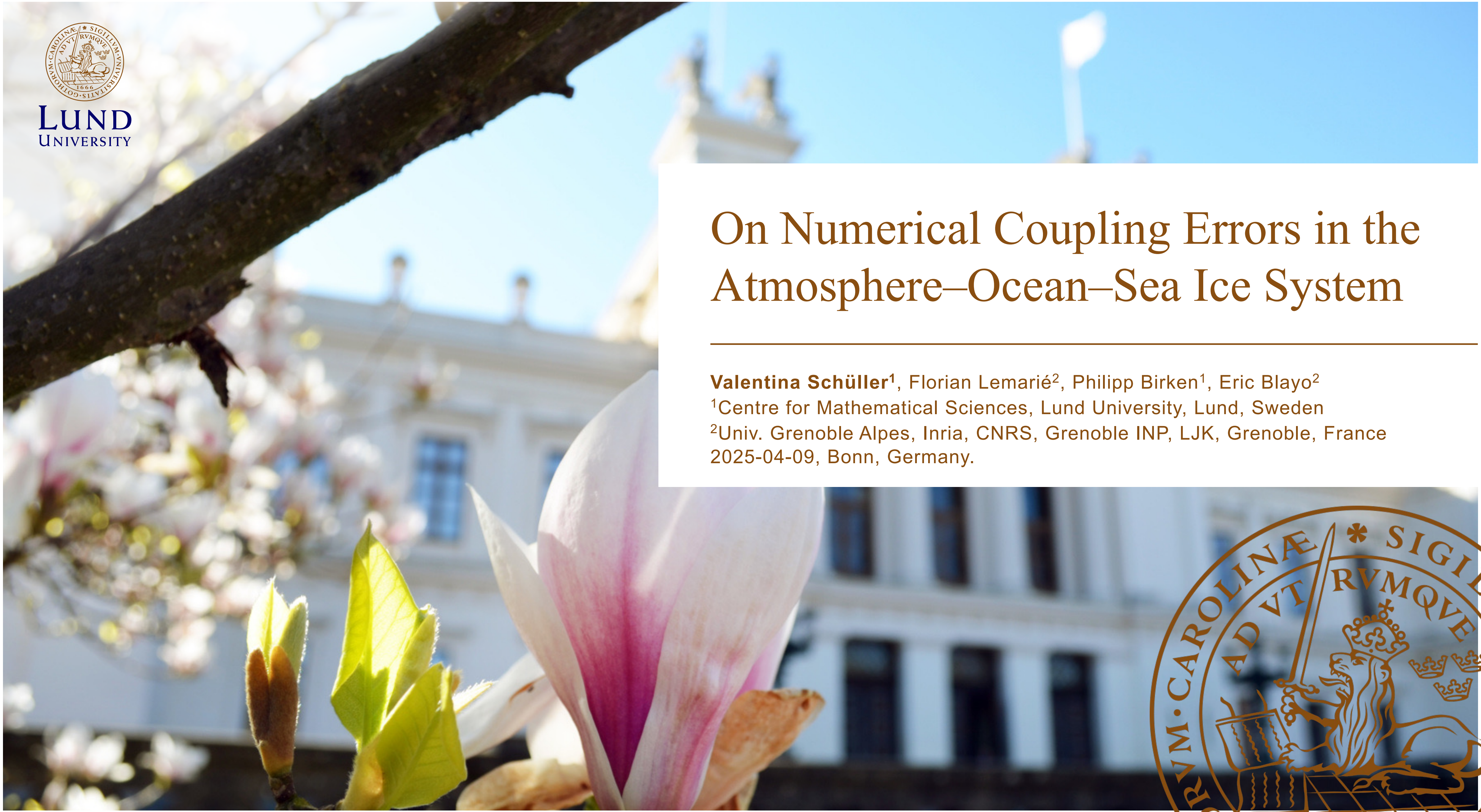

On Numerical Coupling Errors in the Atmosphere–Ocean–Sea Ice System

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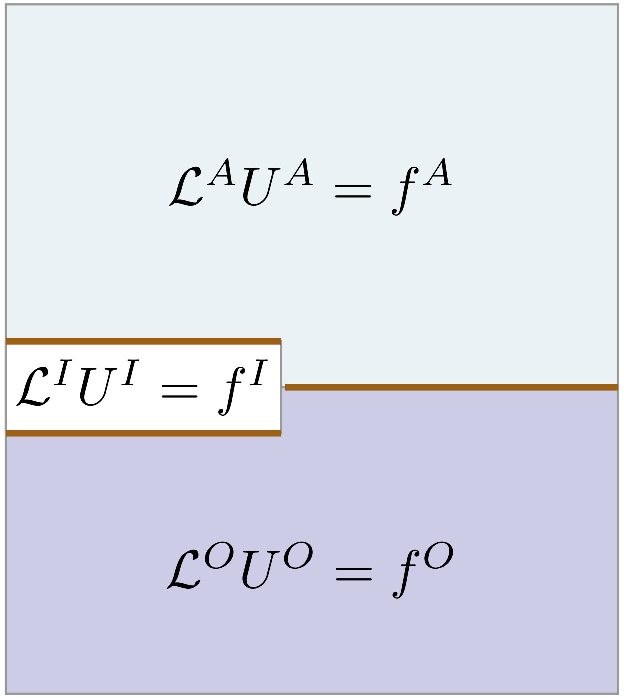
2025-04-09, Bonn, Germany.

