Status and challenges of CESM2.1 Paleoclimate Simulations

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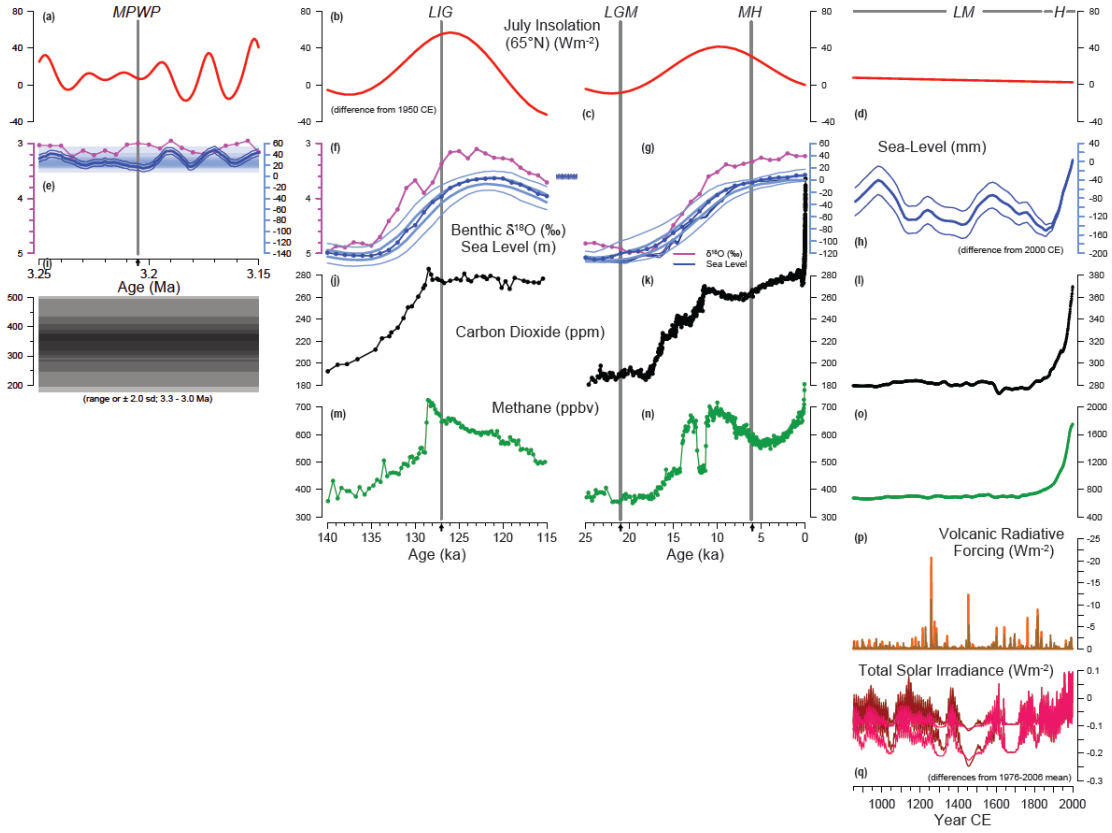
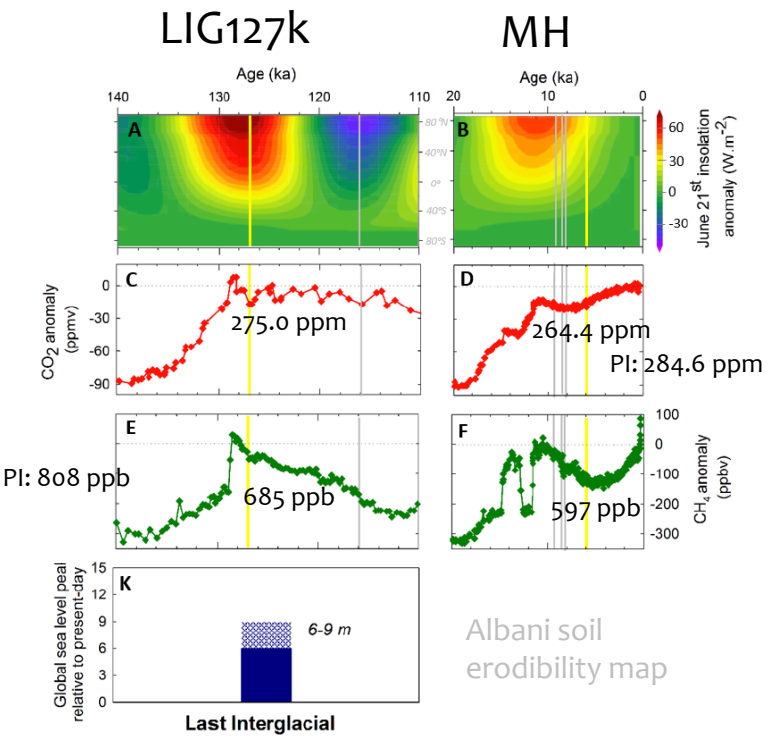
NCAR Mesa Lab, Boulder, CO

5 key time periods of PMIP4/CMIP6

1. Mid-Pliocence warm period ~3.2 ma – Ran Feng
2. Last interglacial 127ka – Bob Tomas
3. Last glacial maximum 21ka - TBD
4. Mid-Holocene 6ka – Bob Tomas
5. Last Millennium 850-2015 CE – Samantha Stevenson



