Project: 1085

Project title: The response theory as a tool for investigating climate predictability and scale separation

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Abstract

The Collaborative Research Centre TRR181 “Energy Transfers in Atmosphere and Ocean” is an inter-institutional project funded by the German Research Foundation (DFG). Its aim is contributing to a better understanding of the energy cycle of the atmosphere and oceans through its fundamental dynamical regimes, i.e. the small-scale turbulence, internal gravity waves and geostrophically balanced motion. More specifically, the final task is to reduce model inconsistencies and the resulting relatively large energy biases.

The specific aim of the S subproject is to develop metrics and diagnostics, in order to quantitatively address model inconsistencies and eventual improvements, as a consequence of better parametrizations of currently poorly understood processes. In this respect, the statistical mechanical formalism of the response theory (see Ruelle et al., 2009 for a review) is crucial to predict the climate response and disentangle the role of individual forcings (Ghil, 2015). This is the natural front-end of the effort for a better implementation of models energetics (Lucarini et al., 2014), given that the forcings alter one or several components of the energy exchanges in the system, either directly or through feedbacks. The response theory is relevant for the TRR-181, also because it provides tools for the investigations of energy conversion through scales, providing hints on the separations of scales between atmosphere and oceans by means of the so-called “susceptibility function” (e.g. Ragone et al., 2016). The response theory is here applied to the MPI-ESM-1.2 coupled model, extending a previous study based on an atmospheric intermediate complexity model (Lucarini et al., 2017). The aim is here to encompass the long timescales spanned by the ocean's variability.

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Model runs

The MPI-ESM v.1.1 model has been run at its coarse resolution (CR), consisting of T31 spectral resolution (amounting to 96 gridpoints in the longitude dimension, 48 in the latitude dimension) and 31 vertical levels for the atmosphere, a curvilinear orthogonal bipolar grid (GR30) (122 longitudinal and 101 latitudinal gridpoints) with 40 vertical levels for the ocean.

A 4000-years control run, CR, has been produced in unforced conditions, representative of present-day atmospheric CO2 concentrations (i.e. 360 ppm). Initial conditions for a 20-members ensemble have been sampled from it every 200 years, in order to ensure reasonable oceanic decorrelation (cfr. Ganopolsky et al., 2002; Wunsch and Heimbach, 2008). Two ensembles have been run, one, E#1, reflecting an instantaneous doubling in CO2 concentration (2xCO2) (for 2000 years), the other one, E#2, an increase in CO2 emissions by 1% every year, until the 2xCO2 level is reached (1pctCO2) (for 1000 years). An additional individual run has been performed under initial abrupt quadrupling in CO2 concentrations, for 2000 years. This is needed, in order to properly scale the Green function. As an additional check, one of the 2xCO2 members has been prolonged by 2000

[1] Previously at UHH (2016-2020).

additional years, in order to investigate the model convergence to the energetic equilibrium and the existence of the model drift.

Furthermore, following (Bodai et al., 2020), using the same model configuration and from the same initial conditions as for E#1 and E#2,, we generated two other ensembles, one, E#3, with an abrupt increase of the solar constant, *S*, and another, E#4, combining the forcing of E#2 with a descending ramp of *S*. For E#3, the new value of *S* is such that it would produce the same GMST as CO2-doubling in E#1. For E#4, the length of the *S* ramp is designed to match that of E#2, and its slope to reach the value of E#3. The latter is known as the G2-type scenario of the GeoMIP (Kravitz et al. 2011).

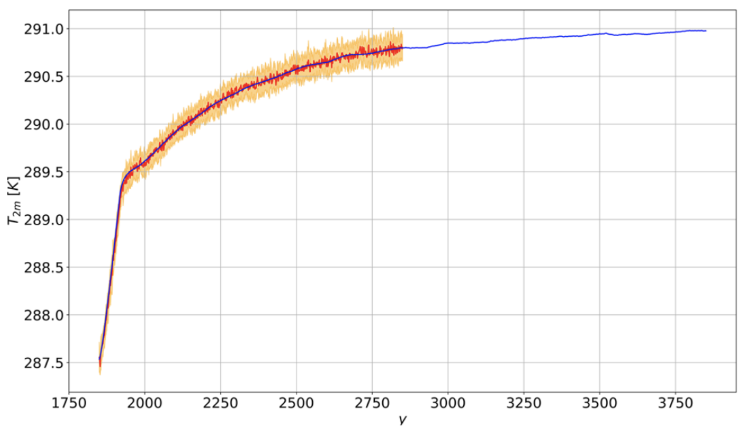
Methods

We have adapted the approach described in Ragone et al. (2016) and Lucarini et al. (2017), where a large ensemble of simulations with an intermediate-complexity atmospheric model had been evaluated. Using a coupled model, such as MPI-ESM-CR, the aim is investigating the scale separation between the atmospheric and oceanic response.