I want to make three cases…

1. … for iterative coupling as a model development tool
2. … against discontinuous physics parameterizations
3. … for revisiting atmosphere–ocean–sea ice coupling

ESMs solve a **coupled problem**

- What data should be exchanged at the interface(s)?
- How big are coupling errors in current models?
- How can we reduce them?



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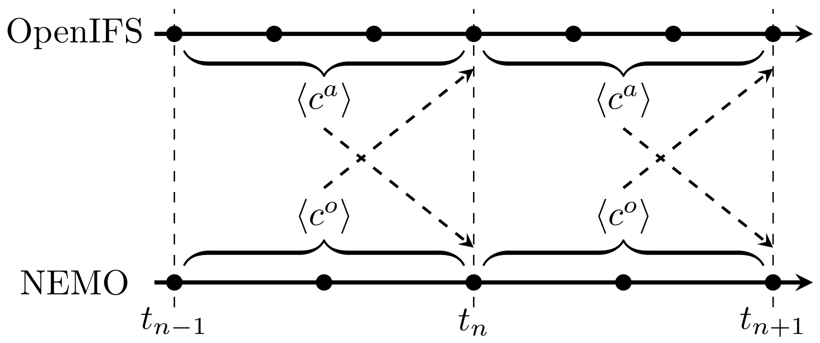
What do we mean by "coupling error"?

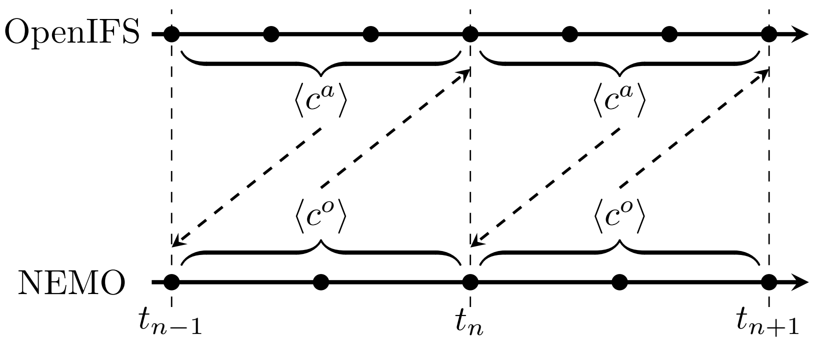
Parallel

(standard in, e.g., EC-Earth)

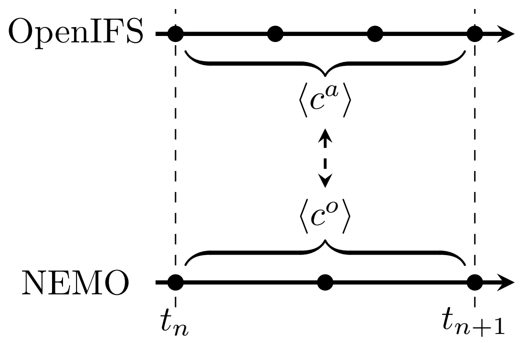


Atmosphere-first

(standard in IFS)



Reference



How big is this difference?

→ **Numerical** coupling error in time

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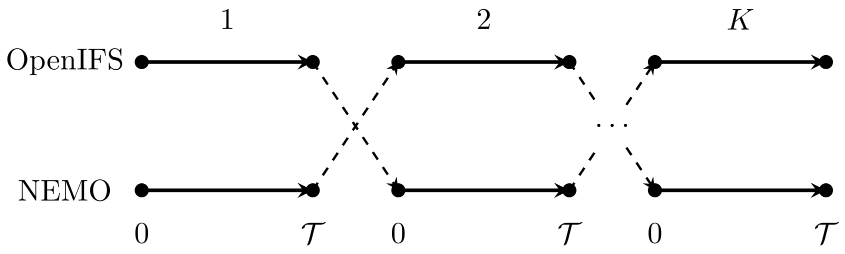
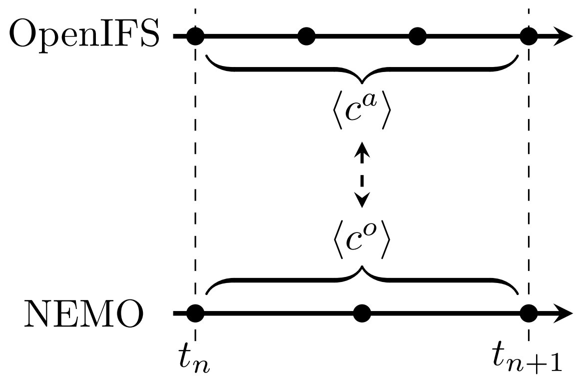
Iterative coupling — The idea



