https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

A conceptual framework linking Heinrich events and Dansgaard–Oeschger cycles

Hartmut Heinrich, Gerrit Lohmann
Alfred Wegener Institute
Helmholtz Centre for Polar and Marine Research
Klussmannstr. 3
27570 Bremerhaven
Germany

Correspondence to: Hartmut Heinrich (hartmutheinrich@icloud.com)

Abstract

Dansgaard–Oeschger (D–O) events and Heinrich events represent the dominant modes of millennial-scale climate variability during the last glacial period, yet their physical linkage remains incompletely understood. Here we propose a conceptual framework in which abrupt glacial variability emerges from the interaction of Atlantic Meridional Overturning Circulation (AMOC) dynamics, atmosphere–ocean CO_2 exchange, and dust-driven biogeochemical feedback operating within an orbitally modulated climate state. During stadial phases, enhanced dust transport and iron fertilization in the tropical Atlantic strengthen the biological pump and promote gradual atmospheric CO_2 drawdown, while reduced ocean ventilation facilitates the accumulation of respired carbon and heat in the ocean interior. Heinrich events represent extreme stadial states that amplify these imbalances through freshwater forcing, sea-ice expansion, and atmospheric circulation changes. The resulting buildup of subsurface heat and carbon may precondition the stratified North Atlantic for abrupt AMOC reinvigoration, releasing stored CO_2 and producing rapid interstadial warming. This framework provides a conceptual perspective on the asymmetry and recurrence of D–O cycles and suggests that orbital forcing could play a role in modulating the probability of Heinrich events through its influence on the background stability of the climate system.

1 Introduction

Despite decades of research, the physical linkage between Heinrich events and Dansgaard–Oeschger cycles remain incompletely understood (Broecker, 1998; Schulz et al., 1999; Rahmstorf, 2002; Lynch-Stieglitz, 2017). Here we propose a conceptual framework in which millennial-scale glacial variability emerges from the interaction of AMOC dynamics, atmosphere–ocean CO_2 exchange, and dust-driven biogeochemical feedback operating within an orbitally modulated climate state. In this view, Heinrich events represent extreme stadial states that amplify imbalances in heat and carbon storage within the ocean–atmosphere system and may precondition the abrupt AMOC reinvigoration that characterizes Dansgaard–Oeschger interstadials (Dansgaard et al., 1984; North Greenland Ice Core Project members, 2004).

One of the most striking features of the last glacial climate is the occurrence of abrupt millennial-scale transitions recorded in Greenland ice cores. These records reveal a sequence of rapid warmings followed by more gradual cooling phases—Dansgaard–Oeschger (D–O) events—that recur irregularly throughout much of the last glacial period (Dansgaard et al., 1984; North Greenland Ice Core Project members, 2004).

Many of these stadial intervals are closely associated with layers of ice-rafted debris in North Atlantic sediments, indicating massive iceberg discharge events known as Heinrich events (Heinrich, 1988; Bond et al., 1993). The apparent coupling between these phenomena suggests that abrupt glacial variability reflects tightly linked interactions between ocean circulation, ice sheets, and the global climate system.

Numerous studies have therefore linked both Heinrich events and Dansgaard–Oeschger variability to changes in the Atlantic Meridional Overturning Circulation (AMOC) and associated feedback involving freshwater forcing, sea ice, and ocean–atmosphere interactions (Broecker, 1998; Rahmstorf, 2002; Dokken et al., 2013; Petersen et al., 2013; Ziemen et al., 2019; Zhang et al., 2021; Schannwell et al., 2024; Malmierca-Vallet, 2024). In many conceptual and modelling studies, D–O events are interpreted as rapid transitions between different circulation states of the AMOC in response to freshwater perturbations, changes in ocean stratification or sea ice coverage.

Several mechanisms have been proposed to explain the triggering of Heinrich events. Early studies emphasized internal oscillations of the Laurentide Ice Sheet, in which binge–purge cycles of basal sliding produce episodic surges of ice streams into the North Atlantic (MacAyeal, 1993; Alley and MacAyeal, 1994). Other studies have highlighted the role of ocean–ice interactions, including subsurface ocean warming and grounding-line retreat that may destabilize marine-based sectors of the Laurentide Ice Sheet (Hendy and Kennett, 2003; Davtian and Bard, 2023). Recent work has also highlighted the potential role of CO_2 and carbon-cycle feedback (Curtis and Fedorov, 2025; Willeit et al., 2024; Slattery et al., 2025). However, a compact framework that connects D–O cycles, Heinrich events, and their potential astronomical pacing is still lacking. Additional hypotheses emphasize interactions between ocean circulation, sea-ice expansion, and freshwater forcing in the North Atlantic and Nordic Seas (Dokken et al., 2013; Petersen et al., 2013). Although these mechanisms differ in their details, they all point to strong coupling between ice-sheet dynamics, ocean circulation, and climate variability during glacial periods.

Despite decades of research, several key questions remain unresolved. In particular, the causal relationship between Heinrich events and Dansgaard–Oeschger cycles, and the mechanisms responsible for their apparent synchronization, remain debated (Menviel et al., 2020). Some studies interpret Heinrich events as catastrophic instabilities of the Laurentide Ice Sheet triggered by binge–purge oscillations of ice streams (MacAyeal, 1993; Alley and MacAyeal, 1994). Other hypotheses emphasize ocean–ice interactions and the role of subsurface ocean warming in destabilizing marine ice margins (Hendy and Kennett, 2003; Davtian and Bard, 2023). Alternatively, abrupt climate variability may arise primarily from internal feedback within the ocean–sea-ice system of the North Atlantic and Nordic Seas (Dokken et al., 2013; Petersen et al., 2013).

Conceptual dynamical-systems approaches provide another perspective. In these models, millennial-scale variability arises from noise-assisted transitions between metastable climate states in a nonlinear system operating near stability thresholds (Crucifix, 2012; Kwasniok and Lohmann, 2012). Such mechanisms can generate irregular sequences of abrupt transitions similar to those observed in ice-core records. Related conceptual models have explored excitable climate dynamics or relaxation oscillations driven by ocean circulation and freshwater forcing (Braun et al., 2007; Menviel et al., 2020).

Another class of studies highlights the potential role of the carbon cycle and dust-driven biogeochemical feedback in glacial climate dynamics. Stadial periods are characterized by enhanced atmospheric dust concentrations and increased deposition of mineral dust in the North Atlantic and adjacent regions (Bond et al., 1993; Újvári et al., 2017; Muhs et al., 2021). Climate model simulations and proxy records further indicate that glacial atmospheric circulation changes substantially increased mineral dust emissions and long-range transport (Mahowald et al., 1999; Murphy et al., 2017; Újvári et al., 2017; Muhs et al., 2021; Krätschmer et al., 2022), leading to enhanced dust deposition over large parts of the Atlantic Ocean and adjacent basins. Because mineral dust can influence marine biogeochemistry and the ocean carbon cycle, these changes have been proposed as a potentially important component of glacial climate variability (Martin, 1990; Mahowald et al., 1999). In particular, dust deposition may enhance marine primary productivity through iron fertilisation and strengthen the biological pump (Shaked et al., 2025). Changes in ocean ventilation associated with AMOC variability may further modulate atmospheric CO_2 concentrations and global climate (Schönfeld et al., 2003; Willeit et al., 2024; Curtis and Fedorov, 2025; Slattery et al., 2025).

