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Wave effects on the morphodynamic evolution of an offshore sand bank

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ABSTRACT

The origin and morphodynamic evolution of linear sand banks have been widely studied in recent years. Several investigations have been carried out in order to understand the influence of tide-related parameters, bathymetry and Coriolis force on sand bank formation and maintenance. However, the effect of waves on the net flux of sediments over the sand banks has often been neglected on grounds of the short duration of significant wave activity compared to that of tidal cycles. Nevertheless, the interaction between wave activity and tidal currents leads to a high increase of bottom shear stress, especially at the sand bank crests and, as a consequence, to an increase of sand tranport. This paper investigates the effects of wave activity on the morphology and morphodynamics of the Kwinte Bank (Belgian shelf). Numerical simulations were carried out under different wave conditions to assess wave influence on sand bank evolution. Model verification involved analysis and comparison with field data collected during two different periods. The study shows that wave activity is not only responsible for a large increase in sediment transport but also for a change in direction of the net flux of sediments. Moreover, the morphological analysis of several sand banks supports the idea that wave activity might also have an impact on the shape of these sand banks. Wave climate data can be used to study long-term sand bank dynamics.

ADDITIONAL INDEX WORDS: *sand bank, waves, morphodynamic evolution, numerical models, wave climate, bed form asymmetry.*

INTRODUCTION

Sand banks are a typical feature on many continental shelves. Their size is in the order of 10 km in length, 2 km in width and they frequently extend to within a few meters of the sea surface. These bed forms are often located in groups of banks and they are found when a considerable amount of sand is available and tidal currents are sufficiently strong (0.5 – 2.5 m/s) (Carbajal and Montano, 2001).

The Belgian continental shelf, in the Southern part of the North Sea, is characterized by a large number of these banks and has been extensively studied (Lanckneus *et al.*, 2001), (Figure 1.). These banks can be grouped in Coastal Banks, Flemish Banks, Hinder Banks and Zeeland Ridges.

Considerable research has been done into understanding the influence of local tidal conditions on sand bank morphology. Using analytical (Huthnance, 1982a) and numerical (Huthnance, 1982b) models, Huthnance showed that strong currents and the presence of initial irregularities on the seabed are sufficient to create and maintain linear sand banks. By coupling a set of depth-averaged equations combined with a bedload transport equation, he predicted spacing between sand banks of about 250 times the mean water depth. The work was subsequently extended by Hulscher *et al.* (1993) to include elliptical tidal currents and secondary currents. Carbajal and Montano (2001), by means of an analytical model, described the relationship among tidal currents, latitude, horizontal length scales and orientation of sand banks. For a fixed water depth they found an almost linear dependence between sand bank wavelength and tidal current amplitude. Furthermore, the

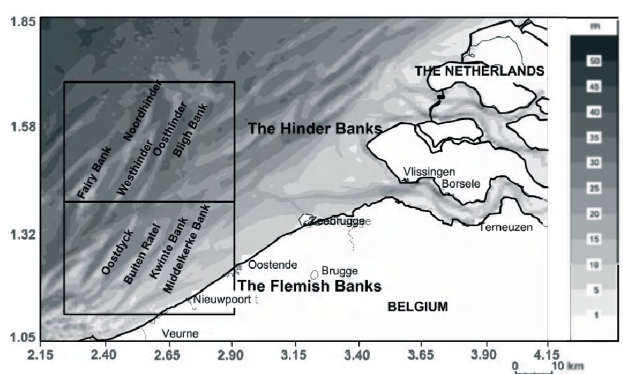

Figure 1. Bathymetry of the Belgian Continental Shelf (Flemish Authorities, Agency for Maritime & Coastal Services, Coastal Division. Gridding Ghent University, Renard Centre of Marine Geology).

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scale of sand banks was found to increase with increasing water depth. The angle between sand bank crest and the principle component of the tidal flow was inversely proportional to the amplitude of the tidal current. Moreover this angle was influenced by the latitude, due to a change in the Coriolis acceleration.

On the other hand, little is known concerning the role played by wave action on sand bank morphology and dynamics. Waves are known to be an agent for sand resuspension and, aided by the currents, to transport finer sediments from the crest to the flanks of the sand banks. COLLINS *et al.* (1995), by means of numerical simulations, showed that wave action tends to intensify the cross-bank component of sand tranport. VINCENT *et al.* (1998) estimated net suspended transport from the product of profile-integrated suspended sand and current meter measurements at two locations on the Middelkerke Bank (Figure 1.). According to these measurements, the combination of high waves and strong currents during four different bursts, explains more than 50 % of the net flux of the whole measurement period. Moreover, these measurements show how waves can influence the average size of material in suspension without considerably affecting the suspended transport direction. VAN DE MEENE and VAN RIJN (2000) concentrated their attention on the long term morphological sand bank behaviour due to the combined effects of currents and waves. With a simplified numerical model they represented the yearly sediment transport across a linear sand bank. The overall result showed that the net sediment transport is mainly determined by currents in combination with the more frequent non-extreme waves ranging between 0 and 2 m. VILLARET and DAVIES (2004) carried out a numerical study in the coastal area near Dunkerque, at the boarder between France and Belgium. The authors applied a wave model, a two-dimensional hydrodynamic model and a morphodynamic model to study sediment transport dynamics on the sand banks characterizing the area. Through successive runs of the hydrodynamic and wave models, they reproduced the effects of tides on the wave propagation, for a winter storm. The output was used to drive a morphodynamic model coupled to the hydrodynamic model. The authors showed that the wave modulation due to tidal effects was the dominant process, leading to a large increase of sediment transport towards the North-East (Belgium).

The present investigation studies the effects of wave activity on the Kwinte Bank (Figure 1.). Two numerical models were implemented and different scenarios simulated to assess the impact of wave conditions of different entities on the bank. The use of two different models revealed some interesting differences in the model intercomparison and, in addition, highlighted limitations of diverse sediment transport formulations. Model verification involved comparison with hydrodynamic, wave, suspended transport and bottom data. A careful analysis of the morphology of other sand banks at the Belgian shelf was carried out in order to derive a relation between local hydrodynamic conditions and the shape of the sand banks. Some ideas on the long term morphodynamic behaviour of the Kwinte Bank are put forward based on past observations and wave climate data.

The paper elaborates on the work of VAN DEN EYNDE *et al.* (this volume) which focused on the effects of currents on sediment transport at the Kwinte Bank and assessed the impact of sand extraction taking place in the area.

AREA UNDER INVESTIGATION

The Kwinte Bank is a southwest-northeast tidal current ridge forming part of the Flemish Bank system (Figure 1.). The sand bank has a length of approximately 15 km and a width varying from 2 km in the south to 1 km in the northern part. The minimum water depth ranges between 7 m below Mean Sea Level (MSL) in the southern part to 10 m below MSL in the northern part. The minimum water depth in the swales around the bank is about 22 m. The cross section of the sand bank is clearly asymmetrical with the steeper slope on the northwest side being up to 3°. This profile is consistent with the other sand banks of the Flemish system that show their steeper side opposite to the flood direction. The crest of the sand bank consists on a very large and flat dune, giving an indication of the importance of wave activity in shaping the sand bank morphology. Large to very large dunes are found up the stoss slope of the Kwinte Bank but they are atypical in the adjacent swales. Small to medium dunes are common in the swales and up the lee slope (steep slope).

The southern part of the bank is characterized by fine and medium sand with D_{50} (the sediment diameter for which 50 % is finer) ranging between 180 and 240 µm. Coarser material is found in the northern part with D_{50} up to 400 µm.

The hydrodynamic conditions at the Kwinte Bank have been widely investigated by VAN DEN EYNDE *et al.* (this volume) and BRIERE *et al.* (this volume). Current ellipses are slightly asymmetrical on the Kwinte Bank, with the main axis orientated at a small angle in clockwise direction with respect to the bank axis as observed for the first time by HUTHNANCE (1973). In the swales the ellipses are more elongated and orientated nearly parallel to the bank axis. Maximum current velocities range between 0.4 – 0.5 m/s during neap tide up to 0.8 – 0.9 m/s during spring tide. Residual currents at the top of the sand bank are almost perpendicular to the sand bank crest and have a north-western direction.

VAN CAUWENBERGHE (1971) compared sea charts of the Belgian shelf mapped during the years 1800-1968. Despite difficulties associated with the analysis of bathymetric surveys carried out by very diverse measuring techniques, he concluded that the Flemish Banks are characterized by a sort of dynamic equilibrium. Specifically, the Kwinte Bank could be considered as stable for the total length of the period considered.

MODELS, DATA AND METHODS

The models

Two different sets of models were implemented separately by the Hydraulics Laboratory of the K.U.Leuven and by the Management Unit of the North Sea Mathematical Models (MUMM), see Table 1. Hydrodynamic conditions, wave field and sediment transport were computed and the results for different simulated scenarios were compared.

The three models used at the K.U.Leuven, part of the same modelling package, are implemented on the same unstructured mesh and adopt a finite element scheme for the equation solution. The domain covers the region from 47°50'N to 71°10'N, and from 12°15'W to 12°15'E. The mesh size ranges between 70 km at the open boundary and 150 m on the Kwinte Bank.

