Project: **1021**

Project title: **Paleo-Constraints on Monsoon Evolution and Dynamics (PACMEDY)**

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Project overview

Monsoon systems influence the water supply and livelihoods of over half of the world. Past climates provide an opportunity to link recent and future changes and to improve understanding of mechanisms and predictability of monsoon variability. This project uses palaeoenvironmental records of climate variability and simulations with Earth System Models over the past 6000 years and investigate the Indian, Africa and South American monsoon systems, to provide a better understanding of their dynamics and interannual to multidecadal variability (IM). The simulations contribute to the Paleo Model Intercomparison Project (Kageyama et al., 2016) as part of the 6^{th} phase of the WCRP Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016).

Work accomplished by MPI/HZG

We have conducted sensitivity experiments with MPI-ESM-LR under mid-Holocene conditions to study the role of changing dust fields.

The mid-Holocene (ca. 6,000 years ago) is a climate period, in which the change of the orbital conditions determined more summer insolation in the Northern Hemisphere than present-day. This had lead to a dramatic change in the vegetation cover, especially in North Africa and a strengthening of the West African Monsoon (WAM). During the mid-Holocene, the Sahara was covered mainly by grassland and savanna and this resulted also in a drastic reduction of the Saharan dust load. However, model experiments are unable to fully reproduce the WAM behavior in the mid-Holocene (according to proxy reconstructions) if they do not account simultaneously for vegetation change and dust reduction. While many modelling groups have integrated interactive dynamic vegetation in different earth system models (ESMs), the dust cycle is computationally extremely expensive for paleo-simulations. Dust reduction can be, however, prescribed in ESMs.

Here, we present preliminary results from two different simulations performed with the MPI-ESM. In the first simulation, the dust has been prescribed by reducing the pre-industrial aerosol optical depth (AOD) by 80% over the Sahara following the experiment carried on EC-EARTH by Pausata et al., 2016. In this simulation modified pre-industrial AOD cycle and related optical properties are given by Kinne et al., 2013, (Fig.1a). We refer to this simulation as ‘idealised dust’. In the second simulation, we prescribed the dust cycle using mid-Holocene dust and its related optical properties from an interactive dust simulation carried on with ECHAM6 (the atmospheric model of MPI-ESM) coupled with HAM module for aerosols (Egerer et al., 2015). We refer to this simulation as ‘realistic dust’ (Fig.1b).

The control simulation here is the midHolocene time slice with climatological pre-industrial AOD, which is mainly due to mineral dust over the Sahara. We refer to the control run as ‘pre-industrial dust’.

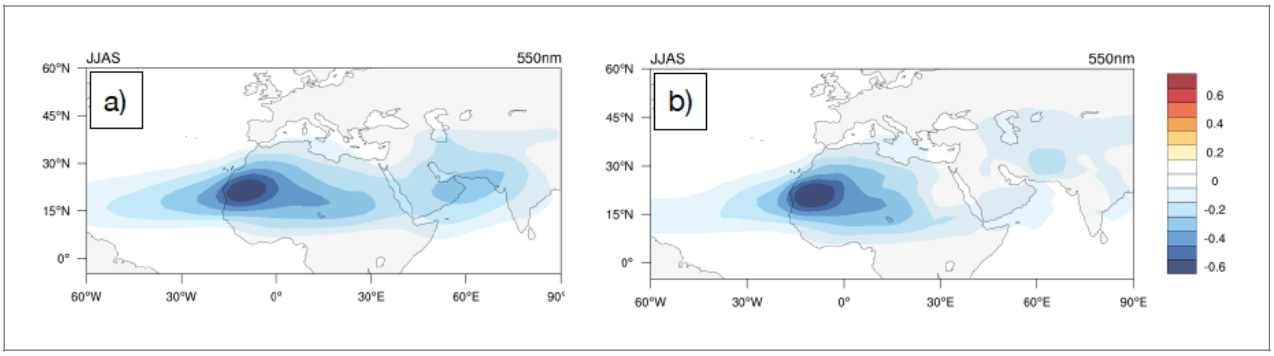


Figure 1: Aerosol Optical Dept (AOD) anomalies at 550 nm for idealised reduced dust (a) and realistic reduced dust (b) experiments relative to pre-industrial dust.

