Projecting future climate: methods, limitations, and challenges

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G | **GENERAL AUDIENCES**

All Ages Admitted ®

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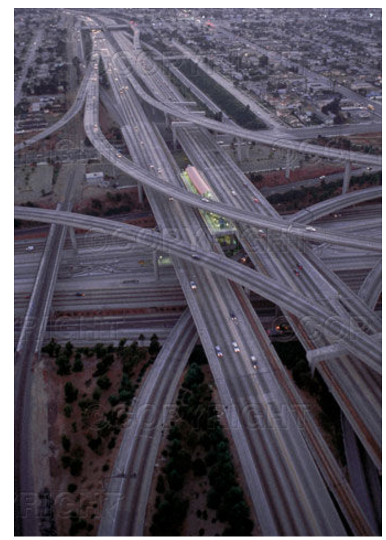
Why do we need climate models?

To understand effects of human influences on climate

Greenhouse gases

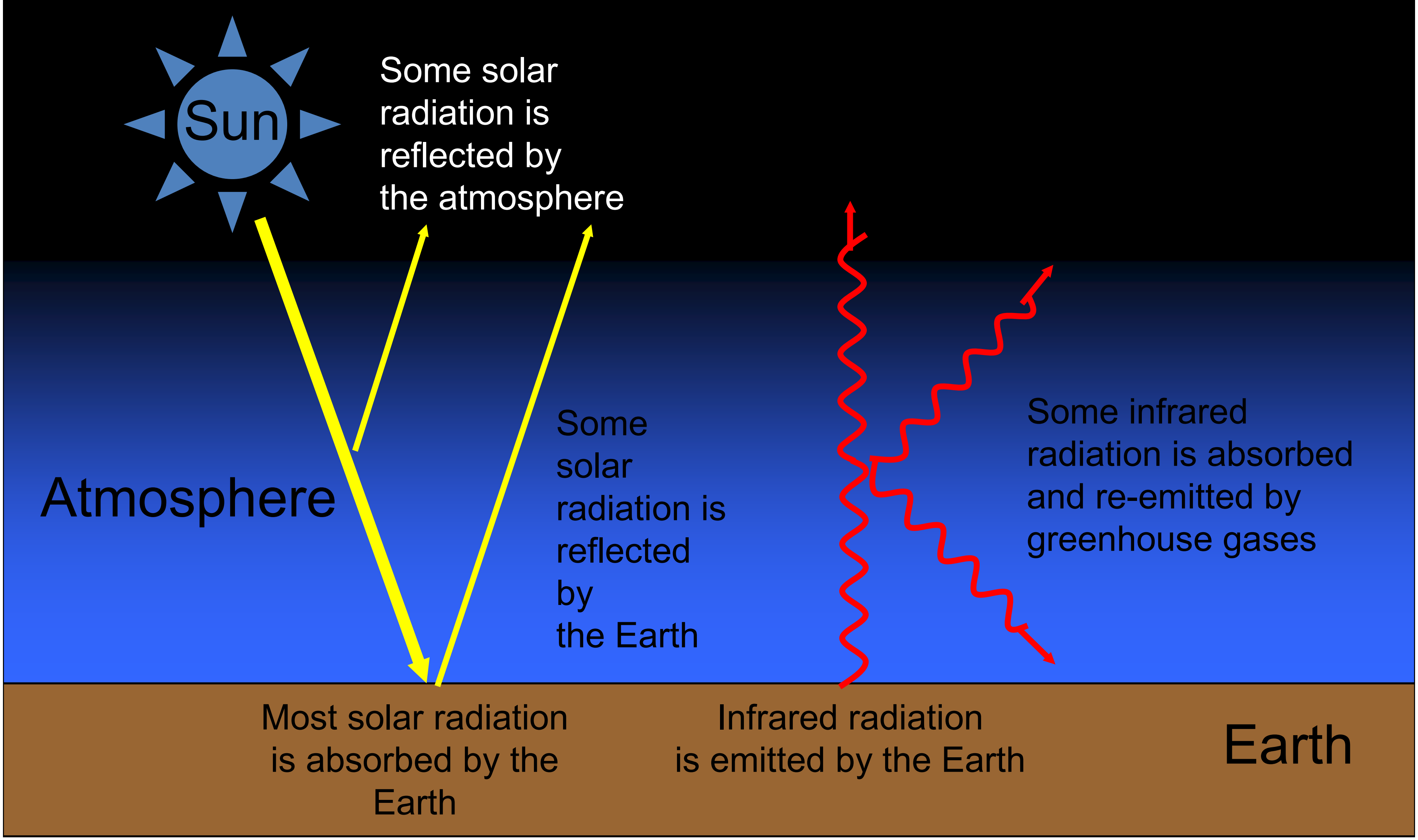
Particulate pollution

Surface properties



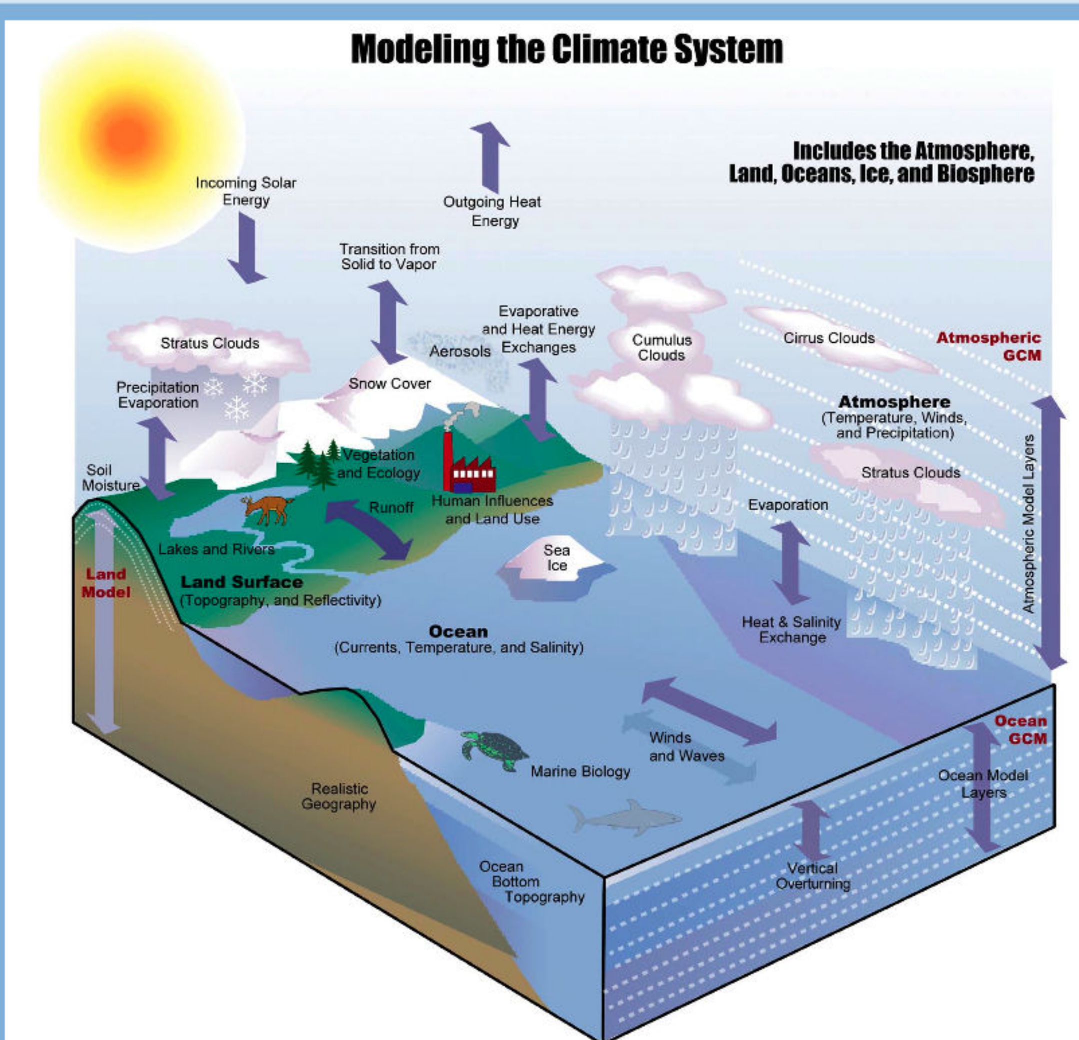
Surface properties

Earth's radiation balance



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

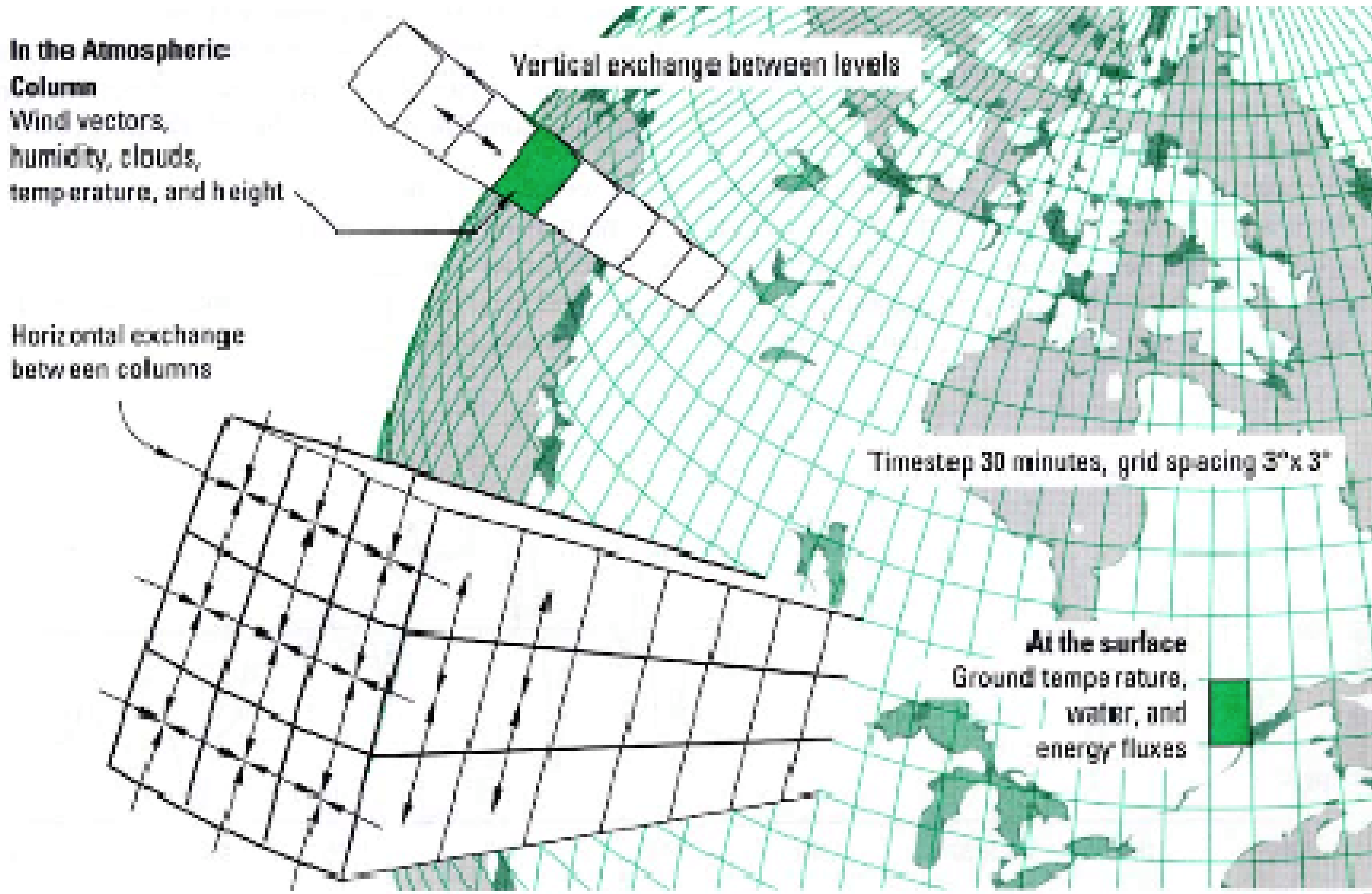
Conservation of momentum: $D\boldsymbol{v}/Dt = -2\,\Omega \times \boldsymbol{v} - \mathbf{grad}(p)/\rho + \mathbf{g}$	Conservation of mass: $\partial_t \rho + \mathbf{div}(\rho\,\boldsymbol{v}) = 0$
Conservation of (thermal) energy: $c_v DT/Dt = -p\,(d\rho^{-1}/dt) + Q$	Equation of state: $\rho = \mu\, p/(RT)$

Unknowns:	Parameters:
ρ = density p = pressure $\boldsymbol{v}$ = velocity (3 components) T = temperature	Ω = Coriolis parameter $\mathbf{g}$ = gravitational acceleration Q = “heating rate” c_v = volume heat capacity R = gas constant μ = 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.”

