

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

F. Lemarié¹, G. Samson², J.L. Redelsperger³, H. Giordani⁴, G. Madec⁵

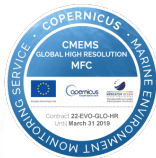
¹ Inria, Université Grenoble Alpes, LJK, Grenoble, France

² Mercator Océan, Toulouse, France

³ Laboratory for Ocean Physics and Satellite remote sensing, Brest, France

⁴ Météo-France, Toulouse, France

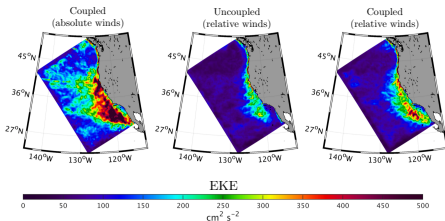
⁵ Sorbonne Universités-CNRS-IRD-MNHN, LOCEAN Laboratory, Paris, France



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)



[Renault et al., 2016]

→ CheapAML [Deremble et al., 2013]

- Designed for large scales (no thermal or dynamical coupling)

→ Full-coupling

- computationally unaffordable when $\Delta x_{\text{oce}} = \Delta x_{\text{atm}}$
- 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

⇒ **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

$$\partial_t \mathbf{u} + \underbrace{\mathbf{u} \cdot \nabla \mathbf{u}}_{\text{advection}} = \underbrace{-f \mathbf{k} \times \mathbf{u}}_{\text{coriolis}} - \underbrace{\frac{1}{\rho} \nabla p}_{\text{hpg}} + \underbrace{\partial_z (K_M(z) \partial_z \mathbf{u})}_{\text{turbulent mixing}}$$

- ▷ 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 ...

⇒ **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

$$\partial_t \mathbf{u} + \underbrace{\mathbf{u} \cdot \nabla \mathbf{u}}_{\text{advection}} = \underbrace{-f \mathbf{k} \times \mathbf{u}}_{\text{coriolis}} - \underbrace{\frac{1}{\rho} \nabla p}_{\text{hpg}} + \underbrace{\partial_z (K_M(z) \partial_z \mathbf{u})}_{\text{turbulent mixing}}$$

- ▷ 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 θ and specific humidity q

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

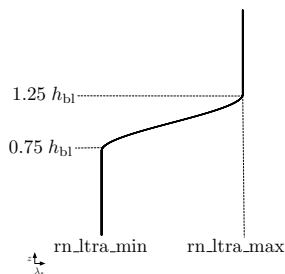
R_{LS} represents a geostrophic "guide" and/or a Newtonian relaxation

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

$$\begin{cases} \partial_t \mathbf{u} &= f \mathbf{k} \times \mathbf{u} + \partial_z (\mathbf{K}_m \partial_z \mathbf{u}) + R_{LS} \\ \partial_t \theta &= \partial_z (\mathbf{K}_s \partial_z \theta) + \lambda_s (\theta - \theta_{LS}) \\ \partial_t q &= \partial_z (\mathbf{K}_s \partial_z q) + \lambda_s (q - q_{LS}) \end{cases}$$

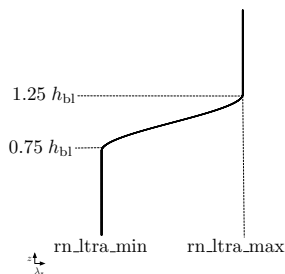
R_{LS} represents a geostrophic "guide" and/or a Newtonian relaxation

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



Closure scheme

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

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

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

$$\mathbf{K}_s = \frac{L}{6} \phi_z \sqrt{\mathbf{e}}, \quad K_e = \frac{4L}{10} \sqrt{\mathbf{e}}, \quad \mathbf{K}_m = \frac{L}{15} \sqrt{\mathbf{e}}, \quad \phi_z(z) = f(L, N^2, \mathbf{e})$$

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 $N^2 = \text{cste}$ (i.e. $L = \sqrt{2e/N^2}$)
- [Bougeault & Lacarrere, 1989] length scale with shear-dependent term of [Rodier et al., 2017]

- 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

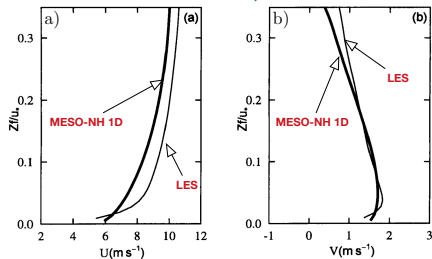
Testcases for the validation of Simbad1D

- 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]

