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Recent developments in NEMO within the Albatross project

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Context: Albatross project funded by CMEMS



→ Representation of ocean/waves/atmosphere interactions in global eddying operational systems

- Focus on the characteristic scales of the oceanic mesoscale (a few kilometers and from a few days to a few weeks)
 - ▷ Demonstrate the contribution of ocean/waves coupling
 - ▷ Account for eddy-scale wind-SST and wind-currents effects

1. Implementation of a 2-way ocean/waves coupling (more conventional)
2. Explore the possibility to dynamically downscale atmospheric data to the oceanic resolution via a simplified model (more exploratory)

1

Inclusion of wave-induced terms in NEMO & coupling infrastructure

Inclusion of wave-induced terms in the PE models

Mathematical derivation

- [McWilliams et al. \(2004\)](#)
 - Eulerian frame
 - Asymptotic expansion of the wave effects to some order in wave steepness
- [Ardhuin et al. \(2008\)](#)
 - Hybrid Lagrangian-Eulerian frame (Generalized Lagrangian Mean)
 - Effects of vertical shear are ignored

- nearly equivalent wave-current equations at leading orders ([Ardhuin et al., 2017](#))
- the wave effects on the current momentum expressed in the form of the vortex force

- ▷ Examples of practical implementations in PE models:
[Uchiyama et al. \(2010\)](#); [Bennis et al. \(2011\)](#)

Curl form of NEMO equations with generalized vert. coordinate ($e_3 = \partial_k z$)

$$\begin{aligned} \partial_t u &= +(f + \zeta)(v + v^s) - \frac{\partial_x \|\mathbf{u}_h\|^2}{2} - \frac{(\omega + \omega^s)}{e_3} \partial_k u - \frac{\partial_x (p_s + p^J)}{\rho_0} - \frac{(\partial_x (p_h + \tilde{p}))_z}{\rho_0} + F^u \\ \partial_t v &= -(f + \zeta)(u + u^s) - \frac{\partial_y \|\mathbf{u}_h\|^2}{2} - \frac{(\omega + \omega^s)}{e_3} \partial_k v - \frac{\partial_y (p_s + p^J)}{\rho_0} - \frac{(\partial_y (p_h + \tilde{p}))_z}{\rho_0} + F^v \\ \partial_k p_h &= -\rho g e_3 - \partial_k \tilde{p} + \rho_0 (u^s \partial_k u + v^s \partial_k v) \quad \text{"wavy hydrostatic" balance} \\ \partial_t (e_3 \theta) &= -\partial_x (e_3 \theta (u + u^s)) - \partial_y (e_3 \theta (v + v^s)) - \partial_k (\theta (\omega + \omega^s)) + F^\theta \\ \partial_t e_3 &= -\partial_x (e_3 (u + u^s)) - \partial_y (e_3 (v + v^s)) - \partial_k (\omega + \omega^s) \\ \rho &= \rho_{eos} \end{aligned}$$

- (u^s, v^s, ω^s) : Stokes drift velocity (assumed to be non-divergent)
- p^J : depth-uniform wave-induced kinematic pressure term
- \tilde{p} : shear-induced 3D pressure term associated with vertical component of VF

$$\mathcal{W}_{\text{St-Cor}} = \begin{pmatrix} f v^s \\ -f u^s \\ 0 \end{pmatrix}, \quad \mathcal{W}_{\text{VF}} = \begin{pmatrix} \zeta v^s - \frac{\omega^s}{e_3} \partial_k u \\ -\zeta u^s - \frac{\omega^s}{e_3} \partial_k v \\ \frac{u^s}{e_3} \partial_k u + \frac{v^s}{e_3} \partial_k v \end{pmatrix}, \quad \mathcal{W}_{\text{Prs}} = \begin{pmatrix} p^J + \tilde{p} \\ p^J + \tilde{p} \\ \tilde{p} \end{pmatrix}$$

