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WAVE-CURRENT NEMO WORKING GROUP
(ATMO-WAVE-OCEAN interactions NEMO WORKING GROUP)
DRAFT DOCUMENT

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Contents

INTRODUCTION

There are many processes occurring at the interface between the Atmosphere and the Ocean. We focus our attention on the Wave-Atmosphere-Ocean coupling. In particular the working group will explore the way in which surface gravity waves can influence the ocean circulation. Waves influence the ocean circulation at least through several different mechanisms. During the first WG meeting these mechanisms have been discussed and prioritized. The resulting list follows:

1. Computation of the Stokes drift currents to be coupled with the ocean hydrodynamics;
2. Enhancement of upper ocean mixing through the wave-induced mixing by breaking and non-breaking waves;
3. Modification of the wind stress due to surface roughness;
4. Modification of the ocean hydrodynamics through large scale wave-current interaction introducing source and sink terms deriving from wave induced motion;
5. Modification of the bottom roughness and thus the bottom shear stress
6. Radiation stresses effects in shallow waters;
7. Sea-Ice – Wave interactions.

The first point is concerned with the different approximations to the full Stokes drift currents due to a given wave spectrum. The second point involves the parameterizations of the wave-induced vertical mixing. The third point is usually addressed considering parameterizations of the surface drag coefficient that can consider the sea surface roughness provided by a wave model. The fourth point is handled by re-defining the primitive equations to contain also Stokes drift effects. The fifth point addresses the parameterization of the interaction between the orbital velocity of the waves and the bottom velocities from the OGCM. The sixth point studies the radiation stresses in shallow water and their coupling with the hydrodynamics crucial in the setup of the coastal sealevel. Finally, the seventh point is concerned with the wave effect on the sea ice.

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ON-GOING WORK in NEMO

INGV contribution

Development of a wind stress parameterization with inclusion of wave processes

Wind stress is the major forcing of ocean general circulation kinetic energy and variability. Estimates of the surface wind stress τ is commonly based on the bulk aerodynamic formulas (Hellerman and Rosenstein, 1983):

$$\tau = \rho_A C_D \left|\vec{U}_a - \vec{U}_o\right|\left(\vec{U}_a - \vec{U}_o\right) \qquad (1)$$

where: ρ_A is the air density at the surface, C_D is the drag coefficient, U_a is the wind speed at 10 m and U_o is the surface current. Janssen (1991) pointed out that the airflow over surface gravity waves experiences a 'wave' wind stress that will induce modifications to the wind drag coefficient in (1) (Janssen, 1989). Given an external wave model that will generate a wave wind stress, modelling issues involve the coupling time step between wave and ocean models, the drag coefficient computation and the two-way coupling between ocean and wave models.

An interface to read wave parameters is already implemented in NEMO 3.4. At present time this interface is coded as a module (**sbcwave**), which manages the reading of a neutral drag coefficient from an external file. The namelist part which handles the wave's external files is called **namsbc_wave**. The total wind drag coefficient is computed in **sbc_coare** routine.

Stokes drift calculation for addition to the NEMO current output

Stokes drift is a wave driven mechanism of mass and momentum transport (Stokes 1847). It is defined as the difference between the average velocity of a fluid parcel (Lagrangian velocity) and the current measured at a fixed point (Eulerian velocity). As waves travel, the water particles that make up the waves travel in orbital motions but without a closed path. Their movement is enhanced at the top of the orbit and slowed slightly at the bottom so the result is a net forward motion of water particles, referred to as the Stokes drift. An accurate evaluation of the Stokes drift and the inclusion of related processes may lead to improved representation of surface physics in ocean general circulation model (OGCM).

The Stokes drift velocity u^{St} in deep water can be computed from the wave spectrum and may be written as:

$$u^{St}(z) = \frac{16\pi^3}{g}\int_0^{\infty}\int_{-\pi}^{\pi}(\cos\theta,\sin\theta) f^3 S(f,\theta) e^{2kz} d\theta df \qquad (2)$$

where: z is the vertical coordinate, θ is the wave direction, f is the wave intrinsic frequency, $S(f,\theta)$ is the 2D frequency-direction spectrum, k is the wavenumber defined as: $k=2\pi/L$ (L=wavelength). In order to evaluate the Stokes drift in a realistic ocean wave field the wave spectral shape is required and its computation quickly becomes expensive as the 2D spectrum must be integrated for each vertical level. To simplify, it is customary to use the following monochromatic approximation to the full Stokes profile:

$$u_m^{St}(z) = u_0 e^{2k_m z} \qquad (3)$$

where u_0 is the Stokes drift velocity at the surface (z=0). In order to evaluate u_0, two approaches can be followed:

1) To run a third-generation wave model that accurately reproduces the wave spectra and makes possible the estimation of the surface Stokes drift for random directional waves in realistic wave conditions (Eq. 4).

$$u_0 = \frac{16\pi^3}{g}\int_0^{\infty}\int_{-\pi}^{\pi}(\cos\theta,\sin\theta)f^3 S(f,\theta)d\theta df \tag{4}$$

2) To use mean parameters derivable from the standard output of a wave model:

$$u_0 = \frac{\pi^3}{g}\frac{H_s^2}{T_p^3}(\cos\theta,\sin\theta) \tag{5}$$

where: H_s is the significant wave height and T_p is the peak period.

Both these options are now being experimented in the NEMO implementation for the Mediterranean Sea.

MERCATOR contribution

Modification of vertical mixing due to waves

Waves impact the ocean boundary layer (OBL) by modifying the available mechanical energy from the wind (through the wind stress) but also by directly providing additional sources of turbulence. Following the review by Cavaleri et al. (2012), these sources can be decomposed in the following three physical processes. We have extended here Cavaleri's discussion to the status of related parameterizations.

1) Wave breaking. Wave breaking in the upper layers provides a substantial increase of dissipation in the upper part of the *OBL*. This has been reported by various observational papers showing turbulent kinetic energy (*TKE*) injection down to several times the significant wave height. Hypothesising a local balance between diffusion and dissipation, this has been successfully parameterized in several turbulence schemes, as long as they make use of a prognostic *TKE* equation (Craig and Banner, 1994; Burchard, 2001). The two necessary inputs in these parameterizations are the surface *TKE* flux (F_{wb}) and the largely unknown surface roughness (*Zos which we recall here is different from the atmospheric roughness length used in bulk formulae*) assumed to scale with the wind sea wave height (H_{sw}). Since wave breaking is highly related to the wind sea, uncoupled ocean models make use of empirical estimates for both F_{wb} and H_{sw}, function of the local wind speed or equivalently the surface friction velocity $u^*=\sqrt{(\tau/\rho)}$ (Mellor and Blumberg, 2004). Obviously, as strongly advised by Rascle et al. (2008), taking advantage of wave models to specify both terms could remove some uncertainties due in particular to the neglected wave age dependency of the problem.
2) Langmuir turbulence. Interaction of Stokes drift currents with mean current shear provide and additional source of mixing, which in turns leads to swell dissipation (Ardhuin and Jenkins, 2006). In the Langmuir turbulence regime (i.e. when the Langmuir number $La=\sqrt{(u^*/U_{so})} < 0.5$; U_{so} being the surface Stokes drift) LES numerical simulations indicate dramatic enhancement of mixing over the whole mixed layer (McWilliams et al., 1997; Grant and Belcher, 2009). Well observed windrows at the sea surface associated with the so called Langmuir cells are one of its most spectacular expressions. Soon after the

early years of its explicit simulation by LES, some attempts to include these non-local processes have been proposed in state of the art vertical mixing schemes (KPP: McWilliams and Sullivan, 2000; Smyth et al., 2002. Mellor Yamada: Kantha and Clayson, 2004; k-ε: Axell, 2002). Since then, their standard use in 3d large-scale ocean models have nevertheless not been that popular although the importance of Langmuir turbulence is acknowledged. Existing parameterizations lumped into local-closures (e.g. not KPP) obviously suffer from the difficulty of representing such a non-local process, but it is likely that additional investigations spanning various sea states regimes were also needed. Systematic scaling issued from LES simulations (such as those provided by Grant and Belcher, 2009; Harcourt and d'Asaro, 2008; Van Roekel et al. 2012) are now available and can certainly help refining initial ideas.

