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Analysis of Ocean-Atmosphere Coupling from the Point of View of Domain Decomposition Methods

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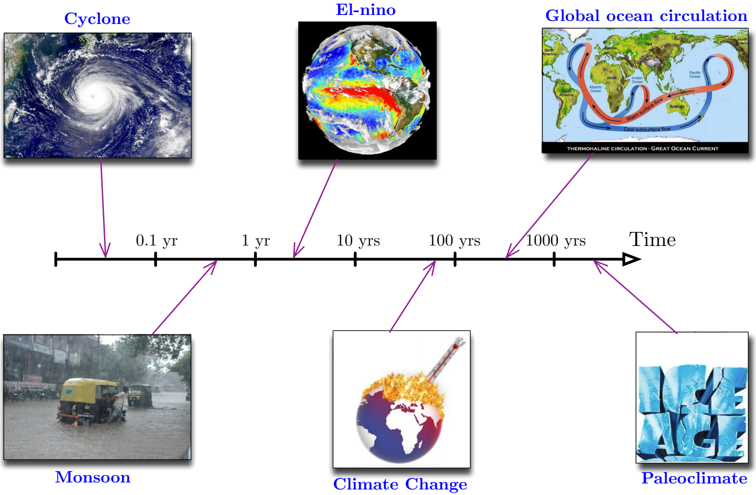
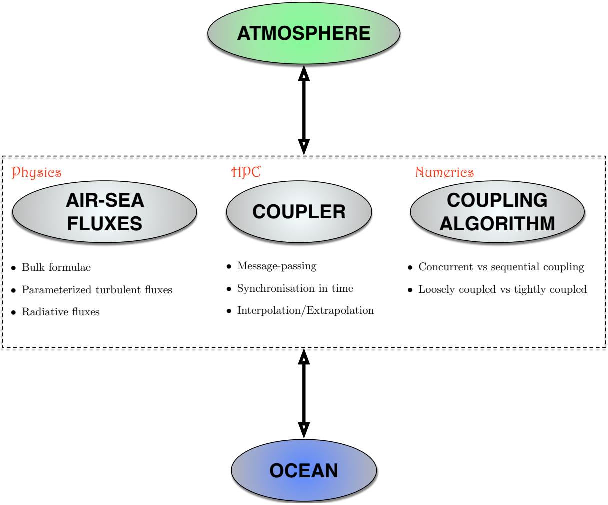
Context

Atmospheric and Oceanic Coupled Models (AOCMs)



Context

Atmospheric and Oceanic Coupled Models (AOCMs)



Content

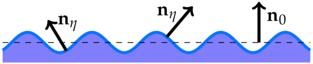
1

Interface conditions and turbulent boundary fluxes

Nature of interface conditions

The ocean and the atmosphere are two open systems exchanging both energy and matter through their common interface.

$\mathbf{n}_0$ unit normal to the interface



- Net mass flux:

$$\mathcal{J}^{\text{mass}} = \mathcal{E} - \mathcal{P}_r - \mathcal{P}_s$$

- Internal energy (enthalpy) flux:

$$h^{(sw)}\mathcal{J}^{\text{mass}} + \mathbf{J}_H^{\text{oce}} \cdot \mathbf{n}_0 = \mathbf{J}_H^{\text{atm}} \cdot \mathbf{n}_0 + h^{(wv)}\mathcal{E} - h^{(liq)}\mathcal{P}_r - h^{(ice)}\mathcal{P}_s$$

Blue terms represent energy associated to phase changes.
$\mathbf{J}_H^{\text{atm}} = \mathbf{J}_{\text{sen}}^{\text{atm}} + \mathbf{J}_{\text{rad}}^{\text{atm}}$ denotes the sum of sensible and radiative heat fluxes.

- Mechanical energy flux: continuity of stresses at the free boundary
Normal stress: $-p^{\text{oce}} + \sigma_{33}^{\text{oce}} = -p^{\text{atm}} + \sigma_{33}^{\text{atm}}$
Tangential stress: $\sigma_{i3}^{\text{atm}} = \sigma_{i3}^{\text{oce}} = \tau_i^{\text{atm}}, \qquad (i = 1, 2)$

