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Multi-model comparison of causal relationships between atmospheric and marine biogeochemical variables

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Time series of in situ observations and remote sensing data suggest variability in epipelagic ecosystems at seasonal to multiannual time scales. These go along with changes in physical-biogeochemical conditions. While a consensus exists on the proximate causes of observed ecosystem variability (e.g. mixed layer variability, availability of nutrients, grazing pressure), the role of large-scale drivers (e.g. natural climate modes) still needs to be better understood. Moreover, differences in the implementation of marine ecosystem processes exist among Earth System Models, and it is important to understand the uncertainty around the representation of specific interactions via inter-model comparison.

We use output from 5 multi-centennial Earth system model simulations under pre-industrial climate to identify modes of low-frequency biogeochemical properties and the importance of individual drivers. The study focuses on the North Atlantic subpolar gyre (NASPG), a region of high primary productivity and considerable observed natural variability in physical and biogeochemical conditions. We explore causality between modes of climate variability, ocean physics and biogeochemistry by applying a Knowledge-Data-Discovery method, PCMCI. This method enables causal links with a potential time lag to be established between different domains. It proposes a novel way for the comparison of differences between model dynamics.

First, six geographic subregions are identified, based on their physical-biogeochemical characteristics (e.g. deep convection zones, intensity of spring bloom), followed by by the selection of physical and biogeochemical variables. These variables are the maximum winter mixed layer depth due to the role in supplying nutrients to the surface fueling the spring bloom, the North Atlantic Oscillation (NAO), a dominant natural mode climate variability, for its contribution to sea surface temperature (SST) and nutrient variability in the subpolar gyre, and the Gyre Strength, an index reflecting the response of the NASPG to wind forcing. We focus on one micronutrient (Iron) and one macronutrient (Nitrate). They were chosen because both can limit the primary production in this region.

Next, PCMCI is applied to search for the temporal relationships (potentially lagged) between different regions and variables. These relationships are computed from partial correlations which, for gaussian distributed data, is equivalent to a causal link. The application of this method allows networks of causality to be identified, highlighting drivers of nutrient variability under varying natural climate forcing. The approach enables the quantification of intermodel differences either by analyzing one link after another or by looking directly at the entire causal graphs with a newly proposed method to quantify the dissimilarity between two models.

This method verified expected interactions such as the role of mixed layer depth for nutrient supply and quantified the strength of this interaction across the models. It also highlighted model-specific dynamics such as the role of temperature (via sea-ice formation) for iron in two biogeochemical models out of 5.