The role of African dust on AMOC during Heinrich events

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1. Motivation

Increased ice discharge in the North Atlantic is thought to cause a weakening, or collapse, of the Atlantic Meridional Overturning Circulation (AMOC) during Heinrich events. Paleoclimate records indicate these periods were marked by severe tropical aridity and dustiness. Recently, it was proposed that iceberg discharge may not even be a cause of these events, but rather a consequence of ocean cooling [Barker et al., 2015]. Although the driver of these events is still under debate, strong freshwater input (~1 Sv) is necessary for climate models to simulate the magnitude, geographical extent, and abruptness of these events, indicating that they may be missing feedbacks. We hypothesize the dust-climate feedback is one such mechanism that can alter the paleo-AMOC and has not been previously considered. Here, we parameterize the anomalous Heinrich dust loading and its associated effects on radiation in the University of Victoria Earth System Climate Model and take into account uncertainties due to wind stress forcing, the amounts of atmospheric dust loading, and freshwater hosing.

2. Model experiments

Name	Length	Winds	Dust	Freshwater (FW)
UVic LGM control	3000 year spin up + 1000 years	UVic	none	none
CAM LGM control	3000 year spin up + 1000 years	CAM	none	none
UVic H1	1000 years	UVic	H1.0(-LGM)	none
UVic H1.5	1000 years	UVic	H1.5(-LGM)	none
UVic H2	1000 years	UVic	H2.0(-LGM)	none
CAM H1	1000 years	CAM	H1.0(-LGM)	none
CAM H2	1000 years	CAM	H2.0(-LGM)	none
UVic FW	1000 years	UVic	none	[0.01,0.02,0.03,0.04,0.05] Sv
CAM FW	1000 years	CAM	none	[0.1,0.2,0.3] Sv
UVic FW+H1	1000 years	UVic	H1.0(-LGM)	[0.01,0.02,0.03,0.04,0.05] Sv
CAM FW+H1	1000 years	CAM	H1.0(-LGM)	[0.1,0.2,0.3] Sv

Table 1. Experiments

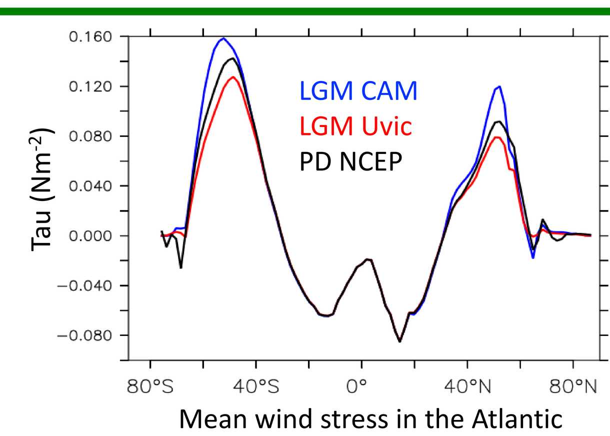


Figure 1. (left): Annual mean zonal wind stress (Taux in N m^{-2}) averaged zonally over the Atlantic basin for NCEP present day climatology (black), the LGM control with UVic-winds (red), and the LGM control with CAM-winds (blue).

