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Beyond Forcing Scenarios: Predicting Climate Change through Response Operators in a Coupled General Circulation Model

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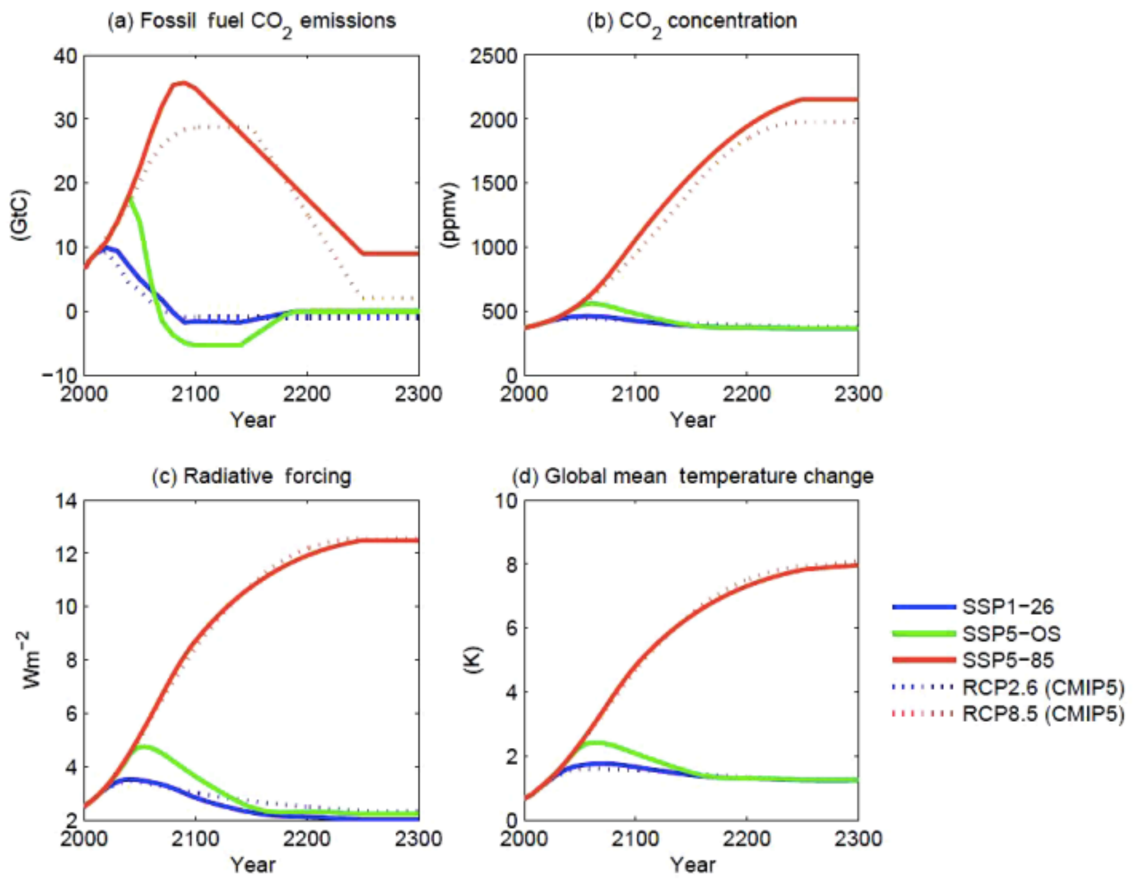
An increasing number of climate model simulations, based on different forcing scenarios...

Experiment short name	CMIP6 label	Experiment description	Forcing methods	Start year	End year	Minimum no. years per simulation	Major purpose
DECK experiments							
AMIP	*amip*	Observed SSTs and SICs prescribed	All; CO_2 concentration prescribed	1979	2014	36	Evaluation, variability
Pre-industrial control	*piControl* or *esm-piControl*	Coupled atmosphere–ocean pre-industrial control	CO_2 concentration prescribed or calculated	n/a	n/a	500	Evaluation, unforced variability
Abrupt quadrupling of CO_2 concentration	*abrupt-4×CO2*	CO_2 abruptly quadrupled and then held constant	CO_2 concentration prescribed	n/a	n/a	150	Climate sensitivity, feedback, fast responses
1 % yr^{-1} CO_2 concentration increase	*1pctCO2*	CO_2 prescribed to increase at 1 % yr^{-1}	CO_2 concentration prescribed	n/a	n/a	150	Climate sensitivity, feedback, idealized benchmark
CMIP6 historical simulation							
Past ~ 1.5 centuries	*historical* or *esm-hist*	Simulation of the recent past	All; CO_2 concentration prescribed or calculated	1850	2014	165	Evaluation

CMIP6 DECK experiments



CMIP6 future climate scenarios

(Eyring et al., 2016)

… require an increasing amount of computational resources (also given the increasing complexity of the models)

Computational resources – CMIP6

CMIP3: 17 institutes (groups) and 25 models (40 TB)
- Total years simulated: 70,000
- Individual models simulated 500 to 8,400 years (mean: 2,800 yr)
- Individual groups simulated on average 70,000/17 = 4,100 yr

x50

CMIP5: 26 institutes (groups) and 60 models (2 PB)
- Total years simulated: 330,000 (estimate Oct 2014)
- Individual models simulated on average 330,000/60 = 5,500 yr
- Individual groups estimated on average 330,000/26 = 13,000 yr

→ 4.3 Mio files

CMIP6: length of simulations similar to CMIP5, but higher resolution models, larger ensemble sizes, more diverse experiment structure

→ **Factor of 20: 36 PB in 86 Mio files**
→ **Factor of 50: 90 PB in 215 Mio files**

→ Careful planning required to determine subset of CMIP6 model output to best serve WHOI community

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

According to Taylor & Balaji (2015) and Denvil (2015)

(Ummenhofer, 2019)

Can we select what forcing scenarios are actually relevant?

