Equilibrium Climate Sensitivity in AWI-ESM: Mechanisms and Effects

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1 Introduction

The equilibrium or effective climate sensitivity (ECS) is used to quantify the global surface temperature change under a doubling atmospheric carbon dioxide (CO_2) concentration. Based on the assumption that the surface air temperature and radiative imbalances (induced through e.g. CO_2 forcing) exhibit a linear relationship, global circulation model (GCM) sensitivity experiments can be used to determine an ECS estimate although not being fully in equilibrium (Gregory et al. 2004).

Recently, results of state-of-the-art GCMs indicate an increased ECS compared to former numerical experiments (Climate Modeling Intercomparison Project Phase 6 (CMIP6) versus CMIP5). The increased ECS is attributed to enhanced radiative feedbacks of low extratropical clouds, partially induced through updated numerical aerosol schemes (Zelinka et al. 2020). Whether the reported high ECSs are realistic or not is important to know when society faces a warmer world in the near future. Non-linear feedback mechanisms may lead to unforeseen climate change dynamics, hampering mitigation.

In this study, we use the newly developed AWI-ESM, the Alfred-Wegener-Institute Earth System Model, a fully coupled GCM and perform sensitivity and paleo-climate experiments with different model configurations to investigate its climate sensitivity. The model coupling framework esm-tools (Barbi et al. 2020, www.esm-tools.net) allows for a highly flexible modularity that helps to understand the behavior of the different climate spheres (i.e. atmosphere, ocean, biosphere, cryosphere) and their potential impact on climate sensitivity.

3 Climate dependency of modeled ECS

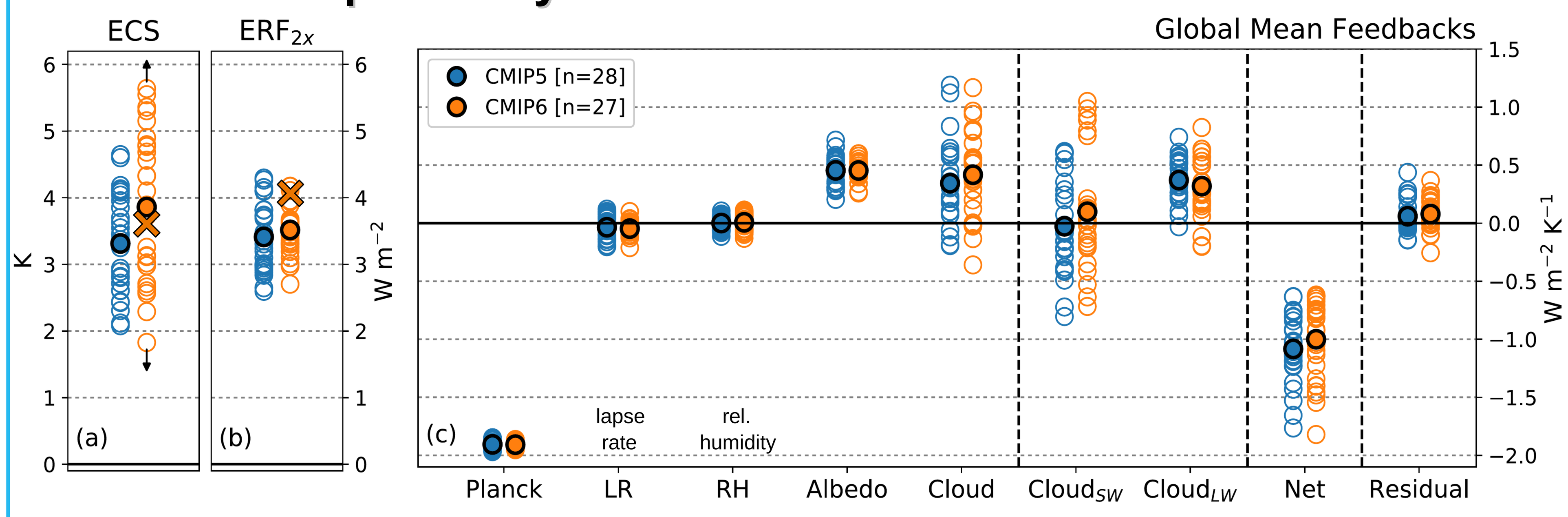

Fig. 3: Modified from Figure 1 of Zelinka et al. 2020. Comparison of modeled ECS of CMIP5 and CMIP6. Orange crosses in a and b show approximate location of AWI-ESM model suite. (Non-significant) increase of global radiative feedbacks from CMIP5 to CMIP6 through increased shortwave radiative feedbacks of low extratropical clouds. An increased radiative feedback parameter leads to a weaker radiative damping and eventually to higher warming under an increased forcing (e.g. CO_2).

