



HAL
open science

Sensitivity of the Tropical Dust Cycle to Glacial Abrupt Climate Changes

Peter O Hopcroft, Sylvain Pichat, Paul J Valdes, Stephanie S Kienast

► **To cite this version:**

Peter O Hopcroft, Sylvain Pichat, Paul J Valdes, Stephanie S Kienast. Sensitivity of the Tropical Dust Cycle to Glacial Abrupt Climate Changes. *Geophysical Research Letters*, 2022, 50 (1), 10.1029/2022GL101197 . hal-04823108

HAL Id: hal-04823108

<https://hal.science/hal-04823108v1>

Submitted on 6 Dec 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Sensitivity of the tropical dust cycle to glacial abrupt climate changes

Peter O. Hopcroft¹, Sylvain Pichat^{2,3}, Paul J. Valdes^{4,5} & Stephanie S. Kienast⁶

¹School of Geography, Earth & Environmental Sciences, University of Birmingham, UK.

²Université de Lyon, Ecole Normale Supérieure de Lyon, CNRS, LGL-TPE, F-69007 Lyon, France.

³Max Planck Institute for Chemistry, Climate Geochemistry, Mainz, Germany.

⁴Bristol Research Initiative for the Dynamic Global Environment, School of Geographical Sciences,

University of Bristol, UK.

⁵Cabot Institute, University of Bristol, UK.

⁶Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada.

Key Points:

- Freshwater hosing forcing increases tropical dust loading in Earth System model simulations of the LGM
- Simulated response is non-linear with forcing in some regions particularly North Africa
- Weaker events improve agreement with data and emitted dust produces a self-amplifying feedback

Corresponding author: P. Hopcroft, p.hopcroft@bham.ac.uk

This paper is in open source and can be downloaded here:

Hopcroft, P. O., Pichat, S., Valdes, P. J., & Kienast, S. S. (2023). Sensitivity of the tropical dust cycle to glacial abrupt climate changes. *Geophysical Research Letters*, 50, e2022GL101197. <https://doi.org/10.1029/2022GL101197>

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL101197>

Together with the Supporting Information (Suppl. Material):

<https://agupubs.onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1029%2F2022GL101197&file=2022GL101197-sup-0001-Supporting+Information+SI-S01.pdf>

Abstract

During abrupt climate changes of the last glacial period records show large amplitude changes in the dust cycle. We use Earth System model simulations to evaluate dust processes operating across these events. Idealised Heinrich Stadial-like simulations show a southwards migration of tropical rainfall that dries the Sahel and reduces wet deposition causing a widespread enhancement of tropical dust loading. However, several discrepancies with marine core dust deposition reconstructions are evident. Simulations with a more limited freshwater forcing (0.4 Sv) and hence weaker cooling over North Atlantic (less than around 3°C) show a switch in sign of the stadial dust deposition anomaly in several key regions, improving agreement with paleorecords. The simulated dust cycle therefore displays in places a non-linear response to abrupt climate change. The global-mean stadial dust radiative forcing in the more realistic simulations is around -0.2 to -0.6 Wm⁻² and so could represent an important amplifying feedback during these events.

Plain Language Summary

Mineral dust in the atmosphere is mostly sourced from arid regions like the Sahara desert. The amount and geographical spread of this dust in the atmosphere is sensitive to environmental conditions such as drought. Paleoclimate records show that rapid cooling events centred on the North Atlantic during the last ice-age also saw large increases in the rate of dust deposited over the ocean. Earth System models are a computational tool that can be used to understand the links between climate and the dust cycle. Using a series of such simulations we found that abrupt cooling events in the North Atlantic can lead to a massive increase in dust over the equatorial (tropical) regions. However, the model's response is in many places non-linear, meaning that the change in dust is very sensitive to the magnitude of the climate changes occurring. This non-linearity is mostly due to interactions between changes in the water cycle and the dust. We show that a less severe cooling produces a more realistic dust response when evaluated against paleo-dust records. Since dust scatters incoming sunlight, increased atmospheric dust during these events may have amplified and even extended the cold phases.

