PMIP3/CMIP5 Last Millennium Model Simulation Effort

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Outline

• Background to the last millennium simulations in IPCC and PMIP
• Overview of experimental design for PMIP3 – CMIP5
• PMIP3 – CMIP5 simulations
• Other modeling efforts
• Next steps: CMIP6 and next PMIP
- Last Millennium (LM) simulations were an ‘ensemble of opportunity

Table 6.2. Climate model simulations shown in Figure 6.13.

<table>
<thead>
<tr>
<th>Series</th>
<th>Model</th>
<th>Model type</th>
<th>Forcingsb</th>
<th>Reference</th>
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<tbody>
<tr>
<td>GSZ2003</td>
<td>ECHO-G</td>
<td>GCM</td>
<td>SV -G - - - -</td>
<td>González-Rouco et al., 2003</td>
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<td>TBC..2006</td>
<td>HadCM3</td>
<td>GCM</td>
<td>SVOG -ALZ</td>
<td>Tett et al., 2007</td>
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<td>AJS..2006</td>
<td>NCAR CSM</td>
<td>GCM</td>
<td>SV -G -A -Z</td>
<td>Mann et al., 2005b</td>
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<td>BLC..2002</td>
<td>MoBiDiC</td>
<td>EMIC</td>
<td>SV -G -AL -</td>
<td>Bertrand et al., 2002b</td>
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<td>EBMc</td>
<td>SV -G -A -</td>
<td>Crowley et al., 2003</td>
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<td>GRT..2005</td>
<td>ECBilt-CLIO</td>
<td>EMIC</td>
<td>SV -G -A -</td>
<td>Goosse et al., 2005b</td>
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<td>B..03-14C</td>
<td>Climber2</td>
<td>EMIC (solar from $^{14}$C)</td>
<td>SV -C -L -</td>
<td>Bauer et al., 2003</td>
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<td>B..03-10Be</td>
<td>Climber2</td>
<td>EMIC (solar from $^{10}$Be)</td>
<td>SV -C -L -</td>
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<td>GBZ..2006</td>
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<td>GCM</td>
<td>SV -G - - - -</td>
<td>González-Rouco et al., 2006</td>
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Notes:

- Models: ECHO-G = ECHAM4 atmospheric GCM/HOPE-G ocean GCM, MAGICC = Model for the Assessment of Greenhouse-gas Induced Climate Change, HadCM3 = Hadley Centre Coupled Model 3; NCAR CSM = National Center for Atmospheric Research Climate System Model, MoBiDiC = Modèle Bidimensionnel du Climat, ECBilt-CLIO = ECBilt-Coupled Large-scale Ice Ocean, Bern CC = Bern Carbon Cycle-Climate Model, CLIMBER2 = Climate Biosphere Model 2, ECHAM4/OPYC3 = ECHAM4 atmospheric GCM/Ocean Isopycnal GCM 3.
- Forcings: S = solar, V = volcanic, O = orbital, G = well-mixed greenhouse gases, C = CO$_2$ but not other greenhouse gases, A = tropospheric sulphate aerosol, L = land use change, Z = tropospheric and/or stratospheric ozone changes and/or halocarbons.
- EBM = Energy Balance Model.
IPCC AR4 LM radiative forcings – simulated NH temperature anomalies

(a) Volcanic forcing

(b) Solar irradiance forcing

(c) All other forcings

(d) Simulated NH temperature

[Graph showing various forcing and temperature data over time]
IPCC AR4 LM – sensitivity to weak or strong solar irradiance variations
CMIP5 and PMIP3 —> IPCC AR5 (2013)

- New set of simulations that provide climate information and knowledge of particular relevance to future assessments of climate science

Last Millennium (850-1850) – officially CMIP5 and PMIP3
- Evaluate the ability of models to capture observed variability on multidecadal and longer time-scales.
- Determine fractions of the variability attributable to “external” forcing and purely internal variability.
- Provides a longer-term perspective for detection and attribution studies.