Main concern: necessity to conserve energy and mass at the air–sea interface

Coupled problem (without phase changes)

$$\partial_t \mathbf{v}^{\text{oce}} + 2\boldsymbol{\Omega} \times \mathbf{u}^{\text{oce}} + \nabla \cdot (\mathbf{u}^{\text{oce}} \otimes \mathbf{v}^{\text{oce}}) = -\frac{1}{\rho_0}\nabla p^{\text{oce}} - \frac{\rho^{\text{oce}}}{\rho_0}\mathbf{g} + \nabla \cdot \boldsymbol{\sigma}^{\text{oce}}$$

$$\begin{aligned} \mathbf{u}^{\text{oce}} &= (u^{\text{oce}}, v^{\text{oce}}, w^{\text{oce}}) \\ \mathbf{v}^{\text{oce}} &= (u^{\text{oce}}, v^{\text{oce}}, 0) \end{aligned}$$

$$\nabla \cdot \mathbf{u}^{\text{oce}} = 0$$

$$\rho_0 c_p^{\text{oce}} \frac{D\theta^{\text{oce}}}{Dt} = -\nabla \cdot \mathbf{J}_H^{\text{oce}} = -\nabla \cdot (\mathbf{J}_T^{\text{oce}} + \mathbf{J}_{\text{rad}}^{\text{oce}})$$

$$\rho^{\text{oce}} = \rho(\theta^{\text{oce}}, p_0(z))$$

$$\rho^{\text{atm}} \left(\partial_t \mathbf{u}^{\text{atm}} + 2\boldsymbol{\Omega} \times \mathbf{u}^{\text{atm}} + \nabla \cdot (\mathbf{u}^{\text{atm}} \otimes \mathbf{u}^{\text{atm}})\right) = -\nabla p^{\text{atm}} - \rho^{\text{atm}}\mathbf{g} + \rho^{\text{atm}}\nabla \cdot \boldsymbol{\sigma}^{\text{atm}}$$

$$\partial_t \rho^{\text{atm}} + \nabla \cdot (\rho^{\text{atm}} \mathbf{u}^{\text{atm}}) = 0$$

$$\rho^{\text{atm}} c_p^{\text{atm}} \frac{D\theta^{\text{atm}}}{Dt} = -\nabla \cdot \mathbf{J}_H^{\text{atm}} = (\mathbf{J}_T^{\text{atm}} + \mathbf{J}_{\text{rad}}^{\text{atm}})$$

$$p^{\text{atm}} = g(\rho^{\text{atm}}, \theta^{\text{atm}})$$

Interface conditions

$$\begin{aligned} p^{\text{oce}}\big|_{z=\eta} &= p^{\text{atm}} & \\ \mathbf{J}_H^{\text{oce}} \cdot \mathbf{n}_0 &= \mathbf{J}_H^{\text{atm}} \cdot \mathbf{n}_0 &= \mathcal{J}_{\text{sen}} + \mathcal{J}_{\text{LW}} + \mathcal{J}_{\text{SW}} \\ \rho^{\text{oce}}(\boldsymbol{\sigma}^{\text{oce}}\mathbf{n}_0) &= \rho^{\text{atm}}(\boldsymbol{\sigma}^{\text{atm}}\mathbf{n}_0) &= (\boldsymbol{\tau}^a, 0)^T \end{aligned}$$

Computation of the boundary fluxes τ^a and $\mathcal{J}_{\rm sen}$

The boundary fluxes are the result of processes in turbulent boundary layers

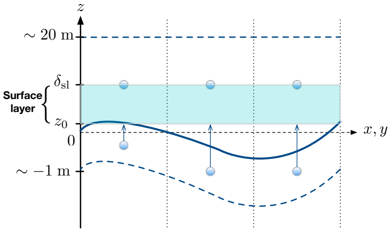
$\Rightarrow$ they need be parameterized in terms of resolved (Reynolds-averaged) quantities of the model

$\Rightarrow$ **Semi-empirical Monin-Obukhov similarity theory** is the basis to derive turbulent quantities from the mean variables available from the models

$\rightarrow$ Generalization of the classical law of the wall to stratified conditions

The MO theory provides functional relationships to compute fundamental turbulent parameters $u_\star$ and $\theta_\star$ from quantities at the first model level

$$\|\boldsymbol{\tau}^a\| = \rho^{\rm atm} {u_\star}^2, \qquad \mathcal{J}_{\rm sen} = -\rho^{\rm atm} c_p^{\rm atm} u_\star \theta_\star$$



