Thermodynamic Scaling of the Hydrological Cycle of the Last Glacial Maximum

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Is LGM a useful cold analogue for future warming?

i.e., can we use proxy observations from past climates to check theories and models used to predict next-century hydrological change?

Here I will:
• briefly summarize a thermodynamic scaling used for next-century hydrological change
• show how well this scaling describes simulations of the Last Glacial Maximum
• discuss relevance to proxy collection & interpretation
Thermodynamic scaling for next-century warming

following Held & Soden (2006):

If winds and lower-tropospheric relative humidity do not change, then $P - E$ will increase with temperature at same rate as saturation humidity. i.e.:

$$P - E = -\nabla \cdot \vec{F}$$

(P = precipitation; E = evaporation; $F$ = vertically-integrated moisture flux)

neglecting changes in relative humidity, winds, and horizontal T gradients,

$$\delta (P - E) = \alpha \delta T (P - E)$$

typically, $\alpha \approx 7 \%/K$

Ensemble zonal mean from IPCC models, 21st - 20th century

1. good first-order match between scaling & simulated P-E
2. Scaling underestimates width of subtropical drying ... due to dynamics (e.g. Seager et al. 2010)
Are glacial climate simulations consistent with this theory?

-Analyze output from 8 ocean-atmosphere GCMs run with LGM & modern boundary conditions as part of PMIP2 project

Modern

280 ppmv CO$_2$
760 ppbv CH$_4$

LGM

185 ppmv CO$_2$
350 ppbv CH$_4$

Examine:
1. water vapor
2. P-E

Models used:
CCSM3
CNRM-CM3.3
ECHAM5.3
ECHAM5.3 dynamic veg
FGOALS-g1.0
HadCM3M2
IPSL-CM4-V1-MR
MIROC3.2
Results: LGM is colder with less water vapor

For constant relative humidity, vapor pressure $e$ in two climate states is:

$$\left\{ \frac{e_2}{e_1} \simeq \exp(\alpha[T_2 - T_1]) \right\}$$

Precipitable water, LGM

Modern

Surface air temperature, LGM - modern (K)

multi-model mean of 8 PMIP2 models
Global mean precipitable water scaling

Models follow Clausius-Clapeyron scaling quite well in global mean (one symbol for each model in PMIP2 ensemble)

\[ \text{global mean } \log(X_{\text{LGM}} / X_{\text{modern}}) = \text{global mean change in surface air temperature (K)} \]
Lower relative humidity in LGM tropical northern hemisphere

Will show that this deviation from constant relative humidity does not matter for P-E
Now examine $\delta(P-E)$

recall: if relative humidity, winds, and $T$ gradients do not change:

$$\delta(P - E) \simeq \alpha \delta T (P - E)$$

Thermodynamic scaling does well qualitatively, but:

- underestimates width of subtropical change
- overestimates extratropical drying by factor of 2-4

... and note lack of ITCZ shift!
Lat-lon distribution of $\delta(P-E)$

- Subtropical moistening is wider & more intense in $P-E$ than in just $P$ ... important for proxies
- Pattern is highly zonally asymmetric, so zonal mean is of limited utility

Changes normalized by global mean $|\Delta T|_s$ for each model

Contours surround regions significant at 95% level

$\delta(P-E)$, LGM - modern

$\delta P$, LGM - modern

mm/day/K
Does the scaling describe lat-lon pattern of $\delta(P-E)$?

- Back to our “theory” for P-E:

$$\delta(P - E) = -\nabla \cdot (\alpha \delta T \vec{F})$$

$$= \alpha \delta T (P - E) - \alpha \vec{F} \cdot \nabla (\delta T)$$

- $(P = \text{precipitation}; E = \text{evaporation}; F = \text{vertically-integrated moisture flux})$

$$\alpha \approx 7 \% / \text{K}$$

- LGM has much larger horizontal gradients of temperature change than simulations of next-century warming, and these matter for P-E

This term neglected for next-century change, but is important for LGM!
Terms in thermodynamic scaling for $\delta(P-E)$

- Total simulated change
  - **Standard thermodynamic scaling** (e.g. Held & Soden 2006) is too weak
  - Large changes in horizontal temperature gradients are important in extratropics
  - Complete thermo scaling has correct peak amplitudes, but poor spatial patterns

The diagrams illustrate the different terms in scaling due to change in temperature gradients.

- $\delta(P-E)$
- $\alpha\delta T(P-E)$
- $-\alpha\vec{F} \cdot \nabla(\delta T)$
- $-\nabla \cdot (\alpha\delta T\vec{F})$
There are dynamical changes too

→ LGM Hadley circulation is stronger and contracted toward equator
Poleward, vertically-integrated moisture transports

\[
\int [\bar{v}q] \, dp = \int [\bar{q}][\bar{v}] \, dp + \int [\bar{q}^*\bar{v}^*] \, dp + \int [q'v'] \, dp
\]

moisture transport decomposition

total mean meridional circulation stationary eddies transient eddies

LGM transports are weaker & contracted toward equator

larger LGM stationary wave transport

solid = total; dashed = MMC

solid = transient eddies; dashed = stationary eddies

flux, kg m^{-1} s^{-1}

latitude
Changes in transient eddy moisture transports dominate total $\delta(P-E)$, even in the deep tropics.

Poleward transient moisture transports weaken and contract equatorward, but detailed mechanism unclear.

Importance of maritime continent (DiNezio et al. 2011)?
1. Precipitable water in LGM simulations does scale with Clausius-Clapeyron, to first-order

2. Thermodynamic scaling for P-E qualitatively describes tropical drying & subtropical moistening in LGM models, but the total simulated distribution is highly zonally asymmetric. This complicates proxy interpretation and makes the LGM a poor cold analogue for next-century climate change

3. Thermodynamic $\delta(P-E)$ in N. Hemisphere extratropics is dominated by increase in temperature gradients

4. Transient eddy transports dominate $\delta(P-E)$; mechanisms unclear

5. Largest $\delta(P-E)$ not dominated by changes in ice sheets occurs in Pacific & Indian Oceans

More details in:
Why do stationary waves dry subtropics?
Comparison with lake proxy locations

green dots = some closed-basin lakes with chronologies, courtesy Wally Broecker