Table 1. *Numerical models and settings used in this work.*

	HYDRODYNAMICS MODELS	
Parameter	TELEMAC-2D	COHERENS
Model type	Two dimensional – finite element	Three dimensional – finite difference
Discretization	24851 nodes with resolution between 70 km – 150 m	Two regional models plus two coupled grids at the Belgian Shelf. Highest resolution: 272 m – 257 m and 10 σ-layers on the vertical.
Tidal components at the boundary	8	8 (for the regional model)
Time step	60 s	4 s (for the highest resolution model)
Law of bottom friction	Chezy with Chezy's coefficient variable with water depth	Quadratic friction law
Turbulence model	Constant viscosity	k-ε model
	WAVE MODELS	
Parameter	TELEMAC-2D	MU-WAVE
Model type	Third generation – finite element	Second generation – finite difference
Discretization	24851 nodes with resolution between 70 km – 150 m	Two coupled grids. Highest resolution: 5 km – 5 km
Time step	100 s	Highest resolution model: 180 s
Number of directions	12	24
Number of frequencies	25	20
Minimal frequency	0.04 Hz	0.045 Hz
Wind input	JANSSEN (1989,1991)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Bottom friction dissipation	Jonswap model (HASSELMANN et al., 1973)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Whitecapping dissipation	KOMEN, HASSELMANN S., and HASSELMANN K. (1984), JANSSEN (1991)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Quadruplets wave-wave interaction	DIA method (HASSELMANN et al., 1985)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Triads wave-wave interaction	No	No
	MORPHODYNAMIC MODELS	
Parameter	SISYPHE	MU-SEDIM
Model type	Two dimensional – finite element	Two dimensional – finite difference
Discretization	24851 nodes with resolution between 70 km – 150 m	Finest grid of the COHERENS model (resolution: 272 m – 257 m)
Time step	600 s	180 s
Sediment transport formula	Soulsby-Van Rijn (SOULSBY, 1997)	ACKERS and WHITE (1973) adapted by SWART (1976, 1977)
Sediment diameter	250 μm	Variable in space
Bottom roughness	Ripple bed conditions z0 = 0.006 m	Skin roughness z0s function of D65 according to: z0s = (2· D65)/30

The models implemented by MUMM are based on a series of nested grids and adopt a finite different scheme. The highest resolution grid covers part of the Belgian shelf with a resolution of 272 m in longitude and 257 m in latitude. The bathymetric data were provided by the Ministry of the Flemish Community (Flemish authorities, Agency for Maritime and Coastal Services, Coastal Division. Gridding was done by Ghent University, Renard Centre of Marine Geology).

The main advantage of the use of an unstructured mesh consists in the possibility of running at once the computation over the whole domain, with the possibility to highly refine, at the same time, the area of interest.

Atmospheric data (wind velocity at 10 m height and atmospheric pressure) were obtained from the United Kingdom Meteorological Office (Van den Eynde *et al.*, 1995).

Hydrodynamic models

Open sea boundary conditions were provided, taking into account four semi-diurnal tidal components (M_2, S_2, N_2, K_2) and four diurnal tidal components (O_1, K_1, P_1, Q_1).

The two-dimensional finite element model TELEMAC-2D (v.5.5) (Hervouet and Bates, 2000) solves the depth averaged Saint-Venant equations. Turbulent viscosity was considered constant over the whole domain.

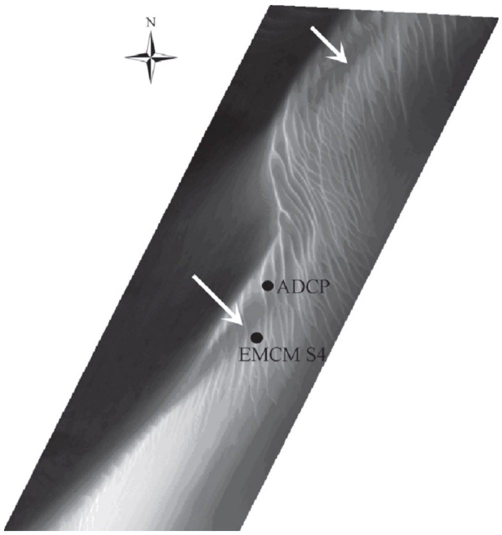

Figure 2. ADCP measurements at three different heights for a tidal cycle.

The three-dimensional MU-OPTOS model is based on the COHERENS model (LUYTEN *et al.*, 1999). The model solves the equations of momentum, continuity, temperature and salinity on a series of nested grids. The high resolution model employs 10 σ-layers over the vertical. The k-ε turbulence model was adopted.

The use of two different hydrodynamic models (depth averaged and three dimensional) to drive the morphodynamic models, was considered not to bias the overall results of the study. TONNON, VAN RIJN and WALSTRA (2007) compared results from morphodynamics simulations on an artificial sand wave using one-dimensional horizontal (1DH) and two-dimensional vertical (2DV) hydrodynamic models. The authors showed that the overall sand transport direction did not depend on the use of a 1DH or 2DV model. However, the sand wave growth could only be modelled by the 2DV model, due to the creation of a vertical circulation cell leading to a net sand transport towards the sand bank crest.

A plot of ADCP velocity vectors at three different heights is shown in Figure 2. The Figure shows that flow direction is unidirectional with minor differences in current direction at different water depths. This supports the validity of using a depth-averaged hydrodynamic model.

Wave models

The TOMAWAC model (v.5.5) (BENOIT et *al.*, 1996) is a third generation wave model which solves the balance equation of wave action density. The model was implemented with a spectral discretisation in 12 directions and 25 frequencies. Source terms included input from the wind, dissipation from whitecapping and from bottom friction and quadruplet nonlinear interactions.

The core of the MU-WAVE model (VAN DEN EYNDE, 1992) is formed by the second generation HYPAS spectral wave model (GÜNTHER and ROSENTHAL, 1985). The model has been tested extensively and is used as an operational model for the prediction of waves on the Belgian continental shelf. The North Sea grid has a resolution of 50 km × 50 km, whereas for the Southern Bight a resolution of 5 km × 5 km is implemented.

Both wave models were run in non coupled mode. No effect of wave modulation due to the presence of tide was taken into account in the present work. However, previous work on the coupling between currents and waves in the Southern North Sea, showed that the tide modulation accounts only for a small variation of the wave height and period (OSUNA, 2002; OSUNA, and MONBALIU, 2004). This variation should not lead to a sensible variation of the transport direction.

Morphodynamic models

The SISYPHE model (v.5.5) (VILLARET, 2004) calculates the total load transport and the morphodynamic evolution as a function of the hydrodynamic conditions, through internal coupling with the TELEMAC-2D model, and the wave field, calculated by a previous uncoupled run of the TOMAWAC model. Total load transport was estimated by means of the Soulsby–Van Rijn formulation (SOULSBY, 1997) assuming a constant sediment diameter equal to 250 μm. The total transport rate due to the combined action of currents and waves is given by:

$$Q_{bs} = A_s U \left[\left(U^2 + \frac{0.018}{C_D} U_0^2 \right)^{0.5} - U_{cr} \right]^{2.4} (1 - 1.6 \tan \beta) \quad (1)$$

$$A_s = A_{sb} + A_{ss} \quad (2)$$

$$A_{sb} = \frac{0.005 h (D_{50}/h)^{1.2}}{\left[(s-1) g D_{50}\right]^{1.2}} \quad (3)$$

$$A_{ss} = \frac{0.012 D_{50} D_*^{-0.6}}{\left[(s-1) g D_{50}\right]^{1.2}} \quad (4)$$

$$C_D = \left[\frac{0.40}{\ln(h/z_0) - 1} \right]^2 \quad (5)$$

$$D_* = \left(\frac{g(s-1)}{\nu^2} \right)^{1/3} D \quad (6)$$

where A_{sb} is the bedload component, A_{ss} is the suspended load component, U the depth-averaged flow velocity, C_D the drag coefficient due to current alone, U_0 the RMS wave orbital velocity at the bottom, U_{cr} the critical entrainment velocity, β the bed slope in streamwise direction here assumed equal to 0, h the water depth, D_* the non-dimensional diameter, s the relative density of sediment, g the acceleration due to gravity, z_0 the bed roughness length assumed equal to 0.006 m as suggested by SOULSBY (1997) in case of rippled beds and ν the kinematic viscosity of the water.

The MU-SEDIM model computes total load transport and morphodynamic evolution in function of the depth averaged current velocity calculated by the MU-OPTOS model and the wave field computed by MU-WAVE. The sediment transport was estimated by means of the ACKERS and WHITE (1973) formulation adapted by SWART (1976) AND SWART (1977) as reported in SLEATH (1984), to include the effects of waves on sediment transport. The total sediment transport is given by:

$$\frac{Q_s}{U} = D_{35}\left(\frac{U}{u_{*cw}}\right)^{n} C_l\left(\frac{F-A}{A}\right)^{m} \tag{7}$$

where Q_s is the total transport, D_{35} the sediment diameter for which 35 % is finer, u_{*cw} the wave-current friction velocity, n, m, A, C_l are dimensionless parameters and F the sediment mobility number. The latter can be determined as:

$$F = \left(\frac{U}{5.66 \log \dfrac{10h}{D_{35}}}\right)^{1-n} \frac{u_{*cw}^{n}}{\left((s-1)gD_{35}\right)^{1/2}} \tag{8}$$

The wave-current friction velocity $u_{*cw}=(\tau_{cw}/\rho)^{1/2}$ is calculated based on the formulation proposed by BIJKER (1966) for the wave-current shear stress τ_{cw}:

$$\tau_{cw} = \tau_c\left[1+\frac{1}{2}\left(\frac{c}{\sqrt{2g}}\sqrt{f_w}\,\frac{u_b}{u_c}\right)^2\right] \tag{9}$$

being τ_c the current shear stress, c an empirical constant, f_w the wave friction factor, u_b the bottom orbital velocity and u_c the current velocity.

More details on the equations implemented in the MU-SEDIM model can be found in VAN DEN EYNDE and OZER (1993).

The D_{50} was considered variable over the area. The D_{50} grid was calculated based on 2200 samples collected in the area. A weighted distance based method was used to interpolate the measured values on the model grid (FETTWEIS and VAN DEN EYNDE, 2000). The D_{35} was calculated assuming a constant ratio equal to 0.82193 between the D_{35} and the D_{50} (COOREMAN *et al.*, 2000).

