Climate prediction for decision support: intellectual and computational challenges

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Who Am I?

- Physicist
- Climate research since 1990
- Mostly modeling
- Recent focus on societal impacts of climate change, esp. in California.

THIS TALK APPROVED FOR

G | GENERAL AUDIENCES

All Ages Admitted

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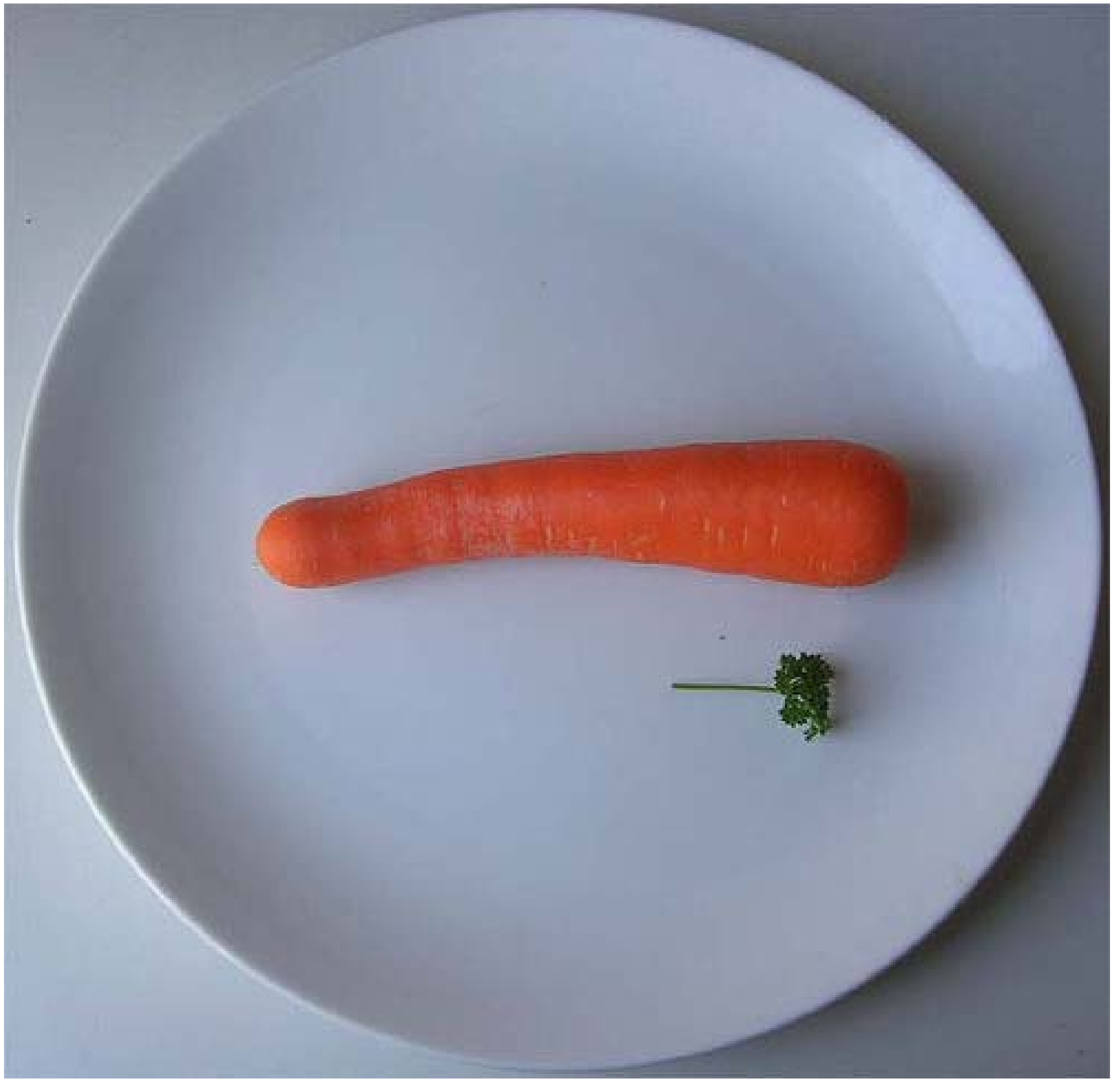
Thanks for dinner!



Outline

- Origins of climate modeling
  - Climate vs. weather
- Some detail about models of the atmosphere
- How well do climate models work?
- Societal impacts of climate change
  - Importance
  - Implications for climate modeling
- Parting thoughts

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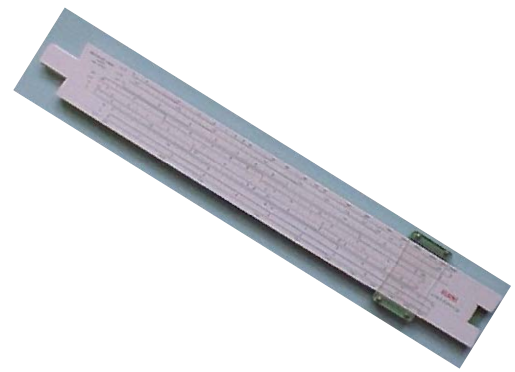
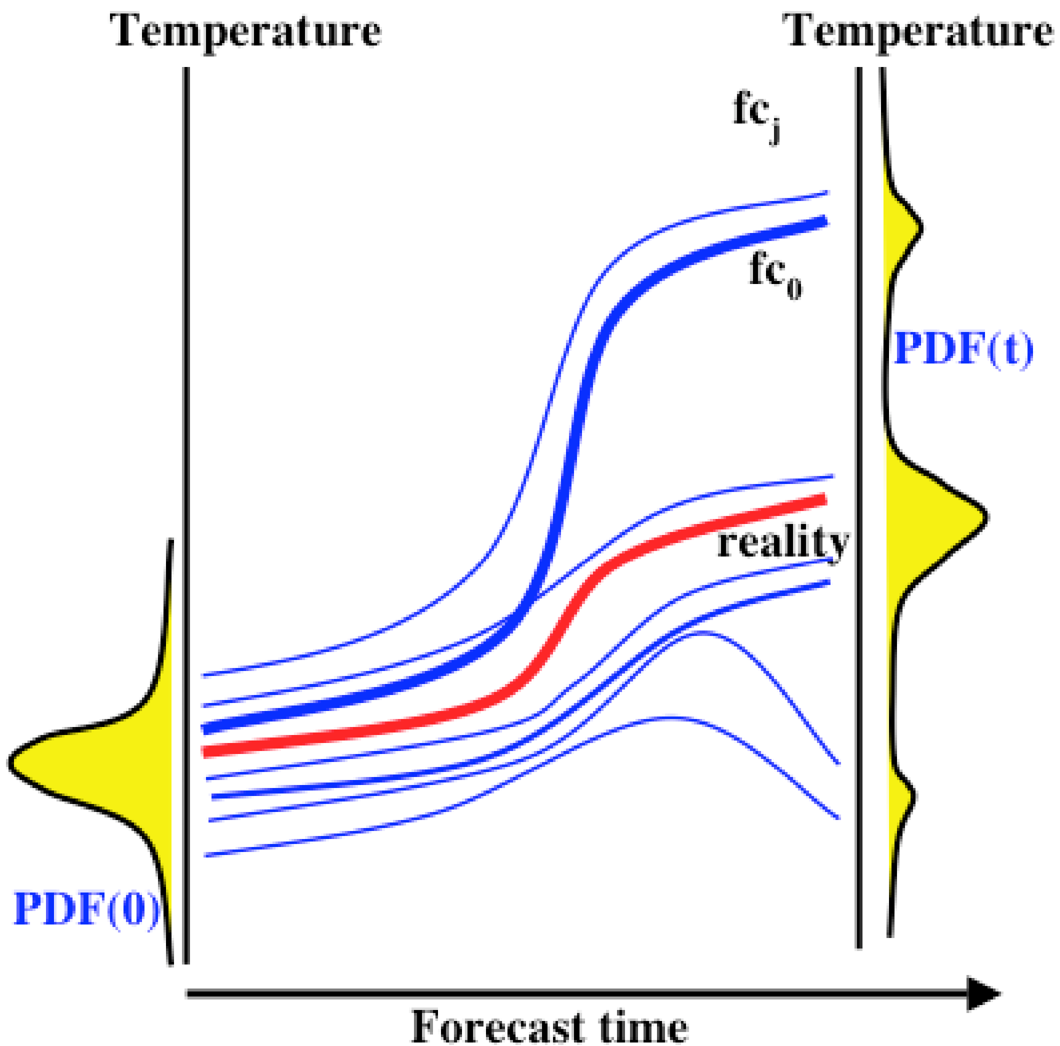
Two fathers of numerical weather prediction

Vilhelm Bjerknes
Conceived of numerical weather prediction (1904)



Lewis Fry Richardson (1881 – 1953)
Performed first numerical weather forecast

Weather prediction is an *initial* value problem



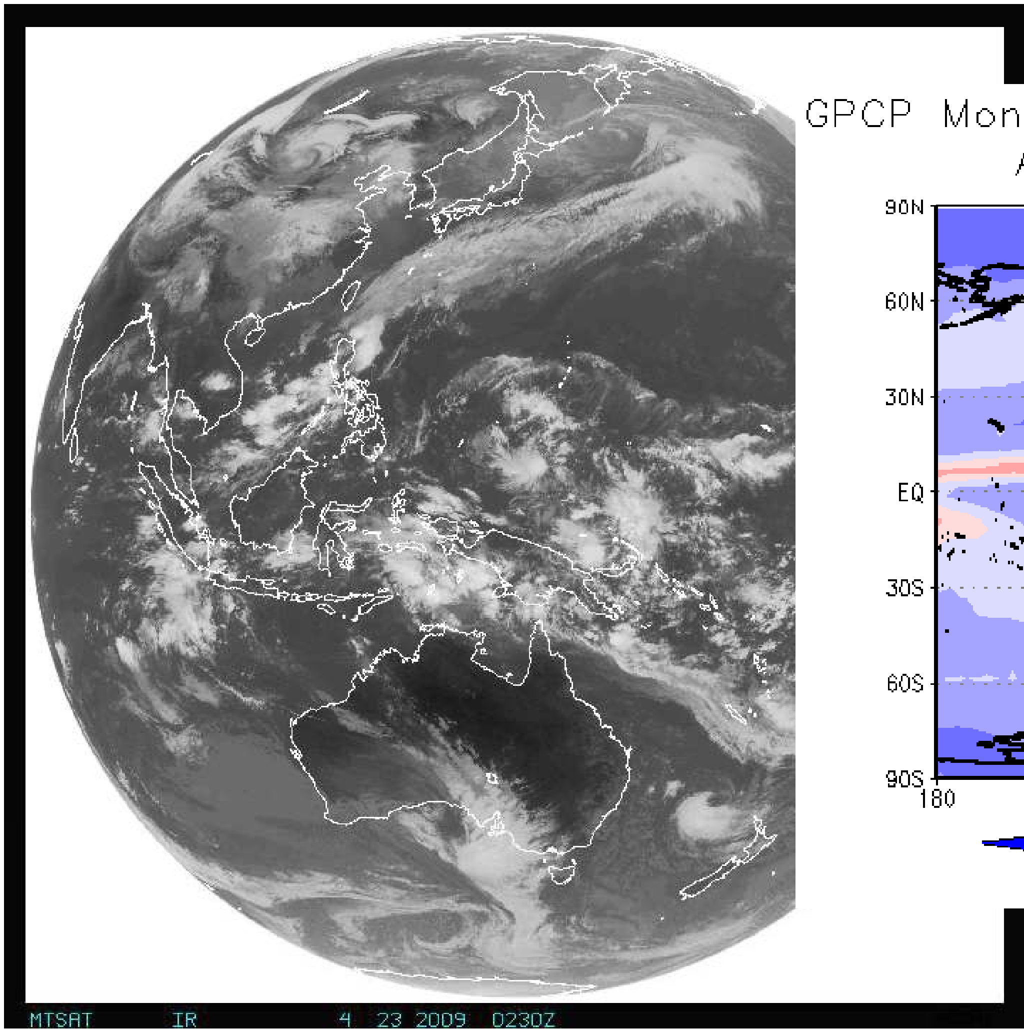
Source: Roberto Buizza, European Centre for Medium-Range Weather Forecasting

Chaos theory arose in meteorology

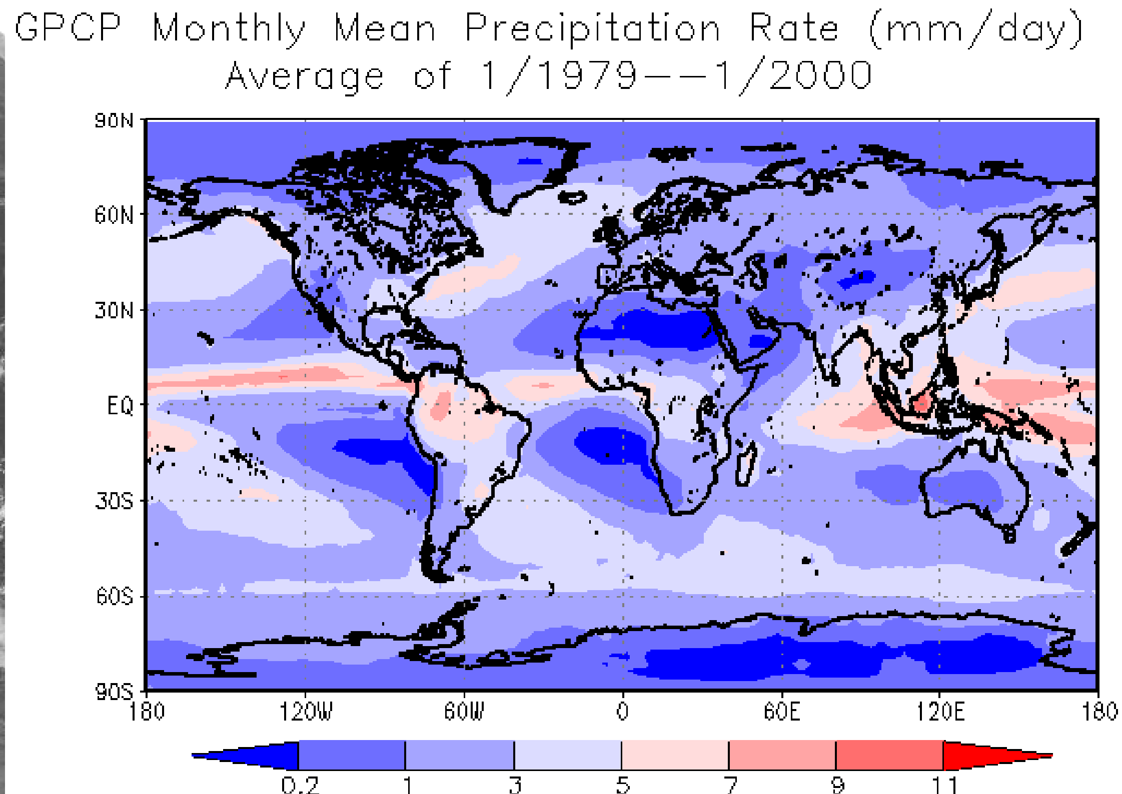
Ed Lorenz (1917-2008)
Discovered the concept of chaos
as a meteorologist at MIT

Climate: a statistical description of weather

Weather:



Climate:



Climate prediction is a *boundary* value problem

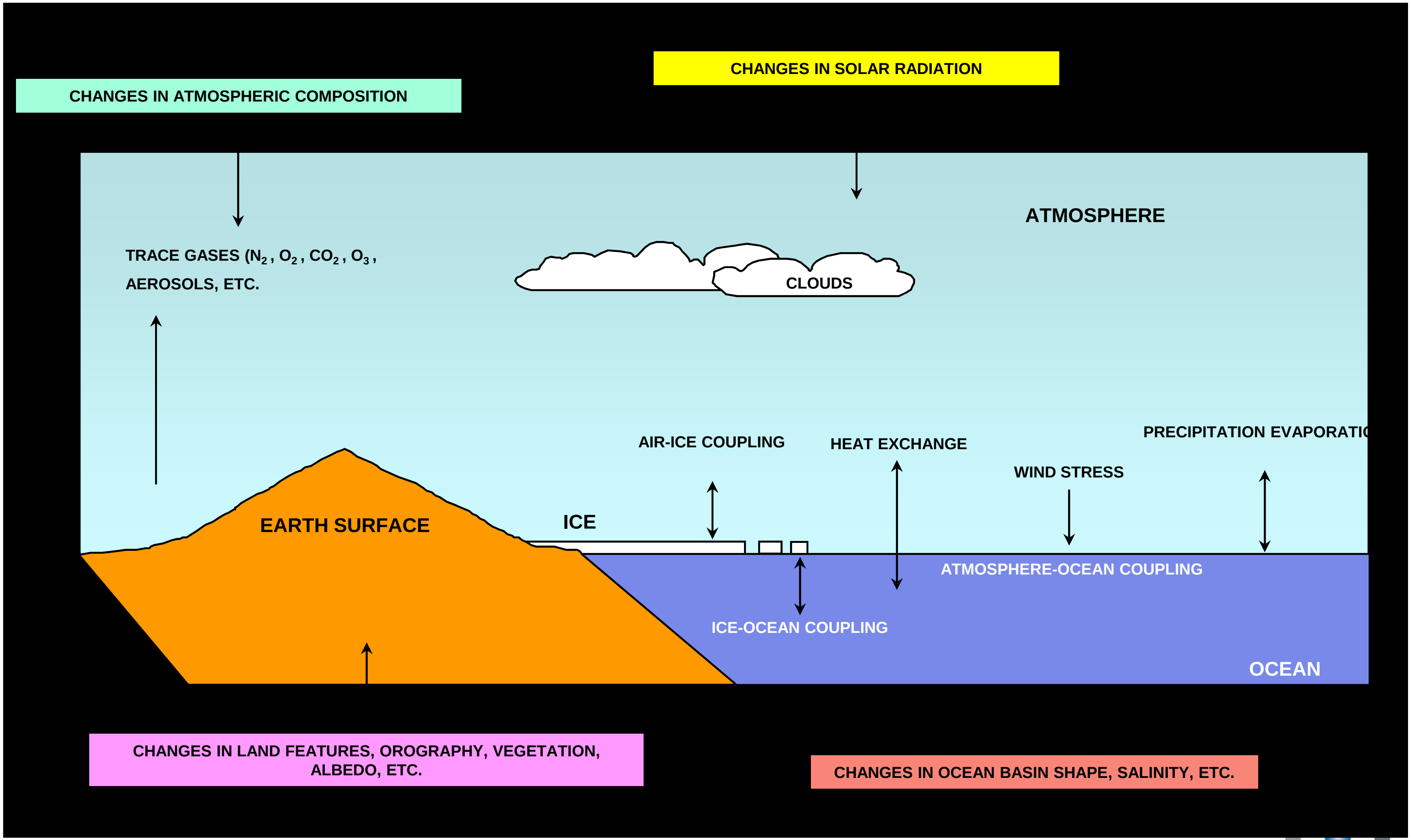
Fossil fuel burning

Particulate pollution

Agriculture

Urbanization

Climate models treat ocean, sea ice, land surface, etc.



