NEMO-Wave WG workshop, ECMWF, 13-14 May 2014

Summary document on meeting outcomes

P. Oddo, E. Clementi

General Consensus

Addressing the issue of primitive equation and Wave model coupling, two different approaches have been proposed in the literature: the "vortex force" (McWilliam 2004, Ardhuin 2008, Bennis et al. 2011, Kumar et al., 2011) and the "radiation stress" (Mellor 2003, 2008, 2011) formulations. The differences in the two formulations are mainly due to the choice of the control volume used to derive the equations: within the radiation stress formulation of Mellor (2011) the prognostic velocities can be interpreted as Lagrangian wave-averaged velocities (related to Eulerian wave-averaged velocities within a wave-following vertical coordinate); while the vortex force formulation of Ardhuin et al. (2008) is based on the GLM equations for the Quasi-Eulerian wave-averaged velocities. Formally the radiation stress and vortex force representations are equivalent, related to two alternative representations of the inertial acceleration (Lane et al., 2007).

Differences in the adopted implementations of the two methods can be small under particular circumstances; however the "vortex" formulation equations have a more rigorous mathematical derivation and a larger range of applicability. There is a general consensus within the NEMO-WAVE working group and the external experts to adopt the "vortex" formulation in defining the NEMO-WAVE related development.

It has been discussed and agreed on the possibility to define and adopt a NEMO-WAVE development plan on the base of the ocean motion scales: open ocean from mesoscale to large scale phenomena, will be addressed first, while the inclusion of the wave effect on coastal areas regimes will be considered in a second stage.

To represent the wave current coupling effect accounting for the full spectra of scales and phenomena the momentum equations are re-written in terms of the quasi-Eulerian velocities $(\hat{u},\hat{v},\hat{w})$ according to Bennis et al. (2011, doi:10.1016/j.ocemod.2011.09.003) where:

$$(\hat{u},\hat{v},\hat{w}) = (u,v,w) - (U_s,V_s,W_s) \qquad (1)$$

where (u,v,w) are the mean Lagrangian velocities and (U_s,V_s,W_s) the 3D Stokes Drift in the horizontal (x,y) and vertical (z) directions. They are valid from the bottom $z = -h$ to the local phase-averaged free surface $z = \hat{\eta}$.

$$\frac{\partial \hat{u}}{\partial t}+\hat{u}\frac{\partial \hat{u}}{\partial x}+\hat{v}\frac{\partial \hat{u}}{\partial y}+\hat{w}\frac{\partial \hat{u}}{\partial z}-f\hat{v}+\frac{1}{\rho}\frac{\partial p^H}{\partial x}=\left[f+\left(\frac{\partial \hat{v}}{\partial x}-\frac{\partial \hat{u}}{\partial y}\right)\right]V_s-W_s\frac{\partial \hat{u}}{\partial z}-\frac{\partial J}{\partial x}+\widehat{F}_{m,x}+\widehat{F}_{d,x}+\widehat{F}_{b,x} \quad (2)$$

$$\frac{\partial \hat{v}}{\partial t}+\hat{u}\frac{\partial \hat{v}}{\partial x}+\hat{v}\frac{\partial \hat{v}}{\partial y}+\hat{w}\frac{\partial \hat{v}}{\partial z}+f\hat{u}+\frac{1}{\rho}\frac{\partial p^H}{\partial y}=-\left[f+\left(\frac{\partial \hat{v}}{\partial x}-\frac{\partial \hat{u}}{\partial y}\right)\right]U_s-W_s\frac{\partial \hat{v}}{\partial z}-\frac{\partial J}{\partial y}+\widehat{F}_{m,y}+\widehat{F}_{d,y}+\widehat{F}_{b,y} \quad (3)$$

where the left hand side is the classical primitive equation model for the quasi-Eulerian velocity with:

- ρ the mean density;
- p^H the hydrostatic pressure;
- f the Coriolis parameter;
- $\left(\widehat{F}_{m,x};\widehat{F}_{m,y}\right)$ related to the mixing effects (that redistribute momentum).

The right hand side contains the forcing terms where:

- $\left(\left[\left(\frac{\partial \hat{v}}{\partial x}-\frac{\partial \hat{u}}{\partial y}\right)\right]V_s-W_s\frac{\partial \hat{u}}{\partial z};\quad \left[\left(\frac{\partial \hat{v}}{\partial x}-\frac{\partial \hat{u}}{\partial y}\right)\right]U_s-W_s\frac{\partial \hat{v}}{\partial z}\right)$ is the vortex force;
- $\left(fV_s;\quad -fU_s\right)$ is the Stokes-Coriolis force;
- $\left(-\frac{\partial J}{\partial x};-\frac{\partial J}{\partial y}\right)$ is the force linked to the wave-induced mean pressure J (Bernoulli pressure head) where $J=g\frac{kE}{\sinh(2kD)}$, E is the surface elevation variance, $D=h+\hat{\eta}$ is the water depth, k is the wavenumber;
- $\left(\widehat{F}_{d,x};\widehat{F}_{d,y}\right)$ is the source of quasi-Eulerian momentum that is equal to the sink of wave momentum due to breaking and wave-turbulence interaction;
- $\left(\widehat{F}_{b,x};\widehat{F}_{b,y}\right)$ is the source of quasi-Eulerian momentum that is equal to the sink of wave momentum due to bottom friction (included if the bottom boundary layer is resolved).

