Science in the Age of Models

Is Theory still Relevant?

Geoffrey K. Vallis

GFDL & Princeton University

Starr Lecture, MIT; Ulam, LANL 2012

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A bit philosophical, but hopefully down to Earth too.
I do not aim to be provocative for its own sake. . .

Why do we do Science?

Just one answer: For the betterment of society.

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Two aspects of that:

1. To increase the material quality of life: from the elimination of poverty and having clean drinking water, to having nicer racing yachts.
2. Increasing the non-material quality of life: intellectual and aesthetic pleasures, the quest to understand the universe and the planet on which we live. The human adventure.
   - Mathematics is not important because it enables us to build machines. Machines are important because they give us more time for mathematics.
     Henri Poincaré, Science and Method, 1908.

But note: federal funding comes mainly for task one!

Also, personal motivation can be different from societal motivation, and may be purely aesthetic.

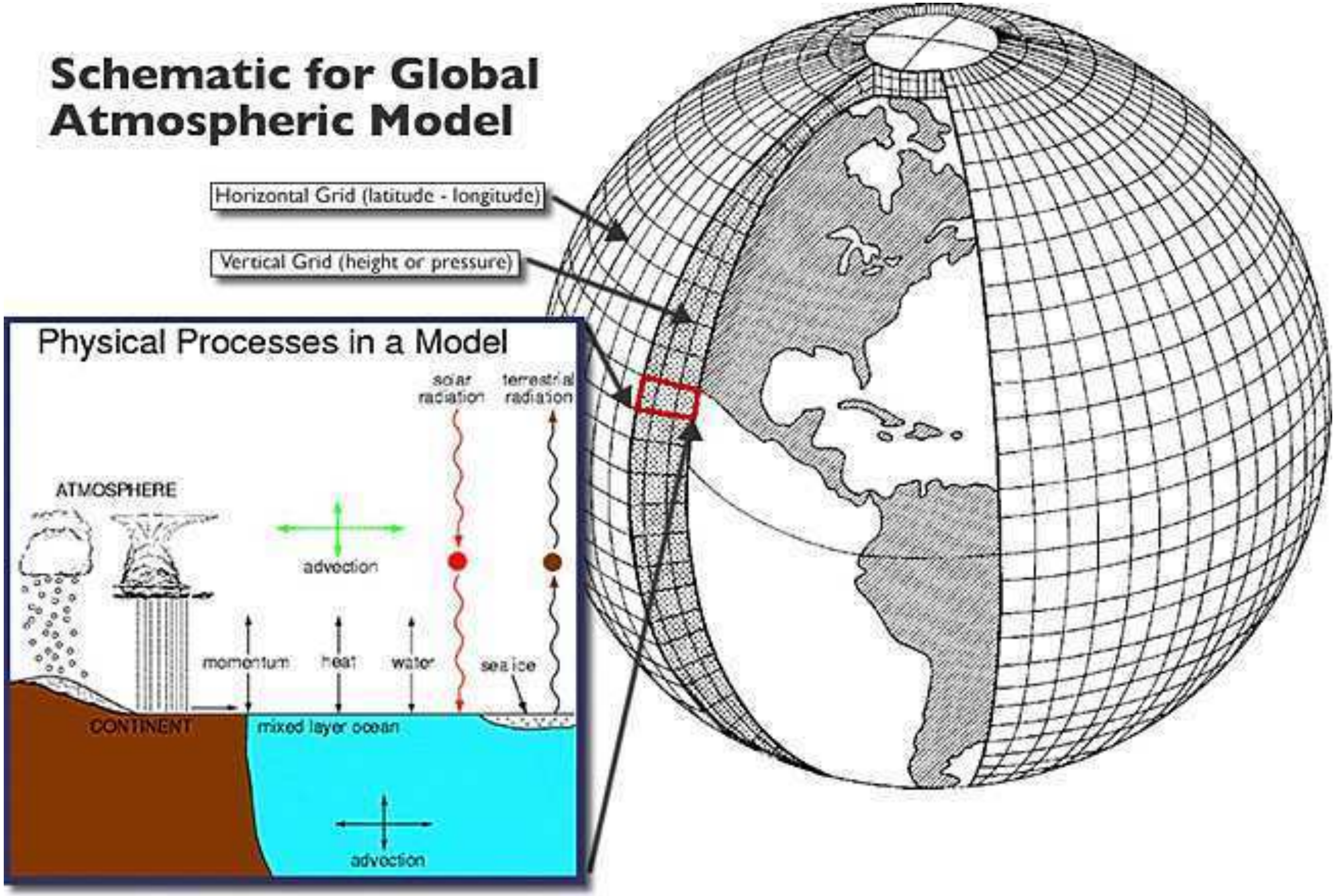
The Practice of Climate Science

How is it studied?

- A branch of the earth sciences.
- A very complex dynamical system, with aspects of physics, chemistry, biology and a flavour unto itself.
- Study using:
  1. General Circulation Models on large computers. Incorporate all of the ‘microscopic’ laws of nature we know. The computer model integrates this, in both time and in concept.
  2. Theory, which might be mathematical models. Try to predict macroscopic behaviour ab initio.
- Test using observations (present and past): from daily tests (weather forecasts!) to paleorecords.

Aside: Observations are as important than ever, but that is another lecture.

General Circulation Models



Fluid equations of motion are typically finite-differenced or expressed in spherical harmonic functions. Add 'physics' (radiation, precipitation etc) at each grid point.

Climate Research (Excepting Observations)

- Climate research (or at least its funding) is becoming dominated more and more by large models, so called 'General Circulation Models' (GCMs) and now by 'Earth System Models' (ESMs). Some of the largest and most complex computer code ever developed.

- Similar developments are occurring in other branches of science: ecology and evolutionary biology, astrophysics, condensed matter physics.

- 'Theory', in the traditional sense, seems to be playing a smaller role. Is such 'theory' still relevant to our scientific enterprise?

- Perhaps GCMs, as the embodiment of our collective understanding, *are* our modern-day theory of climate?

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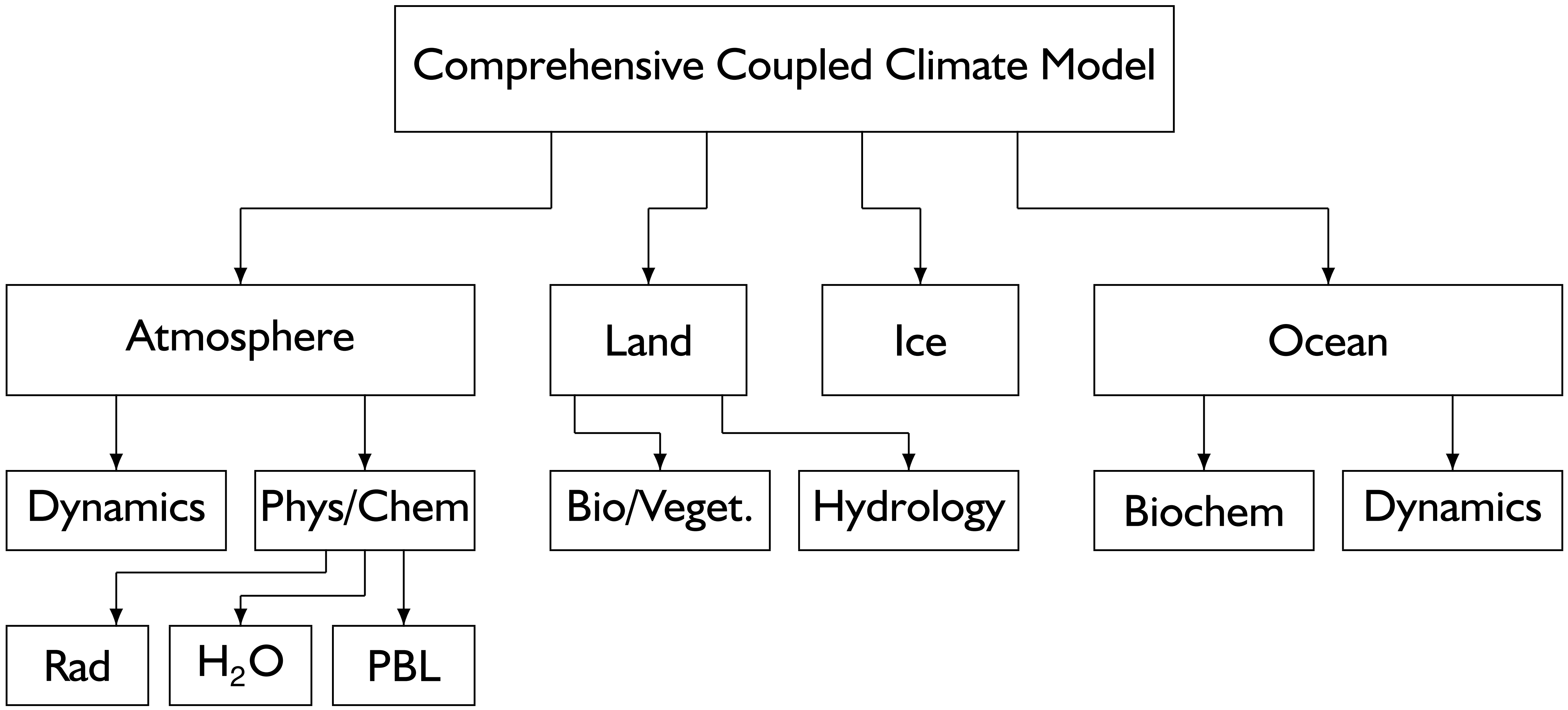
This is meant to be a science talk, not just a philosophy talk, so I'll connect these questions to particular issues in climate science, for example