Curl form of NEMO equations with generalized vert. coordinate ($e_3 = \partial_k z$)

$$\begin{aligned} \partial_t u &= +(f + \zeta)(v + v^s) - \frac{\partial_x \|\mathbf{u}_h\|^2}{2} - \frac{(\omega + \omega^s)}{e_3} \partial_k u - \frac{\partial_x(p_s + p^J)}{\rho_0} - \frac{(\partial_x(p_h + \tilde{p}))_z}{\rho_0} + F^u \\ \partial_t v &= -(f + \zeta)(u + u^s) - \frac{\partial_y \|\mathbf{u}_h\|^2}{2} - \frac{(\omega + \omega^s)}{e_3} \partial_k v - \frac{\partial_y(p_s + p^J)}{\rho_0} - \frac{(\partial_y(p_h + \tilde{p}))_z}{\rho_0} + F^v \\ \partial_k p_h &= -\rho g e_3 - \partial_k \tilde{p} + \rho_0 (u^s \partial_k u + v^s \partial_k v) \quad \text{"wavy hydrostatic" balance} \\ \partial_t(e_3 \theta) &= -\partial_x(e_3 \theta(u + u^s) - \partial_y(e_3 \theta(v + v^s))) - \partial_k(\theta(\omega + \omega^s)) + F^\theta \\ \partial_t e_3 &= -\partial_x(e_3(u + u^s)) - \partial_y(e_3(v + v^s)) - \partial_k(\omega + \omega^s) \\ \rho &= \rho_{eos} \end{aligned}$$

- ▶ Small vertical shear limit (Bennis et al., 2011) → hydrostatic relation is unchanged
- ▶ Neglect wave-induced non-conservative forces (wave dissipation, rollers, etc)
- ▶ Adjustments in the barotropic mode due to the convergence of the Stokes drift
- ▶ No need to explicitly compute ω^s

Reconstruction of Stokes drift velocity profile

Inputs from wave model: $\mathbf{u}_h^s(\eta)$, $\|\mathbf{T}^s\|$, $\rightarrow \mathbf{u}_h^s(z, k_e) = \mathbf{u}_h^s(\eta)\mathcal{S}(z, k_e)$

- k_e : degree of freedom to impose that $\|\int \mathbf{u}_h^s(z, k_e) dz\| = \|\mathbf{T}^s\|$
- $\mathcal{S}(z, k_e)$ from Breivik et al., 2016
- Stokes drift interpreted in a FV sense $\mathbf{u}_h^s(z_k) = \frac{\mathbf{u}_h^s(\eta)}{(e_3)_k} \int_{z_{k-1/2}}^{z_{k+1/2}} \mathcal{S}(z, k_e) dz$

Computation of surface momentum flux

- **In NEMO** : τ^{atm} from IFS bulk formulation (Aerobulk) using α_{ch} from wave model.
- **In wave model** : $\tau_{\text{ww3}}^{\text{atm}}$ assumes neutral stratification (wave models hyper sensitive to stress computation).

A way to account for the momentum flux consumed by the wave field

$$\tau^{\text{oce}} = \tau^{\text{atm}} - (\widehat{\tau_{\text{ww3}}^{\text{atm}} - \tau_{\text{ww3}}^{\text{oce}}})$$

▷ Pragmatic choice which breaks momentum conservation.

Wave-enhanced mixing (1-equation TKE scheme)

Additional terms in wavy hydrostatic balance affects TKE equation

$$\mathbf{u}_h^s \partial_z \langle \mathbf{u}'_h w' \rangle = \langle \mathbf{u}'_h w' \rangle \partial_z \mathbf{u}_h^s + \partial_z (\mathbf{u}_h^s \langle \mathbf{u}'_h w' \rangle)$$

▷ Modification of shear production term + adjust A^{ve} value

$$\partial_t e = \frac{A^{vm}}{e_3^2} \left[(\partial_k u)^2 + (\partial_k v)^2 + (\partial_k u)(\partial_k u^s) + (\partial_k v^s)(\partial_k v^s) \right] - A^{vt} N^2 + \frac{1}{e_3} \partial_k \left[\frac{A^{ve}}{e_3} \partial_k e \right] - c_\epsilon \frac{e^{3/2}}{l_\epsilon^2}$$

$$\text{Surface B.C. for } e : \left(\frac{A^{ve}}{e_3} \partial_k e \right)_{z=z_1} = -\rho_0 g \int_0^{2\pi} \int_0^\infty S_{ds} d\omega d\theta$$

$$\text{Surface B.C. for mixing length} : l_{z=\eta} = \kappa \frac{(C_m c_\epsilon)^{1/4}}{C_m} (\eta + z_0), \quad z_0 = 1.6 H_s$$

