SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year 2015

Project Title: Simulations with climate model EC-Earth

Computer Project Account: SPSEZHAN

Principal Investigator(s): Qiong Zhang

Affiliation: Department of Physical Geography, Stockholm University

Name of ECMWF scientist(s) collaborating to the project (if applicable) …………………………………………………………………

Start date of the project: 2015-01-01

Expected end date: 2017-12-31

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	N/A		250000000	9500000
Data storage capacity	(Gbytes)	N/A		50000	20

Summary of project objectives

The global coupled climate model EC-Earth is built on the knowledge of present day and the physical parametrisations are based on present-day observation. However we don't know if such a model is valid for another unknown climate condition, i.e. either a future scenario or climate in the past. The current project aims to perform various simulations for past climate with the latest version of EC-Earth. We follow the PMIP protocols to perform two time slice simulations: Mid-Holocene (MH, 6000 years BP) and Last Glacier Maximum (LGM, 21,000 years BP), as well as a transient simulation for Last Millennium (LM, 850 AD to 1850 AD). The model will be tuned if necessary and the results will be validated against paleo proxy data and other model simulations. The climate sensitivity will be evaluated under different climate forcing. More sensitivity experiments under these climate conditions will be performed to understand the mechanisms of past climate variability.

Summary of problems encountered (if any)

LGM is a cold climate condition that differs quite a lot from today, due to the large extension of the Llaurentide and Fennoscandian ice sheet, sea level was ~130m lower than today. Therefore the topography, coastline and runoff in IFS as well as the bathymetric in ocean model NEMO need to be modified. Model crashes when revised topography does not match the initial conditions based on present day climate, therefore some techniques are applied based on the suggestions from DMI colleagues. We further introduced a new ice-sheet surface process following the work done by DMI with EC-Earth 2.3. We also identified extremely low sea-ice surface temperature in large area of Arctic due to the different resolutions of IFS and NEMO. This problem is especially severe in LGM simulation, which led to unreasonable sea-ice thickness that can be 200 meters. Applying a re-distribution of heat flux over the sea ice solves the problem.

During setup of Last Millennium transient simulation, implementation of various forcings into EC-Earth proved be to more difficult than expected. Especially, the estimation of the albedo and vegetation changes due to land-use change turns out to be a difficult issue, where for present day it is kept as fixed fields based on MODIS data. Following Houldcroft et al (2009), we derived the snow-free surface albedo for EC-Earth. The new land surface albedo scheme can be applied for simulations with varied land-surface type such as last millennium, as well as for the coupled dynamical vegetation model LPJ-GUESS where immediate change of vegetation type takes place.

Some computation issues are related to the new CRAY super computer. The I/O performance sometimes degrades severely, and results in a three-fold or even more CPU time consumed than what it should be. We are expecting that technical experts on HPC could look into the issue and find a good solution to maximize the computation efficiency.

Summary of results of the current year (from July of previous year to June of current year)

Part of our planned simulations is run on National Computer Centre (NSC) in Sweden in parallel, and we perform most of the model data analysis on NSC supercomputer. The computer resources both from NSC and ECMWF therefore support the results summarised below. Here we acknowledge DMI for sharing the ECMWF computer resources in previous year for paleo-simulation setup and test.

1. New implementations in EC-Earth

As previously mentioned, when a climate model that developed for present-day is applied to a different climate condition, some new components need to be implemented to facilitate the simulation for the past climate. For EC-Earth, we have done three implementations including the **orbital forcing**, **ice-sheet surface processes** and **Land surface albedo**.

1.1 Orbital forcing

Orbital forcing related parameters in IFS (EC-Earth 3) are treated as constants for the present day climate; follow the recommendations of the International Astronomical Union (ARPEGE-Climate Version 5.1, 2008). It is noted that the formulas are not valid for dates too far away from the 1st January 2000 (more than one century). Therefore for paleoclimate simulations it is crucial to have the varied orbital parameters according to the given time.