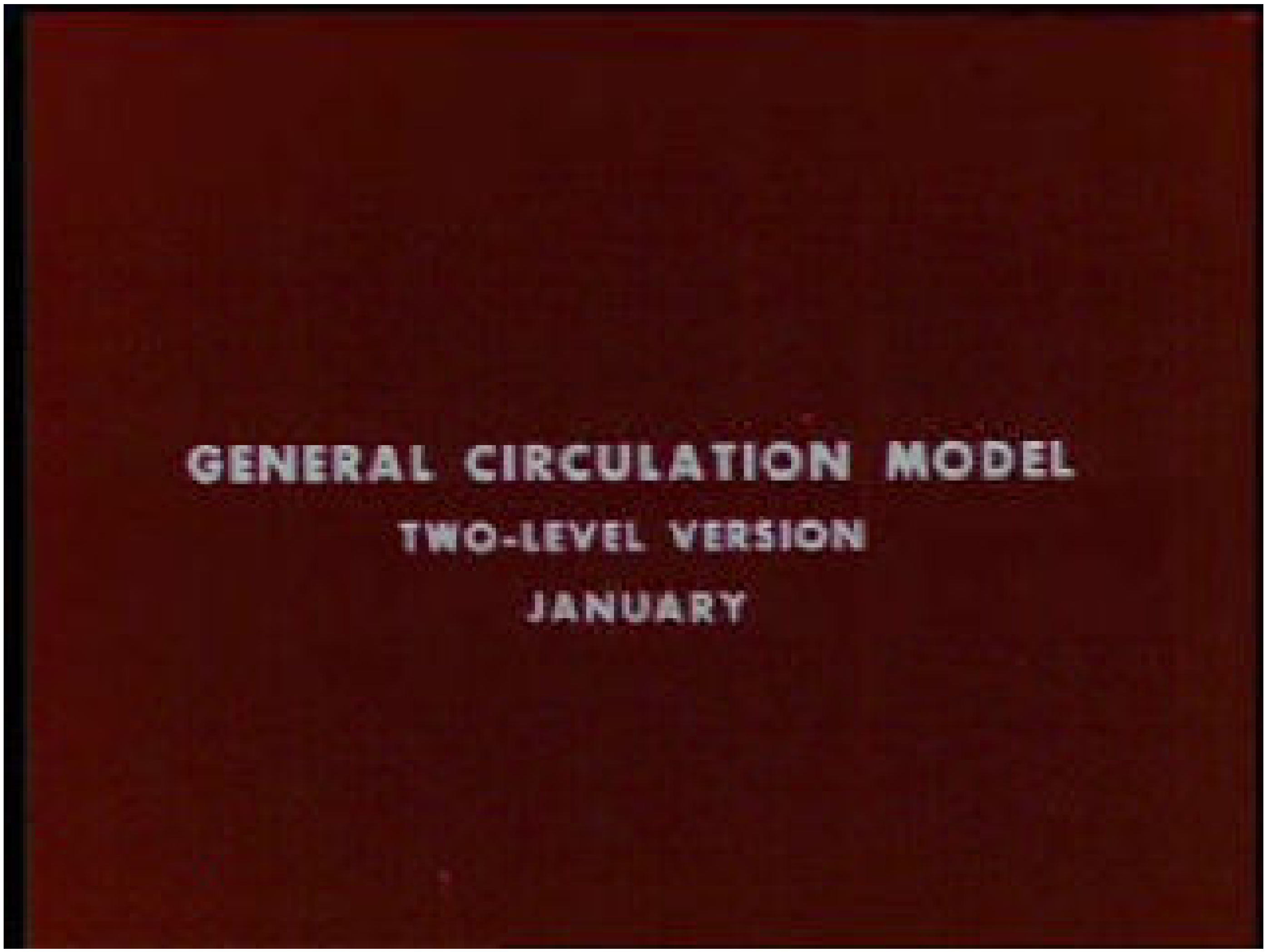
Ernesto Colnago

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?

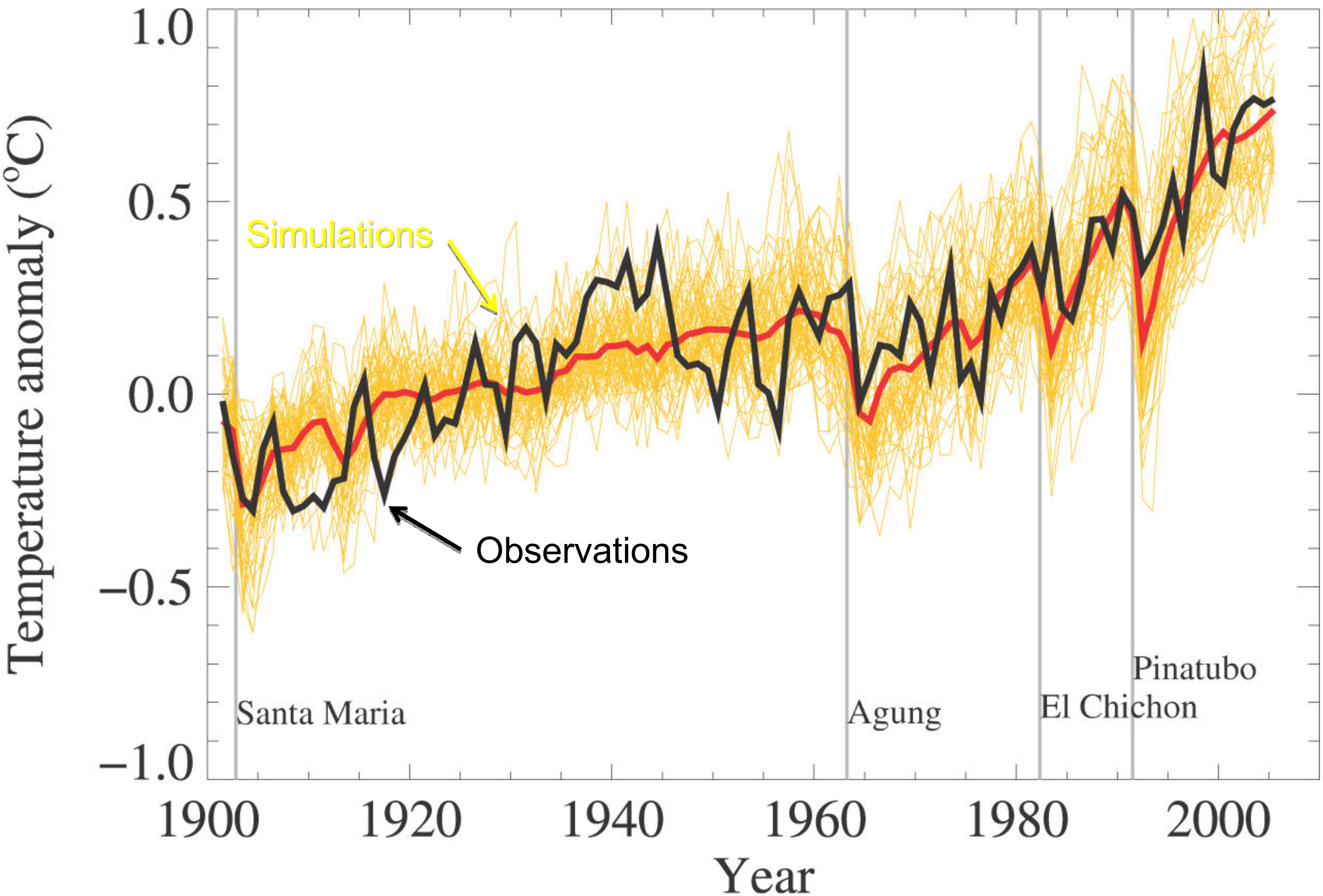
Climate simulation by Warren Washington, circa 1969



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 20th century pretty well



We evaluate climate models by using them to forecast weather

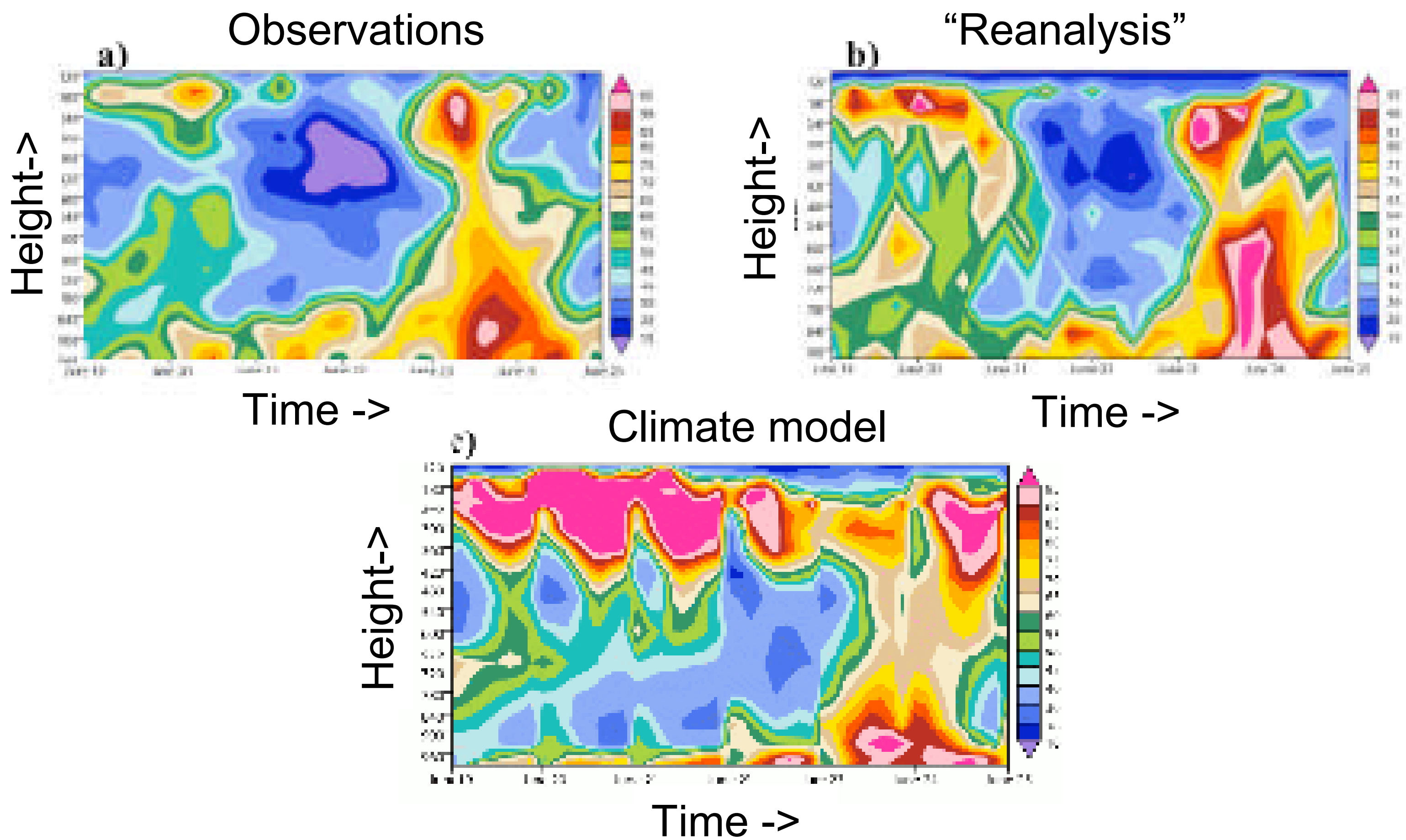
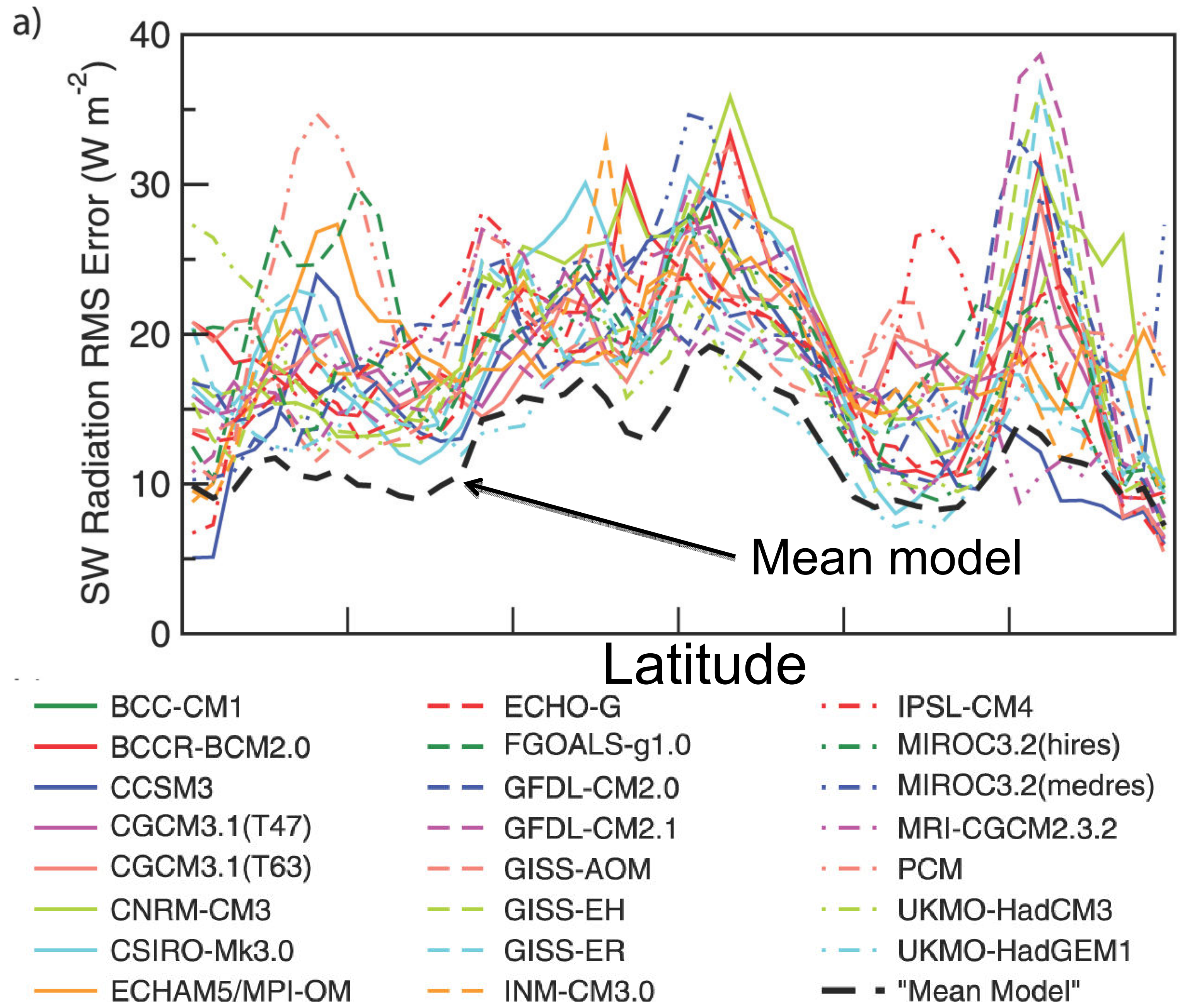
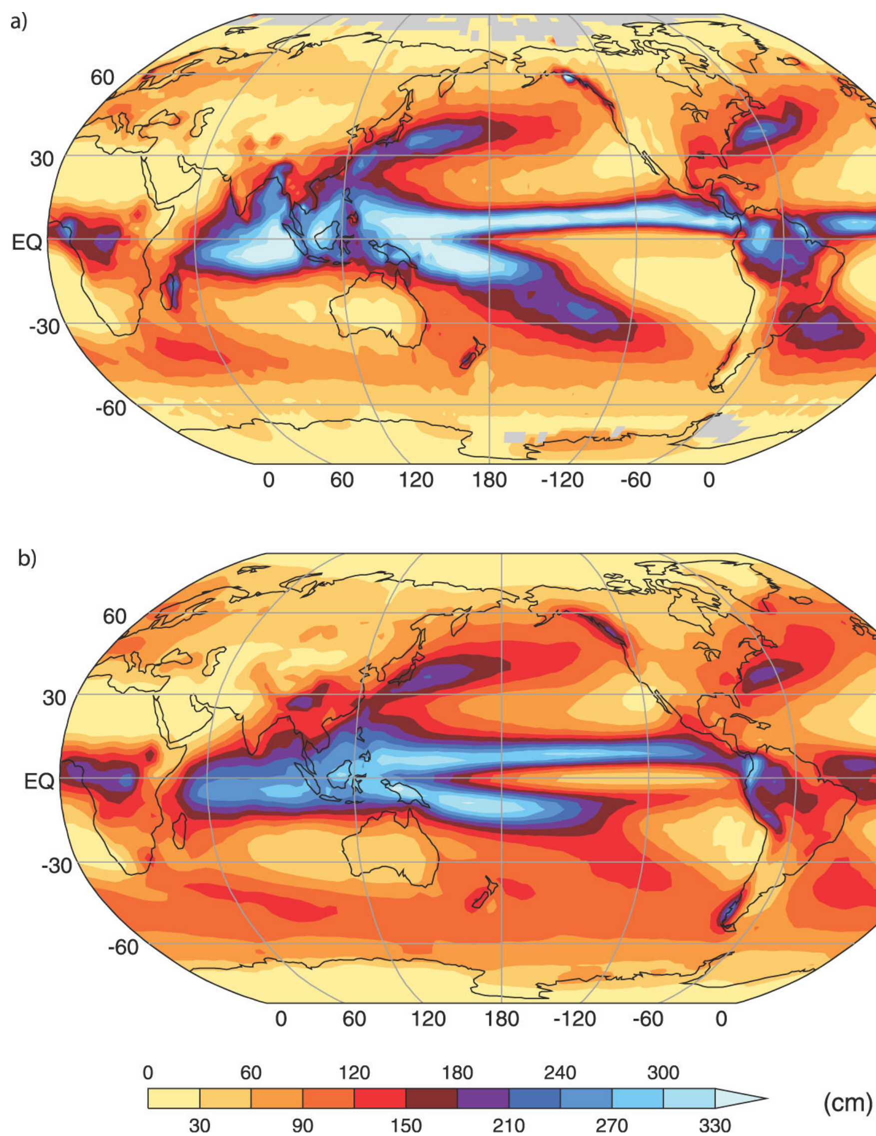