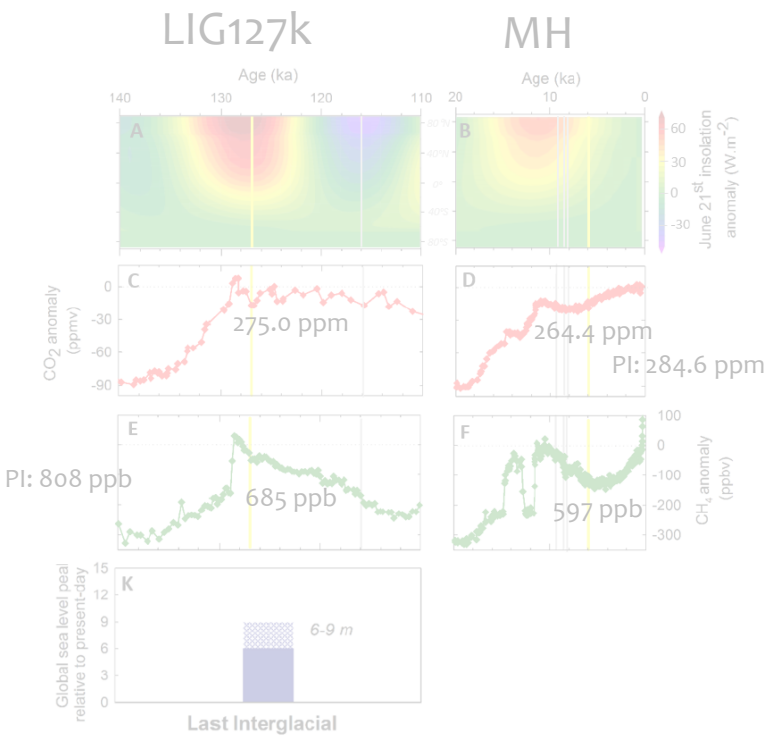
LIG127ka and MH Tier 1 Forcing & Boundary Conditions



Volcanic: background from PI
Yellow vertical lines: 127ka and 6ka

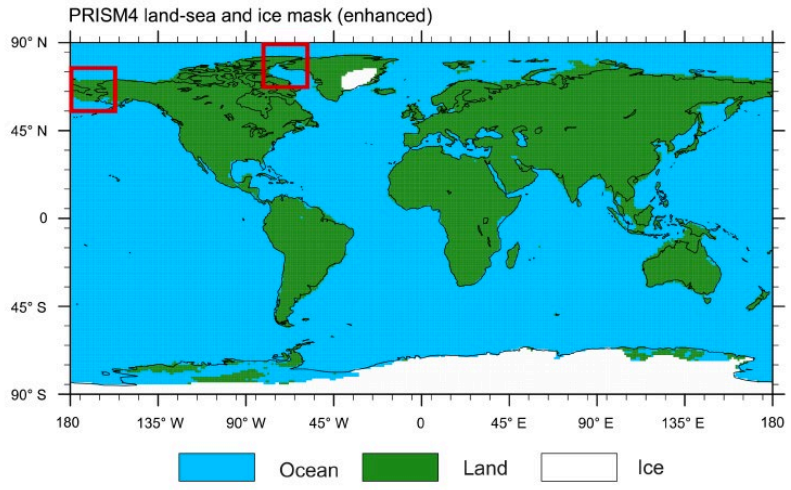
- Orbital parameters result in large + solar insolation anomalies during NH summer
- GHG concentrations are similar to PI & continental configuration identical to modern
- Interactive dust with soil erodibility maps for MH
- Sea-level & ice sheets: from PI owing to uncertainties in records
- **Land Surface: Had planned on PI file but decided better to *remove anthropogenic effects*. Peter Lawrence and Erik Kluzek produce land surface file with "Potential Natural Vegetation" + namelist changes (Thanks Peter Lawrence & Eric Kluzek)**
- Aerosols & volcanic (background): prescribed as

LIG127ka and MH Status



- 300 year fully coupled simulations completed
- Offline land spin up (BGC/CN/abiotic ^{13}C, ^{14}C) to equilibrium completed
- Scripts for offline ocean spin up (Ecosystem, abiotic ^{13}C, ^{14}C) not available yet – proceed with PI control ocean state
- Next steps: Start run using, CYLC wfm, check output streams, diagnostics, then onto production

Mid-Pliocene Warm Period Forcing

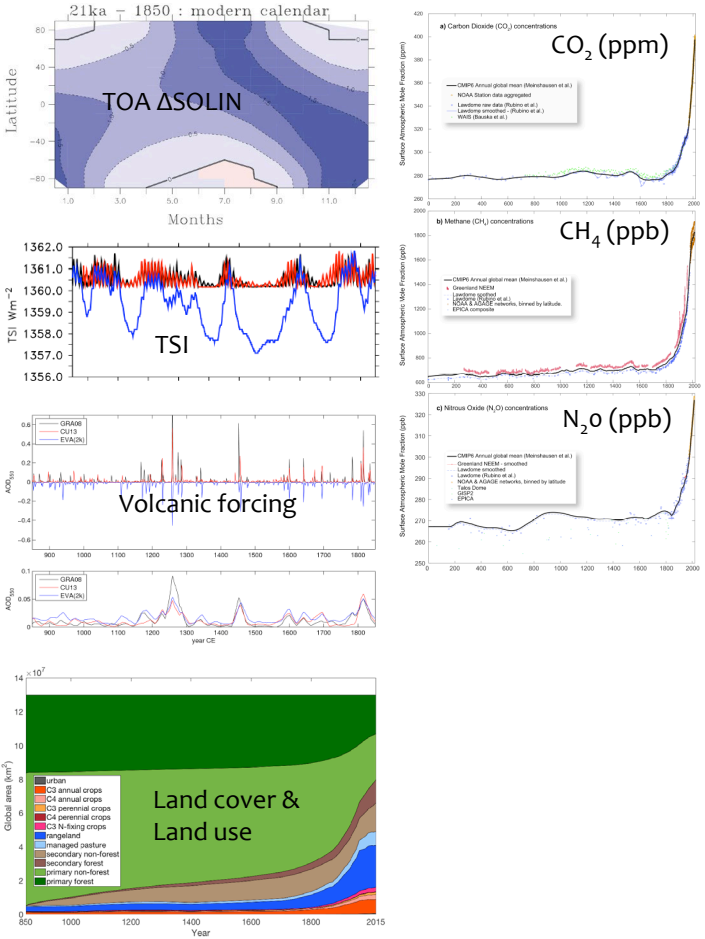


- Smaller ice sheets
- Land/sea mask
  - Higher sea level by 22m - large changes around Indonesian Seaway
  - West Antarctic ice shelf removed
  - Canadian Archipelago closed
  - Bering Straight closed
- CO_2 = 400 ppm, close to PI; other GHG's at PI

