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Implementation of a wave-current interaction module for the POLCOMS system

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Abstract

In this report, a description of the wave–current interaction module implemented in the Proudman Oceanographic Laboratory Coastal–Ocean Modelling System (POLCOMS) is presented. The performance of the system is assessed in the Irish Sea region, with a high spatial resolution (about $1.85 km$). Preliminary results indicate that the effect of currents on the waves (e.g., modulations of wave height and mean period) is uniformly distributed in the Irish Sea area. Larger effects are observed around headlands and shoals, where the magnitude and shear of currents are large. The effect of waves on currents is also evident around headlands and shoals. During stormy periods, differences in the daily mean current speed are mainly produced by the use of a wave dependent surface stress. The effect of using a combined wave–current bottom shear stress is constrained to coastal areas, and is one order of magnitude smaller than the effect of using a wave dependent surface stress.

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1 Introduction

It is well known that the hydrodynamics in coastal areas is controlled by the interaction between a number of physical process. On continental shelves and in enclosed seas, the effect of this interaction has an important impact on the description of a number of processes, like sediment transport, dynamics of nutrients and pollutants, movement of larvae, etc.

The Proudman Oceanographic Laboratory Coastal–Ocean Modelling System (POLCOMS) is a numerical coupled system intended to account for the relevant physical processes that occur in coastal waters. The core of POLCOMS is the three dimensional model POL3DB. The governing equations are solved on a staggered B-grid (Arakawa, 1972), and uses sigma coordinates for the vertical domain. Details on the numerics of the model can be found in Holt and James (2001).

Presently, the system includes a one–way interaction module for sediment transport and resuspension, as well as an interaction module for the European Regional Sea Ecosystem Model (ERSEM). The system has been structured to allow its execution on parallel and serial computers. The partitioning and message passing between subdomains implemented in POLCOMS is described in Ashworth et al. (2004).

A procedure to include the two–way interaction between currents and waves in POLCOMS is described here. A description of the coupling terms included in this version is given. Some preliminary results corresponding to the implementation of the wave–current coupling module in the Irish Sea region are presented.

2 The wave model

The wave module uses the model ProWAM, a modified version of the spectral WAM *Cycle_4 model* (Monbaliu et al., 2000). ProWAM solves an action balance equation in terms of energy to describe the spatial evolution of the energy density spectrum F in terms of a discrete number of intrinsic frequencies, σ, and directions, θ.

As user defined option, the wave model equation is solved in spherical or cartesian coordinates. The equation in cartesian coordinates reads,

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial x}(C_x F) + \frac{\partial}{\partial y}(C_y F) + \frac{\partial}{\partial \theta}(C_\theta F) + \sigma \frac{\partial}{\partial \sigma}(C_\sigma \frac{F}{\sigma}) = S, \qquad (1)$$

where S is a function that represents the input, sink and nonlinear energy transfer in spectral (σ, θ) domain. In (1), (x, y) are east–west and south–north space coordinates, respectively, and C_x, C_y, C_σ, C_θ, are

$$\begin{aligned}
C_x &= c_g \sin\theta + u, && (2)\\
C_y &= c_g \cos\theta + v, && (3)\\
C_\theta &= \frac{\sigma}{\sinh(2kh)}\left[\sin\theta\frac{\partial h}{\partial y} - \cos\theta\frac{\partial h}{\partial x}\right] \\
&\quad + \sin\theta\left[\sin\theta\frac{\partial u}{\partial y} - \cos\theta\frac{\partial u}{\partial x}\right] \\
&\quad + \cos\theta\left[\sin\theta\frac{\partial v}{\partial y} - \cos\theta\frac{\partial v}{\partial x}\right], && (4)\\
C_\sigma &= \frac{k\sigma}{\sinh(2kh)}\left[\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y}\right] \\
&\quad - c_g k \sin\theta\left[\sin\theta\frac{\partial u}{\partial x} + \cos\theta\frac{\partial u}{\partial y}\right] \\
&\quad - c_g k \cos\theta\left[\sin\theta\frac{\partial v}{\partial x} + \cos\theta\frac{\partial v}{\partial y}\right], && (5)
\end{aligned}$$

where c_g is the wave group velocity, and (u,v) are the longitudinal and latitudinal current components, respectively.

The source term, S, includes explicit expressions for the wave generation by wind (S_{in}), quadruplet wave–wave interaction (S_{nl}), wave breaking on deep waters (S_{wc}), and wave dissipation by bottom friction (S_{wc}). A thorough description of the source term formulations included in WAM *Cycle_4* can be found in Komen et al. (1994). In this report, only the S term formulations where currents play any role are described in any detail.

The WAM model (and therefore ProWAM) uses a splitting method for the solution of (1). The propagation and refraction terms are solved in flux form using a first order upwind scheme. In order to assure numerical stability, a time step for the lowest frequency is computed (Δt_{prop}). The energy rate of change produced by the effect of source terms in (1) is given by,

$$\frac{\partial F}{\partial t} = S. \tag{6}$$

The equation (6) is evaluated using an implicit scheme with a time step ($\Delta t S$) that matches the evolution time scale of the significant waves (i.e., the waves around the peak). The time scale involved in $\Delta t S$ is given by the variability of the physical processes that affect the evolution of the wave field. For open ocean applications, ΔtS is usually chosen to be about $20min$. In coastal region, where the bathymetry and currents induce a spectral variability on shorter time and spatial scales than that induced by the wind, ΔtS can be even smaller than the propagation time step.

The governing equation is solved on a relative frame (moving with the current) and, when outputs are required, the resulting spectra is "Doppler–shifted" using the relationship

$$\omega = \sigma + k \cdot \mathbf{u} = (gk \tanh kh)^{1/2} + k \cdot \mathbf{u}, \tag{7}$$

where ω is the absolute frequency, g is the gravity acceleration, k is the wave number, and $h = H + \eta$ (where H is the undisturbed water depth and η is the sea–surface elevation) is the total depth.

3 Terms for coupling and procedure

The wave–current interaction module is prepared to allow the synchronous exchange of information between POL3DB and ProWAM. In this implementation ProWAM works as a module of POLCOMS, so the wave model uses the same bathymetry and wind information supplied to the hydrodynamic model. The different time steps used by the models are independent but, as the wave model is embedded in the baroclinic step of POL3DB, ProWAM time stepping must be an integer ratio of the POL3DB baroclinic time step. An example of the time stepping in the coupled system is presented in Figure 1.

3.1 Data from POLCOMS to ProWAM: surface

It is evident from equations (2)–(5) that the propagation of wave energy and refraction is affected by the level of inhomogeneity and unsteadiness of the current field.

In order to be used by (2)–(5), surface and bottom layer (u, v) components and total depth, h, are updated every baroclinic time step. The current values at nodes (i, j) in the POL3DB grid are imposed at the corresponding (i, j) nodes of the wave model (see Figure 2). As soon as those values are transferred, the tables used to compute shallow water kinematic wave parameters (i.e., group velocity and wave number) are also updated.

The spatial derivatives of (u, v) in (4)–(5) are evaluated internally by the wave model using central differences, for instance,

$$\frac{\partial u}{\partial x} \cong \frac{u(i+1,j) - u(i-1,j)}{2\Delta x}.$$

The spatial derivative of the total depth are evaluates as,

$$\frac{\partial h}{\partial x} \cong \frac{h(i+1,j) - h(i-1,j)}{2\Delta x}$$

and

$$\frac{\partial h}{\partial y} \cong \frac{h(i,j+1) - h(i,j-1)}{2\Delta y}.$$

The time derivative of the total depth, $\partial h/\partial t$ in (5), is not included in the present implementation.

The time interpolated wind components, (W_{10}^x, W_{10}^y), are also transferred from POLCOMS. In ProWAM, these values are transformed to a moving frame according to

$$\begin{aligned} U_{10}^x(i,j) &= W_{10}^x(i,j) - u(i,j) \\ U_{10}^y(i,j) &= W_{10}^y(i,j) - v(i,j) \end{aligned}$$

where (u, v) are the surface current components.

3.2 Data from POLCOMS to ProWAM: bottom

Current components corresponding to the bottom layer, (u_b, v_b), are transferred from POLCOMS to the wave model. The current values are used to compute bottom friction in a combined wave–current flow, as well as other parameters to be transferred back to POLCOMS, according to Madsen (1994).

