A NUMERICAL STUDY ON THE EFFECT OF WAVE–CURRENT INTERACTION PROCESS IN THE HYDRODYNAMICS OF THE IRISH SEA

P. Osuna[1] and J. Wolf[2]

Abstract: The effect of the wave–current interaction process is evaluated in the Irish Sea region using a parallel coupled system based on the baroclinic three–dimensional Proudman Oceanographic Laboratory Coastal–Ocean Modellling System (POLCOMS) and the third–generation spectral wave model WAM. 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.

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

[1]Proudman Oceanographic Laboratory, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK. poc@pol.ac.uk

[2]Proudman Oceanographic Laboratory, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK. jaw@pol.ac.uk

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 was includes as a module of the POLCOMS system. The wave module uses the model ProWAM (Monbaliu et al., 2000), a modified version of the third–generation spectral wave model WAM *Cycle_4* (Komen et al., 1994). 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. The performance of WAM as a module to synchronously exchange wave information with two–dimensional tide/surge models has been assessed by Zhang and Li (1996) and Osuna and Monbaliu (2004). The three–dimensional structure of the current field on the wave–current interaction process has been accounted by Davies and Lawrence (1995) and Xie et al. (2003). A common conclusion in all these studies is that the wave–current interaction is an important process for the hydrodynamics in coastal areas.

The main objective of this study is to quantify the effect of the interaction in the Irish Sea region under realistic atmospheric conditions. In order to deal with the strong spatial and temporal variability of the hydrodynamic fields induced by the complex bathymetry and coastline, a high spatial resolution (about 1.85km) is used.

COUPLING 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.

Data from POLCOMS to ProWAM

The propagation of wave energy and refraction is affected by the level of inhomogeneity and unsteadiness of the current field. In order to account for the effect of currents on waves, barotropic and bottom layer (u, v) components and total depth (h) used by ProWAM, 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. 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 the (u, v, h) field, used for the wave energy refraction in spectral space, are evaluated internally by the wave model using central differences. Temporal changes of the total depth $(\partial h/\partial t)$ are not included in the present implementation.

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

$$U^x_{10} = W^x_{10} - u \tag{1}$$
$$U^y_{10} = W^y_{10} - v \tag{2}$$

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

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).

Data from ProWAM to POLCOMS

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

$$\tau_s^x = C_s \rho_a W_{10}^x |W_{10}| \tag{3}$$
$$\tau_s^y = C_s \rho_a W_{10}^y |W_{10}| \tag{4}$$

where ρ_a is the air density, and

$$C_s = (0.63 + 0.066|W_{10}|) \times 10^{-3} \tag{5}$$

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.

In the coupled system, if the appropriate option is activated, C_s is computed as,

$$C_s = \left[\frac{\kappa}{\ln(10/z_0)}\right]^2, \tag{6}$$

where the roughness length, z_0, dependent on the wave field development according to the formulation of Janssen (1991),

$$z_0 = \frac{0.01\tau}{g\sqrt{1 - (\hat{\tau}_w/\tau)}}. \tag{7}$$

In (7), $\tau = \rho_a u_*^2$ is the surface stress, u_* is the friction velocity, and τ_w is the wave induced stress. τ_w is computed by integrating the wave input source term, S_{in},

$$\boldsymbol{\hat{\tau}_w} = \rho_w \int_0^\infty \int_0^{2\pi} c^{-1} \mathrm{S}_{\mathrm{in}}(\omega, \theta) d\omega d\theta, \tag{8}$$

where c is the phase celerity of the waves and ρ_w is the water density. Detailed about Janssen's theory can be found in Janssen (2004), while its implementation in WAM is described in Mastenbroek et al. (1993).

The effect of the wave–current interaction at the bottom is taken into account using a similar approach as the one described in Souza et al. (2001). The current induced bed shear stress is computed as,