MO theory: standard wall law + stability corrections

$$
\begin{aligned}
\mathbf{u}^{\text{atm}}(z) &= \mathbf{u}^{\text{oce}}(z_0) - \frac{u_\star}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L_{\text{Ob}}}\right) + \psi_m\left(\frac{z_0}{L_{\text{Ob}}}\right)\right] e^{i\theta_\tau} \\
\theta^{\text{atm}}(z) &= \theta^{\text{oce}}(z_0) - \frac{\theta_\star}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \psi_s\left(\frac{z}{L_{\text{Ob}}}\right) + \psi_s\left(\frac{z_0}{L_{\text{Ob}}}\right)\right]
\end{aligned}
$$

- **Usual form :**

$$
\begin{aligned}
\boldsymbol{\tau}^a &= \rho^{\text{atm}} C_D \|\mathbf{u}^{\text{atm}}(z^1_{\text{atm}}) - \mathbf{u}^{\text{oce}}(z^1_{\text{oce}})\|(\mathbf{u}^{\text{atm}}(z^1_{\text{atm}}) - \mathbf{u}^{\text{oce}}(z^1_{\text{oce}})) \\
\mathcal{J}_{\text{sen}} &= \rho^{\text{atm}} c_p^{\text{atm}} C_H \|\mathbf{u}^{\text{atm}}(z^1_{\text{atm}}) - \mathbf{u}^{\text{oce}}(z^1_{\text{oce}})\|(\theta^{\text{atm}}(z^1_{\text{atm}}) - \theta^{\text{oce}}(z^1_{\text{oce}}))
\end{aligned}
$$

General comments

- Even under ideal conditions, the theory has an accuracy of only about 10–20% [**Foken, 2006**]
- Bill Large (2006) "Surface fluxes for practitioners of global ocean data assimilation"
  - *For hourly fluxes on a spatial scale of* $10\ \mathrm{km}$*, there is at least a factor of* 2 *uncertainty due to transfer coefficient variability on these scales*
  - *Long-term averaging is required before the uncertainty in bulk fluxes is minimized*

$\Rightarrow$ Internal time-scale Δt_{MO} to keep uncertainty on turbulent flux estimates at a "reasonable level"

2

Algorithmic considerations and shortcomings of existing approaches

Various alternatives

- ▷ Concurrent coupling vs sequential coupling (aka parallel vs multiplicative)
- ▷ Global-in-time vs local-in-time
- ▷ Intergrid transfer operator in time

Some criteria to choose an appropriate coupling algorithm

- Practical aspects
  - Computational efficiency (time to solution & scalability)
  - Minimal modification to existing codes
- Numerical & physical aspects
  - Numerical stability and consistency
  - Conservation properties
    (in a weak or strong sense $\sim$ local-in-time vs global-in-time)
  - Consistent with underlying assumptions of physical parameterizations
    (e.g. $\Delta t_{\rm MO}$, $\Delta t_{\rm rad}$, PBL scheme, ...)
  - Vertical physics is handled implicitly in time

Standard partitioned time-stepping methods in CMs

4 variants:

- Global-in-time concurrent coupling (e.g. IPSL-CM6, CNRM-CM)
- Global-in-time ”atmosphere first” sequential coupling (e.g. ECMWF)
- Global-in-time ”atmosphere first” concurrent coupling (e.g. RPN)
- Local-in-time (used exclusively in regional coupled models so far)

Illustration on a simplified 1D coupling problem

Momentum exchange between two vertical columns

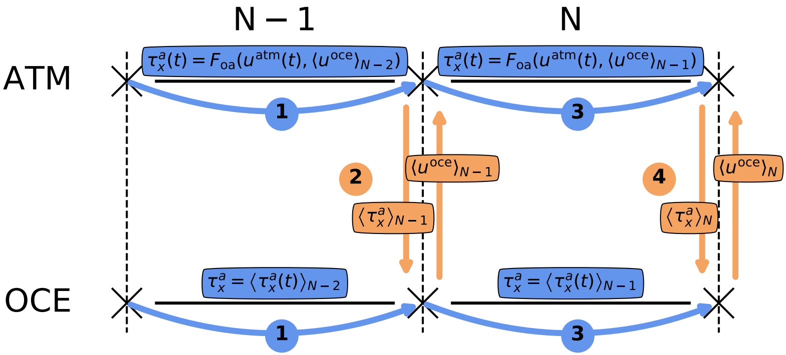
$$
\begin{aligned}
\partial_t u^{\mathrm{atm}} &= -\partial_z \sigma_{xz}^{\mathrm{atm}} = \partial_z \left(K_z^a \partial_z u^{\mathrm{atm}} \right), && \text{in } (0, h_{\mathrm{atm}}) \times (0, T) \\
\partial_t u^{\mathrm{oce}} &= -\partial_z \sigma_{xz}^{\mathrm{oce}} = \partial_z \left(K_z^o \partial_z u^{\mathrm{oce}} \right), && \text{in } (-h_{\mathrm{oce}}, 0) \times (0, T)
\end{aligned}
$$

