Projecting future climate: methods, limitations, and challenges

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Why do we need climate models?

To understand effects of human influences on climate

Greenhouse gases

Surface properties

Particulate pollution

Surface properties
Some solar radiation is reflected by the atmosphere.

Most solar radiation is absorbed by the Earth.

Infrared radiation is emitted by the Earth.

Some infrared radiation is absorbed and re-emitted by greenhouse gases.
What are climate models?
Climate models are large computer programs that simulate the atmosphere, ocean, sea ice, etc.

**Time scales:**
- Atmosphere - days
- Sea ice – days to centuries
- Vegetation – days to centuries
- Oceans – months to centuries
- Ice sheets - years

Source: Bette Otto-Bliesner, NCAR
Atmospheric models solve differential equations

<table>
<thead>
<tr>
<th>Conservation of momentum:</th>
<th>Conservation of mass:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{D\mathbf{v}}{Dt} = -2 \Omega \times \mathbf{v} - \nabla \rho / \rho + \mathbf{g}$</td>
<td>$\partial_t \rho + \text{div}(\rho \mathbf{v}) = 0$</td>
</tr>
<tr>
<td>Conservation of (thermal) energy:</td>
<td>Equation of state:</td>
</tr>
<tr>
<td>$c_v \frac{DT}{Dt} = -\rho \left( \frac{d\rho^{-1}}{dt} \right) + Q$</td>
<td>$\rho = \mu p / (RT)$</td>
</tr>
</tbody>
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Unknowns:
- $\rho$ = density
- $p$ = pressure
- $\mathbf{v}$ = velocity (3 components)
- $T$ = temperature

Parameters:
- $\Omega$ = Coriolis parameter
- $\mathbf{g}$ = gravitational acceleration
- $Q$ = “heating rate”
- $c_v$ = volume heat capacity
- $R$ = gas constant
- $\mu$ = molecular weight

+ tracer-conservation law (q for atmosphere, S for ocean) $\Rightarrow$ 7 equations in 7 unknowns
Climate models divide the world into little boxes (actually, not so little)
Clouds: the Achilles heel of climate models
Why are clouds hard to model?

Clouds

• Are smaller than climate model grid boxes
• Are not well-understood
• Respond in unknown ways to increasing greenhouse gases and other climate insults
“Computers only tell you what you already know.”

Ernesto Colnago
Clouds and precipitation are treated “quasi-empirically:”

- Using rules that are derived from observations as well as basic science
- Even if they reproduce observations well, these might not work right in a warmer climate
How well do climate models work?
Climate simulation by Warren Washington, circa 1969
Climate model evaluation

• Models are thoroughly evaluated
  – They are not perfect, but we know their flaws
  – The naysayers who claim that climate models are not evaluated are not telling the truth.

• We evaluate models by comparing to the past, and hope that this tells us how well they predict the future.
  – It is difficult to directly evaluate the predictions of climate models (unlike weather models).
Models reproduce the 20\textsuperscript{th} century pretty well.
We evaluate climate models by using them to forecast weather.

Figure 4: Maps of the vertical profile of atmospheric water vapor at the ARM SCF site are shown at 3-h intervals for the period of 18-25 June 1992, as obtained from in-situ ARM observations, by the ECMWF ERA-15 reanalysis, and as a sequence of CAM2 forecasts that are initialized at 0Z each day and valid for the period 05Z-23Z (left with the 16Z value shown for June 19), supplied by the 24Z forecast for June 19. Note the apparent diurnal cycle in the relative humidity profile in situ, in reanalysis, evidence of the rapid departure of the CAM2 forecasts from realistic humidity profile after their initialization at 0Z each day.
RMS errors in simulated outgoing solar radiation

![Graph showing RMS errors in simulated outgoing solar radiation across different latitudes for various models. The x-axis represents latitude, and the y-axis represents SW radiation RMS error (W m⁻²). The graph includes multiple lines representing different models, such as BCC-CM1, BCCR-BCM2.0, CCSM3, and others, with the mean model indicated by a dashed line.](image-url)
Global climate models do well on the global scale...

Observed precipitation

Simulated precipitation (multimodel mean)
...but less well on smaller scales
We evaluate simulated variability as well as means.
Societal Impacts of Climate Change
Societal impacts of climate change: The basis of policy decisions

- Air quality
- Extreme events
- Agriculture
- Recreation
- Human health
- Water availability
Mitigation

• Reducing GHG emissions to minimize climate change;
• Requires understanding of societal impacts because we need to know “how much climate change is OK.”
Adaptation

• Significant climate change is inevitable;
• *We need to develop coping strategies.*
• This requires understanding of societal impacts.
Societal-impacts studies need climate projections having:

- **Fine resolution**
  - to provide regional-scale fidelity
- Reliable information on **extremes**
  - because these have disproportionate societal impacts
- Quantified **uncertainties**
  - usually by analyzing a large family of simulations

It’s difficult impossible to make projections having all these properties!
Why we need fine resolution:

Annual mean precipitation

Global climate model

~300 km

Observations (PRISM) 4 km

Reliable on a regional scale

Global climate model results are too coarse to be
Wintertime precipitation rate

Refining resolution improves fidelity...

