Modeling the General Circulation of the Atmosphere. Topic 1: A Hierarchy of Models

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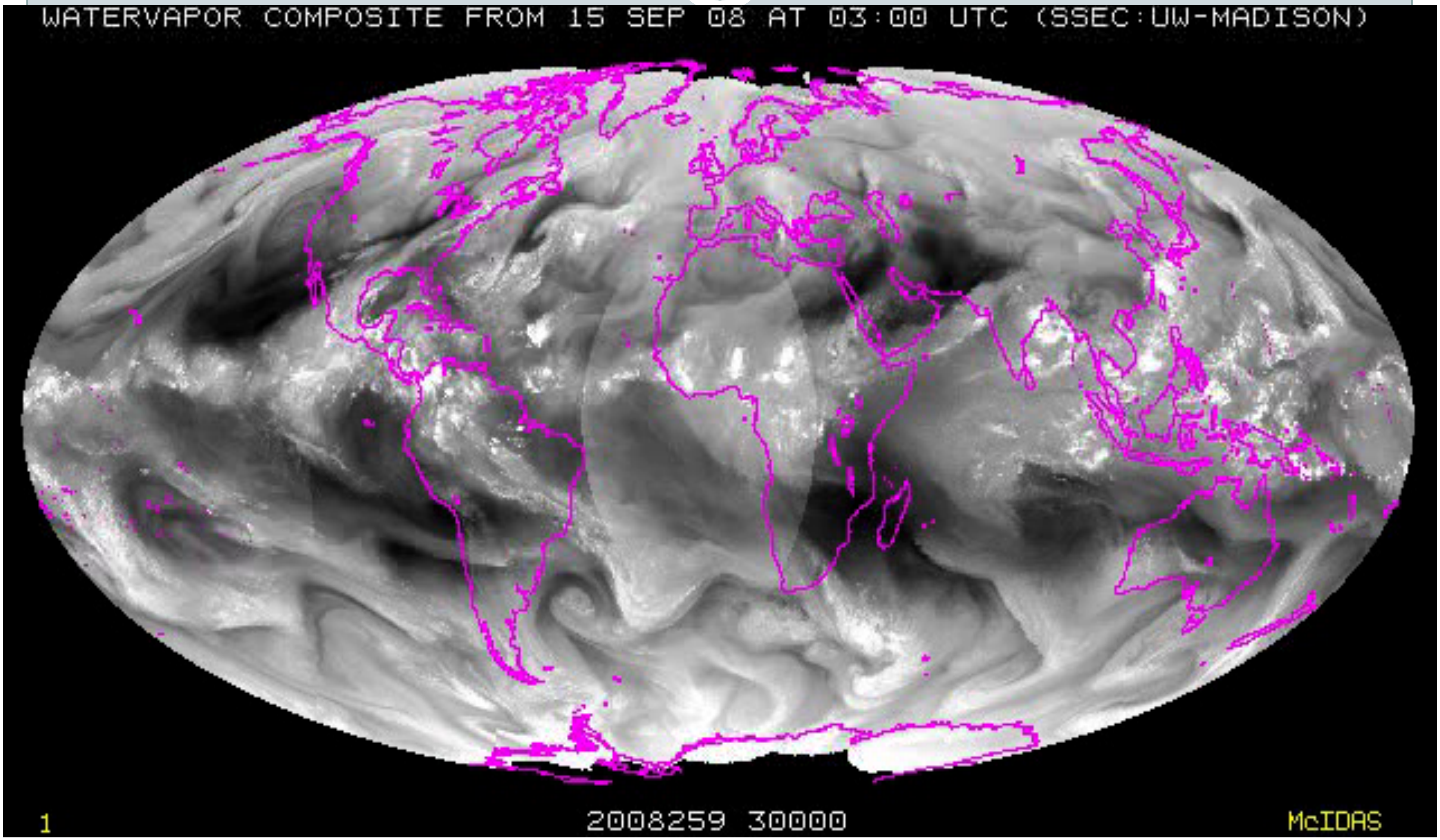
TOPIC 1: 1-7-16

Modeling the General Circulation

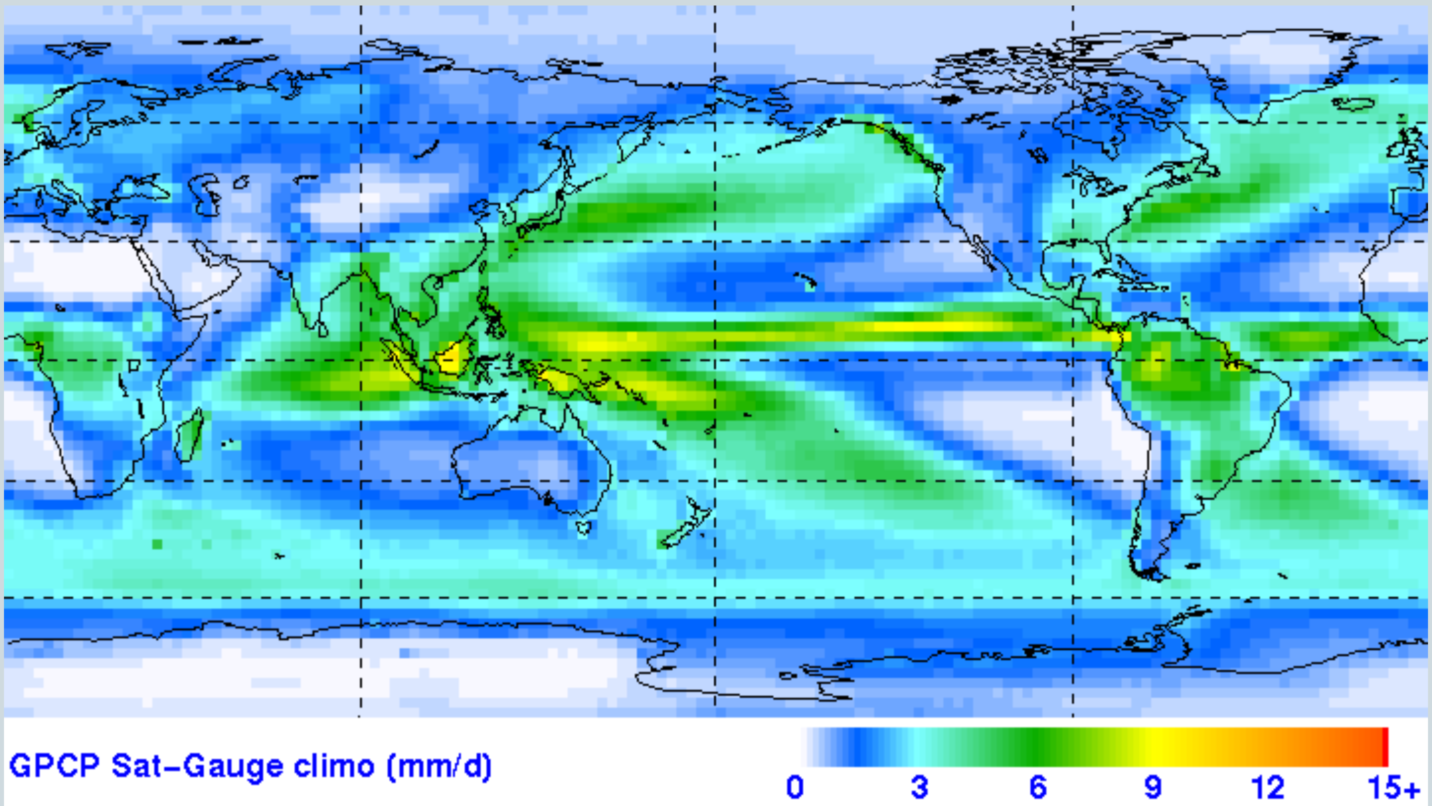


In this class…

- We'll study:
  - The "general circulation" of the atmosphere
  - Large scale features of the climate

Questions like…

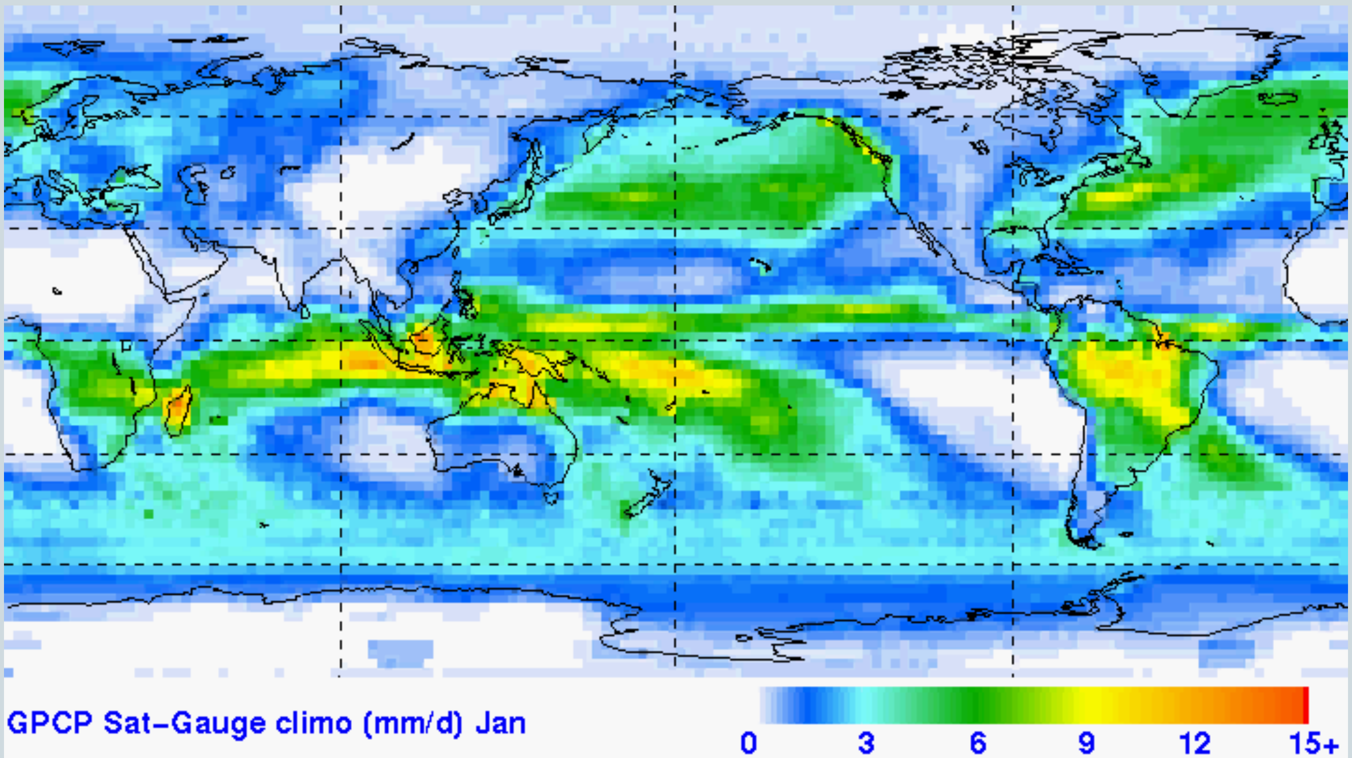
- What determines the precipitation distribution on Earth?



GPCP Climatology (1979-2006)

Questions like...

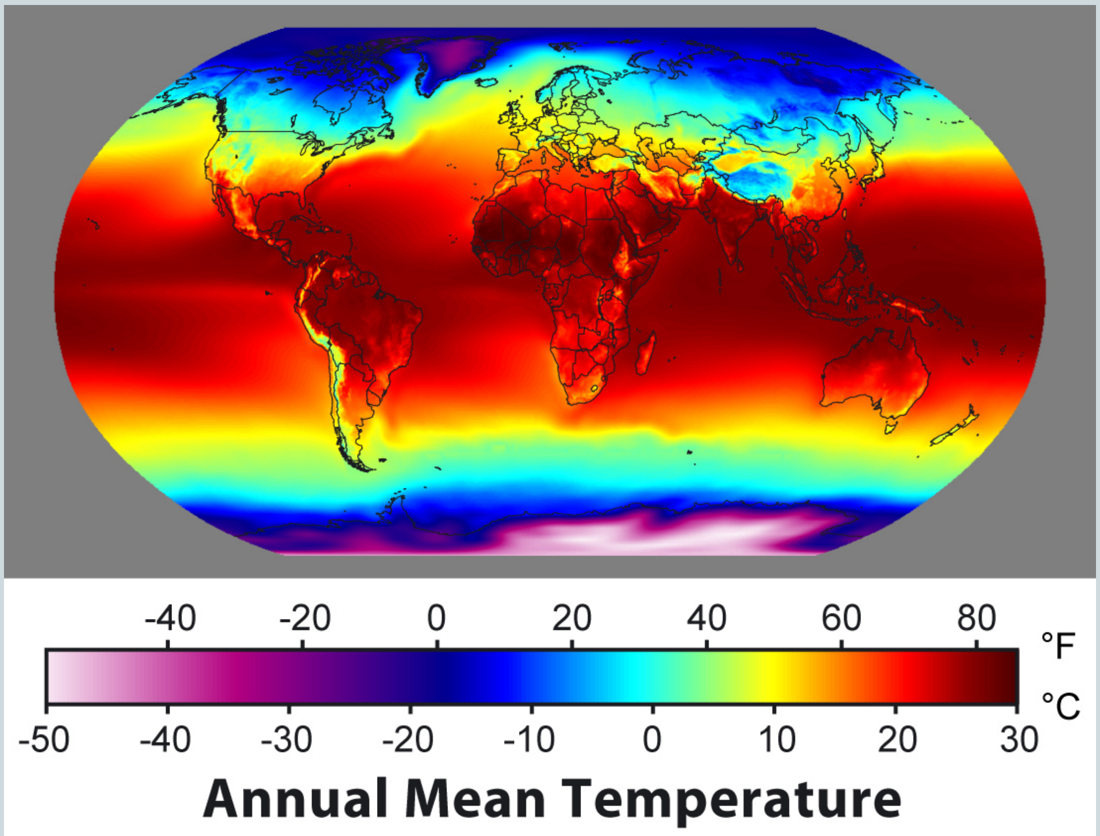
- What determines the precipitation distribution on Earth?



GPCP (1979-2006)

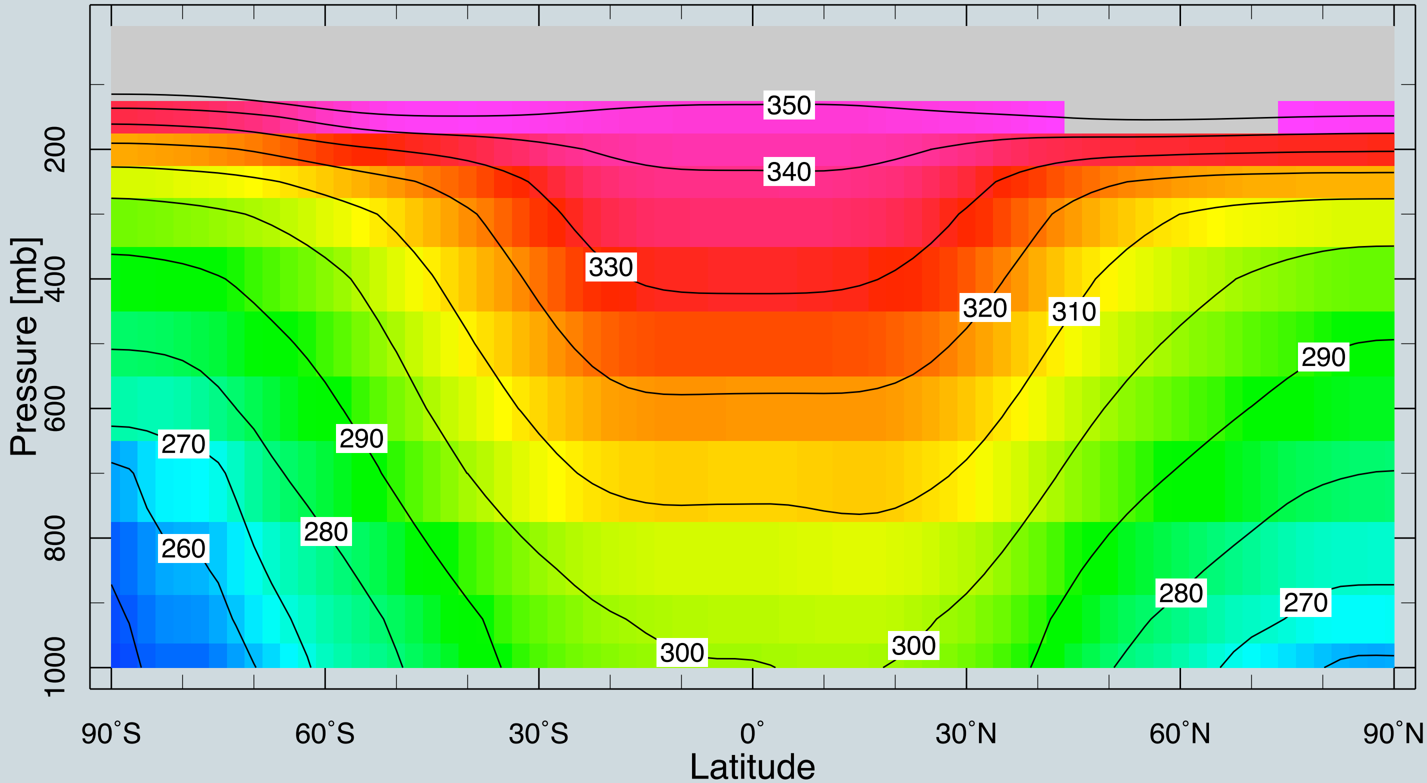
Questions like…

- What determines the north-south temperature distribution on Earth?



Questions like…

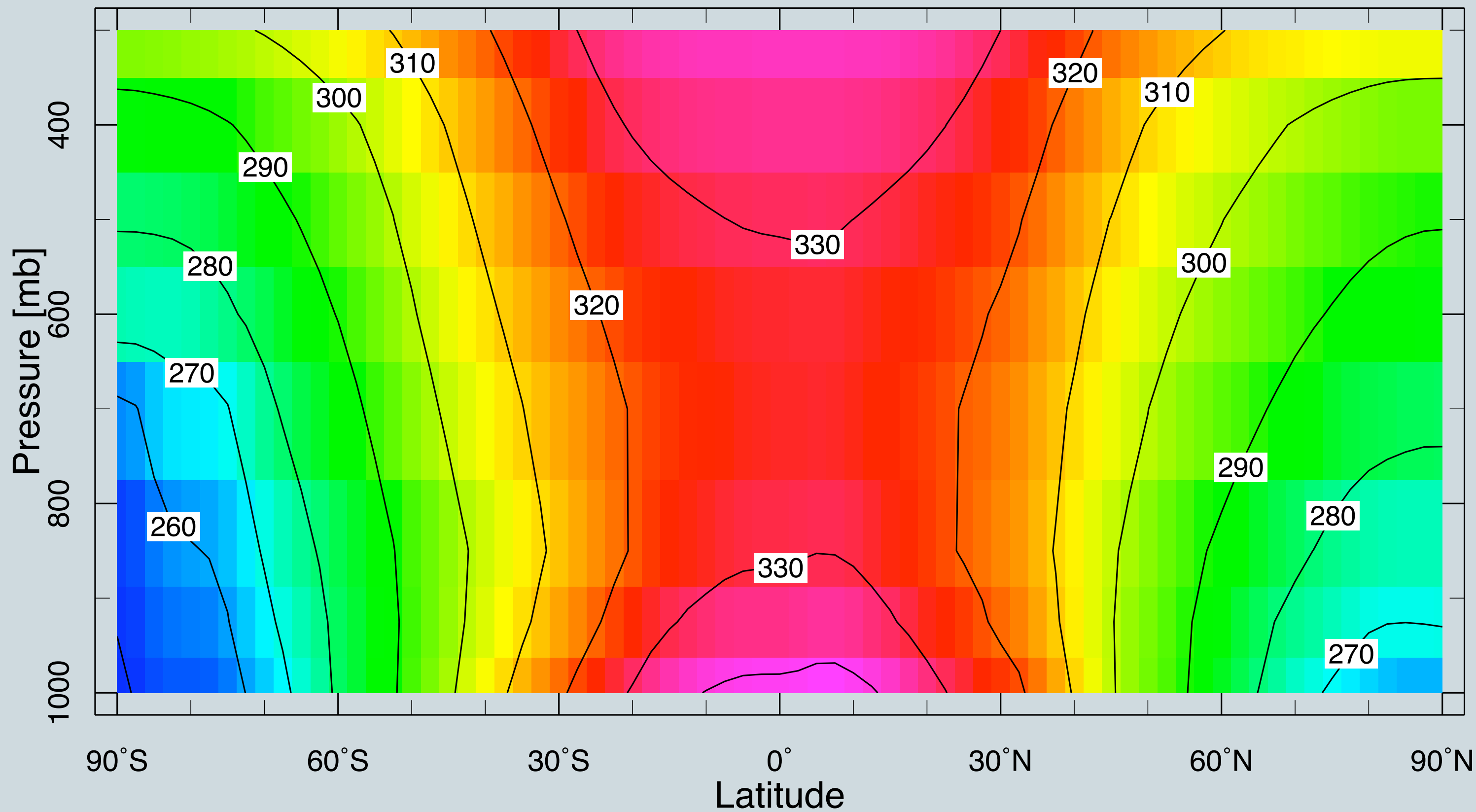
- What determines the vertical temperature structure on Earth?



Dry static energy from NCEP reanalysis

Questions like…

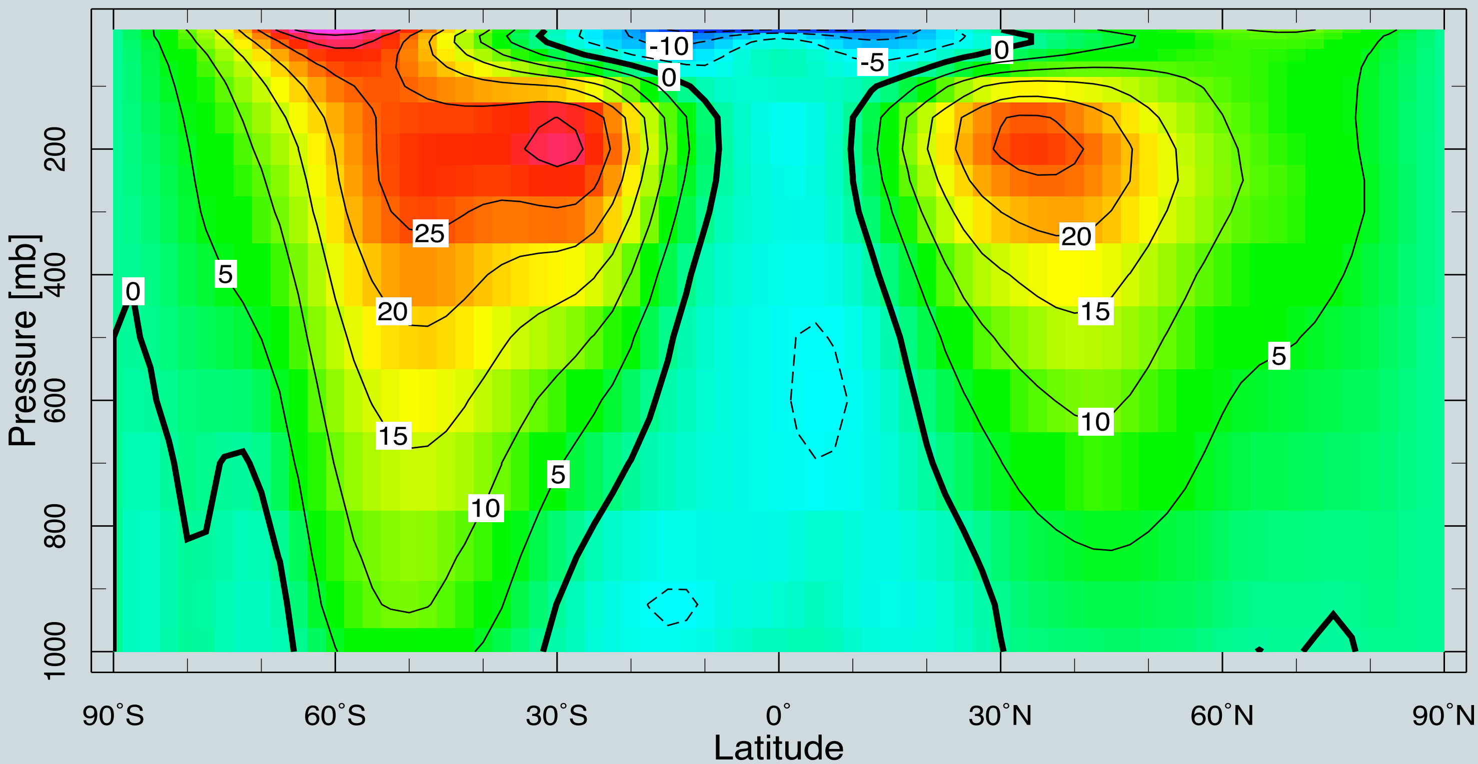
- What determines the vertical temperature structure on Earth?



