Fundamentals of Climate Change (PCC 587): Climate Models

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12-2-13

Types of Climate Models

- There are many different types of climate models
  - Huge range of complexities, physical processes represented, etc
  - E.g., compare a seasonal forecast model to an ice age cycle model
- Today we'll focus primarily on the climate models for global warming predictions (from IPCC AR4/AR5)
  - Data is publicly available from PCMDI website

General Circulation Models (GCMs)

- What are the components of these models?
- What are the essential physical processes that are being modeled?
- How have the models of these physical processes evolved over the history of climate modeling?

AMERICA'S NEXT
top climate model

Using Climate Models to Build Understanding

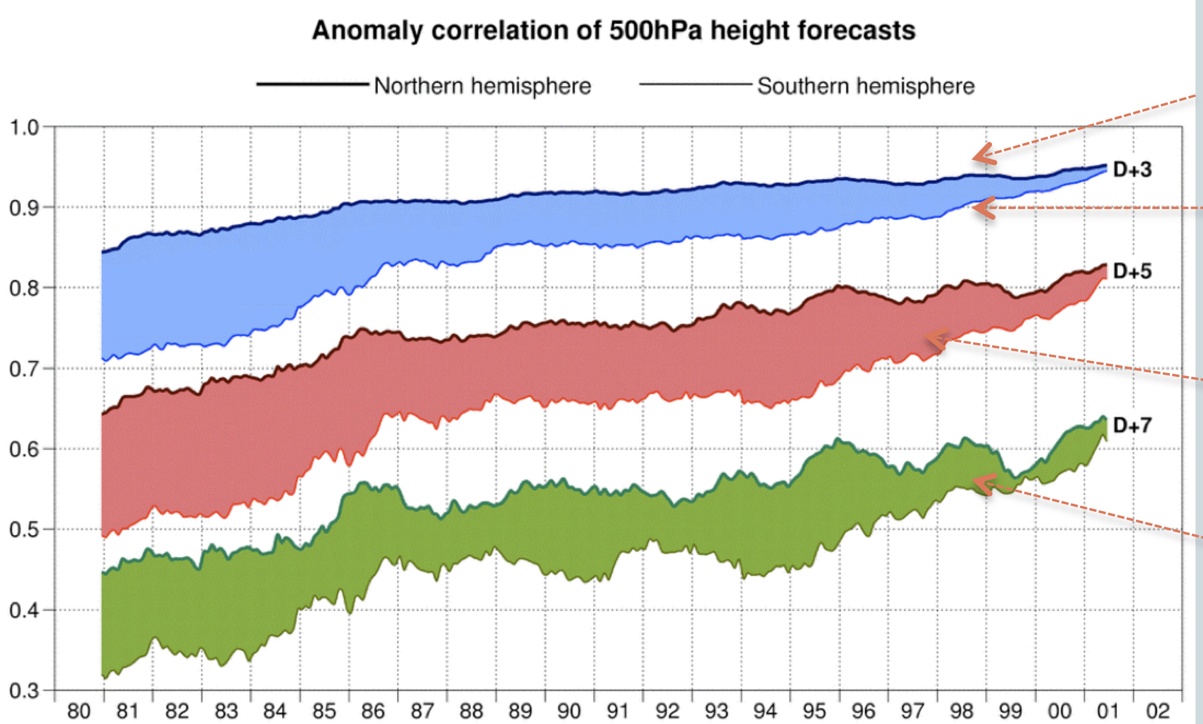
- Often climate models are thought of as forecast tools (what's the climate going to be like in 50 years?)
- Models are equally useful for developing understanding though
  - We only have one Earth to observe
  - We're only limited by our creativity in making our own computer worlds

Climate Models

- We'll discuss with two examples:
  - 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
    - And the first attempt at numerical weather forecasting by Lewis Fry Richardson

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)

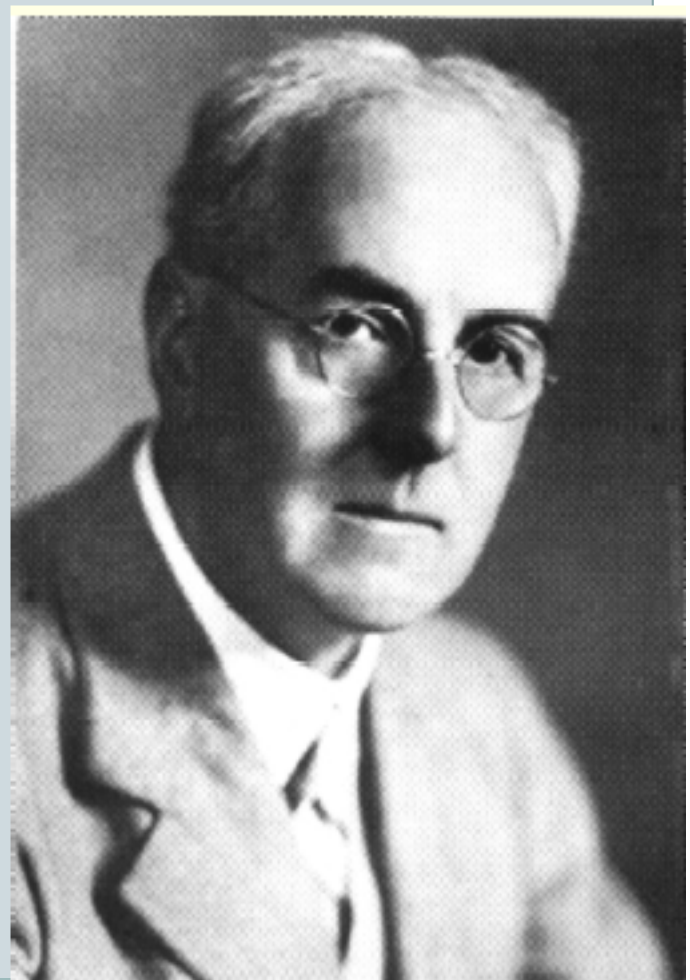
7 day forecasts (NH & SH)

1980 2002 Simmons & Hollingsworth '02

Lewis Fry Richardson

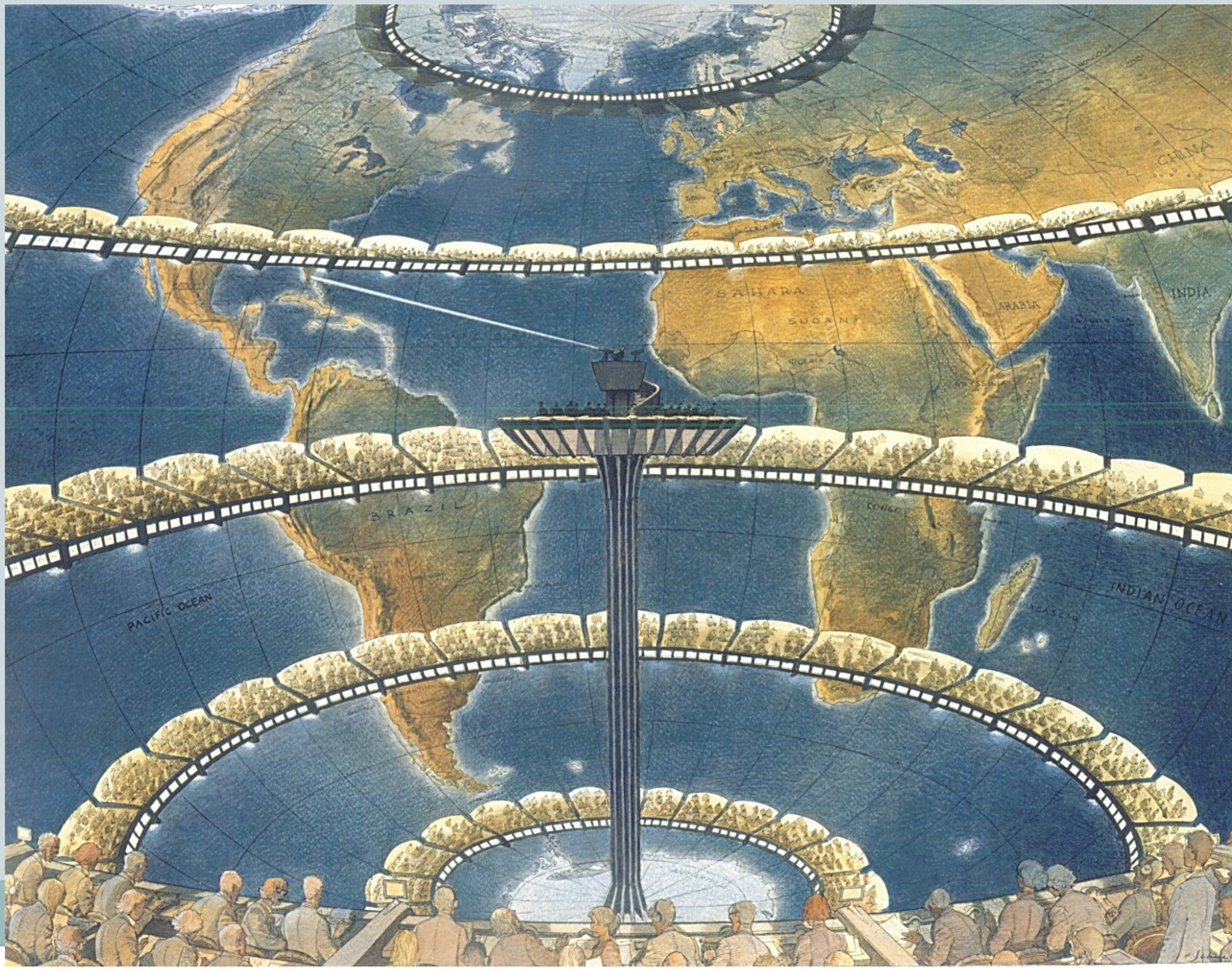
- British mathematician, physicist, atmospheric scientist
- Scientific career very influenced by his Quaker beliefs (pacifism)
- Made the first numerical weather prediction in ***1922***