1 Introduction

Abrupt climate change events of the glacial period are among the most striking climate events in the geological record. Much focus has been on the abrupt changes in Greenland (Dansgaard et al., 1993), where recurrent warming events called Dansgaard-Oeschger (DO) events of around 5 to 16.5°C occurred in a few decades or less (Kindler et al., 2014) and all major chemical records including dust show approximately synchronous abrupt changes (Wolff et al., 2010). Paleoclimate records from across the northern hemisphere show coincident abrupt events (Peterson et al., 2000; Y. Wang et al., 2001; Deplazes et al., 2013; Gibson & Peterson, 2014; X. Wang et al., 2017). The abrupt DO warming phases are followed by a gradual cooling with a return to stadial conditions. Some of the stadials are characterized by the occurrence of massive ice-rafted debris layers in high- to mid-latitude Atlantic sediment. These are called Heinrich stadials (HS). Particularly large re-organisations of the hydrological cycle are associated with HS phases (Stager et al., 2011) including southward shifts in the tropical rainbelts (e.g. Y. Wang et al., 2001; Deplazes et al., 2013; X. Wang et al., 2017; Peck et al., 2004; Tierney & deMenocal, 2013; Shanahan et al., 2015; Schulz et al., 1998).

The iconic record of rapid dust fluctuations over Greenland shows variations of several orders of magnitude during D-O events (Fischer et al., 2007) but not during Heinrich stadials. In the tropics dust deposited during the late-glacial also varied abruptly as recorded in marine sediment cores (e.g. McGee et al., 2013; J. Collins et al., 2013; Kienast et al., 2013; Loveley et al., 2017; Middleton et al., 2018; Safaierad et al., 2020; Marcantonio et al., 2020; Kinsley et al., 2022) - presumably in response to these rapid cli-

69 mate fluctuations. Although it is difficult to reconstruct dust fluxes this far back in time
70 at sufficient temporal resolution to analyse abrupt changes, marine sediment records do
71 show a relatively coherent signal of a dustier tropical Atlantic (McGee et al., 2013; Mid-
72 dleton et al., 2018; Kinsley et al., 2022), with up to doubling of dust deposition rates dur-
73 ing Heinrich stadial 1 but with much smaller signals during D-O warming events (McGee
74 et al., 2013; Kinsley et al., 2022). Elsewhere there are abrupt changes in the Eastern Pa-
75 cific (Loveley et al., 2017; Marcantonio et al., 2020), the middle-East (Safaierad et al.,
76 2020) and the Arabian Sea (Pourmand et al., 2007).

77 While some previous model simulations have focussed on understanding the abrupt
78 dust variations over Greenland (Tegen & Rind, 2000) or Europe (Sima et al., 2009, 2013),
79 few modelling studies have examined the dust response to these events over the trop-
80 ics (Murphy et al., 2014). Here we investigate the role of mineral dust aerosols in Hein-
81 rich stadial climate phases using a suite of Earth System model simulations. We focus
82 on the tropics and North Africa because the Sahara is today the largest single source of
83 atmospheric aerosols (e.g. Knippertz & Todd, 2012) and because it is known that the
84 desert expanded significantly during glacial times and stadials (J. Collins et al., 2013).
85 The Sahara is also adjacent to the Atlantic Ocean which is a critical region for under-
86 standing abrupt climate change (Clement & Peterson, 2008; Roberts & Hopcroft, 2020).
87 We evaluate whether the model can reconstruct the processes that caused these rapid
88 changes with a new compilation of HS 1 dust deposition records. We also quantify dust
89 radiative forcing and hence the potential for dust to act as a feedback.