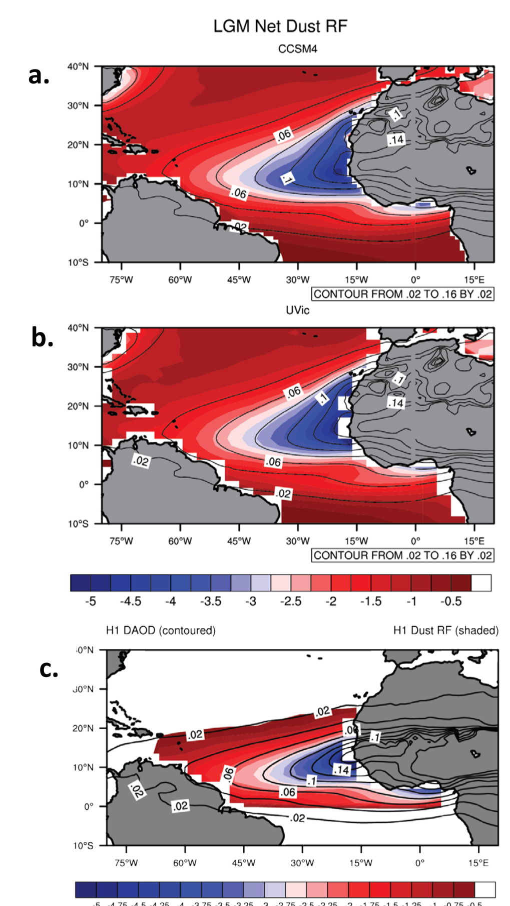


Figure 2. (right): The mean LGM dust aerosol optical depth (DAOD; contours) and net surface radiation (shading) calculated in CCSM4 (a.) and parameterized in UVic (b.), and the anomalous (H1-LGM) DAOD prescribed in UVic and the associated reduction in net radiation due to the anomalous DAOD (c.)

3. AMOC response to H1 dust

- Under CAM-wind stress forcing, H1 dust forcing results in no significant AMOC change relative to control (Fig. 3a).
- In contrast, under UVic-wind stress forcing, H1 dust forcing results in an abrupt 20% (2.8 Sv) reduction in AMOC after roughly 600 years of model integration (Fig. 3b). Although the magnitude of the AMOC reduction is similar under all dust scenarios (H1, H1.5, H2), the timing decreases under increasing dust loads.

The CAM-wind control LGM has a stronger AMOC (Fig. 3a, 22 Sv) and meridional heat transport (0.8 PW), compared to the UVic-wind control LGM, which has a much weaker AMOC (Fig. 3b, 13 Sv) with less meridional heat transport (0.6 PW). Accordingly, the LGM mean state under UVic-winds is characterized by higher surface salinity and temperatures in the Tropics and lower surface salinity and temperatures in the subpolar North Atlantic (not shown). The stronger LGM AMOC under CAM-winds is due to the stronger westerly winds (Fig. 1).

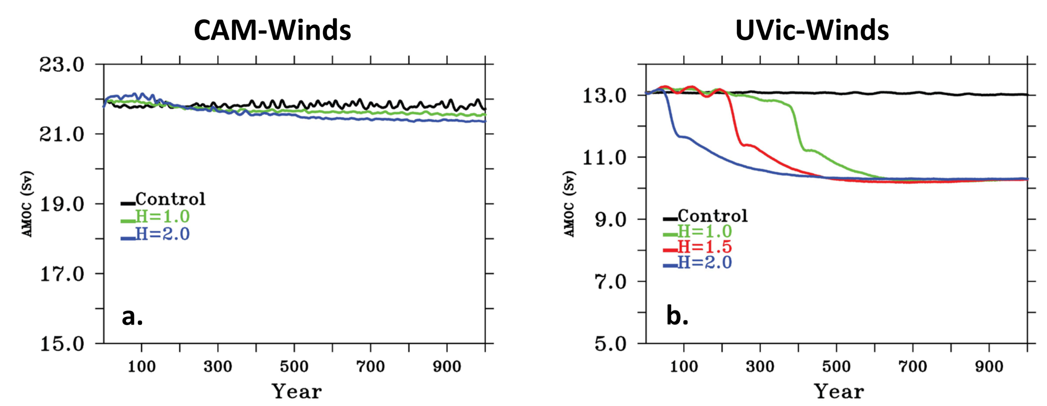


Figure 3. AMOC strength for the CAM-wind (a.) and UVic-wind (b.) LGM control simulations (black), and for the dust experiments with dust forcing equal to: H=1.0 (green), H=1.5 (red), and H=2.0 (blue).