Mid-Pliocene Warm Period Status

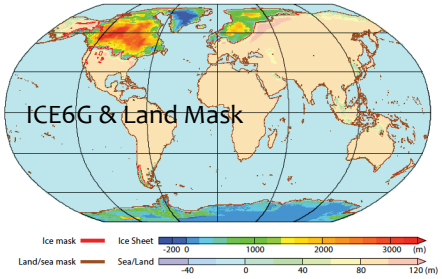
- Ocean grid extended where WAI removed
  - BGC failing on first time step
  - Ice initialization – bug
  - Glacial run off maps related to CISM
  - Various BGC files need to be put onto new grid
- Other components need lower BC files
  - Atmosphere PHIS & GWD forcing
  - Land surface file (no anthro?)
- Exploring using spun up CLM4.5 file

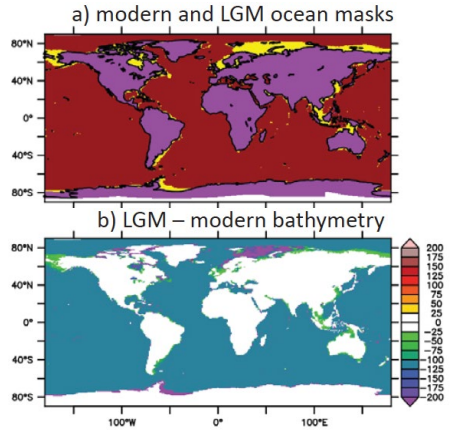
Last Millennium (LM) Teir 1 forcings and Status



- Transient 850 to 1849 + 1850 to 2015 CE
- Forcing (should be seamless with CMIP6, but need to check):
  - GHG's (ACOM)
  - Volcanic aerosols (ACOM)
  - Solar variations (ACOM)
  - Land cover & use (P.L. & E.K.)
  - Orbital (namelist)
- As soon as forcing files are assembled, begin an 850 control for I.C.'s

LGM Tier 1 Forcing & Boundary Conditions



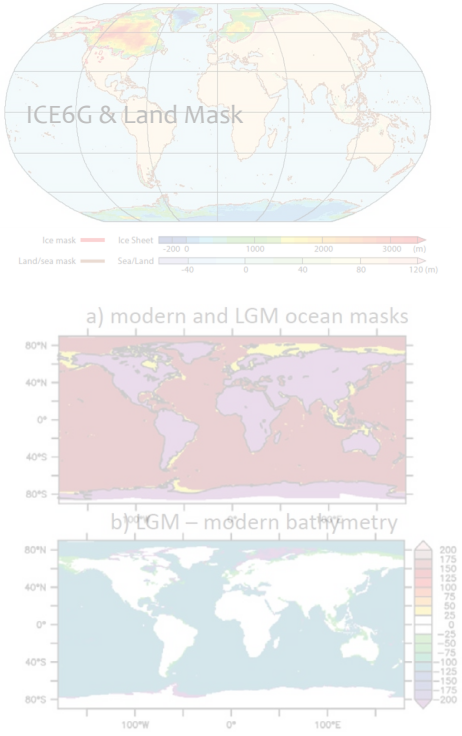


CO2: 190 ppm
CH4: 375 ppb
N20: 200 ppb
CFC: 0

Forcings:

- Ice sheet, land mask and bathymetry: ICE-6G_C, PMIP3, GLAC-1D
  - albedo, topography and circulation, small scale topographical variability, sea-level (-115 to -130m) and land/ocean masks
- GHG's lower than PI
- Ice sheets and GHG's contributed to a much colder climate
- Dust: interactive with LGM soil erodibility map available from PMIP
- Ocean BGC on to be consistent with PI DECK

LGM Tier 1 Status

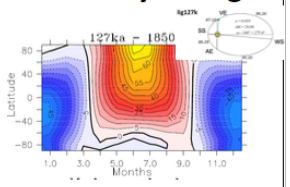
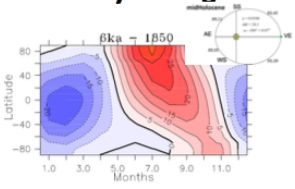


- On back burner while until other runs have started
- From past experience we know this is a difficult run to set up – similar complexity to Pliocene

CO2: 190 ppm
CH4: 375 ppb
N20: 200 ppb
CFC: 0

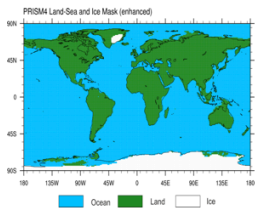
Extra slides

LIG127k & Mid-Holocene (MH) Overview

Five key periods The simulations can be run independently	**Last Interglacial ~127000 years ago**	**Mid-Holocene 6000 years ago**
		
Why?	a) Model evaluation for warm period, high sea-level stand b) Impacts of smaller ice-sheets/higher sea-level on climate	a) Comparison to paleodata for a warmer climate in the NH, with enhanced hydrological cycle (monsoons) b) Mean climate and variability
How?	. Orbital parameters . Greenhouse concentration of well-mixed greenhouse gases	. Orbital parameters . Atmospheric concentration of well-mixed greenhouse gases . Dust (if possible) . Interactive vegetation (if possible)

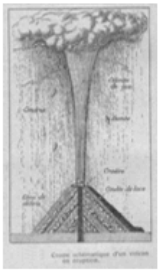
- Two most recent interglacial epochs
- Explore climate model response in a warmer climate and allow for comparison to paleo-environmental and paleoclimate data
- Test our understanding of interplay between radiative forcing and atmospheric circulation

Mid-Pliocene Warm Period Overview

Five key periods The simulations can be run independently	**Mid-Pliocene Warm Period ~3.2 milllion years ago** 
Why?	a) Evaluation of response to long term to CO2 forcing analogous to that of the modern? b) Impact of smaller ice-sheets, higher-sea-level
How?	. Ice-sheet and land-sea mask, topography (smaller ice-sheets) . Greenhouse concentration of well-mixed greenhouse gases

