Coupling of the Regional Ocean Modeling System (ROMS) and Wind Wave Model

Dutour Sikirić M.(1) Roland A.(2) Kuzmić M.(1) Janeković I.(1) Tomažić I.(3)

(1) Rudjer Bošković Institute, Croatia

(2) Technische Universität Darmstadt, Germany

(3) European Space Agency, Darmstadt

May 26, 2014

I. Wave modelling

Stochastic wave modelling

- Oceanic models are using grids (structured or unstructured) of size $1km \leq d \leq 10km$ to simulate the ocean
- But oceanic waves have a typical wavelength $2m \leq L \leq 100m$. So, we cannot resolve waves in the ocean.
- But if one uses phase averaged models and uses stochastic assumptions then it is possible to model waves by a spectral wave action density $N(\mathbf{x}, \mathbf{k})$
- This density satisfies a Wave Action Equation (WAE) which represents advection, refraction, frequency shifting and source terms:

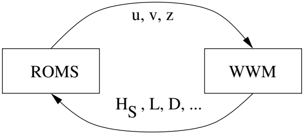
$$\frac{\partial N}{\partial t} + \nabla_x((\mathbf{c}_g + \mathbf{u}_A)N) + \nabla_k(\dot{k}N) + \nabla_\theta(\dot{\theta}N) = S_{tot}$$

with

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{bot} + S_{ds} + S_{break} + S_{bf}$$

Wave coupling

- Wave models use surface currents for the advection of wave energy and the free surface enters into the dispersion relation.
- On the other hand oceanic model can use wave information to:
  - Compute the Stokes drift (current induced by waves, a nonlinear effect).
  - Compute the wave radiation pressure term in the primitive equation.
  - Improve the computation of the surface stress, turbulence.
  - Be used in sediment transport models.
- Thus it makes sense to have oceanic and wave models coupled both ways. We chose to work with the `ROMS` model (a finite difference model) and the `WWM` model (a finite element model by Aron Roland).



The WWM model

The Wind Wave Model is a third generation wave model authored by Aron Roland and which shares many common features with WaveWatch III.

- The Wind Wave Model (WWM) is a unstructured grid spectral wave model.
- It incorporates most existing source term formulation for wind input and dissipation (Cycle III, Cycle IV, Ardhuin, Makin, ...)
- It has been coupled to SELFE, SHYFEM, TIMOR and ROMS.
- It uses Residual Distribution schemes for the horizontal advection.
- It integrates the WAE by using the Operator Splitting Method in explicit or implicit mode.
- It has NETCDF output/input/hotfile.
- Parallelization is done by ParMETIS.

Stokes drift

- For a complete description, the vertical Stokes drift is needed. It is obtained from the equation

$$\frac{\partial u_s}{\partial x} + \frac{\partial v_s}{\partial y} + \frac{\partial w_s}{\partial z} = 0$$

  and so we can get w_s by vertical integration from the bottom at $z = -h$ to $z = \xi$.

- For a phase averaged wave model we can compute the horizontal Stokes drift as an integral over the spectrum ($E(\mathbf{k}) = \sigma N(\mathbf{k})$):

$$(u, v)_s = \int_{\mathbf{k}} \frac{E(\mathbf{k})}{2\sinh^2(k(h+\xi))} \sigma \mathbf{k} \cosh(2k(z+h)) d\mathbf{k}.$$

  Note that the formula is actually an approximation assuming that the current shear is small. See Ardhuin (2008) for higher order formulas.