$$
\begin{aligned}
\rho^{\mathrm{oce}} K_z^o \partial_z u^{\mathrm{oce}}(0^-, t) &= \rho^{\mathrm{atm}} K_z^a \partial_z u^{\mathrm{atm}}(0^+, t) = \tau_x^a, && t \in (0, T) \\
\tau_x^a &= \rho^{\mathrm{atm}} C_D \| u^{\mathrm{atm}}(z_{\mathrm{atm}}^1) - u^{\mathrm{oce}}(z_{\mathrm{oce}}^1) \| (u^{\mathrm{atm}}(z_{\mathrm{atm}}^1) - u^{\mathrm{oce}}(z_{\mathrm{oce}}^1))
\end{aligned}
$$

+ appropriate initial and external B.C.

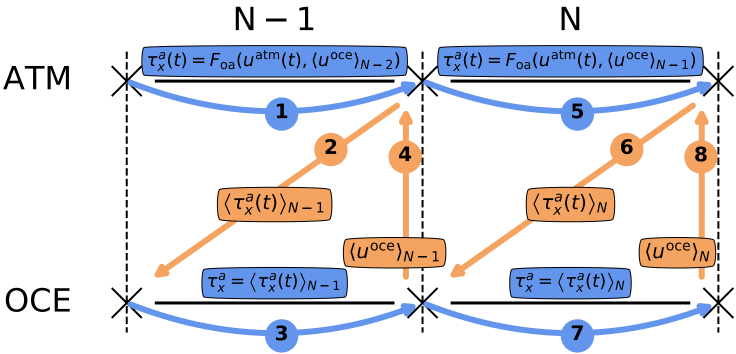
Global-in-time concurrent coupling $(0,T) = \bigcup_{N=0}^{K} \mathcal{T}_N, \mathcal{T}_N = (t_N, t_{N-1})$

- $\tau_x^a = F_{\rm oa}(u^{\rm atm}(z_a^1), u^{\rm oce}(z_o^1))$
- Boundary fluxes are computed within the atmospheric component
  - ▷ Flux conservation: $\left(\sum_{N=1}^{K} \langle \tau_x^a(t) \rangle_N\right)^{\rm oce} = \left(\langle \tau_x^a(t) \rangle_{0,\dots,K-1}\right)^{\rm atm}$



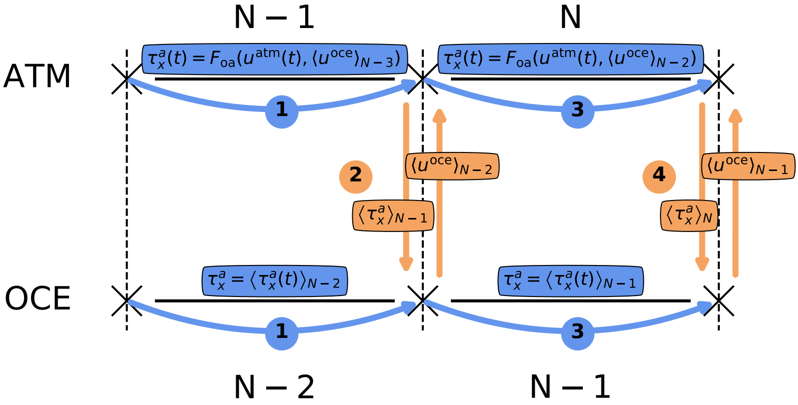
Global-in-time "atmosphere first" sequential coupling

- $\tau_x^a = F_{\rm oa}(u^{\rm atm}(z_a^1), u^{\rm oce}(z_o^1))$
- Boundary fluxes are computed within the atmospheric component
- Flux conservation is re-synchronized in time



Global-in-time "atmosphere first" concurrent coupling

- $\tau_x^a = F_{\text{oa}}(u^{\text{atm}}(z_a^1), u^{\text{oce}}(z_o^1))$
- Boundary fluxes are computed within the atmospheric component



Global-in-time approach (sequential or concurrent)