T42 (300 km)  T85 (150 km)  T170 (75 km)

0 1 2 3 4 5 6 7 8 mm/day

T239 (50 km)  0.4° x 0.5° (40 x 50 km)  Observations (VEMAP)
... at a high computational price

- A 2x decrease in horizontal grid dimensions —> an 8x or 16x increase in CPU time
- Our simulations at 50 km resolution are 200x slower than simulations at the standard resolution of 300 km
300 km grid spacing
50 km grid spacing
Dynamical downscaling:

Uses a nested, limited-domain climate model that is based on physical laws
Nested models *can* work beautifully
Dynamical downscaling: GIGO

Nested model

Global model

Obs.

Precipitation (mm/day)

Month of year ->
Uncertainty: what are limits of climate prediction?

For a minute you had me worried.

Based on what?

My calculations.

I believe we are entering another ice age!
Sources of uncertainty:

- Imperfect knowledge of initial conditions in the atmosphere, etc.
Example of initial condition uncertainty

Simulated and observed regional sea-surface temperatures
courtesy Ben Santer

Anomaly relative to 1900-1909 (°C)

-0.2
0
0.2
0.4
0.6
0.8
1
1900 1920 1940 1960 1980 2000

CCSM3, realizations 1-9
OBS (NOAA ERSST)
CCSM3 ensemble mean
Sources of uncertainty: imperfect knowledge of

- future behavior of climate “forcings,” e.g. greenhouse gas concentrations;
Future CO$_2$ concentrations are *unknowable*; this is true of other influences also.
About half of future uncertainty in temperature comes from uncertainty in future CO$_2$ emissions.

Each vertical bar shows the range of results obtained for one greenhouse gas emissions scenario.

Global T will increase by 1.4° - 5.8 ºC before 2100.

0.6° C is the amount of warming that occurred during the 20th century.
Sources of uncertainty: imperfect knowledge of

- how the climate system behaves.

These errors arise from:

- Imperfect representation of unresolved phenomena (notably clouds)
- numerical discretization
- “unknown unknowns”.
Different models respond differently to same inputs

Simulated temperature responses to 1%/yr CO$_2$ increase
Parting Thoughts

- Climate models work amazingly well.
- Climate models have serious errors.
- Some important sources of error in future climate predictions are irreducible.
- Climate prediction is no longer an academic exercise!
- The need to incorporate climate change into real-world decisions has “raised the bar” for climate modelers.
- Quantifying and reducing uncertainties are major challenges.
Let's have dinner!
How do we estimate climate uncertainty?

- Expert elicitation
- Ensembles of opportunity
- Perturbed physics ensemble
- Why none of these is perfect
“Expert Elicitation”

• Fancy term for asking a bunch of so-called experts.

• Why I don’t like this approach:
  – It’s completely subjective
  – (but often made to look quantitative)
  – Groupthink creates false consensus
“Ensemble of opportunity:”

a collection of results from a number of available models

Projected changes in annual temperature in CA

Results from 15 models, each simulating 3 CO₂ scenarios
What’s good about quantifying uncertainty in this way?

1. It’s a start
What’s **good** about quantifying uncertainty in this way?

1. It’s a start
2. The mean of a large number of models consistently performs better than any single model
   • This is true in climate simulation and in seasonal weather prediction
   • So having results from multiple models seems to give a better estimate of the most likely outcome.
What’s **bad** about quantifying uncertainty in this way?

1. Results can be influenced by selection of models, which can be haphazard.

2. Can be misleading because errors common to many models may be important. I.e., even if models agree with each other, they could all be wrong.
   - Superiority of mean model *suggests* that this is not important
   - Hence this approach measure consensus more than uncertainty
What’s **bad** ... 

3. Some evidence that GCMs have been unconsciously “tuned”

Source: Kiehl, GRL (2007)
What's bad ...

4. Often values all models equally, which can’t be optimal
   – But we can’t agree on best way to combine models

Tebaldi C., Knutti R. Phil. Trans. R. Soc. A; 2007; 365: 2053-2075
What’s bad ...

5. Does not include outcomes that all agree have low (but non-zero) likelihood.

Source: Roe and Baker, UW

A range of model results estimates the uncertainty in the most likely outcome, not the full range of possible values.

Source: Roe and Baker, UW
What’s **bad** ...

6. Uncertainty in future forcings (e.g. greenhouse gases) is difficult to quantify.
A better and cooler way to quantify uncertainty: climateprediction.net

- 48,000 participants are running a climate model “in background” on their computers.
- 43,672,873 simulated years had been run as of April 23.
- Each participant runs a slightly different model version, with a unique combination of parameter values.
- The result is a thorough exploration of parameter space.