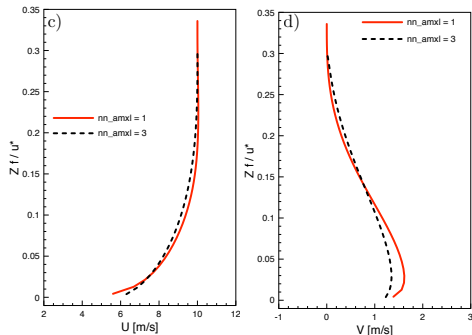
Simulations of reference obtained thanks to MESO-NH in LES mode

Neutrally stratified boundary layer

Cuxart et al., 2000



SIMBAD1D



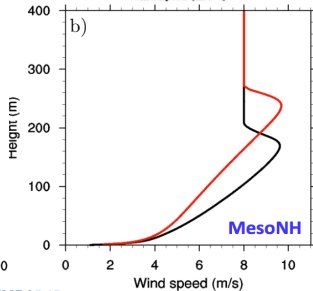
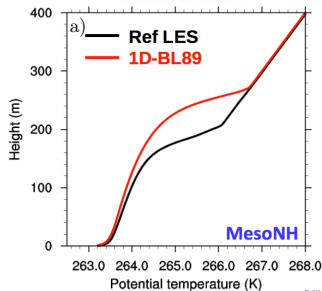
A neutral turbulent Ekman layer at 45°N

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

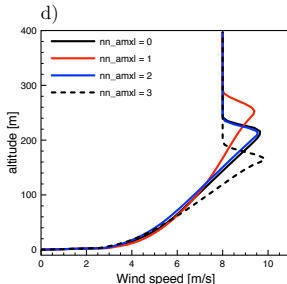
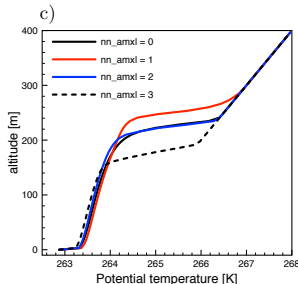
→ Improved results thanks to the discrete consistency with MO theory in surface-layer

Stably stratified boundary layer (GABLS1)

Rodier et al., 2017



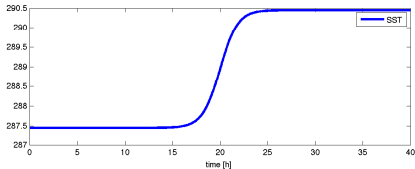
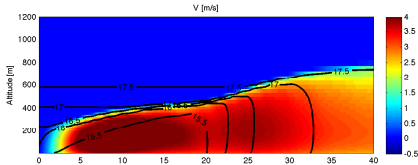
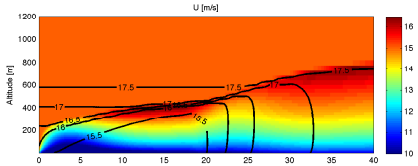
SIMBAD1D



- $(u_G, v_G) = (8, 0)$ m/s
- Simulation of 9 hours
- $\theta_s(t) = -10^\circ\text{C} - t/4$
- $\Delta\theta_{ini} = 2^\circ\text{C}$

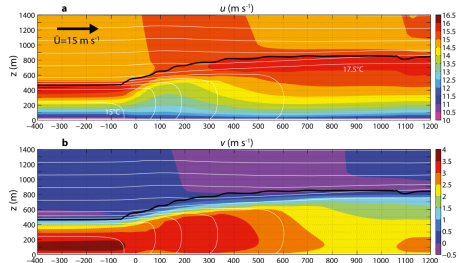
Langrangian advection of an air column over a SST front (dry case)

SIMBAD 1D



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

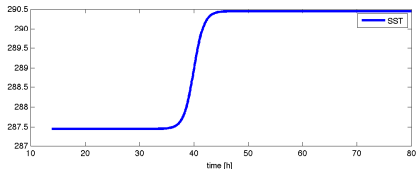
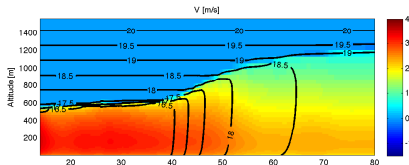
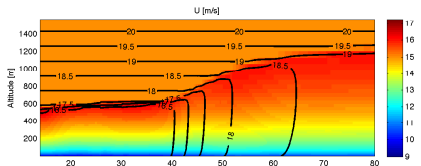
WRF [Kilpatrick et al., 2014]



2D x-z (solution at equilibrium)

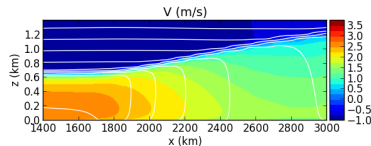
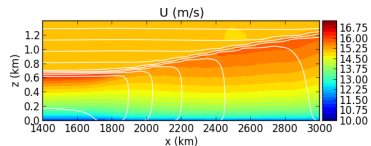
Langrangian advection of an air column over a SST front (moist case)