- Last time in Earth's history that CO_2 concentrations approached modern
- Study long term response to modern levels of CO_2 including
  - Ocean circulation
  - Arctic sea-ice
  - Modes of climate variability
  - Hydrological cycle and regional monsoon changes

Last Millennium (LM)

Five key periods The simulations can be run independently	**Last Millenium 850-1850 AD**  
Why?	a) observed variability (multi-decadal and longer time-scales) b) Internal variability vs. external forcing (volcanic, solar, land use) c) Longer-term perspective for detection and attribution studies
How?	· Solar variations · Volcanic aerosols · Well mixed greenhouse gases · Land use · Orbital parameters

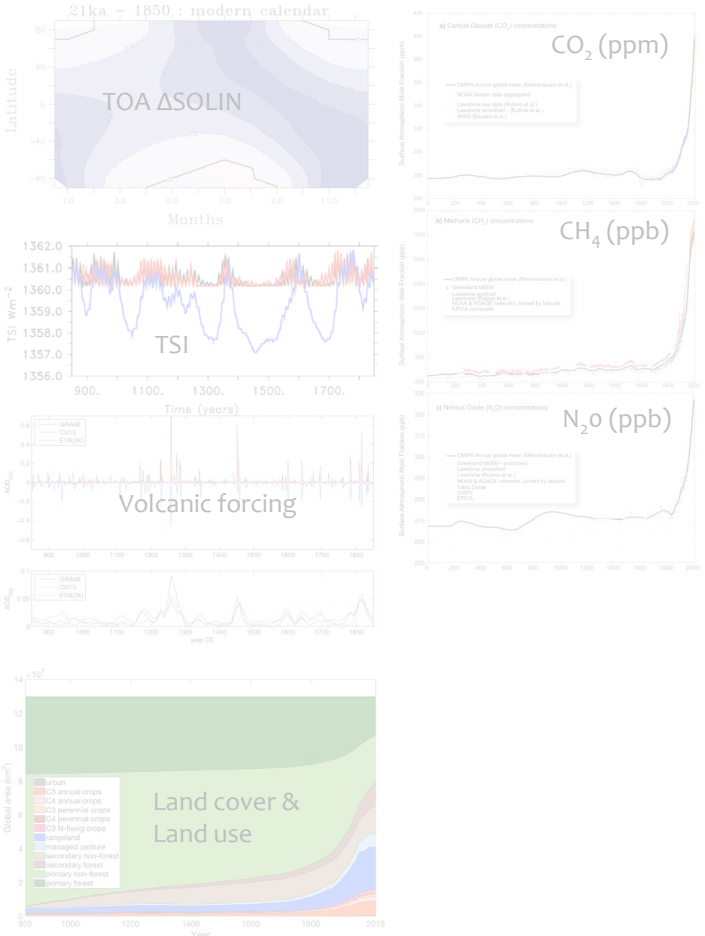
- Best documented interval of decadal to centennial climate changes, including the contrasting climate periods:
  - Medieval Climate Anomaly
  - Little Ice Age
- Investigate contributions of internal variability and external forced fluctuations
- Longer term perspective for detection and attribution studies

Last Glacial Maximum (LGM)

Five key periods The simulations can be run independently	**Last Glacial Maximum 21000 years ago** 
Why?	a) Comparison to paleodata for an extreme cold climate, b) Attempt to provide empirical constraints on global climate sensitivity.
How?	· Ice-sheet and land-sea mask · Greenhouse concentration of well-mixed greenhouse gases · Orbital parameters · Dust (if possible) · Interactive vegetation (if possible)

- Focus of PMIP since its inception – many problems associated with simulating extreme cold climate are documented
- Explore climate model response and sensitivity for an extreme cold climate – temperature response similar magnitude to project end of 21st century temperature response
- Allow a comparison of a simulated extreme cold climate to abundant paleodata

Last Millennium (LM) Status



- Assembling forcing files -
  - GHG's (ACOM)
  - Volcanic aerosols (ACOM)
  - Solar variations (ACOM)
  - Land cover & use (Peter Lawrence & Eric Kluzek)
  - Orbital - namelist
- Next steps: Start the 850 control for ~300 year spin up and IC's

PMIP's Main Objectives

Modelling past climates to:

- Understand mechanisms for documented past climate changes
- Test models for climates very different from today
- Compare past and future climates

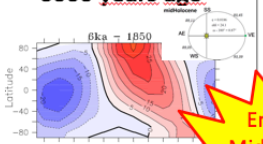
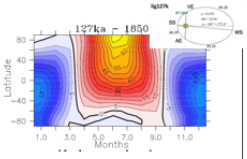
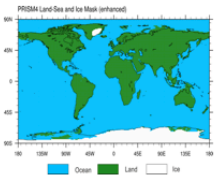
Papers, web links

➢ Overview	Kageyama et al., GMD
➢ Last Millennium	Jungclaus et al., GMD
➢ Interglacials	Otto-Bliesner et al.,
➢ LGM	Kageyama et al, GMD
➢ Mid- Pliocene	Haywood et al., CP 2016

PMIP4 index page:
https://pmip4.lsce.ipsl.fr/doku.php/index
Links:
Experimental design (associated data)
Events
Publications
Database
Participating groups

PMIP Experiments

Documentation and on-going discussions, please take part on the PMIP wiki: https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:cmip6:design:index