The Ruelle's response theory allows to consider the response as a property of the system, independently from the forcing

A dynamical system is perturbed with a vector field perturbation of the form $\Psi(x,t) = X(x)f(t)$ **.**
The expectation value of any observable in the system is:

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

The 1st order perturbation is given by:

$$\langle \Phi \rangle_f^{(1)}(t) = \int d\sigma G_\Phi^{(1)}(\sigma_1) f(t - \sigma_1) \qquad \textbf{(2)}$$

- **If the time modulation of the perturbation is a Heaviside function, the observable-dependent Green function is:**

$$f(t) = \kappa H(t) \qquad \textbf{(3)}$$

where H(t)=0 for t=0 and 1 for t>0, k is a constant value of the forcing

- **The evolution of any observable is related to its 1st order (linear) Green function as:**

$$\frac{d\Phi^{(1)}_{f2CO2}}{dt}(t) = \kappa G^{(1)}_{\Phi}(t) \qquad \textbf{(4)}$$

- **f(t) in (3) is equivalent to the typical forcing scenario with instantaneous CO2 doubling (or quadrupling);**
- **The Green function obtained by inverting (4) is independent of the forcing —> The problem reduces to a simple impulse-response experiment!**

Experimental setting

We use a step forcing scenario to construct a linear Green function for an observable and predict its evolution in another forcing scenario

PREDICTOR

- **A step increase in CO_2 concentrations at time t=0 until 2x the preindustrial value (0-2000 yrs);**

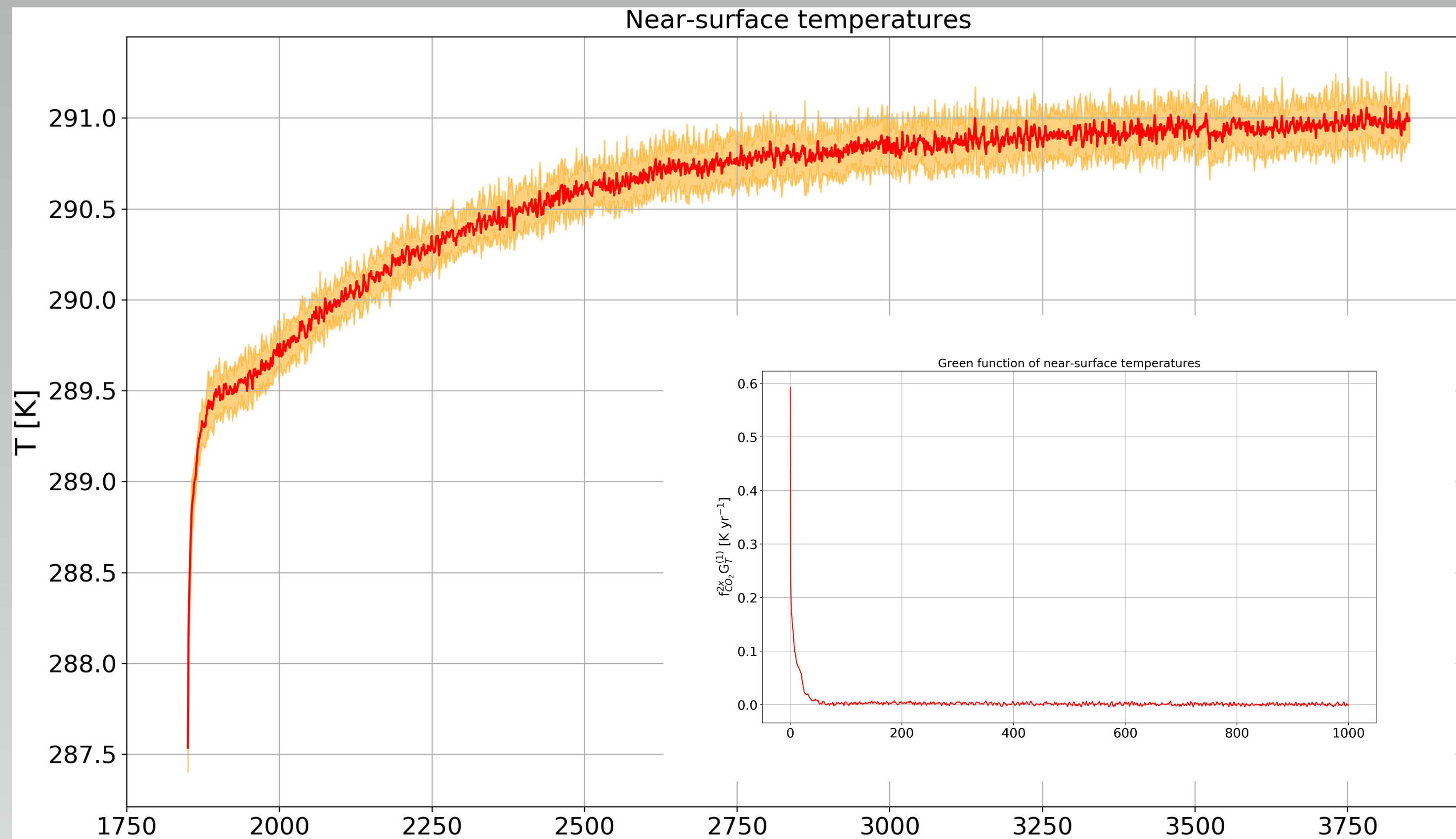
PREDICTAND

- **A ramp function experiment:**
  1. **CO_2 linear increase by 1% until doubling (0-70 yrs);**
  2. **Stationary CO_2 with 2x the preindustrial value (70-1000 yrs);**

- **Model version: MPI-ESM-CR v1.2 - ECHAM6 (T31L31) + MPIOM (GR30L40);**
- **2 ensembles, 20 members for each ensemble with same initial conditions;**
- **Focus on: 2-metre temperature, ocean heat uptake, AMOC at 26N and ACC;**