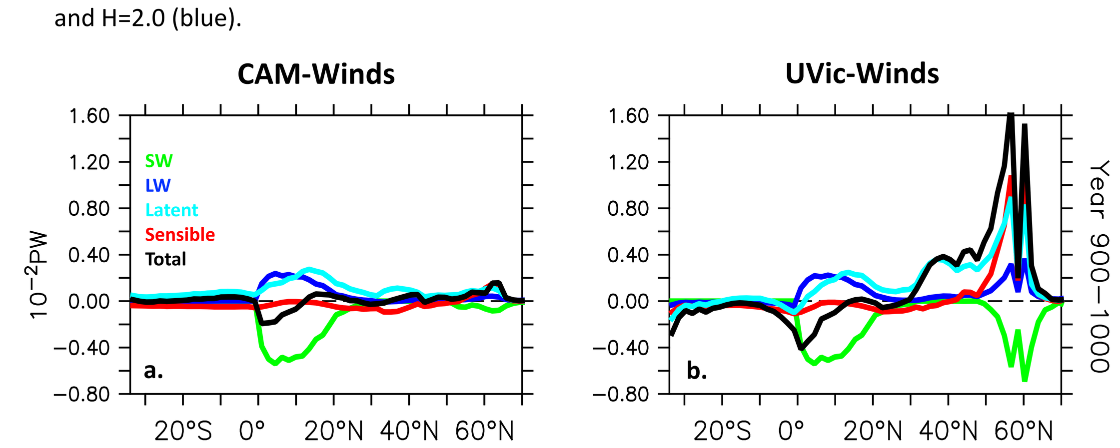


Figure 4 (right). Shortwave (SW), longwave (LW), sensible, latent and total heat flux components integrated at every grid point and zonally averaged over the last century (model years 900-1000) for CAM-winds (a.) and UVic-winds (b.). Fluxes are defined as positive downward and are given in units of 10^{-2} Petawatt (PW).

At the end of the simulations (model years 900-1000), differences in the surface heat flux arise due to the differences in the AMOC response (Fig. 4a and b). The 20% reduction in AMOC under H1 dust forcing (UVic-winds) cools the North Atlantic, shoals the ventilation depth in the subpolar North Atlantic (Fig. 5b) and enhances sea-ice coverage (Fig. 5a). Increased sea ice reduces the SW radiation and deceases the ocean-to-atmosphere turbulent heat fluxes in the subpolar North Atlantic (Fig. 4b).

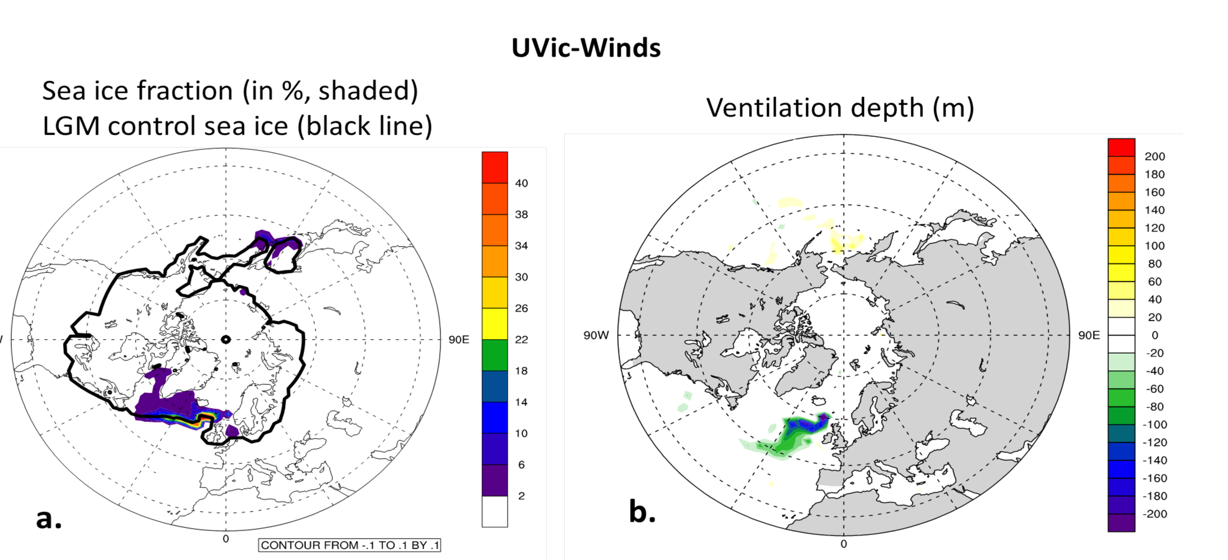


Figure 5. UVic-wind H1-LGM anomalies of sea ice fraction (shaded; in %) with the ice edge in the control simulation overlaid with black contour line (a.), and ventilation depth (shaded; m) (b.). All variables were averaged over the last decade (years 990-1000)

4. Freshwater Budget

The AMOC response to dust forcing under two different wind regimes is examined as an adjustment of the Atlantic freshwater budget. The freshwater budget consists of the balance between the transport of freshwater by the ocean circulation and the water loss due to net evaporation. The net freshwater content anomaly (FWCA) [de Vries and Weber, 2005] of the Atlantic basin (integrated from 34◦S to the Bering Strait) is:

$$FWCA = \frac{1}{S_0}\frac{\partial S'}{\partial t} = Mov + Maz + NET + Res$$

In equilibrium, FWCA may be neglected. Figure 6 a and b show the mean Atlantic surface freshwater budget under the different prescribed climatological winds.