Preliminary results show that accounting for reliable pattern of dust warms substantially the mid-Holocene summers both locally on the Sahara and globally, with a global warming at about +1.2 K relative to pre-industrial dust in the control simulation (Fig. 2).

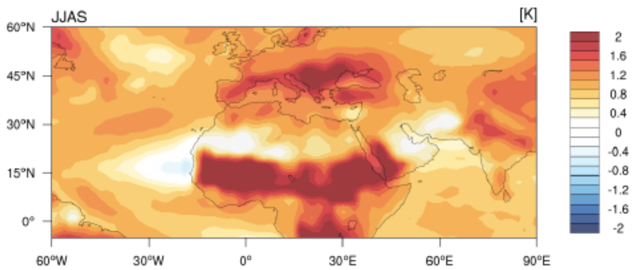


Figure 2: Surface temperature difference between „reduced dust“ and preindustrial.

The local hydrological cycle changed substantially: Evaporation increases in the region between 10°N - 20°N, in the correspondence of the ascending branch of the Hadley Circulation, determining a dramatic change in the P-E balance there relative to pre-industrial dust (Fig. 3).

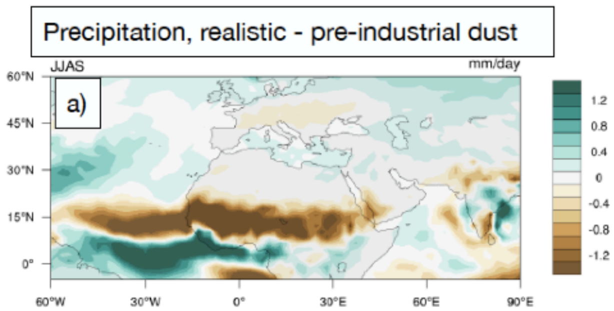
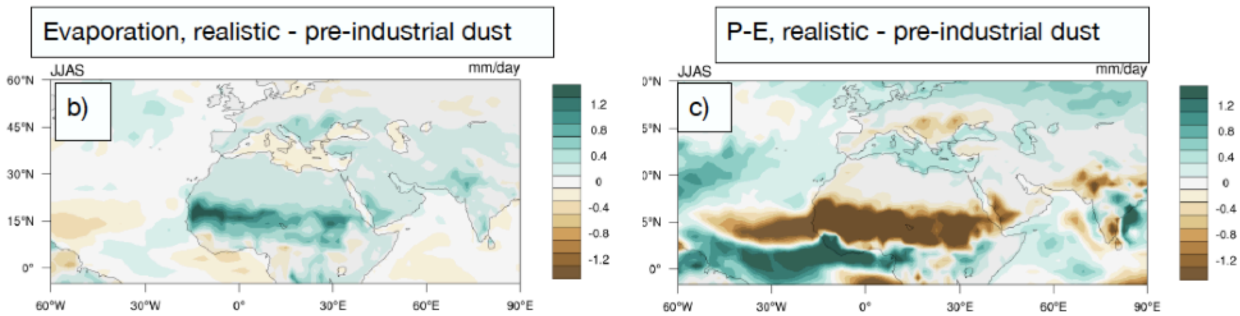


Figure 3: Precipitation minus Evaporation (P-E) for realistic dust (a) and idealised dust (b) experiments relative to pre-industrial.



The dust reduction plays a crucial role on a local secondary shallow circulation associated to the Saharan heat-low in low tropospheric levels. This shallow circulation depends on gradient in low-level potential temperature (Thorncroft and Blackburn, 1999; Nolan et al., 2007; Zhang et al., 2008) and it advects mainly drier air equatorwards at mid-levels, influencing the strength of local

Hadley circulation updraft and its local moisture release (Thorncroft et al., 2011). In fact, the moistening at low levels, given also by a moisture advection from the Mediterranean, and drying at mid-levels associated with the shallow circulation can have potentially a blocking effect on convection over land (Peyrille and Lafore, 2007). Reducing substantially the dust emission over the Sahara allows to the increased temperature there, and a stronger Saharan heat-low leads strengthens the shallow meridional circulation. This weakens the main updraft of the cross-equatorial Hadley Circulation and reduces precipitation in deep tropics, affecting therefore the strength of West African monsoon. The net effect of the realistic reduced dust in these simulations counteracts therefore the effect due to orbital forcing on strengthening the African monsoon in the mid-Holocene.