The Development of Climate models, Past, Present and Future

Weather vs. climate prediction: summary

Weather models

- Predict conditions at specific times and locations, a few days ahead.
- Are carefully initialized from recent observations.
- Typically use finer resolution.
- Can be run in ensembles.

Climate models

- Also predict weather! We analyze the statistics of the predicted weather, but not the weather itself.
- Treat the ocean, sea ice, and interactive vegetation more thoroughly than weather models do, because longer time scales are simulated.
- Can be run in ensembles.

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Climate simulation by Warren Washington, circa 1969

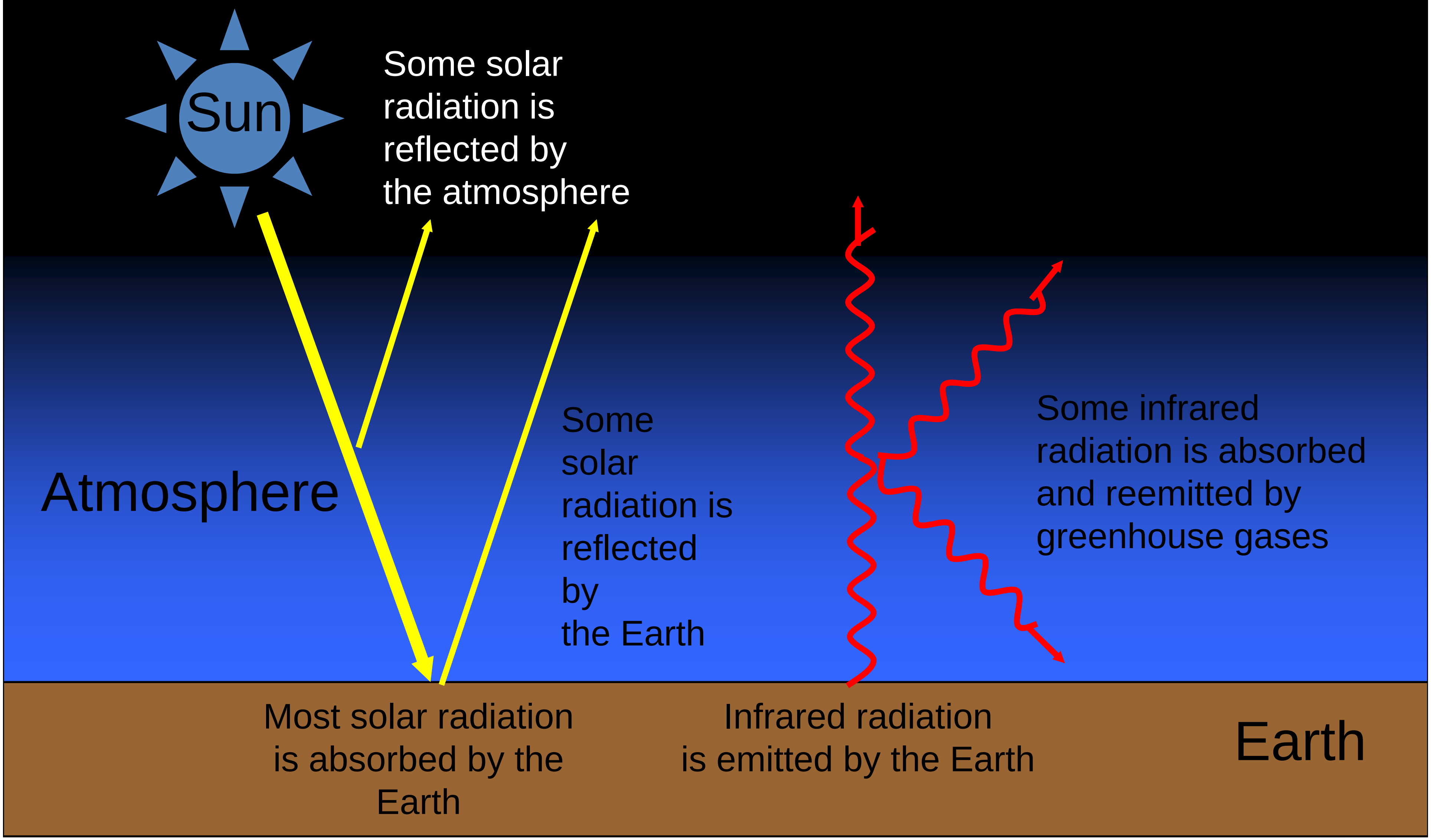
Atmospheric modeling involves computational fluid dynamics

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

Earth's radiation balance



Clouds: the Achilles heel of climate models

Why are clouds important?

They

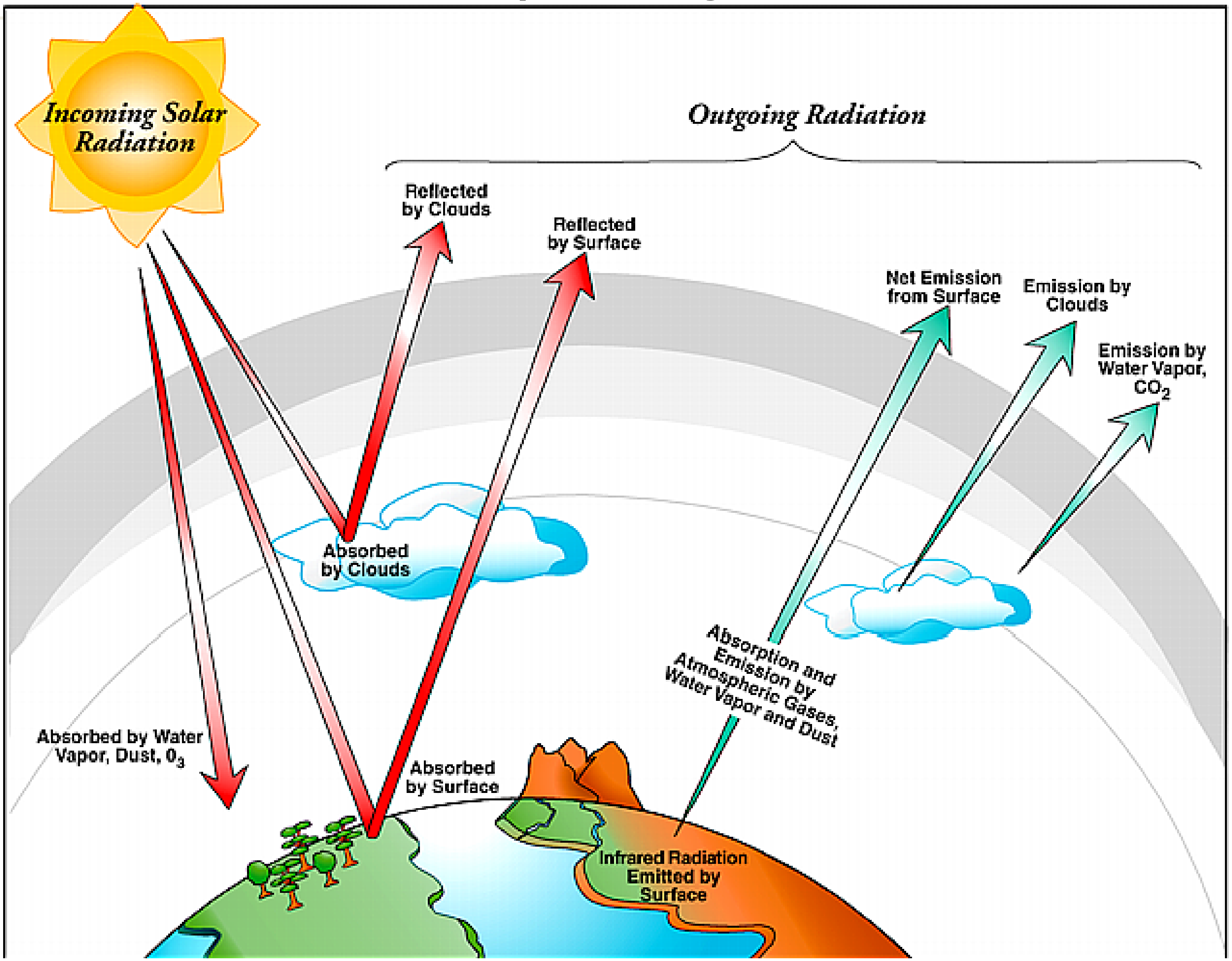
- strongly affect both solar and terrestrial radiation
- control precipitation

Why are clouds hard to model?

They

- are much smaller than model grid cells (I.e. are unresolved)
- are very complex and not well understood
- respond in unknown ways to increasing greenhouse gases and other climate insults.

Clouds and precipitation are treated quasi-empirically



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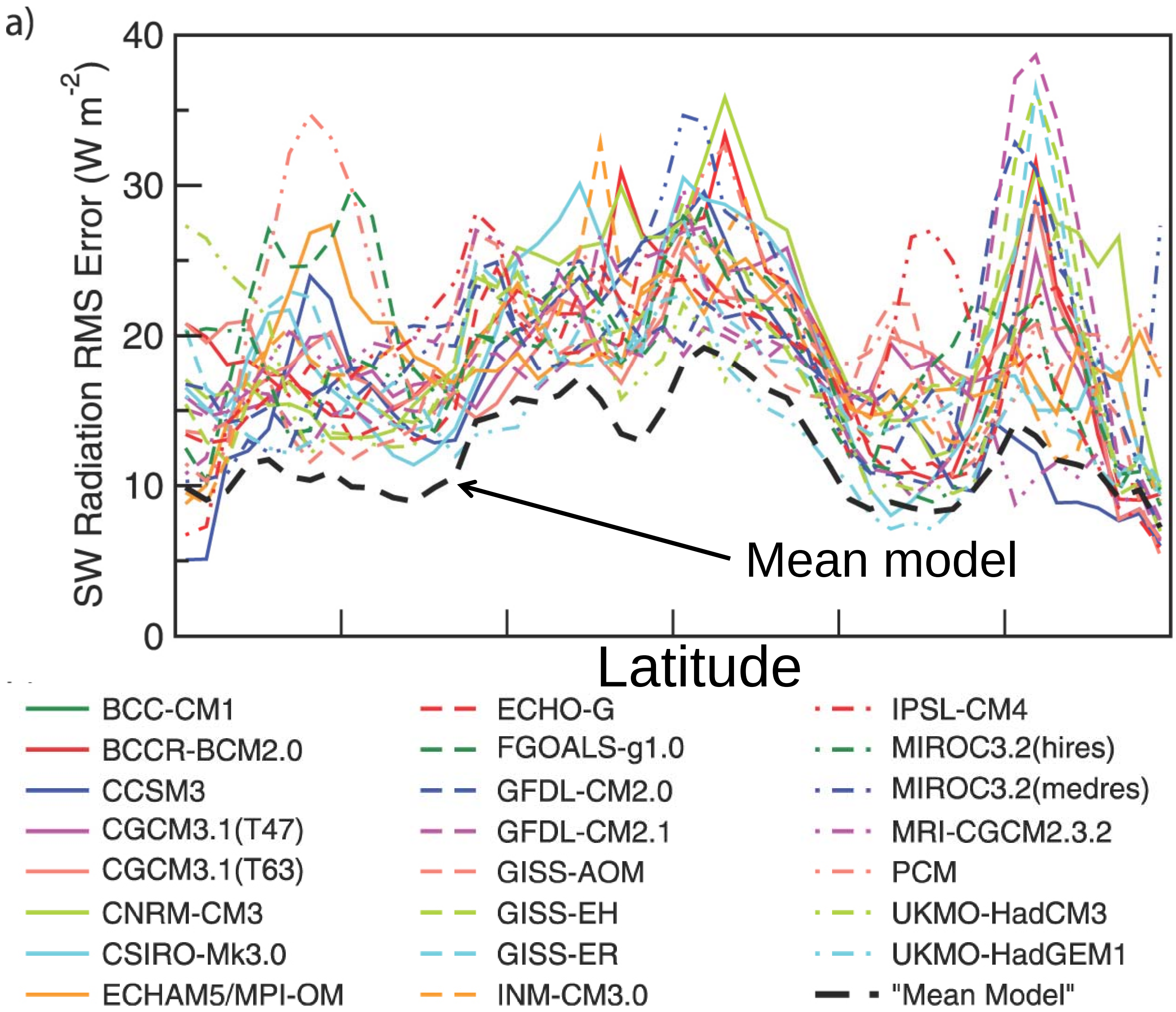
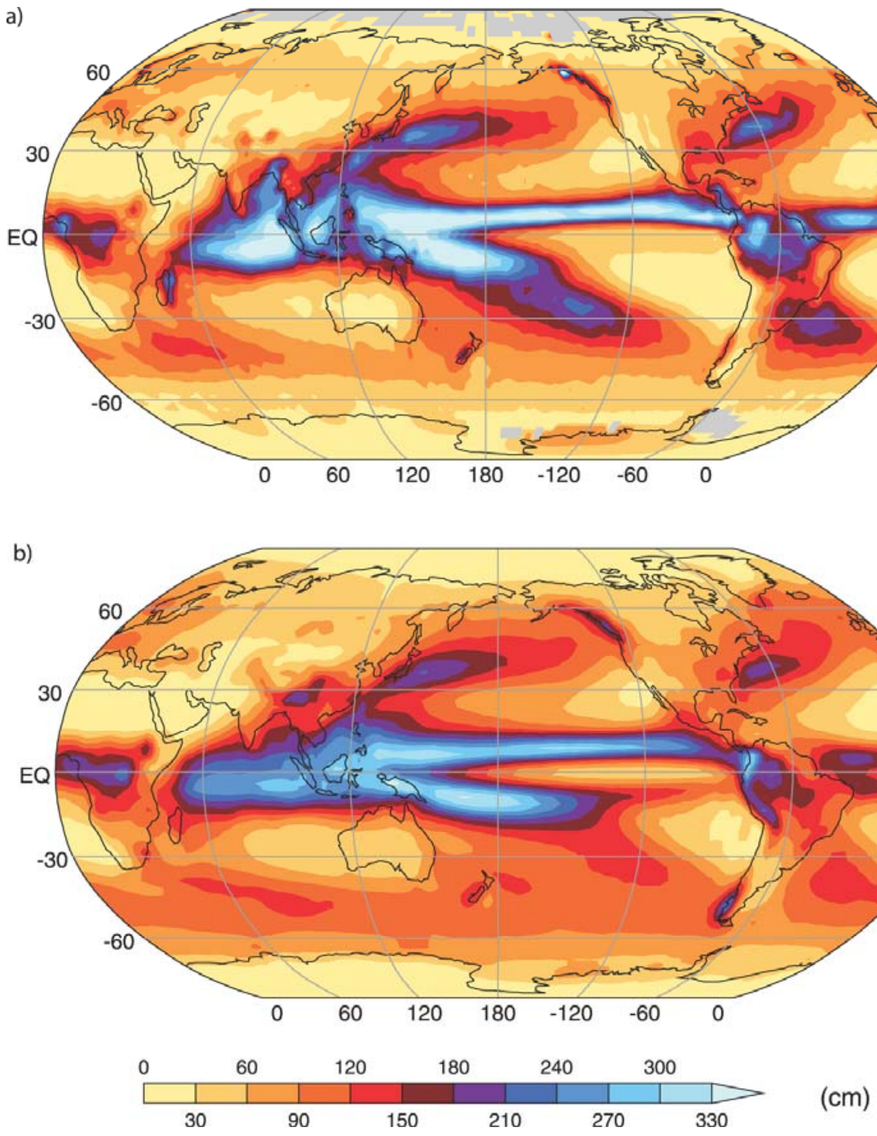
RMS errors in simulated outgoing solar radiation



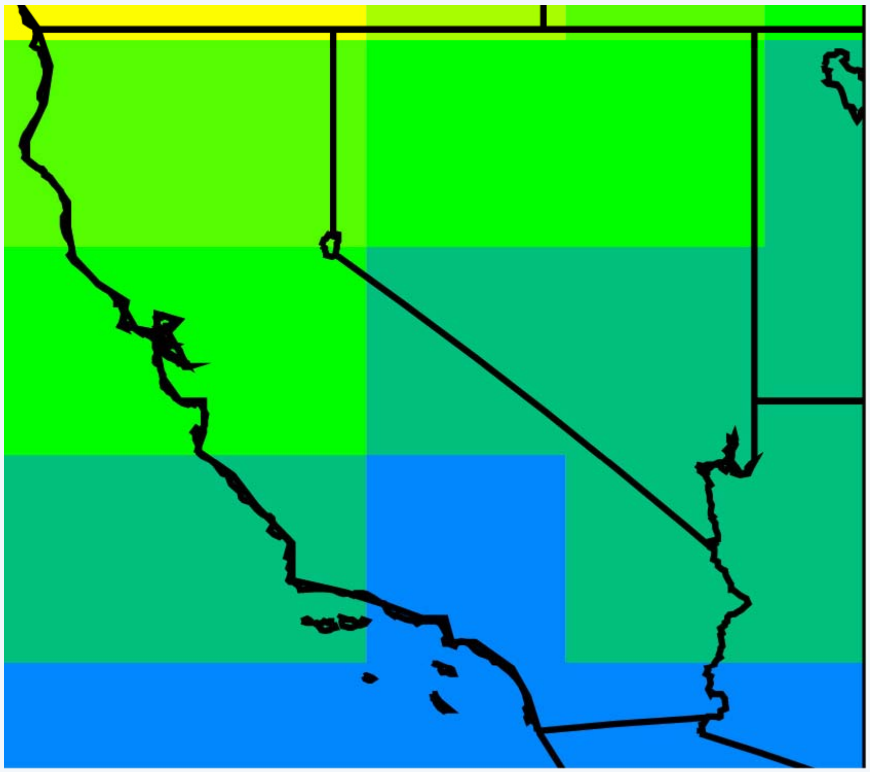
Global climate models do well on the global scale…