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

At the same time, millennial-scale variability during the last glacial cycle depends strongly on the background climate state, which is influenced by orbital forcing and atmospheric CO_2. In particular, precession-driven variations in low-latitude insolation may influence monsoon dynamics, dust emissions, and ocean and atmosphere circulation patterns (Huybers and Wunsch, 2005; Clement et al., 2004; Huybers, 2006; Huybers and Curry, 2006; Lohmann, 2017). Climate model experiments further suggest that orbitally driven insolation changes can modulate the occurrence of abrupt climate transitions under glacial boundary conditions (Zhang et al., 2021; Kravchinsky et al., 2025).

In contrast to previous conceptual models, the framework explicitly links dust-driven biogeochemical feedback with ocean circulation and carbon storage, providing a mechanism for coupling atmospheric, oceanic, and biogeochemical processes in millennial-scale variability.

2 Conceptual framework: CO_2 exchange, dust, and AMOC

Although research into the physical links between the ocean and ice sheets is well advanced, important processes such as biogeochemical influences on the carbon cycle are not yet incorporated into Earth system models (e.g., Menviel et al., 2020). In the framework proposed here, millennial-scale glacial climate variability arises from coupled interactions between ocean carbon storage and Atlantic Meridional Overturning Circulation (AMOC) variability, mediated by atmospheric dust transport and ocean circulation changes (Broecker, 1998). The central element of this framework is the link between gradual carbon and heat accumulation during stadial conditions and their rapid release during interstadial transitions.

2.1 Positive feedback: persistence of Heinrich stadials

Under stadial conditions, reduced deep-water formation weakens ocean ventilation and promotes the accumulation of respired carbon in intermediate and deep waters of the Atlantic Ocean (Schönfeld et al., 2003; Butzin et al., 2005; Willeit et al., 2024). At the same time, enhanced atmospheric dust transport increases iron fertilisation in the tropical Atlantic, particularly in upwelling regions off northwest Africa, strengthening the biological pump and contributing to atmospheric CO_2 drawdown (Martin, 1990; Mahowald et al., 1999; Roettig et al., 2017; Shaked et al., 2025).

Heinrich events represent extreme perturbations of this stadial state. Massive iceberg discharge injects freshwater into the North Atlantic, expanding the cold, low-salinity surface layer and suppressing deep convection (Heinrich, 1988; Broecker, 1998). The resulting stratification further weakens the AMOC, while expanded sea ice reinforces surface stability (Ziemen et al., 2019; Dokken et al., 2013).

Marine sediment records from the Iberian Deep Sea indicate enhanced deposition of dust driven quartz reaching up to ~80 % in the sand fraction of Heinrich layers. (Heinrich, 1988). Various records from sediment cores in the North Atlantic show very similar sedimentary records to that in the Iberian Deep Sea (Tzedakis et al, 2018).

Reduced overturning circulation enhances meridional temperature gradients and strengthens atmospheric circulation, promoting aridity across major dust source regions, including North America, the Sahara, and particularly from desiccated lakes in the Sahel (Petersen et al., 2013; Gherboudj et al., 2017, Hopcroft et al., 2022). Stronger winds, especially during boreal summer, increase dust mobilization and long-range transport, leading to enhanced deposition of quartz-rich and iron-bearing material in the subtropical/tropical eastern North Atlantic and adjacent regions (Itambi et al., 2009; Muhs et al., 2021; Heinrich et al., 2021; Proestakis et al., 2025). Dune sediments deposited on the Canary Islands during Heinrich event originate from kaolinite- and iron-rich lateritic dust and aeolian quartz from the Sahel/Sahara (Fig. 1) (Roettig et al., 2017; Heinrich et al., 2021; Muhs et al., 2021). Iron-rich dust deposited during the He has been found in deep-sea sediments off the coast of Northwest Africa (Haslett and Davies, 2006)

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

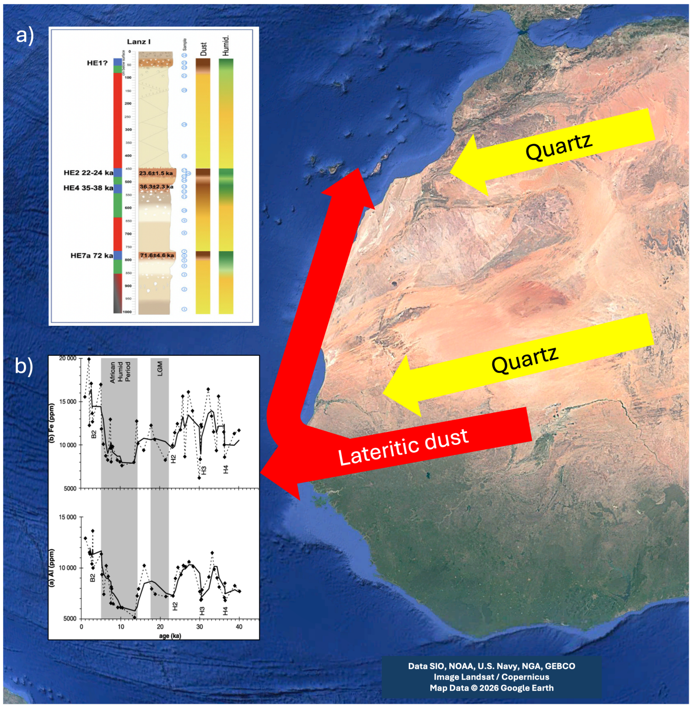
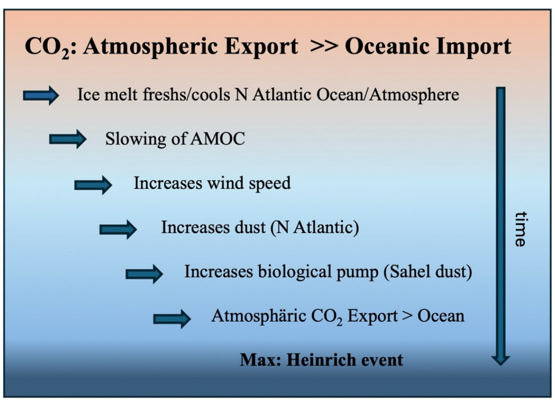


Figure 1: Transport of lateritic dust rich in Fe from the Sahel (red) to the Canary Islands (a: Heinrich et al., 2021) and quartz from the Sahara (yellow) to the deep-sea off Cape Blanc (b: Haslett and Davies; 2006) during Heinrich events. Fig b_a: Aluminium; Fig. b_b: Iron dotted lines: IRD.

These processes act in concert: increased dust supply rich in iron enhances biological carbon export, while reduced ventilation associated with AMOC weakening increases the residence time of respired carbon in the ocean interior (Butzin et al., 2005; Willeit et al., 2024). Together, they promote CO_2 export from the atmosphere into the ocean, progressive carbon storage and cooling during stadial phases (Fig. 2). Such conditions are consistent with evidence for increased acidification and reduced oxygen levels, down to anoxia in the bottom water and in intermediate waters during Heinrich intervals of the NE Atlantic Ocean (Fig. 3) (Baas et al., 1998; Tamburini et al., 2002; Schönfeld et al., 2003, Yamamoto et al., 2019; Chen et al., 2025). Elevated levels of dust in the atmosphere during Heinrich events can dim solar radiation and lower atmospheric and oceanic temperatures (Lau et al., 2007, Murphy et al., 2017).



https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

Figure 2: Processes controlling the uptake of CO_2 from the atmosphere into the ocean during stadial conditions. Reduced ocean ventilation and enhanced dust mobilization increase iron fertilization in the tropical Atlantic, strengthening the biological pump and promoting the export of organic carbon to the ocean interior. The resulting accumulation of respired carbon contributes to gradual atmospheric CO_2 drawdown and cooling during stadial phases, with maximum effects during Heinrich events.

