Northern High-latitude Climate Response to Mid-Holocene Insolation: Model-data Comparisons

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BBCC project: Holocene climate variability over Scandinavia

1. A number of reconstructions are available for Holocene over high latitudes.

2. The mid-Holocene is a key period of interest for the Palaeoclimate Modeling Intercomparison Project (PMIP), the different types of model simulations are available for studying.

3. To increase the understanding of the climate change of the mid-Holocene through integrating proxy data analysis and global climate modelling.
Holocene temperature changes

IPCC AR4
Outline

1 Evidence of 6 ka climate change in reconstructions
2 Climate response in PMIP1 and PMIP2
3 Model-data comparison with an optimal selection method
4 The feedback mechanism
5 Application of stable water isotope modeling in palaeoclimate
Climate reconstructions from proxy data

The collected reconstructions have records both in mid-Holocene (~6000yrs BP) and pre-industrial (~1750)

Number of reconstructions: 72
Number of sites: 61
Summer temperature: 48
Winter temperature: 7
Annual mean temperature: 16
### Type of proxy data used

#### Terrestrial, 65
- Pollen, 40
- Chironomids, 12
- Diatoms, 6
- Borehole, 2
- Ice-cores, 1
- Tree-rings, 1
- Speleothems, 2
- Density of sediment, 1

#### Marine, 7
- Foraminifera, 3
- Diatoms, 2
- Alkenones, 1
- Dinocysts, 1
Uncertainty of the reconstructions

1. Statistical calibration uncertainty, $\sigma_c$
2. Internal variability uncertainty, $\sigma_v$

$$\sigma_{com}^2 = \sigma_c^2 + \sigma_v^2$$

Calibration error $\sigma_c$

The frequency distribution of calibration $\sigma_c$ and internal variability $\sigma_v$
Temperature change in reconstructions (6ka-0ka)

Annual mean T(16 data)  
Averaged difference  
2.1°C±0.72°C

Summer T(48 data)  
Averaged difference  
1.0°C±0.96°C

Winter T(6 data)  
Averaged difference  
1.8°C±1.7°C
Motivation of PMIP

* Study the role of climate feedbacks
  * Atmosphere --------PMIP1
  * Ocean, sea-ice-----PMIP2-OA
  * Vegetation--------PMIP2-OAV

* Model evaluation
  * Testing climate models
    * Model-model comparison
    * Model-data comparison

* Key periods:
  * LGM (21 ka)
  * Mid-Holocene (6ka)
  * Pre-industrial (0ka) ----Control run
  * Last Millennium (PMIP3)
### Boundary Conditions for Mid-Holocene (6ka) and Pre-Industrial (0ka)

**Ice sheets, topography, trace gases and Earth’s orbital parameters**

<table>
<thead>
<tr>
<th></th>
<th>Ice Sheets</th>
<th>Topography Coastlines</th>
<th>CO2 (ppmv)</th>
<th>CH4 (ppbv)</th>
<th>NO2 (ppbv)</th>
<th>Eccentricity</th>
<th>Obliquity(°)</th>
<th>Angular precession(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0ka</strong></td>
<td>Modern</td>
<td>Modern</td>
<td>280</td>
<td>760</td>
<td>270</td>
<td>0.0167724</td>
<td>23.446</td>
<td>102.04</td>
</tr>
<tr>
<td><strong>6ka</strong></td>
<td>Same as 0k</td>
<td>Same as 0k</td>
<td>280</td>
<td>650</td>
<td>270</td>
<td>0.018682</td>
<td>24.105</td>
<td>0.87</td>
</tr>
</tbody>
</table>
Insolation forcing (Change between 6ka and 0ka)

Change in incoming solar radiation at the top of the atmosphere (6Ka-0Ka)
The insolation change at Northern high latitude (60°N-90°N)

Summer: 23.5 W/m²
Winter: -2.3 W/m²
Annual: 2.9 W/m²

60-90°N average
### PMIP models used in comparison

#### PMIP1-Atmosphere only model, fixed SST

**19 models:**
- bmrc, ccc2.0, ccm3, ccsr1, climber2, cnrm2, csiro, echam3, gen2, gfdl,
- giss-iip, lmcelmd4, lmcelmd5, mri2, msu, ugamp, uic11, ukmo, yonu

10 years simulation under the 6ka and 0ka boundary condition

#### PMIP2-OA: Atmosphere-ocean coupled model

**13 models:**
- CCSM, CSIRO_Mk3L-1.0, CSIRO-Mk3L-1.1, ECBILTCLIOVECODE, ECHAM5-MPIOM1, FGOALS-1.0g, FOAM, GISSmodelE, IPSL-CM4-V1-MR, MIROC3.2, MRI-CGCM2.3.4fa, MRI-CGCM2.3.4nfa, UBRIS-HadCM3M2

100 years simulation under the 6ka and 0ka boundary condition

#### PMIP2-OAV: Atmosphere-ocean-vegetation coupled model

**6 models:**
- ECBILTCLIOVECODE, ECHAM53-MPIOM1-LPJ, FOAM, MRI-CGCM2.3.4fa, MRI-CGCM2.3.4nfa, UBRIS-HadCM3M2

100 years simulation under the 6ka and 0ka boundary condition
The climate response to the insolation is considered as the mean climate change between two time periods, that is **6ka minus 0ka**.

