Boundary conditions for the CMIP5 paleoclimate simulations: Last Glacial Maximum, Mid-Holocene and Last Millennium.

Decembre 7, 2009

This note describes the boundary conditions for paleoclimate experiments that are part of the CMIP5 protocol. Three key periods of the Paleoclimate Modelling Intercomparison project enter into CMIP5 (see Taylor et al. 2008). Their purposes are described in table 1. The boundary conditions have been finalised on November 2009. They are summarised below, and we invite the groups that are ready to run these simulations to connect to the PMIP3 website where the different forcing files are available (http://pmip3.lsce.ipsl.fr/).

Table 1. Paleoclimate simulations to be run as part of PMIP3/CMIP5.

	Period	Purpose	Imposed boundary conditions	# of years
TIER1	Last Glacial maximum (21 kyr ago)	a) Compare with paleodata the model response to ice-age boundary conditions. b) Attempt to provide empirical constraints on global climate sensitivity.	• Ice-sheet and land-sea mask • Greenhouse concentration of well-mixed greenhouse gases • Orbital parameters	≥100 (after spin-up period)
TIER1	Mid-Holocene (6kyr ago)	a) Compare with paleodata the model response to known orbital forcing changes and changes in greenhouse gas concentrations.	• Orbital parameters • Atmospheric concentration of well-mixed greenhouse gases	≥100 (after spin-up period)
TIER2	Last millennium (850-1850)	a) Evaluate the ability of models to capture observed variability on multi-decadal and longer time-scales. b) Determine what fraction of the variability is attributable to "external" forcing and what fraction reflects purely internal variability. c) Provides a longer-term perspective for detection and attribution studies	• Solar variations • Volcanic aerosols • Well mixed greenhouse gases • Land use • Orbital parameters	1000 (after spin-up period)

For all these periods the model to be used is the same as the one used for future climate projections. Therefore depending on the groups the model will be only atmosphere-ocean coupled models or Earth System models, and the reference for the analyses will be the CMIP5 pre-industrial simulation.

21ka Experimental Design

Boundary conditions

Summary of 21ka boundary conditions

	PMIP3	**Minimum solution**
Orbital parameters	[**ecc** = 0.018994] - [**obl** = 22.949°] - [**peri-180°** = 114.42°]	
Date of vernal equinox	March 21 at Noon	
Trace gases	[$\mathbf{CO_2}$ = 185 ppm] - [$\mathbf{CH_4}$ = 350 ppb] - [$\mathbf{N_2O}$ = 200 ppb] - [**CFC** = 0] - [$\mathbf{O_3}$ = same as in PI]	
Aerosols	Same as in CMIP5 PI (see *Dust forcing* note below)	
Solar constant	Same as in CMIP5 PI	
Vegetation	Same as in CMIP5 PI	
Ice sheet	Ice sheet provided (see below)	
Topography and coastlines	land-sea mask provided (see below)	minimum changes (see note below)
Ocean bathymetry	up to groups depending of the flexibilty of the model	
River outflow	Modified according to a river pathway map (provided, see below)	Same as in CMIP5 PI
Ice sheet ice stream	add excess LGM freshwater to ocean (see below)	Same as in CMIP5 PI
Mean ocean salinity	+1PSU everywhere	

Insolation

Note that insolation should follows PMIP requirements. Please check it carefuly using the following tables (LGM insolation tables [http://pmip2.lsce.ipsl.fr/design/tables/inso_tables_21k.shtml])

Check carefully the date of the Vernal equinox, because it has implications to compare the paleo and PI seasonal cycles

Ice-sheet

The ice sheet provided for PMIP3/CMIP5 LGM experiments is a blended product obtained by averaging three different ice sheets:

- ICE6G provided by Dick Peltier
- MOCA provided by Lev Tarasov
- ANU provided by Kurt Lambeck

A short description and references for the different ice sheets is provided under the link below: LGM icesheet description

This solution was proposed by PMIP bureau in light of a community checking. Given the uncertainties that still exist on the reconstruction of the ice-sheet, resulting from uncertainties in datation for the data used for global or regional constraints, climate intput from ice core temperature reconstructions or climate model simulations, etc… it sounds reasonable to consider that the average is a best estimate of the LGM ice-sheet.

The ice sheet should be implemented following PMIP2 protocol by considering the CHANGE in surface elevation (over ice sheets and land due to sea level lowering) in order that all models will be perturbed (forced) in the same way. This change in elevation would be added by each modeling group to the topography used in their control run.

