Spatial Hierarchical Bayes Model for AOGCM Climate Projections

Bayes Model for Climate Projections

Synthesizing temperature and precipitation climate projections from the outputs of several AOGCMs' weighted according to model bias and convergence.

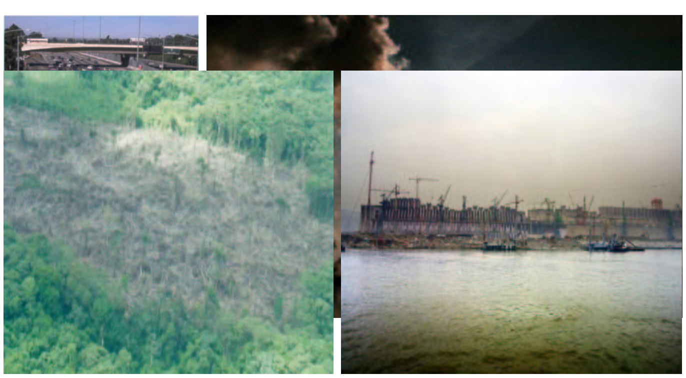
In collaboration with: Stephan Sain - CU at Denver
Tom Wigley - NCAR
Doug Nychka - NCAR

As Beautiful. . .

. . . So Dangerous

lostate.edu/flood97.html

Climate, a Sensitive System



calpi.nativeweb.org/proyectos.htm pic.templetons.com/ ... /photo/china/dam/

Why Study the Climate?

- Better understand the natural long-term cycles in climate (e.g. Pacific Decadal Variability, North Atlantic Oscillation)
- Improve the capability to forecast seasonal to interannual cycles of variability (e.g. El Niño-La Niña events)
- Sharpen the understanding of climate extremes and determine whether any changes in their frequency or intensity lie outside the range of natural variability
- Increase public and scientific awareness in the reality and the causes of climate change

What Is Climate Anyway?

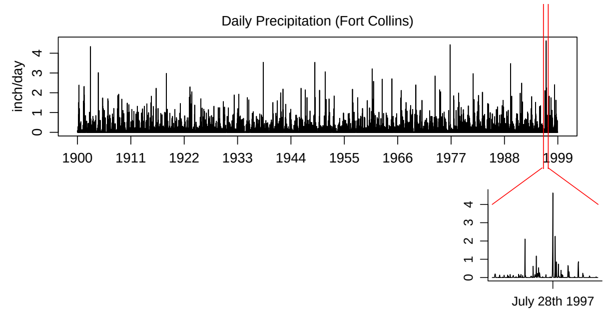
Two of Google's responses to "define:climate"

- the typical or expected (average) weather pattern, as opposed to the actual weather at any given instant.
- The sum total of the meteorological elements that characterize the average and extreme condition of the atmosphere over a long period of time at any one place or region of the earth's surface.

  The collective state of the atmosphere at a given place or over a given area within a specified period of time.

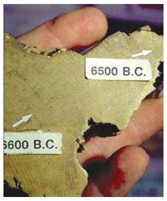
How to Study Climate?

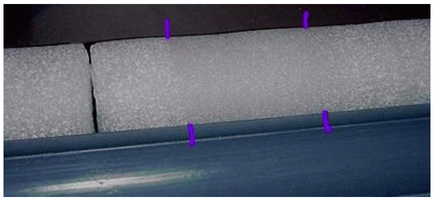
Too limited approaches:
- use localized time series of observations



How to Study Climate?

Too limited approaches:
- use localized time series of observations
- use "ancient" proxy observations





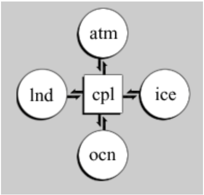
www.worldviewofglobalwarming.org/pages/ tea.rice.edu/pennycook/12.14.1999.html

AOGCM

Complicated approach:

AOGCM's: Atmospheric-Ocean General Circulation Models

Computer models that calculate the detailed large-scale motions of the atmosphere or the ocean explicitly from hydrodynamical equations.