CMIP5: Same model – same resolution as projections; simulations available in CMIP5 database

PMIP3 in charge of experimental design

Taylor et al., BAMS (2012)
• Background to the last millennium simulations in IPCC and PMIP

• **Overview of experimental design for PMIP3 – CMIP5**

• PMIP3 – CMIP5 simulations

• Other modeling efforts

• Next steps: CMIP6 and next PMIP
### Last Millennium experimental design (850-1850AD)

<table>
<thead>
<tr>
<th>Feature</th>
<th>PMIP3 recommendation</th>
<th>Alternate solution</th>
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<tr>
<td>Orbital parameters</td>
<td>Annually varying</td>
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<td>Date of vernal equinox</td>
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<tr>
<td>Well-mixed greenhouse gases</td>
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<td>Volcanic aerosols</td>
<td>Two reconstructions (AOD, effective radius):</td>
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<td></td>
<td>GRA (Gao et al., 2008)</td>
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<td>CEA (Crowley et al., 2008)</td>
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<tr>
<td>Solar irradiance</td>
<td>Multiple reconstructions (including spectral variations):</td>
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<td>WLS (back/noback)* (Wang et al., 2005)</td>
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<td>1610–2005</td>
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<td>VSK (Vieira et al., 2010)</td>
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<td>850–1850 and merge to WLS (back)</td>
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<td>SBF (Steinhilber et al., 2009)</td>
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<td>MEA (back/noback) (Muscheler et al., 2007)</td>
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<td>DB (back/noback) (Delaygue and Bard, 2010)</td>
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<td>850–1610 and merge to WLS (back/noback)</td>
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<td>Tropospheric aerosols</td>
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<td>No changes from PI-control</td>
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<tr>
<td>Topography and coastlines</td>
<td>Same as in PI-control</td>
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</tbody>
</table>
Greenhouse gas forcing – CO$_2$, CH$_4$, and N$_2$O

- **CO$_2$ and CH$_4$:** Law Dome Ice data.
- **N$_2$O:** spline fit through various ice cores (DomeC, GRIP, EUROCORE, H15)
- **Industrial period** trace gases are linked with splines with ice core data

Schmidt et al., GMD (2011)
Greenhouse gas forcing – into historical period

GHG Concentrations 850-1850 CE

- CO₂ (ppm)
- CH₄ (ppb)
- N₂O (ppb)

Year

Landrum et al., JClimate (2013)
Orbital forcing – two options

- Calculated in model using Berger
- Specified from table on web site
Land use boundary conditions

Global Cropland and Pasture Area

Global Combined Cropland and Pasture

Schmidt et al., GMD (2011, 2013)
Pasture and Crops at 1500 from Hurtt vs Pongratz

**Pasture**

1500 Pasture from Hurtt et al (2006)

1500 Pasture from Pongratz (2009)

**Crop**

1500 Crop from Hurtt et al (2006)

1500 Crop from Pongratz (2009)
Volcanic forcing – two options – many implementations

- Crowley & Unterman (CEA) and Gao-Robock-Ammann(GRA) based on multiple ice cores: Antarctic and Greenland

- Combined with atmospheric modeling of aerosol distribution and optical depth
Solar irradiance variations – many options

- ΔTSI at Maunder Minimum: 0.04 to 0.1% (RF -0.1 to -0.23 W m\(^{-2}\))
- 11-year solar cycle (synthetic before 1610 AD)
- Scaling of spectral variations to TSI
- Solar-related ozone changes

Shapiro et al., 2011

~ - 6 W/m\(^2\)
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• Next steps: CMIP6 and next PMIP
## PMIP3 – CMIP5 Last Millennium simulations

<table>
<thead>
<tr>
<th>Institute</th>
<th>Country</th>
<th>Model cycle</th>
<th>Past1000 (1000 years)</th>
<th>Ocm</th>
<th>Model ID</th>
<th>Ensemble</th>
<th>Orti parameters</th>
<th>Vernal equinox</th>
<th>GHG</th>
<th>Volcanic aerosols</th>
<th>Solar irradiance</th>
<th>Ozone</th>
<th>Tropos aerosols</th>
<th>Land Use</th>
<th>Land Cover</th>
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<td>Yes</td>
<td>128x64 x L26</td>
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<td>GRA</td>
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<td>GRA</td>
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<td>VSK</td>
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<td>Same as pControl before 1850, as historical afterward</td>
<td>PEA</td>
<td></td>
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</tr>
</tbody>
</table>