3) Mixing by wave orbital motions. No matter pre-existing mean eulerian current shear in the OBL, Babanin (2006) proposed that wave orbital motions alone generate mixing. As stressed by Cavaleri et al (2012), the physical significance of this process is still debated in the community. Several papers have recently shown that adding non-breaking wave induced turbulence* improves global ocean model thermohaline properties, reducing the long standing difficulty in ocean models to realistically flux heat below the summertime thermocline (Quiao et al, 2004, Wang et al., 2010, Shu et al., 2011, Huang et al., 2011). Since the scaling used in some of these parameterizations (based on Stokes drift shear in Huang and Quiao, 2010) shares some similarities with the scaling of Langmuir turbulence, it is however not clear how existing parameterizations consider one process or both. For instance, it seems that Huang and Quiao (2010) treated non-breaking wave mixing processes as a whole by involving wind speed in its argumentation but he refers to Quiao's work also. Thus the partition between the two processes in their parameterization does not appear clear. Still they have shown a disconcerting agreement of their parameterized dissipation profiles with measurements, and in particular below the mixed layer where Langmuir turbulence is supposed to vanish (still there is one order of magnitude variation in the proposed constant issued from the fit to observations).

NOC Southampton contribution

Mixing induced by wave-orbital motion.

Qiao, Chu; FIO, Qingdao, China

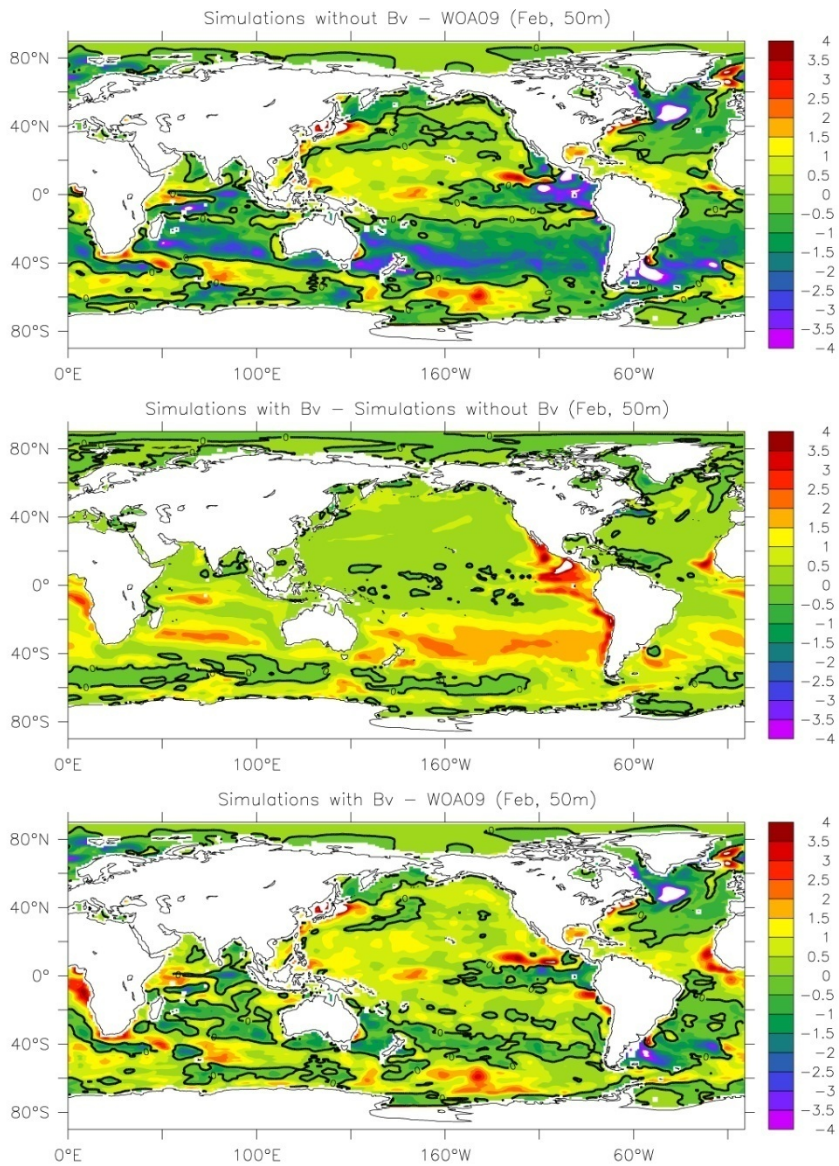
Fangli Qiao and his co-workers have suggested in a considerable body of work e.g. (Qiao et al., 2004; 2010) that the wave orbital motions may directly drive mixing. They have developed the so-called BV parameterization, which reduces to a simple formula for an extra vertical diffusivity

