UNIVERSITY OF BREMEN
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Constraining uncertainties in multi-model projections of future climate with observations

DISSERTATION

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Abstract (English version)

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Abstract (German version)

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Contents

List of Figures ix

List of Tables xi

1. Introduction 1
- 1.1. Structure of the thesis . . . 1

2. Scientific Background 3
- 2.1. Earth System Models: Simulations and Analysis . . . 3
- 2.2. Techniques to reduce uncertainties in climate model projections . 5
- 2.3. The global Carbon Cycle . . . 5

3. Improving routine Climate Model Evaluation 7

4. Assessment of Policy-relevant Climate Metrics in CMIP6 9

5. Evaluation of Emergent Constraints on the Equilibrium Climate Sensitivity in CMIP6 11

6. Constraining Uncertainties in future Gross Primary Productivity with Machine Learning 13

7. Summary and Outlook 15

Appendix 17
- A. TBA . . . 17
  - A.1. test . . . 17
- B. TBA . . . 18

List of Acronyms 19

Integrated Author's References 21

References 23

Declaration of Authorship 27

List of Figures

2.1. Historical evolution of coupled climate models over the last 45 years. In early days, these models were so-called Atmosphere-Ocean General Circulation Models (AOGCMs) and only included three components: the atmosphere, the land surface and the ocean. Over the time, the individual components grew in complexity and included a wider range of processes (illustrated by the growing cylinders). Eventually, more and more components (aerosols, carbon cycle, etc.) were added to the coupled system, forming the modern Earth System Models (ESMs). Taken from Cubasch et al. (2013). 4

List of Tables

1. The effects of treatments X and Y on the four groups studied. . . . 18
2. Logarithmic frequency ratios c of certain intervals in the equal temperament (ET) and the just intonation (JI). x cents correspond to a frequency ratio of $2^{x/1200}$. 18

1. Introduction

1.1. Structure of the thesis

Parts of this thesis are published in multiple peer-reviewed publications (two first-author studies and six co-author studies). If applicable, this is clearly stated at the beginning of each chapter. Chapter 2 introduces the scientific background for this thesis. This includes relevant literature that is used as a baseline for this thesis. Chapter 3 gives an overview over the contributions made to the Earth System Model Evaluation Tool (ESMValTool), an open-source software for the analysis of ESMs. These contributions helped improving the routine evaluation of ESMs which is useful for the whole scientific community and lead to co-authorship in four peer-reviewed studies (Eyring et al., 2020; Lauer et al., 2020; Righi et al., 2020; Weigel et al., 2020). Chapter 4 covers the assessment of policy-relevant climate metrics like the Equilibrium Climate Sensitivity (ECS) and the Transient Climate Response (TCR) in the latest generation of ESMs. This work is already published in two scientific publications (Bock et al., 2020; Meehl et al., 2020). Since the ECS and TCR are considerably higher in this new climate model generation, chapter 5 describes the assessment of emergent constraints (a technique to reduce uncertainties in climate model projections, see section 2.2 on page 5) on the ECS for these ESMs. The contents of this chapter are published in *Earth System Dynamics* (Schlund, Lauer, et al., 2020). Chapter 6 focuses on a new method to reduce climate model uncertainties based on Machine Learning (ML). As an example, the method is applied to the photosynthesis rate at the end of the 21st century, which is already published in the *Journal of Geophysical Research: Biogeosciences* (Schlund, Eyring, et al., 2020). Finally, chapter 7 provides a summary of the results of this thesis and gives an outlook of possible future works.

2. Scientific Background

This chapter introduces the scientific background necessary for the work presented in this thesis. After a brief introduction to climate model simulations and associated uncertainties, we present state-of-the art techniques used to evaluate climate model simulations and reduce uncertainties in projections of the future climate. These methods form the basis for the new techniques developed in this thesis.

