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Forcing mechanisms behind the nonlinear response of Western Europe climate to the onset of the Younger Dryas

Igor Obreht (1), Lars Wörmer (1), Jenny Wendt (1), Susanne Alfken (1), Marcus Elvert (1), Achim Brauer (2), and Kai-Uwe Hinrichs (1)

(1) University of Bremen, MARUM – Center for Marine Environmental Sciences and Department of Geosciences, Organic Geochemistry Group, Bremen, Germany (iobreht@marum.de), (2) GFZ – German Research Centre for Geosciences, Section 5.2 Climate Dynamics and Landscape Evolution, Telegrafenberg, 14473 Potsdam, Germany

The last glacial cycle is characterized by repeating abrupt millennial-scale climate oscillations known as the Dansgaard–Oeschger events. Nature and causes of these abrupt climate transitions represent one of the biggest mysteries in our understanding of Earth's climate system. The Younger Dryas, as the most recent abrupt cooling of these climatic oscillations, is arguably the best studied. Recent studies have pointed to a nonlinear climatic response of Europe to its onset. However, climate teleconnections and mechanisms behind such nonlinear response remind elusive. Understanding the mechanisms behind the observed period of nonlinear response is crucial for our understanding of abrupt climate transitions. To address this question, we present ultra-high-resolution lipid biomarker data of the Allerød/Younger Dryas transition recorded in Meerfelder Maar sediments with exceptionally robust chronology.

To obtain ultra-high-resolution of lipid biomarkers, we applied a novel approach in palaeoclimate reconstruction, mass spectrometry imaging (MSI). MSI is a laser-based, extraction-free technique that collects mass spectra of organic compounds and visualises their spatial distribution at μm-scale, allowing for detection of biomarkers on intact sediment core sections with unprecedented details. We applied MSI on 65 cm from Meerfelder Maar sediment core to obtain detailed information on fatty acid distribution during the Allerød/Younger Dryas transition. The spatial resolution of 200 μm allows for several measurements within one year (number depends on varve thickness), generating a sub-annual signal.

We show that although abrupt cooling and climate reorganization recorded in Greenland ice-core records likely happened within a few years, the establishment of stadial Younger Dryas climate in Europe lagged this cooling for $\sim$170 years because of complex causal relations among ocean, sea-ice and atmosphere. Our data show a good correlation to Greenland deuterium excess (a proxy of Greenland precipitation moisture), indicating that observed delayed response of Western Europe climate was related to a shift of the westerlies to southeast-northwestern track due to amplified sea-ice formation west of Greenland. Such track of the westerlies forced low latitude warmer air masses to reach Europe. However, when a certain threshold in sea-ice extent over the Northern Atlantic was reached, the westerlies shifted to a zonal track, increasing the storminess and allowing for the establishment of the strong Polar Front influence on Western Europe.

We suggest that abrupt cooling was only possible when certain thresholds in the interaction between ocean, atmosphere, ice-sheets and sea-ice systems were reached, which enabled small changes in one system to amplify changes in another dramatically. Moreover, we point out that overall ocean-atmosphere system reorganization at the onset of the Younger Dryas required a certain transition period. Consequently, we highlight a need to consider nonlinear respond to abrupt climate transitions and responsible causal relations of ocean and atmosphere in the future state of the art climate model simulations.