Generalized Lagrangian mean

- The idea is to decompose the current as $\mathbf{u}_{tot} = \mathbf{u} + \mathbf{u}_{wave} + \mathbf{u}_{turb}$ with $\mathbf{u}$ the steady motion, $\mathbf{u}_{wave}$ the wave motion and $\mathbf{u}_{turb}$ the microscopic turbulent motion.
- Under the assumption that $\mathbf{u}_{turb}$ is uncorrelated to other motion, we have to investigate the relation between $\mathbf{u}_{wave}$ and $\mathbf{u}$ (called Quasi-Eulerian).
- We can thus introduce a new particular derivative operator

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + (u + u_S)\frac{\partial}{\partial x} + (v + v_S)\frac{\partial}{\partial y} + (w + w_S)\frac{\partial}{\partial z}$$

and the equation for tracers T (i.e. salinity, temperature, turbulent kinetic energy, etc.) is then

$$\frac{DT}{Dt} = S_{source/sink}(T) + S_{diffusion}(T)$$

Equations of the Bennis/Ardhuin 2011 formulation I

- For the conservation of momentum we have the equation

$$\frac{D\mathbf{u}}{Dt} = \mathbf{F}_{pres} + \mathbf{F}_{turb} + \mathbf{F}_{cor} + \mathbf{F}_{wave} + \mathbf{F}_{bottom} + \mathbf{F}_{surf}$$

  where $\mathbf{F}_{pres}$ and $\mathbf{F}_{turb}$ are the pressure and turbulence terms respectively, while $\mathbf{F}_{cor} = f_{cor}(v + v_s, -u - u_s)$ is the Coriolis term with f_{cor} the Coriolis factor.

- The wave pressure term is a

$$\mathbf{F}_{wave} = u_s \nabla u + v_s \nabla v - \nabla J$$

  with J the 2D wave pressure term given by

$$J = \int_{\mathbf{k}} g \frac{kE(\mathbf{k})}{\sinh(2k(h+\xi))} d\mathbf{k}$$

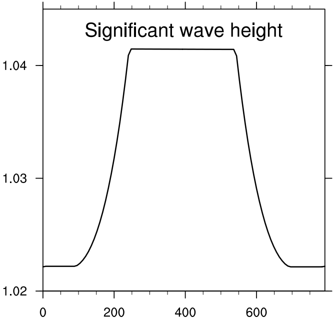
Equations of the Bennis/Ardhuin 2011 formulation II

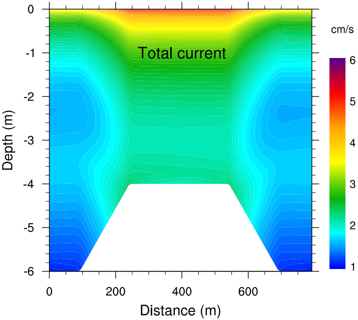
- The equation for the free surface is changed to

$$\frac{d\xi}{dt} + (u + u_s)\frac{d\xi}{dx} + (v + v_s)\frac{d\xi}{dy} = w + w_s$$

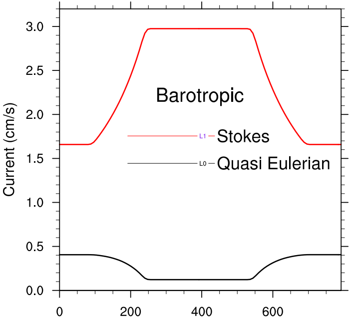
- Boundary conditions are changed from $u = 0$ to $u = -u_s$ and similarly for other kind of boundary conditions.
- The Stokes drift must also be added to the computation of floats trajectories.
- (Ardhuin, 2008) actually proposed a more complex system of equations with higher order terms.
- (Mellor, 2003) proposed some expression for the baroclinic stress but some incoherent results were obtained with it.
- (Longuet-Higgins, 1953) derived an expression for the barotropic stress induced by waves.

Exchange between Stokes current and current





- The stokes drift flux is not conservative
- But the flux $(h+\xi)(\overline{u}+\overline{u}_s)$ is constant in that test case.



Surface stress

- Surface stress is a key unknown in many oceanographic simulations.
- Many formulas depending on the wind $\mathbf{u}_{10m}$ have been proposed and the Charnock parameter was introduced

$$\alpha = z_{0,air} \frac{g}{u_*^2}$$

  with z_0 the roughness length and u_* the friction velocity. But the variability remains very large.
- Janssen (1989) proposed to decompose the stress into

$$\tau = \tau_{viscous} + \tau_{wave} + \tau_{high.\ freq.}$$

- The term $\tau_{viscous}$ is negligible.
- Janssen (1989) proposed a parameterization of the high frequency stress
- And τ_{wave} is obtained as an integral over the wind input formula of the wave model.

II. Numerical and computer aspects

Model coupling library, PGMCL

- The exchange between coupled models (via COMM_SPLIT) requires the sending of data between them.
- A priori the grids are different, the model nature may be different (Structure/Unstructured grids) and so interpolation is needed between the models.
- There are several existing libraries MCT, OASIS, PALM, etc but when considering them, they appear all relatively complicated.
- We considered MCT and it appeared to be impossible to achieve the goals that we wanted (optimal exchanges, interpolation, performance, etc.).
- Henceforth, we designed our own library PGMCL (Parallel Geophysical Model Coupling Library) for coupling models.
- After declarations, the commands become as simple as

```
CALL MPI_INTERP_SEND(TheArr_WAVtoOCN, Hwave)
CALL MPI_INTERP_RECV(TheArr_WAVtoOCN, Hwave)
```

Numerics of the coupling I

- The mathematical expressions occurring in wave coupling theories are dangerous expressions like:

$$\frac{\cosh(2k(z+h))}{\sinh(2k(h+\xi))}$$

- This kind of function is very singular. Their large values are concentrated on the surface. On the other hand it satisfies a specific integral property:

$$\frac{1}{h+\xi}\int_{-h}^{\xi}\frac{\cosh(2k(z+h))}{\sinh(2k(h+\xi))}dz = \frac{1}{2k(h+\xi)}$$

  which has to be reproduced in the model.
- The solution that we choose is for every vertical cell of the model, to compute explicitly the integral and put the average value at the relevant point.
- We also use a $k_{eff} = \frac{1}{D}\min(300, kD)$.

Numerics of the coupling II

- For the Stokes drift the model value for a vertical cell between depth z and z' is

$$(u_s^{model}, v_s^{model}) \quad = \quad \frac{1}{z'-z} \int_k \int_z^{z'} (u_s, v_s) dz dk = (*)$$

- After computation this gives:

$$(*) \quad = \quad \int_k \sigma \mathbf{k} E(k) dk \frac{1}{\sinh^2(k(h+\xi))} \frac{\sinh(2k(z'+h)) - \sinh(2k(z+h))}{2k(z'-z)}$$

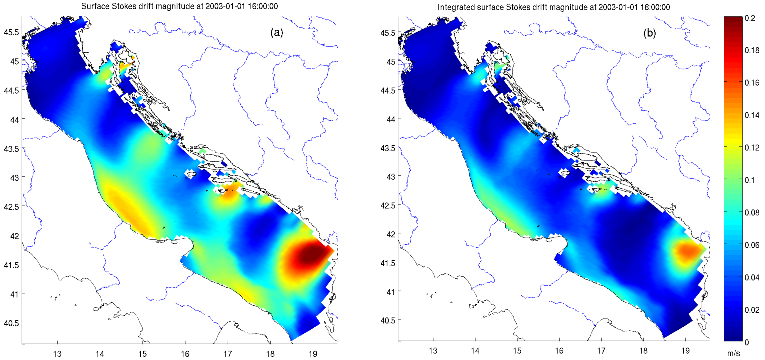
- After simplification this gives:

$$(*) \quad = \quad \int_k \sigma \mathbf{k} E(k) dk \frac{\cosh(kz+kz'+2kh)}{\sinh^2(k(h+\xi))} \frac{\sinh(k(z'-z))}{k(z'-z)}$$

  which is numerically stable.

- If one does not add the final part then the baroclinic Stokes drift does not match the analytical value.