2.1. Earth System Models: Simulations and Analysis

In contrast to other fields of science, researching the future evolution of the Earth's climate cannot be purely done by performing experiments in a laboratory. Due to the immense complexity of the Earth system (including physical, biological and chemical processes on various temporal and spatial scales), we do not have access to a mini version of the Earth that we can expose to varying external conditions and analyze its response to it (G. M. Flato, 2011). While observing the current state of the Earth System is (relatively) straightforward, gaining evidence about the future climate by only considering present-day observations is rather difficult. A possible way out is given by numerical climate models, which offer the possibility to simulate the Earth's climate on a computer. The first numerical climate models came up in the 1960s and were based on weather prediction models (G. M. Flato, 2011). Early models from the 1970s simulated only the physical components of the climate system: atmosphere, land surface, ocean and sea ice (see figure 2.1). The main aim of these so-called Atmosphere-Ocean General Circulation Models (AOGCMs) (G. Flato et al., 2013) is to numerically solve the differential equations that describe the exchange of energy and matter between these physical components.

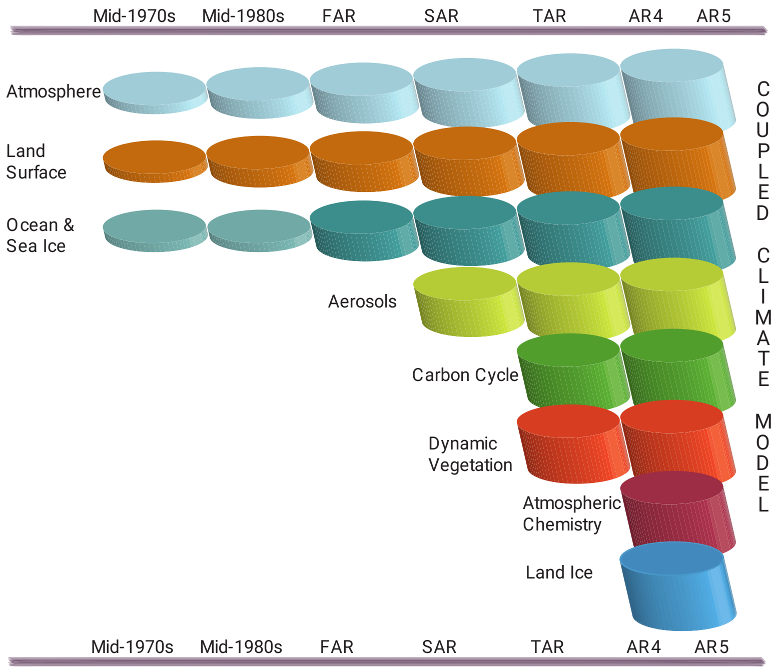

Figure 2.1.: Historical evolution of coupled climate models over the last 45 years. In early days, these models were so-called Atmosphere-Ocean General Circulation Models (AOGCMs) and only included three components: the atmosphere, the land surface and the ocean. Over the time, the individual components grew in complexity and included a wider range of processes (illustrated by the growing cylinders). Eventually, more and more components (aerosols, carbon cycle, etc.) were added to the coupled system, forming the modern Earth System Models (ESMs). Taken from Cubasch et al. (2013).