+ Both models forced by the exact same mean flux on a given time window (except a one-window lag in the concurrent coupling)
+ Models communicate only once per time window
+ Consistent with the underlying assumptions of some physical parameterizations (decouples the dynamical and physical time steps)
- Shifted retroaction $\rightarrow$ loosely coupled solution
- Sequential coupling suppresses a level of parallelism and generally increases time to solution
- In the oceanic component: discontinuity in forcing fields between two successive time windows

• Existing global-in-time approaches = one single iteration of a global-in-time Schwarz algorithm

Local-in-time approach ($\Delta t_{\text{oce}} = \Delta t_{\text{atm}}$)

ATM model

$$\left\{ \begin{array}{rcl} u_{\text{atm}}^{n+1} & = & u_{\text{atm}}^{n} + \Delta t_{\text{atm}} \partial_z \left(K_z^{\text{a}} \partial_z u_{\text{atm}}^{n+1} \right) \\ K_z^{\text{a}} \partial_z u_{\text{atm}}^{n+1}(z=0) & = & C_D \| u_{\text{atm}}^{n}(z_a^1) - u_{\text{oce}}^{n}(z_o^1) \| (u_{\text{atm}}^{n+a}(z_a^1) - u_{\text{oce}}^{n}(z_o^1)) \end{array} \right.$$

OCE model

$$\left\{ \begin{array}{rcl} u_{\text{oce}}^{n+1} & = & u_{\text{o}}^{n} + \Delta t_{\text{oce}} \partial_z \left(K_z^{\text{o}} \partial_z u_{\text{oce}}^{n+1} \right) \\ \rho_{\text{o}} K_z^{\text{o}} \partial_z u_{\text{o}}^{n+1}(z=0) & = & \rho_{\text{a}} K_z^{\text{a}} \partial_z u_{\text{atm}}^{n+1}(z=0) \end{array} \right.$$

- $a = 1$: implicit flux coupling (sequential)
- $a = 0$: explicit flux coupling (conditionally stable, e.g. [**Zhang et al., 2020**])

Local-in-time approach

- lagged coupling $\rightarrow$ loosely coupled partitioned scheme
- Relevance of instantaneous air-sea fluxes ? (large uncertainties)
- Very frequent exchanges/remapping of interface data between models

+ Ability to represent processes related to diurnal cycle

- Existing local-in-time approaches = one single iteration of a local-in-time Schwarz algorithm

How to achieve a tighter coupling: Schwarz algorithms

- [**Keyes et al. (2013)**]: *" Using an approach that ignores strong couplings between components gives a false sense of completion"*

  If the iterations actually fail to converge, using only one iteration won't reveal this fact but in this case numerical results would be questionable

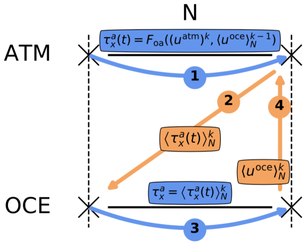
$$\left\{ \begin{array}{rcll} \partial_t u_1^k - \nabla \cdot (\nu_1 \nabla u_1^k) & = & f_1, & x \in \Omega_1 \\ \partial_t u_2^k - \nabla \cdot (\nu_2 \nabla u_2^k) & = & f_2, & x \in \Omega_2 \\ u_1^k & = & u_2^{k-1}, & x \in \Gamma \\ \nu_2 \nabla u_2^k & = & \nu_1 \nabla u_1^k, & x \in \Gamma \end{array} \right.$$

Convergence rate : $R = \sqrt{\nu_2/\nu_1}$

- **BUT:** tight coupling between components require smoothness

- *Easy way to try it :* Schwarz algorithms (global-in-time for multiphysics problems; only require "perfect" restartibility of numerical models)

Global-in-time domain decomposition based on Schwarz method



Repeat steps 1 to 4 iteratively

For $t \in (t_{N-1}, t_N)$:

$$\begin{aligned} \partial_t u^k_{\text{atm}} &= \partial_z \left(K^a_z \partial_z u^k_{\text{atm}} \right) \\ \partial_t u^k_{\text{oce}} &= \partial_z \left(K^o_z \partial_z u^k_{\text{oce}} \right) \\ K^a_z \partial_z u^k_{\text{atm}}(0^+, t) &= F_{\text{oa}}(u^k_{\text{atm}}, \left\langle u^{k-1}_{\text{oce}} \right\rangle_N) \\ \rho_{\text{oce}} K^o_z \partial_z u^k_{\text{oce}}(0^-, t) &= \left\langle \rho_{\text{atm}} K^a_z \partial_z u^k_{\text{atm}}(0^+, t) \right\rangle_N \end{aligned}$$

Does it converge ? If yes, what's the impact on the physics ?