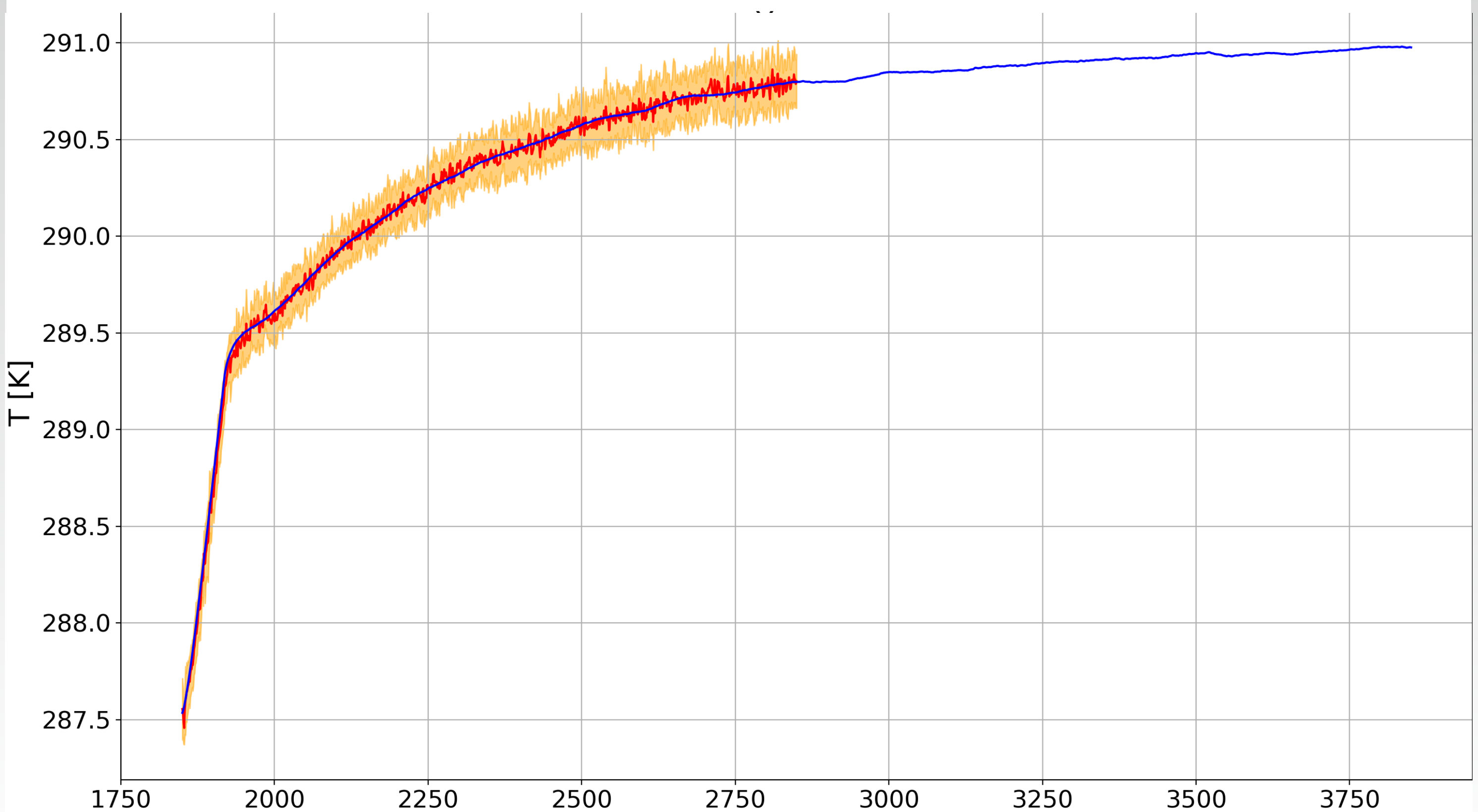
Prediction of 2-metres temperature

2xCO2 step forcing at t=0 (predictor)



The Green function is shown in the inset for the first 1000 years

1% CO2 increase (predictand)