$$\tau_c = \frac{1}{2} \rho_w f_c \mathrm{u_b}^2, \tag{9}$$

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

$$f_c = \left[\frac{\kappa}{\ln(30 z_r/k_{bc})}\right]^2. \tag{10}$$

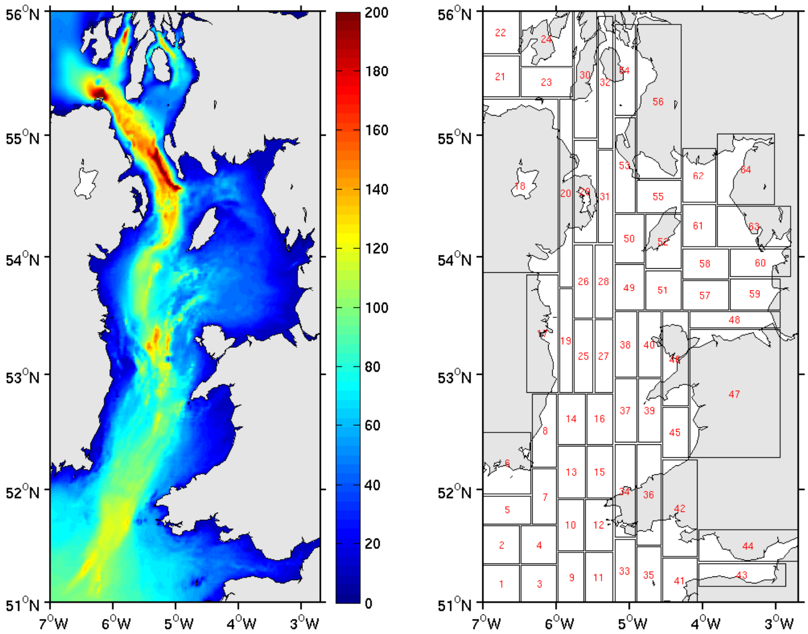

Fig. 1: Bathymetry (in metres) of the Irish Sea region and domain decomposition for the parallel solution.

In (10), 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 (10) is reduced to the expression implemented in POLCOMS (see Holt and James, 2001). Conversely, when the effect of waves on the bottom is important (and the corresponding option is activated in the model), an apparent roughness length, z_{0a}, is used for the definition of k_{bc} in (10). In the coupled system, z_{0a} is computed using the formulation of Madsen (1994) for the solution of a combined wave–current bottom boundary layer flow.

PRELIMINARY ASSESSMENT: 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 1. 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.

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 $1.0^o \times 1.0^o$ 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 during the fine grid application.

In both coarse resolution applications, six–hourly, $1.0^o \times 1.0^o$ resolution, European Centre for Medium-Range Weather Forecasting (ECMWF) ERA40 Reanalysis surface wind and pressure were used. For the Irish Sea application, hourly winds with a longitude–latitude resolution of $1/60^o \times 1/60^o$, respectively, from the United Kingdom Meteorological Office (MetOffice), were used. Surface pressure from ECMWF ERA40 Reanalysis was also used in this implementation. The analysis covers the period from 26/01/2003 to 06/02/2003, when two northwesterly wind events were observed. In both cases, the MetOffice dataset reported wind magnitudes between 15 and $20 m/s$.

Models setup

In order to account for the relatively high space–time variability of currents, the spectral resolution of ProWAM was increased, with respect to the standard 30–degree resolution. Some details about the setup of POLCOMS and ProWAM are given in Table 1. 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 Linux Cluster using 64 nodes (each node has a two Intel 2.4GHz Xeon processor, with 2GB of memory per node). The coupled system is coded in Fortran 90, and the parallel communication is handled using MPI (Message Passing Interface) standard. The domain decomposition used in the present configuration is shown in Figure 1.

Table 1: Models setup for the present implementation.

POLCOMS			ProWAM		
Δt_{barot}	:	$8 sec$	Δt_{prop}	:	$60 sec$
Δt_{baroc}	:	$240 sec$	$\Delta t S$	:	$120 sec$
No. levels	:	34	No. freq.	:	25
			No. dir.	:	24

Results

In Figure 2, the effect of the wave–current interaction on significant wave height, Hs (panel a), and second moment wave period,Tm02 (panel d), at 03:00GMT of the 03/02/2003, are presented. Currents and the elevation field (panel c and f, respectively) during this period correspond to a spring tidal period. The Hs and Tm02 values computed by the uncoupled version of ProWAM are shown in panels b and d, respectively. It is possible to observe regions of large positive differences (coupled-uncoupled) of Hs (about 15% with respect to the values computed by a stand alone implementation of ProWAM), associated to waves and currents travelling in opposite direction between the Isle of Man and Anglesey, and the Isle of Man and the headlands on the Scotish

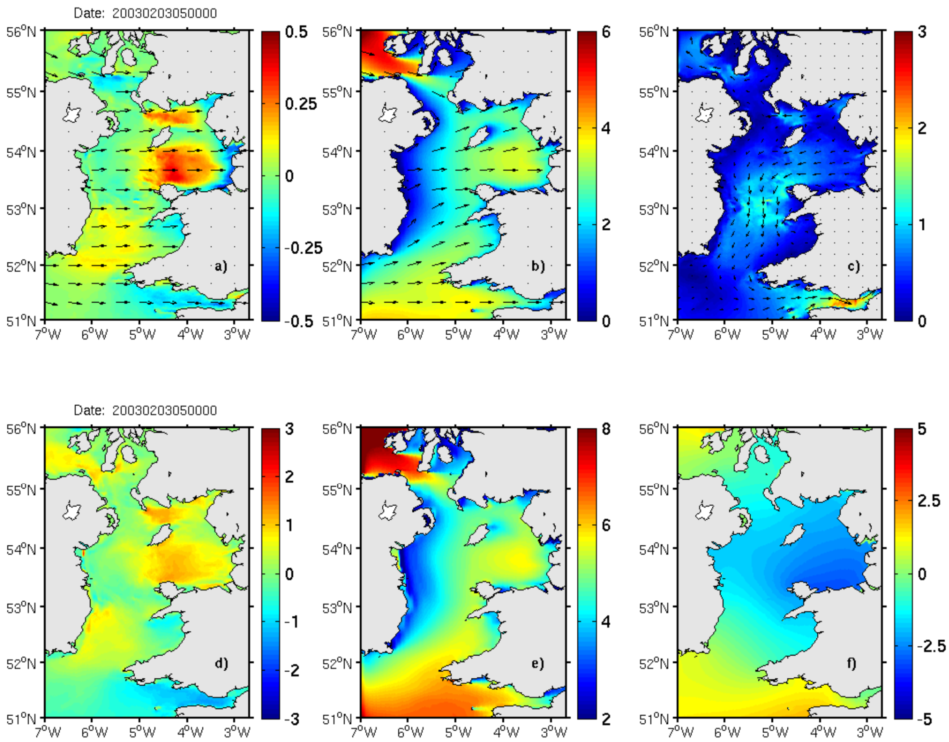

Fig. 2: Effect of wave–current interaction on waves; a) differences in Hs (m) and wind direction, b) Hs and wave direction computed by uncoupled ProWAM, c) current magnitude (m/s) and direction, d) differences in Tm02 (s), e) Tm02 computed by uncoupled ProWAM, and f) sea surface elevation (m).

coast. Negative differences associated to the same pattern are observed in the Bristol Channel. At this specific time, negative differences of Hs are also observed in the Eastern coast of the Liverpool Bay. In this case the differences are in phase with the tidal elevation and are associated to a stronger wave energy dissipation by bottom friction. The oscillations of Tm02 are induced by the local currents through Doppler shifting, so the spatial distribution of the differences resemble those computed for Hs in places where bottom friction is not important. The magnitude of the Tm02 differences are of the order of 20% of the values computed by the stand alone implementation of ProWAM.

The daily mean apparent roughness length, z_{0a}, computed by the formulation of Madsen (1994) on February 03 is presented in Figure 3a. It is possible to observe that, during this period, z_{0a} reach values up to $3cm$, one order of magnitude larger than the constant values of $3mm$ defined in the standard version of POLCOMS. Values larger than $3mm$ are found in regions shallower than $60m$. In the coupled system, the bottom friction coefficient is computed as $C_b = [\kappa/\ln(z_r/z_{0a})]^2$, using the values of z_{0a} transferred from ProWAM (Figure 3b). As shown in Figure 3c, where C_b is computed using $z_{0a} = z_{0a} = 0.003m$, considering a wave dependent roughness length has an important effect on the computation of the drag coefficient in coastal areas.

The effect of wave induced sea surface stress and wave–current interaction in the

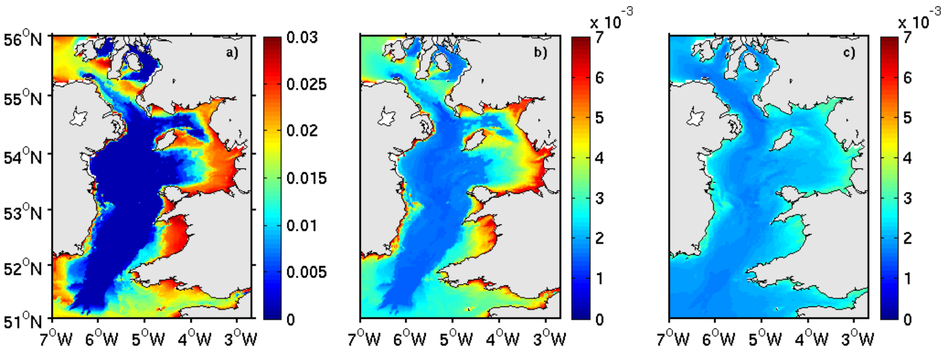

Fig. 3: Daily mean values of; a) apparent roughness, z_{0a}, in meters, b) bottom friction coefficient, C_d, computed by the coupled system, and c) bottom friction coefficient computed by the stand alone POLCOMS. Values corresponding to February 03, 2003.

