Abstract
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Long-term variability and change of the Atlantic Meridional Overturning Circulation in a hierarchy of climate models

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The Atlantic Meridional Overturning Circulation (AMOC) transports heat and carbon from the southern hemisphere and the tropics to the northern hemisphere mid-latitudes, playing an important role in shaping the Earth's climate and climatic changes. For instance, AMOC variations have often been invoked as a driver of natural climate variations (internal variability) on timescales of decades to millennia. Under global warming, the AMOC is expected to weaken, but the magnitude of this weakening is uncertain, which is in turn a key contributor to the uncertainty in surface climate projections. This includes uncertainties related to the potential low-likelihood, high-impact event of an abrupt, irreversible AMOC change (tipping).

While the AMOC is one of the most well-studied elements of the global ocean from both direct observations and ocean and climate models, so far, comparatively little is known about its long-term behavior on timescales of centuries. This is due to the short observational record, limited paleoclimate reconstructions and the computational cost of long integrations with comprehensive climate models. Yet, as we approach an uncharted territory of global warming, it is essential to improve our understanding of long-term AMOC variations, both forced and unforced.

In this thesis, several aspects of internal variability and externally forced changes of the AMOC on timescales of centuries are studied in a hierarchy of climate models of different complexity. The two main lines of research focus on (1) mechanisms of centennial-scale AMOC variability, and (2) the potential of AMOC tipping due to global warming, meltwater from the Greenland ice sheet and, more fundamentally, chaotic atmosphere–ocean interactions.

First, we perform a model intercomparison of centennial-scale AMOC variability in state-of-the-art coupled climate models used for the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. We identify significant centennial-scale variability and a consistent pattern of freshwater exchanges between the Arctic and the North Atlantic in a subset of these models. Through ocean–sea ice feedbacks in the Labrador Sea, the amplitude of AMOC variability is linked to the sea ice mean state, which could provide an observational constraint for centennial-scale AMOC variability in climate models.

To improve process understanding of the mechanisms behind centennial-scale AMOC variability, it then seems beneficial to reduce model complexity to achieve faster integrations by using a climate model of intermediate complexity (PlaSim–LSG). Analysis of a pre-industrial control simulation indicates that Arctic Ocean salinity anomalies induced by changes in high-latitude precipitation drive the AMOC oscillations in PlaSim–LSG. This mechanism is corroborated with a suite of millennial-length sensitivity experiments and a conceptual three-box model, demonstrating the robustness of centennial-scale AMOC variability across the model hierarchy.

Shifting focus towards projections of future climate change, we investigate the effect of meltwater from the Greenland ice sheet on the AMOC under strong global warming and whether ice sheet melt could trigger an abrupt AMOC weakening. Two ensembles of future projections are conducted with the state-of-the-art climate model EC-Earth3, one in which ice sheet melt is neglected and one in which a physically plausible, high-end estimate of Greenland meltwater flux is prescribed. The meltwater-induced additional AMOC weakening is mostly driven by changes in the Arctic Ocean, but no abrupt AMOC weakening is identified. These results elucidate, for the first time, how future AMOC changes could be shaped by the combined effect of the northward shift of AMOC source regions and increasing runoff from Greenland.

Finally, we address the more conceptual question of inherent limits to predictability of the asymptotic AMOC state close to a tipping point. Using a conceptual climate model in which the bistable AMOC is coupled to a chaotic atmosphere, we identify two limitations to long-term predictability: long chaotic transients, which can mask a loss of stability near bifurcations, and a high-dimensional fractal basin boundary, which implies vanishing predictability for trajectories initialized near the basin boundary. The chaotic saddle, which is constructed using the so-called edge tracking algorithm, is linked to the properties of the basin boundary, demonstrating its importance for predicting climatic tipping points.

In summary, this thesis (i) quantifies internal AMOC variability on centennial timescales in state-of-the-art climate models, (ii) identifies robust mechanisms of potentially large centennial-scale AMOC variability, (iii) elucidates the mechanisms of AMOC weakening due to Greenland ice sheet melt under global warming, and (iv) contributes to an improved conceptual understanding of long-term predictability of the AMOC close to a critical transition. Taken together, the results will help inform the interpretation of past, present, and future AMOC changes in paleoclimate reconstructions, observations, and climate models.