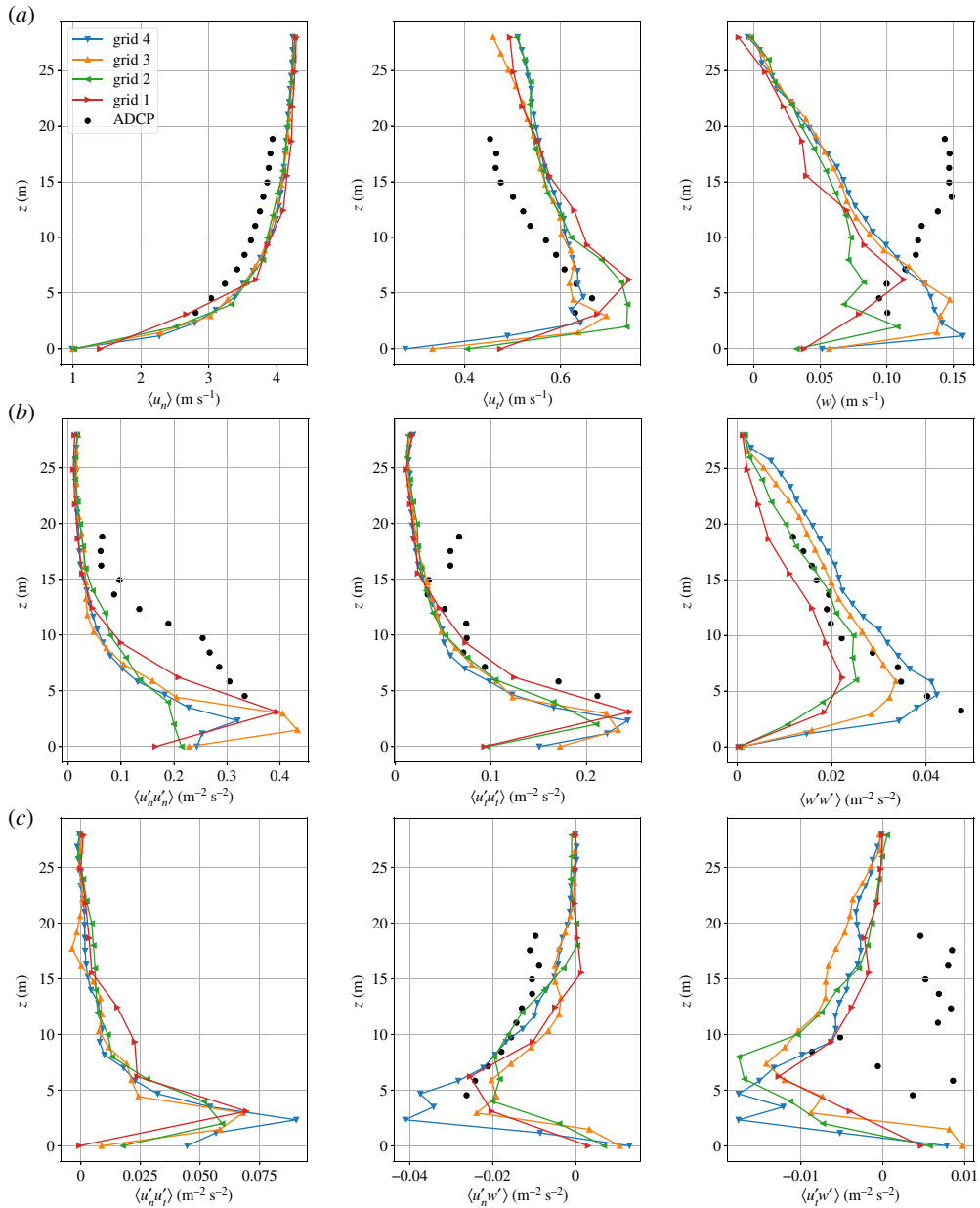


Figure 8. Vertical profiles of flow statistics obtained with the several mesh resolutions at the location *P0* on 7 October 2017, at 01.00. (ebb peak), compared with ADCP measurements. The results are given in the local frame. (a) Mean velocity components, (b) Reynolds tensor axial components, (c) Reynolds shear stress components. (Online version in colour.)