Figure 4. Plots of the vertical profile of atmospheric relative humidity (in %) at the ARM SGP site are shown at 3-h intervals for the period for 18-25 June 1997, as obtained from a) ARM observations, b) the ECMWF ERA-40 reanalysis, and c) a sequence of CAM2 forecasts that are initialized at 00Z each day and valid for the period 03Z-24Z (but with the 00Z value shown for June 19 supplied by the 24h forecast for June 18). Note the apparent diurnal cycle in the relative humidity profile in c) is, in actuality, evidence of the rapid departure of the CAM2 forecasts from a realistic humidity profile after their initialization at 00Z each day.

RMS errors in simulated outgoing solar radiation



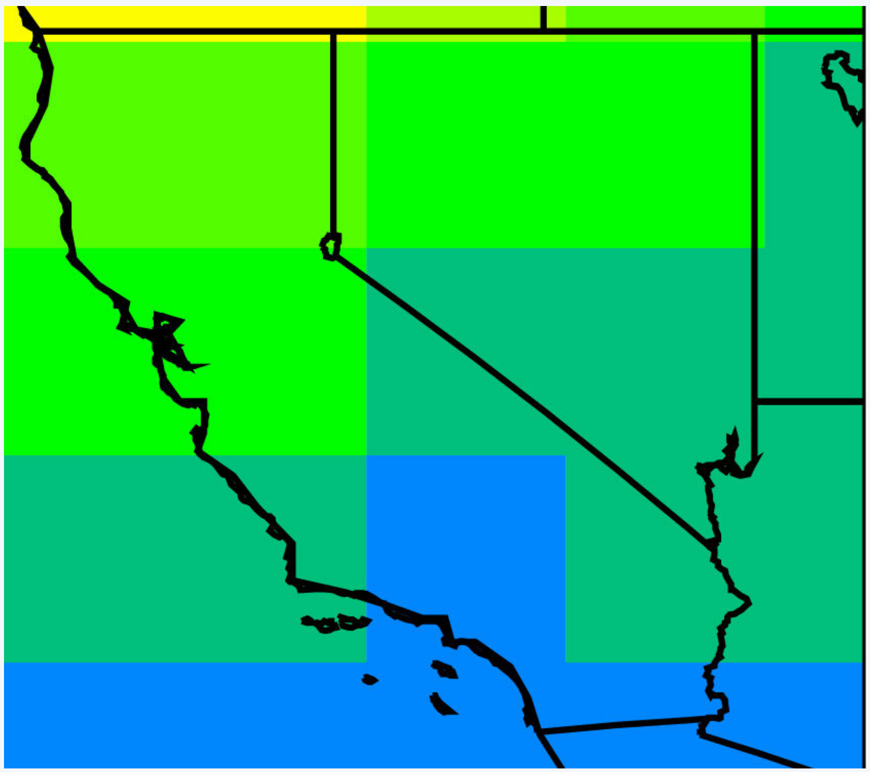
Global climate models do well on the global scale…



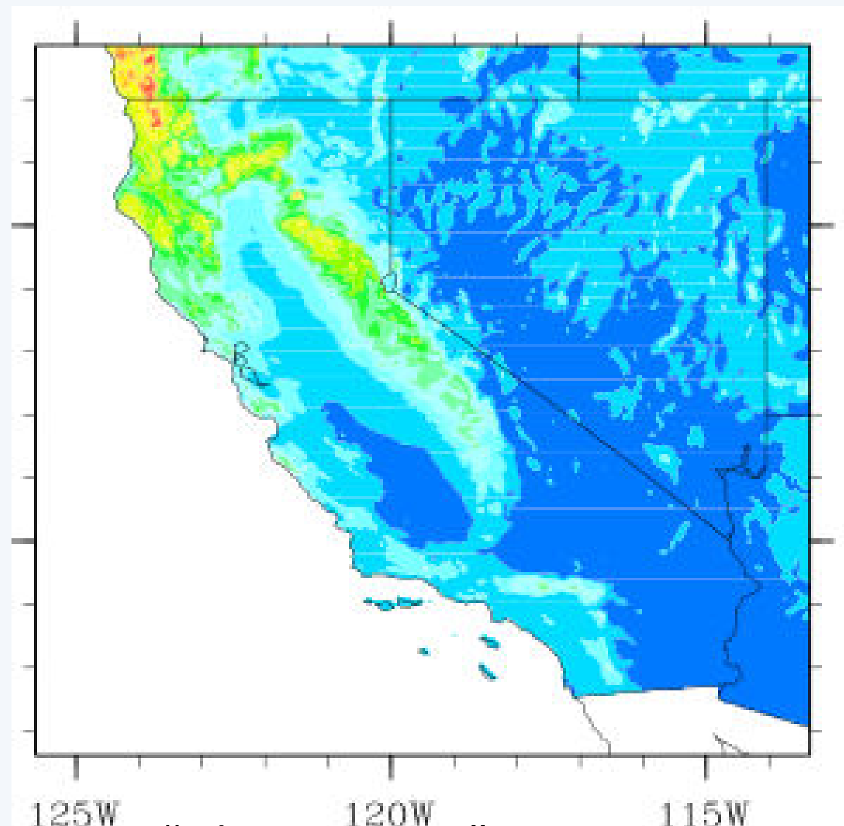
Observed precipitation

Simulated precipitation (multimodel mean)

…but less well on smaller scales



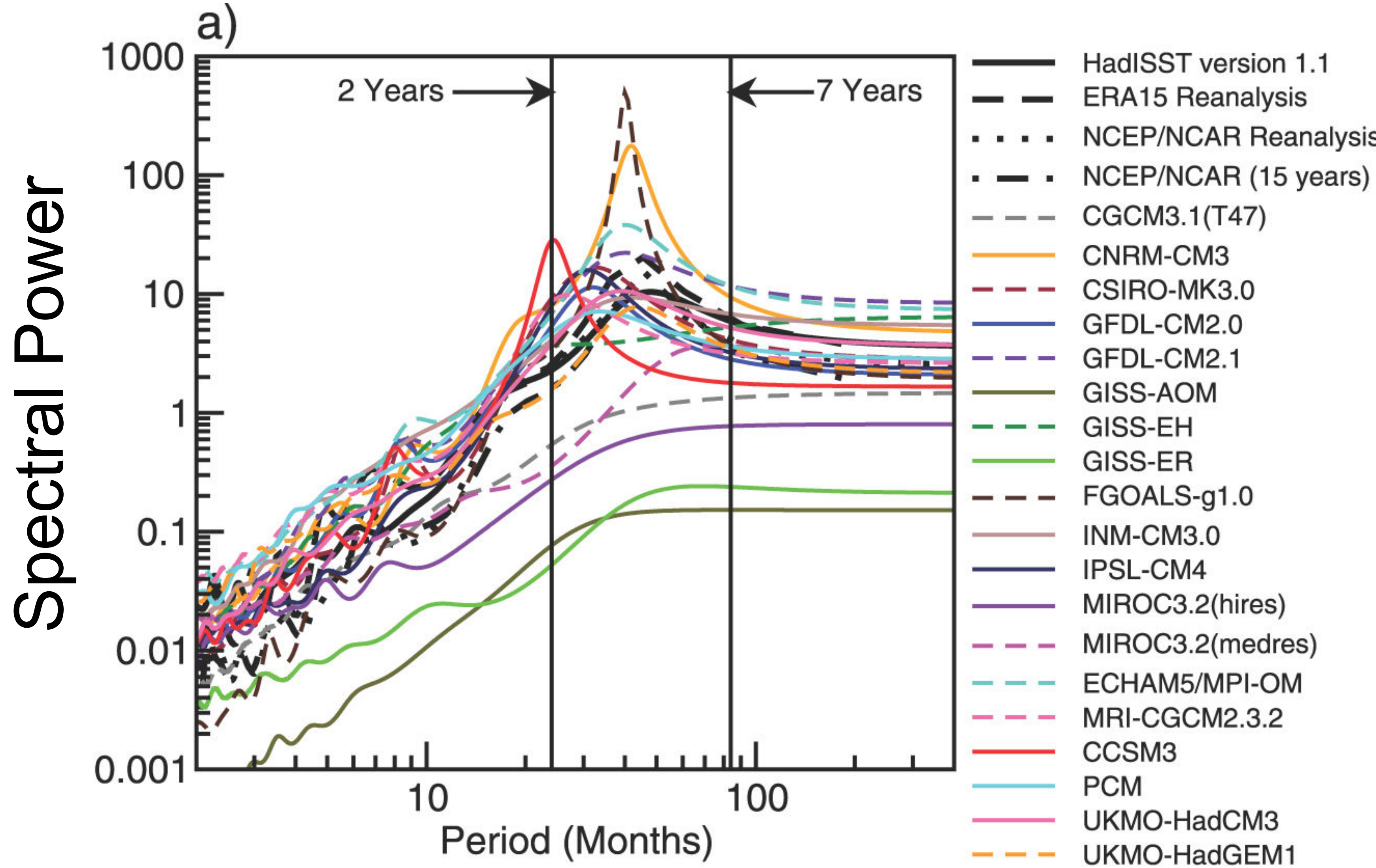
Global climate model
~300 km



"Observations"
(PRISM) 4 km

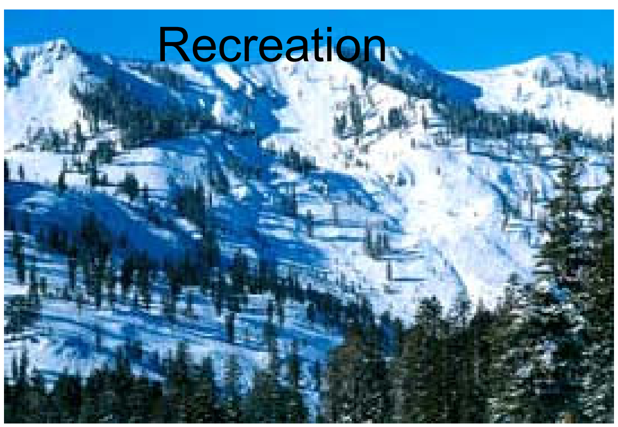
Annual mean precipitation

We evaluate simulated variability as well as means



Societal Impacts of Climate Change

Societal impacts of climate change: The basis of policy decisions



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.

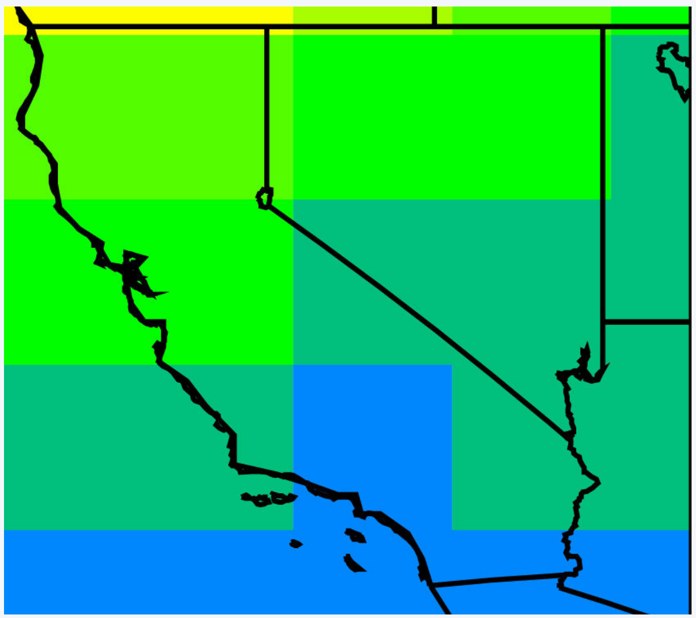
Societal-impacts studies need climate projections having:

- **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

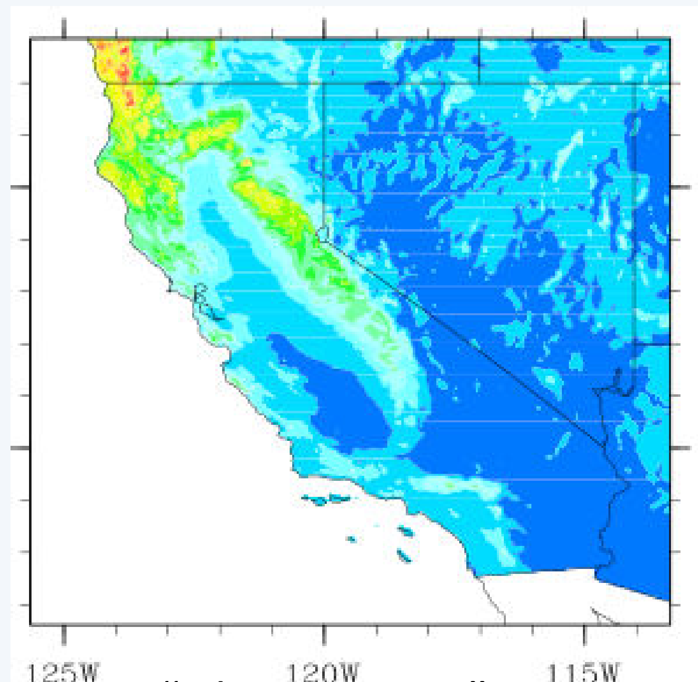
It’s ~~difficult~~ impossible to make projections having all these properties!