3.3 Data from ProWAM to POLCOMS: surface

In POLCOMS, the standard formulation for computing sea surface stress, τ_s, is given by the expression proposed by Smith and Banke (1975),

$$\begin{aligned} \tau_s^x &= C_s \rho_a W_{10}^x |W_{10}| \\ \tau_s^y &= C_s \rho_a W_{10}^y |W_{10}| \end{aligned}$$

where ρ_a is the air density, and

$$C_s = (0.63 + 0.066|W_{10}|) \times 10^{-3}$$

is a non-dimensional drag coefficient. In this formulation, any dependency of the transfer of momentum from the atmosphere to the ocean on the sea–surface development is implicitly included through C_s.

As indicated by Janssen (1991), the kinematic stress at the sea surface is given as,

$$\tau = \left[\frac{\kappa U(z_r)}{\ln(z_r/z_0)}\right]^2, \tag{8}$$

where $\kappa = 0.41$ is the von Karman parameter, $U(z_r)$ is the wind speed at the reference level z_r (normally $10m$), and

$$z_0 = \frac{0.01\tau}{g\sqrt{1-(\hat{\tau}_w/\tau)}} \tag{9}$$

is the roughness length. In (9), $\hat{\tau}_w$ is the wave induced stress given as,

$$\hat{\boldsymbol{\tau}}_{\boldsymbol{w}}(z_o) = \rho_w \int_0^\infty \int_0^{2\pi} \omega \mathrm{S}_{\mathrm{in}}(\omega, \theta) \frac{|k|}{k} d\omega d\theta, \tag{10}$$

where ρ_w is the water density, and $S_{in} = \gamma F(\omega, \theta)$ is the source term representing the growth of spectra energy by wind. In ProWAM, γ represents the Miles' wave growth mechanism and is computed as a function of the sea–state parameters obtained at a previous time step. The method to compute (8)–(10) is described in Mastenbroek et al. (1993).

In ProWAM, the sea surface stress is computed by means of a table, which is constructed as a function of wind speed (referred to $10m$) and $\hat{\tau}_w$ values; for a given wind speed and the computed $\hat{\tau}_w$ the new surface stress is obtained. If the appropriate option is activated, the computed sea–state dependent surface stress at the node (i, j) is transferred to the corresponding point in POLCOMS.

3.4 Data from ProWAM to POLCOMS: bottom

In order to take into account the effect of waves on currents at the bottom, a similar approach as the one described in Souza et al. (2001). The total instantaneous bed shear stress, τ_b, is defined as the combined effect of currents, τ_c, and waves, τ_w, in such a way that

$$\tau_b = \tau_c + \tau_w. \tag{11}$$

The current induced bed shear stress is given by

$$\tau_c = \frac{1}{2}\rho_w f_c \mathrm{u_b}^2, \tag{12}$$

where f_c is a non–dimensional friction factor defined as,

$$f_c = \left[\frac{\kappa}{\ln(30 z_r/k_{bc})}\right]^2. \tag{13}$$

In (13), z_r represents a reference height, and k_{bc} is the apparent roughness felt by the current due to the presence of wind waves. When the effect of waves is small, k_{bc} is taken to be $k_{bc} = K_N = 30z_0$ (where K_N is the Nikuradse length scale and $z_0 = 0.003m$ is the roughness length at the bottom) and (13) is reduced to the expression implemented in POLCOMS (see Holt and James, 2001).

For the computation of τ_w, the formulation of Madsen (1994) for the solution of a combined wave–current bottom boundary layer flow is used. In Madsen's formulation, a maximum combined shear velocity at the bottom is defined as

$$\mathrm{u_{*cw}}^2 = \mathrm{u_{*c}}^2 + \mathrm{u_{*wm}}^2, \tag{14}$$

where $\mathrm{u_{*c}}$ is the current shear velocity and $\mathrm{u_{*wm}}$ is the maximum wave shear velocity of a representative wave. He introduces a coefficient that defines the relative importance of the current shear velocity and the maximum wave shear velocity, i.e., $C_\mu = (1+2\mu|\cos\phi_{cw}|+\mu^2)^{1/2}$, where $\mu = (\mathrm{u_{*c}}/\mathrm{u_{*wm}})^2$, and ϕ_{cw} is the angle between current direction and direction of wave propagation.

According to Madsen (1994), the maximum wave shear stress is defined as

$$\tau_w = \frac{1}{2}\rho_w f_{wc} \mathrm{u_{br}^2} = \rho_w \mathrm{u_{*wm}^2}, \tag{15}$$

where ρ_w is the water density, f_{wc} is a wave–current combined friction coefficient, and $\mathrm{u_{br}}$ is a representative amplitude (i.e., the root–mean–square amplitude) of the near–bottom wave orbital velocity, which is given by

$$\mathrm{u_{br}} = \sqrt{2\iint F_{\mathrm{u_b}}(\omega,\theta)\,d\omega d\theta}, \tag{16}$$

where $F_{\mathrm{u_b}}(\omega,\theta)$ is the spectral density of the near–bed wave velocity computed from $F(\omega,\theta)$ using linear theory.

In (15), the combined friction velocity is defined as

$$f_{wc} = C_\mu \exp\left\{7.02\left(\frac{C_\mu \mathrm{u_{br}}}{K_N \omega_r}\right)^{-0.078} - 8.82\right\} \tag{17}$$

$$\text{for } 0.2 < C_\mu \mathrm{u_{br}}/(K_N\omega_r) < 10^2,$$

and

$$f_{wc} = C_\mu \exp\left\{5.61\left(\frac{C_\mu \mathrm{u_{br}}}{K_N \omega_r}\right)^{-0.109} - 7.30\right\} \tag{18}$$

$$\text{for } 10^2 < C_\mu \mathrm{u_{br}}/(K_N\omega_r) < 10^4,$$

where ω_r is a representative radial frequency given by,

$$\omega_r = \frac{\iint \omega F_{\mathrm{u_b}}(\omega,\theta) d\omega d\theta}{\iint F_{\mathrm{u_b}}(\omega,\theta) d\omega d\theta}. \tag{19}$$

In Madsen (1994), the wave boundary layer thickness is given as,

$$\delta_{wc} = \begin{cases} 2\kappa \mathrm{u_{*cw}}/\omega_r & \text{for} \quad C_\mu \mathrm{u_{br}}/(K_N\omega_r) > 8 \\ \\ K_N & \text{for} \quad C_\mu \mathrm{u_{br}}/(K_N\omega_r) > 8 \end{cases} \tag{20}$$

with the maximum combined shear velocity, $\mathrm{u_{*cw}}$, defined as $\mathrm{u_{*cw}} = (C_\mu \mathrm{u_{*wm}})^{1/2}$. Following Madsen (1994) [his equations (9) and (10)], it is possible to estimate the apparent bottom roughness experienced by the current in presence of waves by matching the current velocities at $z = \delta_{wc}$,

$$\mathrm{u_c}(\delta_{wc}) = \frac{\mathrm{u_{*c}}^2}{\kappa \mathrm{u_{*cw}}} \ln \frac{30\delta_{wc}}{K_N}, \tag{21}$$

with the expression for the current velocity profile outside the boundary layer, i.e.,

$$\mathrm{u_c}(\delta_{wc}) = \frac{\mathrm{u_{*c}}}{\kappa} \ln \frac{\delta_{wc}}{z_{0a}}, \tag{22}$$

and solving for the apparent roughness length, z_{0a}.

The set of equations (15)–(20) is solved using the iterative technique described in Madsen (1994). When the corresponding option is chosen, the computed z_{0a} obtained from the solution of (21) and (22) are transferred from ProWAM to POLCOMS at the corresponding nodes. The z_{0a} values are used to evaluate (13) in POLCOMS.

4 Preliminary assessments: The Irish Sea

The Irish Sea area is covered by a grid with a spatial resolution of 1/60 by 1/40 degree in latitude and longitude, respectively. The total coverage is from $51.0^{o}N$ to $56.0^{o}N$ latitude and from $7.0^{o}W$ to $2.5^{o}W$ longitude. The bathymetry of the area is shown in Figure 3. According to the total area coverage and the spatial resolution, the computational grid for the Irish Sea implementation contains 173×301 points. In this implementation, a minimum depth of $10m$ is used.