1. LOVECLIM1-2: Changes in sulfate aerosol load are taken into account through modifications in the surface albedo (Charlon et al., 1991)
2. MPI-CGCM3: RCP scenario in 1765 other than biomass burning. Biomass burning in 1850
3. MPI-ESM-P: In the case of Oslo we construct the data using monthly data from the ACC/SPARC climatology recommended for CMIP5 averaged over the years 1850-1860, and add solar dependence by using regression coefficients calculated from the full ACC/SPARC climatology together with 1850 solar flux from the VSK data. For details, see e.g., Schmidt et al., 2005, The response of the middle atmosphere to anthropogenic and natural forcing in MIROC-ESM, accepted for publication, Journal of Advances in Modeling Earth Systems
4. GISS-E2-R: Due to a conversion factor error in the specification, the forcing is twice as large as it should be

http://pmip3.lse.ipsl.fr/
IPCC AR5 LM: Simulated NH temperatures

(a) Reconstructed (grey) and simulated (red/blue) NH temperature

(b) NH temp (950-1250) minus (1450-1850)

(c) NH temp (1900-2000) minus (1450-1850)
Response = f(forcing, implementation, climate “sensitivity”, internal variability)
IPCC AR5 LM – sensitivity to weak or strong solar irradiance variations
IPCC AR5 LM – sensitivity to weak or strong solar irradiance variations
IPCC AR5 LM – Spread of responses to volcanic and solar forcing

![Graphs showing volcanic and solar forcing effects](image-url)
Response $= f(\text{forcing}, \text{implementation}, \text{climate sensitivity}, \text{internal variability})$

- Forcing: CEA, GRA ... satellite measurements

CCSM4 (GRA-like)

Satellite

Courtesy of A. Conley et al.
Response = f(forcing, implementation, climate sensitivity, internal variability)

- Implementation: alter TSI, single size aerosols in layers above tropopause, multiple size distributions
Response = f(forcing, implementation, climate “sensitivity”, internal variability)

• Climate “sensitivity”

1258 eruption
CCSM4-CAM4: 2.7° C
CESM1-CAM5: 1.4° C
Response = f(forcing, implementation, climate “sensitivity”, internal variability)

• Internal variability

Deser et al., NCC (2012)
IPCC AR5 Historical and LM – Power spectrum

(b) Power spectra of 1901-2010 surface temperature

(c) Power spectra of last millennium surface temperature

Legend:
- Reconstructed
- Pre-PMIP3
- BCC-CSM1.1
- CCSM4
- CSIRO-Mk3.6.0
- GISS-E2-R
- HadCM3
- HadGEM2-ES
- INM-CM4
- IPSL-CM5A-LR
- IPSL-CM5A-MR
- MIROC5
- MIROC-ESM
- MIROC-ESM-CHEM
- MPI-ESM-LR
- MRCGCM3
- NorESM1-M
- NorESM1-ME

Power Spectral Density (°C² y⁻¹)

Period (Years)

% of spectral density accumulated over 50 yrs
IPCC AR5 LM – Hydrologic changes

(f) China: Huangye (f1), Wanxian (f2) caves

(i) Peru: Cascayunga (i1) cave, Pumacocha (i2) lake

(c) Proxy data locations

IPCC AR5 – Chapter 5 (2013)
Correlation of past 1000 ensemble members with NH temperature

Bothe et al. (2013), Climate of the Past Discussions, 9, 3789-3824.
Evolution of zonal-mean temperature within the past 1000 ensemble

• Individual ensemble members generally simulate relatively warm conditions, punctuated by short, volcanically-driven cool periods.

• Long-term cooling trend becomes more apparent in the ensemble mean.

Bothe et al. (2013), Climate of the Past Discussions, 9, 3789-3824.
Stability of teleconnections in the past 1000 ensemble

Coats et al. (2013), Geophysical Research Letters, 40, 4927-4932.
Spectrum of hydroclimate variability in the past 1000 ensemble

- The spectra of the North American PDSI for the past 1000 ensemble members are essentially indistinguishable from an AR(1) process.

