Toward an improved representation of air-sea interactions in high-resolution global ocean forecasting systems

PPR Simbad

F. Lemarié¹, G. Samson², J.L. Redelsperger³, H. Giordani⁴, G. Madec⁵, R. Patoum¹, R. Bourdallé-Badie², T. Brivoal²

¹ Inria, Université Grenoble Alpes, LJK, Grenoble, France
² Mercator Océan, Toulouse, France
³ Laboratory for Ocean Physics and Satellite remote sensing, Brest, France
⁴ Météo-France, Toulouse, France
⁵ Sorbonne Universités-CNRS-IRD-MNHN, LOCEAN Laboratory, Paris, France
General context – Composite averaging in an eddy-centric coordinate

Eddy composites for the southern ocean from obs. [Frenger et al., 2013]

Eddy-induced vertical velocities from obs. [Chelton, 2013]

TKE in MABL from coupled model [Lemarié et al.]

Strong thermal and dynamical coupling at the characteristic scales of the oceanic mesoscale

⇒ Ocean is not passive and only forced by the atmosphere

+ Work by F. Colas, V. Echevin, H. Giordani, S. Jullien, S. Masson, V. Oerder, L. Renault, …
Limitation of current practices in global models

→ **Bulk forcing** (i.e. via an atmospheric surface-layer parameterization)
  - effect of thermal coupling is **under-estimated** (no downward mixing)
  - effect of dynamical coupling is **over-estimated** (wrong energy transfers)

![Image of EKE](image)

[Renault et al., 2016]

→ **CheapAML** [Deremble et al., 2013]
  - Designed for large scales (no thermal or dynamical coupling)

→ **Full-coupling**
  - computationally unaffordable when $\Delta x_{oce} = \Delta x_{atm}$
  - hard to find a good "set" of parameterizations
  - Initialization issues

What are the alternatives to force an eddying global operational model (?)
1 Proposed methodology

2 Simbad1d: a simplified marine atmospheric boundary layer model

3 Atmosphere-only numerical tests

4 Coupling with an OGCM and preliminary tests
Proposed methodology

⇒ General approach: dynamical downscaling of atmospheric data to the oceanic resolution via a simplified MABL model (called SIMBAD) guided by operational weather forecasts or reanalysis (e.g. ERAI, operational IFS)

Momentum equation

$$\partial_t u + u \cdot \nabla u = -f k \times u - \frac{1}{\rho} \nabla p + \partial_z(K_M(z) \partial_z u)$$

- Advection
- Coriolis
- Pressure gradient
- Turbulent mixing

- Radiative forcing is kept as it is
- Which term should be recomputed at the resolution of the ocean?

What is the appropriate level of complexity ...
Proposed methodology

⇒ General approach: dynamical downscaling of atmospheric data to the oceanic resolution via a simplified MABL model (called SIMBAD) guided by operational weather forecasts or reanalysis (e.g. ERAi, operational IFS)

Momentum equation

\[
\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -f \mathbf{k} \times \mathbf{u} - \frac{1}{\rho} \nabla p + \frac{\partial}{\partial z} (K_M(z) \partial_z \mathbf{u})
\]

▷ Radiative forcing is kept as it is
▷ Which term should be recomputed at the resolution of the ocean?

1. Derive a single-column model (SCM) (Coriolis + turbulent mixing)
2. Define a coupling between SCMs [e.g. giordani, 2006]
3. Define an integral "shallow-water like" version with slab model
Continuous formulation of single-column MABL model

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

\[
\begin{align*}
\partial_t \mathbf{u} &= f_k \times \mathbf{u} + \partial_z (K_m \partial_z \mathbf{u}) + R_{LS} \\
\partial_t \theta &= \partial_z (K_s \partial_z \theta) + \lambda_s (\theta - \theta_{LS}) \\
\partial_t q &= \partial_z (K_s \partial_z q) + \lambda_s (q - q_{LS})
\end{align*}
\]

$R_{LS}$ represents a geostrophic "guide" and/or a Newtonian relaxation

Surface boundary conditions for $K_m \partial_z \mathbf{u}|_{z=0}$, $K_s \partial_z \theta|_{z=0}$, $K_s \partial_z q|_{z=0}$