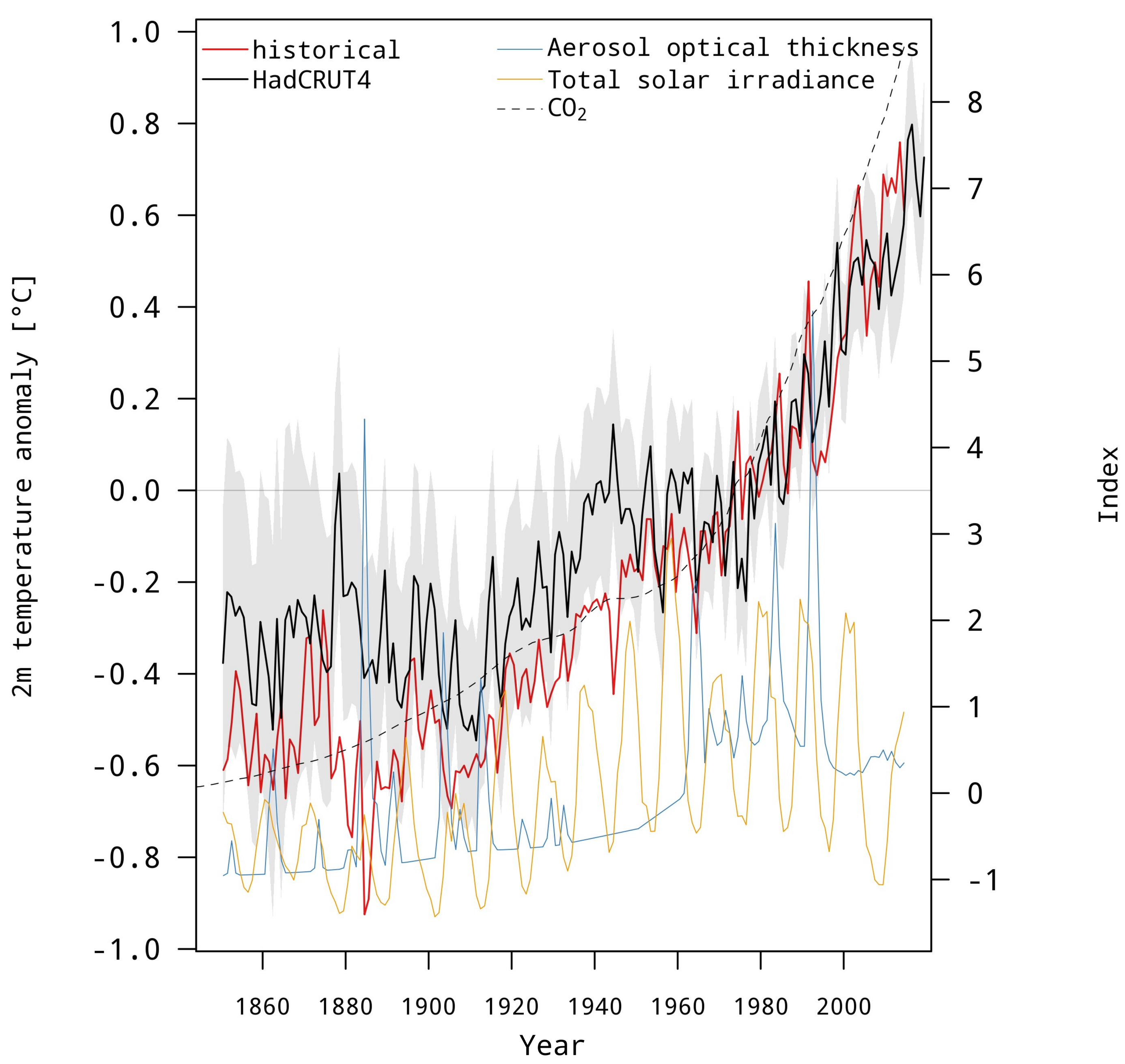

Fig. 4: Globally averaged 2m temperature anomaly with respect to the globally averaged 1961-1990 mean (left axis) as observed (HadCRUT4; Morice et al. 2012; black solid line; gray envelope shows uncertainties) and modeled with AWI-ESM-1-1-LR (red line). Forcing components aerosol optical thickness, total solar irradiance and atmospheric CO_2 concentration are given as indices (mean removed and divided by standard deviation; right axis). The overestimation of volcanic cooling (e.g. Krakatoa 1883, Agung 1963, Pinatubo 1991; spikes in blue line), the missing warming period between the 1920s-1940s and the warming slowdown in early 2000s are common problems of state-of-the-art GCMs (e.g. Guo et al. 2019).

4 Upcoming comparison of paleo-climate model performance

The probability of higher than expected ECS may be inferred by validation of the model performance in simulating past climates. For instance, Zhu et al. (2020) note that if a high-ECS-model is biased too warm under CO_2 forcing in past climates, the reported ECS for our recent climate is not necessarily realistic.

The AWI-ESM model suite enables us to study the performance of our model to simulate past climates and, hence, the ability of predicting a realistic ECS. Recent results indicate a good performance for the mid-Holocene (Brierley et al. 2020) as well as the Last Glacial Maximum (LGM, Kageyama et al. 2020).