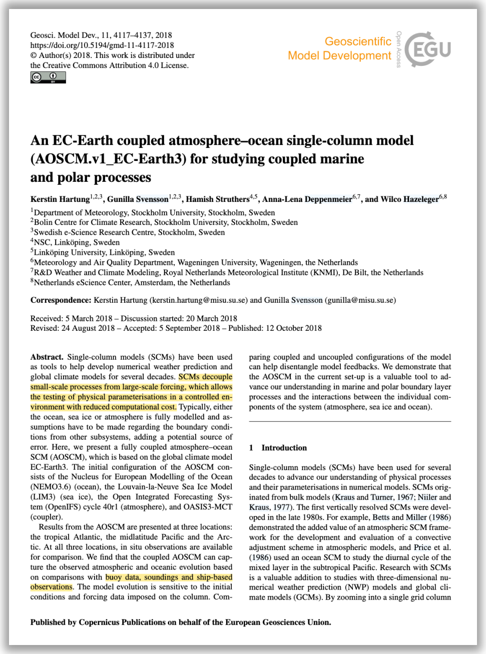
$$K \to \infty$$



- If the coupled problem is set up **correctly**, the iteration will **converge**
  - Well-posed problem?
  - Parameterizations compatible?
  - Is the right data exchanged?
- Idea: Use coupling iteration, with K large
  - If the iteration does not converge: 🚨
  - If iteration converges:
    we get a **reference solution** (the limit) and a **metric** ("coupling error")

Model: EC-Earth AOSCM

- Single column version of EC-Earth
- OpenIFS SCM, NEMO1D (including LIM3/SI^3)
- Cheap to run
- Same physics as in 3D, forced dynamics
- Note: Coupling is part of vertical physics!



Geosci. Model Dev., 11, 4117–4137, 2018
https://doi.org/10.5194/gmd-11-4117-2018

Geoscientific Model Development
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An EC-Earth coupled atmosphere–ocean single-column model (AOSCM.v1_EC-Earth3) for studying coupled marine and polar processes

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Received: 5 March 2018 – Discussion started: 20 March 2018
Revised: 24 August 2018 – Accepted: 5 September 2018 – Published: 12 October 2018

Abstract. Single-column models (SCMs) have been used as tools to help develop numerical weather prediction and global climate models for several decades. SCMs decouple small-scale processes from large-scale forcing, which allows the testing of physical parameterisations in a controlled environment with reduced computational cost. Typically, either the ocean, sea ice or atmosphere is fully modelled and assumptions have to be made regarding the boundary conditions from other subsystems, adding a potential source of error. Here, we present a fully coupled atmosphere–ocean SCM (AOSCM), which is based on the global climate model EC-Earth3. The initial configuration of the AOSCM consists of the Nucleus for European Modelling of the Ocean (NEMO3.6) (ocean), the Louvain-la-Neuve Sea Ice Model (LIM3) (sea ice), the Open Integrated Forecasting System (OpenIFS) cycle 40r1 (atmosphere), and OASIS3-MCT (coupler).

Results from the AOSCM are presented at three locations: the tropical Atlantic, the midlatitude Pacific and the Arctic. At all three locations, in situ observations are available for comparison. We find that the coupled AOSCM can capture the observed atmospheric and oceanic evolution based on comparisons with buoy data, soundings and ship-based observations. The model evolution is sensitive to the initial conditions and forcing data imposed on the column. Comparing coupled and uncoupled configurations of the model can help disentangle model feedbacks. We demonstrate that the AOSCM in the current set-up is a valuable tool to advance our understanding in marine and polar boundary layer processes and the interactions between the individual components of the system (atmosphere, sea ice and ocean).

1 Introduction

Single-column models (SCMs) have been used for several decades to advance our understanding of physical processes and their parameterisations in numerical models. SCMs originated from bulk models (Kraus and Turner, 1967; Niiler and Kraus, 1977). The first vertically resolved SCMs were developed in the late 1980s. For example, Betts and Miller (1986) demonstrated the added value of an atmospheric SCM framework for the development and evaluation of a convective adjustment scheme in atmospheric models, and Price et al. (1986) used an ocean SCM to study the diurnal cycle of the mixed layer in the subtropical Pacific. Research with SCMs is a valuable addition to studies with three-dimensional numerical weather prediction (NWP) models and global climate models (GCMs). By zooming into a single grid column