4.1 Boundary and atmospheric forcing

In order to incorporate swell information, a previous coarser resolution grid, which includes part of the Northeastern Atlantic Ocean (NEA), was used. The spatial resolution of the NEA implementation is $1.0^{o}\times1.0^{o}$ and covers the area from $40.0^{o}N$ to $65.0^{o}N$ latitude and from $25.0^{o}W$ to $15.0^{o}E$ longitude. Directional wave spectra at the open boundary points of the Irish Sea region were stored every hour. The open boundary information is internally interpolated in time and space by ProWAM during the Irish Sea application.

The open boundary conditions for the hydrodynamic model were generated by an implementation of POLCOMS for the northwest European continental shelf. The implementation cover the area from $40.0^{o}N$ to $65.0^{o}N$ latitude and from $20.0^{o}W$ to $13.0^{o}E$ longitude, with a resolution of $1/9^{o}$ by $1/6^{o}$ in latitude and longitude, respectively. Hourly values of η, u, and v, interpolated to the open boundary points of the fine–grid domain (in this case the Irish Sea), are provided offline. The values are internally interpolated in time by the fine grid application.

In order to force the coupled system in the Irish Sea region, six–hourly, $1.0^{o}\times1.0^{o}$ resolution, ECMWF ERA40 Reanalysis surface winds and atmospheric pressure, corresponding to the period from 02/02/1997 to 16/02/1997, are used. The same data set is used to force the respective coarser implementation. During the analysis period, the winds in the Irish Sea region were predominantly west–southwesterly (see daily mean winds in Figure 4), with magnitudes not larger than $15m/s$.

4.2 Models setup

For this preliminary test, a relatively coarse resolution in spectral space (ProWAM) and vertical domain (POLCOMS) is used. Some details about the setup of the models are given in Table 1.

In the Irish Sea region, the complicated bathymetry and topographic features (i.e., headlands and shoals) produce currents that exceed $3.0m/s$ in some locations. The strong current gradients in some areas of the Irish Sea enhance the spectral variability, therefore the use of small time steps for the solution of the source terms becomes necessary. In order to deal with the amount of computational power required by the implementation of the system in the Irish Sea, a parallel version is executed on a SGI Origin 3800 using 64 nodes (each node is a 400MHz MIPS R12000 processor). The area partitioning is shown in Figure 5.

Before giving a description of the numerical results, it is worthwhile to mention that the wave–current interaction module is an expensive sub–model of POLCOMS. Normally, using the wave module increases the computation time in a factor 20 with respect to the standard POLCOMS system. For the Irish Sea, due to the reasons described above, the system must be set up in such a way that the coupled system uses 40 times more computer time than the standard POLCOMS implementation.

4.3 Results

In Figure 6, differences in daily mean significant wave height (Hs) and second moment wave period (Tm02) between the results from the coupled and uncoupled systems are shown. The results correspond to 10/02/1997, when the strongest winds (about $15m/s$) from the ERA40 reanalysis wind data set are observed (see Figure 4). This period also corresponds to a spring tidal period. The corresponding daily mean values for Hs and Tm02 computed by the uncoupled version of ProWAM are shown in Figure 7. Larger absolute differences in Hs are computed around headlands and shoals, with values in the order of $0.3 - 0.5m$. These differences are between 5 and 10% of the maximum daily mean wave height (observed in the Celtic Sea area) but represent, in some places, more than 10% of the local value.

The oscillations of Tm02 induced by currents through Doppler shifting is typically a local effect. The daily mean differences observed in Figure 6 are relatively small (between 2 and 5% of the maximum computed by the uncoupled version), but instantaneous values can reach up to 20% at some locations.

The daily mean wave shear velocity and apparent roughness length computed by the formulation of Madsen (1994) on 10/02/1997 are presented in Figure 8. It is possible to observe that, during this period, large wave shear velocities are almost constrained to the eastern coast of the Irish Sea. In the Liverpool Bay area the values reach over $3cm/s$ in places where the water depth is less than $20m$. Large values are also observed in the exposed side of the Cardigan Bay and the Bristol Channel. Below the $40m$ contour, the wave induced shear velocities are under $0.5cm/s$. The daily mean apparent roughness length computed during this period reach values up to $3cm$, one order of magnitude larger than the constant values used by POLCOMS (as mentioned above, this value is set as $3mm$ in POLCOMS). According to Madsen's theory, apparent roughness length values larger than $3mm$ are found in regions shallower than $60m$. Large values of apparent roughness length are also observed on the eastern coast of Ireland, possibly associated to the arrival of small amplitude, refracted swell from the Celtic Sea.

A deeper insight into the effect of using a wave dependent roughness length, as well as the wave induced shear velocity, on the computation of the total shear stress can be attained by the computation of the wave shear stress and the bottom friction coefficient from the values shown in Figure 9. The wave shear stress and bottom friction coefficient are computed as (15) and $C_b = [\kappa/\ln(z_r/z_{0a})]^2$, respectively. In the definition of C_b, z_r is taken to be the midpoint between the bottom and the top of the bottom sigma layer. Results show the same pattern observed in Figure 8, but the values are restricted to shallower areas (less than $20m$ depth). Daily mean wave shear stress values of about $1.0m^2s^{-2}$ are computed in some shallow places (less than $20m$ depth) in the Liverpool Bay, Cardigan Bay, Bristol Channel and southern Ireland. Values of the bottom friction coefficient between 0.003 and 0.007 are computed in places with less than $40m$ depth. In the standard version of POLCOMS, the value of the bottom friction coefficient is forced to be larger or equal than 0.005, the average of the values computed by the coupled system in coastal areas, between $10m$ and $40m$ depth. It is worthwhile to mention that, for the present application, the restriction $C_b \geq 0.005$ is also used in the coupled system.

The effect of wave induced sea surface stress and wave–current interaction in the bottom stress on the daily mean current is shown in the Figure 10. It is possible to observe that the pattern of the effect is homogeneous in the whole water column. Absolute values of the differences in the surface layer are about

$2 - 3cm/s$ in the southern Liverpool Bay, southern Cardigan Bay and the Caernarfon Bay. Larger values (up to $5cm/s$) are observed around headlands and shoals. A similar pattern is observed in the bottom layer, but with values of the differences reduced to about 30%. As the presence of waves tends to increase the bottom shear stress, smaller current values should be expected from the coupled system (at least in the bottom layer). However, positive values in shallow areas indicate that the magnitude of the current computed by the coupled system is larger than the values computed by POLCOMS. This result suggests that the excess in current speed is produced by the use of a wave dependent sea surface stress in the coupled system. This assumption is supported by the results shown in Figure 11, where the effect of the coupling through bottom friction only on the currents is evaluated. As expected, the daily mean differences in coastal areas are mostly negative and, in the bottom layer, the effect shows the same pattern as the field of τ_w presented in Figure 9. The magnitude of the (daily mean) effect of wave enhanced bottom friction on currents is almost two order of magnitudes less than the effect of using a sea–state (or wave) dependent surface stress.

The temporal evolution of the wave–current interaction effect on the waves and currents is evaluated at several stations in the Irish Sea. Results at two coastal station in Liverpool Bay ($10.2m$ and $29.5m$) and one in the St. George's Channel ($97.9m$) are presented. The results at the shallowest station, in southern Liverpool Bay, are shown in Figure 12. There, the effect of currents on waves is clearly observed as semi–diurnal modulations of Hs. Those modulations are in phase with the sea surface elevation, which would explain the Hs oscillations in terms of wave dissipation by bottom friction (note that the tidal range is between $5m$ and $8m$). The magnitude of the sea surface stress computed by the coupled system is about 35% larger during the stronger wind event (around the 10/02/1997). This also produces an excess in the sea surface elevation computed by the coupled system of about $20cm$ at some instances during the same period. At this position, the magnitude of the combined bottom shear stress computed by the coupled system tends to be larger (about two times during stormy periods) than the values computed by POLCOMS.

The second station in the Liverpool Bay ($29.5m$) is located a few kilometres to the northwest of the shallowest station. Results corresponding to this station are shown in Figure 13. Even when the tidal range is similar to the one observed in the shallowest station, modulations in Hs are clearly smaller. The effect of using a wave dependent surface stress on the sea surface elevation is very similar to the previous example (maximum excess of surface elevation of about $15cm$). Here, the computed bottom shear stress is even larger than in the shallowest station due to the presence of stronger bottom currents. During the stormy period, the combined bottom shear stress is slightly larger than the one computed by the uncoupled version of POLCOMS.