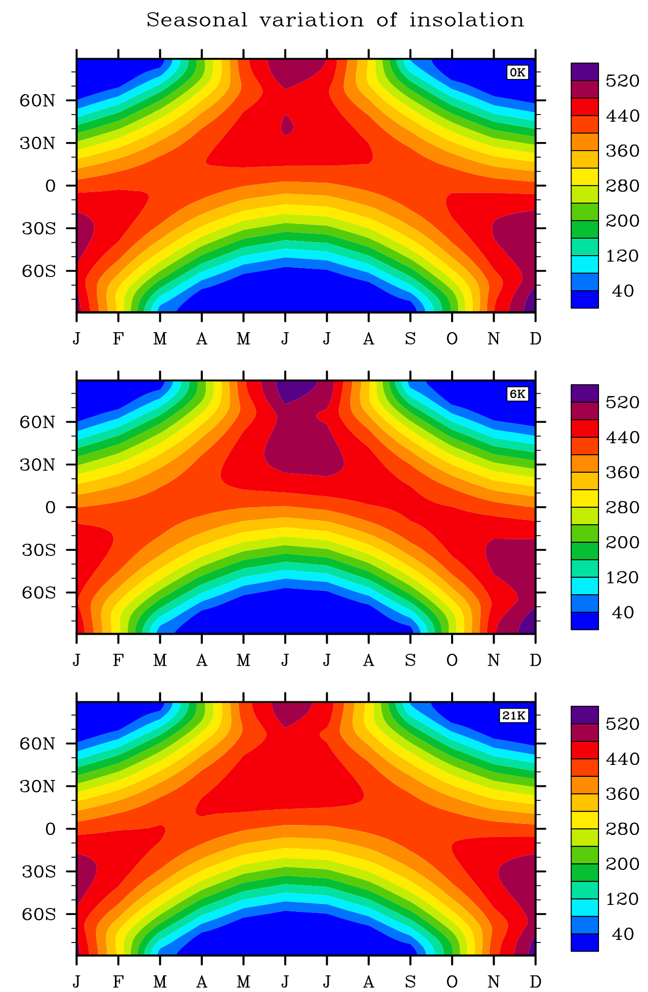
New calculation for the orbital forcing is referred from CAM3.0. The below description for computing orbital parameters is adopted from NCAR technical note (2004) on "Description of the NCAR Community Atmosphere Model (CAM 3.0)", section 4.8 "Parameterization of Shortwave Radiation", with modifications that appropriate to IFS.

The insolation is computed using the method of Berger (1978). Using this formulation, the insolation can be determined for any time within 10 6 years of 1950 AD. This facilitates paleoclimate simulations. The formulation determines earth-sun distance factor and solar zenith angle. The annual and diurnal cycle of solar insolation are represented with a repeatable solar year of exactly 365 days and with a mean solar day of exactly 24 hours, respectively. The repeatable solar year does not allow for leap years.

The orbital state used to calculate the insolation is held fixed over the length of the model integration. This state may be specified in one of two ways. The first method is to specify a year. The value of the year is held constant for the entire length of the integration. The year must fall within the range of 1950 ± 10^6. The second method is to specify the orbital parameters: eccentricity, longitude of perihelion, and obliquity. This set of values is sufficient to specify the complete orbital state. Settings for AMIP II style integrations under 1995 AD conditions are obliquity = 23.4441, eccentricity = 0.016715, and longitude of perihelion = 102.7.

We run the EC-Earth 3.0 (with configuration T159L62-ORCA1L46/LIM3) to test the new implemented orbital forcing. Model computes the orbital parameters according to the given year. Different orbital parameters will produce different insolation. In order to compare with the insolation from other models that use the same computation methods, we particularly run the test experiments for pre-industrial (0 ka,1850 AD), mid-Holocene (6 ka, 6000 BP) and Last Glacier Maximum (21 ka, 21000 BP) as shown in Figure 1. We compared the insolation with those from CESM and MPI-CSM provided by PMIP3 database and verified that the insolation from these three models is the same for 0 ka, 6ka and 21ka.

Figure1 also shows insolation change in mid-Holocene (6 ka) and LGM (21 ka) relative to pre-industrial, where demonstrating significant change in seasonality in 6 ka. Therefore the orbital forcing is regarded as the major forcing for mid-Holocene.