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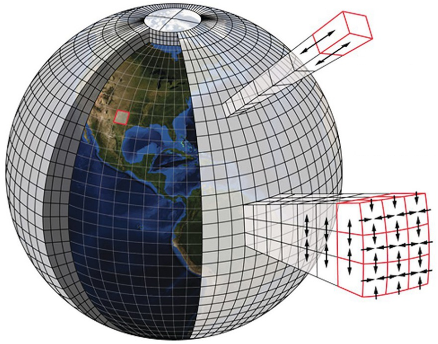
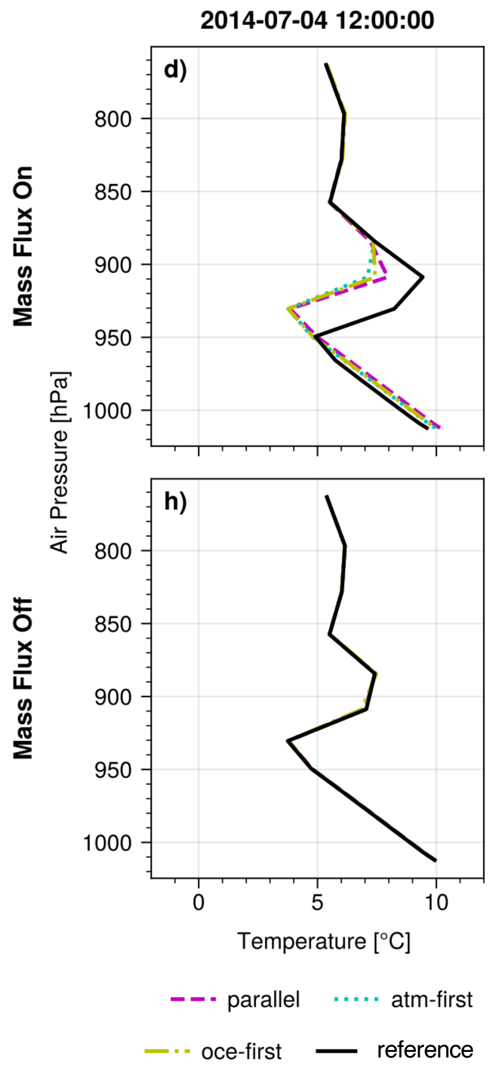
(Hartung et al., 2018)



AOSCM results — Open ocean

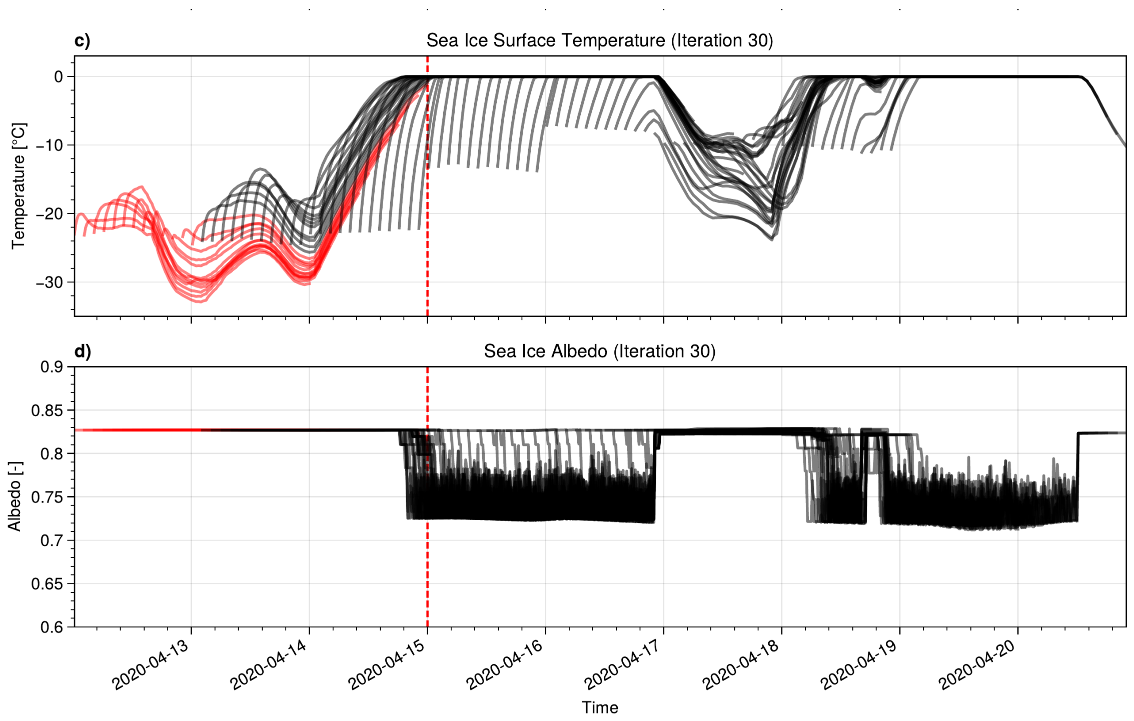
- Iteration converges consistently ✔
- Coupling errors small in the ocean
  - usually well below $0.1\ °\mathrm{C}$ for SST
  - Main source of error: phase shift in solar radiation
  - Simple fix: atmosphere-first scheme
- Coupling errors significant for atmospheric BL temperature T^a
  - Error $\in [0.7, 3.7]°\mathrm{C}$ for 25% of experiments
  - Related to discontinuity in OpenIFS mass flux scheme
  - No simple fix



AOSCM results — With sea ice (I)