Additional formulations were applied to validate the results: the BIJKER (1968) and BAILARD (1981) equations available in the SISYPHE model and the VAN RIJN (1989), BAGNOLD (1966) and YALIN (1963) in the MU-SEDIM model.

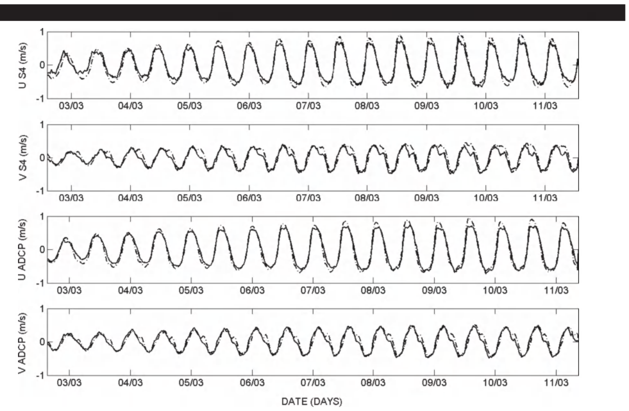

Figure 3. Modelled and measured depth averaged flow velocities for the period 2-12 March 2004.

Fieldwork

The data used in this study were collected within the framework of the MAREBASSE project (VAN LANCKER *et al.* 2002).

During two measurement campaigns (23-30 June 2003; 2-11 March 2004), a bottom mounted Acoustic Doppler Current Profiler (ADCP) and a multisensor benthic lander (tripod) were used. Both instruments were deployed from the oceano-

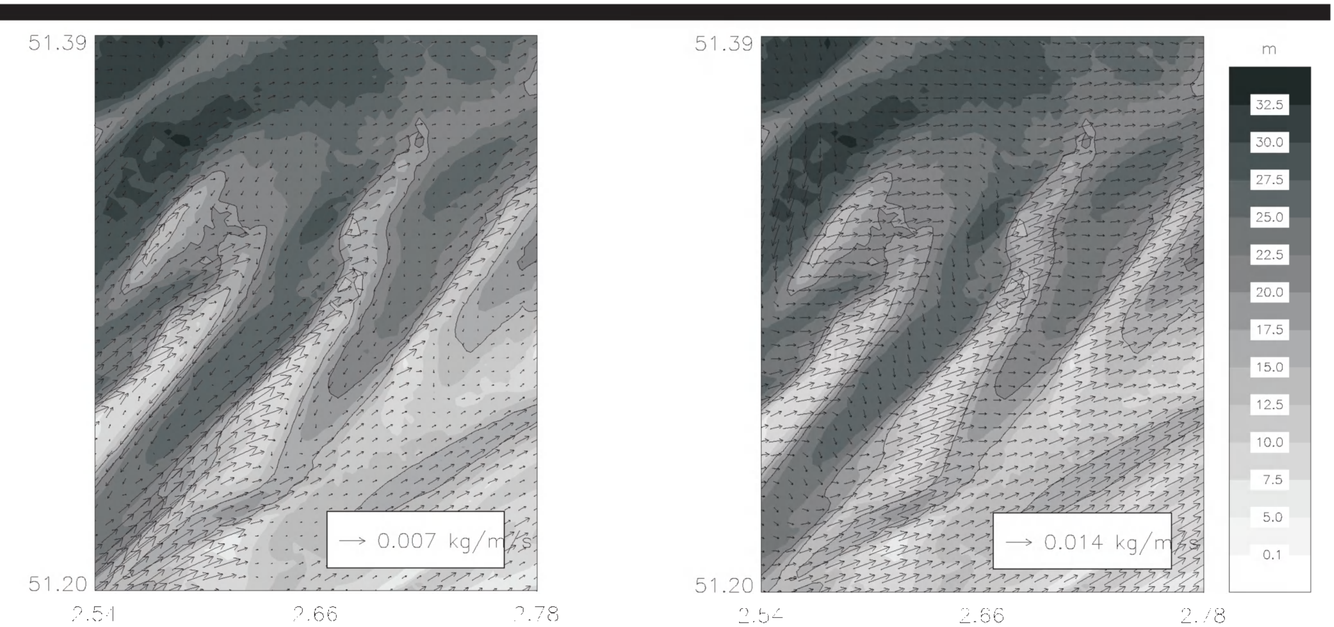

Figure 4. Sediment transport with only tides taken into account for the period 2-16 March 2004. The bathymetry is shown in the background. (a) Left: results of MU-SEDIM. One vector for each four grid points is shown. (b) Right: results of the SISYPHE model. Results on the same grid as the MU-SEDIM model.

graphic research vessel *RV Belgica*. A Conductivity, Temperature and Depth instrument (CTD), three Optical Backscatter Sensors (OBS) at 0.25, 0.5 and 1 m from the bottom and a Laser In-Situ Scattering & Transmittometer (LISST-100C) at 1 m from the bottom were attached to the tripod. ADCP measurements were used to validate the output from the hydrodynamic model, showing a general good agreement between modelled and observed data (Van den Eynde *et al.*, this volume) and Figure 3.

The OBS and LISST measurements gave volume concentration and particle diameters of material in suspension.

A wave buoy was deployed at the North of the Kwinte Bank during the campaign of June 2003. Additional buoy data were available for both periods from operational buoys at the locations Westhinder (51.38°N; 2.44° E) and Akkaert (51.41°N; 2.77°E). A validation of the wave models was carried out by means of these measurements. The root mean square error between model output (both TOMAWAC and MU-WAVE) and buoy measurements ranged between 0.2 and 0.3 m (Van Lancker *et al.*, 2005).

RESULTS

In order to assess the separate impact of tidal and wave action, three different scenarios were simulated by the two sets of models. First, a morphodynamic simulation was carried out considering tidal currents only as forcing. Two additional simulations include the effect of currents and waves of different intensity, *i.e.* one period with moderate wave and one with storm wave activity. All runs were carried out for a period corresponding to a spring-neap tidal cycle.

Tidal currents alone

This first run was carried out for the period 2-16 March 2004, neglecting the influence of waves and meteorological forces. Figure 3. shows a comparison of the simulated and measured depth averaged flow velocities for that period. Both models give a good representation of the current field, which supports the hyphothesis that flow characteristics at the Kwinte Bank can be well represented by a 2D model. The results from this scenario were discussed in Van den Eynde *et al.* (this volume).

The outputs from the two models show a general trend of residual transport going towards the northeast (Figure 4.).

This direction is due to effects of tidal asymmetry, which are especially evident at the sand bank crest and are characterized by the highest current velocities occurring during flood, directed towards the northeast and lower velocities during ebb, going to southwest. Peak currents during flood are about 10 % larger than currents during ebb (Figure 5.).

It follows that, and this is typical for a tidally dominated regime, strong flood currents more easily exceed the critical entrainment velocity U_{cr}. Estimated values for U_{cr}, for a sand diameter equal to 250 µm and water depth ranging between 5 and 20 m (typical values for the Kwinte Bank area), range between 0.3 m/s at the crest and 0.4 m/s in the swales (Van Rijn, 1984). The difference in critical velocity between crest and swales is due to a different value of the water depth, which influences the calculation of U_{cr}. Sand transport at the Kwinte Bank crest is more important than in the swales due to higher flow velocities and lower critical velocity for sediment.

As a result of the sediment transport pattern, erosion occurs at the western flank of the sand bank while deposition takes place at the eastern flank (Figure 6.).

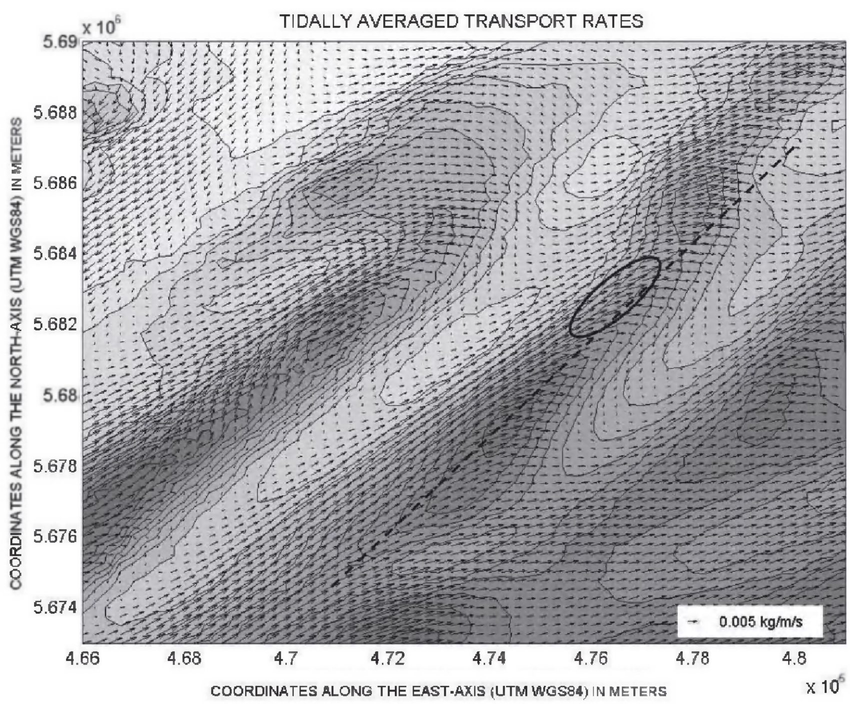

Figure 5. Asymmetry of tidal currents.