To access the files click here

Land-sea mask

The land-sea mask is provided by the ICE6G model, except for Antarctica where you should deduce it from the averaged ice-sheet

To access the files click here

The minimum change is to close the Bering Strait by changing the land-sea mask or imposing rero flux on water and sea-ice across the Bering Strait

River outflow

The river pathways and basins should be at least adjusted so that fresh water is conserved at the Earth's surface: care should be taken that rivers reach the ocean (due to the lower sea level at LGM, some river mouths have to be displaced towards the coast).

You can use the river routing provided by Lev Tarasov to change the routing scheme in your code, so that the river pathways is consistent with the presence of the ice-sheet.

To access the files click here

Ice-sheet mass balance

It is advised to ensure a closed fresh water balance at the Earth's surface: snow accumulating on the ice-sheets should be redistributed to the oceans, either globally or in the adjacent oceans (see PMIP2 recommendation mass balance recommendation [http://pmip2.lsce.ipsl.fr]).

Vegetation

The vegetation should be treated as in the CMIP5 PI experiment. The reason is that in CMIP5 we test the version of the model used for future climate projections. Since OA and ESM models will be considered, depending on the model used the vegetation will be

- prescribed to PI (which means both vegetation types and LAI are prescribed)
- Prescribed to PI with interactive LAI (models with interactive carbon cycle, but no vegetation dynamics)
- Computed by the model (models with dynamic vegetation)

For Earth System Models with interactive carbon cycle

The simulations should be forced by the prescribed LGM CO2 concentrations. Please use the same protocol as in CMIP5 to store the diagnostic carbon fluxes and the variables needed for PCMIP (see pcmip Project [http://www.bridge.bris.ac.uk/projects/pcmip/experiments.html] and CMIP5 [http://cmip-pcmdi.llnl.gov/cmip5/])

Dust forcing

Some ESM have interative aerosols. In that case compute dust and associated forcing online, as in PI. If this is not the case then the recommendation is to keep dust and aerosols as in PI (I.E no change for 21 ka).

Initial conditions

The surface pressure field must be adjusted to the change in surface elevation over the continents.

This can be done:

- either by gradually changing the surface elevation in order to avoid generating gravity waves,
- or by adjusting the initial pressure field to the LGM surface elevation.

If you choose the second option, you must be careful to conserve atmospheric mass.

The spin up procedure is up to group, following CMIP5 approach or from a previous cold state

Note several groups share the same ocean models for which an initial state can be provided from PMIP2 experiments.

If you need an initial state from a other group, you can contact Olivier.marti@lsce.ipsl.fr

Groups with high resolution model for which it is too difficult to run long simulations should contact Olivier.marti@lsce.ipsl.fr to find the best alternative solution.

6ka Experimental Design

Boundary conditions

Summary of 6ka boundary conditions

	PMIP3/CMIP5
Orbital parameters	[**ecc** = 0.018682] - [**obl** = 24.105°] - [**peri-180°** = 0.87°]
Date of vernal equinox	March 21 at noon
Trace gases	[$\mathbf{CO_2}$ = 280 ppm] - [$\mathbf{CH_4}$ = 650 ppb] - [$\mathbf{N_2O}$ = 270 ppb] - [**CFC** = 0] - [$\mathbf{O_3}$ = same as in CMIP5 PI]
Aerosols	Same as in CMIP5 PI
Solar constant	Same as in CMIP5 PI
Vegetation	prescribed or interactive as in CMIP5 PI
Ice sheets	Same as in CMIP5 PI *
Topography and coastlines	Same as in CMIP5 PI *

* Sensitivity experiments will be proposed as part of a working group to test the uncertainties due to the remnant ice-sheet. If you are interested in participating to this working group contact Pascale Braconnot

Vegetation

The vegetation should be treated as in the CMIP5 PI experiment. The reason is that in CMIP5 we test the version of the model used for future climate projections. Since OA and ESM models will be considered, depending on the model used the vegetation will be

- prescribed to PI (which means both vegetation types and LAI are prescribed)
- Prescribed to PI with interactive LAI (models with interactive carbone cycle, but no vegetation dynamics)
- Computed by the model (models with dynamic vegetation)

A 6ka reconstructed vegetation map from a combination of model outputs and data analyses will be provided for sensitivity experiments. If you are interested please contact Bette Otto-Bliesner, Sandy Harrison and Pat Bartlein who will lead the corresponding working group.