Also had a dream of the future of weather prediction…



Richardson's Dream: The Forecast Factory

- Filled with employees ("computers") doing calculations

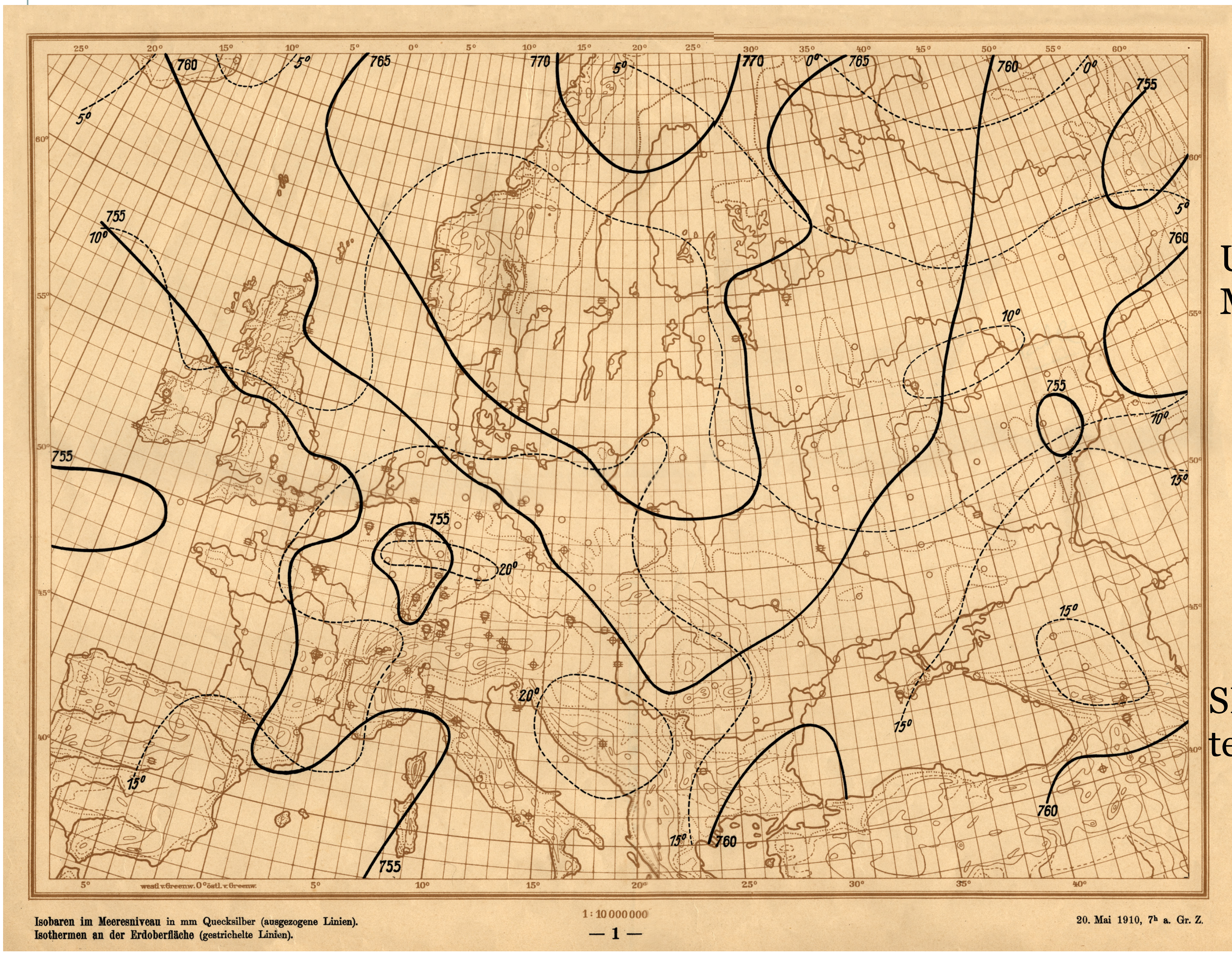


Richardson's dream in 1922 of a global forecasting system

He estimated 64,000 "computers" (people) would be necessary to forecast over the globe

Much info from the next few slides is from a book by **Peter Lynch** (U Coll Dublin)

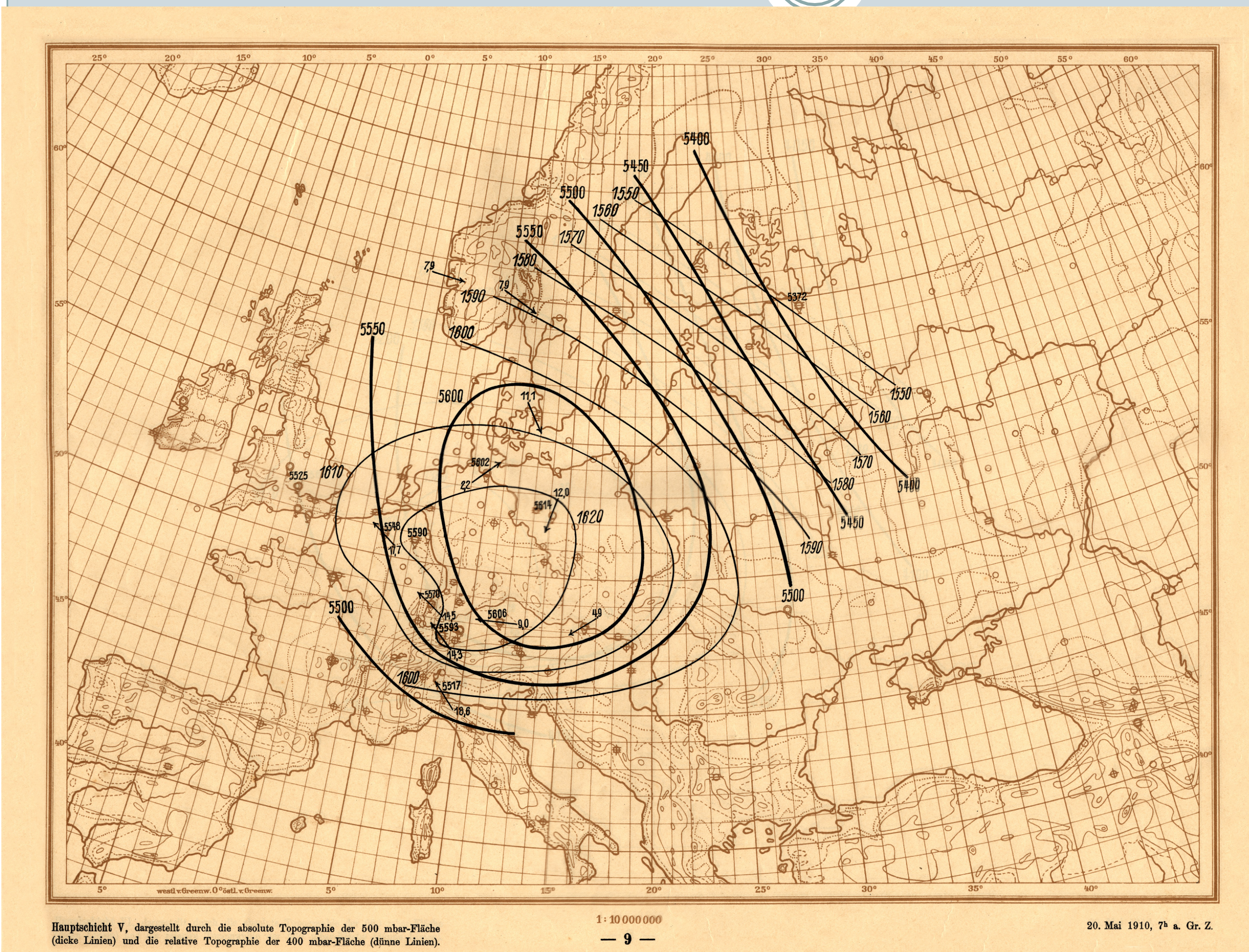
Richardson's Experiment



Used data from May 20, 1910

SLP and surface temperature

Richardson’s Experiment



Data taken when Halley’s Comet was passing through the atmosphere

Tabulated values from these charts by hand!

Upper atmosphere temperature and pressure

Richardson’s Calculations

- Served as ambulance driver with the Friends’ Ambulance Unit in France during WWI
  - Transported injured soldiers, often under heavy fire
- Took 1000 hours of work to perform the calculations
  - “My office was a heap of hay in a cold rest billet”
- Calculation book was lost during the battle of Champagne
  - But recovered months later under a heap of coal
- Eventually published in 1922

Richardson's results

Richardson's *Spread-sheet*

COMPUTING FORM P XIII. Divergence of horizontal momentum-per-area. Increase of pressure

The equation is typified by: $-\frac{\partial R_{96}}{\partial t} = \frac{\partial M_{E96}}{\partial e} + \frac{\partial M_{N96}}{\partial n} - M_{N96}\frac{\tan\phi}{a} + m_{H8} - m_{H8}^{\bullet} + \frac{2}{a}M_{H96}$. (See Ch. 4/2 #5.)

• In the equation for the lowest stratum the corresponding term $-m_{G8}$ does not appear

Longitude *11° East* $\delta e = 441 \times 10^5$	Latitude *5400 km North* $\delta n = 400 \times 10^5$	Instant *1910 May 20ᵈ 7ʰ G.M.T.* $a^{-1}.\tan\phi = 1{\cdot}78 \times 10^{-9}$	Interval, δt *6 hours* $a = 6{\cdot}36 \times 10^8$

REF.:—				previous 3 columns	previous column		Form P XVI	Form P XVI	equation above	previous column	previous column	previous column
h	$\frac{\delta M_E}{\delta e}$	$\frac{\delta M_N}{\delta n}$	$-\frac{M_N \tan\phi}{a}$	$\mathrm{div}'_{EN}M$	$-g\delta t\,\mathrm{div}'_{EN}M$	Leave the subsequent columns to be filled up after the vertical velocity has been computed on Form P XVI	m_H	$\frac{2M_H}{a}$	$-\frac{\partial R}{\partial t}$	$+\frac{\partial R}{\partial t}\delta t$	$g\frac{\partial R}{\partial t}\delta t$	$\frac{\partial p}{\partial t}\delta t$
	$10^{-5}\times$	$10^{-5}\times$	$10^{-5}\times$	$10^{-5}\times$	$100\times$		$10^{-5}\times$	$10^{-5}\times$	$10^{-5}\times$		$100\times$	$100\times$
h_0							0					0
	−61	−245	−6	−312	656				−229	49·5	483	
h_2							−83					483
	367	−257	2	112	−236			0·06	−136	29·4	287	
h_4							165					770
	93	−303	−16	−226	478			0·11	−124	26·8	262	
h_6							63					1032
	32	−55	−12	−35	74			0·07	−110	23·8	233	
h_8							138					1265
	−256	38	−8	−226	479			0·03	−88	19·0	186	
h_G												1451
	NOTE: $\mathrm{div}'_{EN}M$ is a contraction for $\frac{\delta M_E}{\delta e} + \frac{\delta M_N}{\delta n} - M_N\frac{\tan\phi}{a}$				SUM = 1451 $= \frac{\partial p_G}{\partial t}\delta t$							check by $\Sigma - g\delta t\,\mathrm{div}'_{EN}M$

Richardson's Computing Form $\mathrm{P_{XIII}}$

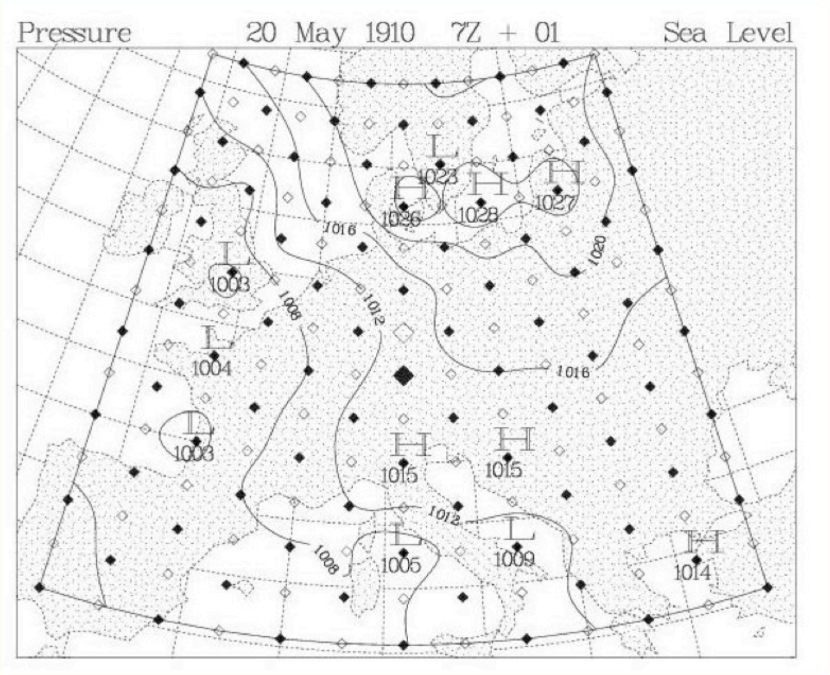
The figure in the bottom right corner is the forecast change in surface pressure: 145 mb in six hours!