Considering the abovementioned representation of the momentum equation, it has been decided to first implement processes occurring from meso-scale to large-scale. The representation of the wave-induced effect in this range involves the introduction of five additional terms in the primitive equations:

1. Stokes-Coriolis force;

   $$\left(fV_s;\quad -fU_s\right) \quad (4)$$

2. Surface boundary conditions for the momentum (modification of the wind stress to account the amount of energy stored into the wave field);

$$\tau_{oc} = \tau_a - (\tau_{in} + \tau_{dis})$$

$$\tau_{oc} = \tau_a - \rho_w g \int_0^{2\pi}\int_0^{\infty} \frac{\mathrm{K}}{\omega}(S_{in} + S_{dis}) d\omega d\theta \tag{5}$$

where τ_{oc} is the water-side stress felt by the ocean, τ_a is the air-side stress, τ_{in} is the momentum absorbed by the wave field and the amount released from breaking waves τ_{dis}, K is the wave number vector, ω is the angular wave frequency, θ is the wave direction, S_{in} and S_{dis} are the wind input and dissipation.

3. Transport of active and passive tracers (*C*) by the 3D Stokes drift:

$$\frac{\partial C}{\partial t} + \frac{\partial(\hat{u} + U_s)C}{\partial x} + \frac{\partial(\hat{v} + V_s)C}{\partial y} + \frac{\partial(\hat{w} + W_s)C}{\partial z} = 0 \tag{6}$$

4. Source/Sink term in the vertical turbulence model:

$$\Phi_{oc} = \Phi_{in} - \rho g \int_0^{2\pi}\int_0^{\infty} (S_{in} + S_{dis}) d\omega d\theta \tag{7}$$

where Φ_{oc} is the energy flux to the ocean column, Φ_{in} is the energy flux from the atmosphere, $\rho g \int_0^{2\pi}\int_0^{\infty} (S_{in} + S_{dis}) d\omega d\theta$ represents the wave energy flux at the sea surface.

5. Surface vertical velocity accounting for the Stokes drift.
The Eulerian vertical velocity at the surface $\hat{w}$ is related (Bennis et al., 2011, Eq (16)) to the surface height $\hat{\eta}$ by:

$$\hat{w} = \frac{\partial \hat{\eta}}{\partial t} + (\hat{\mathbf{u}} + \mathbf{U}_s)\big|_{z=\eta} \cdot \nabla_h(\hat{\eta}) + P - E - W_s\big|_{z=\eta} \tag{8}$$

where the vertical Stokes velocity at the surface is:

$$W_s\big|_{z=\eta} = -\nabla \cdot \int_{-h}^{\eta} \mathbf{U}_s \, dz \tag{9}$$

and E is evaporation, P is precipitation.

Regarding the 4th term, there is a general consensus within the enlarged working group members that basic research is still needed. None of the presently available turbulent closure models (TKE, KPP, GLS, Richardson number) correctly deal with the wave induced turbulence. Approximations are available and will be adopted in the first phase (Qiao term or modification of TKE). The representation of non-local effect in KPP have some appeal but it should be reformulated according the wave dynamics.

Actions and technical notes

There are 2 wave coupling developments streams: ECMWF, INGV

ECMWF: Coriolis, TKE modification (SBC) and Tau

INGV: Qiao

- NOC (Andrew Coward) has created a new branch from the trunk with ECMWF modifications starting from the one created before the meeting: svn+ssh://forge.ipsl.jussieu.fr/ipsl/forge/projets/nemo/svn/branches/2014/dev_r4642_WavesWG
- INGV to include in the NOC-ECMWF branch the Qiao implementation. Keep the ECMWF 3D Stokes Drift computation.
- INGV-ECMWF to review the interface for external data (sbc_wave and related namelist consider tides) check compatibility with WWIII/WAM ….
- ?INGV/ECMWF? to define how to include SD in tracer advection / implement / test
- Uk-MetO modify sbc_coupled according previous actions
- INGV include Bidlot jean.bidlot@ecmwf.int in the maling list
- External experts (Ardhuin and Benshila) to provide literature references necessary to modify the open boundary conditions

Issues

ECMWF/CNRS(Rachid)/NOC(Nurser, sbc) The introduction of the Stokes Coriolis must be reviewed considering different options available and reducing code lines.

There is the need to create and maintain a new reference configuration to test the wave related developments (academic). Sharing input data bathy, forcing, and results!!

ECMWF provides wave forcing fields from ERA-Interim that can be downloaded from the address: http://gws-access.ceda.ac.uk/public/nemo/forcing/ECMWF_waves/regular/

DISCUSSION

For the padding (ECMWF global coupled, land sea masks mismatch) of the external data, should we provide a tool? Yes, but in the future, now the recipe can be provided;

Aksenov suggests to define the group of experts in terms of technical (model developments) and theoretical experts;

How to disseminate the Wave WG outcomes and ongoing discussions to nemo_user, nemo_st, nemo_dev???

Can the WG provide a contribution to the NEMO white paper? A chapter on wave coupling has been suggested.

Wave models and NEMO, how to ensure the data availability, connection, incorporation? It is suggested to create a climatological static dataset.