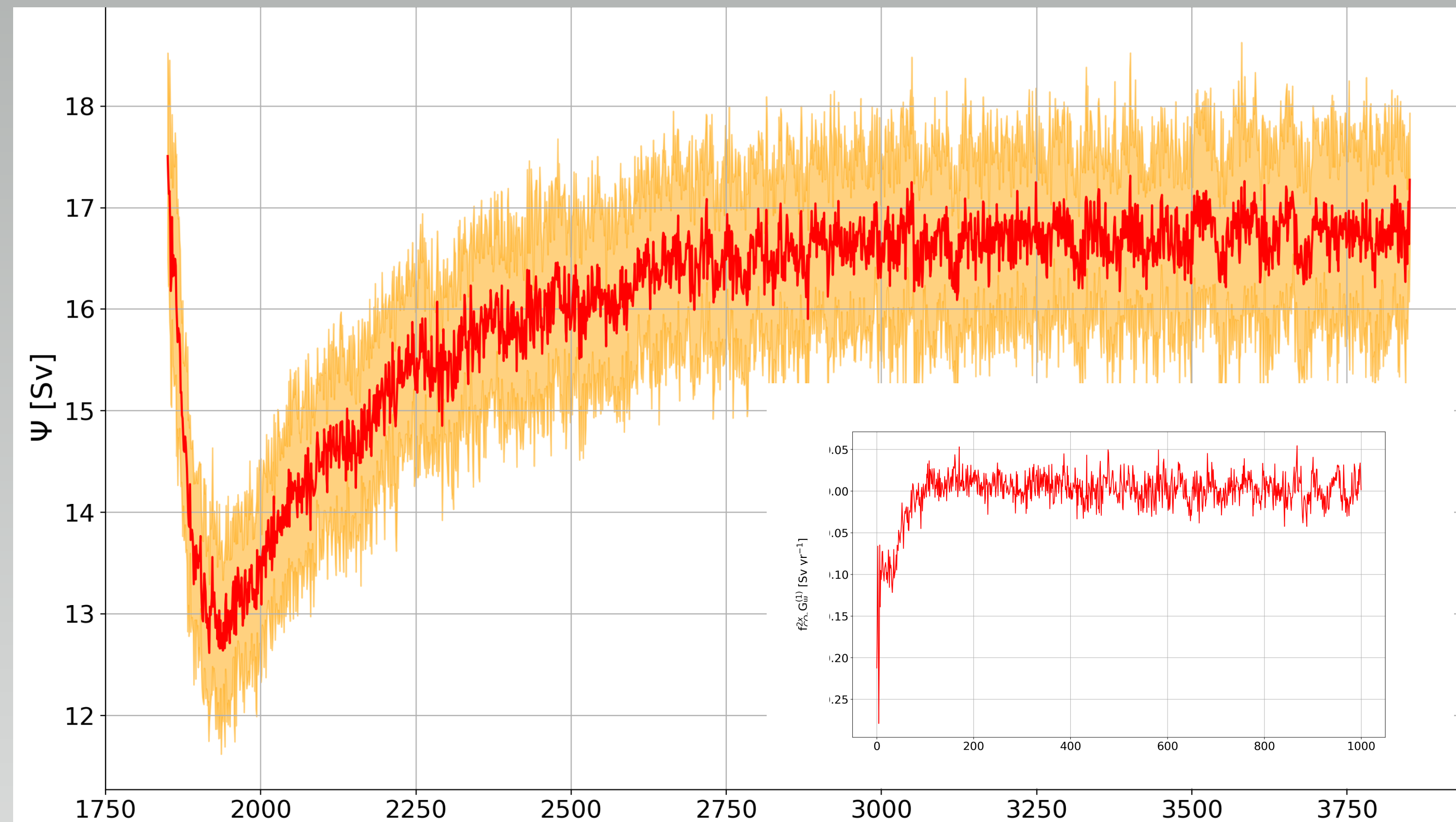
Red: ensemble mean evolution

Blue: predicted evolution with linear response

Prediction of oceanic large-scale circulation

Prediction of AMOC at 26N

2xCO2 step forcing at t=0 (predictor)



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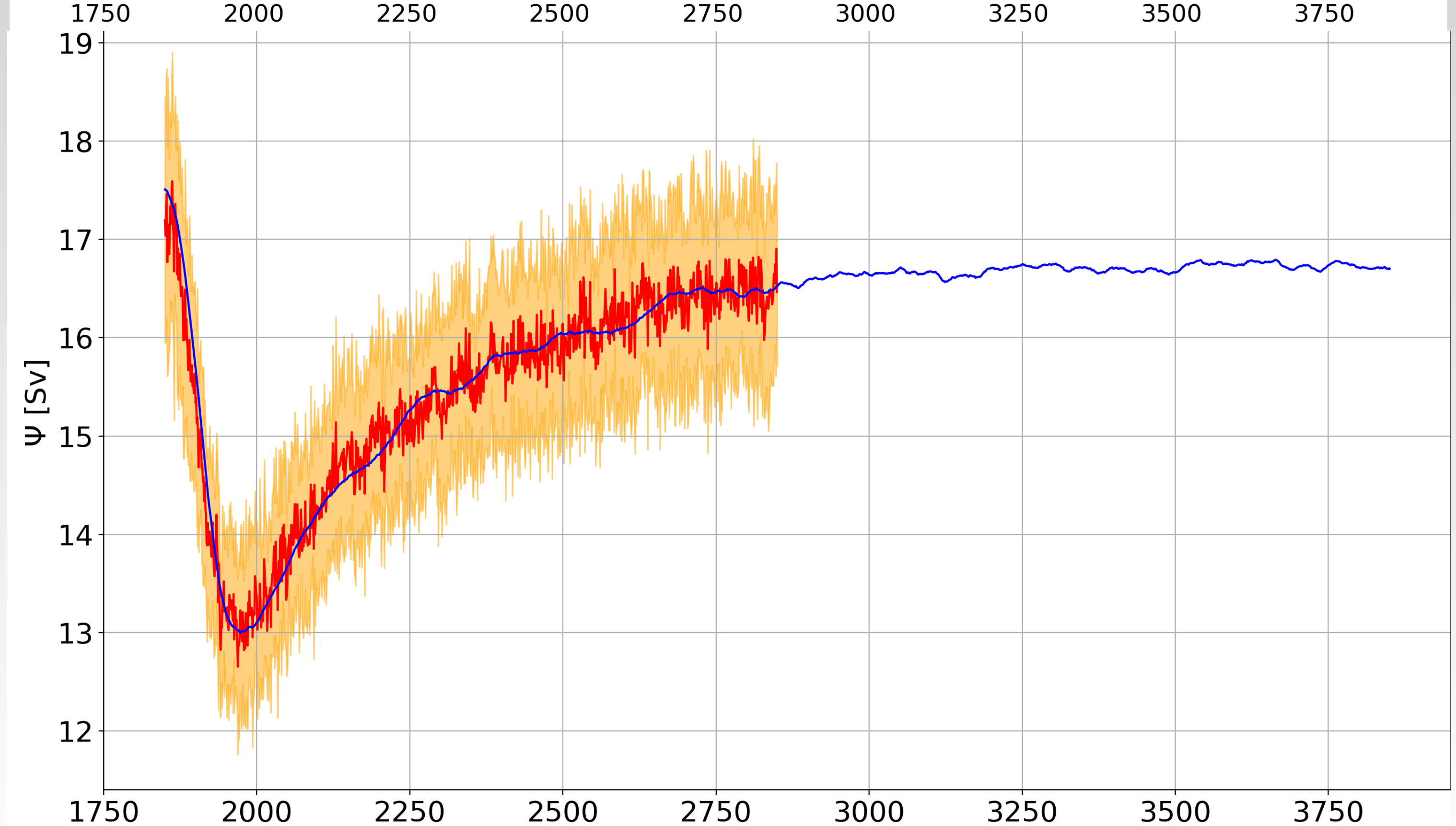
1% CO2 increase (predictand)