2 Equilibrium Climate Sensitivity of AWI-ESM

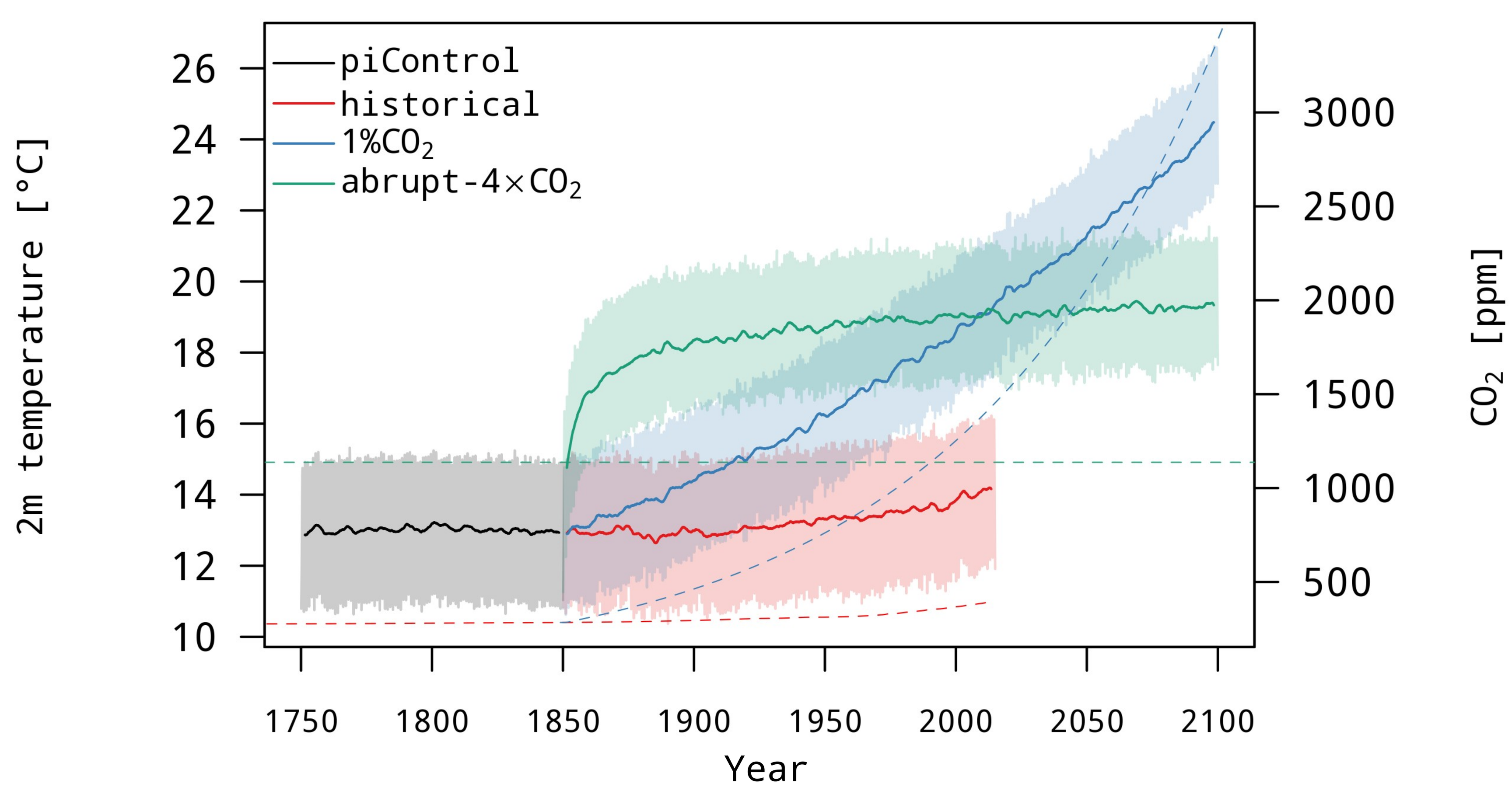

Fig. 1: Evolution of globally averaged 2m temperature (solid; left axis) and CO_2 forcing (dashed; right axis) of CMIP6 DECK experiments piControl, historical, 1%CO_2 and abrupt-4×CO_2 (Eyring et al. 2016) as modeled with AWI-ESM-1-1-LR.