Five key periods The simulations can be run independently	**Last Millenium 850-1850 AD**	**Mid-Holocene 6000 years ago**	**Last Glacial Maximum 21000 years ago**	**Last Interglacial ~127000 years ago**	**Mid-Pliocene Warm Period ~3.2 milllion years ago**
		 Entry card: Mid-Holocene or LGM 			
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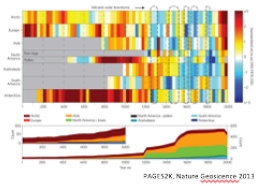
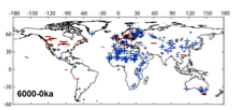
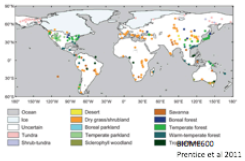
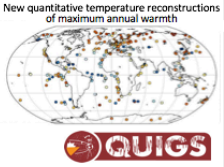
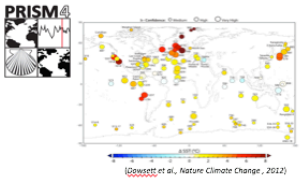
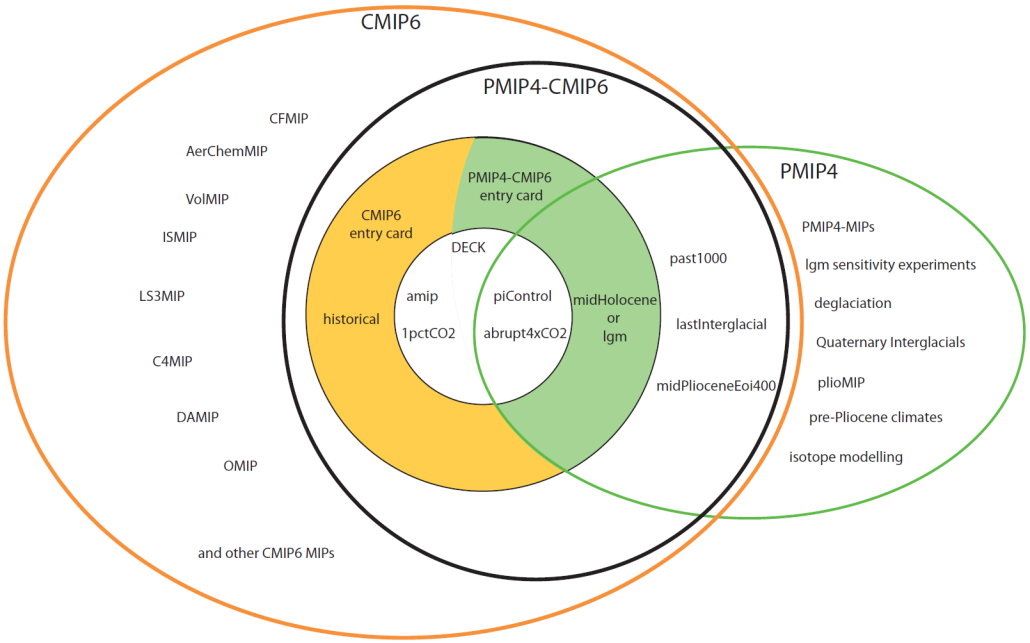
How?	. Solar variations . Volcanic aerosols . Well mixed greenhouse gases . Land use . Orbital parameters	. Orbital parameters . Atmospheric concentration of well-mixed greenhouse gases . Dust (if possible) . Interactive vegetation (if possible)	. Ice-sheet and land-sea mask . Greenhouse concentration of well-mixed greenhouse gases . Orbital parameters . Dust (if possible) . Interactive vegetation (if possible)	. Orbital parameters . Greenhouse concentration of well-mixed greenhouse gases	. Ice-sheet and land-sea mask, topography (smaller ice-sheets) . Greenhouse concentration of well-mixed greenhouse gases
Paleodata (examples)		PMIP systematic benchmarking data sets (examples)  			
Link with other PMIP activities	Long reference run for other PMIP runs + reference for sensitivity runs	Initial state for transient Holocene	Initial state for deglaciation	Initial state for transient last interglacial	Reference state for Mid-Pliocene experiments
Link with other CMIP6-MIPs	**VolMIP, DAMIP, LS3MIP**			ISMIP6	
	CFMIP, C4MIP, RFMIP, AerChemMIP, OMIP, ScenarioMIP				
Required output	**Cf. link with other MIPs + specific output to compare with climatic/environmental reconstructions : biogeochemical variables and isotopes if available**				

PMIP4 and CMIP6 with CESM2

- Our current plans are to do 5 tier 1 simulations, one for each time period – also some tier 2 & 3 experiments
- Use same model configuration as CMIP6: nominal 1 degree resolution in the atmosphere, ocean, land and sea-ice (f09_g1)
- Data (SVT) will be made available via ESG
- Start with CMIP6 DECK and make changes to B.C.'s and/or forcing
- If B.C.'s and/or forcing are unknown, leave unchanged
- Tier2 & tier3 experiments may be good opportunities for other groups to expand on the NCAR efforts

PMIP4-CMIP6 Experiments



Tier 1 experiments are within PMIP4-CMIP6

Tier 2 & 3 experiments are within PMIP4

Taking part in PMIP4-CMIP6:

It is mandatory to perform:

- the CMIP6 DECK
- the CMIP6 entry card (i.e. historical simulation)
- one of the PMIP4-CMIP6 entry cards: lgm or mid-Holocene

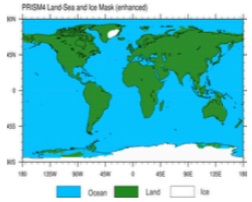
Taking part in PMIP4:

It is mandatory to perform:

- the CMIP6 piControl and abrupt4xCO2 runs
- one of the PMIP4-CMIP6 entry cards: lgm or mid-Holocene

This is the minimum set to make comparisons of past and future climates possible

Mid-Pliocene Warm Period (mPWP)

Five key periods The simulations can be run independently	**Mid-Pliocene Warm Period ~3.2 milllion years ago** 
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How?	. Ice-sheet and land-sea mask, topography (smaller ice-sheets) . Greenhouse concentration of well-mixed greenhouse gases