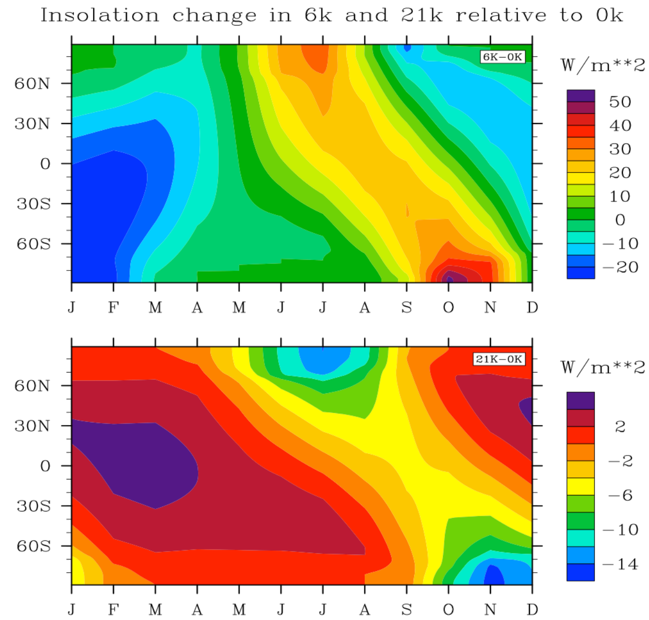


Figure1. Left: Seasonal variation of zonal mean insolation (W/m^2) in 0 ka, 6 ka and 21 ka. Right: Insolation change in 6 ka and 21 ka relative to 0 ka.

1.2 ice-sheet surface processes

Concerning the ice-sheet mass balance, the surface scheme (H-TESSEL) used in IFS does not treat ice sheet explicitly. The surface scheme models the ice sheet as 10m of perennial snow at which there is land ice and it is in thermal contact with the underlying soil. The albedo and density is fixed at 0.8 and 300 kg/m^3, respectively. In such setting, feedback process is not considered due to fixed parameters and problems of conservation of water exist since snow and ice-sheet melting are not allowed.

Therefore, a new surface process for the ice-sheet is introduced. The new land ice mask is applied on top of the original tiles. If a grid box is covered with at least 50% land ice, properties of soil like thermal conductivity and volumetric heat capacity are changed with those of ice as well as surface properties (i.e. albedo, long wave emissivity, roughness lengths for heat, momentum and moisture and skin layer conductivity) of land tiles not covered by snow (i.e. intercepted water, low/high vegetation and bare ground).

Snow is allowed to accumulate on ice sheets, but only with a net positive energy flux at the surface, the accumulated snow is allowed to melt under consideration of energy conservation. In the end, the melt snow will be redistributed to the ocean. Note that for the present setup which is not coupled to any ice-sheet model, all the melting only occurs on the surface, neither basal melt nor ice discharge is taken into account. In addition, a new albedo parametrization for snow on land ice is introduced. The albedo is fixed at 0.8 for perennial snow while for seasonal snow, the albedo is set to 0.85 after snow fall and linearly decrease with ageing and exponentially decrease with melting with a minimum value of 0.6. Once the land-ice is not covered by the snow, it is also allowed to melt as long as the land ice coverage is larger than 10% and the skin temperature is greater than zero degree. This new surface process is adopted from previous work at DMI with EC-Earth 2.3. Therefore this implementation highly benefits from the collaboration with DMI, both from technical assistance and ECMWF computer resources sharing during the test stage.

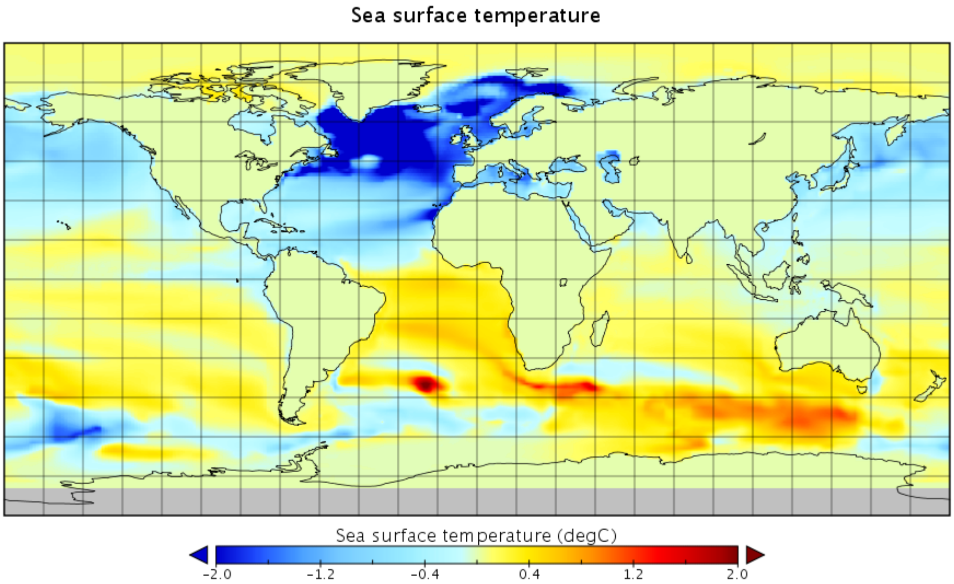


Figure 2. Global SST change between without and with ice-sheet surface process scheme for PI climate condition.