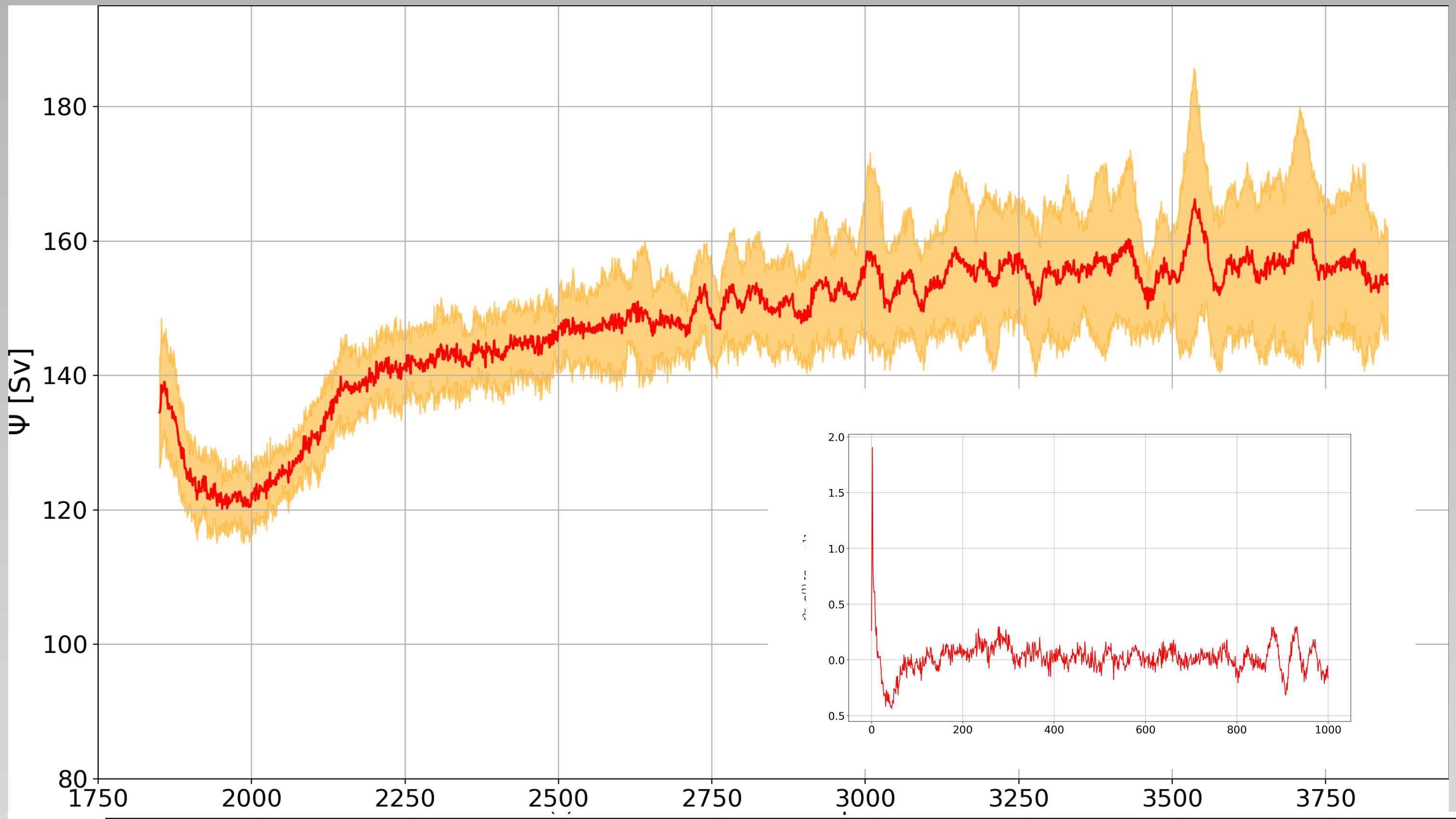


Red: ensemble mean evolution

Blue: predicted evolution with linear response

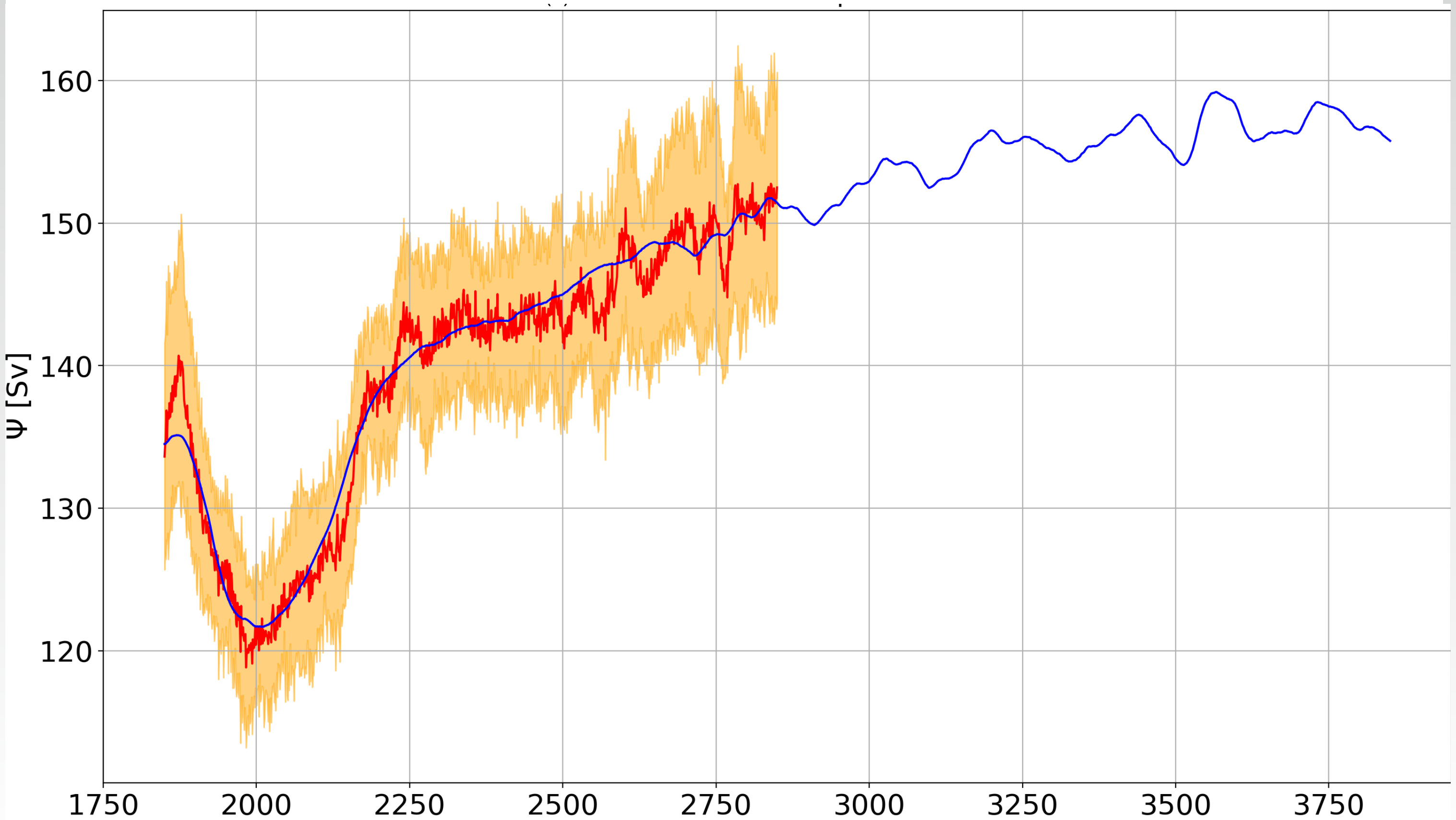
Prediction of ACC at Drake passage

2xCO2 step forcing at t=0 (predictor)



The Green function is shown in the inset for the first 1000 years

1% CO2 increase (predictand)

