The evolution of the Atlantic Meridional Overturning Circulation and its implications for surface warming

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The Atlantic Meridional Overturning Circulation (AMOC) is likely the most well-known system of ocean currents on Earth, redistributing heat, nutrients and carbon over a large part of the Earth's surface and affecting global climate as a result. Due to enhanced freshwater fluxes into the subpolar North Atlantic as a response to global warming, the AMOC is expected, and may have already started, to weaken and these changes will likely have global impacts. It is therefore of considerable relevance to improve our understanding of past and future AMOC changes. My thesis tries to answer some of the open questions in this field by giving strong evidence that the AMOC has already weakened over the last century, by narrowing future projections of this slowdown and by studying the impacts on global surface warming.

While there have been various studies trying to reconstruct the strength of the overturning circulation in the past, often based on model simulations in combination with observations (Jackson *et al.*, 2016, Kanzow *et al.*, 2010) or proxies (Frajka-Williams, 2015, Latif *et al.*, 2006), the results so far, due to lack of direct measurements, have been inconclusive. In the first paper of my thesis I build on previous work that links the anomalously low sea surface temperatures (SSTs) in the North Atlantic with the reduced meridional heat transport due to a weaker AMOC. Using the output of a high-resolution global climate model, I derive a characteristic spatial and seasonal SST fingerprint of an AMOC slowdown and an improved SST-based AMOC index. The same fingerprint is seen in the observational SSTs since the late 19th Century, giving strong evidence that since then the AMOC has slowed down. In addition, the reconstruction of the historical overturning strength with the new AMOC index agrees well with and extends the results of earlier studies as well as the direct measurements from the RAPID project and shows a strong decline of the AMOC by about 15% (3±1 Sv) since the mid-20th Century (Caesar *et al.*, 2018).

The reconstruction of the historical overturning strength with the AMOC index enables us to weight future AMOC projections based on their skill in modeling the historical AMOC as described in the second paper of my thesis (Olson *et al.*, 2018). Using Bayesian model averaging we considerably narrow the projections of the CMIP5 ensemble to a decrease of -4.0 Sv and -6.8 Sv between the years 1960-1999 and 2060-2099 for the RCP4.5 and RCP8.5 emission scenarios, respectively. These values fit to, yet are at the lower end of, previously published estimates.

In the third paper I examine how the AMOC slowdown affects the global mean surface temperature (GMST) with a focus on how it will change the ocean heat uptake (OHC). Accounting for the effect of changes in the radiative forcing on the GMST, I test how AMOC variations correlate with the residual part of surface temperature changes in the past. I find that the correlation is positive which fits the understanding that the deep-water formation that is important in driving the AMOC cools the deep ocean and therefore warms the surface (Caesar *et al.*, 2019). The future weakening of the overturning circulation could therefore delay global surface warming.

Due to nonlinear behavior and scale specific changes it can be difficult to study the dominant processes and modes that drive climate variability. In the fourth paper we develop and test a new technique based on the wavelet multiscale correlation (WMC) similarity measure to study climate variability on different temporal and spatial scales (Agarwal *et al.*, 2018). In a fifth contribution to my thesis this method is applied to the observed sea surface temperatures. The results reconfirm well-known relations between SST anomalies such as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) on inter-annual and decadal timescales, respectively. They furthermore give new insights into the characteristics and origins of long-range teleconnections, for example, that the teleconnection between ENSO and Indian Ocean dipole exist mainly between the northern part of the ENSO tongue and the equatorial Indian Ocean, and provides therefore valuable knowledge about the regions that are necessary to include when modeling regional climate variability at a certain scale (Agarwal *et al.*, 2019).

In summary, my PhD thesis investigates past and future AMOC variability and its effects on global mean surface temperature by utilizing a combination of observational sea surface data and the output of historical and future climate model simulations from both the high-resolution CM2.6 model as well as the CMIP5 ensemble. It further includes the development and validation of a new method to study climate variability, that, applied to the observed sea surface temperatures, gives new insight about teleconnections in the Earth System. My findings provide evidence that the AMOC has already slowed down, will continue to do so in the future, and will impact the global mean temperature. Further impacts of an AMOC slowdown may include increased sea-level rise at the U.S. east coast (Ezer, 2015), heat extremes in Europe (Duchez *et al.*, 2016) and increased storm activity in the North Atlantic region (Jackson *et al.*, 2015), all of which have significant socio-economic implications.

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