Wave-enhanced mixing (1-equation TKE scheme)

Additional terms in wavy hydrostatic balance affects TKE equation

$$\mathbf{u}_h^s \partial_z \langle \mathbf{u}'_h w' \rangle = \langle \mathbf{u}'_h w' \rangle \partial_z \mathbf{u}_h^s + \partial_z (\mathbf{u}_h^s \langle \mathbf{u}'_h w' \rangle)$$

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Langmuir cells parameterization : Axell (2002)

→ Additional source term in TKE equation $\Delta t P_{LC}$ with $P_{LC} = w_{LC}^3 / H_{LC}$

$$w_{LC} = \begin{cases} c_{LC} \|\tilde{\mathbf{u}}_s\| \sin\left(-\frac{\pi z}{H_{LC}}\right), & \text{if } -z \leq H_{LC} \\ 0, & \text{otherwise} \end{cases}, \quad - \int_{-H_{LC}}^{\eta} N^2(z) z dz = \frac{\|\tilde{\mathbf{u}}_s\|^2}{2}$$

$\|\tilde{\mathbf{u}}_s\| = \max \{ \mathbf{u}_s(\eta) \cdot \mathbf{e}_\tau, 0 \}$ intensity of LC scales with $\theta_{\mathbf{u}_s \tau}$ (Van Roekel et al., 2012)

Practical implementation

- OASIS – MCT Interface shared with Croco and Mars3d
- Interface in NEMO inline with the generic interface with atmosphere

Variable	description	
$\mathbf{u}_h(z = \eta)$	Oceanic surface currents	O→W
$\mathbf{u}_{10}^{\text{atm}}$	10 m-winds from external dataset	O→W
$\mathbf{u}_h^s(z = \eta)$	Sea-surface Stokes drift	W→O
$\ \mathbf{T}^s\ $	norm of the Stokes drift volume transport	W→O
Φ_{oc}	TKE surface flux multiplied by ρ_0	W→O
α_{ch}	Charnock parameter	W→O
H_s	Significant wave height	W→O
τ_w^{ww3}	Wave-supported stress	W→O
\tilde{p}^J	Bernoulli head	W→O

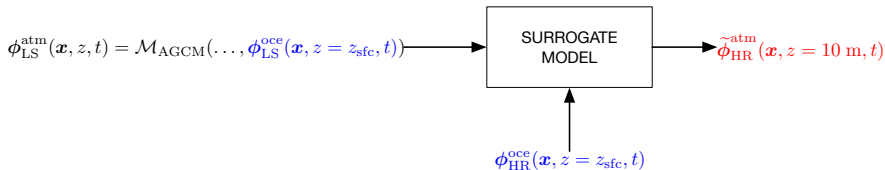
Table : Variables exchanged between NEMO and WW3 via OASIS – MCT.

- Examples of ORCA025 numerical results in next talk

2

Downscaling of atmospheric data at the oceanic resolution

Objectives



How to define such surrogate model ?

- Estimate $\partial \mathcal{M}_{AGCM} / \partial \phi_{sfc}^{oce}$ via sensitivity analysis and subsequent model reduction
- Build a surrogate model via learning strategies (huge computational and data requirements)
- Select feedback loops of interest and mimic the physical mechanisms

→ The newly developed computational framework allows all those possibilities to be investigated

Air-sea interactions at the oceanic mesoscales

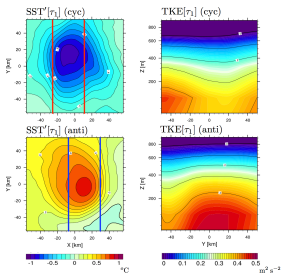
Wind-SST coupling (thermal coupling)

1. Modulation of PBL turbulence (e.g. Chelton, 2013; Frenger et al., 2013)

$$\begin{cases} \nabla \times \boldsymbol{\tau} = F_1(\nabla \text{SST}) \\ \nabla \cdot \boldsymbol{\tau} = F_2(\nabla \text{SST}) \end{cases}$$

2. Pressure gradient adjustment (e.g. Minobe 2008; Lambaerts et al. 2013)

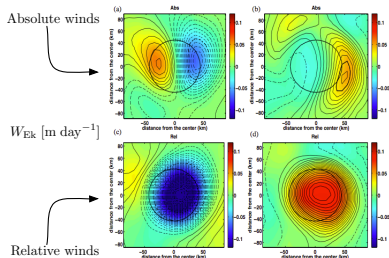
$$\nabla \cdot \boldsymbol{\tau} \propto -\|\nabla^2 \text{SST}\|$$



Current feedback (dynamical coupling)

$$\boldsymbol{\tau} = \rho_a C_D \|\mathbf{u}_a - \mathbf{u}_o\| (\mathbf{u}_a - \mathbf{u}_o)$$

- Strongly reduced mesoscale activity ("eddy damping") (e.g. Dewar & Flierl, 1987; Renault et al., 2016)
- Strongly increases vertical velocity anomalies associated to eddies (e.g. Oerder et al., 2017)



Air-sea interactions at the oceanic mesoscales

- ▷ A good representation of those interactions requires an interactive MABL
 - Under-estimation of wind-SST coupling in bulk mode
 - Over-estimation of wind-current coupling in bulk mode
- ▷ The atmospheric resolution must be "eddy-resolving" (i.e. $\Delta x_{\text{oce}} \approx \Delta x_{\text{atm}}$)
- ▷ Interactive MABL required for a consistent integration of surface waves

Similar initiatives :

- Advective atmospheric mixed layer model of [Seager et al., 1995](#)
- CheapAML ([Deremble et al., 2013](#)) → dynamically passive ABL model

Current status of the project (1/2)

1. Definition of a single-column model (ABL1d)

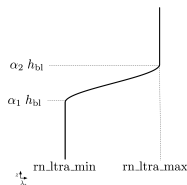
Integrate winds \mathbf{u} , potential temperature θ and specific humidity q

$$\begin{cases} \partial_t \mathbf{u} &= f \mathbf{k} \times \mathbf{u} + \partial_z (\mathbf{K}_m \partial_z \mathbf{u}) - \left(\frac{1}{\rho} \nabla p \right)_{LS} \\ \partial_t \theta &= \partial_z (\mathbf{K}_s \partial_z \theta) + \lambda_s (\mathcal{S}(\theta) - \theta_{LS}) \\ \partial_t q &= \partial_z (\mathbf{K}_s \partial_z q) + \lambda_s (\mathcal{S}(q) - q_{LS}) \end{cases}$$

Blue terms are specified via large-scale data

Red terms are given by turbulent closure

- ▶ **Radiative forcing** is kept as it is
- ▶ **Surface boundary conditions** for $K_m \partial_z \mathbf{u}|_{z=0}$, $K_s \partial_z \theta|_{z=0}$, $K_s \partial_z q|_{z=0}$ via IFS (aerobulk) bulk formulation
- ▶ **Relaxation term** scales with PBL height



Current status of the project (2/2)

2. Turbulent closure scheme : TKE-based scheme of Cuxart et al. (2000)

- ▷ used operationally at Meteo-France (e.g. in Arome and Meso-NH models)
- ▷ recoded from scratch to allow more flexibility and better performances

3. Development of preprocessing tools for large-scale forcing

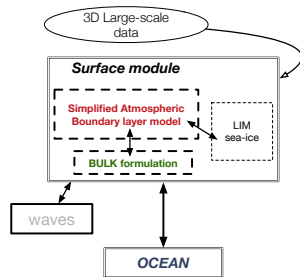
4. Implementation in NEMO surface module

- Option to split NEMO and SAS on separate nodes
- Standalone mode
- **Compatible with sea-ice**

Computational cost (50 vertical levels, no sea-ice)

- + 12% in memory
- + 7 - 12 % en elapsed time (depending on options)

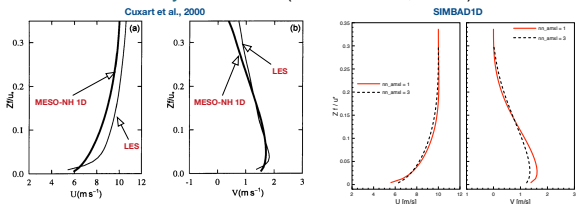
	GLS	ext. mode	ABL1d	I/O
Bulk mode	19.44%	11.3%	-	0.34%
ABL mode	18.06%	10.5%	6.3%	0.64%