The ice-sheet surface processes improved the cold biases in northern Hemisphere and warm biases in southern Hemisphere, as shown in Figure 2. The annual mean global averaged SST increased about 0.25C, which is closer to the observation.

1.3 Land surface albedo

One crucial forcing for the past climate is the land-use, this will lead to the change in the surface type and consequently changes of land surface albedo and surface energy balance. In current H-TESSEL the land-surface albedo is specified from MODIS 16-day albedo product (MOD43) over the year 2000-2003.

Apparently for a different land surface type this albedo data should not held as fixed field. This is particularly important for our Last Millennium (LM) simulation setup where land-use is believed to vary significantly. PMIP protocol has provided two land cover reconstructions are provided. In order to obtain a more realistic corresponding land-surface albedo, we have followed the calculations by Houldcroft et al (2009) to translate the modern MODIS albedo according to the land surface type. The land surface classification in H-TESSEL/EC-Earth and reconstructions are different, there are 20 vegetation types in H-TESSEL and 14 vegetation types in reconstructions. First we have translated the 14 LM types to 20 BATS type that used in H-TESSEL. Houldcroft et al (2009) uses MODIS data to estimate the albedo of each cover type in which the classification of vegetation cover is based on IGBP classification scheme. We further translate BATS types to IGBP and calculate the land albedo. Since this work is preliminary and our estimation is very crude at this stage. For example, in H-TESSEL for each grid box, the 20 vegetation types are further categorised into: a high or low vegetation or bare ground or ocean/water.

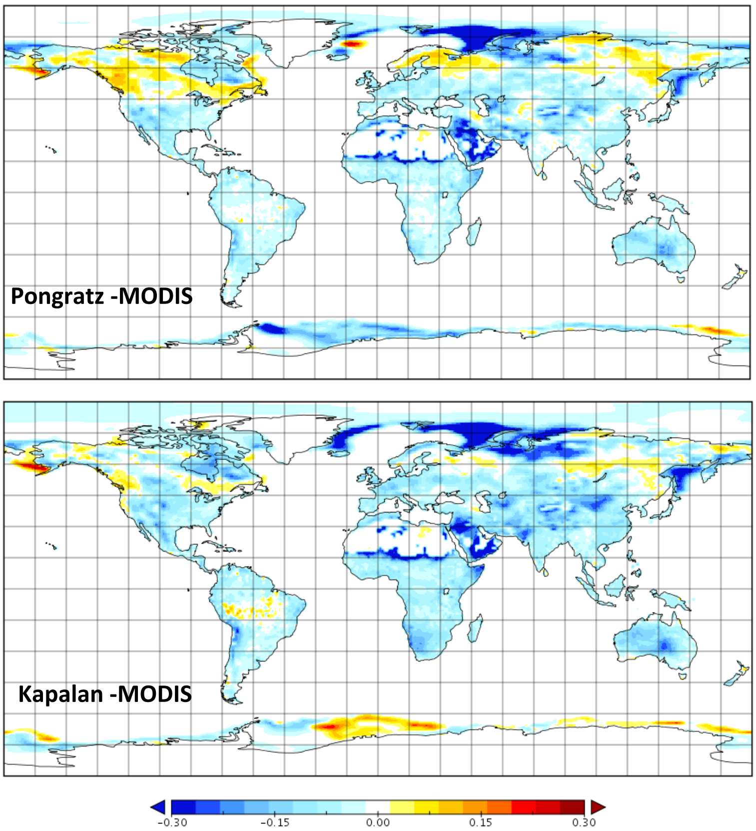


Figure 3. Difference between MODIS albedo and modified albedo according to land cover reconstruction for 1850AD, upper: Pongratz (2009); lower: Kapalan (2010).

