ATM S 111, Global Warming
Climate Models

Jennifer Fletcher

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Using Climate Models to Build Understanding

- Often climate models are thought of as forecast tools (what's the climate going to be like in 50 years?)
- Models are equally useful for developing understanding though
  - We only have one Earth to observe
  - We're only limited by our creativity in making our own computer worlds

Climate Models

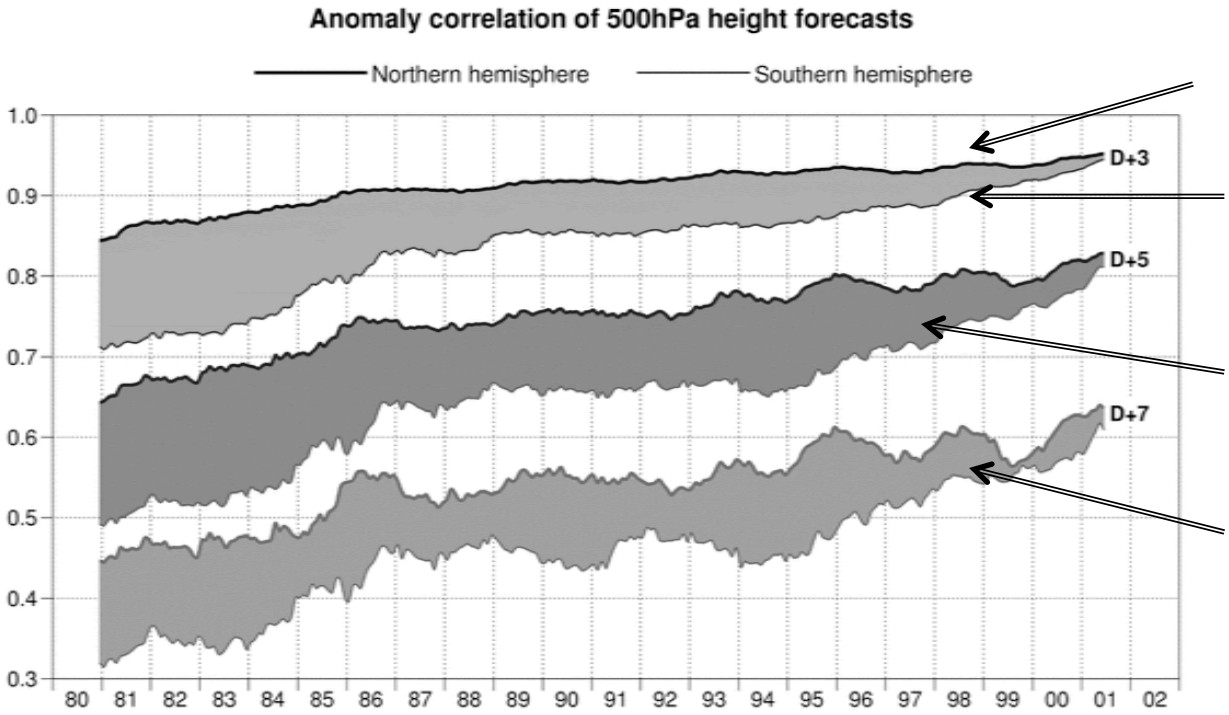
- We'll discuss via :
  - The discovery of chaos by Ed Lorenz
  - The first climate models of Suki Manabe
- But first:
  - Climate models are closely related to weather prediction models
  - Let's discuss some history of weather prediction using computer models

First Weather Prediction on Computers

- 1946: test case by von Neumann and others
- May 1955: Joint Numerical Weather Prediction Unit, Maryland
  - First operational computer forecasts in US
- Global coverage since 1973
- Computers surpassed human forecasts: 1980s?

Numerical Weather Prediction (NWP)

- Improvements in weather prediction over the last 60 years are among the most impressive accomplishments of society



Northern Hem. 3 day forecast

Southern Hem. 3 day forecast

5 day forecasts (NH & SH)

7 day forecasts (NH & SH)

1980

2002

Simmons & Hollingsworth '02

Model Components

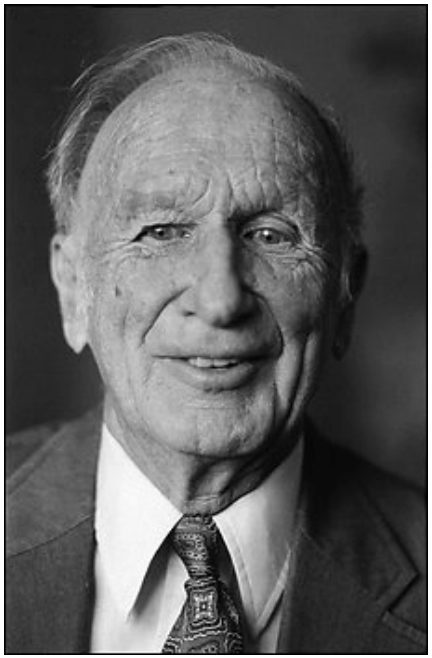
- Components of GCMs & NWPs:
  - Equations of **fluid motion** on a rotating sphere
    - Both the atmosphere and the ocean are fluids
    - Equations put simple physics principles in mathematical form:
      - **Mass** is neither created nor destroyed
      - Heating/cooling changes **temperature**
      - Forces & pressure change **momentum**
      - Compressibility of air
      - Etc etc
  - Given the current state of the atmosphere (temperature, pressure, winds, etc over a given region), these equations predict how that state will change with time.

Weather Forecasting vs Climate Forecasting

- Weather models and climate models are similar in a lot of ways
  - Use very similar mathematical equations
- But weather forecasting and climate forecasting have very different goals
  - How can we predict the climate in 50 years if we can't predict the weather 2 weeks from now?

Chaos

- Ed Lorenz was running a computer model & put in slightly different inputs
  - He found the predictions were similar for a while but then wildly diverged to different solutions



Edward Lorenz (1908 - 2008) meteorologist, M.I.T.

- **Chaos**: when small changes make a big & unpredictable difference

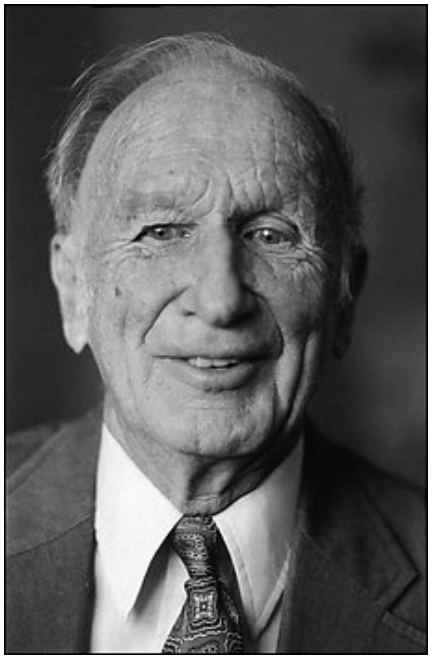
Limit to weather forecast skill: **Chaos**

"Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" [Lorenz, 1972]

Weather forecasts depend very sensitively on the **initial observations.**

We can't observe every butterfly flapping its wings, so weather forecasts lose "skill" (ability to predict storms, not just the right season) after ~2 weeks.