Tier 1 Forcing & Boundary Conditions LIG & MH

	1850 C.E. (DECK *piControl*)[1]	6ka (*midHolocene*)[2]	127ka (*lig127k*)[2]
Orbital parameters (2.1)	CMIP DECK *piControl*		
Eccentricity	0.0167643	0.018682	0.039378
Obliquity (degrees)	23.459277	24.105	24.040
Perihelion - 180	100.32687	0.87	275.41
Vernal equinox	Fixed to noon on March 21	Fixed to noon on March 21	Fixed to noon on March 21
Greenhouse gases (2.2)			
Carbon dioxide (ppm)	284.6	264.4	275
Methane (ppb)	808	597	685
Nitrous oxide (ppb)	273	262	255
Other GHG gases	CMIP DECK *piControl*	0	0
Solar constant (Wm^{-2}) (2.1) CMIP DECK *piControl*	TSI: 1360.747 SSI, ap if needed	Same as *piControl*	Same as *piControl*
Paleogeography (2.3)	Modern	Same as *piControl*	Same as *piControl*
Ice sheets (2.3)	Modern	Same as *piControl*	Same as *piControl*
Vegetation (2.5)	CMIP DECK *piControl*	Prescribed or interactive as in *piControl*	Prescribed or interactive as in *piControl*
Aerosols (2.6) Dust, Volcanic, etc.	CMIP DECK *piControl*	Prescribed or interactive as in *piControl*	Prescribed or interactive as in *piControl*

LGM surface types & ocean boundaries

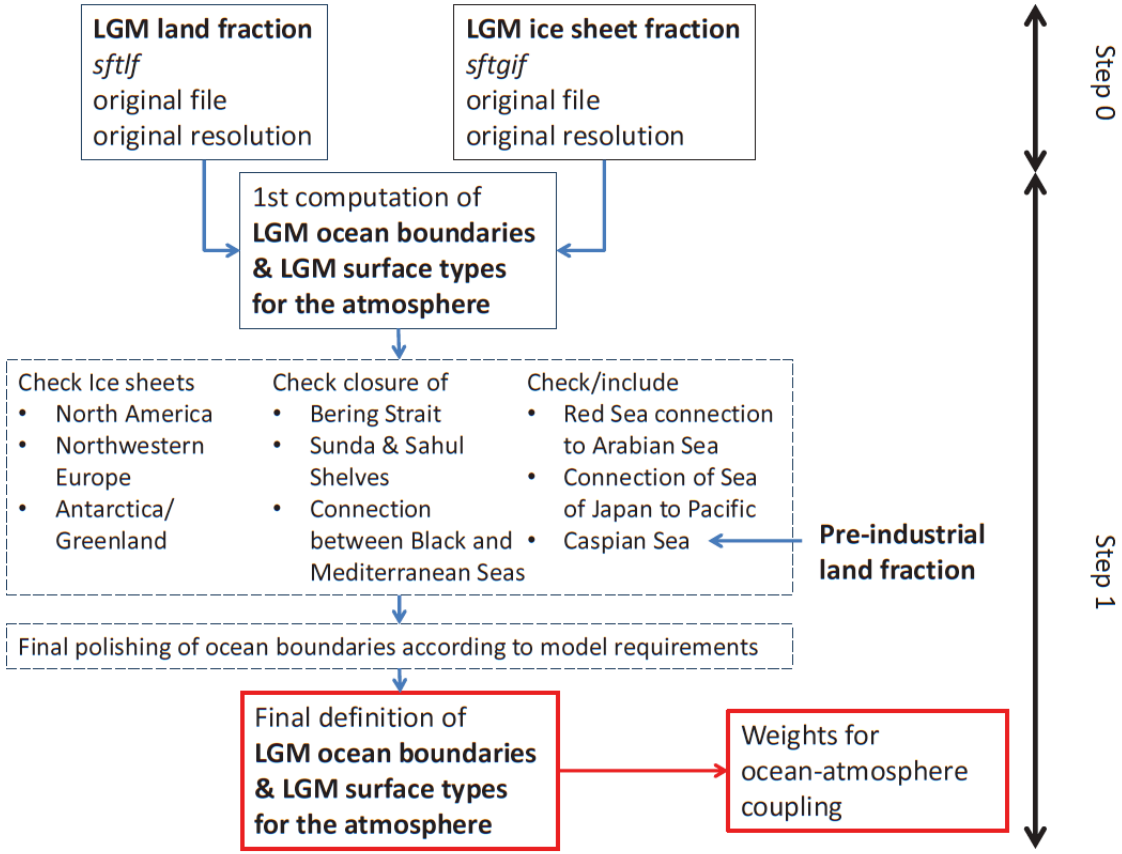

Figure 3: Summary of steps to be followed for the definition of the basic surface types for the atmosphere and ocean boundaries.

LGM orography

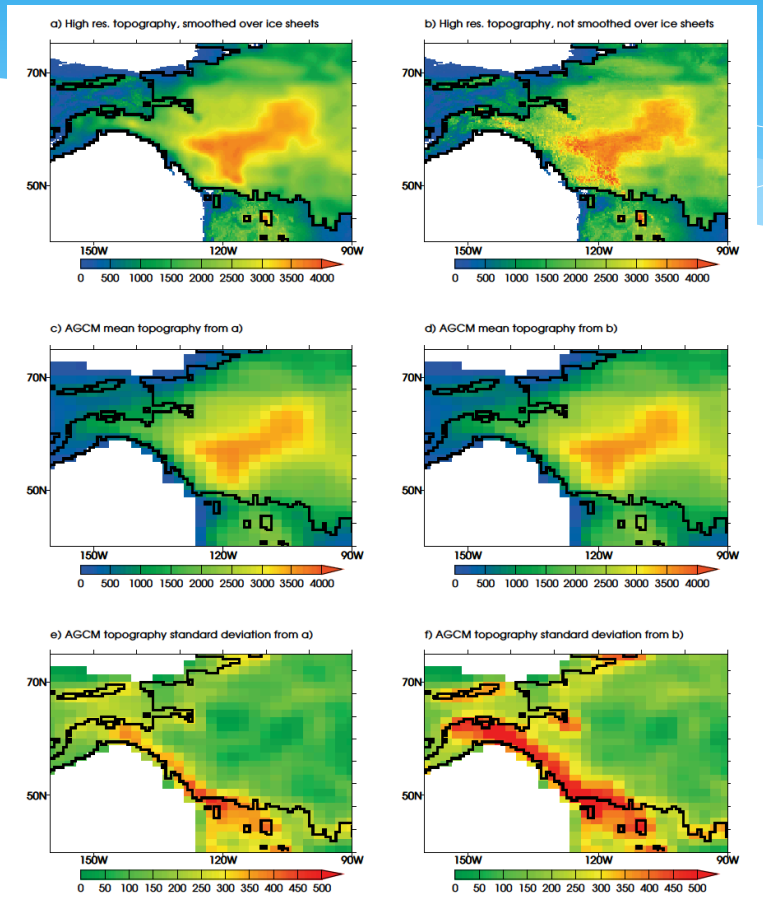

Figure 4: (a,b) High resolution orography obtained for northwestern North America, by adding the ICE_6G-C orography anomaly on the piControl orography used for the LMDZ model. (c,d) The corresponding mean altitude over each grid point. (e,f) Standard deviation of the altitude within each grid point, to represent one of the parameters used in the gravity wave drag parameterisations. a, c, e) without smoothing on the ice sheets; b, d, f) after smoothing on the ice sheets. The high resolution ocean mask is plotted in white and the land ice mask in outlined in black.

