# EFFECTS OF BED-SEDIMENT GRAIN-SIZE DISTRIBUTION ON WAVE HEIGHT PREDICTIONS IN THE ENGLISH CHANNEL

Nicolas Guillou[1]

**Abstract**

The present study examines the energy dissipation of wind-generated surface-gravity waves by bottom friction in relation to the seabed roughness magnitude. The investigation is based on the phase-averaged numerical wave model SWAN (Simulating WAves Nearshore) implemented in the English Channel. Two formulations of bottom drag coefficients are considered: the JONSWAP expression and the eddy-viscosity model of Madsen. Numerical predictions of significant wave height are compared with available field data collected at (1) three offshore lightships and (2) two nearshore wave buoys off Cherbourg and Le Havre harbours. Best estimates are found with the heterogeneous bottom roughness associated with the grain size of seabed sediments. Mappings of coastal areas influenced by bottom friction are produced exhibiting significant energy dissipation in the Normano-Breton Gulf and the surroundings of the Isle of Wight.

**Key words:** modelling, SWAN, bottom friction, English Channel, Le Havre, Cherbourg.

## 1. Introduction

Wind-generated surface-gravity waves propagating in shallow water may experience significant energy dissipation due to seabed interactions when the orbital motions of the water particles extend down to the seabed (*e.g.*, Johnson and Kofoed-Hansen, 2000). Neglecting this energy loss is liable to result in substantial overestimation of nearshore wave height with consequences in the quantification of sediment transport rates or the design of coastal structures (Work *et al.*, 2004). During extreme storm events such as hurricanes, this dissipation of wave energy is likely to decrease by 40-50 % the significant wave height along the coastline (*e.g.*, Riedel *et al.*, 2005; Siadatmousavi *et al.*, 2011).

Bottom friction is considered to be the dominant mechanism of wave-bottom interaction in many continental shelves with fine sandy bottom of median diameter $d_{50}$ in the range of 0.1 – 0.4 mm (*e.g.*, Shemdin *et al.*, 1978; Bertotti and Cavaleri, 1994). In the action or energy balance equation of third-generation wave models, it is generally expressed with the formulation proposed by Weber (1991a, b). The key point of this mathematical expression is the parameterisation of a dissipation coefficient $C_b$ on the basis of hydrodynamics and bed sediment properties. Numerous formulations have been proposed to approach this coefficient (see Luo and Monbaliu, 1994 or the WISE group, 2007 for a detailed review). The simplest method commonly used in operational prediction models consists in prescribing constant empirical values on the basis of the JONSWAP parameterisation adopted by Hasselmann *et al.* (1973) and reviewed later by Bouws and Komen (1983). Although this approach performs well in a number of idealised test cases with wind-wave conditions (Tolman, 1994), more complicated models have been developed to integrate the effects of hydrodynamics and sediment properties (*e.g.*, Hasselmann and Collins, 1968; Collins, 1972; Madsen *et al.*, 1988; Weber, 1991a,b). Given the lack of information on bottom materials, numerous investigations were dedicated to comparisons of dissipation coefficients formulations in relation with sea roughness and wind-drag coefficient (*e.g.*, Luo and Monbaliu, 1994; Johnson and Kofoed-Hansen, 2000; Padilla-Hernandez and Monbaliu, 2001; Zijlema *et al.*, 2012). The nature and properties of bottom sediments were considered in few applications (*e.g.*, Ardhuin *et al.*, 2003a, b; Siadatmousavi *et al.*, 2011).

The purpose of the present study is to evaluate the effects of bed-sediment grain-size distributions on

[1] , CETMEF/DS/LGCE, Laboratoire de Génie Côtier et Environnement, Technopôle Brest Iroise, 29280 Plouzané, France. nicolas.guillou@developpement-durable.gouv.fr, http://www.cetmef.developpement-durable.gouv.fr/, http://memphys-lgce.fr.ht/ .

predicted significant wave height in the English Channel (Fig. 1). This shelf environment is characterised by a highly heterogeneous spatial distribution of bottom sediments with (1) very fine sands, silts and muds in bays and estuaries and (2) pebbles and gravels in the Dover Strait, off the "Pays de Caux" and over an extensive zone in the Central Channel between the Isle of Wight and the Cotentin Peninsula (*e.g.*, Vaslet *et al.*, 1979; Larsonneur *et al.*, 1982). Furthermore, it is occasionally subjected to storm events.

The approach retained here relies on a comparison between numerical predictions and observations. Field measurements are realised at three offshore lightships and two nearshore wave buoys off Cherbourg and Le Havre harbours (Fig. 1, Section 2.1). Modelling is based on the phase-averaged wave model SWAN (Simulating WAves Nearshore) (Booij *et al.*, 1999) modified to account for a new parameterisation of wind drag coefficient proposed by Zijlema *et al.* (2012) at high wind speeds (Sections 2.2 and 2.3). A pre-processing module computes the required surficial sediment granulometric distribution from a series of bottom samples and the associated heterogeneous frictional parameters. Numerical predictions are compared with observations over the period from December 2007 to March 2008 characterised by an extreme storm event on 10 March 2008 with significant wave height over 10 m at the western entrance of the English Channel (Section 3.1). The role of bottom friction on wind waves is evaluated comparing numerical predictions obtained with the formulations of wind-drag coefficients proposed by Wu (1982) and Zijlema *et al.* (2012) (Section 3.2). The effects of bottom friction on the dissipation of wave energy are investigated considering the JONSWAP expressions proposed by Hasselmann *et al.* (1973) and Bouws and Komen (1983) and the eddy-viscosity model of Madsen *et al.* (1988) to integrate the hydrodynamics and heterogeneous distribution of bottom-sediment grain size (Section 3.3). Finally, mappings of numerical predictions are produced over the entire computational domain to encompass the spatial and temporal changes of (1) the significant wave height and (2) bottom dissipation coefficient $C_b$ with respect to constant default values (Section 3.4).