AOGCM: the NCAR Model

CCSM3, the newest NCAR model (June 23, 2004):

- Resolution: T85L26v1
- Approximately 500,000 lines of code
- 3.45 years per simulation day (192 CPUs, 32-way nodes)
- 10Gbytes output per simulation year (daily and monthly data)

Example: Atmospheric Model

Input {
- External forcings (radiation, volcanos,. . .)
- Anthropogenic forcings (GHG, aerosols,. . .)
- Initial conditions

↓

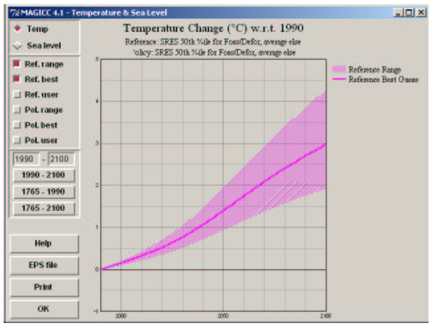
- Flow dynamics, PDEs
- Large scale discretization and simplifications
- Parametrization

↓

Output {
- "Mean" temperatures and precipitation
- Pressure, wind, . . .

Differences in Results

Variability of global temperature increase across 16 models.
MAGICC/SCENGEN program (Wigley, 2003).



Simple Statistical Model

Precipitation or surface temperature.
For models $i = 1, \dots, N$, stack the gridded output into vectors:

$$\begin{aligned}
\mathbf{X}_0 &= \text{observed present climate} = \text{present climate} + \text{meas. error} \\
\mathbf{X}_i &= \text{simulated present climate}_i = \text{present climate} + \text{model bias}_i \\
\mathbf{Y}_i &= \text{simulated future climate}_i = \text{future climate} + \text{model bias}_i
\end{aligned}$$

Objective:

Probabilistic description of modeled climate change

Simple Statistical Model

$$\begin{aligned}
\mathbf{X}_0 &= \boldsymbol{\mu}_x + \boldsymbol{\varepsilon} && \text{(observed present climate)} \\
\mathbf{X}_i &= \boldsymbol{\mu}_x + \mathbf{u}_i && \text{(simulated present climate)} \\
\mathbf{Y}_i &= \boldsymbol{\mu}_y + \mathbf{v}_i && \text{(simulated future climate)}
\end{aligned}$$

Data from MAGICC/SCENGEN 4.1 (Wigley, 2003):

- 16 models (CSM, ECHx, HADx, GFDL,...)
- $5^\circ \times 5^\circ$ resolution (2592 data points)
- Perturbation experiment with 1% CO_2 increase per year
- Averages over 20 years, 1-20 and 61-80
- ...

Statistical Model

$$\begin{aligned}
\mathbf{X}_0 &= \boldsymbol{\mu}_x + \boldsymbol{\varepsilon} && \text{(observed present climate)} \\
\mathbf{X}_i &= \boldsymbol{\mu}_x + \mathbf{u}_i && \text{(simulated present climate)} \\
\mathbf{Y}_i &= \boldsymbol{\mu}_y + \mathbf{v}_i && \text{(simulated future climate)}
\end{aligned}$$

$$\begin{aligned}
& & \boldsymbol{\varepsilon} &\sim \mathcal{N}(\mathbf{0}, \mathbf{S}) \\
\boldsymbol{\mu}_x &= \mathbf{M}_x \boldsymbol{\theta} & \mathbf{u}_i &\sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Sigma}_i) \\
\boldsymbol{\mu}_y &= \mathbf{M}_y \boldsymbol{\eta} & \mathbf{v}_i &= \mathbf{w}_i + \rho_i \mathbf{u}_i \\
& & \mathbf{w}_i &\sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Omega}_i) \quad \mathbf{w}_i \perp \mathbf{u}_i
\end{aligned}$$

Covariance Matrices

The covariance matrices $\mathbf{S}$, $\boldsymbol{\Sigma}_i$, $\boldsymbol{\Omega}_i$ are positive definite.

Examples of positive definite functions on the sphere:

1. representation of an infinite series of Legendre polynoms
$$c(h; \sigma, \eta) = \sigma \Big(1 - 2\eta \cos(h) + \eta^2\Big)^{-3/2}$$
2. restriction of a positive definite function to the sphere
$$c(h; \sigma, \eta) = \sigma \exp\Big(-\eta \sin(h/2)\Big)$$

We only parameterize the scale σ of the covariance matrices.