References:

Egerer, S., Claussen, M., Reick, C., & Stanelle, T. (2015). Marine sediment records as indicator for the changes in Holocene Saharan landscape: simulating the dust cycle. *Climate of the Past Discussions*, *11*(6), 5269-5306.

Kinne, S., O'Donnel, D., Stier, P., Kloster, S., Zhang, K., Schmidt, H., ... & Stevens, B. (2013). MAC-v1: A new global aerosol climatology for climate studies. *Journal of Advances in Modeling Earth Systems*, *5*(4), 704-740.

Nguyen, H., Hendon, H. H., Lim, E. P., Boschat, G., Maloney, E., & Timbal, B. (2018). Variability of the extent of the Hadley circulation in the southern hemisphere: a regional perspective. *Climate Dynamics*, *50*(1-2), 129-142

Nolan, D. S., Zhang, C., & Chen, S. H. (2007). Dynamics of the shallow meridional circulation around intertropical convergence zones. *Journal of the atmospheric sciences*, *64*(7), 2262-2285.

Work accomplished by AWI

Based on AWI-CM, several early-Holocene time-slice experiments have been performed based on different early-Holocene regimes, including the application of sub-grid orographic parameters and the freshwater flux. We find the sub-grid orographic parameters can greatly affect the winter climate over the Northern Hemisphere, especially over the Eurasia, by manipulating the sea level pressure and wind. Besides, four 9k-to-0k transient experiments have been carried out, one without acceleration, and the other three with 10-year acceleration technique. For the accelerated simulations, different sub-grid orographic regimes are applied.

2 Experiments

Experiment	Description	length
PI	A pre-industrial control simulation.	900
EH0K	9k simulation, which applies pre-industrial sub-grid orographic parameters.	2000
EH9K	9k simulation, which applies 9k sub-grid orographic parameters.	300 (initialized from EH0K)
EH9KG	9k simulation, which applies 9k sub-grid orographic parameters over the Laurentide ice sheet, and pre-industrial sub-grid orographic parameters for other regions.	100 (initialized from EH0K)
TST	9k-to-0k transient experiment without acceleration.	Not finished (initialized from EH9KG)
TST9KG	9k-to-0k transient experiment with 10 years acceleration, which applies 9k sub-grid orographic parameters over the Laurentide ice sheet, and pre-industrial sub-grid orographic parameters for other regions.	Not finished (initialized from EH9KG)
FWF0.15	Hosing experiment, with 0.15 Sv freshwater flux over the Labrador Sea for 100 years.	FWF0.15
FWF2.5_0.13	Hosing experiment, with 2.5 Sv freshwater flux over the Labrador Sea for 1 year, and then 0.13 Sv for 99 years.	FWF2.5_0.13