Ault et al. (2013), Journal of Climate, 26, 5863-5878.
Variability in the annular modes within the past 1000 ensemble

- The temporal evolution of each of the three modes appears to be incoherent between different members of the ensemble.

- At the 5% probability level, the null hypothesis that the evolution is dominated by internal variability cannot be rejected.

Atlantic Multidecadal Variability within the past1000 ensemble

Zanchettin et al. (in press), Climate Dynamics.
Feedbacks in the past 1000 ensemble

LIA (1450-1500) – MCA (1150-1200), Annual, Multi-Model

Flavio Lehner, PhD thesis
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Pre-PMIP3 simulations analysed in the IPCC AR5 WG1 report

<table>
<thead>
<tr>
<th>Model</th>
<th>(No. runs) Period</th>
<th>Forcings(^a)</th>
<th>Reference</th>
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<tbody>
<tr>
<td><strong>Pre PMIP3/CMIP5 Experiments</strong></td>
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<tr>
<td>CCSM3</td>
<td>(1x) 1000–2000</td>
<td>(SS^{11}, V^{22}, G^{30,31,35})</td>
<td>Hofer et al. (2011)</td>
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<td>(4x) 1500–2000</td>
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<tr>
<td>CNRM-CM3.3</td>
<td>(1x) 1001–1999</td>
<td>(SS^{11}, V^{21}, G^{30,34,35}, A^{44}, L^{54})</td>
<td>Swingedouw et al. (2011)</td>
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<td>CSIRO-MK3L-1-2</td>
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<td>(SW^{14})</td>
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<td>(3x) 1–2001</td>
<td>(SW^{14}, G^{34}, O^{70})</td>
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<td>(3x) 501–2001</td>
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<td>ECHAM4/OPYC</td>
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<td>(3x) 800–2005</td>
<td>(SS^{10}, V^{25}, G^{34,39}, A^{40}, L^{53}, O^{61})</td>
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<td>ECHO-G</td>
<td>(1x) 1000–1990</td>
<td>(SS^{11}, V^{20}, G^{31,36,37})</td>
<td>González-Rouco et al. (2003) (^b)</td>
</tr>
<tr>
<td></td>
<td>(1x) 1000–1990</td>
<td>(SS^{11}, V^{20}, G^{31,36,37})</td>
<td>Gonzalez-Rouco et al. (2006)</td>
</tr>
<tr>
<td>HadCM3</td>
<td>(1x) 1492–1999</td>
<td>(SS^{11}, V^{23}, G^{32}, A^{43}, L^{50,54,55}, O^{60})</td>
<td>Tett et al. (2007)</td>
</tr>
<tr>
<td>IPSLCM4</td>
<td>(1x) 1001–2000</td>
<td>(SS^{11}, G^{30,34,35}, A^{44}, O^{63})</td>
<td>Servonnat et al. (2010)</td>
</tr>
<tr>
<td>FGOALS-gl</td>
<td>(1x) 1000–1999</td>
<td>(SS^{11}, V^{20}, G^{30,31,35})</td>
<td>Zhou et al. (2011)(^c)</td>
</tr>
</tbody>
</table>
MCA-LIA transition in the pre-PMIP3 simulations

- For each simulation, the temperature change can be directly related to the change in radiative forcing.

- Simulations that use solar forcing with weaker changes in amplitude exhibit weaker temperature changes.

- Intra-model variability can be larger than inter-model differences, suggesting a major role of internal variability.

Fernandez-Donado et al. (2013), Climate of the Past, 9, 393-421.
Estimating transient climate response using the pre-PMIP3 simulations

- The simulations are generally strongly correlated with external forcing.

- The relationship between the forcing and the temperature response allows a “Last Millennium Transient Climate Response” to be calculated. This describes the instantaneous response to external forcing.

- LMTCR is smaller than ECS, but the range overlaps with the range of TCR.

- Intra-model variability can again be large.

Fernandez-Donado et al. (2013), Climate of the Past, 9, 393-421.
Adding external forcings sequentially

- Individual forcings are progressively added to an ensemble of climate model simulations.

- Orbital forcing by itself gives no long-term trend. The addition of GHGs causes the model to reproduce the observed warming since the 19th century.

- Solar forcing introduces weak centennial-scale variability.