- NET (E-P-R) is negative, i.e., there is a net loss of surface freshwater fluxes.
- Under CAM-winds, NET is compensated almost equally by the input of freshwater into the basin via the gyre (Maz) and overturning (Mov) circulation.
- Under UVic-winds, Mov is negative and nearly zero, therefore NET is balanced almost completely by the Maz term → AMOC is in a bistable regime.
- The transient FWCA response to dust under UVic winds is initially driven by NET, followed by ice growth and increased OcT during AMOC slowdown (Fig 6d)

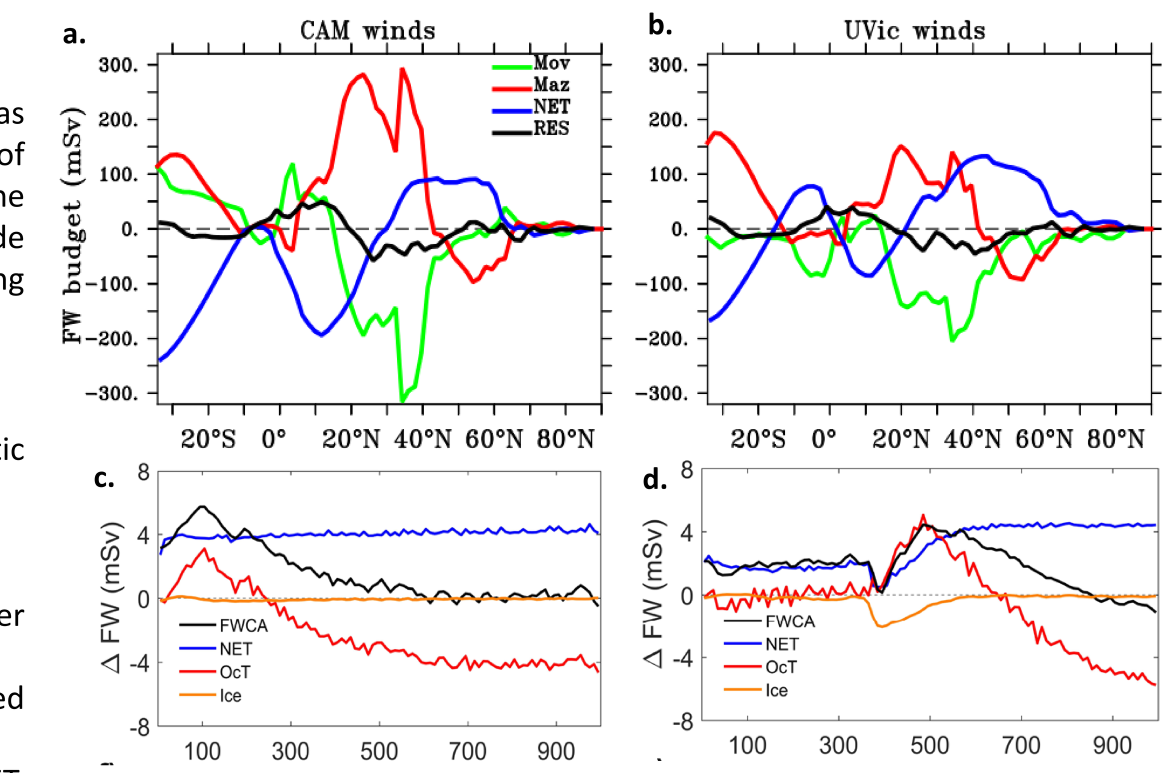


Figure 6. Mean freshwater budget in the Atlantic Ocean for the LGM control simulations under CAM-winds (a.) and UVic-winds (b.), and evolution of the FW budget anomalies (H1 – LGM control)

5. Influence of dust and FW on the Heinrich AMOC

Freshwater hosing (FW) is imposed for 200 years and then turned off. Both FW+H1 dust forcing results in a slowdown of the AMOC and a reversal in the North Atlantic OHT under both CAM and UVic-wind forcing (not shown), but differences arise when freshwater forcing is terminated (Fig. 7a and b).

