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# Towards numerical modelling of marine dunes in a shallow shelf sea

**Noémie DURAND [1,3], Pablo TASSI [2,3], Olivier BLANPAIN [1], Alice LEFEBVRE [4]**

1. France Energies Marines, 525 Av. Alexis de Rochon, 29280 Plouzané, France.
   *noemie.durand@france-energies-marines.org*
2. EDF Recherche & Développement, 6 Quai Watier, 78400 Chatou, France.
3. Laboratoire d'Hydraulique Saint-Venant, 6 Quai Watier, 78400 Chatou, France.
4. MARUM, University of Bremen, Leobener Str. 8, D-28359 Bremen, Germany.

**Abstract:**

Tides, winds, and waves drive the hydrodynamics in the coastal zone. Under their action, the seabed can be mobilised to form what is collectively known as “bed forms”. This study focuses on one type of bed form: marine dunes in shallow shelf seas.

Marine dunes are dynamic, rhythmic, large-scale, flow-transverse sedimentary structures. They are characterised by wavelengths in hundreds of metres, heights of a few metres and can migrate up to tens of metres per year. They have been found in shallow shelf seas all over the world, e.g. in the North Sea, the Barents Sea, the South China Sea, and the Bisanseto Sea. As mapping of the world’s continental shelves progresses, we may find that marine dunes are recurrent shallow shelf sea features.

This study aims at improving our understanding of the hydrodynamics, the sediment transport and morphological processes at play in a marine dune environment. Indeed, the morphology and dynamics of dunes are still poorly understood in open marine environments.

A three-dimensional coastal area model is being developed for an application in the southern North Sea. The site is subjected to relatively strong tidal flows, with a predominance of the flood towards the North-East. Waves primarily come from the South-West, travelling through the English Channel, but some significant events have been noted from the North-North-East. Recurrent bathymetric surveys indicate dune migration rates of up to 30 metres per year towards the North-East.

Different steps towards the development and validation of this numerical model are presented.

**Keywords:**
Marine environment, Marine dunes, Hydrodynamics, Sediment transport, Model calibration, TELEMAC-3D, TOMAWAC, GAIA.

## 1. Introduction

Hydrodynamics in shallow shelf seas are mainly driven by tides, winds, and waves. Under their action, the seabed can be mobilised to form what is collectively known as “bed forms”. Many types are observed in nature. In sandy marine environments, they include sand ripples, nearshore bars (also called breaker bars), sand banks, sand ribbons, and marine dunes. Our interest is in marine dunes, examples of which are shown in figure 1.

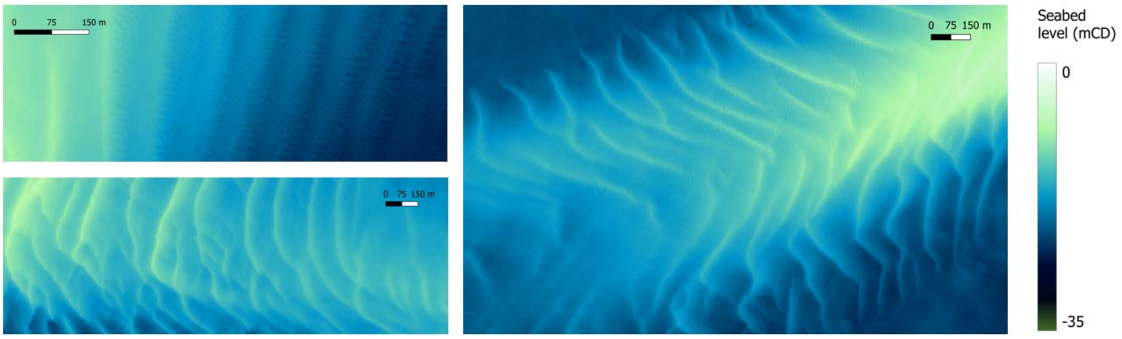

*Figure 1. Example marine dune fields, observed offshore of Dunkirk.*
*Data source: Eoliennes en Mer de Dunkerque (EMD), 2021.*

In keeping with the Society for Sedimentary Geology terminology (ASHLEY, 1990), we call marine dunes large, flow-transverse, dynamic bed forms with height of 1 m to 5 m and wavelength of the order of hundreds of metres. They develop almost exclusively on sandy seabeds, in settings where bedload is the predominant mechanism of sediment transport. They are very active bed forms: growing, evolving and migrating, at rates of up to tens of metres per year, in response to the combined action of tidal currents, winds and waves. Marine dunes are sometimes referred to as sand waves in the literature.

Figure 1 illustrates the diversity of morphologies occurring in natural marine settings, from regular trains of linear dunes with superimposed smaller dunes (top left), to sinuous plan shapes with bifurcations (bottom left) and convergence of dunes towards the crest of the sand bank they are associated with (right).

Marine dunes have been observed all over the world in a variety of environments (figure 2), and in shallow shelf seas: in the North Sea, the Barents Sea, the South China Sea, or the Bisanseto Sea for example. As mapping of the world’s continental shelves progresses, we may find that marine dunes are recurrent shallow shelf sea features. They are often present where offshore wind farms (OWF) are (or will be) located. However, the morphology and dynamics of dunes are still poorly understood in open marine environments.

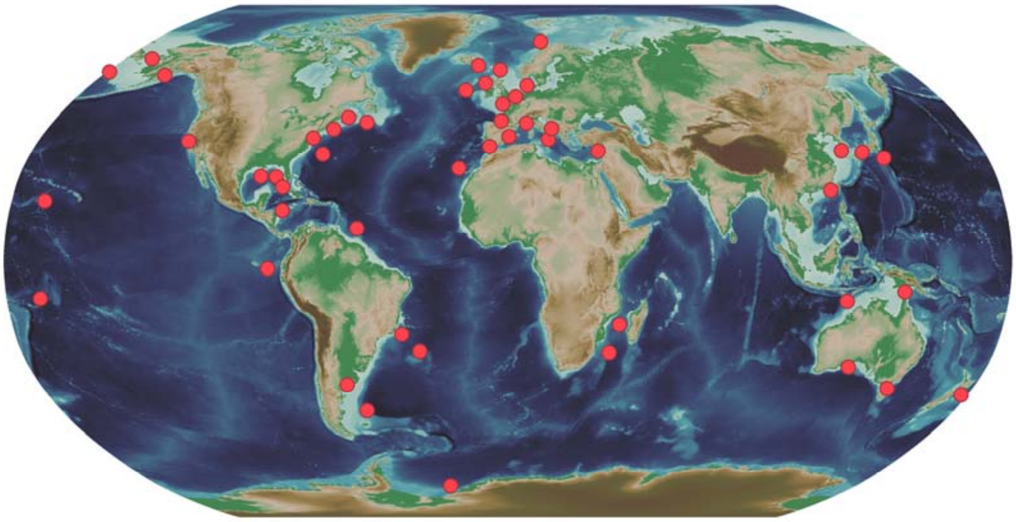

*Figure 2. Distribution of observed marine dunes in the world (not an exhaustive list of locations). Background imagery from GEBCO 2021.*

This work is carried out in the context of the 3-year MODULLES project: "MOdelling of marine DUnes: Local and Large-scale EvolutionS in an offshore wind farm context", led by France Energies Marines (FEM). It focuses on the future OWF site of Dunkirk, North of France. MODULLES was preceded by the DUNES project, during which comprehensive in-situ data were collected. The project aims at improving our understanding of the hydrodynamics, the sediment transport and morphological processes at play in a marine dune environment, and eventually their interaction with OWF elements, through numerical modelling. We present here the site characterisation and the hydrodynamic model set up and calibration (tide only).

## 2. Methods

### 2.1 Metocean and bathymetric surveys

A large metocean and bathymetric data set has been collected in support of Dunkirk OWF project. Site-specific meteorological and hydrodynamic campaigns have been carried out for up to six months (Sites 1 and 2 from SHOM, Sites 3 to 5 from FEM, Sites 6 and 7 from EMD, figure 4). In addition, long-term metocean observations were obtained from the Flanders Marine Institute (VLIZ) at Westhinder. These records inform the wind speed and direction, atmospheric pressure, water level, current speed and direction (at various elevations in the water column), and wave conditions. They provide a valuable data set against which to compare our model capabilities.

Recurrent and detailed bathymetric surveys have also been carried out with a view to provide a more accurate representation of the seabed and of the dune morphological dynamics over time. Two large-area surveys covering the OWF footprint (marked by a dashed outline in figures 3 and 4) were conducted in 2016-2017 (SHOM) and in June 2021 (EMD).

Separately, eight surveys were performed between 2019 and 2021 (FEM), in three predefined tiles selected to include a variety of bed forms. It is noteworthy that their extent was also selected such that they could be surveyed within a day, the area being very dynamic. The general location of these three survey tiles is shown in figure 3.

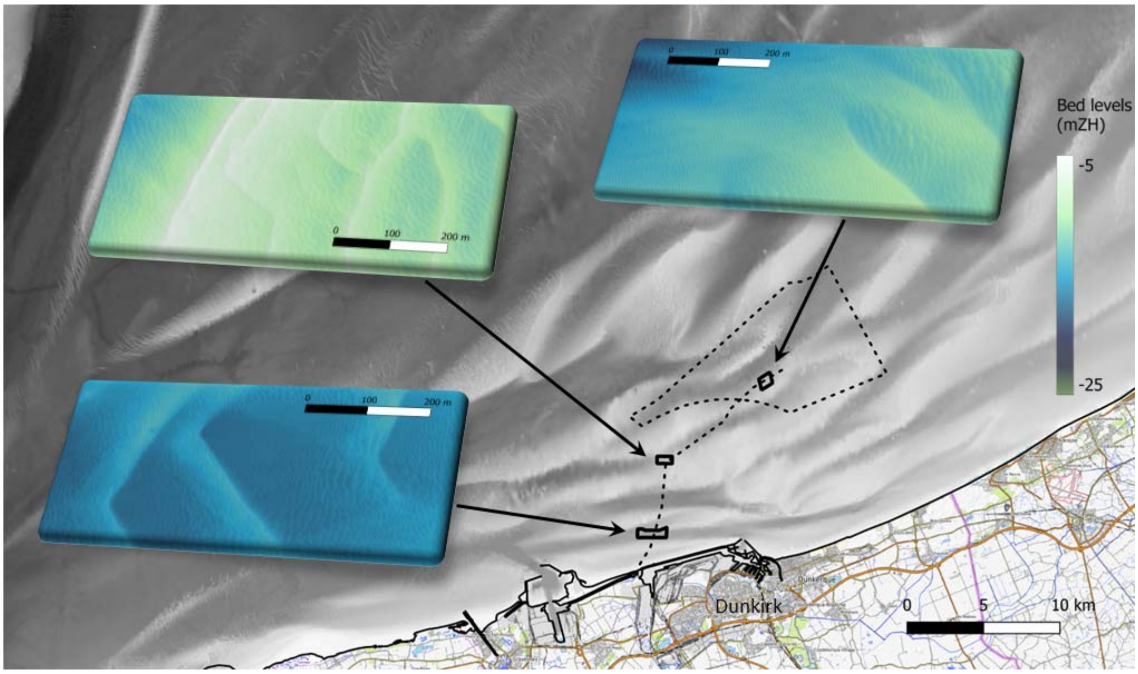

*Figure 3. Map showing the location of 2019-2021 bathymetric survey tiles (FEM). The footprint of the OWF is marked as a dashed outline. Background data: OpenTopoMap, GSHHG shoreline and HOMOMIM bathymetry.*

2.2 <u>Three-dimensional coastal area model</u>

Idealised models have been proposed in the literature to study the effect of targeted parameters / processes on marine dune formation, growth and equilibrium (HULSCHER, 1996; ROOS, 2019). The role of residual currents, grain size distribution, bio-physical processes, suspended transport, storms was investigated in that way. In a nature-based setting, marine dunes react to spatial variations in the hydrodynamic and wave conditions, which cannot be described in idealised models. We are, therefore, developing a three-dimensional coastal area model of Dunkirk and approaches to investigate the dynamics of marine dunes in a shallow shelf sea environment. This model is based on the open TELEMAC system (*http://www.opentelemac.org*).

