COASTAL BATHYMETRY FROM SATELLITE AND ITS USE ON COASTAL MODELLING

Rodolfo Bolaños[1], Lars Boye Hansen[2] Mikkel Lydholm Rasmussen[3], Maziar Golestani[4], Jesper Sandvig Mariegaard[5] and Lisbeth Tangaa Nielsen[6]

Offshore wind farms around the world are being developed with the objective of increasing the contribution of renewable energy to the global energy consumption. Bathymetric features at the wind farm sites have a strong influence on waves and currents, controlling the propagation and dissipation of flows during normal and extreme conditions. In this work we use a state-of-the-art cost-effective method for bathymetric mapping based on high resolution satellite images to characterize a coastal wind farm region and assess the added value of such data when performing wave modelling. The study area is characterized by the presence of offshore wind farms and a complex bathymetry that feature sand bars and channels. For this study, a satellite derived bathymetry (SDB) was produced using imagery from the Sentinel-2A satellite. The Sentinel-2a data allows for more detailed SDB retrieval than is available in the existing accessible bathymetric datasets. The data is then used in a spectral wave model (MIKE21SW) with different resolutions outlining the impact of large bedforms on surface waves, mainly due to wave breaking. The bathymetry data is also used in a phase-resolving model (MIKE3waveFM) where regular and irregular waves are simulated, outlining the impact of bedforms on individual wave dissipation. Discussion on the satellite derived bathymetry and wave models results are presented in this paper.

Keywords: spectral wave; phase resolving model; sand bars, coastal processes

INTRODUCTION

Offshore wind farms around Denmark are being developed with the objective of increasing the contribution of renewable energies to the energy national consumption. This type of activity is also being developed in other countries such as Germany, Belgium, UK, US and China among others (for example Windeurope (2018) and Broehl (2018)). New challenges will arise especially during storm conditions that may directly affect the estimation of wind turbine design parameters (like extreme metocean conditions), the secure operation of the national and international electrical system (regarding e.g. the turbine cut-off speed), the fatigue and the extreme wave loads. Bathymetric features at the wind farm sites have a strong influence on waves and currents, controlling the propagation and dissipation of flows during normal and extreme conditions. Therefore, accurate measurements of bathymetry and its evolution is critical to the coastal marine industry. The goal of the present work is twofold. First, the use of a state-of-the-art cost-effective method for bathymetric mapping based on high resolution satellite images to characterize a coastal wind farm region and second, to assess the added value of such high resolution data when performing wave modelling with both spectral and phase resolving models. The structure of the paper is as follows; first the case study is presented outlining the locations and storm event used for wave modelling. Secondly the methodology for deriving bathymetry from satellite is summarized followed by the description of the wave models and their implementations. A summary of the results and discussion is then presented.

CASE STUDY

For this work, the area called Horns Rev (HR) is used to obtain bathymetry from the satellite and assess its use in high resolution wave modelling. HR is located in the North Sea, west of Denmark, the area is along the Danish North Sea coast, characterized by the presence of offshore wind farms (Figure 1) as well as a complex bathymetry that feature sand bars and a channel. Additionally, the area is exposed to storm events from the North Sea producing large waves coming from the northwest that dissipate on the sand bars. A particularly intense event occurred on the 6th November 1985 when waves approaching from northwest reached a significant wave height offshore from HR of approximately 7m (see Figure 2). HR is a wave dissipation area where waves are reduced significantly due to their interactions with the seabed via bottom friction and depth induced breaking.

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[1] DHI, Ports and Offshore Technology Department, Agern Alle 5, Hørsholm, Denmark. rbol@dhigroup.com
[2] DHI-Gras, Agern Alle 5, Hørsholm, Denmark. lbh@dhigroup.com
[3] DHI-Gras, Agern Alle 5, Hørsholm, Denmark. mlra@dhigroup.com
[4] DHI, Ports and Offshore Technology Department, Agern Alle 5, Hørsholm, Denmark. mgo@dhigroup.com
[5] DHI, Ports and Offshore Technology Department, Agern Alle 5, Hørsholm, Denmark. jem@dhigroup.com
[6] DHI-Gras, Agern Alle 5, Hørsholm, Denmark. litn@dhigroup.com

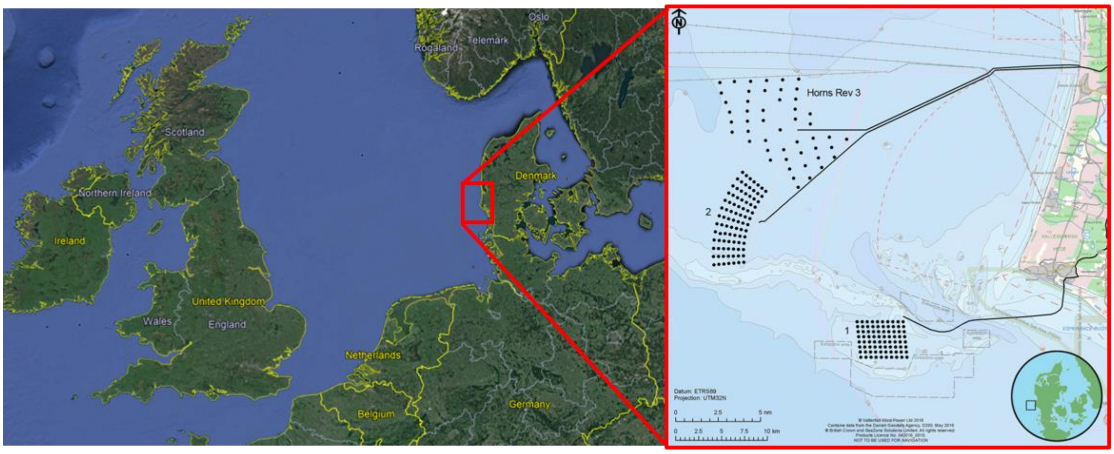

Figure 1 - Location of the Horns Rev area in the North sea. Detailed figure on the right indicates positions of the three wind farms HR1, HR2 and HR3 (image from Vattenfall https://corporate.vattenfall.com/globalassets/corporate/about_energy/3c_map_horns_rev_123.png).