- Under prescribed UVic-winds, the Mov term is slightly negative (Fig. 6b), AMOC is bistable, and thus the recovery depends on the magnitude of FW forcing (Fig. 7a). A bifurcation occurs at FW = 0.03 Sv.
- However, under prescribed CAM-winds, the Mov term is positive (Fig. 6a), AMOC is monostable, and thus the AMOC recovers after FW ceases under all H1+FW and FW only cases (Fig. 7b).

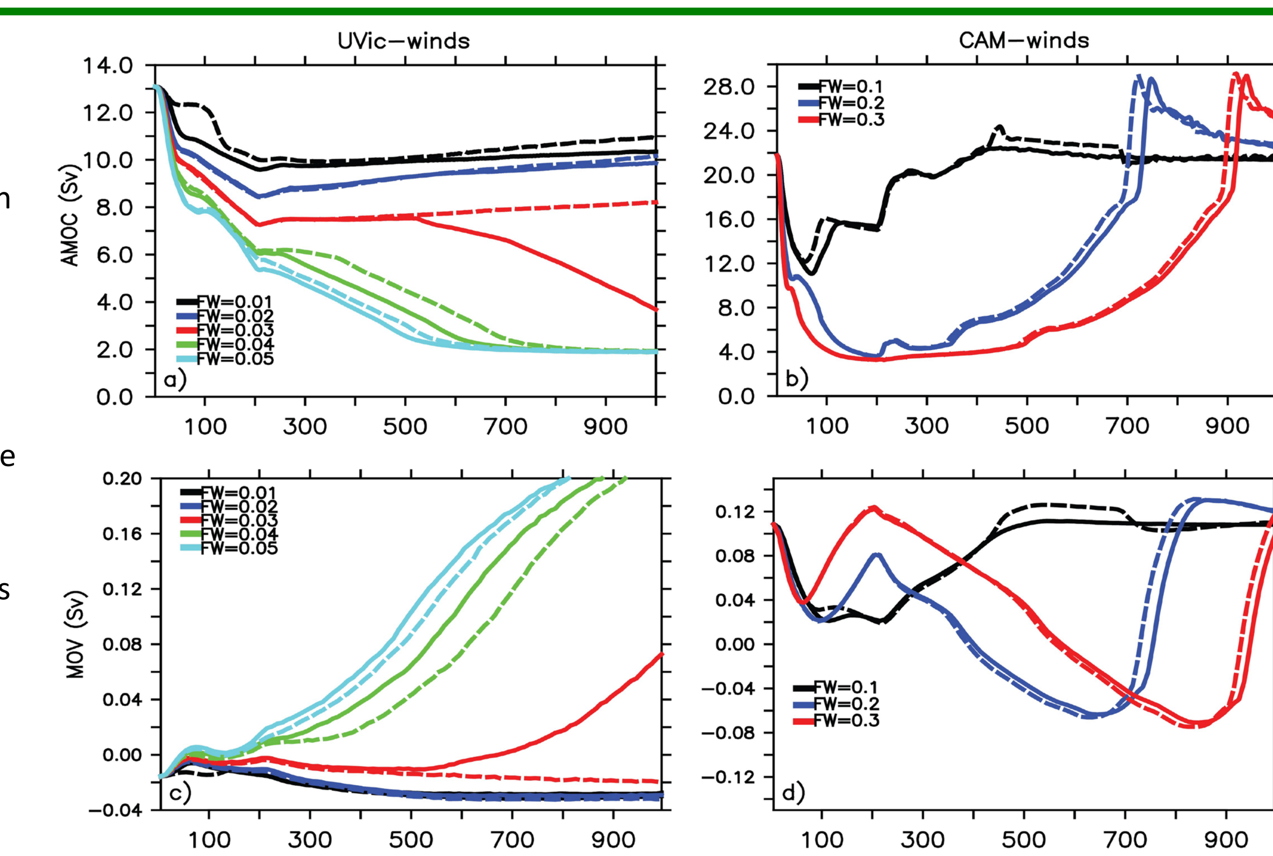


Figure 7. AMOC strength (upper) and Mov (lower) timeseries for the experiments with FW (dashed lines) and FW + H1 dust (solid lines) using UVic-winds (left) and CAM-winds (right). Colors represent the different FW amounts added to the Ruddiman Belt (45° to 65°N).

