Abstract

Droughts, heatwaves and other hydroclimatic extremes are among the most sever and societally disruptive manifestations of climate variability and change. Observed increases in their frequency, intensity, and persistence in many areas highlight the urgent need to understand their physical drivers and identify sources of climate memory that can enhance their predictability across timescales. This doctoral dissertation investigates the role of Atlantic Ocean variability and change in modulating climate extremes from seasonal to multi-decadal timescales. Using an ensemble-based approach that combines initialized seasonal forecast systems, large-ensemble climate simulations, multi-model climate projections, and targeted idealized experiments, the study examines how ocean circulation and sea surface temperature (SST) variability influence hydroclimate over Europe and the tropical Atlantic.

At seasonal timescales, the skill of six initialised seasonal forecast systems is assessed for predicting European summer droughts. Forecast skill for the Standardized Precipitation Evapotranspiration Index (SPEI) is shown to benefit from the high predictability of the diurnal temperature range, which reflects the influence of slowly varying large-scale ocean initialisation. When forecasts are initialized at the onset of the summer season, all models show, on average, good performance in terms of correlation, accuracy, reliability, and discrimination, although with marked local variability. Skill is consistently higher in Southern Europe, indicating greater predictability of SPEI there compared to Northern Europe. A multi-model ensemble provides the most reliable tool for operational drought forecasting.

Building on the assessment of seasonal forecast skill, the thesis next explores why some summers exhibit more coherent and potentially informative forecasts than others. By decomposing forecasted drought anomalies into leading spatial modes, the analysis highlights an illustrative case in which a dipole-like North Atlantic

SST anomaly configuration favors one specific mode of summer drought variability, namely a pronounced east–west SPEI-3 gradient across Europe. In this situation, the forecast ensemble shows reduced dispersion in the associated phase space, suggesting that specific large-scale SST anomalies can help constrain the forecast ensemble.

At interannual timescales, the influence of North Atlantic variability on European summer heatwaves is examined using a large ensemble of coupled climate simulations. The results show that persistent European heatwaves are most likely when extreme cold anomalies in the Subpolar Gyre coexist with subtropical warming, strengthening the inter-gyre SST gradient and promoting quasi-stationary large-scale pressure systems over Europe. This pattern resembles the SST configuration associated with enhanced ensemble coherence, and thus emerges here as a key oceanic preconditioning factor for summer heat extremes. In mid-century projections, the relationship between cold SST anomalies and heatwaves is shaped by differences in the magnitude and timing of Atlantic Meridional Overturning Circulation (AMOC) decline, with a weaker or delayed AMOC weakening associated with a reduced probability of exceptionally persistent heatwaves.

On multi-decadal timescales, the role of AMOC changes in shaping end-of-century tropical Atlantic hydroclimate is investigated using a 30-model CMIP6 ensemble complemented by idealized experiments. The magnitude of AMOC weakening emerges as a key source of intermodel spread in projected precipitation minus evaporation ($P-E$). Models exhibiting a stronger AMOC decline show a pronounced southward displacement of tropical $P-E$ anomalies. By disentangling thermodynamic amplification from circulation-driven responses through a moisture budget, the analysis demonstrates that atmospheric response to AMOC changes can modulate the classical "wet-get-wetter, dry-get-drier" paradigm. Results from idealized experiments further support these findings, highlighting the AMOC as a central driver of uncertainty in future tropical Atlantic $P-E$ projections, with direct implications for regional hydrological extremes.

Overall, through this work I demonstrate that the Atlantic Ocean drives hydroclimatic variability, thereby enhancing predictability across seasonal to multidecadal timescales. By linking ocean circulation, SST variability, and large-scale atmospheric responses, the results presented herein uncover the role of Atlantic processes in shaping hydroclimatic risk under present and future climate conditions.