Why we need fine resolution:

Global climate model results are too coarse to be reliable on a regional scale



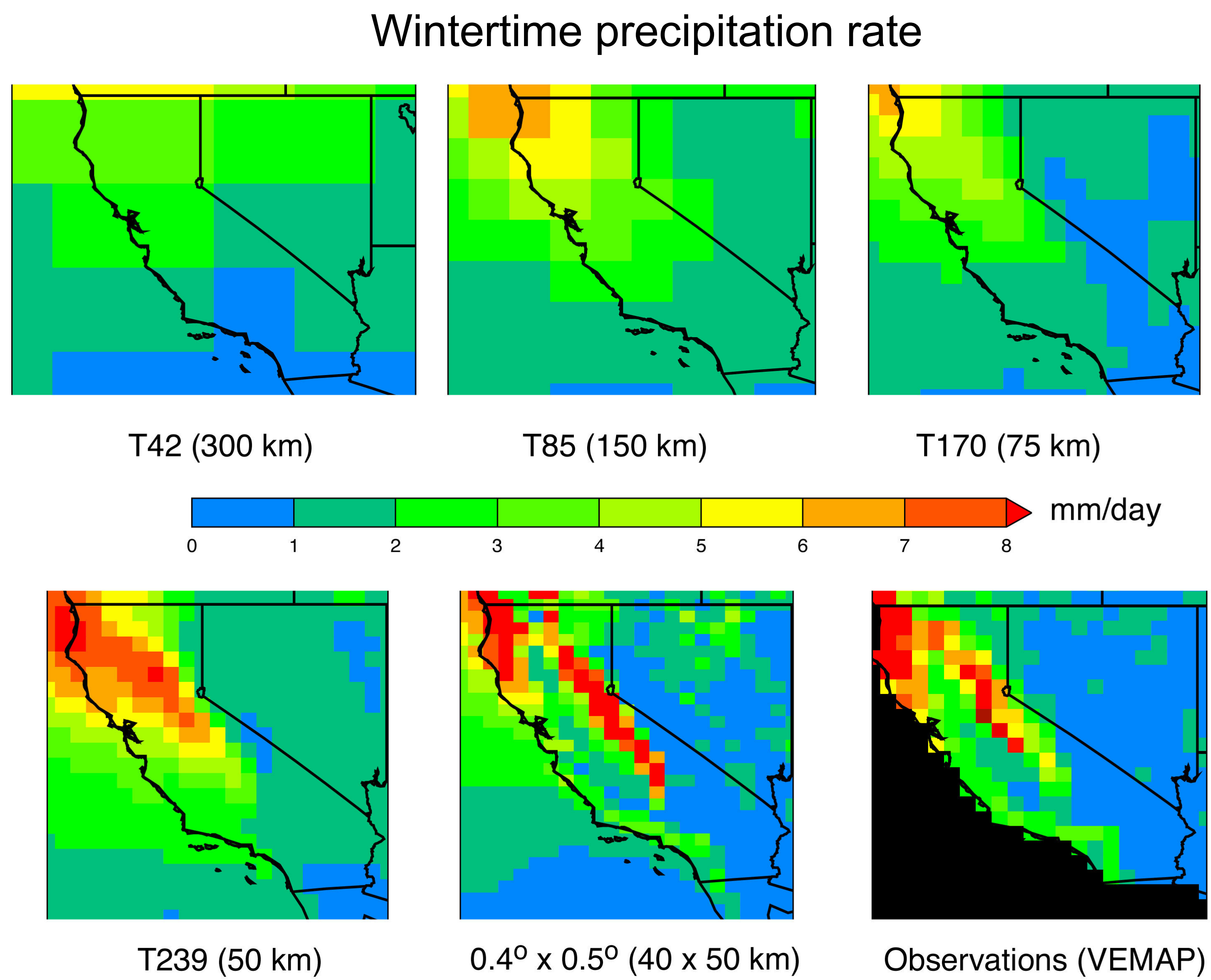
Global climate model
~300 km



"Observations"
(PRISM) 4 km

Annual mean precipitation

Refining resolution improves fidelity…



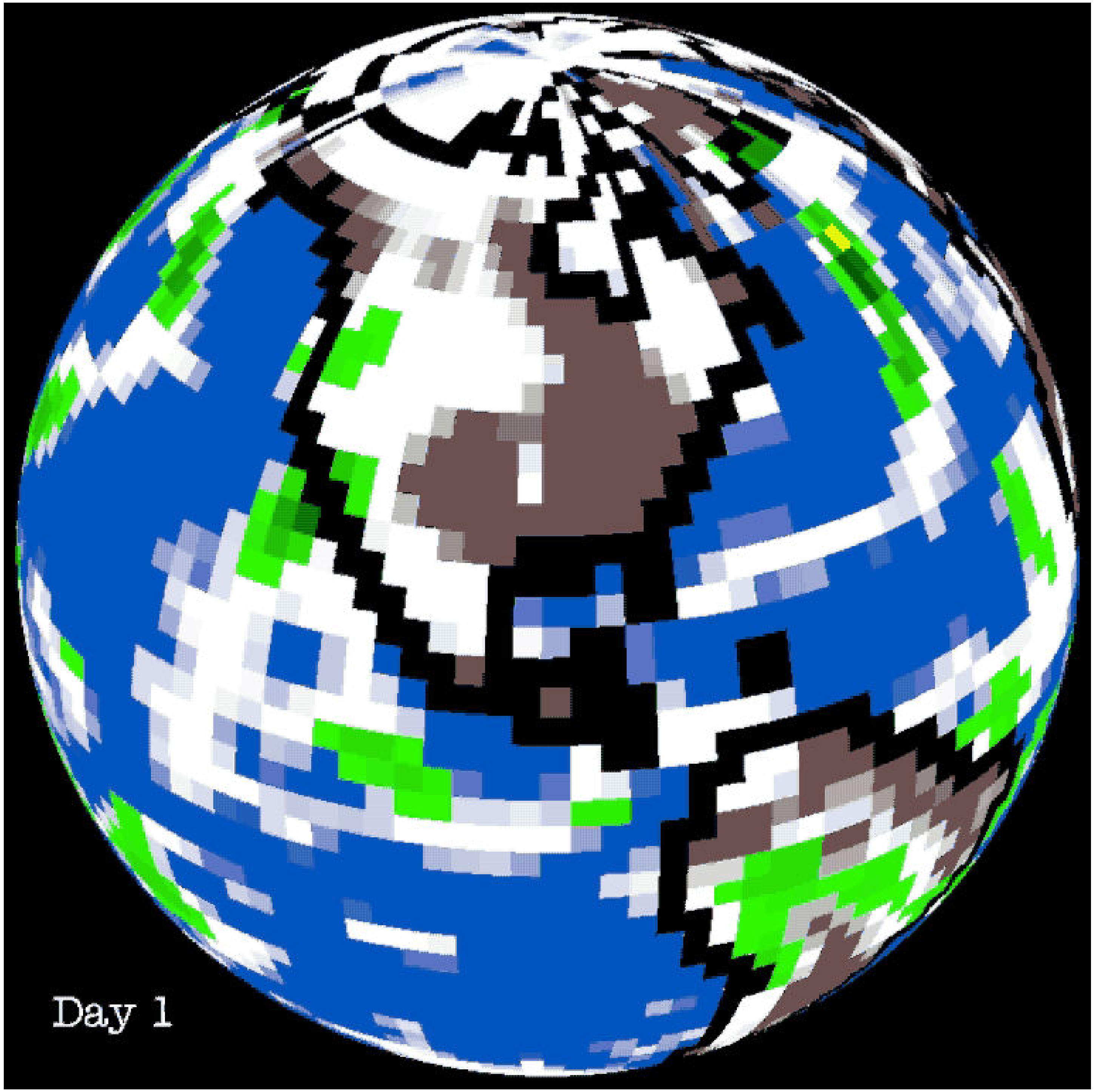