Table 2. *Values of mass transport predicted by the two models for the different scenarios at point (51.27°N, 2.63°E).*

	SISYPHE (kg/m/s)	Variation respect to standard run (SISYPHE)	MU-SEDIM (kg/m/s)	Variation respect to standard run (MU-SEDIM)
H_2004	0.01534	—	0.00861	—
H+W_2004	0.01890	1.23	0.08260	9.59
H+W_1995	1.90548	124.22	0.70182	81.51

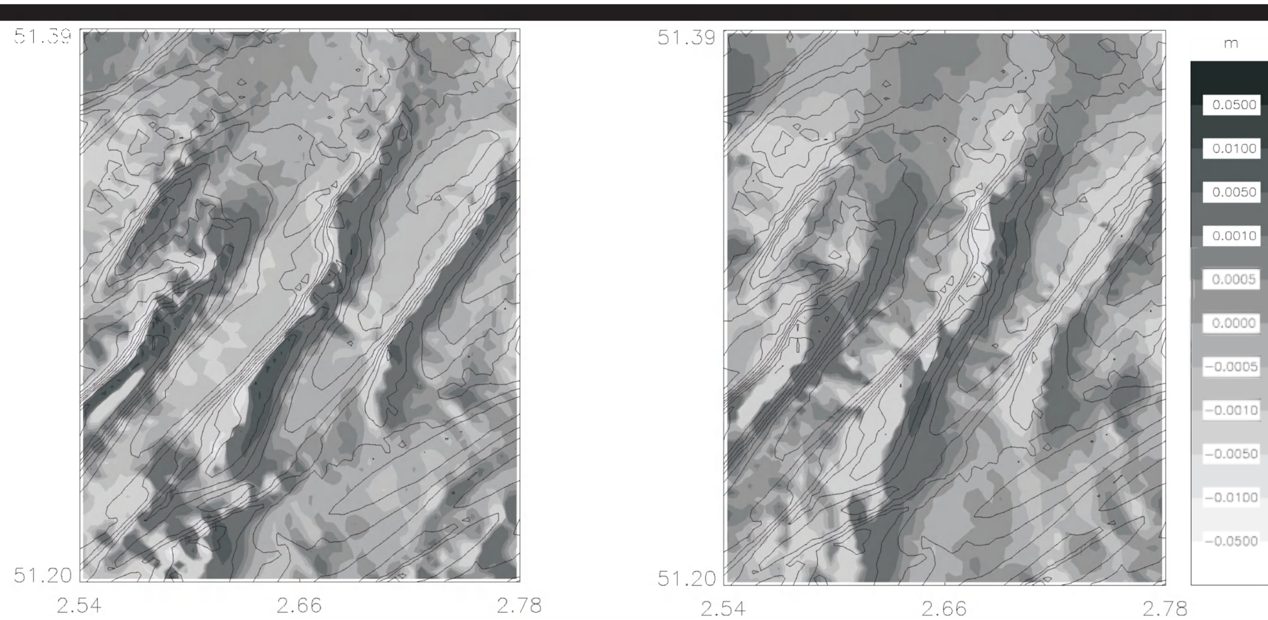

Figure 6. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with only tides taken into account and for the period 2-16 March 2004. (a) Left: results of the MU-SEDIM model. (b) Right: results of the SISYPHE model.

Residual transport predicted by the SISYPHE model is about two times larger than the transport predicted by the MU-SEDIM model. Values of mass transport for a point located close to the crest are indicated in Table 2.

Tidal currents and waves

This simulation was carried out for the same period (2 -16 March 2004) but including the effects of waves and meteorological forces. Wave activity during the period considered was fairly low with maximum wave height reaching about 2 m (Figure 7).

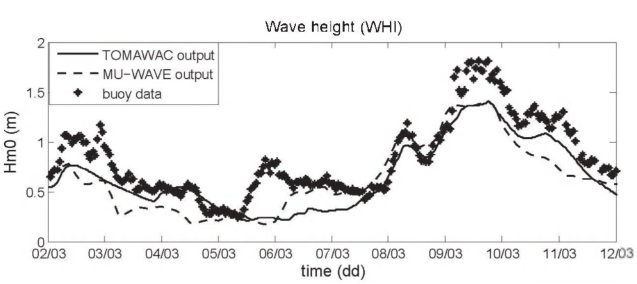

Figure 7. Modelled and measured significant wave height at Westhinder for the period 2-12 March 2004.

Model winds obtained from the United Kingdom Metereological Office were low compared to local wind measurements during that period (not shown). Although the height of the waves in not only a local process, the underestimation of the wave height calculated by the model can most likely be attributed to the limited spatial and time resolution of the model wind.

The residual transport computed by the two models is shown in Figure 8. In both models, the influence of wave activity leads to an increase in residual transport, especially evident at the sand bank crest where wave orbital velocities are higher. The increase in residual transport at the Kwinte Bank crest is about a factor 1.23 for the SISYPHE model, and about a factor 9.59 for the MU-SEDIM model (Table 2.) with respect to the simulation forced by tide only.

Moreover the SISYPHE model predicts a change in residual transport direction, locally visible at the Kwinte Bank crest. This leads to a different erosion-deposition pattern than the one observed considering tidal currents alone. This new pattern is characterized by erosion occurring at the east flank and deposition at the west flank of the sand bank (Figure 9.). The change in direction is not found in the MU-SEDIM results at the Kwinte Bank crest but it is visible, in both models, at the sand bank west of the Kwinte Bank (Buiten Ratel). Compared to the Kwinte Bank, the Buiten Ratel is characterized by a lower water depth at the crest, equal to about 5 m below MSL. Wave activity is therefore more important on this sand bank,

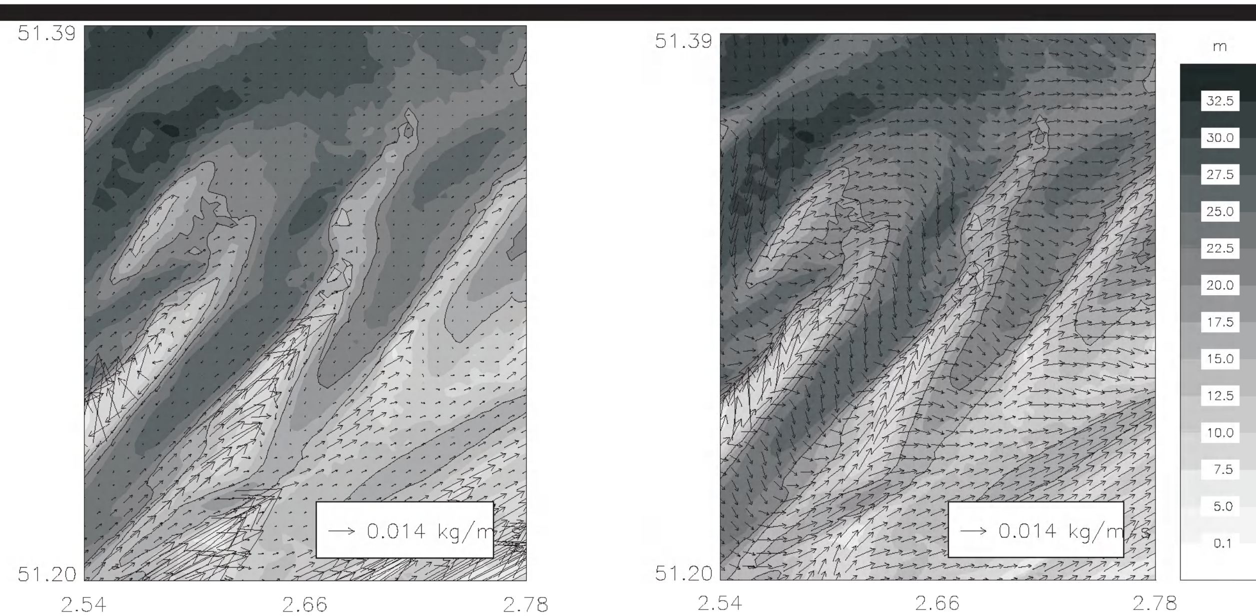

Figure 8. Sediment transport under the influence of tides, meteorological conditions and waves, for the period 2-16 March 2004. The bathymetry is shown in the background. (a) Left: results of MU-SEDIM. One vector for each four grid points is shown. (b) Right: results of the SISYPHE model. Results on the same grid as the MU-SEDIM model.

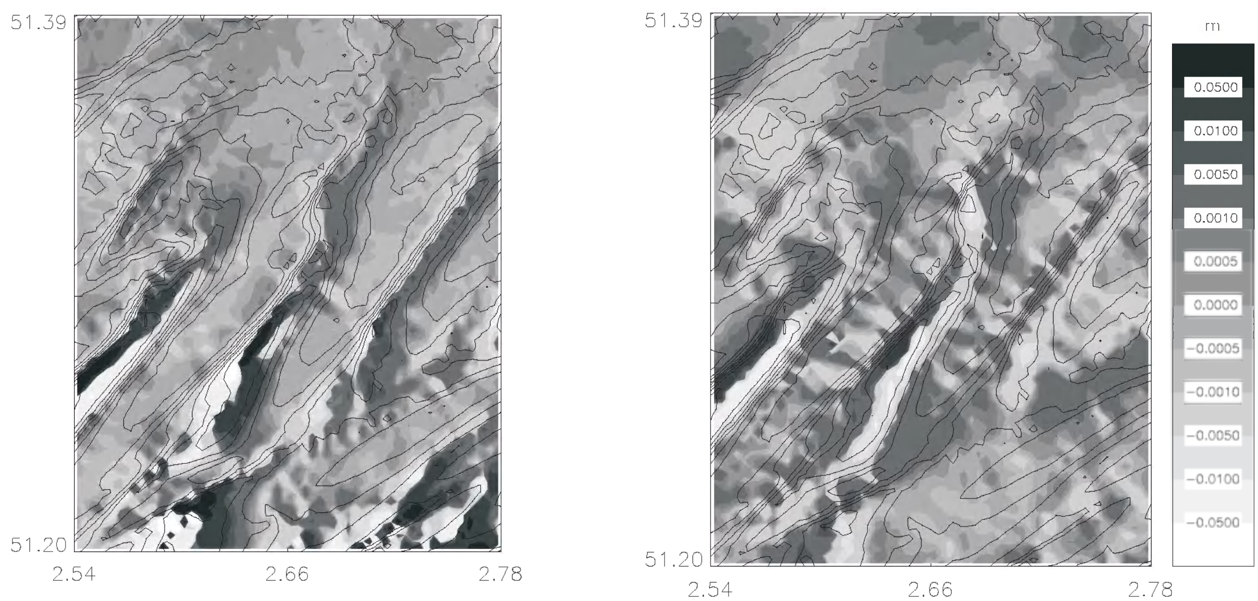

Figure 9. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with tides, waves and meteorological conditions taken into account and for the period 2-16 March 2004. (a) Left: results of the MU-SEDIM model. (b) Right: results of the SISYPHE model.

leading to a change in sediment transport direction represented by both the formulations adopted in the two models.