Failure or Success?

- First prediction was for pressure to change by 145 mbar in 6 hours
  - Hugely, hugely wrong….
- Richardson himself realized that noisy wind data was likely the problem
  - He suggested 5 different filtering methods to fix this
- Obviously he couldn't try this experiment again
  - But we can reproduce the results using today's computers…

Computer Forecast w/ Richardson's Proposed Fix

Forecast with Filtering

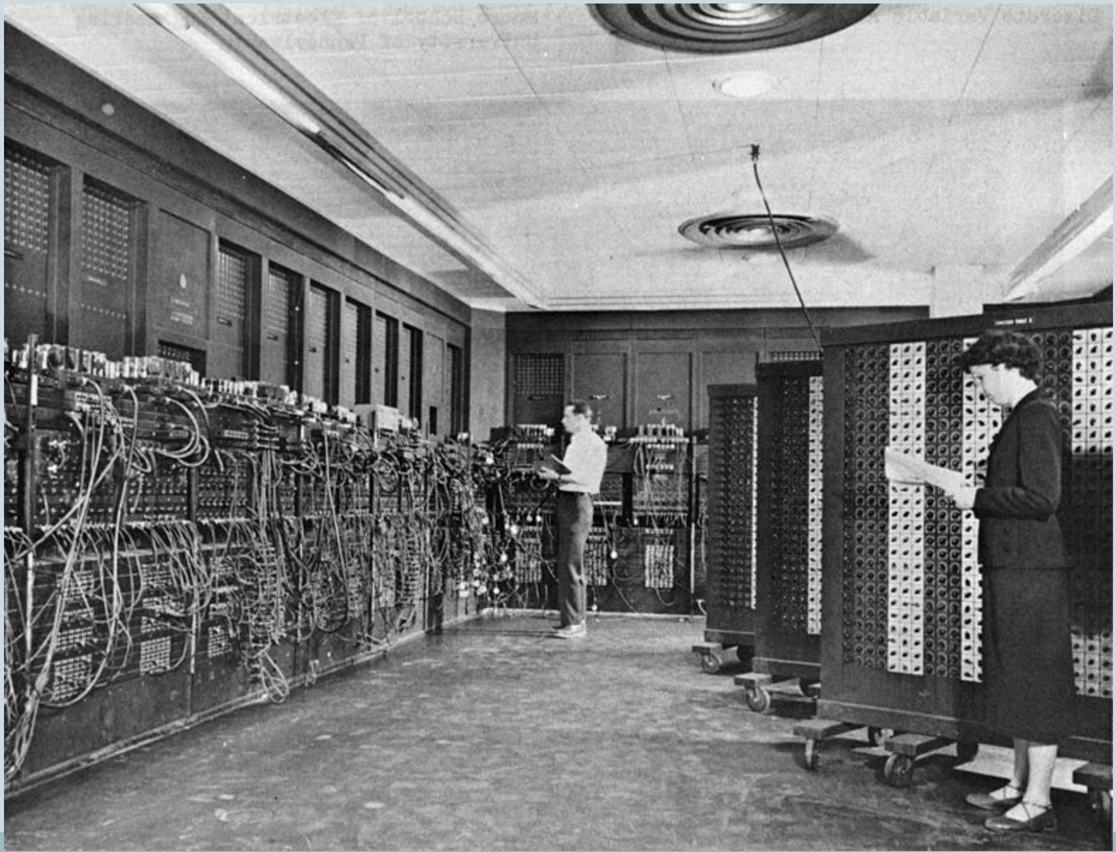


Short-range forecast of sea-level pressure, from *filtered data*. The contour interval is 4 hPa. Single forward time step of size $\Delta t = 3600\,\mathrm{s}$.

A good forecast!

The First Computer

- ENIAC: The Electronic Numerical Integrator and Computer (1946)



The First Computer!

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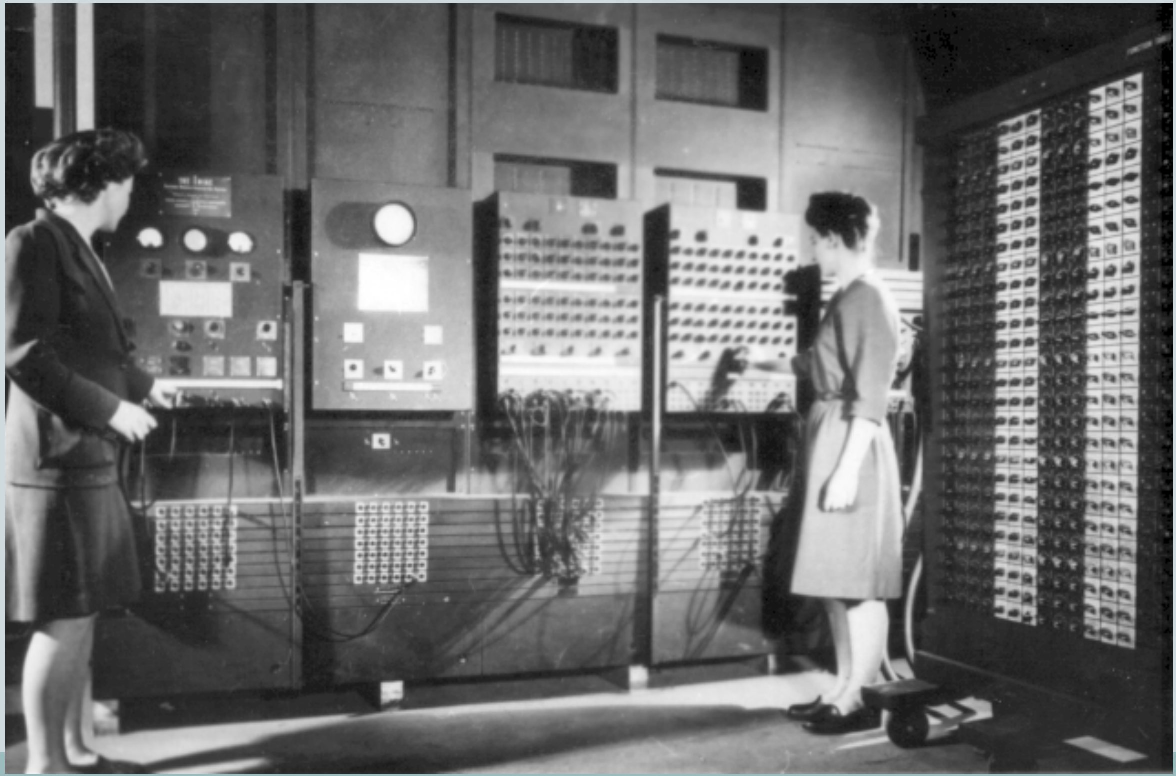


The First Successful NWP Experiment

- John von Neumann, Jule Charney, Ragnar Fjortoft (1950)
- Research proposal proposed three uses for NWP:
  - Weather prediction (duh)
  - Planning where to take observations
  - Weather modification!

ENIAC Forecast Grid

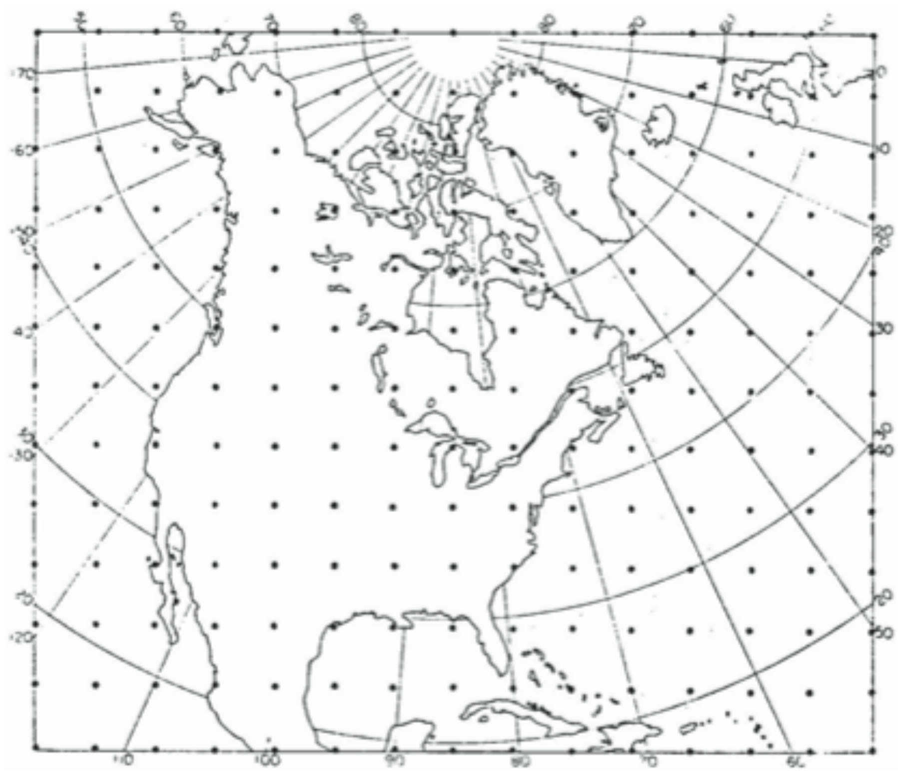


FIG. 2. Computation grid used for the ENIAC forecasts. One line is omitted from the southern edge and two lines from the remaining edges (from CFvN).

First numerical weather prediction (NWP) experiment: 1950

First operational numerical weather forecasts: 1955

First NWP model using "primitive equations": 1960

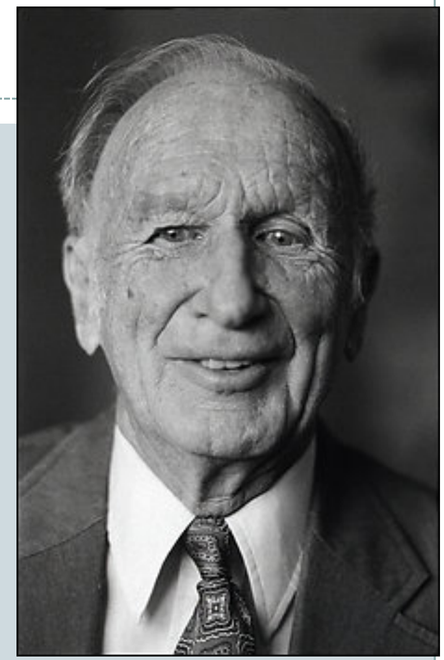
Computer forecast models begin to surpass human forecasts: 1970s?