First, we have computed the Green function for some specific observables from the 2xCO2 experiment. This task is very easily accomplished, because the time modulation of the forcing has the form of a Heaviside function. For the atmosphere, we have taken into account the total precipitation flux and the near-surface temperature. For the ocean, we have considered the global ocean heat uptake (OHU) and the strength of the Atlantic Meridional Overturning Circulation (AMOC), in terms of oceanic mass transport crossing 26N of latitude (in Sv). Convolving the observable-specific Green functions, we predicted the behavior of the chosen observable in the 1pctCO2 scenario.

Results

Results from this first part of the analysis have been published on a Scientific Reports paper: “Beyond forcing scenarios: predicting climate change scenarios through response operators in a coupled general circulation model” by Valerio Lembo, Valerio Lucarini and Francesco Ragone (Lembo et al. 2020). We have shown that the linear response theory is skilfull in predicting the long-term response in the 1% CO2 scenario for near-surface temperatures and also for the AMOC (Figure 1). Specifically, both the fast (inter-annual to decadal) and slow (centennial) response are accurately predicted, in the case of the AMOC even detecting a possible threshold for a critical transition. Figure 2 also shows the limit of this approach, when the Antarctic Circumpolar Current (ACC) across the Drake passage is considered. In this case, a superposition of the response to a fast scale (the response of the wind surface stress) and a slow scale (the response of the buoyancy driven circulation) are interacting non-linearly, and the linear prediction is not accurate for the fast response.



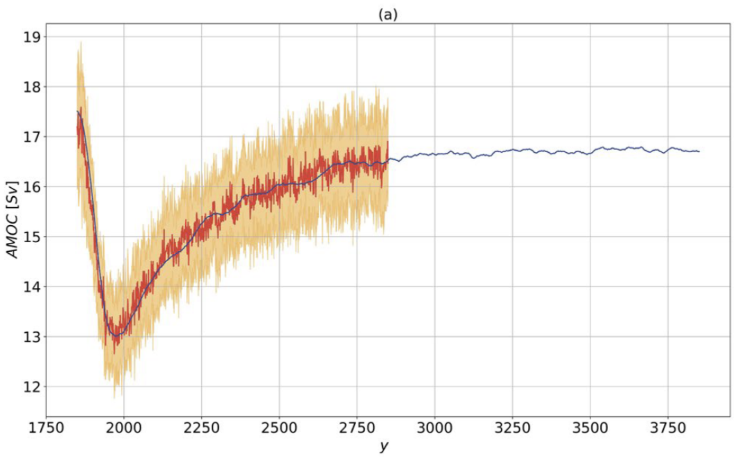


Figure 1: Comparison between the 1% CO2 scenario (thick red line with ensemble mean uncertainty) and the prediction performed using the linear Green function (thick blue), for (top) globally averaged near-surface temperature T2m (in K) in (bottom) the AMOC at 26 N (in Sv).

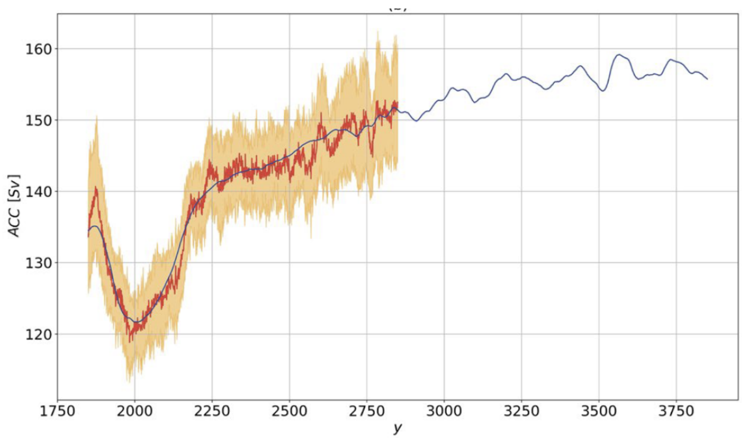


Figure 2: same as in Figure 1, for the Antarctic Circumpolar Current (ACC) across the Drake passage (in Sv).