Moist static energy from NCEP reanalysis

Questions like…

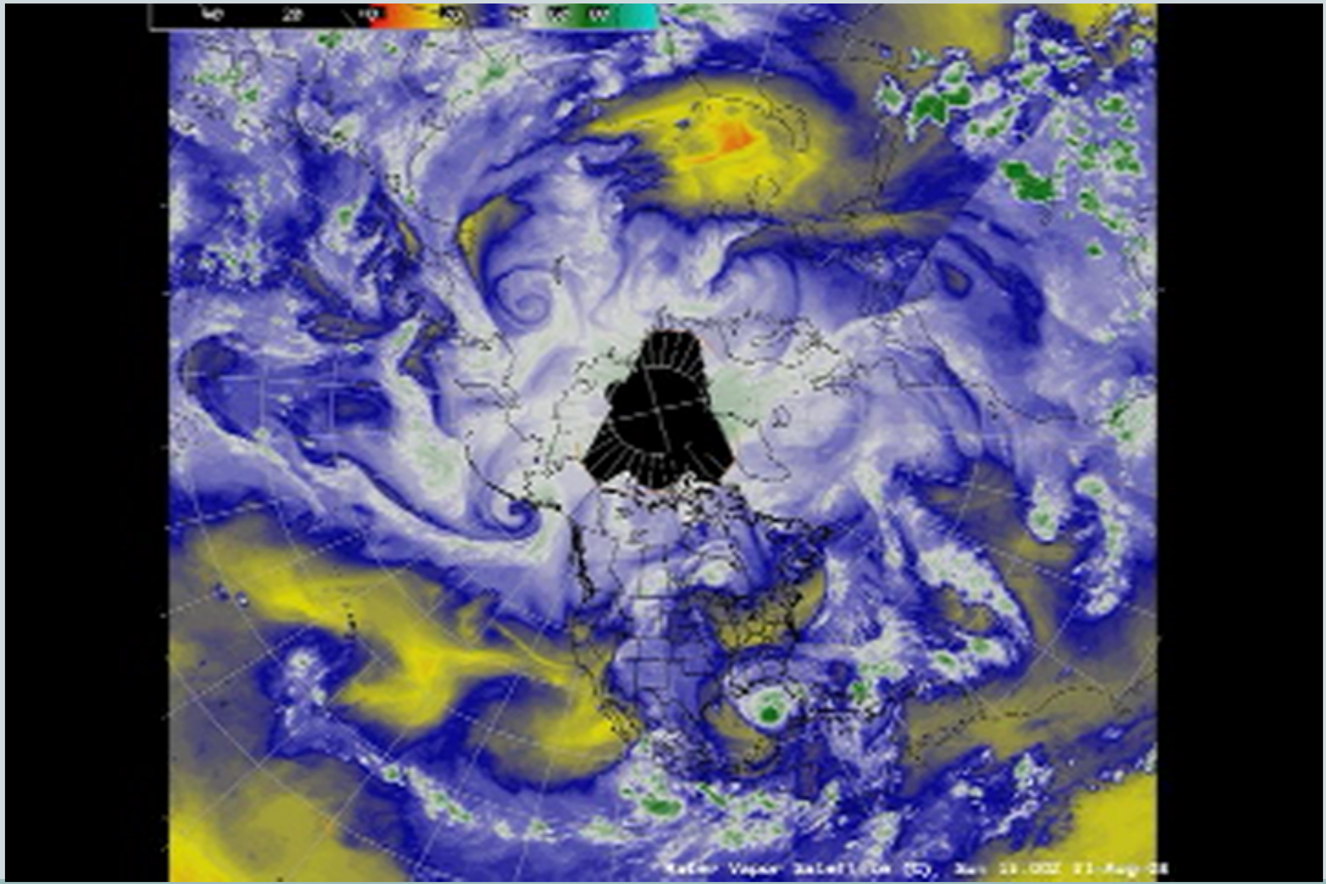
- What determines the location/intensity of the jet streams?



Zonally averaged zonal winds from NCEP reanalysis

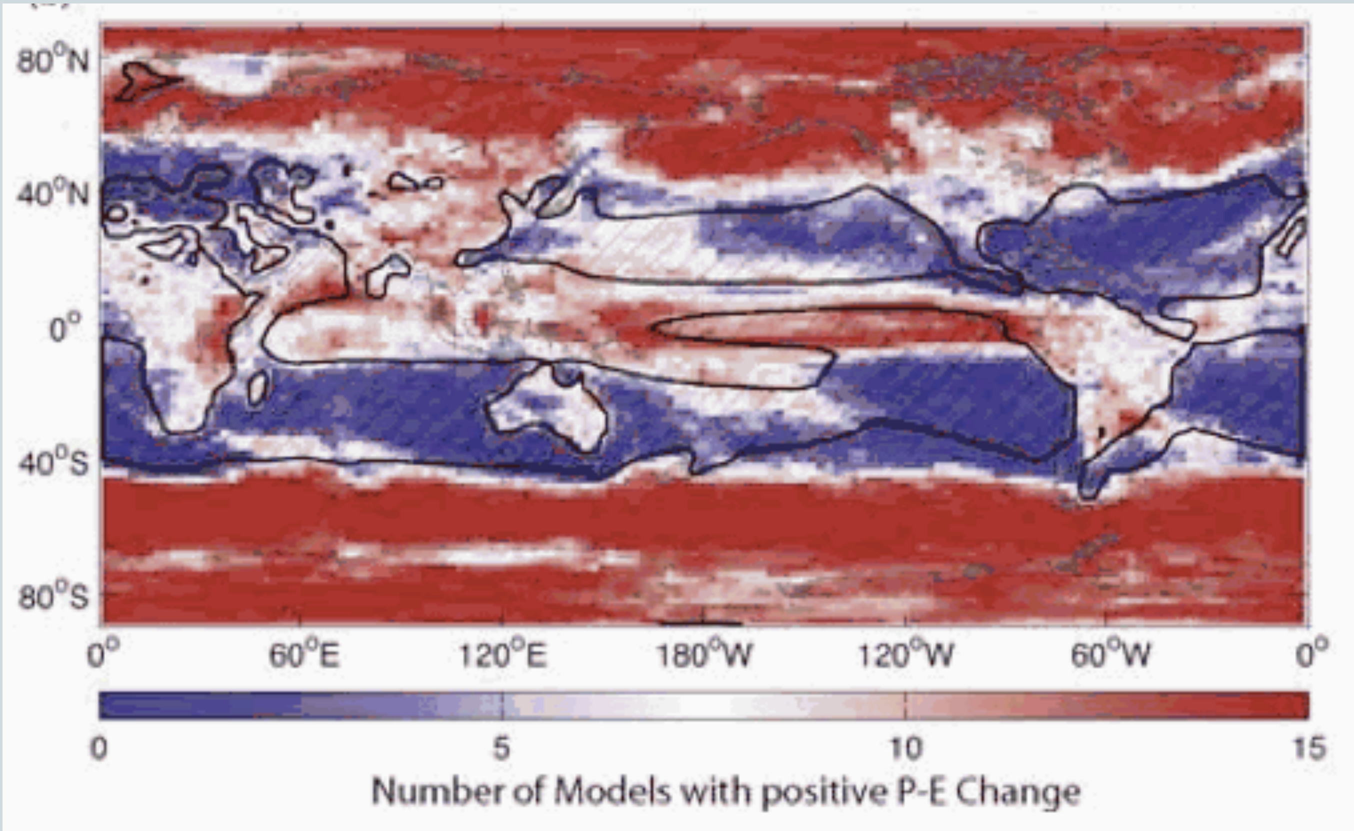
Questions like…

- What determines the intensity of eddies?



Questions like…

- How will these change with global warming?



Rainy regions get rainier, dry regions get drier

From Lu et al 2006

First: General Circulation Models (GCMs)

- What are the components of these models?
- What are the essential physical processes that are being modeled?
- What are the **simplest** mathematical models that can capture the basic physics?
- How have the parameterizations **evolved** over the **history** of climate modeling?

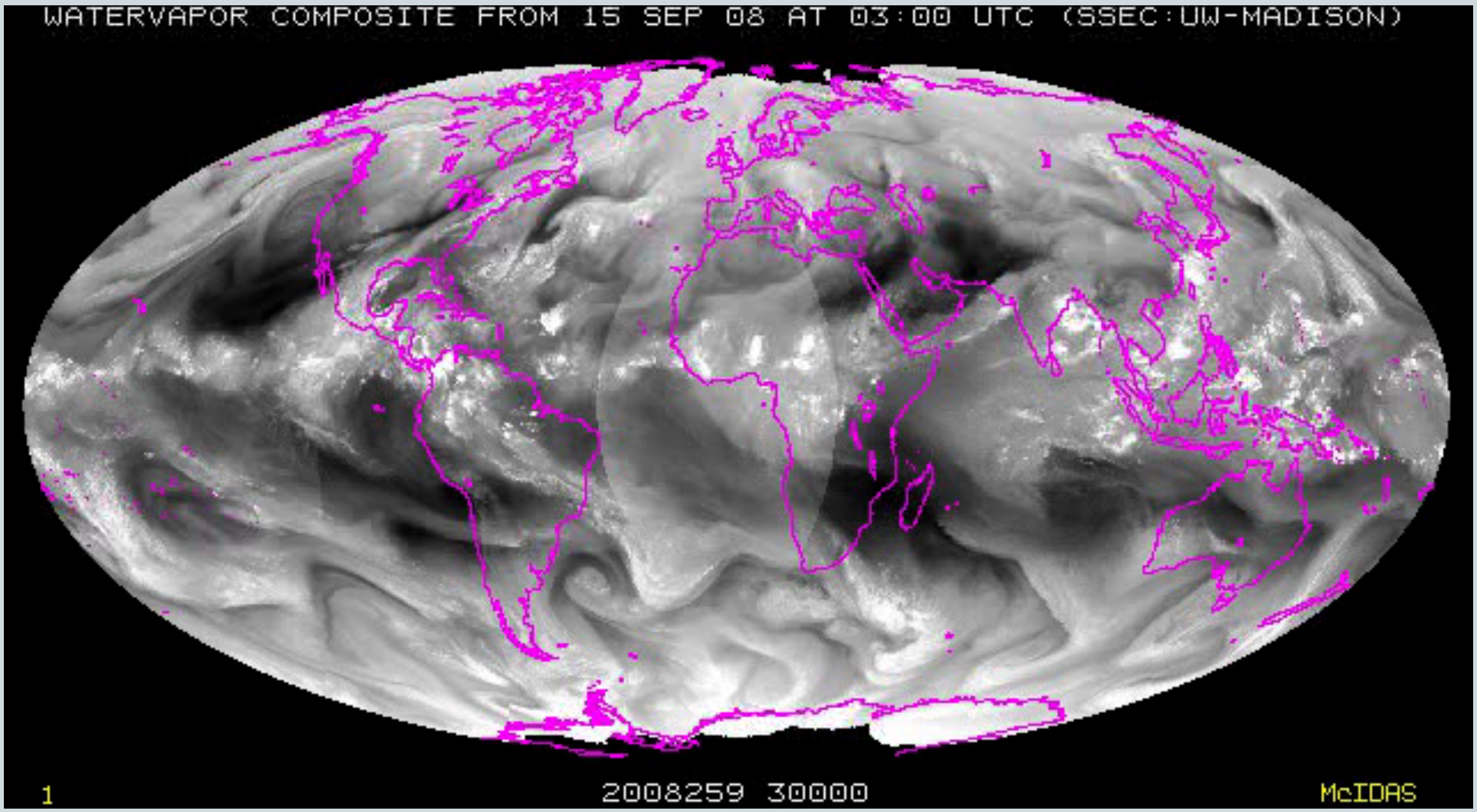
AMERICA'S NEXT
top climate model

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 Cores of AGCMs

- Fluid motion on the sphere!



Dynamical Cores of AGCMs

- The primitive equations:

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} = fv + \frac{uvtan\theta}{a} - \frac{1}{acos\theta}\frac{\partial \Phi}{\partial \lambda} + S_{u,B}$$

$$\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v + \omega \frac{\partial v}{\partial p} = -fu - \frac{u^2 tan\theta}{a} - \frac{1}{a}\frac{\partial \Phi}{\partial \theta} + S_{v,B}$$

$$\frac{\partial \Phi}{\partial lnp} = -R_d T_v$$

$$\nabla \cdot \mathbf{v} + \frac{\partial \omega}{\partial p} = 0$$

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \omega \frac{\partial T}{\partial p} = -\frac{\kappa T \omega}{p} - Q_R + Q_C + Q_B$$

Coordinates: (λ, θ, p) = (longitude, latitude, pressure)

Dynamical Cores of AGCMs

- Horizontal momentum equations:

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} = fv + \frac{uvtan\theta}{a} - \frac{1}{acos\theta} \frac{\partial \Phi}{\partial \lambda} + S_{u,B}$$

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Dynamical Cores of AGCMs

- Horizontal momentum equations:

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} = fv + \boxed{\frac{uv tan\theta}{a}} - \frac{1}{a cos\theta}\frac{\partial \Phi}{\partial \lambda} + S_{u,B}$$

$$\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v + \omega \frac{\partial v}{\partial p} = -fu \boxed{- \frac{u^2 tan\theta}{a}} - \frac{1}{a}\frac{\partial \Phi}{\partial \theta} + S_{v,B}$$

Metric terms

Dynamical Cores of AGCMs

- Horizontal momentum equations:

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} = fv + \frac{uvtan\theta}{a} - \boxed{\frac{1}{acos\theta} \frac{\partial \Phi}{\partial \lambda}} + S_{u,B}$$

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Pressure gradient term

$\Phi = gz$ = geopotential

Primitive equations

- Vertical momentum eqn. is hydrostatic balance

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} = fv + \frac{uvtan\theta}{a} - \frac{1}{acos\theta}\frac{\partial \Phi}{\partial \lambda} + S_{u,B}$$

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$$\boxed{\frac{\partial \Phi}{\partial lnp} = -R_d T_v}$$

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$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \omega \frac{\partial T}{\partial p} = -\frac{\kappa T \omega}{p} - Q_R + Q_C + Q_B$$

Hydrostatic balance

- Vertical momentum equation:

$$\frac{\partial \Phi}{\partial lnp} = -R_d T_v$$

- In z-coordinates, written as:

$$\frac{\partial p}{\partial z} = -\rho g$$

- Key assumption: atmosphere is a very thin film
  - Small aspect ratio (100 km horizontal grid size)
- Cloud resolving models are nonhydrostatic

Hydrostaticity

- 2x2.5 deg GCMs are reeeeally hydrostatic
- Garner Frierson Held Pauluis and Vallis (2007, JAS):
  - Ran a nonhydrostatic model at GCM resolution (2x2.5 degrees)
  - Multiplied nonhydrostatic terms by a constant
    - Makes convection occur at larger scales and have slower growth rates
    - Same as "DARE" method of Kuang, Bretherton & Blossey
  - We had to multiply nonhydrostatic terms by 10000 before we started to see effects!

Dynamical Cores of AGCMs

- Mass conservation:

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} = fv + \frac{uvtan\theta}{a} - \frac{1}{acos\theta}\frac{\partial \Phi}{\partial \lambda} + S_{u,B}$$

$$\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v + \omega \frac{\partial v}{\partial p} = -fu - \frac{u^2 tan\theta}{a} - \frac{1}{a}\frac{\partial \Phi}{\partial \theta} + S_{v,B}$$

$$\frac{\partial \Phi}{\partial lnp} = -R_d T_v$$

Mass conservation equation

$$\boxed{\nabla \cdot \mathbf{v} + \frac{\partial \omega}{\partial p} = 0}$$

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \omega \frac{\partial T}{\partial p} = -\frac{\kappa T \omega}{p} - Q_R + Q_C + Q_B$$

Looks incompressible, but it isn't. Pressure coordinates makes this form possible (requires hydrostatic balance too).

Dynamical Cores of AGCMs

- Thermodynamic equation:

$$\frac{\partial u}{\partial t} + \mathbf{v}\cdot\nabla u + \omega\frac{\partial u}{\partial p} = fv + \frac{uvtan\theta}{a} - \frac{1}{acos\theta}\frac{\partial \Phi}{\partial \lambda} + S_{u,B}$$

$$\frac{\partial v}{\partial t} + \mathbf{v}\cdot\nabla v + \omega\frac{\partial v}{\partial p} = -fu - \frac{u^2tan\theta}{a} - \frac{1}{a}\frac{\partial \Phi}{\partial \theta} + S_{v,B}$$

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Temperature changes due to compression and expansion

Dynamical Cores of AGCMs

- Source terms: where much of the complexity comes in

$$\frac{\partial u}{\partial t} + \mathbf{v} \cdot \nabla u + \omega \frac{\partial u}{\partial p} = fv + \frac{uv tan\theta}{a} - \frac{1}{a cos\theta} \frac{\partial \Phi}{\partial \lambda} \boxed{+ S_{u,B}}$$

$$\frac{\partial v}{\partial t} + \mathbf{v} \cdot \nabla v + \omega \frac{\partial v}{\partial p} = -fu - \frac{u^2 tan\theta}{a} - \frac{1}{a} \frac{\partial \Phi}{\partial \theta} \boxed{+ S_{v,B}}$$

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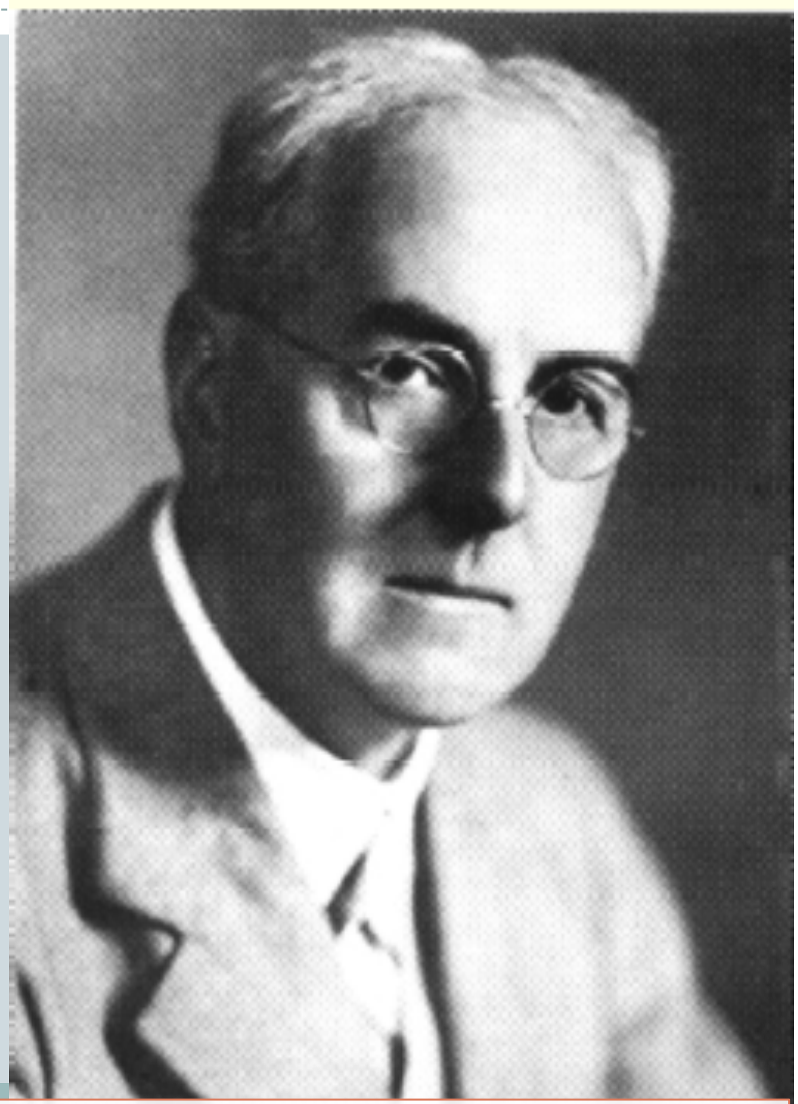
$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \omega \frac{\partial T}{\partial p} = -\frac{\kappa T \omega}{p} \boxed{- Q_R + Q_C + Q_B}$$

"Physics"

The First Numerical Model of the Atmosphere

- 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***
  - Did the calculations completely **by hand**! Took over **1000 hours**!

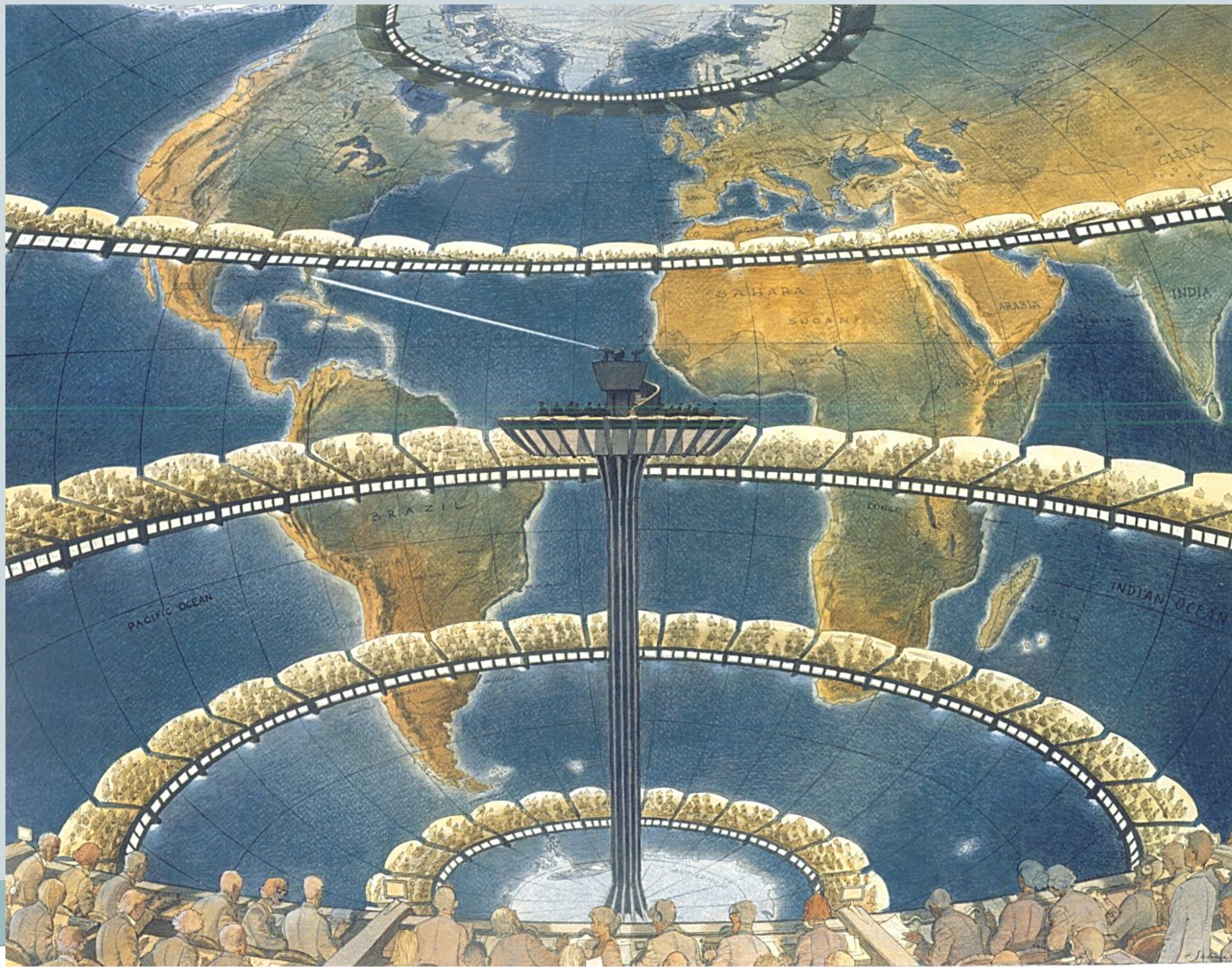
Also had a dream of the future of weather prediction…



All info on this topic is from Peter Lynch: Check out his book "The Emergence of NWP"!