The discrepancies on w could be imputed to a small deviation of the ADCP orientation with respect to the vertical. A 3° rotation would indeed lead to the results presented in figure 9. Nevertheless, the simulation is in rather good agreement with all of the field data and provides good confidence in estimating the turbulence in that area.

(b) Influence of the seabed morphology on the turbulence generation

The spatial distribution of the velocity magnitude and the turbulent kinetic energy (figure 10) extracted 8 m above the seabed, on 7 October 2017, at, respectively, 01.00 and 07.00, indicates that

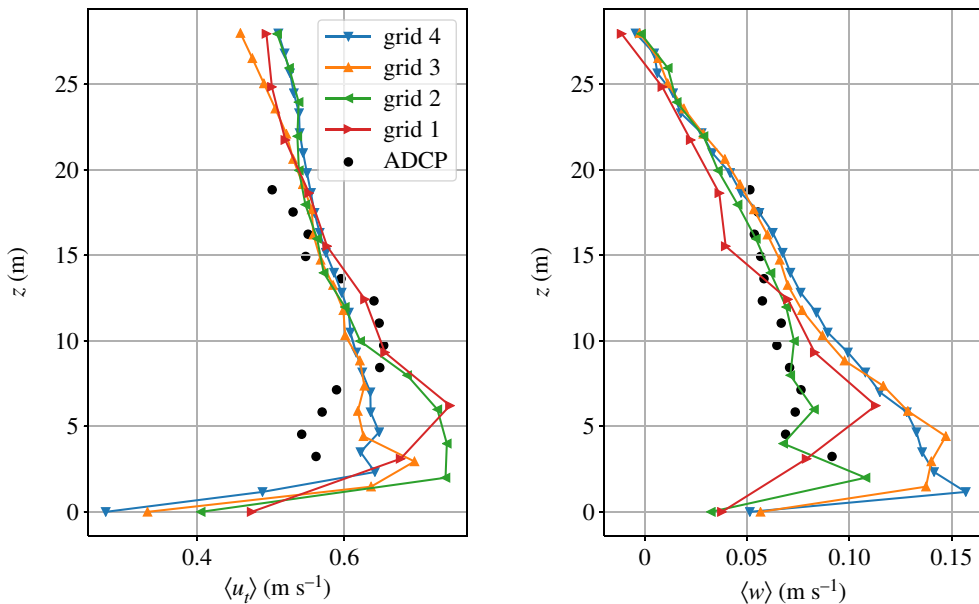


Figure 9. Vertical profiles of two velocity components obtained with the several grids at the location *P0* on 7 October 2017, at 01.00 (ebb peak), compared with ADCP measurements rotated by 3° . (Online version in colour.)

the seabed morphology greatly impacts the flow. The highest velocity magnitudes are reached over the rocky plateau, where they reach 5 ms^{-1} . The influence of the abrupt change of water depth (near coordinates $[57.22, 550.82] \times 10^4$) induces an important loss of velocity and greatly increases the turbulent intensity during flood tide. Turbulent kinetic energy maps (figure 10*b*) reflect the significant turbulent production occurring on the rocky plateau and near the dune crests, above which the turbulent kinetic energy is particularly intense. It is nevertheless broadly lower during the ebb period.

The rocky plateau may be responsible for the formation of numerous vortices (as shown in figure 11), some of them reaching the water surface. Deeper eddies can also be distinguished at the seabed dunes' crests located in the northern part of the LES domain. Such a turbulent structure could have an impact on the tidal turbines and is of importance for the placement of the turbines.

(c) Influence of the seabed morphology on turbulent statistics vertical profiles

Figure 12*a* shows that the vertical profiles of velocity components are highly heterogeneous spatially. The flow trajectory is mainly in the direction defined by 101.3° with respect to the west-east axis. The flow is accelerated between *P3* and *P1*, as the water depth decreases. The velocity component u_t changes sign between the northern and southern part of the area, which reveals a change in direction. The u_n velocity component profiles differentiate two zones (0–10 m and 10 m–free surface). This distinction is clearly marked on locations *P1* and *P2* but less so on *P3*. This is correlated to the abrupt variation of the seabed in the first locations. The vertical velocity is mainly positive along the water column. It reaches its maximum 5 m above the bottom, and decreases to zero at the free surface. The higher vertical velocity among those profiles is obtained at the position *P3*. This location is indeed located just before a hilltop (figure 7), which induces this upwards deviation of the flow.