Model resolution (atmos/ocean): ECHAM6:T63L47 FESOM:CORE2L47

3 Results

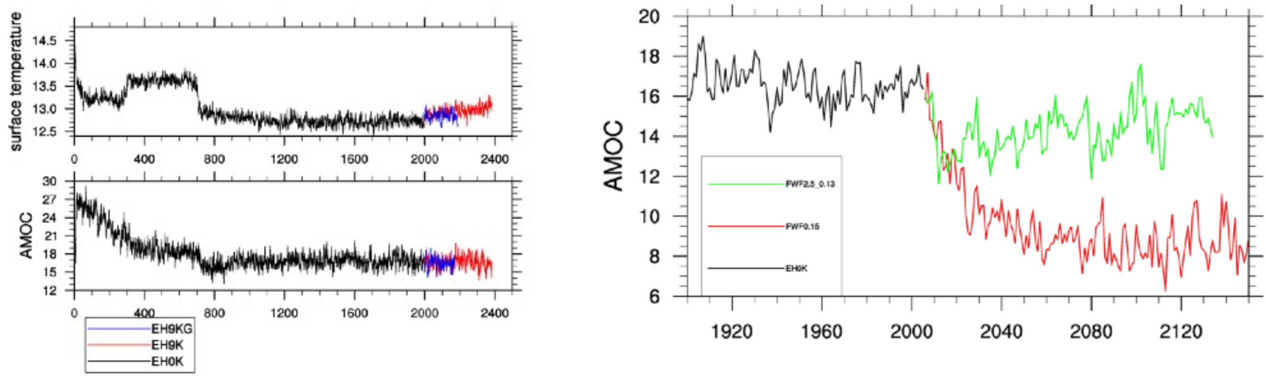


Figure AWI 1: Time series of global annual mean surface temperature and AMOC in PI early Holocene (left) and AMOC in hosing experiments (right).

The left plot of Fig.1 shows the time series of global annual mean surface temperature and AMOC indices in experiment PI. Over the last 200 model years, PI has an averaged surface temperature of 13.65 C with the trend being -0.01 C/century. The mean AMOC strength over the final years is 15.6 Sv with the trend being -0.02 Sv/century, which shows a quasi equilibrium state of the PI simulation. For the early Holocene experiments, as shown in the right plot of Fig. 2, we find the surface temperature in EH0K and EH0KG having the mean value of 12.8 C, while in EH9K it is warmer, being 13.0 C. All of the three early Holocene experiments simulate an AMOC of 16.5 Sv. In FWF2.5_0.13, we observe a spin-down of AMOC when the meltwater release occurs over the Labrador Sea, with a reduction to 50% of its pre-hosing strength within the first 5 years, due to the sudden strong hosing of 2.5 Sv in the first year, and then AMOC experiences no spin-down during the rest hosing years with 0.13 Sv freshwater perturbation, but several great oscillations and a slight recover. In experiment FWF0.15, AMOC decreases fast from about 16 Sv to less than 10 Sv within 20 years, then a more gradual but continued decline over the next 80 years.