… at a high computational price

- 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

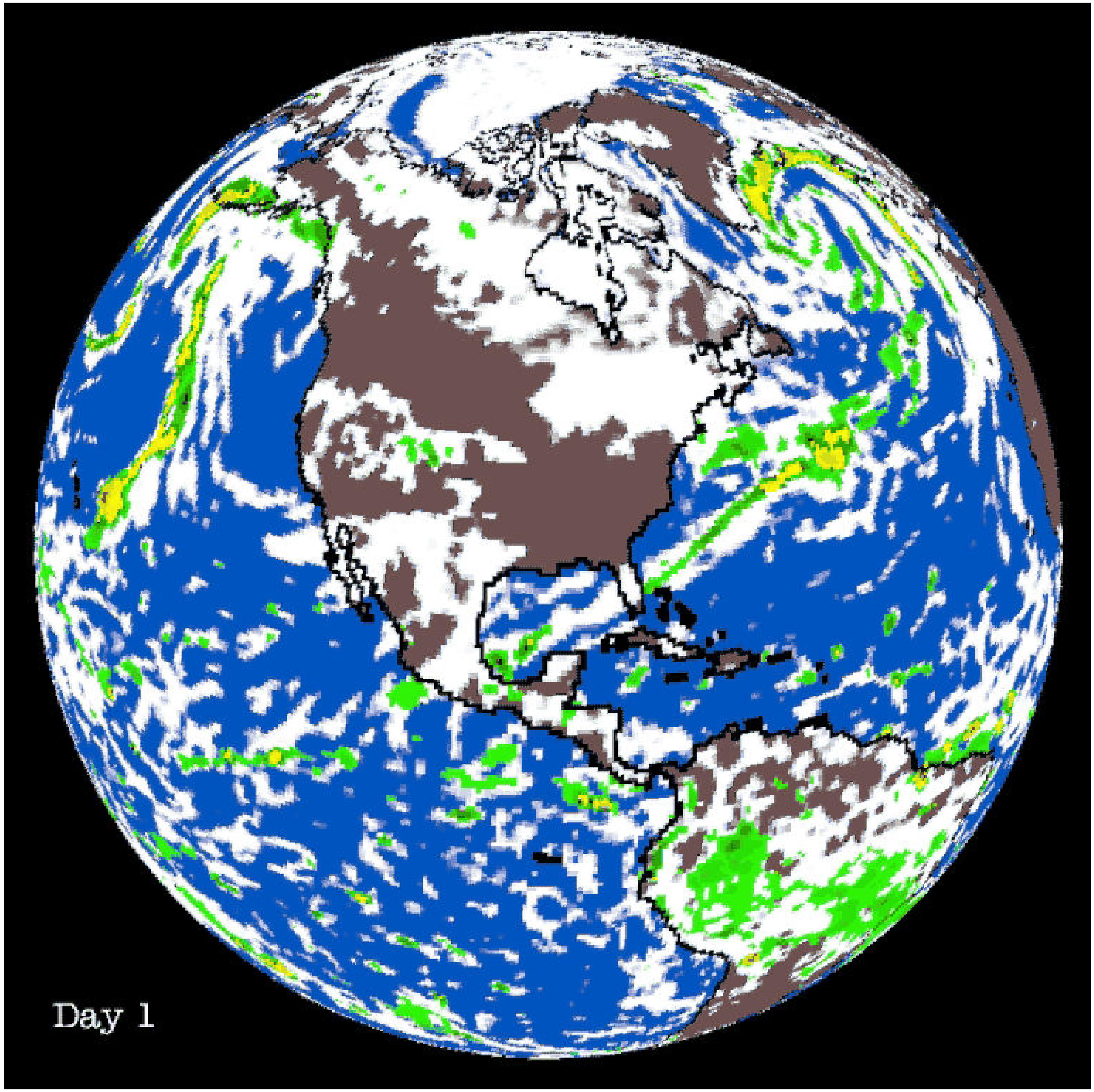
300 km

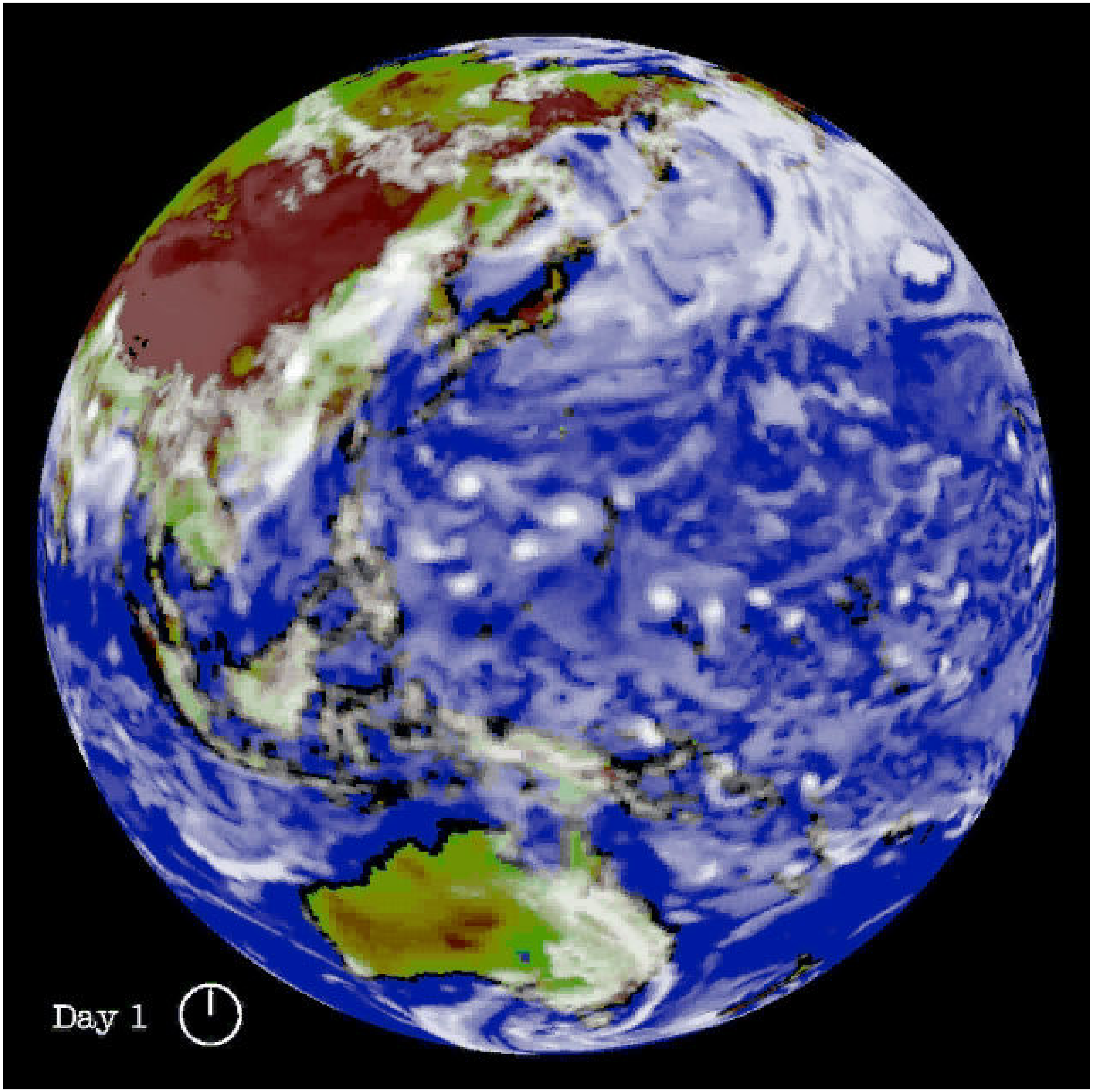
grid spacing



50 km

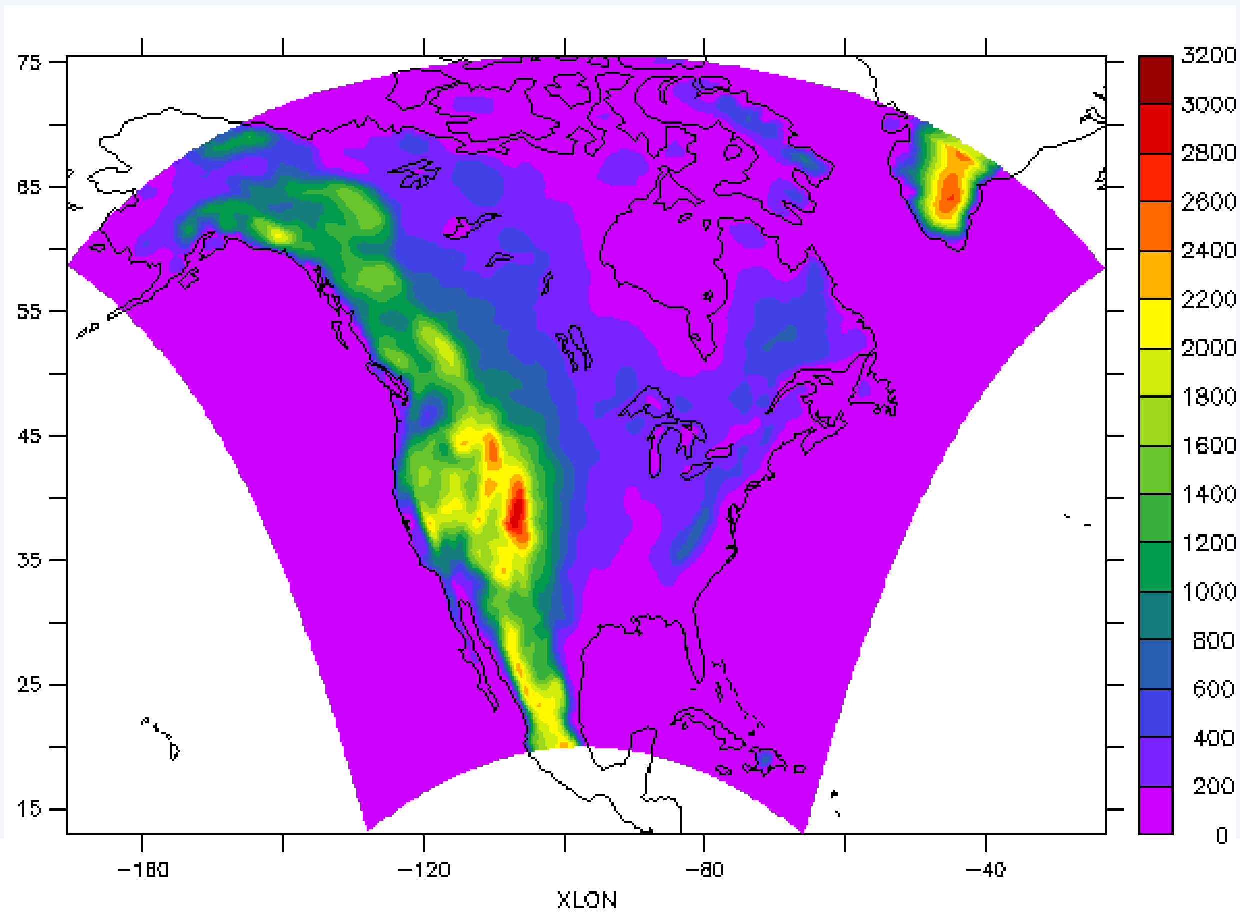
grid spacing




Day 1

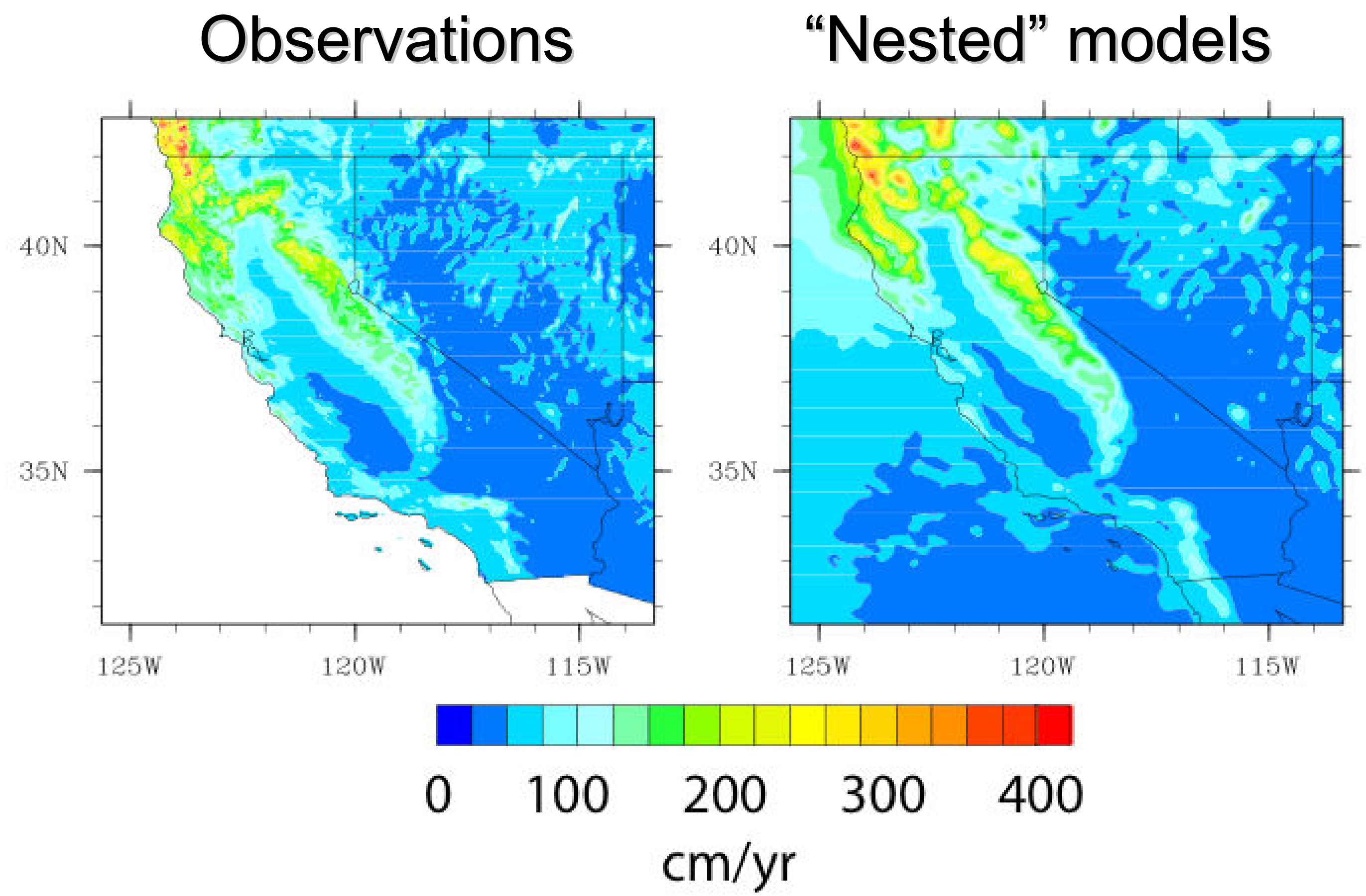
Dynamical downscaling:

Uses a nested, limited-domain climate model that is based on physical laws

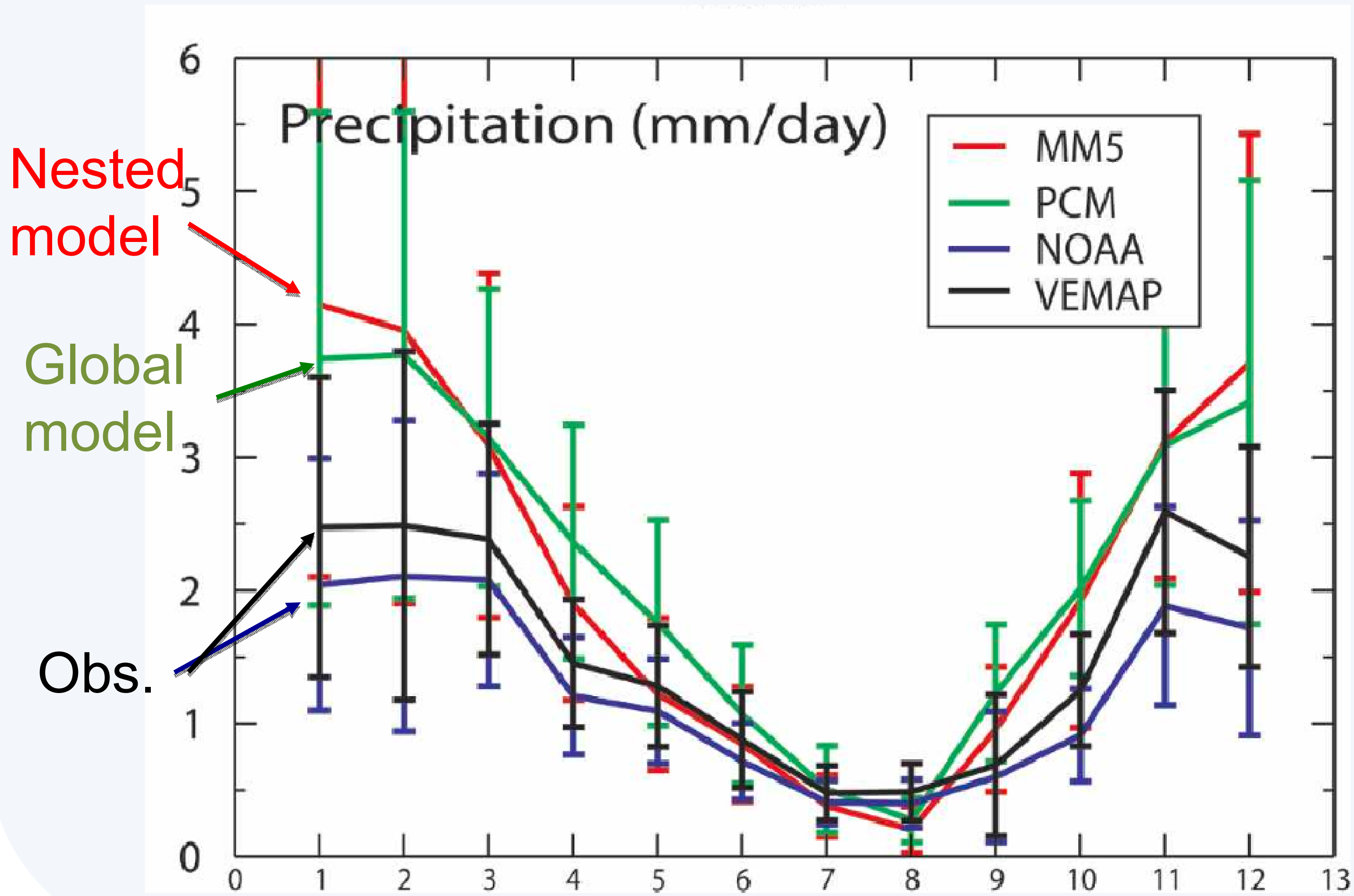


Nested models *can* work beautifully

Annual Mean Precipitation

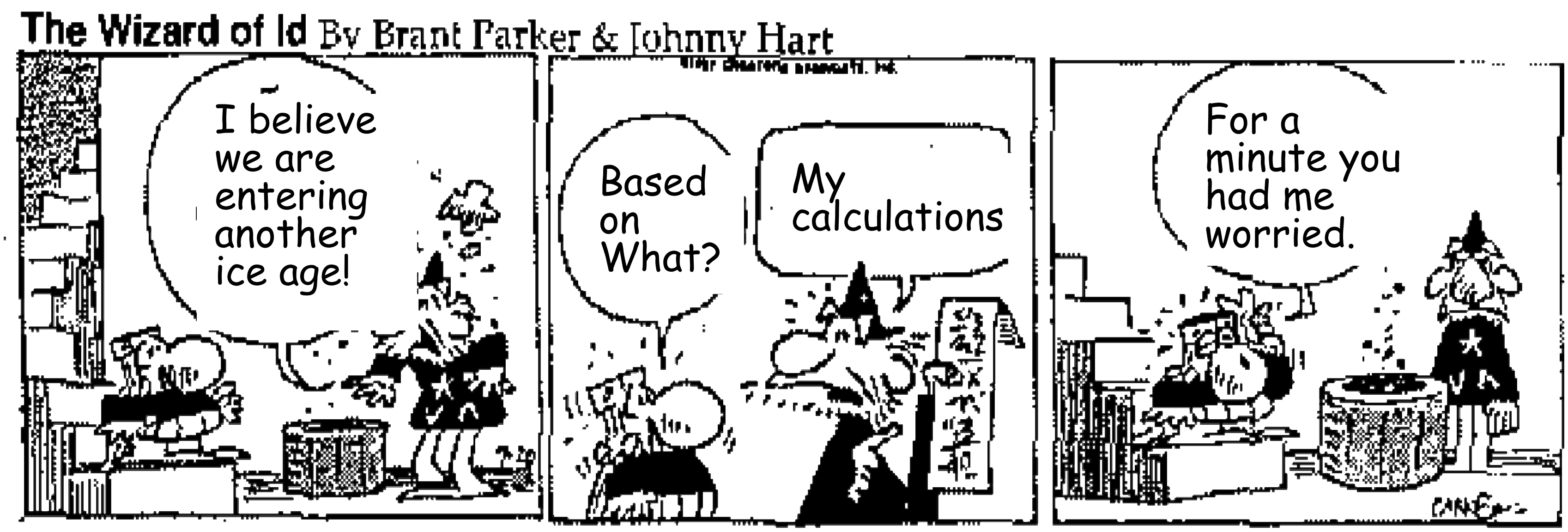


Dynamical downscaling: GIGO



Month of year->

Uncertainty: what are limits of climate prediction?

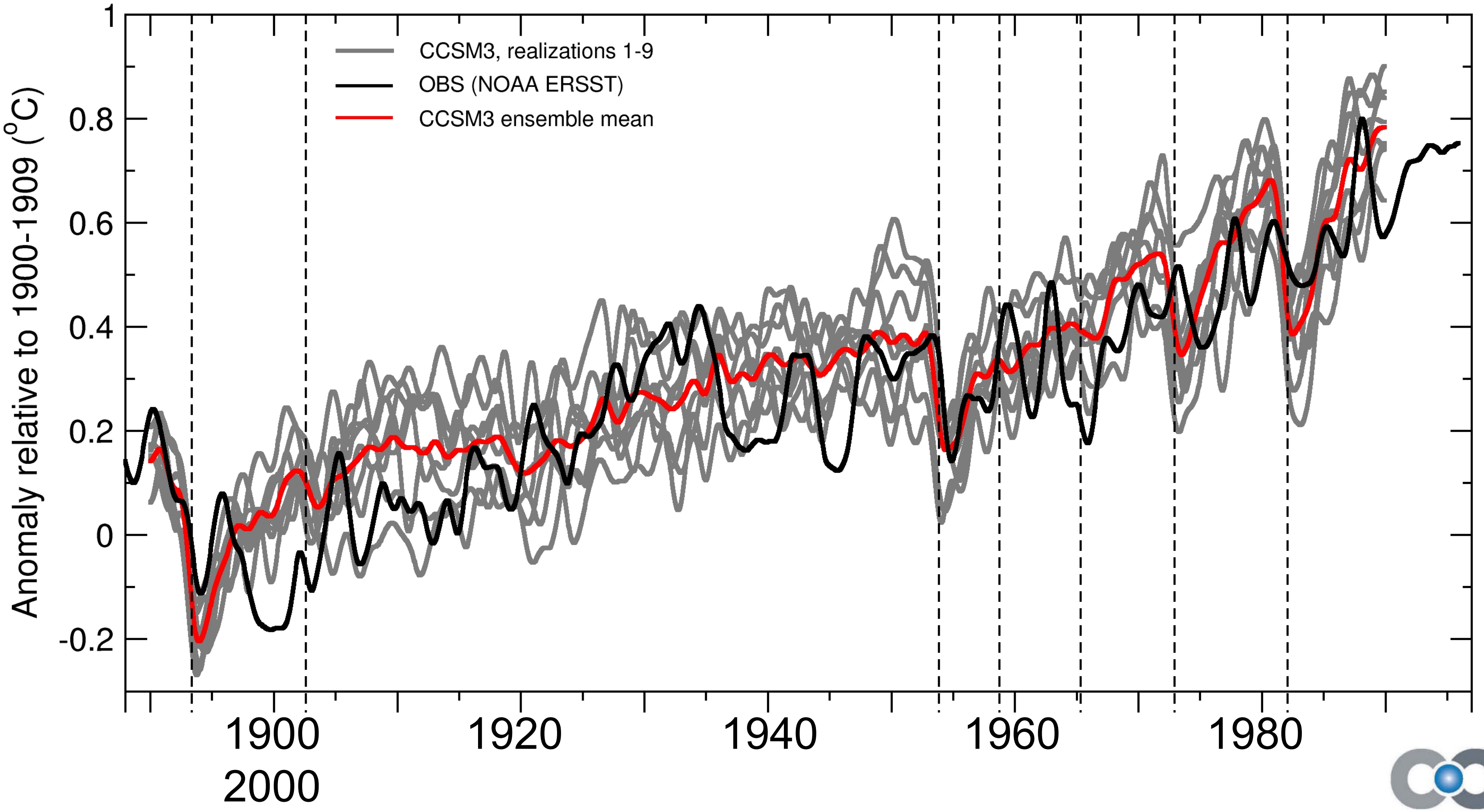


Sources of uncertainty: imperfect knowledge of

- initial conditions in the atmosphere, etc.;

Example of initial condition uncertainty

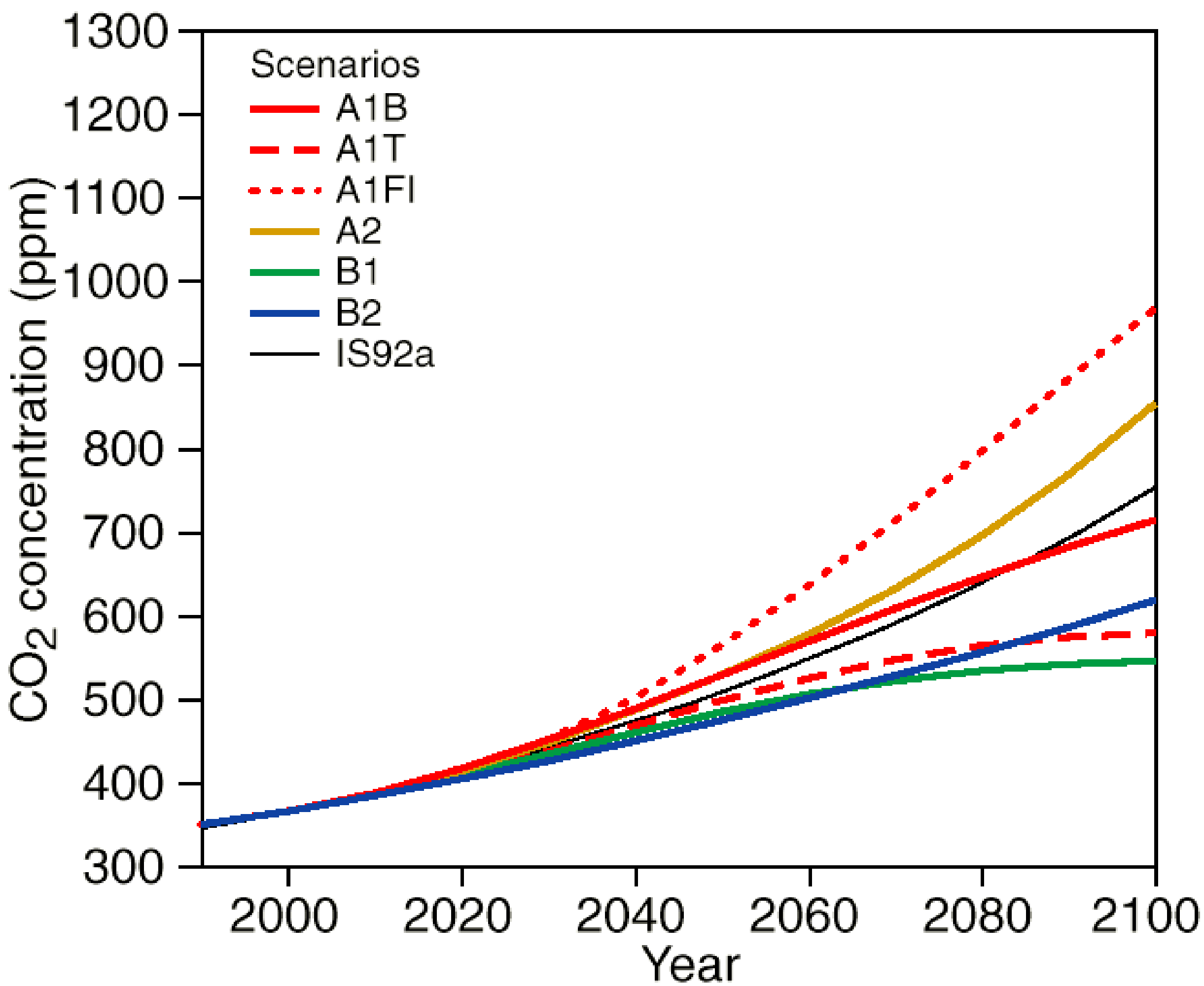
Simulated and observed regional sea-surface temperatures
courtesy Ben Santer



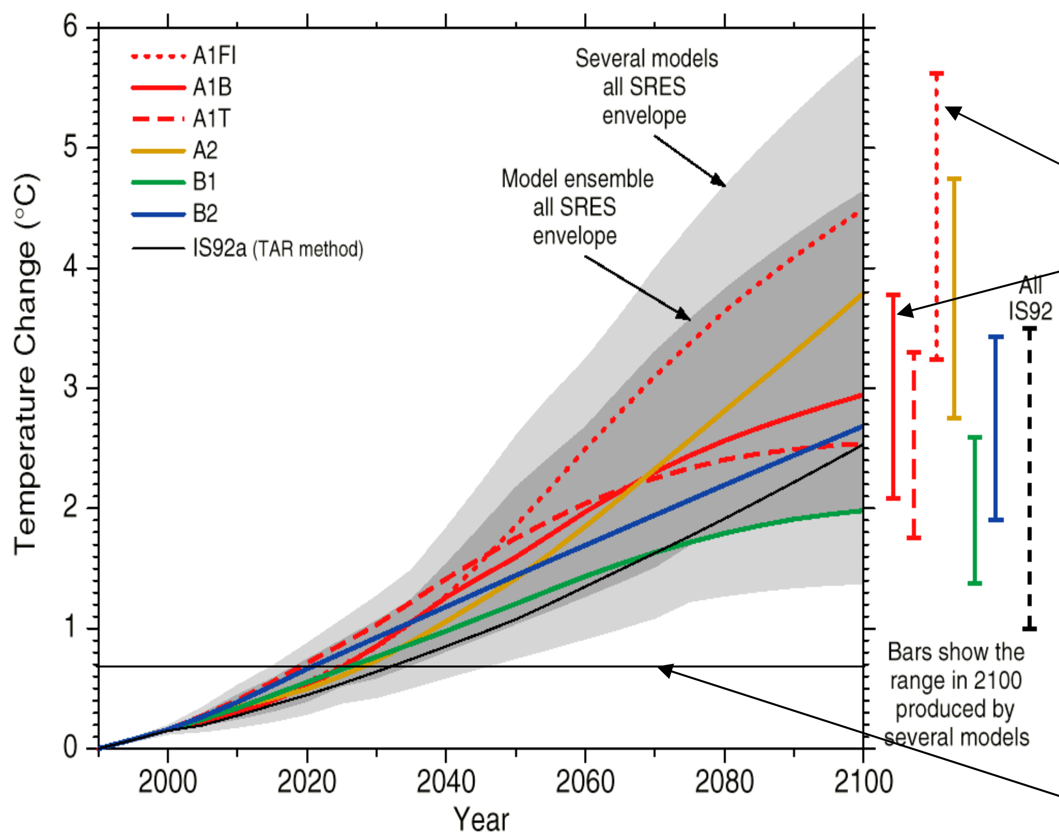
Sources of uncertainty: imperfect knowledge of

- 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

0.6° C is the amount of warming that occurred during the 20th century.