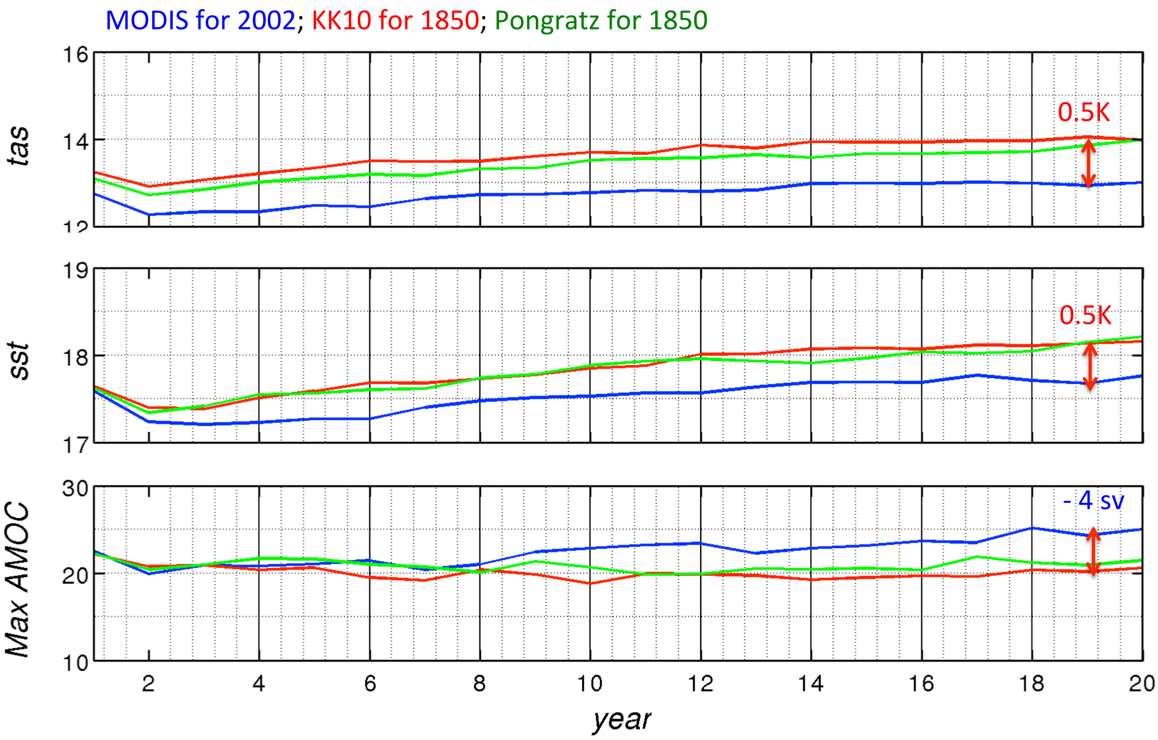


Figure 4. Evolution of global mean surface air temperature, SST and maximum AMOC in 20-year simulations for MODIS albedo, modified albedo corresponding to land-use reconstruction from Pangratz and Kapalan for year 1850 climate condition.

In CMIP5 historical simulations for 1850-2005, the land surface albedo is kept as MODIS value in EC-Earth. It means the effect of land-use change in last 100 years has not been taken into account in EC-Earth simulations. Figure 3 shows that the albedo in large area of continent could be 10 to 20% lower in 1850 than today. If we use the fixed land surface albedo, it would underestimate about

0.5°C of the global mean surface air temperature and SST (Figure 4). With the modified land albedo, global mean SST is about 18°C in 1850 and close to HadiSST data. We also notice a more reasonable maximum Atlantic meridional overturning circulation (AMOC) with 20 SV.

2. Setup of the paleo-simulations with EC-Earth

With above implementations in EC-Earth, we have setup several simulations by following PMIP protocol. The boundary conditions are given for mid-Holocene (6 ka), LGM (21 ka) and last millennium (850-1850 AD). For mid-Holocene we set the orbital year as 6000 years before present day and modified the CH_4 concentration in forcing file. For LGM, except change the orbital forcing and green house gas, we also modified the ice-sheet extension, topography, coastline and runoff in IFS as well as the bathymetry in ocean model NEMO due to the absence of large area of ice-sheet and 130 metre drop of sea level. For LM, we set yearly varied orbital forcing and we adopted the yearly-varied reconstruction files for volcanic forcing, green house gas concentration, solar radiation (differ from orbital forcing), and land-use.

The above described new component implementation and the paleo simulation setup is documented in a manuscript (Zhang et al., 2015).

Several scientific question oriented sensitivity simulations have been run for mid-Holocene and LGM, which are summarized below. Last millennium setup is still in testing and we expect to have first 1000-year transient simulation in coming months.