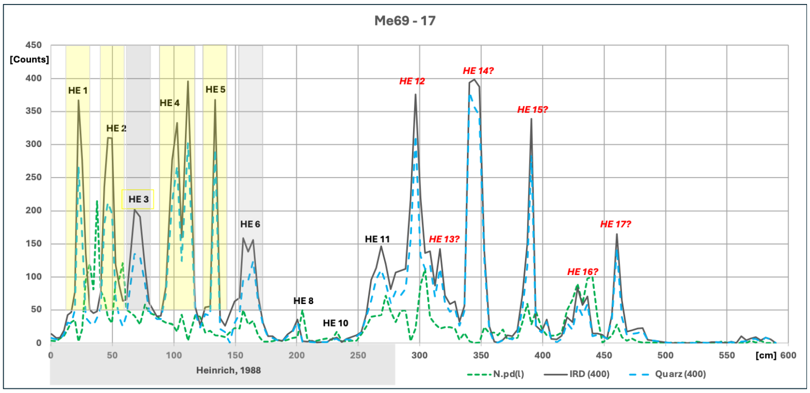


Figure 3: Heinrich events based on counts of ∑IRD, quartz and *N. pachyderma (l.)* in NOAMP core Me-17 from the Iberian deep sea (Heinrich, 1988). The layers He 1, He 2, He 4 and He 5 marked in yellow represent anoxic Heinrich layers with well-preserved foraminiferal test and authigenic Mg/Ca carbonates. Mineralogical compounds point to the Laurentide ice sheet as main source of IRD. He 3 and He 6 represent layers rich in corroded foraminiferal test and smectites. Smectites, a weathering product of volcanic rocks point to Iceland and/or the Nordic Seas as important source of IRD. Since the amount of organic carbon in the layers is very low, even lower than in the oxic layers below and above, it is assumed that the chemical status of the sediment is a consequence of low to very low oxygen content in the deep water produced further south (Gallego-Torres et al., 2014). The geochemical status of He older than He 11 is unknown. The high quartz content in the sand fraction probably represents dust input rather than IRD in the strict sense.

2.2 Out of the Heinrich stadial

As stadial conditions persist, reduced overturning circulation allows heat to accumulate in subsurface waters of the North Atlantic and adjacent basins. Over time, this subsurface warming weakens the cold, low-salinity surface layer that suppresses convection. Once this stratification becomes unstable, deep-water formation can resume abruptly, leading to rapid reinvigoration of the AMOC (Rühlemann et al., 2004; Kim et al., 2012; Lohmann et al., 2020).

The recovery of the AMOC restores northward heat transport and produces rapid warming in the North Atlantic region, marking the onset of an interstadial phase. At the same time, renewed ventilation releases part of the carbon stored during the preceding stadial interval, contributing to rising atmospheric CO_2 concentrations (Schönfeld et al., 2003; Willeit et al., 2024) (Fig. 4). Methane produced in oxygen-depleted environments during stadial phases may also be released during this transition. Even modest changes in ocean carbon storage may influence climate stability when combined with nonlinear ocean-circulation feedback (Zhang et al., 2017).

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

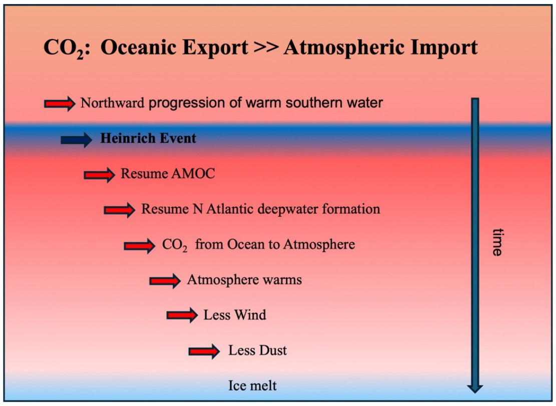


Figure 4: Processes controlling the release of CO_2 from the ocean to the atmosphere during interstadial transitions. Abrupt reinvigoration of the AMOC enhances ocean ventilation and releases carbon stored during the preceding stadial phase. The associated northward heat transport produces rapid warming in the North Atlantic and contributes to the abrupt atmospheric CO_2 increase characteristic of Dansgaard–Oeschger interstadials.

2.3 The conceptual model

Dansgaard–Oeschger warm events can therefore be interpreted as the abrupt release phase of a system in which heat and carbon gradually accumulate during stadial conditions (Dansgaard et al., 1984; North Greenland Ice Core Project members, 2004). Heinrich events represent extreme stadial states that intensify this feedback, while abrupt AMOC recovery terminates the stadial phase and initiates rapid interstadial warming.

The carbon-cycle feedback described above is closely linked to atmospheric circulation responses associated with AMOC variability. Climate model freshwater-hosing experiments show that AMOC weakening produces large-scale atmospheric circulation anomalies, including a southward shift and strengthening of the mid-latitude jet stream and strengthened trade winds over the subtropical Atlantic and North Africa (Ziemen et al., 2019; Ma et al., 2024). Dust mobilization in major source regions such as the Sahara and Sahel and increase aeolian transport into the tropical Atlantic (Kinsley et al., 2021), thereby reinforcing the feedback illustrated in Fig. 3.

Together, these processes define a coupled feedback loop linking dust mobilization, ocean carbon storage, and AMOC variability, providing a mechanistic basis for millennial-scale climate variability, as summarized schematically in Fig. 5.

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

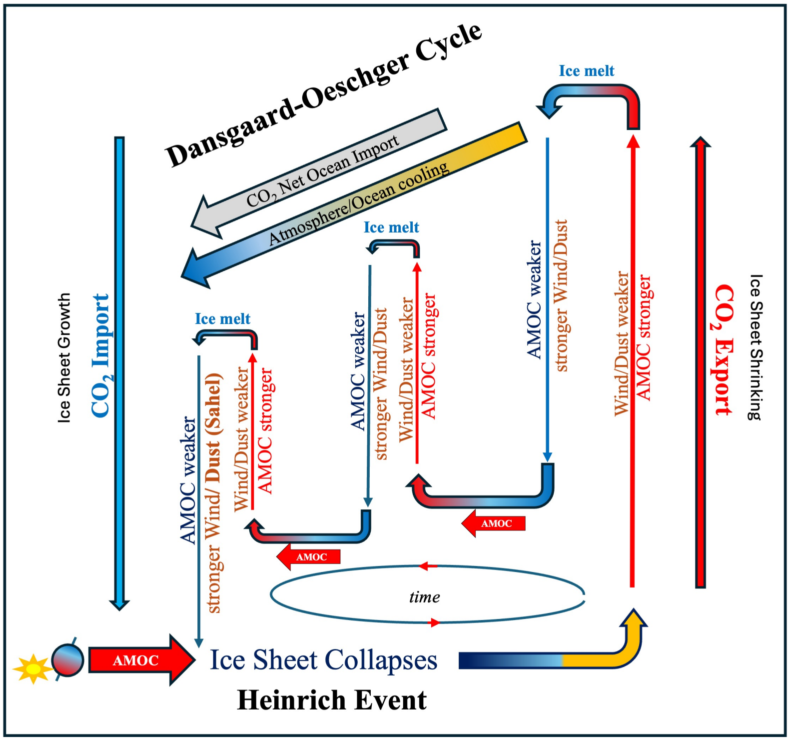


Figure 5: Conceptual schematic of the Heinrich–Dansgaard–Oeschger loop. Gradual stadial cooling is driven by enhanced dust mobilization, strengthened biological carbon export, and reduced AMOC ventilation, leading to progressive ocean carbon storage. Heinrich events amplify these feedback through land ice melt, freshwater forcing and atmospheric circulation changes. The subsequent reinvigoration of the AMOC releases stored heat and carbon, producing abrupt interstadial warming and resetting the climate system for the next cycle.