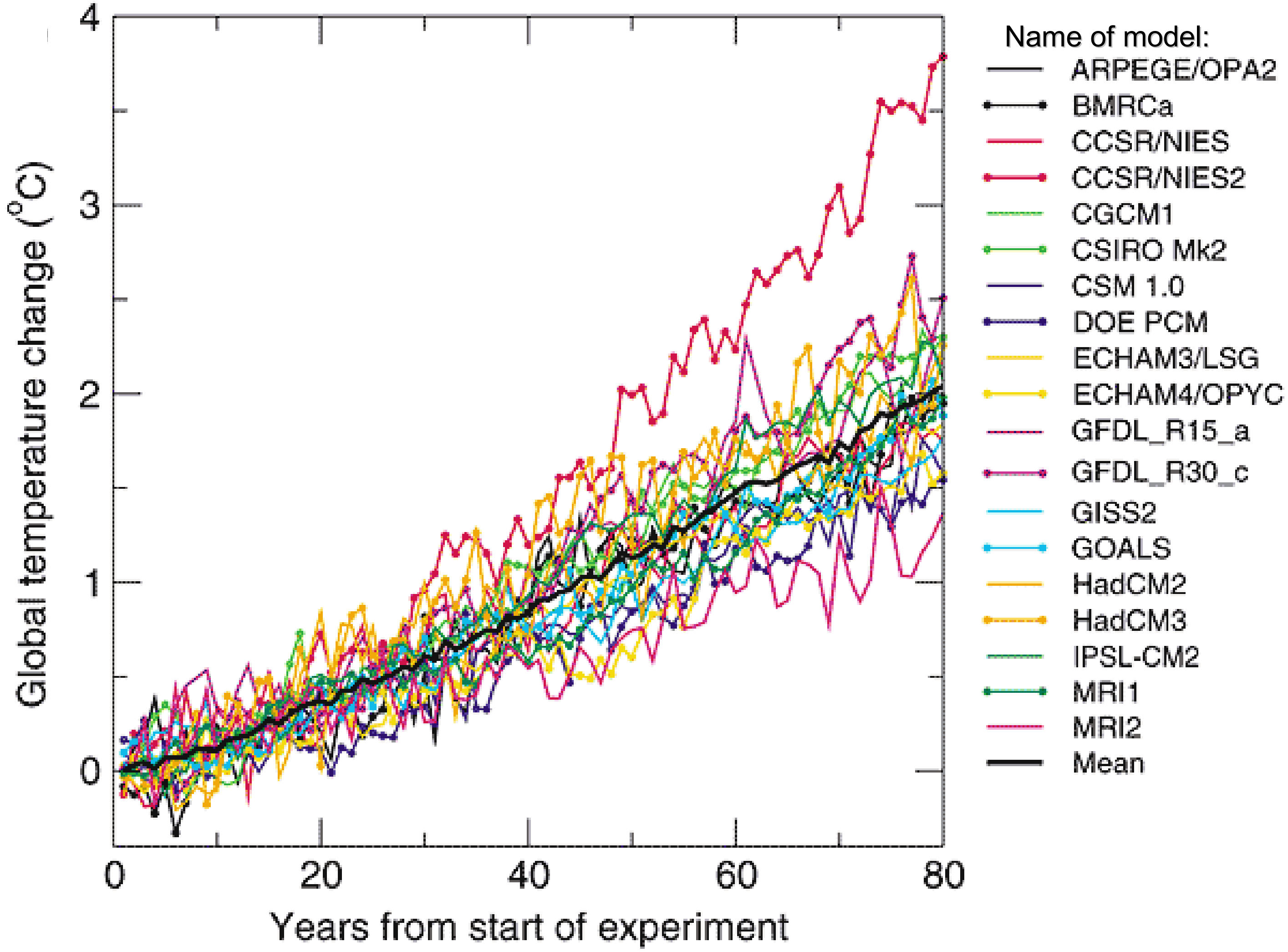
Global T will increase by 1.4° - 5.8 °C before 2100.

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

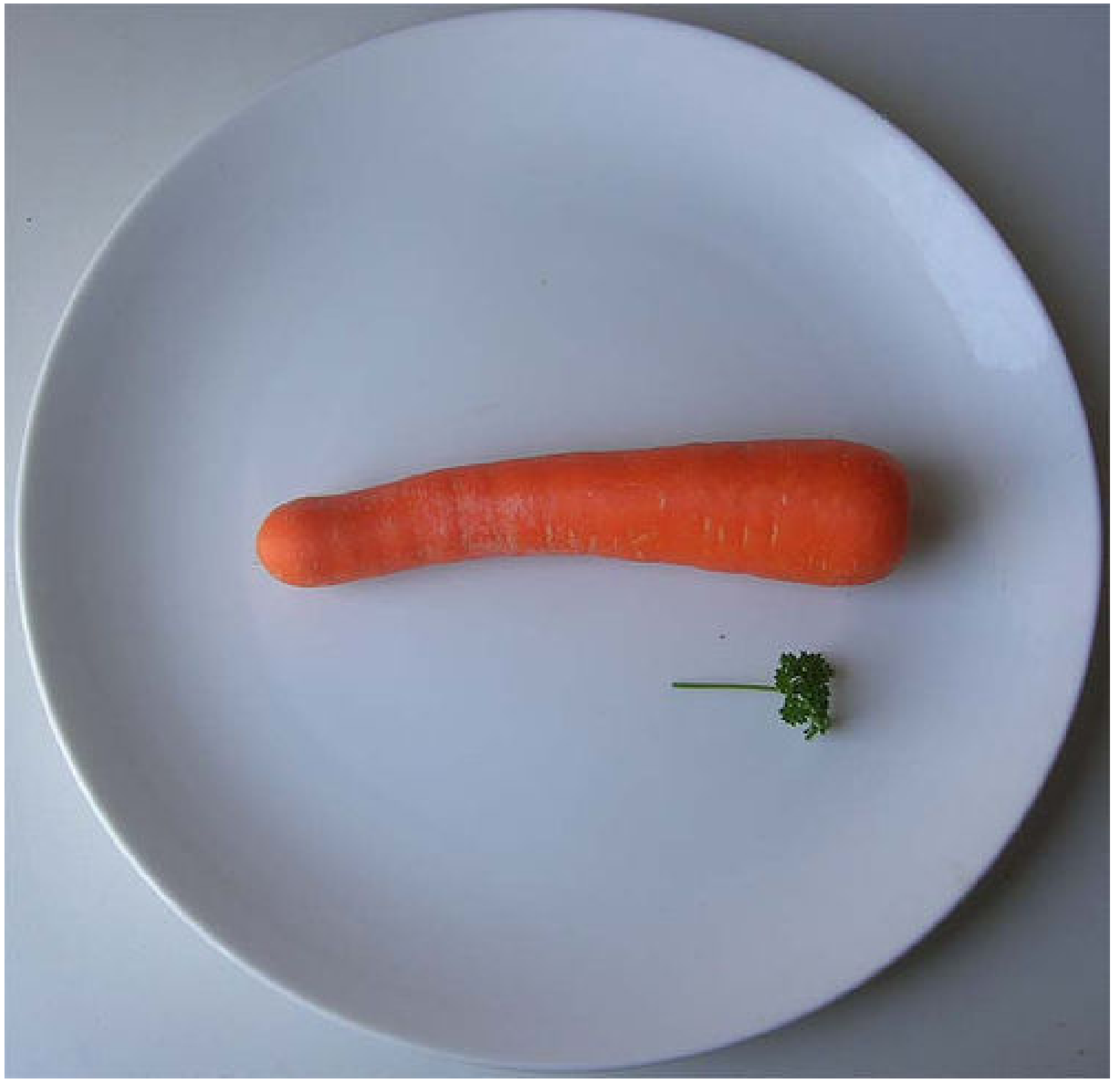


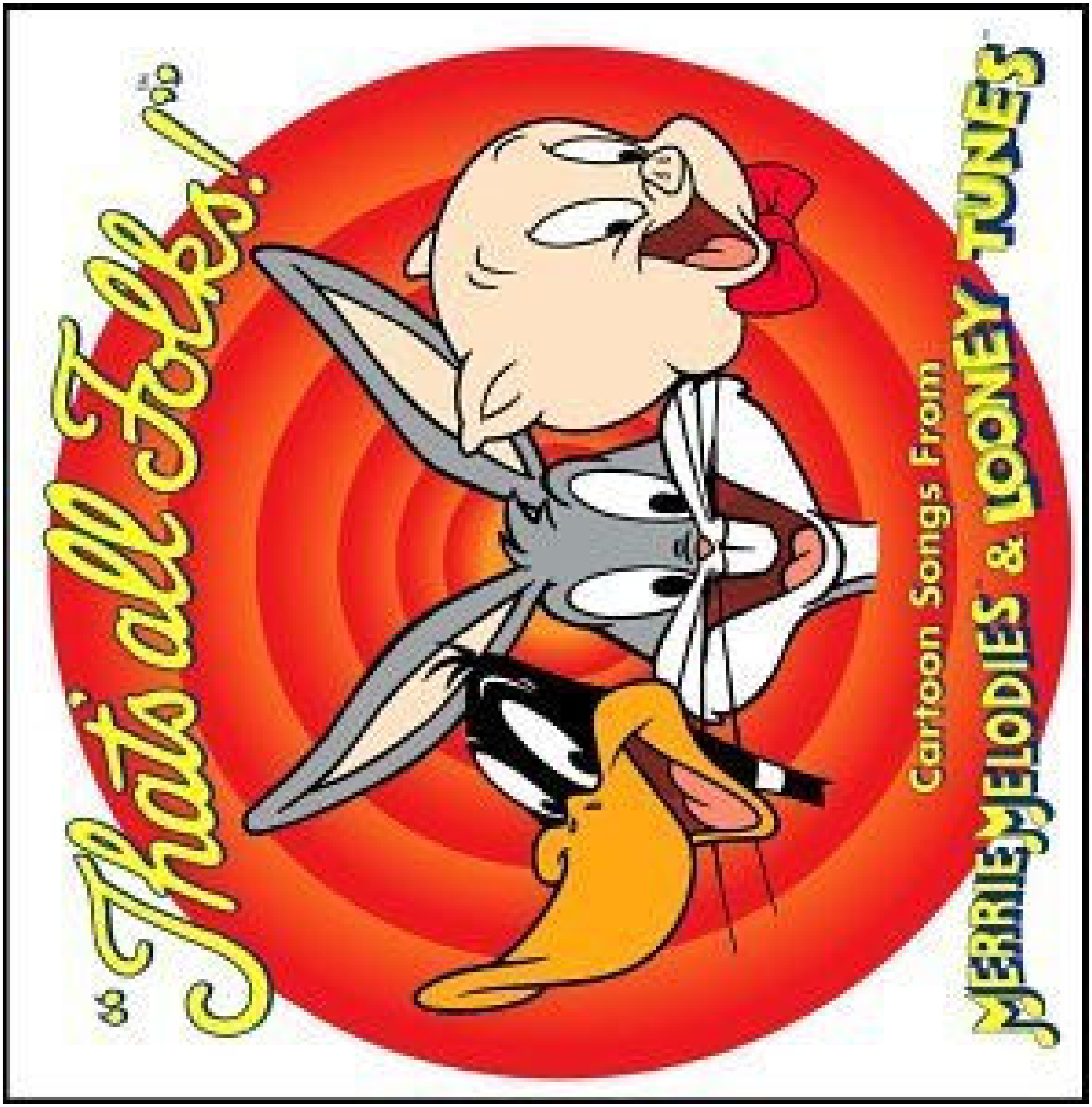
Simulated temperature responses to 1%/yr CO_2 increase

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!




That's all Folks!
Cartoon Songs From
MERRIE MELODIES & LOONEY TUNES

How do we estimate climate uncertainty?

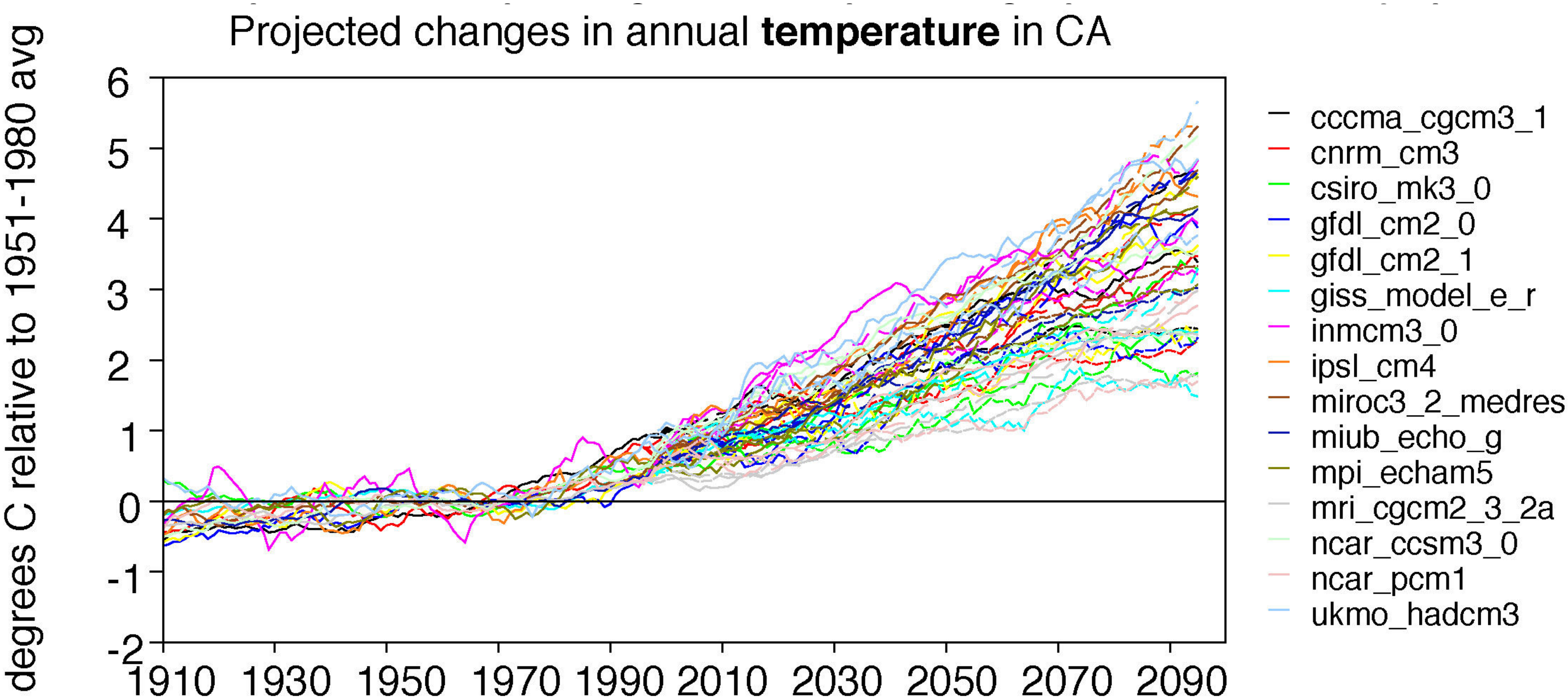
- Expert elicitation
- Ensembles of opportunity
- Perturbed physics ensemble
- Why none of these is perfect

“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



Results from 15 models, each simulating 3 CO_2 scenarios

What’s **good** about quantifying uncertainty in this way?

1. It’s a start

What's **good** about quantifying uncertainty in this way?

