



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

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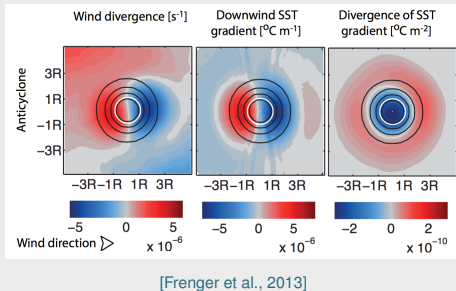
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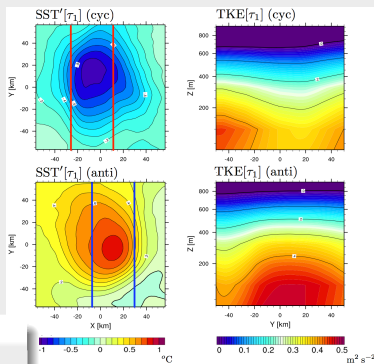
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General context: air-sea interactions in global eddying operational systems

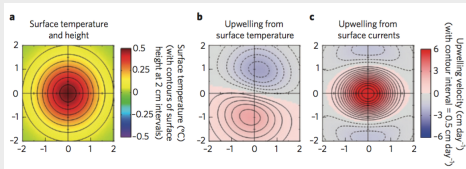
Eddy composites for the southern ocean from obs.



TKE in MABL from coupled model



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



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

Air-sea interactions at the oceanic mesoscales

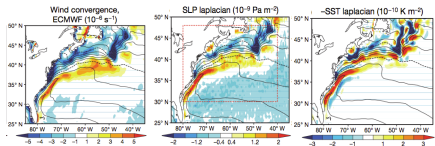
Wind-SST coupling (thermal coupling)

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

$$\begin{cases} \nabla \times \boldsymbol{\tau} = F_1(\nabla \text{SST}) \\ \nabla \cdot \boldsymbol{\tau} = F_2(\nabla \text{SST}) \end{cases}$$

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

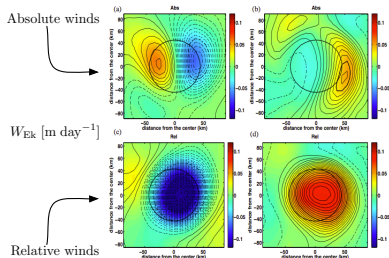
$$\nabla \cdot \boldsymbol{\tau} \propto -\|\nabla^2 \text{SST}\|$$



Current feedback (dynamical coupling)

$$\boldsymbol{\tau} = \rho_a C_D \|\mathbf{u}_a - \mathbf{u}_o\| (\mathbf{u}_a - \mathbf{u}_o)$$

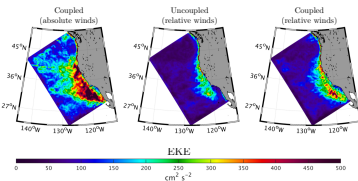
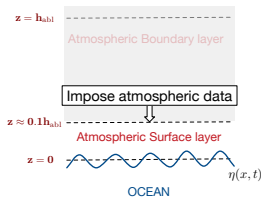
- Strongly reduced mesoscale activity ("eddy damping") (e.g. Dewar & Flierl, 1987; Renault et al., 2016)
- Strongly increases vertical velocity anomalies associated to eddies (e.g. Oerder et al., 2017)



Limitation of current practices in global eddying 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 and dynamically passive

→ **Full-coupling**

- Computationally intensive when $\Delta x_{oce} \approx \Delta x_{atm}$
- Initialization issues

What are the alternatives to obtain a coherent forcing of eddying global operational model (?)

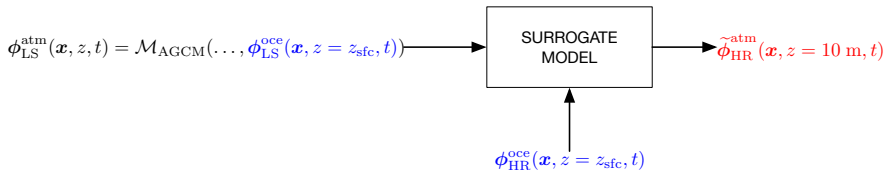
Outline

1. Proposed approach
2. Validation strategy
3. Planned work within IMMERSE

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Proposed approach

Objectives

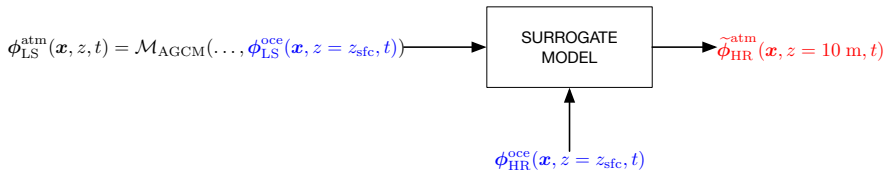


How to define such surrogate model ?