3 Astronomical pacing and Heinrich events

Broecker et al. (1985) interpreted the Dansgaard-Oeschger cycles as oscillations between a very warm and a very cold state of ocean circulation, driven by changes in summer insolation at the northern polar latitudes. While the feedback described above can generate internal millennial-scale variability, several studies suggest that Heinrich events may also be modulated by orbital forcing, too. In particular, Heinrich events during the earlier part of the last glacial cycle appear to cluster near maxima of precession-driven insolation at low latitudes and in the South Atlantic (Oeschger et al., 1983; Heinrich, 1988; Kravchinsky et al., 2025).

In the framework proposed here, orbital forcing seems to play a role (Fig. 6) but it does not necessarily determine the timing of individual Dansgaard–Oeschger events but instead modulates the background stability of the climate system. In more extreme situations, such as between HE3 and HE1, these oscillations are absent, consistent with a more stable climate characterized by persistently cold North Atlantic cold conditions (Heinrich, 1988). Variations in low-latitude insolation influence tropical hydroclimate, atmospheric circulation, and dust mobilization, thereby affecting the distribution of heat within the ocean–atmosphere system.

Periods of enhanced low-latitude insolation may promote ocean heat storage and favour subsurface warming in the North Atlantic (Rühlemann et al., 2004; Kim et al., 2012). Under conditions of a weakened AMOC, such subsurface warming may penetrate farther northward and destabilize marine ice margins, potentially destabilizing marine ice margins of the Northern Hemisphere ice sheets,

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

thereby triggering Heinrich events. The resulting freshwater input further weakens the AMOC and amplifies the feedback described in Section 2.

The collapse and subsequent reorganization of the AMOC during and after a Heinrich event provide an efficient mechanism for ventilating deep waters that have accumulated excess carbon during preceding Dansgaard-Oeschger stadial phases (Broecker, 1998; Schönfeld et al., 2003). In this interpretation, Heinrich events act as large-scale perturbations that reorganize ocean circulation and reset the background state of the ocean–atmosphere carbon reservoir. Modelling results support this view: Using a climate model, Zhang et al. (2021) demonstrated that abrupt glacial climate variability can exhibit persistent precession-band modulation under intermediate glacial boundary conditions. Their results suggest that orbital forcing influences the clustering of Dansgaard–Oeschger events by modifying the stability of the climate system rather than imposing a strict periodic pacing. Within this framework, Heinrich events represent episodic disturbances that terminate sequences of stadial–interstadial oscillations and reset the ocean–atmosphere carbon reservoir, thereby initiating a new sequence of Dansgaard–Oeschger cycles.

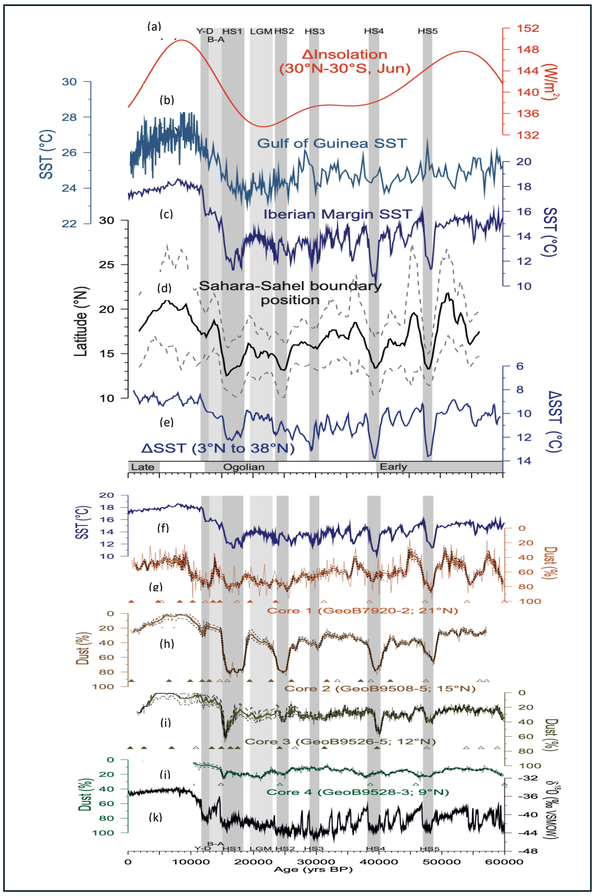


Figure 6: Palaeoproxy data from the Last Glacial Maximum (0–60 ka) off the north-western African continent (Collins et al., 2013; modified). The decline in sea surface temperature (SST) and the southward shift of the Sahara–Sahel boundary due to increasing cooling can be attributed to the decline in insolation in the tropics. (a) Boreal summer (JAS) insolation 30°N - 30°S; (b) SST Gulf of Guinea; (c) SST Iberian margin; (d) Latitudinal margin of the sedimentary Sahara/Sahel boundary; (e) sst difference between Iberian margin and Gulf of Guinea; (f)SST Iberian margin; (g) dust value

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

21°N; (h) dust value 15°N; (i) dust value 12°N; (j) dust value 9°N; (k) $\partial^{18}O$ (‰, VSMOV). Heinrich events are marked by grey stripes.

4 Alternative mechanisms and open questions

Several additional mechanisms have been proposed to explain Heinrich events and Dansgaard–Oeschger variability, highlighting the complexity of abrupt glacial climate dynamics. These processes may operate alongside, or interact with, the feedback proposed in the conceptual framework above.

Ice-sheet dynamics provide one possible explanation for the episodic occurrence of Heinrich events. In particular, binge–purge oscillations of the Laurentide Ice Sheet have been proposed as a mechanism capable of producing periodic ice-stream surges and large iceberg discharge into the North Atlantic (MacAyeal, 1993). Related hypotheses emphasize marine ice-sheet instabilities affecting ice streams in Hudson Strait and adjacent marine basins (Alley and MacAyeal, 1994). In such models, internal instabilities of the ice sheet may generate Heinrich events independently of ocean circulation changes. The framework proposed here therefore focuses primarily on the climatic consequences of large freshwater perturbations rather than on the detailed ice-sheet processes responsible for initiating iceberg discharge.

Sea-ice feedback represents another important component of abrupt climate dynamics. Expanding sea-ice cover during stadial phases modifies surface heat exchange, enhances ocean stratification, and influences deep-water formation in the Nordic Seas and northern North Atlantic (Sarnthein et al., 2003, Dokken et al., 2013). Interactions between sea ice, ocean circulation, and atmospheric dynamics may therefore contribute to threshold behaviour within the climate system and help trigger abrupt transitions between stadial and interstadial states.

Ocean gateways may also influence glacial climate variability. Closure of the Bering Strait during glacial periods alters freshwater exchange between the Pacific and Arctic oceans and affects the salinity balance of the North Atlantic. Changes in Pacific Ocean circulation, including variations in North Pacific Intermediate Water formation, may further influence the storage and redistribution of carbon within the global ocean (Hendy and Kennett, 2003).

Finally, the atmospheric CO_2 response to Heinrich events varies across the glacial cycle, indicating a strong dependence of carbon-cycle feedbacks on the background climate state. This variability likely reflects the interplay of multiple processes, including ocean circulation, ice-sheet dynamics, sea-ice feedback, and biogeochemical interactions, in shaping millennial-scale variability.