At the St. George's Channel station (Figure 14), the effect of coupling becomes independent of the depth. The time series computed by the coupled version of ProWAM shows semi-diurnal modulations, probably associated to the modulation on the wave propagation induced by currents. Those oscillations are between 5 and 10% of the maximum value computed by the uncoupled ProWAM around the spring tidal period. At this station, the wave dependent surface stress show modulations of the order of 25% with respect to the maximum value computed by the standard formulation in the uncoupled POLCOMS. As expected, no effect on the computation of the sea surface elevation is observed. Here, the effect of waves on the computation of bottom shear stress is negligible. Large values (about three times larger than the combined values computed in the Liverpool Bay area) are computed because the use of a constant C_b ($= 0.005$) and the presence of bottom currents in the order of $1m/s$.

5 Conclusions

We present a description of the wave–current interaction procedure implemented in the Proudman Oceanographic Laboratory Coastal–Ocean Modelling System (POLCOMS). The wave component is provided by the third–generation spectral model WAM *Cycle_4*, modified to run in coastal areas. The performance of the system is assessed in the Irish Sea region using a high spatial resolution (about $1.85km$). The period of analysis is characterized by the presence of west–southwesterly winds, with magnitudes not larger than $15m/s$, and corresponds to a spring tidal cycle.

The results indicate that the effect of currents on wave parameters (observed as semi–diurnal modulations) is uniformly distributed in the whole area, with typical values of the order of 5% for wave height and 20% for mean period. The maximum effect is observed in places where the magnitude and shear of the currents are larger (i.e., headlands and shoals) where currents increase the wave height by more than 10% of the values computed by the uncoupled wave model. The effect of waves on currents is also evident around headlands and shoals, with daily mean current differences larger than $5.0cm/s$. Differences in the daily mean current speed of the order of $3.0cm/s$

are observed on the eastern coastal areas during strong wave events. Most of the differences are explained by the use of a wave dependent sea surface stress.

The wave–current interaction module in POLCOMS is still a sub–model in development. At the moment, the most important task is to improve the performance of the system in terms of computation time. The optimization of the numerical code is now well underway.

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Table 1: Setup of the coupled system for the present implementation.

POLCOMS	ProWAM
$\Delta t_{barot} = 6sec$	$\Delta t_{prop} = 30sec$
$\Delta t_{baroc} = 60sec$	$\Delta tS = 30sec$
No. levels = 6	No. freq. = 25
	No. dir. = 12

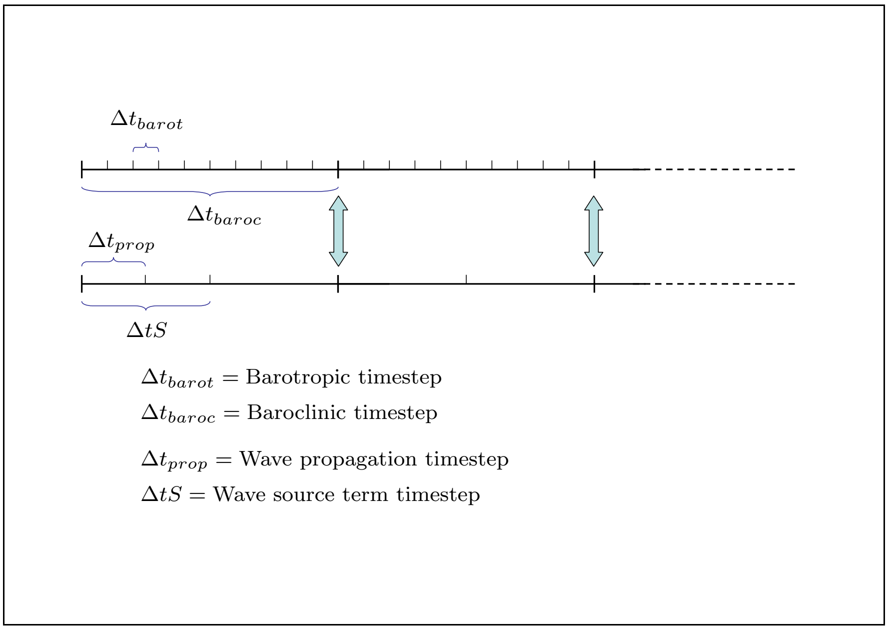

Figure 1: Time stepping in the wave–current interaction module.

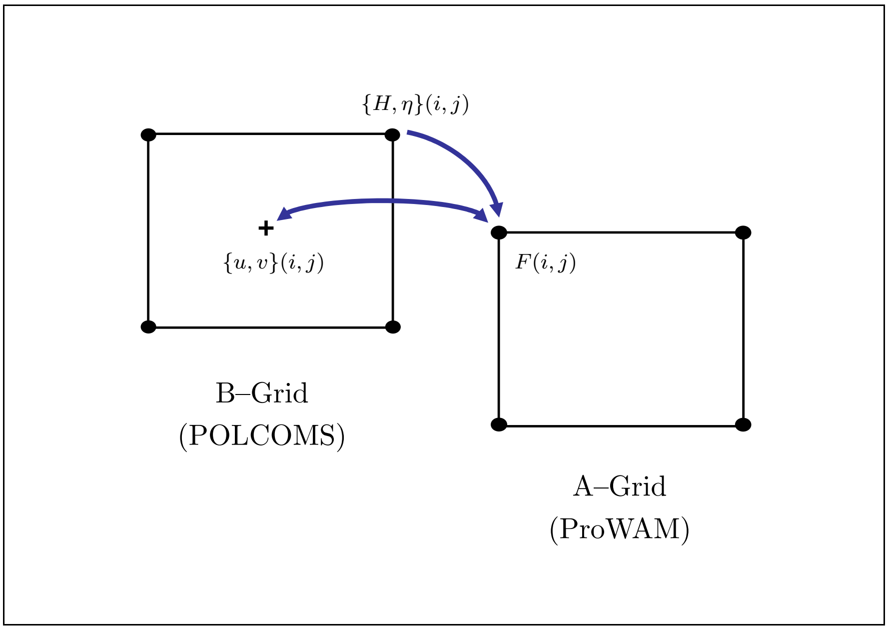

Figure 2: Matching point where the information transfer between the two model grids is carried out.

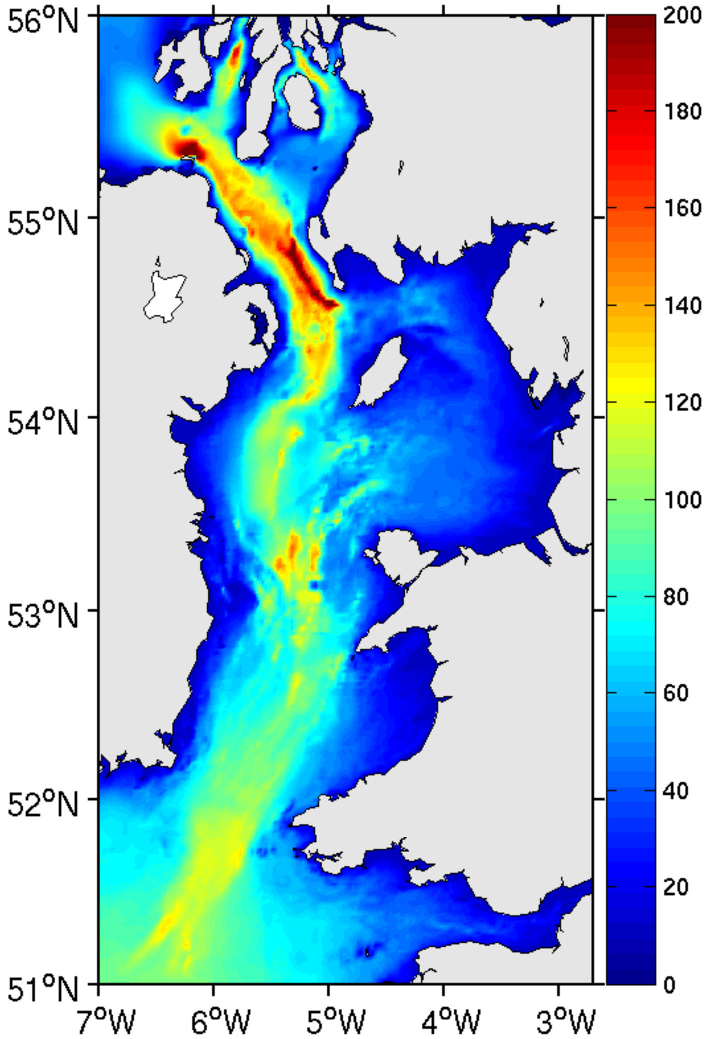

Figure 3: Bathymetry (in metres) of the Irish Sea region.