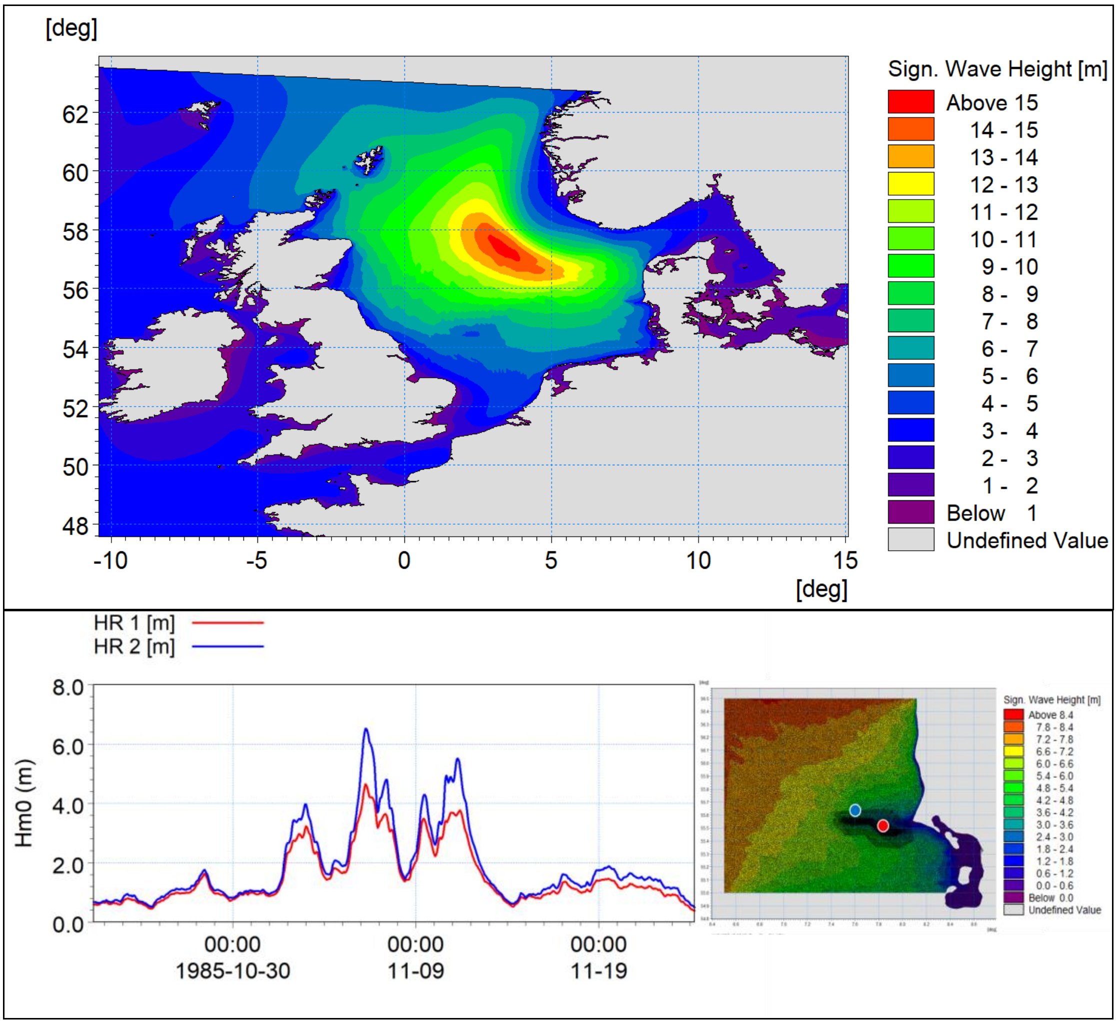

Figure 2 – Top panel shows the significant wave height (H_{m0}) in the North Sea on the 06/11/1985. Bottom left panel shows regional model H_{m0} time series at two locations within the Horns Rev area showing large dissipations produced by the shallow sand bars (compare red and blue lines whose locations are shown by the blue and red circles in the right panel).

SATELLITE DERIVED BATHYMETRY

For this study, satellite derived bathymetry (SDB) was produced using imagery from the Sentinel-2A satellite. The Sentinel-2 mission is based on a constellation of two identical satellites in the same orbit, 180° apart for optimal coverage and data delivery. Together they cover all Earth's land surfaces, large islands, inland and coastal waters every five days at the equator. Sentinel-2A was launched on 23 June 2015 and Sentinel-2B followed on 7 March 2017. The satellite carries a wide swath high-resolution multispectral imager with 13 spectral bands. It performs terrestrial observations in support of services such as forest monitoring, land cover changes detection, and natural disaster management.

There are multiple approaches to deriving bathymetry from satellite imagery. In this case, a DHI GRAS proprietary physical radiative transfer model (extended version of Guzinski et al. 2016; Klonowski et al, 2007; Lee et al. 1998, 1999, 2001) was used. Other methods commonly used for deriving SDB are the empirical models based on the early work of Lyzenga (1978) added upon in Stumpf (2003), and other radiative transfer based models, such as the SAMBUCA model developed by CSIRO (Brando and Dekker, 2003; Wettle and Brando, 2006). The fundamental difference between the empirical models, and the radiative transfer models, is that the empirical models calculate an index that correlates with depths, but has to be transformed into water depths, while the radiative transfer methods model the water column as a function of, amongst other parameters, the water depth.

The model used in this study minimizes the differences between an observed satellite image and a modelled satellite image, which is created as a function of six parameters – depth, bottom type, backscattering, chlorophyll-A, gelbstoff, and the slope of the backscattering function, with the bottom type being further split into fractional cover of two different bottom types, specifically unconsolidated sand and submerged aquatic vegetation. Through minimizing the difference between the observed and the modelled satellite images, accurate water depths can be retrieved in optically shallow waters, meaning light reflecting from the seabed is observed.

Essentially, the SDB can be reduced to the following series of pseudo equations:

$$rrs_{modelled} = f(chlorophyl, gelbstoff, b_b, b_x, \rho, H) \tag{1}$$

Where $rrs_{modelled}$ is the modelled satellite image, b_b is the backscattering, b_x is the slope of the backscattering function, ρ is the summed up bottom reflectance, and H is the depth.

