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# Diagnosing the ocean-atmosphere coupling schemes by using a mathematically consistent Schwarz iterative method

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## 1 Introduction

Coupling algorithms implemented in coupled general circulation models (CGCMs) are driven by the necessity to conserve energy and mass at the air-sea interface. The discretization of the coupling problem leads to inconsistencies in time. It splits the simulation into small time intervals (coupling periods) over which averaged-in-time boundary data are exchanged. Atmosphere computes the fluxes at the interface (heat, water and momentum), and ocean computes the sea surface properties (water and sea ice temperatures, sea ice fraction, albedos, surface current). Two main algorithms are used, the *parallel* and the *sequential atmosphere-first*. In the *parallel* algorithm, both models run a coupling period with the boundary conditions of the other model from the previous coupling period. In the *sequential atmosphere-first* algorithm, atmosphere runs with oceanic boundary conditions from the previous coupling time. Then ocean runs with atmospheric boundary conditions of the current coupling period. Both algorithms are lagged: there is a time lag (of one coupling period) between the model and its boundary conditions, for one (*sequential* algorithm) or both (*parallel* algorithm) models.

Schwarz algorithms are attractive iterative coupling methods to cure the temporal inconsistencies and provide tightly and mathematically consistent coupled solutions. As discussed in Lemarié (2008), the standard coupling methods correspond to one single iteration of a global-in-time iterative Schwarz method.

## 2 The Schwarz iterative method

A Schwarz iterative method has been implemented in the IPSLCM5A Earth System model (Sepulchre et al., 2020; Marti et al., 2010, 2021). The model repeats each coupling period, with the same initial state (the result from the previous coupling period). The boundary conditions are updated at each iteration, using the result of the previous iteration, until convergence. The solution is mathematically consistent: during a coupling period, each model uses the boundary conditions from the other model for the same coupling period. There is no lag.

The method has a huge computational cost, as each coupling period is iterated. It is not affordable for production runs, but allows us to compare the legacy coupling algorithms used in state-of-the art GCM to a mathematically consistent and synchronous algorithm, which is used as a reference to compute the error made with legacy algorithms.

We run 5-day experiments with the Schwarz iterative method, using three algorithms (*parallel*, *sequential atmosphere-first* and *sequential ocean-first*), and two coupling periods $\Delta t = 1h$ and $\Delta t = 4h$. The Schwarz method can be used over all these algorithms. If the method is run until perfect convergence, the result is not dependant of the underlying coupling algorithm. In practice, the iterative method will be stopped before perfect convergence with an ad hoc criterion, and the different algorithms will give slightly different results.

## 3 Results

Fig. 1 shows the relative error in the change of sea surface temperature (SST) during one coupling period when the Schwarz method is not used. At each Schwarz iteration, the model computes an occurrence of the SST trend. At the first iteration, the trend is the one that the model would calculate with the legacy lagged coupling. It is compared with the trend obtained after convergence. The comparison is done on a unique trajectory of the model. The error is computed as the ratio between the correction due to the iterative procedure and the solution change with no Schwarz iteration. We consider each case of the iterative process, i.e. each point of the atmosphere grid, and for each coupling period.

In the *parallel*-$\Delta t = 1h$ experiment, the relative error is negligible (less than 0.01) in about 15 % of the cases. It is small (less than 0.1) in almost 50 % of the

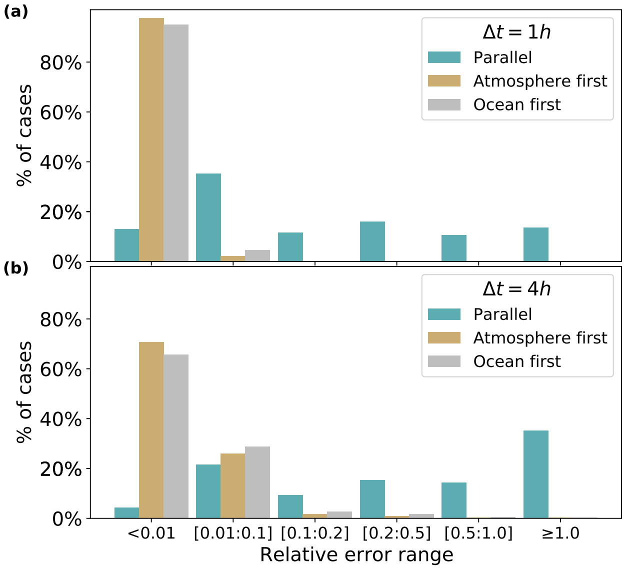

Figure 1: Relative error of the change of sea surface temperature during a coupling period. The error is computed as the ratio between the correction due to the iterative procedure and the solution change during a coupling period with no Schwarz iteration. The ordinates show the number of cases in percentage of the total number of cases in *time* × *space*.

cases. But it is larger than 0.1 for the other half. The relative error is even larger than 0.5 in 25 % of the cases. The *atmosphere-first* shows strongly improved results, with a negligible error for 97 % of the points. The results of the *ocean-first* experiment are close to the *atmosphere-first* experiments, with a slight deterioration. For the $\Delta t = 4h$ experiments, the errors are larger than in the $\Delta t = 1h$ case, but with the same hierarchy between the algorithms.

The error shows a strong diurnal cycle (not shown) with the lowest errors during the night. Errors are larger at noon than at midnight. The error is maximum after sunset and before sunrise, when the change of the insolation forcing evolves at the fastest pace.

We propose two hypotheses to explain the *atmosphere-first* algorithm performance compared to *ocean-first*. First, the atmosphere has shorter characteristic time scales than the ocean, with a more marked diurnal cycle. The atmospheric lower boundary conditions evolves slowly, and the atmospheric solution after the first half-iteration is then already quite close to its converged value, and provides a relevant and synchronized forcing to compute the oceanic solution in the second half-iteration. Second, the better performance of the *atmosphere-first* case can also be linked to the phasing of the solar radiation, which is the only external forcing and constrains the diurnal cycle. In the *ocean-first* case, the ocean is forced by fluxes, including solar radiation, calculated by the atmosphere at the previous coupling period. For *atmosphere-first*, the solar forcing is correctly phased.

Most current GCMs use the *parallel* algorithm which appears to have very large errors (see Marti et al. (2021) for a short review). Our analysis shows that implementing *sequential* algorithms are simple ways to strongly reduce the error, with the *atmosphere-first* algorithm showing the best performance. The *sequential* algorithms, however, have a major drawback. The models do not run concurrently as, while one model is running, the other model waits for its boundary conditions. This eliminates a level of parallelism, and increases the time to solution of the coupled model.

## 4 Acknowledgements

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