A key uncertainty concerns the response of marine productivity to AMOC variability and its implications for the ocean carbon cycle. In the framework proposed here, enhanced dust deposition during stadial conditions increases iron fertilization, strengthens the biological pump, and promotes carbon storage in the ocean interior. The role of dust-driven iron fertilization for glacial carbon-cycle dynamics is well established (Martin, 1990; Mahowald et al., 1999) and supported by proxy evidence linking enhanced dust deposition to increased biological productivity in glacial oceans (e.g. Jaccard et al., 2016). Earth system modelling studies further suggest that dust-driven iron fertilization may enhance the global ocean carbon uptake under glacial conditions (Völker and Köhler, 2013). This mechanism is not exclusive but may operate alongside Southern Ocean processes.

However, the productivity response to a weakened AMOC remains debated. Some modelling studies suggest that reduced overturning circulation limits the supply of nutrient-rich deep waters to the surface ocean and decreases plankton biomass and export production, particularly in the North Atlantic (Schmittner, 2005). Others indicate that circulation changes redistribute nutrients between ocean basins or modify nutrient limitation regimes, potentially enhancing productivity in some regions despite reduced overturning circulation (Marinov et al., 2006; Tagliabue et al., 2009; Oschlies et al., 2008). More systematic model experiments are required. Proxy evidence further points to enhanced

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

biogeochemical activity in the northeastern Atlantic during Heinrich events, associated with suboxic to anoxic conditions in Heinrich layers and deep waters at the time of deposition.

Changes in ocean ventilation further complicate this picture. Even without large increases in biological export production, weaker overturning circulation can increase the residence time of respired carbon in the ocean interior. Radiocarbon-based modelling studies show that reduced overturning circulation can substantially enhance the storage of respired carbon in poorly ventilated intermediate and deep waters during glacial conditions and Heinrich-type perturbations (Butzin et al., 2005). The resulting carbon storage therefore depends not only on productivity changes but also on ventilation and circulation-driven redistribution of carbon within the ocean.

Consequently, although AMOC variability is widely recognized as a key control on ocean carbon storage during abrupt climate events, the relative contributions of dust-driven fertilization, biological productivity changes, and circulation-driven ventilation changes remain uncertain. The simulated response of marine productivity to circulation changes may also depend on model resolution and ecosystem representation. Mesoscale eddies can substantially influence nutrient supply to the euphotic zone and thereby modulate biological productivity (Oschlies, 2002). Because many Earth system models operate at coarse spatial resolution, the representation of such processes remains uncertain. Multi-model comparisons of marine ecosystem models further show large inter-model uncertainty in projections of marine primary production, reflecting differing assumptions about physical transport, nutrient limitation, and ecosystem structure (Laufkötter et al., 2015).

5 Implications, testable predictions, and outlook

The framework proposed here interprets Heinrich events and Dansgaard–Oeschger (D–O) cycles as coupled expressions of feedback linking Atlantic Meridional Overturning Circulation (AMOC) variability, dust-driven oceanic biological productivity, and atmosphere–ocean CO_2 exchange. The strength—and potentially even the sign—of these feedbacks may depend on regional circulation patterns, nutrient limitation regimes, dust availability, and the background climate state, as discussed in Section 4.

Under stadial conditions, reduced ocean ventilation promotes the accumulation of subsurface heat and respired carbon in the ocean interior, while enhanced dust deposition may strengthen iron fertilization and the biological pump, contributing to atmospheric CO_2 drawdown. Together, these processes provide a possible explanation for the asymmetric structure of D–O cycles, characterized by gradual cooling followed by rapid warming (Dansgaard et al., 1984; North Greenland Ice Core Project members, 2004).

Within this framework, Heinrich events can be viewed as extreme stadial states in which these feedbacks can be amplified by large freshwater perturbations. Expanded sea ice and freshwater stratification can weaken the AMOC and alter atmospheric circulation in ways that favour dust mobilization and transport, potentially intensifying the carbon-cycle imbalances preceding abrupt interstadial warming.

Several uncertainties remain. The triggering mechanisms of Heinrich events are still debated and may involve ice-sheet instabilities, ocean–ice interactions, or subsurface warming processes. The framework presented here focuses on the climatic consequences of freshwater perturbations rather than on the detailed mechanisms initiating iceberg discharge. Another key issue is the state dependence of millennial-scale variability: the persistence of D–O interstadials likely depends on ice-sheet extent and background climate conditions (Schulz, 2002a,b; Zhang et al., 2021).

The framework proposed here is conceptual and seeks to integrate processes identified in proxy records and model experiments, rather than to provide a quantitative attribution of individual feedback strengths. It nevertheless suggests several testable expectations. Stadial phases may be associated with

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

increased dust deposition and enhanced indicators of marine productivity. Proxy records may also indicate greater storage of respired carbon in poorly ventilated intermediate and deep waters, as well as progressive subsurface warming in the North Atlantic before abrupt interstadial transitions. In addition, Heinrich events may coincide with atmospheric circulation anomalies consistent with enhanced dust mobilization.

The interpretation is consistent with the view that millennial-scale variability arises in a climate system operating near stability thresholds (Crucifix, 2012; Kwasniok and Lohmann, 2012). In such a regime, stochastic variability or weak external forcing can trigger transitions between metastable states without requiring strictly periodic forcing, as described in conceptual oscillator models and excitable climate dynamics (Braun et al., 2007; Menviel et al., 2020). In dynamical-systems terms, the feedback described here can be interpreted as a stochastic oscillator underlying Dansgaard–Oeschger variability, coupled to a slower threshold process associated with Heinrich-event preconditioning (Kwasniok and Lohmann, 2012). Heinrich events would then emerge as intermittent, threshold-amplified stadial extremes within or triggering sequences of D-O variability.

This perspective is also consistent with the view that abrupt glacial variability reflects interactions between regional North Atlantic dynamics and larger-scale climate controls, and that changes in the structural stability of the AMOC can shift the system between distinct dynamical regimes (Dima et al., 2018, 2025). More broadly, millennial-scale glacial variability emerges from the interaction of internal climate feedback and slow external modulation. Heinrich events act as episodic reorganizations of the ocean–atmosphere carbon reservoir that reset the system and initiate new sequences of D–O variability. The framework proposed here provides a basis for future work aimed at quantifying this feedback and clarifying the links between ocean circulation, carbon cycling, and abrupt climate change.

Author contributions

HH initiated and developed the conceptual framework. GL further developed the scientific arguments and wrote the manuscript. Both authors jointly refined the concepts and contributed equally to the final version of the paper.

Code/Data availability

The article is a purely theoretical study that does not make use of data generated specifically for this purpose and does not involve any physical modelling.

Competing interests

The authors declare that they have no conflict of interests.

Disclaimer

Copernicus Publications adds a standard disclaimer: “Copernicus Publications remains neutral concerning jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.”
Please feel free to add disclaimer text at your choice, if applicable.

Acknowledgements

We acknowledge the digital resources provided by the Alfred Wegener Institute for Polar and Marine Research.

Financial support

The study was carried out without financial support.

Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

References

Alley, R. B. and MacAyeal, D. R.: Ice-rafted debris associated with binge/purge oscillations of the Laurentide Ice Sheet. Paleoceanography, 9, 4, 503 - 511, https://doi.org/10.1029/94PA01008, 1994.

Baas, J. H., Schönfeld, J., and Zahn, R.: Mid-depth oxygen drawdown during Heinrich events: evidence from benthic foraminiferal community structure, trace-fossil tiering, and benthic $\partial^{13}C$ at the Portuguese margin, Marine Geology, 152, 25 - 35, https://doi.org/10.1016/S0025-3227(98)00063-2, 1998.