The next step is to minimize the difference between the modelled and observed satellite images using:

$$\chi^2 = \frac{1}{N}\left[\sum(rrs_{observed} - rrs_{modelled})\right] \tag{2}$$

With N being the number of spectral bands, where the satellite image provides information, and $rrr_{observed}$ is the observed satellite image.

Through the two pseudo equations above, and the equations that define the relationship between the parameters in equation 1, the depths can be retrieved in a timely and reliable manner.

The primary strengths of SDB is the timeliness, repeatability, low cost, and easy accessibility to remote or dangerous shallow waters. The spatial resolution of the Sentinel-2 imagery also allows for very detailed bathymetry mapping, typically an order of magnitude better than available bathymetric datasets. Since the approach is based on optical data there is a limit to the depth penetration of around one secchi depth, so clear water is a requirement for optimal SDB retrieval and, thus, it can be a limiting factor for some dynamic environments with high concentration of suspended particle matter.

By deriving SDB at multiple time steps it is possible to detect and quantify sea floor dynamics and movement rates of seabed features. In this study a 10m resolution SDB was derived twice, once in 2016 and once in 2018, to quantify the movement rates of largescale sand bank in the Horns Rev area as illustrated below in Figures 3. This example clearly highlights the need for high resolution and recent bathymetry to accurately resolve hydrodynamic processes in the highly dynamic coastal zone in high spatial resolution. As can be seen on the two illustrations, the sand bank moved between 100m and 200m during a period of 23 months. This sediment transport might be due to a combination of wave impact and tidal current transport.

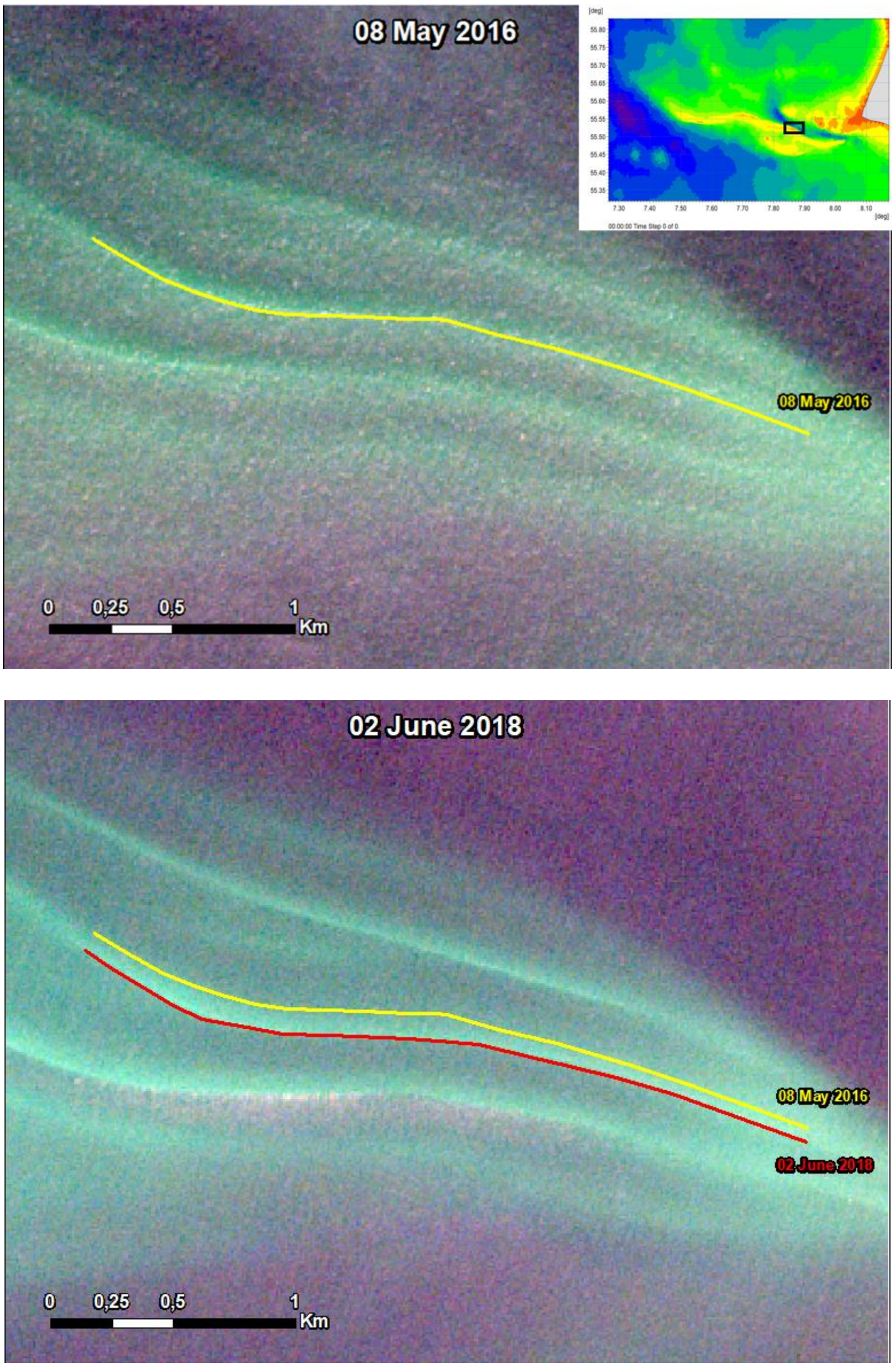

Figure 3 – Top panel shows a crest of a sand wave as observed on 8th of May, 2016, indicated with yellow line. Bottom panel shows bathymetry obtained on 2nd of June, 2018, illustrated by a red line, along with a yellow line showing its position in 2016.

The satellite derived bathymetry dataset was used to assess the impact of the sand banks and bed features in wave modelling and the possible implications for the characterization of extreme wave events for offshore wind farms as described in the following sections.

WAVE MODELLING

Spectral wave models (phase averaged) are typically used to provide wave conditions at offshore wind farms due to their skills for wave generation, propagation and because wave diffraction is normally not important offshore. Typical resolution of spectral wave models in this type of applications go from kilometers to few hundreds of meters.

However, near the coast, bathymetric features can induce significant changes in wave dynamics where higher order statistics become important (e.g. skewness and asymmetry). In such conditions phase-resolving models are more appropriate tools to study wave transformation and can handle situations where phase averaging might be inconsistent. However, phase resolving models are typically used only for smaller domains because the computational grid has to be fine enough to resolve wave lengths and their use is not practical for long period hindcasts.