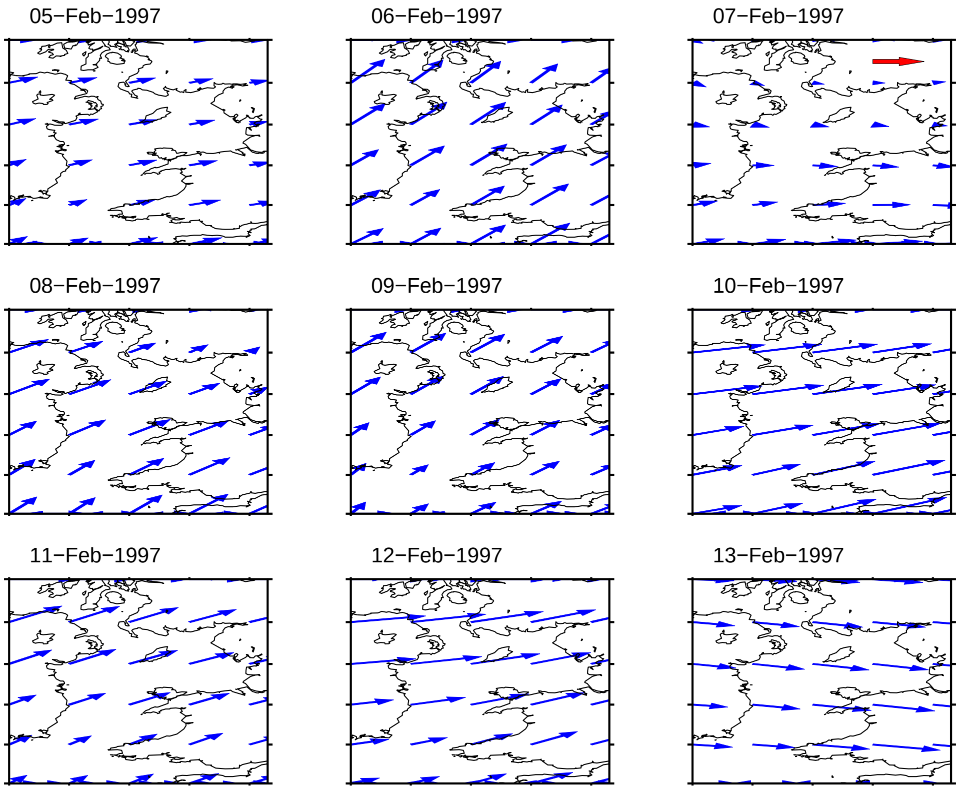

Figure 4: Daily mean winds in the Irish Sea region during part of the analysis period (from 05/02/97 to 13/02/97). The red arrow in the top–right panel indicates $10m/s$.

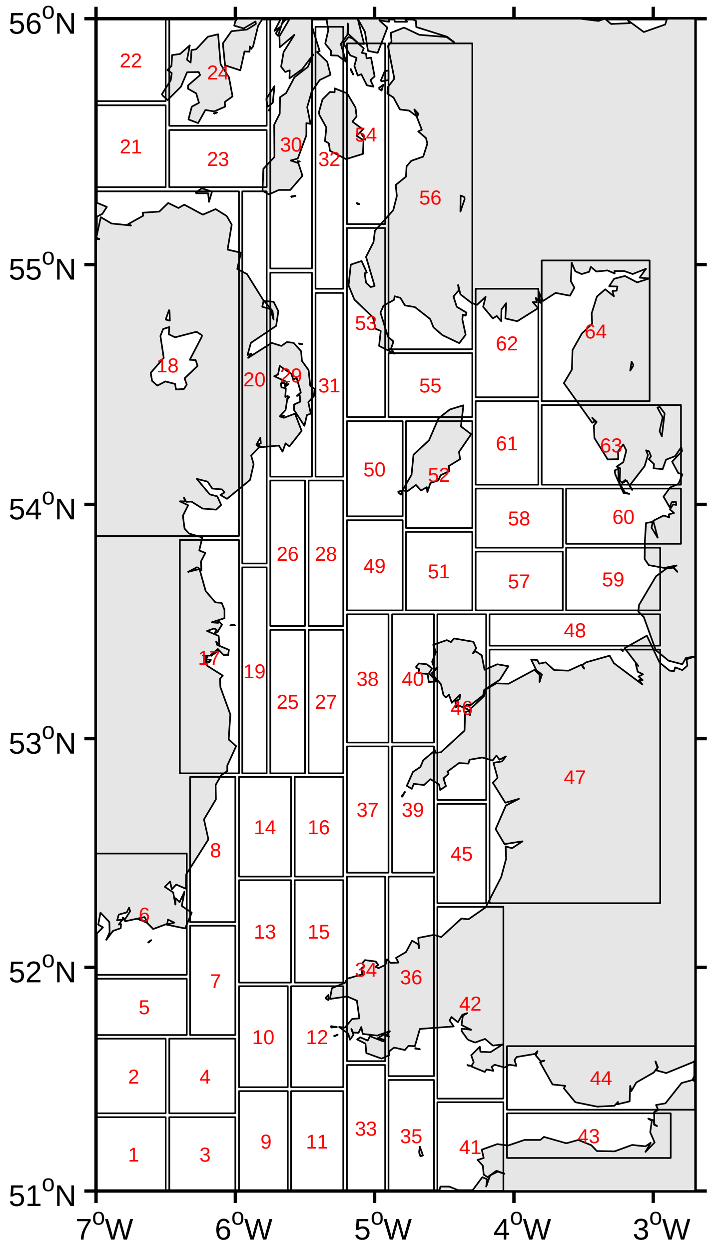

Figure 5: Partition of the Irish Sea domain on 64 processors.

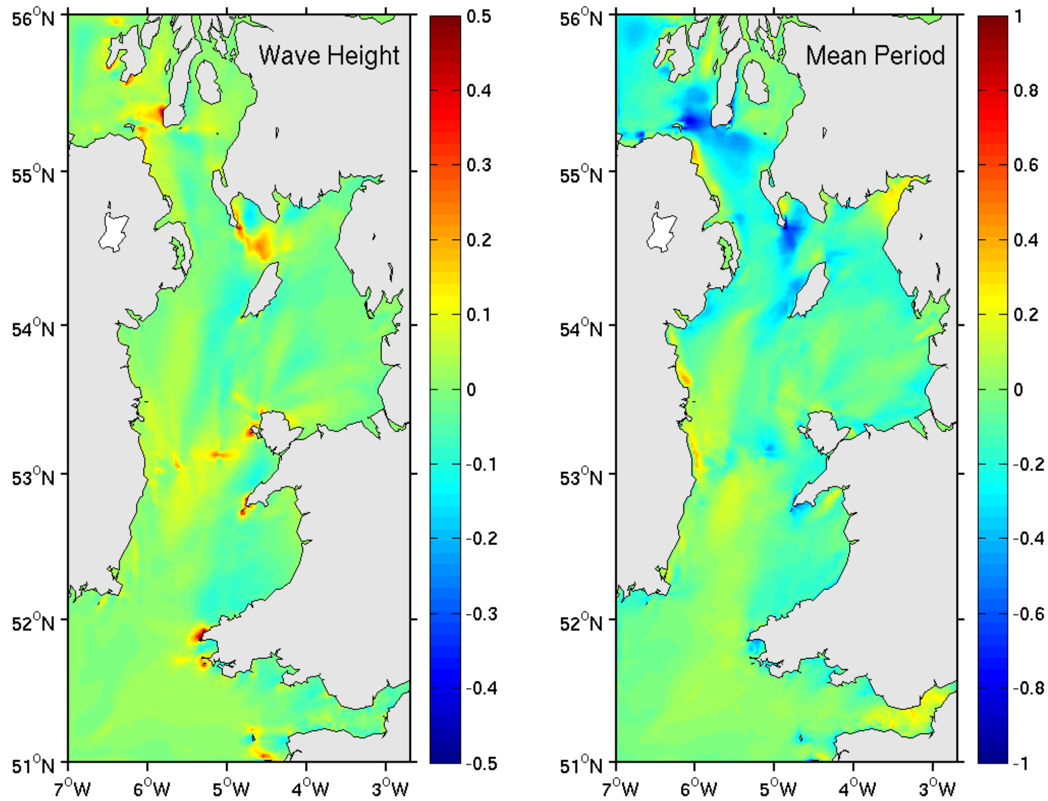

Figure 6: Daily mean differences (coupled minus uncoupled) of Hs (in m) and Tm02 (in seconds) corresponding to the 10/02/1997.

