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Palaeoclimate constraints on the impact of 2 °C anthropogenic warming and beyond

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Supplementary Material for

"Palaeoclimate constraints on a world with post-industrial warming of 2 degrees and beyond"

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providing additional information on Earth System changes

Several additional lines of evidence can be derived from the paleo record, some of which lack sufficient resolution to allow robust conclusions for potential future changes, are not quantitative enough or are not specific in terms of the causes leading to these past changes. In Sections I-VI of this supplement, we summarize the paleo evidence for such changes but refrain from drawing conclusions related to this evidence for a 1.5-2°C warmer world in the future in the main manuscript. In spite of significant progress, these areas are ripe for further detailed study.

I. Atlantic Meridional Overturning Circulation changes

AMOC changes were significant during late deglacial or early interglacial conditions, likely caused by freshwater release from rapidly melting northern-hemisphere continental ice sheets. Some evidence for Holocene AMOC variations after the demise of the Laurentide, Cordilleran, and Fenno-Scandian Ice Sheets can be found, but it lacks sufficient quantitative and spatial resolution to draw robust conclusions for the future.

Deglacial high-latitude freshwater input influenced the HTM and early LIG ocean circulation[1,2]. Accordingly, these strong AMOC variations represent no suitable analog for the AMOC response to a future warming, as (with the exception of Greenland) these ice sheets do not exist anymore. Marine proxy data from the Holocene indicate that Atlantic Meridional Overturning Circulation (AMOC) was more stable than during the last glacial period[3,4], yet still variable[5]. Nevertheless, intervals of low benthic foraminiferal $\delta^{13}C$ in the early Holocene are associated with evidence for melt-water driven stratification of the upper ocean, suggesting high sensitivity to abrupt transient variations in North Atlantic buoyancy forcing[6]. There is evidence for reduced advection but likewise also short-term pulses of significantly increased advection of Atlantic waters to the Nordic Seas during the HTM[1,7]. Models that predict the early Holocene strength of AMOC are notably in disagreement with each other, likely due to model resolution effects on salinity and upper ocean stratification [8].

The AMOC intensity was likely as strong during the LIG as today. However, centennial- to millennial-scale oscillations of reduced AMOC intensity took place following freshwater perturbations from Greenland and Antarctica[9-13] during the LIG, but coherent, large-scale reductions in AMOC and Southern Ocean overturning remain elusive. The GIS continuously melted throughout the LIG[14], but this melt seems to have had only a small impact on AMOC[11].

The MPWP was characterized by slightly warmer tropical warm pools, reduced zonal and meridional temperature gradients, and a poleward displacement and weakening of subtropical upwelling systems, the latter linked to shifting atmospheric circulation[15,16]. Effective northward heat transport to the Nordic Seas took place[17], but there was likely no strong deep-water ventilation in the Nordic Seas[18,19].

II. Ocean deoxygenation

Expansion of North Pacific oxygen minimum zones occurred during the deglacial transition[20], and again in the earliest phases of the HTM associated with regional ocean warming of ~4°C. The marine geological record suggests that during the HTM, these episodes of low-oxygen water expansion occurred in the Indo-Pacific with detrimental consequences for coastal ecosystems[20]. Reconstructed HTM warming appears insufficient to account for observed hypoxic events alone, suggesting that nutrient and productivity feedbacks may amplify impacts and ultimately drive these systems to hypoxia via ecosystem shifts[21].

Long records of oceanic oxygenation to the mid-Pliocene are rare in the paleoceanographic literature. Recently, a 10 million-year long nitrogen-isotope record of denitrification from the Arabian Sea demonstrated that subsurface oxygen content declined during the mid-Pliocene[22] as a result of intensification of the South Asian summer monsoon that drives upwelling and productivity. Additional records are clearly needed to improve spatial coverage and understanding of the causes of such oxygen changes.

III. Fire

HTM biomass burning was globally lower than preindustrial[23], but fire activity increased in NH high latitudes[24] and decreased in the tropics and southern extratropics[23,25]. There are two competing hypotheses to explain the overall increase in biomass burning from HTM to preindustrial. The first involves increasing anthropogenic burning during the late Holocene, overpowering the natural decrease in fire activity due to cooler summer temperatures in northern mid- to high-latitudes[26]. In that case the lesson learnt from the paleorecord cannot be extrapolated to the future, as recent human activity and fire management cannot be compared to the preindustrial Holocene. The second hypothesis links the increasing trend in biomass burning to changes in annual mean temperature and moisture at global scales[25]. In either case, the absence of active fire management, rising summer or annual mean temperatures argue for potentially large increases in burning wherever fuels are not too wet to burn, or too sparse to carry fire at all[27].