→ IFS bulk formulation

▷ used operationally at ECMWF
▷ consistent with large-scale data
▷ include sea-state and convective limit

Relaxation term scales with PBL height
Continuous formulation of single-column MABL model

Integrate winds $u$, potential temperature $\theta$ and specific humidity $q$

\[
\begin{align*}
\partial_t u &= f \mathbf{k} \times u + \partial_z (K_m \partial_z u) + R_{LS} \\
\partial_t \theta &= \partial_z (K_s \partial_z \theta) + \lambda_s (\theta - \theta_{LS}) \\
\partial_t q &= \partial_z (K_s \partial_z q) + \lambda_s (q - q_{LS})
\end{align*}
\]

$R_{LS}$ represents a geostrophic "guide" and/or a Newtonian relaxation.

Surface boundary conditions for $K_m \partial_z u |_{z=0}$, $K_s \partial_z \theta |_{z=0}$, $K_s \partial_z q |_{z=0}$

→ IFS bulk formulation

- used operationally at ECMWF
- consistent with large-scale data
- include sea-state and convective limit

Relaxation term scales with PBL height.
Closure scheme

**TKE-based scheme** following [Cuxart, Bougeault, Redelsperger, 2000]

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

\[
\begin{aligned}
\partial_t e &= K_m \left[ (\partial_z \langle u \rangle)^2 + (\partial_z \langle v \rangle)^2 \right] - K_s N^2 + \partial_z (K_e \partial_z e) - \frac{c_\varepsilon}{L} e^{3/2} \\
e(z = 0) &= 4.63 u_*^2 + 0.2 w_*^2
\end{aligned}
\]

\[
K_s = \frac{L}{6} \phi_z \sqrt{e}, \quad K_e = \frac{4L}{10} \sqrt{e}, \quad K_m = \frac{L}{15} \sqrt{e}, \quad \phi_z(z) = f(L, N^2, e)
\]

**Computation of the diagnostic mixing length \( L \)**

At a discrete level we ensure consistency with

- MO theory in surface layer [Redelsperger et al. 2001] (i.e. \( L = 2.8z \))

- [Deardorff, 1980] scale for \( N^2 = cste \) (i.e. \( L = \sqrt{2e/N^2} \))

- [Bougeault & Lacarrere, 1989] length scale with shear-dependent term of [Rodier et al., 2017]
Evaluation of Simbad1D on standard test-case suite

→ Validation methodology along the lines of the GABLS (GEWEX Atmospheric Boundary Layer Study) initiative

- Definition of standardized test-cases
- Model inter-comparisons between LES and SCMs

Testcases for the validation of Simbad1D

1. Neutrally stratified testcase [Andren et al., 1994]
2. GABLS1 : Stably stratified ABL [Cuxart et al., 2006] (typical situation over sea-ice)
3. Winds across a Midlatitude SST Front [Kilpatrick et al., 2014]

Simulations of reference obtained thanks to MESO-NH in LES mode
A neutral turbulent Ekman layer at 45°N

- \((u_G, v_G) = (10, 0) \text{ m s}^{-1}\)
- Roughness length of \(z_o = 0.1 \text{ m}\)
- Simulation of 28 hours

→ Improved results thanks to the discrete consistency with MO theory in surface-layer
Stably stratified boundary layer (GABLS1)

Rodier et al., 2017

\[(u_G, v_G) = (8, 0) \text{ m/s}\]

Simulation of 9 hours

\[\theta_s(t) = -10^\circ C - t/4\]

\[\Delta \theta_{ini} = 2^\circ C\]
Lagrangian advection of an air column over a SST front (dry case)

**SIMBAD 1D**

- \((u_G, v_G) = (15, 0) \text{ m/s}\)
- Cold side: SST = 14.3°C
- Warm side: SST = 17.3°C
- \(N^2_v = 10^{-4} \text{s}^{-2}\), \(\theta(z = 0) = 15.8^\circ \text{C}\)
- \(q(z) = 0\)

**WRF** [Kilpatrick et al., 2014]

2D x-z (solution at equilibrium)
Lagrangian advection of an air column over a SST front (moist case)