2.1 Green Sahara experiments for mid-Holocene

Paleo-proxy data suggest that one of the most dramatic changes in rainfall over Africa occurred around 15000 years ago, when increased summer precipitations led to an expansion of the North African lakes and wetlands and an extension of grassland and shrubland into areas that are now desert, giving origin to the so-called "Green Sahara", or African Humid Period. However model simulations have shown limited skill in reproducing the wide range of monsoon amplification responses when forced with Mid-Holocene insolation forcing only. These discrepancies must lie in a shortcoming common to all models such as the improper dust emissions and land surface cover.

With EC-Earth 3.1, we have designed several sensitivity experiments to investigate how potential change in Saharan dust emissions and land surface properties may have altered the climate system in the past. The experiments are listed in table 1.

Table 1. The forcings setup for Green Sahara experiments. The changes in vegetation and dust are applied to the northern African domain 11-33°N, 15°W-35°E.

Experiment	Exp-name	Orbital year	GHG-CH4	Sahara vegetation	Sahara dust
PI control	B400	1850	760	As CMIP5 PI	As CMIP5 PI
6k control	B6KA	- 6000	650	As CMIP5 PI	As CMIP5 PI
6k green dust	G501	- 6000	650	Sahara as shrub	Reduced dust
6k desert dust	P501	- 6000	650	As CMIP5 PI	Reduced dust
PI green	C100	1850	760	Sahara as shrub	As CMIP5 PI
PI green dust	C600	1850	760	Sahara as shrub	Reduced dust
PI desert dust	C700	1850	760	As CMIP5 PI	Reduced dust

The local and remote climate responses based on these experiments have been investigated within the collaboration in Bolin centre where involving PhD student and postdoc fellows, and the corresponding manuscripts have been submitted. The major results from these experiments are:

- Western African monsoon became stronger and extended northward under a green Sahara and reduced dust condition. Monsoon season also lasted longer. However, reduced dust alone would not lead to northward extension of the monsoon (Pausata et al., 2015).
- Arctic became cooling after the Green Sahara changed into Desert. Local albedo change results in decrease of thermal gradient between Arctic and subtropical region, lead to decrease of heat transport both in atmosphere and ocean and consequently lead to cooling over Arctic (Muschitiell et al., 2015).
- Under a green Sahara with reduced dust condition, the amplitude and periodicity of the ENSO is reduced, which is suggested by a few proxy data (Ballarotta et al., 2015).

Through the publications and presentations of these scientific results, we expect that more interests will be drawn to these Green Sahara experiments and more investigations can be established within collaboration.

2.2 Different initial conditions for LGM simulation

We have performed two time slice last glacial maximum (LGM) simulations starting from different ocean initial conditions. Both initial conditions are taken from previous LGM runs by Zhang et al (2013) and interpolated to the present numerical grid. The two initial ocean states differ by their vertical stratification, and in terms of the vertical profile of the ocean, one initial condition is more like a glacial ocean (hereafter named LGM1 run), while the other is more like a present-day ocean (hereafter named LGM2 run). Up to now, a total of 800 years spin-up run has been made to LGM1 run and 500 years spin-up for LGM2 run. In Figure 5, the temporal evolutions of the global sea surface temperature from both runs are shown. In addition, a previous control run i.e. pre-industrial (PI) run, is added for comparison. Though we already start simulations by using initial conditions from a previous LGM simulation, and after several hundred years of spin up, the surface temperature still seems not reach a quasi-equilibrium state, indicating the expansive nature of such paleo simulations. The global mean SST in LGM runs is about 13-14°C and about 3°C less than the PI run.

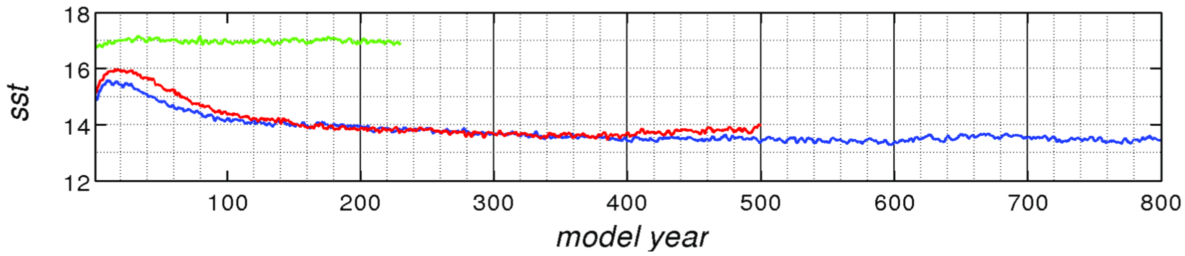


Figure 5. The evolution of global mean sea surface temperature (SST) of two LGM runs and the control run. LGM1 run in blue, LGM2 run in red and PI run in green.

