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Strong seasonality in the northern high latitudes is a prerequisite for glacial abrupt climate change: perspectives from the 3-D earth system model LOVECLIM

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Dansgaard-Oeschger events occurred frequently during Marine Isotope Stage 3 (MIS 3). The main hypothesis for these climatic shifts involves fluctuations in the strength of the glacial Atlantic Thermohaline Circulation (THC), caused by changes in the surface freshwater flux. Rapid warming in Greenland and the North Atlantic region, known as Dansgaard-Oeschger onsets, would be associated with a THC resumption from a weak or shutdown state during stadials to a strong state during interstadials. Transient climate simulations performed with several simple climate models have shown this THC behaviour. However, the models were run with Last Glacial Maximum (LGM) climate forcings and boundary conditions. The latter period was part of MIS 2 during which Dansgaard-Oeschger events were nearly absent. The same is found during MIS 4. To investigate why the occurrence of Dansgaard-Oeschger events was facilitated during MIS 3, we compared two new equilibrium climates to an existing LGM equilibrium climate, all simulated with the three-dimensional earth system model LOVECLIM. Typical stadial and interstadial Greenhouse Gas and dust content forcings were applied for the first, respectively second simulation. Orbital parameters, which drive insolation changes, were set for 56000 BP values. In addition, average MIS 3 ice sheet extent and volume, and a modified glacial land-sea mask were applied. Both resulting

climate states were warmer than the LGM state in LOVECLIM, with enhanced summer warming in the Northern Hemisphere compared to winter warming. The enhanced seasonality is primarily due to higher insolation, while smaller ice sheets contribute to global warming throughout the year. We tested the robustness of our findings with four additional experiments. The only difference with our previous setup was orbital parameters fixed at 32000 BP and 21000 BP. We observed reduced Northern Hemisphere seasonality, with the reduction being greater for 21000 BP insolation. This pattern reflects the decrease in June insolation at 60˚N. However, climate forcing differences between both initial simulations did not result in remarkable differences as opposed to those between stadial and interstadial climate, as THC strength remained the same. To obtain a cold climate resembling stadials more closely, we performed a freshwater hosing experiment spun up from our colder simulation. The result of this sensitivity study suggests that freshwater forcing may have been necessary for climate to return from warm interstadials to cold stadials during MIS 3. We postulate that enhanced northern high latitude seasonality during MIS 3 explains the frequent occurrence of Dansgaard-Oeschger events, as warm summers facilitate ice melting, thus providing more freshwater to the North Atlantic. Conversely, during MIS 2 and MIS 4 the seasonal amplitude of insolation at high northern latitudes was much reduced. If reduced insolation during both periods were responsible for the larger ice sheets, and for decreased summer ice melting, cold glacial climate conditions could prevail, and the occurrence of Dansgaard-Oeschger events may have been prevented.

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