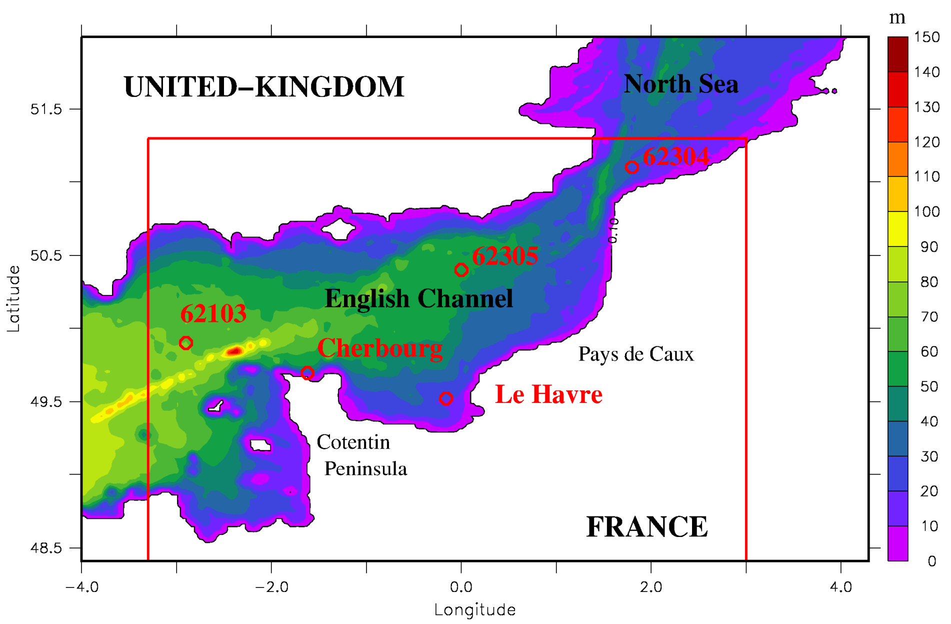



Figure 1. Bathymetry of the computational domain with the locations of the measurements points. The red rectangle shows the area where the spatial heterogeneous bottom roughness is introduced.

## 2. Materials and Methods

### 2.1. *Experiment description*

Wave measurements here used were obtained at the three offshore lightships 62103 (λ=-2.90°W, φ=49.90°N), 62305 (λ=0°W, φ=50.40°N) and 62304 (λ=1.80°W, φ=51.10°N) of the UK Meteorological

Office and the two nearshore wave buoys off Le Havre (λ=-0.16°W, φ=49.52°N) and Cherbourg (λ=-1.62°W, φ=49.70°N) harbours of the French CANDHIS database (Centre d'Archivage National de Données de Houle In Situ) (Fig. 1). The instrumentation network is deployed in water depths ranging from 70 m at lightship 62103 to 20 m at the wave buoy of Le Havre.

### 2.2. *Model description*

SWAN solves the time-dependent spectral action balance equation. It accounts for depth shoaling, refraction, non-linear transfer of energy through wave-wave interactions and wave-energy dissipation due to whitecapping, bottom friction and depth-induced breaking. The modelling procedure ignored the modifications of waves components by the current and the free-surface elevation. The parameterisation adopted for sources and sinks are briefly detailed hereafter. Energy dissipation in random waves due to depth-induced breaking is quantified according to Battjes and Janssen (1978).
The sink term of bottom friction is computed according to the following formulation:

$$S_{ds,b}=-C_b\frac{\sigma^2}{g^2\sinh^2 kd}E(\sigma,\theta) \quad (1)$$

where k is the wave number of the spectral component, σ is the relative radian frequency equals to the absolute radian frequency in the absence of ambient current, θ is the direction of the wave component, $d$ is the water depth, $g$ is the acceleration of gravity taken equal to $g$=9.81 m $s^{-2}$ and $E(\sigma,\theta)$ is the two-dimensional frequency spectrum. Two formulations are considered for the computation of the bottom friction coefficient $C_b$. The first parameterisation here retained consists in prescribing constant empirical values. In the JONSWAP experiment, Hasselman *et al.* (1973) suggested to use a value of $C_b$=0.038 $m^2s^{-3}$ for swell dissipation over sandy bottoms. This value was re-examined by Bouws and Komen (1983) for fully developed wind-seas as $C_b$=0.067 $m^2s^{-3}$. The second parameterisation follows Madsen *et al.* (1988) who derived a formulation which integrates the effects of wave conditions and bed roughness. The bottom friction coefficient is given by:

$$C_b=f_\omega\frac{g}{\sqrt{2}}U_{rms} \quad (2)$$

where $U_{rms}$ is the root mean square bottom-orbital velocity. $f_\omega$ is the non-dimensional friction factor estimated with the formulation proposed by Jonsson (1966):

$$\frac{1}{4\sqrt{f_\omega}}+\log_{10}\left(\frac{1}{4\sqrt{f_\omega}}\right)=m_f+\log_{10}\left(\frac{a_b}{k_n}\right) \quad (3)$$

where $m_f$ is taken equal to $m_f$=-0.08 according to Jonsson and Carlsen (1976), $a_b$ is the representative near-bottom excursion amplitude and $k_n$ is the bottom roughness length scale. This formulation is retained when the condition $a_b/k_n$>1.57 is satisfied. For values $a_b/k_n$<1.57, $f_\omega$ is taken equal to $f_\omega$=0.3. Whereas numerous algorithms have been developed to integrate the effects of wave ripples generation in numerical wave models (*e.g.*, Graber and Madsen, 1988; Tolman, 1994; Ardhuin *et al.*, 2003a; Smith *et al.*, 2011), the present investigation is restricted to the consideration of current ripples mainly because of the strong influence of tidal currents on sediment transport in the English Channel (*e.g.*, Guillou *et al.*, 2009; Guillou and Chapalain, 2010). As this study constitutes a first estimate of the effects of the heterogeneous spatial distribution of bottom-sediment grain-size on wave conditions, more complex predictors of sand ripple geometry under the combined influence of tidal current and waves (*e.g.*, Li and Amos, 1998, 2001) are ignored. Bed features are considered over sandy bottom with median diameter $d_{50}$<800 µm (Soulsby, 1997). The associated roughness length scale is parametrised according to Yalin (1985) and Wooding *et al.* (1973) resulting in value of $k_n$ around $k_n$~240$d_{50}$. This relationship is consistent with the linear formulation proposed by Siadatmousavi *et al.* (2011): $k_n$=200$d_{50}$. Seabeds made of coarser sediments (*i.e.*, $d_{50}$>800 µm) remain featureless with a roughness length scale equals to $k_n$=3$d_{90}$ where $d_{90}$ is the grain diameter for which 90 % of the grains by mass is finer.
Wave growth by wind is computed with the exponential term of Komen *et al.* (1984). Two formulations are considered for the wind drag coefficient: (1) the default value proposed by Wu (1982) and (2) the

relationship derived by Zijlema *et al.* (2012) to fit a compilation of observations at high wind speeds. Finally, processes of whitecapping are described with the pulse-model equation of Hasselmann (1974).
The wave action balance equation is expressed in a spherical coordinate system. Further details about the mathematical expressions of sources and sinks are available in SWAN technical documentation (SWAN team, 2009).