Over the course of the years, climate models became more and more complex by including a wider range of processes within the components, but also by introducing new components to the coupled system. Examples of these are aerosols, the carbon cycle, a dynamic vegetation, atmospheric chemistry and land ice (see figure 2.1). AOGCMs coupled to these additional components are called Earth System Models (ESMs), which are the current state-of-the-art models that allow the most sophisticated simulations of the Earth's climate. In contrast to AOGCMs, ESMs enable the simulation of biological and chemical processes in addition to the dynamics of the physical components of the Earth system. Especially in the context of anthropogenic climate change, these additional processes are of uttermost importance for realistic climate model simulations, since the anthropogenic interference with the Earth system directly influences the various biogeochemical cycles of the Earth. For example, the emission of the most prominent Greenhouse Gas (GHG), carbon dioxide (CO_2), immediately impacts the global carbon cycle by introducing an additional carbon source to the cycle (for details see section 2.3). Due to the global carbon cycle, only about 50 % of the emitted CO_2 remains in the atmosphere, where it can act as GHG by introducing an additional radiative forcing to the Earth System, which eventually leads to increasing surface temperatures. Thus, this uptake of CO_2 by the global carbon cycle slows down global warming. Further examples include land use changes like the deforestation of tropical rainforests, which also directly influences several biogeochemical cycles (e.g. carbon cycle, nitrogen cycle, phosphorus cycle, etc.) by altering respective sinks and sources.

2.2. Techniques to reduce uncertainties in climate model projections

2.3. The global Carbon Cycle

3. Improving routine Climate Model Evaluation

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4. Assessment of Policy-relevant Climate Metrics in CMIP6

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5. Evaluation of Emergent Constraints on the Equilibrium Climate Sensitivity in CMIP6

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6. Constraining Uncertainties in future Gross Primary Productivity with Machine Learning

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7. Summary and Outlook

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Appendix

A. TBA

A.1. test

test

hi The Equilibrium Climate Sensitivity (ECS) is really cool. I like it very much!

This is e.g. without an "at" and this is it with an "at" e.g. difference? Test space. Real dot!

E.g.blaa. E.g. blaaaa. i.e.blaaaa, i.e. blaa.

These are really cool papers: (Schlund, Lauer, et al., 2020; Schlund, Eyring, et al., 2020)

autocite: (Lauer et al., 2018)

cite: Lauer et al., 2010 (Anav et al., 2015) (Anav et al., 2013) (Allen & Ingram, 2002)

textcite: Lauer et al. (2010)

And this one, too: (Lauer et al., 2020)

This is a reference to the equation: equation (1)

Three authors: (Bao et al., 2020)

Many many authors: (Eyring et al., 2020)

`input <iostream>`

$$c_{k_1,k_2} := 1200 \log_2 \left(\frac{f_1^{(k_2)}}{f_1^{(k_1)}} \right) \text{ cents.} \tag{1}$$

Table 1.: The effects of treatments X and Y on the four groups studied.

Groups	**Treatment X**	**Treatment Y**
1	0.2	0.8
2	0.17	0.7
3	0.24	0.75
4	0.68	0.3

Semitones	Interval	c / cents (ET)	c / cents (JI)
0	Perfect unison	0	0
1	Minor second	100	112
2	Major second	200	204
3	Minor third	300	316
4	Major third	400	386
5	Perfect fourth	500	498
6	Augmented fourth	600	590
7	Perfect fifth	700	702
8	Minor sixth	800	814
9	Major sixth	900	884
10	Minor seventh	1000	996
11	Major seventh	1100	1088
12	Perfect octave	1200	1200

Table 2.: Logarithmic frequency ratios c of certain intervals in the equal temperament (ET) and the just intonation (JI). x cents correspond to a frequency ratio of $2^{x/1200}$.

B. TBA

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List of Acronyms

AOGCM Atmosphere-Ocean General Circulation Model 3

CO_2 carbon dioxide 5

ECS Equilibrium Climate Sensitivity 17

ESM Earth System Model 4

ESMValTool Earth System Model Evaluation Tool 1

GHG Greenhouse Gas 5

GPP Gross Primary Productivity

ML Machine Learning 1

TCR Transient Climate Response 1

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Declaration of Authorship

I assure that this thesis is a result of my personal work and that no other than the indicated aids have been used for its completion. Furthermore I assure that all quotations and statements that have been inferred literally or in a general manner from published or unpublished writings are marked as such. Beyond this I assure that the work has not been used, neither completely nor in parts, to pass any previous examination.

Oberpfaffenhofen, March 2021

Manuel SCHLUND