For Earth System Models with interactive carbon cycle

The simulations should be forced by the prescribed 6ka CO2 concentrations. Please use the same protocol as in CMIP5 to store the diagnostic carbon fluxes and the variables needed for PCMIP (see pcmip Project [http://www.bridge.bris.ac.uk/projects/pcmip/experiments.html] and CMIP5 [http://cmip-pcmdi.llnl.gov/cmip5/])

Insolation

Note that insolation should follows PMIP requirements. Please check it carefully using the following tables (6ka BP insolation tables [http://pmip2.lsce.ipsl.fr/design/tables/inso_tables_6k.shtml])

Check carefully the date of the Vernal equinox, because it has implications to compare paleo and PI seasonal cycle

6ka for groups only running PMIP3 experiments

If you only run PMIP3 experiments we recommand that you follow CMIP5 (see taylor_cmip5_dec31.pdf) or PMIP2 (PMIP2 web site [http://pmip2.lsce.ipsl.fr]) for the PI simulation

Initial conditions

	PMIP3	**Alternative solution**
Initial conditions	Branch off PI after adjustment	Same as in PI
Model spin up	Same as in PI	

Last Millennium Experimental Design

The basic principle is that we should strive to include all relevant transient forcings over this period if the functionality exists in the model, noting that conformability with the CMIP5 controls and 20th Century transient is crucial.

Boundary conditions

Summary of Last Millennium boundary conditions

	PMIP3	**Alternative solution**
Orbital parameters	Annually varying Table provided (0-2100 CE/AD), if not internally calculated	
Date of vernal equinox	March 21 at Noon	
Trace gases	Annually varying (850-1850) (Table provided)	
Volcanic Aerosols	Multiple reconstructions (of AOD, Effective Radius, Mass)	
Solar irradiance	choose at least one between Multiple reconstructions provided below	
Ozone	solar related variations (parameterised as function of change in solar irradiance - Drew Shindell)	same as in CMIP5 PI
Aerosols	biomass burning changes????	same as in CMIP5 PI
Vegetation	Land use conversion (forests to C3/C4 crops) (Pongratz, 2009, Foley and Ramunkutty) Provided below	same as in CMIP5 PI
Ice sheets	No changes from Pre-Ind control	
Topography and coastlines	same as in CMIP5 PI	

Total Solar Irradiance

Multiple reconstructions of annual total solar irradiance are provided. These are designed to either fit smoothly with the reconstructions used in the post-1850 CMIP5 simulations (Wang, Lean and Sheely (2005)), or to explore independent estimates of the long term solar trends. Each series has an 11 year solar cycle throughout the time series (synthetic for pre-1610, based on a relationship between cycle magnitude and long-term TSI) and comes with an estimate of the spectral changes (as a function of the TSI anomaly). Each reconstruction is calibrated to the WLS modern values.

Wang, Lean and Sheely (WLS): 1610-2000 CE

Spectral reconstruction based on a flux transport model of the open and closed flux using the observed sunspot record as the main input. This comes in two versions, A) a “no-background” version that just has TSI variations similar to that seen over a solar cycle today, and B) a “with background” version with longer term trends in the solar minimum.

Lean J, "Calculations of Solar Irradiance" [http://www.geo.fu-berlin.de/en/met/ag/strat/forschung/SOLARIS/Input_data/Calculations_of_Solar_Irradiance.pdf]

Wang, Y.-M., J. L. Lean, and N. R. Sheeley, Jr. (2005), Modeling the Sun’s Magnetic Field and Irradiance since 1713, ApJ, 625, 522–538, doi:10.1086/429689.

Delaygue and Bard (DB): 850-1609 CE

Reconstruction based on an Antarctica stack of 10Be records scaled linearly to the modern-to-Maunder Minimum TSI in the two WLS reconstructions.

Delaygue, G and E. Bard, (2009), Solar forcing based on Be-10 in Antarctica ice over the past millennium and beyond, EGU 2009 General Assembly, #EGU2009-6943 [http://meetingorganizer.copernicus.org/EGU2009/EGU2009-6943.pdf]

Muscheler, Joos, Beer, Müller, Vonmoos and Snowball (MEA): 850-1609 CE

Reconstruction based on the 14C record scaled based on an inverse regression to the two WLS reconstructions.