Richardson’s Dream: The Forecast Factory

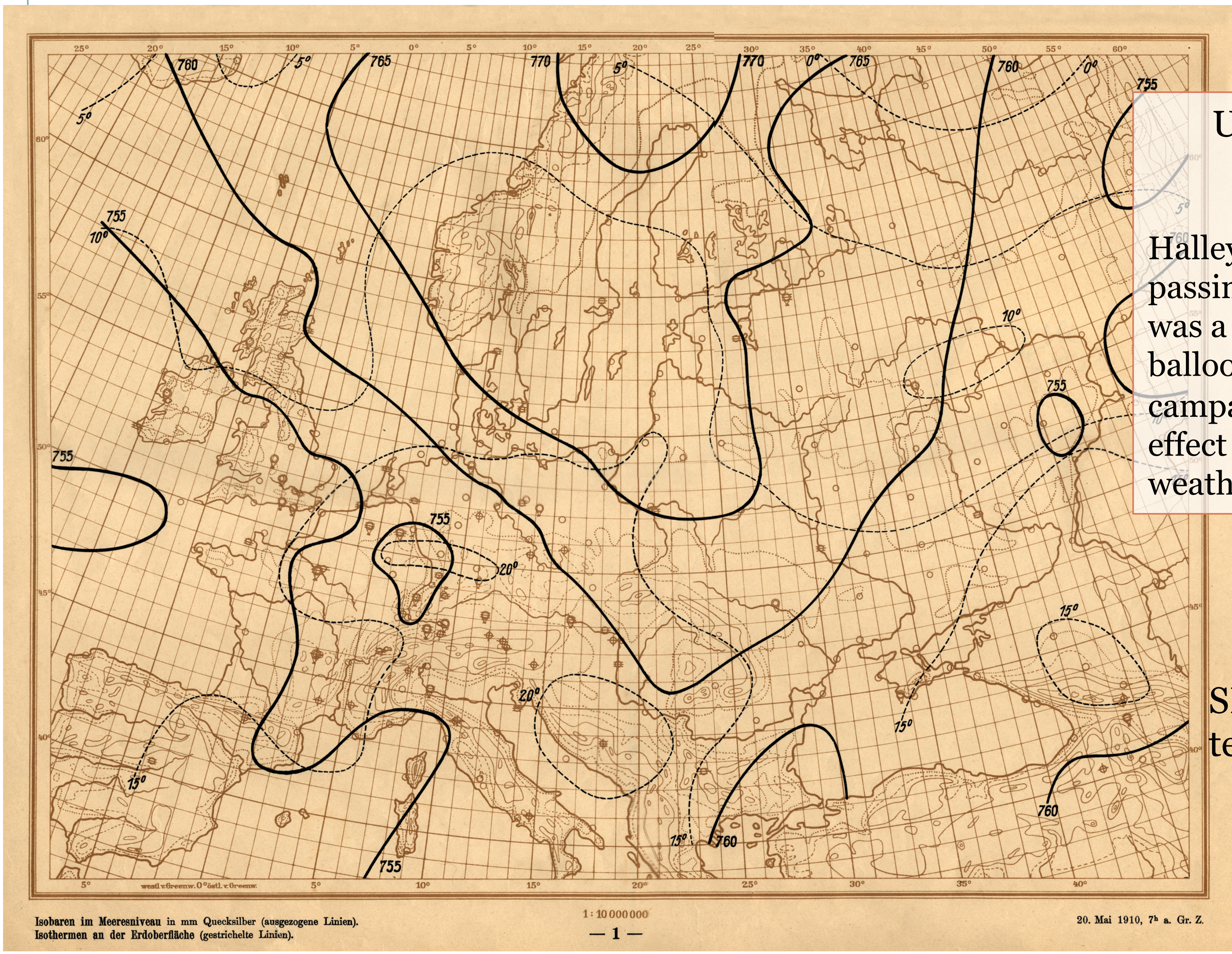
- Filled with employees (“computers”) doing calculations



Richardson’s dream in 1922 of a global forecasting system

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

Richardson’s Experiment

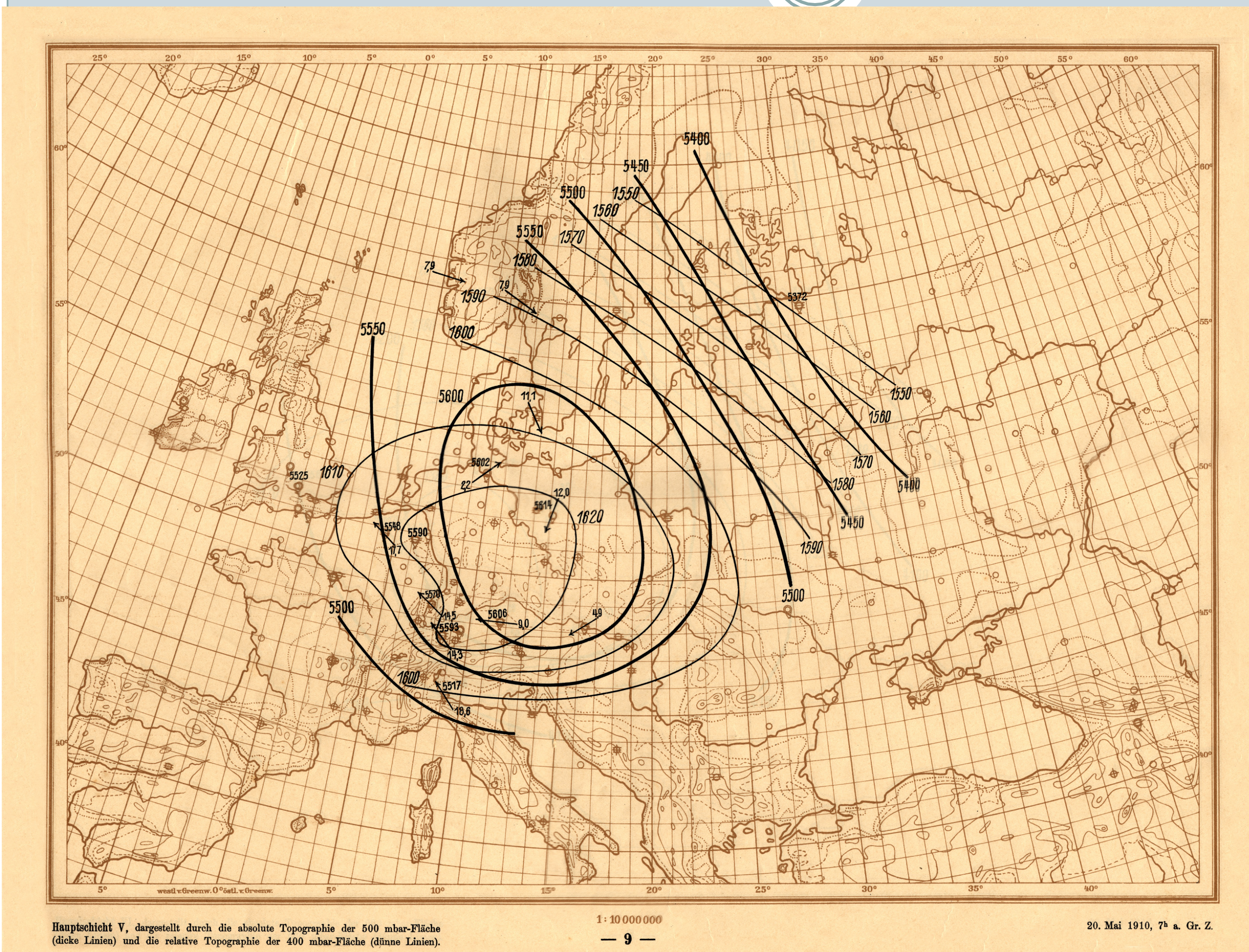


Used data from May 20, 1910

Halley’s comet was passing, and there was a large hot air balloon observational campaign to study effect of comets on weather.

SLP and surface temperature

Richardson’s Experiment



Tabulated values from these charts by hand!

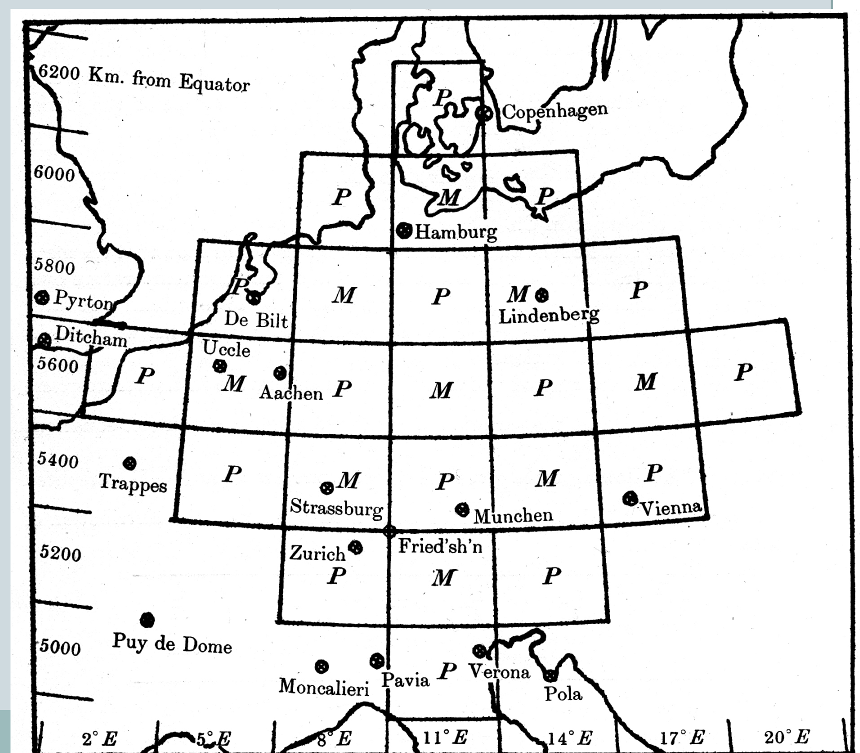
500 mbar heights and 500-400 mbar thickness

Richardson's Calculations

- Served as ambulance driver with the Friends' Ambulance Unit in France during WWI
  - Transported injured soldiers, often under heavy fire
- Took six weeks to perform the calculations
  - "My office was a heap of hay in a cold rest billet"
  - Peter Lynch thinks he meant 6 weeks*7 days*24 hours = 1000 hours of computation!
    - I.e., it took him the whole time he was in France, 2 years
- Calculation book was lost during the battle of Champagne
  - But recovered months later under a heap of coal
- Eventually published in 1922

Richardson's Calculations

- Goal: calculate the **surface pressure** tendency at one point (in Bavaria), 6 hours in the future
- Discretized into five layers in the vertical
- Used **primitive equations**
  - Assuming hydrostatic balance
- Used finite differences to calculate changes in momentum, temperature, and pressure



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: $-\frac{\partial R_{96}}{\partial t} = \frac{\partial M_{E96}}{\partial e} + \frac{\partial M_{N96}}{\partial n} - M_{N96}\frac{\tan\phi}{a} + m_{H8} - m_{H8}^{*} + \frac{2}{a}M_{H96}$. (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	$\frac{\delta M_E}{\delta e}$	$\frac{\delta M_N}{\delta n}$	$-\frac{M_N \tan\phi}{a}$	$\mathrm{div}'_{EN}M$	$-g\delta t\,\mathrm{div}'_{EN}M$		m_H	$\frac{2M_H}{a}$	$-\frac{\partial R}{\partial t}$	$+\frac{\partial R}{\partial t}\delta t$	$g\frac{\partial R}{\partial t}\delta t$	$\frac{\partial p}{\partial t}\delta t$
	$10^{-5}\times$	$10^{-6}\times$	$10^{-5}\times$	$10^{-5}\times$	$100\times$	Leave the subsequent columns to be filled up after the vertical velocity has been computed on Form P XVI	$10^{-5}\times$	$10^{-5}\times$	$10^{-5}\times$		$100\times$	$100\times$
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 $\Sigma - g\delta t\,\mathrm{div}'_{EN}M$

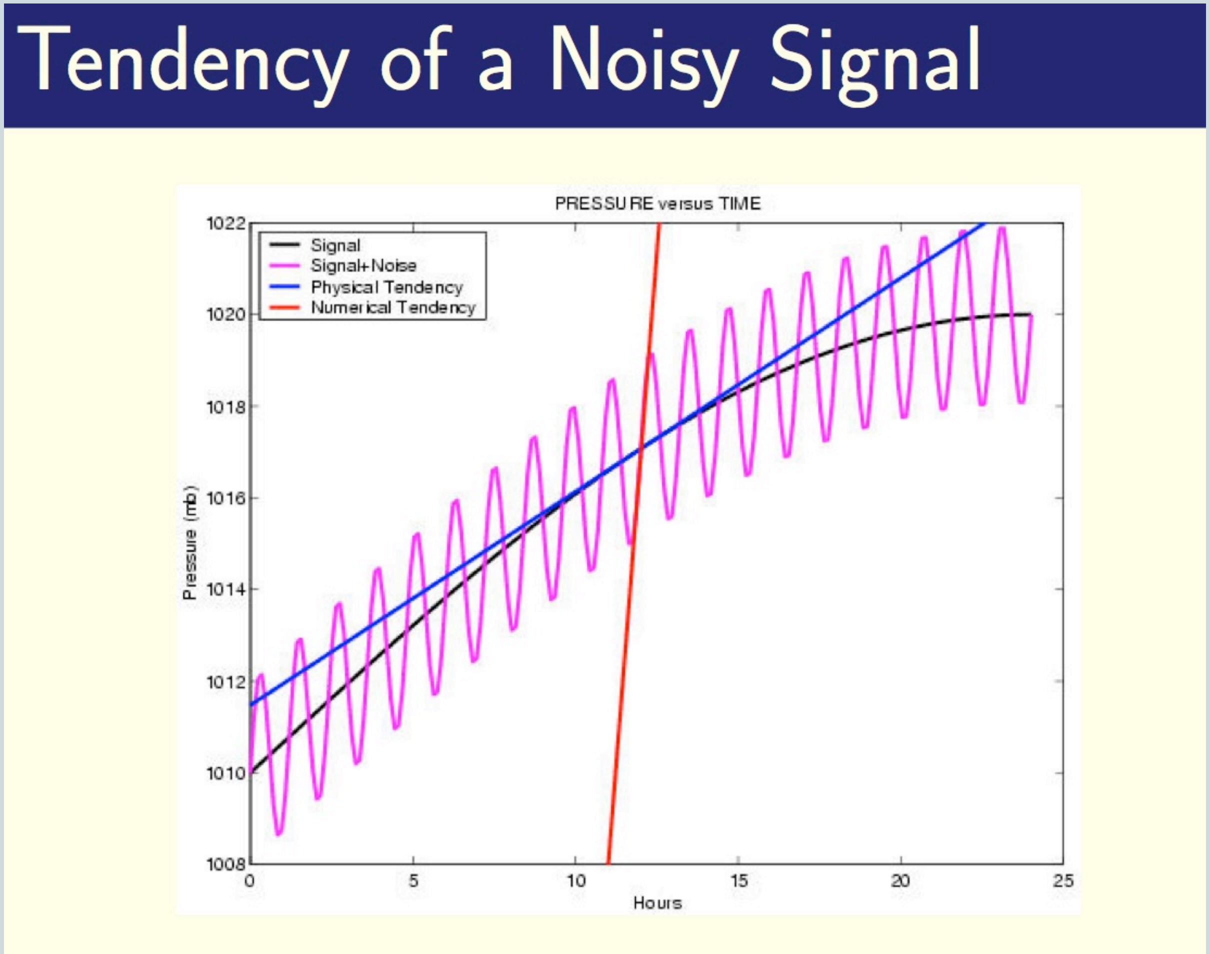
Richardson's Computing Form P_{XIII}

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

Richardson’s Forecast Bust

- Why such a failure?
- Not due to bad numerics, as many claim
  - He only took one time step, so numerical instabilities can’t develop
- Rather it has to do with fast & slow manifolds

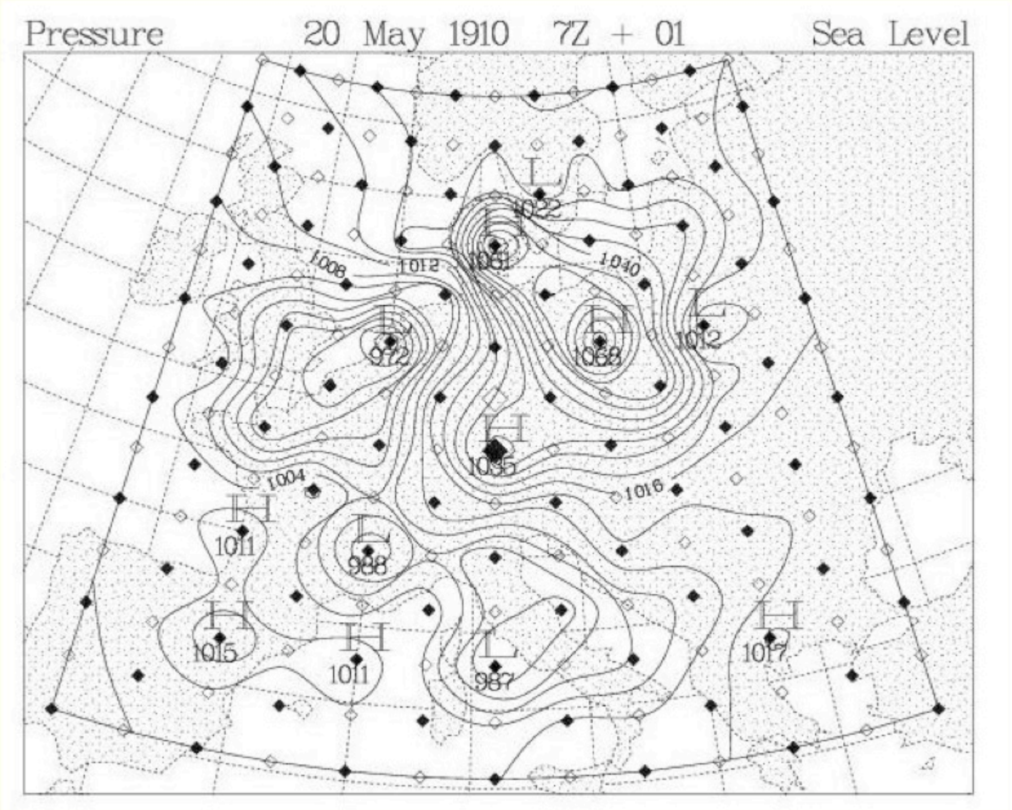
Extrapolating noisy rates of change



A simple schematic illustrating how extrapolating a noisy signal is dangerous…

Richardson's forecast

Forecast without Filtering



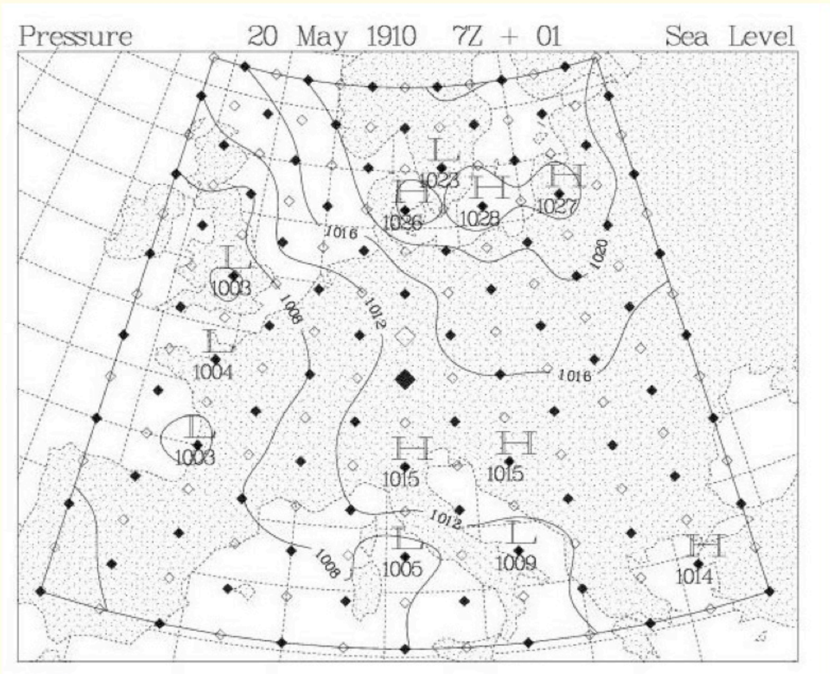
Short-range forecast of sea-level pressure, from *uninitialized data*. The contour interval is 4 hPa. Single forward time step of size $\Delta t = 3600\,\mathrm{s}$.

Richardson’s Forecast

- Richardson himself realized that gravity waves were the problem.
- He suggested smoothing of initial conditions
  - And proposed 5 different methods for this
- Unfortunately he couldn’t implement them due to computational expense
  - But we can reproduce the results using today’s computers…

"Balancing" the initial conditions

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 $\Delta t = 3600\,\text{s}$.

The First Successful NWP Experiment

- Fast gravity waves were the problem:
  - Why not try predicting with a model that has no gravity waves?
- John von Neumann, Jule Charney, Ragnar Fjortoft
- Research proposal proposed three uses for NWP:
  - Weather prediction (duh)
  - Planning where to take observations
  - Weather modification!

ENIAC Forecast Grid

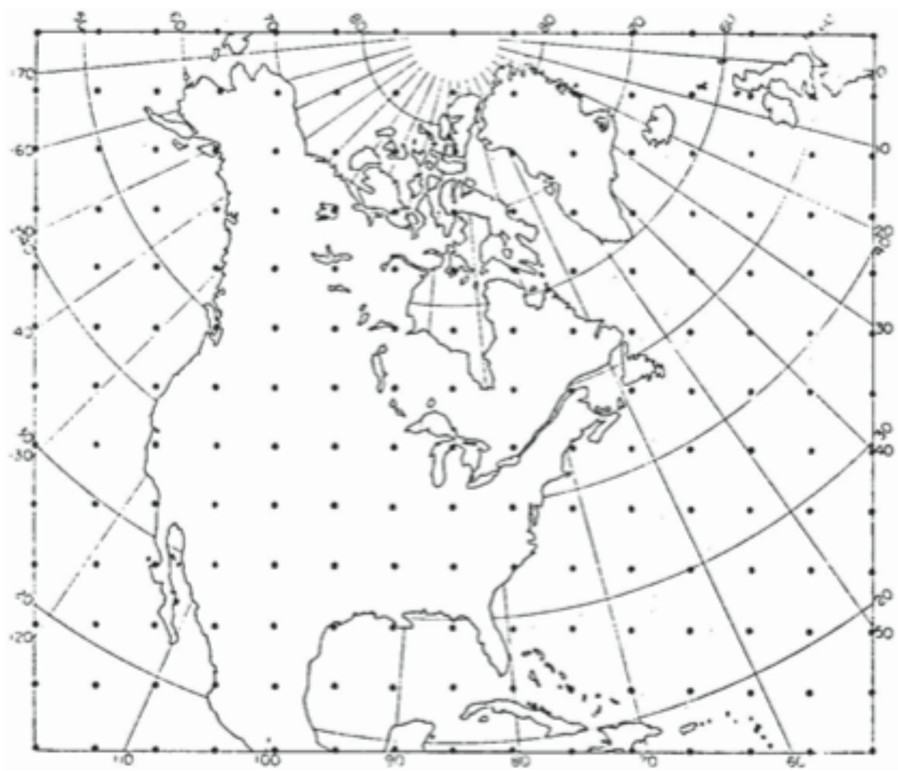


FIG. 2. Computation grid used for the ENIAC forecasts. One line is omitted from the southern edge and two lines from the remaining edges (from CFvN).

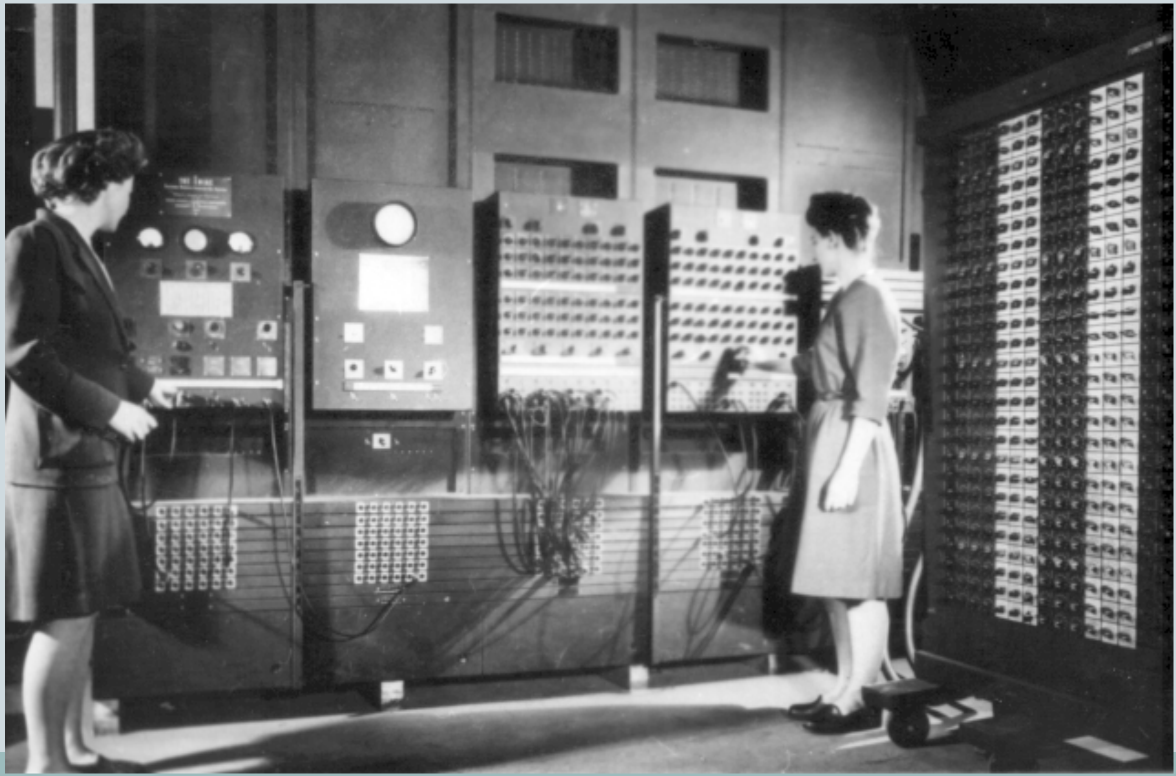
Used barotropic model (no gravity waves, no problems with imbalanced initial conditions)

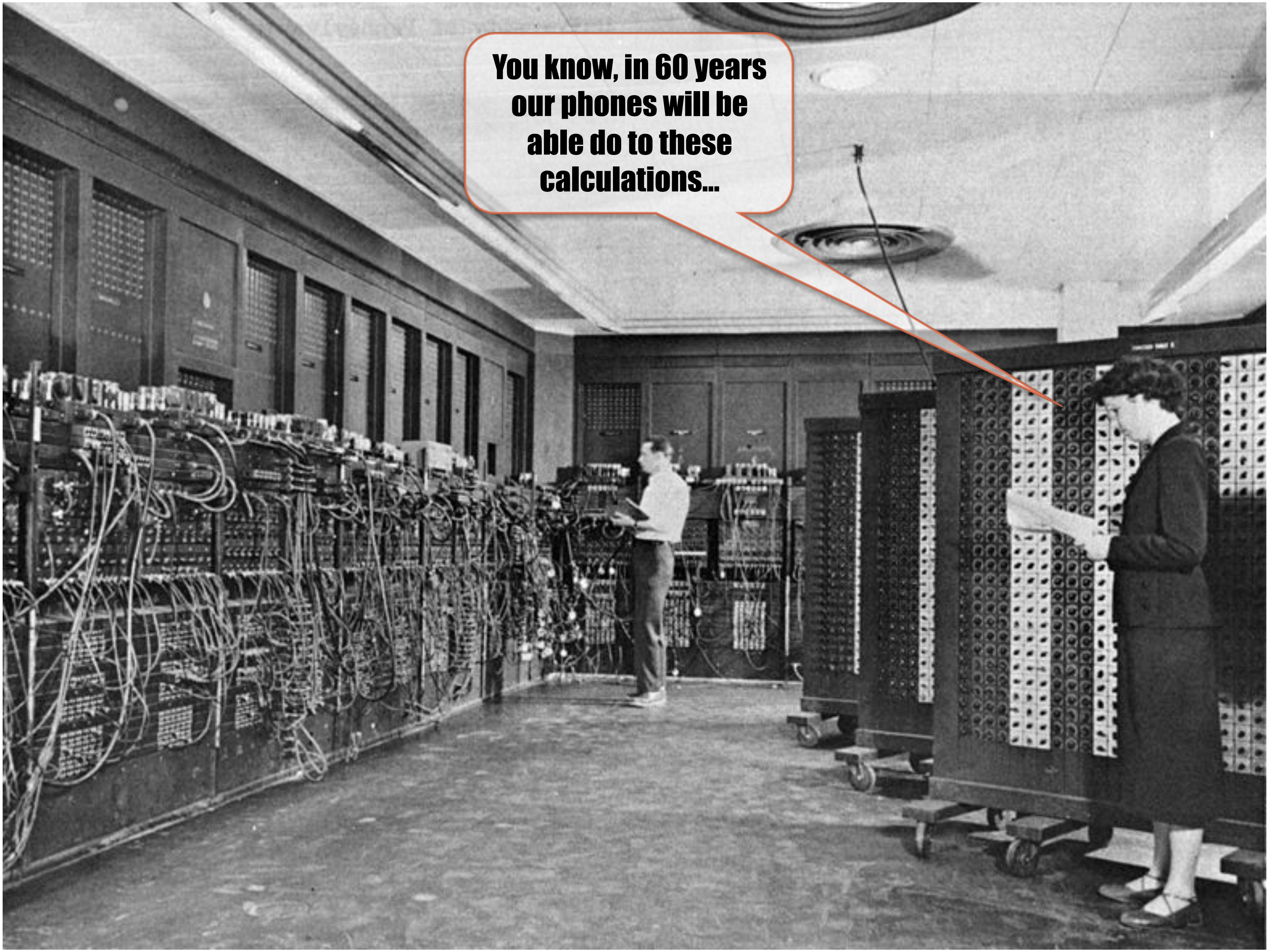
Simplest model w/ Rossby waves

We have this model running on pynchon!