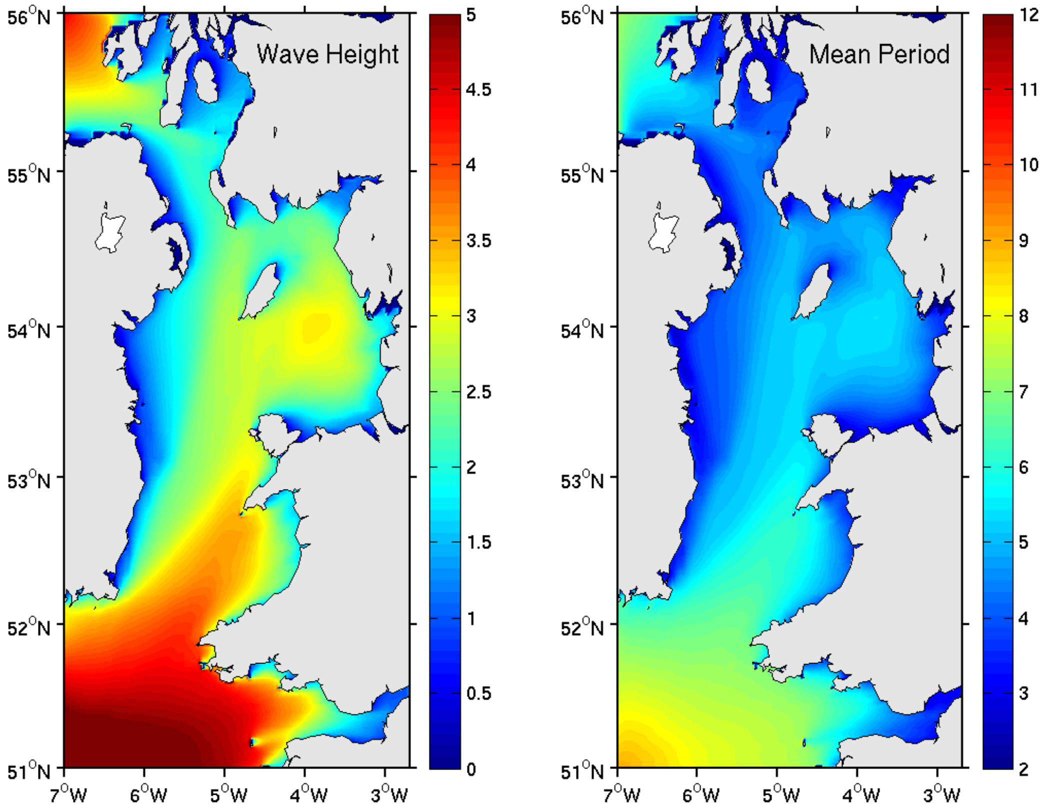

Figure 7: Daily mean values of Hs (in m) and Tm02 (in seconds). Fields corresponding to the same date as in Figure 6.

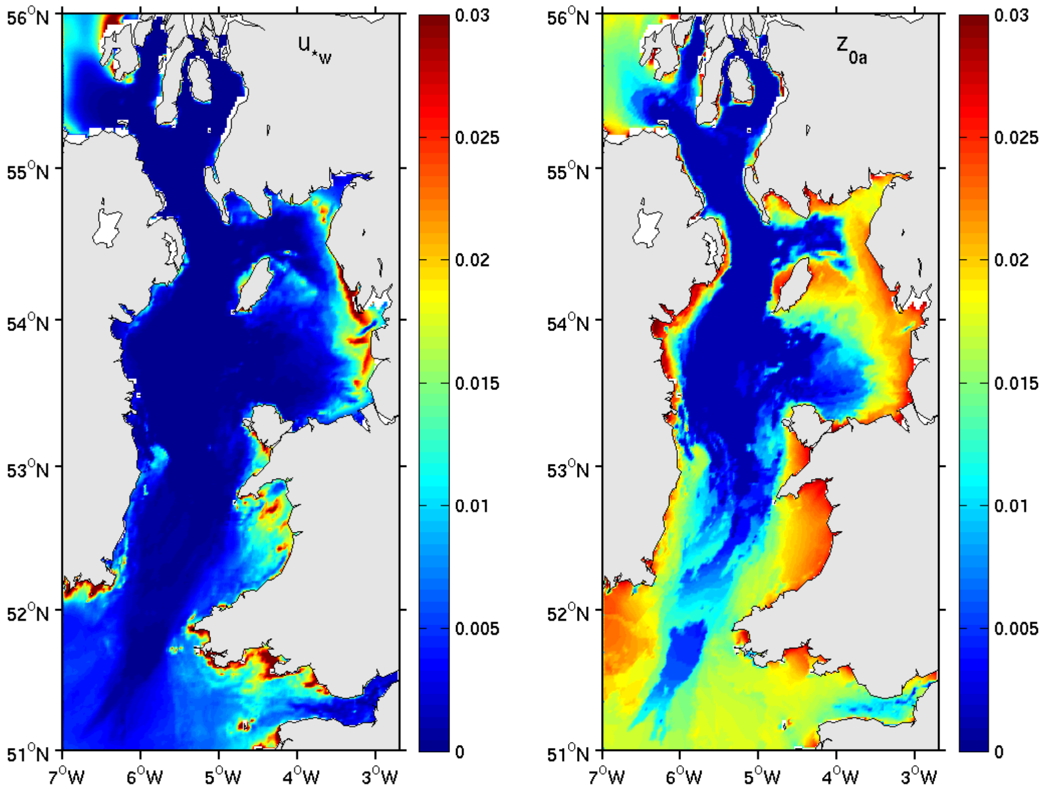

Figure 8: Daily mean values of wave shear velocity (in m/s) and apparent roughness length (in m) computed according to the theory of Madsen (1994). Fields corresponding to the same date as in Figure 6.