1. Mixing in the ocean.
2. Global warming.
3. Understanding paleo-climate regimes.

The Very Model of a Modern Major General

The Very Model of a Modern Major General Circulation Model



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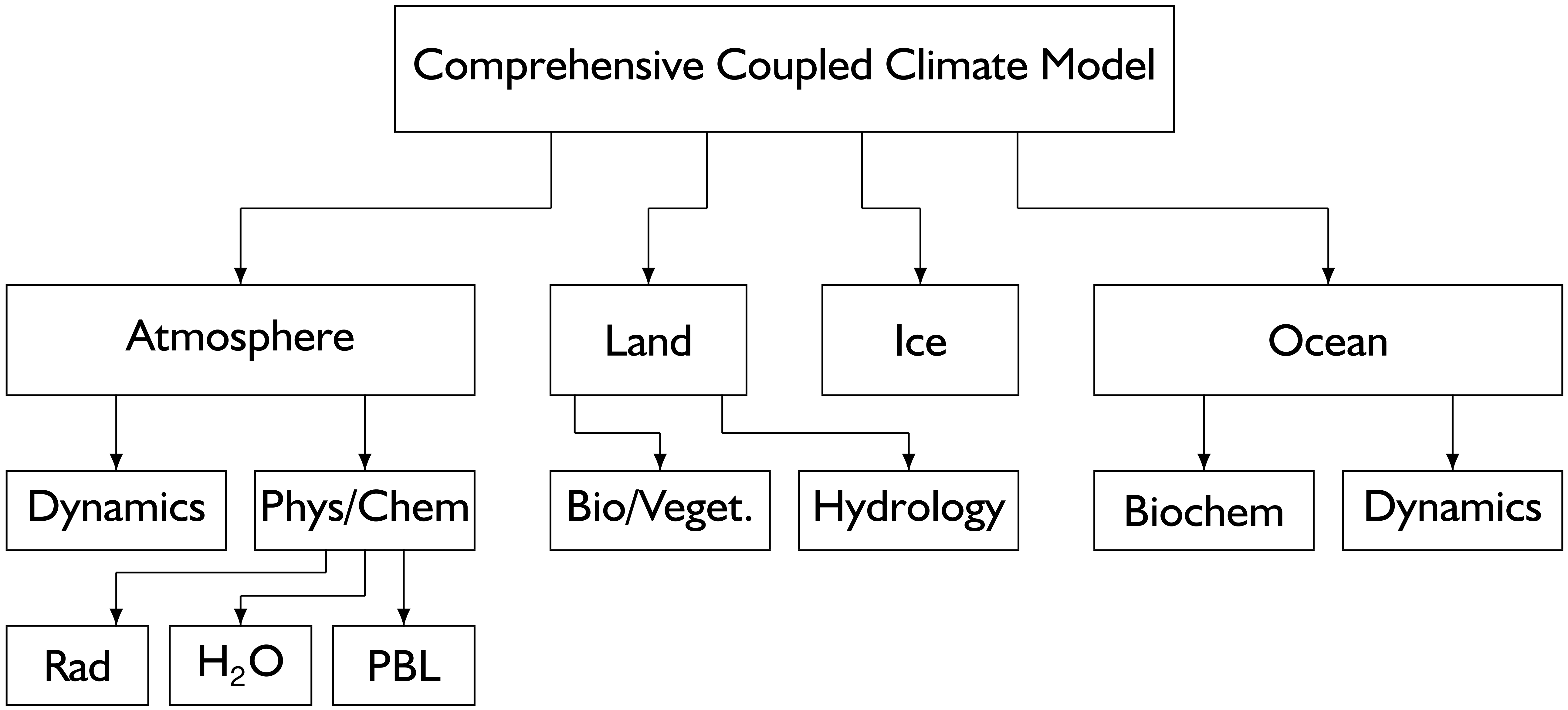

Theory:

$$\frac{\mathrm{D}q}{\mathrm{D}t} = 0, \qquad q = \nabla^2\psi + \beta y \qquad \text{(in a doubly-periodic domain!)}$$

The Chasm

A caricature

Modellers think that theory is:

1. Overly simple, and quantitatively poor.
2. Irrelevant in the modern scientific enterprise.
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Models and Theories. What are they?

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A Model

A *model* is a representation ('re-presentation') of some phenomena. It may be empirical, or based on physical laws, laboratory or numerical, analog or digital.

Examples

- Rotating tank in the laboratory.
- Computer model of a virtual reality (the video game SimCity, the Holodeck from Star Trek, the Matrix movie).
- Conceptual/mathematical models (e.g., the Ising model, the Big Bang and Steady State models in cosmology).
- Complicated numerical models (e.g., GCM)

Properties

- Comprehensiveness and verisimilitude are often virtues.
- Predictive power is a virtue
- Parsimony is not a requirement.
- Generality is not a requirement.
- A priori nature not a requirement.

Models and Theories

What are they?

A Theory

A scientific *theory* is a set of principles or a framework that explains some phenomena, and that is:

(i) Testable
  - Otherwise it is not scientific. Karl Popper says a theory should be *falsifiable*.

(ii) Economical, or parsimonious
  - A theory should be in some sense simpler than the phenomena it explains, or it is merely a description.

(iii) General
  - A theory should be able to explain a class of phenomena, not just a single instance.

Examples: Darwinian evolution, Relativity, Quantum Mechanics, Plate Tectonics

- Ideally based on some a priori foundation, at some level.
- Theories are subsets of models: A theory is a model, but not all models are theories.
- No need for a theory to be based on equations.

Understanding

What is that? — Is that what we seek?

I shall not today attempt further to define the kinds of material. . . embraced within that shorthand definition. . . . But I know it when I see it.
Potter Stewart, Supreme Court Associate Justice, *Jacobellis vs. Ohio,* 1964.

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Understanding is a subjective concept that is almost undefinable. It is being able to grasp all sides and all levels of a problem simultaneously. It is not the same as having a theory, because

- You can intuitively understand something without being able to formalize it.
- You can have a theory that you don't understand!

Understanding might be regarded as knowing the *meaning* of a theory.

Arguably understanding is not the end point of science, just a means to the end.

Understanding aids the construction of new theories... and better models.

Thoughts on Theory and Understanding

Theories are not permanent:

> *No fairer destiny [has] any physical theory, than that it should of itself point out the way to the introduction of a more comprehensive theory, in which it lives on as a limiting case.*
>
> Albert Einstein

We don't really care about understanding:

> *The only object of theory is to calculate results that can be compared with experiment. . . it is unnecessary that the whole course of the phenomenon be given.*
>
> Paul Dirac

Indeed, it may be hubris to think that we actually construct theories or understand:

> *The sciences do not try to explain. . . they mainly make models. The justification [of a model] is solely and precisely that it is expected to work.*
>
> John von Neumann

Models in Other Scientific Fields

- Astrophysics
  - Computing the universe. . . numerical models of galaxies, accretion disks, extra-solar planets etc.
- Theoretical physics
  - Use models make quantitative predictions and understand the phenomenology of string theory, etc. The Standard Model (or is that a theory?). The Ising model in condensed matter.
- Economics
  - Numerical models in game theory, and how the macro-economy works, or doesn't.
- Ecology and Evolution
  - Trying to make quantitative predictions in evolution, speciation, etc. Evolutionary dynamics.
- Making nuclear bombs
  - Avoids the need for actual testing?

Climate seems to have the most developed models, in comparison with extant theory.

Evolution has an underlying theory (Darwinian theory et seq.), as well as various models of particular situations. Is there an underlying theory of climate?

Theories — Good and Bad

Chris Garratt (U. Victoria):

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So our theory of climate is

(i) The Navier-Stokes equations
(ii) Thermodynamical laws
(iii) Radiative transfer (EM) equations
(iv) Boundary conditions

This is what a GCM is — so GCMs are our theory? *Yes,* in some sense, but it is

1. low level, and so not very economical;
2. in parts ad hoc, and so not very general.

and therefore, perhaps, not a good theory. Is there a better, 'higher level' theory?

Theories at Different Levels and Emergent Phenomena

- A theory may try to predict ‘emergent phenomena’ directly, without reducing it to the detailed behaviour of its constituent parts.
- A numerical model or a simulation is a calculation from which phenomena naturally emerge from the basic building blocks, maybe as a by-product. Very reductionist.

Emergent Phenomena - examples

— Temperature.

— The Gulf Stream, the Hadley Cell.

— Galaxies, clusters of galaxies, solar systems.

— Species in biological evolution. Consciousness.

Explicit Large Numerical Calculations

— Numerical calculations of colliding molecules, Maxwellian distributions.

— GCMs simulating the Gulf Stream and the Hadley Cell.

— Smoothed particle hydrodynamics for galaxies, cosmological N-body codes etc.

— [Species in evolutionary biology? Consciousness?] *Not yet!*

Some Differences Between Fields

- In biology, theories about some emergent phenomena (e.g., Darwin's theory of species) came first.
  - No accepted 'equations of motion' for constituent parts. A few explicit 'microphysics' calculations been attempted (evolutionary dynamics) with synthetic equations.
  - There are natural hierarchies — simpler systems (drosophila) — to help understand.
- In statistical physics, the scale separation between macrophysical phenomena (e.g., temperature) and microphysics (e.g., bouncing molecules) is very large.
  - Sensible to have theories of both: thermodynamics and kinetic theory.
- In astrophysics
  - Similar to geosciences in some ways. Well accepted equations of motion, complicated phenomena.
  - Sometimes use numerics just to flesh out a theory and make it testable (e.g., general relativity). No parameterizations in that case.
- In geosciences and climate, large computers allow direct computation of complex phenomena (e.g., the climate system, the Gulf Stream).
  - Well accepted equations of motion.
  - No natural hierarchies — just one climate system. So we must construct our own synthetic hierarchies.

I come not to bury Models, but to praise them.

GCMs are Pretty Darned Good. . .

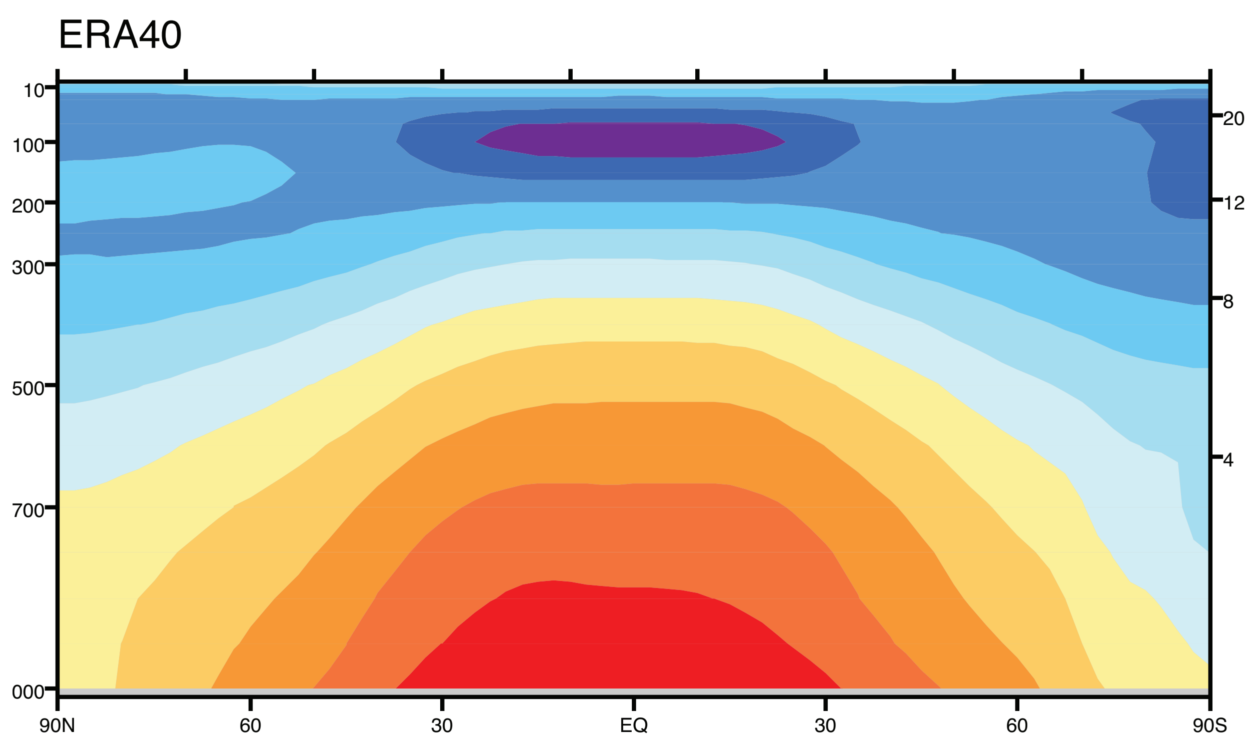
They are the single most effective and accurate tool we have for describing and predicting the climate.

(Which is not to say that they are perfect, or even necessarily good).

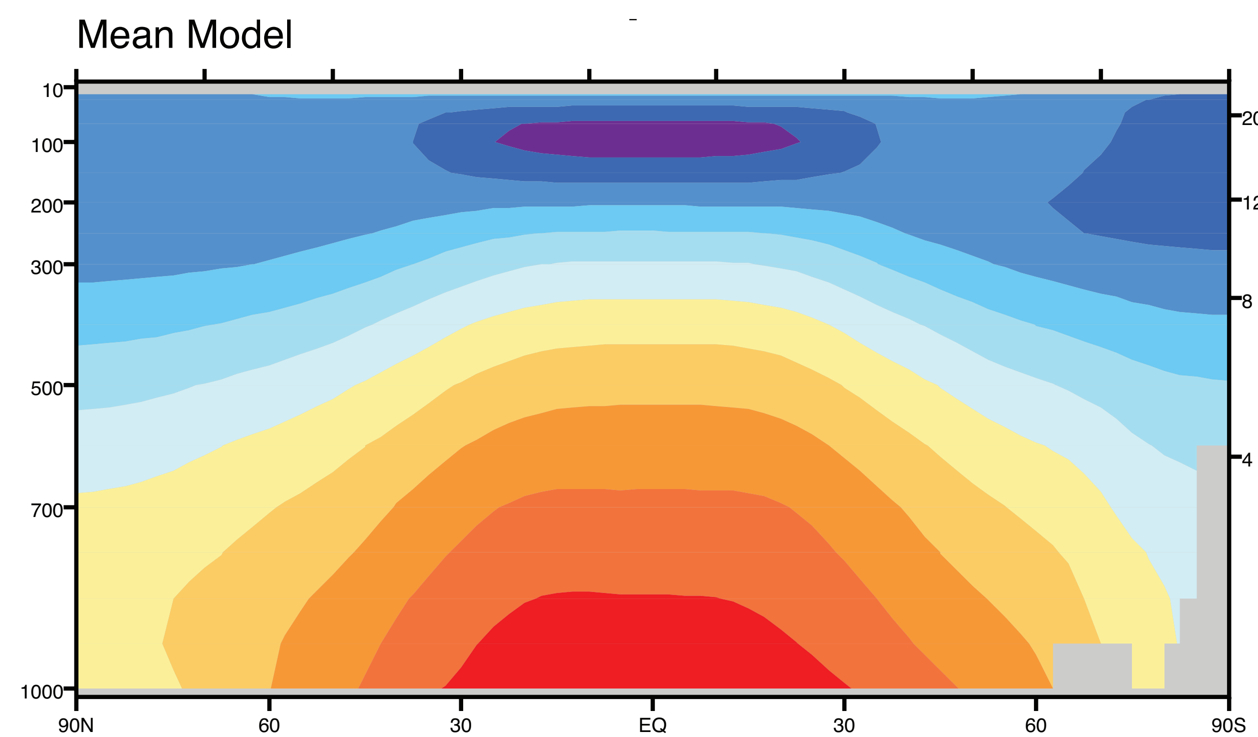
Temperature

Zonally Averaged

Observations

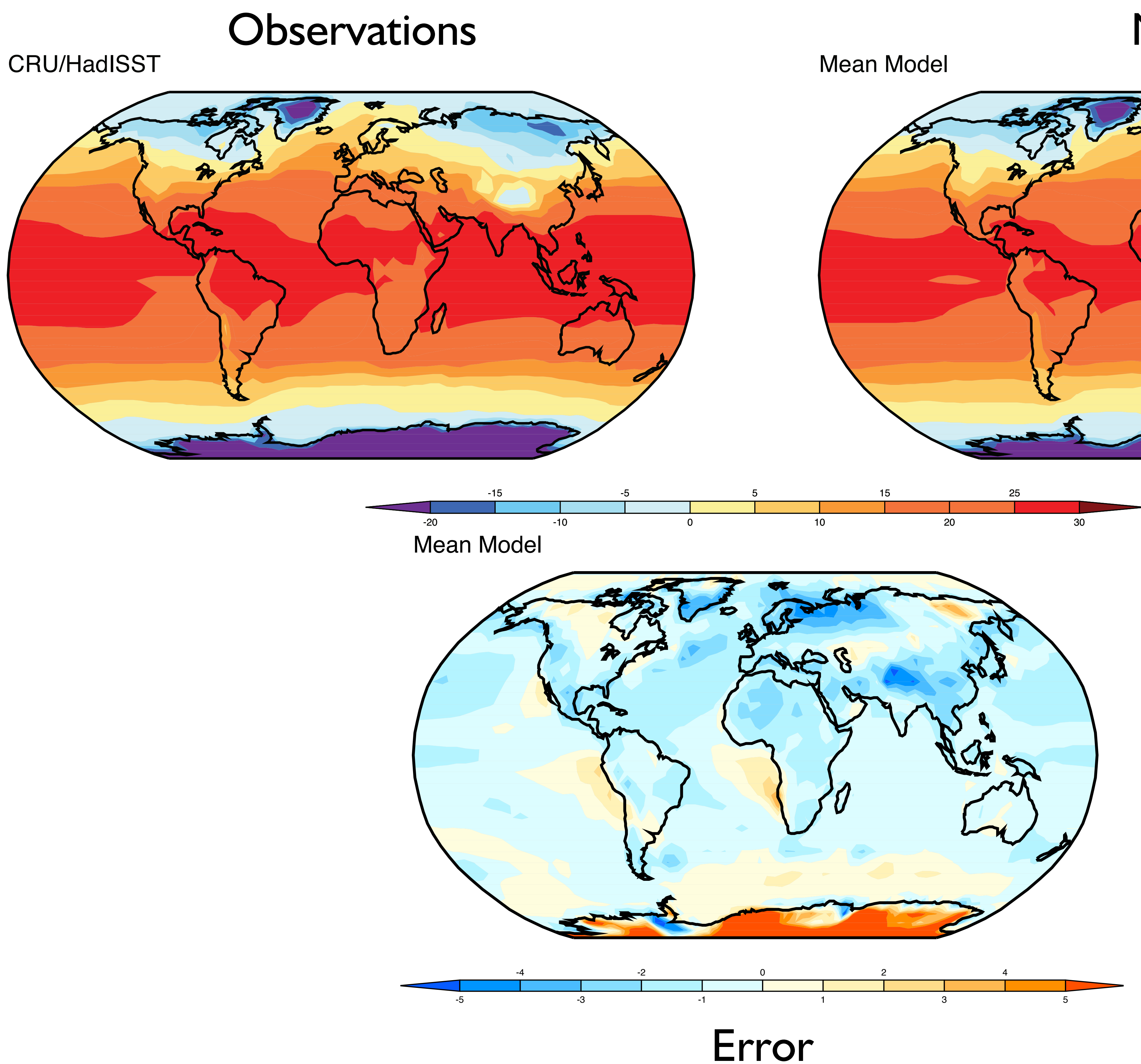


Model



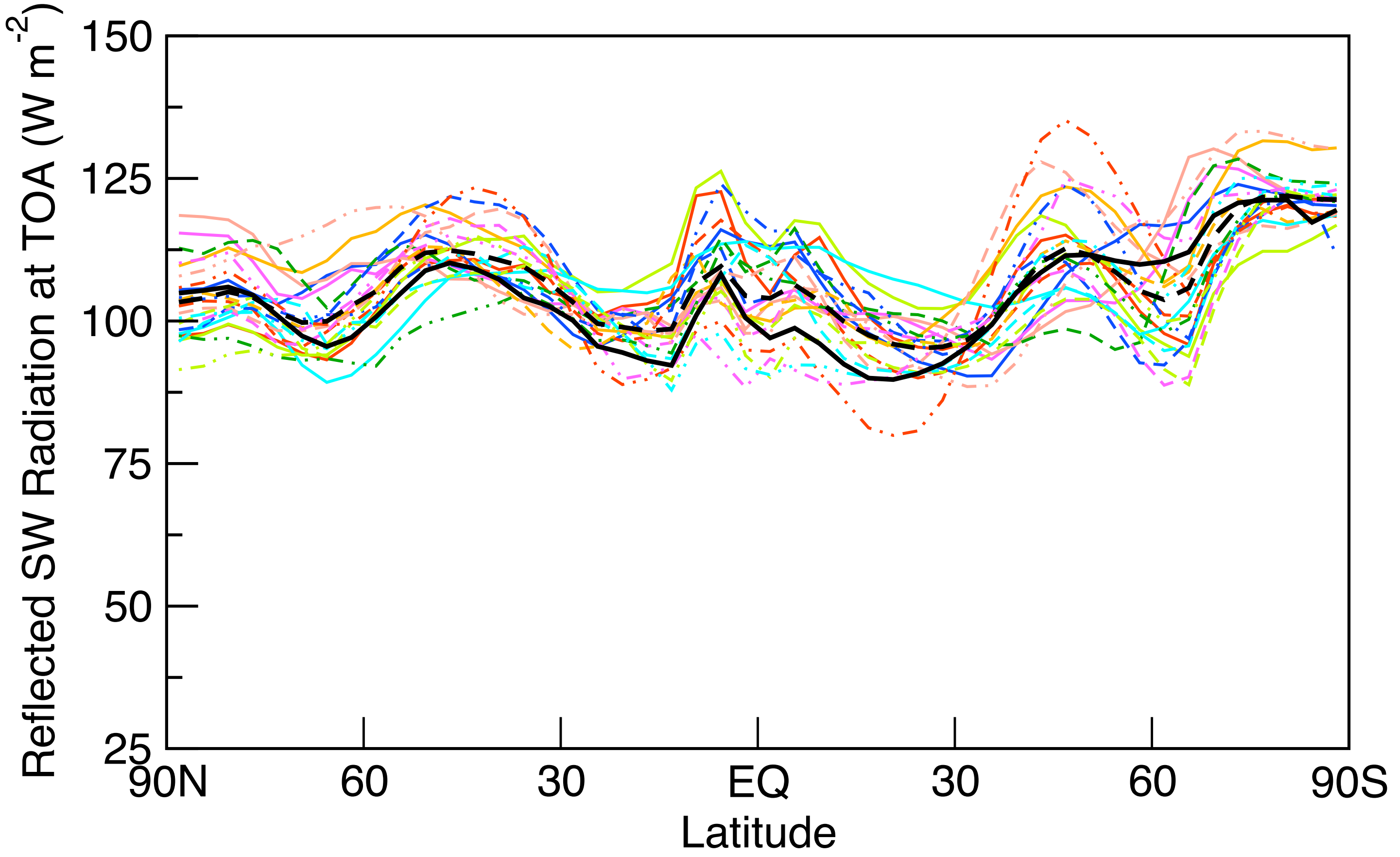
IPCC AR4

SST and Surface Air Temperature

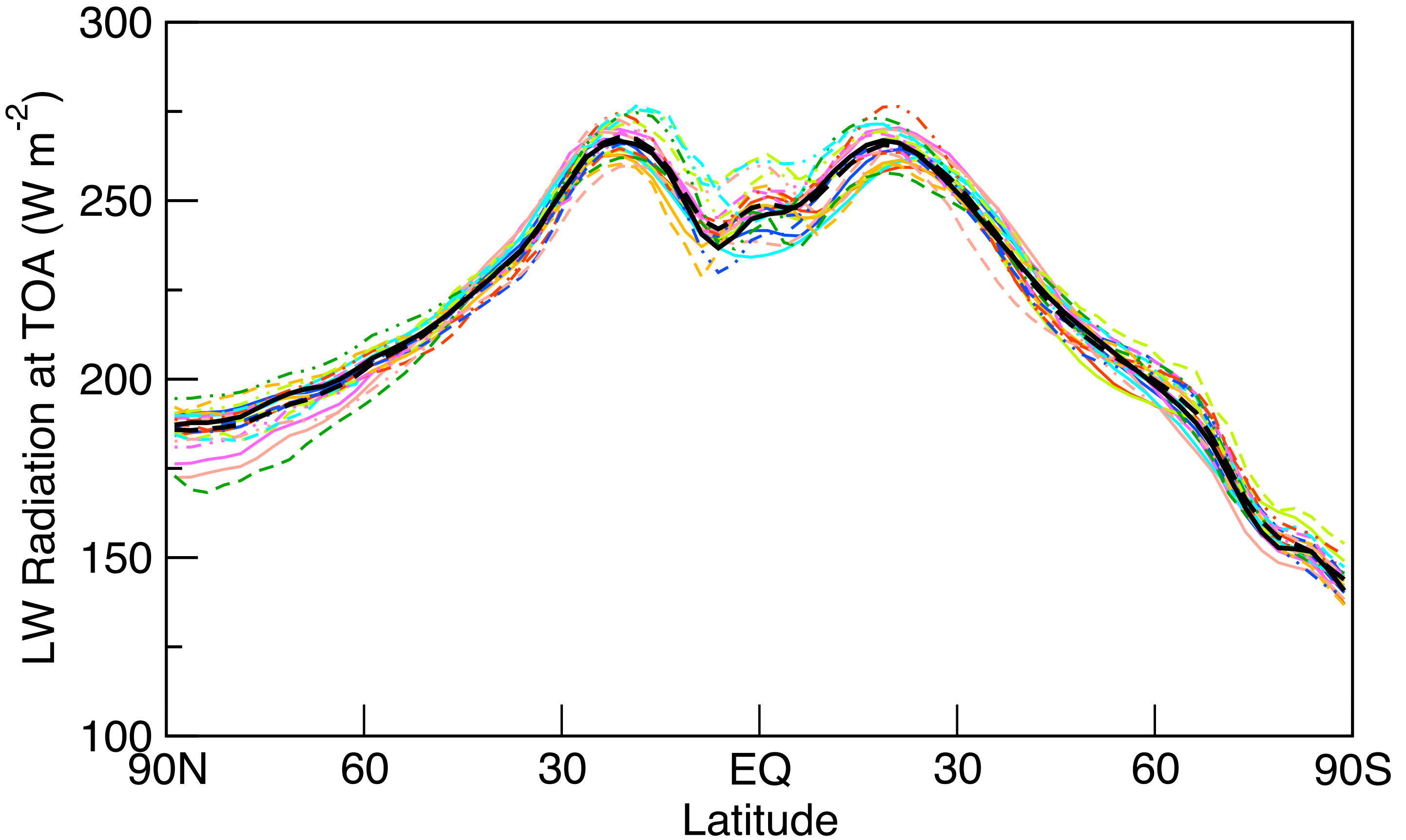


Solar and Infra-red Radiation

Reflected Solar:



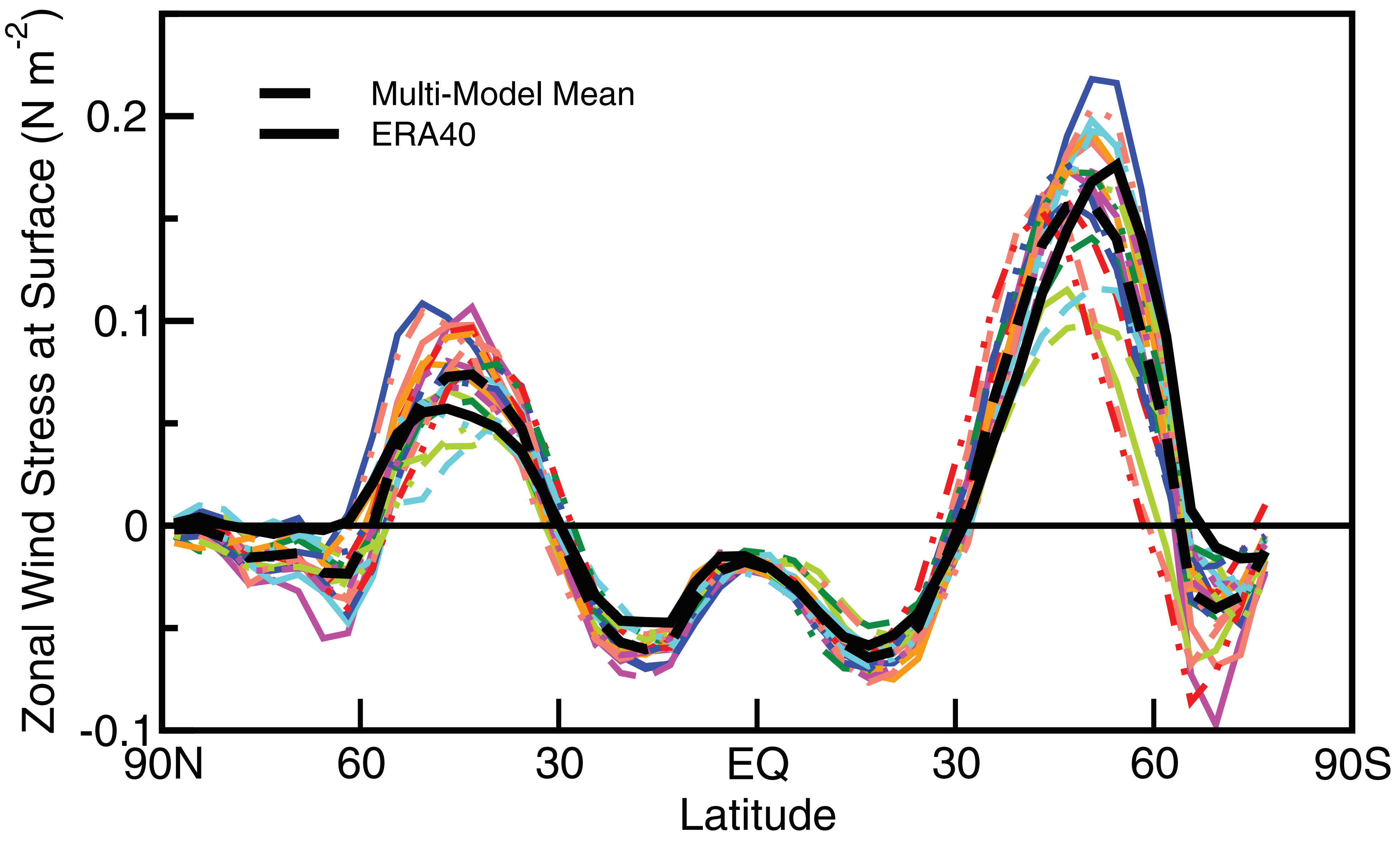
Outgoing IR:



Zonally Averaged Surface Stress

1980–1999

IPCC AR4

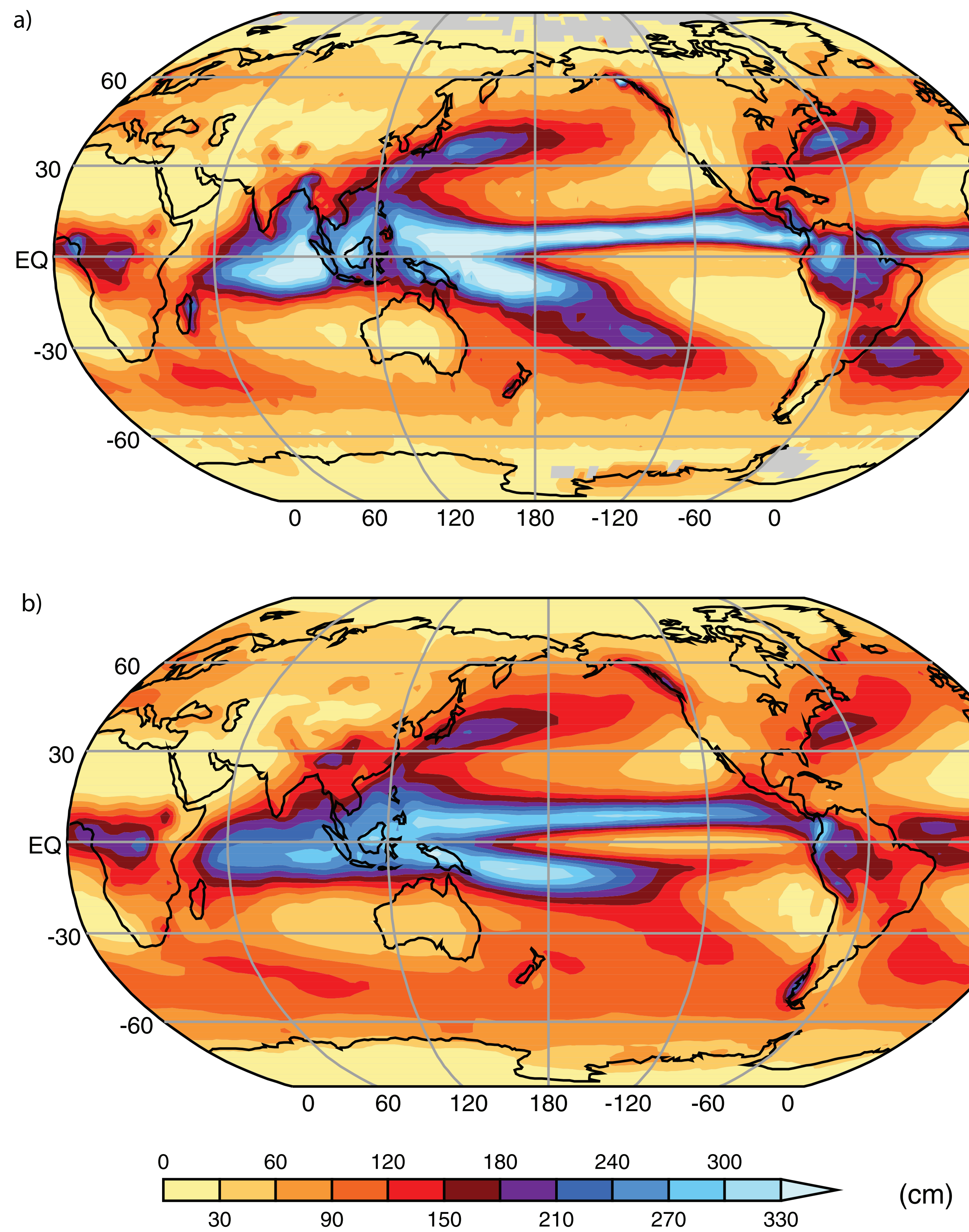


Surface stress is a proxy for momentum convergence in the atmosphere by large-scale, turbulent eddies (i.e., the weather)

Global Rainfall

Observations

Model
(Multi-model ensemble,
IPCC AR 4)



What have we learned from Models?

How do we find them useful?

Let me count the ways.

1. Weather forecasts
2. Estimating state of the ocean.
3. Quantitative estimates of global warming.
4. El Nino simulation and prediction. Climate forecasts generally.
5. etc etc etc

How do we find them fundamental:

1. Show some theories are wrong: numerical models are like lab experiments.
2. Unpredictability of weather (chaos theory, with caveats)
3. Some modern ideas about ocean circulation (‘paradigm’ shifts of how the MOC works).
4. More?

So what's wrong with complicated models?

1. They are very complex, and not an economical theory of large-scale phenomena. An aesthetic objection.
2. They have empirical components (so not wholly a theory).
3. They are imperfect.
    - They are not always in quantitative agreement with observations.
    - They appear to fail miserably in some past climates (equable climates).
4. They work by cancellation of errors.

Corollary and Practical Consequence

- They are not always trusted.
- They are hard to improve.

The Crux of the Matter

If models (simulations) were perfect, then conceptual theory and understanding would be an indulgence, a mere intellectual conceit, of little value beyond personal satisfaction.

What's wrong with Conceptual Theories?

- They doesn't always connect with the real world; they are a theory of some idealization, like a western boundary in a square ocean.
- For many problems, theory does a *worse* job of describing, and providing a basis for understanding, a phenomenon than does a direct simulation.
  - Polewards transport of heat in the atmosphere. Turbulence in general.

Consequence

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A Theory of Climate

(or Theory in Climate?)

Is there an underlying theory of the ‘whole thing’, rather like in evolution?

No: In the sense that there are no easily stated grand principles that underpin the enterprise, aside from the basic laws of physics, chemistry etc.

But simpler theory *is* important:

- Improving GCMs. Tomorrow’s generation of numerical models will depend on today’s theory.
- As an end in itself, as part of scientific progress.

Two particular classes of theory are needed:

1. Subgrid processes where models are imperfect.
2. The behavior of the system as a whole.

If there comes a time when theory is permanently stalled, then progress in the field halts and the subject stagnates. The end of that branch of science.

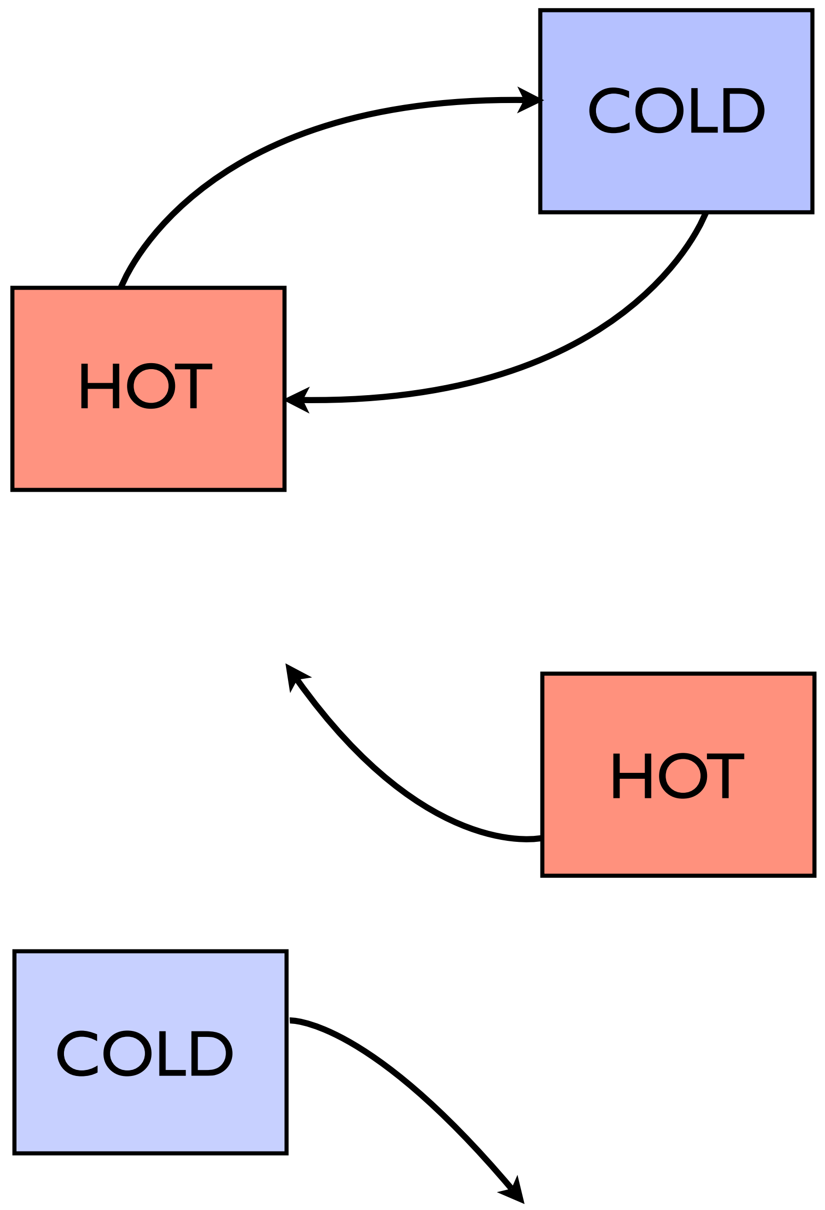
Ocean Mixing

Mixing makes the ocean go round (with caveats).

Sandstrom's Effect

Roughly speaking, if diapycnal mixing is small and if there is no mechanical forcing the heating needs to be at a lower level than the cooling of a fluid in order to maintain a vigorous overturning circulation.

Winds and tides can lead to diapycnal mixing and enable such a buoyancy-driven circulation to occur.



Conclusion: the overturning circulation of the ocean would be noticeably weaker, and so the climate would be different, without mixing.

Ocean Mixing

Scope for theory

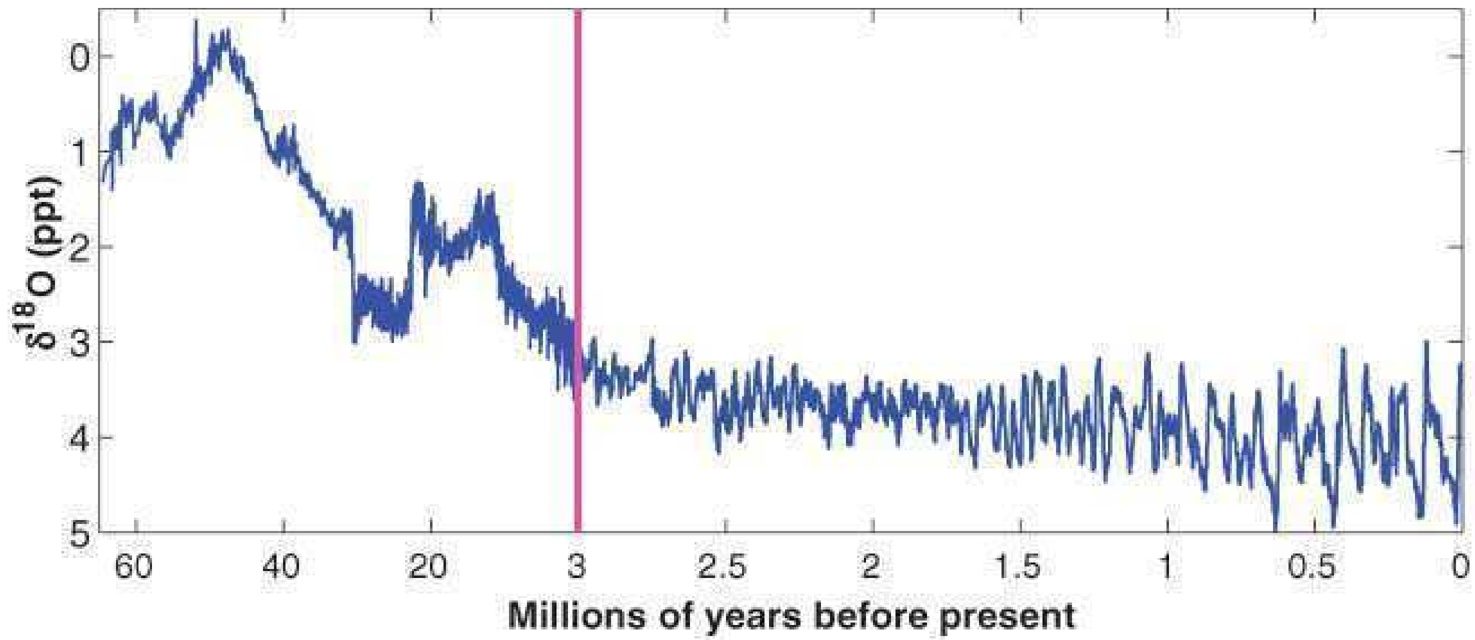
1. Where does the mixing come from?
   - Mechanical forcing: tides, wind forcing. Mesoscale eddies.
2. How and why does it affect the circulation?
   - Mixing creates a diffusivity, which enables water to cross density surfaces, and to circulate.
3. Having said this, there are theories of the deep circulation that *do not need eddy mixing*.
   - Role of the ACC

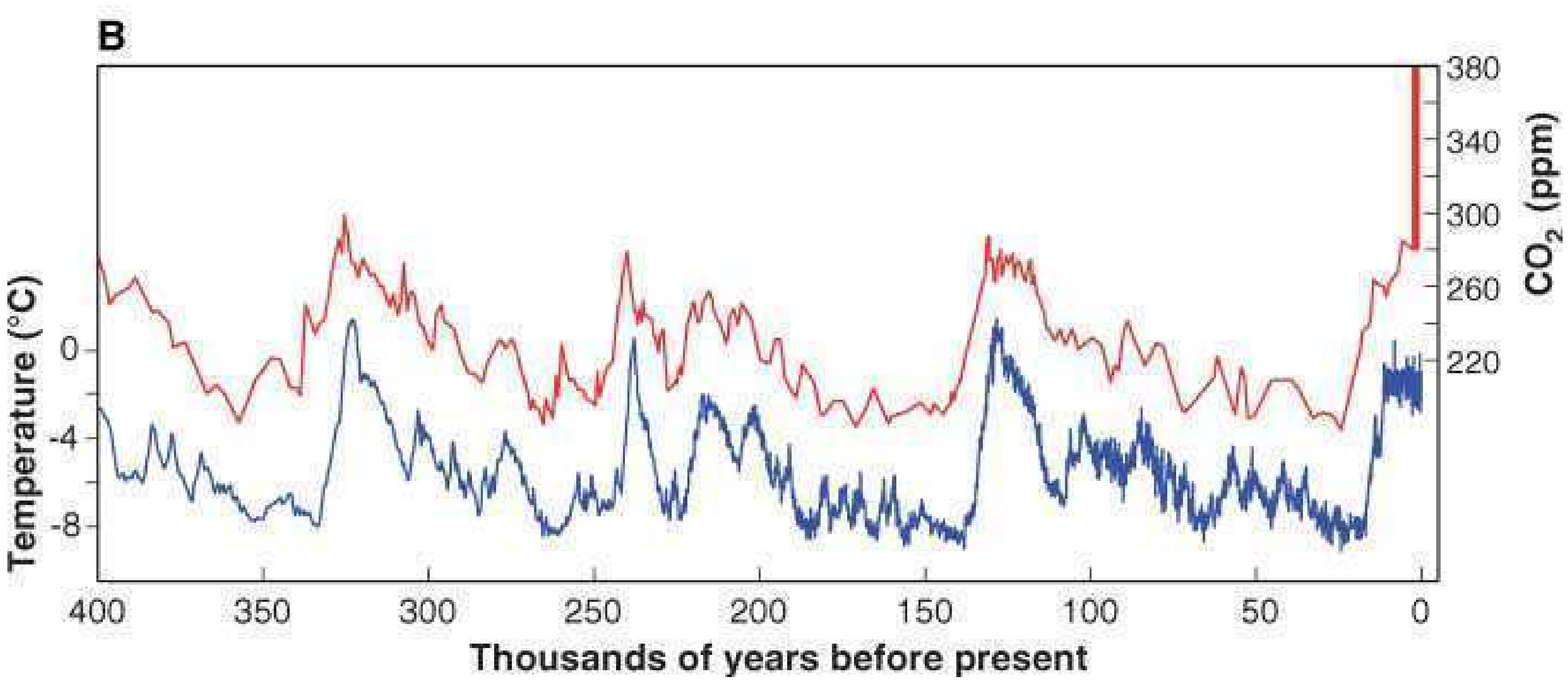
The quantification of all this remains an enormous theoretical and observational challenge. Without theory to guide us, modelling (and the taking of observations, I might add) is blind.

Paleo-Climate

What might we expect of theory?

Zachos et al (2001). High $\delta^{18}O$ is said to be cold (more ice volume).





Petit (1999), Antarctic ice core

- Should also encompass modern climate, but is at a higher level and covers less detail.
- Milankovitch 'theory' (hypothesis) suggests that climate variability is associated with variability in the distribution of solar radiation on the Earth, associated with orbital variations. Remains coarse-grained and the details obscure.
- Other natural and forced variability in the climate system. Equable climates. Mechanisms?

Also, we certainly need models to translate theory into something testable.

Paleo-Climate

Equable Climates (and taking the observations on faith)

- Much higher temperatures at continental high latitudes in Paleocene-Eocene boundary
  - Crocodilian remains (champsosaurs, lizards, tortoises etc) found in high latitudes in continental Canada, Ellesmere Island (78° N). Winter no colder than 4° C.
  - Change in vegetation types in (for example) Wyoming indicative of warm climates (Koch, Wing etc)
  - Large warming of oceanic bottom waters.
- Somewhat higher temperatures at low latitudes.
  - So apparently a much reduced pole-equator temperature gradient.

No GCM has been able to simulate such a climate. Difficulties are:

(i) Pole–equator temperature gradient.

(ii) Mild continental climates in winter.

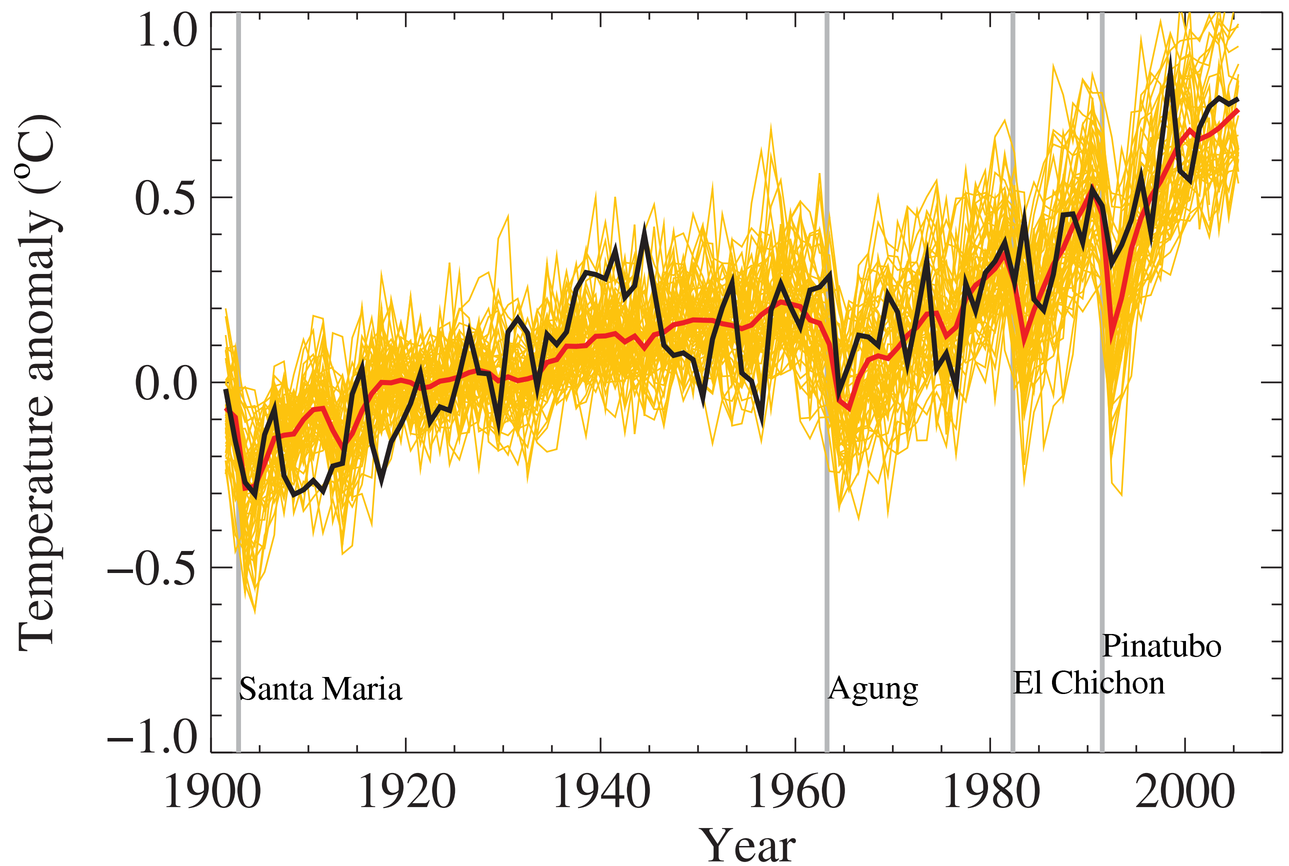
Unlikely that a GCM will ever be able to provide such a simulation without some hypothesis about what is going on, because our present-day prejudices are built in.

Theory alone is unlikely to be sufficient: will not be quantitative.

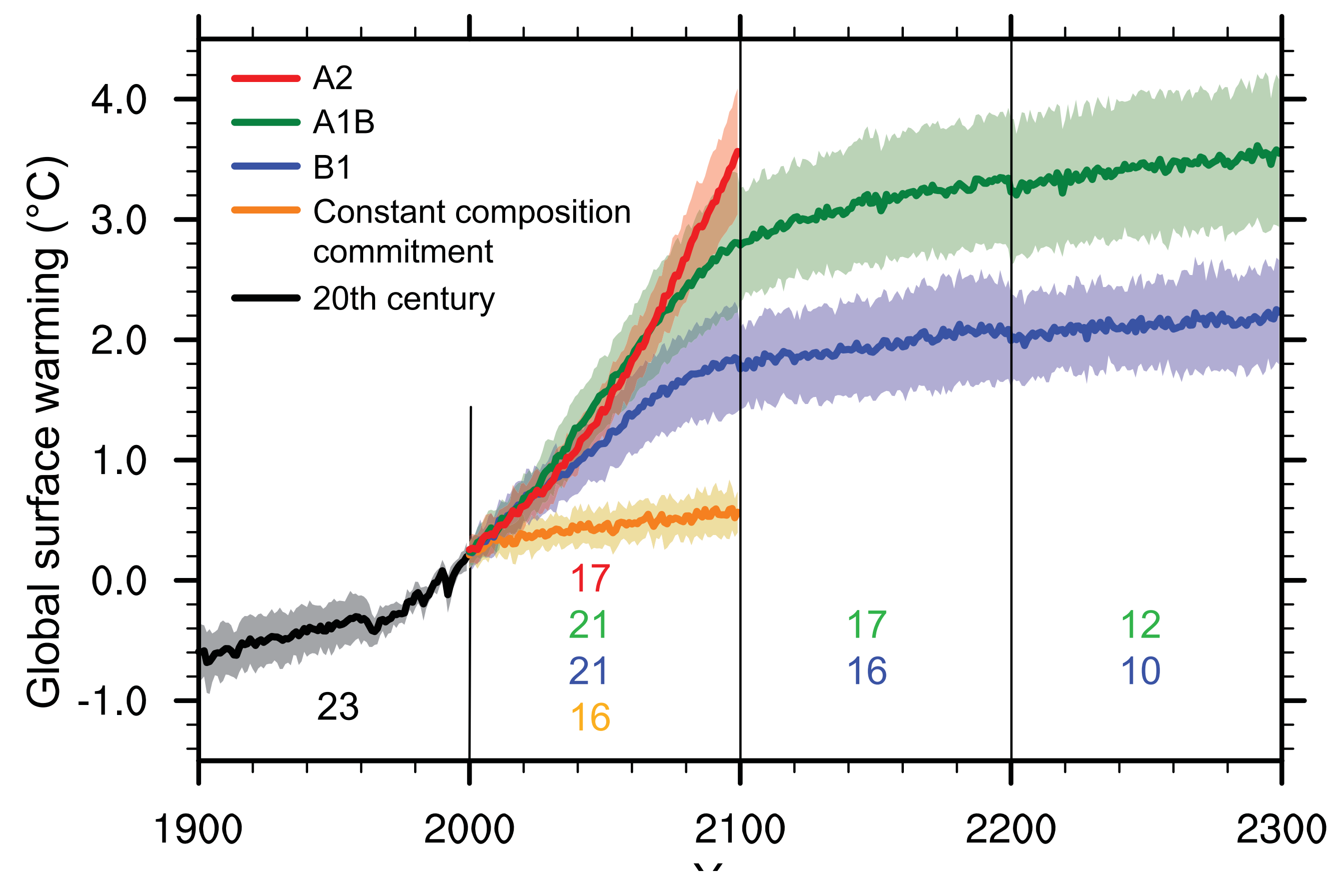
Uncertainty

Simulation of 20 and 21 Century

Past climate (IPCC)



Future climate: (IPCC)



Uncertainty of future climate is greater than our seeming ability to simulate past climate.

We have no good theory for climate sensitivity.

Climate Sensitivity

Scope for Theory

- What level of uncertainty can be expected?
  - Is the climate structurally stable?
- Propagation of uncertainty through the system.
  - What processes are key?
    - Clouds? Land-ice? Ocean heat uptake?
  - Do feedbacks really matter?
- Are the observational constraints sufficient?
  - Levels of aerosols in 20’th century?
  - Climate variations and sensitivity in the past.

(There are activities in some of these areas, fortunately.)

How do we Improve Big Models?

apart from blood, sweat and tears

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- Algorithmically.
  - For example, use an adjoint model to determine what some aspect of the model is sensitive to (be it numerical resolution, a physical parameterization).
- By tuning, and intuition.
  - May seem ad hoc at times, but much experience goes into it.
- By improving the 'sub-grid' parameterizations.
  - Need to understand the process because the whole point is not to use a brute force simulation.
- By understanding models' overall behaviour — and that requires the use of a hierarchy simpler models (that is, using theory!)
  - Suppose a complex model gives the wrong answer — how should we fix it?
  - Just as biologists have fruit flies, climate modellers must construct their own simpler systems to give better understanding (I. Held).

Whither Research?

- Big numerical models are here to stay. That's life. No complaining.
  - If the electric field has a non-zero curl, the magnetic field changes. We don't complain about that!
- The models are a way-station on the road to reality.
  - Thus, it's okay to have a theory of the models, and models of models.
- We don't need less theory (or less thinking) because we have complex models — we need more.

Final Thoughts

Don’t always trust the speaker

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2. Theory can be irrelevant without models and simulations.

Modern science needs both paths, but they don't always intersect as they should.

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'When you follow two separate chains of thought, Watson, you will find some point of intersection that approximates the truth.' (Sherlock Holmes)

The most important thing: whatever you do, have fun doing it!