3

Schwarz algorithms for OA coupling: analysis of the iterative process

A convenient framework: Schwarz methods

- Huge gap to fill between the theory and practical applications in the analysis of the iterative process
- The convergence analysis usually done at a continuous level for linear problems with constant coefficients and no averaging of boundary data

In the OA coupling case:

- Non-linear transmission conditions defined in a semi-discrete sense
- Turbulent viscosities and diffusivities vary greatly in time and space
- Boundary data are averaged in time

▷ The convergence properties depend on the whole viscosity profile $\nu(z)$. Strong influence of the turbulent zone [**Thery et al. (2021)**]

▷ Impact of boundary averaging for linear problems: solution has the correct average [**Thery (2020)**]

Semi-discrete coupled Ekman problem

$$\partial_t (\mathbf{u}_m^{\text{atm}})^k + f\mathbf{e_z} \times (\mathbf{u}_m^{\text{atm}})^k = \frac{\nu^a_{m+1/2}}{h_m}\left(\frac{\mathbf{u}_{m+1}^{\text{atm}} - \mathbf{u}_m^{\text{atm}}}{h_{m+1/2}}\right)^k - \frac{\nu^a_{m-1/2}}{h_m}\left(\frac{\mathbf{u}_{m}^{\text{atm}} - \mathbf{u}_{m-1}^{\text{atm}}}{h_{m-1/2}}\right)^k$$

$$\partial_t (\mathbf{u}_m^{\text{oce}})^k + f\mathbf{e_z} \times (\mathbf{u}_m^{\text{oce}})^k = \frac{\nu^o_{m+1/2}}{h_m}\left(\frac{\mathbf{u}_{m+1}^{\text{oce}} - \mathbf{u}_m^{\text{oce}}}{h_{m+1/2}}\right)^k - \frac{\nu^o_{m-1/2}}{h_m}\left(\frac{\mathbf{u}_{m}^{\text{oce}} - \mathbf{u}_{m-1}^{\text{oce}}}{h_{m-1/2}}\right)^k$$

$$\left(\nu^a_{1/2}\frac{\mathbf{u}_1^{\text{atm}} - \mathbf{u}_0^{\text{atm}}}{h_{1/2}}\right)^k = C_D \|(\mathbf{u}_1^{\text{atm}})^{k-1} - (\mathbf{u}_N^{\text{oce}})^{k-1}\| \left((\mathbf{u}_1^{\text{atm}})^{k-1+\theta} - (\mathbf{u}_N^{\text{oce}})^{k-1}\right)$$

$$\left(\nu^o_{N+1/2}\frac{\mathbf{u}_{N+1}^{\text{oce}} - \mathbf{u}_N^{\text{oce}}}{h_{N+1/2}}\right)^k = \frac{\rho^{\text{atm}}}{\rho^{\text{oce}}}\left(\nu^a_{1/2}\frac{\mathbf{u}_1^{\text{atm}} - \mathbf{u}_0^{\text{atm}}}{h_{1/2}}\right)^k$$

with $(\mathbf{u}_1^{\text{atm}})^{k-1+\theta} = \theta(\mathbf{u}_1^{\text{atm}})^k + (1-\theta)(\mathbf{u}_1^{\text{atm}})^{k-1}$.

Asymptotic convergence rate independent from iterates $\left(\varepsilon = \frac{\rho^{\text{atm}}}{\rho^{\text{oce}}}\right)$

$$\lim_{(\omega+f)\to 0} \xi = \frac{1}{\theta}\left|\frac{3}{2} - \theta + \frac{3}{2}\varepsilon\sqrt{\frac{\nu_a}{\nu_o}}\right|, \qquad \lim_{(\omega+f)\to\infty} \xi = 0$$

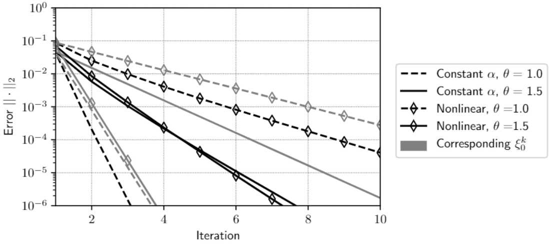
- Optimization for low frequencies: $\theta^{\text{opt}} = 3/2$