The First Computer!

- ENIAC: The Electronic Numerical Integrator and Computer




You know, in 60 years our phones will be able do to these calculations...

First Forecast

Initial conditions

Observed height 24 hrs later

Observed and computed change in height

Forecast height 24 hrs later

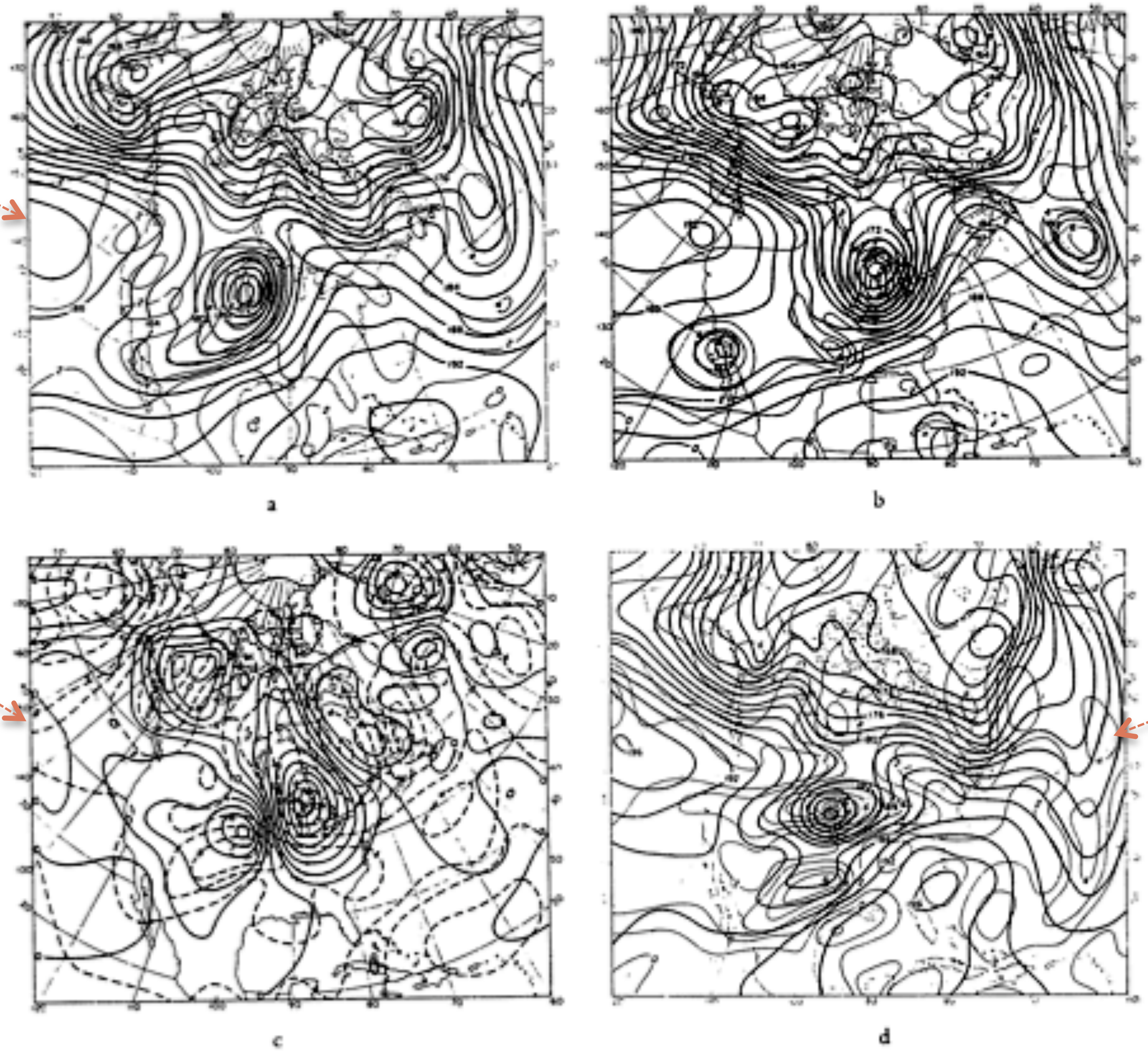


Fig. 2. Forecast of January 5, 1949, 0300 GMT: (a) observed z and η at $t = 0$; (b) observed z and η at $t = 24$ hours; (c) observed (continuous lines) and computed (broken lines) 24-hour height change; (d) computed z and η at $t = 24$ hours. The height unit is 100 ft and the unit of vorticity is $1/3 \times 10^{-4}$ sec^{-1}.

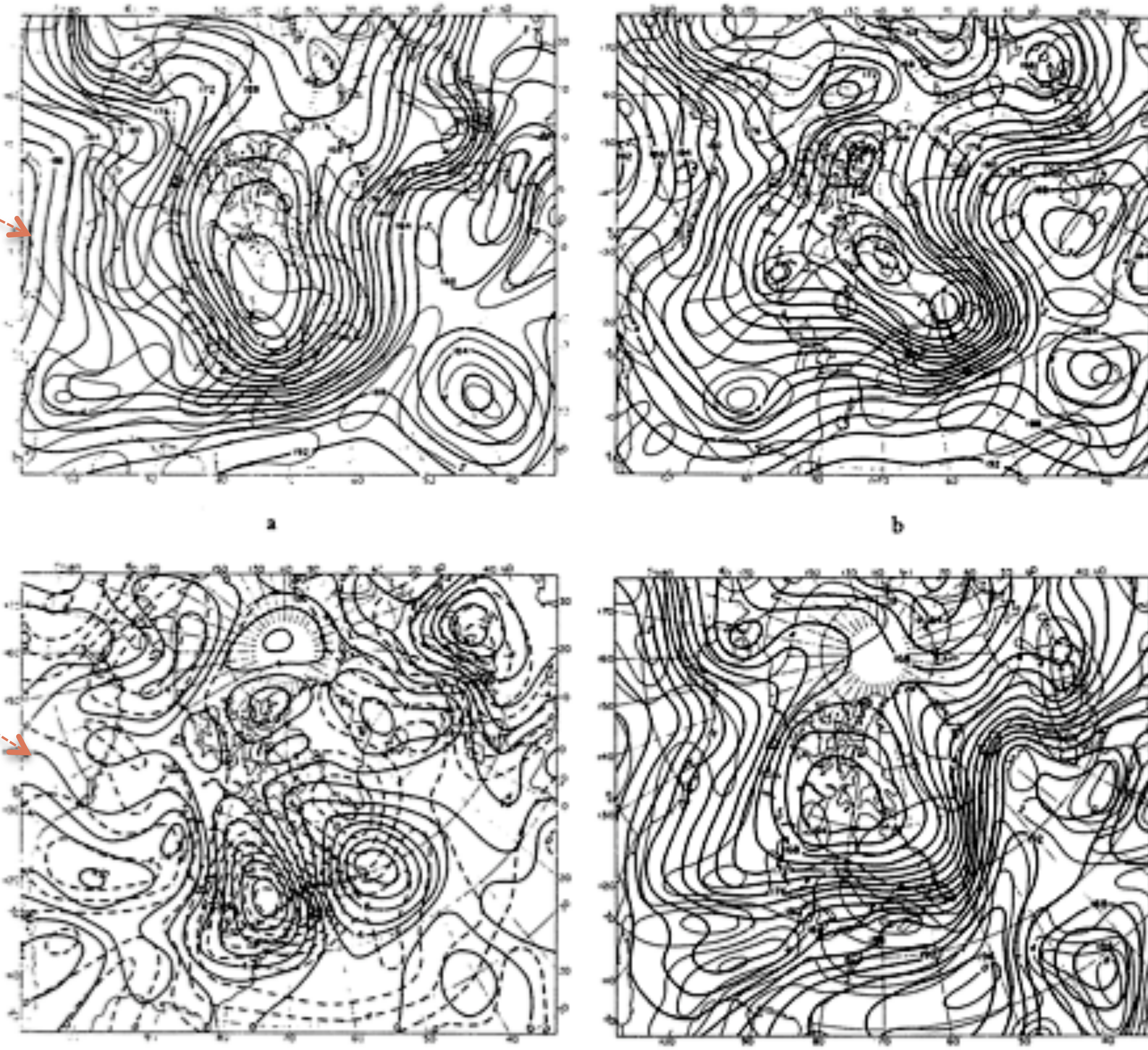
Second Forecast

Initial conditions

Observed height 24 hrs later

Observed and computed change in height

Forecast height 24 hrs later



a b c d

Fig. 3. Forecast of January 30, 1949, 0300 GMT. (See Fig. 2 for explanation of diagrams.)

Third Forecast

Initial conditions

Observed height 24 hrs later

Observed and computed change in height

Forecast height 24 hrs later

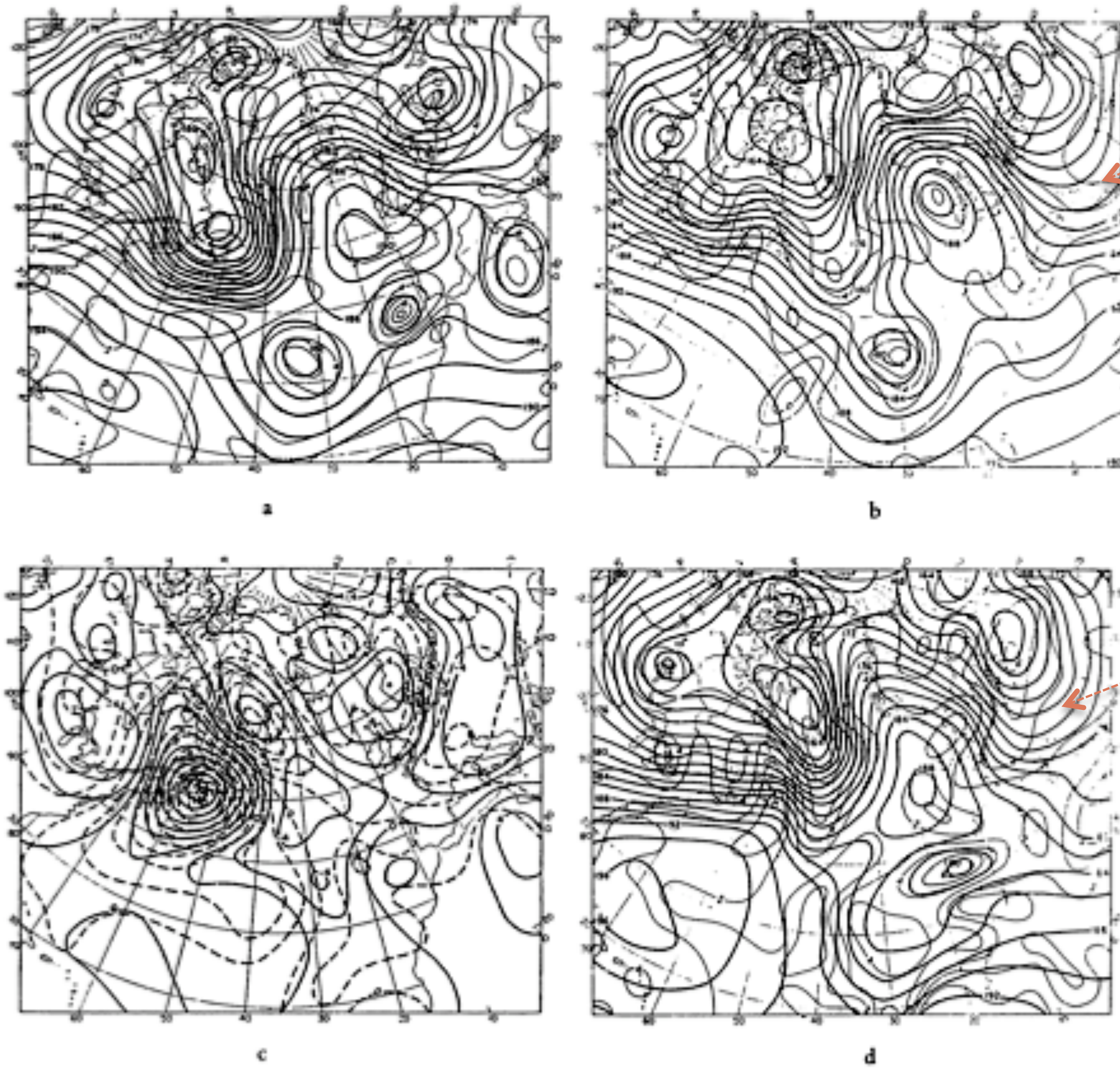


Fig. 4. Forecast of January 31, 1949, 0300 GMT. (See Fig. 2 for explanation of diagrams.)

Fourth Forecast

Initial conditions

Observed height 24 hrs later

Observed and computed change in height

Forecast height 24 hrs later

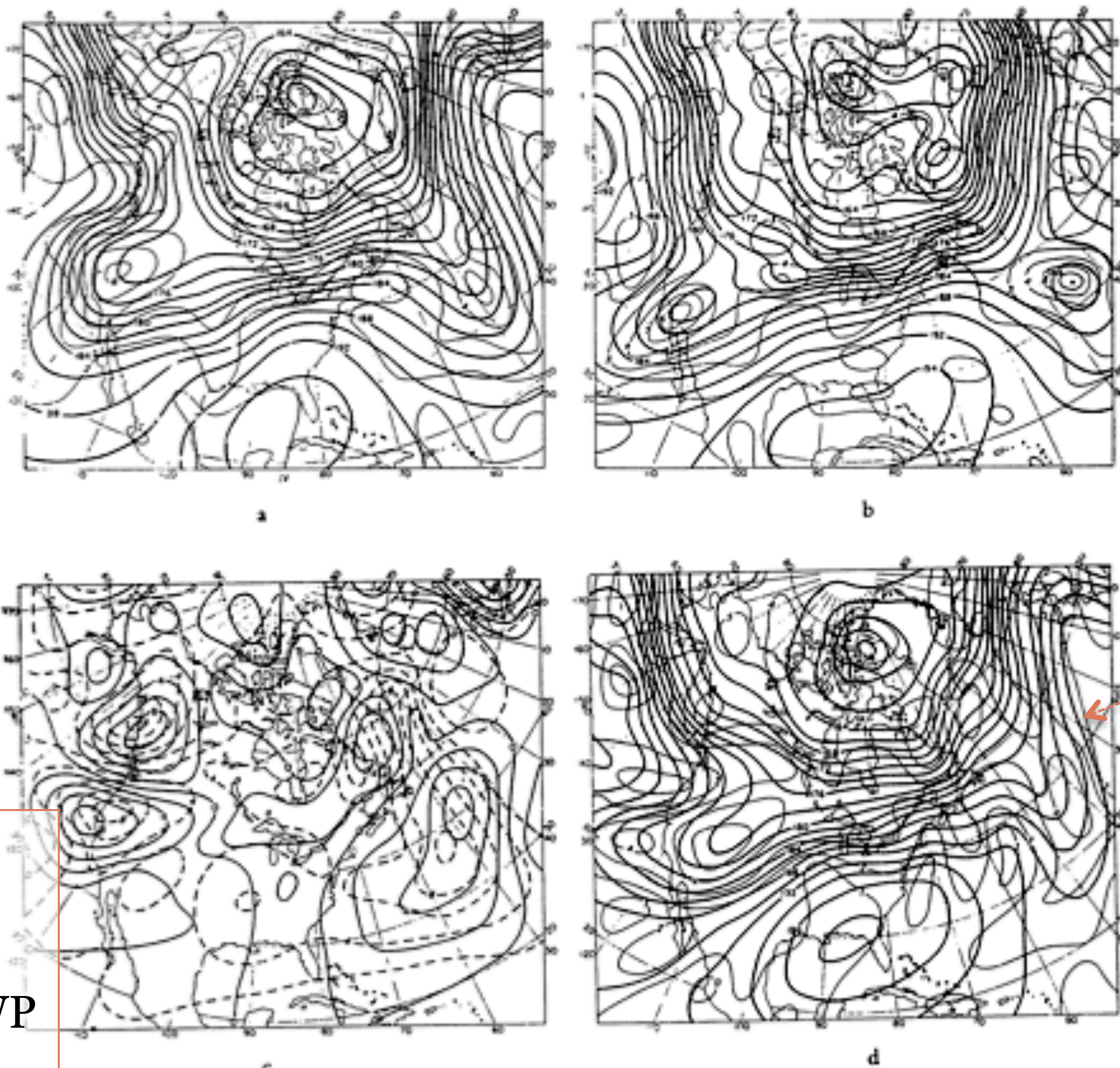


Fig. 5. Forecast of February 13, 1949, 0300 GMT. (See Fig. 2 for explanation of diagrams.)

Results are not that impressive for first "successful" NWP forecast!

First Operational NWP Systems

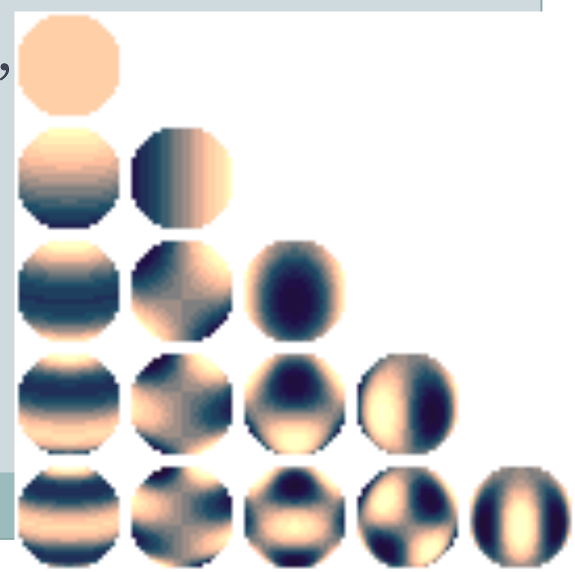
- NWP really took off though & quickly improved!
- December 1954: Royal Swedish Air Force Weather Service in Stockholm
  - Model developed at the Institute of Meteorology at the University of Stockholm (Rossby, etc)
  - Barotropic model, 3 forecasts per week of North Atlantic
- May 1955: Joint Numerical Weather Prediction Unit, Maryland
  - 3 level QG model
- 1966: US uses 3-level primitive equation model
- Global coverage since 1973

Numerical Methods

- Gridpoint methods:
  - Fields specified at points
  - Often staggered to support ease of taking derivatives
  - "B-grid": velocity is on different grid as geopotential, temperature and tracers
  - Common resolutions: 2x2.5 deg (90x144 points)

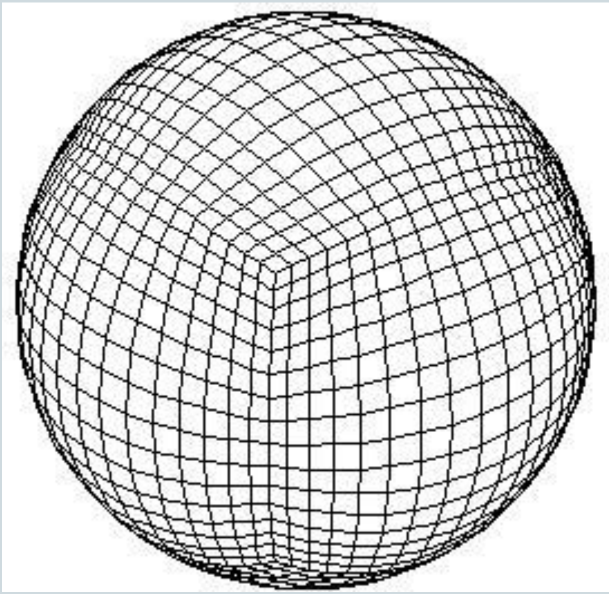
Numerical Methods

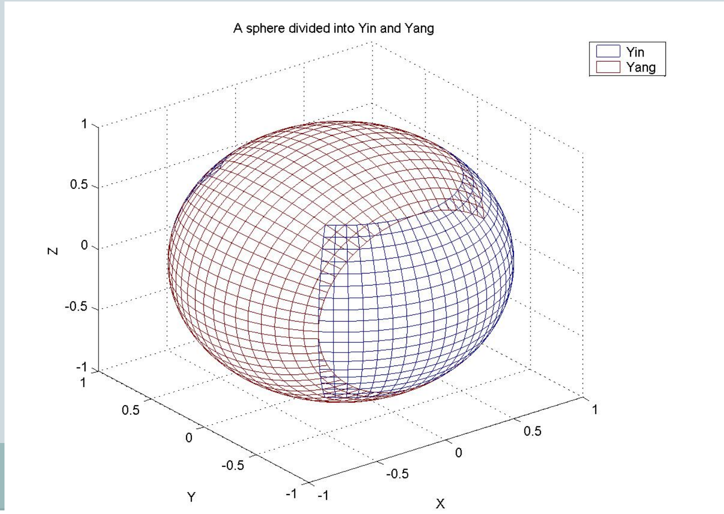
- Spectral methods:
  - Uses spherical harmonics to represent fields
  - Different ways to truncate (triangular or rhomboidal)
    - Triangular has uniform resolution around the sphere, rhomboidal focuses resolution in midlatitudes more
    - Triangular is the preferred choice now, rhomboidal is only used in very low res GCMs
  - Common resolutions: T42 (64x128; 2.8 deg), T85 (128x256; 1.4 deg)
  - Highest resolution model in CMIP3: 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"