LGM

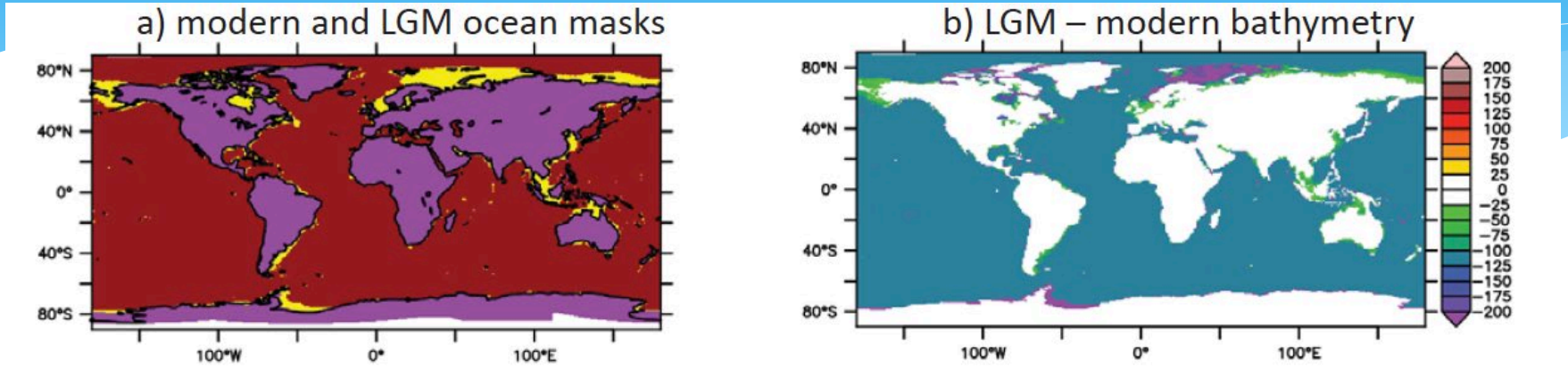

Figure 5: Checking the bathymetry and coastlines (example of figures obtained with the ferret script verif_all.jnl provided in the supplementary material). (a) modern and LGM ocean masks (purple: continents both in modern and LGM configurations, yellow: continent in LGM configuration, ocean in modern configuration, red: ocean both in modern and LGM configurations; (b) anomaly (LGM – modern) in bathymetry; (c, d, e) details for the Demark Strait/Iceland area; (c) modern bathymetry, (d) LGM bathymetry: (e) LGM – modern bathymetry anomaly.

CMIP6 organization

CMIP6 is organized around **3 key scientific questions**:

- How does the Earth System respond to forcing?
- What are the origins and consequences of systematic model biases?
- How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?

+ **7 WCRP grand challenges**

- Clouds, Circulation and Climate Sensitivity
- Changes in Cryosphere
- Climate Extremes
- Water Availability
- Regional Sea-level Rise
- Decadal Predictions
- Biogeochemical forcings and feedbacks

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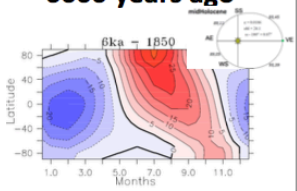
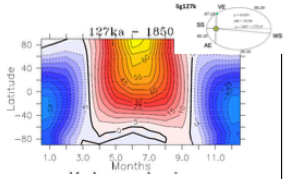
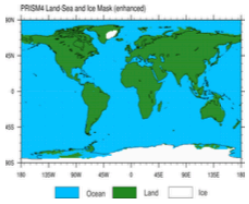
					
Why?	a) observed variability (multi-decadal and longer time-scales) b) Internal variability vs. external forcing (volcanic, solar, land use) c) Longer-term perspective for detection and attribution studies	a) Comparison to paleodata for a warmer climate in the NH, with enhanced hydrological cycle (monsoons) b) Mean climate and variability	a) Comparison to paleodata for an extreme cold climate, b) Attempt to provide empirical constraints on global climate sensitivity.	a) Model evaluation for warm period, high sea-level stand b) Impacts of smaller ice-sheets/higher sea-level on climate	a) Evaluation of response to long term to CO2 forcing analogous to that of the modern? b) Impact of smaller ice-sheets, higher-sea-level
How?	· Solar variations · Volcanic aerosols · Well mixed greenhouse gases · Land use · Orbital parameters	· Orbital parameters · Atmospheric concentration of well-mixed greenhouse gases · Dust (if possible) · Interactive vegetation (if possible)	· Ice-sheet and land-sea mask · Greenhouse concentration of well-mixed greenhouse gases · Orbital parameters · Dust (if possible) · Interactive vegetation (if possible)	· Orbital parameters · Greenhouse concentration of well-mixed greenhouse gases	· Ice-sheet and land-sea mask, topography (smaller ice-sheets) · Greenhouse concentration of well-mixed greenhouse gases

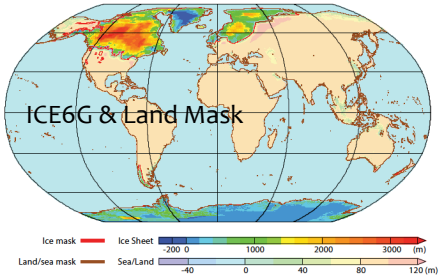
Five key periods The simulations can be run independently
Why?
How?