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

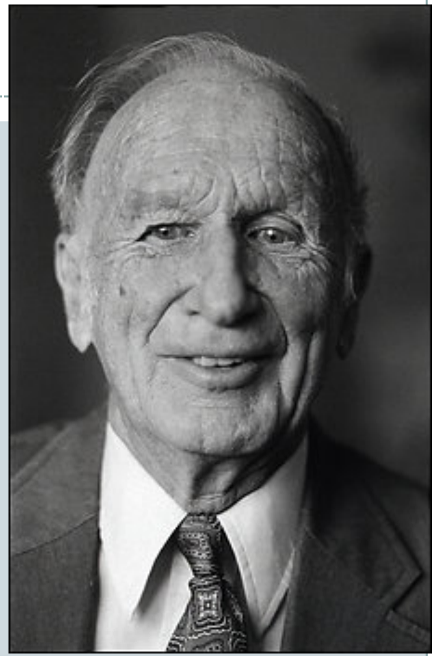
- Ed Lorenz was running a computer model & put in slightly different inputs
  - He found the predictions were similar for a while but then wildly diverged to different solutions



Edward Lorenz
(1908 - 2008)
meteorologist, M.I.T.
father of chaos theory

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

Chaos



Edward Lorenz
(1908 - 2008)
meteorologist, M.I.T.
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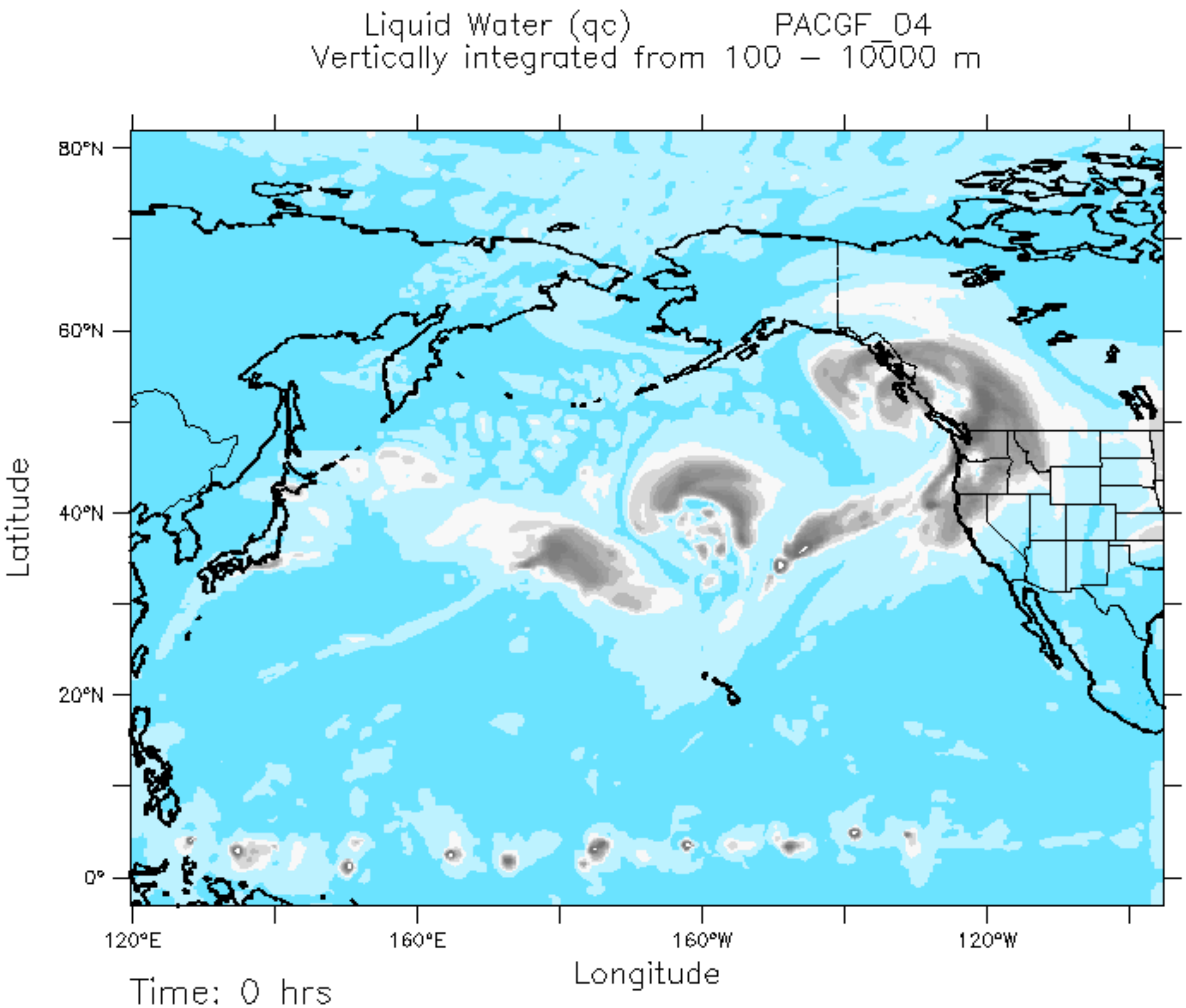
- **The Butterfly Effect**: "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" [Lorenz, 1972]
  - Weather forecasts depend very sensitively on the **initial observations**
  - We can't observe every butterfly, so weather forecasts can't predict the exact path/strength of storms after 2 weeks
- In contrast, climate models are all about modeling seasons…

Climate Forecasts

- This limit to weather prediction doesn't affect climate forecasts
  - It all averages out after a few months 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…

Climate vs Weather Forecasting



Weather forecasting: Getting the timing/ location/intensity of a single storm

Climate forecasting: Getting the average location/intensity of storms

Suki Manabe: Father of Climate Modeling

- Syukuro Manabe (born 1931):



  - Worked at GFDL from 1958-1997
  - 1997-2001: Director of Earth Simulator, Japan

Early Manabe Modeling Studies

- Radiative model: M. and Moller (1961)
- Radiative-convective model: M. and Strickler (1964)
- Atmosphere only model: Smagorinsky, M. and Holloway (1965)

First Coupled Climate Model

- Manabe and Bryan (1969):
  - First coupled climate model

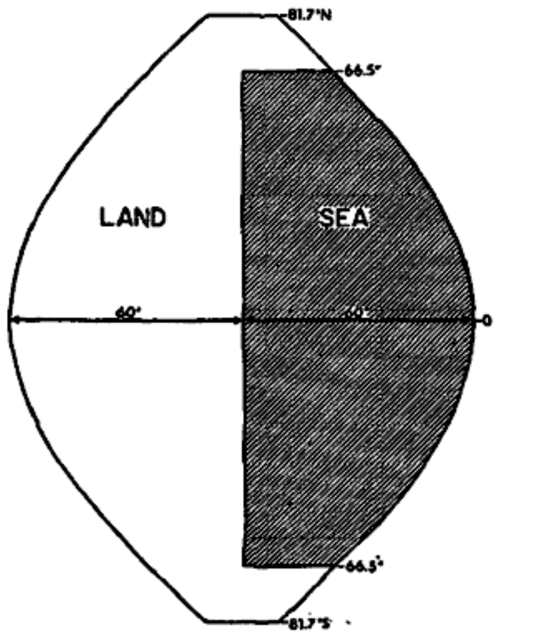


FIG. 1. Ocean-continent configuration of the model

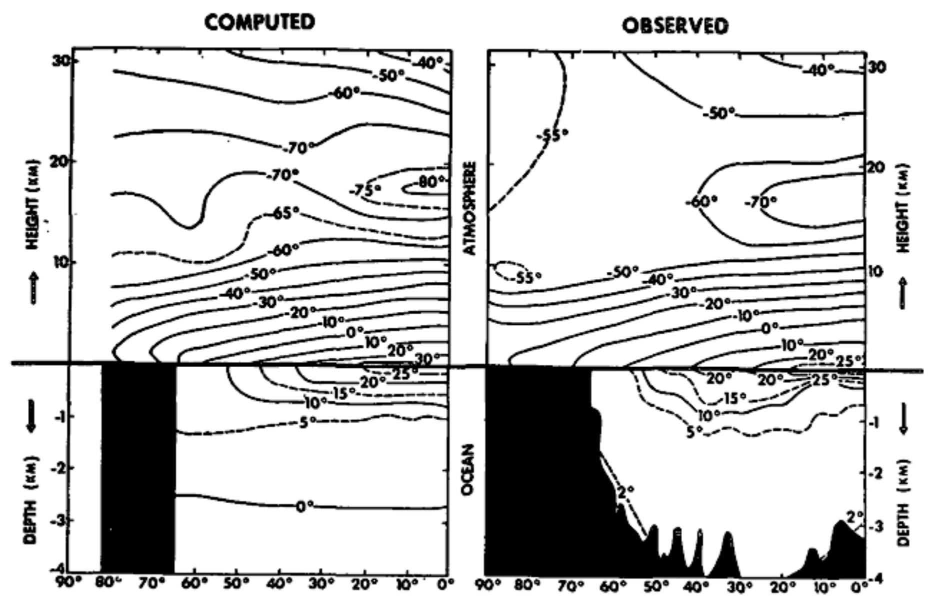


FIG. 2. Zonal mean temperature of the joint ocean-atmosphere system, left-hand side. This distribution, which is the average of two hemispheres, represents the time mean over two-sevenths of the period of the final stage of the time integration. The right-hand side shows the observed distribution in the Northern Hemisphere. The atmospheric part represents the zonally averaged, annual mean temperature. The oceanic part is based on a cross section for the western North Atlantic from Sverdrup *et al.* (1942).

First Global Warming Forecast

- Manabe and Wetherald (1975):

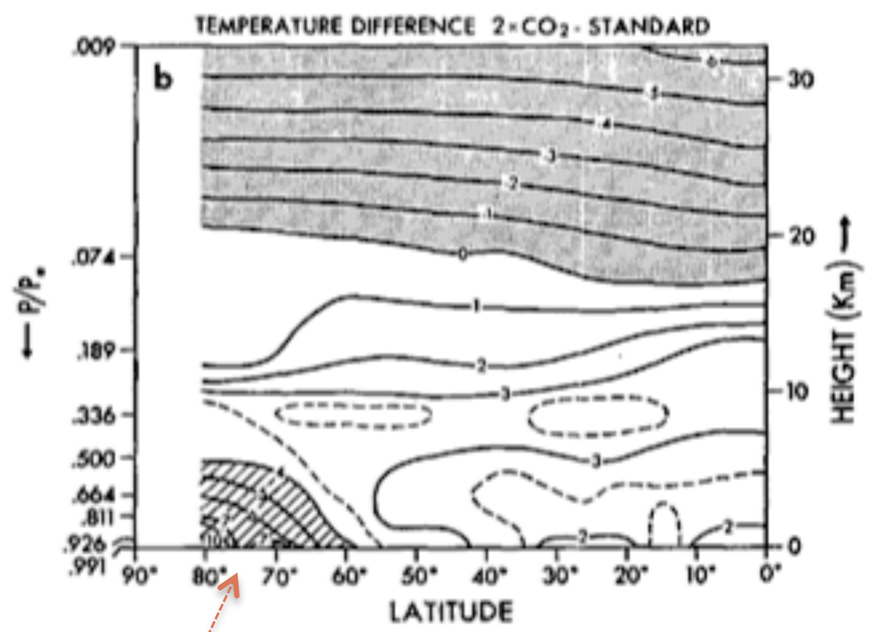


Fig. 4. Latitude-height distribution of the zonal mean temperature (K) for the standard case (a) and of the increase in zonal mean temperature (K) resulting from the doubling of CO_2 concentration (b). Stippling indicates a decrease in temperature.