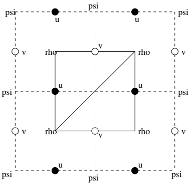
Computation of the Stokes drift

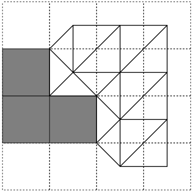


- For N_{freq} frequencies, N_{dir} directions, N_{vert} vertical levels and N_{node} grid level points the computation of the Stokes drift is takes $N_{freq} \times N_{dir} \times N_{vert} \times N_{node}$ operations.
- We can reduce it to $N_{node} \times N_{freq} \times (N_{dir} + N_{vert})$.
- Truncation formulation is comparable in complexity.

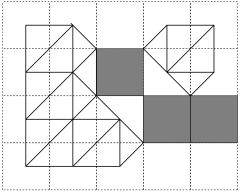
Grid subdivizion schemes

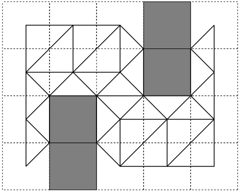
- Our standard interpolation strategy is to subdivide the squares in two triangles. Then near the coast, we add some more triangles.





- Those additional triangles allow us to respect the straits and isthmus of the original grid.



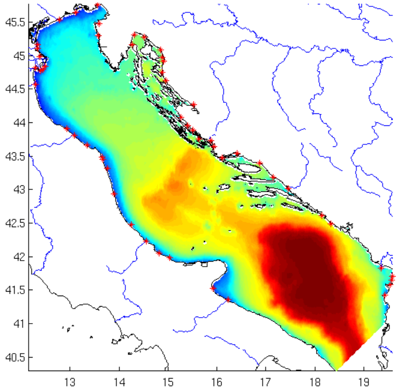


- But the system also allows some finite element grid to be used.

III. Application to the Adriatic Sea

Bathymetry and rivers of the Adriatic Sea

- The bathymetry varies a lot from 1200m to 50m.
- The island structure on the Croatian side is quite complex.
- River inflow is more important than in other parts of the Mediterranean.

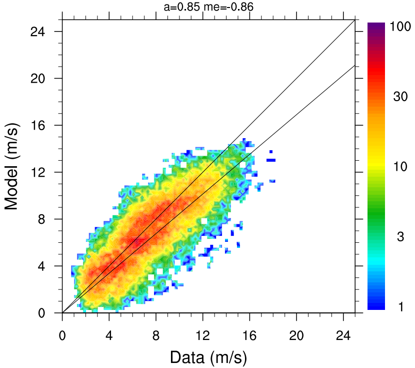


- Significant inflow/outflow occurs at the Ottranto strait and generates the highest tides of the Mediterranean.
- Two winds bora and Sirocco dominate the general circulation.

Chosen forcing information

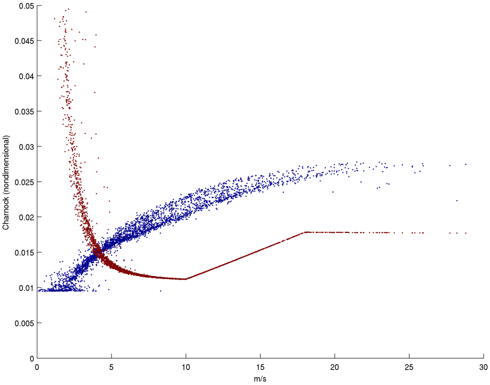
- The chosen modelization of the Adriatic Sea uses the atmospheric forcing fields from `DHMZ` using the `ALADIN` model (sea surface pressure, temperature, humidity, rain, cloud factor, short wave radiation).
- For river forcing, we used:
  - Hourly measurements for Po river and Neretva river.
  - Daily flux measurements for 9 other rivers and temperature for 5 more.
  - For other Italian rivers, we used climatological information from Raicich, 1994. For other Croatian rivers we rescale according to Neretva inflow.
  - For temperature we took nearest river.
- We used an initial state obtained from `AREG` which is an operational model using a modification of `POM`.
- At the open boundary of the Ottranto strait, we used daily average from the `AREG` model and we add tidal signal to it.