### 2.3. *Model setup*

SWAN is set up on a computational domain covering the English Channel between longitudes -4.000°W and 4.291°W and latitudes 48.410° N and 51.992°N (Fig. 1). It is discretised on a 280 x 200 horizontal grid with a spacing of 2 km. The model runs with 30 exponentially spaced frequencies ranging from 0.05 to 1 Hz, 60 evenly spaced directions (6 ° resolution) and a time step of 10 min. Wind velocity components at 10 m above the free surface are provided by the meteorological model ALADIN ("Aire Limitée, Adaptation dynamique, Développement InterNational", Bénard, 2004, Météo-France). SWAN is driven by the wave components predicted along each open boundary from a regional run of WaveWatch III on the North-Western European continental shelf (F. Ardhuin, Institut Français de Recherche pour l'Exploitation de la MER, France, personal communication issued from the NORGAS configuration, 2010). The heterogeneous spatial distribution of the median diameter $d_{50}$ is computed in an inner domain extended in longitude from 3.300°W to 3.000°E and in latitude from 48.410°N to 51.300°N (Fig. 1). The statistical mixed SFA-kriging (Spherical Factor Analysis) interpolation method proposed by Leprêtre *et al.* (2006) is applied to a series of 2318 bottom sediment samples collected in the framework of the "RCP 378 Benthos de la Manche" program (Cabioch *et al.*, 1977). Further details about the application of this method in the English Channel are available in Guillou (2007) and Guillou and Chapalain (2010). The resulting spatial heterogeneous bottom roughness length scale is displayed in Figure 2. When the formulation of Madsen *et al.* (1988) is retained, $k_n$ is set to its default value $k_n$=0.05 m (SWAN team, 2009) outside of this inner domain.

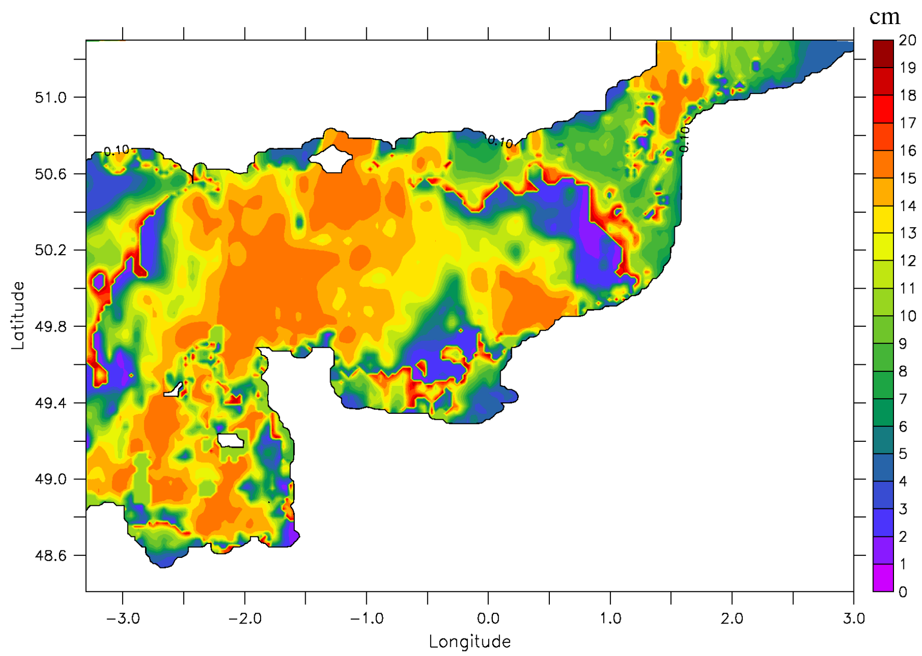



Figure 2. Spatial heterogeneous bottom roughness length-scale $k_n$ in the inner computational domain.

SWAN is run over the period from December 2007 to March 2008 when continuous observations of wave conditions in winter were available at the five measurements sites (Fig. 3). This period is characterised by the succession of six major storm events of averaged significant wave height of 3.5 m in the central English Channel. It presents also an extreme storm event on 10 March 2008 with wave height exceeding 10 m at the western entrance of the English Channel. In order to investigate the effect of the sensitivity of model predictions to the formulations of wind-drag coefficient, four numerical experiments titled A1 to A4 are conducted (Table 1). The influences of bottom-friction formulations is evaluated on the basis of five experiments titled B1 to B3b (Table 2). These numerical experiments are compared with the standard statistical parameters of the averaged and maximum absolute differences and the relative error or index of agreement introduced by Willmott (1981) as

$$\mathrm{re} = 1 - \frac{\sum_i |y_i - x_i|^2}{\sum_i \left(|y_i - \bar{X}| + |x_i - \bar{X}|\right)^2} \tag{4}$$

where ($x_i$) and ($y_i$) represent the two sets of measured and simulated wave heights and X is the averaged of the observations ($x_i$) over the time period considered. The relative error varies between 0 and 1. It equals to unity for perfect agreement.

Table 1. List of numerical experiments for the estimation of wind-drag formulations.

| Numerical experiments | Bottom drag formulations | | Wind-drag formulations | |
|---|---|---|---|---|
| | JONSWAP $C_b$=0.067 $m^2.s^{-3}$ | JONSWAP $C_b$=0.038 $m^2.s^{-3}$ | Wu (1982) | Zijlema *et al.* (2012) |
| A1 | X | | X | |
| A2 | | X | X | |
| A3 | X | | | X |
| A4 | | X | | X |

Table 2. List of numerical experiments for the estimation of bottom-drag formulations with the wind-drag formulation proposed by Zijlema *et al.* (2012).

| Numerical experiments | B1 | B2a | B2b | B3a | B3b |
|---|---|---|---|---|---|
| Formulation of the bottom dissipation coefficient | No friction | JONSWAP $C_b$=0.038 $m^2.s^{-3}$ | JONSWAP $C_b$=0.067 $m^2.s^{-3}$ | Madsen *et al.* (1988) $k_N$=0.05 m | Madsen *et al.* (1988) $k_N$=f($d_{50}$) |

## 3. Results and Discussion

### 3.1. *Comparisons with point measurements*

Figure 3 displays the observed and predicted from configuration A1 time series of the significant wave height at offshore and nearshore measurement points in December 2007 – March 2008. The model reproduces fairly well the magnitude of the storms heights of early December, January and March 2008 at the five sites of observation. Best estimates are obtained at the wave buoy of Le Havre with a relative error of 0.96. Predictions tend however to slightly overestimate measurements by 5-10 % at lightships 62103 and 62305 and the wave buoy of Cherbourg. This tendency appears in particular during the storms of January 2008. Numerical results at lightship 62304 tend however to underestimate observations. Whereas these predictions present the most important differences with measurements, the relative error stands over 0.88.