The vertical profiles of the Reynolds tensor components are composed of two parts: above and below 20 m (figure 12*b,c*); 20 m above the seabed, the $\langle u'_n u'_n \rangle$ and $\langle u'_t u'_t \rangle$ Reynolds stress variations are weak and similar at all locations. Below this altitude, the quantity increases, reaches a peak

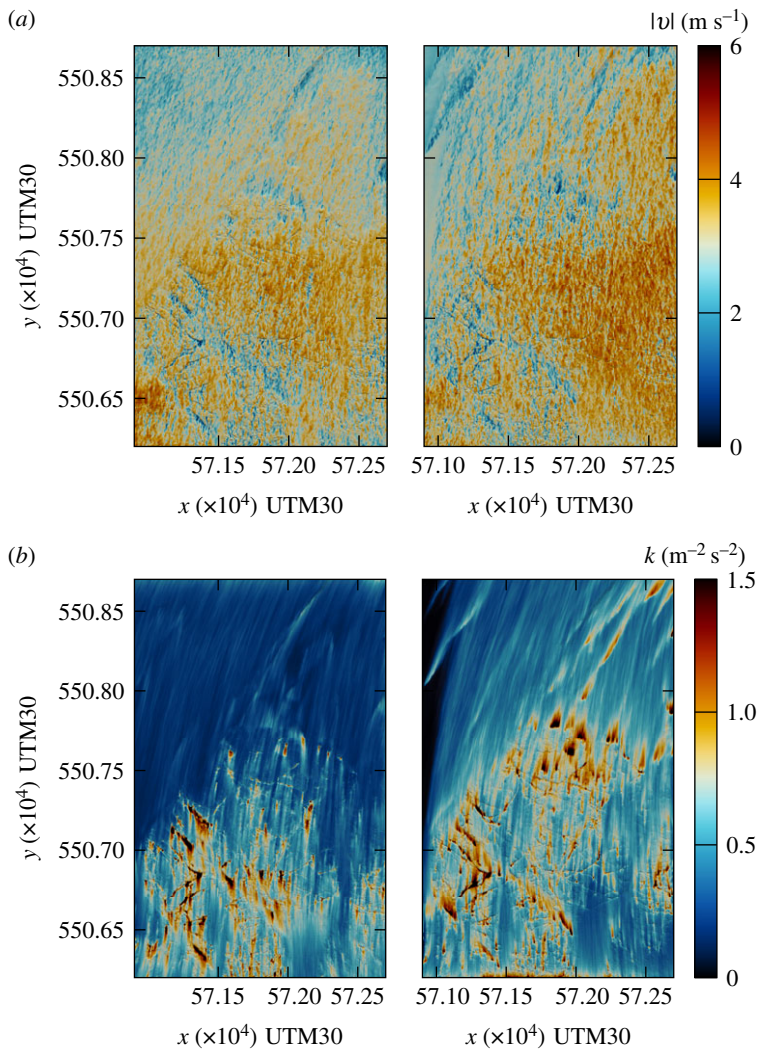


Figure 10. Spatial distribution of instantaneous velocity magnitude (a) and turbulent kinetic energy (b) at 8 m above the seabed on 7 October 2017, at the ebb peak 01.00 and at the flood peak 07.00 (right). (Online version in colour.)

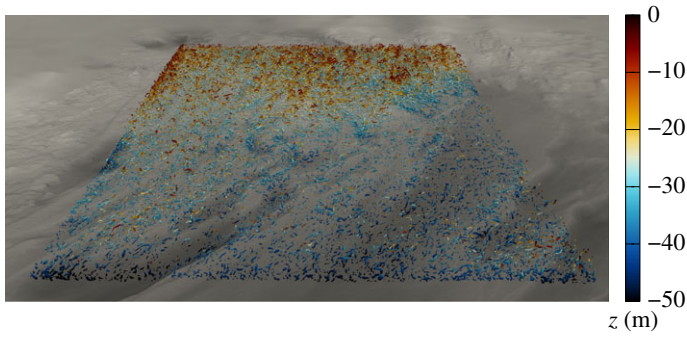


Figure 11. Snapshot of λ_2 isosurfaces coloured by the elevation in the Alderney Race, on 7 October 2017 during the ebb tide. The bottom morphology is represented in grey. The view is oriented from the north to the south. (Online version in colour.)

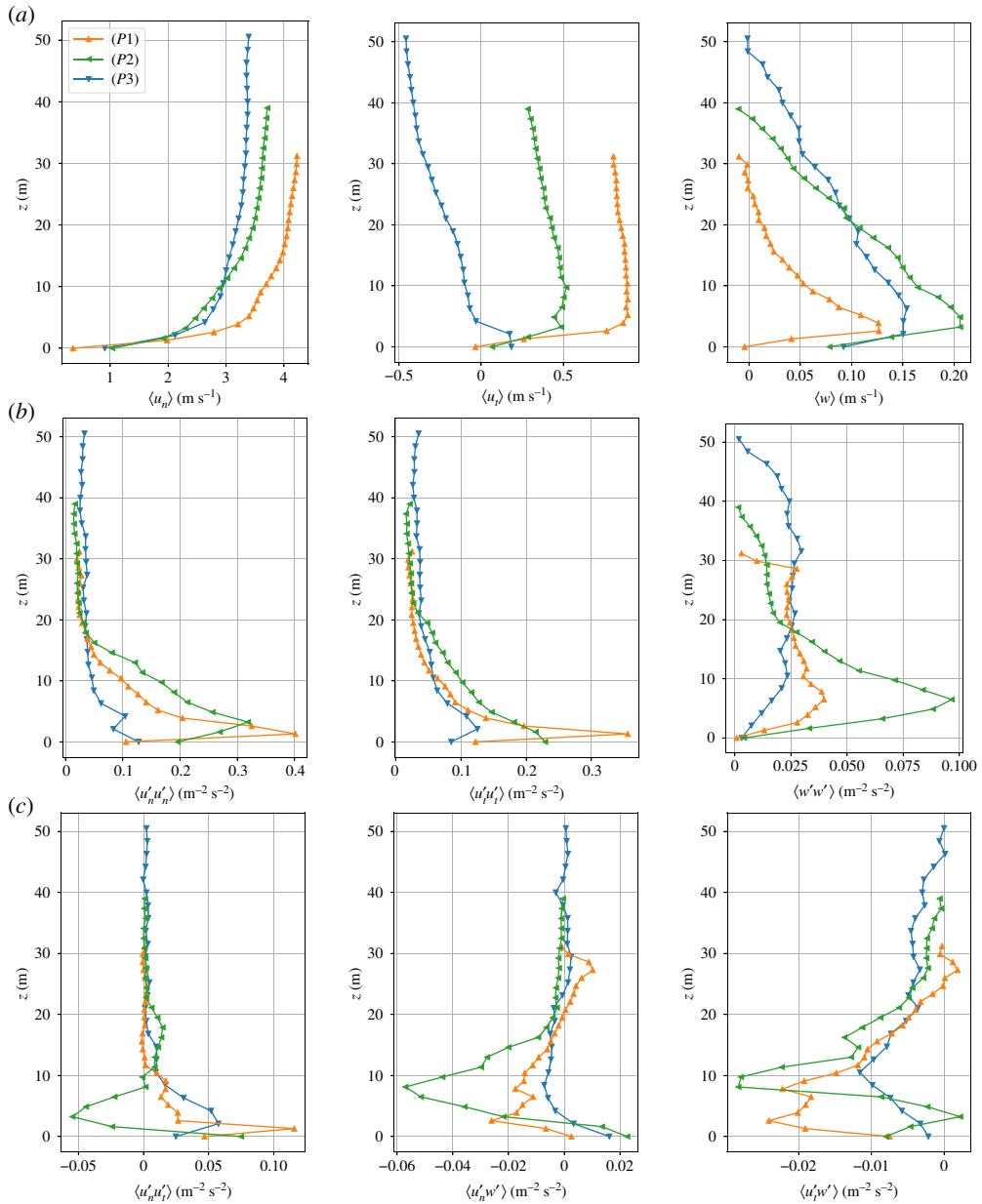


Figure 12. Vertical profiles of average velocity components (a), diagonal (b) and extra-diagonal (c) Reynolds components at the locations denoted P1, P2 and P3 at high tide during the ebb peak (7 October 2017, 01.00). (Online version in colour.)

and then decreases. The maximum value of $\langle u'_n u'_n \rangle$ is small for P3 (it reaches approximately $0.1 \text{ m}^2 \text{ s}^{-2}$) but is much higher for P2 ($0.3 \text{ m}^2 \text{ s}^{-2}$) and P1 ($0.4 \text{ m}^2 \text{ s}^{-2}$). This reflects the high level of turbulent production in points P1 and P2, which are located in areas of high bottom variations and higher speeds. Moreover, the seabed is constituted of rock and outcrop in those areas, which increases the roughness. This effect can also be seen on the $\langle w' w' \rangle$ Reynolds stress even if it is globally much lower than the horizontal Reynolds stress tensor components. Hence, the $\langle w' w' \rangle$ Reynolds stress presents an important peak at 8 m above the seabed at the position P2, for which there is a steep and abrupt variation of the bottom (figure 7). This effect is more visible on the shear stresses (figure 12c), which increase as they approach the bottom with the presence of a

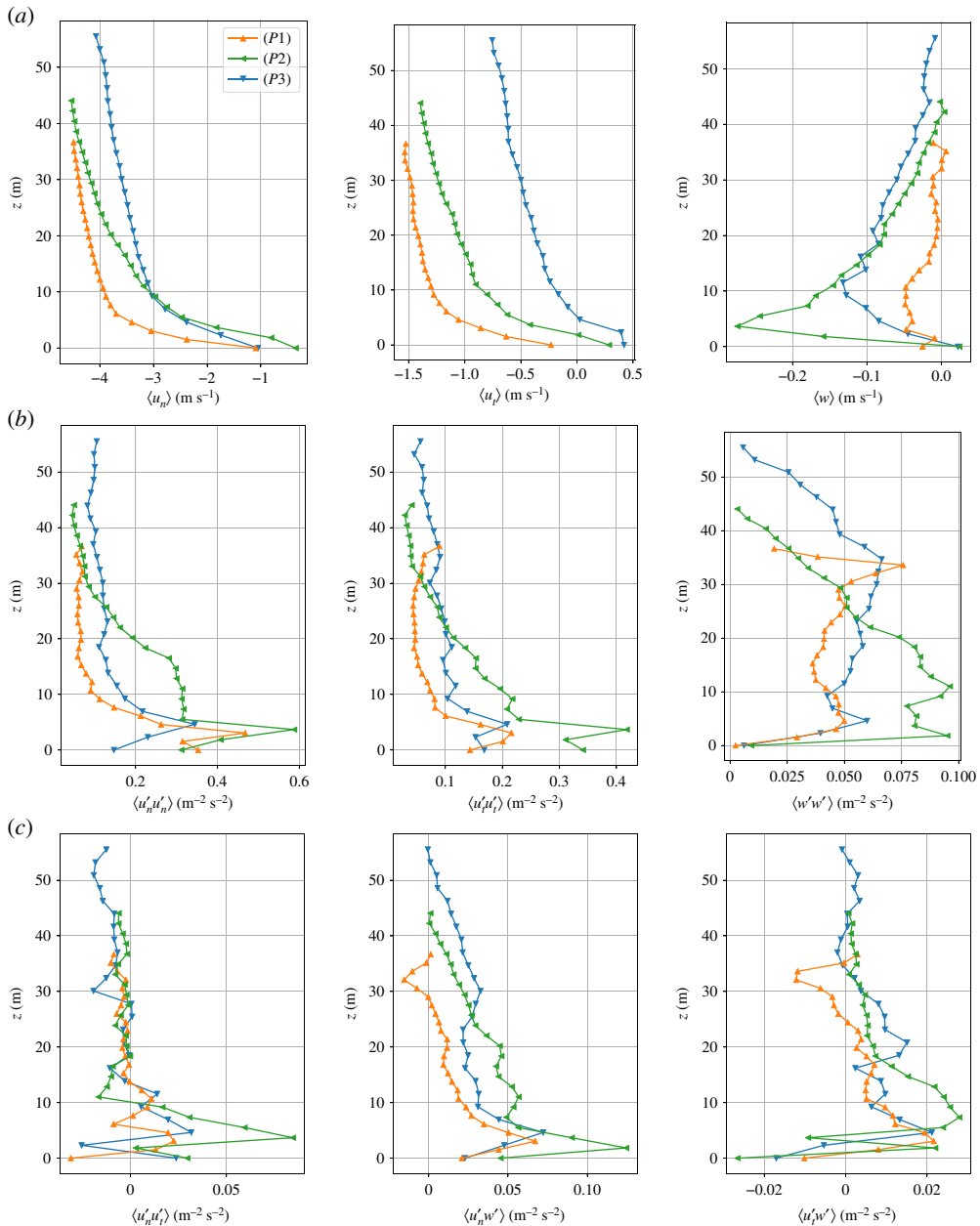


Figure 13. Vertical profiles of average velocity components (a), diagonal (b) and extra-diagonal (c) Reynolds components at the locations denoted P1, P2 and P3 at high tide during the flood peak (on 7 October 2017, 07.00). (Online version in colour.)

peak between 5 and 8 m depending on the profile. This peak is also higher at location P2 for all the shear components. This implies a vertical effect induced by the steep and rapid variation of the bottom in both horizontal directions. In all cases, the shear stress is lower for point P1. The turbines installed on the seabed will have a hub placed about 15 m from the bottom and a rotor diameter of about 16 m. The rotor is therefore two-thirds in the high shear zone of turbulence generated from the sea floor. As the intensity of this production is different in different areas, it is essential to take this parameter into account when positioning the turbines.

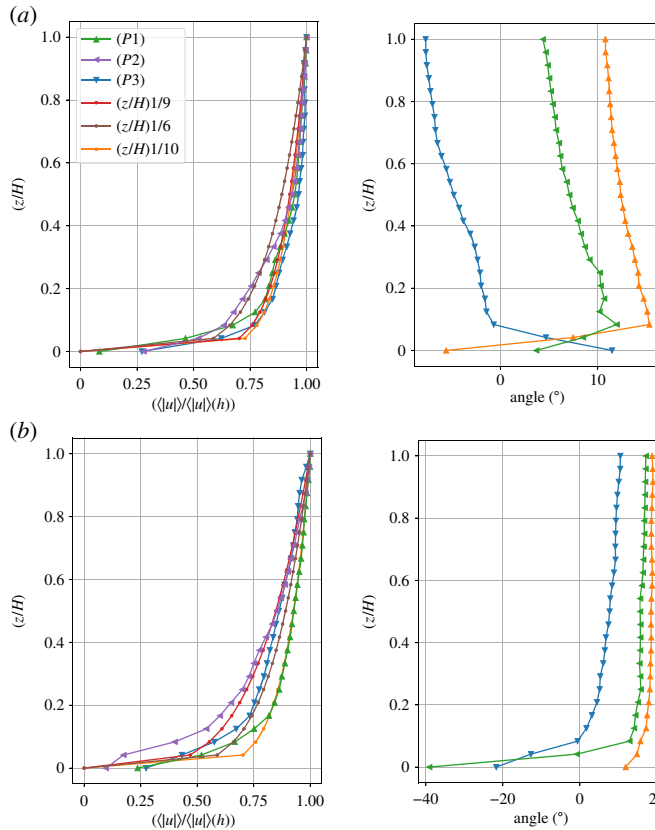


Figure 14. Dimensionless velocity magnitude vertical profiles and angle in the (u_n, u_t, w) coordinate system during the high tide (7 October 2017) ebb peak (a) and flood peak (b) at the locations P1, P2 and P3. (Online version in colour.)

During flood tide (figure 13), the vertical profiles of velocity components also depend strongly on their locations (figure 13a). The velocity logically increases from P3 to P1 due to the decreasing of the depth but with distinct vertical profiles. The horizontal velocity profiles at P1 and P3 are similar whereas the one at point P2 presents a deficit for $z < 20$ m, which can be explained by the abrupt change of water depth near point P2 and the presence of a hilltop (at the position $y = 1000$ m in figure 7). This is confirmed by the vertical velocity profiles, which show a vertical velocity for $z < 20$ m at point P3 that is almost doubled in comparison with the velocity magnitude at P2 and drops to zero at P1 on the rocky plateau. This induces a wake effect which can affect a turbine up to 20 m above the seabed. The ascendant current close to the bottom could also transport some particles towards a turbine rotor place near the location P2.

The axial statistics ($\langle u'_n u'_n \rangle$, $\langle u'_t u'_t \rangle$ and $\langle w' w' \rangle$) (figure 13b) are similar at points P1 and P3 (maximal value close to the bottom) with an increase above $z = 10$ m whereas it presents a large increase for $z < 20$ m at point P2. This increase at P2 is much higher than the turbulence generated during ebb at the same location (figure 12b) and is higher in the water column ($\langle u'_n u'_n \rangle$ is about $0.3 \text{ m}^2 \text{ s}^{-2}$ until $z = 20$ m). It is related to the variation in bottom elevation upstream of point P2 (figure 7) and to an eddy detachment phenomenon. It is also observed on the vertical Reynolds shear stresses ($\langle u'_n w' \rangle$ and $\langle u'_t w' \rangle$) (figure 13c). This high level of turbulence can reach a large part of the turbine swept area at P2, whereas it will only reach the bottom of a turbine situated at point P1 and point P3 as the bottom of the blades could be 7 m above the bottom. Placing a turbine at P2 could increase the risk of fatigue especially during the flood tide.

The flow structure is different during flood and ebb tides at the three points studied (figure 14). In particular, we noticed a difference in the velocity profile shape. Indeed, during ebb tide

(figure 14a), vertical distribution of the velocity magnitude follows a 1/10 power law at $P1$ and $P3$, whereas at point $P2$ this law is only valid up to $z/h = 0.4$. Below this altitude a velocity deficit is apparent. During flood tide (figure 14b), a power law with, respectively, exponent 1/4.2 (point $P2$), 1/6 ($P3$) and 1/9 ($P1$) can be fitted to the velocity profile predicted by the model. The vertical angular variations of the current also differ along the vertical direction. The orientation slightly varies along the vertical direction during flood tide whereas during ebb tide, the deviation is close to 8° . A good estimate of the vertical speed profile is necessary to refine the estimate of the energy assessment according to the vertical position of the turbine. In addition, an angular deviation of 10° induces a power loss of 10%. Thus, the information provided by the results should help the tidal energy stakeholder to place their turbines.

5. Conclusion

An LES-based Alderney Race model has been introduced in the solver TELEMACH-3D. The LES domain is embedded in a larger domain in which the flow is simulated with a RANS approach. The combination of RANS and LES permits investigating a large range of time- and space-scales. Simulations have been performed focusing on a spring tide. Results of mean velocity and turbulent statistics obtained with ADCP measurements and LES simulations have been compared, and gave satisfying agreements. The simulations enable the identification of high current magnitude areas and highly turbulent regions.

The most turbulent regions have been identified. The obtained results have shown that the turbulence and the time-mean velocities depend highly on the local depth and seabed morphology. The rocky plateau and the dune crests appear to be the zones that generate the highest turbulent kinetic energy values (turbulence intensity ranges from $I_\infty = 7\%$ to $I_\infty = 20\%$ along the vertical), as well as the most coherent structures identified with the λ_2 criterion. Some large eddies have been observed over the plateau during both the ebb and the flood tides. Those structures may damage tidal turbines and cables. A smoother zone can nevertheless be identified in the northern part of the domain with a much lower level of turbulence and eddies. The entire Reynolds tensor evaluation resulting from this, in a whole three-dimensional domain, considerably enriches knowledge and understanding of the turbulence, and enables a better estimation of the potential stress exercised on these structures.

Flood tide is found to be the more turbulent. The velocity magnitude is indeed higher during this period of the tide, and the rocky plateau influence is greater due to the flow orientation (from south to north). The velocity and Reynolds stress vertical profiles are highly dependent on the time of the tide. Moreover, the vertical distribution of the velocity magnitude is highly heterogeneous spatially. This should have a great influence on the tidal resource and on the loading conditions applied to the turbines. Following the spatial location, the velocity profile is different and so is that of the turbulence statistics.

Further investigations should concern the estimation of the impact of the simulated turbulent flow on a turbine placed on the bottom in different places with a hub 15 m above the seabed. Moreover, more tidal conditions should also be simulated.

Data accessibility. This article has no additional data.

Authors' contributions. I (A.C.L.B.) was a PhD student. S.S.G., J.T. and R.A. were my great supervisors. The paper presents my PhD thesis results, and has been written by each one of us.

Competing interests. We declare we have no competing interests.

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