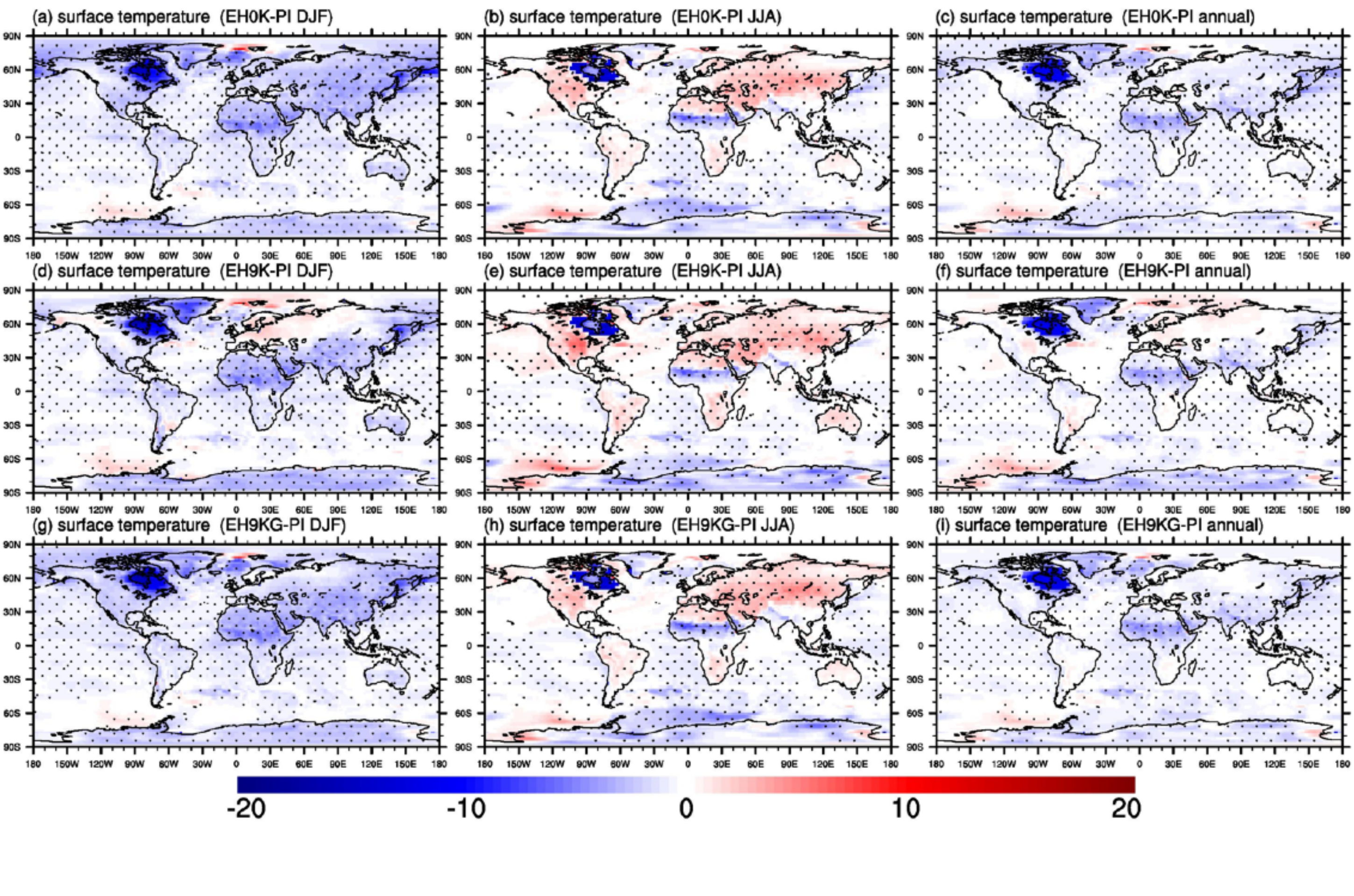


Figure AWI 2: Anomalies of surface temperature in (a-c) EH0K, (d-f) EH9K and (g-i) EH0KG compared to PI, for (a,d,g) December to February, (b,e,h) June to August and (c,f,i) annual mean. The area with black dots indicate a significant level above 95% based on T-test. Units are K.

Fig. 2 shows the anomalies of surface temperature. As can be seen, all early Holocene experiments simulate a significant boreal summer warming especially over the continents of low and mid latitudes, forced by the large positive solar anomalies in JJA. Besides, there are mainly four regions with JJA cooling: the Greenland, the Laurentide ice sheet, the Sahel zone, and the Antarctic. The Greenland and Antarctic cooling is due to higher elevation in early Holocene compared to PI. The presence of Laurentide ice sheet has a strong cooling effect due to its elevation and high surface albedo. The cooling of Sahel region is related to an increased precipitation in boreal summer. In boreal winter, we observe a general global cooling. Only the experiment EH9K shows a warming in JJA over northwestern Eurasia, which is due to a stronger western wind anomaly which brings relative warmer air from the ocean to the continent. Such wind anomaly is caused by an anomalous positive AO pattern. The annual surface temperature anomaly resembles its respective DJF pattern, only smaller in magnitude.

4. Publications

Shi, X., & Lohmann, G. , 2016, Simulated response of the mid‐Holocene Atlantic meridional overturning circulation in ECHAM6‐FESOM/MPIOM. *Journal of Geophysical Research: Oceans*, *121*(8), 6444-6469.

Sjolte, J., Sturm, C., Adolphi, F., Vinther, B. M., Werner, M., Lohmann, G., and Muscheler, R.: Solar and volcanic forcing of North Atlantic climate inferred from a process-based reconstruction. Clim. Past, 14, 1179-1194, 2018. doi:10.5194/cp-14-1179-2018

Shi, X., and G. Lohmann, 2017: Sensitivity of open-water ice growth and ice concentration evolution in a coupled atmosphere-ocean-sea ice model. Dynamics of Atmospheres and Oceans 79, 10-30. doi: 10.1016/j.dynatmoce.2017.05.003

Gierz, P., M. Werner, G. Lohmann, 2017: Simulating Climate and Stable Water Isotopes during the Last Interglacial using a Coupled Climate-Isotope Model. Journal of Advances in Modeling Earth Systems, 9(5), 2027-2045. doi: 10.1002/2017MS001056