SIMBAD 1D

\[(u_G, v_G) = (15, 0) \text{ m/s}\]
- Cold side: SST = 14.3°C
- Warm side: SST = 17.3°C
- \(N_v^2 = 10^{-4} \text{s}^{-2}\), \(\theta(z = 0) = 14°C\)
- \(q(z) = 10^{-2} \text{kg kg}^{-1}\)

MESO-NH LES

2D x-z (solution at equilibrium)
Implementation in NEMO surface module

Main developments

- Preprocessing tool to handle 3D IFS data
- Plug Simbad1D with a generic interface with the NEMO bulk routines
- Handle 3D atmospheric data instead of 2D relatively minor modifications overall

Take advantage of existing features

- Online interpolation of external data & I/Os
- Split NEMO and SAS on separate nodes
- Bulk formulae from Aerobulk (Brodeau et al.)
Performances : a first evaluation

TOY Configuration :

- 50 x 50 points, 75 vertical levels with the default Mercator settings
- 50 vertical levels in SIMBAD1D

→ ifort with optimization options on Intel Xeon CPU E5-1650 @ 3.20GHz

<table>
<thead>
<tr>
<th>module</th>
<th>subroutine</th>
<th>Bulk mode elapsed time</th>
<th>Bulk mode % time</th>
<th>ABL mode elapsed time</th>
<th>ABL mode % time</th>
</tr>
</thead>
<tbody>
<tr>
<td>zdflgs</td>
<td>zdf_gls</td>
<td>287.52 s</td>
<td>19.44</td>
<td>287.23 s</td>
<td>18.06</td>
</tr>
<tr>
<td>dynspg_ts</td>
<td>dyn_spg_ts</td>
<td>166.50 s</td>
<td>11.26</td>
<td>166.67 s</td>
<td>10.48</td>
</tr>
<tr>
<td>traadv_tvd</td>
<td>nonosc</td>
<td>117.66 s</td>
<td>7.95</td>
<td>114.96 s</td>
<td>7.23</td>
</tr>
<tr>
<td>traadv_tvd</td>
<td>tra_adv_tvd</td>
<td>54.32 s</td>
<td>3.67</td>
<td>54.26 s</td>
<td>3.41</td>
</tr>
<tr>
<td>dynzdf_imp</td>
<td>dyn_zdf_imp</td>
<td>49.21 s</td>
<td>3.33</td>
<td>49.66 s</td>
<td>3.12</td>
</tr>
<tr>
<td>ablmod</td>
<td>abl_stp</td>
<td>-</td>
<td>-</td>
<td>49.08 s</td>
<td>3.09</td>
</tr>
<tr>
<td>dynldf_bilap</td>
<td>dyn_ldf_bilap</td>
<td>47.44 s</td>
<td>3.21</td>
<td>47.92 s</td>
<td>3.01</td>
</tr>
<tr>
<td>domvvl</td>
<td>dom_vvl_interpol</td>
<td>47.34 s</td>
<td>3.20</td>
<td>47.66 s</td>
<td>3.00</td>
</tr>
<tr>
<td>eosbn2</td>
<td>rab_3d</td>
<td>42.74 s</td>
<td>2.89</td>
<td>42.57 s</td>
<td>2.68</td>
</tr>
<tr>
<td>ablmod</td>
<td>abl_zdf_tke</td>
<td>-</td>
<td>-</td>
<td>49.59 s</td>
<td>2.49</td>
</tr>
<tr>
<td>trazdf_imp</td>
<td>tra_zdf_imp</td>
<td>28.42 s</td>
<td>1.92</td>
<td>28.13 s</td>
<td>1.77</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>fldread</td>
<td>fld_read</td>
<td>5.00 s</td>
<td>0.34</td>
<td>10.10 s</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Increase of memory size ≈ 12% 24m39 26m30
Ongoing work & perspectives

- NEMO1D / SIMBAD1D coupling at the PAPA station (50.1°N, 144.9°W)

  - Sensitivity tests and comparison with IFS surface fluxes at global scale
  - Increased level of complexity (add horizontal/vertical advection and fine-scale pressure gradient)
  - Shallow-water like 2D $x$-$y$ integral layer version
  - SIMBAD over sea-ice
  - Initialization of the NEMO/SIMBAD coupled system (in collaboration with Arthur Vidard, Inria)