Considering the fact that these two simulations were carried out applying equations which consider sediment transport direction determined by the direction of the currents, the observation that the addition of waves might change this direction is somehow unexpected. Two phenomena have to be considered to understand this change. Firstly, the asymmetry of the tide leads to ebb currents lasting about 10 % longer in time than flood currents. When wave activity is superimposed on current action, the critical entrainment velocity is exceeded for a longer period during ebb tide, weaker in intensity but longer in time. This can cause sediment transport to veer from flood to ebb current direction. Secondly, ebb currents reach their maximum intensity just before the water elevation is at its lowest. Considering the fact that the Kwinte Bank crest has a minimum water depth of about 7 m and that the tidal range, at spring tide, is about 5 m, it follows that orbital velocities at the bottom are, in average, considerably higher at ebb tide than at flood tide. This leads to a considerable increase in sediment transport at ebb tide.

The same simulation was repeated adopting other formulations for sediment transport. The BAILARD (1981), BIJKER (1968) formulations were tested in the SISYPHE model, while the VAN RIJN (1989), BAGNOLD (1966) and YALIN (1963) formulations were adopted in the MU-SEDIM model. Despite the fact that the results are quite different in magnitude, the change in sediment transport direction was predicted by all formulations.

Tidal currents and waves during a storm

A final simulation was carried out during a stormy period (1 - 15 January 1995) to assess the impact of an extreme event on the Kwinte Bank morphodynamics. Wave height at Westhinder reached in that period a maximum of about 5 m (Figure 10.).

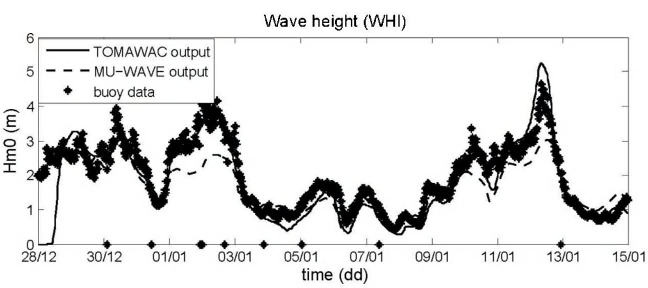

Figure 10. Modelled and measured significant wave height at Westhinder for the period 28 December 1994 to 15 January 1995.

Figure 11. shows the simulated residual transport during the stormy period. Sediment transport was increased by the presence of these exceptional waves by a factor 124.22 in the SISYPHE model and by a factor 81.51 in the MU-SEDIM model (Table 2.).

As a result, a bottom evolution in the order of one meter was predicted after this period (Figure 12.).

Concerning the direction in which sediments move, the SISYPHE model predicts a significant veering in residual transport, in the direction of the ebb currents. In this case the change in direction takes place not only at the Kwinte Bank crest but over the whole area due to the high wave intensity. The extreme waves that occurred during that period caused water particle velocity at the bottom to exceed the critical entrainment velocity during most of the period considered. Therefore, residual transport follows the direction of the ebb currents occurring for a longer period of time and when water depths are lower. In this respect, the output from the MU-SEDIM model is quite different, predicting a change in residual transport direction occurring only at the Buiten Ratel crest. An explanation for this difference may be found by looking at Figure 13. This Figure shows a sensitivity analysis of total load transport computed by the Ackers-White and by the Soulsby-Van Rijn formulas to a change in flow velocity and wave height. It is clear that the Ackers-White formula, as implemented in the MU-SEDIM model, is considerably more sensitive to strong currents than the Soulsby-Van Rijn formula. This causes transport to be dominated by tidal currents in the MU-SEDIM model, while the SISYPHE model is more sensitive to wave activity.

Once again, the calculation was repeated for different sediment transport formulations, showing the importance of wave activity in modifying the direction of residual transport and the proportionality of this change in direction to the increase in wave height.

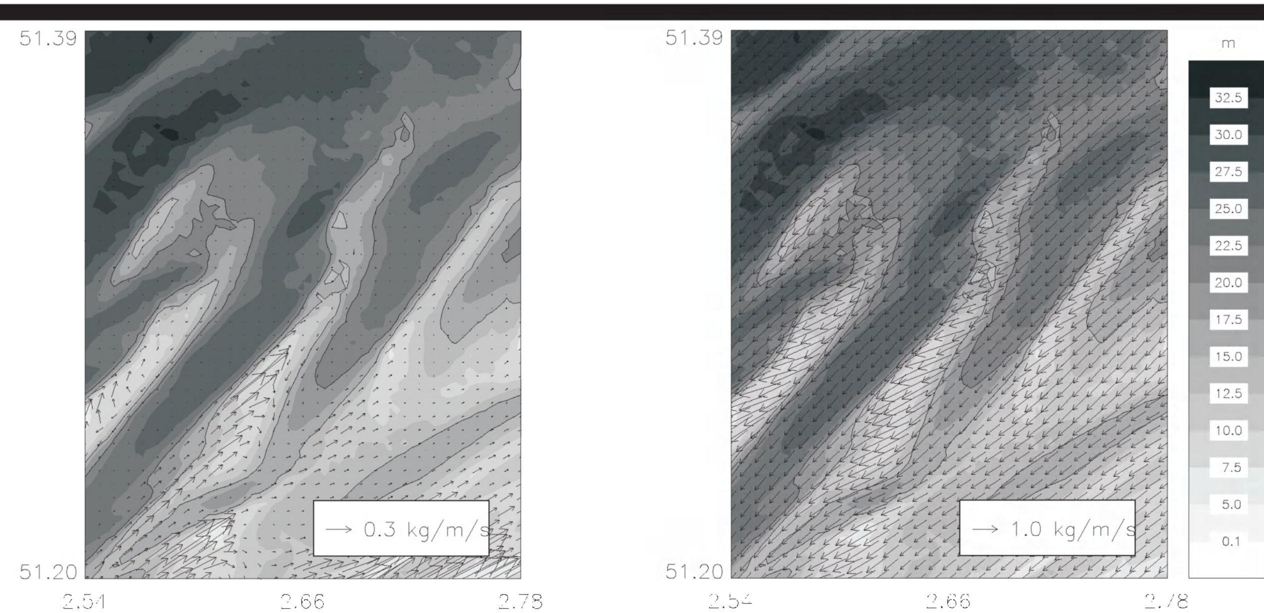

Figure 11. Sediment transport under the influence of tides, meteorological conditions and waves, for the period 1-15 January 1995. The bathymetry is shown in the background. (a) Left: Results of MU-SEDIM. One vector for each four grid points is shown. (b) Right: results of the SISYPHE model. Results on the same grid as the MU-SEDIM model.

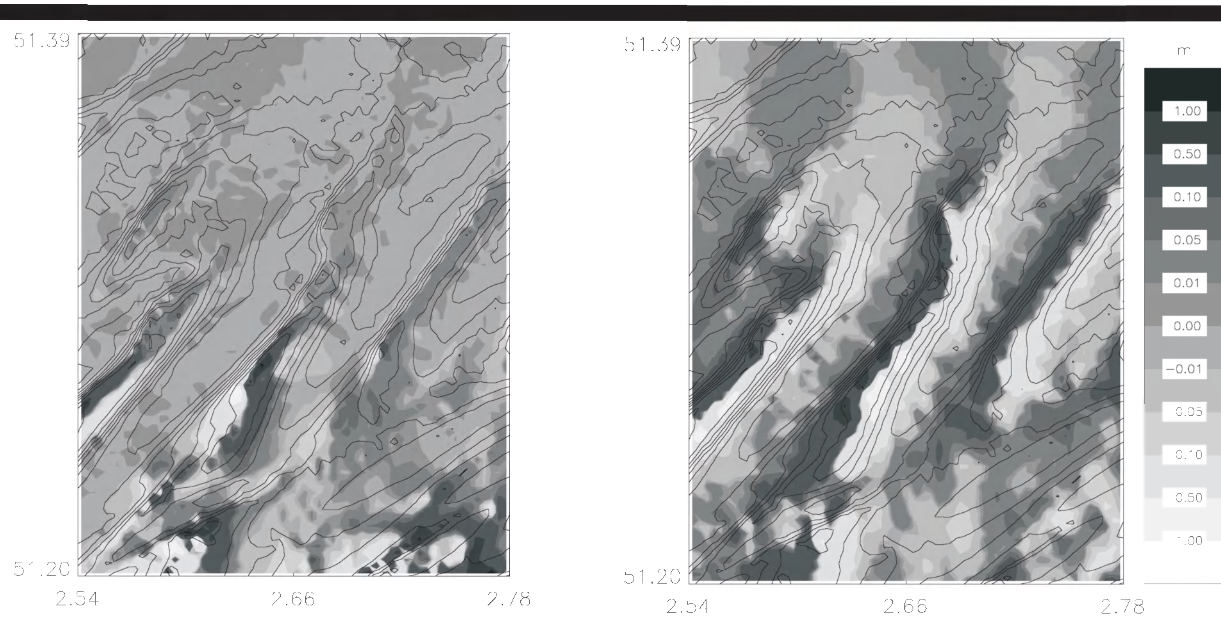

Figure 12. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with tides, waves and meteorological conditions taken into account and for the period 1-15 January 1995. (a) Left: results of the MU-SEDIM model. (b) Right: results of the SISYPHE model.