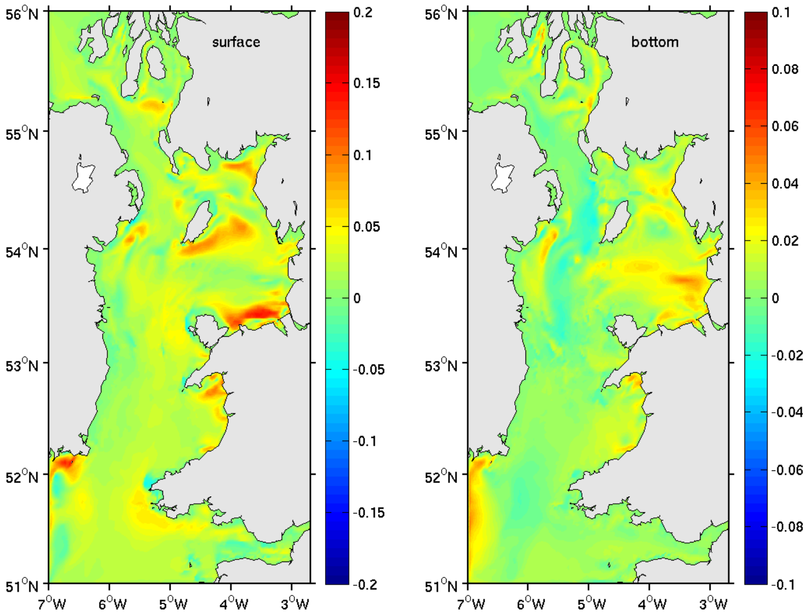

Fig. 4: Daily mean currents at the surface (left panel) and the bottom (right panel) corresponding to February 03, 2003. The values are given in m/s.

bottom stress on the daily mean current, on February 03, is shown in the Figure 4. Absolute values of the differences in the surface layer are about $1 - -2cm/s$ in the southern Liverpool Bay and the northern Cardigan Bay. Larger values are also observed in the shallow area surrounding the Isle of Man. In the bottom layer, the magnitude of the is reduced to about 30%. Positive differences in the bottom layer indicate that the excess in current speed is produced mainly by the use of a wave dependent sea surface stress in the coupled system.

The system is evaluated using observations from a waverider buoy and Doppler instruments (ADCP and ADV) deployed in the Liverpool Bay area. The Doppler instruments were located on the sea bed, at about $22m$ depth. Comparison of observed wave parameters and those computed by the models are shown in Figure 5. The effect of currents on waves is observed as semi–diurnal modulations of Hs. Those modulations