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

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Definition of a single-column model (ABL1d)

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

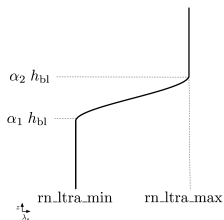
$$\begin{cases} \partial_t \mathbf{u} &= f \mathbf{k} \times \mathbf{u} + \partial_z (\mathbf{K}_m \partial_z \mathbf{u}) - \left(\frac{1}{\rho} \nabla p \right)_{\text{LS}} \\ \partial_t \theta &= \partial_z (\mathbf{K}_s \partial_z \theta) + \lambda_s (\mathcal{S}(\theta) - \theta_{\text{LS}}) \\ \partial_t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

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 $K_m \partial_z \mathbf{u}|_{z=0}$, $K_s \partial_z \theta|_{z=0}$, $K_s \partial_z q|_{z=0}$
- **IFS bulk formulation (Aerobulk)**
 - ▷ used operationally at ECMWF
 - ▷ consistent with large-scale data
 - ▷ include sea-state and convective limit

- ▷ **Relaxation term** scales with PBL height



Practical implementation

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

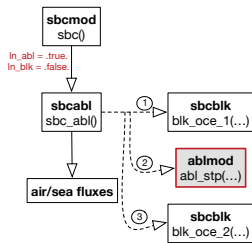
4. Implementation in NEMO surface module

- Online interpolation of external 3D data
- 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%



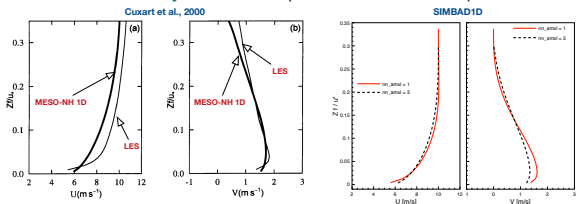
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Validation strategy

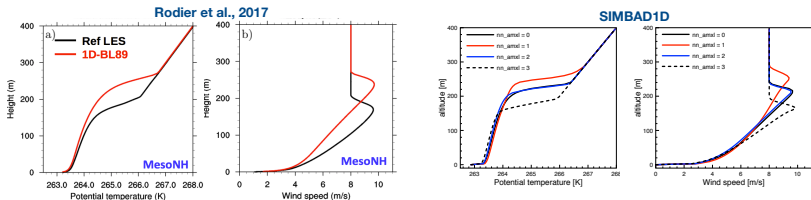
Current status of the validation strategy (1/2)

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

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

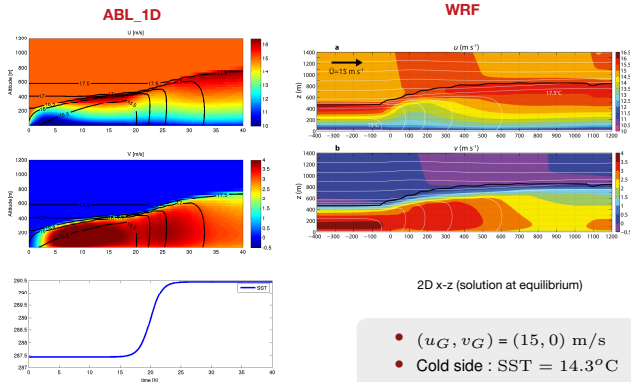


→ Stably stratified boundary layer (typical situation over sea-ice)



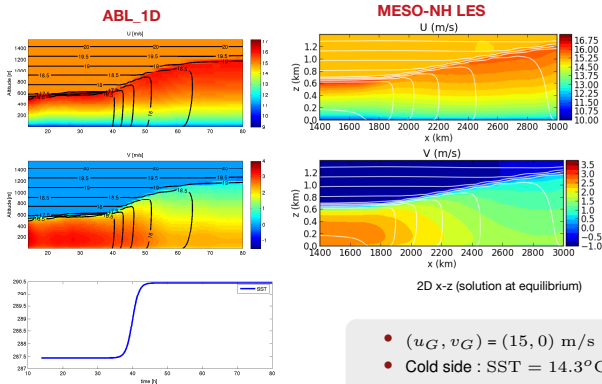
Current status of the validation strategy (2/2)

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



Current status of the validation strategy (2/2)

- Winds across a Midlatitude SST Front (Moist case)

