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Loss of Earth System Resilience during Early Eocene Global Warming Events

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The Paleocene-Eocene Thermal Maximum (PETM; 56 Ma) and Eocene Thermal Maximum 2 and 3 (ETM2; 54.06 Ma and ETM3; 52.87 Ma) were three of a series of abrupt climate and carbon cycle perturbations, characterized by massive carbon input into the ocean-atmosphere system and strong global warming. These abrupt events, termed hyperthermals, potentially represent 'tipping points' at moments in time when the resilience of the system was low and reinforced by strong internal feedbacks, such as the catastrophic release of carbon from submarine methane hydrates. Alternatively, external mechanisms such as volcanism may have played a pronounced external role during the PETM. Here, we evaluate if the hyperthermals indeed resulted from reduced Earth System resilience and tipping point behaviour through the mathematical analyses of climate and carbon cycle indicators, namely, oxygen and stable carbon isotope ratios of deep ocean foraminifer calcite, across the late Paleocene and early Eocene. Our combined analysis using Dynamic Indicators of Resilience (DIORs) and Convergent Cross Mapping (CCM) reveals a loss of resilience and an increase in the causal interaction between the carbon cycle and climate towards the PETM, ETM2, and ETM3. A novel, windowed CCM approach indicates a tight coupling between carbon and climate across the early Eocene, further supporting dominant climate forcing on carbon cycle dynamics. This indicates that the internal rather than external mechanisms were responsible for the hyperthermals, suggesting a secondary role for endogenic processes such as volcanism. Furthermore, the CCM analysis in conjunction with the absence of major positive feedbacks such as the presence of polar ice caps during early Eocene could be employed to stipulate that these hyperthermal events may be caused by the increase in coupling between the carbon cycle and climate systems, eventually pushing both systems towards a tipping point through increasing positive feedbacks.