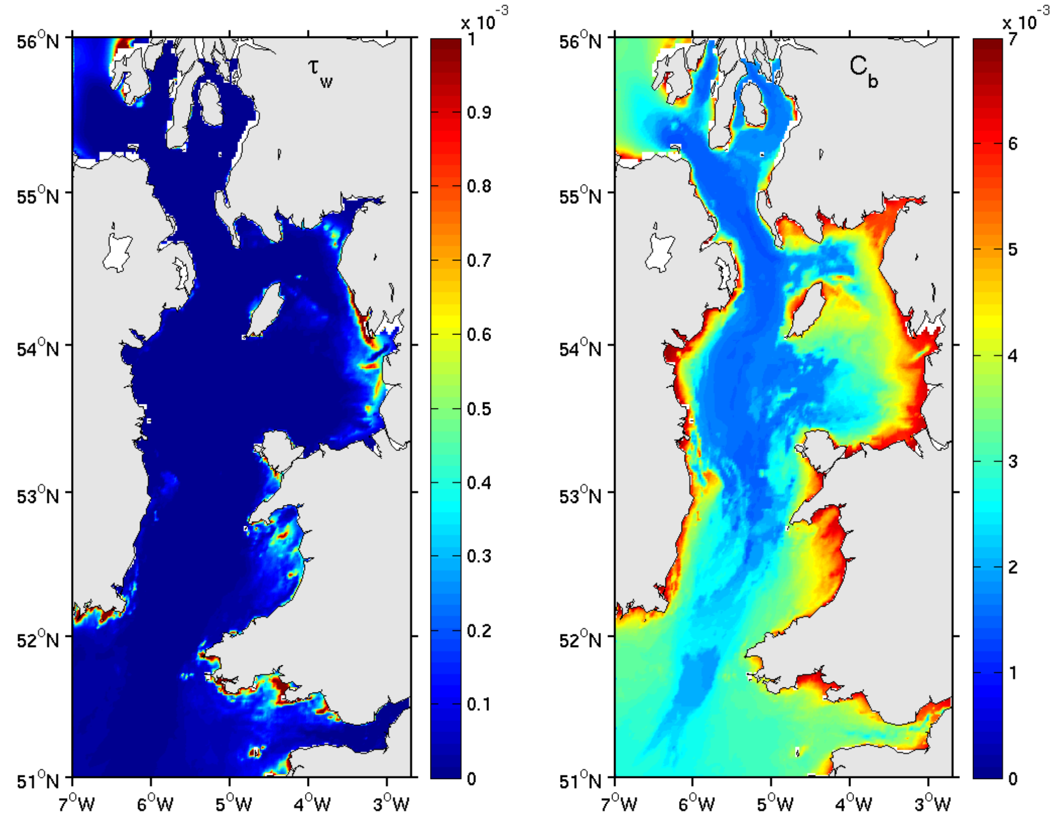

Figure 9: Wave induced bottom shear stress (in m^2/s^2) (left panel) and bottom friction coefficient, C_b, (right panel) computed from the values in Figure 8

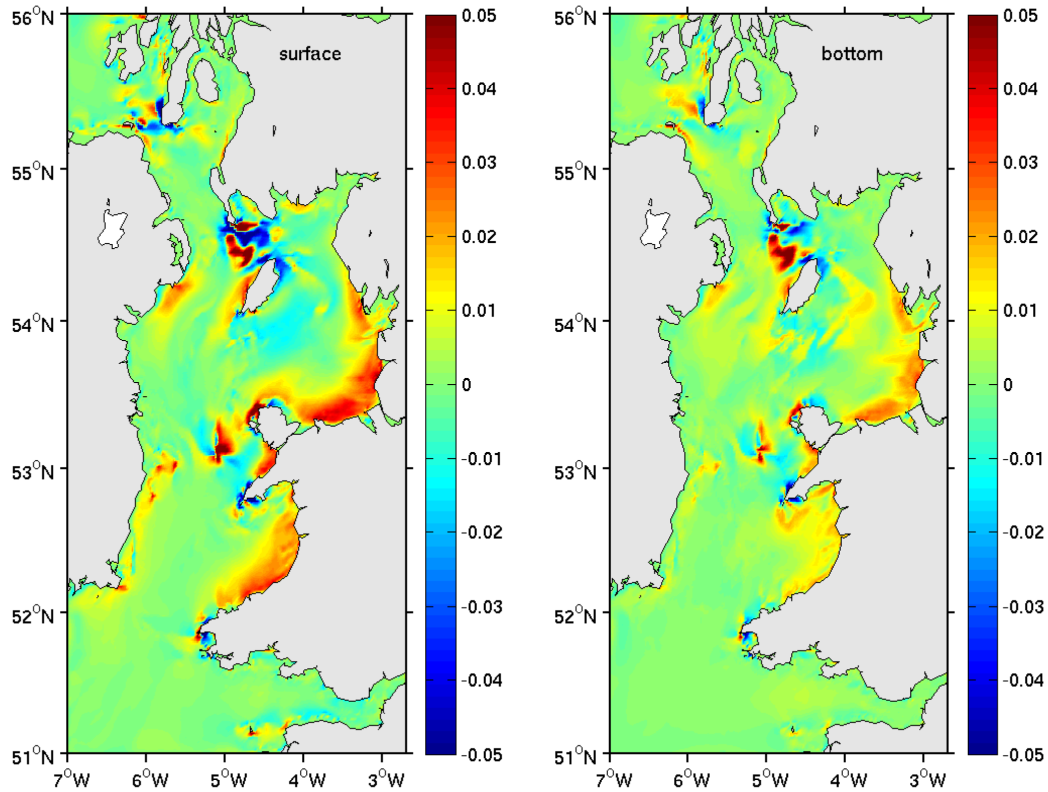

Figure 10: Daily mean differences (coupled minus uncoupled) of currents at the surface (left panel) and the bottom (rigth panel). The values are computed by the fully coupled version and are reported in (m/s). Values corresponding to the 10/02/1997.

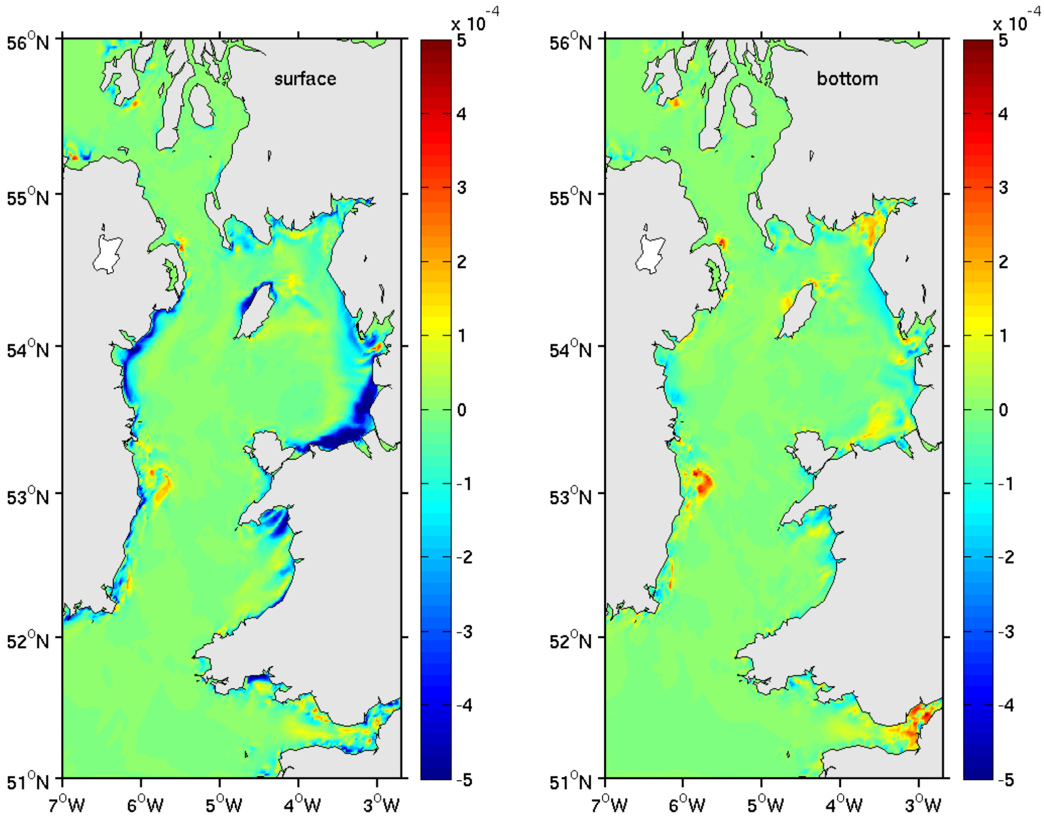

Figure 11: Same as in Figure 10 but for the two–way coupling through bottom friction only.

