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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 ($e_3 = \partial_k z$)

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

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

\[ \begin{align*}
W_{St-Cor} &= \begin{pmatrix} f v^s \\ -f u^s \\ 0 \end{pmatrix}, \quad W_{VF} = \begin{pmatrix} \zeta v^s - \frac{\omega^s}{e_3} \partial_k u \\ -\zeta u^s - \frac{\omega^s}{e_3} \partial_k v \\ \frac{\omega^s}{e_3} \partial_k u + \frac{v^s}{e_3} \partial_k v \end{pmatrix}, \quad W_{Prs} = \begin{pmatrix} p^J + \tilde{p} \\ p^J + \tilde{p} \\ \tilde{p} \end{pmatrix}
\]
Curl form of NEMO equations with generalized vert. coordinate \((e_3 = \partial_k z)\)

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

▷ Small vertical shear limit (Bennis et al., 2011) \(\rightarrow\) 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: $u^s_h(\eta), \|T^s\|$, $\rightarrow u^s_h(z, k_e) = u^s_h(\eta)S(z, k_e)$

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

Computation of surface momentum flux

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

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

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

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

Additional terms in wavy hydrostatic balance affects TKE equation

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

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

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

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

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

Surface B.C. for mixing length:

\[ l_{z=\eta} = \kappa \frac{(C_mC_{e})^{1/4}}{C_m} (\eta + z_0), \quad z_0 = 1.6 H_s \]
Wave-enhanced mixing (1-equation TKE scheme)

Additional terms in wavy hydrostatic balance affects TKE equation

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

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

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


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

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

\[ \| \tilde{u}_s \| = \max \{ u_s(\eta) \cdot e_\tau, 0 \} \] 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>From</th>
<th>To</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_h(z = \eta) )</td>
<td>Oceanic surface currents</td>
<td>O→W</td>
<td></td>
</tr>
<tr>
<td>( u_{atm}^{10} )</td>
<td>10 m-winds from external dataset</td>
<td>O→W</td>
<td></td>
</tr>
<tr>
<td>( u_s^s(z = \eta) )</td>
<td>Sea-surface Stokes drift</td>
<td>W→O</td>
<td></td>
</tr>
<tr>
<td>( |T^s| )</td>
<td>norm of the Stokes drift volume transport</td>
<td>W→O</td>
<td></td>
</tr>
<tr>
<td>( \Phi_{oc} )</td>
<td>TKE surface flux multiplied by ( \rho_0 )</td>
<td>W→O</td>
<td></td>
</tr>
<tr>
<td>( \alpha_{ch} )</td>
<td>Charnock parameter</td>
<td>W→O</td>
<td></td>
</tr>
<tr>
<td>( H_s )</td>
<td>Significant wave height</td>
<td>W→O</td>
<td></td>
</tr>
<tr>
<td>( \tau_{w}^{ww3} )</td>
<td>Wave-supported stress</td>
<td>W→O</td>
<td></td>
</tr>
<tr>
<td>( \tilde{p}^J )</td>
<td>Bernoulli head</td>
<td>W→O</td>
<td></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

\[ \phi_{\text{atm}}(x, z, t) = \mathcal{M}_{\text{AGCM}}(\ldots, \phi_{\text{oce}}^L(x, z = z_{\text{sfc}}, t)) \]

How to define such surrogate model?

- Estimate \( \frac{\partial \mathcal{M}_{\text{AGCM}}}{\partial \phi_{\text{oce}}^\text{sfc}} \) 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

\[ \phi_{\text{HR}}(x, z = 10 \text{ m}, t) \]

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)

---

**Absolute winds**

**Relative winds**

**$W_{Ek \ [m \ day^{-1}]$**

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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 $q$

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

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

EKE(ABL)

EKE(ABL_rel) - EKE(rel)

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