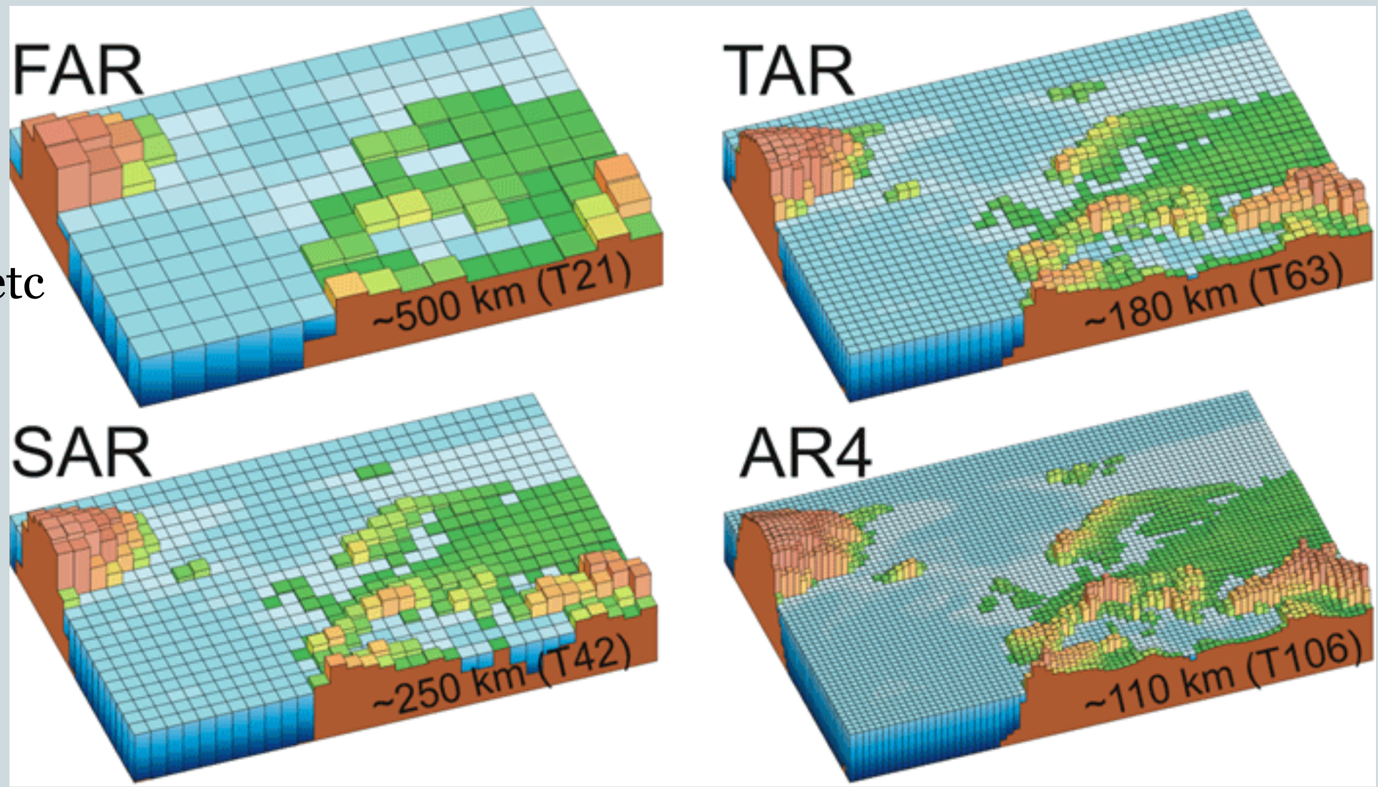
Model Resolution Evolution

- Changes in resolution over time:

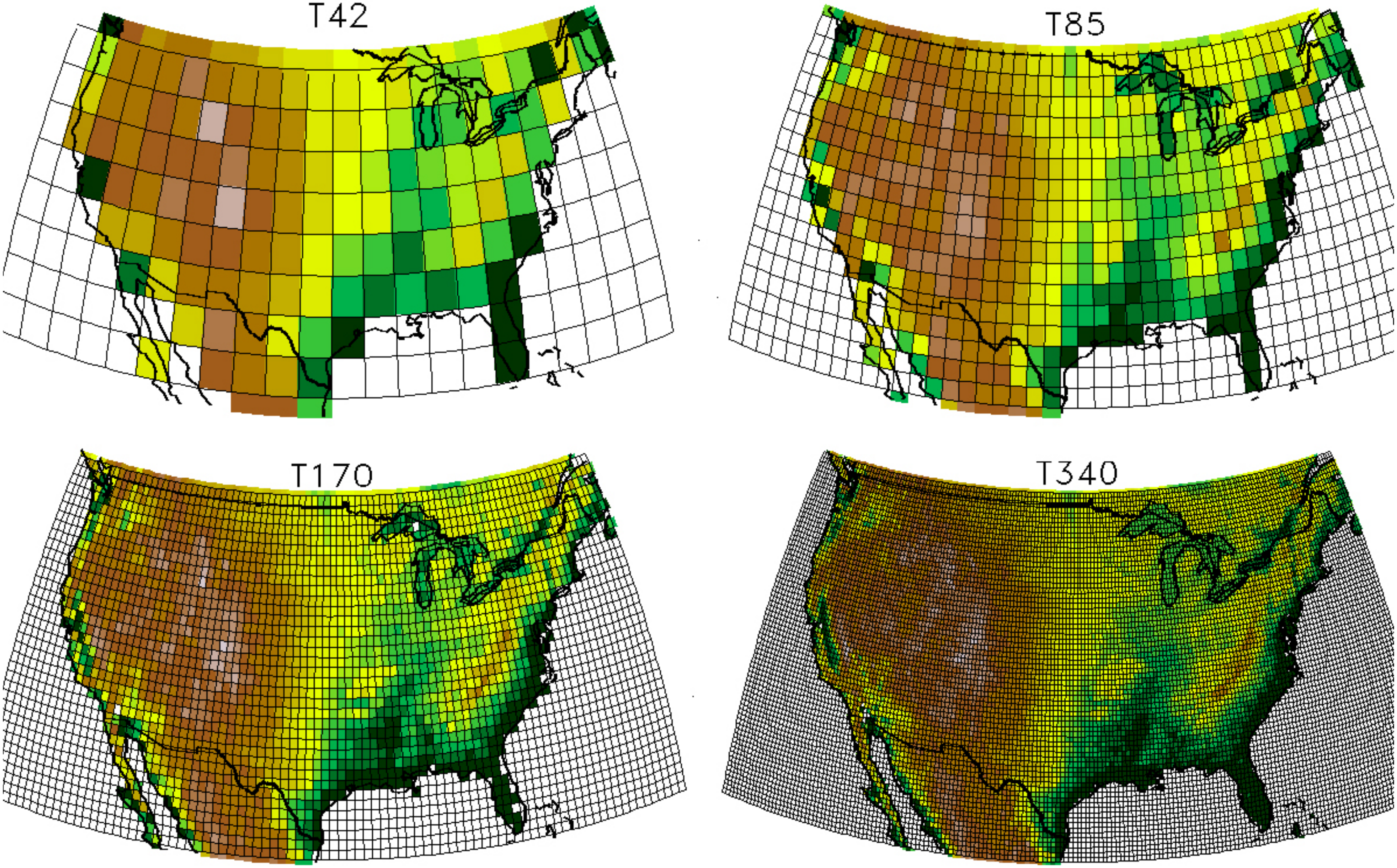
AR = "assessment report"

FAR = "first" AR, etc

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



Model Resolutions



Numerical Methods

- Vertical coordinates:
  - Topography introduces significant complication (pressure levels can disappear)
  - "Sigma coordinates": p/ps
    - Makes the surface a coordinate (not true in pressure coords)
- Models are trending towards higher vertical resolution
  - In recognition of the importance of the stratosphere on surface climate
  - CMIP3: Most around 25 vertical levels
  - GFDL AM3: 48 levels

Numerical Methods

- Since not all aspects of the numerical methods conserve energy, a correction is usually applied
  - Energy calculated before and after dynamics is called
  - Temperature multiplied by a constant everywhere to assure energy stays the same

Dynamical Core Key Points

- 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)

Next: Physics of AGCMs

- Climate models have some very complex parameterizations of physical processes
- We'll describe general ideas of how these are parameterized
- The history of some of the parameterizations
- And talk about simple ways to parameterize these effects as well

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

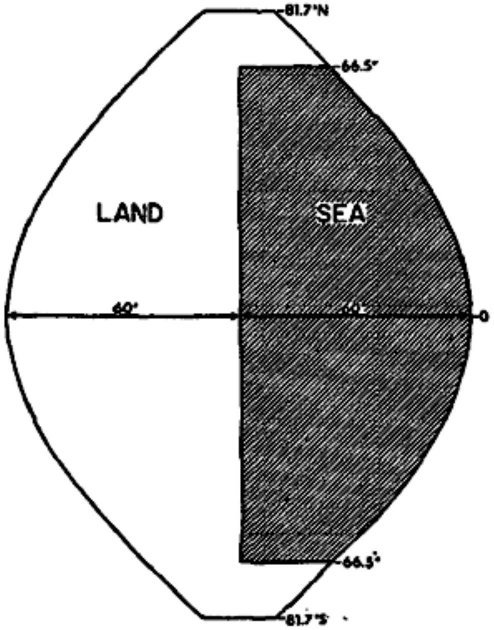


Fig. 1. Ocean-continent configuration of the model

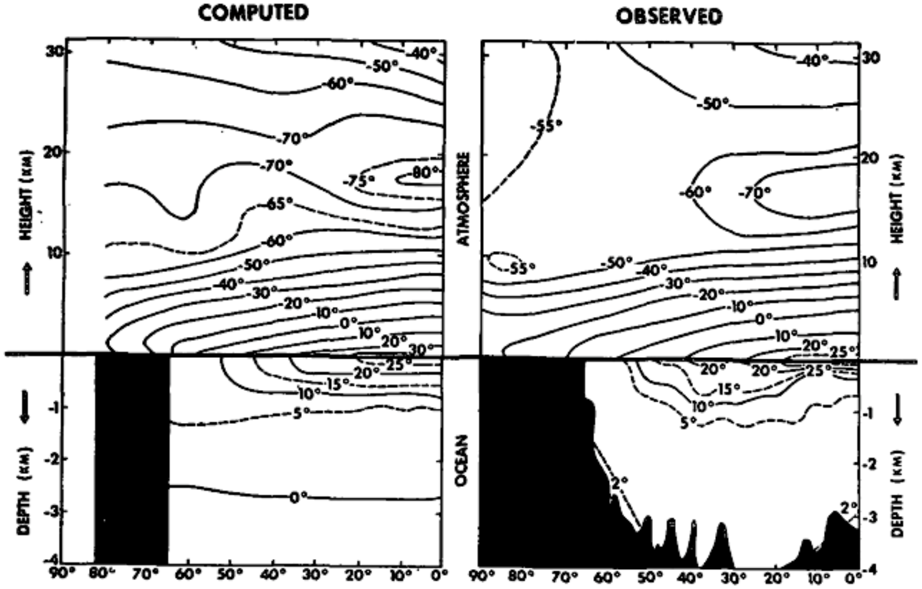


Fig. 2. Zonal mean temperature of the joint ocean-atmosphere system, left-hand side. This distribution, which is the average of two hemispheres, represents the time mean over two-sevenths of the period of the final stage of the time integration. The right-hand side shows the observed distribution in 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):

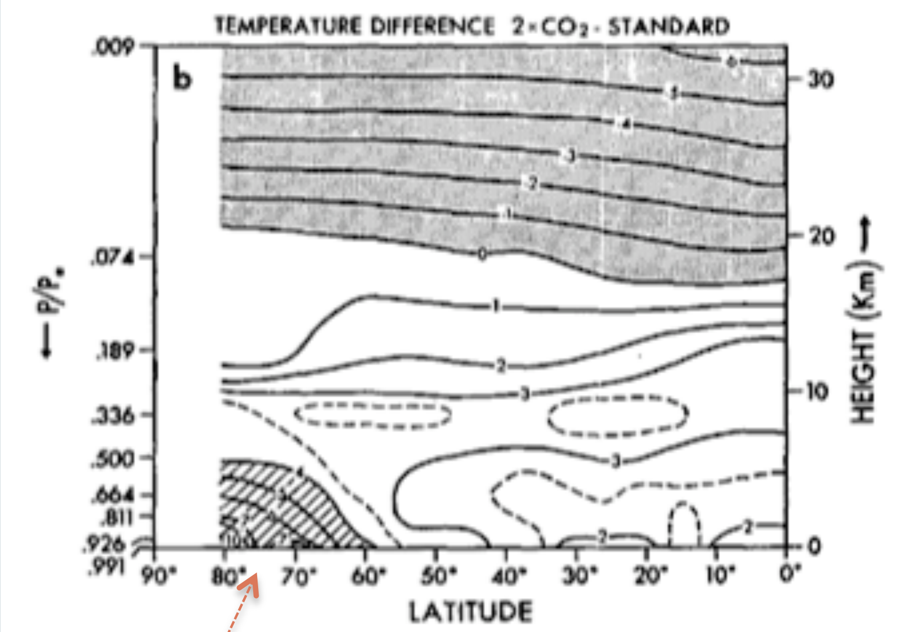


FIG. 4. Latitude-height distribution of the zonal mean temperature (K) for the standard case (a) and of the increase in zonal mean temperature (K) resulting from the doubling of CO_2 concentration (b). Stippling indicates a decrease in temperature.

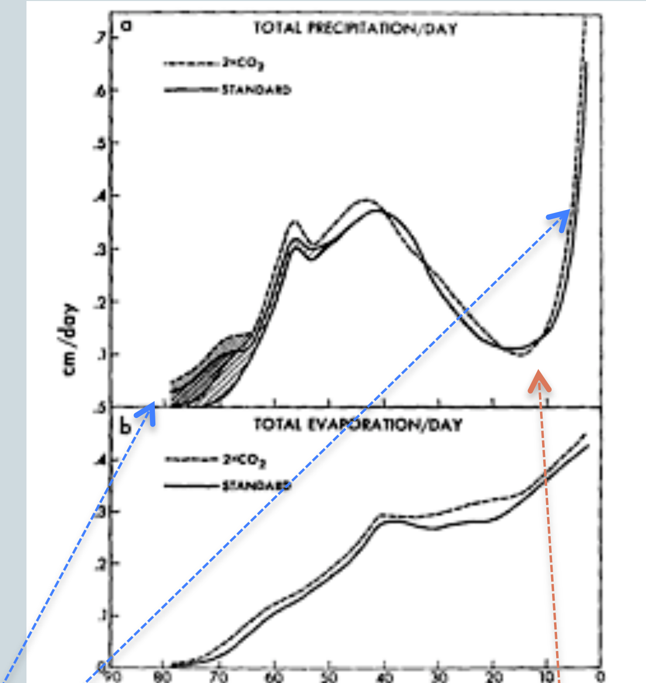


FIG. 7. Zonal mean rates of total precipitation, where shaded areas denote the rates of snowfall (a), and zonal mean rates of evaporation (b).

Polar amplification

Wet areas get wetter & subtropical drying

Other Early Manabe Studies

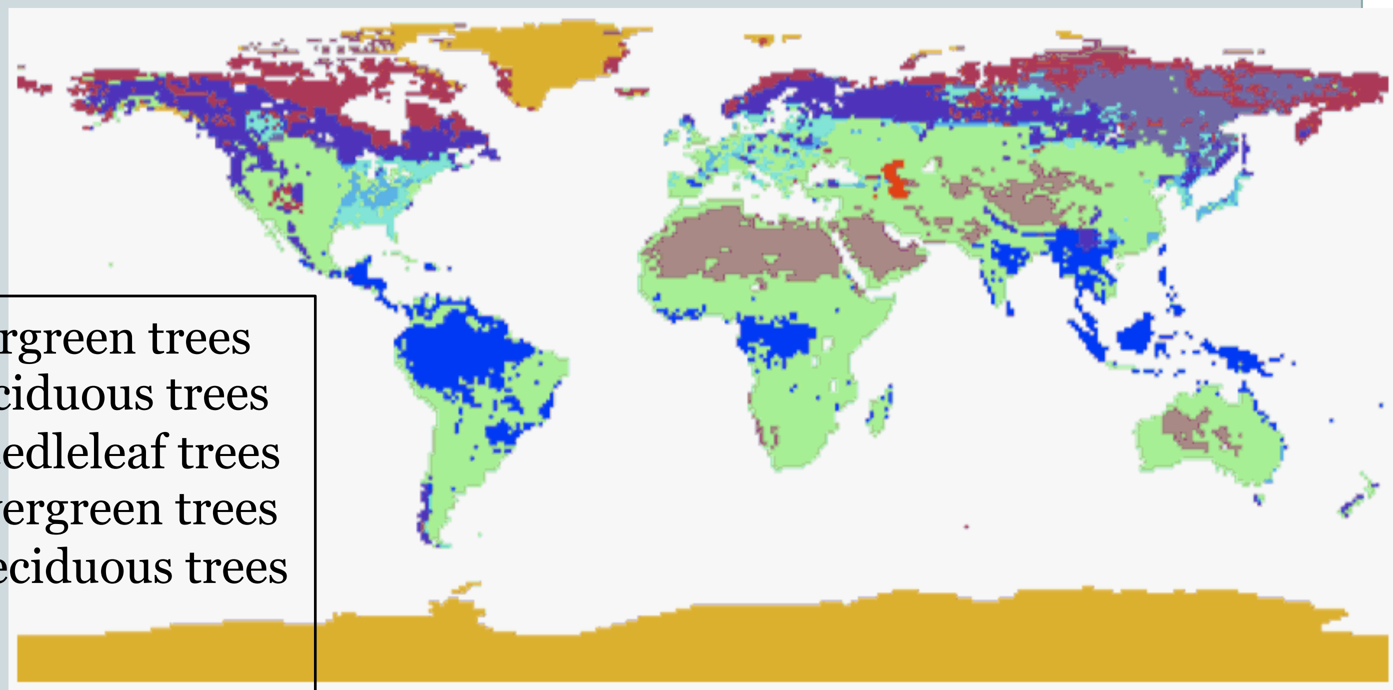
- I find these early modeling papers still really fascinating…
- Effect of ocean circulation on climate:
  - Turn off ocean model
- Effect of moisture:
  - Turn off latent heating
- Effect of mountains:
  - Bulldoze all topography
- Effect of changing **solar radiation**, doubling **CO_2**, **ice sheets**,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

Present Day GCMs

- Next we'll discuss state-of-the-art GCMs
  - CMIP = coupled model intercomparison project
    - CMIP3: for IPCC 4th assessment report
    - CMIP5: for IPCC 5th assessment report
- But first, a list of things the CMIP3 models **didn't even try** to do:
  - Carbon cycle
  - Dynamic vegetation

Vegetation Types

- Land types:



1: (BE) broadleaf evergreen trees
2: (BD) broadleaf deciduous trees
3: (BN) broadleaf/needleleaf trees
4: (NE) needleleaf evergreen trees
5: (ND) needleleaf deciduous trees
6: (G) grassland
7: (D) desert
8: (T) tundra
9: (A) agriculture
10: (I) ice
11: (L) lake

What Models Don't Parameterize (yet)

- But first, a list of things the CMIP3 GCMs didn't even try to do:
  - Carbon cycle
    - They used prescribed CO2 distributions
  - Dynamic vegetation
    - Prescribed to be current climate values
  - Dynamic ice sheet models
    - Prescribed to current size
  - Interactive chemistry (e.g., ozone chemistry)
    - Prescribed ozone hole
  - Aerosol effects on cloud formation
    - Not often considered

"Earth system models" are trying to parameterize many of these

Physical Parameterizations

- We'll discuss the following physical parameterizations:
  - Radiative transfer
  - Convection
  - Clouds
  - Surface fluxes/boundary layer schemes

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
  - GFDL AM2 model uses 18 bands of solar radiation
  - Aerosols are sea salt, dust, black & organic carbon, and sulfate aerosols
    - Aerosol and chemical concentrations are prescribed as monthly mean climatologies

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 ~50% of the total CPU usage is running the radiation code
  - Often not called every time step
  - Faster implementations such as neural networks have been developed

Moist convection schemes

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

Ocean is heated from above: key difference between atmosphere and ocean!

Ocean temps across Pacific

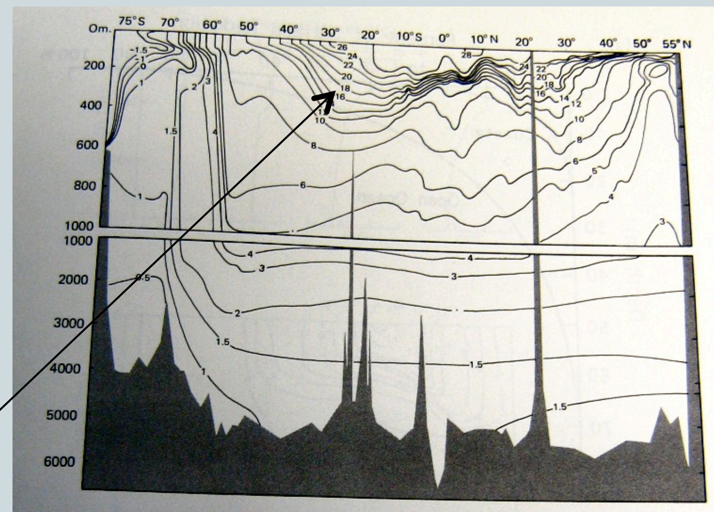


Figure 1.3 Temperature along approximately 160° W in the Pacific from the Antarctic to Alaska. Vertical exaggeration is 5.5×10^3 in the upper 1000 m and 1.11×10^3 below 1000 m. (After Reid, *Intermediate Waters of the Pacific Ocean*, The John Hopkins Oceanography Studies, The John Hopkins Press, 1965.)

Warm ocean water is confined within a few 100 meters of the surface

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 tracer advection)
  - 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
  - Derivation (on board):
    - First dry convective adjustment, then conditional instability & moist convective adjustment

Moist convection schemes

- Simplified Betts-Miller convection scheme:
  - Relax temperature to moist adiabat
  - Relax humidity to some profile
  - This won't conserve energy though (heating must equal drying): adjust so it does
  - But then negative precipitation can occur: "shallow (nonprecipitating) convection"

Moist convection schemes

- Most CMIP3/5 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

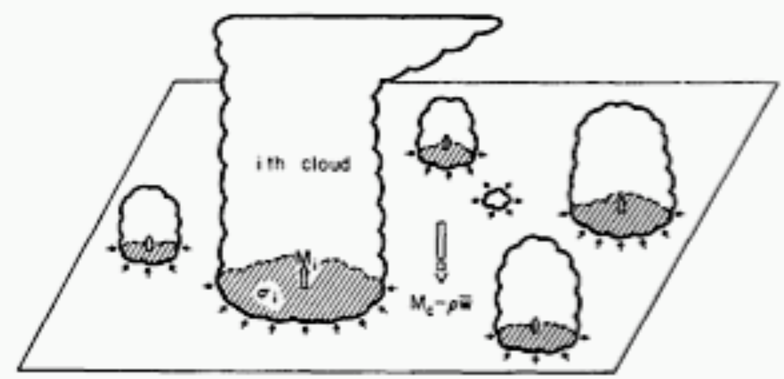
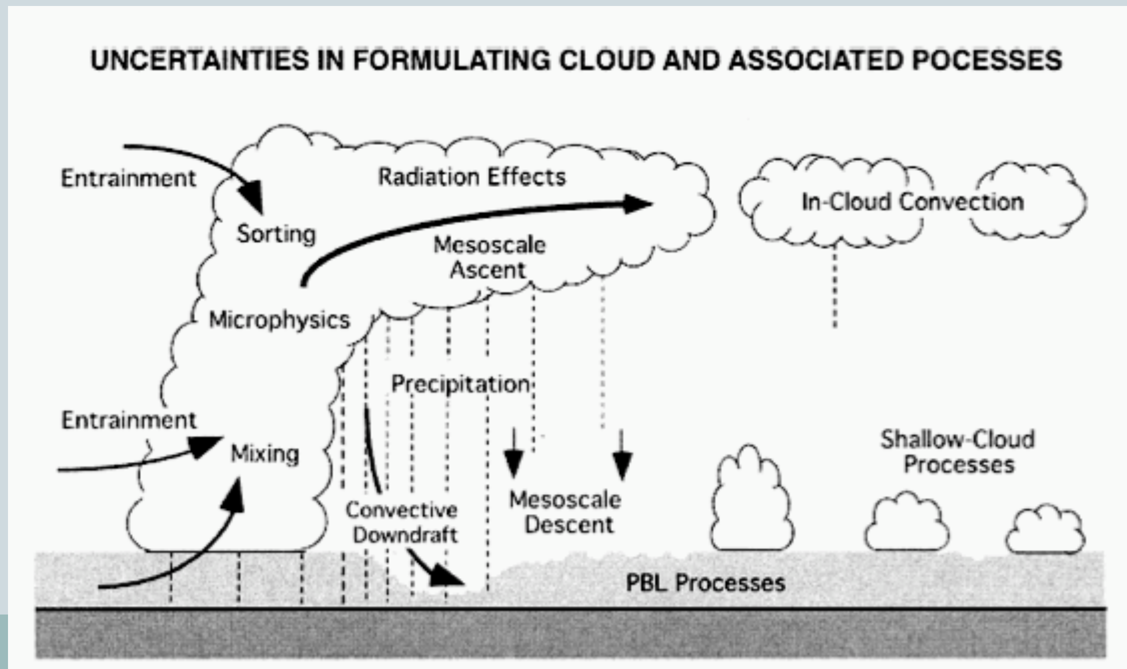


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

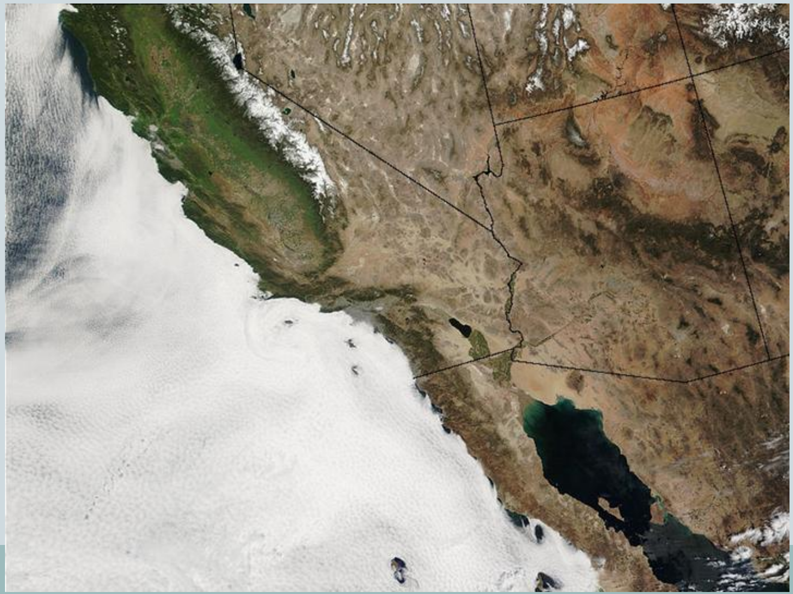
Moist convection schemes

- "Mass flux" schemes:
  - Convective intensity determined by "quasi-equilibrium" of CAPE (*closure*)
  - Easy to trigger convection in these schemes (get weak, steady convection)



Cloud schemes

- Cloud interactions are the most uncertain process in GCMs
  - Lead to the largest differences among 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 = sensible heat flux = 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

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

Surface roughness values for different surfaces

Surface Flux Parameterization (continued)

- Monin-Obukhov theory for drag coefficient C
  - SH = C |v| (T – Ts)
  - Neutral drag coefficient: just a function of surface roughness & von Karman coefficient
  - Under stable or unstable conditions: function of Richardson number
    - C is larger under unstable conditions
    - C gets smaller (and approaches zero) under stable conditions
  - Stable side drag coefficients are currently pretty uncertain

Surface Flux Parameterization (continued)

- Monin-Obukhov theory for drag coefficient C
  - GCMs have their lowest layers very close to the surface (typically within 20 m)
    - So Monin-Obukhov theory can be used to calculate drag coeffs

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 CMIP5)
  - This scheme is a single-plume mass flux scheme
  - Other ways:
    - Diffusive schemes
    - Adjustment schemes
- Cumulus momentum transport
- Gravity wave drag
  - Momentum fluxes due to gravity waves near topography

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

CMIP3 GCM Summary

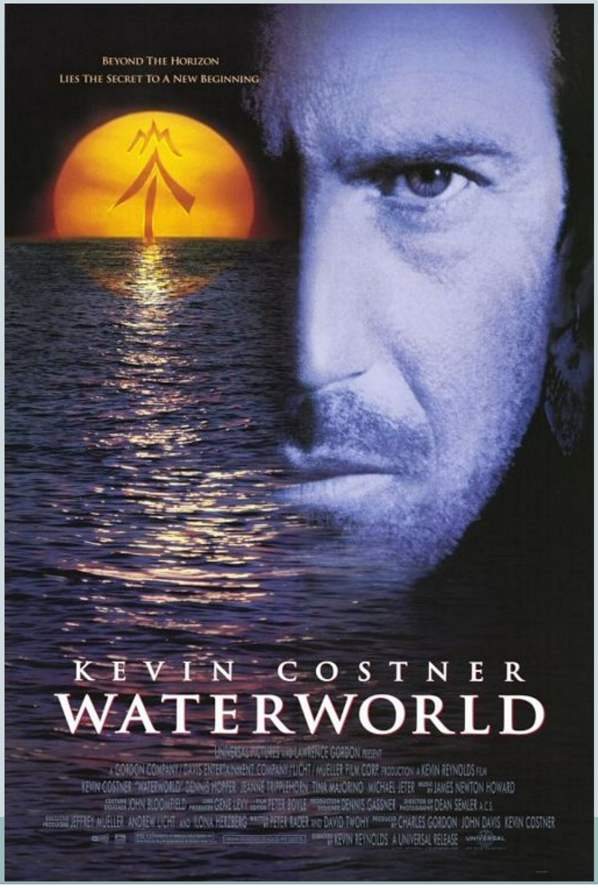
- Of 24 models in the CMIP3 archive:
  - 1 is non-hydrostatic (Had-GEM)
  - 4 have aerosol indirect effect (on clouds)
  - 4 have some kind of chemistry
    - 3 of these are sulfate aerosol production from SO2
    - 1 has simplified ozone chemistry (CNRM)
    - 1 has GHG (methane, nitrous, CFC-11 and CFC-12) concentration modifications from chemistry (NCAR CCSM3)
  - 0 have dynamic vegetation, carbon cycle, or dynamic ice sheets
- Whew!