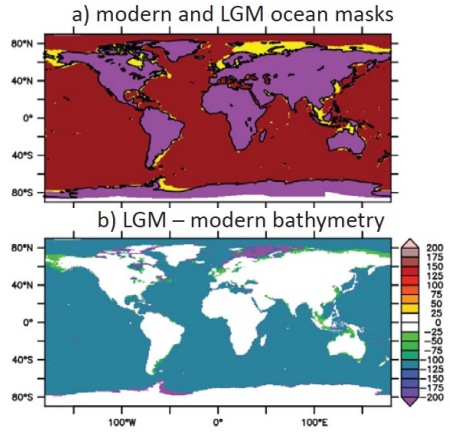
LIG127k & MH Tier 2 & 3 Forcing & Boundary Conditions

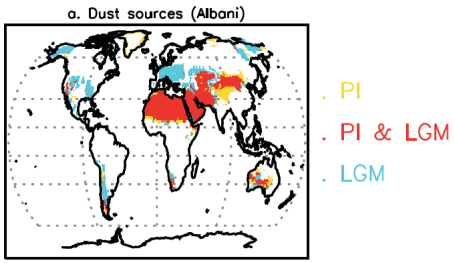
PMIP4-CMIP6 Tier 1 simulations		
	Entry card: *midHolocene*	*lig127k*
PMIP4-CMIP6 sensitivity experiments: Tier 2 simulations		
Experiments	Holocene	Last Interglacial
Orbital forcing and trace gases (3.1)	*hol9.5k*: Early Holocene • Orbital: 9.5 ka • Ice sheet: ICE-6G or GLAC-1D reconstruction[1] • GHG: same as for the deglaciation experiment[1]	*lig116k*: Glacial inception • Orbital: 116 ka • CO_2: 280, 240 ppm • Other forcings and boundary conditions: as for *lig127k*
Sensitivity to vegetation (3.2)	*midHolocene_veg* • prescribed boreal forests in Arctic and shrub/savanna over Sahara • vegetation reconstructions[2] • *midHolocene* equilibrium veg with dgvm in *piControl*	*lig127k_veg* • prescribed boreal forests in Arctic and shrub/savanna over Sahara
Sensitivity to Ice-Sheet (3.3)		*lig127k_ais* and *lig127k_gris* • Antarctic ice sheet at its minimum LIG extent • Greenland ice sheet at its minimum LIG extent
Test to freshwater flux (3.4)	*hol8.2k:* 8.2 ka event • Orbital: 8.2 ka • Ice sheet: ICE-6G or GLAC-1D reconstruction[1] • GHG: same as for the deglaciation experiment[1] • Initial state: 8.5 ka simulation • Meltwater flux of 2.5 Sv for one year added to the Labrador Sea plus 0.05 Sv for 500 years • Run length: preferably until evidence for the recovery of the AMOC.	*lig127k_H11*: Heinrich 11 meltwater event • Meltwater flux of 0.2 Sv to the North Atlantic between 50 and 70°N for 1000 years • Other forcings and boundary conditions: as for *lig127k* • Initial state: *lig127k* simulation
PMIP4-CMIP6 sensitivity experiments: Tier 3 simulations		
Transient simulations (3.5) (Note : Exploratory and flexible set up)	*past0k*: transient Holocene • Transient evolution in Earth's orbit and trace gases • Other boundary conditions (land use, solar, volcanism) may be considered by some groups • Initial state: *midHolocene*	*lig128to122k*: transient LIG • Transient evolution in Earth's orbit and trace gases • Other boundary conditions (ice sheets) may be considered by some groups • Initial state: *last127k*

- There are opportunities for groups interested in performing CESM2 Tier2 and Tier3 simulations
- Tier2 sensitivity experiments:
  - Orbital and GHG
  - Vegetation
  - Ice-sheet (lig127ka)
  - Freshwater flux
- Tier3 transient simulations
  - orbital & trace gases
  - possibly B.C.'s
  - I.C.'s MH and lig127ka

LGM Sensitivity experiments







CO2: 190 ppm
CH4: 375 ppb
N20: 200 ppb
CFC: 0

Tier 2&3(?) sensitivity experiments:

- Dust & Vegetation –
- Single forcing experiments
  - GHG's same as PI
  - Ice extent & height same as PI
  - GHG's & Ice extent & height same as PI

Last Millennium (LM) Tier 1-3 Description

Table 1:

Category	Experiment	Simulation years (single realisation)	Short name	extension
tier-1	PMIP4-CMIP6 last millennium experiment using default forcings	1000 (850 – 1849 CE)	past1000	r<N>i1p1f1
"	CMIP6 historical experiment initialized from past1000	165 (1850 -2014 CE)	historical	r<N>i<M>p1f1
tier-2	PMIP4 last millennium experiment using alternative or single forcings	1000 (850 – 1849 CE)	past1000	r<N>i1p1f<L>
"	CMIP6 historical experiment initialized from past1000	165 (1850-2014 CE)	historical	r<N>i<M>p1f1
tier-3	PMIP4 last two millennia experiment	1850 (1 – 1849 CE)	past2k	r<N>i1p1f<L>
"	CMIP6 historical experiment initialized from past2k	165 (1850-2014 CE)	historical	r<N>i<M>p1f1
"	PMIP4 volcanic cluster ensemble experiment (in cooperation with VolMIP)	60 (1790-1849)	volc_cluster_mill	r[1..3]i1p1f<L>
"	PMIP4 last millennium experiment with interactive carbon cycle	1000	esmPast1000	r<N>i1p1f<L>
"	PMIP4 historical experiment with interactive carbon cycle initialized from esmPast1000	165	esmHistorical	r<N>i<M>p1f1

Alternative single forcing

Last two millennia

Volcanic cluster ensemble

LM with interactive carbon cycle

Table 1: List of experiments. In the right column the extension defines the ensemble member by the quad N, M, P, L of integer indices for "realization" (r), "initialization" (i), "perturbed physics" (p), and "forcing (f). Modelling groups need to document the choices, in particular for initialization and forcing.