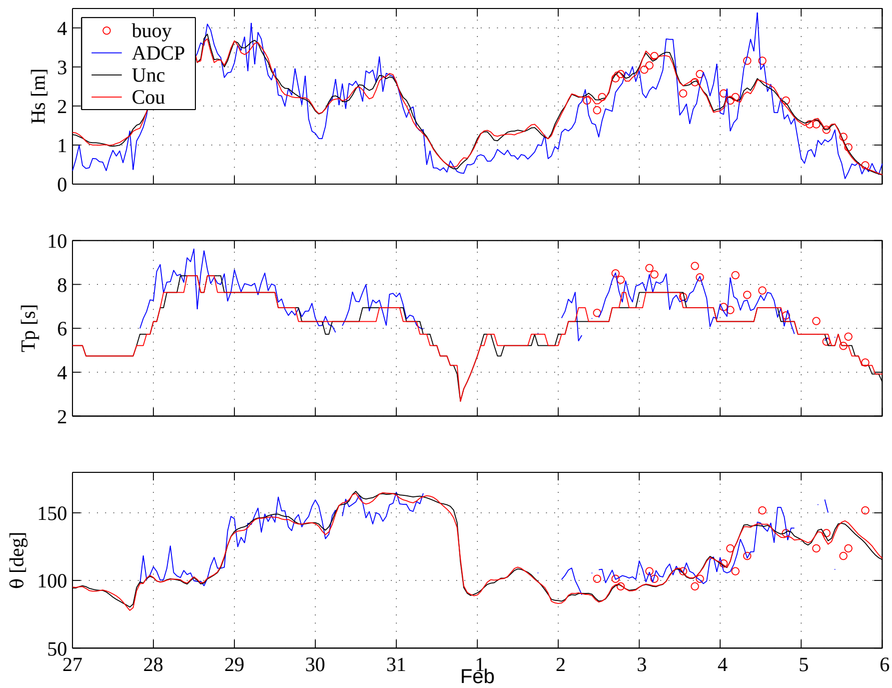

Fig. 5: Significant wave height (Hs), peak period (Tp), and wave direction (θ) computed from observations and models in the Liverpool Bay area. In the legend, (Unc) represent values computed by the stand alone ProWAM, and (Cou) represent values computed by the coupled system.

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 during the analysis period 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.

CONCLUSION

In this work, the process of wave–current interaction in the Irish Sea region is studied using an efficient parallel numerical system that includes the three–dimension POLCOMS model and the spectral wave model WAM. The results indicate that the effect of currents on wave parameters is uniformly distributed in the whole area, with typical values of the order of 10% for wave height and 20% for mean period. The largest 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 west-southwesterly wave events.

Most of the differences are explained by the use of a wave dependent sea surface stress.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Dr. Mike Ashworth (CCLRC Daresbury, Warrington) and Dr. Kevin Roy (HPC–CSAR, University of Manchester) for developing the parallel code used in this work. The buoy data were kindly provided by the Centre for Environment Fisheries and Aquaculture Science (CEFAS). We would like to thank Dr. Alex Souza for providing the ADCP and ADV observations in Liverpool Bay, and for his comments on the material in this work. This study was partially supported by MetOffice (?).

REFERENCES

Arakawa, A., 1972. Design of the UCLA general circulation model. Tech. Rep. 7, University of California, Los Angeles, USA.

Ashworth, M., Holt, J.T., and Proctor, R., 2004: Optimization of the POLCOMS hydrodynamic code for terascale high–performance computers. Proceedings of the 18th International Parallel & Distributed Processing Symposium, 26th–30th April 2004, Santa Fe, New Mexico.

Davies, A.M., and J. Lawrence, 1995. Modeling the effect of wave-current interaction on the three dimensional wind driven circulation of the eastern Irish Sea. J. Phys. Oceanogr., 25, 29–45.

Holt, J.T., and James, D.J., 2001. An *s* coordinate density evolving model of the northwest European continental shelf: 1, Model description and density structure. J. Geophys. Res., 106, 14,015–14,034.

Janssen, P.A.E.M., 1991. Quasi–linear theory of wind–wave generation applied to wave forecastin. J. Phys. Oceanogr., 19, 745–754.

Janssen, P., 2004. The interaction of ocean waves and wind. Cambridge University Press, Cambridge, 300 pp.

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, S., Hasselman, K., and Janssen, P.A.E.M., 1994. Dynamics and modelling of ocean waves. Cambridge University Press, Cambridge, 532 pp.

Madsen, O.S., 1994. Spectral wave–current bottom boundary layer flows. Proc. 24th ICCE. ASCE, 1:384–398.

Mastenbroek, C., Burgers, G., and Janssen, P.A.E.M., 1993. The dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer. J. Phys. Oceanogr., 23, 1856–1866.

Monbaliu, J., Padilla-Hernández, R., Hargreaves, J.C., Carretero-Albiach, J.C., Luo, W., Sclavo, M., and Günther, H., 2000. The spectral wave model WAM adapted for applications with high spatial resolution. Coastal Eng., 41, 41–62.

Osuna, P., and Monbaliu, J., 2004. Wave–current interaction in the Southern North Sea. J. Marine Sys., 52, 65–87.

Smith, S.D., and Banke, E.G., 1975. Variation of the sea surface drag coefficient with wind speed. Quart. J. Roy. Meteor. Soc., 101, 665–673.

Souza, A.J., Dickey, T.D., and Chang, G.C., 2001. Modeling water column structure and suspended particulate matter on the Middle Atlantic continental shelf during the passages of Hurricanes Edouard and Hortense. J. Marine Res., 59, 1021–1045.

Xie, L., Pietrafesa, L.J., and K. Wu, 2003. A numerical study of wave-current interaction through surface and bottom stresses: Coastal ocean response to Hurricane Fran of 1996. J. Geophys. Res., 108(C2), 3049, doi:10.1029/2001JC001078.

Zhang, M.Y., and Li, Y.S., 1996. The synchronous coupling of a third–generation wave model and a two–dimensional storm surge model. Ocean Eng., 23, 533–543.