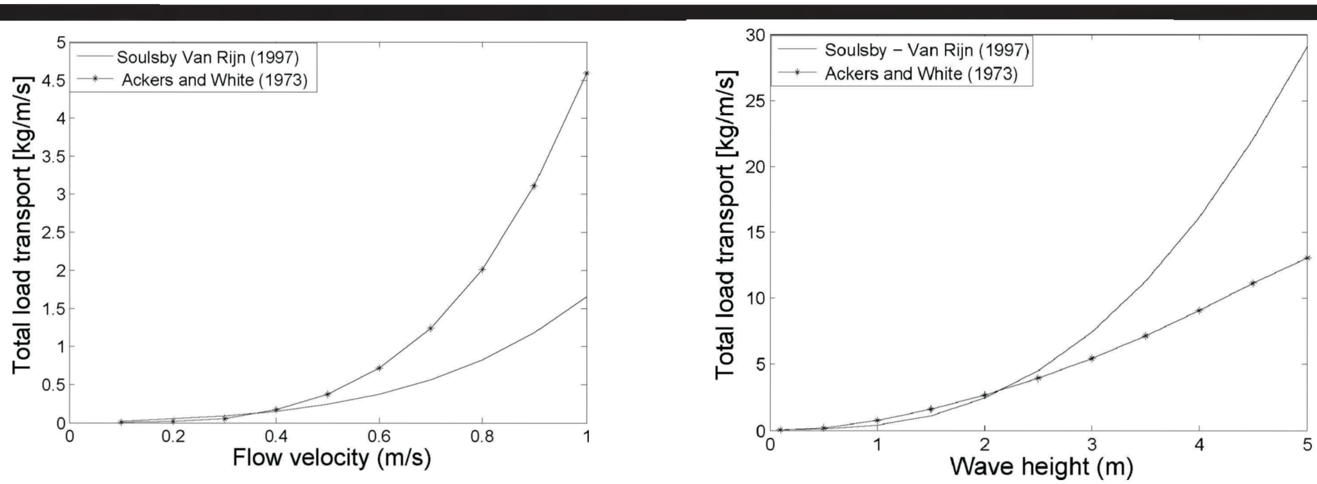

Figure 13. Sensitivity analysis of total load transport to flow velocity (left) and wave height (right). (a) Left: the flow velocity is combined with a constant wave field with significant wave height equal to 1 m and peak period equal to 6 s. Right: the wave height is combined with a constant flow velocity equal to 0.6 m/s.

Measurements of suspended sediment and bed form analysis

Suspended sediment measurements were collected by means of OBS and LISST devices during the March 2004 campaign. These data were analyzed in Giardino and Monbaliu (2006). Directions of residual transport were calculated by integrating over the vertical the product of flow velocities and sediment concentrations measured at different heights above the bottom. The set of measurements available did not give any confirmation concerning a change in residual transport direction for different wave heights. However, only concentration measurements at 0.25, 0.5 and 1 m from the bottom were collected. Calculation of suspended transport by integration of theoretical concentration profiles and flow velocity showed that, for standard flow conditions, more than 90 % of the transport occurs between 0 and 25 cm from the bottom, where no measurement was available. Moreover the instruments were located at a water depth ranging between 12 – 16 m, where wave effects are not as important as at the sand bank crest.

An indirect confirmation of the simulation results was found by looking at the asymmetry of the bed forms. Since little information, in this respect, was available for the Kwinte Bank, the sand bank west of the Kwinte Bank (Buiten Ratel) was taken into consideration. However, hydrodynamic and wave conditions can be considered comparable at the two sand bank and observations on the Buiten Ratel translatable to the Kwinte Bank. Baeye (2006) derived a map of sediment transport direction by

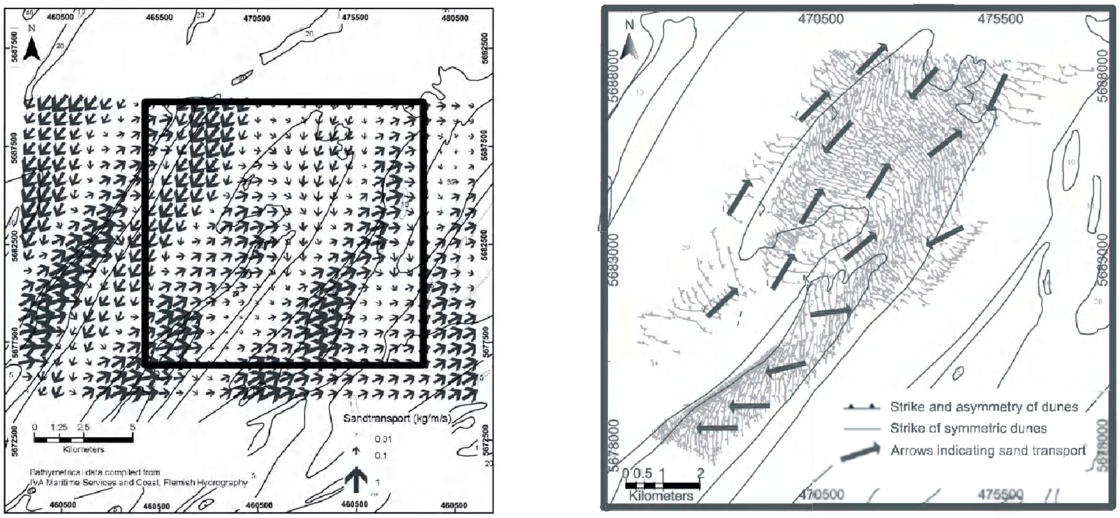

Figure 14. (a) Left: modelled residual sand transport under tidal action only (results of the MU-SEDIM model without taking waves into consideration). (b) Right: sand transport direction from dune asymmetry. The study was carried out at the Buiten Ratel sand bank (west of the Kwinte Bank) (Baeye, M., 2006).

looking at the shape of bedforms covering the Buiten Ratel (Figure 14.). Bottom images collected by means of a multibeam instrument during 5 different campaigns between 2002 and 2003 were used to reconstruct the shape of these bed forms.

Figure 14. shows a comparison of sediment transport direction derived from numerical simulations, with the direction of transport derived from dune asymmetry.

The numerical simulation was carried out by means of the MU-SEDIM model without taking waves into considerations. The modelled transport follows a general pattern similar to the pattern shown in Figure 4., driven by the stronger flood currents over the sand bank. However, dune asymmetry supplies a different picture of the overall transport, with sediment following the flood current direction in the northern part of the sand bank and transport towards the west flank in the southern part. In fact, the southern part is characterized by smaller water depth than the northern part. This would allow waves to penetrate more easily to the bottom, leading to a modification of the transport direction compared to the one determined by tidal currents only as shown by the previous numerical simulations. On the other hand, the larger water depths in the northern part would prevent waves from considerably influencing bottom dynamics, and in this case transport would be current dominated.

DISCUSSION

Long-term morphodynamic prediction of the Kwinte Bank

Analysis of the previous numerical simulations suggests the idea that wave activity, superimposed on the action of tidal currents, might lead to a variation in residual transport direction and to an inversion of the erosion-deposition pattern on the sand banks. However, different sediment transport formulations imply distinct wave thresholds responsible for this change in transport direction. These differences are essentially due to different weights entered in the formulations to the actions of waves and currents. As a consequence, equations in which wave action is considered more important, predict a change in transport direction up to deeper water depths while, according to other formulas, this change occurs only at the crest of the shallowest sand banks.

General conclusions on long-term morphodyamics of the Kwinte Bank may be drawn by looking at the output of the previous numerical simulations and relating them to wave climate statistics in the area. Table 3. shows statistical values for significant wave height registered at the Westhinder buoy during the period January 1977 – December 2002. Numerical simulations carried out adopting the Soulsby-Van Rijn formulation for sand transport, for example, show that an inversion of the erosion-

Table 3. *Significant wave height (cm) at Westhinder for the period January 1977 – December 2002 (from http://www.lin.vlaanderen.be/awz/hydro/www/klimaat/ golf_klimaat/mp7sb1h33/evst.htm)*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
90% percentile	248	238	224	196	176	161	162	160	197	238	233	247
75% percentile	179	175	157	146	129	123	121	117	146	169	173	190
median	115	119	104	93	89	88	86	80	99	115	113	128
25% percentile	74	81	69	61	61	61	59	52	70	74	79	86
10% percentile	51	57	49	42	45	44	40	36	51	50	57	57

Table 4. *Sand banks at the Belgian Shelf and their morphology*

		Water depth at the crest (m below Mean Sea Level)	Steeper flank
Flemish banks	Oostdyck	5.05	West
	Buiten Ratel	5.03	West
	Kwinte Bank	7.46	West
	Middelkerke Bank	6.78	West
Hinder banks	Fairy Bank	10.75	East-West
	Noordhinder	15.57	East
	Westhinder	8.90	East - West
	Oosthinder	11.93	East
	Bligh Bank	12.43	East

deposition pattern due to wave action is visible at the Kwinte Bank crest whenever the average wave height, averaged during the period considered, exceeds a critical value of 0.4 – 0.6 m. In other words, whenever the average wave height is below this value, the western flank of the Kwinte Bank behaves as erosive and the eastern one as depositional. Inverse erosion-deposition pattern characterizes higher values of wave height. In terms of the wave climate, this threshold is exceeded about 80-90 % of the time. Hence, for most of the time, sediment transport as predicted by the Soulsby-Van Rijn formulation, will be directed from the eastern towards the western flank of the Kwinte Bank. In the long term, this would produce a migration of the sand bank towards the northwest. On the other hand, according to different historical observations, the Kwinte Bank seems behaving as a stable sand bank (Van Cauwenberghe, 1971). The difference found with the simulations might be due to an excessive weight given to wave activity in the Soulsby-Van Rijn formulation leading to a threshold which is higher in reality.