In contrast, climate models are all about modeling seasons…



Edward Lorenz (1908 - 2008) meteorologist, M.I.T.

see Rough Guide, p. 228

Climate Forecasts

- This limit to weather prediction doesn't affect climate forecasts
  - Climate models don't need to accurately predict individual weather systems, they just need to make them behave, on average, like they do in real life.
  - It all averages out after a month or so of storms
- Climate forecasts:
  - Summer is hotter than winter
  - After a strong volcano blows up, the Earth will cool
  - The Earth will be hotter with more greenhouse gases
  - Shifts in weather patterns when El Niño is present
  - Etc...

First Global Warming Forecast

- Manabe and Wetherald (1975):

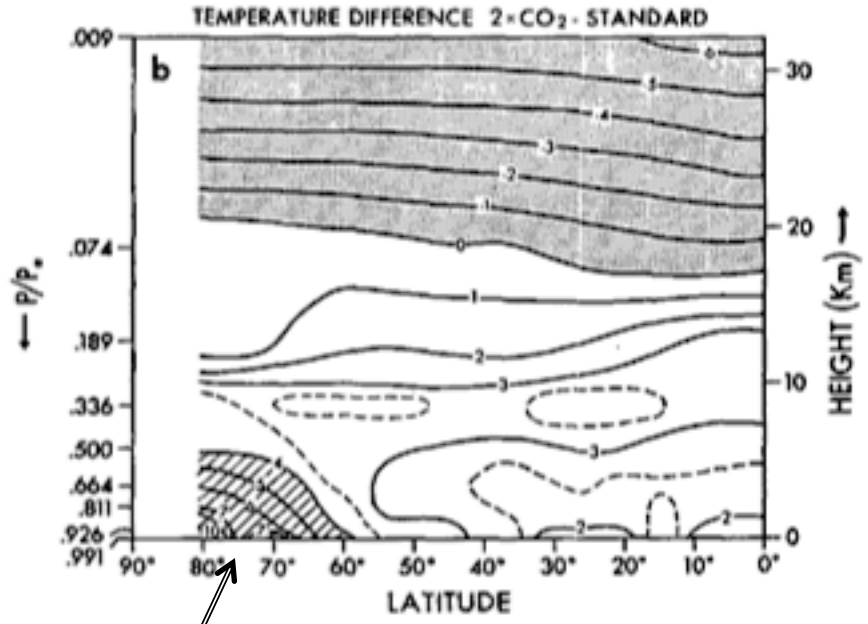


FIG. 4. Latitude-height distribution of the zonal mean temperature (K) for the standard case (a) and of the increase in zonal mean temperature (K) resulting from the doubling of CO_2 concentration (b). Stippling indicates a decrease in temperature.

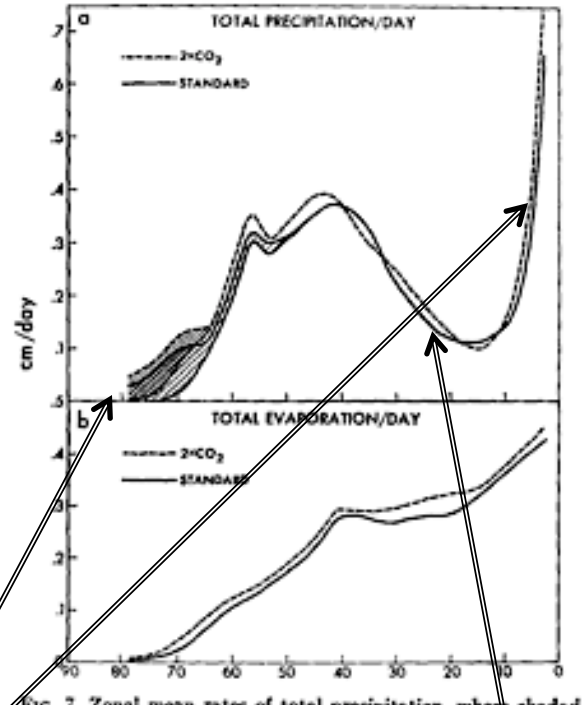


FIG. 7. Zonal mean rates of total precipitation, where shaded areas denote the rates of snowfall (a), and zonal mean rates of evaporation (b).

Polar amplification

Wet areas get wetter & subtropical drying

Other Early Manabe Studies

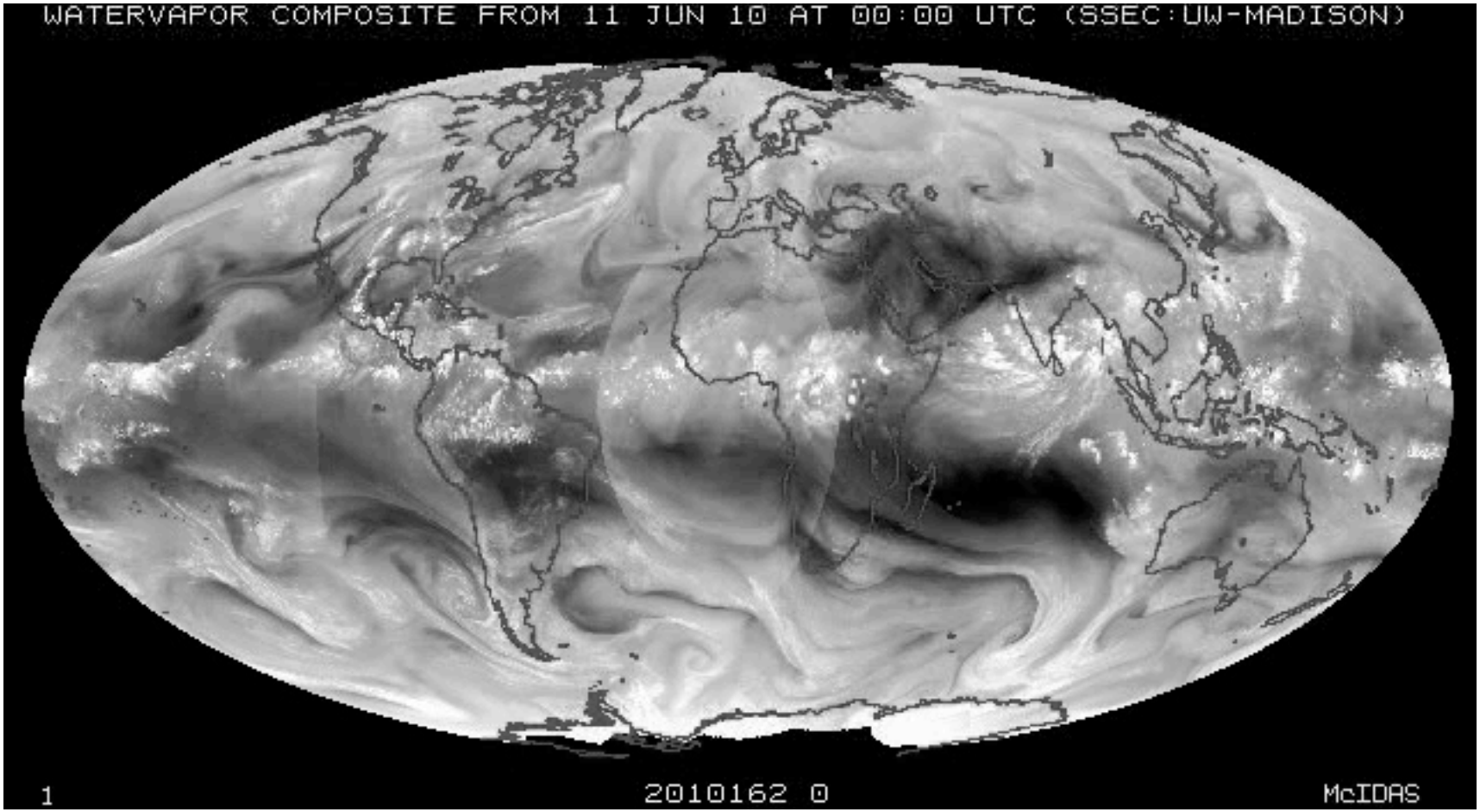
- Effect of ocean circulation on climate:
  - Turn off ocean model
- Effect of moisture:
  - Don't allow condensation to occur
- Effect of mountains:
  - Bulldoze all topography
- Effect of changing **solar radiation**, doubling **CO2**, **ice sheets**, **clouds**, **soil moisture**, etc...