### 3.2. *Sensitivity to wind-drag formulation*

The relative errors for the numerical experiments A1 to A4 are displayed in Figure 4. Best estimates of the significant wave height are globally obtained with the formulation of Zijlema *et al.* (2012) which presents better agreement with observations of wind-drag coefficient than the expression of Wu (1982).

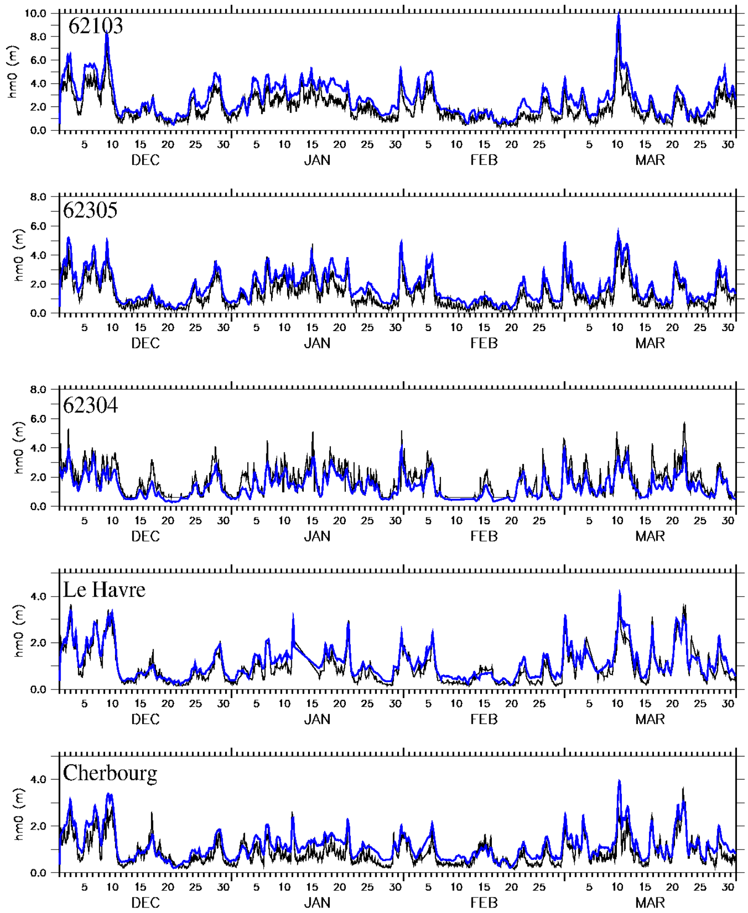
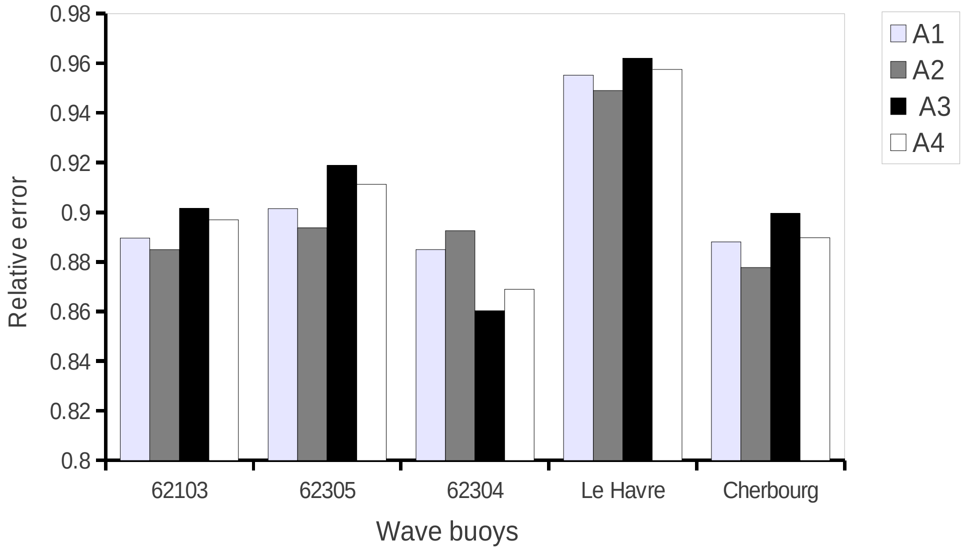



Figure 3. Time series of the (black line) observed and (blue line) predicted (from configurations A1) significant wave height at offshore and nearshore wave buoys in December 2007 –March 2008.




e

errors in predictions of the significant wave height at measurement points
for the four numerical experiments A1 to A4.

Nevertheless, the new formulation tends to increase the differences at the lightship 62304. Indeed, the wind drag formulation of Zijlema *et al.* (2012) results in lower values than with the original formulation proposed by Wu (1982). During the period of simulation, these differences are exhibited at high wind speeds over 14 m $s^{-1}$ with wind-drag coefficients by 10-30 % higher with the expression of Wu (1982) than with the formulation of Zijlema *et al.* (1982) (Fig. 5). For the same dissipation coefficient by bottom friction, lower significant wave heights are thus obtained with the new formulation  As initial predictions from configuration A1 (Fig. 3) present a global tendency to underestimate measurements at lightship 62304, the expression of Zijlema *et al.* (2012) increases these differences. Nevertheless, the energy balance of the waves at this measurement point appears consistent with conclusions of Zijlema *et al.* (2012) during the Texel storm in the southern North Sea. Best results are obtained with (1) the default wind drag parameterisation of Wu (1982) combined with high bottom friction ($C_b$=0.067 $m^2s^{-3}$) and (2) the new wind drag of Zijlema *et al.* (2012) with low friction ($C_b$=0.038 $m^2s^{-3}$). This may be related to stronger wind seas in this area than in the central or western English Channel. For the four remaining measurements sites, best estimates are reached with the new wind-drag formulation and the highest bottom friction proposed by Bouws and Komen (1983).

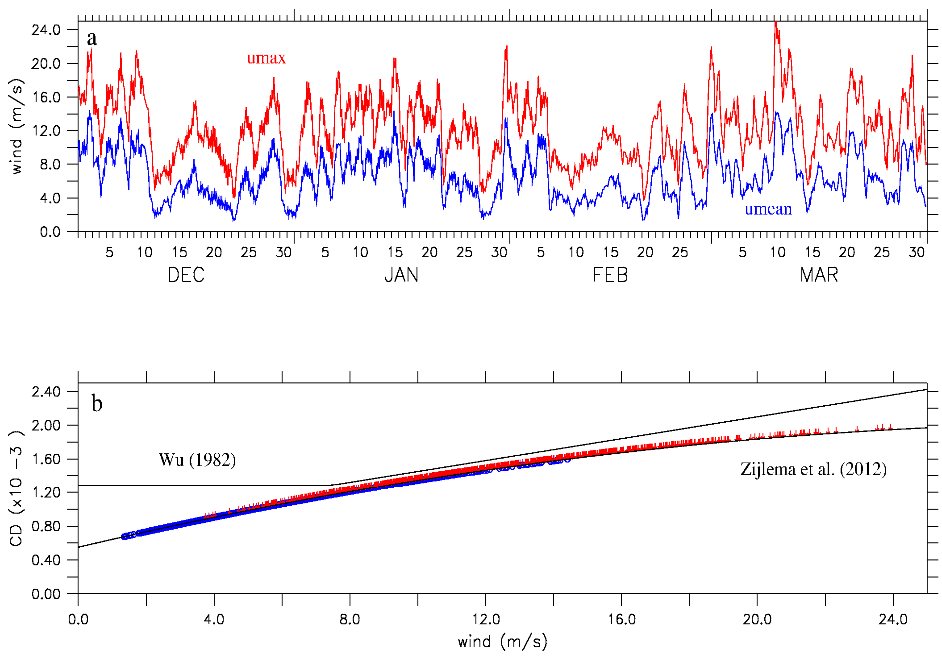



Figure 5. Time series of (a) the averaged and maximum wind speed predicted by ALADIN meteorological model over SWAN computational domain in December 2007-March 2008 and (b) the associated evolution of wind drag coefficients obtained with the formulations of Wu (1982) and Zijlema *et al.* (2012).

### 3.3. ***Sensitivity to bottom-friction formulation***

The sensitivity of model predictions to bottom-friction formulations is evaluated retaining the expression of Zijlema *et al.* (2012) for the wind-drag coefficient. Figure 6 displays the relative errors for the five numerical experiments titled B1 to B3b at the lightship 62305 and the wave buoys of Le Havre and Cherbourg during the period of interest. Predictions at lightships 62103 and 62304 are not considered here because of the proximity of these measurement points to the boundaries of the inner domain where the heterogeneous roughness length scale is introduced. In spite of a global weak sensitivity of predictions to bottom friction, comparing predicted time series at the wave buoy of Cherbourg shows that neglecting the energy dissipation by bottom friction results in a local overestimation by 17 % of the significant wave height during the storm of 10 March 2008. Estimates obtained with the constant empirical value of Bouws and Komen (1983) (B2b) are very close to numerical results issued from the formulation of Madsen *et al.* (1988) integrating the default roughness length scale of $k_n$=0.05 m (B3a). This is consistent with the estimation of wave models performance by Tolman (1991) who found satisfactory results for $k_n$ in the range of 2-5 cm. The integration of the grain-size distribution of bottom sediments improves the numerical estimates at the lightship 62305 and the wave buoy of Cherbourg. Nevertheless, predictions at the wave buoy of Le Havre are slightly modified. This may be related to the fact that the surroundings values of $k_n$ displayed in Figure 2 are very close to the uniform value adopted in configuration B3a.

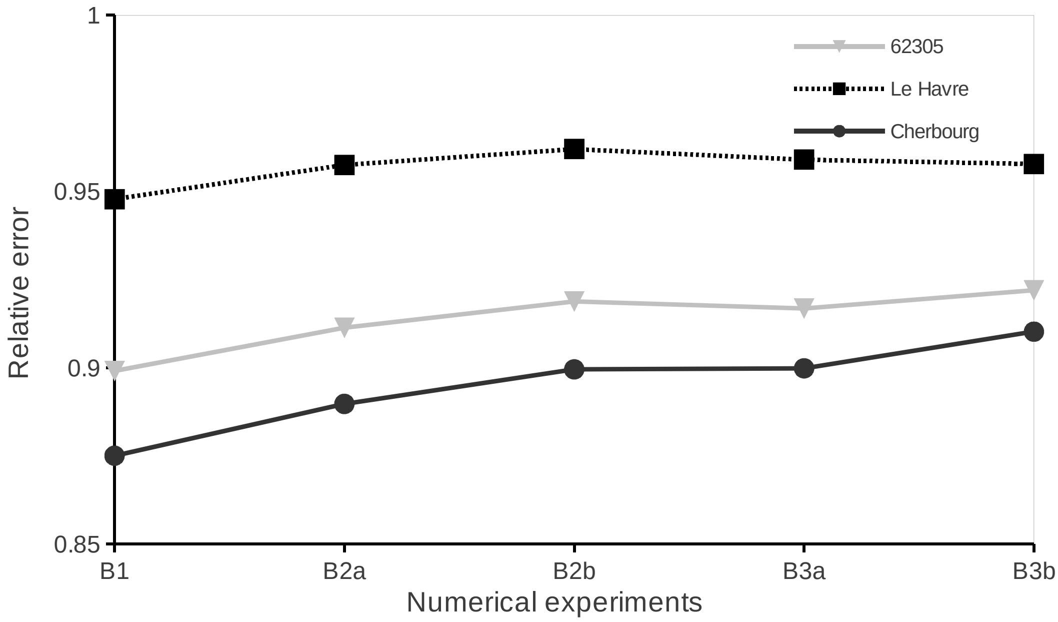



Figure 6. Relative error in predictions of the significant wave height at lightship 62305 and wave buoys of Le Havre and Cherbourg for the four numerical experiments B1 to B3b.

### 3.4. *Mappings of bottom friction effects on wave height*

Numerical predictions are exploited further to encompass the spatial and temporal changes of the significant wave height in relation to the integration of the spatial heterogeneous roughness length scale (Fig. 7). Figures 7-b and 7-c confirm the weak sensitivity of measurement points to wave-energy dissipation by bottom friction. The integration of the bed grain-size distribution has an impact in areas of pebbles and gravels exposed to the incoming waves from the North Atlantic Ocean: the Normano-Breton Gulf, the surroundings of the Isle of Wight and the french coastline off the Pays-de-Caux and the southern Dover Strait. Differences are particularly noticeable in the eastern extend of the Isle of Wight reaching the maximum absolute value of 1 m.