Simplified physics GCMs

- There is 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



Simplified GCM Experiments

- See Held (2005, BAMS) for biological analogy:
  - In biology, hierarchy occurs naturally: bacteria, fruit flies, mice, etc
  - This has allowed rapid progress in understanding molecular biology, the genome, etc
- In atmospheric science, we have to create our own hierarchies
  - Have to additionally argue that the simplified models are worth studying though

An Idealized GCM

- Held-Suarez model (1994, BAMS)
- Radiation and convection parameterized as

$$Q = -k(T - T_{eq})$$

Warmer than T_{eq} => cooling

Cooler than T_{eq} => warming

That's it

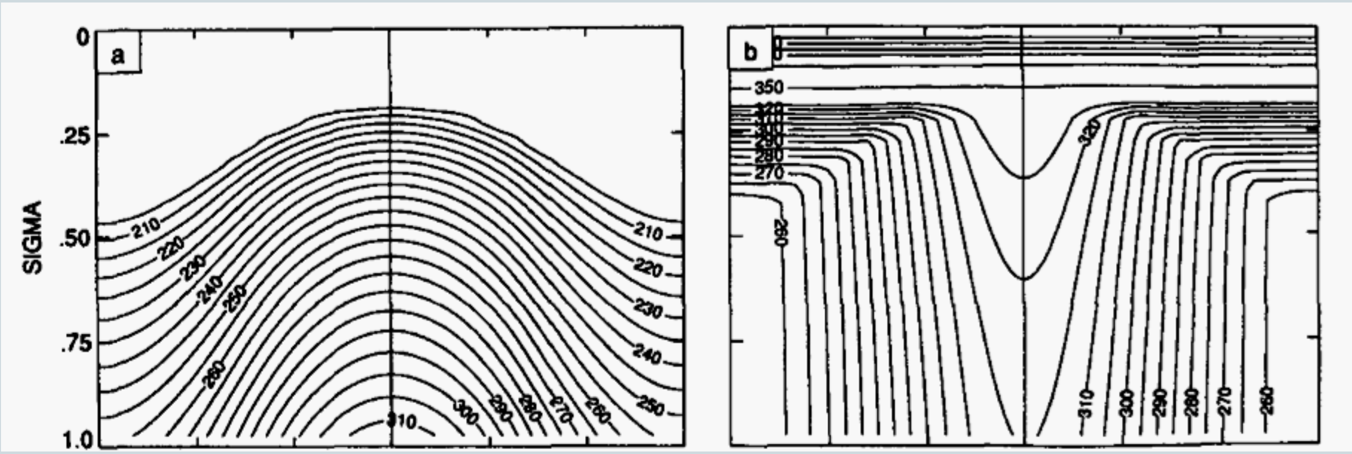
How to parameterize equilibrium temp?

- Equilibrium temperature = what would happen if dynamics didn't act
- Radiation and convection

The Held-Suarez Dry GCM

- Equilibrium distribution is what radiation and convection would produce without dynamics

Temperature | Potential Temperature



Latitude | Latitude

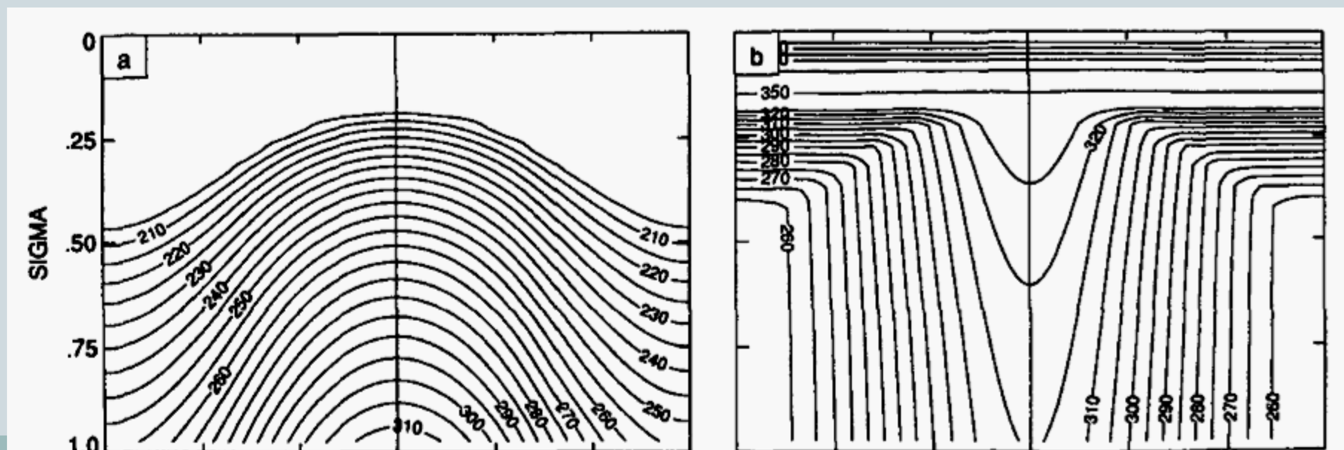
Equator is hotter than observed
Pole is colder than observed
Constant stratospheric temperature

Roughly moist adiabatic vertical structure

The Held-Suarez Dry GCM

- Radiation parameters:
  - Horizontal gradient of radiative equilibrium: 60 K
  - Vertical gradient of potential temperature at the equator: 10 K
  - Free tropospheric relaxation time: 40 days
  - Boundary layer relaxation time: 4 days at surface

Temperature　　　　Potential Temperature



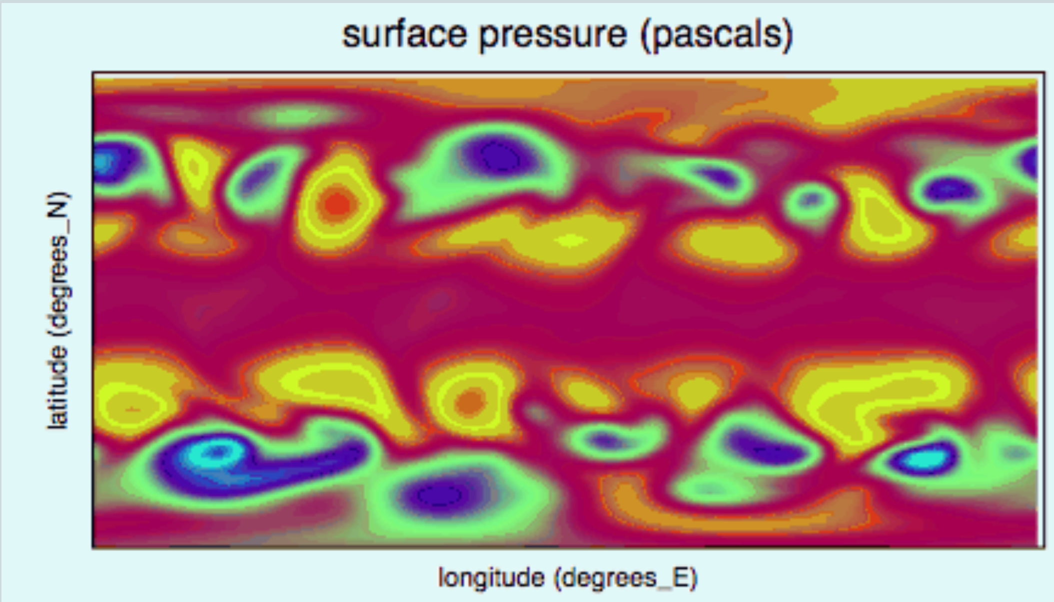
Latitude　　　　Latitude

The Held-Suarez Dry GCM

- Strong damping in the boundary layer is required to prevent a strong inversion from occurring
- Also friction within boundary layer:
  - Frictional damping time: 1 day at surface
  - Boundary layer depth: up to 700 hPa
- Other physical parameters:
  - Mean surface pressure = 1000 hPa, g = 9.8 m/s2
  - Dry air constants: R = 287.04 J/kg, cp = 1004 J/kg
  - a = 6.371 x 10^6 m
  - Omega = 7.292 x 10^-5 (s^-1)

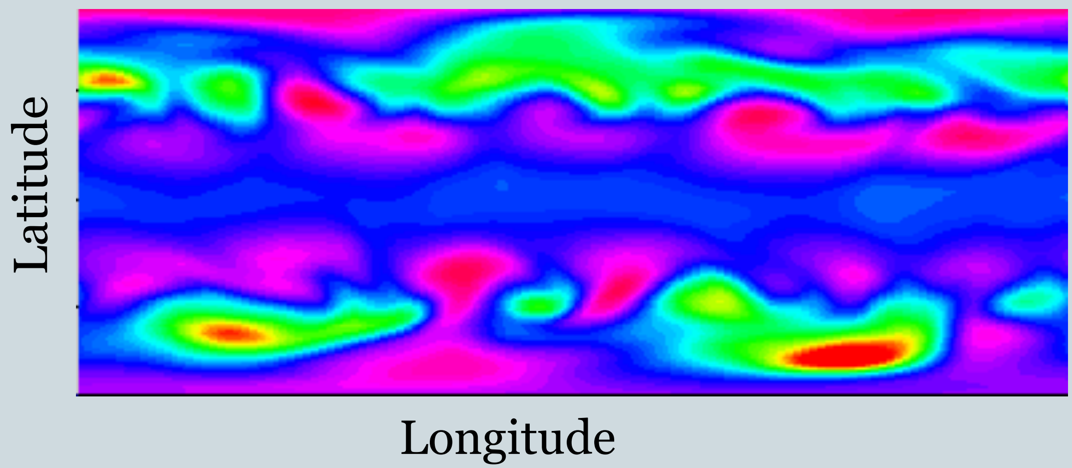
The Held-Suarez Dry GCM

- Instantaneous surface pressure:



The Held-Suarez Dry GCM

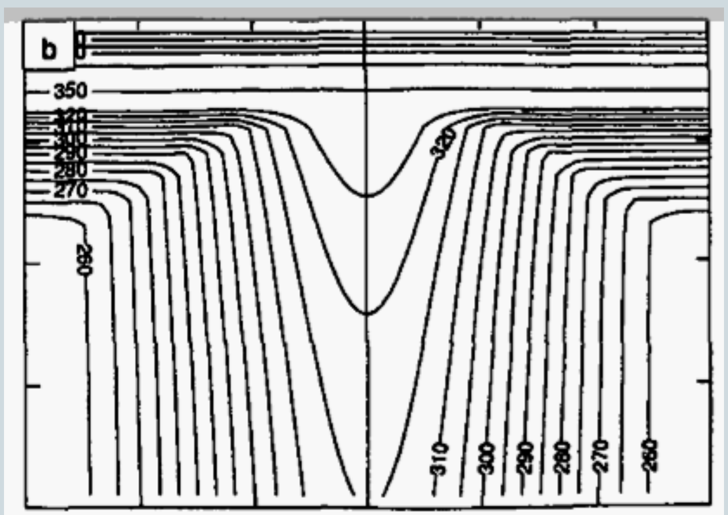
- Instantaneous surface pressure:



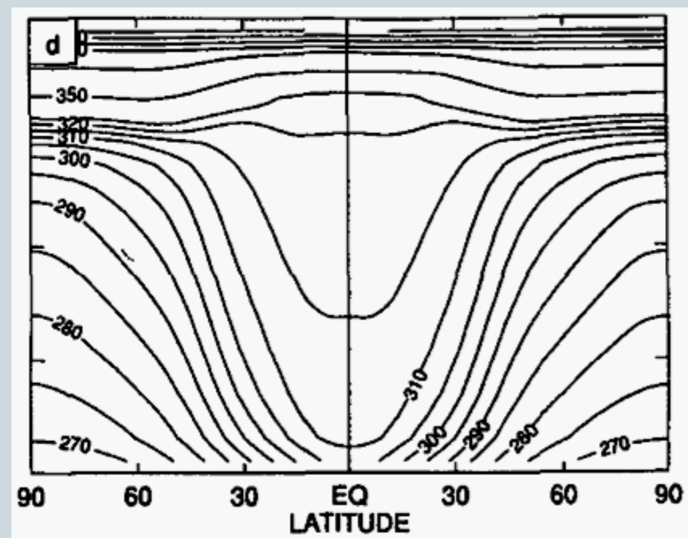
The Held-Suarez Dry GCM

- Potential temperature climatology

θ_{eq}



θ

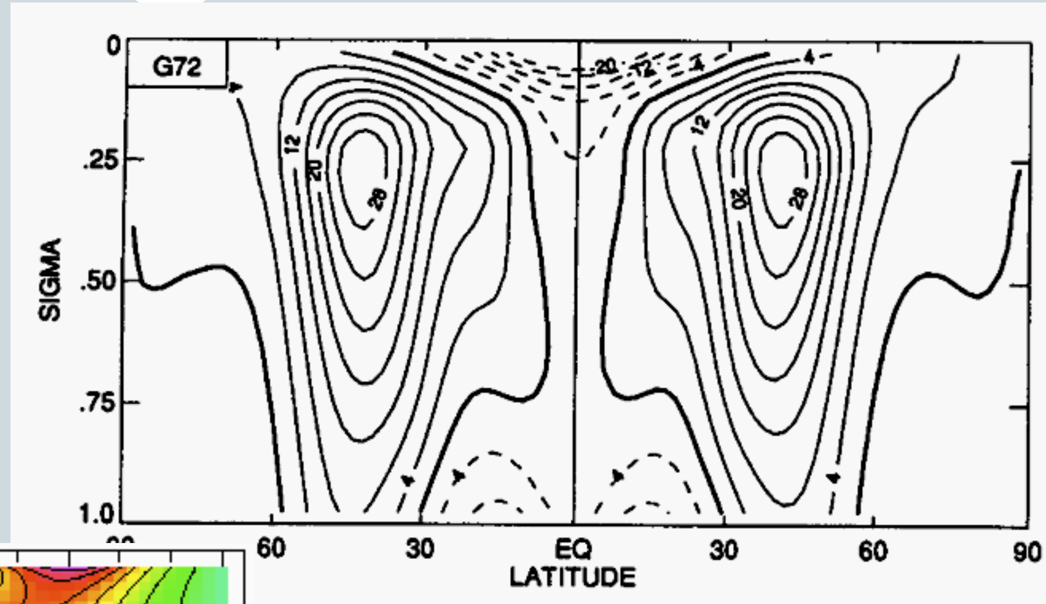


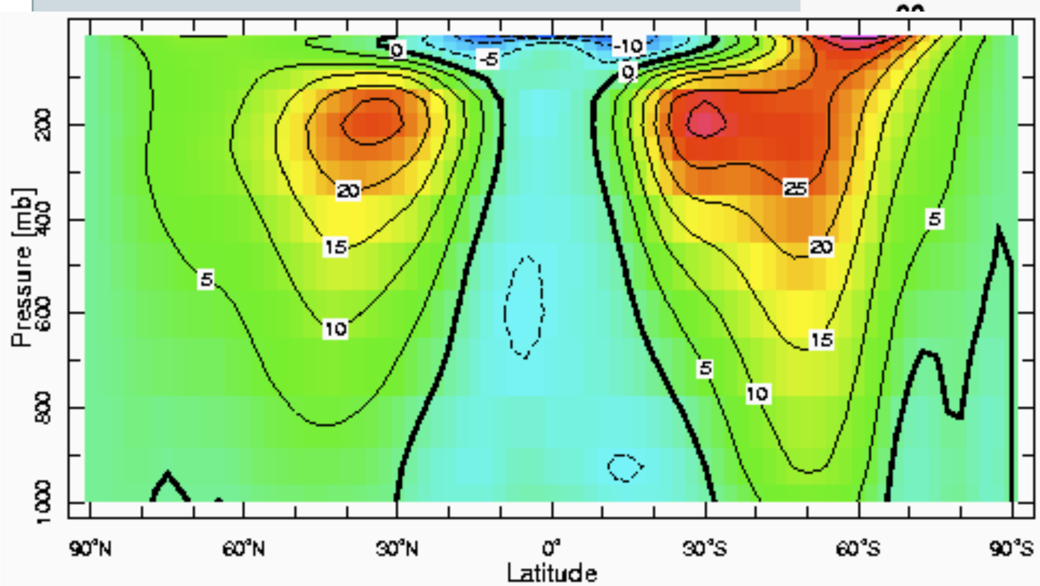
Circulation transports heat poleward and upward

From Held and Suarez (1994)

The Held-Suarez Dry GCM

- Zonal winds versus observations:





The Held-Suarez Dry GCM

- Held-Suarez model has been used to study:
  - Annular modes of extratropical variability (Gerber and Vallis)
  - Sensitivity of extratropical circulation to tropopause height (Williams; Lorenz and DeWeaver)
  - Winds in equatorial troposphere (Kraucunas and Hartmann)
  - Stratosphere-troposphere coupling (Reichler, Kushner and Polvani)

Held-Suarez Extensions

- More realistic stratospheric winds (Polvani and Kushner)
- Statically unstable reference profile + convection scheme (Schneider)
- Perpetual austral winter (Ring and Plumb)

Held-Suarez Model

- Strengths:
  - Remarkably simple formulation
  - Gives realistic circulation in many aspects
- Weaknesses:
  - No surface fluxes, no possibility of land-sea contrast
  - Says nothing about precipitation, clouds, ice, etc
  - Not heated from below like real atmosphere
  - Tropics are very quiet
  - Diabatic processes are weak
  - Baroclinic eddies tend to do everything

Introduction to Moisture in the Atmosphere

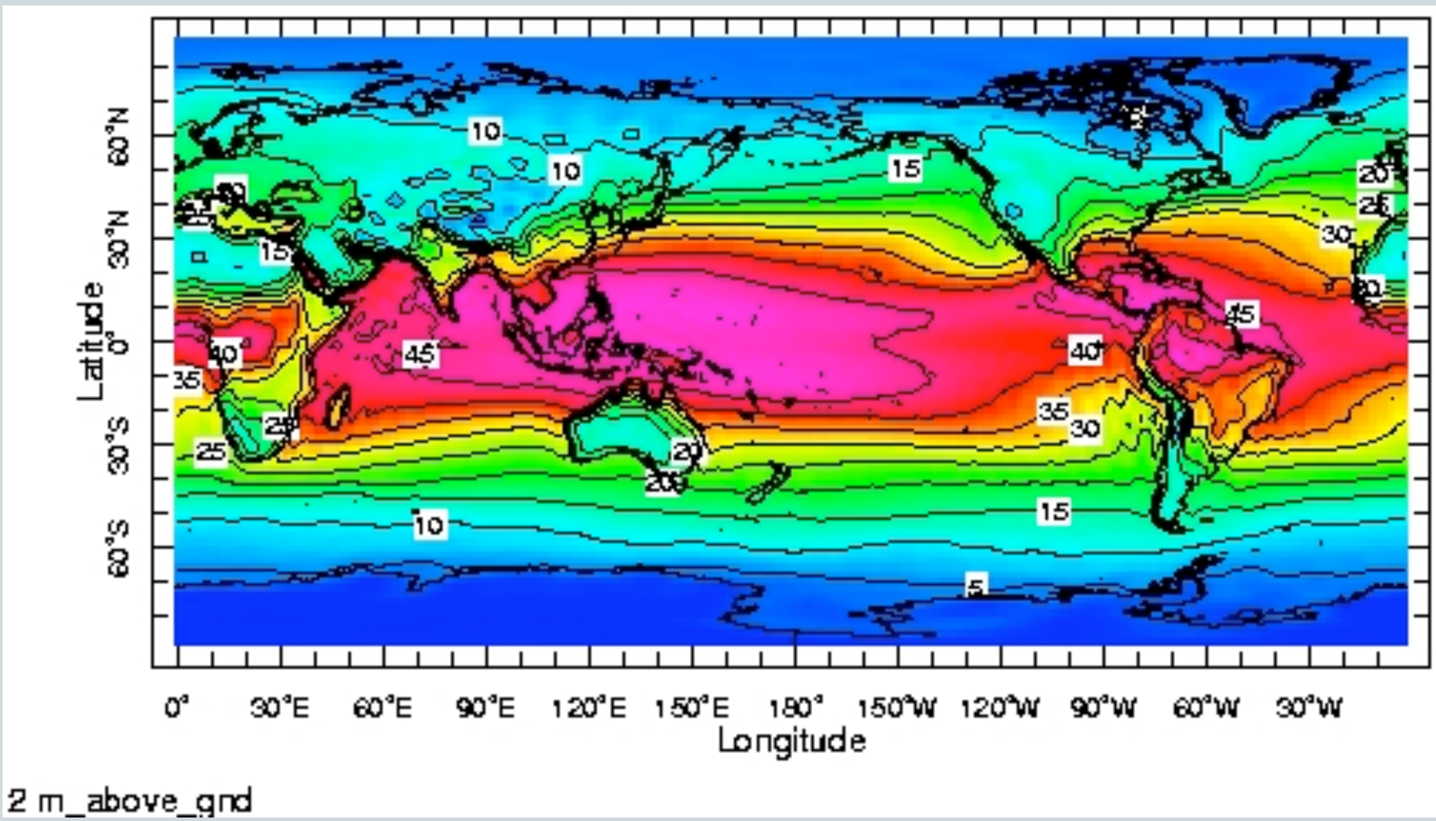
- Saturation vapor pressure e_s is a function of temperature T in the Clausius-Clapeyron equation:

$$e_s = e_{s0}\ exp\left(-\frac{L}{R_V}\left(T^{-1} - T_0^{-1}\right)\right)$$

- Roughly exponential for temperatures on Earth
  - Warmer air can hold much more moisture
  - 7% per K increase in temperature
- Condensation of water vapor can be huge heat source on Earth
  - Typical tropical lower tropospheric moisture content: 45 K

Introduction to Moisture in the Atmosphere

- Surface specific humidity, measured in Kelvin:

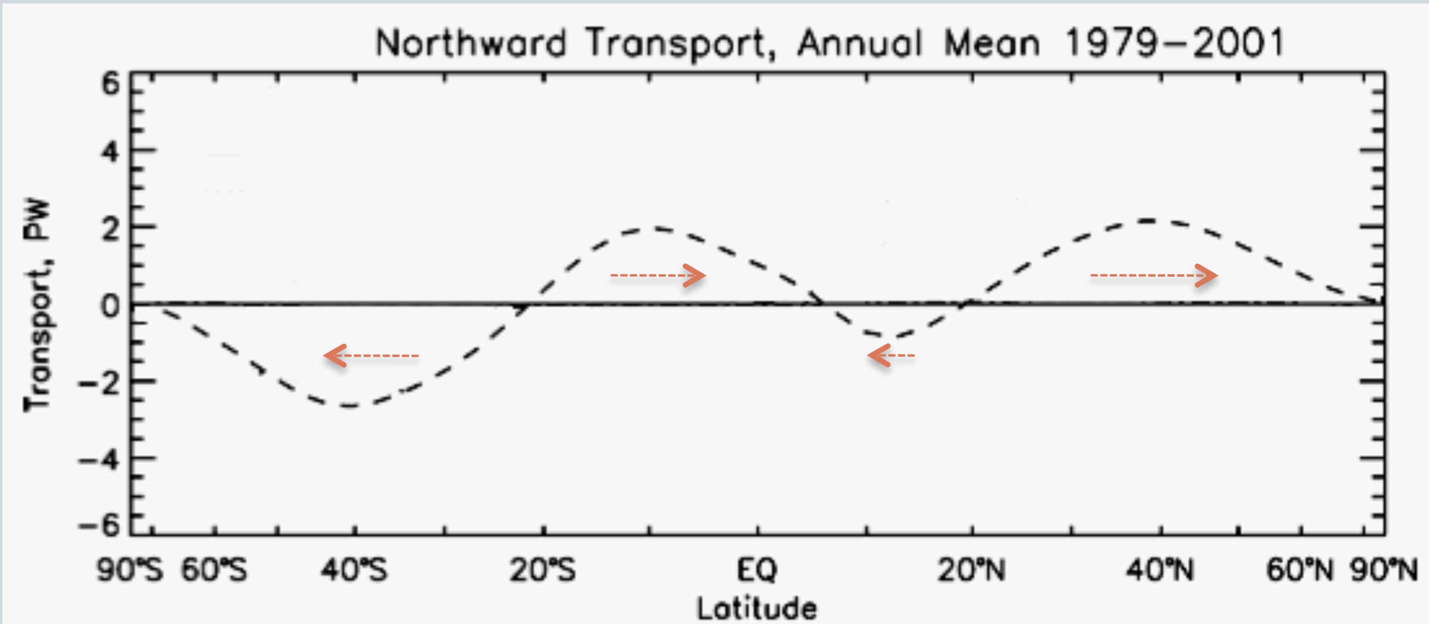


$$\frac{Lq}{c_p}$$

Source: NCEP Reanalysis

Introduction to Moisture in the Atmosphere

- Moisture flux in the atmosphere:

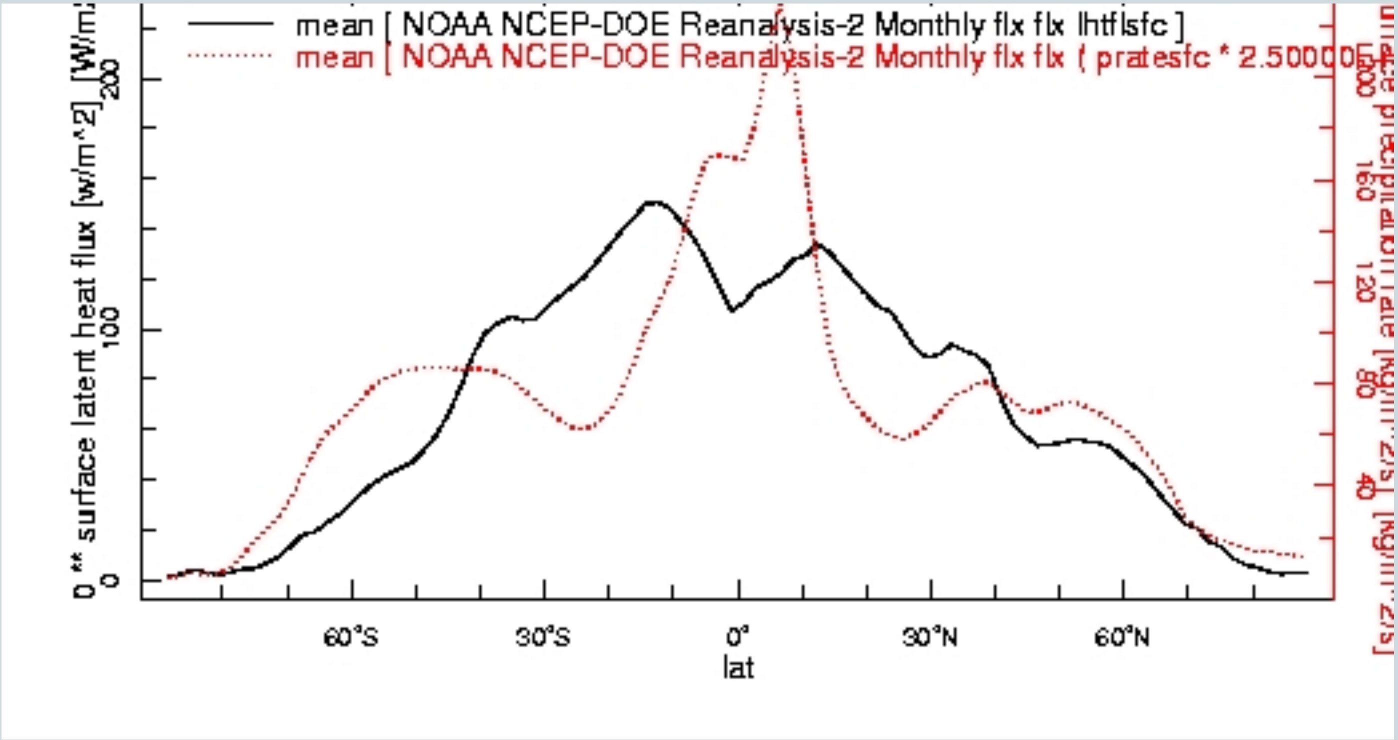


  - Equatorward moisture flux in tropics
  - Poleward moisture flux in midlatitudes

Source: Trenberth and Stepaniak (2003)

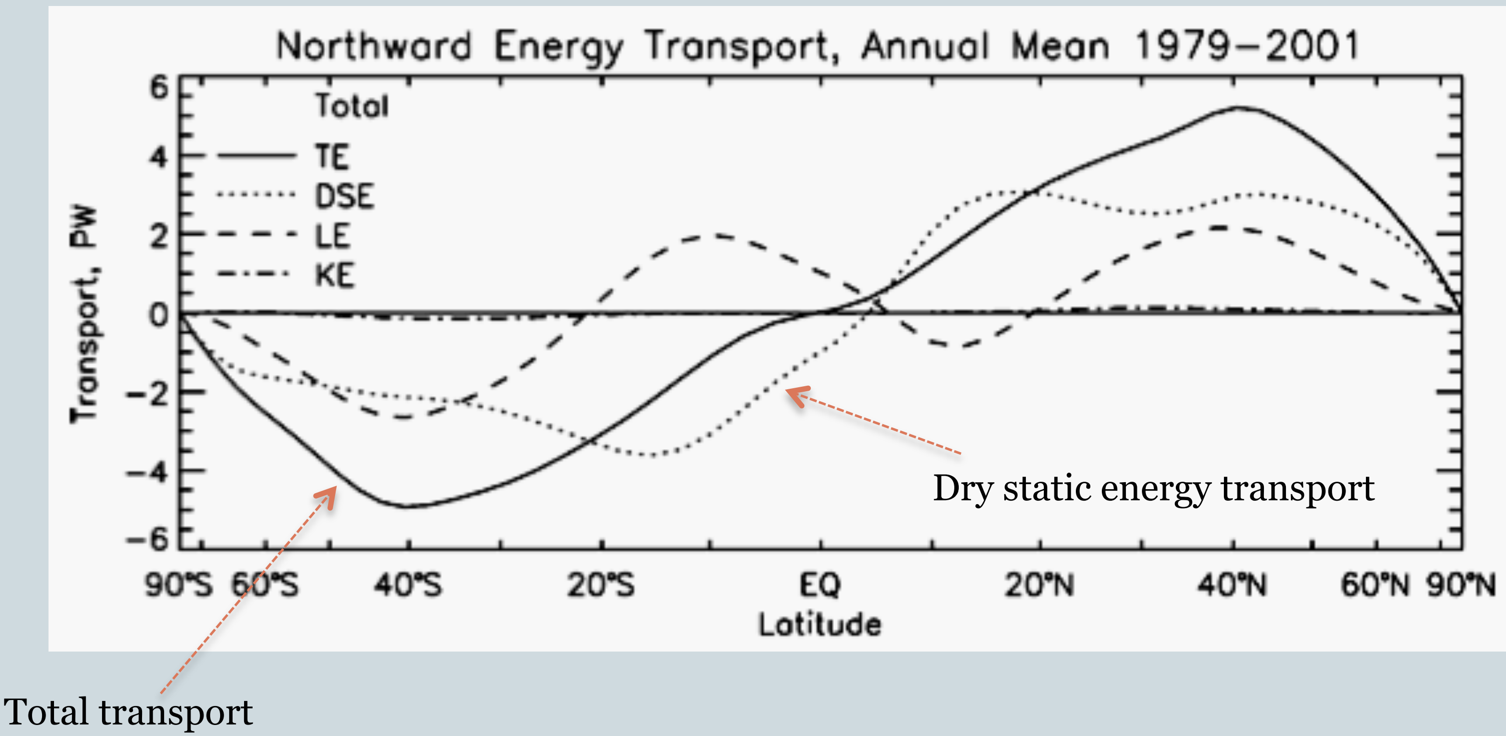
Introduction to Moisture in the Atmosphere

- Precipitation and evaporation:



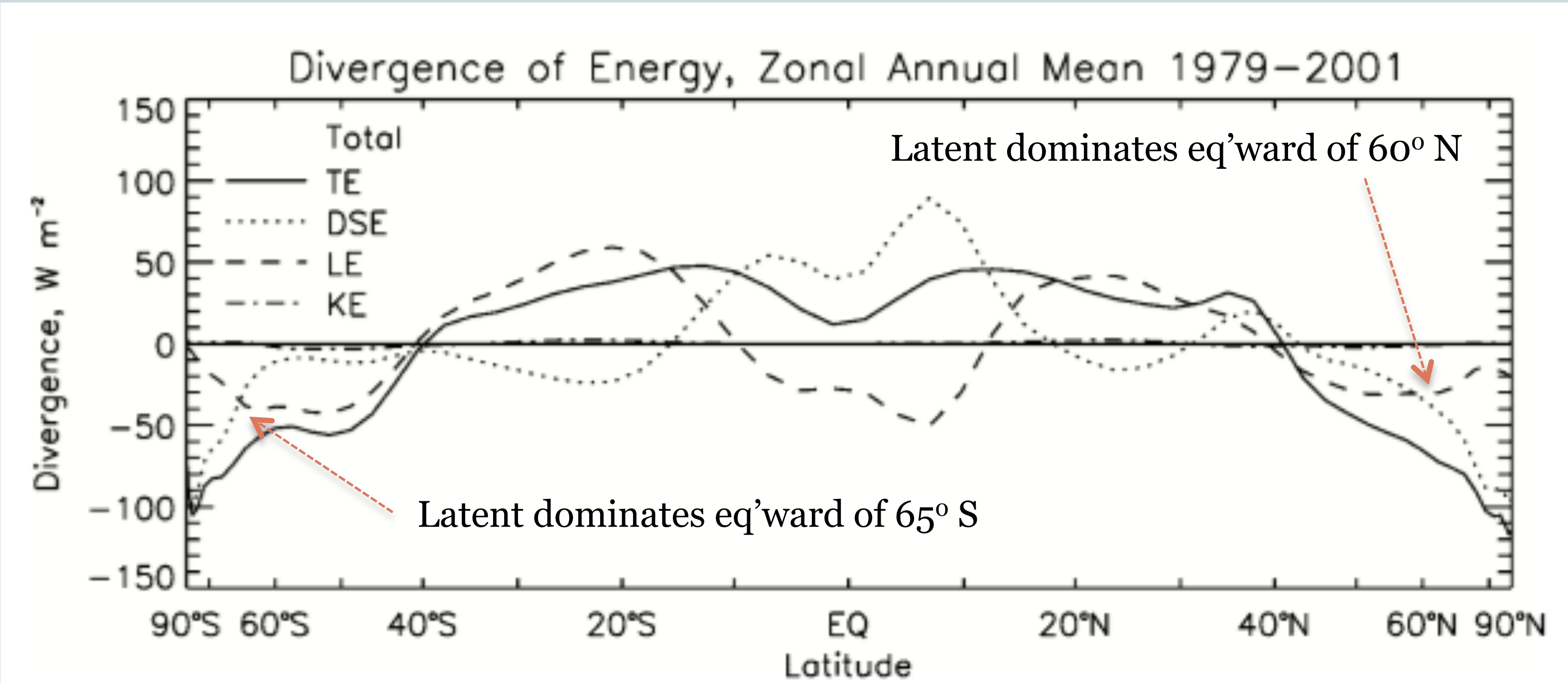
Introduction to Moisture in the Atmosphere

- Effect of moisture on energy transports:
  - Comparison with dry flux:



Introduction to Moisture in the Atmosphere

- Components of **divergence of** energy transport:

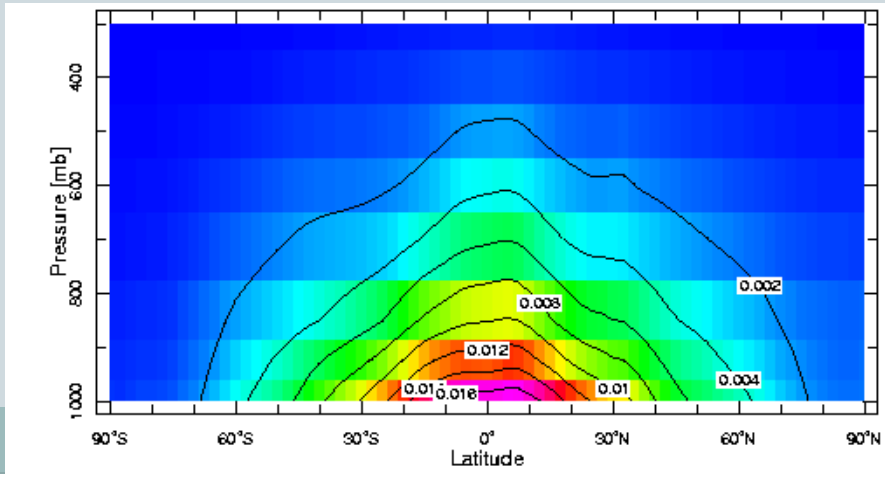


  - Moisture divergence dominates dry throughout the midlatitudes

Source: Trenberth and Stepaniak (2003)

Introduction to Moisture in the Atmosphere

- Moisture is concentrated in the lower levels of the atmosphere
  - Upper atmosphere is too cold to hold much water vapor
- Freezing is also associated with latent heat release
  - It's a significantly smaller heat source though:
    - Latent heat of vaporization: 2.5 x 10^6 J/kg
    - Latent heat of fusion: 3.3 x 10^5 J/kg



Zonal mean moisture content

Water Vapor and Global Warming

- With global warming, atmospheric moisture content will increase
  - 20% increase with 3 K global temperature increase
- What effects will the increased moisture content have on the general circulation of the atmosphere?
  - Motivation for developing a simplified moist GCM

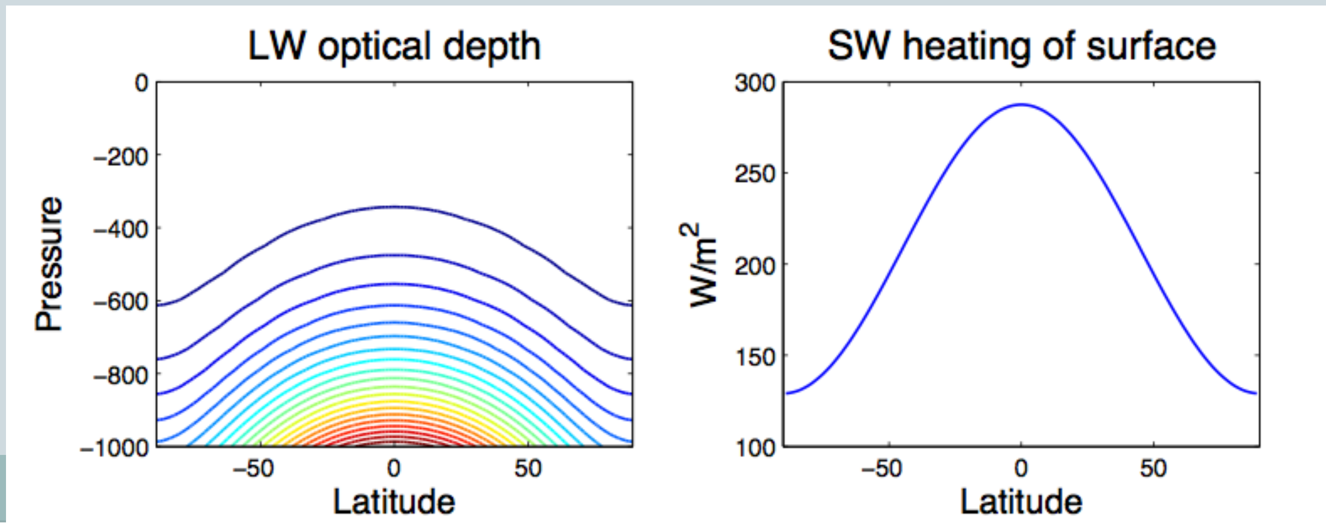
GRaM: An Idealized Moist GCM

- **G**ray **Ra**diation **M**oist GCM
  - Most GCMs have a metric ton of physics, but you can get a long way with just a GRaM!
- Primitive equations
- Gray radiative transfer
  - Water vapor, cloud, & other radiative feedbacks suppressed
  - Radiative fluxes only a function of temperature
- Aquaplanet surface (ocean-covered Earth)
  - Slab mixed layer
  - Zonally symmetric
- Simplified Monin-Obukhov surface fluxes
- K-profile boundary layer scheme
- Simple convection schemes
  - Grid-scale condensation or simplified Betts-Miller scheme

See Frierson, Held & Zurita-Gotor 2006 for details

Gray radiation

- Upward and downward streams
- Prescribed optical depths for longwave radiation
  - Designed to look roughly like water vapor
- Idealized shortwave radiation profile
  - Based on idealized profile (Legendre polynomial)
  - All SW goes into the surface (in simplest version of set-up)

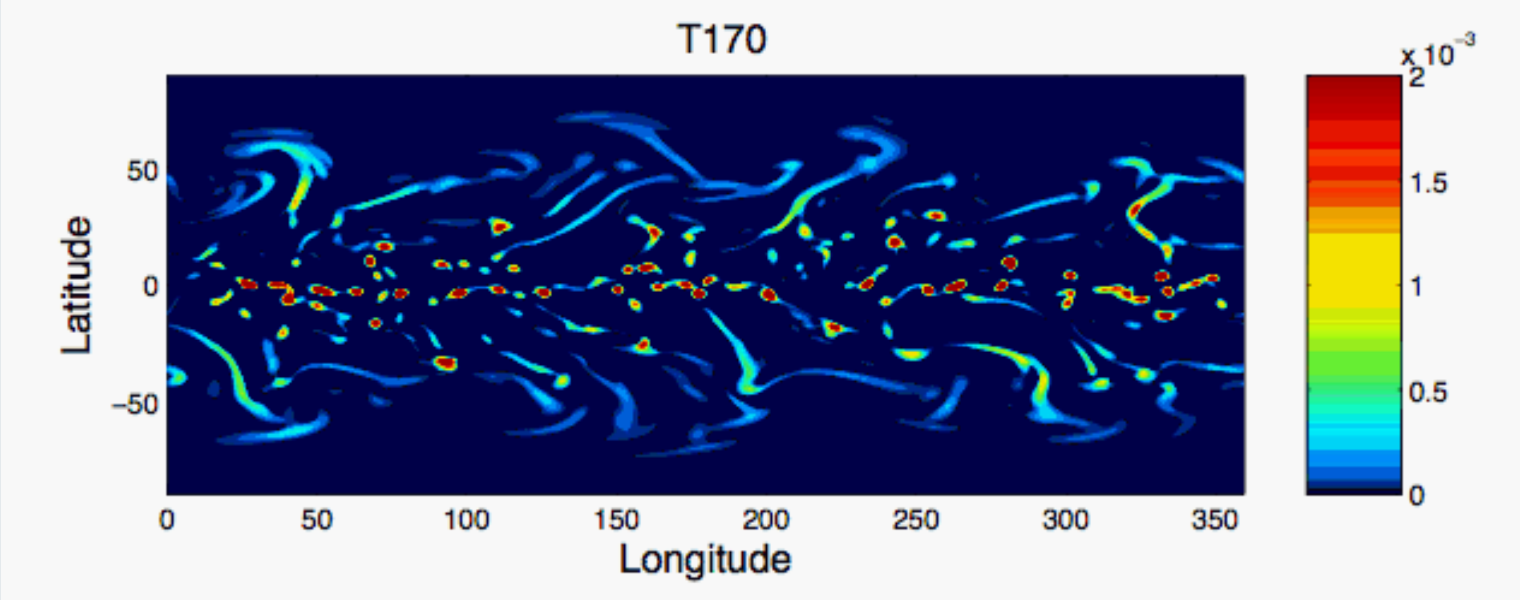


Slab mixed layer ocean

- Specify a heat capacity and solve energy equation
  - Heat capacity is always equivalent to a depth of water (e.g., 2.5e7 J/m2/K is equivalent to 60 m)
- A nice alternative to fixed SST
  - Fixed SST doesn't respect energy conservation
    - E.g., faster surface winds cause more evaporation, but surface doesn't cool in response
- SST biases can develop though (obviously)
  - Q-flux: a prescribed surface heat flux designed to simulate ocean heat transport divergence
    - Also used to correct model biases in practice though

