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 ($e_3 = \partial_k z$)

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

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

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

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

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

- 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 $\mathbf{u}_h^s(z_k) = \frac{\mathbf{u}_h^s(\eta)}{(\mathrm{e}_3)_k} \int_{z_{k-1/2}}^{z_{k+1/2}} \mathcal{S}(z,k_e)dz$

Computation of surface momentum flux

- **In NEMO :** $\boldsymbol{\tau}^{\mathrm{atm}}$ from IFS bulk formulation (Aerobulk) using α_{ch} from wave model.
- **In wave model :** $\boldsymbol{\tau}_{\mathrm{ww3}}^{\mathrm{atm}}$ assumes neutral stratification (wave models hyper sensitivite to stress computation).

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

$$\boldsymbol{\tau}^{\mathrm{oce}} = \boldsymbol{\tau}^{\mathrm{atm}} - \left(\widehat{\boldsymbol{\tau}_{\mathrm{ww3}}^{\mathrm{atm}} - \boldsymbol{\tau}_{\mathrm{ww3}}^{\mathrm{oce}}}\right)$$

▷ Pragmatic choice which breaks momentum conservation.

Wave-enhanced mixing (1-equation TKE scheme)

Additional terms in wavy hydrostatic balance affects TKE equation

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

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

$$\partial_t e = \frac{A^{vm}}{\mathrm{e}_3^2} \left[(\partial_k u)^2 + (\partial_k v)^2 + (\partial_k u)(\partial_k u^s) + (\partial_k v^s)(\partial_k v^s) \right] - A^{vt} N^2 + \frac{1}{\mathrm{e}_3} \partial_k \left[\frac{A^{ve}}{\mathrm{e}_3} \partial_k e \right] - c_\epsilon \frac{e^{3/2}}{l_\varepsilon^2}$$

Surface B.C. for e : $\left(\frac{A^{ve}}{\mathrm{e}_3} \partial_k e \right)_{z=z_1} = -\rho_0 g \int_0^{2\pi} \int_0^\infty S_{\mathrm{ds}} d\omega d\theta$

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

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

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

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Langmuir cells parameterization : Axell (2002)

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

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

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

Practical implementation

- $\mathrm{OASIS-MCT}$ 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
$\mathbf{u}_{10}^{\mathrm{atm}}$	$10\ \mathrm{m}$-winds from external dataset	O→W
$\mathbf{u}_h^s(z=\eta)$	Sea-surface Stokes drift	W→O
$\lVert\mathbf{T}^s\rVert$	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
$\boldsymbol{\tau}_{\mathrm{w}}^{\mathrm{ww3}}$	Wave-supported stress	W→O
$\widetilde{p}^J$	Bernoulli head	W→O

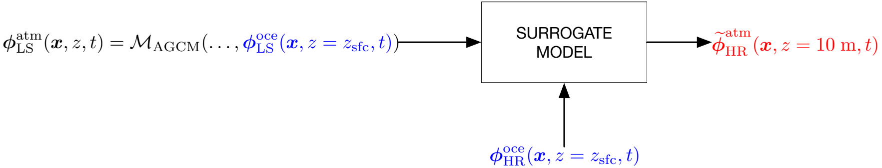
Table : Variables exchanged between NEMO and $\mathrm{WW3}$ via $\mathrm{OASIS-MCT}$.

- Examples of $\mathrm{ORCA025}$ numerical results in next talk

2

Downscaling of atmospheric data at the oceanic resolution

Objectives



How to define such surrogate model ?

- Estimate $\partial\mathcal{M}_{\mathrm{AGCM}}/\partial\phi^{\mathrm{oce}}_{\mathrm{sfc}}$ 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

$\rightarrow$ The newly developed computational framework allows all those possibilities to be investigated

Air-sea interactions at the oceanic mesoscales

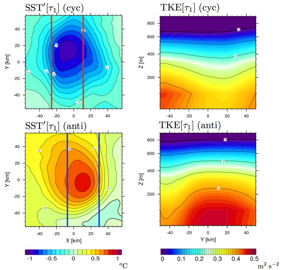
Wind-SST coupling (thermal coupling)

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

$$\left\{ \begin{array}{rcl} \nabla \times \boldsymbol{\tau} & = & F_1\left(\nabla \mathrm{SST}\right) \\ \nabla \cdot \boldsymbol{\tau} & = & F_2\left(\nabla \mathrm{SST}\right) \end{array} \right.$$