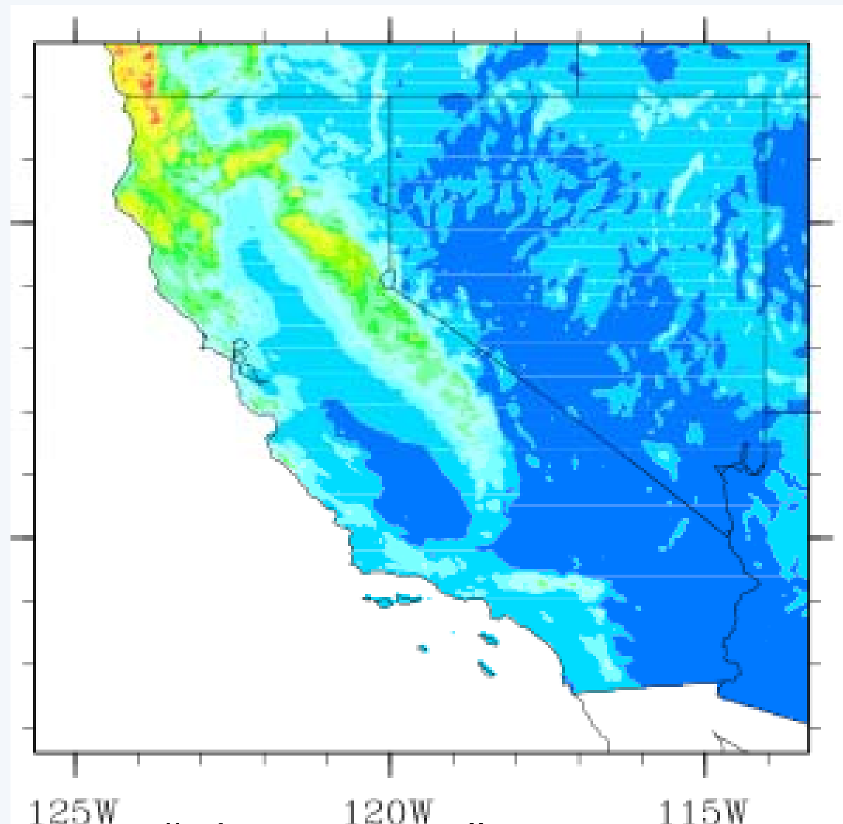
Observed precipitation

Simulated precipitation

…but less well on finer scales



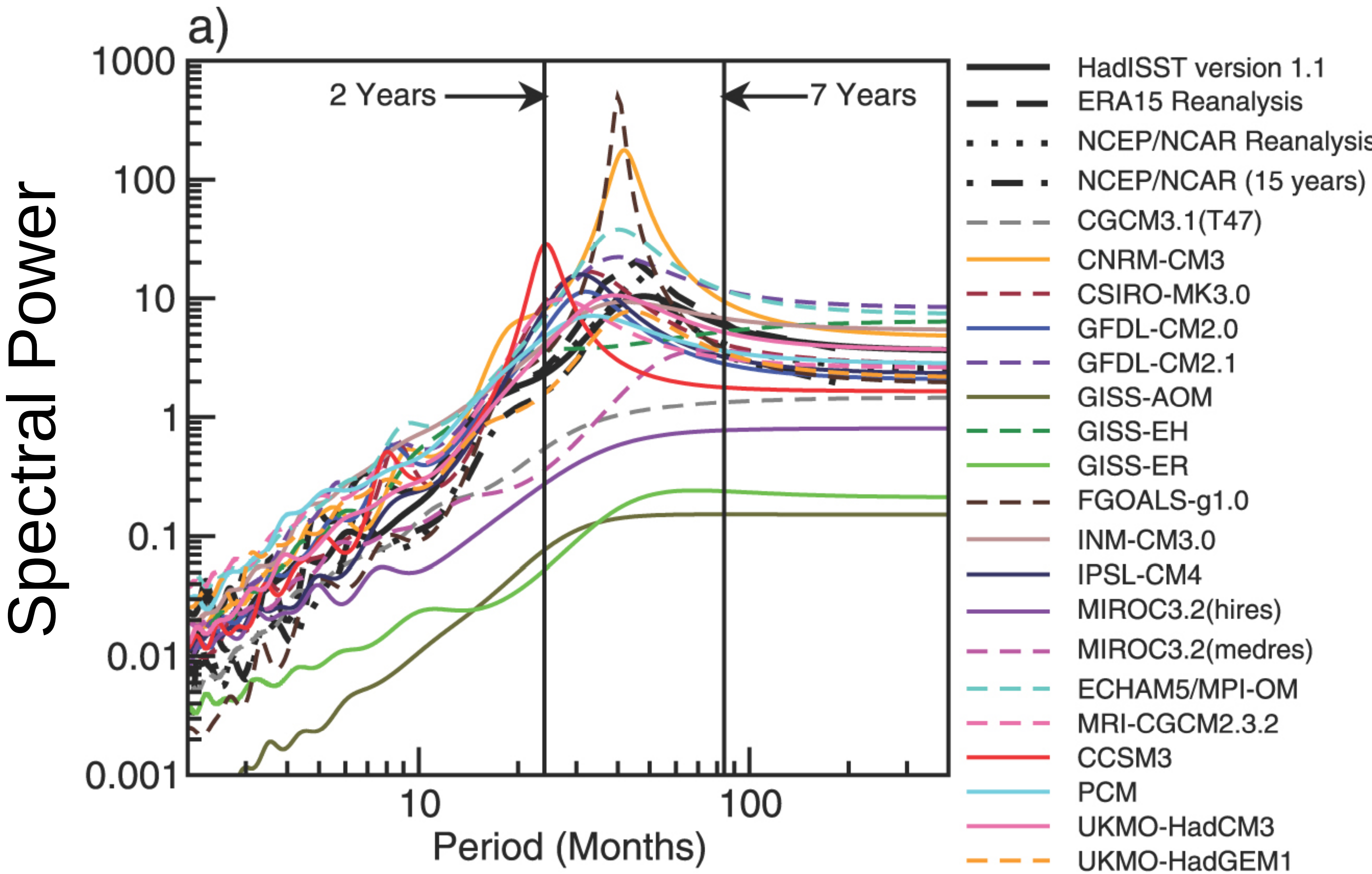
Global climate model
~300 km



"Observations"
(PRISM) 4 km

Annual mean precipitation

We evaluate simulated variability as well as means



Outline

- Origins of climate modeling
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- The increasing scope of climate models
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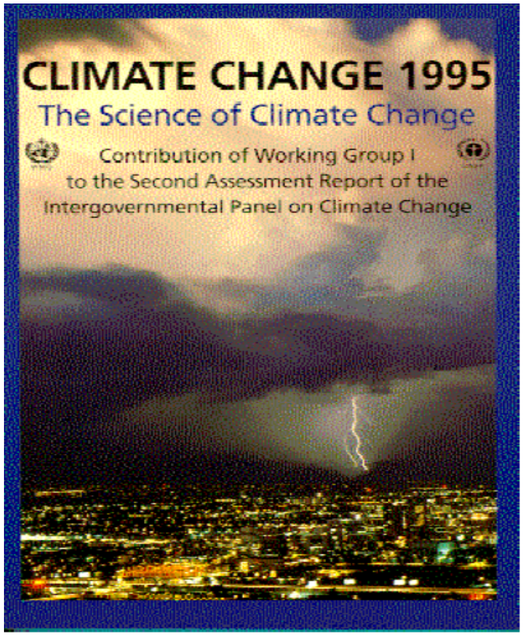
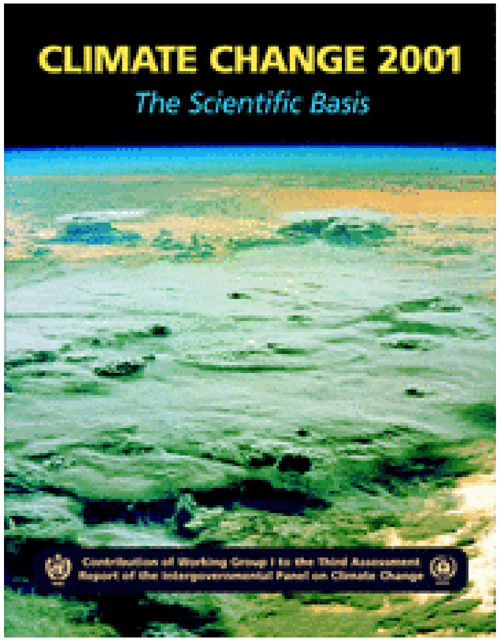
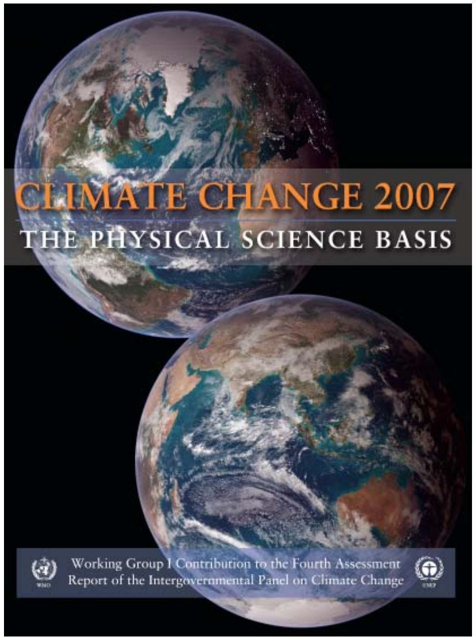
We have increasing confidence that humans are changing global climate



"The balance of evidence suggests a discernible human influence on global climate"



"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities"



"Most of the observed increase in globally averaged temperatures since 1950 is very likely [>90%] due to the observed increase in anthropogenic greenhouse gas concentrations"

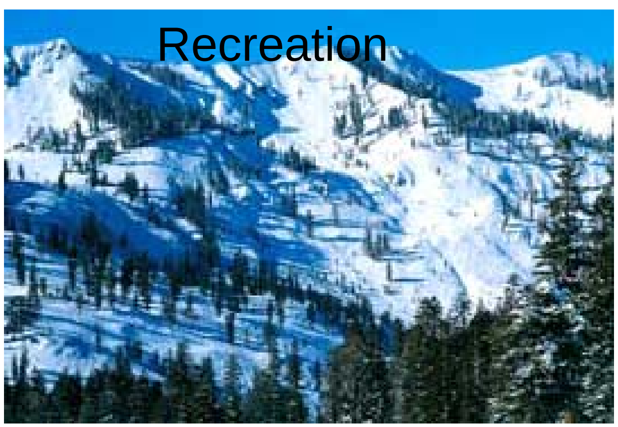
Societal impacts of climate change: The basis of policy decisions

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.

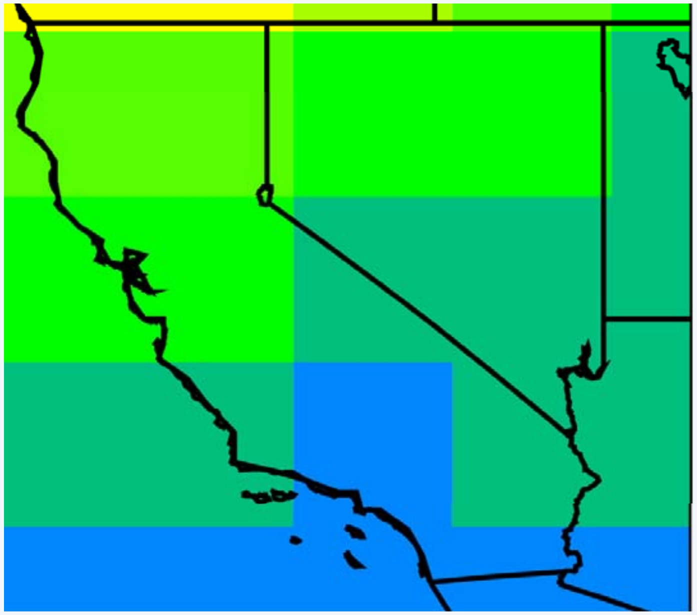
Societal-impacts studies need climate projections having:

- **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:

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



Global climate model
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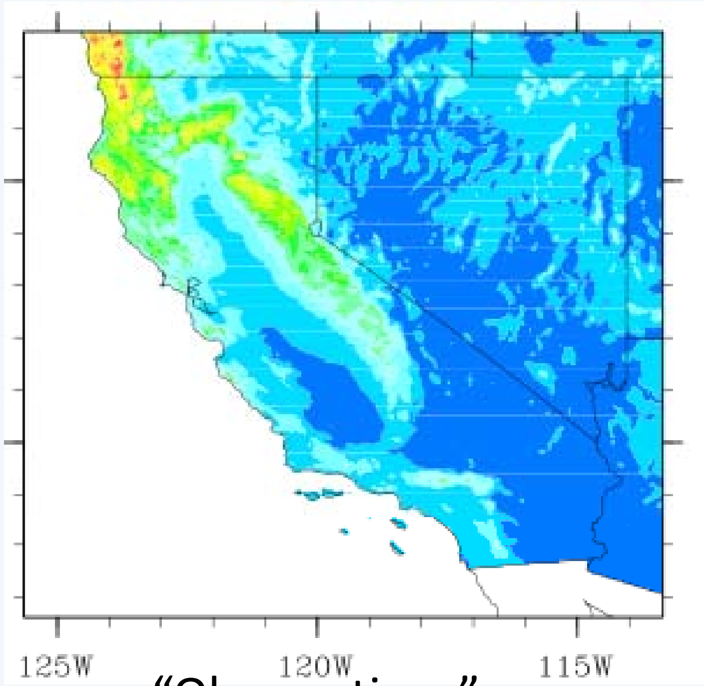
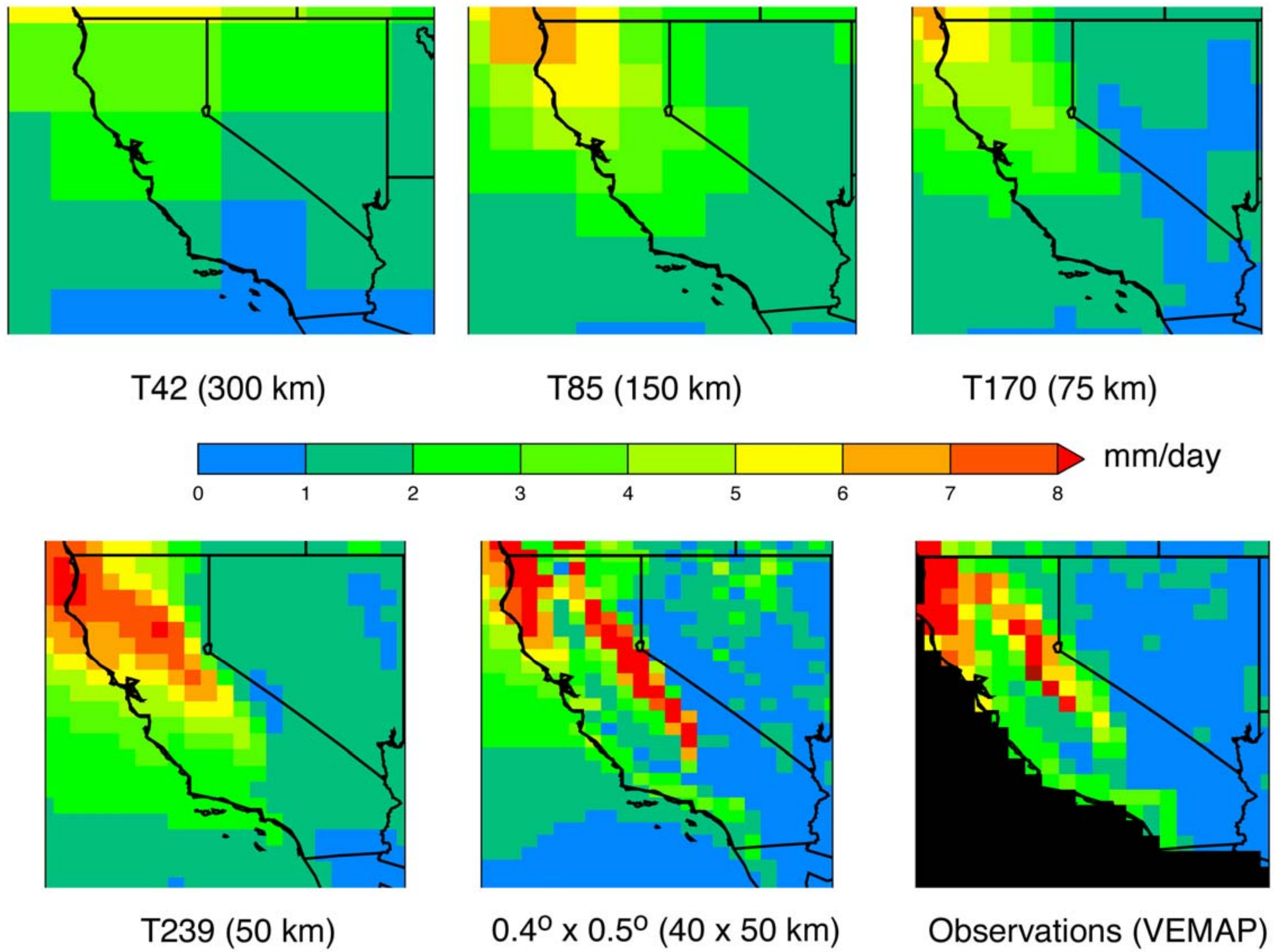