6. Comparison to proxies

We compare the recorded temperature change off the northwestern coast of Africa at gravity core GeoB9508-5 (star in Fig. 8a) [Niedermeyer et al., 2009] to the temperature change in our FW and FW+H1 dust experiments with different prescribed wind fields (Fig. 9). The observed temperature anomaly (H1-LGM) is ~-1.6 °C (solid black line).

Our CAM-wind forcing with FW+H1 dust forcing best matches the observed cooling found in the eastern subtropical Atlantic.

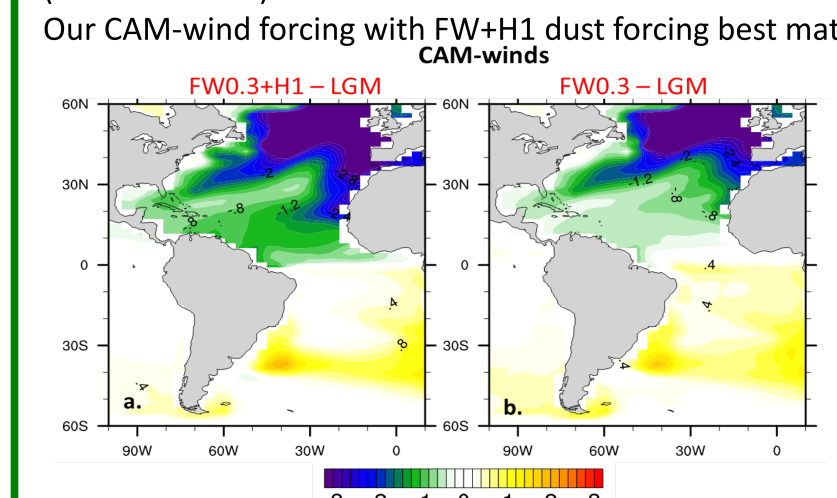
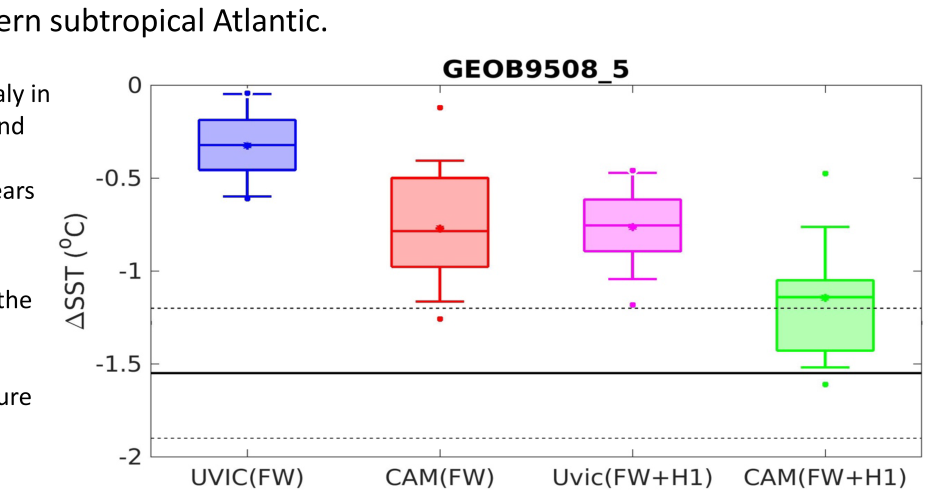


Figure 8. (left) Near surface temperature anomaly in the CAM-wind FW+H1 dust experiments (left) and FW only experiments (right) with respect to the LGM. Temperatures are averaged over model years 200-300. FW is set to 0.3 Sv.

Figure 9. (right): Box and whisker plot based on the temperature difference between our FW experiments with and without H1 dust and the control LGM experiment. The H1-LGM temperature anomaly (black line) at the GeoB9508-5 core is shown.



7. Conclusions

- We simulate both monostable (CAM-winds) and bistable (UVic-winds) LGM AMOC regimes by changing the background wind stress climatology.
- Under a bistable AMOC regime, enhanced dust loading during Heinrich stadials can cause an abrupt 20% reduction in AMOC without freshwater input.
- Including both freshwater and dust forcing (FW+H1) best matches the magnitude of eastern subtropical Atlantic cooling shown in proxy data.

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