GCM Components

- GCM: Global Climate Model
- Components of GCMs:
  - Equations of **fluid motion** on a rotating sphere
  - **Heat sources**
    - Shortwave and longwave radiation
    - Condensation
    - Surface fluxes
  - Have to parameterize small-scale processes which are the primary heat sources for the atmosphere
    - Clouds
    - Moist convection

Components of GCMs: Dynamical Core

- Essentially just basic physical laws in equation form on the rotating sphere

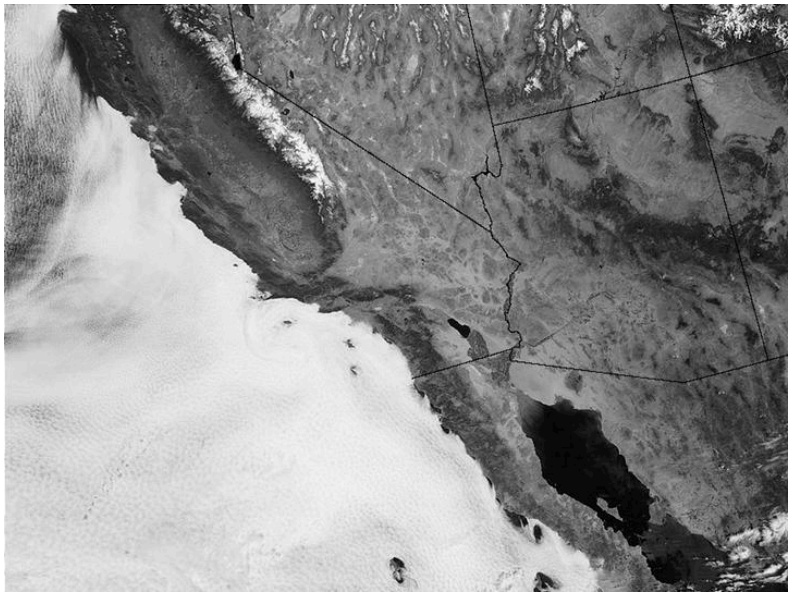


Components of GCMs: Parameterization

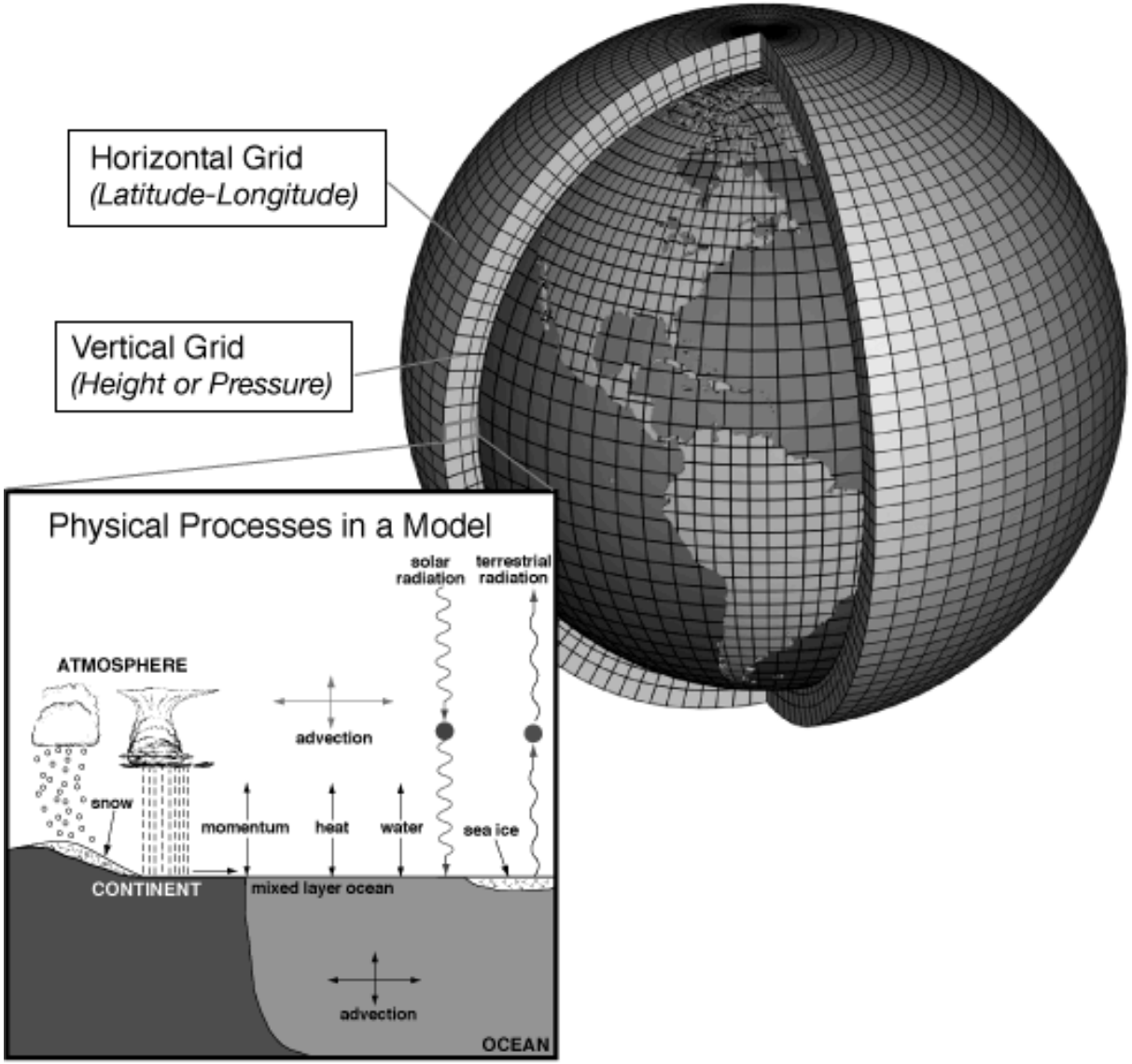
Within each grid cell, there are things that are not explicitly modeled (e.g., clouds) that must be approximated or "parameterized" (e.g., cloud cover from relative humidity)

Cloud schemes

- Cloud interactions are the most uncertain process in GCMs
  - Lead to the largest differences between models

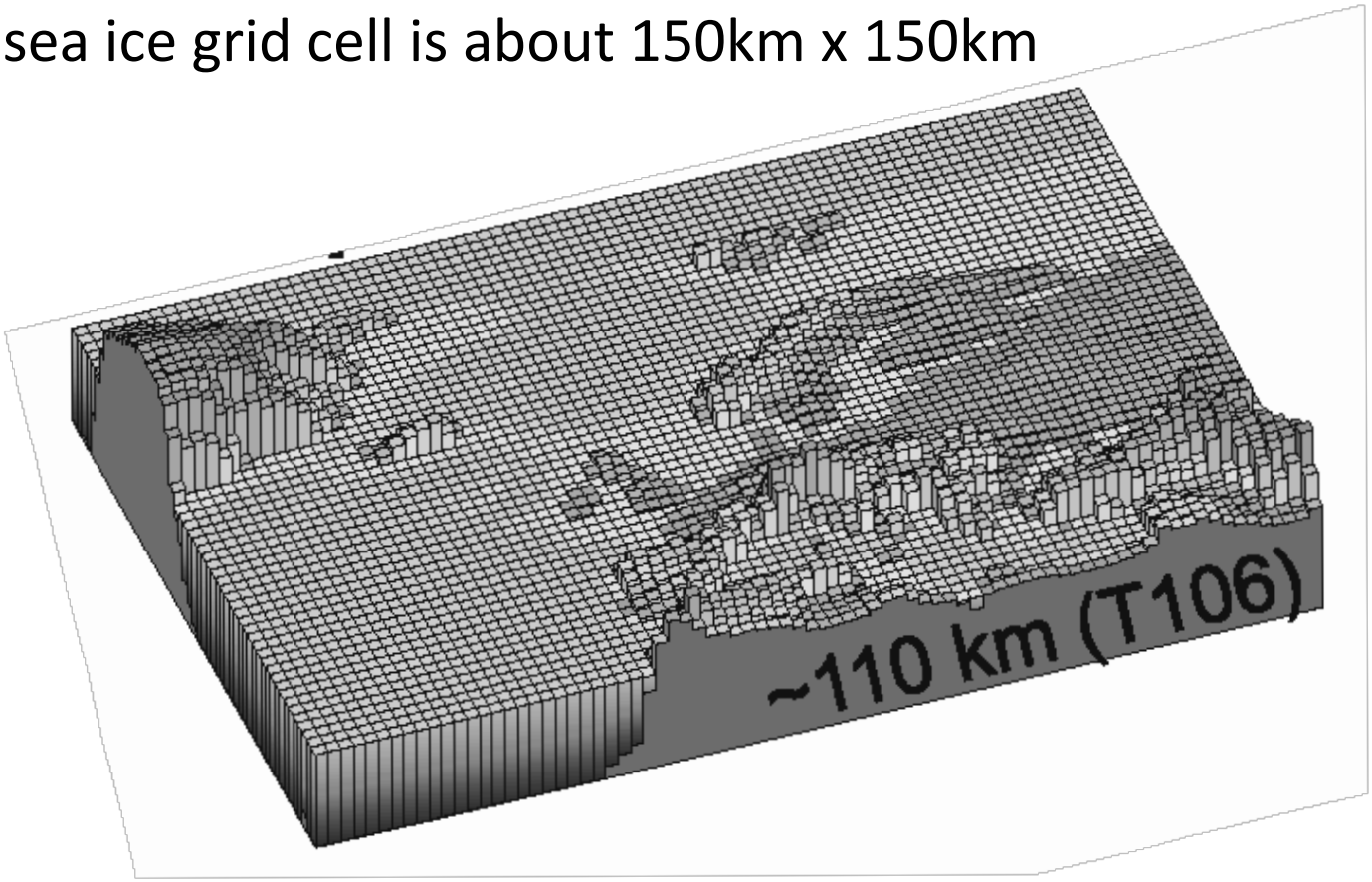


Climate Models Chop up the Earth into Grid Cells



A close up of Europe

- The current horizontal size of an atmosphere, land, ocean or sea ice grid cell is about 150km x 150km



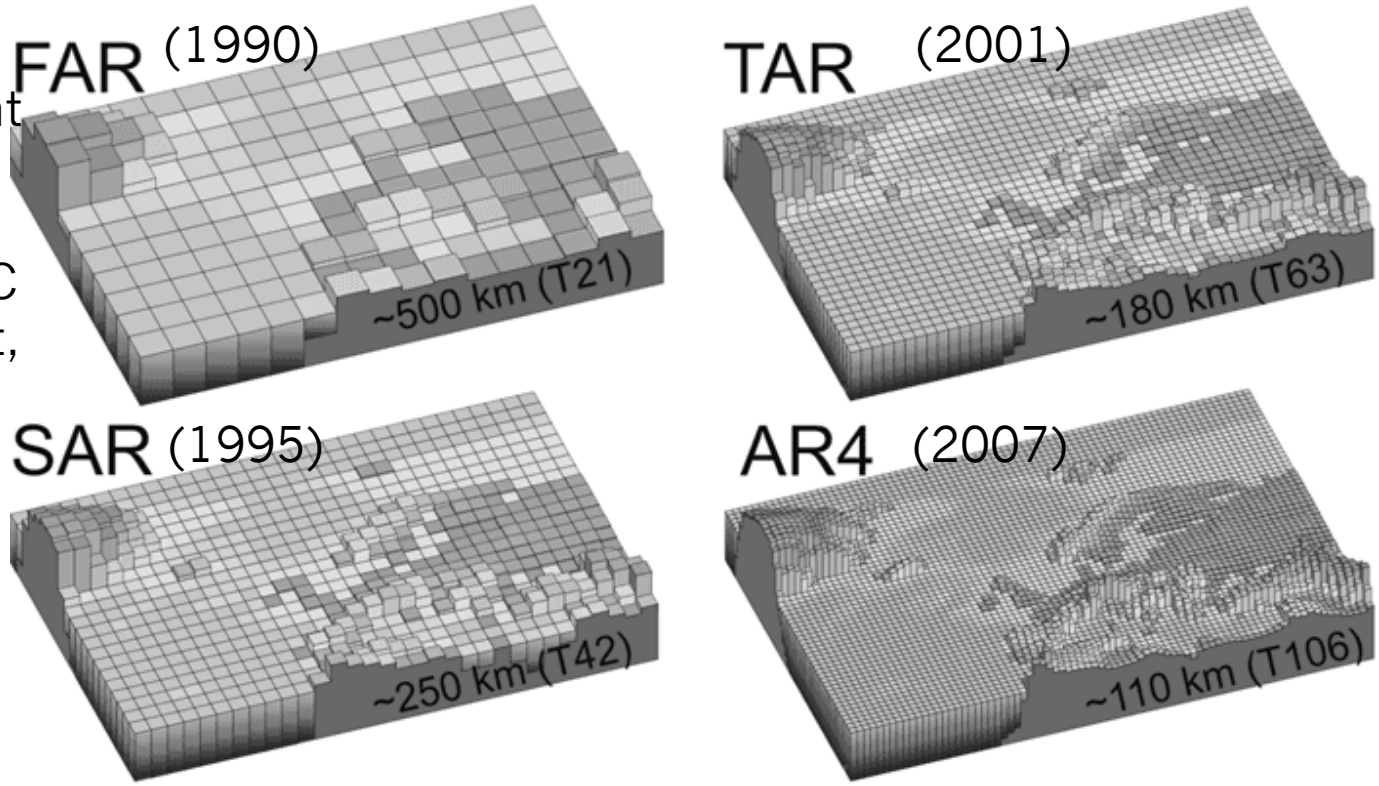
The vertical extent of a box is typically:
Atmosphere/Ocean: 80-500m Sea Ice: 50cm Land: 10cm

Model Resolution Evolution

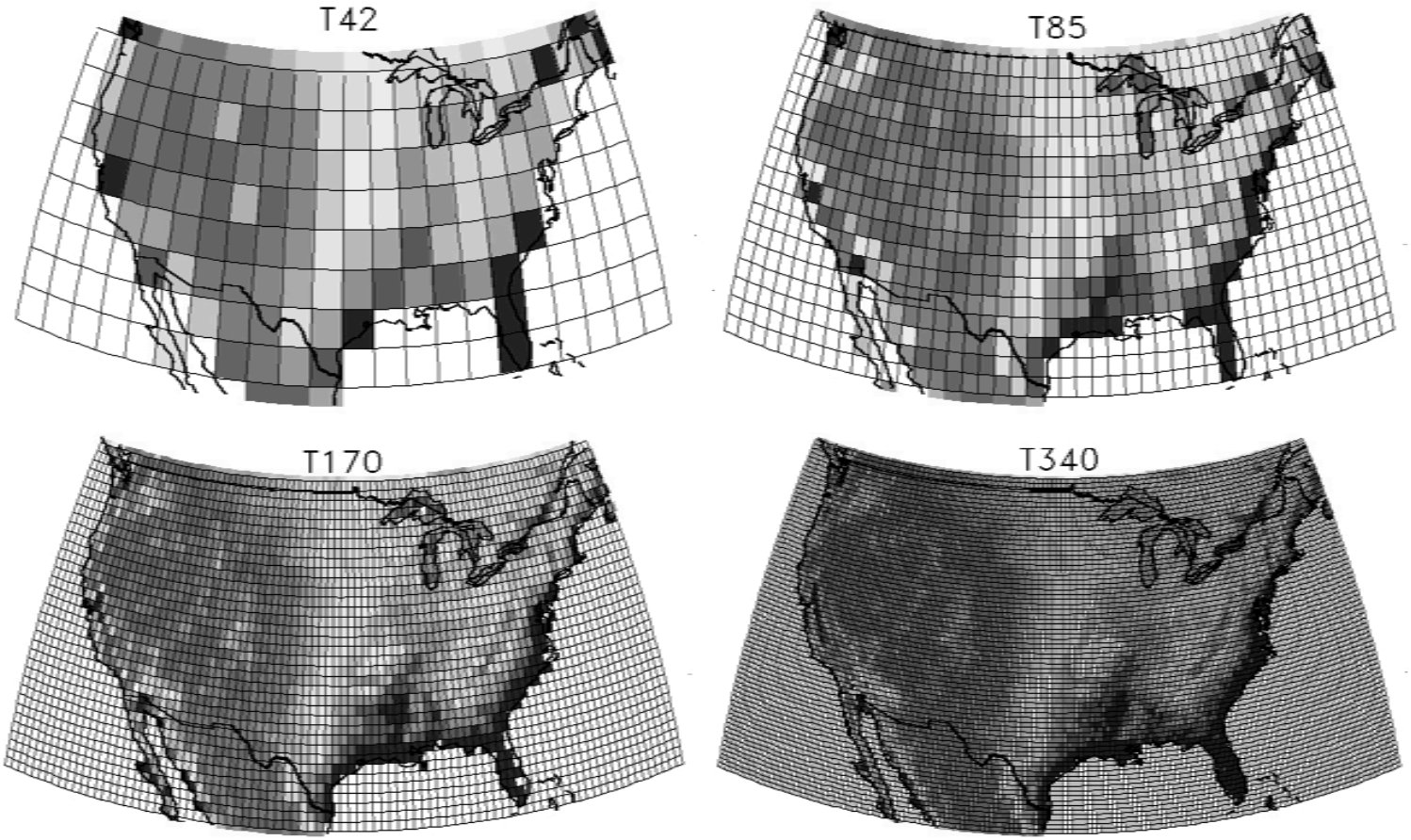
- Changes in resolution over time:

AR = “assessment report” of IPCC

FAR = “first” IPCC assesment report, etc.



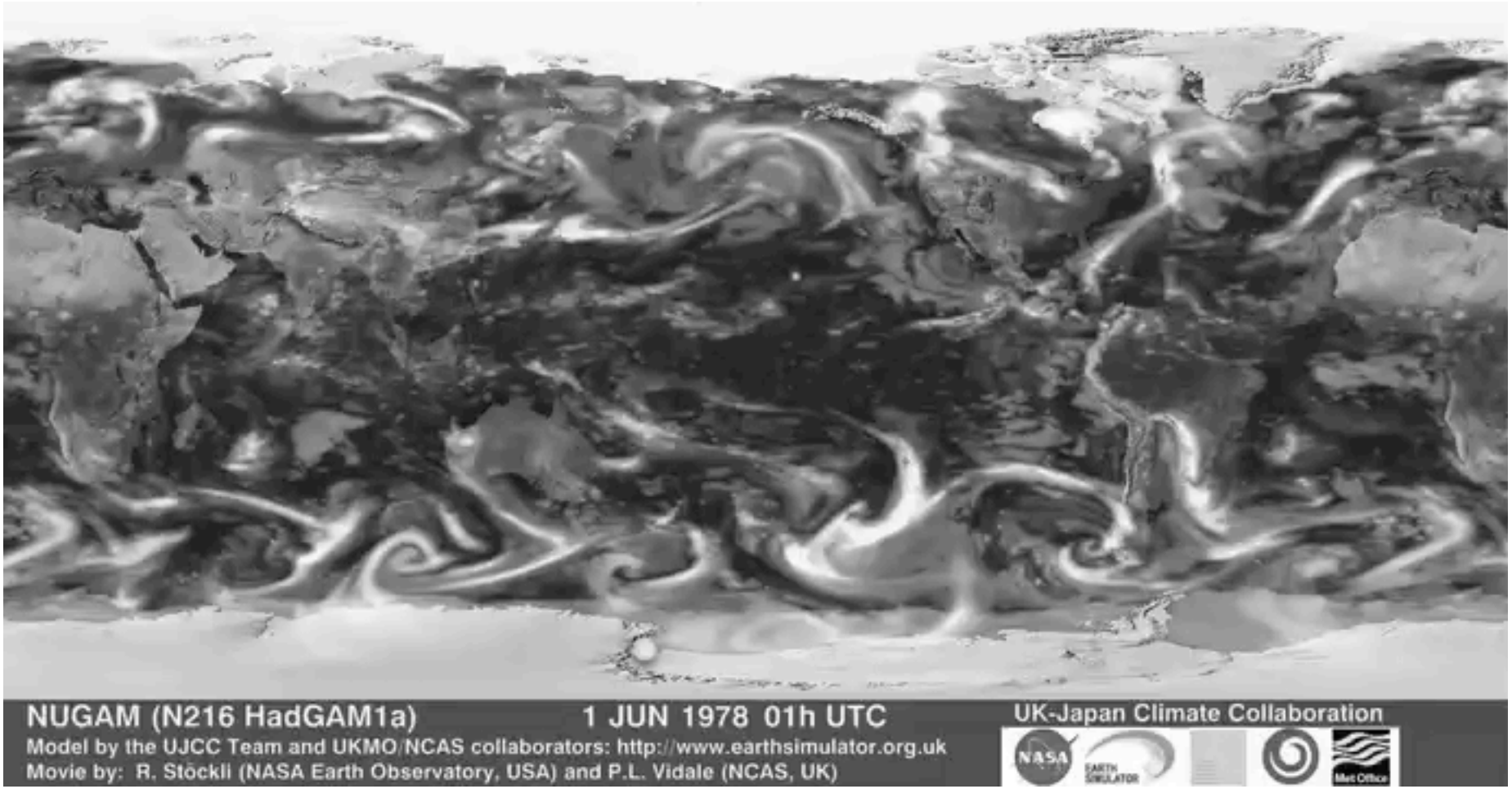
Model Resolutions



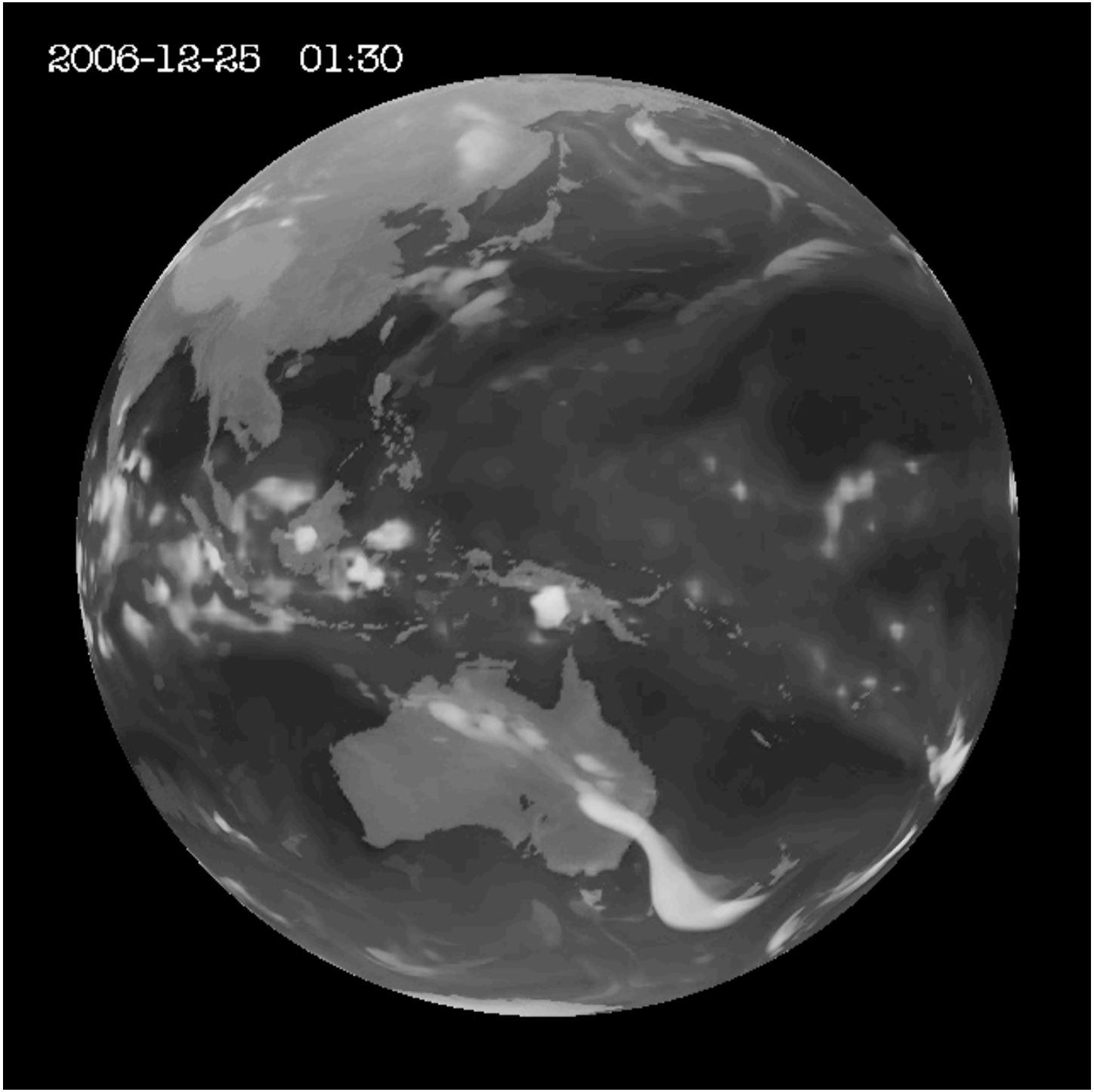
Why do climate models give different answers?

- Partially due to different **forcings**
  - E.g., some models specify **air pollution** will **increase**, others specify **decrease**
  - IPCC **emissions scenarios** standardize most forcings though so this is not the main factor
- Mostly due to different **feedbacks** produced by the models
  - Primarily differences in how **clouds** respond to warming
  - Feedback strengths are not *specified* in the models!
  - Rather formulas for cloud formation are specified, and the model predicts its own strength of feedbacks
  - So, differences in their parameterizations (especially clouds) are the major source.

	Weather Model	Climate Model
Goal	Predict weather	Predict climate
Time Range	days	years
Spatial Resolution	5-10 km	20-100km
Relevance of initial conditions	high (thus taken from weather balloon network)	low (only the ocean and sea ice matter much)
Relevance of GHG concentration	low	high
Relevance of ocean dynamics	low	high
Relevance of energy balance	low	high



Climate models have weather variability,
they just aren't designed to make day-to-day forecasts

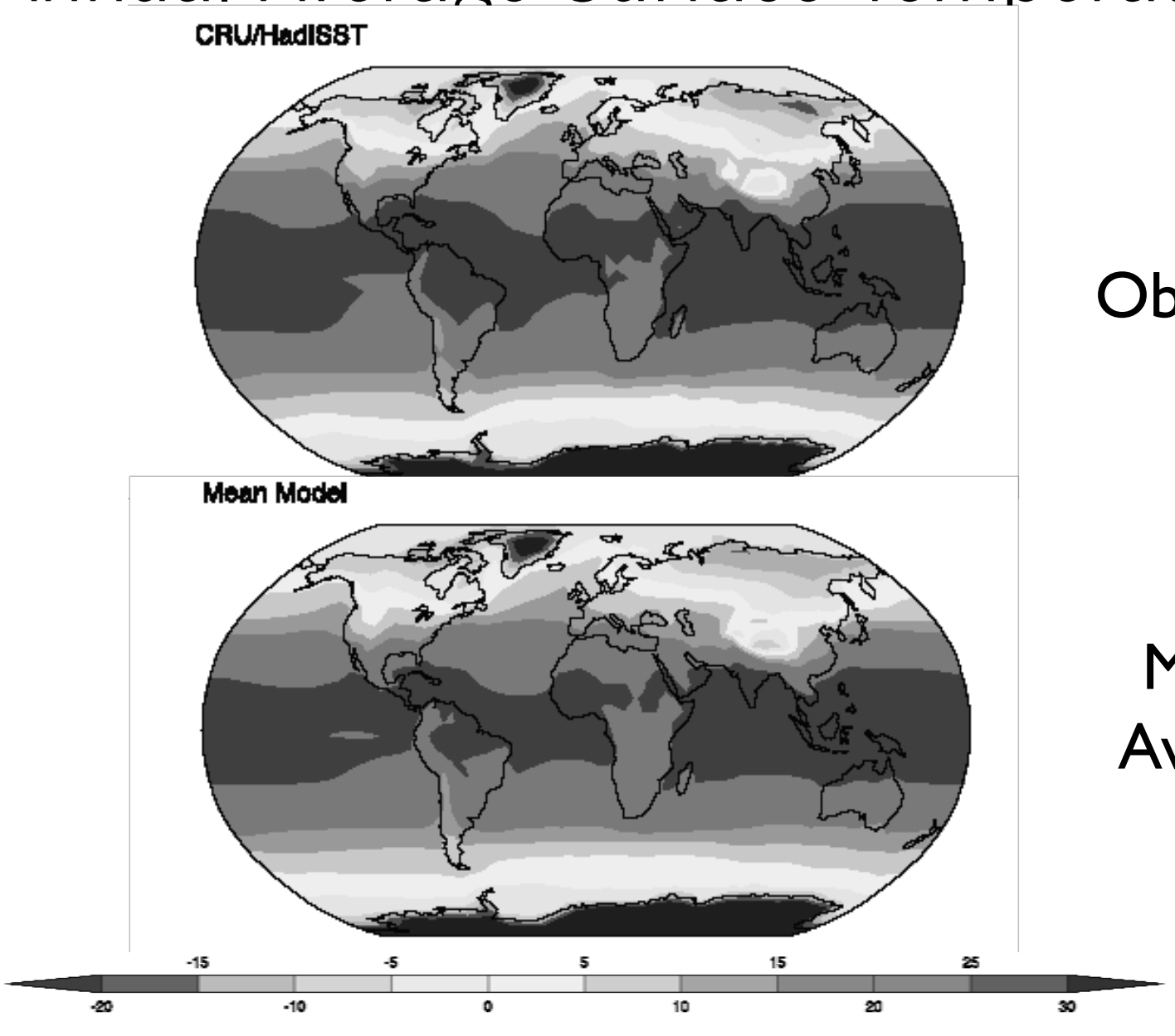


Highest resolution models can capture more details of cloud structures

This will be the resolution of the future

How do we know if climate models are right?

Annual Average Surface Temperature



Observed

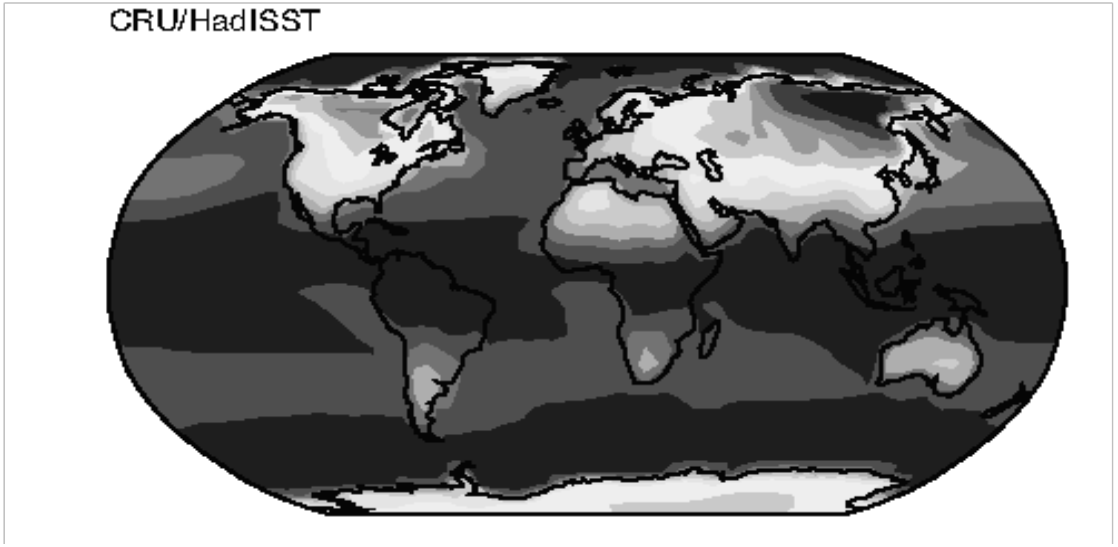
Model Average

°C

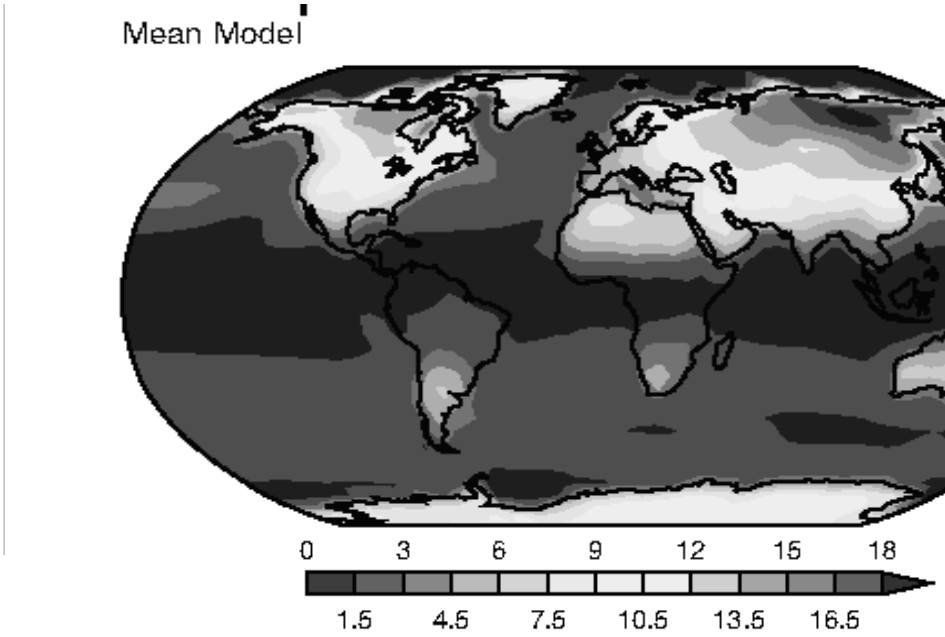
IPCC 2007

“Annual Cycle*” in Temperature

* Multiply by ~3 to get approximately the difference in July and January temperature



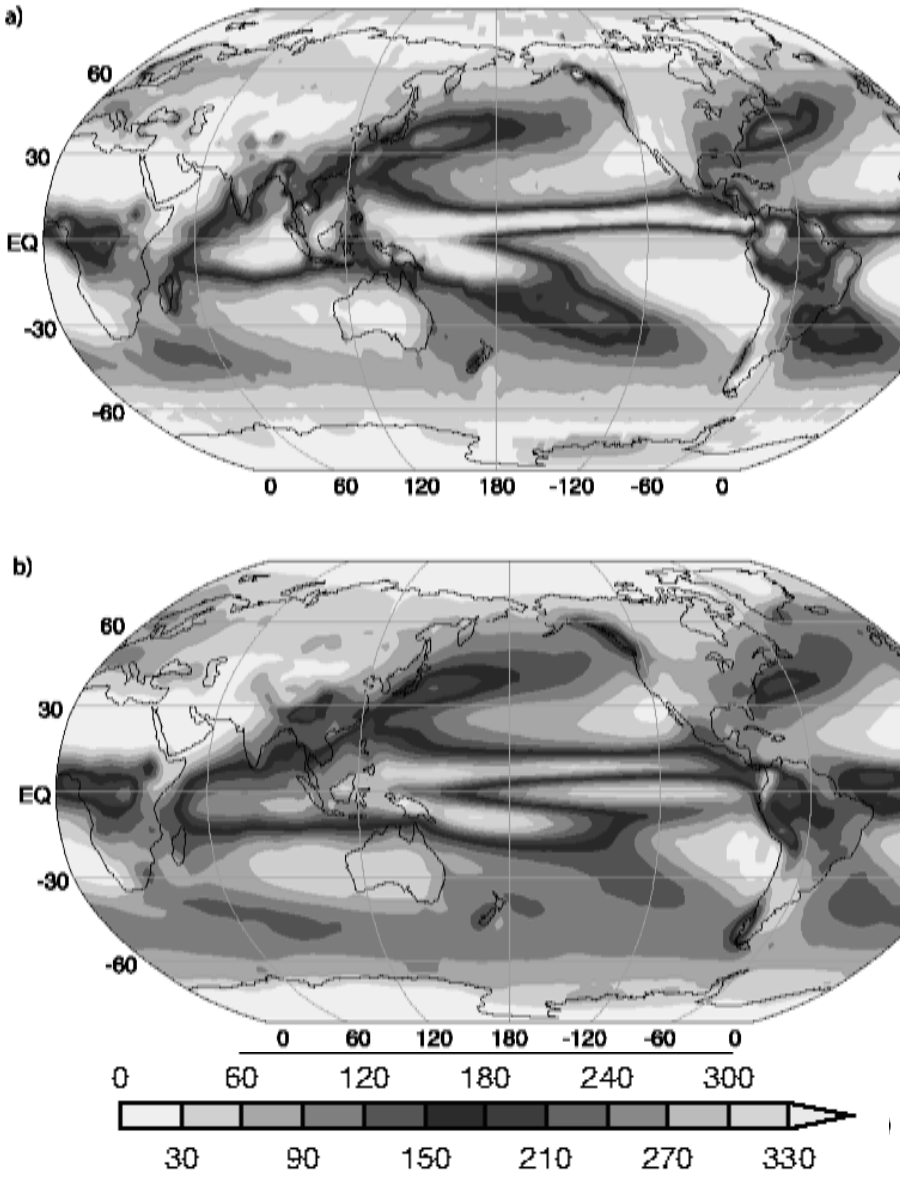
Observed



Model Average

IPCC 2007

Annual Average Precipitation



Observed (cm/year)

Average of the models

IPCC 2007

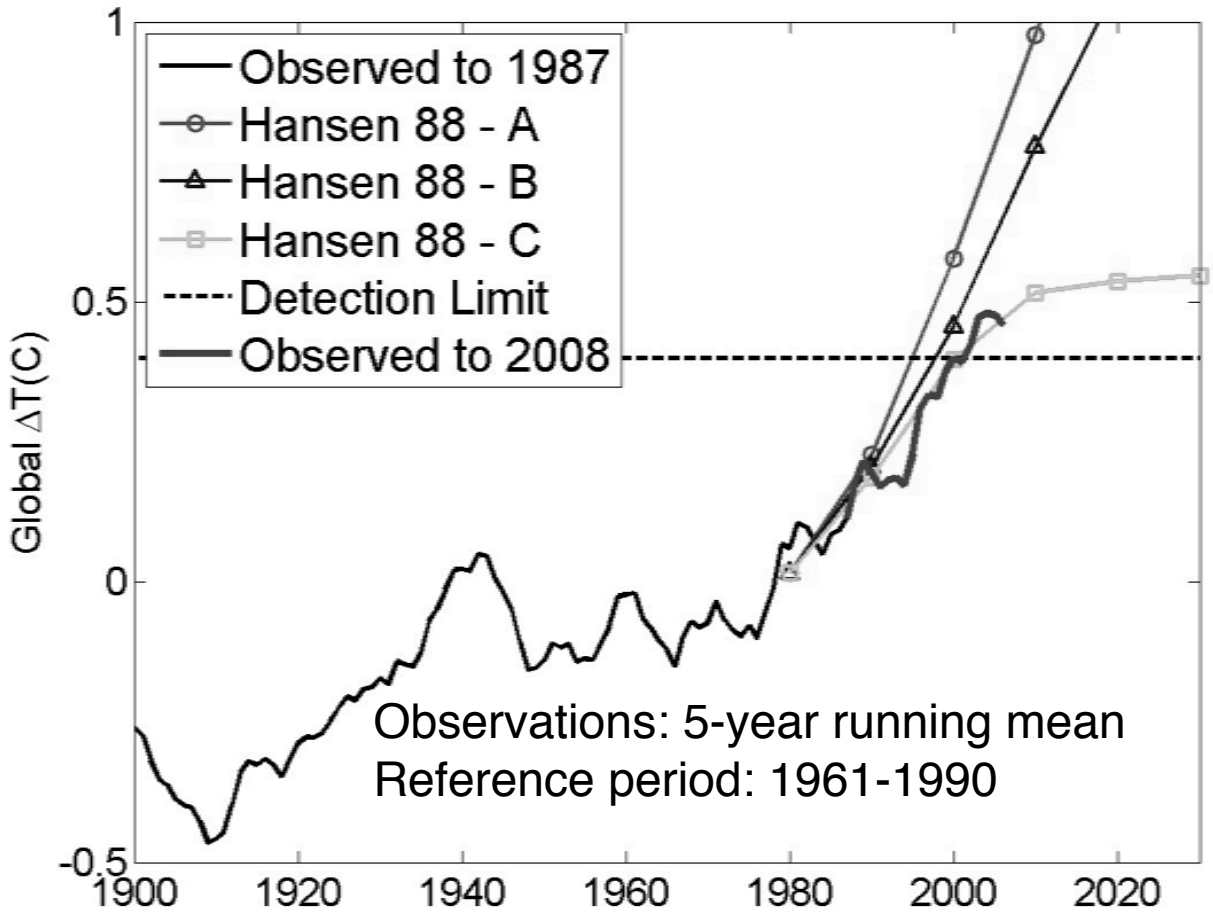
Other Ways to Validate Climate Models

- How much cooling after a volcano?
- Can we reproduce the last Ice Age conditions given CO2, solar, etc conditions?
- Can the climate of the 20th century be reproduced given greenhouse gas, solar, volcanoes, and aerosols?

“Prediction is very difficult, especially about the future” Niels Bohr

Niels Bohr with
Albert Einstein

Climate model projection made in 1980: How well did it do?



Models: heavily smoothed

In 1980, little was known about how fast CO2 would rise.
Version C was a more modest assumption.

Other Successful Predictions of Climate Models

- More warming at night than day
- Most warming in Arctic than anywhere else (especially during winter)
- Least warming in/around Antarctica
- Wet regions get wetter, subtropical ocean regions dry
- Tropopause (at the top of the weather layer of the atmosphere) moves upward
- Large scale tropical circulations weaken

Summary: Climate Models

- Are complicated codes written by large teams of scientists. There are several dozen different models. Comparing them offers another means of verification.
- Are composed of equations that describe fluid motions and have parameterizations of small scale processes involving clouds, glacial calving, plants processing moisture, etc
- Are strenuously tested and have been shown to give reliable forecasts.
- Differ from weather models because the initial conditions are mostly unimportant. Instead energy balance (between incoming solar radiation and outgoing longwave radiation) is critical. They produce storms but they are not in sync with reality. Only their statistics are relevant.