"Observations"
(PRISM) 4 km

Annual mean precipitation

Refining resolution improves fidelity…

Wintertime precipitation rate



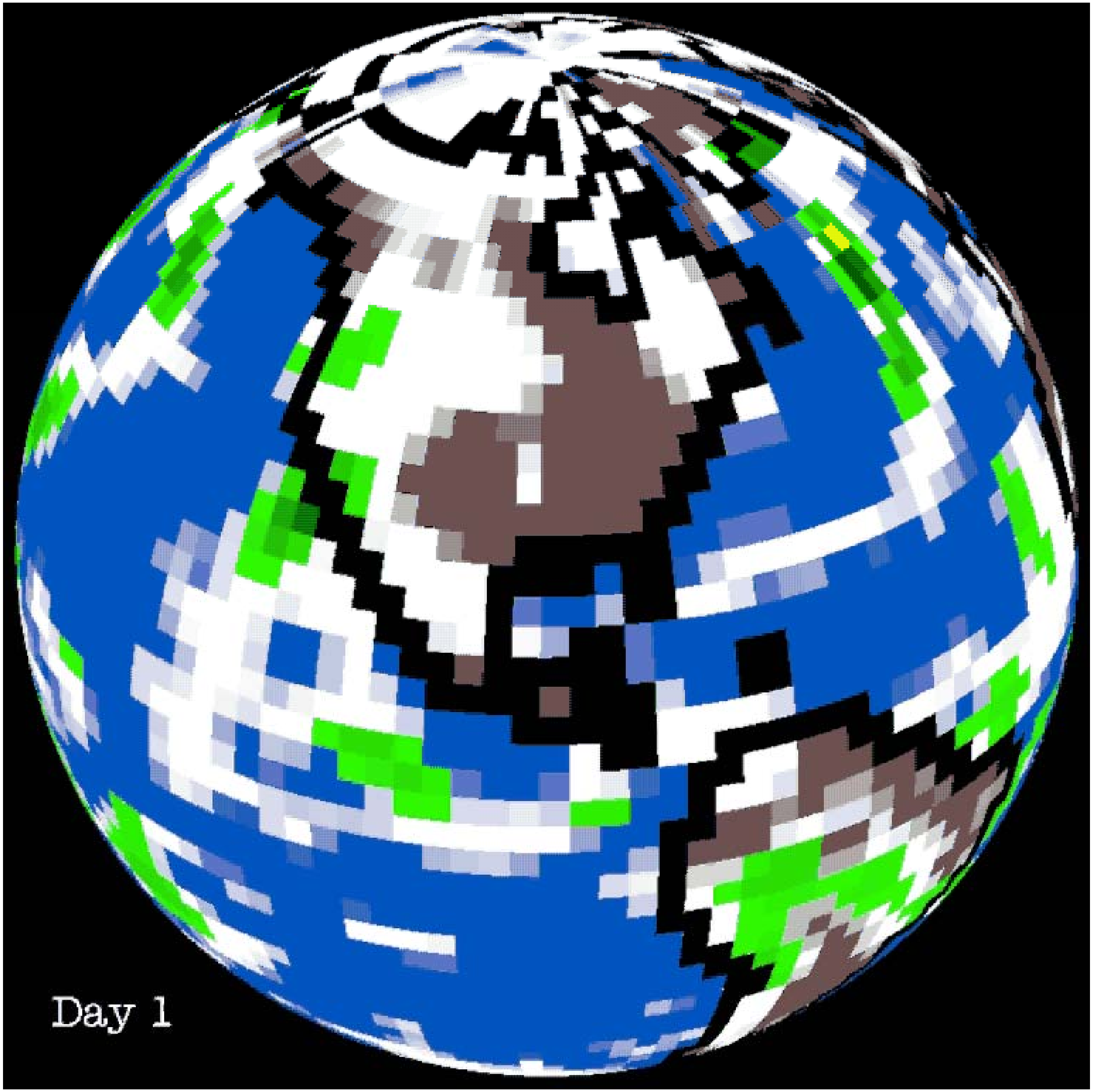
… at a high computational price

• 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

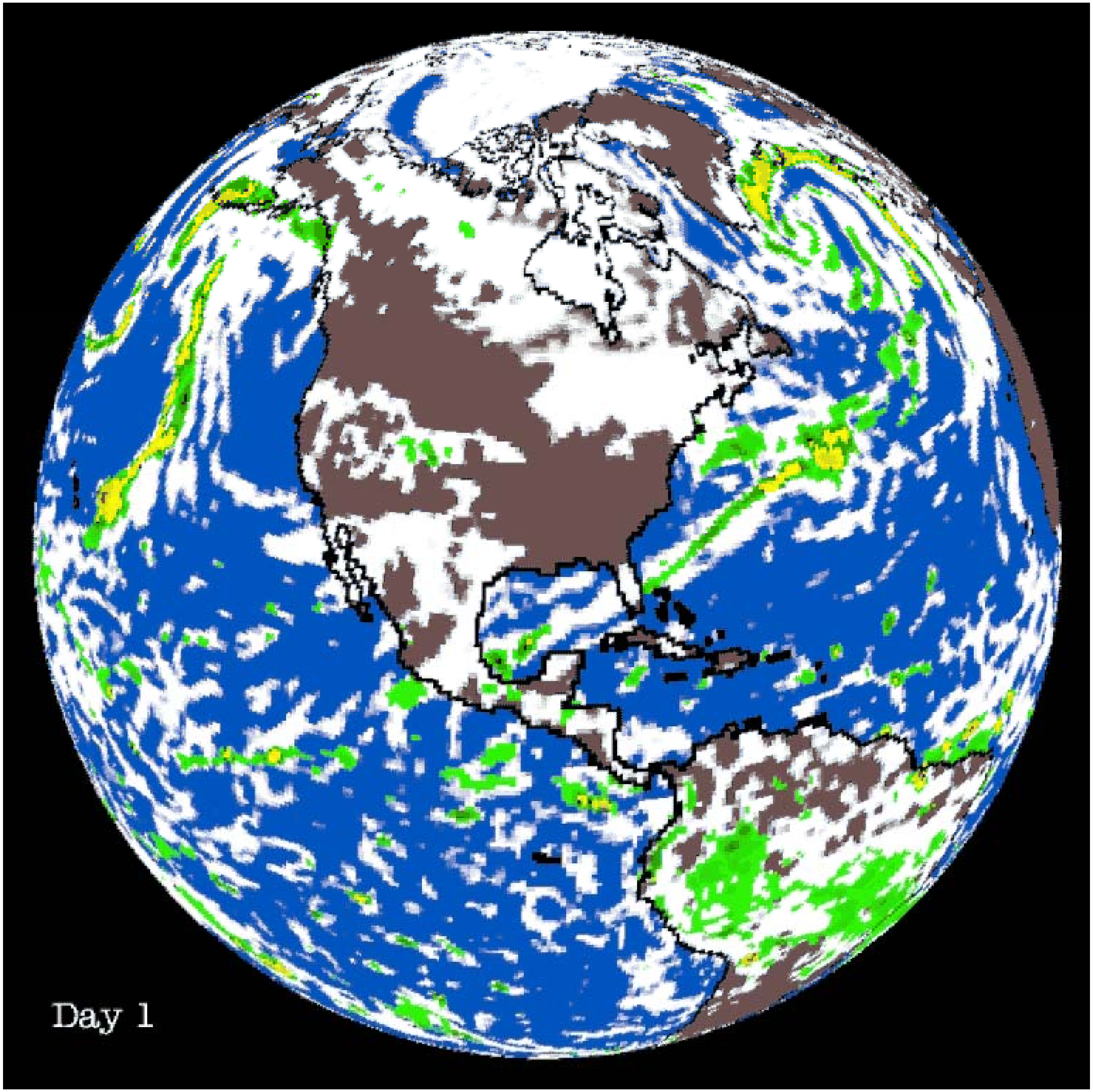
300 km

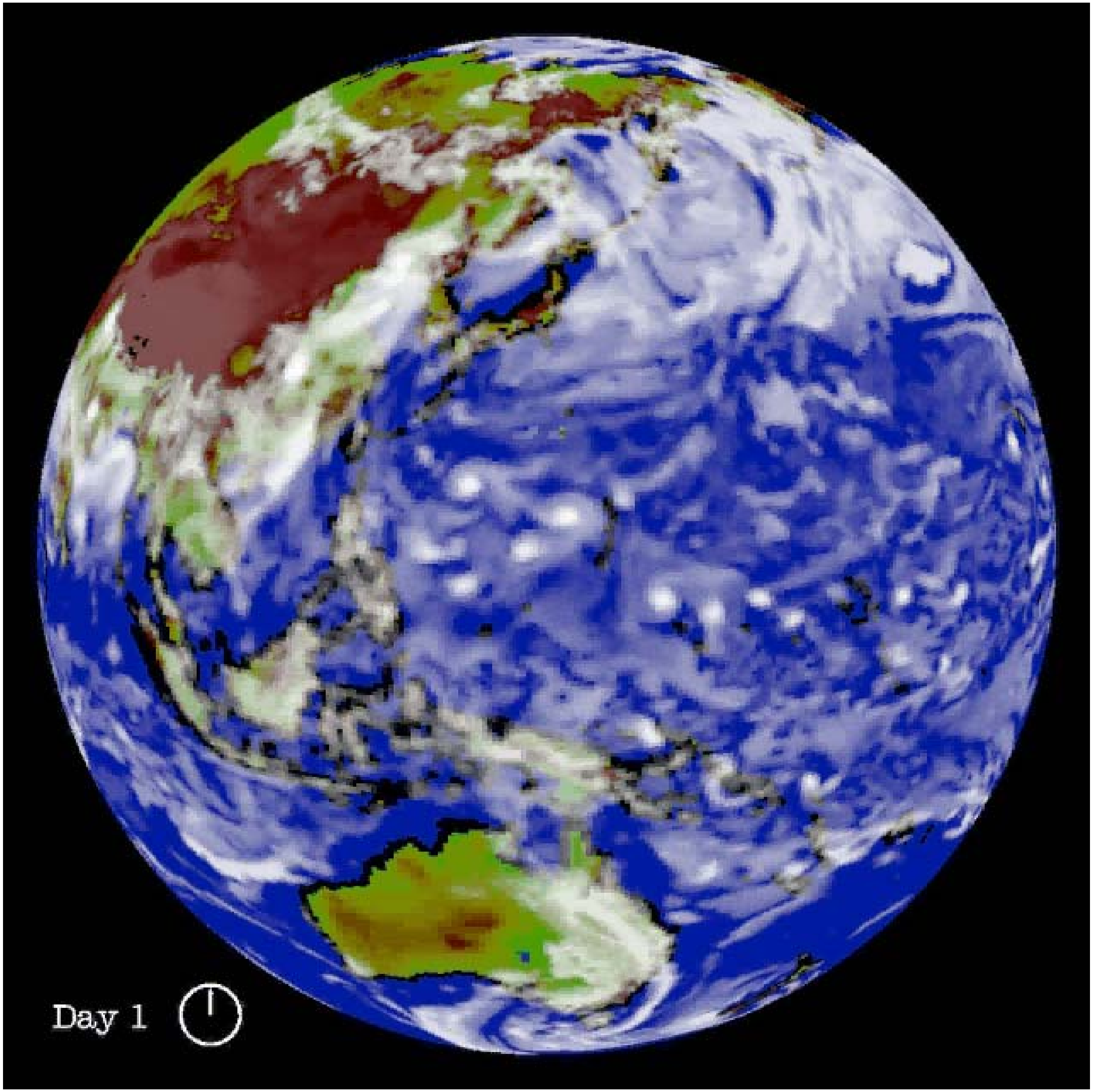
grid spacing



50 km

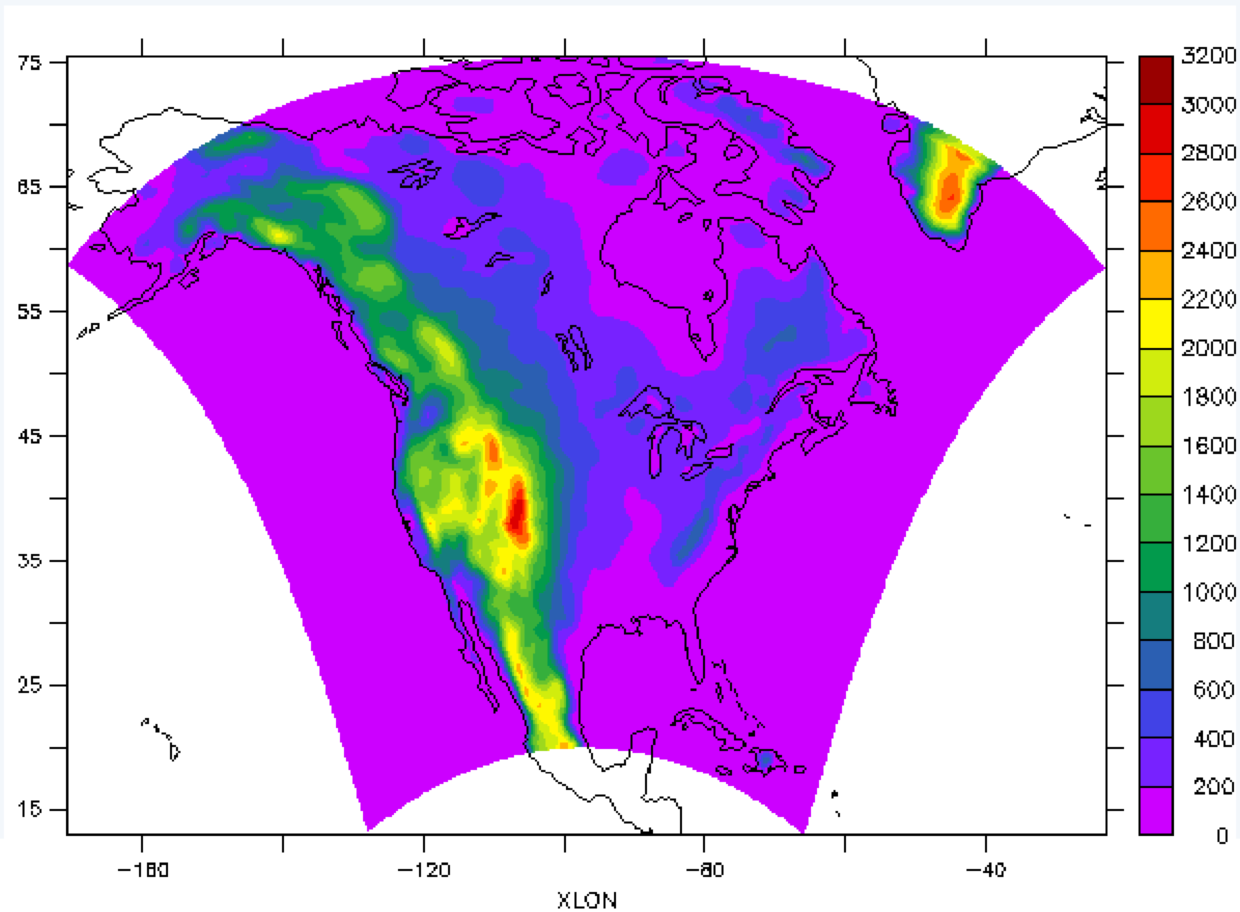
grid spacing



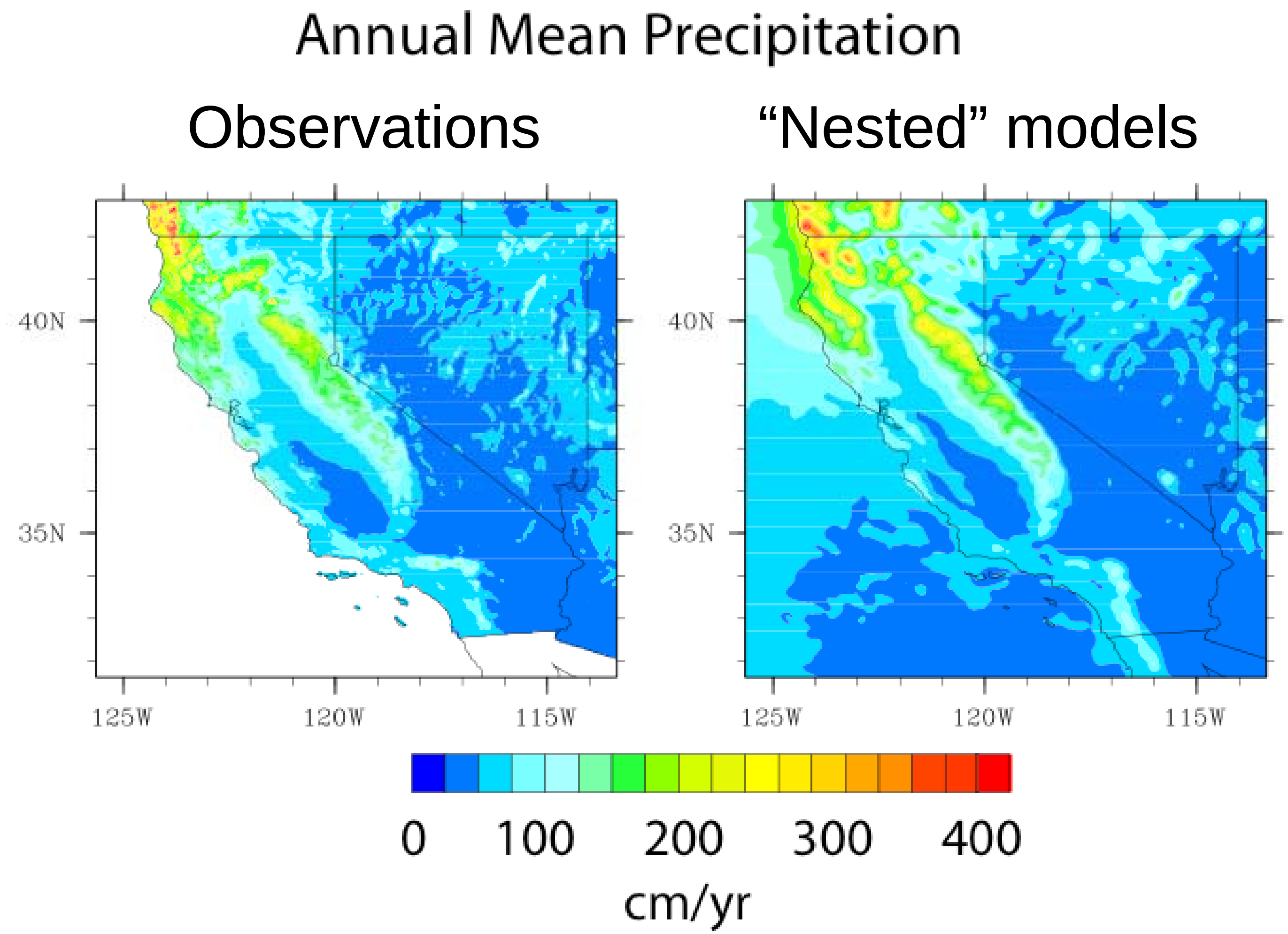

Day 1

Dynamical downscaling:

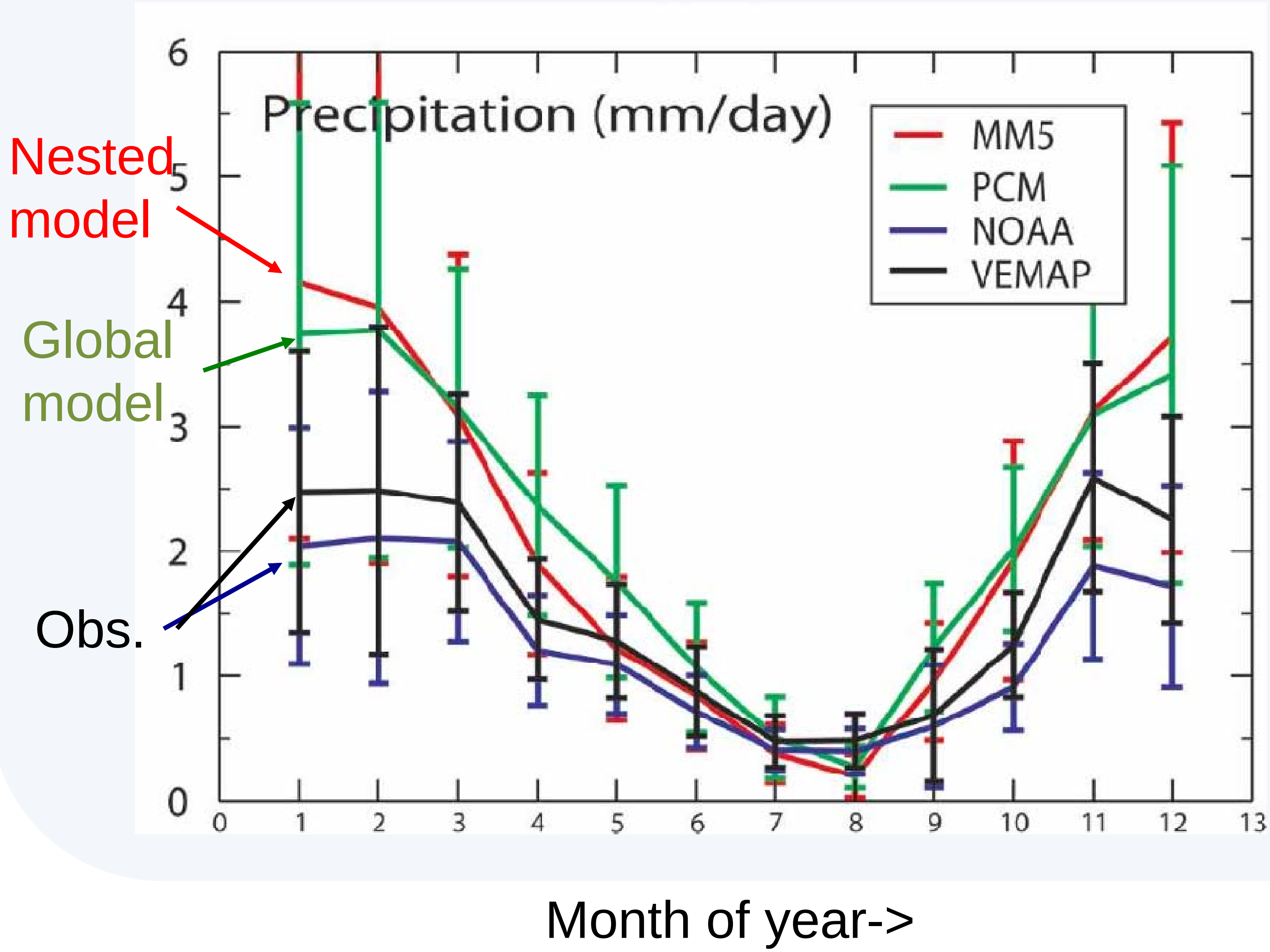
Uses a nested, limited-domain climate model that is based on physical laws



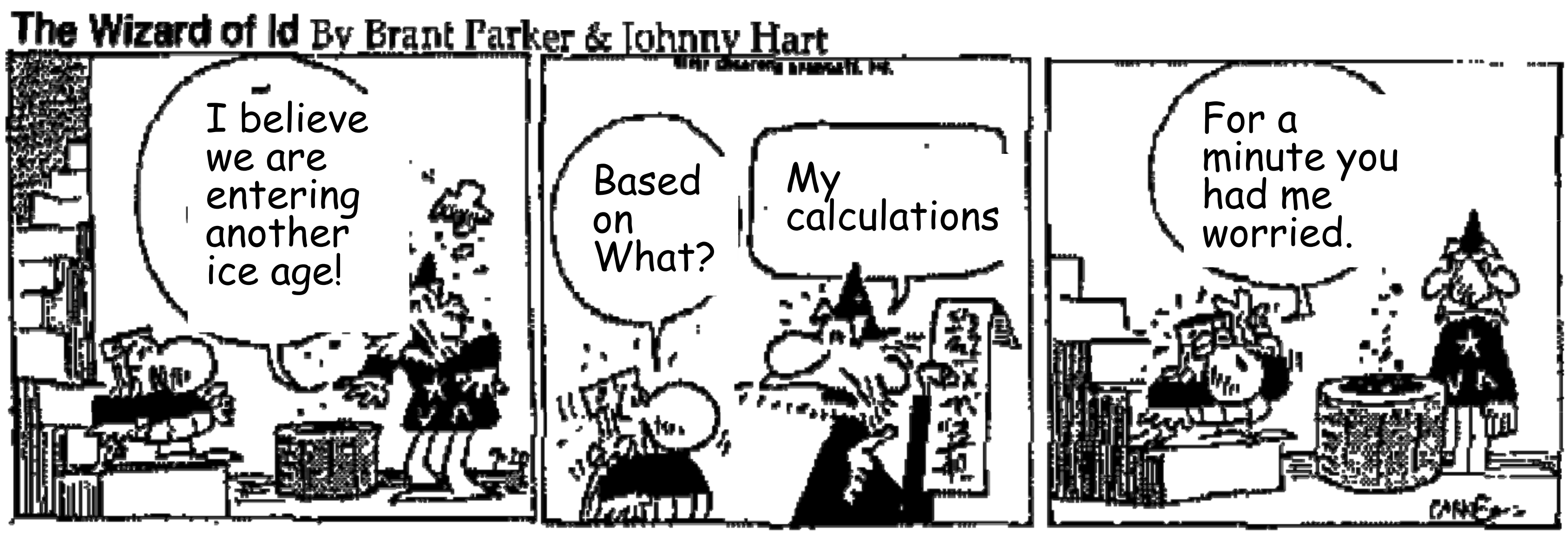
Nested models *can* work beautifully



Dynamical downscaling: GIGO



Uncertainty: what are limits of climate prediction?



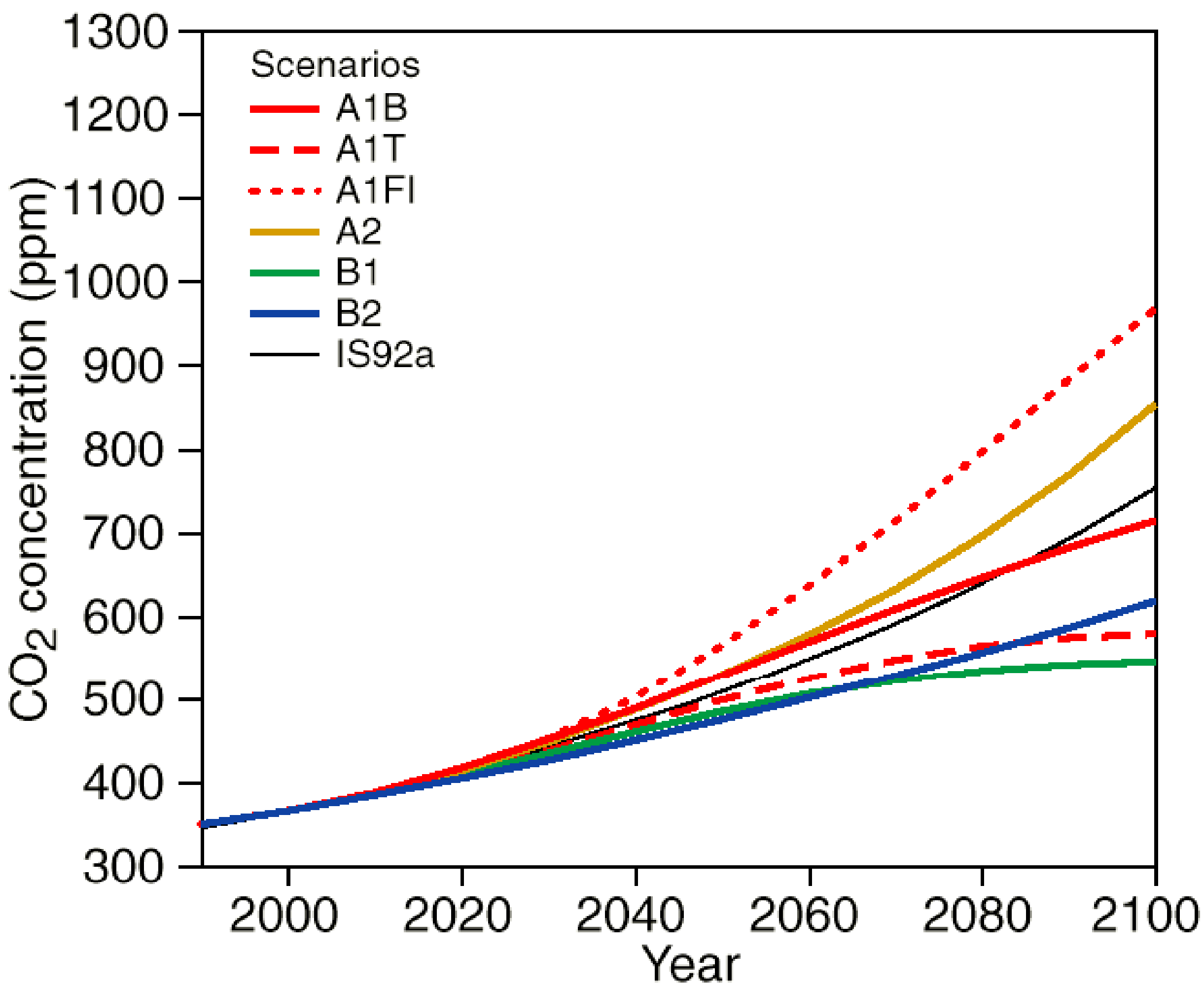
Sources of uncertainty: imperfect knowledge of

- future behavior of climate “forcings,” e.g. greenhouse gas concentrations;
- initial conditions in the atmosphere, etc.;
- how the system responds to forcings.

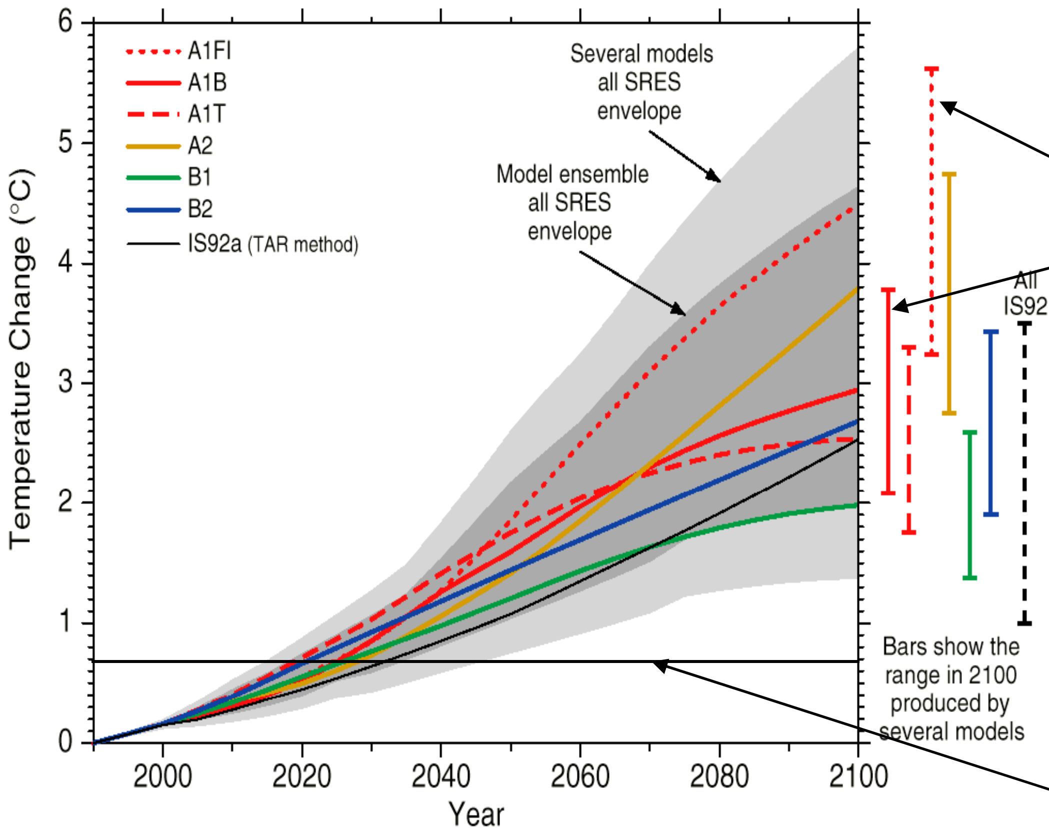
  These errors arise from:

  – numerical discretization
  – unresolved phenomena
  – relevant processes that are omitted.

Increases in future CO_2 concentrations are *unknowable;* this is true of other influences also



Uncertainty in future CO_2 concentrations account for about half of future uncertainty in temperature



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 1.4º - 5.8 ºC before 2100.

Sources of uncertainty: imperfect knowledge of

- future behavior of climate "forcings," e.g. greenhouse gas concentrations;
- initial conditions in the ocean, etc.;
- how the system responds to forcings.

  These errors arise from:

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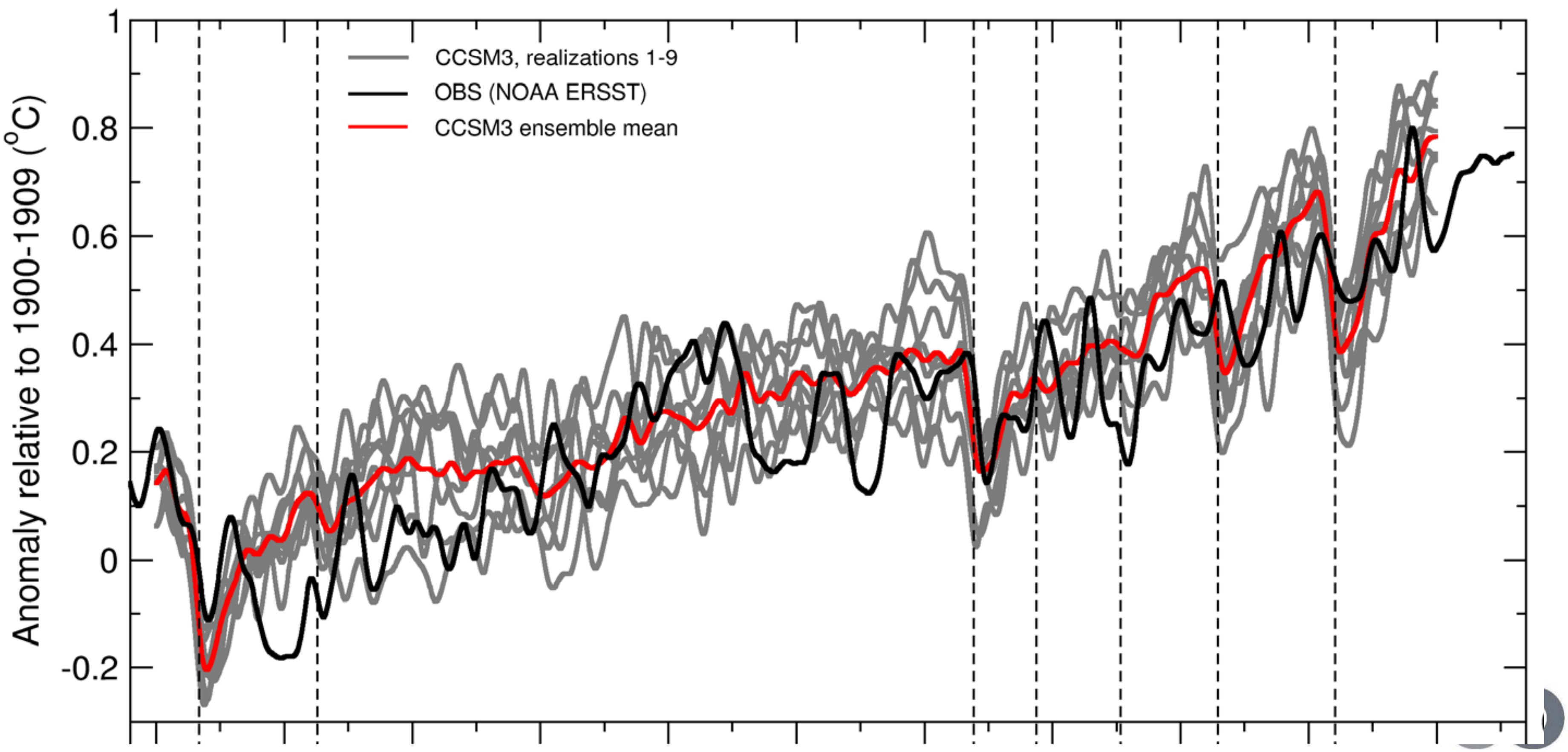
  – unresolved phenomena
  – relevant processes that are omitted.