$$\kappa_{\mathrm{BV}} = \alpha A u_{s0} \exp(3kz)$$

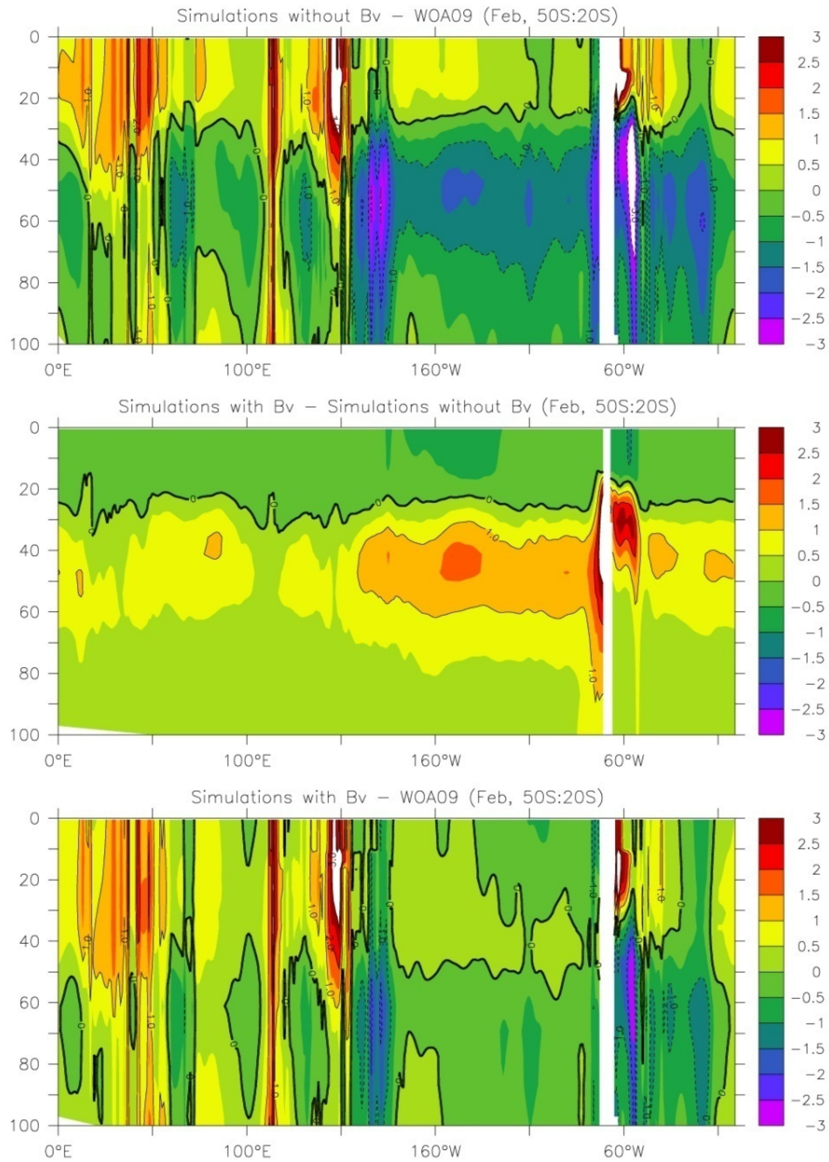
for monochromatic waves with amplitude A, wavenumber k, and surface Stokes drift u_{s0} ; here α is a non-dimensional constant. We are however a little skeptical about the physical basis for this parameterization. Although scattering between orbital motions with different wavenumber might possibly drive mixing, their derivation seems to have little physical justification.

* In practice, a vertical 3d diffusivity/viscosity computed through suitable integration of wave model spectral outputs is added.

A member of his group, Qi Shu, visited NOC Southampton in Spring 2013, and implemented this parameterization into NEMO, at 2°, 1° and ¼ ° resolution. All resolutions showed similar behaviour: a marked reduction in the cold bias immediately below the summer mixed-layer in subtropical regions that was otherwise evident in NEMO model runs without TKE penetration below the mixed-layer i.e. nn_etau=0. However NEMO runs with TKE penetration below the mixed-layer nn_etau=1 were changed little by the BV parameterization.



ORCA1, nn_etau=0: temperature differences (° C) at 50m depth in Austral summer
Courtesy of Qi Chu



ORCA1, nn_etau=0: temperature differences (° C) on section along 20° S in Austral summer

Courtesy of Qi Chu

Development of a mixed-layer model involving Langmuir circulation

Belcher, UKMO/Reading; Grant, Reading; Nurser, NOCS; Siddorn, Calvert, UKMO.