SIMBAD 1D



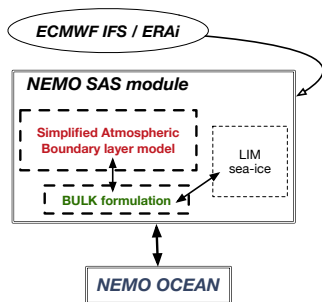
- $(u_G, v_G) = (15, 0)$ m/s
- Cold side : SST = 14.3°C
- Warm side : SST = 17.3°C
- $N_v^2 = 10^{-4} \text{s}^{-2}$, $\theta(z = 0) = 14^\circ\text{C}$
- $q(z) = 10^{-2} \text{kg kg}^{-1}$

MESO-NH LES



2D x-z (solution at equilibrium)

Implementation in NEMO surface module

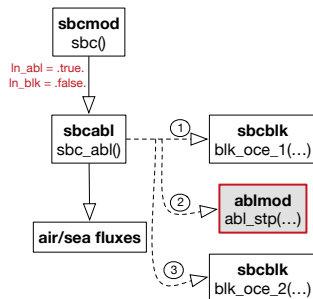


Main developments

- 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 :

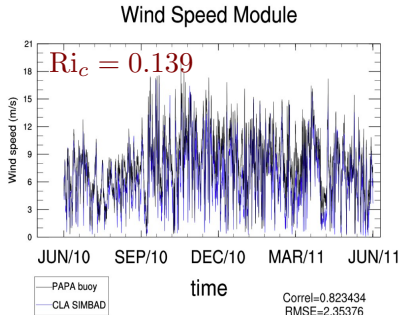
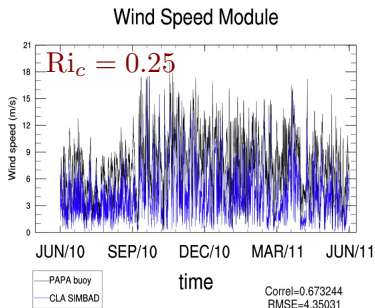
- 50 x 50 points, 75 vertical levels with the default Mercator settings
- 50 vertical levels in SIMBAD1D

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

		Bulk mode		ABL mode	
module	subroutine	elapsed time	% time	elapsed time	% time
zdfgls	zdf_gls	287.52 s	19.44	287.23 s	18.06
dynspg_ts	dyn_spg_ts	166.50 s	11.26	166.67 s	10.48
traadv_tvd	nonosc	117.66 s	7.95	114.96 s	7.23
traadv_tvd	tra_adv_tvd	54.32 s	3.67	54.26 s	3.41
dynzdf_imp	dyn_zdf_imp	49.21 s	3.33	49.66 s	3.12
ablmod	abl_stp	-	-	49.08 s	3.09
dynldf_bilap	dyn_ldf_bilap	47.44 s	3.21	47.92 s	3.01
domvvl	dom_vvl_interpol	47.34 s	3.20	47.66 s	3.00
eosbn2	rab_3d	42.74 s	2.89	42.57 s	2.68
ablmod	abl_zdf_tke	-	-	49.59 s	2.49
trazdf_imp	tra_zdf_imp	28.42 s	1.92	28.13 s	1.77
...
fldread	fld_read	5.00 s	0.34	10.10 s	0.64
Increase of memory size $\approx 12\%$		24m39		26m30	

Ongoing work

- ▷ NEMO1D / SIMBAD1D coupling at the PAPA station (50.1°N , 144.9°W)
 - Extension of the study [Reffray et al., 2015] with NEMO1d to the coupled case
 - Work done by T. Brivoal & G. Samson (Mercator-Ocean)

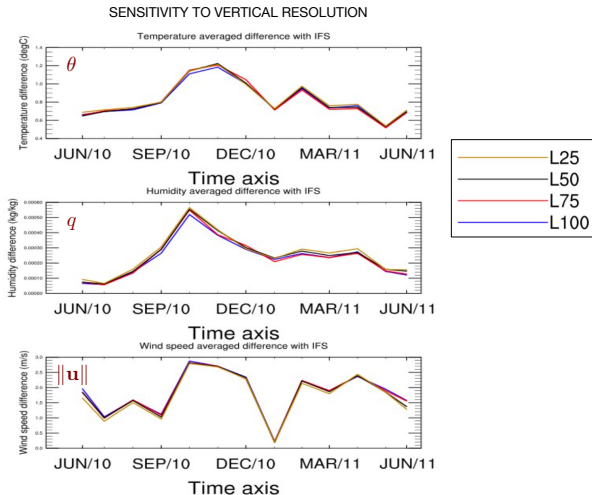


Large-scale data from operational IFS product

Ongoing work

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

- Extension of the study [Reffray et al., 2015] with NEMO1d to the coupled case
- Work done by T. Brivoal & G. Samson (Mercator-Ocean)



- 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)