Figure 8 displays the spatial distribution of the averaged bottom friction coefficient $C_b$ predicted from configurations B3a and B3b in the inner domain where the grain size of bottom sediments has been introduced. The default formulation of Madsen *et al.* (1988) ($k_n$=0.05 m) results in a bottom friction coefficient between 7 and 20 times greater than the constant empirical value proposed by Bouws and Komen (1983) in the exposed areas of the Normano-Breton Gulf or the surroundings of the Isle of Wight. The integration of the heterogeneous grain size of bottom sediments leads to a global reduction of the dissipation coefficient smoothing the range of predicted values. The averaged bottom friction coefficient is thus varying between 0.04 and 0.09 $m^2$ $s^{-3}$ in the western English Channel. This weak spatial variability of predicted values may explain the relative success of constant empirical coefficients of Hasselmann *et al.* (1973) and Bouws and Komen (1983) as exhibited by Tolman (1994).

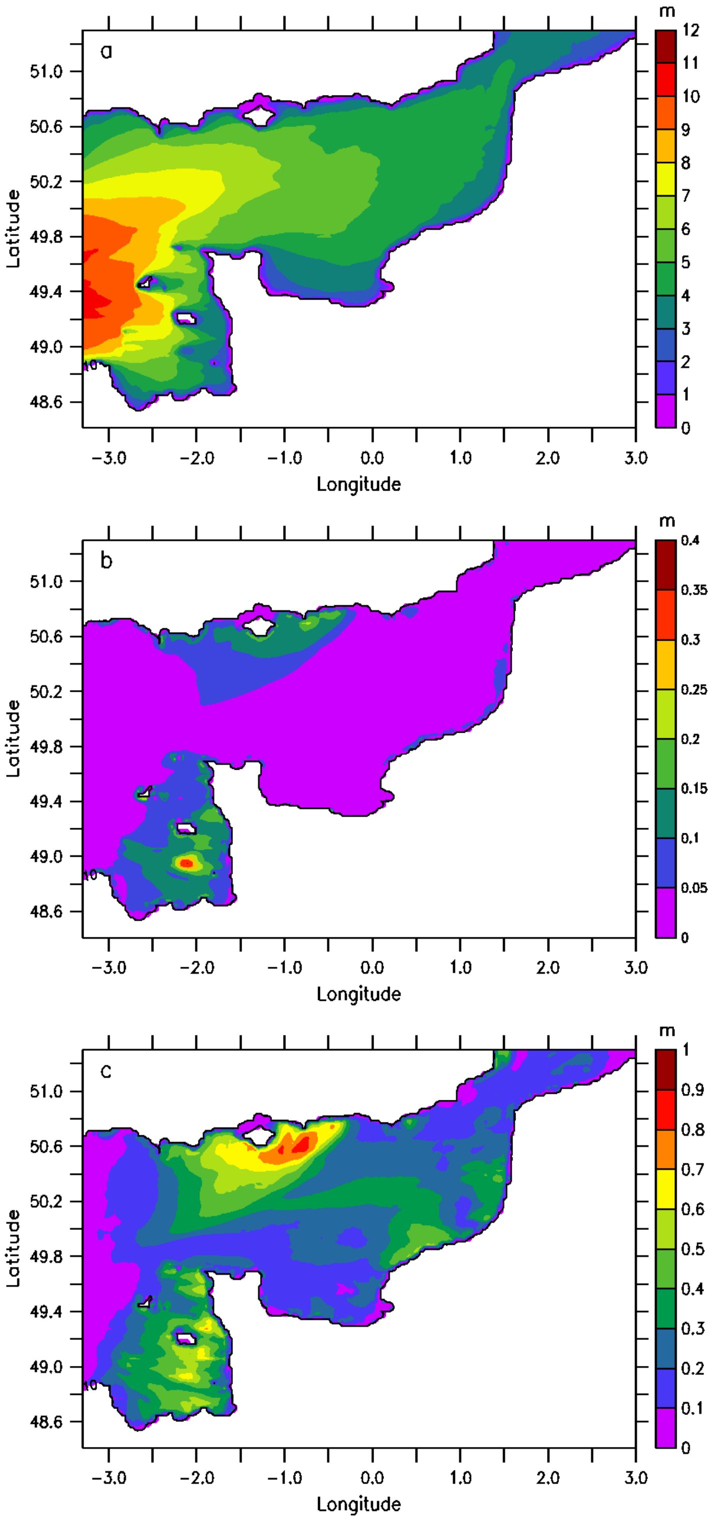



Figure 7. (a) Maximum significant wave height predicted from configurations B3a in December 2007 - March 2008. (b) Averaged and (c) maximum absolute differences

between significant wave height predicted from configurations B3b and B3a.