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

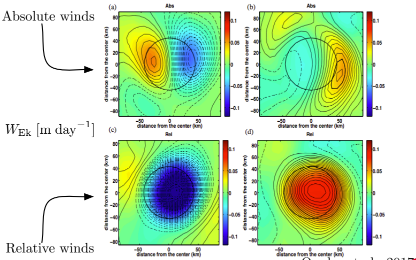
$$\nabla \cdot \boldsymbol{\tau} \propto -\|\nabla^2 \mathrm{SST}\|$$



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)



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. $\Delta x_{\rm oce} \approx \Delta x_{\rm atm}$)
- ▷ 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) $\rightarrow$ dynamically passive ABL model

Current status of the project (1/2)

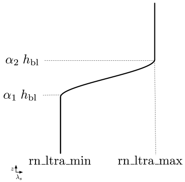
1. Definition of a single-column model (ABL1d)

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

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

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

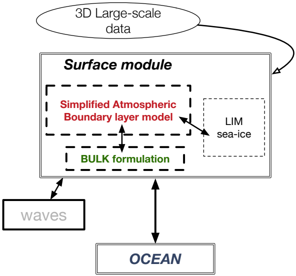


Current status of the project (2/2)

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)

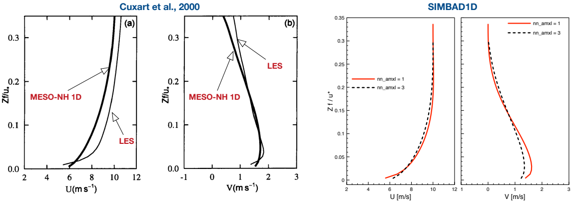
- + 12% in memory
- + 7 - 12 % en elapsed time (depending on options)

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

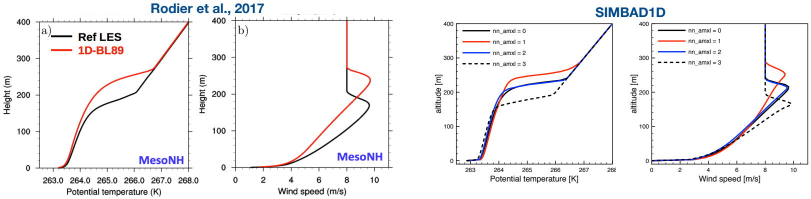
Current status of the validation strategy (1/2)

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

→ Neutral turbulent Ekman layer at 45^0N (Cuxart et al., 2000)



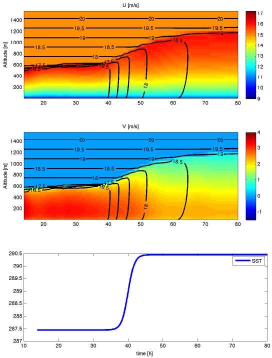
→ Stably stratified boundary layer (typical situation over sea-ice)



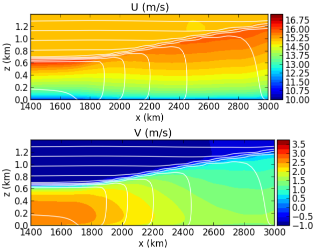
Current status of the validation strategy (2/2)

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

ABL_1D



MESO-NH LES



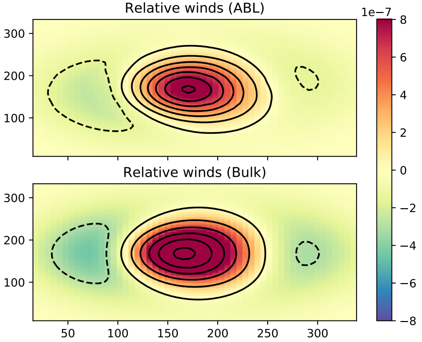
2D x-z (solution at equilibrium)

3. NEMO1D / ABL1D coupling at PAPA station (50.1^oN, 144.9^oW)

$\rightarrow$ Théo Brivoal MSc

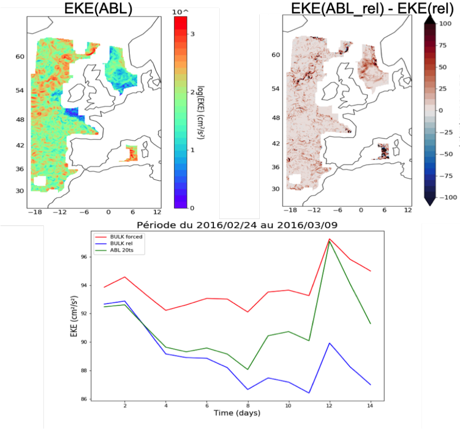
Examples of numerical results

Large-scale winds over an idealized eddy



$\Rightarrow$ Reduction by 30% of wind stress curl

Bay of Biscay $1/12°$ realistic simulations



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
    $\rightarrow$ 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.