The "range" η is choosen according an "empirical Bayes" approach.

Priors

Let $\mathbf{C}$ be a positive definite matrix using $c(\cdot; 1, \eta)$ and put

$$\mathbf{S} = \phi_0 \mathbf{C} \qquad \boldsymbol{\Sigma}_i = \phi_i \mathbf{C} \qquad \boldsymbol{\Omega}_i = \psi_i \mathbf{C}$$

We use vague (disperse) priors

$$\begin{aligned}
\boldsymbol{\theta} &\sim \mathcal{N}(\mathbf{0}, \xi_1^2 \mathbf{I}) \\
\boldsymbol{\eta} &\sim \mathcal{N}(\mathbf{0}, \xi_2^2 \mathbf{I}) \\
\phi_i &\sim \mathrm{I}\Gamma(\xi_3, \xi_4) \\
\psi_i &\sim \mathrm{I}\Gamma(\xi_5, \xi_6) \\
\rho_i &\sim \mathcal{N}(0, \xi_7^2)
\end{aligned}$$

Posteriors

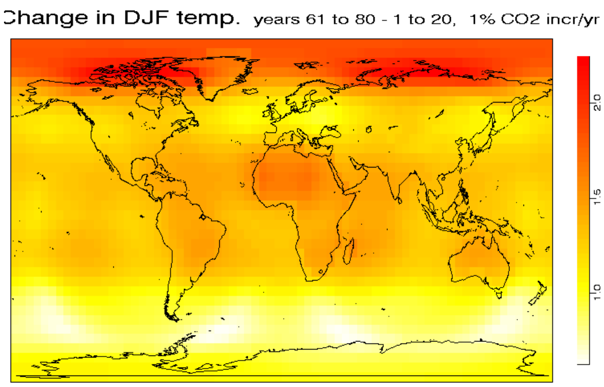
Full conditionals for the parameters are available

$$\begin{aligned} \boldsymbol{\theta}, \boldsymbol{\eta} \mid \ldots &\sim \mathcal{N}(\cdot, \cdot) \\ \phi_i, \psi_i \mid \ldots &\sim \mathrm{I}\Gamma(\cdot, \cdot) \\ \rho_i \mid \ldots &\sim \mathcal{N}(\cdot, \cdot) \end{aligned}$$

Gibbs Sampler

- Gibbs sampler programmed in R
- 4 seconds for one iteration
- Visual inspection of convergence (5000 burn-in, keep every 10th)

Illustration



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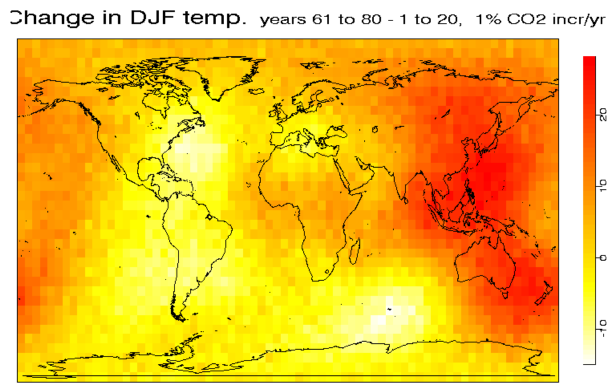

Extended Statistical Model

Different possibilities to extend the model:

$$\begin{aligned} \mathbf{X}_0 &= \boldsymbol{\mu}_x + \boldsymbol{\omega}_x + \boldsymbol{\varepsilon} && \text{(observed present climate)} \\ \mathbf{X}_i &= \boldsymbol{\mu}_x + \boldsymbol{\omega}_x + \mathbf{b}_i + \mathbf{u}_i && \text{(simulated present climate)} \\ \mathbf{Y}_i &= \boldsymbol{\mu}_y + \boldsymbol{\omega}_y + \mathbf{b}_i + \mathbf{v}_i && \text{(simulated future climate)} \end{aligned}$$

Problem is "tractable" if all covariance matrices are of the same form.

No explicit expressions for full conditionals available.

Discussion and Further Work

- A first "running horse"
- Promising approach (statistically and climatologically)

- Evaluate and down-scale first results
- Generalize covariance parameterization
- Use "current" climate for better priors
- Extend to multivariate setting