### 2.3 Extent, resolution, seabed and friction maps

The model extends for approximately 80 km along the coast, from the port of Calais in the West to Ostend in Belgium in the East. Its offshore extent varies between 15 km in the Dover Strait and 75 km in the East (yellow outline in figure 4). A triangular finite element mesh with spatially varying resolution is used to represent the model area. The main advantage of this approach is that it is very flexible: the mesh resolution can be varied spatially to suit the complexity of the shoreline, bathymetry features or tidal flows for example, while growing to be coarser away from areas of interest.

The size of the triangles varies gradually from 1400 m away from the area of interest down to 100 m at the shoreline. A finer resolution of ca. 10 m is used to represent the survey tiles and within the footprint of the OWF, where we aim to reproduce the evolution of the dune field. Although this element size is deemed adequate for the purposes of calibration and validation of the hydrodynamic and wave models, it is important to note that further mesh refinements may be necessary for the morphodynamic modelling.

A digital elevation model of the seabed throughout the model area was constructed by combining the HOMONIM and TANDEM data sets (SHOM, 2015 and 2016), where finer resolution data took precedence over coarser resolution data. The bottom roughness is parameterised with the Chézy formulation, and a spatially constant coefficient of 65 $m^{1/2}/s$. This value is appropriate for sandy seabeds.

### 2.4 Tidal forcing

Time-varying sea levels are applied along the open water boundaries of the hydrodynamic model. These time histories were computed from the 15 constituents available from the OSU TPXO9 atlas: eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long-period (Mf, Mm), three shallow-water (M4, MS4, MN4) and two small-amplitude constituents (2N2, S1). TPXO is a series of regional and global models of ocean tides, which best fit, in a least-squares sense, the Laplace Tidal Equations and altimetry data (EGBERT & EROFEEVA, 2002). TPXO9 is the latest in the series with a 1/30° global resolution. It should be noted that sea levels derived from the TPXO database are astronomical levels devoid from other influences (e.g. meteorological).

### 2.5 Calibration and validation

In shallow shelf seas, coastal hydrodynamics (tides, winds and waves) is the force driving sediment transport. An accurate description of the wave and current fields is, therefore, necessary for a reliable description of morphodynamic processes. It follows that the first step of the modelling exercise consists in the calibration and validation of the flow (astronomical tides alone, then adding meteorological influences) and wave models against independent observed in-situ data sets.

A later step will consist in the calibration and validation of the morphodynamic model against the bathymetric survey data collected in recent years (Section 2.1) and illustrating the evolution of a relatively wide range of marine dunes. Performance will be assessed primarily based on agreement with cross-sectional profiles.

Hydrodynamic calibration is carried out over a complete 14.5-day spring-neap tidal cycle (May 20th to June 3rd, 2021), by tuning the Chézy bed friction parameter until good overall agreement is reached against tidal levels observed at Site 6, within the OWF footprint. Validation is performed against independent sets of current speed records collected at Sites 3, 4 and 5 for the same time period. The model is further validated against longer-term data at the same locations for the following two tidal cycles (June 3rd to July 2nd, 2021), to ensure that it performs well for a range of tidal conditions.

It is important to recognise that observations include effects other than that of the tide alone. To allow a direct comparison of the numerical model output (obtained without meteorological influences as a first step) with the measured data, tidal harmonic analyses are performed on the observed water depth and current velocity time records (CODIGA, 2011). Tidal harmonic analysis seeks to break the overall tide into the summation of several simple and quasi-independent oscillations of varying periods, each corresponding to the cycle of an astronomical force or tidal harmonic constituent. The amplitude and phase of a tidal constituent are defined by harmonic constants that are unique to a given location. The derivation of these constants by harmonic analysis enables the prediction of the overall astronomical tide at any time in the future or past (FOREMAN, 1977, 1978). In the following, the terms “observations” or “observed” will be loosely used to refer to the re-synthesised level and current data.