Muscheler, R., F. Joos, J. Beer, S.A. Müller, M. Vonmoos, and I. Snowball (2007), Solar activity during the last 1000 yr inferred from radionuclide records Quaternary Science Reviews, Vol. 26, pp. 82-97. doi:10.1016/j.quascirev.2006.07.012

Vieira, Krivova and Solanki (VK): 850-1849 CE

Reconstruction based on a model of the open and closed magnetic flux including an estimate of the 11 yr cycle. We recommend patching this into the WLS w/background values in 1850.

Vieira, L.E.A., and S. Solanki (2009), Evolution of the solar magnetic flux on time scales of years to millenia, arXiv/0911.4396 [http://eprintweb.org/S/authors/All/so/Solanki/2], doi:10.1051/0004-6361 /200913276

Steinhilber, Beer, and Frohlich (SBF): 850-1849 CE

Reconstruction based on a Greenland 10Be core and a different model of solar flux. 11yr cycle is synthetic. We recommend patching this into the WLS w/background values in 1850.

Steinhilber, F., J. Beer, and C. Frohlich (2009), Total solar irradiance during the Holocene, Geophys. Res. Lett., 36, L19704, doi:10.1029/2009GL040142.

Solar-driven Ozone variations

A parameterisation of ozone changes in the atmosphere (lat, lon, altitude) as a function of changing solar irradiance (including spectral variations) is available based on the results of Shindell et al (2006).

Shindell, D.T., G. Faluvegi, R.L. Miller, G.A. Schmidt, J.E. Hansen, and S. Sun, 2006: Solar and anthropogenic forcing of tropical hydrology. Geophys. Res. Lett., 33, L24706, doi:10.1029/2006GL027468,2006. http://pubs.giss.nasa.gov/docs/2006/2006_Shindell_etal_4.pdf [http://pubs.giss.nasa.gov/docs/2006/2006_Shindell_etal_4.pdf]

Volcanic Forcings

Two alternative data sets are provided below. It is up to the groups to choose the Gao-Robock-Amann or the Crowley reconstruction for their last millenium simulation.

The Gao-Robock-Ammann data set

Time series of global hemispheric total stratospheric sulphate injections from volcanic eruptions for the past 1500 years as well as estimates of stratospheric loading as a function of latitude, altitude, and month are available from IVI2link [http://climate.envsci.rutgers.edu/IVI2/]

The data are derived from 54 ice core records, 32 from the Arctic, and 22 from Antarctica. It is based on the most comprehensive set of ice cores, an updated extraction record, updated ice core deposition to global stratospheric aerosol loading conversion factors, and an advanced spatial-temporal transport parameterization scheme (Gao et al., 2008)

The stratospheric aerosol loadings (in units of Tg) provided in the IVI2 data set may be converted into aerosol optical depth (AOD) by dividing the loadings by 150 Tg (Stothers, 1984). The AOD time series can then be used to calculate the corresponding radiative forcing (in units of Wm-2) by multiplying it by (-20) (Wigley et al., 2005). The conversion to AOD is valid for aerosols with effective radius in the visible spectral range.

Further explanation is provided here : ivi2aodtsiconversion.pdf

Gao, C., A. Robock, and C. Ammann: Volcanic forcing of climate over the last 1500 years: An improved ice-core based index for climate models. J. Geophys. Res., 113, D2311, doi:10.1029/2008JD010239 (2008).

Stothers, R.B., The great Tambora eruptions in 1815 and its aftermath. Science, 224(4654), 1191-1198 (1984). Wigley, T.M.L., C.M. Ammann, B.D. santer, and S.C.B. Raper: Effect of climate sensitivity on the response of volcanic forcing. J. Geophys. Res., 110,D09107, doi:10.1029/2004JD005557

The Crowley data set

The volcanic forcing is calculated using time series of aerosol optical depth (AOD) at 0.55µm and of the effective radius (Reff) (Crowley et al., 2008). The time resolution of the series is ten days and the data are provided at four equal area latitude bands.

AOD estimates are based on a correlation between sulphate in Antarctic ice cores and satellite data (Sato et al., 1993).

Reff growth and decay is based on satellite observations of the Pinatubo eruption in 1991, with eruptions larger than that of Pinatubo (maximum is 0.15) being scaled by the theoretical calculations for very large eruptions (Pinto et al., 1989). In the model AOD is distributed between 20-86 hPa over three vertical levels, with a maximum at 50 hPa.