Bond, G., Broecker, W. S., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G.: Correlations between climate records from the North Atlantic and Greenland ice, Nature, 365, 143 - 147. https://doi.org/10.1038/365143a0, 1993.

Braun, H., Ganopolski, A., Christl, M., and Chialvo, D. R.: A simple conceptual model of abrupt glacial climate events. Nonlinear Processes in Geophysics, 14, 6, 709 - 721, https://doi.org/10.5194/npg-14-709-2007, 2007.

Broecker, W. S., Peteet, D., and Rind, D.: Does the ocean-atmosphere system have more than one stable mode of operation?, Nature, 315 (6014), 21 - 26, https://doi.org/10.1038/315021a0, 1985.

Broecker, W. S.: Paleocean circulation during the last deglaciation: A bipolar seesaw?, Paleoceanography, 13, 2. 119-121, https://doi.org/10.1029/97PA03707, 1998.

Butzin, M., Prange, M., and Lohmann, G.: Radiocarbon simulations for the glacial ocean: The effects of wind stress, Southern Ocean sea ice and Heinrich events, Earth Planet. Sci. Lett., 235, 45 – 61, https://doi.org/10.1016/j.epsl.2005.03.003, 2005.

Clement, A. C., Seager, R., Cane, M. A., and Zebiak, S. E.: An ocean dynamical thermostat, J. Climate, 17, 397 – 412, https://doi.org/10.1175/1520-0442(1996)009<2190:AODT>2.0.CO;2, 1996.

Chen, S-C., Li, X-M., Battisti, N., Guan, G., Montoya, M. A., Osvatic, J., Pjevac, P., Pollak, S., Richter, A., Schintlmeister, A., Wanek, W., Mussmann, M., and Loy., A.: Microbial iron oxide respiration coupled to sulfide oxidation, Nature, 646, 925 – 933. https://doi.org/10.1038/s41586-025-09467-0, 2025.

Collins, J. A., Govin, A., Mulitza, S., Heslop, D., Zabel, M., Hartmann, J., Röhl, U., and Wefer, G.: Abrupt shifts of the Sahara-Sahel boundary during Heinrich stadials, Clim. Past , 9, 1181 - 1191. https://doi.org/ 10.5194/cp-9-1181-2013, 2013.

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

Crucifix, M.: Traditional and novel approaches to paleoclimate modelling, Quaternary Science Reviews, Vol. 57, 1 - 16, https://doi.org/10.1016/j.quascirev.2012.09.010, 2012.

Curtis, P. E., and Fedorov, A.V.: Dansgaard-Oeschger Events under Global Cooling without Continental Ice Sheets, Journal of Climate, 38, 17, 4299 - 4313, https://doi.org/10.1175/JCLI-D-24-0377.1, 2025.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N., Hammer, C. U., and Oeschger, H.: North Atlantic climatic oscillations revealed by deep Greenland ice cores, Climate processes and climate sensitivity, 29, 288 -2 98. https://doi.org/10.1029/GM029p0288, 1984.

Davtian, N. and Bard, E.: A new view on abrupt climate changes and the bipolar seesaw based on paleotemperatures from Iberian Margin sediments, Proceedings of the National Academy of Sciences, 120,12, https://doi.org/10.1073/pnas.2209558120, 2023.

Dima, M., Lohmann, G., and Knorr. G.: North Atlantic versus global control on Dansgaard–Oeschger events, Geophysical Research Letters, 45, 12991 – 12998, https://doi.org/10.1029/2018GL080035, 2018.

Dima, M., Lohmann, G., Nichita, D., Knorr, G. ,and Scholz, P.: Structural stability changes of the Atlantic Meridional Overturning Circulation, npj Climate and Atmospheric Science, 8, 73. https://doi.org/10.1038/s41612-025-00960-x, 2025.

Dokken, T. M., Nisancioglu, K. H., Li, C., Battisti, D. S. and Kissel, C.: Dansgaard-Oeschger cycles: Interactions between ocean and sea ice intrinsic to Nordic seas, Paleoceanography, 28. 491 - 502, https://doi.org/10.1002/palo.20042, 2013.

Gallego-Torres, D., Romero, O. E., Martinez-Ruiz, F., Kim, J-H., Donner, B., and Ortega-Huertas, M.: Rapid bottom-water circulation changes during the last glacial cycle in the coastal low-latitude NE Atlantic, Quaternary Research, 81, 330 - 338. https://doi.org/10.1016/j.yqres.2013.11.004, 2014.

Gherboudj, I., Naseema Beegum, S., and Ghedira, H.: Identifying dust source regions over Middle East and North Africa: Estimation of dust emission potential, Earth-Science Reviews, 165, 342 - 355, https://doi.org/10.1016/j.earscirev.2016.12.010, 2017.

Haslett, S. K., and Davies, C. F. C.: Late Quaternary climate-ocean changes in western North Africa: offshore geochemical evidence, Transactions of the Institute of British Geographers, 31(1), 34 - 52. https://doi.org/10.1111/j.1475-5661.2006.00193.x, 2006.

Heinrich, H.: Origin and Consequences of Cyclic Ice Rafting in the Northeast Atlantic Ocean during the Past 130,000 years, Quaternary Research, 29, 142 - 152, https://doi.org/10.1016/0033-5894(88)90057-9, 1988.

Heinrich, H., Schmidt, C., Ziemen, F., Mikolajewicz, U., and Roettig, C.-B.: Massive deposition of Sahelian dust on the Canary Island Lanzarote during North Atlantic Heinrich Events, Quaternary Research, 101, 51 - 66, https://doi.org/10.1017/qua.2020.100, 2021.

Hendy, I. L., and Kennett, J. P.: Tropical forcing of North Pacific intermediate water distribution during Late Quaternary rapid climate change?, Quaternary Science Reviews, 22, 673 - 689, https://doi.org/10.1016/S0277-3791(02)00186-5, 2003.

Hopcroft, P.O., Pichat, S., Valdes, P.J. and Kienast, S.: Sensitivity of the Tropical Dust Cycle to Glacial Abrupt Climate Changes. Geophysical Research Letters, 50, e2022GL101197. https://doi.org/10.1029/2022GL101197, 2022.

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

Huybers, P.: Early Pleistocene glacial cycles and the integrated summer insolation forcing, Science, 313, 5786, 508 - 511, https://doi.org/10.1126/science.1125249, 2006.

Huybers, P. and Wunsch, C.: Obliquity pacing of the late Pleistocene glacial terminations. Nature, 434,7032. 491-494. https://doi.org/10.1038/nature03401, 2005.

Huybers, P., and Curry, W.: Links between annual, Milankovitch, and continuum temperature variability, Nature, 441, 329 – 332, https://doi.org/10.1038/nature04745, 2006.

Itambi, A. C., von Dobeneck, T., Mulitza, S., Bickert, T., and Heslop, D.: Millennial-scale northwest African droughts related to Heinrich events and Dansgaard-Oeschger cycles: Evidence in marine sediments from offshore Senegal, Paleoceanography, 24, PA1 205. https://doi.org/10.1029/2007PA001570, 2007.

Jaccard, S. L., Galbraith, E. D., Martínez-García, A., and Anderson, R. F.: Covariation of deep Southern Ocean oxygenation and atmospheric CO_2 through the last ice age, Nature, 530, 207 – 210, https://doi.org/10.1038/nature16514, 2016.