Semi-discrete coupled Ekman problem

Asymptotic convergence rate independent from iterates $\left(\varepsilon = \frac{\rho^{\text{atm}}}{\rho^{\text{oce}}}\right)$

$$\lim_{(\omega+f)\to 0} \xi = \frac{1}{\theta}\left|\frac{3}{2} - \theta + \frac{3}{2}\varepsilon\sqrt{\frac{\nu_a}{\nu_o}}\right|, \qquad \lim_{(\omega+f)\to\infty} \xi = 0$$

- Optimization for low frequencies: $\theta^{\text{opt}} = 3/2$
- Assuming $C_D\|(\mathbf{u}_1^{\text{atm}})^{k-1} - (\mathbf{u}_N^{\text{oce}})^{k-1}\| = \text{cst}$ would give $\theta^{\text{opt}} = 1$



[Clément et al. (2021), DD26 proceedings]

Fig. 2 Evolution of the L^2 norm of the errors. Black lines represent the observed convergence; grey lines are the estimated convergence with slopes ξ_0 for linear cases and ξ_0^q for quadratic cases.

4

Application of Schwarz iterations in a climate model

Application of Schwarz iterations in a realistic CM

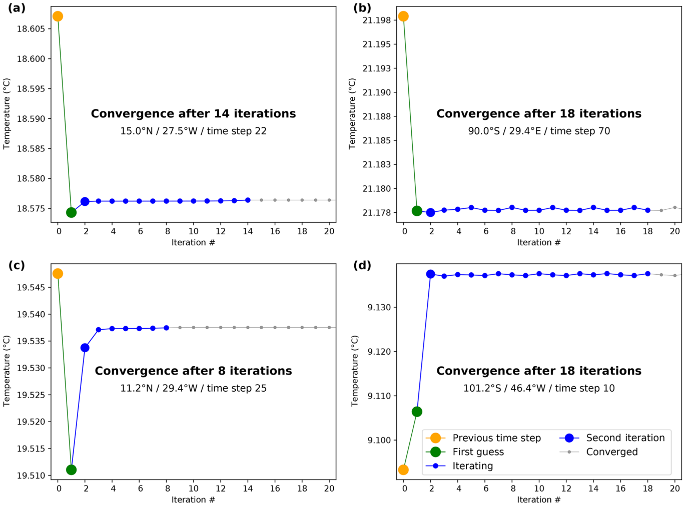
Marti O., S. Nguyen, P. Braconnot, S. Valcke, F. Lemarié, and E. Blayo, 2021: *A Schwarz iterative method to evaluate ocean-atmosphere coupling schemes. Implementation and diagnostics in IPSL-CM6-SW-VLR*, **Geosci. Model Dev.**

Experiments:

- State of the art model: ocean, atmosphere, sea-ice, land (used for CMIP6)
- Atm. component: $3.75^o \times 1.875^o$ (39 vertical levels)
- Oce. component: $2^o \times 2^o$ (31 vertical levels)
- 3 numerical coupling methods:
  - Global-in-time concurrent (parallel)
  - Global-in-time "atmosphere first" sequential
  - Global-in-time Schwarz (50 iterations with $\theta = 1$)
- 5 day experiments
- Time windows: 1 hour or 4 hours

Behavior during iterations

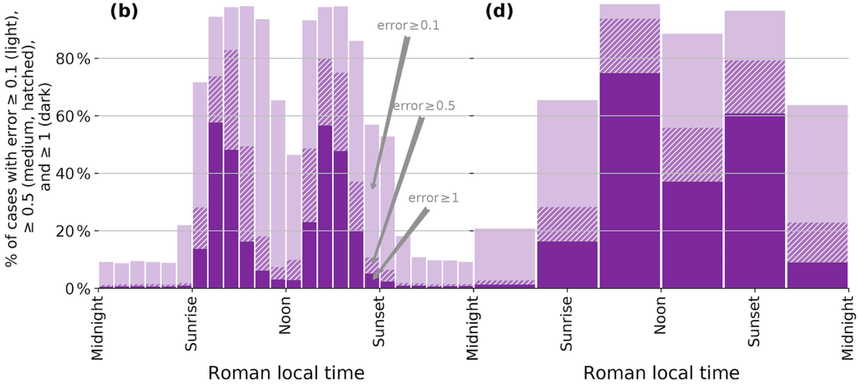
Sea surface temperature evolution with respect to the iterations at 4 different locations