The LGM climate is characterised by not only colder but also drier comparing to present day. This is shown in Figures 6 and 7 where averaging of the last 100 years of 2m air temperature and precipitation comparing with the control run. Figure 6 shows the global 2-metre air temperature of the control run and the difference between the LGM1 run and PI run. Large cooling over the ice sheet is observed while the cooling over the ocean is much smaller. The global averaged value is about 6.6°C lower in LGM1 run than PI run.

The changes of the annual precipitation are shown in Figure 7. For most of the area the precipitation is reduced. Compared to PI run, large decreases of precipitation mainly occur along the coast, e.g. the northwestern coast of north America and west coast of Japan. In the tropical region, slight decrease of the precipitation occurs in the Intertropical convergence zone (ITCZ) which is also consistent with previous studies, see e.g. Toracinta et al 2004. In the South Pacific convergence zone (SPCZ), an increase of the precipitation is observed relative to PI run, and this enhancing of precipitation is also shown in the previous studies and attributed to the difference in surface temperature gradients (Toracinta et al., 2004). For the present LGM runs, the change of precipitation over the ice sheet is marginal, and this is different from a previous LGM run by Otto-Bliesner et al (2006) in which up to 2 mm/day of precipitation decreases over the continental ice sheets are observed.

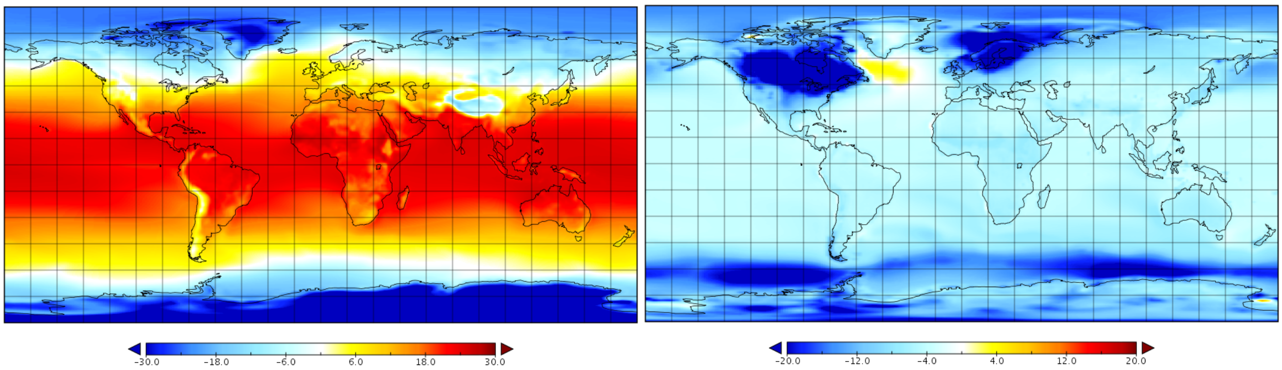


Figure 6. The global 2m air temperature (°C). Left: The PI control run; Right: The difference between the LGM1 run and PI run.

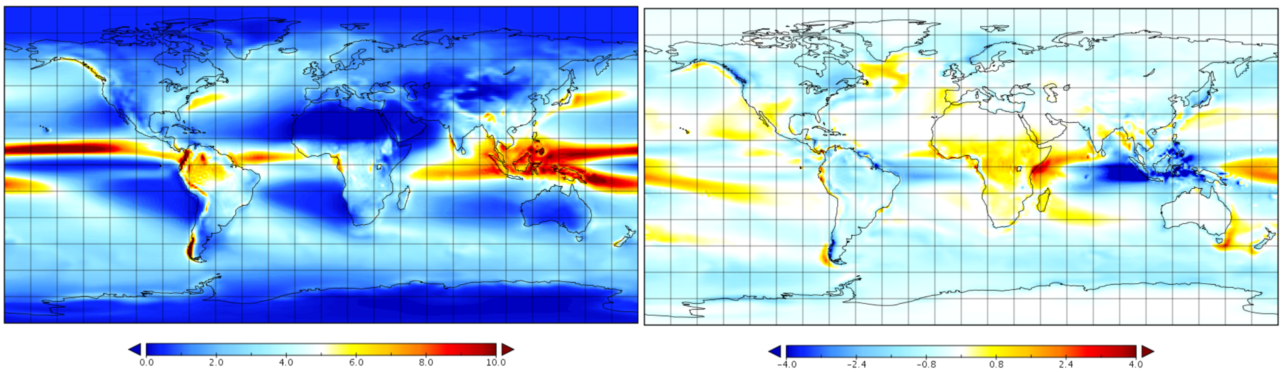


Figure 7. The global precipitation (mm/day). Left: The control run; Right: The difference between the LGM1 and PI run.