🚨 Non-convergence 🚨 as soon as ice surface temperature $T^i = 0°C$

- Reason: ice albedo **jumps** between melting & drying conditions
- Fix: **regularized** albedo scheme
  - Replace jumps with narrow, smooth transition region
  - Result: consistent convergence ✔

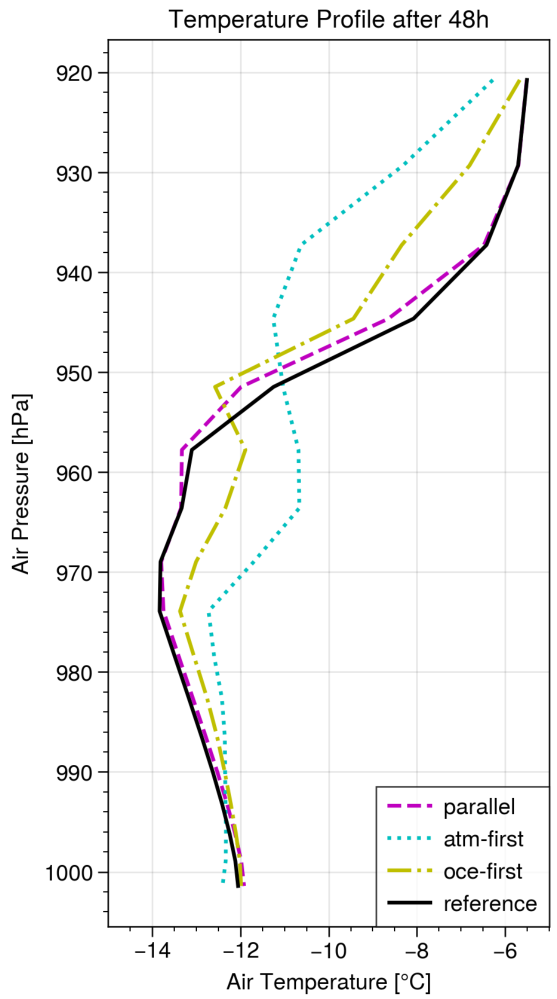


Iteration converged only for the red experiments.

AOSCM results — With sea ice (II)

(with regularized albedo)

- Coupling errors significant for ice surface temperature T^i & atmospheric BL temperature T^a
- T^i error after 48h $\in [0.9, 4.7]\,°C$ for 25% of experiments
  - "Winner" highly test case–dependent (here: parallel scheme)
- No simple fix that addresses both!

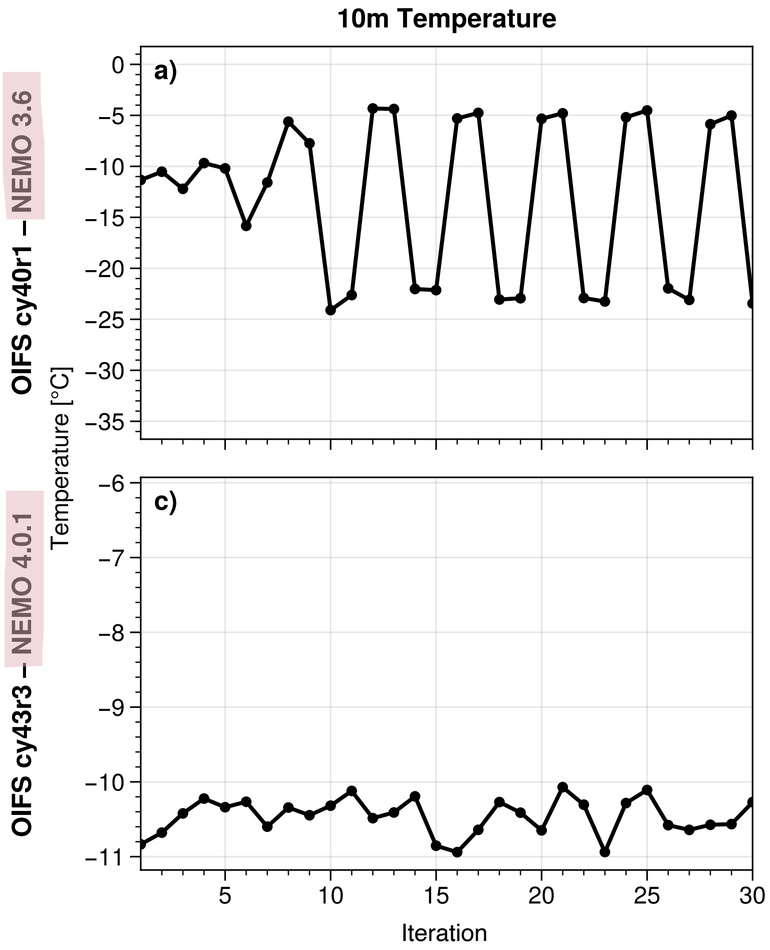


A–O–SI coupling: Research needed!

1. Convergence strongly model-dependent! Much better results with NEMO 4, but why?

2. Lack of mathematical analysis for atmosphere–ocean–sea ice interaction

3. Atmosphere–sea ice: cf. atmosphere–surface coupling
   - T^{skin} over land is computed inside the atmosphere
   - T^{i} is computed inside SI^{3}
   - Is this the right approach? Matter of time scales?

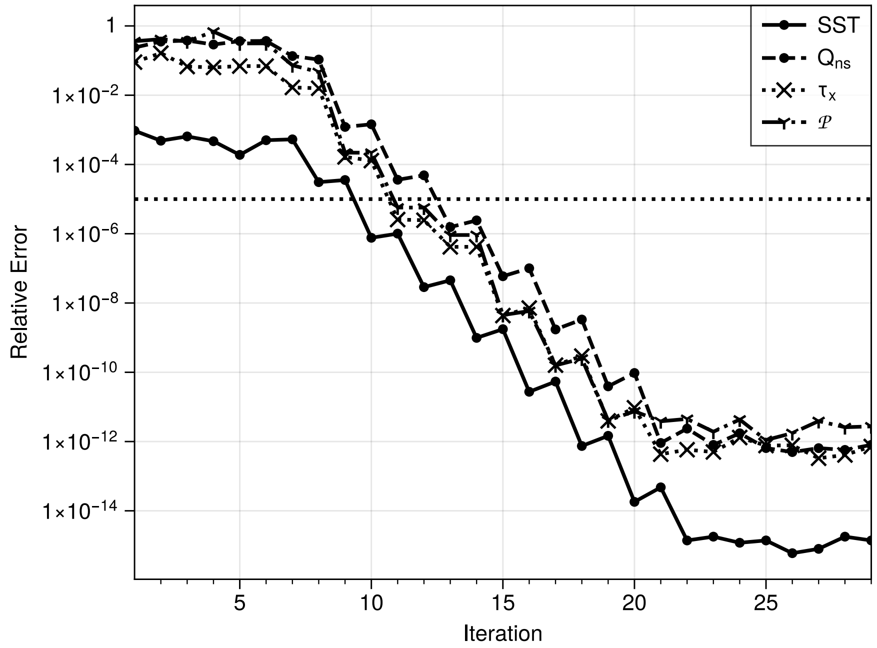


Summary

1. Coupling iterations might not converge for your coupled GCM 🚨
2. Jumps in physics amplify perturbations: We suggest smooth transitions.
3. Atmosphere–ocean–sea ice coupling is not well-studied!

Paper submitted to GMD

Outlook



How much error reduction is possible with 2 iterations?

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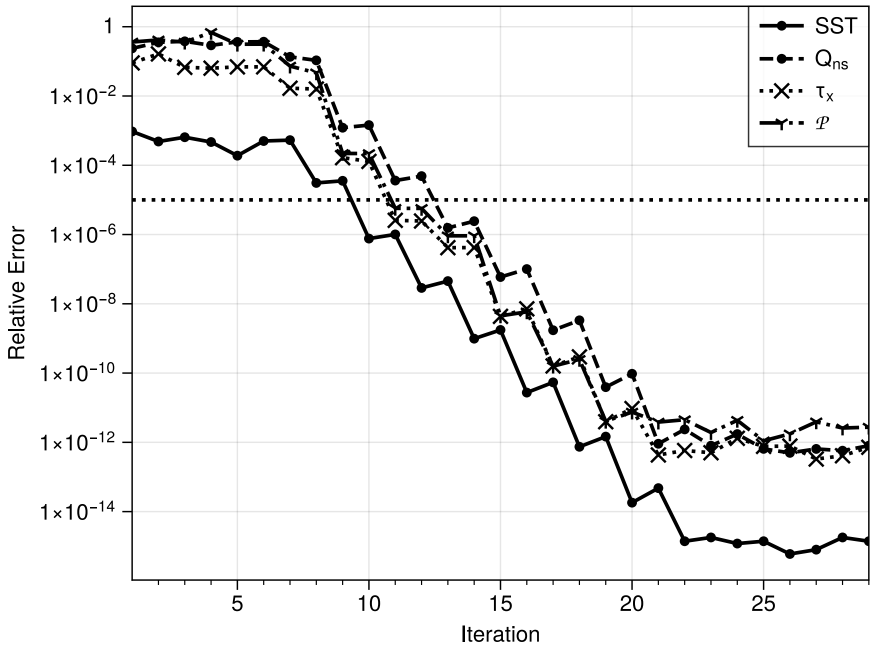
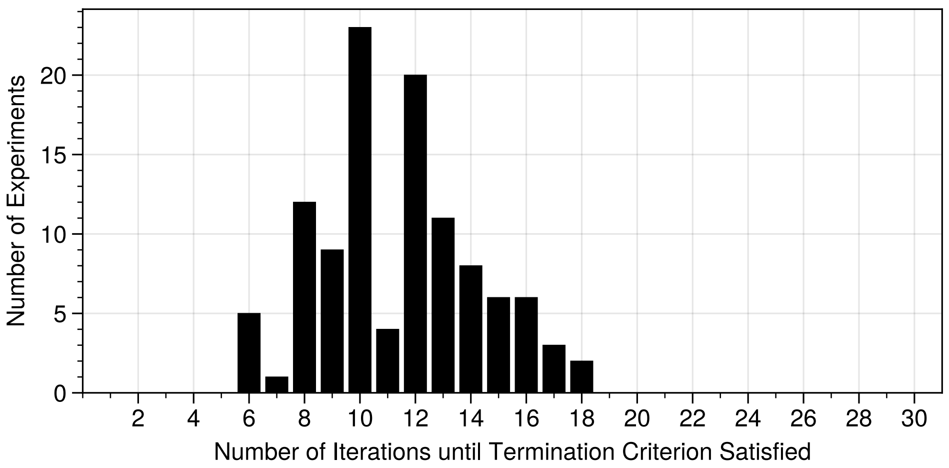
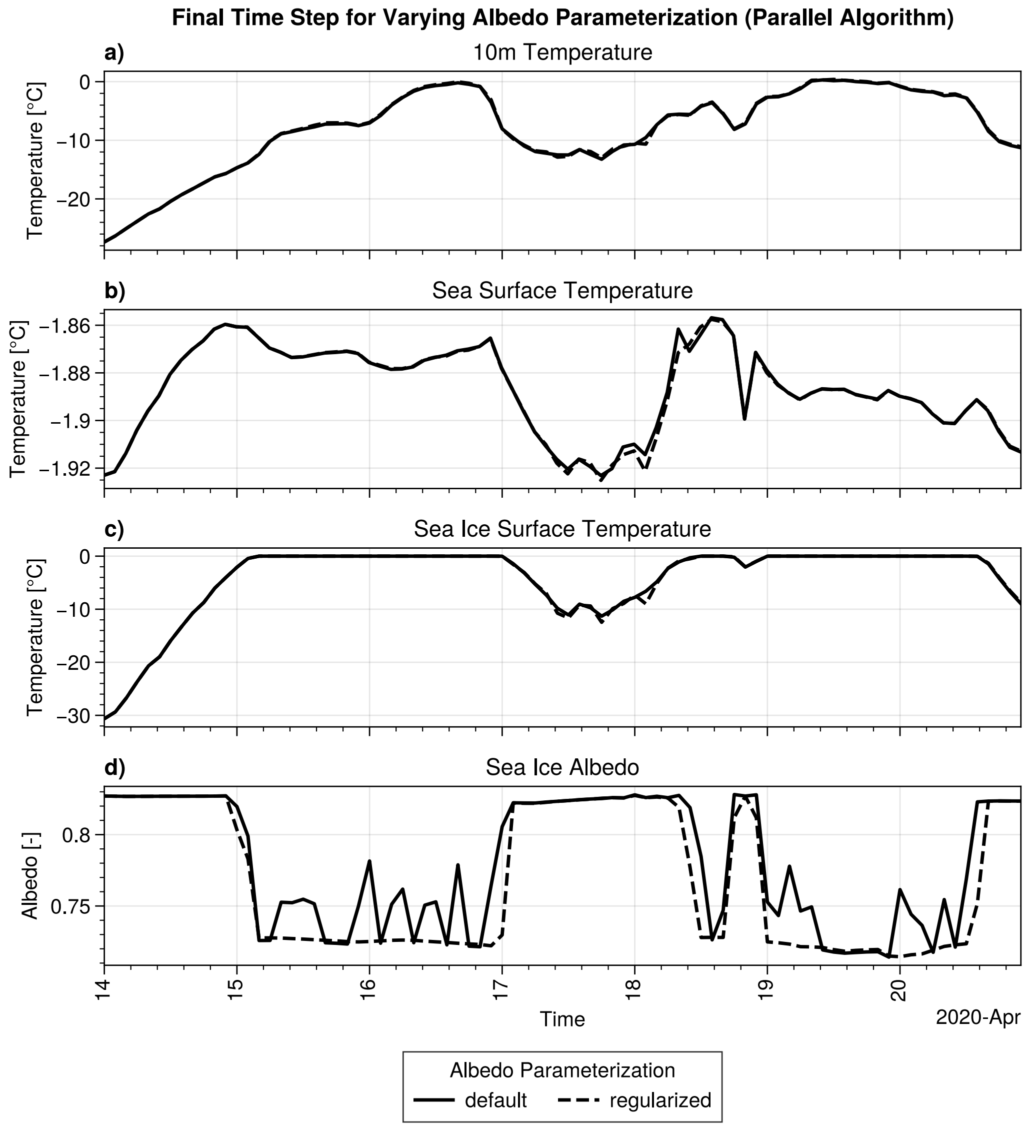
How many iterations do you need?