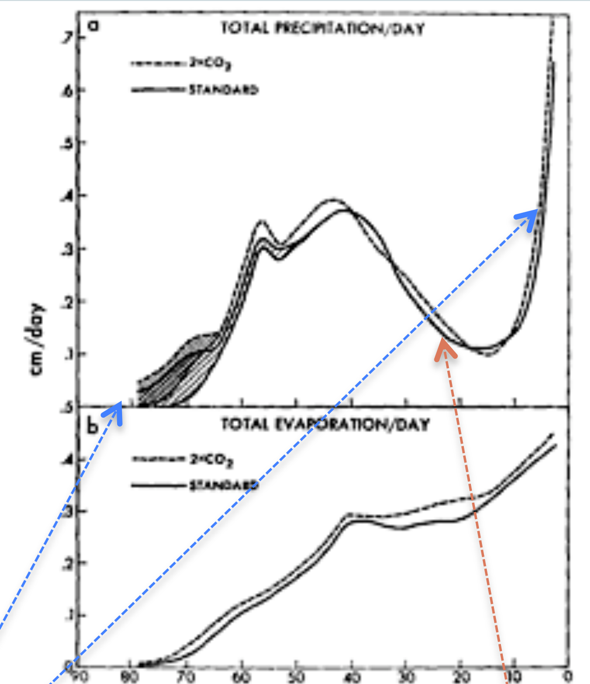


Fig. 7. Zonal mean rates of total precipitation, where shaded areas denote the rates of snowfall (a), and zonal mean rates of evaporation (b).

Polar amplification

Wet areas get wetter & subtropical drying

Other Early Manabe Studies

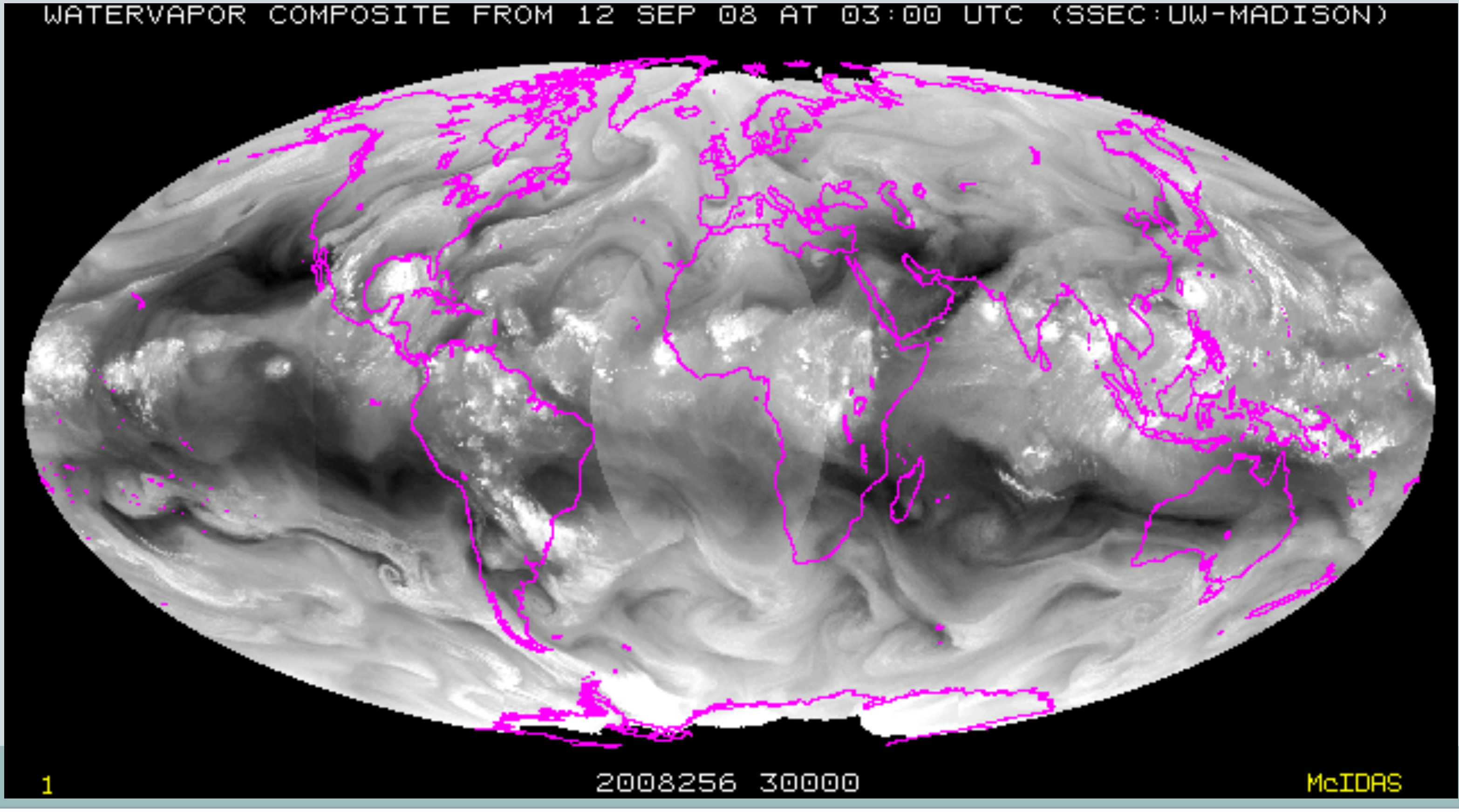
- I find these early modeling papers still really fascinating…
- Effect of ocean circulation on climate:
  - Turn off ocean model
- Effect of moisture:
  - Turn off latent heating
- Effect of mountains:
  - Bulldoze all topography
- Effect of changing **solar radiation**, doubling **CO_2**, **ice sheets**, **clouds**, **soil moisture**, etc…

AGCM Components

- AGCM: Atmospheric General Circulation Model
- "Dynamics":
  - Fluid equations on a rotating sphere
- "Physics":
  - Radiative transfer
  - Surface fluxes/boundary layer scheme
  - Clouds
  - Moist convection

Dynamical Core of AGCMs

- Essentially just fluid equations on the rotating sphere



Dynamical Core Details

- Hydrostatic approximation is made
  - Because the atmosphere is a thin film → → →
- Hydrostatic => pressure can be used as a vertical coordinate
  - This simplifies form of equations quite a bit
  - Typically a "hybrid coordinate" is used due to complications from **topography**
- This (and other accompanying small aspect ratio approximations) are **the only approximations** made in dynamical cores
  - Geostrophic balance occurs at large scales, but isn't hard-coded in

More Dynamical Core Details

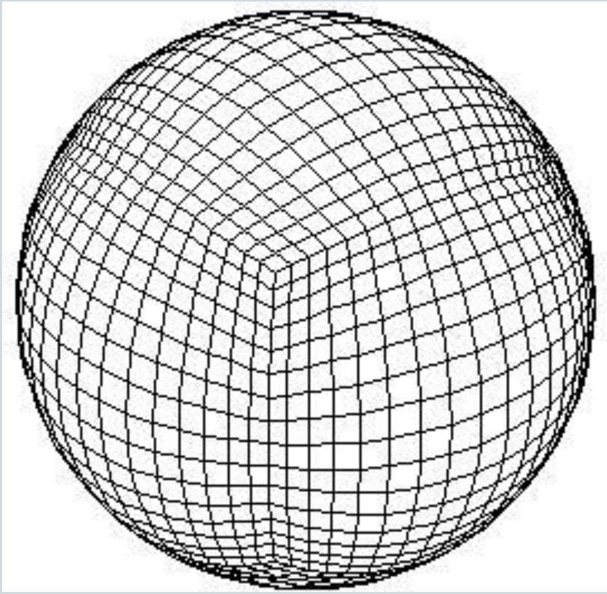
- Momentum equations:
  - Coriolis terms: due to rotation of Earth (*not sphericity*)
  - "Metric terms": to account for sphericity
- Energy equation:
  - Energy balance is in the standard fluid equations
  - Goes into the GCM without approximation

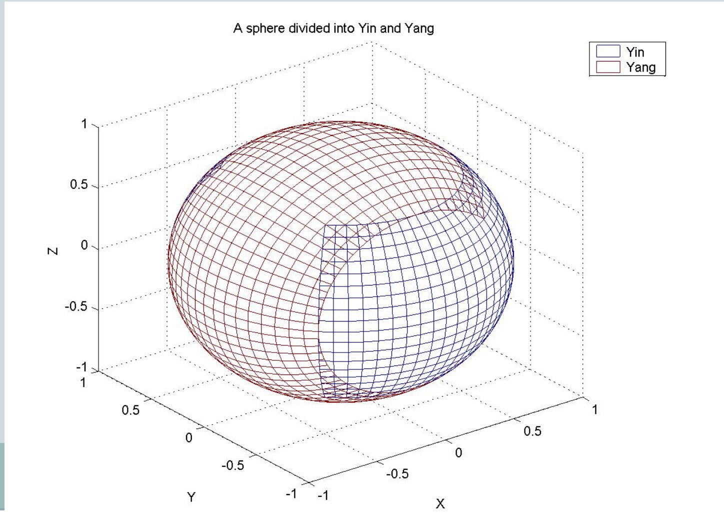
Numerical Methods

- Gridpoint methods:
  - Fields specified at points
  - Common resolutions: 2x2.5 deg (90x144 points)
- Spectral methods:
  - Uses Fourier representations of fields around latitude circles
  - Common resolutions: T42 (64x128; 2.8 deg), T85 (128x256; 1.4 deg)
  - Highest resolution model in AR4: T106 (1.1 deg resolution)

Numerical Methods

- Many modeling centers are developing more sophisticated numerical methods
- New GFDL dynamical core: finite volume
  - Better conservation properties
- Different meshes:
  - "Cubed sphere"
  - "Yin-yang"





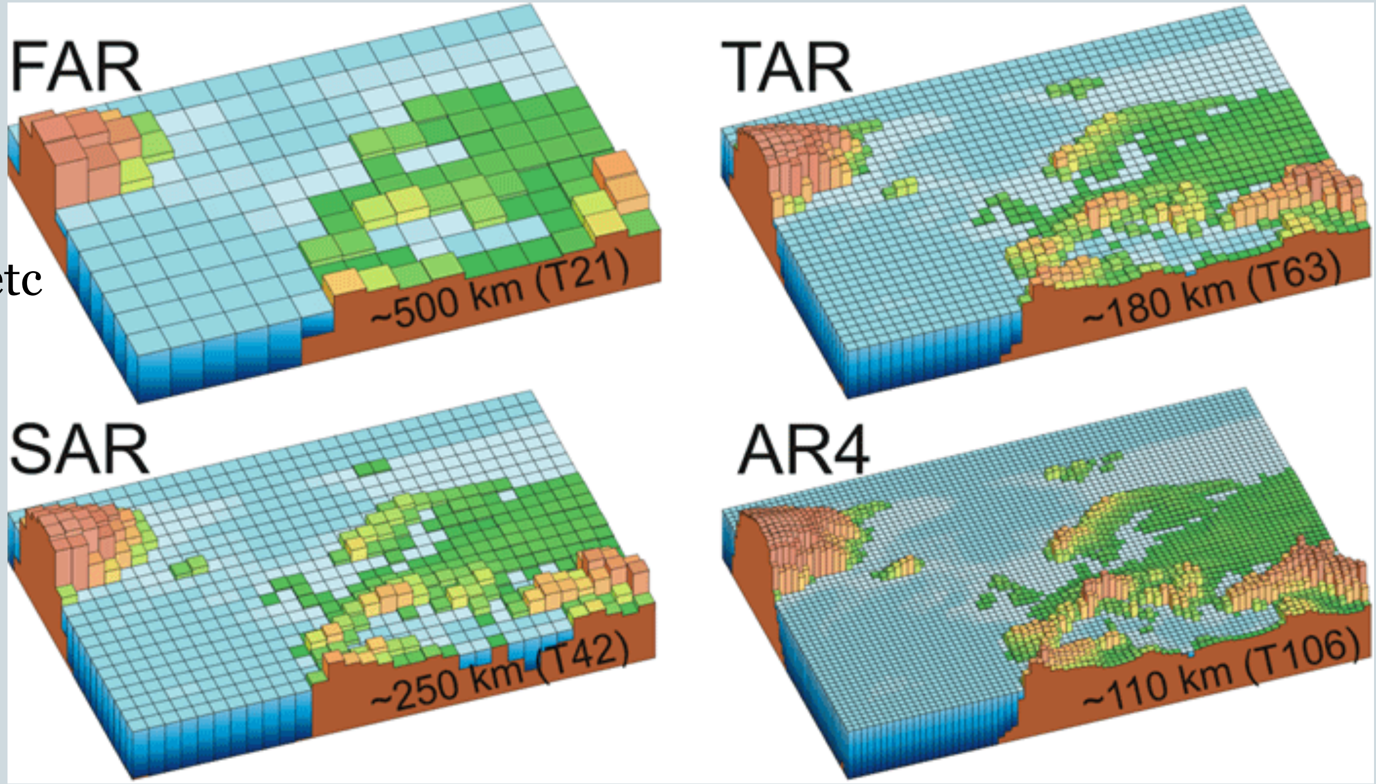
Model Resolution Evolution

- Changes in resolution over time:

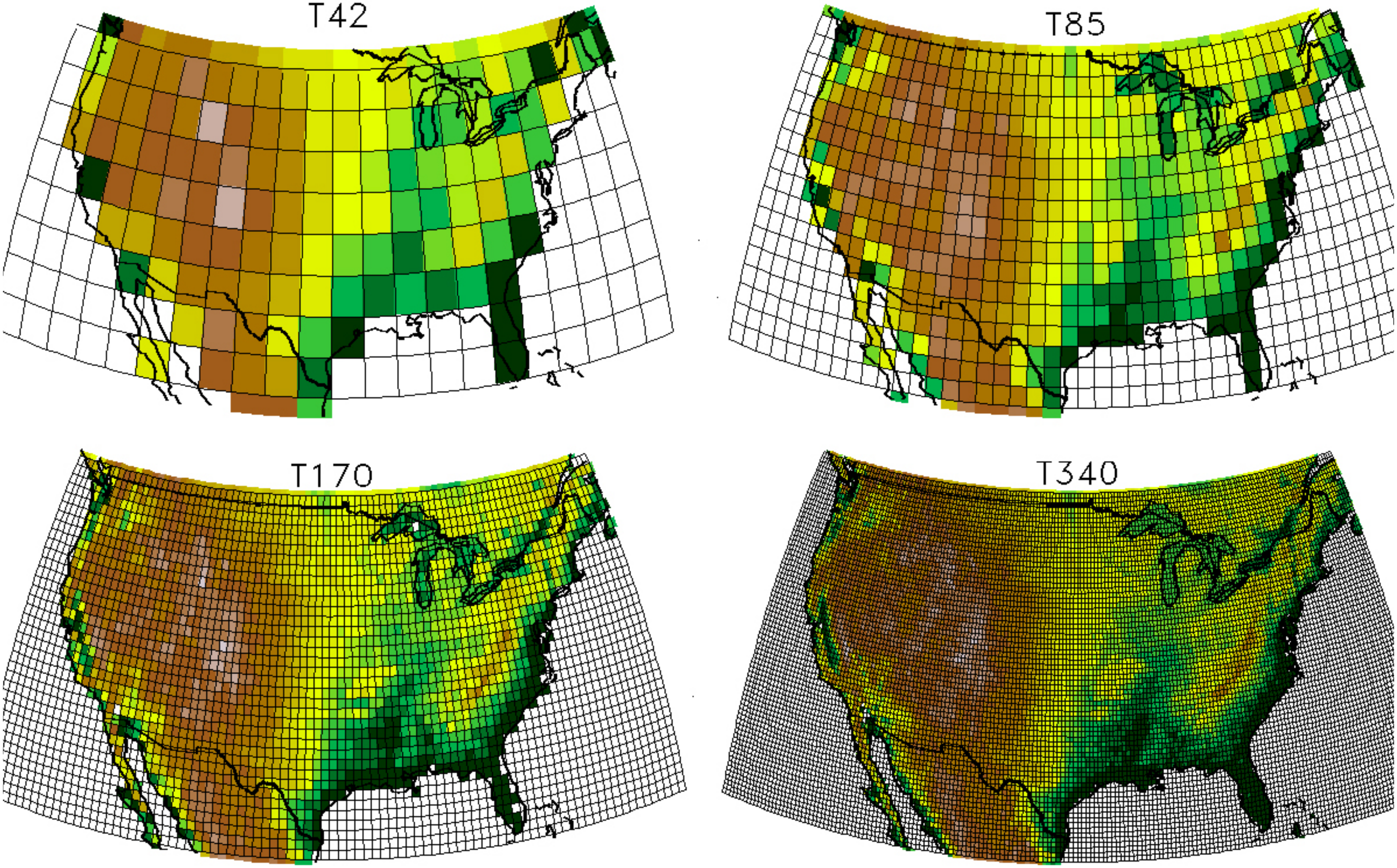
AR = "assessment report"

FAR = "first" AR, etc

FAR: 1990
SAR: 1995
TAR: 2001
AR4: 2007
AR5: 2014



Model Resolutions



Dynamical Core Summary

- Hydrostatic fluid equations on sphere
  - The future will be *nonhydrostatic*: more expensive though and not necessary at the moment
- Numerics
  - Wouldn't it be nice if we lived on Flatland…
    - Poles and topography lead to difficulties
  - No clear winner for numerical schemes
    - Spectral methods
    - Gridpoint methods (e.g., B-grid)
    - Finite volume
- Resolution
  - Much better local effects near topography in higher res models
  - Also can begin to resolve tropical storms at high res
  - Climate sensitivity doesn't change much with resolution
  - Large scale fidelity with obs isn't all that dependent on resolution (as long as the model isn't really low res)

Physics of AGCMs

- Climate models have some very complex parameterizations of physical processes
  - Radiative transfer
  - Convection
  - Clouds
  - Surface fluxes/boundary layer schemes
- We'll describe general ideas of how these are parameterized
- And the history of some of the parameterizations

Radiative transfer models

- Clear sky radiative transfer is essentially a solved problem
- Divide electromagnetic spectrum into bands
- Solar absorption and scattering by H_2O, CO_2, O_3, O_2, clouds, aerosols

Radiative transfer models

- Longwave absorption and emission by H_2O, CO_2, O_3, N_2O, CH_4, CFC-11, CFC-12, CFC-113, HCFC-22, aerosols, clouds
  - 8 longwave bands
- Very computationally expensive!
  - Often a large percentage of the total CPU usage is running the radiation code
  - In some models, not called every time step

Moist convection schemes

- Convection: vertical overturning due to density differences
- Atmosphere is strongly heated from below, leading to large amounts of convection
- Moisture complicates convection significantly (huge heat source)

Moist convection schemes

- Classical goals of cumulus parameterization (Cu param):
  - Precipitation
  - Vertical distribution of heating and drying/moistening
- Non-classical goals of Cu param:
  - Mass fluxes (for movement of pollution, etc)
  - Generation of liquid and ice phases of water
  - Interactions with PBL, radiation, and flow (momentum transport)

Goals from review by Arakawa (2004)

Moist convection schemes

- Simplest convection scheme:
  - Condense whenever a gridbox hits 100% saturation
- Earliest convection scheme:
  - Moist convective adjustment (Manabe et al 1965)
  - Above plus neutralizing convective instability

Moist convection schemes

- Most AR4 convection schemes are “mass flux” schemes
  - Based on models of sub-grid scale entraining plumes
  - Entrainment adds to vertical mass flux, dilutes plume
  - Humidity, etc advected by updrafts and compensating subsidence

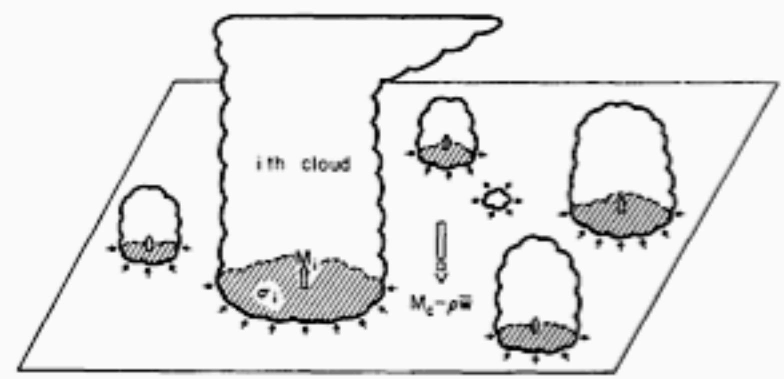
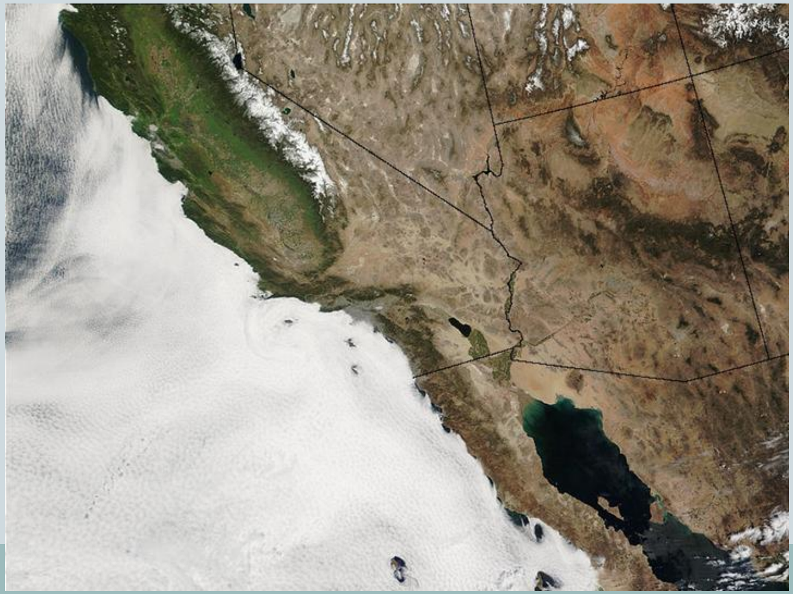


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

Cloud schemes

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



Cloud schemes

- Historical implementations of cloud parameterizations:
  - First, **climatological** cloud distributions were used (e.g., Holloway and Manabe 1971)
  - After that, diagnostic cloud parameterizations were used
    - Based on properties such as relative humidity, vertical velocity, and static stability
    - E.g., Wetherald and Manabe 1988: clouds when relative humidity exceeds 99%
    - Slingo 1987: Diagnostic scheme based on convective precipitation, humidity, vertical velocity, and stability

Cloud schemes

- Now schemes are prognostic:
  - Cloud water and cloud ice are tracked as separate variables
    - Stratiform anvils & cirrus clouds can be quite long lived
  - Cloud fraction is prognostic too in many models
  - A certain percentage of condensation from the convection scheme goes into cloud water instead of precipitation
    - “Precipitation efficiency”

