University of Bremen
Institute of Environmental Physics (IUP)

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

Dissertation

Author:
Manuel Schlund

Supervisors:
Prof. Dr. Veronika Eyring
Prof. Dr. Pierre Gentine

This thesis is submitted for the degree
Doktor der Naturwissenschaften (Dr. rer. nat.)

March 2021

Abstract (English version)

TBA.

Abstract (German version)

TBA.

Contents

List of Figures

List of Tables

1. Introduction

1.1. Structure of the thesis

Parts of this thesis are published in multiple scientific publications (two as first author six as co-author). If applicable, this is clearly stated at the beginning of each chapter. Chapter 2 introduces the scientific background for this thesis. This includes basic principles of Earth System Modeling, sources of uncertainty in future projections of the climate, relevant definitions and state-of-the-art methods used to evaluate ESM simulations and reduce associated uncertainties. 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 (EqCS) 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 EqCS 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 3) on the EqCS 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

2.1. Earth System Models: Simulations and Analysis

An Earth System Model (ESM) is really cool! Yes, ESMs!!

TBA.

2.2. Techniques to reduce uncertainties in climate model projections

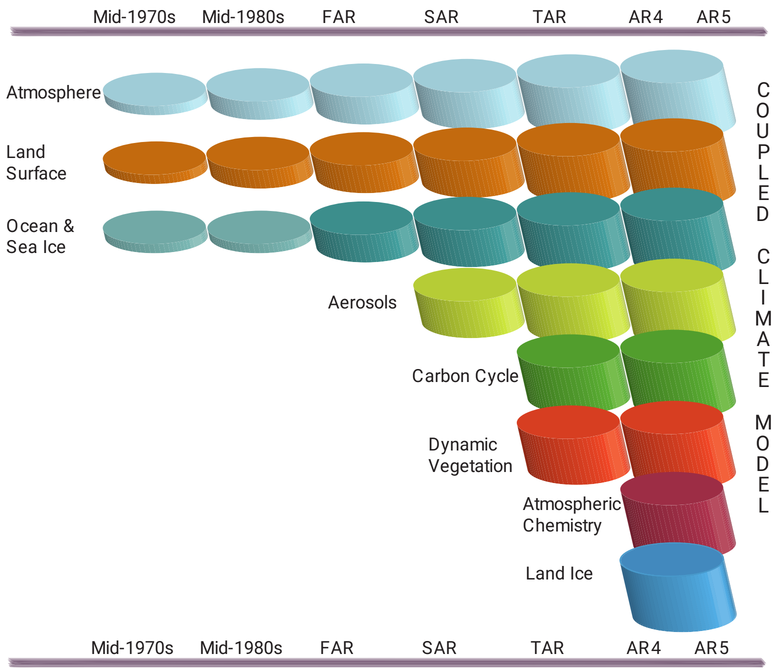

Figure 2.1.: Historical evolution of coupled climate models over the last 45 years. In early days, these models were Atmosphere-Ocean General Circulation Models (AOGCMs) and only included three components: the atmosphere, the land surface and the ocean. Over the time, the individual components grew in 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).

3. Improving routine Model Evaluation

TBA.

4. Assessment of Policy-relevant Climate Metrics in CMIP6

TBA.

5. Evaluation of Emergent Constraints on ECS in CMIP6

TBA.

6. Constraining Uncertainties in future GPP with Machine Learning

TBA.

7. Summary and Outlook

TBA.

Appendix

A. TBA

A.1. test

test

hi The Effective 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

TBA.

List of Acronyms

Integrated Author's References

Bock, L., Lauer, A., **Schlund**, **M.**, Barreiro, M., Bellouin, N., Jones, C., Meehl, G. A., Predoi, V., Roberts, M. J., & Eyring, V. (2020). Quantifying Progress Across Different CMIP Phases With the ESMValTool. *Journal of Geophysical Research: Atmospheres*, *125*(21). https://doi.org/10.1029/2019jd032321

Eyring, V., Bock, L., Lauer, A., Righi, M., **Schlund**, **M.**, Andela, B., Arnone, E., Bellprat, O., Brötz, B., Caron, L.-P., Carvalhais, N., Cionni, I., Cortesi, N., Crezee, B., Davin, E. L., Davini, P., Debeire, K., de Mora, L., Deser, C., Docquier, D., Earnshaw, P., Ehbrecht, C., Gier, B. K., Gonzalez-Reviriego, N., Goodman, P., Hagemann, S., Hardiman, S., Hassler, B., Hunter, A., Kadow, C., Kindermann, S., Koirala, S., Koldunov, N., Lejeune, Q., Lembo, V., Lovato, T., Lucarini, V., Massonnet, F., Müller, B., Pandde, A., Pérez-Zanón, N., Phillips, A., Predoi, V., Russell, J., Sellar, A., Serva, F., Stacke, T., Swaminathan, R., Torralba, V., Vegas-Regidor, J., von Hardenberg, J., Weigel, K., & Zimmermann, K. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0 – an extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP. *Geoscientific Model Development*, *13*(7), 3383–3438. https://doi.org/10.5194/gmd-13-3383-2020

Lauer, A., Eyring, V., Bellprat, O., Bock, L., Gier, B. K., Hunter, A., Lorenz, R., Pérez-Zanón, N., Righi, M., **Schlund**, **M.**, Senftleben, D., Weigel, K., & Zechlau, S. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0 – diagnostics for emergent constraints and future projections from Earth system models in CMIP. *Geoscientific Model Development*, *13*(9), 4205–4228. https://doi.org/10.5194/gmd-13-4205-2020

Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., & **Schlund**, **M.** (2020). Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, *6*(26), eaba1981. https://doi.org/10.1126/sciadv.aba1981

Righi, M., Andela, B., Eyring, V., Lauer, A., Predoi, V., **Schlund**, **M.**, Vegas-Regidor, J., Bock, L., Brotz, B., de Mora, L., Diblen, F., Dreyer, L., Drost, N., Earnshaw, P., Hassler, B., Koldunov, N., Little, B., Tomas, S. L., & Zimmermann, K. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0-technical overview. *Geoscientific Model Development*, *13*(3), 1179–1199. https://doi.org/10.5194/gmd-13-1179-2020

Schlund, **M.**, Lauer, A., Gentine, P., Sherwood, S. C., & Eyring, V. (2020). Emergent constraints on Equilibrium Climate Sensitivity in CMIP5: do they hold for CMIP6? *Earth System Dynamics Discussions*, *2020*, 1–40. https://doi.org/10.5194/esd-2020-49

Schlund, **M.**, Eyring, V., Camps-Valls, G., Friedlingstein, P., Gentine, P., & Reichstein, M. (2020). Constraining uncertainty in projected gross primary production with machine learning. *Journal of Geophysical Research: Biogeosciences*, *125*, e2019JG005619. https://doi.org/10.1029/2019jg005619

Weigel, K., Bock, L., Gier, B. K., Lauer, A., Righi, M., **Schlund**, **M.**, Adeniyi, K., Andela, B., Arnone, E., Berg, P., Caron, L.-P., Cionni, I., Corti, S., Drost, N., Hunter, A., Lledó, L., Mohr, C. W., Paçal, A., Pérez-Zanón, N., Predoi, V., Sandstad, M., Sillmann, J., Sterl, A., Vegas-Regidor, J., von Hardenberg, J., & Eyring, V. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0 – diagnostics for extreme events, regional and impact evaluation and analysis of Earth system models in CMIP. *Geoscientific Model Development Discussions*, *2020*, 1–43. https://doi.org/10.5194/gmd-2020-244

References

Allen, M. R., & Ingram, W. J. (2002). Constraints on future changes in climate and the hydrologic cycle. *Nature*, *419*(6903), 224–+. https://doi.org/10.1038/nature01092

Anav, A., Friedlingstein, P., Kidston, M., Bopp, L., Ciais, P., Cox, P., Jones, C., Jung, M., Myneni, R., & Zhu, Z. (2013). Evaluating the Land and Ocean Components of the Global Carbon Cycle in the CMIP5 Earth System Models. *Journal of Climate*, *26*(18), 6801–6843. https://doi.org/10.1175/Jcli-D-12-00417.1

Anav, A., Friedlingstein, P., Beer, C., Ciais, P., Harper, A., Jones, C., Murray-Tortarolo, G., Papale, D., Parazoo, N. C., Peylin, P., Piao, S., Sitch, S., Viovy, N., Wiltshire, A., & Zhao, M. (2015). Spatiotemporal patterns of terrestrial gross primary production: A review. *Reviews of Geophysics*, *53*(3), 785–818. https://doi.org/10.1002/2015rg000483

Bao, Y., Song, Z. Y., & Qiao, F. L. (2020). FIO-ESM Version 2.0: Model Description and Evaluation. *Journal of Geophysical Research-Oceans*, *125*(6). https://doi.org/10.1029/2019JC016036

Bock, L., Lauer, A., **Schlund, M.**, Barreiro, M., Bellouin, N., Jones, C., Meehl, G. A., Predoi, V., Roberts, M. J., & Eyring, V. (2020). Quantifying Progress Across Different CMIP Phases With the ESMValTool. *Journal of Geophysical Research: Atmospheres*, *125*(21). https://doi.org/10.1029/2019jd032321

Cubasch, U., Wuebbles, D., Chen, D., Facchini, M. C., Frame, D., Mahowald, N., & Winther, J.-G. (2013). Introduction. Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2017/09/WG1AR5_Chapter01_FINAL.pdf

Eyring, V., Bock, L., Lauer, A., Righi, M., **Schlund, M.**, Andela, B., Arnone, E., Bellprat, O., Brötz, B., Caron, L.-P., Carvalhais, N., Cionni, I., Cortesi, N., Crezee, B., Davin, E. L., Davini, P., Debeire, K., de Mora, L., Deser, C., Docquier, D., Earnshaw, P., Ehbrecht, C., Gier, B. K., Gonzalez-Reviriego, N., Goodman, P., Hagemann, S., Hardiman, S., Hassler, B., Hunter, A., Kadow, C., Kindermann, S., Koirala, S., Koldunov, N., Lejeune, Q., Lembo, V., Lovato, T., Lucarini, V., Massonnet, F., Müller, B., Pandde, A., Pérez-Zanón, N., Phillips, A., Predoi, V., Russell, J., Sellar, A., Serva, F., Stacke, T., Swaminathan, R., Torralba, V., Vegas-Regidor, J., von Hardenberg, J., Weigel, K., & Zimmermann, K. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0 – an extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP. *Geoscientific Model Development*, *13*(7), 3383–3438. https://doi.org/10.5194/gmd-13-3383-2020

Lauer, A., Hamilton, K., Wang, Y. Q., Phillips, V. T. J., & Bennartz, R. (2010). The Impact of Global Warming on Marine Boundary Layer Clouds over the Eastern Pacific-A Regional Model Study. *Journal of Climate*, *23*(21), 5844–5863. https://doi.org/10.1175/2010jcli3666.1

Lauer, A., Jones, C., Eyring, V., Evaldsson, M., Stefan, H. A., Makela, J., Martin, G., Roehrig, R., & Wang, S. Y. (2018). Process-level improvements in CMIP5 models and their impact on tropical variability, the Southern Ocean, and monsoons. *Earth System Dynamics*, *9*(1), 33–67. https://doi.org/10.5194/esd-9-33-2018

Lauer, A., Eyring, V., Bellprat, O., Bock, L., Gier, B. K., Hunter, A., Lorenz, R., Pérez-Zanón, N., Righi, M., **Schlund**, **M.**, Senftleben, D., Weigel, K., & Zechlau, S. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0 – diagnostics for emergent constraints and future projections from Earth system models in CMIP. *Geoscientific Model Development*, *13*(9), 4205–4228. https://doi.org/10.5194/gmd-13-4205-2020

Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., & **Schlund**, **M.** (2020). Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, *6*(26), eaba1981. https://doi.org/10.1126/sciadv.aba1981

Righi, M., Andela, B., Eyring, V., Lauer, A., Predoi, V., **Schlund**, **M.**, Vegas-Regidor, J., Bock, L., Brotz, B., de Mora, L., Diblen, F., Dreyer, L., Drost, N., Earnshaw, P., Hassler, B., Koldunov, N., Little, B., Tomas, S. L., & Zimmermann, K. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0-technical overview. *Geoscientific Model Development*, *13*(3), 1179–1199. https://doi.org/10.5194/gmd-13-1179-2020

Schlund, **M.**, Lauer, A., Gentine, P., Sherwood, S. C., & Eyring, V. (2020). Emergent constraints on Equilibrium Climate Sensitivity in CMIP5: do they hold for CMIP6? *Earth System Dynamics Discussions*, *2020*, 1–40. https://doi.org/10.5194/esd-2020-49

Schlund, **M.**, Eyring, V., Camps-Valls, G., Friedlingstein, P., Gentine, P., & Reichstein, M. (2020). Constraining uncertainty in projected gross primary production with machine learning. *Journal of Geophysical Research: Biogeosciences*, *125*, e2019JG005619. https://doi.org/10.1029/2019jg005619

Weigel, K., Bock, L., Gier, B. K., Lauer, A., Righi, M., **Schlund**, **M.**, Adeniyi, K., Andela, B., Arnone, E., Berg, P., Caron, L.-P., Cionni, I., Corti, S., Drost, N., Hunter, A., Lledó, L., Mohr, C. W., Paçal, A., Pérez-Zanón, N., Predoi, V., Sandstad, M., Sillmann, J., Sterl, A., Vegas-Regidor, J., von Hardenberg, J., & Eyring, V. (2020). Earth System Model Evaluation Tool (ESMValTool) v2.0 – diagnostics for extreme events, regional and impact evaluation and analysis of Earth system models in CMIP. *Geoscientific Model Development Discussions*, *2020*, 1–43. https://doi.org/10.5194/gmd-2020-244

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