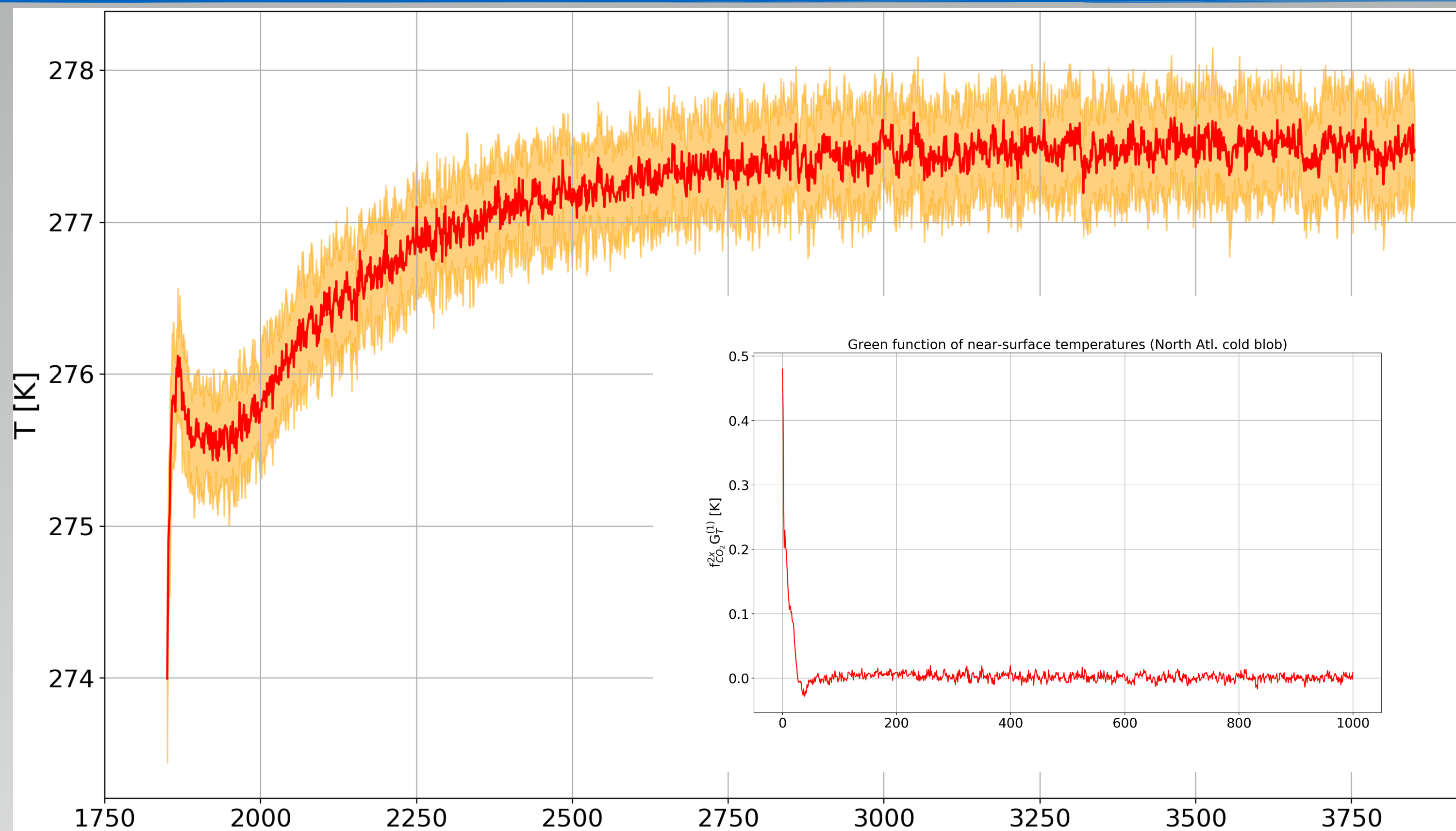


Red: ensemble mean evolution

Blue: predicted evolution with linear response

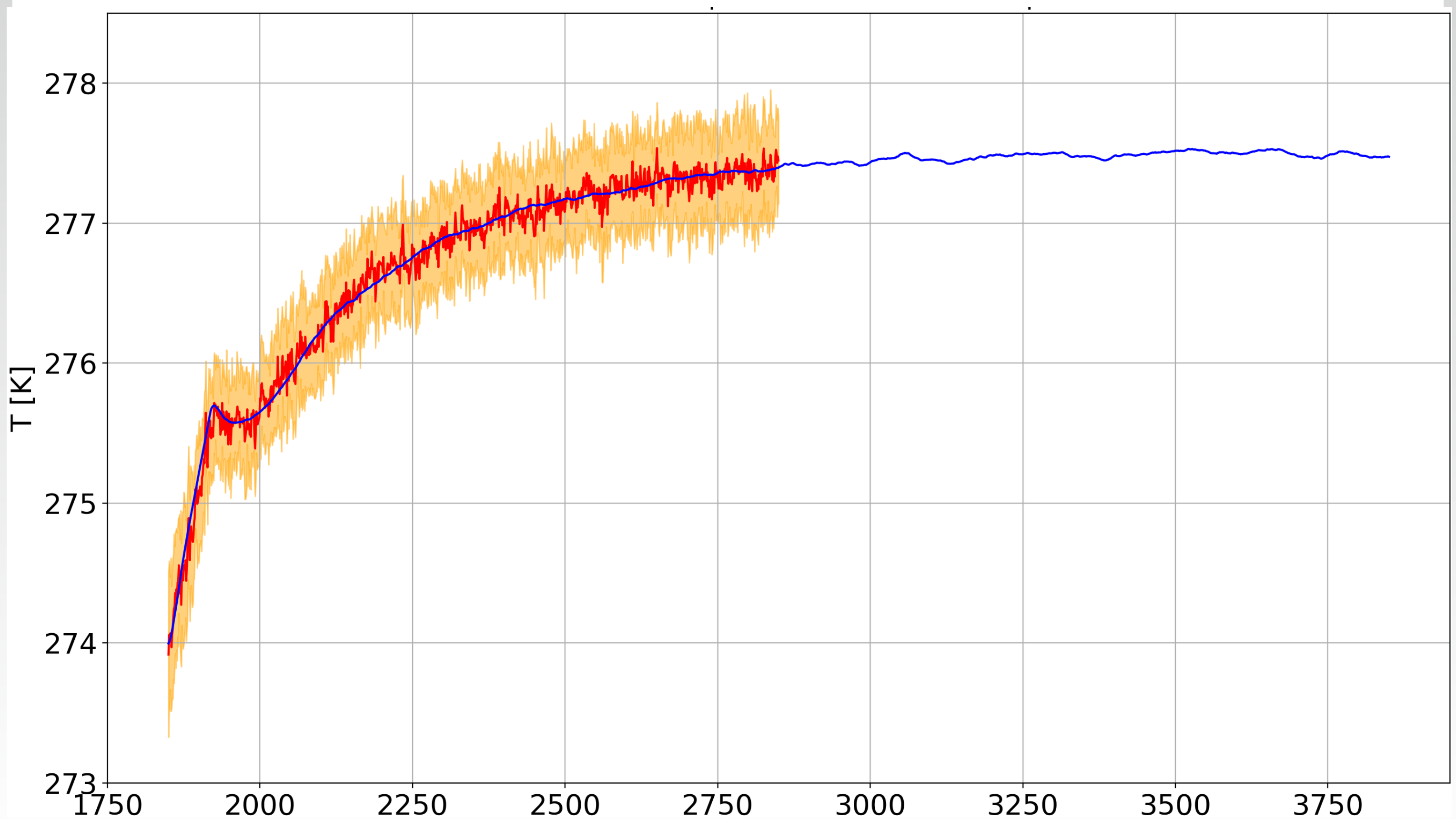
Prediction of SSTs in the extratropical Northern Atlantic

2xCO2 step forcing at t=0 (predictor)



The Green function is shown in the inset for the first 1000 years

1% CO2 increase (predictand)

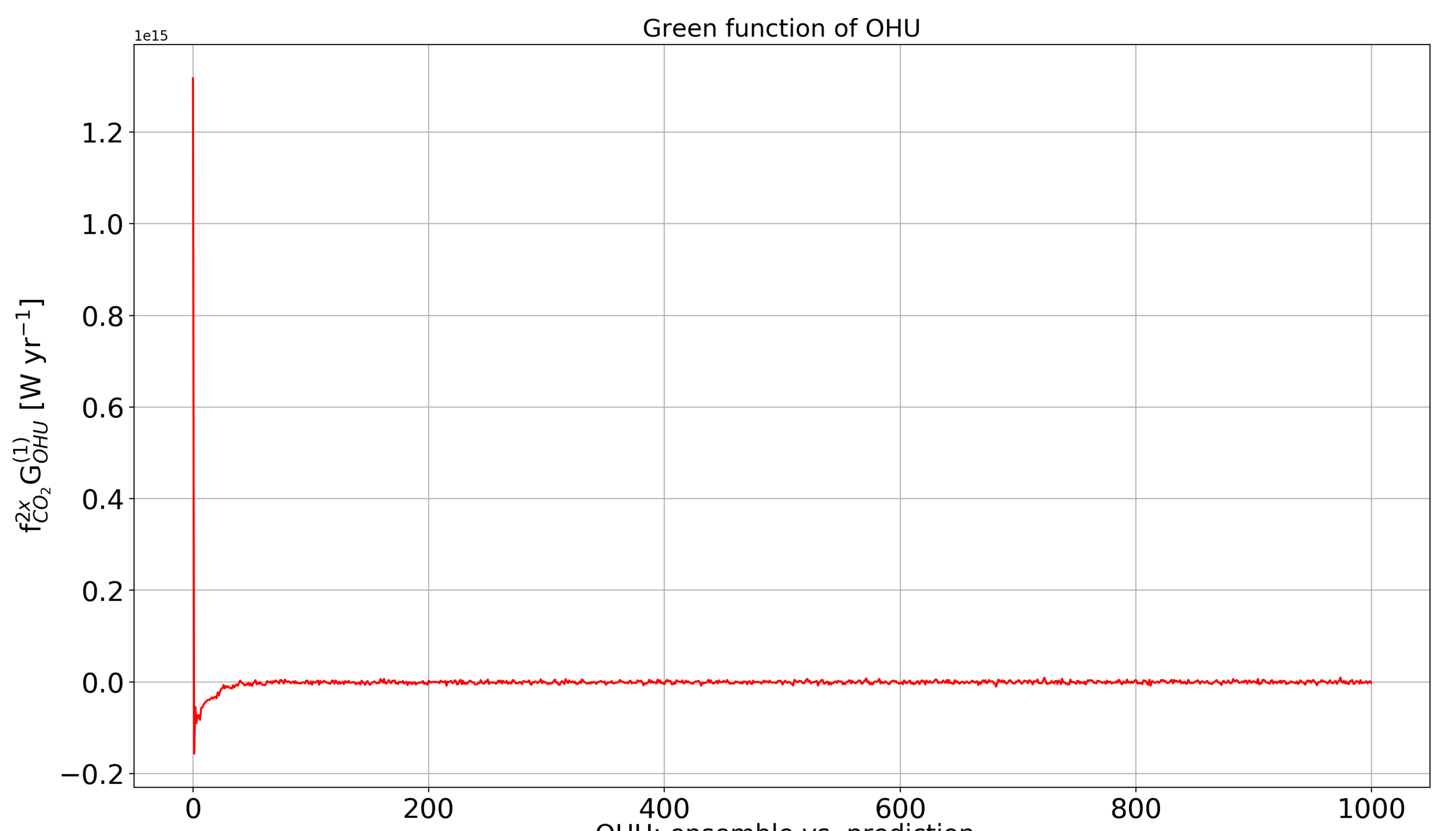


Red: ensemble mean evolution

Blue: predicted evolution with linear response

Ocean Heat Uptake (OHU): A Green function with a Dirac's

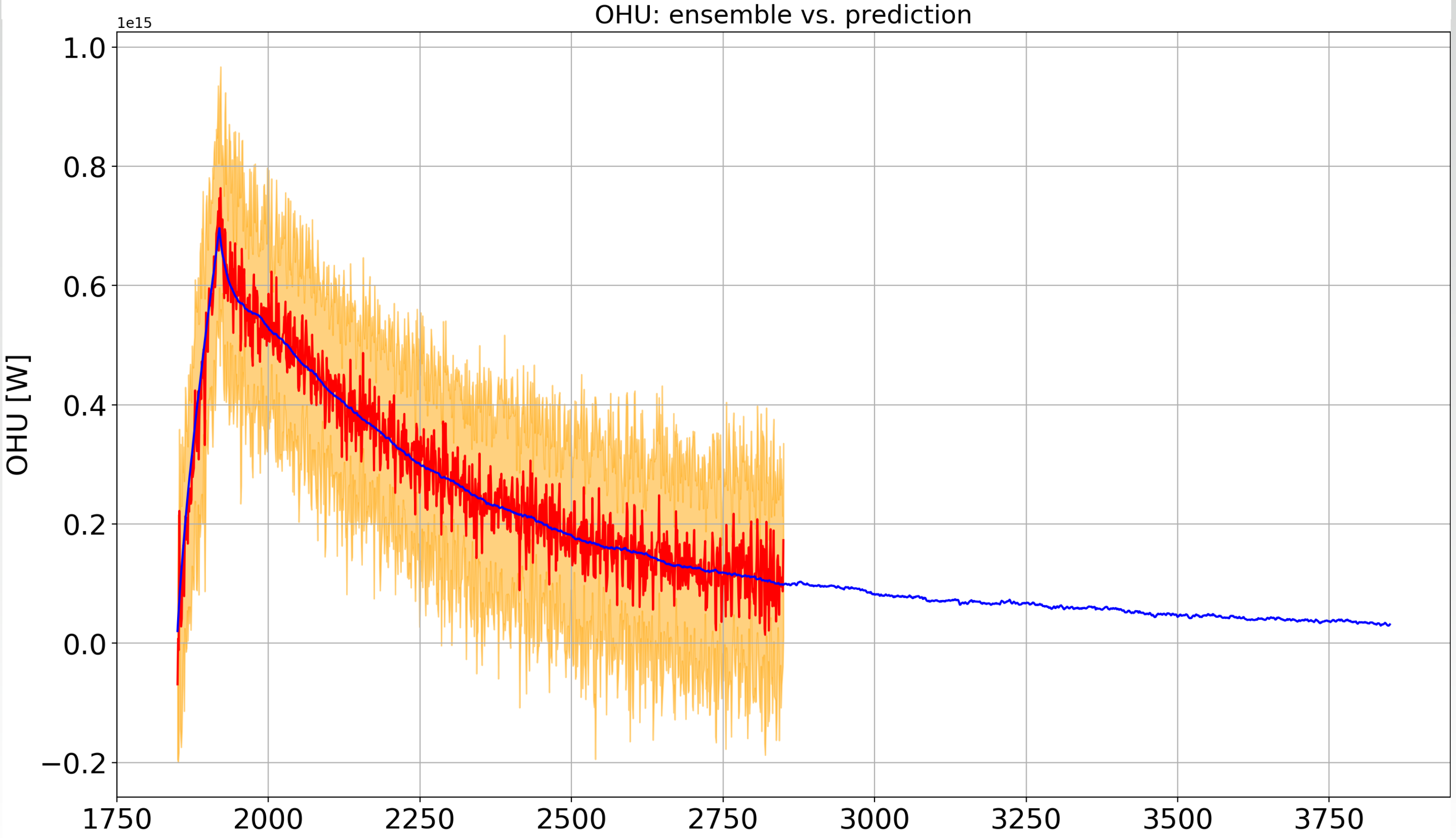
Green function



The OHU is representative of the TOA energy imbalance at these scales

The OHU anomaly is largest at t=0, as the step forcing drives the system out of balance

1% CO2 increase (predictand)



OHU tends to vanishing values as the system approaches statistically steady state

Conclusions

- We have applied an algorithm to retrieve the first order Green function for the response of a generic observable in the climate system;
- For suitable choices of the forcing, the retrieval of the Green function is straightforward;
- We demonstrated the power of the algorithm predicting the evolution of key observables in a typical forcing scenarios;
- The response of the overturning circulation is to a large extent predicted via the linear response;
- A key feature of the regional climate response, the North Atlantic cold blob, is also well predicted;
- The response theory is a valid alternative to running fully coupled climate models for various applications related to climate prediction;

References

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- **Ragone, F., Lucarini, V. and Lunkeit, F., 2016, A new framework for climate sensitivity and prediction: a modelling perspective, Clim. Dyn. 46 , 1459–1471, DOI: 10.1007/s00382-015-2657-3**
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