It is important to point out that for a long term morphodynamic analysis and prediction, additional phenomena related to climate change should be taken into account, such as possible increase in storminess and the sea level rise. The increase in storminess would contribute to increase the transport towards the western flank of the Kwinte Bank. However, a possible increase in storminess is still argument of debate between scientists. Results of several studies during the last decades show that the storm climate has been subjected to significant variations on time scales of decades (Wasa Group, 1998). Weisse, Von Storch, and Feser (2005) predicted for the Southern North Sea very little increase in storm frequency for the period 1958-2001 (about 1% - 2%). On the other hand, the rise in sea level would cause waves to be less effective at the bottom due to a reduction of the bottom orbital velocities, with a consequent decrease in sand transport. The rise in sea level for the southern North Sea has been estimated at about 1.2 mm/yr from observations over a 100 year period (Jensen *et al.,* 1990). This would reduce the wave penetration at the bottom counterbalancing the increase in storminess. An increase in wave height is also to be expected due to a reduction of bottom dissipation when sea level rises, in this case accompanied to an increase in sand transport. However, as pointed out by MacDonald and O'Connor (1996), the change in wave height for possible scenarios of sea level rise would be minor if not irrelevant at the Kwinte Bank.

Numerical simulations carried out by means of other sediment transport formulations produced different values for this threshold and, therefore also differences in long-term morphodynamic behaviour. Unfortunately, it remains unclear which formulation provides the better agreement with the real morphodynamic situation due to a lack of extensive measurements in space and time.

Sand bank morphology

The Kwinte Bank is part of a more complex sand bank system named *the Flemish Banks*. Various sand banks of this system present a tidal current and wave regime similar to the Kwinte Bank: the Oostdyck, the Buiten Ratel and the Middelkerke Bank (Figure 1.). Moreover, water depth and shape of these sand banks are similar, with a minimum water depth at the crest of about 5 – 7 m and the steeper side facing northwest (Van Lancker *et al.*, 2004) (Table 4.).

Another sand bank system, the *Hinder Banks*, is located north of the Flemish Banks. This system includes the Fairy Bank, the Noordhinder, the Westhinder, the Oosthinder and the Bligh Bank. The crests of these banks are slightly deeper than those of the Flemish Banks and are characterized by a steeper flank commonly facing the southeast side (Deleu *et al.*, 2004).

General belief has always attributed the difference in shape between the Flemish Banks and the Hinder Banks to a different equilibrium existing between flood and ebb currents. In this regard, wave action has always been neglected. The results from this study have brought new insight into the importance of waves in changing sediment transport patterns. A new hypothesis, which relates flow velocity at the bottom due to the combined effects of currents and waves to sand banks morphology, can therefore be formulated. This hypothesis is based on the fact that sand banks generally migrate in the direction of their steep side (Dyer and Huntley, 1999). For the Flemish Banks, which have their steeper flank facing northwest, this could be explained by the direction in which sediments are moving only when both waves and currents are considered. When only currents, or currents together with weak waves are taken into account, sediment transport would occur towards the stoss slope (gentle slope). This would create a sort of dynamic equilibrium due to the alternation between periods with low wave and periods with large wave activity. On the other hand, the steepest side of the Hinder Banks faces the southeast. This is the direction in which sediments move on those sand banks both when only currents are considered, and when waves and currents are superimposed. This phenomenon can be explained by the higher depth of these sand banks, which causes waves to be less effective at the bottom and sediment motion to be determined by the strongest flood currents. In other words, for both sand bank systems, a relationship seems to exist between water depth, wave activity at the bottom and sand bank shape.

Numerical modelling and physical observations seem to support the hypothesis that currents alone can not explain the difference in shape of the two sand bank systems. However, considerable additional research will be needed to really prove and to assess quantitatively the importance of wave activity in shaping the sand banks.

CONCLUSIONS

The present paper focused on the impact of wave activity on the bottom evolution of a sand bank (Kwinte Bank). Two different models were set up in order to compute the morphodynamic evolution of the Kwinte Bank under the combined effects of currents and waves. Despite differences between the two models, wave effects were found to be important for increasing the magnitude of sand transport. Moreover, wave activity together with tidal asymmetry seems to play an important role in changing the direction of residual sand transport. Several formulations for sand transport were compared, suggesting the idea that wave activity and tidal asymmetry give rise to a change in residual sand transport direction from a typical flood tide dominated environment towards an ebb tide dominated situation. This behavior was visible especially at the crest of the most shallow sand banks and increased in importance with increasing wave height. Bed form analysis from bottom images seems to confirm the idea that residual transport is occurring in some areas in the ebb tide direction. The change in residual transport direction would result in a change in the erosion deposition pattern at the Kwinte Bank producing an evolution of the sand bank towards its steeper west flank, in contrast to what could be expected considering the transport due to currents alone. In the long term, the two mechanisms (sand transport due to currents and low waves towards the eastern flank, and sand transport due to currents and significant waves towards the western flank) would balance each other out, leading to a sort of dynamic equilibrium.

Sediment concentration measurements did not give any confirmation regarding a change in residual transport direction at different wave heights. However, several limitations for this kind of study were found in the set of measurements currently available. For future research, sediment concentration and flow velocity profile measurements should be carried out at the sand bank crest and possibly cover a period with different wave conditions.

In conclusion, a new hypothesis was formulated, which relates the shape of the sand banks on the Belgian shelf to their water depth and, as consequence, to the local bottom dynamics. This hypothesis would explain why the Flemish Banks are characterized by a steeper flank facing the northwest, while the Hinder Banks system is characterized by a reversed morphology. According to this hypothesis the different shape would be related to the different water depth of the two sand bank systems, which would reflect on a different wave impact at the bottom and on a different residual transport direction.

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LITERATURE CITED

ACKERS, P. and WHITE, W. R., 1973. Sediment transport: new approach and analysis. *Proceedings of the ASCE Journal of Hydraulics Division*, 99, 2041-2060

BAEYE, M., 2006. Sediment - en morfodynamische evaluatie van de "Buiten Ratel" zandbank in het perspectief van een duurzame ontginningsstrategie, Ghent University, Renard Centre of Marine Geology, Master's thesis, 1-163

BAGNOLD, R., 1966. An approach to the sediment transport model from general physics, *US Geological Survey Professional Paper*, 422-I

BAILARD, J., 1981. An energetics total load transport model for a plane sloping beach, *Journal of Geophysical Research*, 86, C11, 10938-10954

BENOIT, M.; MARCOS, F., and BECK, F., 1996. Development of a third generation shallow-water wave model with unstructured spatial meshing, *Proceedings of the 25th International Conference on Coastal Engineering*, (Orlando, Florida, USA, ASCEE), 465-478

BIJKER, E.W., 1966. The increase of bed shear in a current due to wave motion. *Proceedings of the 10th Conference on Coastal Engineering*, American Society of Civil Engineers, Tokyo, Japan, 746-765

BIJKER, E. W., 1968. Development of a third generation shallow-water wave model with unstructured spatial meshing, *Proceedings of the 11th Coastal Engineering*, (London, UK, ASCEE), 415-435

BRIÈRE, C.; ROOS, P.C.; GAREL, E., and HULSCHER, S.J.M.H., this volume. Modelling the morphodynamic effects of sand extraction from the Kwinte Bank, Southern North Sea. *Journal of Coastal Research, Special Volume of Eumarsand - Marebasse project*

CARBAJAL, N. and MONTANO, Y., 2001. Comparison between Predicted and Observed Physical Features of Sandbanks, *Journal of Estuarine, Coastal and Shelf Science*, 52, 435-443

COLLINS, M. B.; SHIMWELL, S. J.; GAO, S.; POWELL, H.; HEWITSON, C., and TAYLOR, J. A., 1995. Water and sediment movement in the vicinity of linear sandbanks: the Norfolk Banks, southern North Sea, *Journal of Marine Geology*, 123, 3-4, 125-142

COOREMAN, K.; HILLEWAERT, H.; GUNS, M., and VAN HOEYWEGHEN, P., 2000. Biological monitoring of dumping of dredged material at the Belgian coast (1997-1999) (in Dutch). Ministerie van Middenstand en Landbouw, Departement Zeevisserij, Oostende, *Report 97060/BAG/5*.

DELEU, S.; VAN LANCKER, V.; VAN DEN EYNDE, D., and MOERKERKE, G., 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea), *Journal of Continental Shelf Research*, 24, 1587-1610

DYER, K. R. and HUNTLEY, D. A., 1999. The origin, classification and modelling of sand banks and ridges, *Continental Shelf Research*, 19, 1285-1330

FETTWEIS, M. and VAN DEN EYNDE, D., 2000. Assessment of the sediment balance for the Belgian coastal waters: calculation with sediment transport models (in Dutch). Management Unit of the North Sea Mathematical Models, *Report SEBAB/1/MF/200006/NL/AR/2*, 45 pp.