Chaotic variability affects large-scale climate

Regional sea-surface temperatures



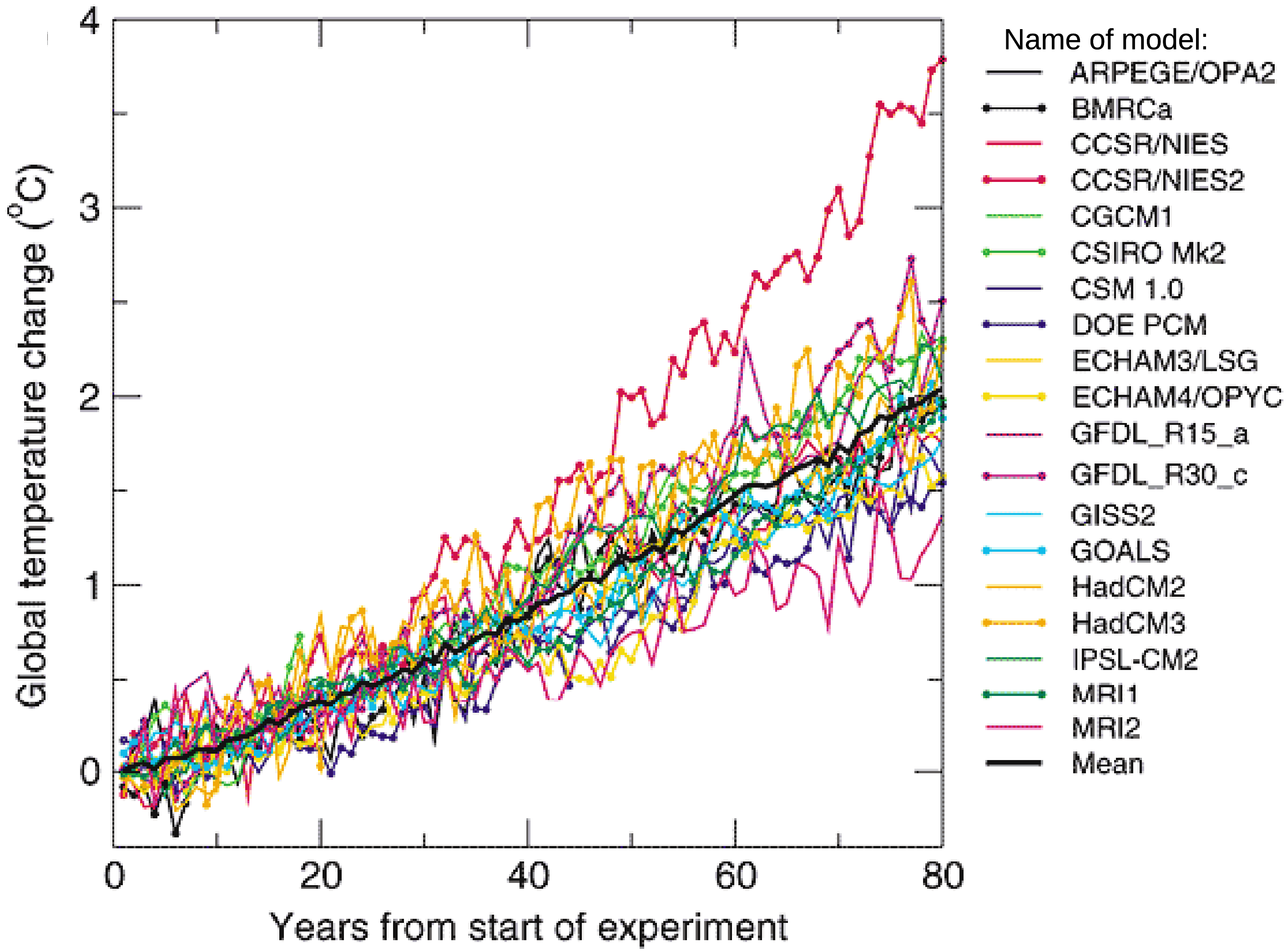
Sources of uncertainty: imperfect knowledge of

- future behavior of climate “forcings,” e.g. greenhouse gas concentrations;
- initial conditions in the atmosphere, etc.;
- how the climate system behaves.

  These errors arise from:

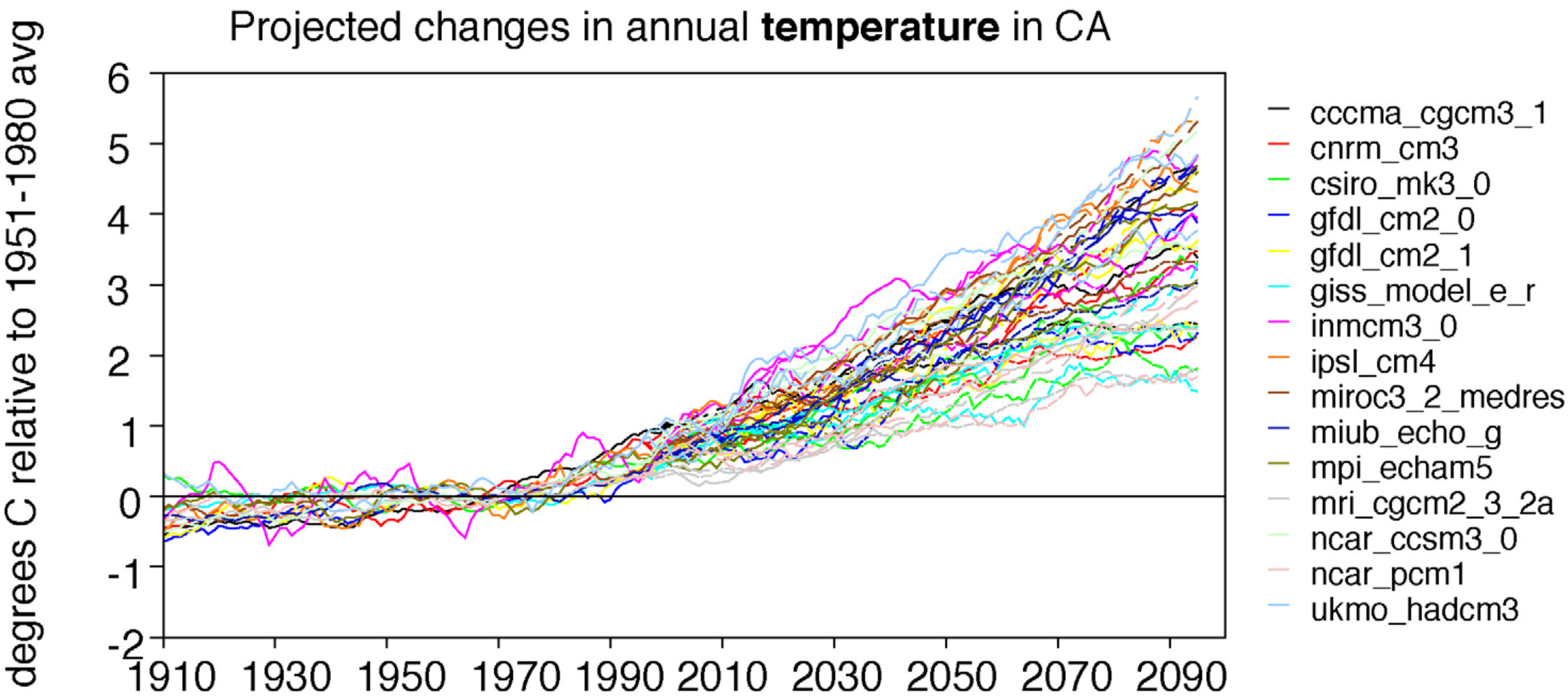
  – Imperfect representation of unresolved phenomena (notably clouds)
  – numerical discretization
  – “unknown unknowns”.

Different models respond differently to same inputs



Simulated temperature responses to 1%/yr CO_2 increase

Typical uncertainty quantification



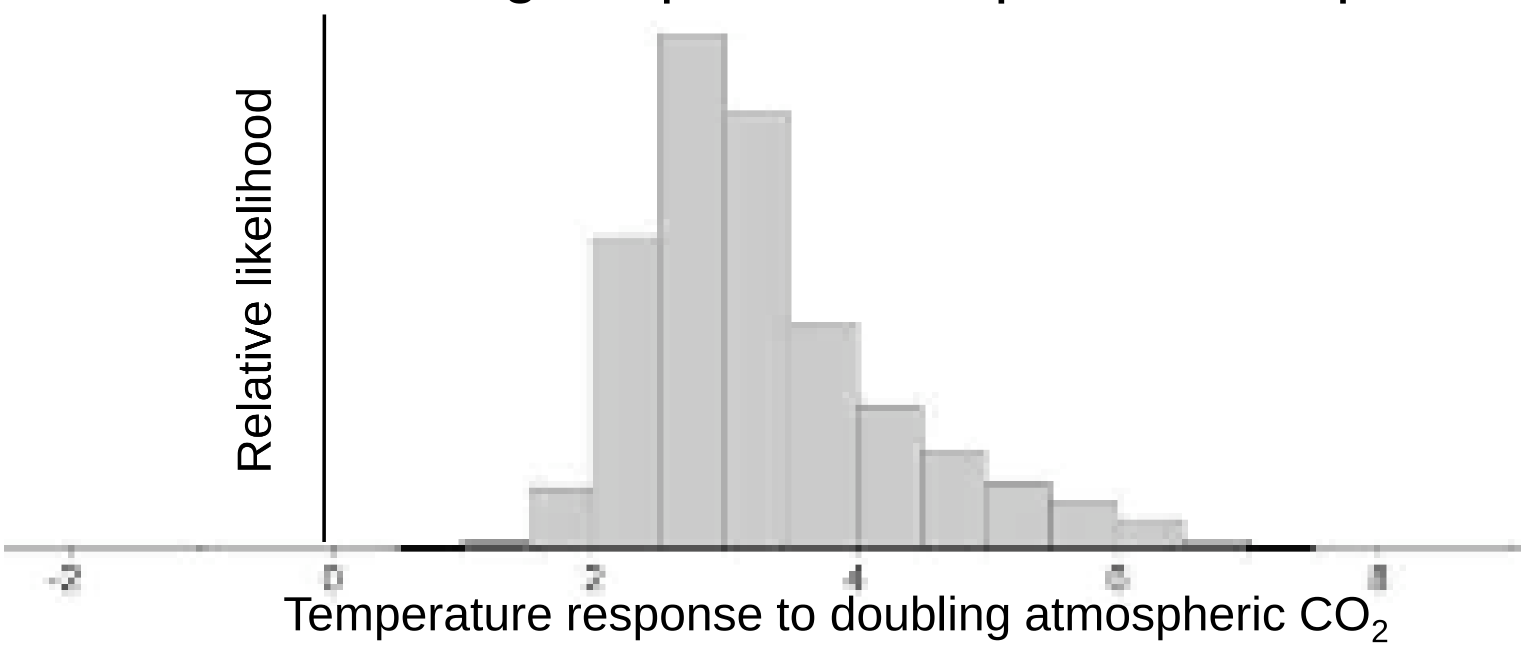
Results from 15 models, each simulating 3 CO_2 scenarioss

What's wrong with quantifying uncertainty in this way?

1. It combines uncertainties from all sources – the contributions of individual sources can't be disentangled.
2. It can be misleading because errors common to multiple models may be important. I.e. even if models agree with each other, they could all be wrong.
3. It does not give more weight to models that reproduce observations well.
4. It does not show the full range of possibilities, because each model tries to give the best answer. I.e. it does not show outcomes that all agree have low likelihood.

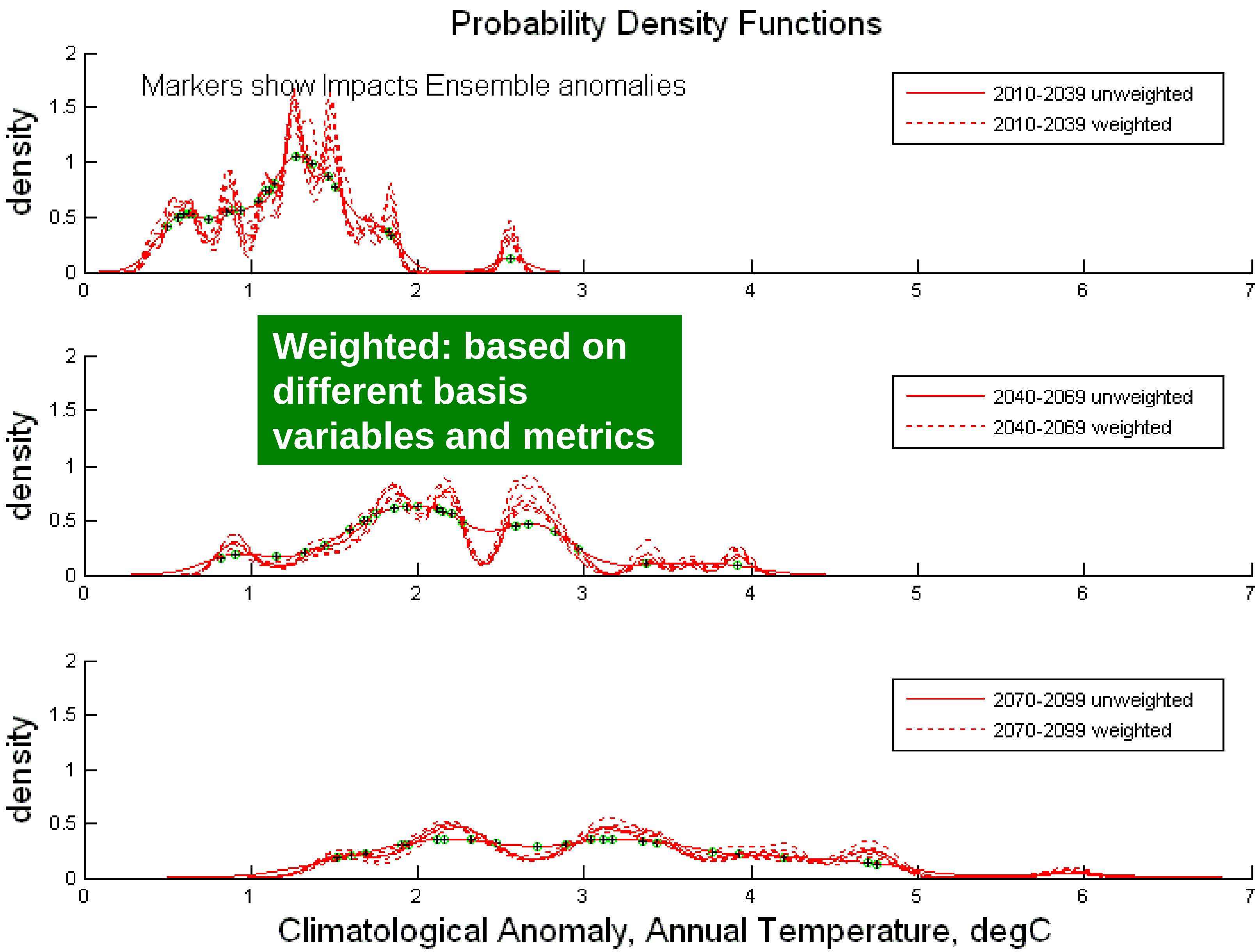
A better and cooler way to quantify uncertainty: climateprediction.net

• 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.



How do climate projections depend on apparent model skill?

They don’t!!!



Source: Levi Brekke (USBR)

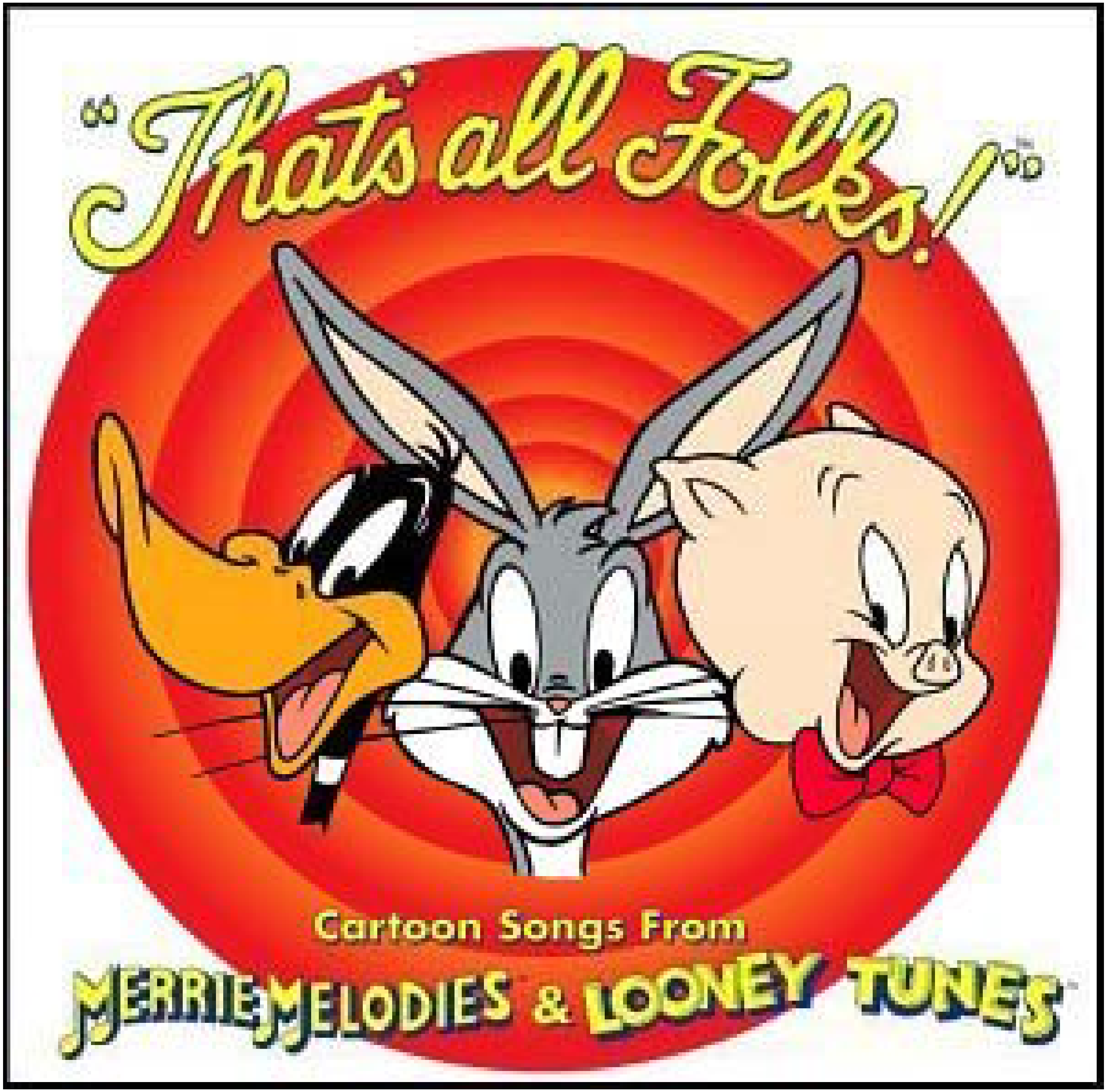
- Predictions of “better” models are indistinguishable from projections of “worse” models.

- Climate model evaluation is based on the assumption that better ability to reproduce observations implies better predictions of the future.

- The evidence does not support this assumption.