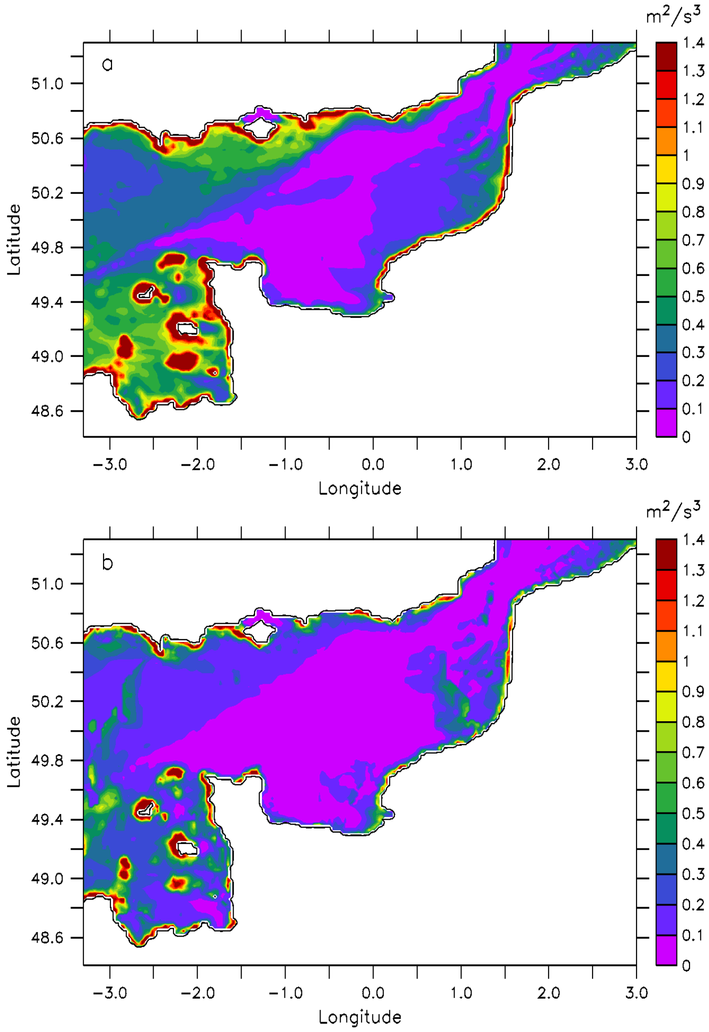



Figure 8. Averaged bottom friction coefficients predicted from configurations (a) B3a and (b) B3b in December 2007 – March 2008.

## 4. Conclusions

The numerical wave propagation model SWAN has been set up in the English Channel and the southern North Sea to investigate the effects of bed grain-size distributions on predicted significant wave height . Numerical results have been compared with in situ measurements at three offshore lightships and two nearshore wave buoys off Le Havre and Cherbourg harbours. The main outcomes of the present study are the following.

(1) Numerical predictions appear to be sensitive to the formulation of wind-drag coefficient. Best estimates are globally obtained with the expression recently established by Zijlema *et al.* (2012) to fit a set of observations at high wind speeds.
(2) Whereas predictions at measurement points show in averaged a slight sensitivity to bottom friction, differences are exhibited during storm events with overestimation of the significant wave height liable to reach 17 % by neglecting the dissipation of wave energy by bottom friction.
(3) The integration of the grain-size distribution of bottom sediments improves the numerical

estimates at the lightship 62305 and the wave buoy of Cherbourg. Furthermore, the combined effects of hydrodynamics and bed sediment properties in the formulation of Madsen *et al.* (1988) tends to reduce the spatial variability of the averaged dissipation coefficient by bottom friction. This is consistent with the use of constant empirical values as suggested by Hasselmann *et al.* (1973) and Bouws and Komen (1983).

The present study provides thus interesting insights into the effects of bottom friction on wind-generated surface-gravity waves in the English Channel, its dependency with the formulation of wind drag and the parameterisation of bottom roughness length scale. The present study was however restricted to the significant wave height neglecting the effects of the tide. Prospectives of this research will consist in (1) extending the comparison of numerical predictions to the wave period and (2) integrating the tide in waves computation and the generation of waves/current sand ripples. These results will help to improve the computation of nearshore waves condition along the English and French coastlines of the English Channel of utmost interest for numerous coastal engineering applications.

## Acknowledgements

The author is particularly grateful to Météo-France for supplying wind fields obtained with the meteorological model ALADIN and Dr. Fabrice Ardhuin (Institut Français de Recherche pour l'Exploitation de la MER, France) for giving access to wave data issued from regional runs of WaveWatch III. Measurements of the significant wave height were provided by the UK Meteorological Office and the French CANDHIS database. Simulations were performed on computer facilities CAPARMOR (CAlcul PARallèle Mutualisé pour l'Océanographie et la Recherche). The present paper is a contribution to the research program of the Laboratory of Coastal Engineering and Environment (**http://memphys-lgce.fr.ht**).

## References

Ardhuin, F., O'Reilly, W.C., Herbers, T.H.C. and Jessen, P.F., 2003a. Swell transformation across the continental shelf. Part I: Attenuation and directional broadening. *Journal of Physical Oceanography*, 33, 1921-1939.

Ardhuin, F., Herbers, T.H.C., Jessen, P.F. and O'Reilly, W.C, 2003b. Swell transformation across the continental shelf. Part II: Validation of a spectral energy balance equation. *Journal of Physical Oceanography*, 33, 1940-1953

Battjes, J. and Janssen, J., 1978. *Energy loss and set-up due to breaking of random waves.* Proceedings of the 16th International Conference of Coastal Engineering, Hambourg, 569-587.

Bénard, P., 2004. *ALADIN-NH/AROME dynamical core; status and possible extension to IFS.* Proceedings of the ECMWF Seminar, 27-40.

Bertotti, L. and Cavaleri, L., 1994. *Accuracy of wind and wave evaluation in coastal regions.* Proceedings of the 24th International Conference of Coastal Engineering, ASCE, 57-67.

Booij, N.R.C., Ris, R.C. and Holthuijsen, L.H., 1999. A third generation wave model for coastal regions, Part 1, model description and validation. *Journal of Geophysical Research*, 104 (C4), 7649-7666.

Bouws, E. and Komen, G.J., 1983. On the balance between growth and dissipation in an extreme, depth-limited wind-sea in the southern North Sea. *Journal of Physical Oceanography*, 13, 1653-1658.

Cabioch, L., Gentil, F., Glacon, R. and Retière, C., 1977. *Le macrobenthos des fonds meubles de la Manche : distribution générale et écologie.* In: Keegan, B.F., Ceidigh, P.O., Caston, P.J. (Eds.), Biology of Benthic Organisms. Pergamon Press, Oxford, 115-128.

Collins, J.I., 1972. Prediction of shallow-water spectra. *Journal of Geophysical Research*, 77, 15, 2693-2707.

Graber, H.C. and Madsen, O.S., 1988. A finite-depth wind-wave model. Part 1: Model description. *Journal of Geophysical Research*, 87, 469-481.

Guillou, N. and Chapalain, G., 2010. Numerical simulation of tide-induced transport of heterogeneous sediments in the English Channel. *Continental Shelf Research.* 30, Issue 7, 806-819, doi: 10.1016/j.csr.2010.01.018.

Guillou, N., Chapalain, G. and Thais, L., 2009. Three-dimensional modeling od tide-induced suspended transport of seabed multicomponent sediments in the eastern English Channel. *Journal of Geophysical Research.* 114, C07025, doi: 10.1029/2008jc004791.

Guillou, N., 2007. Rôles de l'hétérogénéité des sédiments de fond et des interactions houle-courant sur l'hydrodynamiquye et la dynamique sédimentaire en zone subtidale – applications en Manche orientale et à la pointe de la Bretagne. Ph.D. Thesis in Physical Oceanography, Université de Bretagne Occidentale, 469 pp.. Available via http://tel.archives-ouvertes.fr/tel-00376679/en/.