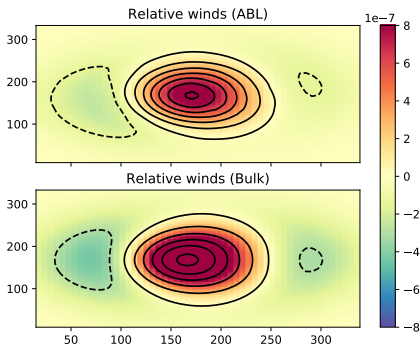


2D x - z (solution at equilibrium)

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

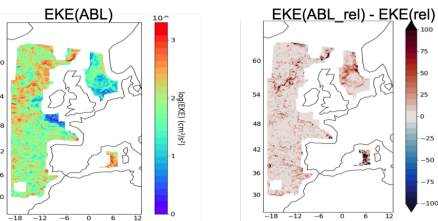
Preliminary realistic results

Large-scale winds over an idealized eddy

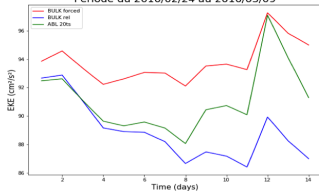


⇒ Reduction by 30% of wind stress curl

Bay of Biscay 1/12° realistic simulations



Période du 2016/02/24 au 2016/03/09



Courtesy of Mercator Ocean

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Planned work within IMMERSE

T5.1: Integration of an ABL model in NEMO

- Complete ABL-1D integration: proof of concept of the one dimensional version
- Ensure its full compatibility with the different functionalities of NEMO (AGRIF, fractions of open water and sea-ice categories)
- Toward a 3D-ABL model: development of a first version of a 3D ABL model

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- **Toward a 3D-ABL model: development of a first version of a 3D ABL model**

Toward a 3D-ABL model

- **Prognostic variables** = perturbation around a known large-scale solution
 - **Perturbations** = modification of the ambient state due to the higher resolution surface B.C.
- ▷ Atmospheric primitive equations (in 2D x - z , no rotation)

$$\left\{ \begin{array}{l} \frac{D\tilde{u}}{Dt} = -c_p\theta\partial_x\tilde{\pi} + \partial_z \left(K_m(\tilde{u}, \tilde{\theta})\partial_z\tilde{u} \right) + P_u(\tilde{\theta}, \tilde{u}) \\ c_p\theta\partial_z\tilde{\pi} = -g \\ \partial_t\tilde{\rho} + \nabla \cdot (\tilde{\rho}\tilde{\mathbf{u}}) = 0 \\ \frac{D\tilde{\theta}}{Dt} = \frac{\dot{Q}(\tilde{\theta}, \tilde{u})}{\tilde{\pi}} + \partial_z \left(K_s(\tilde{u}, \tilde{\theta})\partial_z\tilde{\theta} \right) \\ \tilde{\rho} = \frac{p_0}{R\tilde{\theta}}\tilde{\pi}^\gamma \end{array} \right.$$

- \dot{Q} external heating and molecular diffusion
- P_u parameterized physics
- Turbulent vertical mixing is isolated
- Ambient state \neq reference state (e.g. Durran, 2008; Arakawa & Konor, 2009)

- We assume a known ambient state $(\tilde{\pi}, \tilde{\theta}, \tilde{\rho}, \tilde{u})$
= Solution obtained with large-scale surface B.C..
- **Objective:** define a perturbed state $(\delta\pi, \delta\theta, \delta\rho, \delta u)$ which would account for an increase in B.C. resolution while being realistic.

Assumptions:

- Small perturbations for thermodynamical variables

$$\frac{\delta\rho}{\tilde{\rho}}, \quad \frac{\delta\pi}{\tilde{\pi}}, \quad \frac{\delta\theta}{\tilde{\theta}} \ll 1$$

- $P_u(\tilde{u} + \delta u, \tilde{\theta} + \delta\theta) \approx P_u(\tilde{u}, \tilde{\theta})$
- $\dot{Q}(\tilde{u} + \delta u, \tilde{\theta} + \delta\theta) \approx \dot{Q}(\tilde{u}, \tilde{\theta})$

Conclusions

- 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)

Ongoing work & perspectives

- Initialization of the NEMO/ABL1d coupled system
(in collaboration with Arthur Vidard, Inria)

Objectives :

- Avoid initialization shocks (e.g. Mulholland et al. 2015) and more generally inconsistencies at the interface
→ consistency of air-sea fluxes in the analyzed state
- Account for cross-correlations in the error covariance matrices
→ ensemble method
- Enforce good regularity in time
→ iterative ensemble Kalman smoother (IEnKS)