Sensitivity experiments for the model response to the Pinatubo eruption yield an average global temperature change (0.4 K) comparable to observations. For the largest eruption of the last millennium, the 1258 AD eruption, a NH summer temperature anomaly over land of 1.2 K is found in agreement with reconstructions (Timmreck et al., 2009)

Crowley, T. et al. Volcanism and the Little Ice Age. PAGES Newsletter, 16, 22-23 (2008).

Sato, M., Hansen, J.E., McCormick, M.P. & Pollack, J.B. Stratospheric aerosol optical depths, 1850-1990. J. Geophys. Res., 98(D12), 22,987-22,994, doi:10.1029/93JD02553 (1993).

Pinto, J.P., Turco, R.P., & Toon, O.B. Self-limiting physical and chemical effects in volcanic eruption clouds. J. Geophys. Res., 94(D8), 11,165-11,174, doi:10.1029/JD094iD08p11165 (1989).

Timmreck, C. et al. Limited temperature response to the very large AD 1258 volcanic eruption. Geophys. Res. Lett., 36, L21708, doi:10.1029/2009GL040083 (2009).

Reconstructed evolution of trace gases

The evolution of CO_2, CH_2, N_2O over past 2 millennia table has been provided by Fortunat Joos [mailto:joos@climate.unibe.ch] (University of Bern). Methods and references are provided in the downloadable file.

Orbital forcing

The following orbital parameters parameters should be used, if they are not internally calculated.

Note: calculation from Berger (1978), annually varying.

Precomputed table

The parameters' table has been supplied by Gavin Schmidt [mailto:gschmidt@giss.nasa.gov] (GISS).

Linear regressions

Over the period 0-2100 CE, the parameters are well approximated by the following linear regressions:

Parameter	Linear approximation
ECC	0.017475 - 0.000000382 * Year
OBL	23.697 - 0.000128 * Year
PERI-180	68.79 + 0.0170 * Year

Vegetation

Anthropogenic land cover change is considered by applying the reconstruction of global agricultural areas and land cover (Pongratz et al., 2008).

The global maps with a spatial resolution of 0.5° and an annual timescale contain 14 vegetation types and discriminate between the agricultural categories cropland, and C3 and C4 pastures. The reconstruction merges published maps of agriculture from AD1700 to 1992 and a population-based approach to quantify agriculture from AD 800 to 1700.

The data set can be obtained from the World Data Center for Climate (doi:10.1594/WDCC/RECON_LAND_COVER_800-1992).

Pongratz, J., Reick, C.H., Raddatz, T. & Claussen, M. A reconstruction of global agricultural areas and land cover for the last millennium. Global Biogeochem. Cycles, 22, GB3018, doi:10.1029/2007GB003153 (2008).

To access the files, click here RECON_LAND_COVER_800-1992 [http://cera-www.dkrz.de/WDCC/ui/Entry.jsp?acronym=RECON_LAND_COVER_800-1992]

Initial conditions

	PMIP3	Alternative solution
Initial conditions	Branch off PI after adjustment	Same as in PI
Model spin up	Same as in PI	

Pre-Industrial Control Run Experimental Design

PI for PMIP3/CMIP5 experiments

The Preindustrial control should be the same as the one used for CMIP5 experiments. It is thus the same reference as the one for 20th century simulations and future climate projections (see taylor_cmip5_dec31.pdf).

Vegetation

Depending on the complexity of the model used the vegetation will be either:

- computed by the model
- prescribed to PI (some ESMs may also only compute vegetation phenology and carbon cycle).

Land use

Land use should be included in the PI vegetation map. In that case, care should be taken that the land use map used in the PI simulation is consistent with the one used for land use evolution either for the 20th century or the last Millennium. Please follow CMIP5 recommendations (see http://cmip-pcmdi.llnl.gov/cmip5/forcing.html?submenuheader=2#land-use_data/landuse data [http://cmip-pcmdi.llnl.gov/cmip5/forcing.html?submenuheader=2#land-use_data/landuse data]).

For Earth System Models with interactive carbon cycle

The simulations are forced by the CO_2 concentrations. Please use the same protocol as in CMIP5 to store the carbon fluxes and the variables needed for PCMIP (see pcmip Project [http://www.bridge.bris.ac.uk/projects/pcmip/experiments.html] and CMIP5 [http://cmip-pcmdi.llnl.gov/cmip5/])

PI for groups only running PMIP3 experiments

If you only run PMIP3 experiments we recommand that you follow CMIP5 (see taylor_cmip5_dec31.pdf) or PMIP2 (PMIP2 web site [http://pmip2.lsce.ipsl.fr]) for the PI simulation.