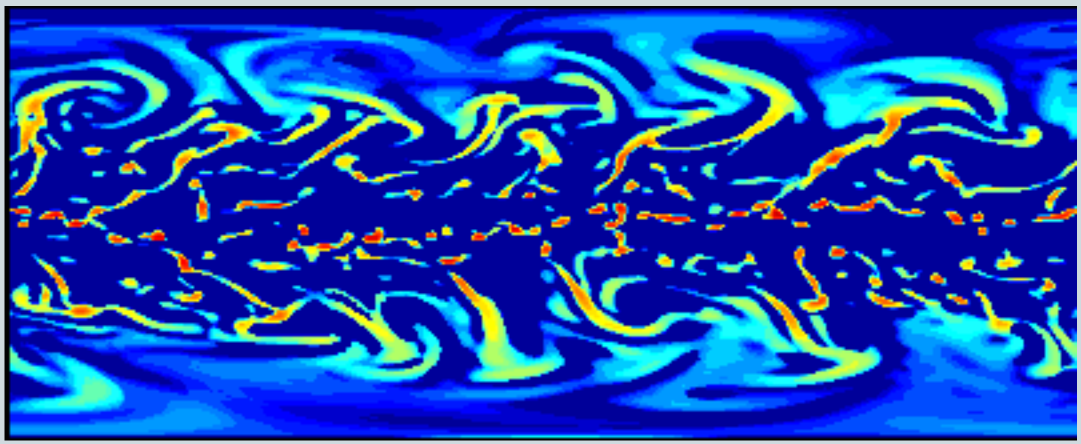
Model Climatology

- Instantaneous precipitation



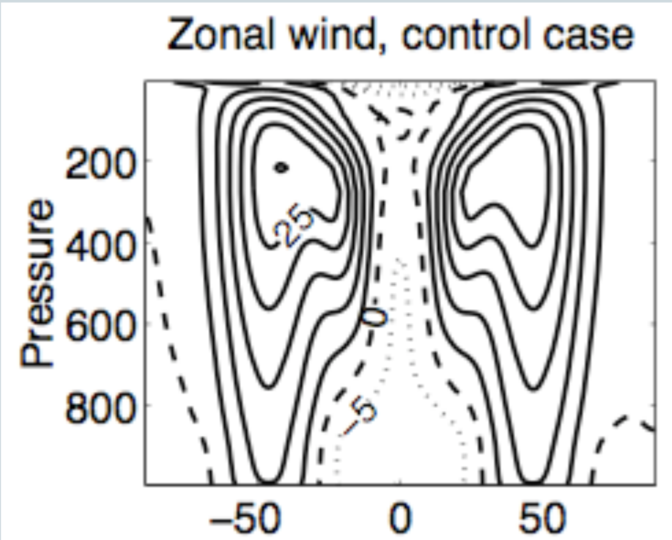
Model Climatology

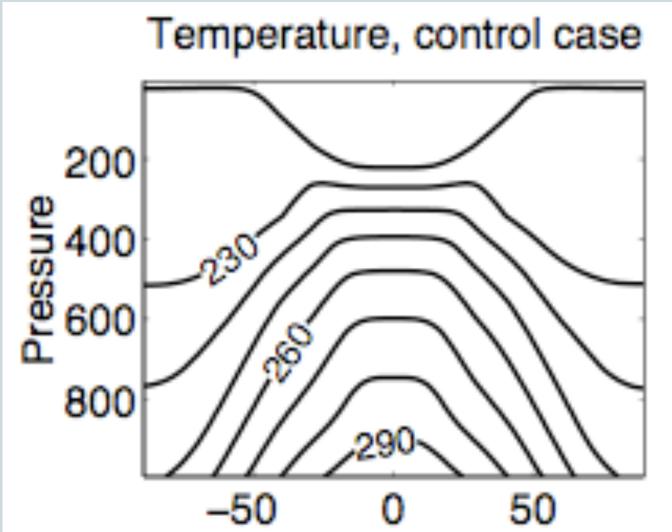
- Instantaneous precipitation



Model Climatology

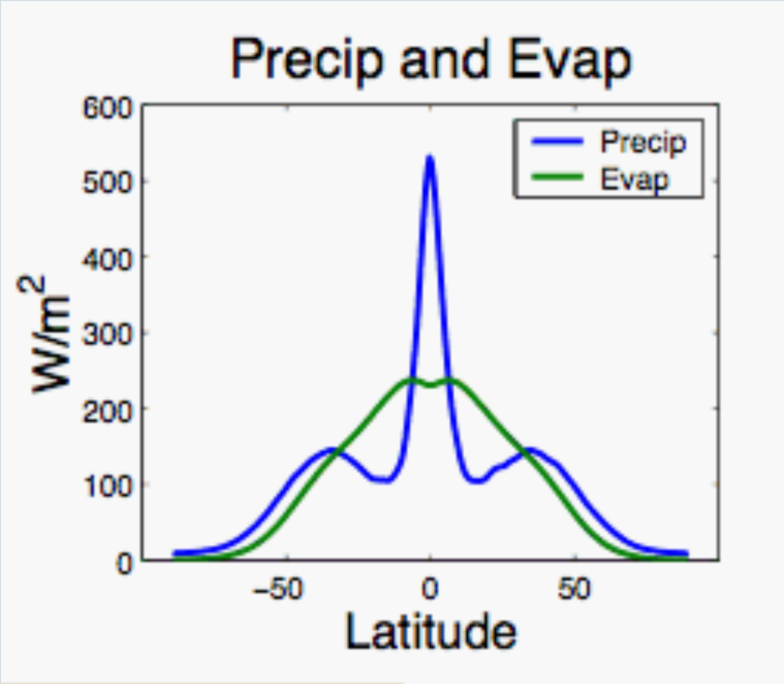
- Zonal wind and temperature





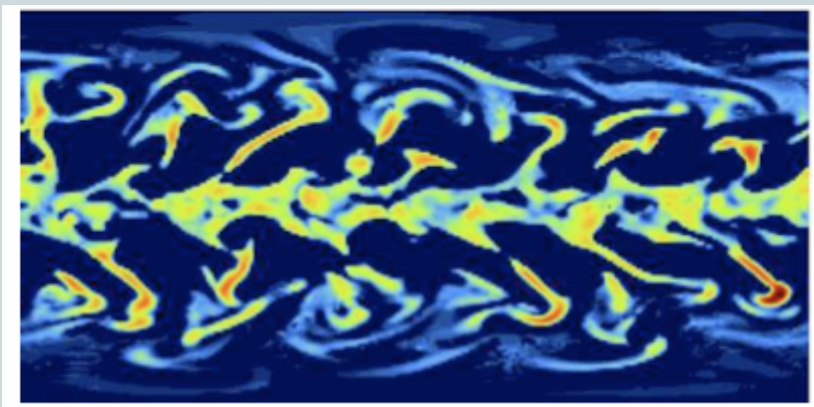
Model Climatology

- Precipitation and evaporation

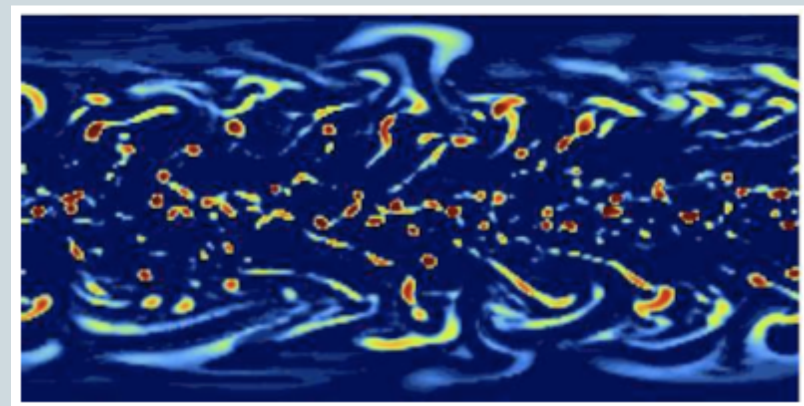


Effect of convection scheme

- Instantaneous precipitation



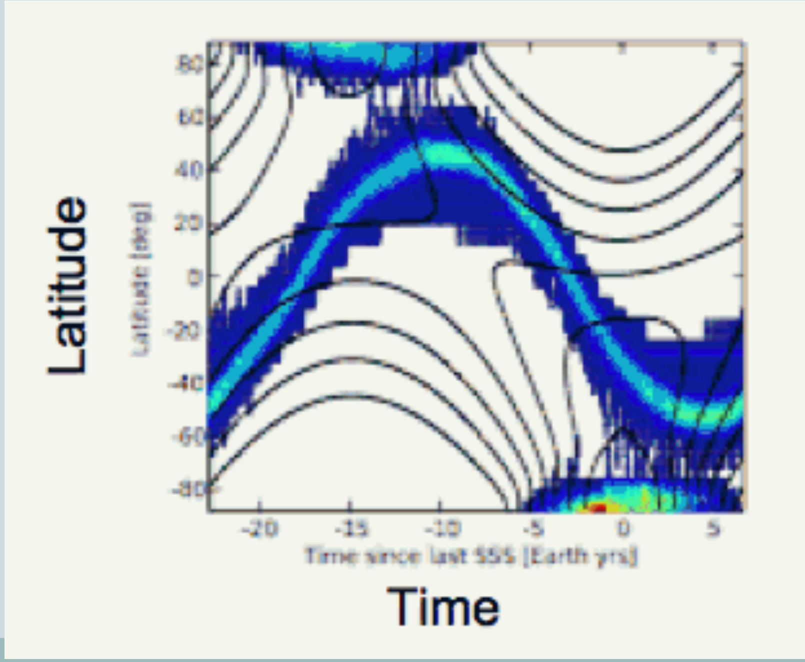
Simplified Betts-Miller convection scheme



Grid scale condensation only

GRaM GCM

- Model is very adaptable to different physical regimes
  - Nothing is tuned to current climate parameters
  - Allows large parameter variations
  - Applicable to other climates as well



Simulation of seasonal cycle of convection on Titan (Mitchell et al 2006)

General Circulation Changes with Moisture

- Vary moisture content over wide range
  - Goal: to understand the effect of moisture on the general circulation
- Strategy:
  - Vary Clausius-Clapeyron constant e_{s0}:

$$e_s = e_{s0}\, exp\left(-\frac{L}{R_V}\left(T^{-1} - T_0^{-1}\right)\right)$$

Control: $e_{s0} = 610.78\ Pa$

Dry limit: $e_{s0} = 0$

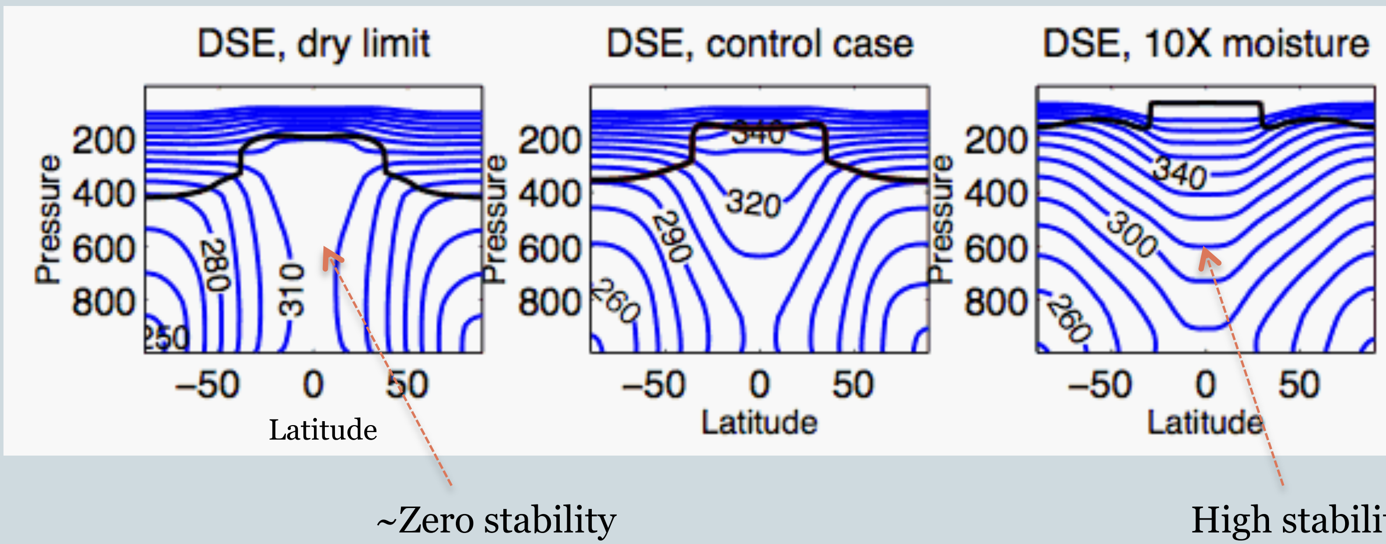
Up to: $e_{s0} = 6107.8\ Pa$ (10 times moisture)

Varying Moisture Content

- Dry limit: similar to very cold climates on Earth
- High moisture case: similar to post-snowball hothouse climates?
- We are using just as an understanding tool though
  - Direct comparisons should be made using more comprehensive models

Static Stability Changes

- Dry static energy, idealized GCM simulations:

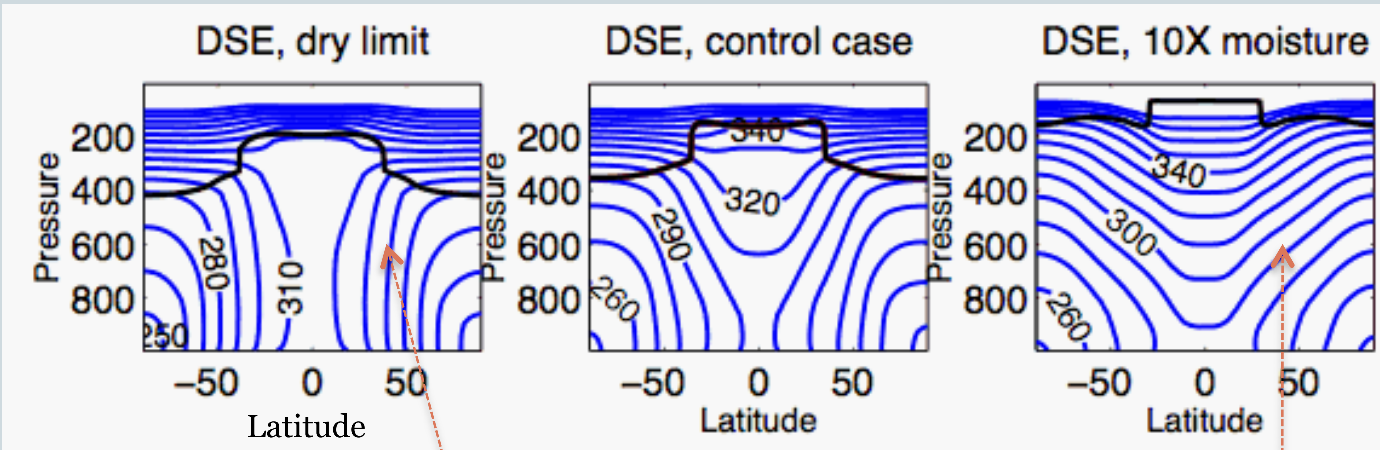


- Static stability ($\frac{d\theta}{dz}$) increases in tropics (as expected)

From Frierson, Held and Zurita-Gotor (2006)

Static Stability Changes

- Static stability also increases in midlatitudes:



~Zero stability

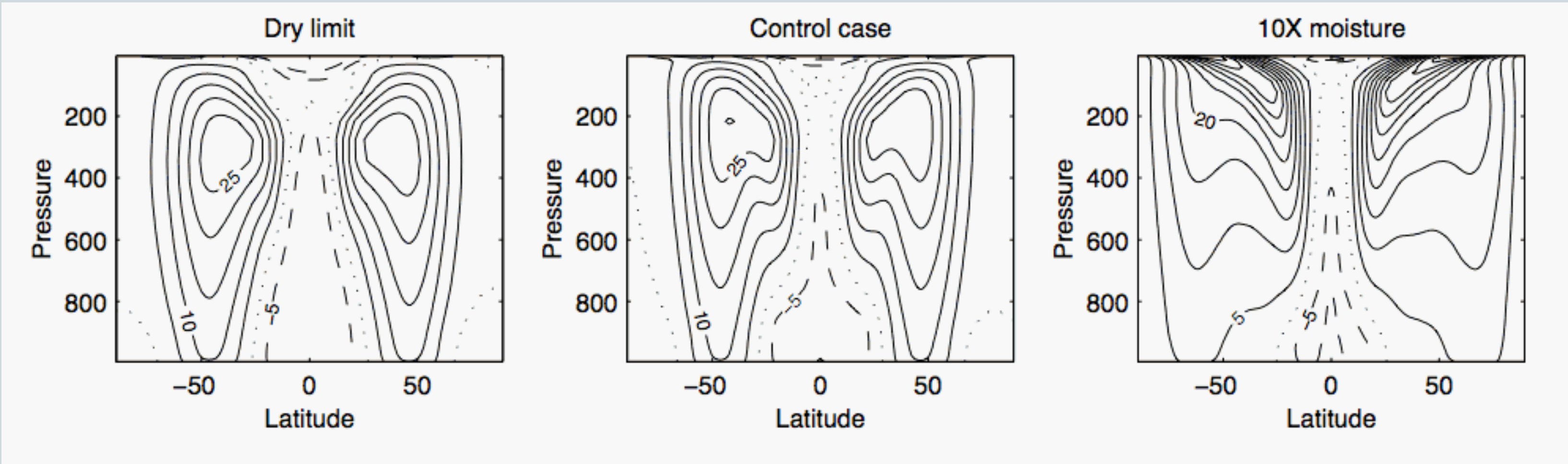
High stability

- Further investigated in Frierson (2008), Frierson and Davis (2011)
- Seen in IPCC simulations as well (Frierson 2006)

From Frierson, Held and Zurita-Gotor (2006)

Midlatitude Jet Changes

- Zonal winds:

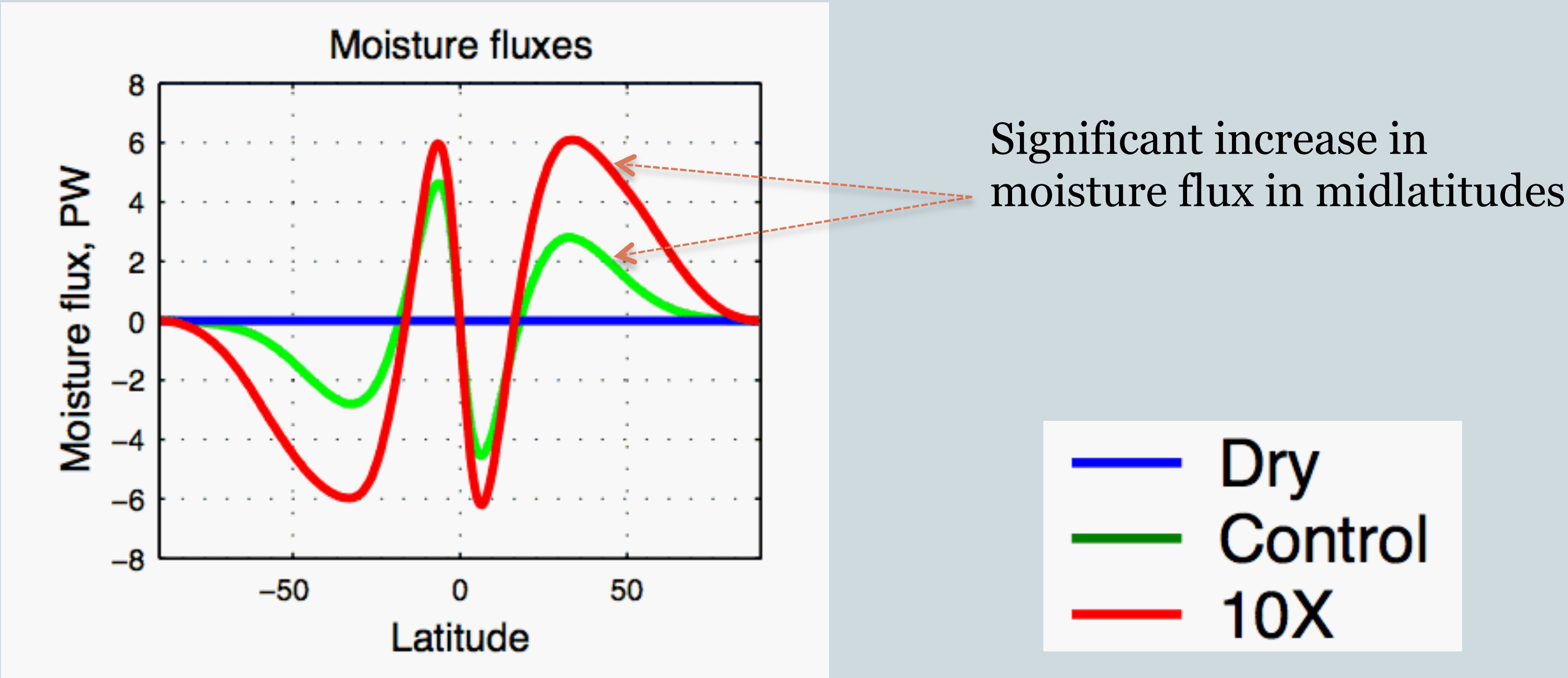


- Poleward and upward shift with increased moisture
  - Similar to global warming simulations (Yin 2005)
- Related to static stability changes?
  - Static stability increases preferentially on equatorward side of storm tracks (work with Jian Lu & Gang Chen: LCF08, CLF08)

From Frierson, Held and Zurita-Gotor (2006)

Energy Fluxes in Simplified Moist GCM

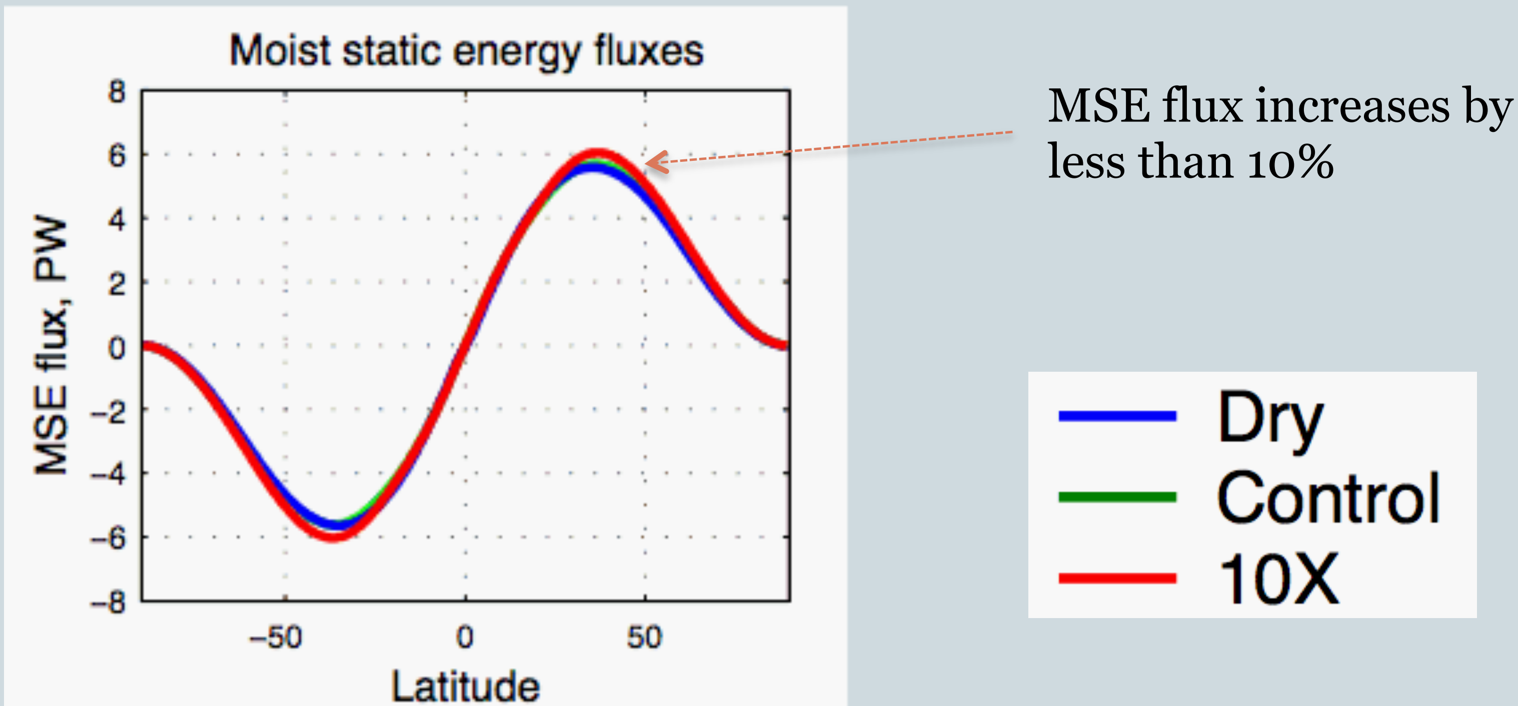
- Moisture flux in idealized simulations:



From Frierson, Held and Zurita-Gotor (2007)

Energy Fluxes in Simplified Moist GCM

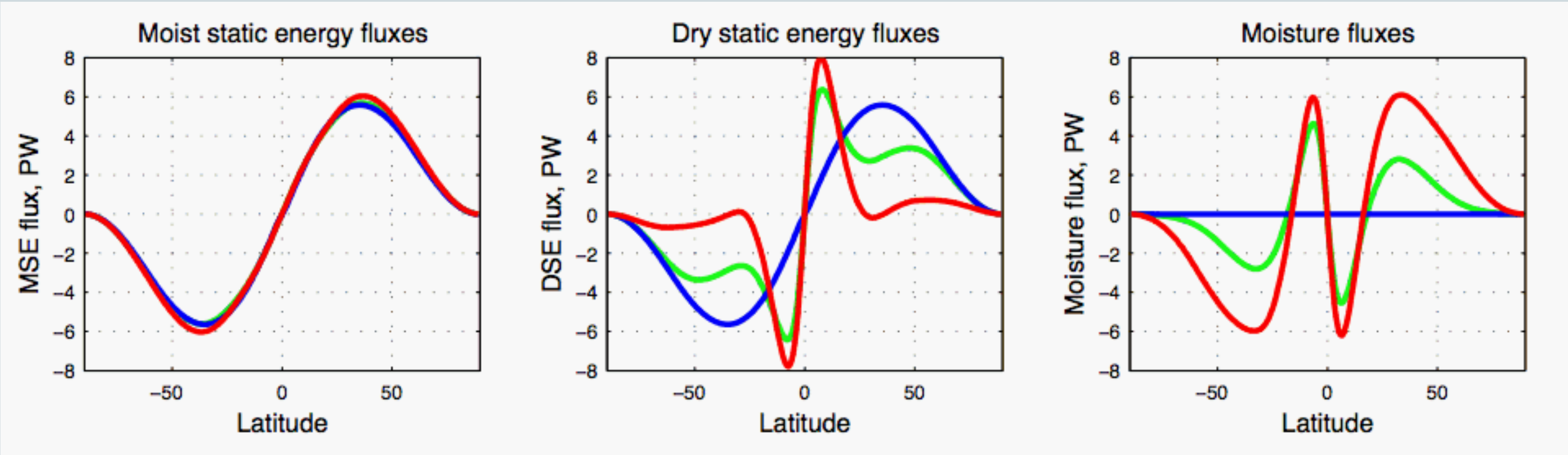
- Moist static energy flux in idealized simulations:



From Frierson, Held and Zurita-Gotor (2007)

Energy Fluxes in Simplified Moist GCM

- Fluxes in idealized simulations:



Decrease in dry static energy flux to almost perfectly compensate the increase in moisture flux!

From Frierson, Held and Zurita-Gotor (2007)

Strengths/Weaknesses of GRaM GCM

- Strengths:
  - Simple consideration of condensation
  - Closed energy budget, active surface
  - Not tuned to current climate parameters
  - Allows large parameter variations
  - Expandable into a full GCM
- Weaknesses:
  - Too awesome?
  - Much more complex than Held-Suarez
  - Stratosphere
  - Lack of water vapor/clouds in radiative transfer

End of Topic 1: Model Hierarchies

- We have running on pynchon:
  - Held-Suarez dry dynamical core model
    - With spectral, finite volume, or B-grid dynamical core
  - Idealized moist GCM (GRaM)
  - GFDL's AM2 model
    - Full GCM over realistic geography
  - Aquaplanet version of AM2
  - Models with simplified vertical structure:
    - Barotropic vorticity equation model on the sphere
    - Shallow water model on the sphere