90 2 Methods

91 2.1 Earth System Model simulations

92 To simulate the global dust cycle we use the HadGEM2 Earth System (-ES) model
93 (W. Collins et al., 2011; HadGEM2 Development Team, 2011) in an atmosphere-only
94 formulation. The atmosphere/land component of HadGEM2-ES has a resolution of $1.875 \times 1.25^\circ$
95 (longitude-latitude) with 38 unequally spaced levels vertically in the atmosphere (HadGEM2
96 Development Team, 2011). HadGEM2-ES has been widely used for simulating past (Hopcroft
97 & Valdes, 2019; Tindall & Haywood, 2020), historical (Booth et al., 2012) and future cli-
98 mate (Caesar et al., 2013). In HadGEM2-ES the mineral dust cycle is fully coupled with
99 the atmosphere and interactive vegetation (Bellouin et al., 2011; Woodward, 2011). Emis-
100 sions are calculated at every model time-step and are a function of dynamically deter-
101 mined bare soil area, soil moisture and wind speed. Emissions and atmospheric trans-
102 port are calculated for 6 size bins which have radii of 0.0316 to 31.6 μm , with bin bound-
103 aries at 0.1, 0.316, 1.0, 3.16 and 10.0 μm . Dry and wet deposition are considered sep-
104 arately but direct dust-cloud interactions are not represented.

Acknowledgments

POH and PJV received funding from NERC (Earth System Modelling of Abrupt Climate Change: NE/I010912/1) and POH is grateful for ongoing support from a Birmingham Fellowship.

SP received funding from CNRS INSU LEFE (project DUST). Additional measurements for core TR163-19P were made using the INSU/CNRS MC-ICP-MS national facility at ENS de Lyon.

This paper is Tipping Points in the Earth System (TiPES) contribution xxx: P.J.V. has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 820970

SSK received support from NSERC.

We thank NCAS for supporting HadGEM2-ES simulations performed on the UK National HPC facility. HadCM3 simulations were carried out using the computational facilities of the Advanced Computing Research Centre, University of Bristol - <http://www.bris.ac.uk/acrc>. POH is grateful for computational support from the Birmingham Environment for Academic Research <http://www.bear.bham.ac.uk>.

HadGEM2-ES is part of the Met Office Unified Model and is subject to Crown Copyright but is available for use under licence: <http://www.metoffice.gov.uk/research/collaboration>.

Open Research

All HadGEM2-ES model output is available for further analysis from <https://www.paleo.bristol.ac.uk/ummodel/scripts/papers>.

References

- Albani, S., Mahowald, N., Perry, A., Scanza, R., Zender, C., Heavens, N., . . . Otto-Bleisner, B. (2014). Improved dust representation in the Community Atmosphere Model. *Journal of Advances in Modeling Earth Systems*, *6*, 541-570. doi: 10.1002/2013MS000279
- Armstrong, E., Hopcroft, P., & Valdes, P. (2019). A simulated Northern Hemisphere terrestrial climate dataset for the past 60,000 years. *Scientific Data*, *6*, 265. doi: 10.1038/s41597-019-0277-1
- Bellouin, N., Rae, J., Jones, A., Johnson, C., Haywood, J., & Boucher, O. (2011). Aerosol forcing in the CMIP5 simulations by HadGEM2-ES and the role of ammonium nitrate. *J. Geophys. Res.*, *116*(D20206). doi: 10.1029/2011JD016074
- Berger, A. (1978). Long-Term Variations of Daily Insolation and Quaternary Climatic Changes. *J Atmos Sci*, *35*, 2362-2367. doi: 10.1175/1520-0469(1978)035<2362:LTVODI>2.0.CO;2
- Booth, B., Dunstone, N., Halloran, P., Andrews, T., & Bellouin, N. (2012). Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, *484*(7393), 228-232. doi: 10.1038/nature10946
- Caesar, J., Palin, E., Liddicoat, S., et al. (2013). Response of the HadGEM2 Earth System Model to Future Greenhouse Gas Emissions Pathways to the Year 2300. *J Clim*, *26*, 3275-3284.
- Clement, A., & Peterson, L. (2008). Mechanisms of Abrupt Climate Change of the Last Glacial Period. *Rev. Geophys.*, *46*(RG4002).
- Collins, J., Govin, A., Mulitza, S., et al. (2013). Abrupt shifts of the sahara-sahel boundary during heinrich stadials. *Climate of the Past*, *9*, 1181-1191. doi: 10.5194/cp-9-1181-2013
- Collins, W., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton,

- 399 T., ... others (2011). Development and evaluation of an Earth-system model -
 400 HadGEM2. *Geosci Model Dev.*, *4*, 1051-1075. doi: 10.5194/gmd-4-1051-2011
- 401 Costa, K., Hayes, C., Anderson, R., Pavia, F., Bausch, A., et al. (2020). 230Th Nor-
 402 malization: New Insights on an Essential Tool for Quantifying Sedimentary Fluxes
 403 in the Modern and Quaternary Ocean. *Paleoceanography and Paleoclimatology*,
 404 *35*(e2019PA003820). doi: 10.1029/2019PA003820
- 405 Dansgaard, W., Johnsen, S., Clausen, H., Dahl-Jensen, D., Gundestrup, N., Ham-
 406 mer, C., ... Bond, G. (1993). Evidence for general instability of past climate from
 407 a 250 kyr ice-core record. *Nature*, *364*, 218-220. doi: 10.1016/j.epsl.2006.01.002
- 408 Deplazes, G., et al. (2013). Links between tropical rainfall and North Atlantic cli-
 409 mate during the last glacial period. *Nature Geosciences*, *6*, 213-217.
- 410 EPICA Community Members. (2006). One-to-one coupling of glacial climate vari-
 411 ability in Greenland and Antarctica. *Nature*, *444*, 195-198.
- 412 Evan, A., Flamant, C., Fiedler, S., & Doherty, O. (2014). An analysis of aeolian dust
 413 in climate models. *Geophys Res Lett*, *41*, 5996-6001. doi: 10.1002/2014GL060545
- 414 Fischer, H., et al. (2007). Glacial/interglacial changes in mineral dust and sea-salt
 415 records in polar ice cores: Sources, transport, and deposition. *Rev. Geophysics*,
 416 *45*(RG1002). doi: 10.1029/2005RG000192
- 417 Flamant, C., Lavaysse, C., Todd, M., Chaboureaud, J.-P., & Pelon, J. (2009). Multi-
 418 platform observations of a springtime case of bodélé and sudan dust emission,
 419 transport and scavenging over west africa. *Q. J. Royal Meteorol. Soc.*, *135*, 413-
 420 430. doi: 10.1002/qj.376
- 421 Garcia-Carreras, L., Marsham, J., Stratton, R., & Tucker, S. (2021). Capturing
 422 convection essential for projections of climate change in African dust emission. *npj*
 423 *climate and atmospheric science*, *4*(44).
- 424 Gibson, K., & Peterson, L. (2014). A 0.6-Million Year Record of Millennial-
 425 Scale Climate Variability in the Tropics. *Geophys Res Lett*, . doi: 10.1002/
 426 2013GL058846
- 427 Goudie, A. (2018). Dust storms and ephemeral lakes. *Desert*, *23*(153-164).
- 428 HadGEM2 Development Team. (2011). The HadGEM2 family of Met Office Unified
 429 Model climate configurations. *Geosci Model Dev.*, *4*, 7233-757. doi: 10.5194/gmd
 430 -4-723-2011
- 431 Heinrich, H., Schmidt, C., Zieme, F., et al. (2021). Massive deposition of Sahelian
 432 dust on the Canary Island Lanzarote during North Atlantic Heinrich Events. *Qua-*
 433 *ternary Research*, *101*(51-66). doi: {https://doi.org/10.1017/qua.2020.100}
- 434 Hopcroft, P., & Valdes, P. (2015). Last Glacial Maximum constraints on the Earth
 435 System model HadGEM2-ES. *Climate Dynamics*, *45*(5), 1657-1672. doi: 10.1007/
 436 s00382-014-2421-0
- 437 Hopcroft, P., & Valdes, P. (2019). On the role of dust-climate feedbacks during
 438 the mid-Holocene. *Geophysical Research Letters*, *46*, 1612-1621. doi: 10.1029/
 439 2018GL080483
- 440 Hopcroft, P., Valdes, P., O'Connor, F., Kaplan, J., & Beerling, D. (2017). Under-
 441 standing the glacial methane cycle. *Nature Communications*, *8*(14383). doi: 10
 442 .1038/ncomms14383
- 443 Hopcroft, P., Valdes, P., Wania, R., & Beerling, D. (2014). Limited response of
 444 peatland CH₄ emissions to abrupt changes in Atlantic ocean circulation in glacial
 445 states. *Climate of the Past*, *10*, 137-154. doi: 10.5194/cp-10-137-2014
- 446 Hopcroft, P., Valdes, P., Woodward, S., & Joshi, M. (2015). Last glacial maximum
 447 radiative forcing from mineral dust aerosols in an Earth system model. *J Geophys*
 448 *Res*, *120*, 8186-8205. doi: doi:10.1002/2015JD023742
- 449 Joos, F., et al. (2020). N₂O changes from the Last Glacial Maximum to the prein-
 450 dustrial Part 2: terrestrial N₂O emissions and carbonnitrogen cycle interactions.
 451 *Biogeosciences*, *17*(351-3543).
- 452 Kageyama, M., Merkel, U., Otto-Bliesner, B., et al. (2013). Climatic impacts of fresh

- 453 water hosing under Last Glacial Maximum conditions: a multi-model study. *Clim*
 454 *Past*, *9*, 935-953. doi: 10.5194/cp-9-935-2013
- 455 Kienast, S., Friedrich, T., Dubois, N., Hill, P., Timmermann, A., Mix, A., & Kien-
 456 ast, M. (2013). Near collapse of the meridional SST gradient in the eastern
 457 equatorial Pacific during Heinrich Stadial 1. *Paleoceanography*, *28*, 4. doi: {}
- 458 Kienast, S., Kienast, M., Mix, A., Calvert, S., & Francoise, R. (2007). Thorium-230
 459 normalized particle flux and sediment focusing in the Panama Basin region during
 460 the last 30,000 years. *Paleoceanography*, *22*, 4. doi: 10.1029/2006PA001357
- 461 Kienast, S., Winckler, G., Lippold, J., et al. (2016). Tracing dust input to the global
 462 ocean using thorium isotopes in marine sediments: ThoroMap. *Global Biogeochem.*
 463 *Cycles*, *30*, 15261541. doi: {10.1002/2016GB005408}
- 464 Kindler, P., Guillevic, M., Baumgartner, M., et al. (2014). Temperature recon-
 465 struction from 10 to 120 kyr b2k from the NGRIP ice core. *Climate of the Past*,
 466 *10*, 887-902. doi: 10.5194/cp-10-887-2014
- 467 Kinsley, C., Bradtmiller, L., McGee, D., Galgay, M., et al. (2022). Orbital- and
 468 Millennial-Scale Variability in Northwest African Dust Emissions Over the Past
 469 67,000 years. *Paleoceanography Paleoclimatology*, *37*, e2020PA004137.
- 470 Knippertz, P., & Todd, M. (2012). Mineral dust aerosols over the sahara: Mete-
 471 orological controls on emission and transport and implications for modeling. *Rev*
 472 *Geophys*, *50*, RG1007.
- 473 Kohfeld, K., et al. (2013). Southern Hemisphere westerly wind changes during the
 474 Last Glacial Maximum: paleo-data synthesis. *Quat Sci Rev*, *68*, 76-95. doi: 10
 475 .1016/j.quascirev.2013.01.017
- 476 Lippold, J., et al. (2012). Boundary scavenging at the East Atlantic margin does not
 477 negate use of $^{231}\text{Pa}/^{230}\text{Th}$ to trace Atlantic overturning. *Earth Planet. Sci. Lett.*,
 478 *22*, 333-334. doi: 10.1016/j.epsl.2012.04.005
- 479 Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B.,
 480 ... Chappellaz, J. (2008). Orbital and millennial-scale features of atmospheric
 481 CH_4 over the past 800,000 years. *Nature*, *453*, 383-386.
- 482 Loveley, M., Marcantonio, F., Wisler, M., et al. (2017). Millennial-scale iron fertil-
 483 ization of the eastern equatorial Pacific over the past 100,000 years. *Nature Geo-*
 484 *science*, *10*, 760-766. doi: 10.1038/NGEO3024
- 485 Mahowald, N. M., Muhs, D., Levis, S., Rasch, P., Yoshioka, M., Zender, C., & Luo,
 486 C. (2006). Change in atmospheric mineral aerosols in response to climate: Last
 487 glacial period, preindustrial, modern, and doubled carbon dioxide climates. *J*
 488 *Geophys Res*, *111*(D10202). doi: 10.1029/2005JD006653
- 489 Marcantonio, F., Hostak, R., Hertzberg, J., & Schmidt, M. (2020). Deep Equatorial
 490 Pacific Ocean Oxygenation and Atmospheric CO_2 Over The Last Ice Age. *Scien-*
 491 *tific Reports*, *10*, 6606.
- 492 McGee, D., deMenocal, P., Winckler, G., Stuut, J., & Bradtmiller, L. (2013).
 493 The magnitude, timing and abruptness of changes in north african dust deposi-
 494 tion over the last 20,000 yr. *Earth Planetary Sci Lett*, *371-372*, 163-176. doi:
 495 10.1016/j.epsl.2013.03.054
- 496 Middleton, J., Mukhopadhyay, S., Langmuir, C., et al. (2018). Millennial-scale vari-
 497 ations in dustiness recorded in Mid-Atlantic sediments from 0 to 70ka. *EPSL*, *482*,
 498 1-20.
- 499 Missiaen, L., Pichat, S., Waelbroeck, C., et al. (2018). Downcore Variations of
 500 Sedimentary Detrital ($^{238}\text{U}/^{232}\text{Th}$) Ratio: Implications on the Use of ^{230}Th s
 501 and ^{231}Pa s to Reconstruct Sediment Flux and Ocean Circulation. *Geochem.*
 502 *Geophys. Geosyst.*, *19*(2560-2573). doi: 10.1029/2017GC007410
- 503 Mulitza, S., Chiessi, C., et al. (2017). Synchronous and proportional deglacial
 504 changes in Atlantic meridional overturning and northeast Brazilian precipitation.
 505 *Paleoceanography*, *32*(6), 622-633. doi: 10.1002/2017PA003084
- 506 Mulitza, S., Prange, M., Stuut, J.-B., et al. (2008). Sahel megadroughts triggered by

- 507 glacial slowdowns of atlantic meridional overturning. *Paleoceanography*, *23*. doi:
508 10.1029/2008PA001637.
- 509 Murphy, L., Goes, M., & Clement, A. (2017). The role of African dust in Atlantic
510 climate during Heinrich events. *Paleoceanography*, *32*, 1291-1308. doi: 10.1002/
511 2017PA003150
- 512 Murphy, L., et al. (2014). Simulated changes in atmospheric dust in response to a
513 heinrich stadial. *Palaeoclimatology*, *29*, 1-14. doi: 10.1002/2013PA002550
- 514 Nenes, A., Murray, B., & Bougiatioti, A. (2014). Mineral Dust and its Microphys-
515 ical Interactions with Clouds. In P. Knippertz & J.-B. Stuut (Eds.), *Mineral*
516 *Dust: A Key Player in the Earth System* (p. 287-325). Dordrecht: Springer Sci-
517 ence+Business Media. doi: 10.1007/978-94-017-8978-3_12
- 518 Overpeck, J., Rind, D., Lacy, A., & Healy, R. (1996). Possible role of dust-induced
519 regional warming in abrupt climate change during the last glacial period. *Nature*,
520 *384*, 447-449.
- 521 Peck, J., Green, R., & Shanahan, T. o. (2004). A magnetic mineral record of Late
522 Quaternary tropical climate variability from Lake Bosumtwi, Ghana. *Palaeogeogr.*
523 *Palaeoclimatol. Palaeoecol.*, *215*, 37.
- 524 Peltier, W. (2004). Global glacial isostasy and the surface of the ice age earth: The
525 ICE-5G (VM2) model and GRACE. *Annu. Rev. Earth Planet. Sci.*, *32*, 111-149.
- 526 Peterson, L. C., Haug, G. H., Hughen, K. A., & Rohl, U. (2000). Rapid changes in
527 the hydrologic cycle of the tropical Atlantic during the last glacial. *Science*, *290*,
528 1947-1951.
- 529 Petit, J., Jouzel, J., Raynaud, D., Barkov, N., Barnola, J.-M., Basile, I., ... Stieve-
530 nard, M. (1999). Climate and atmospheric history of the past 420,000 years from
531 the Vostok Ice Core, Antarctica. *Nature*, *399*, 429-436.
- 532 Pichat, S., Sims, K., Francois, R., et al. (2004). Lower export production during
533 glacial periods in the equatorial Pacific derived from (231Pa/230Th)_{xs,0} mea-
534 surements in deep-sea sediments. *Paleoceanography*, *19*, PA4023.
- 535 Pourmand, A., Marcantonio, F., Bianchi, T., et al. (2007). A 28-ka history of sea
536 surface temperature, primary productivity and planktonic community variability
537 in the western Arabian Sea. *Paleoceanography*, *22*, PA4208.
- 538 Rhodes, R., Brook, E., Chiang, J., Blunier, T., Maselli, O., McConnell, J., ...
539 Severinghaus, J. (2015). Enhanced tropical methane production in response
540 to iceberg discharge in the North Atlantic. *Science*, *348*, 1016-1019. doi:
541 10.1126/science.1262005
- 542 Ringeval, B., Hopcroft, P., Valdes, P., Ciais, P., Ramstein, G., Dolman, A., &
543 Kageyama, M. (2013). Response of methane emissions from wetlands to the
544 Last Glacial Maximum and an idealised Dansgaard-Oeschger event: Insights
545 from two models of different complexity. *Climate of the Past*, *9*, 149-171. doi:
546 10.5194/cp-0-149-2013
- 547 Roberts, W., & Hopcroft, P. (2020). Controls on the tropical response to abrupt cli-
548 mate changes. *Geophysical Research Letters*, *47*(6), e2020GL087518. doi: 10.1029/
549 2020GL087518
- 550 Roberts, W., Valdes, P., & Payne, A. (2014). A new constraint on the size of Hein-
551 rich Events from an iceberg/sediment model. *Earth Planet Sci Letts*, *386*, 1-9.
- 552 Ryder, C., Marenco, F., Brooke, J., et al. (2018). Coarse-mode mineral dust size
553 distributions, composition and optical properties from aer-d aircraft measurements
554 over the tropical eastern atlantic. *Atmos Chem Phys*, *18*, 17225-17257. doi:
555 10.5194/acp-17-17225-2018
- 556 Safaierad, R., Mohtadi, M., Zolitschka, B., et al. (2020). Elevated dust depositions
557 in West Asia linked to ocean-atmosphere shifts during North Atlantic cold events.
558 *PNAS*, *117*(31), 18272-18277. doi: 10.1073/pnas.2004071117
- 559 Sago, N., & Storelvmo, T. (2017). Testing the sensitivity of past climates to the in-
560 direct effects of dust. *Geophys Res Lett*, *44*. doi: 10.1002/2017GL072584

- 561 Schmittner, A. E., & Galbraith, E. D. (2008). Glacial greenhouse gas fluctuations
562 controlled by ocean circulation changes. *Nature*, *456*, 373-376. doi: 10.1038/
563 nature07531
- 564 Schulz, H., von Rad, U., & Erlenkeuser, H. (1998). Correlation between Arabian Sea
565 and Greenland climate oscillations of the past 110,000 years. *Nature*, *393*, 54-57.
- 566 Shanahan, T., McKay, N., Hughen, K., Overpeck, J., Otto-Bliesner, B., Heil, C., ...
567 Peck, J. (2015). The time-transgressive termination of the African Humid Period.
568 *Nature Geoscience*, *8*, 140-144. doi: 10.1038/NGEO2329
- 569 Sima, A., Kageyama, M., Rousseau, D.-D., et al. (2013). Modeling dust emission
570 response to north atlantic millennial-scale climate variations from the perspective
571 of east european mis 3 loess deposits. *Clim Past*, *9*, 1385-1402.
- 572 Sima, A., et al. (2009). Imprint of north-atlantic abrupt climate changes on western
573 european loess deposits as viewed in a dust emission model. *Quat Sci Rev*, *28*(25-
574 26), 2851-2866. doi: 10.1016/j.quascirev.2009.07.016
- 575 Singarayer, J., & Valdes, P. (2010). High-latitude climate sensitivity to ice-sheet
576 forcing over the last 120 kyr. *Quaternary Science Reviews*, *29*(1-2), 43-55. doi: 10
577 .1016/j.quascirev.2009.10.011
- 578 Skonieczny, C., McGee, D., et al. (2019). Monsoon-driven Saharan dust variabil-
579 ity over the past 240,000 years. *Sci Adv*, *5*(1), eaav1887. doi: {10.1126/sciadv
580 .aav1887}
- 581 Spahni, R., Chappellaz, J., Stocker, T., Loulergue, L., Hausammann, G., Kawamura,
582 K., ... Jouzel, J. (2005). Atmospheric methane and nitrous oxide of the late
583 pleistocene from Antarctic ice cores. *Science*, *310*, 1317-1321.
- 584 Stager, J., et al. (2011). Catastrophic Drought in the Afro-Asian Monsoon during
585 Heinrich Event 1. *Science*, *331*, 1299-.
- 586 Tegen, I., & Rind, D. (2000). Influence of the latitudinal temperature gradient
587 on soil dust concentration and deposition in Greenland. *J Geophys Res*, *105*(D6),
588 7199-7212.
- 589 Tierney, J., & deMenocal, P. (2013). Abrupt Shifts in Horn of Africa Hydroclimate
590 Since the Last Glacial Maximum. *Science*, *342*, 843-846. doi: {10.1126/science
591 .1240411}
- 592 Tindall, J., & Haywood, A. (2020). Modelling the mid-Pliocene warm period using
593 HadGEM2. *Glob Planetary Change*, *186*, 103110. doi: 10.1016/j.gloplacha.2019
594 .103110
- 595 Valdes, P., Armstrong, E., Badger, M., Bradshaw, C., Bragg, F., Crucifix, M.,
596 ... Williams, J. (2017). The BRIDGE HadCM3 family of climate mod-
597 els: HadCM3@Bristol v1.0. *Geosci Model Dev*, *10*, 3715-3743. doi: 10.5194/
598 gmd-10-3715-2017
- 599 Wang, X., et al. (2017). Hydroclimate changes across the Amazon lowlands over the
600 past 45,000 years. *Nature*, *541*, 204-207. doi: 10.1038/nature20787
- 601 Wang, Y., Cheng, H., Edwards, R., An, Z., Wu, J., Shen, C.-C., & Dorale, J. (2001).
602 A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu
603 Cave, China. *Science*, *24*, 2345-2348. doi: 10.1126/science.1064618
- 604 Williams, R., McGee, D., Kinsley, C., Ridley, D., Hu, S., Fedorov, A., ... de Meno-
605 cal, P. (2016). Glacial to Holocene changes in trans-Atlantic Saharan dust trans-
606 port and dust-climate feedbacks. *Science Advances*, *2*, e1600445.
- 607 Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O., & Svensson, A. (2010).
608 Millennial-scale variability during the last glacial: The ice core record. *Quaternary
609 Science Reviews*, *29*(21-22), 2828-2838. doi: 10.1016/j.quascirev.2009.10.013
- 610 Woodward, S. (2011). Mineral dust in HadGEM2. *Hadley Centre Technical Note*,
611 87.