Prediction of the long-term climate response in a coupled climate model using response theory

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Abstract: This contribution provides new insights on the application of the Ruelle Response Theory (RRT) for the analysis of long-term evolution of the climate. (Lucarini et al., 2017 J. Stat. Phys.; Ragone et al., 2016 Clim. Dyn.) successfully applied the theory to an intermediate complexity atmospheric model in order to predict the global and local response of the climate system to increases in the CO2 concentration. We now investigate the oceanic scales of the response by looking at the long-term evolution of a low-resolution coupled model. We consider two ensembles, each composed of 20 members. Each member is a 2000 year simulation performed with the Max Planck Institute Earth System Model (MPI-ESM v1.2) in its coarse resolution version. The first ensemble, namely "predictor" consists of 20 runs with an initial abrupt CO2 concentrations doubling (2xCO2). The second ensemble, namely the "predictand", consists of runs where CO2 is increased by 1% per year until 2xCO2 threshold is reached (1pctCO2), and then the concentration is kept constant. Results show that the evolution of a number of observables relevant to the climate projections are well captured by the convolution of the observable-dependent Green's function, obtained with the 2xCO2 ensemble, and the time modulation of the predictand's forcing. Remarkably, the prediction is not only able to reproduce the slow relaxation of the system to the equilibrium, but also the transient response of the system to the forcing.

Methods

For an appropriate perturbation **Y** to a state vector **y**, a Schauder decomposition can be defined, so that **Y**(x,t) = **Y**(x)*f(t). RRT states that the expectation value of any observable can be written as:

$$\langle \Phi_f(t) \rangle = \langle \Phi \rangle_0 + \sum_{n=1}^{\infty} \langle \Phi \rangle_f^{(n)}(t)$$

or in other words as an expansion around the unperturbed state Φ_0, where the perturbative terms are the convolution of a function of the unperturbed state with the time modulation of the forcing. The first term of the expansion accounts for the linear response:

$$\langle \Phi_f^{(1)}(t) \rangle = \int d\sigma_1 G_\Phi^{(1)}(\sigma_1 - 1) f(t - \sigma_1)$$

with $G_\Phi^{(1)}$ being the first order Green function of the observable Φ. We evaluate the long-term evolution of climate through the linear response of a subset of observables for the atmosphere and the ocean:

- Near-surface temperature (T2m) and Precipitation flux (P);
- AMOC at 26N (AMOC) and Ocean heat uptake (OHU);

First, we compute the Green function from the 2xCO2 experiment. In fact, the time modulation of the forcing can be expressed in this case as a scaling of a Heaviside function. Secondly, we predict the behavior of the observables in the 1pctCO2 scenario using the Green function obtained from the 2xCO2 experiment.

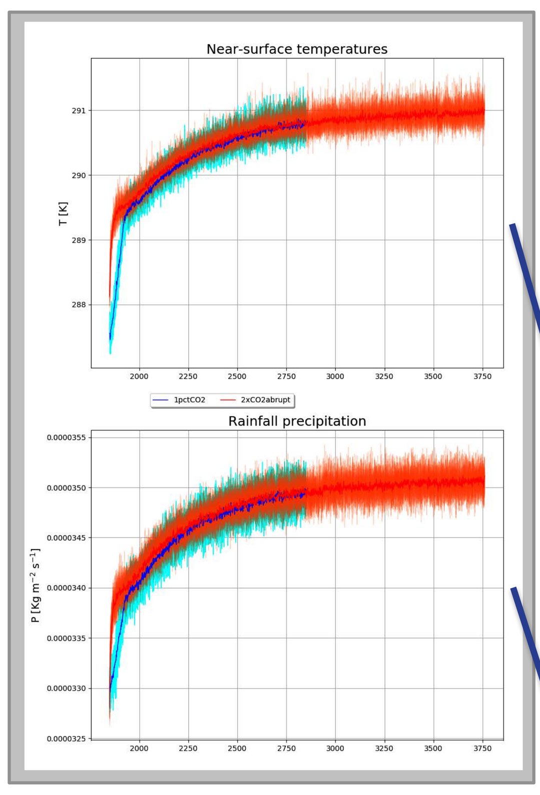
Data

Simulations with MPI-ESM v.1.1 coarse resolution (CR)
- ECHAM6 (T31L31);
- MPIOM (GR30L40);

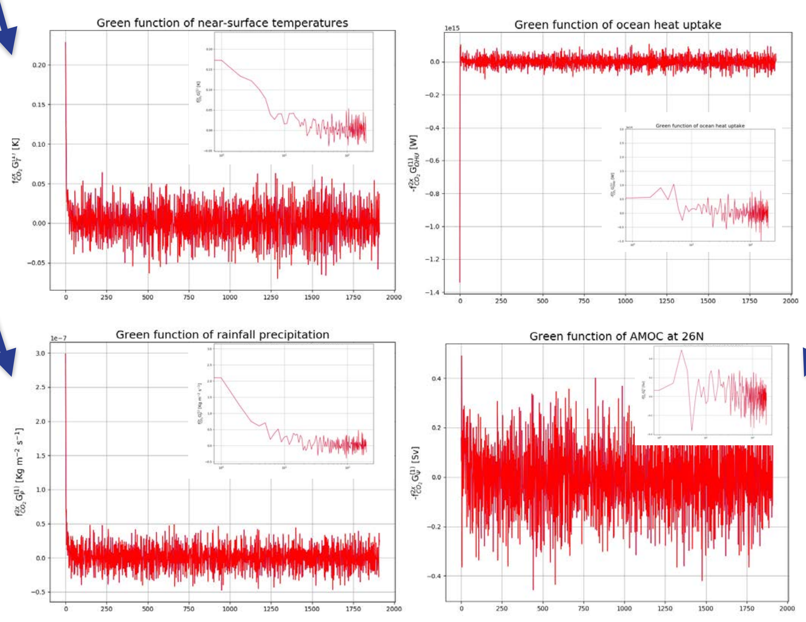
Two ensembles by 20 runs each:
- 2xCO2 (2000 years);
- 1pctCO2 until doubling (2000 years);

Initial conditions for the ensembles are sampled every 100 years from an unforced control run.

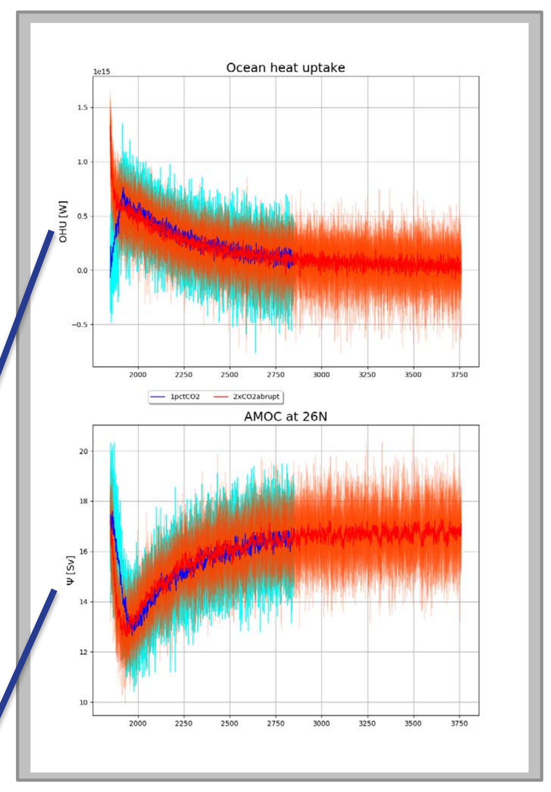
Results



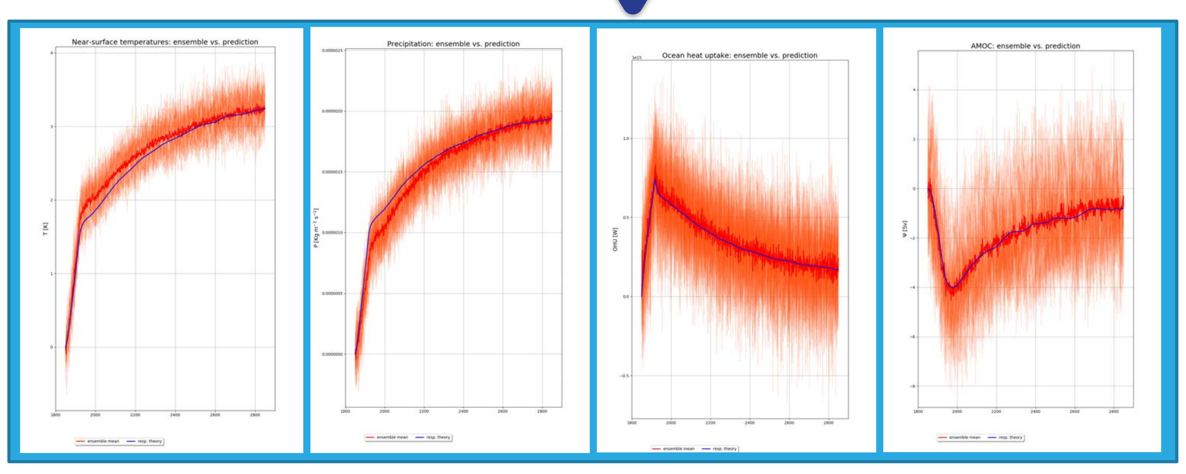
Evolution of 1pctCO2 (blue) and 2xCO2 (red) T2m (top, in K) and P (bottom, in Kg m-1 s-1) anomalies.