Hasselmann, K., 1974. On the spectral dissipation of ocean waves due to whitecapping. *Boundary Layer Meteorology*, 1-2 (6), 107-127.

Hasselmann, K., Barnett, T.P., Bouws, E., Carlson, H., Cartwright, D.E., Enke, K., Ewing, J.A., Gienapp, H., Hasselmann, D.E., Kruseman, P., Meerburg, A., Muller, P., Olbers, D.J., Richter, K., Sell., W., and Walden, H., 1973. Measurements of wind-wave growth and swell decay during the Joint North Sea WAve Project (JONSWAP), *Dtsch. Hydrogr. Z. Suppl.*, 12, A8, 1-95.

Hasselmann, K. and Collins, J.I., 1968. Spectral dissipation of finite-depth gravity waves due to turbulent bottom friction. *Journal of Marine Research*, 26, 1-12.

Johnson, H.K. and Kofoed-Hansen, H., 2000. Influence of bottom friction on sea surface roughness and its impact on shallow water wind wave modeling. *Journal of Physical Oceanography*. 30, 1743-1756.

Jonsson, I.G. and Carlsen, N.A., 1976. Experimental and theoretical investigations in an oscillatory turbulent boundary layer. *Journal of Hydraulic Research*, 14, 45-60.

Jonsson, I.G., 1966. *Wave boundary layers and friction factors.* Proceedings of the 10th Conference on Coastal Engineering. Tokyo, Japan, ASCE, 127-148.

Komen, G.J., Hasselmann, S., Hasselmann, K., 1984. On the existence of a fully developed wind-sea spectrum. *Journal of Physical Oceanography*, 14, 1271-1285.

Larsonneur, C., Bouysse, P. and Auffret, J.P., 1982. The superficial sediments of the English Channel and its western approaches. *Sedimentology*, 29, 851-864.

Leprêtre, A, Chapalain, G. and Carpentier, P., 2006. Une méthode d'interpolation des caractéristiques granulométriques des sédiments superficiels. *Bulletin de la Société Géologique de France*, 177 (2), 89-95.

Li, M.Z. and Amos, C.L., 2001. SEDTRANS96: the upgraded and better calibrated sediment-transport model for continental shelves. *Computers and Geosciences*, 27, 619-645.

Li, M.Z. and Amos, C.L., 1998. Predicting ripple geometry and bed roughness under combined waves and currents in a continental shelf environment. *Continental Shelf Research*, 18, 941-970.

Luo, W. and Monbaliu, J., 1994. Effects of the bottom friction formulation on the energy-balance for gravity-waves in shallow-water. *Journal of Geophysical Research*. 99 (C9), 18501-18511.

Madsen, O.S., Poon, Y.-K. and Graber, H.C., 1988. *Spectral wave attenuation by bottom friction: Theory.* Proceedings of the 21th International Conference on Coastal Engineering, ASCE, 492-504.

Padilla-Hernandez, R. and Monbaliu, J., 2001. Energy balance of wind waves as a function of the bottom friction formulation. *Coastal Engineering*, 43, 131-148.

Riedel, P., O'Brien, P. and Townsend, M., 2005. *The effect of ocean swell on the stability of Adelaide's metropolitan beaches.* Coastal Living Coast. Institution of Engineers, Australia Adelaide, Australia, Coasts and Ports.

Shemdin, O., Hasselmann, K.,Hsiao, V. and Heterich, K., 1978. Nonlinear and linear bottom interaction effects in shallow water. *Turbulent Fluxes through the Sea Surface, Wave Dynamics and Prediction*, A. Farve and K. Hasselmann, Eds., Plenum Press, 347-372.

Siadatmousavi, S.M., Jose, F. and Stone, G.W., 2011. The effects of bed friction on wave simulation: Implementation of an unstructured third-generation wave model, SWAN. *Journal of Coastal Research*, 27, 1, 140-152.

Smith, G.A., Babanin, A.V., Riedel, P., Young, I.R., Oliver, S. and Hubbert, G., 2011. Introduction of a new friction routine into the SWAN model that evaluates roughness due to bedform and sediment size changes. *Coastal Engineering*, Vol. 58, Issue 4, 317-326.

Soulsby, R., 1997. *Dynamics of marine sands*. H.R. Wallingford, 249 pp.

SWAN team, 2009.SWAN Cycle III. *Version 40.72 AB – Scientific and Technical Documentation.* Technical Report, Delft University of Technology, 107 pp.

Tolman, H.L., 1994. Wind-waves and moveable bed bottom friction. *Journal of Physical Oceanography*, 24, 994-1009.

Tolman, H.L., 1991.A third-generation model for wind waves on slowly varying unsteady, and inhomogeneous depths and current. *Journal of Physical Oceanography*, 21, 782-797.

Vaslet, D., Larsonneur, C. and Auffret, J.P., 1979. *Map of the surficial sediments of the English Channel, scale 1:500,000.* Bureau de Recherches Géologiques et Minières, Orléans, France.

Weber, S.L., 1991a. Eddy-viscosity and drag-law models for random ocean wave dissipation, *Journal of Fluid Mechanics*, 232, 73-98.

Weber, S.L., 1991b. Bottom friction for wind sea and swell in extreme depth-limited situations. *Journal of Physical Oceanography*, 21, 149-172.

Willmott, C.J., 1981. On the validation of models. *Phys. Geogr.*, 2 (2), 219-232.

WISE group, 2007. Wave modelling – the state of the art. *Progress in Oceanography* 75, 603-674.

Wooding, R.A., Bradley, E.F. and Marshall, J.K., 1973. Drag due to regular arrays of roughness elements of varying geometry. *Boundary-Layer Meteorology*, 5, 285-308.

Work, P.A., Demir, H., Kaihatu, J.M. and Voulgaris, G., 2004. *Mesoscale wave energy dissipation over heterogeneous sediments.* Proceedings of the 29th International Conference on Coastal Engineering, Lisbon, Portugal, 477-489.

Wu, J., 1982. Wind-stress coefficients over sea surface from breeze to hurricane. *Journal of Geophysical Research*, 87, C12, 9704-9706.

Yalin, M.S., 1985. On the determination of ripple geometry. *Journal of the Hydraulic Division*, 8 (111), 1148-1155.

Zijlema, M., van Vledder, G. Ph. and Holthuijsen, L.H., 2012. Bottom friction and wind drag for wave models. *Coastal Engineering*, 65, 19-26.