Secondly, E#1-4 ensembles are used to consider combined CO2 emission and geoengineering scenarios, to the end of e.g. assessing possibilities to adhere to the Paris 2015 agreement. The G2-type scenario has been considered as an extreme and theoretical scenario, in order to test:

1. the nonlinearity of the response
2. the imperfections of geoengineering in terms of “residual” responses.

Figures. 1 and 2 illustrate linearly predicted PCs of near-surface air temperature. It is clear that:

1. Nonlinearity is reflected in PC1 alone. It is to do with an overestimation at polar locations
2. The true residual response is positive there, and negative in a tropical belt.

We plan to combine the information from E#1 and E#3 in order to discuss these achievements in a manuscript under preparation.

As a follow-up, we also argue that a Paris-2015-oriented analysis would benefit from a CO2-emission-to-atmospheric-CO2-concentration response function like that by Hooss et al. (2001), which is the direction that we want to take.

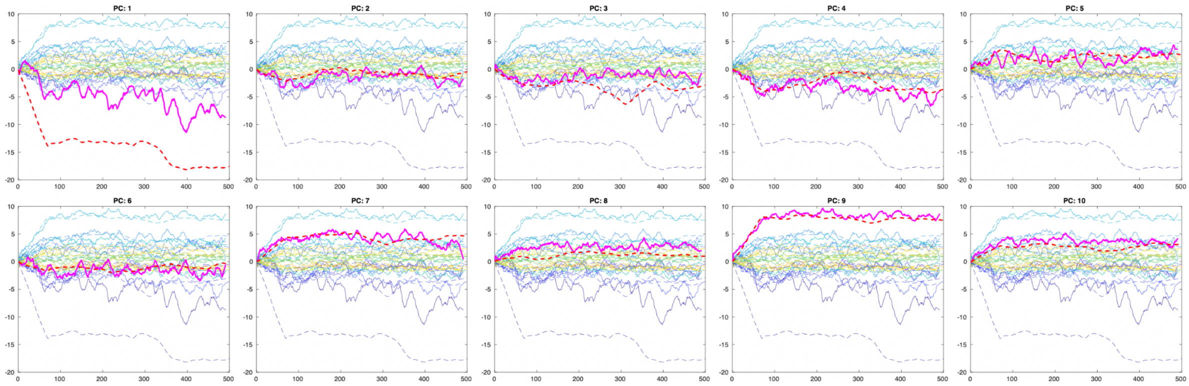


Figure 3: Linear prediction (red, dash) of the GMST response in terms of the PCs (arbitrary units) based on E#1 & E#3 and the truth (magenta, solid) from E#4 (first 10 PCs). The PCs belong to EOFs that are based on E#1 alone; see (Hooss et al., 2001). In all diagrams x shown are the same curves for reference but PCx is highlighted (red, magenta).

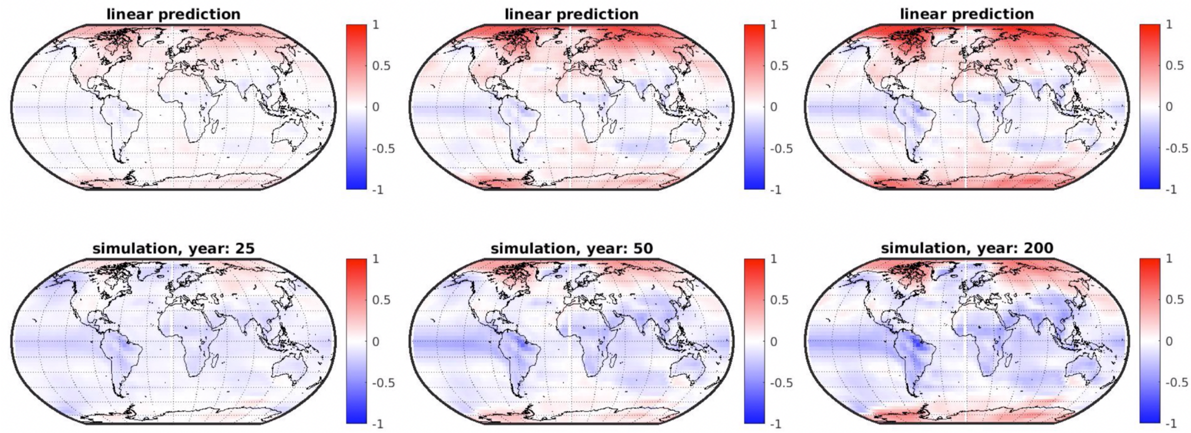


Figure 4: Snapshots of surface temperature fields [degC] (relative to the CR climatology) from a 500 year simulation. The first 20 PCs are used to assemble the fields; refer to Fig. 3.

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