PMIP1 (10yrs mean, 19 models):

- **Atmospheric response**

PMIP2-OA (100yrs mean, 13 models):

- **Atmosphere + ocean + sea-ice response**

PMIP2-OAV(100yrs mean, 6 models):

- **Atmosphere + ocean + sea-ice + vegetation response**
Annual temperature change in 3 types of PMIP models

**PMIP1-SSTf**
1 = bmrc
2 = ccc2.0
3 = ccm3
4 = ccsr1
5 = climber2
6 = cnrm2
7 = csiro
8 = ecam3
9 = gen2
10 = gfdl

**PMIP2-OA**
1 = CCSM
2 = CSIRO-Mk3L-1.0
3 = CSIRO-Mk3L-1.1
4 = ECBILTCLIOVECODE
5 = ECHAM5-MPIOM1
6 = FGOALS-1.0g
7 = FOAM
8 = GISSmodelE
9 = IPSL-CM4-V1-MR1
10 = MIROC3.2
11 = MRI-CGCM2.3.4fa
12 = MRI-CGCM2.3.4nfa
13 = UBRIS-HadCM3M2

**PMIP2-OAV**
1 = ECBILTCLIOVECODE
2 = ECHAM53-MPIOM1-LPJ
3 = FOAM
4 = MRI-CGCM2.3.4fa
5 = MRI-CGCM2.3.4nfa
6 = UBRIS-HadCM3M2

Averaged over 60-90N
Seasonal temperature change in 3 types of PMIP models

Spring (MAM)

-0.51  -0.46  0.22

Summer (JJA)

0.84  1.13  1.50

Autumn (SON)

-0.12  1.35  2.18

Winter (DJF)

-0.33  0.55  1.22
Seasonal changes in temperature (°C) averaged over the locations of available reconstructions

<table>
<thead>
<tr>
<th>Model ensemble and data</th>
<th>Summer</th>
<th>Winter</th>
<th>Annual mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMIP1-SSTf (19 simulations ensemble)</td>
<td>0.80</td>
<td>-0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>PMIP2-OA (13 simulations ensemble)</td>
<td>1.13</td>
<td>0.35</td>
<td>0.42</td>
</tr>
<tr>
<td>PMIP2-OA (5 simulations ensemble)</td>
<td>1.00</td>
<td>0.82</td>
<td>0.57</td>
</tr>
<tr>
<td>PMIP2-OAV (5 simulations ensemble)</td>
<td>1.22</td>
<td>1.17</td>
<td>0.81</td>
</tr>
<tr>
<td>Reconstructions</td>
<td>1.00</td>
<td>1.71</td>
<td>2.04</td>
</tr>
</tbody>
</table>
Uncertainties across the climate model

CCSM

CSIRO_Mk3L_1.1

ECBILTCLILOVECODE

GISSmodelE

MIROC3.2

MRI_CGCM2.3.4fa

Legend:

-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
Model-data comparison: Selection of the optimal simulations

The “optimal” simulation for each PMIP2 is selected as the one that has the minimum of a cost function of:

\[
CF_k = \sqrt{\sum_{i=1}^{n} W_i (F_{rec,i} - F_{mod,i}^k)^2}
\]

\[
W_i = \frac{1}{\sigma^2 + 1}
\]

Hugues Goosse et al, 2006
Cost function for the PMIP ensemble

<table>
<thead>
<tr>
<th>Model type</th>
<th>Summer</th>
<th>Winter</th>
<th>Annual mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w1</td>
<td>w2</td>
<td>w1</td>
</tr>
<tr>
<td>PMIP1-SSTf</td>
<td>1.04</td>
<td>0.73</td>
<td>2.49</td>
</tr>
<tr>
<td>PMIP2-OA</td>
<td>1.05</td>
<td>0.77</td>
<td>2.26</td>
</tr>
<tr>
<td>PMIP2-OAV</td>
<td>1.06</td>
<td>0.77</td>
<td>1.95</td>
</tr>
</tbody>
</table>

\[
W_1 = \frac{1}{N} \quad W_2 = \frac{1}{\sigma^2 + 1}
\]
Cost function for the 18 PMIP2 models

weight=1/(sigma**2+1)