Cloud schemes

- Prognostic cloud schemes (continued):
  - Bulk microphysics parameterizations:
    - Transferring among phases (e.g., autoconversion and accretion of cloud liquid into rain)
  - Erosion of clouds
    - If there's dry air in the gridbox
  - Rain inside and outside of clouds is tracked: determines whether reevaporation is important
  - Cloud overlap is also a key part of the parameterization:
    - Important for radiation, falling precip

Surface Flux Parameterization

- Surface flux schemes
  - How much evaporation & heat flux comes off the ocean/land
  - SH = C |v| (T – Ts)
  - Surface drag coefficient C is a function of stability and shear
    - "Monin-Obukhov" similarity theory
    - Neutral drag coefficient: just a function of "surface roughness" & von Karman coefficient

$$
\begin{aligned}
z_0 &= 0.0002\ m \text{ open water} \\
z_0 &= 0.005\ m \text{ flat land, ice} \\
z_0 &= 0.03\ m \text{ grass or low vegetation} \\
z_0 &= 0.1\ m \text{ low crops} \\
z_0 &= 0.5\ m \text{ forest} \\
z_0 &= 2.0\ m \text{ city center, large forest}
\end{aligned}
$$

Surface roughness values for different surfaces

Boundary Layer Parameterizations

- Boundary layer scheme
  - How heat, moisture and momentum are distributed in the turbulent boundary layer
  - Typically based on turbulent closures with empirical data
  - Matched to Monin-Obukhov surface layer
  - Some have an additional prognostic variable, the turbulent kinetic energy
    - Gives memory to the mixing

Additional GCM Parameterizations

- Shallow convection
  - UW shallow convection scheme is implemented in GFDL's AM3 model (for AR5)
  - UW scheme is a single-plume mass flux scheme
  - Other ways:
    - Diffusive schemes
    - Adjustment
- Cumulus momentum transport
- Gravity wave drag
  - Momentum fluxes due to gravity waves near topography

Earth System Models

- Some processes that modeling centers are just starting to tackle:
  - Carbon cycle
    - Previously, prescribed CO_2 distributions (well-mixed)
  - Dynamic vegetation
    - Previously, prescribed to be current climate values
  - Dynamic ice sheet models
    - Previously, prescribed to current size
  - Interactive chemistry (e.g., ozone chemistry)
    - Often just prescribed ozone hole, etc
  - Aerosol effects on cloud formation

"Earth system models" are trying to parameterize these

Flux Adjustment

- What if your climate model drifts to an unrealistic state?
- Early climate models had to use "flux adjustment":
  - Putting in fluxes of heat and moisture at different locations to make climate more realistic
- For the 2nd assessment report, most models had to use flux adjustment, or had poor mean state
- By the TAR (third assessment report), most models didn't need flux adjustment
- In CMIP3, only 4 of 24 models have flux adjustment
  - They tend to be the models from newer/less funded groups

CMIP3 GCM Summary

- Of 24 models in the CMIP3 archive (models used for IPCC AR4):
  - 1 was non-hydrostatic (Had-GEM)
  - 4 had aerosol indirect effect (on clouds)
  - 4 had some kind of chemistry
    - 3 of these had sulfate aerosol production from SO2
    - 1 had simplified ozone chemistry (CNRM)
    - 1 had GHG (methane, nitrous, CFC-11 and CFC-12) concentration modifications from chemistry (NCAR CCSM3)
  - 0 had dynamic vegetation, carbon cycle, or dynamic ice sheets
- There have been big changes with these in CMIP5 archive
  - Especially in terms of chemistry and aerosol indirect effects
  - Also there are separate archives in AR5 for Earth System Models with carbon cycle modeling, etc

Climate Modeling Centers

- Modeling centers from CMIP3
  - Very international effort!

BCC-CM1, China
BCCR-BCM2.0, Norway
CCSM3, USA
CGCM3.1(T47), Canada
CGCM3.1(T63), Canada
CNRM-CM3, France
CSIRO-Mk3.0, Australia
CSIRO-Mk3.5, Australia
ECHAM5/MPI-OM, Germany
ECHO-G, Germany/Korea
FGOALS-g1.0, China
GFDL-CM2.0, USA
GFDL-CM2.1, USA
GISS-AOM, USA
GISS-EH, USA
GISS-ER, USA
INGV-SXG, Italy
INM-CM3.0, Russia
IPSL-CM4, France
MIROC3.2(hires), Japan
MIROC3.2(medres), Japan
MRI-CGCM2.3.2, Japan
PCM, USA
UKMO-HadCM3, UK
UKMO-HadGEM1, UK

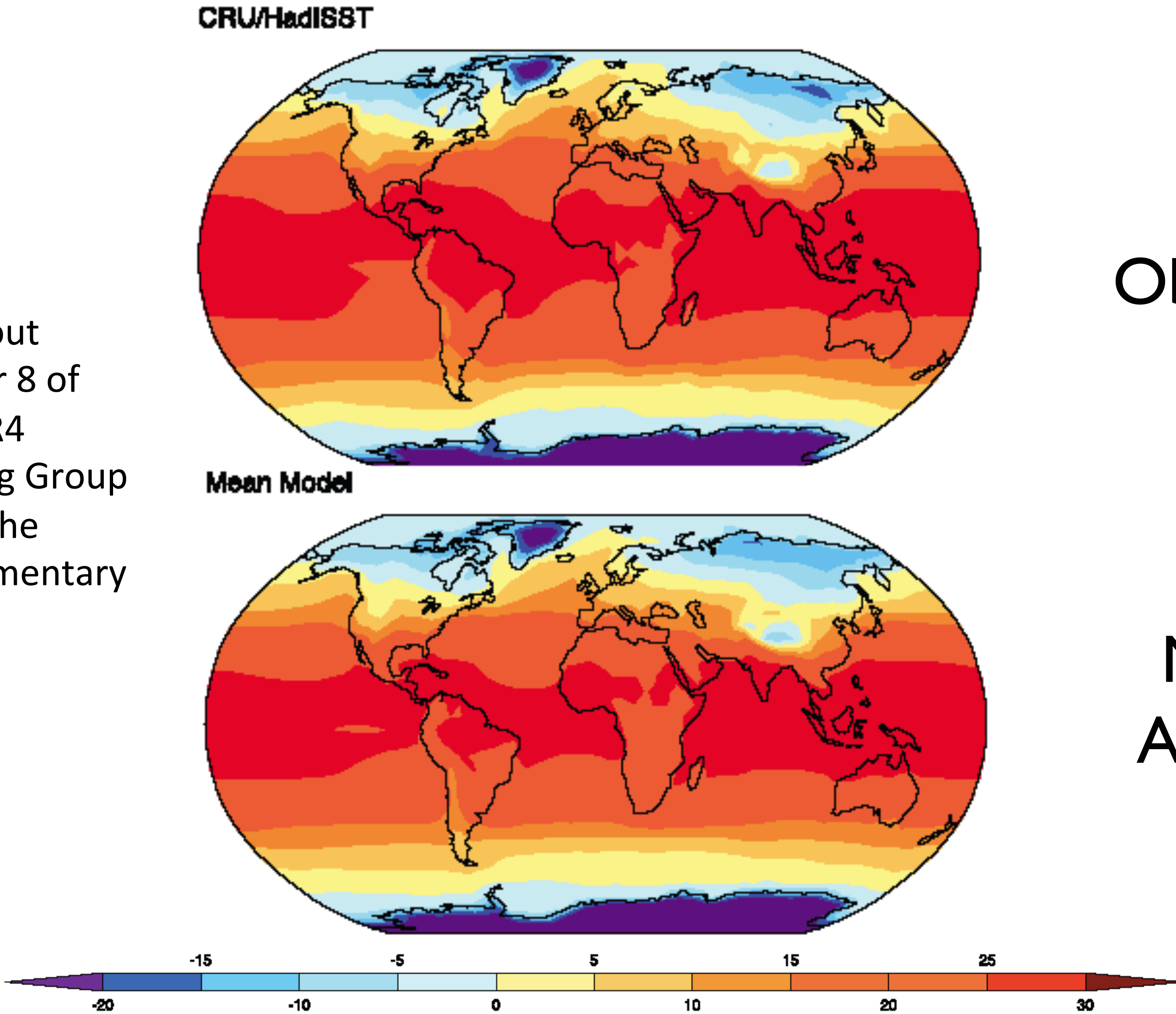
GFDL, Princeton, NJ

NCAR, Boulder, CO

How do we know if climate models are right?

Annual Average Surface Temperature

Check out Chapter 8 of IPCC AR4 Working Group 1 (esp the Supplementary Info)