Therefore, a deep water spectral wave model coupled to a phase-resolving wave model is done to ensure accurate modeling of the local wave field near structures and bathymetric features of relevance (see e.g. Chen et al., 2009; Belibassakis et al., 2014).

In this work we use a spectral wave model and a phase resolving model to simulate extreme waves propagation over an area characterized by sand bars. In the case study, sand waves dimensions are comparable to surface wave length, and thus, phase-averaged models are not expected to provide accurate results. Model descriptions and implementations are presented in the following sections.

Spectral wave model

The spectral wave model (MIKE 21 SW (DHI, 2019a)) used in the present work is part of the MIKE Powered by DHI suite of models. MIKE 21 SW simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. The wave model is based on an unstructured, cell-centered finite volume method and use an unstructured mesh in geographical space.

MIKE 21 SW is a third-generation spectral wave model developed for flexible meshes and allows for high resolution near complicated coastlines. The model includes the Janssen (1991) formulation with the white-capping formulation from Bidlot et al. (2005, 2007). The wave model also includes dissipation due to bottom friction and depth-induced wave breaking, non-linear wave-wave interactions, refraction and shoaling due to depth variations and the effects of time-varying water depth and currents. Additional model developments (Bolaños et al., 2019, Golestani et al., 2015) include the capabilities of using a varying air/water density ratio in the wind input source term, use of a surface current factor to modify wave celerity in the wind input source term and a cap to wind friction velocity (e.g. Jensen et al., 2006) which have all shown improvements on wave model results.

Spectral wave model implementation

The spectral wave model was implemented using the irregular mesh and nesting capabilities of the model. A first model domain (named SW_{NA}) covering the entire North Sea was used to generate boundary conditions for a smaller domain (see Figure 4). Figure 4 shows the model domain covering Northern Atlantic, with a resolution from 40km to about 3km close to the Horns Rev area. The open boundaries of SW_{NA} wave model were forced by directional wave spectra from a global wave model. SW_{NA} used 35 frequencies; 0.03-1.04Hz. (33-0.96s) with a logarithmic frequency increment factor of 1.11) and 36 directions. Wind fields were obtained from CFSR (Climate Forecast System Reanalysis, see section below). The local domain (bottom panel in Figure 4) covers a region around HR of approximately 100km x 160km. The spatial resolution in the most offshore areas was of 1km. However, several mesh configurations were used to assess the impact of model resolution and the high resolution bathymetry available from satellite. Five meshes were generated with high resolution at the Horns Rev area, going from 800m to 25m (see Table 1). Depth induced breaking is accounted for by the formulation of Battjes and Janssen (1978) with a Gamma value of 0.8. Bottom friction uses the formulation described by Johnson and Kofoed-Hansen (2000). The spectral discretization of the high resolution local domain was the same as the larger domain (35 frequencies and 36 directions). Table 1 shows the five runs performed with the local domain of the spectral wave model varying resolution within the area of the sand bars.

Table 1. Spectral Model resolution

Run	Maximum resolution (m)
1	800
2	300
3	100
4	50
5	25

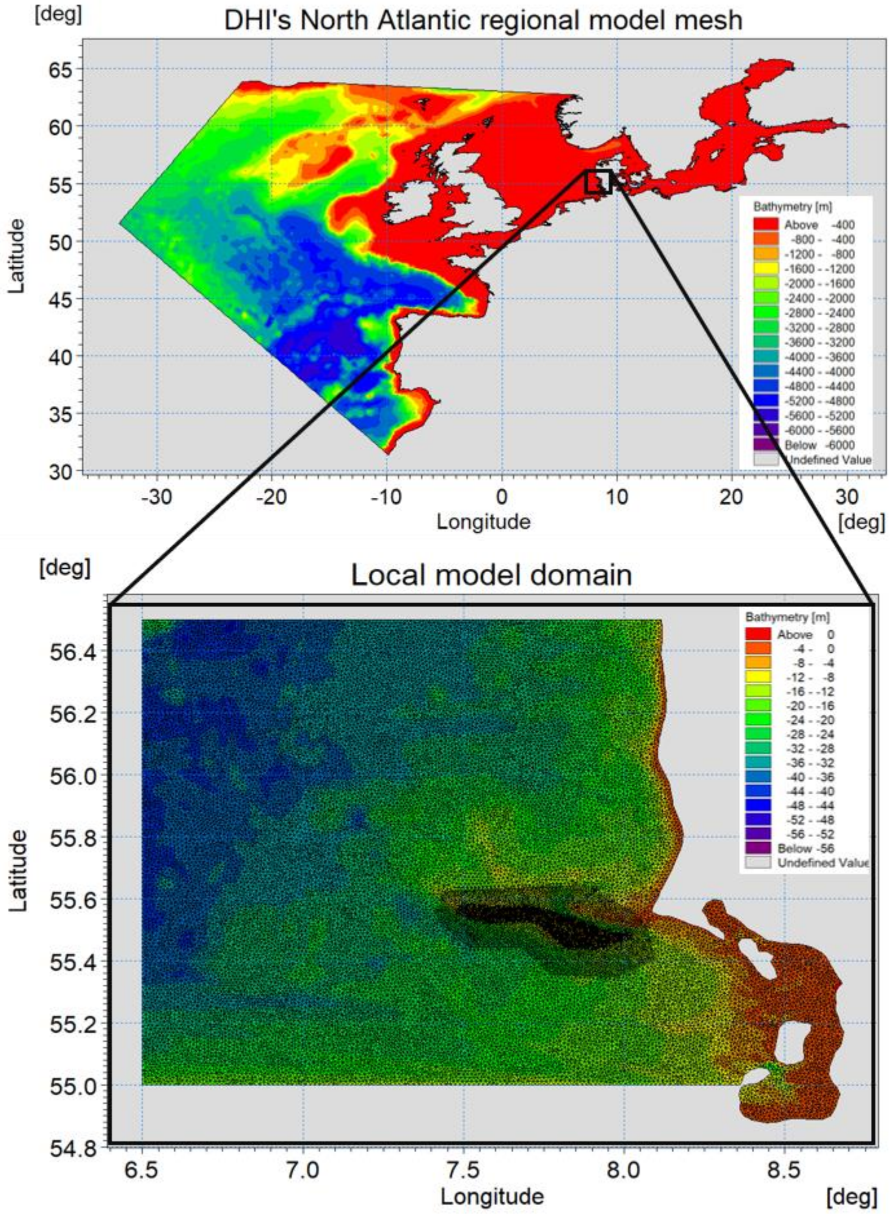

Figure 4 – Spectral wave model domains. Top panel is the regional wave model (SW_{NA}) covering the North Sea. Bottom panel shows the local model domain with high resolution around the Horns Rev area. Colorbar at each panel indicate bathymetry in meters.

Wind forcing

The Climate Forecast System Reanalysis (CFSR, see Saha et al. 2010) dataset is established by the National Center for Environmental Prediction (NCEP). CFSR is a coupled meteorological and oceanographic model system that assimilates synoptic data. The data are available on an hourly basis from 1979-Jan-01 to present. The first version of CFSR data covers the 31-year period from 1979 to 2010, while a latter dataset, the operational re-forecast dataset (denoted CFSV2), covers the period from 2011 to present. The underlying model in CFSV2 is the same as for CFSR; however, the spatial resolution of wind and temperature was improved from 0.3° to 0.2°. The CFSR atmospheric variables used to force the wave model described here are the wind speed components. CFSR has previously provided very good results when compared with offshore wind measurements and when used as forcing for wave models in the North Sea and other parts of the world (e.g. Bolanos et al., 2019; DHI, 2017).

Bathymetry

The model bathymetry used was a blend of the satellite derived bathymetry from 2016 described in the previous sections and data from EMODnet Bathymetry portal (http://www.emodnet-bathymetry.eu). This portal was initiated by the European Commission as part of developing the European Marine Observation and Data Network. The EMODnet digital bathymetry has been produced from bathymetric survey data and aggregated bathymetry data sets collated from public and private organizations. These are processed and quality controlled. A further refinement and expansion is underway, by gathering additional survey data sets and where possible, upgrading the digital terrain model grid resolution, and will result in new releases with time. The portal also includes a metadata discovery service that gives clear information about the background survey data used for the digital terrain model, their access restrictions, originators and distributors. The data has a grid size of 0.125 minute × 0.125 minute.

Phase resolving model. MIKE 3 wave FM

In order to assess the impact of sand waves on individual waves, a non-hydrostatic wave model was implemented. The model (MIKE3 Wave FM (DHI, 2019b)) is based on the incompressible Navier-Stokes equations subject to the assumptions of Boussinesq and with free surface described by a height function. The turbulence is modelled using an eddy viscosity concept (κ-ε) and the vertical discretization uses sigma or combined sigma/z-levels. As with other MIKE models, MIKE3 Wave FM has the capability of using horizontal unstructured meshes. Additionally to the expected better model for individual waves over bed features or structures compared to a spectral model, another advantage of the phase resolving model is that wave kinematics can be obtained which is fundamental information to study wave-structure interactions and sediment transport. Further details on the model can be found in DHI (2019b).

MIKE 3 Wave FM was implemented for a domain of approximately 1 km^2 covering one of the sand bars with satellite bathymetry data and containing clear sand waves on top of it. Several model runs were performed considering regular and irregular waves (taking directional spectra from spectral model) and a flat and real bathymetry in order to outline the impact of the sand waves.

A small area was selected in order to make the influence of wind input and whitecapping negligible. The area was selected to include the presence of the bedforms (see Figure 5). The horizontal spatial resolution was 2m with a quadrangular mesh using 5 sigma vertical levels. The forcing at the boundaries were selected from the output of the spectral wave model at the site during the peak of the storm which corresponded to a significant wave height (H_{m0}) of 2.3m peak period (T_p) of 12s and peak wave direction of 315^o these values were used for simulation of regular wave using stream function theory, but the full directional spectra obtained from the local model (run 5 in Table 1) was also used for the cases of irregular waves. Two bathymetries were used, a flat bed with a depth of 7m and the bathymetry from the satellite for the real case. Since the main direction of waves was around 315^o for the case study a rectangular domain aligned with this direction was chosen in order to reduce the impact of lateral boundaries and the sponge layer. For all the tests the model was run to simulate a 20 minutes period. The wave generation boundary was defined to be the northwest boundary and the sponge boundary was defined as the southeast. The domain spatial units were in meters using a UTM32 projection. Table 2 summarizes the model settings for the runs performed.

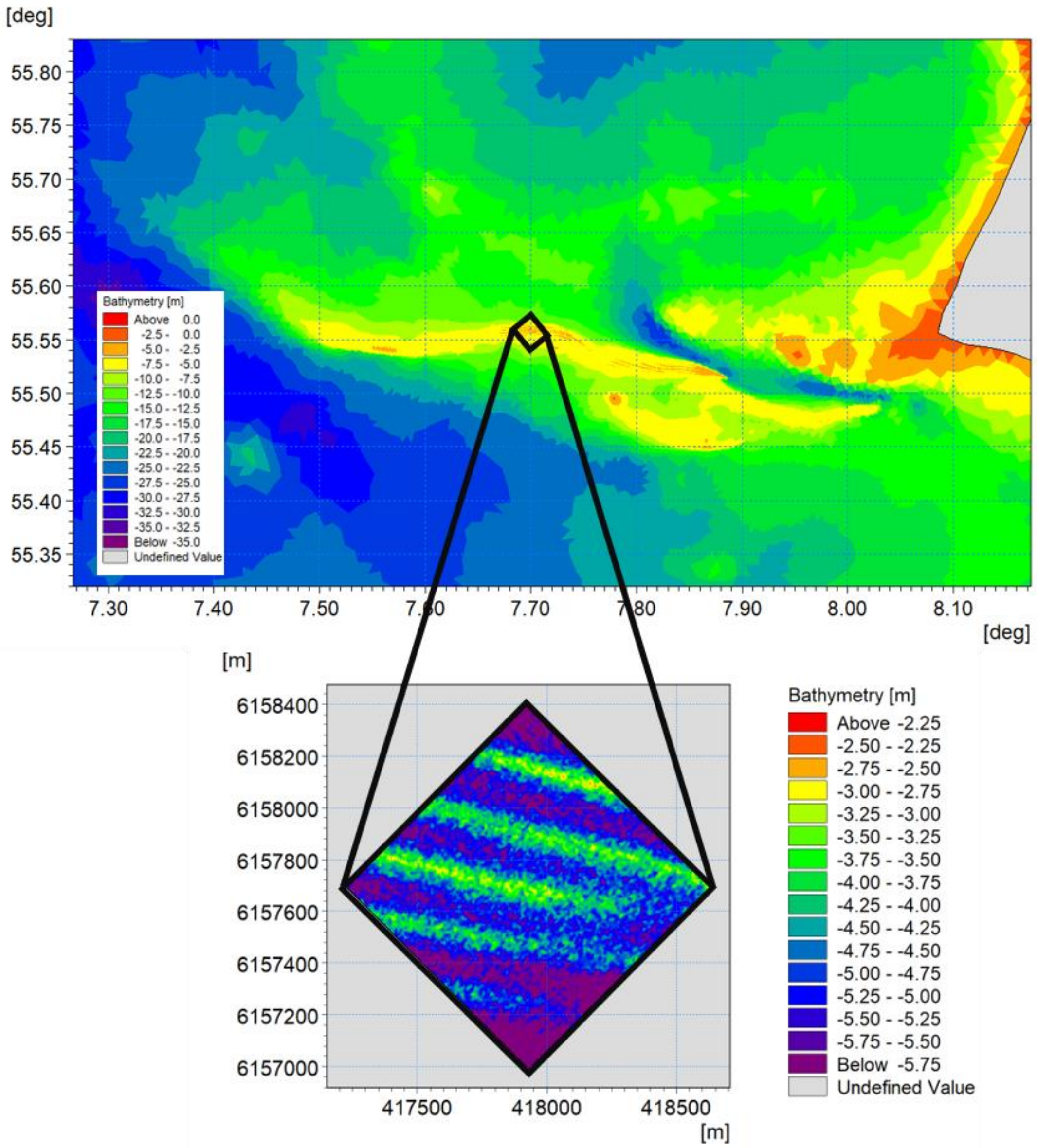

Figure 5 – MIKE 3 Wave FM model location (top panel), domain and bathymetry (bottom panel, UTM32 coordinate system). Colorbar represent water depth in meters.

Table 2. Summary of MIKE 3 Wave FM model runs setup

Run	BC	Bathymetry
R1	Regular wave (H=2.3. T=12s)	Flat (7m)
R2	Regular wave (H=2.3m T=12s)	Real
R3	Directional spectra	Flat (7m)
R4	Directional spectra	Real

WAVE MODELS RESULTS AND DISCUSSION

Figure 6 shows the maximum H_{m0} in each element of the spectral wave model domain, and shows a severe storm with H_{m0} of approximately 11 m offshore and a strong dissipation due to seabed influence in the Horns Rev area. It is expected that a high resolution of the bed features would result in more accurate wave simulation due to better description of wave dissipation (bottom friction and breaking) and transformation (e.g. refraction). Figure 7 present the differences of maximum H_{m0} between the different modelled resolutions (see Table 1) at an area on the sand bars. Figure 7a shows the bathymetry as a reference, figure 7b and 7c show the maximum H_{m0} for the 25m and 50m resolution. Although their patterns are very similar, it is noticeable, by looking at their difference (Figure 7d), that differences occur mainly at the edge of the sand bar. This is due to the different location of the breaking zone as seen by the model. Similarly Figure 7e to 7g show differences between modelled results with resolution of 25m with 100m, 300m and 800m where differences of more than 1 m are observed due to the description of the bed features. The sand waves observed through the satellite bathymetry have a wave length in the order of 250m, while the entire sand bar has a width of few kilometers. This, clearly shows that the impact of such structures is important for wave modelling and therefore an appropriate resolution (of the bathymetry and model) should be utilized, for the present case a resolution of between 100 and 300m is optimal.

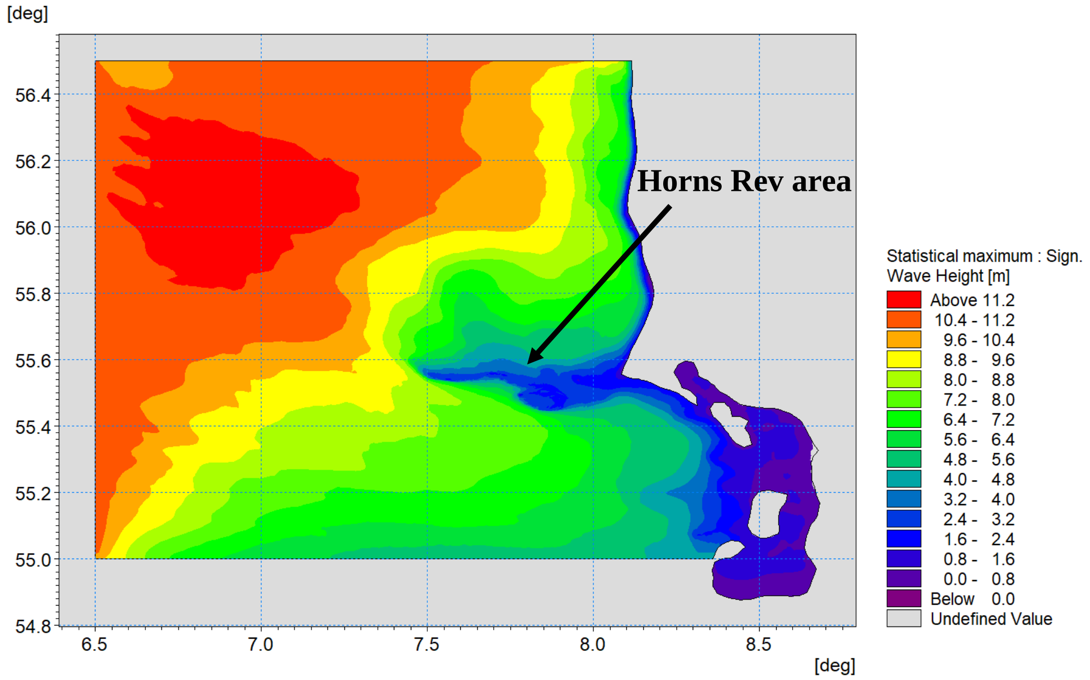

Figure 6 – Maximum H_{m0} at each element of the model mesh during the storm event of November 1985.

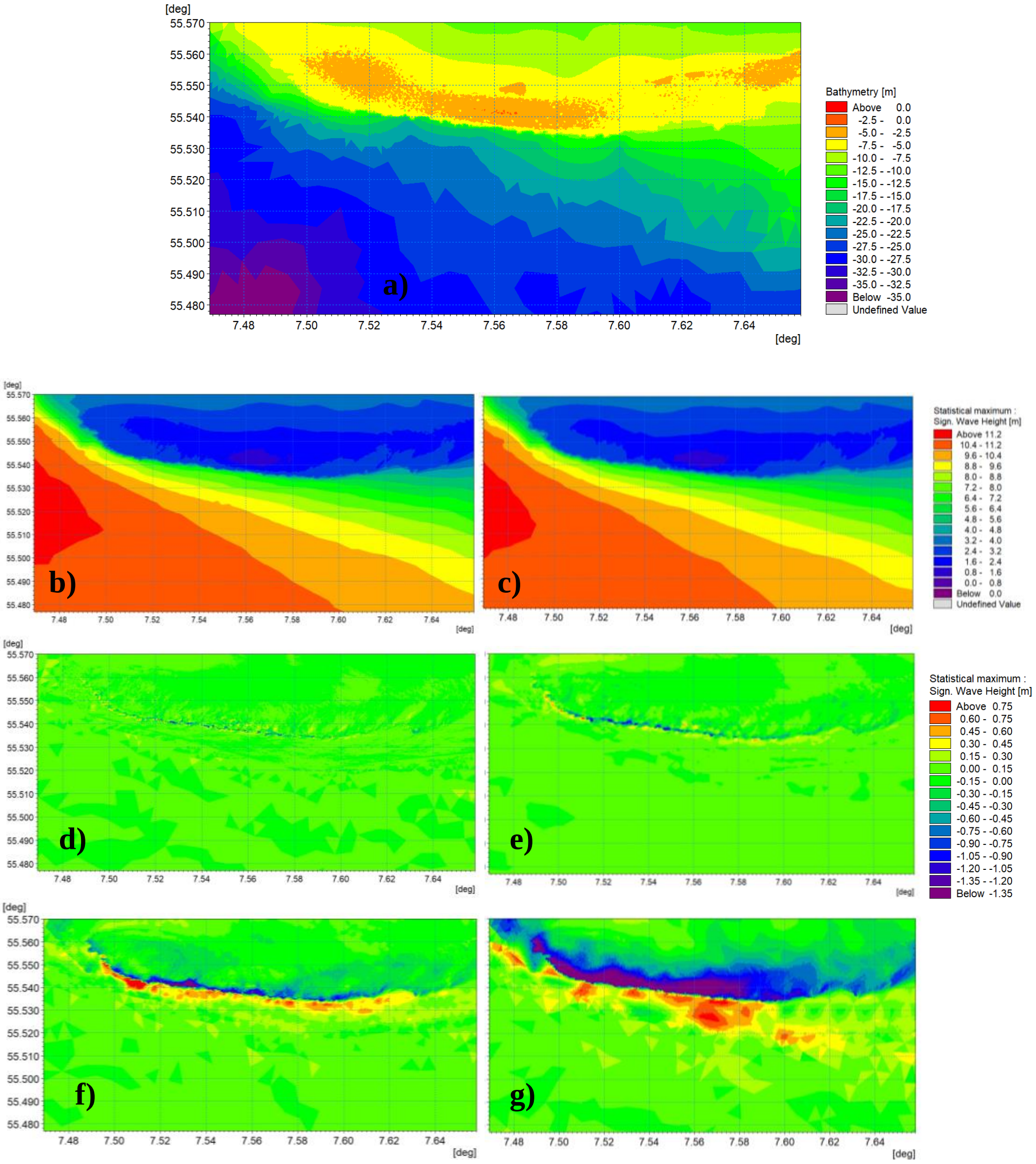

Figure 7 – a) Bathymetry of one of the sand bars at Horns Rev area. b) maximum H_{m0} at each element of the 25 m resolution model for the area shown in panel a, c) maximum H_{m0} at each element of the 50 m resolution model. D) difference between 25 and 50 m resolution. E) difference between the 25m and 100m resolution. F) difference between the 25m and 300m resolution. G) difference between the 25m and 800m resolution.

Figure 8 shows the result of the MIKE3 Wave FM for the case of regular waves propagating over a flat bed and the real bathymetry containing the bed forms. For the case of the flat bed (Figure 8 left panel) it can be seen that waves propagation is steady and no impact of boundaries (e.g. through reflection) is noticeable. For the case of the real bathymetry (Figure 8 left panel), wave breaking occurs when waves reach the sand wave crests which significantly reduce wave energy and produce some refraction of waves. This wave breaking process is expected to be of importance for sediment transport and for the study of wave-structure interactions.

Figure 9 presents the results of the irregular case tests where the first column is the results from the flat bed after 20 minute simulation, central column is for the real bathymetry and right column is the difference between the real bathymetry result minus the flat bed case. Each row shows different variables, from top to bottom are H_{m0}, maximum wave height (H_{max}), mean surface elevation, mean current u component of velocity and mean current v component of velocity. Similarly to the regular case, bed features reduce waves when they first reach the sand bars, this is noticeable in the reduction of H_{m0} and maximum surface elevation. H_{m0} is reduced approximately 60% as waves propagate through the domain (<1km). A clear impact of the sand bars is the modification of the velocities which are significantly increased due to the presence of sand bars. The mean of the u and v components during the simulation period shows an increase in the first section of the domain in agreement with sand wave orientation and the locations where waves lose energy.

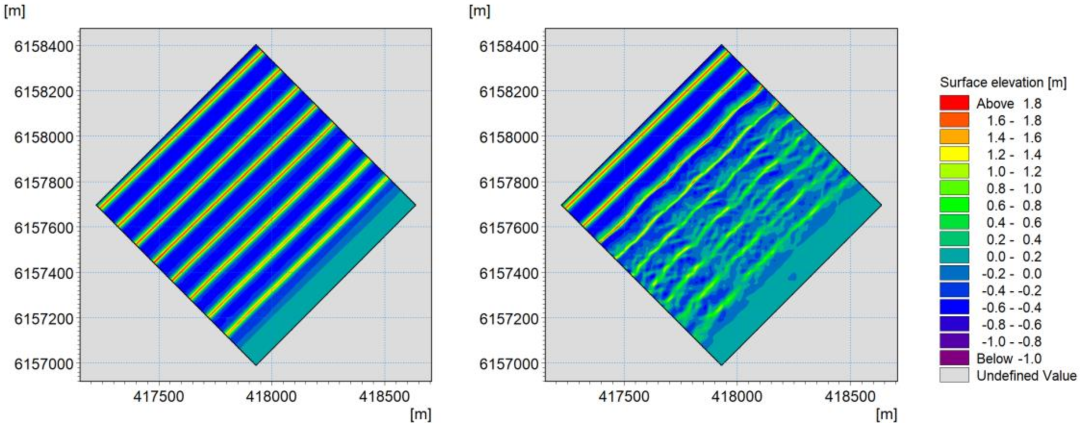

Figure 8 – Surface elevation result for the case of regular waves for a flat (left panel) and real (right panel) bathymetry.

A satellite-based bathymetry was successfully obtained at the Horns Rev area for water depth deeper than 7m. This outlined a limitation of this approach for deeper areas as it requires very clear water conditions for the light to penetrate. Considering that offshore wind farms are typically deployed in deeper water, the satellite derived bathymetry might not be relevant for these applications. However, a more coastal use of such data which, as demonstrated here, was capable of register large bedform movement would be relevant where sediment transport studies, and coastal waters problems would benefit of access of such data. This type of data could also support seabed mobility studies which are required for cabling and pipelines projects with landfalls and where wave and currents produce significant sediment transport near the coast.

As shown in this the sensitivity study presented in this work, the improved location of the breaking zone seems to be the most beneficial when using the high-resolution data in spectral wave modelling. The identification of large sand bedforms was possible and could help in setting the optimal model resolution in order to properly model wave dissipation and transformation. The combination of a spectral wave model with a phase resolving model is a natural approach for such type of environment where resolution lower than hundreds of meters play an important role and become somewhat restrictive for a spectral model.

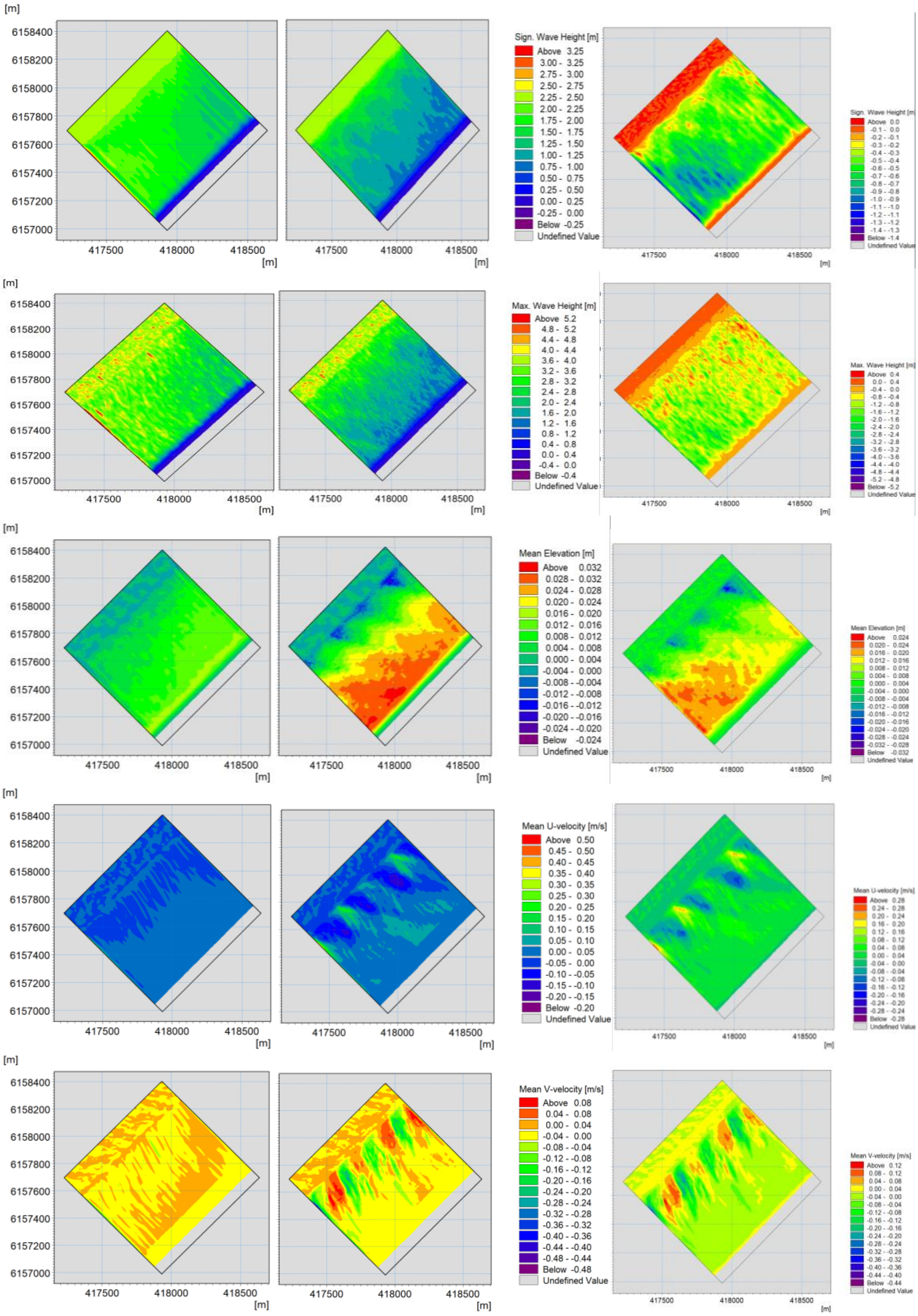

Figure 9 – Surface elevation result for the case of regular waves for a flat (left panel) and real (right panel) bathymetry.

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