The OSMOSIS project is funded by the UK NERC and is a collaboration between modellers and observationalists at Southampton, Reading, East Anglia, Oxford, Bangor and the UK Met Office. One of its purposes is to develop a better mixed-layer model that takes full account of Langmuir circulation.

Alan Grant at Reading is exploring parameter space via a suite of Large Eddy Simulations (LES) with resolutions ~ 1m. Earlier work is described e.g. in Grant and Belcher, (2011).

These results are being used to calibrate parameterisations of terms in a 2nd order moment model. A 1D standalone model is already coded in IDL and is working for the neutral case without convection or surface heating. This code is currently being implemented into NEMO. It will require some measure of the Stokes drift as an input, as well as the wind stress.

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SWARP: Ships and Waves Reaching Polar Regions EU FP7

Bertino (Coordinator: NERSC, Norway), Aksenov, Nurser and Madec (NOCS, UK) and the other six institutional partners

Ships and Waves Reaching Polar Regions (SWARP) is a large international project funded by the FP7 involving institutions from France, Norway, Canada, New Zealand Russia and UK. The project aims to develop techniques and downstream services for sea ice and wave forecasting in the Marginal Ice Zone (MIZ) in the Arctic. NOC will implement into global NEMO an ice floe break-up model, and combined sea ice rheology (CSIR; Dumont et al., 2011) which couples the EVP rheology in the ice pack to the floe collision rheology in the MIZ. NEMO will be coupled to wave forcing from the WAVEWATCH III model. NOC will optimize model parameters for the CSIR and mixing parameterisations and also examine the impact of the wave-ice interaction on the regional and global variability of sea ice and ocean.

NOC Liverpool contribution

Judith Wolf, NOC, Marine Systems Modelling Group, November 2013

The Marine Systems Modelling Group at NOC has several sub-groups. In Liverpool we have the Shelf and Coastal Processes and Shelf Sea Impacts Subgroups.

The aims for the Shelf and Coastal Processes Subgroup are as follows:

- Representation of fine-scale processes in coastal-ocean models
- Development of the next generation of structured and unstructured grid coastal-ocean models
- To develop development fully integrated ocean-land-atmosphere regional modelling system

Within this sub-group we are working on coupled wave-current modelling as part of the latter topic. We are also working on the NEMOcoast model, which includes implementation of a wetting/drying scheme.

Wave-current coupling

Previous work has been carried out during the last 10 years in coupling POLCOMS-WAM, considering the following processes:

- **Effects of currents on waves**
  - Wave propagation i.e. refraction of waves by currents (and water depth), wave blocking and reflection
  - Bottom friction –wave friction factor is modified in the presence of currents
  - Apparent wind, vertical current shear
- **Effects of waves on currents**
  - Surface stress
  - Bottom friction – current friction factor modified by waves
  - Radiation stress
  - Langmuir circulation
  - Wave mixing

The items in red have had some preliminary consideration but have not yet been implemented.

The intention is to work with NEMO-WW3 to implement these processes, in collaboration with the UK Met Office, under the umbrella of the National Centre for Ocean Forecasting (NCOF), Ocean Waves Group.

Met Office contribution

Francois-Xavier Bocquet, MO, Short Range Coupled Forecasting Development Group, March 2014

The short range coupled forecasting development group at the Met Office is involved in the development of global and regional coupled systems, comprising the Unified Model, NEMO and WAVEWATCH III. Our current work, in collaboration with ECMWF, is concerned with the following topics:

Mixed layer modelling

The intention is to incorporate wave effects in the NEMO TKE scheme:

- Modifying the existing wave-breaking parameterisation in NEMO to use wave model data in coupled/forced mode
- Adding Langmuir turbulence representation using the Huang et al. 2011 parameterisation

Stokes-Coriolis forcing

Inclusion in NEMO of the Stokes drift obtained from a wave model and modification of the equations of motion to include the Stokes-Coriolis forcing.

Wave-current coupling

Work in collaboration with NOC to include effects of currents on waves and waves on current.

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POSSIBLE FUTURE DEVELOPMENTS

For each of the seven issues described in the introduction there is a need to plan a consistent development of numerical tools that will effectively couple the atmosphere with waves and the ocean hydrodynamics.
It is suggested that a Working group is set up inside NEMO that will plan such developments and produce a scoping paper with different phases of development.

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