GIARDINO, A. and MONBALIU, J, 2006. Wave effects on Sand Bank Morphodynamics, *Proceedings of the 2nd International Short Course and Workshop on COASTAL PROCESSES and PORT ENGINEERING*, Cosenza (Italy)

GÜNTHER, H., ROSENTHAL, W., 1985. The hybrid parametrical (HYPAS) wave model. *Ocean wave modelling, Swamp group*. Plenum Press, New York, 211-214.

HASSELMANN, K.; BARNETT, T. P.; BOUWS, E.; CARSON, H.; CARTWRIGHT, D.E.; ENKE, K.; WIENG, J.A.; GIENAPP, H.; HASSELMANN, D.E.; KRUSE-

MANN, P.; MEERBURG, A.; MÜLLER, 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), *Deutchen Hydrographischen Zeitung*, suppl. A., 8 (12), 95 pp.

HASSELMANN, K.; ROSS, D.B.; MÜLLER, P., and SELL, W., 1976. A parametrical wave prediction model. *Journal of Physical Oceanography*, 6, 201-228.

HASSELMANN, S.; HASSELMANN,K.; ALLENDER,J.H., and BARNETT, T.P., 1985 Computations and parametrizations of the nonlinear energy transfer in a gravity-wave spectrum. Part 2: Parametrizations of the nonlinear energy transfer for application in wave models. *Journal of Physical Oceanography*, 15, 1378-1391.

HERVOUET, J.-M. and BATES, P., 2000. The TELEMAC Modelling System Special Issue, *Hydrological Processes*, 14, 13, 2207-2363

HULSCHER, S. J. M. H.; DE SWART, H. E., and DE VRIEND H.J., 1993. The generation of offshore tidal sand banks and sand waves, *Journal of Continental Shelf Research*, 13, 1183-1204.

HUTHNANCE, J. M., 1973. Tidal currents asymmetries over the Norfolk sandbanks, *Journal of Estuarine and Coastal Marine Science*, 1, 89-99

HUTHNANCE, J. M., 1982b. On the formation of sand banks of finite extent, *Journal of Estuarine, Coastal and Shelf Science*, 15, 277-299

HUTHNANCE, J. M., 1982a. On one mechanism forming linear sand banks, *Journal of Estuarine and Coastal Marine Science*, 14, 19-99

JANSSEN, P.A.E.M., 1989. Wave-induced stress and the drag of the air flow over sea waves, *Journal of Physical Oceanography*, 19, 745-754

JANSSEN, P.A.E.M., 1991. Quasi-linear theory of wind-wave generation applied to wave forecasting, *Journal of Physical Oceanography*, 21, 1631-1642

JENSEN,J.; MÜGGE, H-E., and Schönfeld, W., 1990. Development of water level changes in the German Bight, an analysis based on single value time series. *Proceedings of the 22nd International Coastal Engineering Conference*, 1, 2839-2851

KOMEN,S.; HASSELMANN, S., and HASSELMANN,K., 1984. On the existence of a fully developed wind-sea spectrum, *Journal of Physical Oceanography,* 14, 1271-1285, 1984

LANCKNEUS, J.; VAN LANCKER, V.; MOERKERKE, G.; VAN DEN EYNDE, D.; FETTWEIS, M.; DE BATIST., and M., JACOBS, P., 2001. Investigation of the natural sand transport on the Belgian continental shelf (BUDGET), Federal Office for Scientific, Technical and Cultural Affairs (OSTC), *Final Report*

LUYTEN, P. J.; JONES, J. E.; PROCTOR, R.; TABOR, A.; TETT, P., and WILD-ALLEN, K., 1999. *COHERENS: A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation*, Management Unit of the North Sea Mathematical Models, Brussels, 1-914.

MACDONALD,N.J., and O'CONNOR,B.A. 1996. Changes in wave impact on the Flemish coast due to increased mean sea level, *Journal of Marine Systems,* 7, 133-144

OSUNA CAÑEDO, J.P., 2002. On the high-resolution simulation of the dynamic interaction between currents and waves in coastal waters: an application to the southern North Sea, Civil Engineering Department, Katholieke Univeristeit Leuven, Belgium, Ph.D. thesis, 196 p.

OSUNA CAÑEDO, J.P., MONBALIU, J., 2004. Wave-current interaction in the Southern North Sea, *Journal of Marine Systems*, 52, 65-87

SLEATH, J.F.A., 1984. _Sea Bed Mechanics_, Wiley-Interscience, New York, 1-335

SOULSBY, R. L., 1997. Dynamic of marine sands, Thomas Telford, London, 1-249

SWART, D. H., 1976. Coastal Sediment Transport. Computation of Longshore Transport, Delft Hydraulics Laboratory, The Netherlands, *Report R968*

SWART, D. H., 1977. Weighted value of depth of initiation of movement, Stellenbosch, South Africa, *Report NR10*

TONNON, P.K., VAN RIJN, L.C., WALSTRA,D.J.R., 2007. The morphodynamic modelling of tidal sand waves on the shoreface, Delft Hydraulics Laboratory, The Netherlands, *Journal of Coastal Engineering*, 54, 279-296

VAN CAUWENBERGHE, C., 1971. Hydrografische analyse van de Vlaamse banken langs de Belgisch-Frans kust, *Het Ingenieursblad 40*, 19, 563-571

VAN DE MEENE, Y. W. H. and VAN RIJN, L. C., 2000. The shoreface-connected ridges along the central Dutch coast - part 2: morphological modelling, Journal of *Continental Shelf Research*, 20, 2325-2345

VAN DEN EYNDE, D.; GIARDINO, A.; PORTILLA, J.; FETTWEIS, M.; FRANCKEN, F., and MONBALIU, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank., *Journal of Coastal Research, Special Volume of Eumarsand - Marebasse project.*

VAN DEN EYNDE, D., 1992. mu-WAVE: an operational wave forecasting system for the Belgian coast. *Proceedings of the Third International Workshop on Wave Hindcasting and Forecasting*, (Montréal, Canada), 313-324.

VAN DEN EYNDE, D. and OZER, J., 1993. Sediment Trend Analysis: calculation of the sediment transport with a numerical model (in Dutch). Management Unit of the North Sea Mathematical Models, *Rapport BMM/STA/TR01*, 1-49

VAN DEN EYNDE, D.; SCORY, S., and MALISSE, J.-P., 1995. Operational modelling of tides and waves in the North Sea on the Convex C230 at MUMM, *Proceedings of the European Convex User's Conference 1995,* (Brussels, Belgium).

VAN LANCKER, V.; MOERKERKE, G.; FETTWEIS, M.; VAN DEN EYNDE, D.; MONBALIU, J.; LANCKNEUS, J., and DEGRAER, S., (2002). Nood aan evaluatiemiddelen voor de opvolging van kustsystemen. [The need for evaluation tools for coastal system monitoring], Colloquium 'Kustzonebeheer vanuit geo-ecologische en economische invalshoek', [Symposium 'Coastal zone management from a geo-ecological and economical perspective'], *VLIZ Special Publication*, 10. Genootschap van Geologen van de Universiteit Gent (GGG)/Vlaams Instituut voor de Zee (VLIZ): Oostende, Belgium, 1-5.

VAN LANCKER, V.; DELEU, S.; BELLEC, V.; LE BOT, S.; VERFAILLE, E.; FETTWEIS, M.; VAN DEN EYNDE, D.; FRANCKEN, F.; PISON, V.; WARTEL.S.; MONBALIU, J.; PORTILLA, J.; LANCKNEUS, J.; MOERKERKE, G., and DEGRAER, S., 2004. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse), Federal Office of Scientific, Technical and Cultural Affairs (OSTC), *Scientific report 2*, 1-144.

VAN LANCKER, V.; DELEU, S.; BELLEC, V.; VERFAILLE, E.; DU FOUR, I.; FETTWEIS, M.; VAN DEN EYNDE, D.; FRANCKEN, F.; MONBALIU, J.; PORTILLA, J.; GIARDINO, A.; MOERKERKE, G., and DEGRAER, S., 2005. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse), Federal Office of Scientific, Technical and Cultural Affairs (OSTC), *Scientific report 3*, 2-103.

VAN RIJN, L., 1989. Handbook Sediment Transport by Currents and Waves, Delft Hydraulics, *Report H461.*

VAN RIJN, L. C., 1984. Sediment transport: part I: bed load transport; part II: suspended load transport; part III: bed forms and alluvional roughness, *Journal of Hydraulic Engineering*, 110, 1431-56; 1613-41; 1733-54.

VILLARET, C., 2004. SISYPHE RELEASE 5.4 User Manual, EDF/LNHE, *Report P75G17*, 1-69.

VILLARET, C., and DAVIES, A.G., 2004. Numerical modelling of littoral sand transport, *Proceedings of the 29th International Conference on Coastal Engineering*, Lisbon, 1678-1689.

VINCENT, C. E.; STOLK, A., and PORTER, C. F. C., 1998. Sand suspension and transport on the Middelkerke Bank (southern North Sea) by storms and tidal currents, *Journal of Marine Geology*, 150, 113-129.

WASA GROUP, 1998. Changing waves and storms in the Northeast Atlantic? *Bulletin of the American Meteorological Society*, 79, 741-760.

WEISSE,R.; VON STORCH,H., and FESER,F., 2005. Northeast Atlantic and North Sea Storminess as Simulated by a Regional Climate Model during 1958-2001 and Comparison with Observations, *Journal of Climate*, American Meteorological Society, 465-479.

YALIN, M.S., 1963. An expression for bed-load transportation, *Journal of the Hydraulics Division*, ASCE, 89, 221-250.