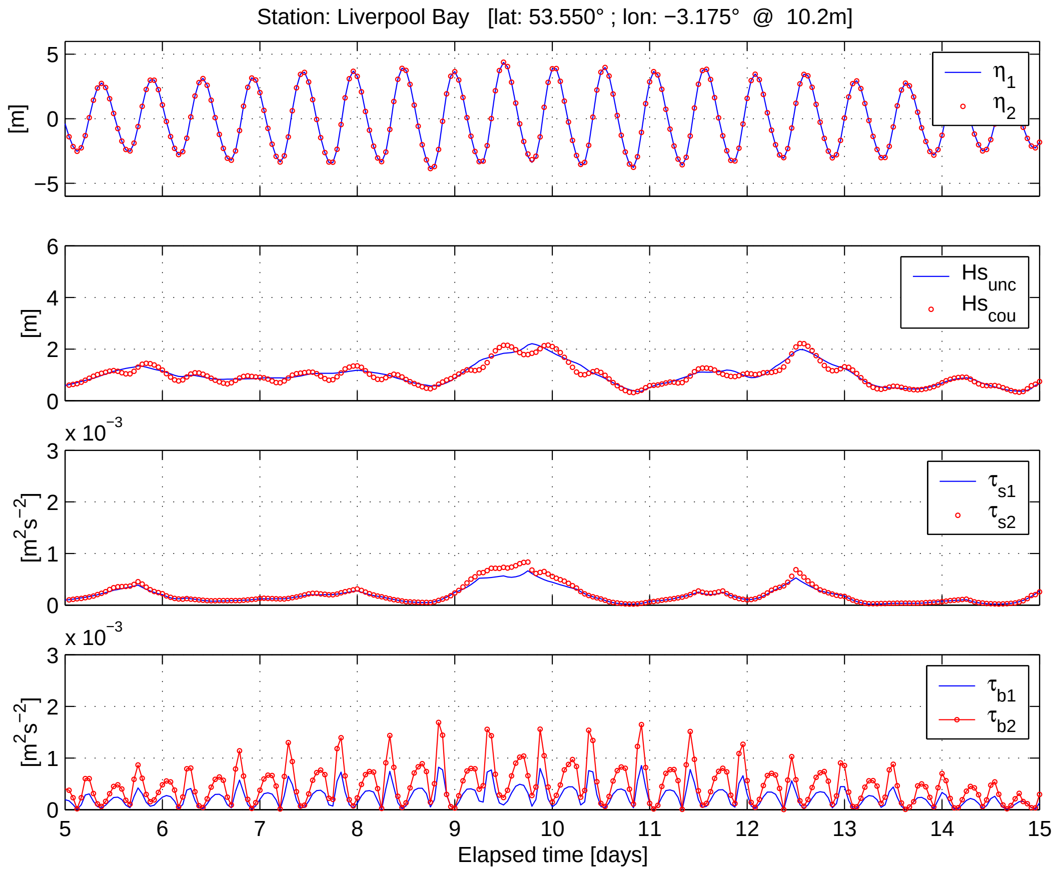

Figure 12: Time series of surface elevation (top panel), significant wave height (second panel from the top), magnitude of the sea surface stress (third panel from the top), and magnitude of the bottom shear stress (bottom panel) corresponding to a station in the Liverpool Bay area.

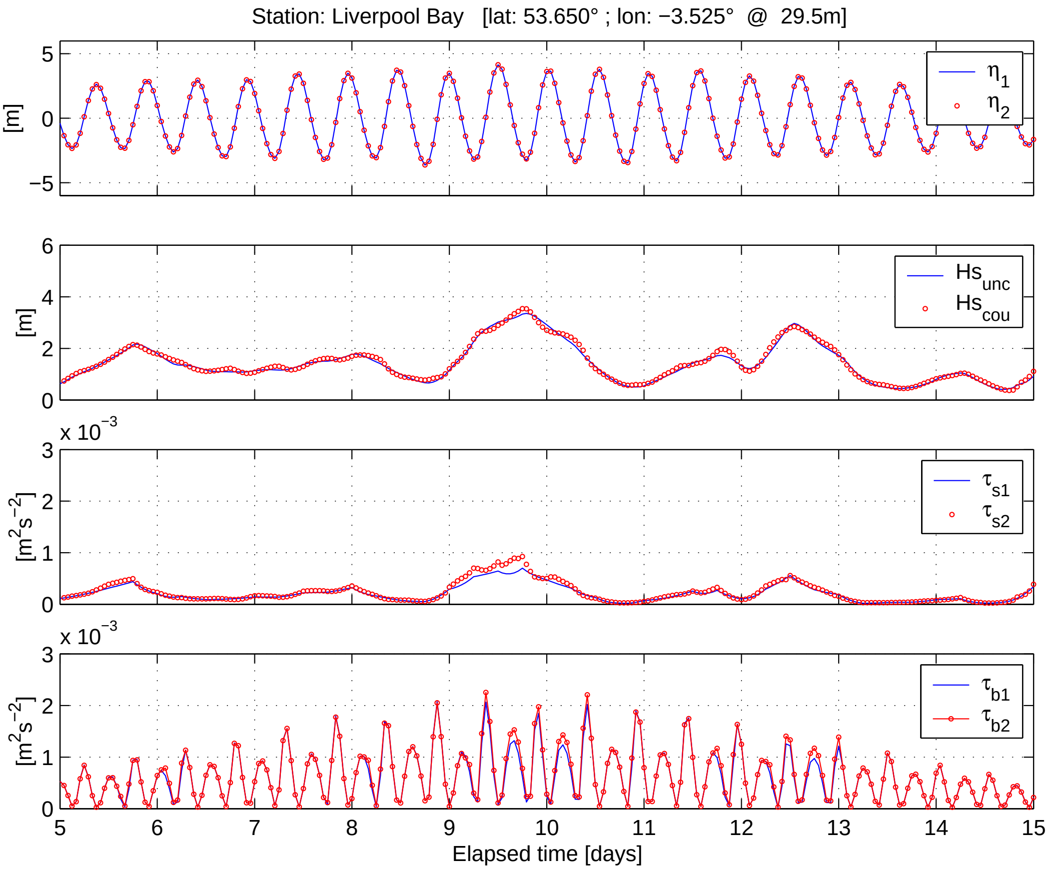

Figure 13: Same as in Figure 12 but for the deepest station in the Liverpool Bay area.

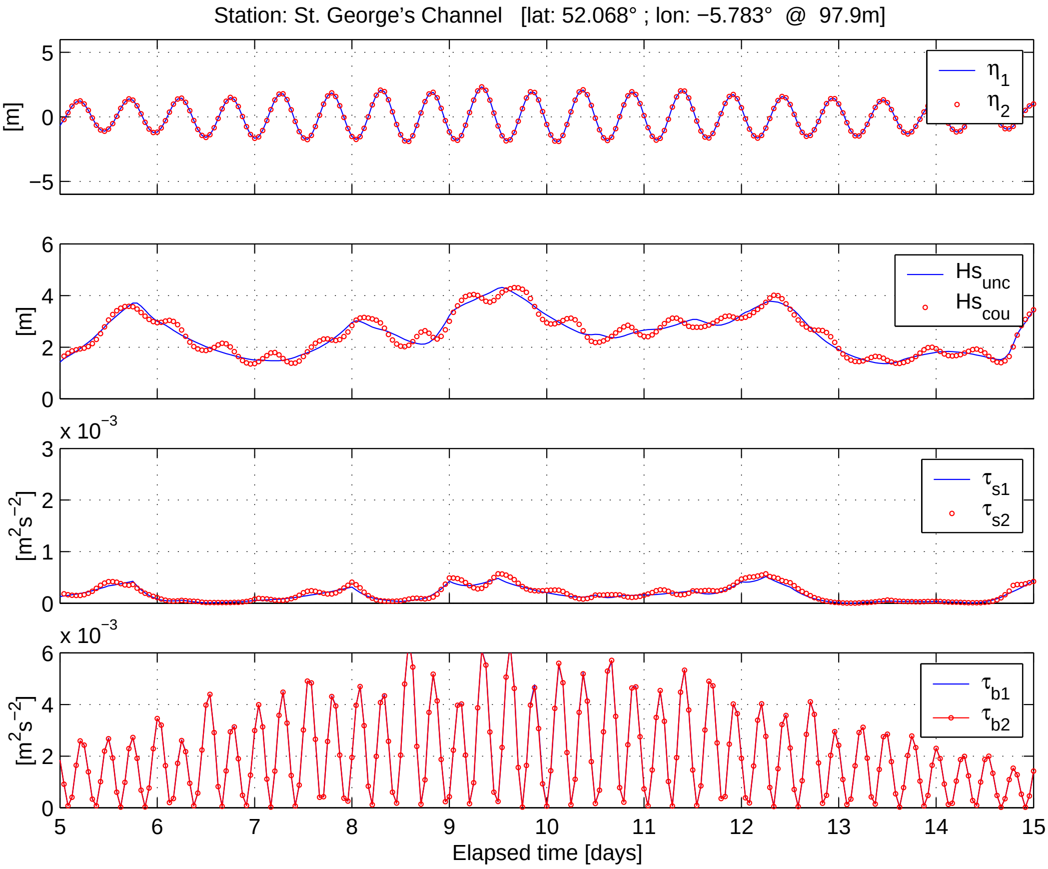

Figure 14: Same as in Figure 12 but for a station in the St. George's Channel area.