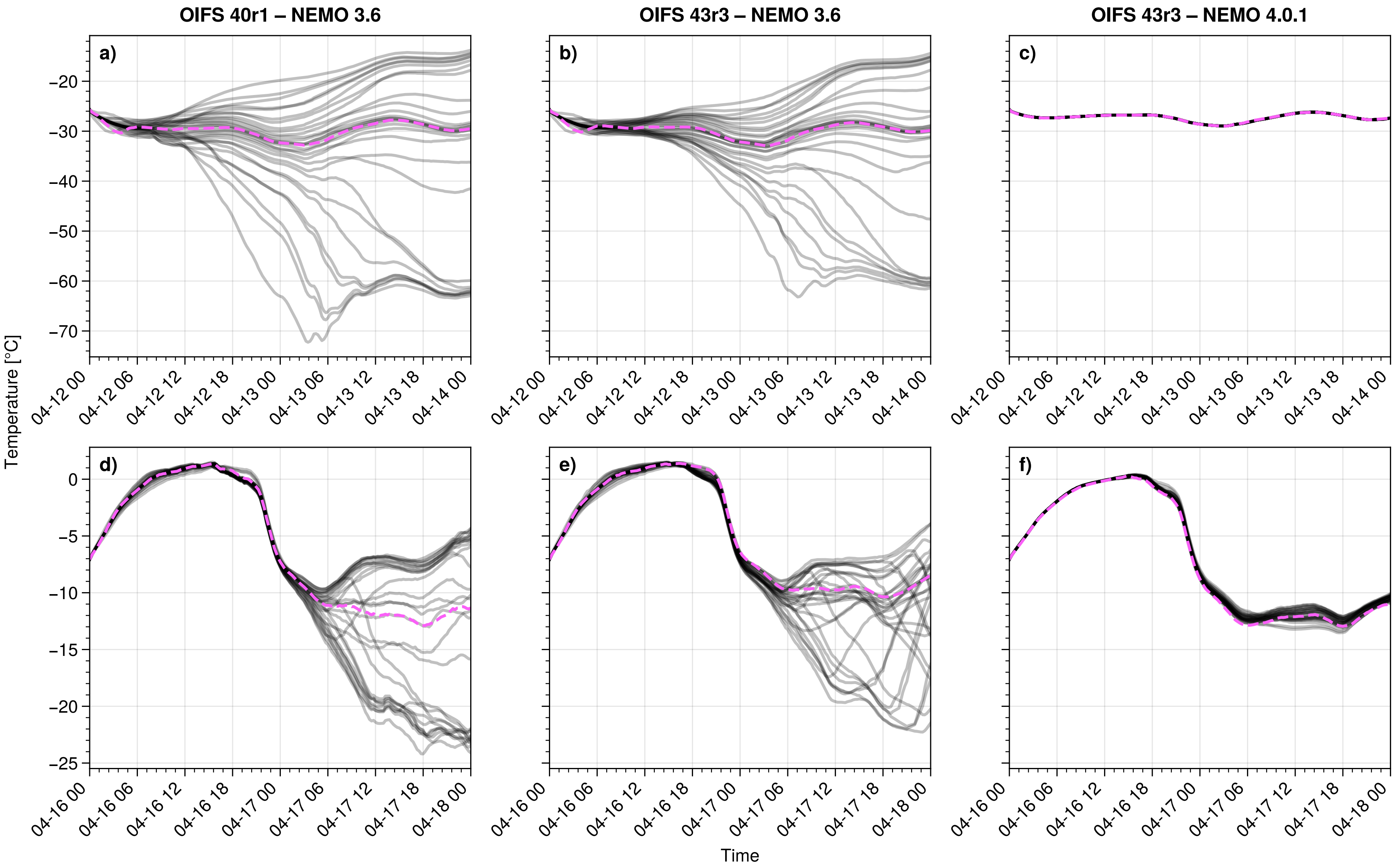


… too many!

Regularized Albedo Scheme



Version-Dependent Sea Ice Oscillations



Improving Coupling: Ideas

- Toy model for atmosphere–ocean–sea ice coupling:
  - Study coupling error for this problem, with increasing model complexity
  - Which parameters drive iteration convergence?
- Introduce a free Robin parameter (cf. optimized Schwarz methods) or relaxation step to get fast coupling error improvement
  - Maximum error reduction for a targeted iteration count (e.g., K=2)
- Improve the initial guess by learning from other coupling time windows

Why do you not compare with observations?

On the one hand…

As with new parameterizations, when a novel coupling scheme is implemented in a tuned model (Hourdin et al. 2017), the solution is likely to be worse for the new coupling method if the model is then not retuned, even if the new coupling scheme would lead to a superior solution in the absence of tuning. Model tuning inevitably tunes against errors that are independent of the parameters tweaked in the tuning process (i.e., compensating errors). In this case, multiple errors may exist, but the superposition of errors introduced to minimize other errors may result in “shadowing of errors” if only the final solution is taken into account during tuning processes. Remove one of these errors, and the result will be worse, despite having eliminated an error. For exam-

(Gross et al., 2018)

On the other hand…

- coupling with ocean & sea ice improves biases, increases forecast skill (Ogata et al.. 2016; Smith et al., 2018)
  → stronger coupling = even better?
- iterative/monolithic coupling reduces spread (Connors & Ganis, 2011, Lemarié et al., 2014)

→ When is it too early to compare to observations?

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