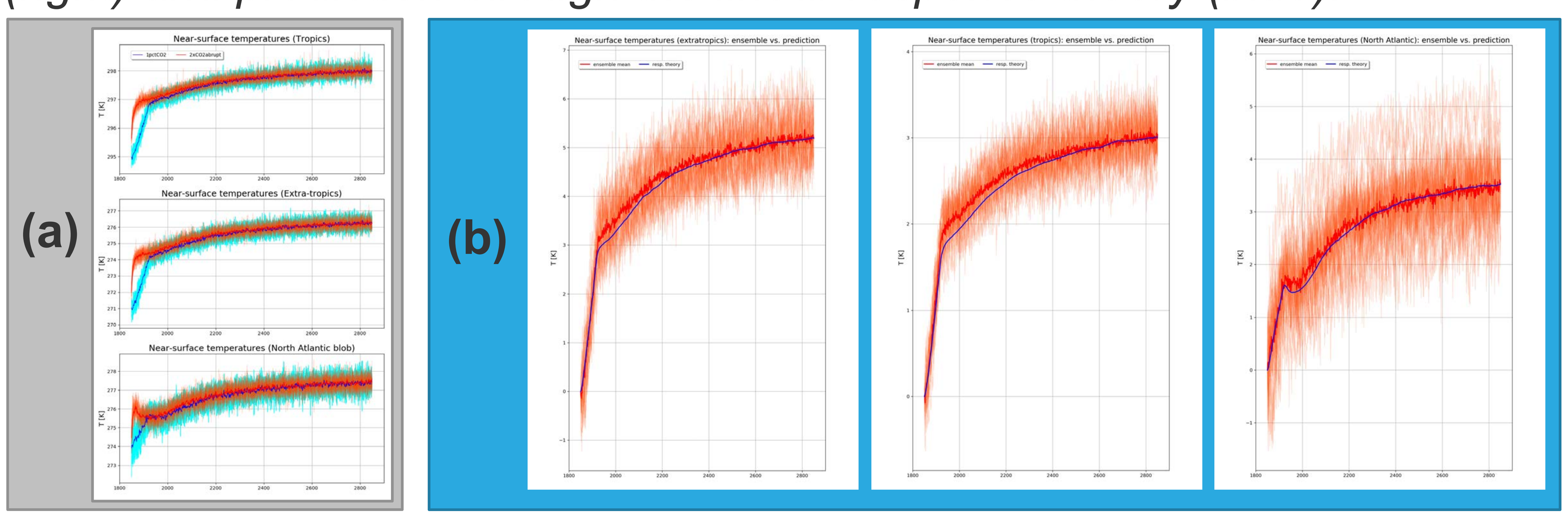
Green functions for T2m (top, left) P (bottom, left) OHU (top, right) AMOC (bottom, right); zoom on first 100 years (logarithmic x-scale).



Evolution of 1pctCO2 (blue) and 2xCO2 (red) OHU (top, in W) and AMOC(bottom, in Sv) anomalies.



Evolution (red) of T2m (left), P (center, left), OHU (center, right), AMOC (right) and prediction through the linear response theory (blue).



(a) Evolution of 1pctCO2 (blue) and 2xCO2 (red) tropical mean T2m (top) extratropical mean T2m (centre) North Atlantic mean (bottom) anomalies. (b) Prediction (blue) of anomalies in (a) from Linear Response Theory.

Conclusions

- The RRT is able to predict the fast and slow modes of crucial atmospheric and oceanic observables;
- Some regional features emerge, such as the North Atlantic cold blob, but here the resolution might be relevant;

References

Lucarini, V., Ragone, F., & Lunkeit, F. (2016). J Stat Phys, 166: 1036
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Ruelle, D. (1998). Phys Lett A, 245:855-870