Parting Thoughts

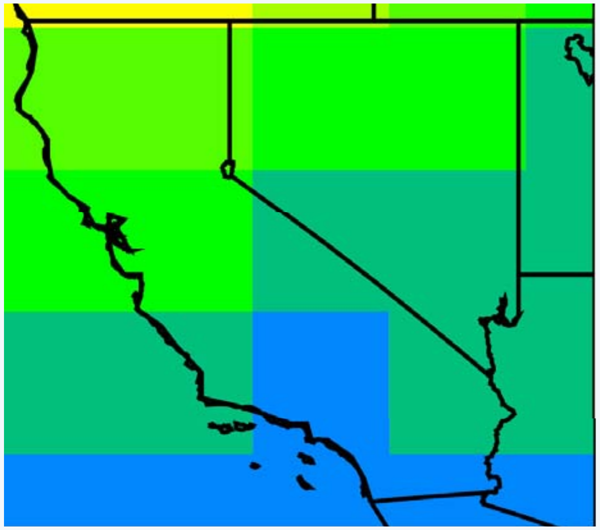
- Climate models work amazingly well.
- Climate models have serious errors.
- Some important sources of error in future climate predictions are irreducible.
- Climate prediction is no longer an academic exercise!
- The need to incorporate climate change into real-world decisions has “raised the bar”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


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

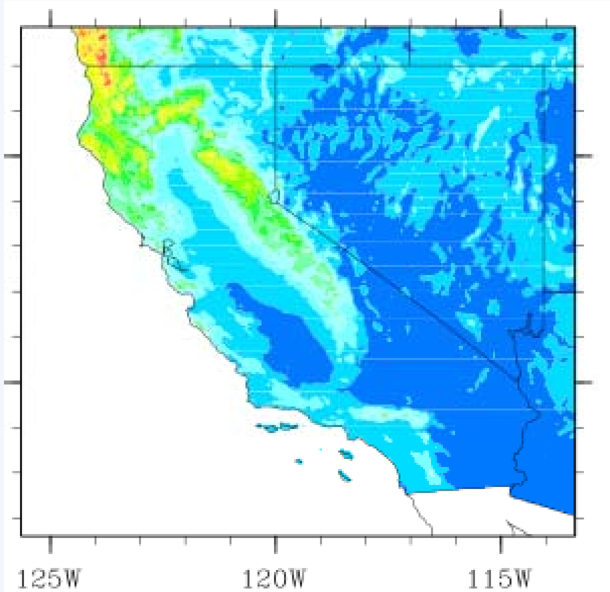
Downscaling

Adds physically meaningful detail

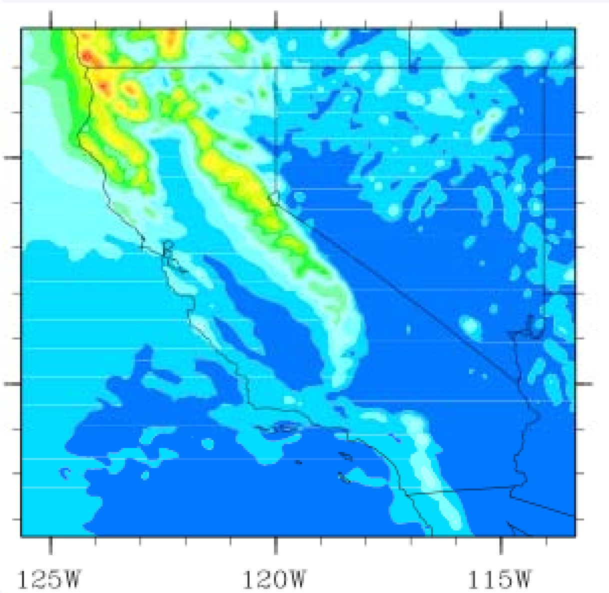
Annual mean precipitation



Global climate model
~300 km



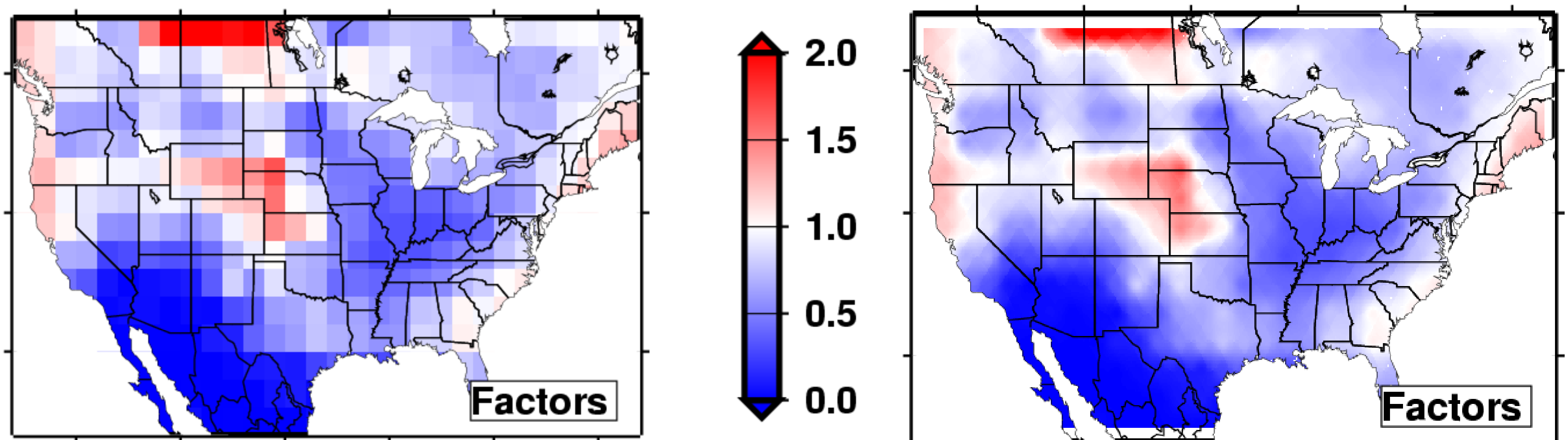
"Observations"
4 km



Downscaled global
climate mode (9 km)

Interpolation

Adds detail through a purely mathematical recipe that has no information about physical laws (e.g. F=ma) or physical properties (e.g. topography). Generally adds only intermediate values.



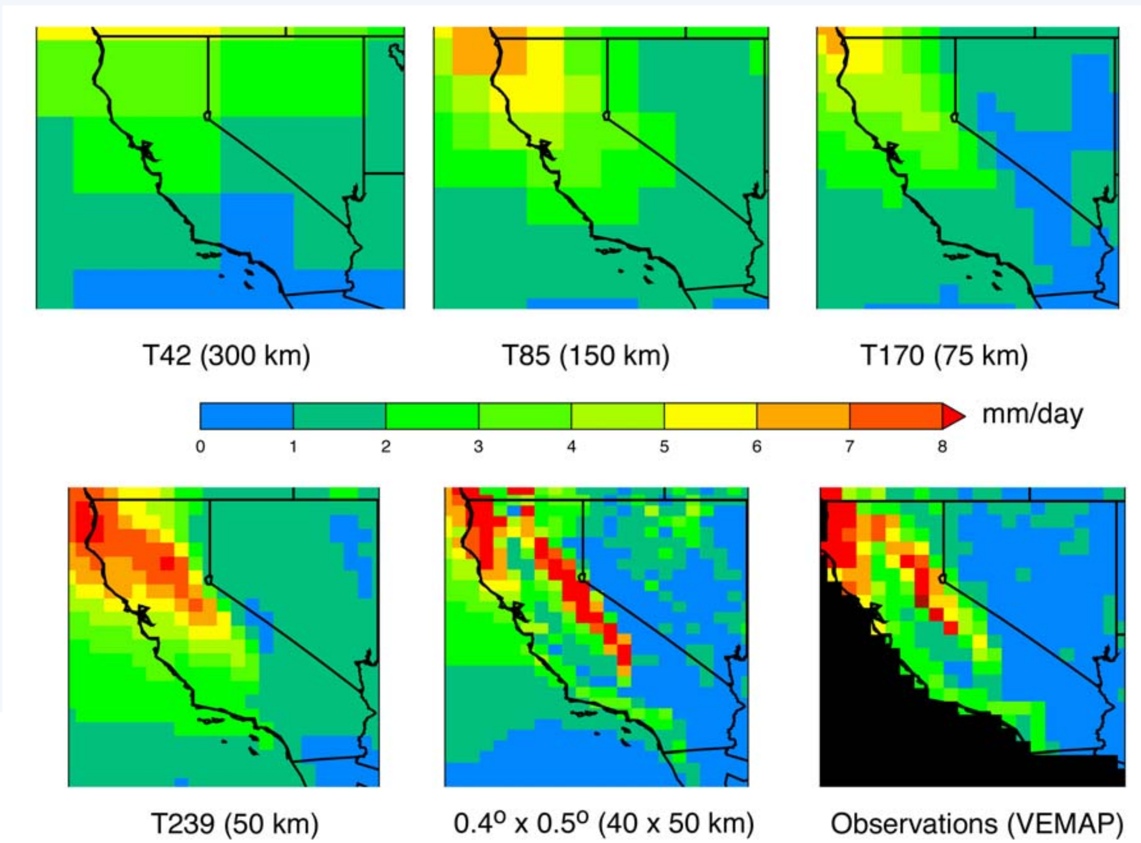
GCM results on 2º grid

Interpolated GCM results

How do we “downscale” climate projections?

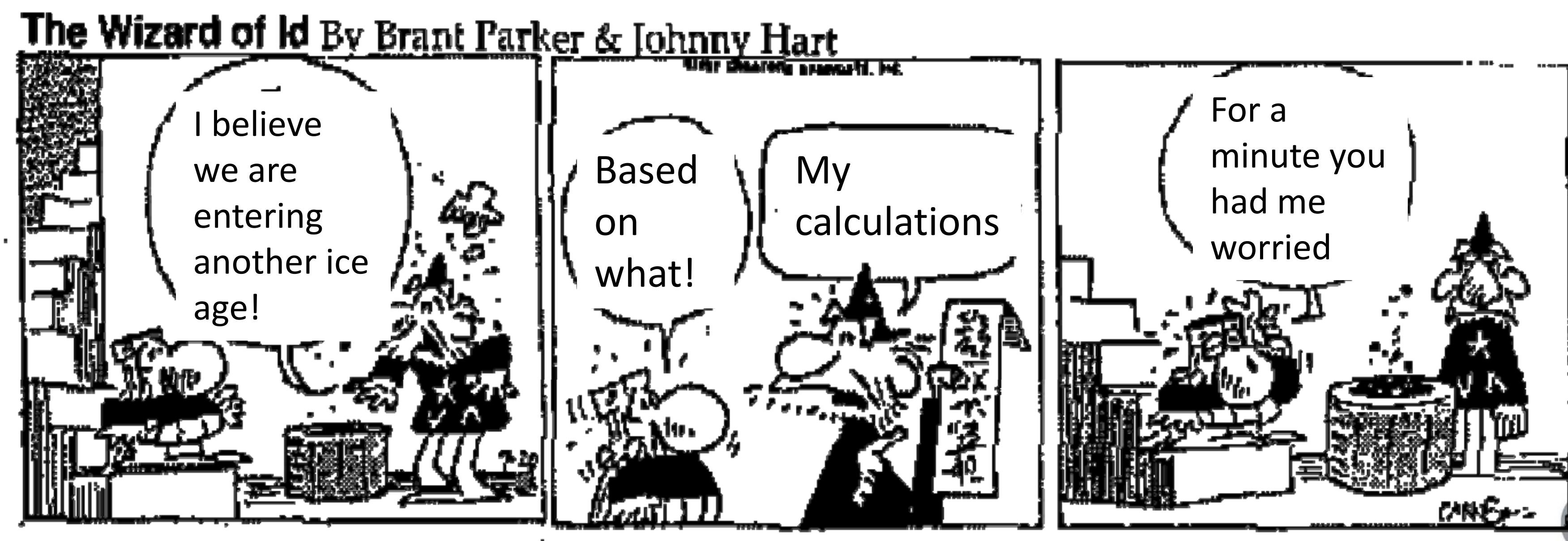
Fine-Resolution atmospheric GCM

- Drive with sea surface temperatures from a GCM.
- In principal, superior to other methods (says me).
- Very expensive computationally.
- Very limited results available.



Parting Thoughts (2)

- The need to assess regional-scale impacts of climate change, like species impacts, challenges the climate modeling community to provide
  - Finer resolution
  - Information on extremes
  - Uncertainty quantification.
- We are making progress, but...
- Fine-resolution historical climate data is also needed...



Dynamical downscaling…

• Based on physical laws, so should correctly simulate all situations, even those where the model hasn't been calibrated or tested.

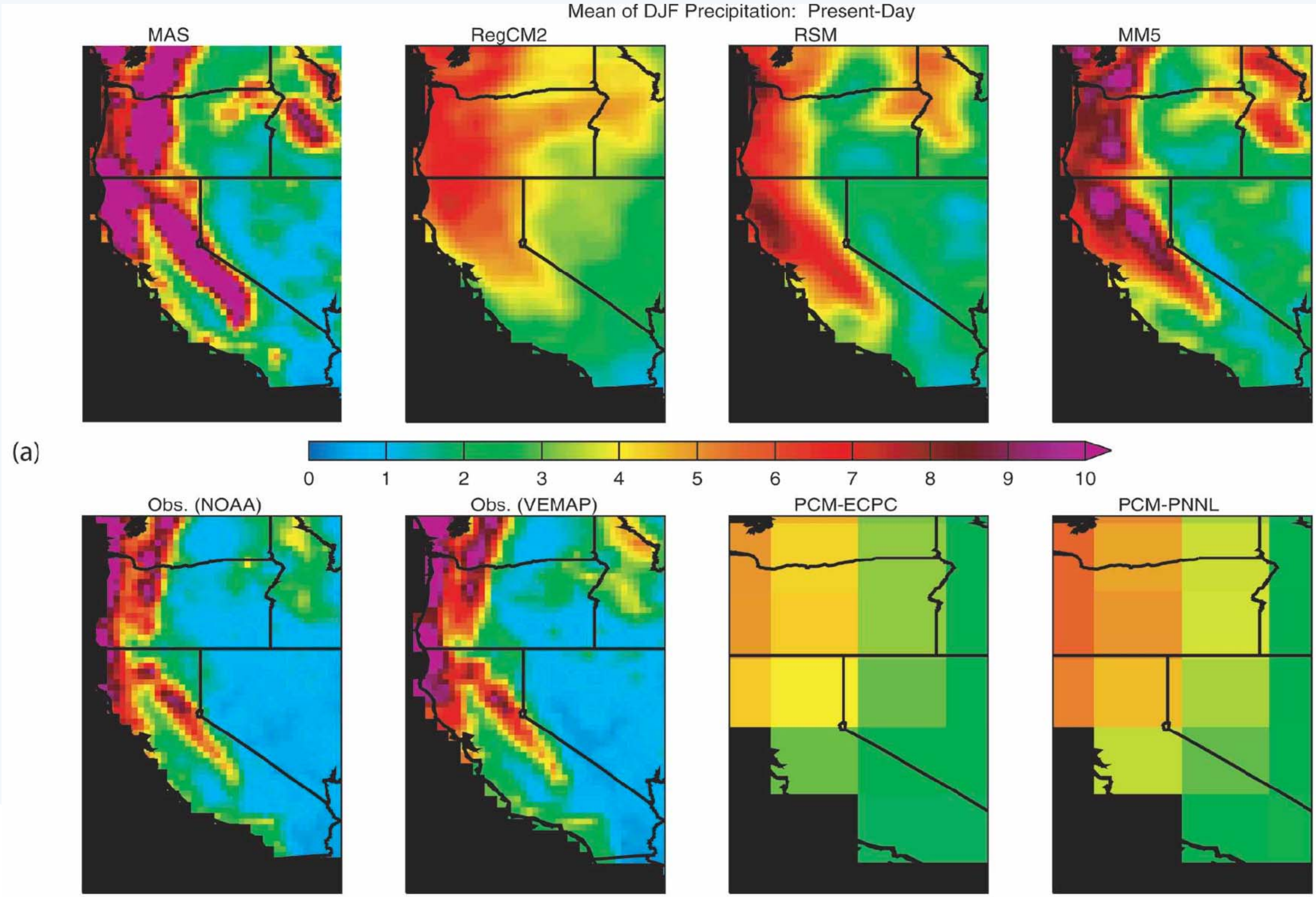
• Produces a full suite of output variables.

• Computationally expensive.

• Generally preserves biases (errors) in the results of the driving GCM.

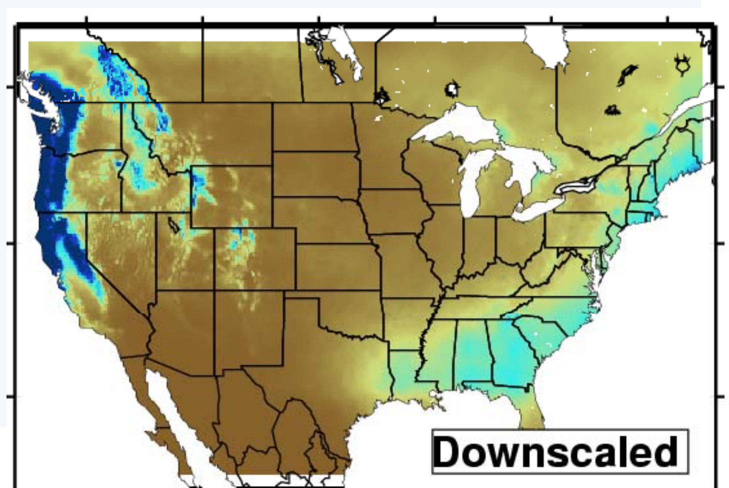
• Most GCM simulations don't save output needed for dynamical downscaling.

Dynamical downscaling…



Statistical downscaling

- Adds detail obtained empirically from observations
- Most methods designed to work at only one location
- Two methods produce spatially gridded output:
  - Bias Correction/Spatial Downscaling (BCSD; Andy Wood, U. of Washington)
  - Constructed Analogs (CA; Hugo Hidlago UCSD
- Both of these get detail from observations.



Statistical downscaling…

- Computationally *not* very demanding
- Does not require special output from the GCM
- Can be applied to large ensembles of GCM simulations
- Can include correction of GCM biases
- Produces results for only a few variables
- Resolution and domain limited by availability of gridded observations
- Critical assumptions:
  - empirical relationships derived from historical observations will apply in the future – this is *not* true where local feedbacks important
  - bias correction derived in historical period will apply in the future.