During the LIG, biomass burning was similar to the average level of the entire Holocene (11.7 kyr BP - present)[28]. The western Mediterranean region[29], Japan[30] and Asia[31] had fewer fires than today, while Anatolia experienced fire excess[32] (see Fig. S2).

During the MPWP global fire activity was low compared to present[33], however, north-eastern Asia and Russia experienced fire excess[34]. In southwestern Australia fire frequency was reduced by a factor of two compared to present at ca. 3.215 Myr BP[35].

IV. Monsoons, extreme rainfall and storms

Warmer climate states have the potential to support higher rainfall. Data showed that all the NH summer monsoon systems were wetter at the HTM and early LIG (little or no change in some regions at LIG) compared to preindustrial, while the Southern Hemisphere summer monsoon systems had more arid conditions (or no change in some regions at LIG)[36,37]. Enhanced Indian and East Asian summer monsoons are reported during the MPWP both by models and data[22,38]. Changes in monsoon are at least in part a direct consequence of the different orbital configuration at those times. Accordingly, the direct applicability of the paleorecords of HTM and LIG monsoon changes in the future can be questioned.

Another potential issue related to climate change is the frequency and intensity of storm events. However, reconstructing large storm frequency during warm intervals of Earth's past is much more uncertain than discerning sustained climate changes, as well-dated proxy records that resolve climate and ocean variability on interannual to centennial timescales are rare. Nevertheless some evidence exists that points to potentially lower Hurricane activity in the tropical western Atlantic during the HTM[39].

Flood events caused by extreme rainfall are difficult to reconstruct prior to the Holocene. Whereas in northern Europe lake records point to flood inactivity during the HTM[40], three clusters of major flood activities (6-5, 7.5, and 10-8.2 kyr BP) have been recognized in central Europe[41]. This activity is in agreement with the identification of short pulses of fluvial activity in southern France[42]. Similarly, in Mediterranean region an increase in flood activity was detected at 7500–7000 kyr BP[43]. In North America, an increase in storminess has been detected at 5.8 and 9.1 kyr BP[44], consistent with an increase in flood activity at 6.8 and 8.1 kyr BP in southeastern North America[45], while paleo flood slackwater deposits support evidence of extreme floods events at 7.5-7 kyr BP in China[46]. In Australia, relict plunge-pool sediments suggest an increase in flood activity during the early to mid-Holocene[47].

V. ENSO

El Niño-Southern Oscillation (ENSO) variability originates in the ocean and atmosphere of the tropical Pacific region, but often exerts extreme impacts on temperature and rainfall at a global scale. Climate simulations currently show no consensus on how interannual variability of ENSO may change with future warming. Seasonally-resolved coral records of coupled SST and rainfall anomalies indicate that while twentieth-century ENSO variance is significantly higher than the average of the past 7000 years, it is not unprecedented relative to the full range of variability observed in Holocene coral archives[48,49].

During warm periods of the LIG and MIS11.3, the interannual variability of ENSO is only detectable from rare fossil coral and mollusk records. These indicate that ENSO variability was active during the LIG[50], but it is unclear whether the magnitude of interannual variability was altered compared to present day as multi-century length records are required for a robust assessment.

Fossil corals from the tropical Pacific also demonstrate that ENSO was active during part of the Pliocene (~3.5-3.8 Ma)[51]. Millennial-length climate model simulations of the MPWP (~3.3-3.0 Ma) also produce ENSO-like events. Although less frequent than today, they were of longer duration and caused larger temperature and rainfall anomalies[52]. For the MPWP, mean SST estimates from marine sediment cores have been used to suggest that ENSO variability was superimposed upon a permanent El Niño-like mean state across the tropical Pacific[53], however this concept is still debated[54].

VI. North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is the dominant mode of wintertime atmospheric variability on interannual to decadal timescales in the NH and forms part of the broader-scale Northern Annular Mode (NAM). Greenland lake sediments, European tree rings and speleothem records show that the HTM was associated with generally positive NAO-like conditions that transitioned to a more variable and negative NAO at the end of the HTM[55].

During the LIG, coral data show that NAO and decadal variability in general were strong[56]. Simulations also suggest that NAO-like variability modulated regional NH climate patterns and seasonality during the LIG, albeit with different spatial expressions than today[56,57].

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