- Volcanic forcing introduces stronger decadal-scale variability.

*Phipps et al. (2013), Journal of Climate, 26, 6915-6936.*
The role of the carbon cycle

- MPI Earth System Model with fully interactive carbon cycle. Two different ensembles using different reconstructions of solar forcing.

- When driven with all natural and anthropogenic forcings, the CO2 concentration is relatively stable over the pre-industrial era.

- Individual forcings have competing effects on the carbon budget.

Fig. 6. CO2 concentrations (31-year running mean) from (a) ensembles E1 (red) and E2 (blue) in comparison with a compilation of ice core reconstructions (grey shading, see Appendix A). Black horizontal lines denote the control experiment mean and its 5th–95th percentile range, (b) the respective CO2 concentrations from the experiments forced by one single component, i.e. standard solar forcing (red), strong solar forcing (blue), land-cover change (green), and volcanic aerosols (purple).

Jungclaus et al. (2010), Climate of the Past, 6, 723-737.
Application of individual forcings

Figure 1. Anomaly in annual and seasonal mean surface temperature (°C) in the Arctic (north of 64°) over the last 1150 years as simulated by LOVECLIM in response to different forcings. Each time series represents the mean of an ensemble of ten simulations. The annual mean is displayed in black, the winter (JFM) in blue, the spring (AMJ) in green, the summer (JAS) in yellow, and the autumn (OND) in red. The reference period is AD 1850–1980. A 31-year running mean has been applied to the time series. Colour figure available online.

Contribution of individual forcings to regional temperature trends

Table S4 | Simulated annual mean temperature trends related to individual forcings in LOVECLIM from 900-1850 CE (°C ka⁻¹).

<table>
<thead>
<tr>
<th>Region</th>
<th>Orbital</th>
<th>Solar</th>
<th>Volcanic</th>
<th>Land use</th>
<th>GHG</th>
<th>All forcings</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic</td>
<td>-0.12</td>
<td>-0.11</td>
<td>-0.15</td>
<td>-0.10</td>
<td>0.04</td>
<td>-0.42</td>
<td>0.07</td>
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<tr>
<td>Europe</td>
<td>-0.05</td>
<td>-0.07</td>
<td>-0.11</td>
<td>-0.02</td>
<td>0.04</td>
<td>-0.23</td>
<td>0.00</td>
</tr>
<tr>
<td>Asia</td>
<td>0.01</td>
<td>-0.05</td>
<td>-0.11</td>
<td>-0.13</td>
<td>0.03</td>
<td>-0.23</td>
<td>0.01</td>
</tr>
<tr>
<td>North America</td>
<td>-0.01</td>
<td>-0.12</td>
<td>-0.08</td>
<td>-0.05</td>
<td>0.08</td>
<td>-0.21</td>
<td>0.00</td>
</tr>
<tr>
<td>Australia</td>
<td>0.04</td>
<td>-0.03</td>
<td>-0.05</td>
<td>-0.03</td>
<td>0.02</td>
<td>-0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>South America</td>
<td>0.05</td>
<td>-0.02</td>
<td>-0.04</td>
<td>-0.03</td>
<td>0.01</td>
<td>-0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Antarctica</td>
<td>-0.05</td>
<td>-0.02</td>
<td>-0.07</td>
<td>-0.05</td>
<td>0.06</td>
<td>-0.20</td>
<td>0.02</td>
</tr>
<tr>
<td>Global (land)</td>
<td>-0.01</td>
<td>-0.05</td>
<td>-0.09</td>
<td>-0.05</td>
<td>0.03</td>
<td>-0.17</td>
<td>0.00</td>
</tr>
</tbody>
</table>

PAGES 2k Consortium (2013), Nature Geoscience, 6, 339-346.
Next Steps: PMIP and CMIP6

WCRP Grand Challenges

- Clouds, circulation and climate sensitivity
- Changes in cryosphere
- Climate extremes
- Regional climate information
- Regional sea-level rise
- Water availability

PMIP6: Experimental design

- LM Ensembles?
- LM single forcing experiments?
- 850-1850AD? 850-2013AD? 0-2013AD?
- Ensembles for LM active periods of volcanic eruptions; solar min/max?