Kim, J.- H., Romero, O. E., Lohmann, G., Donner, B., Laepple, T., Haam, E., and Damsté, J. S. S.: Pronounced subsurface cooling of North Atlantic waters off Northwest Africa during Dansgaard-Oeschger interstadials, Earth and Planetary Science Letters, 339–340, 95- 102, https://doi.org/10.1016/j.epsl.2012.05.018, 2012.

Kinsley, C. W., Bradtmiller, L. I., McGee, D., Galgay, M., Stuut, J. - B., Tjallingi, R., Winckler, G., and deMenocal, P.B.: Orbital- and Millennial-Scale Variability in Northwest African Dust Emissions Over the Past 67,000 years, Paleoceanography and Paleoclimatology, 37, e2020PA004137, https://doi.org/10.1029/2020PA004137, 2021.

Krätschmer, S., van der Does, M., Lamy, F., Lohmann, G., Völker, C., and Werner, M.: Simulating glacial dust changes in the Southern Hemisphere using ECHAM6.3-HAM2.3, Clim. Past, 18, 67–87, https://doi.org/10.5194/cp-18-67-2022, 2022.

Kravchinsky, V.A., Zhang, R., Borowiecky, A., Goguitchaichvili, J., Czarnecki, A., Charnieki, N., Boers, A., Berger, and van der Baan, M.: Millennial Cycles in Greenland and Antarctic Ice Core Records: Evidence of Astronomical Influence on Global Climate, Journal of Geophysical Research: Atmospheres, 130, e2024JD042810, https://doi.org/10.1029/2024JD042810, 2025.

Kwasniok, F. and Lohmann, G.: A stochastic nonlinear oscillator model for glacial millennial-scale climate transitions derived from ice-core data, Nonlin. Processes Geophys., 19, 595 - 603, https://doi.org/10.5194/npg-19-595-2012, 2012.

Lau. K. M., and Kim, K. M.: Cooling of the Atlantic by Saharan dust, Geophysical Research Letters, 34, L23811, https://doi.org/10.1029/2007GL031538, 2007.

Laufkötter, C., Vogt, M., Gruber, N., Aita-Noguchi, M., Aumont, O., Bopp, L., Buitenhuis, E., Doney, S. C., Dunne, J., Hashioka, T., Hauck, J., Hirata, T., John, J., Le Quéré, C., Lima, I. D., Nakano, H., Seferian, R., Totterdell, I., Vichi, M., and Völker, C.: Drivers and uncertainties of future global marine primary production in marine ecosystem models, Biogeosciences, 12, 6955 – 6984, https://doi.org/10.5194/bg-12-6955-2015, 2015.

Lohmann, G.: Atmospheric bridge on orbital time scales. Theoretical and Applied Climatology, 128 (3), 709–718., https://doi.org/10.1007/s00704-015-1725-2, 2017.

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

Lohmann, G., Butzin, M., Eissner, N., Shi, X., and Stepanek, C.: Abrupt climate and weather changes across timescales. Paleoceanography and Paleoclimatology, 35, 9. e2019PA003782, https://doi.org/10.1029/2019PA003782, 2020.

Lohmann, J.: Prediction of Dansgaard-Oeschger Events From Greenland Dust Records, Geophysical Research Letters, 46, 21, 12427 - 12434, https://doi.org/10.1029/2019GL085133, 2019.

Lynch-Stieglitz, J.: The Atlantic Meridional Overturning Circulation and abrupt climate change, Annu. Rev. Mar. Sci., 9, 83 - 104, https://doi.org/10.1146/annurev-marine-010816-060415, 2017.

Ma, Q., Shi, X., Sidorenko, D., Scholz, P., Lohmann, G. and Ionita, M.: Revisiting climate impacts of an AMOC slowdown: dependence on freshwater locations in the North Atlantic, Science Advances 10. eadr3243(2024), https://doi.org/10.1126/sciadv.adr3243, 2024.

MacAyeal, D. R.: Binge/purge oscillations of the Laurentide Ice Sheet as a cause of the North Atlantic's Heinrich events, Paleoceanography, 8(6), 775 - 784, https://doi.org/10.1029/93PA02200, 1999.

Mahowald, N., Kohfeld, K., Hansson, M., Balkanski, Y., Harrison, S. P., Prentice, I. C., Schulz, M., and Rodhe, H.: Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleo data from ice cores and marine sediments, J. Geophys. Res., 104, 15895 - 15916, https://doi.org/10.1029/1999JD900084, 1999.

Malmierca-Vallet, I., Sime, L. C., Valdes, P. J., Klockmann, M., Vettoretti, G., and Slattery, J.: The Impact of CO_2 and Climate State on Whether Dansgaard-Oeschger Type Oscillations Occur in Climate Models, Geophysical Research Letters, 51, e2024GL110068, https://doi.org/10.1029/2024GL110068, 2024.

Marinov, I., Gnanadesikan, A., Toggweiler, J. R., and Sarmiento, J. L.: The Southern Ocean biogeochemical divide, Nature, 441, 964–967, https://doi.org/10.1038/nature04883, 2006.

Martin, J. H.: Glacial–interglacial CO_2 change: The iron hypothesis. Paleoceanography, 5, 1 - 3, https://doi.org/10.1029/PA005i001p00001, 1990.

Menviel, L. C., Skinner, L., Tarasov, L., and Tzedakis, P. C.: An ice-climate oscillatory framework for Dansgaard-Oeschger cycles, Nat Rev Earth Environ, 1, 677 - 693, https://doi.org/10.1038/s43017-020-00106-y, 2020.

Muhs, D. R., Meco, J., Budahn, J. R., Skipp, G. L., Simmons, K. R., Baddock, M. C., Betancort, J. F., and Lomoschitz, A.: Long-term African dust delivery to the eastern Atlantic Ocean from the Sahara and Sahel regions: Evidence from Quaternary paleosols on the Canary Islands, Spain, Quaternary Science Reviews, 265, 107024, https://doi.org/10.1016/j.quascirev.2021.107024, 2021.

Murphy, L. N., Goes, M., and Clement, A. C.: The Role of African Dust in Atlantic Climate During Heinrich Events, Paleoceanography, 32, 1291 - 308. https://doi.org/10.1002/2017PA003150, 2017.

North Greenland Ice Core Project members: High-resolution record of Northern Hemisphere climate extending into the last interglacial period, Nature, 431, 147 - 151, https://doi.org/10.1038/nature02805, 2004.

Oeschger, H., Beer, J., Siegenthaler, U., Stauffer, B., Dansgaard, W., and Langway, C. C.: Late-Glacial Climate History from Ice Cores, In: Ghazi, A. (eds), Palaeoclimatic Research and Models, Springer, Dordrecht, https://doi.org/10.1007/978-94-009-7236-0_12, 1983.

Oschlies, A.: Can eddies make ocean deserts bloom?, Global Biogeochem. Cycles, 16, 1106, https://doi.org/10.1029/2001GB001830, 2002.

Oschlies, A., Koeve, W., and Garçon, V.: An eddy-permitting coupled physical–biological model of the North Atlantic: Sensitivity of ecosystem dynamics to circulation and mixing processes, Global Biogeochem. Cycles, 22, GB4007, https://doi.org/10.1029/2007GB003113, 2008.

Petersen, S. V., Schrag, D. P. and Clark, P. U.: A new mechanism for Dansgaard-Oeschger cycles. Paleoceanography, 28, 24 - 30, https://doi.org/10.1029/2007GB003113, 2013.