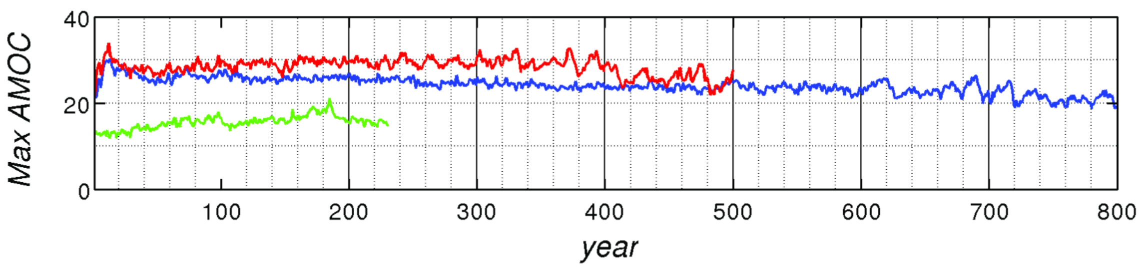


Figure 8. The evolution of AMOC strength of two LGM runs and the control run. LGM1 run in blue, LGM2 run in red and PI run in green.

The Atlantic Meridional Overturning Circulation (AMOC) time series are shown in Figure 8. Thought many proxy data suggest a weakening of AMOC strength, the present results are showing an opposite trend. About 20 SV is reached by LGM1 at model year 800 and LGM2 is consistently slightly higher than LGM1 run and reaches about 25 sv at model year 500. These values are consistent with simulation by Zhang et al (2013) and other previous simulations, e.g. see Sueyoshi et al (2013). Note that Weber et al (2007) found that about half of the PMIP2 models have problem simulating a weaker AMOC and due to coarse resolution, non-realistic diffusion coefficients, no consideration of the mixing due to winds and tides. This suggests large sensitivity with respect to the various forcings of AMOC responses and further investigations need to be done to understand the behaviours.

Moreover, in Zhang et al 2013, they observed that after very long integration time, i.e. about 4000 model years, both the two different ocean states reach equilibrium and are stable. Note that in Zhang et al (2013), they use a much coarser horizontal resolution of the ocean which is about 3 °C while the present study is about 1°C. However, our results show that after few hundred years, the present-day like initial ocean state is unstable and finally both runs becomes a glacial ocean though started differently.

Reference

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Zhang, X., Lohmann, G., Knorr, G., and Xu,X.: Different ocean states and transient characteristics in Last Glacial Maximum simulations and implications for deglaciation, *Clim. Past*, **9**, 2319-2333, 2013.

List of publications/reports from the project with complete references

We do not have published paper with these reported simulations yet. Here we list the submitted/in preparation manuscripts.

Francesco Muschitiello, Qiong Zhang, Hanna S. Sundqvist, Frazer J. Davies4, Hans Renssen. 2015: Arctic climate response to the termination of the African Humid Period. *Quaternary Science Review*, revision submitted.

Francesco F.S. Pausata, Gabriele Messori, Qiong Zhang, 2015: The Mid-Holocene west african monsoon strength modulated by Sahara dust and vegetation, *Nature Geoscience*, in reivew.

Qiong Zhang, Qiang Li, Maxime Ballarotta, Shuting Yang, Marianne Sloth Madsen, Klause Wyser, 2015: Paleo-simulation setup with EC-Earth, manuscript in preparation.

Maxime Ballarotta, Qiong Zhang, Francesco F.S. Pausata, Curt Stager, 2015: A weak ENSO during African Humid Period, manuscript in preparation.

Summary of plans for the continuation of the project

(10 lines max)

We will continue running the LGM spinup, especially LGM2 run, at least up to 800 model years so that it is the same length as LGM1 run. Meanwhile, the Last Millennium simulation will be the focus of the rest of the year. Once the setup and test are done, we will start tunning and the spinup for the LM runs. Once all this is done, a 1000 year last millennium run will be performed.

Within the preparation for CMIP6, EC-Earth earth system will soon be available for our past climate experiments. We will use a dynamical vegetation model LPJ-GUESS coupled EC-Earth version to perform experiments related to land-use change.