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 \((e_3 = \partial_k z)\)

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

- \((u^s, v^s, \omega^s)\) : 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

\[
\mathbf{W}_{\text{St-Cor}} = \begin{pmatrix}
fv^s \\
-fu^s \\
0
\end{pmatrix}, \quad \mathbf{W}_{\text{VF}} = \begin{pmatrix}
\zeta v^s - \frac{\omega^s}{e_3} \partial_k u \\
-\zeta u^s - \frac{\omega^s}{e_3} \partial_k v \\
u^s e_3 \partial_k u + v^s e_3 \partial_k v
\end{pmatrix}, \quad \mathbf{W}_{\text{Prs}} = \begin{pmatrix}
p^J + \tilde{p} \\
p^J + \tilde{p}
\end{pmatrix}
\]
Curl form of NEMO equations with generalized vert. coordinate \((e_3 = \partial_k z)\)

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

▷ 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 \(\omega^s\)
Reconstruction of Stokes drift velocity profile

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

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

Computation of surface momentum flux

- In NEMO: \( \tau_{atm} \) from IFS bulk formulation (Aerobulk) using \( \alpha_{ch} \) from wave model.
- In wave model: \( \tau_{atm}^{ww3} \) assumes neutral stratification (wave models hyper sensitivite to stress computation).

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

\[ \tau_{oce} = \tau_{atm} - (\tau_{atm}^{ww3} - \tau_{oce}^{ww3}) \]

▷ Pragmatic choice which breaks momentum conservation.
Wave-enhanced mixing (1-equation TKE scheme)

Additional terms in wavy hydrostatic balance affects TKE equation

\[ u_h^s \partial_z \langle u'_h w' \rangle = \langle u'_h w' \rangle \partial_z u_h^s + \partial_z \left( u_h^s \langle u'_h w' \rangle \right) \]

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

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

Surface B.C. for \( e \):

\[ \left( \frac{A^{ve}}{e_3} \partial_k e \right)_{z=z_1} = -\rho_0 g \int_0^{2\pi} \int_0^\infty S_{ds} ds d\omega d\theta \]

Surface B.C. for mixing length:

\[ l_z = \eta = \kappa \frac{(C_m c_\epsilon)^{1/4} \left( \eta + z_0 \right)}{C_m} \]

\( z_0 = 1.6H_s \)
Wave-enhanced mixing (1-equation TKE scheme)

Additional terms in wavy hydrostatic balance affects TKE equation

\[
\begin{align*}
\mathbf{u}_h^s \partial_z \langle \mathbf{u}_h' w' \rangle &= \langle \mathbf{u}_h' w' \rangle \partial_z \mathbf{u}_h^s + \partial_z \left( \mathbf{u}_h^s \langle \mathbf{u}_h' w' \rangle \right)
\end{align*}
\]

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

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


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

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

\( \|	ilde{u}_s\| = \max \{ \mathbf{u}_s(\eta) \cdot \mathbf{e}_\tau, 0 \} \) intensity of LC scales with \( \theta_{u_s\tau} \) (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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_h(z = \eta) )</td>
<td>Oceanic surface currents</td>
<td>O→W</td>
</tr>
<tr>
<td>( u_{10}^{\text{atm}} )</td>
<td>10 m-winds from external dataset</td>
<td>O→W</td>
</tr>
<tr>
<td>( u_s(z = \eta) )</td>
<td>Sea-surface Stokes drift</td>
<td>W→O</td>
</tr>
<tr>
<td>(</td>
<td></td>
<td>T^s</td>
</tr>
<tr>
<td>( \Phi_{oc} )</td>
<td>TKE surface flux multiplied by ( \rho_0 )</td>
<td>W→O</td>
</tr>
<tr>
<td>( \alpha_{ch} )</td>
<td>Charnock parameter</td>
<td>W→O</td>
</tr>
<tr>
<td>( H_s )</td>
<td>Significant wave height</td>
<td>W→O</td>
</tr>
<tr>
<td>( \tau_{ww3}^w )</td>
<td>Wave-supported stress</td>
<td>W→O</td>
</tr>
<tr>
<td>( \tilde{p}^J )</td>
<td>Bernoulli head</td>
<td>W→O</td>
</tr>
</tbody>
</table>

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 $\frac{\partial M_{AGCM}}{\partial \phi_{sfc}}$ 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

→ 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)

\[
\begin{align*}
\nabla \times \tau &= F_1 (\nabla \text{SST}) \\
\nabla \cdot \tau &= F_2 (\nabla \text{SST})
\end{align*}
\]

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

\[\nabla \cdot \tau \propto -\|\nabla^2 \text{SST}\|\]

Current feedback (dynamical coupling)

\[\tau = \rho_a C_D \| \mathbf{u}_a - \mathbf{u}_o \| (\mathbf{u}_a - \mathbf{u}_o)\]

- 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 $u$, potential temperature $\theta$ and specific humidity $q$

\[
\begin{align*}
\partial_t u &= f k \times u + \partial_z (K_m \partial_z u) - \left( \frac{1}{\rho} \nabla p \right)_\text{LS} \\
\partial_t \theta &= \partial_z (K_s \partial_z \theta) + \lambda_s (S(\theta) - \theta_\text{LS}) \\
\partial_t q &= \partial_z (K_s \partial_z q) + \lambda_s (S(q) - q_\text{LS})
\end{align*}
\]

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 $K_m \partial_z u|_{z=0}$, $K_s \partial_z \theta|_{z=0}$, $K_s \partial_z q|_{z=0}$ 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)

<table>
<thead>
<tr>
<th></th>
<th>GLS</th>
<th>ext. mode</th>
<th>ABL1d</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk mode</td>
<td>19.44%</td>
<td>11.3%</td>
<td>-</td>
<td>0.34%</td>
</tr>
<tr>
<td>ABL mode</td>
<td>18.06%</td>
<td>10.5%</td>
<td>6.3%</td>
<td>0.64%</td>
</tr>
</tbody>
</table>
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)

F. Lemarié – Recent developments in NEMO within Albatross
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 $1/12^\circ$ 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 → 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