Proestakis, E., Amiridis, V., Garcia-Pando, C. P., Tsyro, S., Griesfeller, J., Gkikas, A., Georgiou, T., Gonçalves Ageitos, M., Escribano, J., Myriokefalitakis, S., Bergas Masso, E., Di Tomaso, E., Basart, S., Stuut, J. - B., and Benedetti, A.: Quantifying Dust Deposition over the Atlantic Ocean, ESSD, 17, 435 - 4395, https://doi.org/10.5194/essd-17-4351-2025, 2025.

Rahmstorf, S.: Ocean circulation and climate during the past 120,000 years, Nature, 419, 6903, 207 - 214, https://doi.org/10.1038/nature01090, 2002.

Roettig, C. - B., Kolb, T., Wolf, D., Baumgart, P., Richter, C., Schleicher, A., L. Zöller, L., and Faust, D.: Complexity of Quaternary aeolian dynamics (Canary Islands), Palaeogeography, Palaeoclimatology, Palaeoecology, 472, 146 - 162. https://doi.org/10.1016/j.palaeo.2017.01.039, 2017.

Rühlemann, C., Mulitza, S., Lohmann, G., Paul, A., Prange, M., and Wefer G.: Intermediate depth warming in the tropical Atlantic related to weakened thermohaline circulation: Combining paleoclimate and modelling data for the last deglaciation, Paleoceanography, 19, 1, https://doi.org/10.1029/2003PA000948, 2004.

Sarnthein, M., Pflaumann, U., and Weinelt, M.: Past extent of sea ice in the northern North Atlantic inferred from foraminiferal paleotemperature estimates, Paleoceanography, 18, 2, 1047, https://doi.org/10.1029/2002PA000771, 2003.

Schannwell, C., Mikolajewicz, U., Kapsch, M. L., and Ziemen, F.: A mechanism for reconciling the synchronisation of Heinrich events and Dansgaard-Oeschger cycles, Nature Communications, 15, 1, 2961, 1 - 8, https://doi.org/10.1038/s41467-024-47141-7, 2014.

Schmittner, A.: Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation, Nature, 434, 628 - 633, https://doi.org/10.1038/nature03476, 2005.

Schulz, M.: The tempo of climate change during Dansgaard-Oeschger interstadials and its potential to affect the manifestation of the 1470-year climate cycle, Geophys. Res. Lett., 29(1), https://doi.org/10.1029/2001GL013277, 2002a.

Schulz, M.: On the 1470-year pacing of Dansgaard–Oeschger warm events, Paleoceanography, 17(2), 1014. https://doi.org/10.1029/2000PA000571, 2002b.

Schulz, M., Berger, W. H. B.; Sarnthein, M., and Grootes, P. M.: Amplitude variations of 1470-year climate oscillations during the last 100,000 years linked to fluctuations of continental ice mass, Geophys. Res. Lett., 26, 3385 - 388, https://doi.org/10.1029/1999GL006069, 1999.

Schönfeld, J., Zahn, R., and de Abreu, L.: Surface and deep-water response to rapid climate changes at the Western Iberian Margin, Global and Planetary Change, 36, 237 - 264, http://dx.doi.org/10.1016/S0921-8181(02)00197-2, 2003.

https://doi.org/10.5194/egusphere-2026-896
Preprint. Discussion started: 28 August 2026

Shaked, Y., Zhang, F., Colussi, A., Mijovilovich, A. E., Eichner, M., Wang, S., Koedooder, C., Prasil, O., Bokhari, S. N. h., and Küpper, H.: Contact-dependant iron uptake from dust revealed by elemental analysis of single Trichodesmium colonies, Limnol. and Oceanogr., 9999, 1 - 17, https://doi.org/10.1002/lno.70194, 2025.

Silvano, A., Narayanan, A., Catany, R. and Naveira Garabato, A. C.: Rising surface salinity and declining sea ice: A new Southern Ocean state revealed by satellites, Proc. Natl. Acad. Sci. U.S.A., 122, (27), e2500440122, https://doi.org/10.1073/pnas.2500440122, 2025.

Slattery, J., Sime, L. C., Rehfeld, K., Weitzel, N., Malmierca-Vallet, I., Zhang, X., Valdes, P.J., and Muschitielleo, F.: A global speleothem-based assessment of spontaneous Dansgaard–Oeschger type oscillations in two isotope-enabled general circulation models, Geophysical Research Letters, 52,18. e2025GL114906, https://doi.org/10.1029/2025GL114906, 2025.

Tagliabue, A., Bopp, L., and Aumont, O.: Evaluating the importance of atmospheric and sedimentary iron sources to Southern Ocean biogeochemistry*,* Biogeosciences, 6, 24 - 270, https://doi.org/10.1029/2009GL038914, 2009.

Tamburini, F., Huon, S., Steinmann, P., Grousset, F. E., Adatte, T., and Föllmi, K. B.: Dysaerobic conditions during Heinrich events 4 and 5: Evidence from phosphorus distribution in a North Atlantic deep-sea core, Geochimica et Cosmochimica Acta, Vol. 66, No. 23, pp. 4069 - 4083, https://doi.org/10.1016/S0016-7037(02)00986-9, 2002.

Tzedakis, P. C., Drysdale, R. N., Margari, V., Skinner, L. C., Menviel, L., Rhodes, R. H., Taschetto, A. S., Hodell, D. A., Crowhurst, S. J., Hellstrom, J. C., Fallick, A. E., Grimalt, J. O., McManus, J. F., Martrat, B., Mokeddem, Z., Parrenin, F., Regattieri, E., Roe, K., and Zanchetta, G.: Enhanced climate instability in the North Atlantic and southern Europe during the Last Interglacial, Nat Commun, 9, 4235, https://doi.org/10.1038/s41467-018-06683-3, 2018.

Újvári, G., Stevens, T., Molnár, M., and Kovács, J.: Coupled European and Greenland last glacial dust activity driven by North Atlantic climate, Proc. Natl. Acad. Sci. U.S.A., 114, (50), E10632 - E10638, https://doi.org/10.1073/pnas.1712651114, 2017.

Völker, C. and Köhler, P.: Responses of ocean circulation and carbon cycle to changes in the iron fertilization of the Southern Ocean*,* Biogeosciences*,* 10**,** 6469 - 6489, https://doi.org/10.5194/bg-10-6469-2013, 2013.

Willeit, M., Dolmenech, D., Liu, B., Ilyina, T. and Ganopolski, A.: Exploring the differing CO_2 response to Dansgaard-Oeschger and Heinrich events, EGU General Assembly 2024, https://doi.org/10.5194/egusphere-egu24-15214, 2024.

Yamamoto, A., Abe-Ouchi, A., Ohgaito, R., Ito, A., and Oka, A.: Glacial CO2 and deep-water deoxygenation by iron fertilization from glaciogenic dust, Clim. Past, 15, 981 - 996, https://doi.org/10.5194/cp-15-981-2019, 2019.

Zhang, X., Knorr, G., Lohmann, G., and Barker, S.: Abrupt North Atlantic circulation changes in response to gradual CO2 forcing in a glacial climate state, Nature Geoscience, 10, 518 - 523, https://doi.org/10.1038/ngeo2974, 2017.

Zhang, X., Barker, S., Knorr, G., Lohmann, G., Sun, Y., Drysdale, R., Hodell, D., and Chen, F.: Direct astronomical influence on abrupt climate variability. Nature Geoscience, 14. 819–826. https://doi.org/10.1038/s41561-021-00846-6, 2021.

Ziemen, F. A., Kapsch, M. - L., Klockmann, M., and Mikolajewicz, U.: Heinrich events show two-stage climate response in transient glacial simulations, Clim. Past, 15, 153 - 168, https://doi.org/10.5194/cp-15-153-2019, 2019.