PMIP2-OA
1 = CCSM
2 = CSIRO-Mk3L-1.0
3 = CSIRO-Mk3L-1.1
4 = ECBILTCLIOVECODE
5 = ECHAM5-MPIOM1
6 = ECHAM53 LPJ
7 = FGOALS-1.0g
8 = FOAM
9 = GISSmodelE
10 = IPSL-CM4-V1-MR1
11 = MIROC3.2
12 = MRI-CGCM2.3.4fa
13 = UBRIS-HadCM3M2

PMIP2-OAV
1 = ECBILTCLIOVECODE
2 = ECHAM53-MPIOM1-LPJ
3 = FOAM
4 = MRI-CGCM2.3.4fa
5 = UBRIS-HadCM3M2

---summer  ---winter  ---annual
The large scale pattern in surface temperature (°C) change in FOAM-OA, MRI-OA, and reconstructions

**Summer**

- **FOAM-OA**
- **MRI-OA**
- **Reconstruction**

**Winter**

- **FOAM-OA**
- **MRI-OA**
- **Reconstruction**

**Annual**

- **FOAM-OA**
- **MRI-OA**
- **Reconstruction**

Fig. 6. The large scale pattern in surface temperature (°C) change in FOAM-OA, MRI-OA, and reconstructions.
The change in seasonal variation of (a) Sea ice area fraction, (b) Sea thickness, (c) Snow area fractions over land, (d) Surface albedo, (e) Downward ocean surface heat flux (positive means ocean receive heat from atmosphere), and (f) Upward ocean heat flux at the ice base (positive means ocean release heat to atmosphere).
Change in Sea-ice coverage (%)

Change in Surface albedo and ocean surface heat flux

(b) Surface albedo

(c) Ocean surface heat flux
The change in seasonal variation of upper ocean potential temperature (°C)
The change in DJF mean sea level pressure (Pa)
Summary

1. The reconstructions from different proxy data show 1.0°C warming in summer and 1.8°C warming in winter and 2.1°C warming in annual mean temperature over northern high latitudes.

2. Comparisons among 3 types of PMIP simulations indicate that when more physical feedbacks (ocean, sea-ice, vegetation) are included in the model, the climate response are better agree with the palaeoclimate records.

3. The optimal selected PMIP-OA models show that the summer warming in high latitude is enhanced by the sea-ice-albedo positive feedback. The response of the ocean and sea ice to the enhanced summer insolation further lead to a warming winter despite the reduced insolation.
**Application of the stable water isotope modeling in palaeoclimate study**

1. $\delta^{18}O$-Temperature calibration ($\delta^{18}O=0.67 \cdot T_{surf} - 13.6$, Dansgaard, 1964)
2. Origin of the moisture

**Stable water isotope enabled GCM**

<table>
<thead>
<tr>
<th>Model</th>
<th>Institute</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAM3</td>
<td>U. Colorado</td>
<td>Noone et al., (2010)</td>
</tr>
<tr>
<td>CAM2</td>
<td>UC Berkeley</td>
<td>Lee et al. (2007)</td>
</tr>
<tr>
<td>ECHAM5</td>
<td>AWI-Bremerhaven</td>
<td>Werner et al., wip</td>
</tr>
<tr>
<td>LMDZ4</td>
<td>LMD-Paris</td>
<td>Risi et al., wip</td>
</tr>
<tr>
<td>MIROC3.2</td>
<td>JAMSTEC-Yokosuka</td>
<td>Kurita et al. (2005)</td>
</tr>
<tr>
<td>GSM</td>
<td>Scripps-San Diego</td>
<td>Yoshimura et al. (2008)</td>
</tr>
<tr>
<td>ACCESS</td>
<td>ANSTO-Sydney</td>
<td>Fischer et al., wip</td>
</tr>
<tr>
<td>HadCM3</td>
<td>U. Bristol</td>
<td>Tindall et al. (2009)</td>
</tr>
<tr>
<td>HadAM3</td>
<td>BAS-Cambridge</td>
<td>Sime et al. (2008)</td>
</tr>
</tbody>
</table>
Change in global annual mean temperature and $\delta^{18}O$ in CAM3-iso

Some climate response, such as the high latitude warming and North Africa cooling, also have the signatures in $\delta^{18}O$. 
$\delta^{18}O-T$ relationship over high latitudes from CAM3-iso

Sturm et al., 2010
Moisture origin with stable water isotope tracer

Acknowledgement to Kei Yoshimura
Outlook

Model-data comparisons for high-latitude climate variability

Climate change: more collected data, and improved PMIP3 simulations

Climate variability:
Challenge in data analysis:
Different time resolution (10yr, 100yr), need downscaling or upscaling method to compile the collected reconstructions

Challenge in climate modelling: transient simulation

FOAM-LPJ: two transient simulations are available, 6500 years
PMIP3 last millennium transient simulation

Stable water isotope modelling
Recent 140 year (1870-2009)
Last millennium (Boundary condition from CESM1.0)
Related publications:

