The POLCOMS-WAM wave-current interaction model: development and performance in the NW Mediterranean

R. Bolaños
Laboratory of Maritime Engineering. Universidad Politecnica de Cataluña, Barcelona, Spain.
Proudman Oceanographic Laboratory. Liverpool, UK.

P. Osuna & J. Wolf
Proudman Oceanographic Laboratory. Liverpool, UK.

J. Monbaliu
Katholieke Universiteit Leuven, Belgium.

A. Sanchez-Arcilla
Laboratory of Maritime Engineering. Universidad Politecnica de Cataluña, Barcelona, Spain.

ABSTRACT: Ocean processes do not take place in isolation but interact with one another to form a complex system. This paper focuses on these processes by using and developing the POLCOMS-WAM model. The Stokes' drift and radiation stress effect on currents have been included, following state of the art formulations. The system is evaluated in the NW Mediterranean and in particular the Catalan coast. Due to oceanographic properties of the Catalan coast, currents are typically less than 20 cm/s and therefore the modification of waves due to the effect of currents is minimum. However, the wave induced currents, mainly caused by enhanced wind drag due to waves, produce a current of about the same magnitude as the ambient one and thus become an important source of mass transport. This may have an important effect in dispersion and transport of particles such as pollutants, larvae, etc.

1 INTRODUCTION

General circulation models are tools used to predict ocean circulation typically on an Eulerian reference and without resolving surface wind-waves and therefore do not consider wave effects. Ocean processes do not take place in isolation but interact with one another to form a complex system. In this way, there have been a number of studies dealing with wave-current interactions (Mellor 2005, Mellor 2003, Mellor & Blumberg 2004, Ardhuin et al. 2004, Rascle et al. 2006). Waves can be affected by the presence of currents due to refraction, modification of bottom drag and blocking. In the same way, currents can be modified by waves due to an increase in turbulence, Stokes drift, Langmuir circulation, radiation stress and indirectly by a modification of the wind stress. Mellor & Blumberg (2004) and Ardhuin & Jenkins (2006) showed the importance of waves on turbulence but also the effect of surface turbulence on wave dissipation. Weber et al (2006) shows the effect of the sea state dependent drag and Stokes drift on surge modelling; they also show the similarity of results of derivation of wave induced mass transport by Eulerian and Lagrangian approximation. Ardhuin et al (2004) derived wave stress and mass flux effects on current momentum and mass equations showing the importance of the wave stresses. Sullivan (2004) simulated and studied wave breaking and its influence in deep areas and vertical motions. Jorda et al (2007) performed a sensitivity study of the effect of Stokes drift and wave modified surface stress when simulating currents and dispersion of particles over the shelf.

Wave current interaction equations have been studied by Craik & Leibovich (1976), McWilliams & Restrepo (1999) among others. Mellor (2003, 2005) derive coupled current and wave equations in three dimensions assuming that the total current is a sum of ambient, wave-induced and turbulence terms taking into account the radiation stress, Stokes effect and Doppler velocity in order to develop a consistent equation for the coupled simulation of such processes.

This paper focuses on the implementation of new terms in the POLCOMS-WAM system as proposed by Mellor (2003, 2005) in the framework of the EU MARIE project (http://lim050.upc.es/projects/marie), and its evaluation for the Mediterranean Sea. The main objectives of the paper are: a) to perform a first attempt at current simulation with POLCOMS in the NW Mediterranean, b) to present the recent modifications of POLCOMS-WAM model, and c) to asses the implication of such modifications for the NW Mediterranean. First, the POLCOMS-WAM model is described, secondly the new implemented terms are explained and finally some results of its effect on modelling waves and currents on the Mediterranean are shown and discussed.

2 THE POLCOMS-WAM MODEL

The coupled POLCOMS-WAM system has been under development at the Proudman Oceanographic Laboratory for the last 4 years. The POLCOMS (Proudman Oceanographic Laboratory Coastal-Ocean Modelling System) is a three dimensional primitive equation numerical model formulated in spherical polar, terrain following coordinate system (sigma coordinates) and on a B-Grid. (Holt & James 2001). It solves the incompressible, hydrostatic, Boussinesq equation of motion dividing into depth varying and depth independent parts to allow time splitting between barotropic and baroclinic components. The turbulence closure scheme uses Mellor & Yamada (1974, 1982) with a modification proposed by Craig & Banner (1994) to take into account surface wave breaking. The system has been structured to allow its execution on parallel and serial computers (Ashworth et al., 2004).

The wave model used is the PRO-WAM model (Monbaliu et al. 2000), adapted for parallel computing (Osuna et al. 2006). The model simulates the 2D wave spectral evolution considering the energy input by wind, energy dissipation by whitecapping, non-linear wave-wave interactions and bottom friction.

The POLCOMS and PRO-WAM models are coupled in a two way mode to consider several processes; taking into account the wave refraction by currents, bottom friction by currents and waves and enhanced wind drag due to waves. The wave current interaction module is prepared to allow the synchronous exchange of information between POLCOMS and WAM, WAM being embedded in the baroclinic step of the model. Data from POLCOMS to WAM include barotropic and bottom layer current components and water depth updated every baroclinic time step. Time interpolated wind components are also transferred from POLCOMS to WAM within a moving framework according to the barotropic current components (Osuna & Wolf 2005). Surface roughness data from WAM to POLCOMS is used to modified the surface wind stress. In POLCOMS a wind dependent drag (Smith & Banke 1975) is used, but when the coupled system is used the wind stress in estimated considering the wave field following Janssen (1991). The effect of the coupling at the bottom due to the presence of waves and currents is estimated using Madsen (1994) formulation.

Osuna and Wolf (2005) presented an evaluation of wave–current coupling using POLCOMS-WAM system in the Irish Sea, they showed differences of up to 15 % in Hs due to waves and currents travelling in opposite direction. Changes in mean period (Tm02) due to Doppler shifting reached 20%. Differences in apparent bottom roughness were of one order of magnitude. The effect of waves on the currents were less evident. Validation with data measured at 23 m depth showed little effect (5% for wave parameters, 2.5 % sea surface elevation, 10 cm/s for current velocity (10%).

3 IMPLEMENTATION OF NEW TERMS INTO THE POLCOMS-WAM

3.1 *Stokes drift*

Stokes drift is a well known high order wave process describing the net transport due to waves. The behaviour of the Stokes drift has been studied theoretically, measured and modelled in several ways. Rascle et al (2006) studied the upper ocean dynamics showing an important surface shear due to the stokes drift, the different Stokes drift estimations for sea and swell waves and the effect of the Stokes drift combined with the coriolis force on Eulerian velocities over the whole water column, leading current magnitudes of 20 – 30% the wind induced currents. Lewis & Belcher (2004) showed the effect of the Stokes drift in the Ekman layer proving to be a better approximation when describing the angular deflections of the currents. Smith (2006) studied the effect of the Stokes drift from measurements with an Eulerian approach showing that the Stokes drift is intermittent and might be related to the groupines of waves.

The Stokes drift effects have been considered following the formulation of Mellor (2003, 2005) defining Stoke velocity for a 2D directional spectrum as:

$$U_{s\alpha} = 2g\int_{\theta}\int_{\sigma}\frac{k_{\alpha}}{c}\frac{\cosh 2kD(1+\varsigma)}{\sinh 2DkD}F\partial\sigma\partial\theta \qquad (1)$$

Where k_α represents the components of the wave number vector k, c their respective celerity, D water depth, $F(\sigma,\theta)$ the wave energy, g acceleration due to gravity. ς is the vertical sigma coordinate system. θ and σ are the direction and frequency of each spectral component.

3.2 *Radiation stress*

Longuet-Higgins & Stewart (1962, 1964) described the radiation stress of surface waves as an excess flux of momentum by the waves. Therefore the momentum conservation modifies the current field induced by changes of the radiation stress. Its effects are more evident in shallow water due to energy flow gradients. Mellor (2003) worked out a formulation to explicitly take into account this process in ocean models. The expressions of Mellor were given for a monochromatic wave but they can be adapted so that a wave spectrum can be accounted for:

$$S_{\alpha\beta}=\int_{\theta}\int_{\sigma} kD\left[\frac{k_\alpha k_\beta}{k^2}F_{CS}F_{CC}+\delta_{\alpha\beta}(F_{CS}F_{CC}-F_{SS}F_{CS})\right]F\partial\sigma\partial\theta$$
$$S_{p\alpha}=\int_{\theta}\int_{\sigma} kD\left[\frac{F_{SS}\partial F}{2\partial x_\alpha}+\left\{(1+\varsigma)F_{CS}-\frac{\cosh kD}{\sinh kD}F_{SS}\right\}F\frac{\partial kD}{\partial x_\alpha}\right](F_{CC}-F_{SS})\partial\sigma\partial\theta \quad (2)$$

Where *α, β* are the horizontal component, $\delta_{\alpha\beta}=1$ for $\alpha=\beta$ and the depth dependent functions are defined as:

$$F_{SS}=\frac{\sinh kD(1+\varsigma)}{\sinh kD};\quad F_{CS}=\frac{\cosh kD(1+\varsigma)}{\sinh kD}$$
$$F_{SC}=\frac{\sinh kD(1+\varsigma)}{\cosh kD};\quad F_{CC}=\frac{\cosh kD(1+\varsigma)}{\cosh kD} \quad (3)$$

3.3 *Doppler velocity*

The Doppler velocity that modifies the wave dispersion relation is evaluated according to the expression based on Kirby & Chen (1989) and analysed and described by Mellor (2003), and it is defined as

$$u_{A\alpha}=2\int_{-1}^{0}U_\alpha\frac{kD\cosh 2kD(1+\varsigma)}{\sinh 2kD}\partial\varsigma \quad (4)$$

Where $U_\alpha = u_\alpha + U_{s\alpha}$ represents the total (wind driven + wave driven (stokes)) flow velocity.

4 IMPLEMENTATION

The above terms are considered in several ways in the momentum equation (see Mellor, 2003). In this paper the terms have been applied to the Coriolis term and adding the radiation stress terms, therefore, the considered terms from the full momentum equation are:

$\in_{\alpha\beta z} f_z u_{S\beta}$ Coriolis influenced Stokes drift

$\frac{\partial S_{\alpha\beta}}{\partial \chi_\beta}$ horizontal gradient of radiation stress (5)

$\frac{\partial S_{p\alpha}}{\partial \zeta}$ vertical gradient of radiation stress

Keeping the nomenclature used for the POLCOMS model (Holt & James 2001, Proctor & James 1996, James, 1996) the modified equations are represented by:

$$
\begin{aligned}
\frac{\partial u_r}{\partial t} &= -L(u) + ((f v_r + f v_{stokes}) + \frac{uv\tan\phi}{R}) - \Pi_\lambda \\
&\quad + D(u) - H^{-1}[F_S - F_B] - NLB_\chi - (\frac{\partial S_{\alpha\beta}}{\partial \chi_\beta} - \frac{\partial S_{p\alpha}}{\partial \zeta}) \\
\frac{\partial v_r}{\partial t} &= -L(v) + ((f u_r + f u_{stokes}) + \frac{u^2\tan\phi}{R}) - \Pi_\phi \\
&\quad + D(v) - H^{-1}[G_S - G_B] - NLB_\phi - (\frac{\partial S_{\beta\alpha}}{\partial \chi_\alpha} - \frac{\partial S_{p\alpha}}{\partial \zeta})
\end{aligned}
\qquad (6)
$$

The u_r and v_r are the depth dependent velocities. The first term on the right is the advection, the second the new wave influenced Coriolis term where v_{stokes} and u_{stokes} are the Stokes currents, the third is buoyancy term, fourth is the diffusion term that replaces the vertical gradient of stresses, the fifth is the bottom and surface boundary conditions, the sixth the depth means of the nonlinear and buoyancy term and the last the radiation stress effect.

The evaluation of the Doppler velocity requires a high vertical resolution, therefore in the model it is solved analytically by assuming constant current at each level and then applied to the WAM model.

5 STUDY AREA AND MODEL SETTINGS. THE NW MEDITERRANEAN

The North-Western Mediterranean (Fig. 1) is a semi-enclosed sea characterized by large depth gradients. The Catalan- Spanish coast is located within the NW Mediterranean, and it has a narrow continental shelf in the north and a widening at the south with the presence of the Ebro delta. It is a microtidal environment characterized by a slope current (continuation of the Northern Current, Millot (1999)) of the order of 20-30 cm/s. Sea level variations are mainly due to atmospheric forcing. Wave climate is mild with a yearly mean of about 0.8 m but significant wave heights can reach more than 6 m in sever storm conditions.

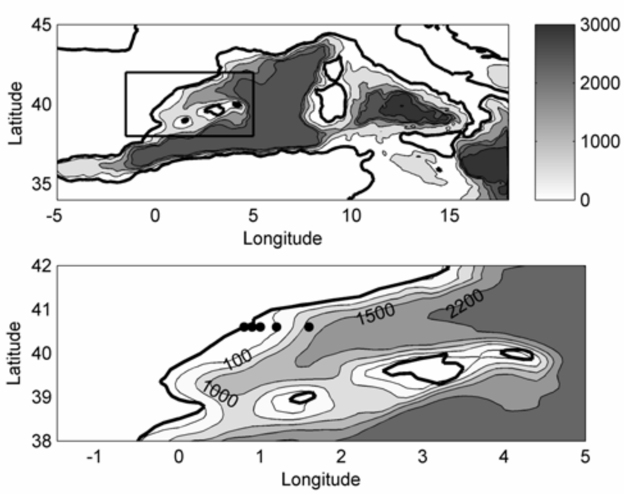

Figure 1. Bathymetry in the NW Mediterranean (top panel) and Catalan coast (bottom panel), circles show the locations used for the evaluation of the model. Color scale is in meters.

5.1 *Model settings*

The main objectives of this work are, first, to perform a good qualitative ocean modelling of the NW Mediterranean with POLCOMS. Secondly, we aim to test the coupled wave–current interaction module and evaluate the effect of the new terms for current and wave modelling. POLCOMS has been validated in different areas such as the Irish Sea (Osuna & Wolf 2005) and the North Sea (Holt & James 1999), but not for the Mediterranean Sea. WAM has been validated for the Mediterranean by Cavaleri & Bertotti (2004) and Bolaños et al (2007).

The POLCOMS–WAM was implemented for the NW Mediterranean Sea with a spatial resolution of 0.1 degree from 5 W to 18 E longitude and 34 N to 45 N latitude (Fig 1) with 20 sigma levels. Initial temperature and salinity conditions are taken from climatological data with a resolution of 0.25 degree and 35 vertical levels based on the MEDATLAS data bank using the MODB analysis technique (www.bo.ingv.it/mfstep/WP8/clim_data.htm) and therefore a 3D interpolation was necessary also considering the terrain following coordinate system of POLCOMS. For the vertical distribution and due to the large depth found in the Mediterranean, a modification of the sigma coordinates (S Coordinates) was used that allows an increased vertical resolution at the surface. Atmospheric forcing was by surface wind stress assuming constant atmospheric pressure, humidity and temperature. From an operational and validation point of view these settings may produce errors due to the coarse representation of initial conditions and the atmospheric forcing, but for the assessment of the terms for reliable conditions they proved to be sufficient. WAM was run on the same spatial grid with a resolution of 25 frequencies and 24 directions and physics of cycle-4 (Janssen (1991) surface stress formulation).

The system was run for 30 days as a spin up period with wind velocity set to zero. Then the system was forced by winds from the atmospheric model MASS that has been used and validated for wave modelling in the Mediterranean (Bolaños et al. 2007) for the November 2001 period. During this period there occurred a severe storm that affected all the NW Mediterranean and in particular the Catalan coast during about 10 days. Significant wave height reached about 8 m in the NW Mediterranean and 6 m at the Catalan coast.

6 RESULTS

Results have been analysed considering surface current fields and profiles of u, v and temperature at 5 locations on the Catalan coast (see table 1 and figure 1 bottom panel). Spatial distribution was also analysed using depth integrated currents. Comparisons are presented switching on/off the coupled terms.

Table 1. Location and depth of control points.

Point	E Longitude degrees	N Latitude degrees	Depth m
1	0.8	40.6	20
2	0.9	40.6	39
3	1	40.6	57
4	1.2	40.6	90
5	1.6	40.6	1204

The qualitative analysis of the POLCOMS performance for the NW Mediterranean and in particular the Catalan coast is acceptable for the surface and barotropic current field. The model is able to produce a continental slope current that flows from NE at the Catalan coast. Figure 2 shows the Catalan coast and the depth integrated current field after 710 hours of run, it is possible to observe some mesoscale features that are common in the area. It is important to note that the present configuration produces discontinuities at the east boundary and large velocities at some locations in the inner domain are present.

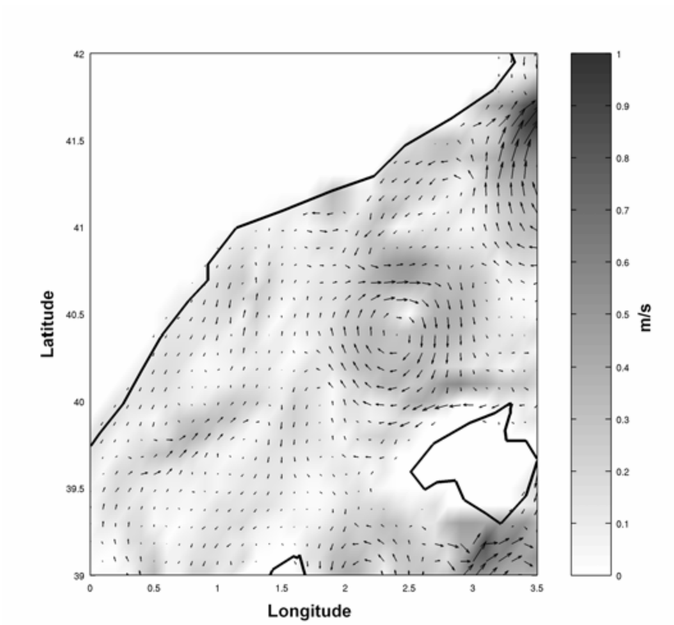

Figure 2. Depth integrated current velocity after 710 hours of model run.

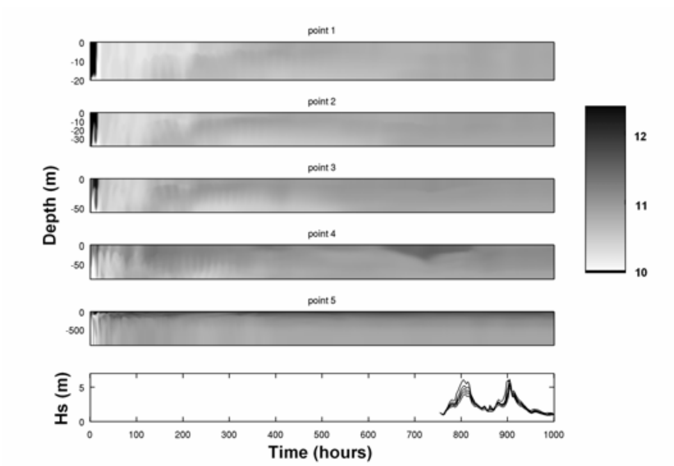

Figure 3. Temperature profile evolution along the run length for the 5 selected locations. Bottom panel shows the significant wave height being the higher as the more offshore. Color scale is in degrees.

Figure 3 shows the temperature profile over the simulation period for a run without WAM and without atmospheric forcing. The bottom panel shows the significant wave height without current interaction for the 5 locations just as a reference. The stratification in the two deeper locations and the well mixed layer in the two shallower ones are evident. Modelled significant wave height reached 6 m for the most offshore location and 4 m in the shallowest.

6.1 *Modification of waves by currents*

Due to the fact that the NW Mediterranean is a microtidal environment its surface currents are mainly due mesoscale circulation and wind induced. Typical values are of the order of 20-30 cm/s. These currents are negligible in terms of their effect on waves; wave refraction or blocking under such conditions are very small. This was observed in the simulations, finding maximum differences of up to 0.2 m (2.5%) of significant wave height at the Catalan coast. It is important to note that this effect might be artificially increased due to the large surface velocities induced by the settings. The mean period showed differences of 0.5 s (6 %).

6.2 *Modification of currents by waves*

Even though the Mediterranean is not one of the most wave-energetic seas it can develop storms with significant wave height of up to 6 m as shown by the storm event occurred in November 2001. Considering the small magnitude of the current that occurs in such area the wave induced currents can be of importance specially near the surface. Figure 4 shows the time evolution of the spatial mean difference of current velocity in the Catalan area for the different runs performed. The first panel shows the surface current difference between the run without and with atmospheric forcing. The second panel shows the difference between the coupling only by the wind modified stress and the POLCOMS alone. It shows mainly positive differences of up to 0.04 m/s highlighting the increased currents due to the higher wind stress. The third panel shows the effect of the full run (effect of radiation stress, Stokes drift, bottom friction and modified wind stress). Higher frequency oscillations are seen than in the previous one but mean differences are not substantially increased; the mean trend is dominated by the wind modified stress.

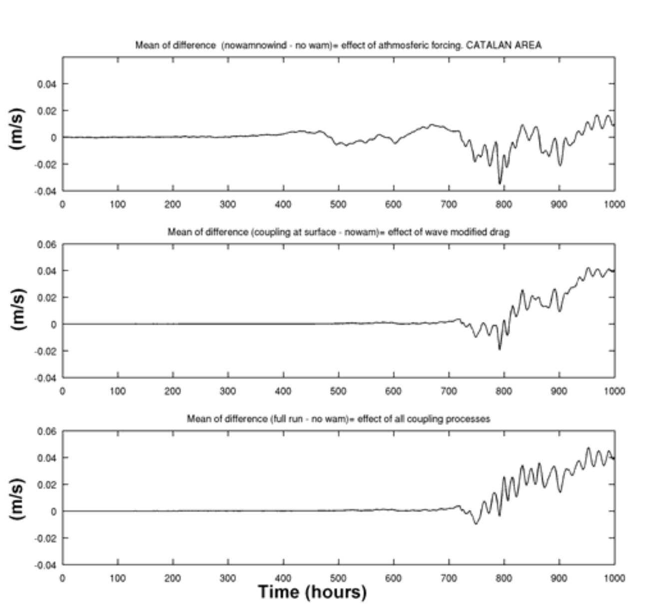

Figure 4. Mean spatial velocity difference for the Catalan area. Top panel effect of atmospheric forcing. Second panel effect of modified wind stress. Third panel effect of full coupled model.

Figure 5 shows the time evolution of the temperature differences profile at the 5 locations. It represents the effect of the full coupled version. An increased temperature at the surface by the coupled model is evident in the two most shallow areas meanwhile in the deepest location the increased temperature in a deeper part is evident.

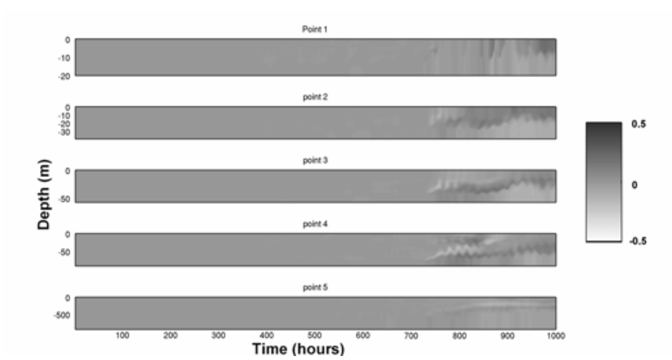

Figure 5. Temperature profile difference between full coupled run and POLCOMS alone.

Figure 6 shows the effect of the fully coupled system when compared with POLCOMS alone at the Catalan coast. It shows an increase in current speed of up to 0.3 m/s in the northern part. However the general effect is of the order of 0.05 m/s (about 25 %) along the coast.

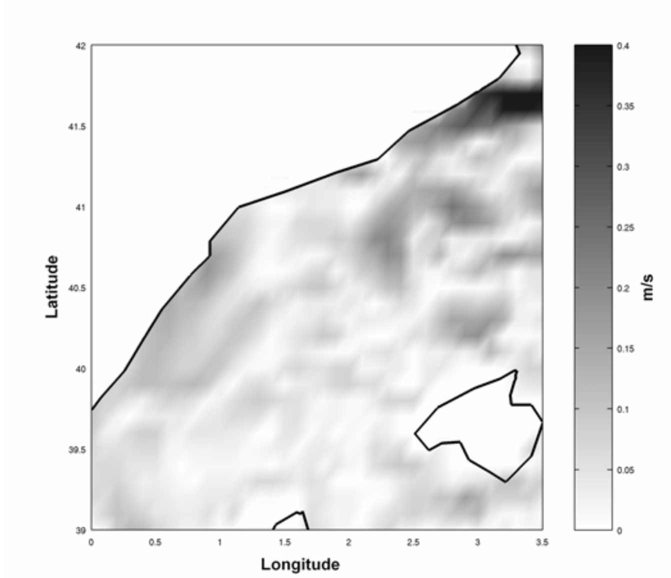

Figure 6. Mean time absolute difference of current velocity. Effect of fully coupled version. Color scale is in m/s.

7 DISCUSSION

The results show a considerable (proportionally to the ambient currents) effect of waves on currents in a microtidal environment such as the NW Mediterranean with an influence of about 20-30 %, this sensitivity is in agreement with other studies (Jorda et al 2007, Rascle et al 2006). The main effect is due to the modified wind stress by the presence of waves. It is important to note that the model is under development and there still some missing terms from the momentum equation in the implementation. Additionally there are some other terms that are not completely clear either in a theoretical nor an empirical way such as the vertical distribution of turbulence due to wave breaking. As outlined by many authors, measurements are needed that allow to validate wave current processes.

The modification of the temperature is mainly due to the horizontal mass transport; however the wave induced turbulence may play an important role near the surface and might be parameterized in a better way.

The settings of POLCOMS proved to be good enough to realistically model the main properties of the system however, for a full validation with measured data the settings might be improved in order to take into account more realistic atmospheric forcing (cloud cover, air temperature and air humidity), initial and boundary conditions. The spatial resolution may be also increased in order to properly consider the Rosby radius in the Mediterranean (about 15 km).

The effect of waves on currents may have an important implication for transport of suspended particle mater in the upper surface layer and may explain some of the discrepancies between models, able to reproduce main large scale features but with some differences when compared with local measured data.

8 AKNOWLEDGMENTS

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