(a,b) 4 hour time window; (c,d) 1 hour time window

Diagnosing the error $\mathcal{E}$ of lagged coupling

For a given time window (t_{N-1}, t_N), $\mathcal{E} = \dfrac{\mathrm{SST}^{\mathrm{cvg}}(t_N) - \mathrm{SST}^{\mathrm{par}}(t_N)}{\mathrm{SST}^{\mathrm{cvg}}(t_N) - \mathrm{SST}^{\mathrm{cvg}}(t_{N-1})}$

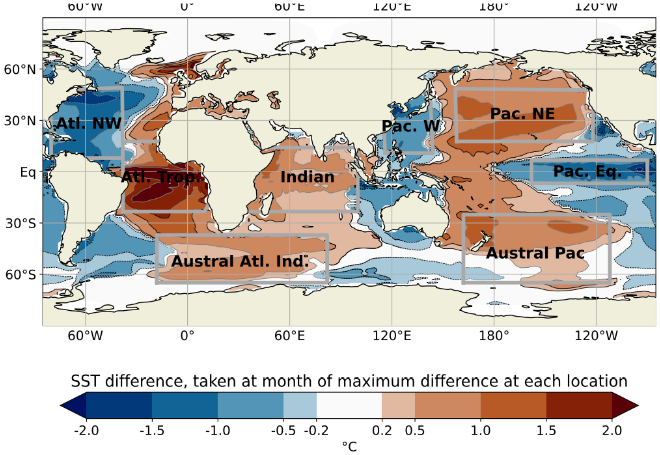


⇒ large differences after sunrise and before sunset, when the external forcing (insolation at the top of the atmosphere) has the fastest pace of change

Application of Schwarz iterations in a realistic CM

Results from 1 year ensemble simulations (20 ensembles)

Monthly average of the ensemble mean sea surface temperature (SST) difference between Schwarz vs concurrent (parallel) coupling



Summary

- Present ocean-atmosphere coupling methods correspond to loosely coupled partitioned scheme
- Schwarz domain decomposition methods due to their inherent simplicity provide a convenient framework for evaluating existing methods
- The convergence/divergence of the iterative Schwarz method can be used as an indicator for the degree of *compatibility* of models and particularly their physical parameterizations
- As soon as the MO theory remains the standard for air-sea fluxes estimate, some form of averaging in the boundary data is needed

Future work

▷ The iterative process is not viable for production runs. How to get the best possible estimate of the converged solution with only 1 or 2 iterations ?

▷ Need for more systematic benchmarking of coupled models under simplified settings (!)

References

- Clément S., F. Lemarié and E. Blayo 2021: *Discrete analysis of Schwarz Waveform Relaxation for a simplified air-sea coupling problem with nonlinear transmission conditions*. Lect. Notes Comput. Sci. Eng., to appear in DD26 proceedings

- Keyes D.E. and coauthors, 2013: *Multiphysics simulations: Challenges and opportunities*. Int. J. High Perform. Comput. Appl.

- Lauritzen, P., N. Kevlahan, A. Adcroft, A. Donahue, T. Dubos, C. Eldred, A. Gassmann, B. Harrop, A. Herrington, C. Jablonowski, H. Johansen, W. Large, V. Larson, F. Lemarié, D. Randall, P. Rasch, B. Shipway, R. Tailleux, H. Wan, 2021: *Reconciling and improving formulations for thermodynamics and conservation principles in Earth system models*. In preparation for J. adv. model. earth syst.

- Marti O., S. Nguyen, P. Braconnot, S. Valcke, F. Lemarié, and E. Blayo, 2021: *A Schwarz iterative method to evaluate ocean-atmosphere coupling schemes. Implementation and diagnostics in IPSL-CM6-SW-VLR*, Geosci. Model Dev.

- Pelletier C., F. Lemarié, E. Blayo, M.-N. Bouin and J.-L. Redelsperger, 2021: *Two-sided turbulent surface layer parameterizations for computing air-sea fluxes*. Quart. J. Roy. Meteorol. Soc.

- Thery, S., C. Pelletier, F. Lemarié and E. Blayo, 2021: *Analysis of Schwarz Waveform Relaxation for the Coupled Ekman Boundary Layer Problem with Continuously Variable Coefficients*. Numer. Algorithms