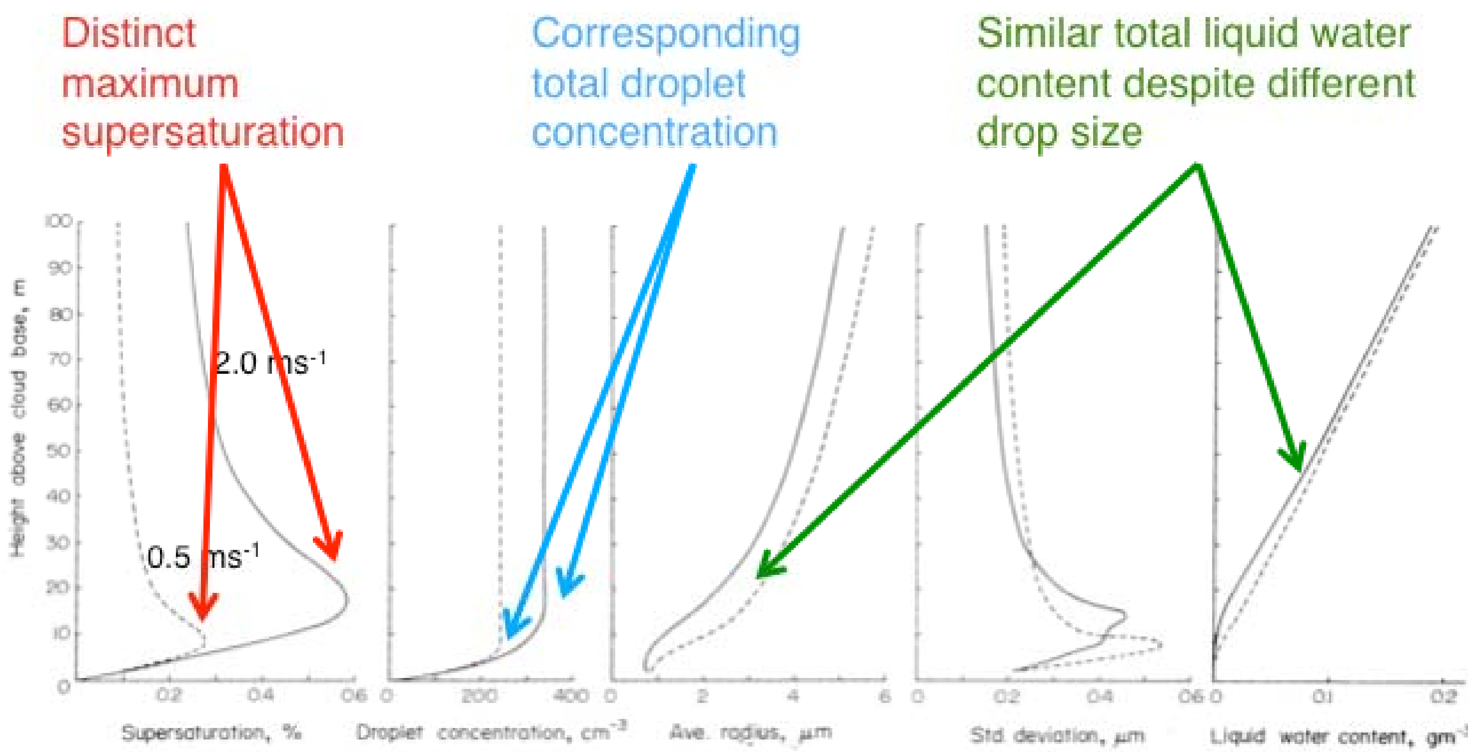
Clouds strongly affect radiation flow…

And they are very complicated…

Warm Cloud Microphysics

Activation and Growth of Cloud Droplets

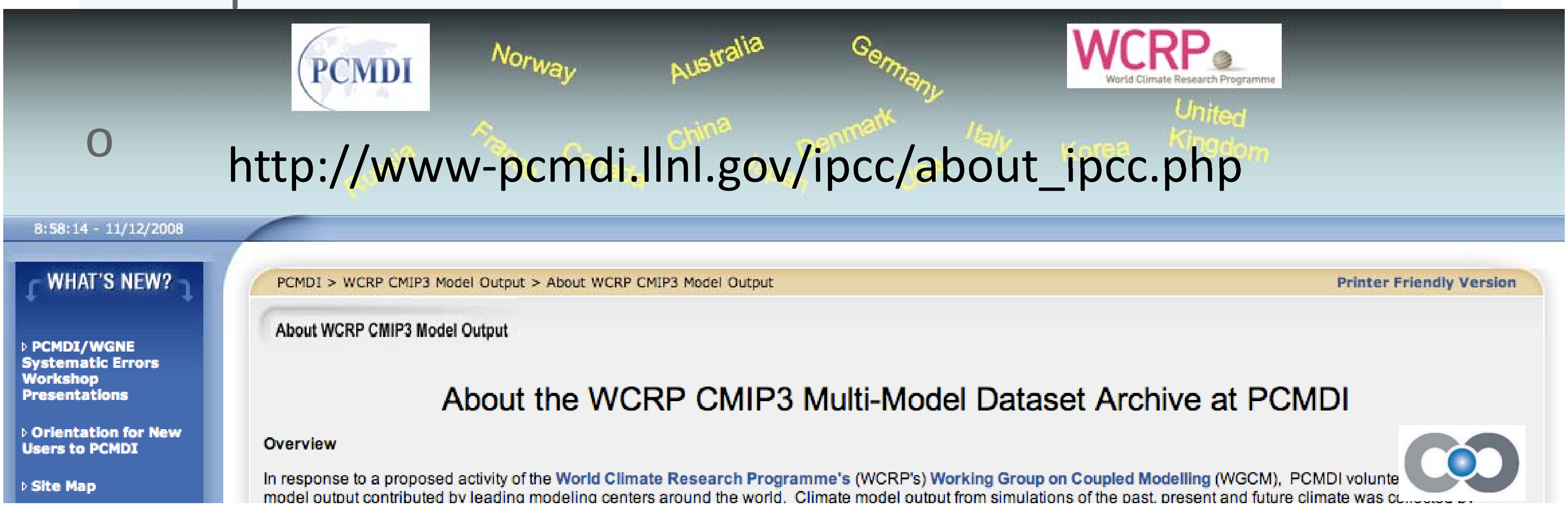
Effect of updraft velocities on cloud microphysical properties:



Simulation of the early development of cloud properties for two different updraft velocities (Rogers & Yau, 1989).

CMIP3 (aka **IPCC AR4**) archive of global climate simulations

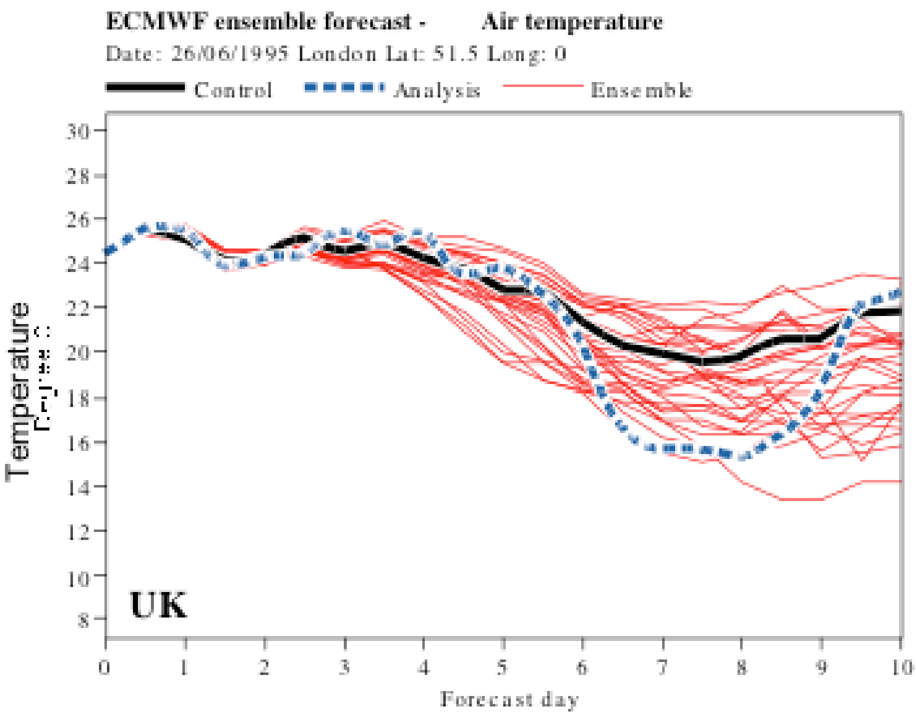
- Results from 20+ GCMs, multiple emissions scenarios
- Common output format
- Monthly and limited daily output.
- Global domain
- Available since ~2005
- But spatial resolutions are COARSE!



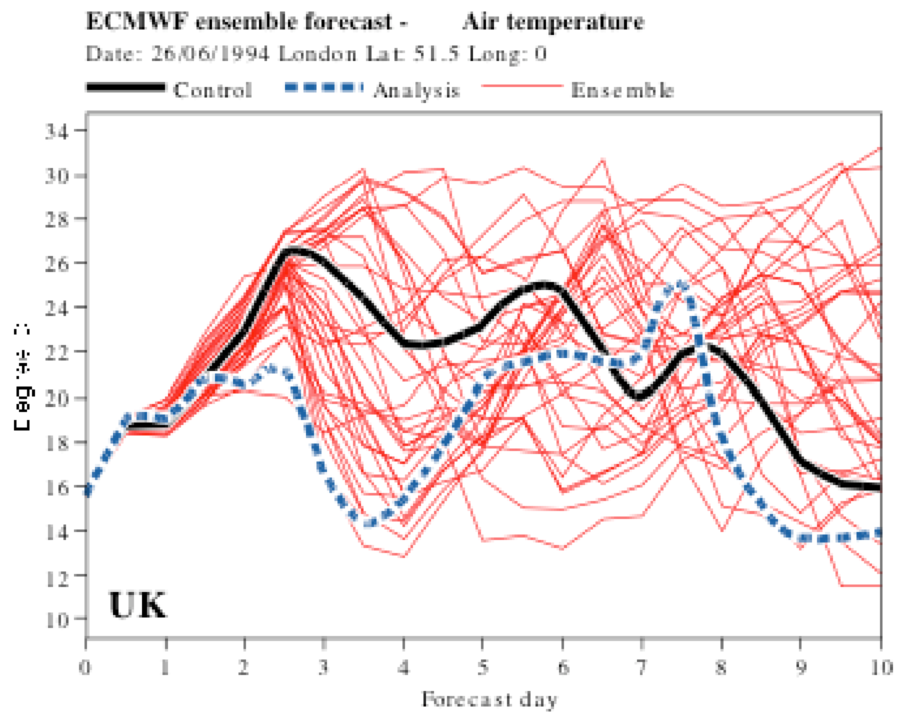
o http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

Atmospheric predictability is non-stationary…

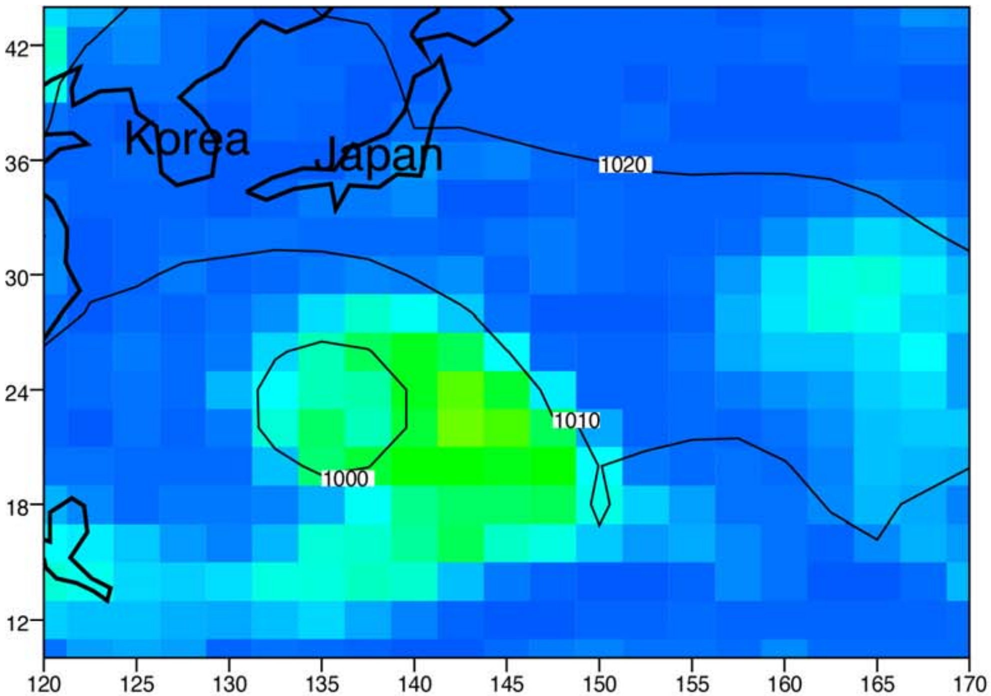
26^{th} June 1995



26^{th} June 1994



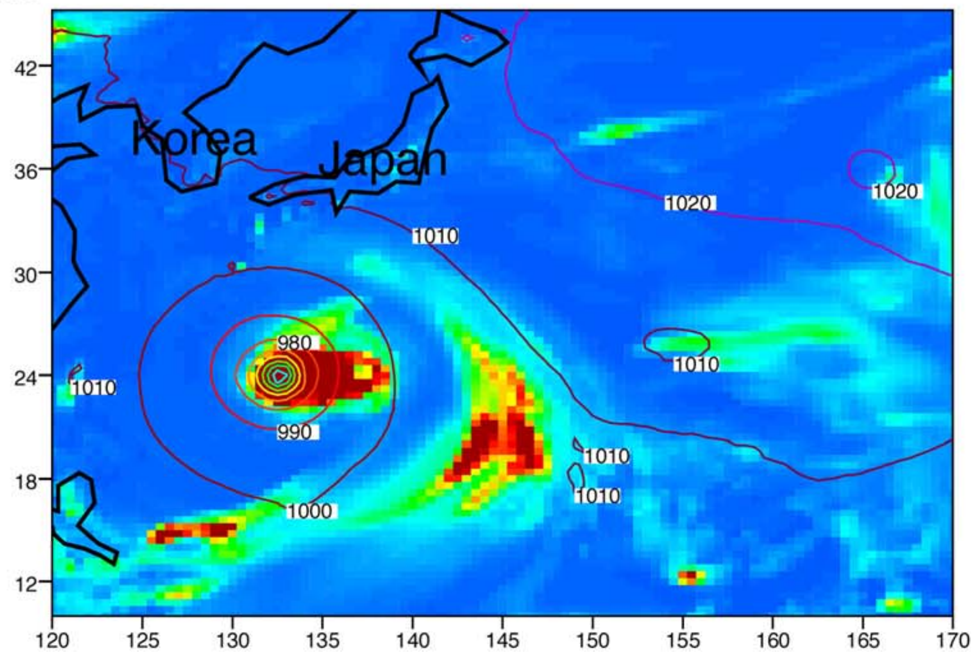
Source: Roberto Buizza, European Centre for Medium-Range Weather Forecasting



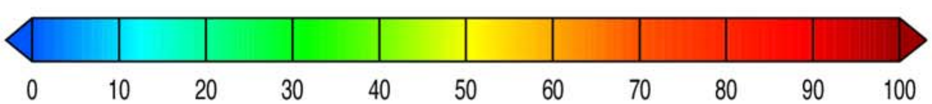
CAM2 at 2.0 x 2.5 resolution

In the eye:
pressure = 996mb
precip rate = 39 mm/day

CAM2 at 0.4 x 0.5 resolution

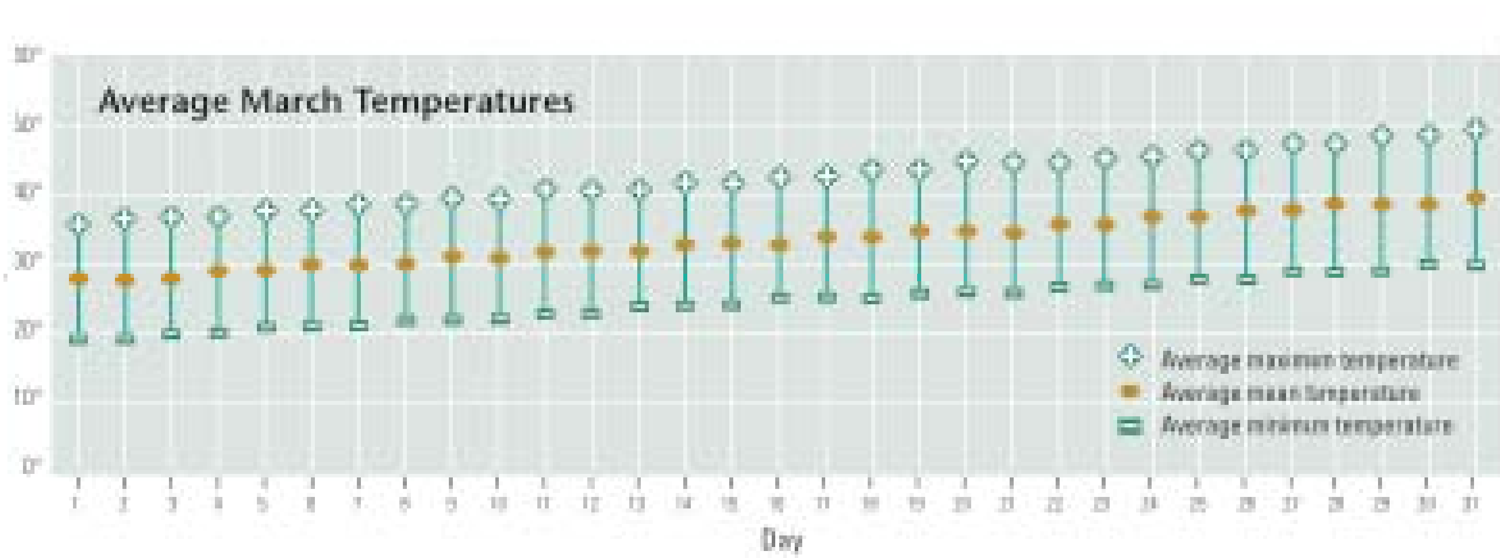


In the eye:
pressure = 921 mb
precip rate = 600 mm/day



Precipitation rate (mm/day)

Climate:



Graph F: March 2007 maximum, mean and minimum temperatures for Madison, Wisconsin

Weather: