Waveform Relaxation for Atmosphere-Sea Ice-Ocean Coupling in the EC-Earth Single Column Model

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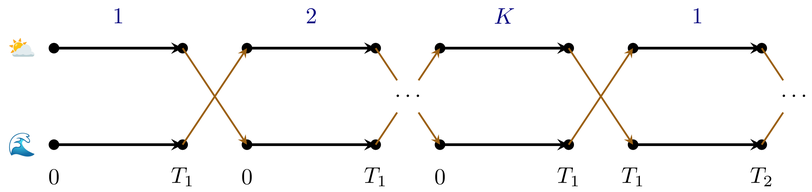
Introduction

Earth system models (ESMs) couple many submodels in time and space. The coupling procedure produces numerical errors. We focus on the errors at the geometrical interfaces between submodels and estimate them with iterative coupling algorithms, so-called waveform relaxation (WR). Standard coupling in ESMs corresponds to the first iteration of a WR algorithm. We systematically study the coupling error of the EC-Earth Atmosphere-Ocean Single Column Model (AOSCM) [1].

Waveform Relaxation (WR)

A simulation is subdivided into coupling windows. After each coupling window, the models exchange time-averaged data. With WR, coupling windows are *repeated* K times, giving a sequence of numerical solutions.



We study:

- the sensitivity of ESMs to changes in the coupling algorithm;
- whether the sequence of WR iterates converges;
- which physics parameterizations affect WR convergence.

Future Work

- Explain convergence issues in cases with sea ice cover
- Use techniques from fluid-structure interaction to improve the solution obtained in the first WR iteration

Selected References

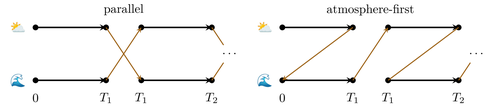
[1] K. Hartung, G. Svensson, H. Struthers, A.-L. Deppenmeier and W. Hazeleger, 'An EC-Earth coupled atmosphere–ocean single-column model (AOSCM.v1_EC-Earth3) for studying coupled marine and polar processes,' *Geosci. Model Dev.*, vol. 11, no. 10, pp. 4117–4137, 2018. DOI: 10.5194/gmd-11-4117-2018.

[2] O. Marti, S. Nguyen, P. Braconnot, S. Valcke, F. Lemarié and E. Blayo, 'A Schwarz iterative method to evaluate ocean–atmosphere coupling schemes: Implementation and diagnostics in IPSL-CM6-SW-VLR,' *Geosci. Model Dev.*, vol. 14, no. 5, pp. 2959–2975, 26th May 2021. DOI: 10.5194/gmd-14-2959-2021.

[3] G. Svensson, S. Murto, M. D. Shupe *et al.*, 'Warm air intrusions reaching the MOSAiC expedition in April 2020—The YOPP targeted observing period (TOP),' *Elementa: Science of the Anthropocene*, vol. 11, no. 1, 2023, ISSN: 2325-1026. DOI: 10.1525/elementa.2023.00016.

Case 1: Atmosphere-Ocean Coupling

The EC-Earth AOSCM simulates a single vertical column of the atmosphere and ocean, coupled at the sea surface. It couples OpenIFS (atmosphere) and NEMO (ocean + sea ice).
By default, the AOSCM uses a parallel coupling algorithm. We have additionally implemented two sequential coupling strategies (atmosphere-first, ocean-first) and WR, to compare their effect on model results.



Results

- Test case: PAPA station, July 2014 (50°N, 145°W)
- Case study with 312 two-day forecasts per coupling algorithm
- The WR iterations **converge** in almost all experiments (Fig. 1)
- We thus consider the converged limit of WR iterations as a **reference solution** and compute a coupling error (Fig. 2)
- For ocean output, the atmosphere-first coupling algorithm gives the smallest coupling error
- In the atmosphere, all standard coupling strategies show similar performance
- The **mass flux scheme** in OpenIFS reacts particularly sensitively to changes in the coupling algorithm

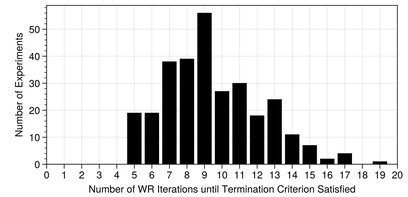


Figure 1: Number of WR iterations necessary to reach convergence for a two-day simulation. The termination criterion is based on [2] and criteria used in other multiphysics couplers. 17312 experiments did not terminate successfully after 20 iterations. Instead, small oscillations developed during the iterative process.

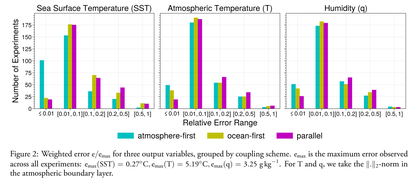


Figure 2: Weighted error e/ϵ_{max} for three output variables, grouped by coupling scheme. ϵ_{max} is the maximum error observed across all experiments: $\epsilon_{max}(SST) = 0.27°C$, $\epsilon_{max}(T) = 5.19°C$, $\epsilon_{max}(q) = 3.25\ g\,kg^{-1}$. For T and q_t we take the $\|.\|_2$-norm in the atmospheric boundary layer.

Case 2: Atmosphere-Sea Ice-Ocean Coupling

MOSAiC Expedition in the Arctic Ocean. Alfred-Wegener-Institut / Steffen Graupner (CC-BY 4.0).

- So far, there exist very few WR results for ESMs including sea ice
- First experiments indicated slow convergence and oscillatory behavior [2]
- Aim: study this behavior systematically in the EC-Earth AOSCM
- Same setup as in Case 1, but with sea ice cover

Results

- Test case: YOPP targeted observation period during the MOSAiC expedition, April 2020 [3]
- In all of our experiments, WR **does not converge** after 50 iterations (Fig. 3)
- The iterates **oscillate** between two regimes
- The spread of model results covered by the iterations is very large
- The cause of the oscillations is unclear

Animated WR iterations for this experiment:

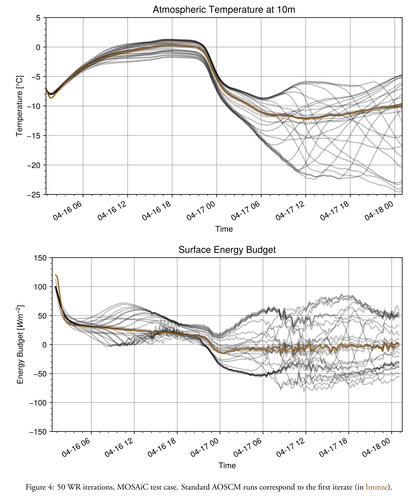


Figure 4: 50 WR iterations, MOSAiC test case. Standard AOSCM runs correspond to the first iterate (in bronze).