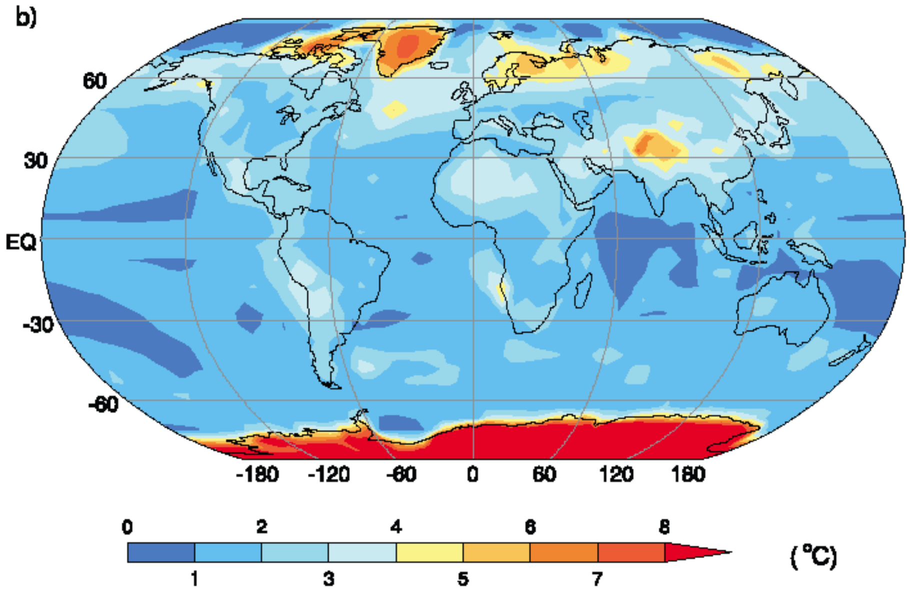


Observed

Model Average

°C IPCC 2007
Fig S8.1a

Annual Average Surface Temperature



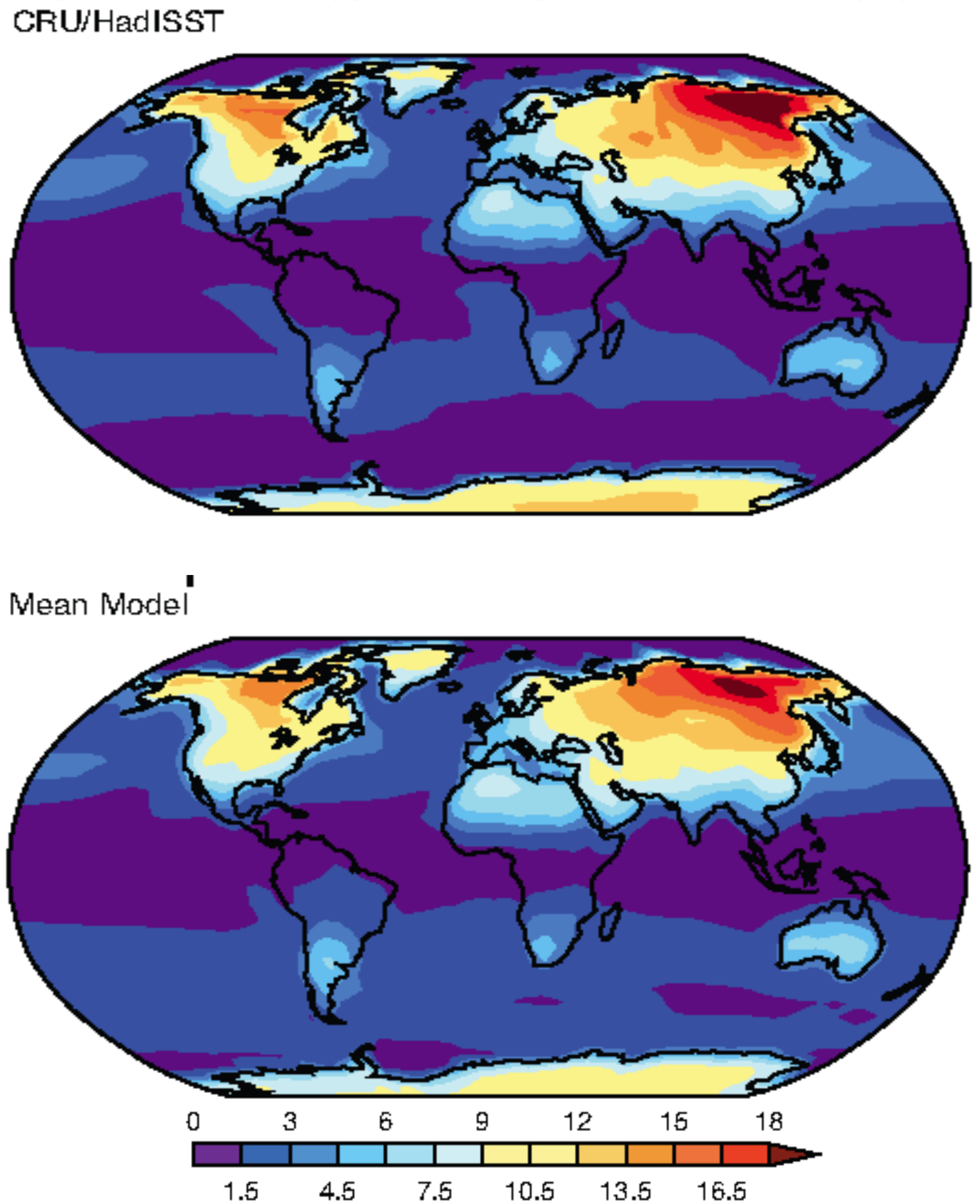
Error in a typical model (RMS of temperature deviations)

IPCC 2007

IPCC 2007
Fig S8.1b

“Annual Cycle*” in Temperature

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

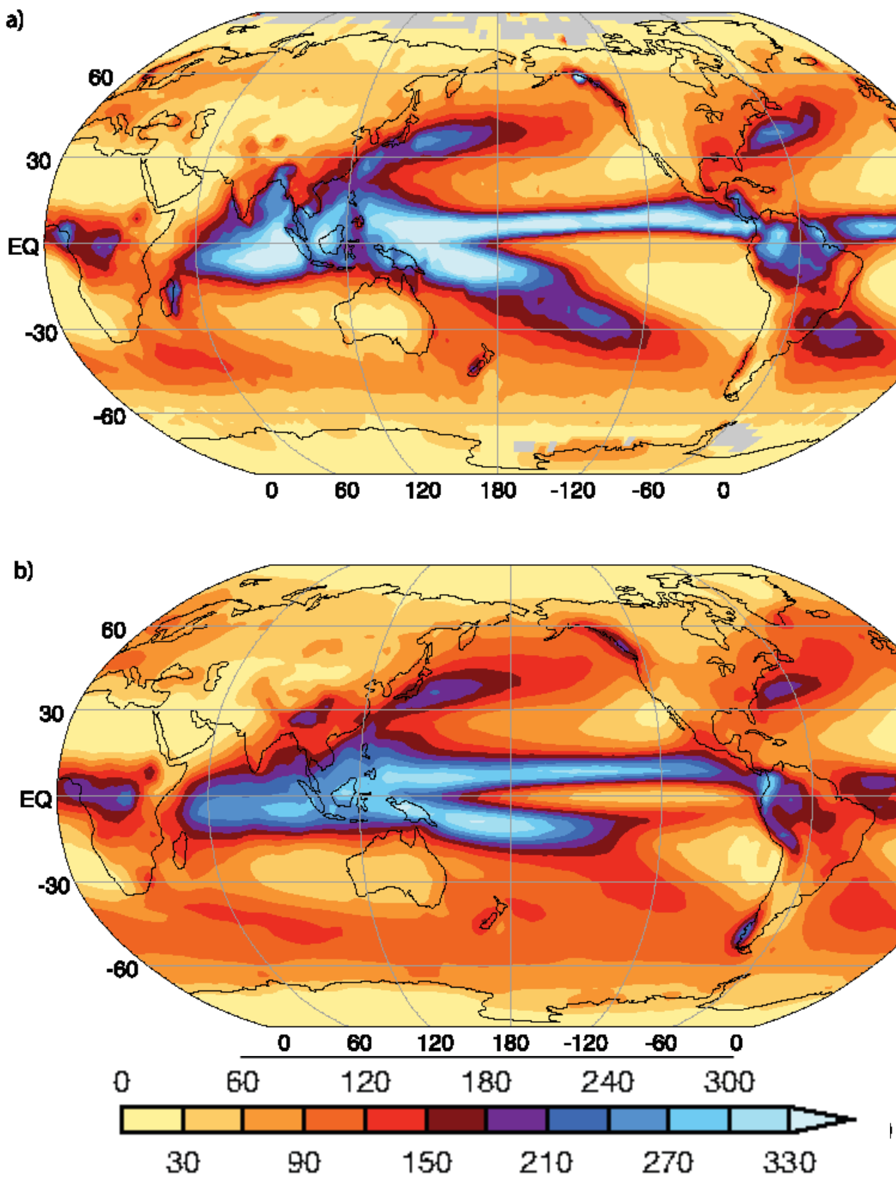


Observed

Model Average

IPCC 2007

Annual Average Precipitation



Observed (cm/year)

Average of the models

IPCC 2007

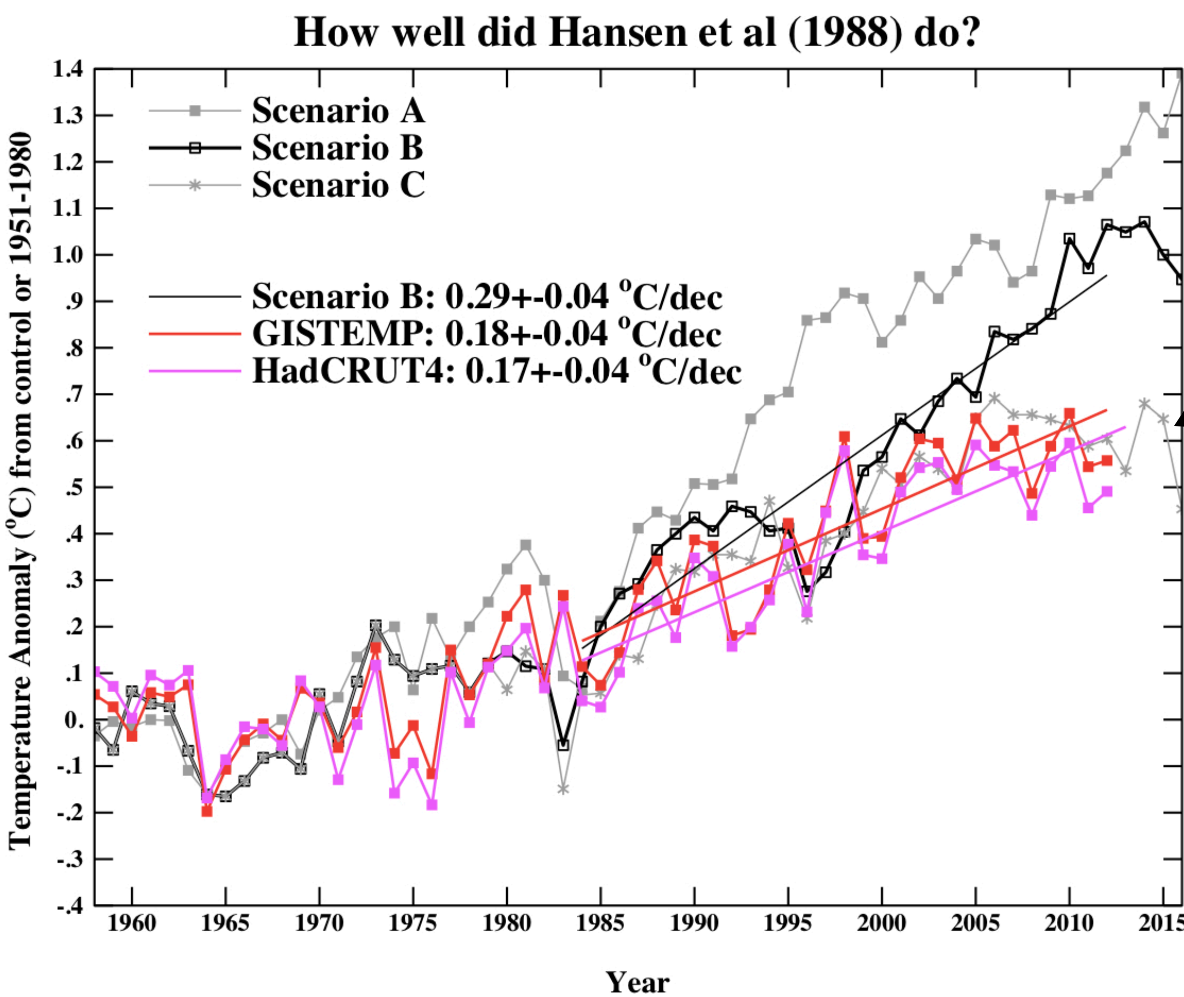
Other Ways to Validate Climate Models

- How much cooling after a volcano?
- Can we reproduce the last Ice Age conditions given CO_2, solar, etc conditions?
- Can the climate of the 20^{th} 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 1984: How well did it do?



CO2 didn't end up rising this fast

Best estimate of emissions

In 1984, little was known about how fast CO2 would rise.
Scenario C ended up being the best assumption about CO2 rise.
The GCM they used had a 50% higher climate sensitivity than the average of current GCMs.

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 regions dry
- Tropopause moves upward
- Large scale tropical circulations weaken

Simplified physics GCMs

- There is also value in developing GCMs with simplified physics:
  - Easier to understand
  - Easier to reproduce results
  - Results more robust (less sensitive to parameters)
  - Less computational expense
  - Test ground for theories of the general circulation

Simplified GCM Experiments

- Nature has only provided us with one planet
- Computer models allow us to explore a range of imaginary planetary climates:
  - Ocean-covered planets
  - Planets with different rotation rates, radius, solar heating
  - Certain physical effects suppressed or enhanced

This is what I do for much of my research!

Can it eventually help improve models?