Comparison with QuikSCAT of ALADIN windspeed



- Wind speed is systematically underestimated by atmospheric models.
- Reasons seems to be too small resolution and less sophisticated model than `IFS`.

Comparison of Charnock coefficient

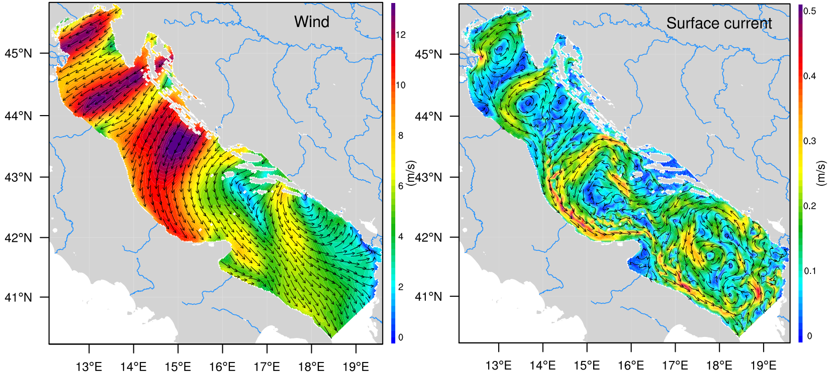


- We see that the bulk formulation introduce an artificial looking Charnock coefficient with no spreading.
- The wave formulation used here is the Ardhuin et al, (2009).

Impact of various parameterizations

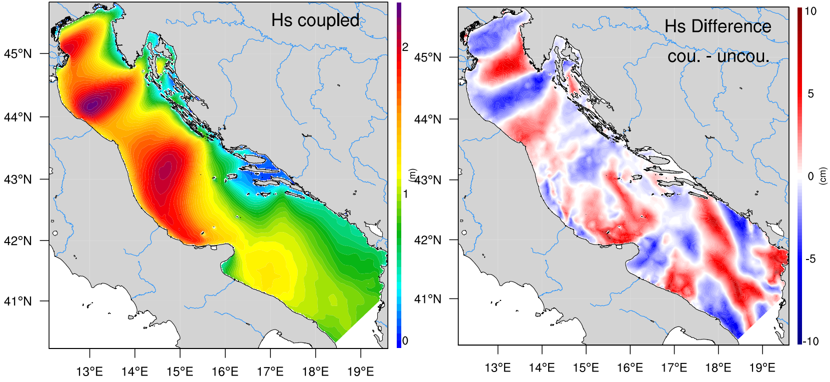
- The most significant impact of coupling with wave model on surface currents is the parameterization $z_{0,sea} = 0.5H_s$ of sea roughness length.
  - Reduction of 15 cm/s of current speed during bora events on the tip of Istria
- The next most significant effect is the effect of GLM formulation with reduction of current speed by 3 cm/s on the Italian coastline
- Finally the use of surface stress from the wave model is difficult to assess but leads to further decrease of surface currents in the bora jet.

Bora event I



- Wind speed and surface current at 2007-11-17 06:00:00 during a bora event.
- The bora jets induce a multiple gyre structure on surface currents.

Bora event II



- Coupling led to a decrease of H_s in the bora jet and an increase outside of the jet due to opposing currents.

Possible extensions

- We did the coupling of COSMO and WAM. Key point is the Charnock coefficient is computed in the WAM model and used by the atmospheric model.
  - The atmospheric model provides the wind and air density to wave model.
  - The wave model provides the Charnock coefficient to the atmospheric model.
- Results on the Mediterranean indicate a slight decrease of wind magnitude and an overall improvements in wave and wind statistics when comparing with altimeter and stations.
- Further coupling with Atmospheric local model, for example COSMO or WRF.
- Key issue is the physical parameterization of the sea surface.