While the time histories give an immediate visual impression of the agreement between model and observations, the quality of the calibration / validation exercise is typically assessed by way of metrics such as the Root Mean Square Error (RMSE) or Mean Absolute Error (MAE). Normalised RMSE is used for tidal levels whereby the RMSE is divided by the average tidal range, taken to be 4.4 m here. A target normalised RMSE value of 10% is often deemed to reflect good model calibration. For currents, it is generally accepted that RMSE values below 0.1 m/s, and differences in direction below 10°, indicate good model performance.

## 3. Results

### 3.1 Site conditions at the study area

The seabed offshore of Dunkirk is relatively shallow and bed levels shallower than 30 m below Mean Sea Level (MSL) extend as far as ca. 20 km from the coastline. The southern North Sea is characterised by a complex network of sand banks, marine dunes, smaller dunes and ripples. Sand banks exhibit crests as high as -6 m relative to MSL.

Marine dunes are generally between 1 m and 5 m high, 100 m to 200 m long. The seabed comprises reasonably well sorted medium sands with $d_{50}$ grain sizes between 240 µm and 450 µm based on recent samples. Diameter $d_{10}$ is estimated to be 210 µm on average. It is, therefore, not expected that the sediments exhibit cohesive properties.
Figure 4 illustrates the near bed current, wind and wave climates at selected locations, in the form of roses.

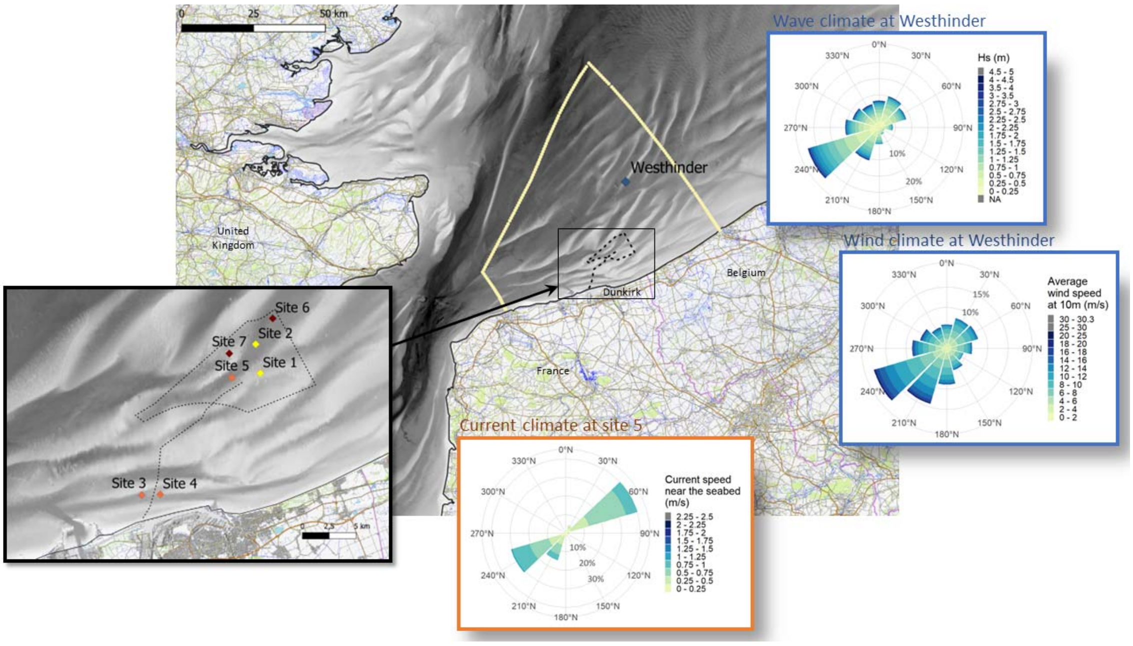

*Figure 4. Map showing the location of meteorological and hydrodynamic observations; and selected near bed current (FEM), wind (VLIZ) and wave (VLIZ) climates. The extent of the numerical model is marked as a yellow outline. Background data: OpenTopoMap, GSHHG shoreline and HOMOMIM bathymetry.*

The spring tidal range in the study area is approximately 5.5 m (macro-tidal); and the neap range 3.3 m. The flow aligns with geographical features and is asymmetric with a generally stronger flood (depth-averaged speed of up to 1.25 m/s, towards the NE) than ebb (depth-averaged speed of up to 0.75 m/s, towards the SW), although the ebb-flood predominance can be reversed within the sand bank system. Near bed currents can reach 0.70 m/s at the peak.
Winds and waves come largely from the SW and the Channel. Some significant storms have been noted from the North-West to the North-East. Data obtained from the Westhinder buoy indicate that 56% of the waves are under 1.0 m. In similar depths, offshore of Calais, 1-year return period waves have been estimated at 4.0 m and 10-year return period waves at 4.7 m (CEREMA, 2021). Associated peak periods are 8 s to 9 s.

### 3.2 Calibration and validation of the hydrodynamic model

Figures 5 and 6 present preliminary results from the calibration and validation exercise respectively. It follows that the flow characteristics are satisfactorily predicted by the model. The turning of the tide is well reproduced even if it is noted that the model can be slightly ahead or behind on occasions. The predicted current directions also compare favourably with observations: differences are generally under 5° on ebb and flood flows. The agreement was assessed quantitatively by computing RMSE statistics on both sea level and velocity for the entire simulation period. These are summarised in table 1.

*Table 1. Performance of the hydrodynamic model against observed data.*

| | ***RMSE on tidal levels (normalised by average tidal range)*** | ***RMSE on current speeds*** |
|---|---|---|
| *Site 3* | *0.23 m (5%)* | *0.12 m/s* |
| *Site 4* | *0.23 m (5%)* | *0.09 m/s* |
| *Site 5* | *0.21 m (5%)* | *0.13 m/s* |
| *Site 6* | *0.14 m (3%)* | -- |
| *Westhinder* | *0.20 m (5%)* | -- |

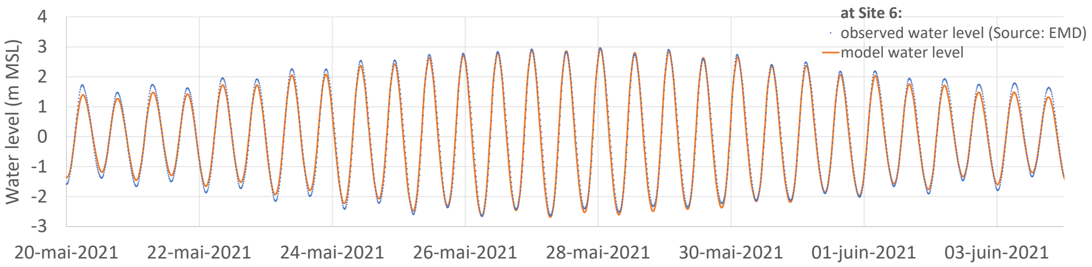

*Figure 5. Model calibration at Site 6 (tide only): comparison against observed data.*

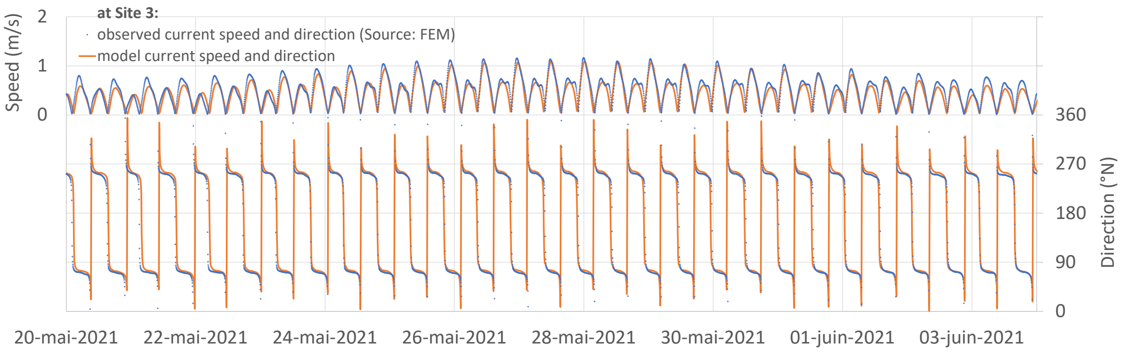

*Figure 6. Model validation at Site 3 (tide only): comparison against observed data.*

Residual currents have been shown to play an important role in marine dune dynamics (NÉMETH *et al.*, 2002). They are usefully represented by Progressive Vector Diagrams

(PVD), drawn from the time histories of u- and v- velocity components at a discrete location. In Dunkirk, the tide generally rises faster than it falls; the flood is stronger than the ebb. This asymmetry of the tidal cycle is apparent in the PVD plotted in figure 7 for Site 3. In this figure, different shades of the same colour indicate each new 14.5-day spring-neap tidal cycle between May 20th to July 2nd, 2021. The observed and predicted traces are shown to be in good agreement, indicating a satisfactory reproduction of both the strength and orientation of the residual currents at this location. Residual current speeds of 0.075 m/s and 0.073 m/s are computed from observed and predicted data respectively. The currents are trending towards the East-North-East at Site 3, following the coastline orientation and the local bathymetry.

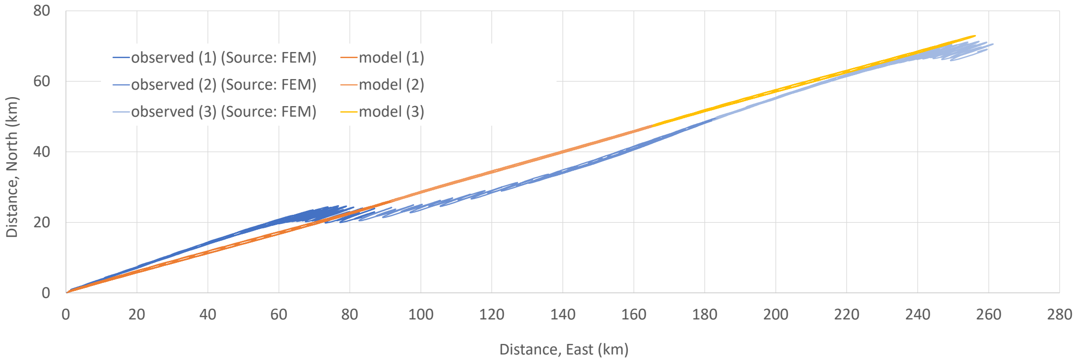

*Figure 7. Residual currents at Site 3 (tide only): comparison against observed data.*

## 4. Conclusion and future work

The comparisons made in figures 5 to 7 give confidence in the capabilities of the hydrodynamic model to reproduce the astronomical tide. The flow characteristics are satisfactorily reproduced at measurement locations offshore of Dunkirk. Normalised RMSE values are generally of the order of 10% on sea levels; RMSE values are 0.12 m/s on average for current speed; directions are generally predicted under 5° on both ebb and flood flows. Agreement could possibly be further improved by considering an alternative source of sea levels to force the open water boundaries with. This will be explored in the future.

The hydrodynamic model will be enhanced to include meteorological influences; a wave model will be developed, coupled to the calibrated hydrodynamic model to include tidal modulations; the sediment transport and bed evolution processes will be modelled by means of a 3-way coupling. Once satisfactory agreement is reached against observed in-situ data, this comprehensive coastal area model will be used as a research tool to better understand marine dune dynamics in the Dunkirk area.

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