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Millennial-scale variations and abrupt steps in atmospheric CO_2 during Marine Isotope Stage 9-11

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Ice core derived high-resolution atmospheric CO_2 reconstructions allow us to study abrupt carbon releases to the atmosphere and their impact on the Earth's climate in the past. Previously published ice core data of the last 100,000 years indicated that pulse-like CO_2 releases to the atmosphere may have happened on sub-millennial-scale at rates of $\sim$10 ppm per century during the last deglaciation and during Heinrich Stadial 4 (HS4). The existence of such events in earlier periods could not be determined, because of insufficient temporal resolution of the CO_2 record. Here we present the first high-resolution record of atmospheric CO_2 covering 330 – 450 ka BP (i.e. Marine Isotope Stage 9e-12b) using the EPICA Dome C ice core. Measurements with threefold increased precision (now: 1 ppm) and five times higher mean temporal resolution (now: 300 yr) than previously available data reveals that superimposed on the well-known millennial scale variations in atmospheric CO_2 connected to the bipolar seesaw, an abrupt CO_2 release mechanism accompanies the onset of abrupt climate change in the northern hemisphere. We show that this mechanism is not unique to the last deglaciation and HS4, but suggest that this represents a persistent mode of operation throughout glacial and early interglacial conditions over the past 450,000 years. Potential causal links of these stepwise increases to overshoots of the Atlantic Meridional Overturning Circulation are discussed.