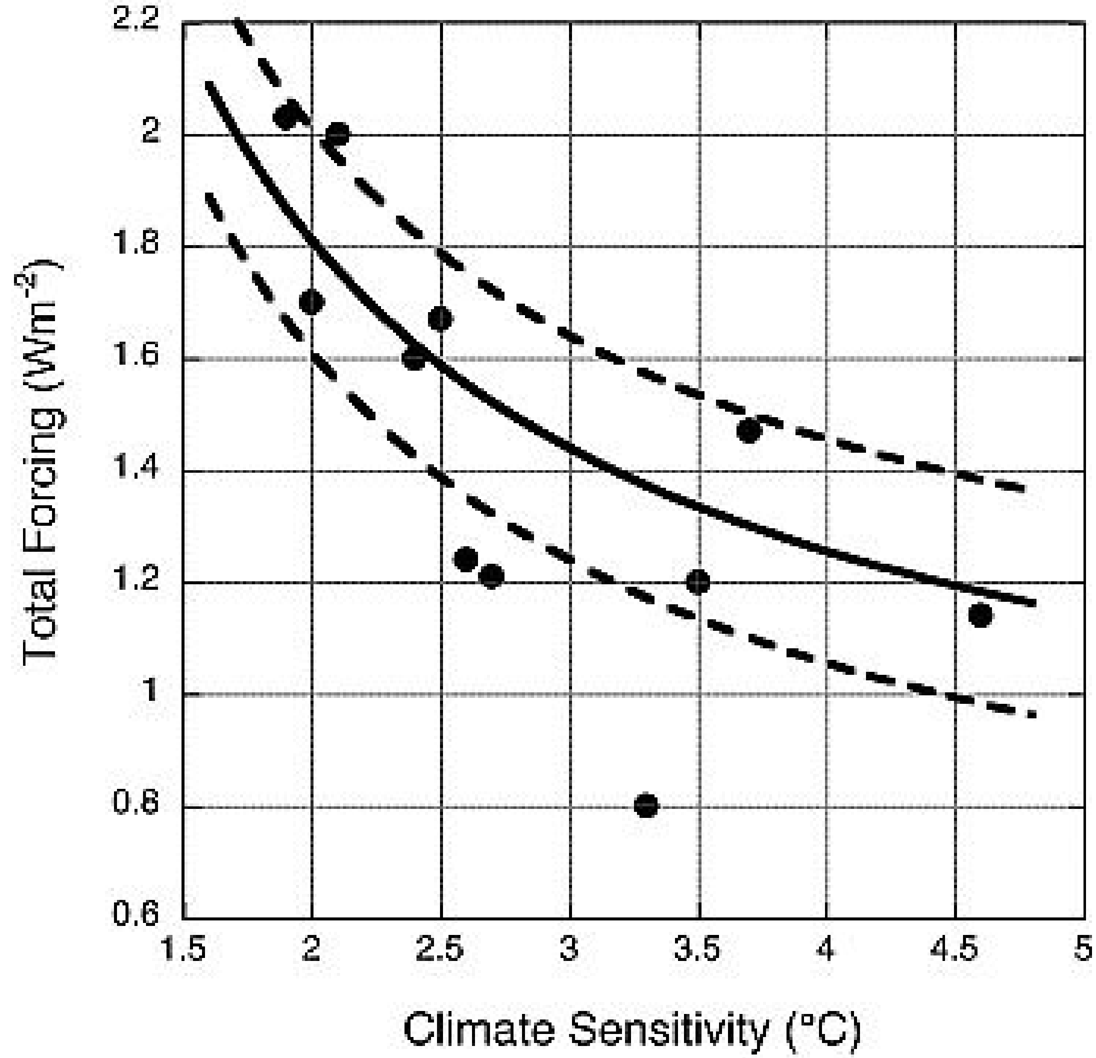
1. It's a start
2. The mean of a large number of models consistently performs better than any single model
   - This is true in climate simulation and in seasonal weather prediction
   - So having results form multiple models seems to give a better estimate of the most likely outcome.

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** …

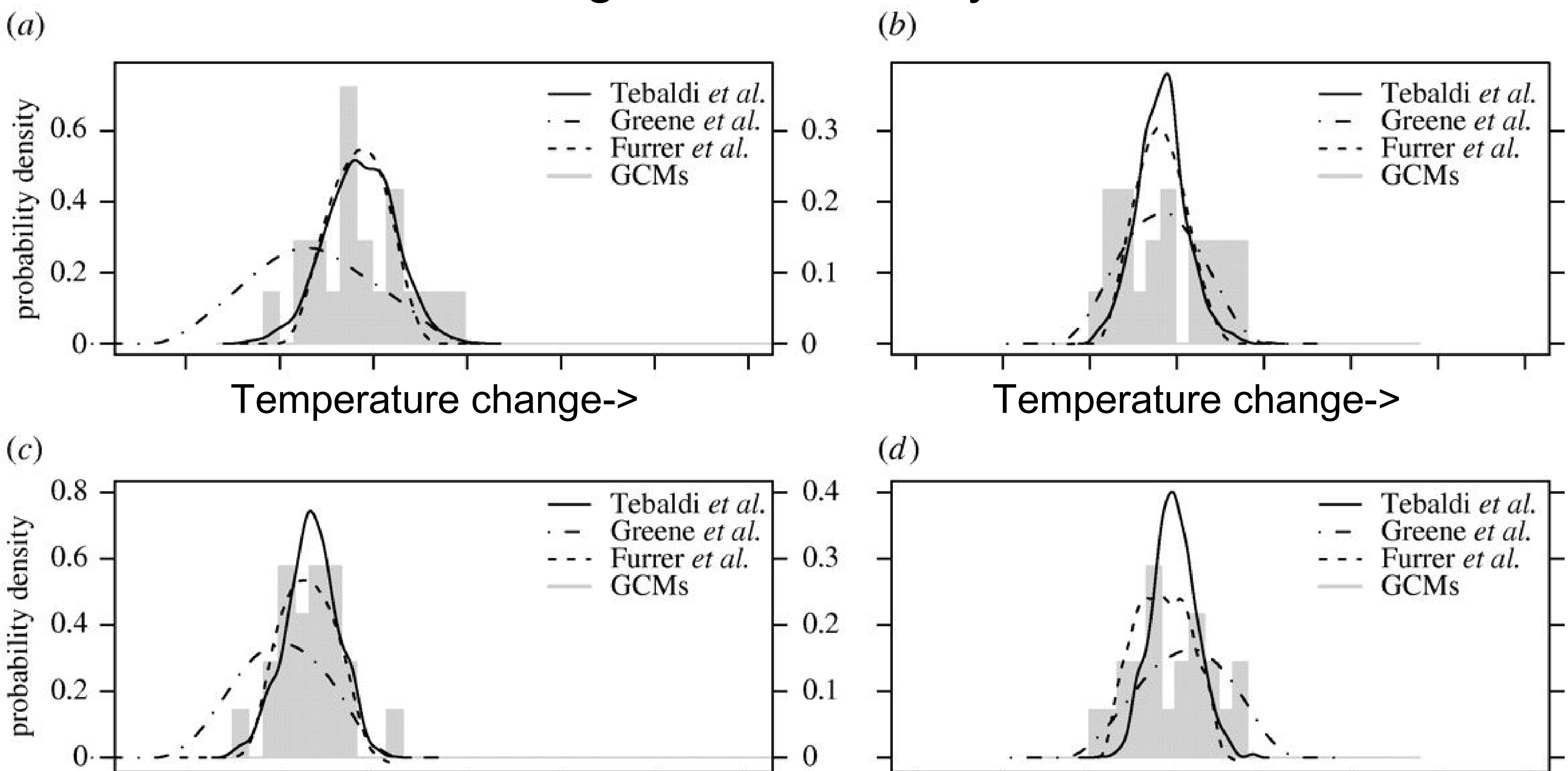
3. Some evidence that GCMs have been unconsciously “tuned”



Source: Kiehl, GRL (2007)

What’s **bad** …

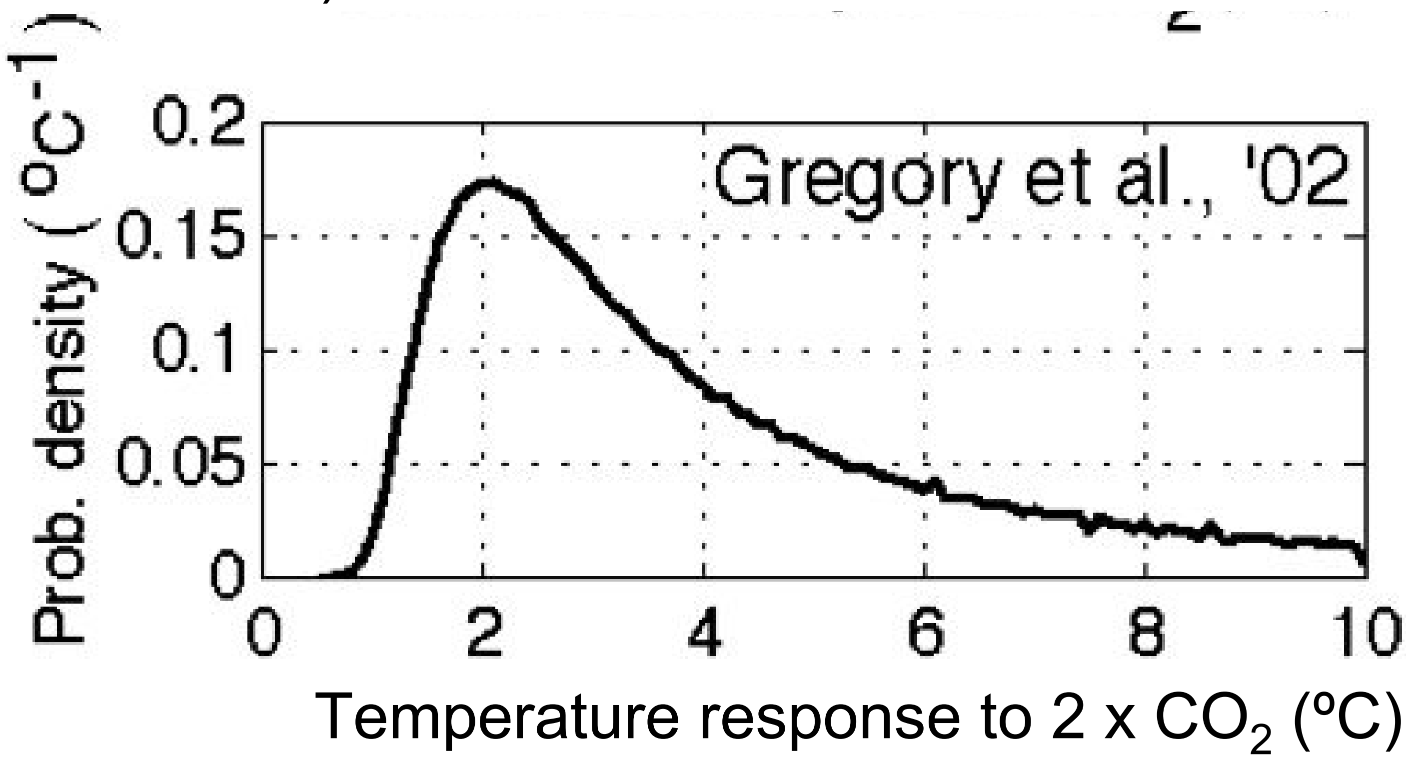
4. Often values all models equally, which *can’t* be optimal
   – But we can’t agree on best way to combine models



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.

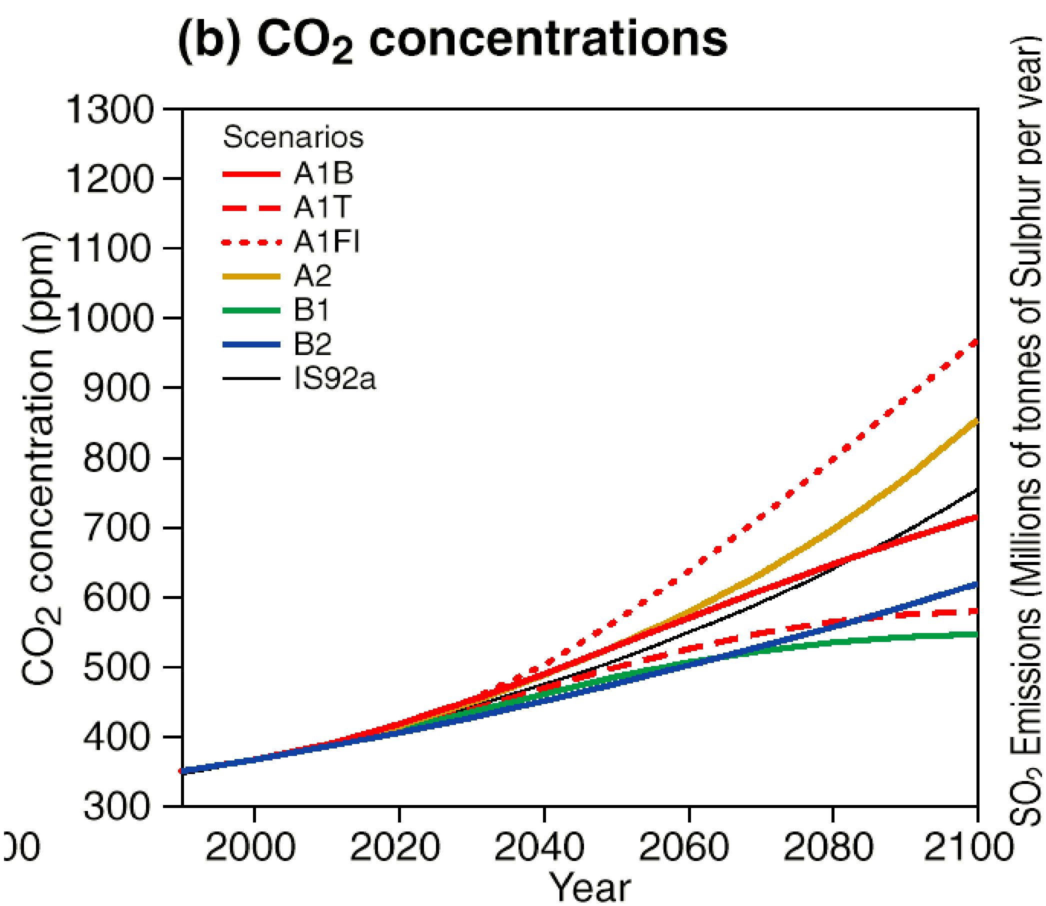


A range of model results estimates the uncertainty in the most likely outcome, not the full range of possible values.

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.