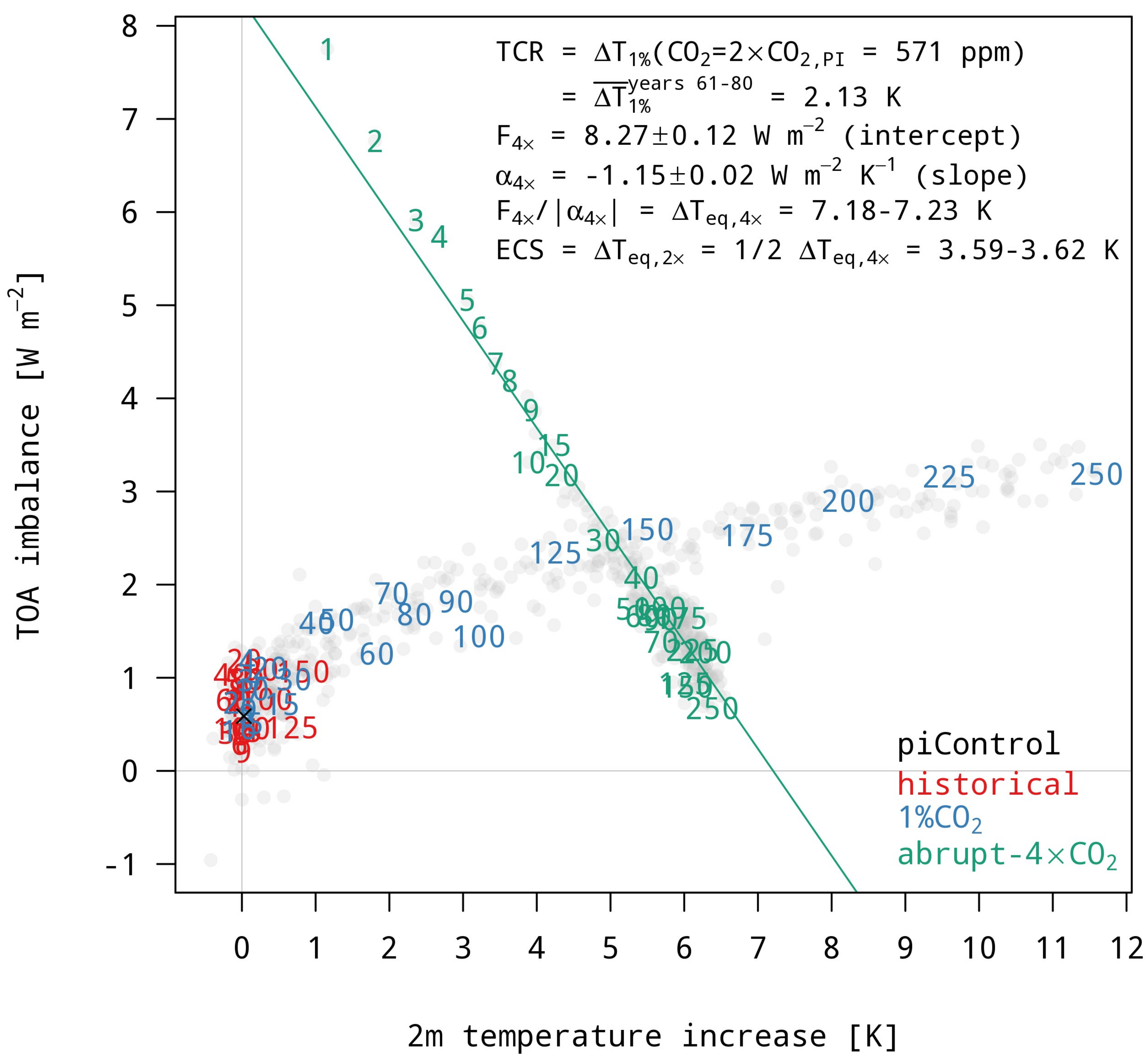

Fig. 2: Gregory plot: increase of 2m temperature (in K) against increase of radiative imbalance (= sum of incoming shortwave and outgoing longwave radiation at top of atmosphere; in W m-2; both globally and yearly averaged and with respect to the piControl run) as modeled with AWI-ESM-1-1-LR. A non-zero TOA imbalance represents a delayed warming of the ocean due to forcing (i.e. the piControl run is not fully in equilibrium). Numbers indicate modeled year with respect to start of the experiment, gray dots all years. For piControl, the mean of the last 100 modeled years is shown (black cross). ECS results from slope and y-intercept of least square regression of the abrupt-4xCO2 experiment (green line).

Tab. 1: ECS of different AWI-ESM configurations. Supporting results from Wyser et al. 2019, a dynamic vegetation has minor influence on modeled ECS.

Model	Equilibrium Climate Sensitivity (ECS) in K	Effective Radiative Forcing (ERF) in W m-2
AWI-CM-1-1-LR → Atmosphere + Land + Ocean	3.65	4.01
AWI-ESM-1-1-LR → Atmosphere + Land + Ocean + Dynamic Vegetation	3.61	4.14
AWI-ESM-1-2-LR → Atmosphere + Land + Ocean + Dynamic Vegetation + Icesheets	3.68	4.33

ESM-Tools

Barbi et al. 2020: ESM-Tools Version 4.0: A modular infrastructure for stand-alone and coupled Earth System Modelling (ESM), GMD
Brierley et al. 2020: Large-scale features and evaluation of the PMIP4-CMIP6 midHolocene simulations, CP
Eyring et al. 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, GMD
Gregory et al. 2004: A new method for diagnosing radiative forcingand climate sensitivity, GRL
Guo et al. 2019: Description and evaluation of NorESM1-F: a fast version of the Norwegian Earth System Model (NorESM), GMD
Kageyama et al. 2020: The PMIP4-CMIP6 Last Glacial Maximum experiments: preliminary results and comparison with the PMIP3-CMIP5 simulations, CP
Morice et al. 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, JGRA
Wyser et al. 2019: On the increased climate sensitivity in the EC-Earth model from CMIP5 to CMIP6, GMD
Zelinka et al. 2020: Causes of Higher Climate Sensitivity in CMIP6 Models, GRL
Zhu et al. 2020: High climate sensitivity in CMIP6 model not supported by paleoclimate, Nature Climate Change

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