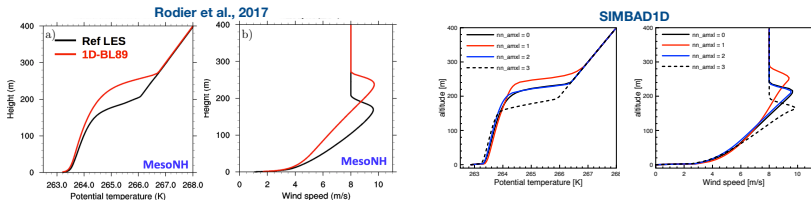
Current status of the validation strategy (1/2)

1. Standardized test-cases from ABL community (see GABLS initiative)

→ Neutral turbulent Ekman layer at 45°N (Cuxart et al., 2000)

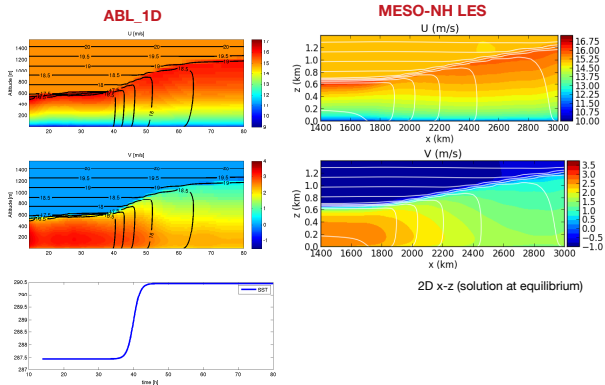


→ Stably stratified boundary layer (typical situation over sea-ice)



Current status of the validation strategy (2/2)

2. Winds across a Midlatitude SST Front (Kilpatrick et al., 2014)

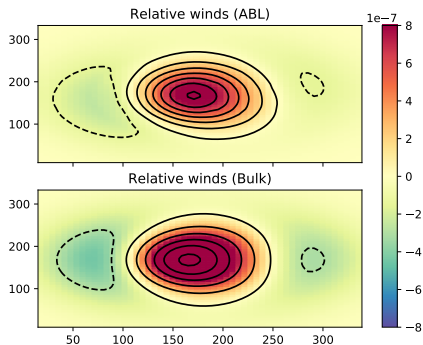


3. NEMO1D / ABL1D coupling at PAPA station (50.1°N, 144.9°W)

→ Théo Brivoal MSc

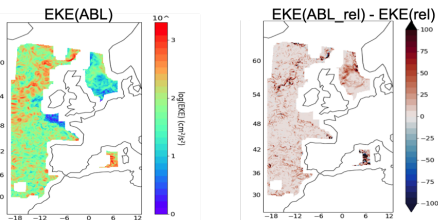
Examples of numerical results

Large-scale winds over an idealized eddy

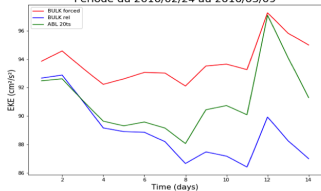


⇒ Reduction by 30% of wind stress curl

Bay of Biscay 1/12° realistic simulations



Période du 2016/02/24 au 2016/03/09



Courtesy of Mercator Ocean

Conclusions

- Implementation of a 2-way ocean-wave model including the wave-induced terms thought to be relevant at global eddying scales
- Representation of some mesoscale air-sea feedbacks with a simplified model
 - ABL response qualitatively and quantitatively ok in idealized experiments
→ extension to realistic cases
 - Validation of implementation over sea-ice
 - More advanced formulation including horizontal advection and fine-scale pressure gradient will be tested (based on Konor, 2013; Durran, 2008)



Publications to come

- Couvelard X., F. Lemarié, G. Samson, J.L. Redelsperger, F. Ardhuin, R. Benshila, G. Madec, *Development of a 2-way coupled ocean-wave model: assessment on a global oceanic configuration*, Geosc. Mod. Dev.
- Lemarié F., G. Samson, J.-L. Redelsperger, H. Giordani, G. Madec, R. Bourdallé Badie, T. Brivoal, *A simplified atmospheric boundary layer model for oceanic modeling purposes*, Geosc. Mod. Dev.