Climate Dynamics (PCC 587): Climate Models

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Types of Climate Models

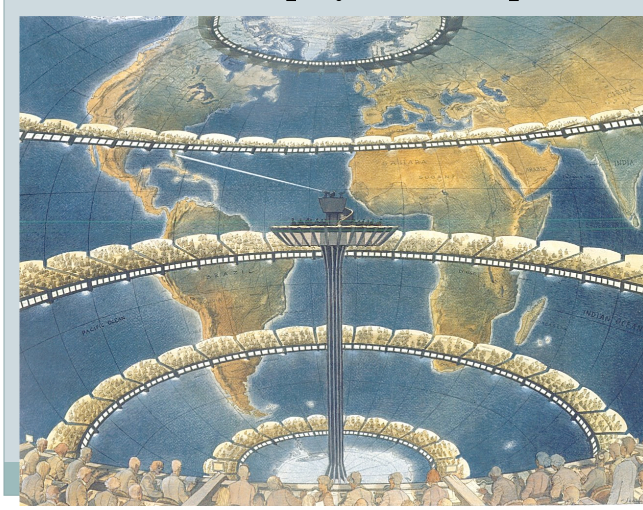
- There are many different types of climate models
  - Huge range of complexities, physical processes represented, etc
  - E.g., compare a seasonal forecast model to an ice age cycle model
- Today we'll focus primarily on the climate models for global warming predictions (from IPCC AR4)
  - Data is publicly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

Richardson's Dream: The Forecast Factory

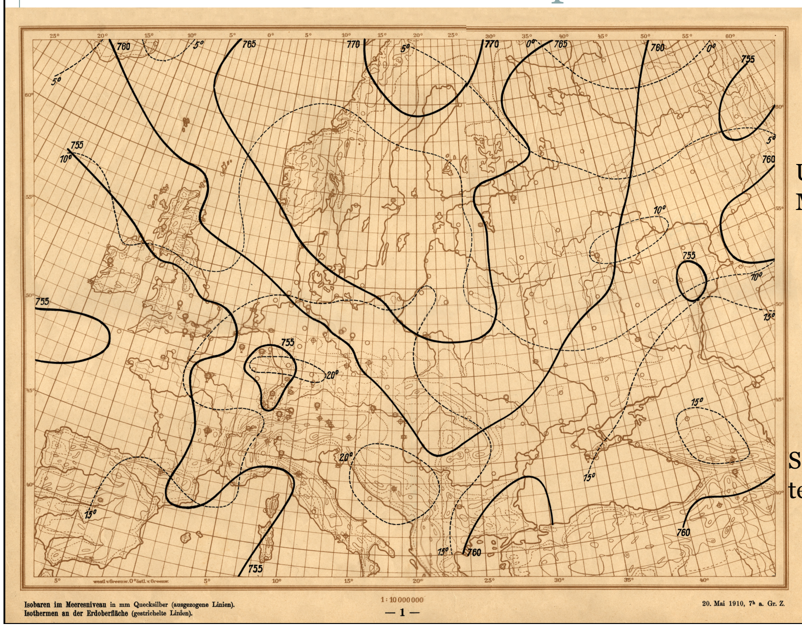
- Filled with employees ("computers") doing calculations



Richardson's dream in **1922** of a global forecasting system

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

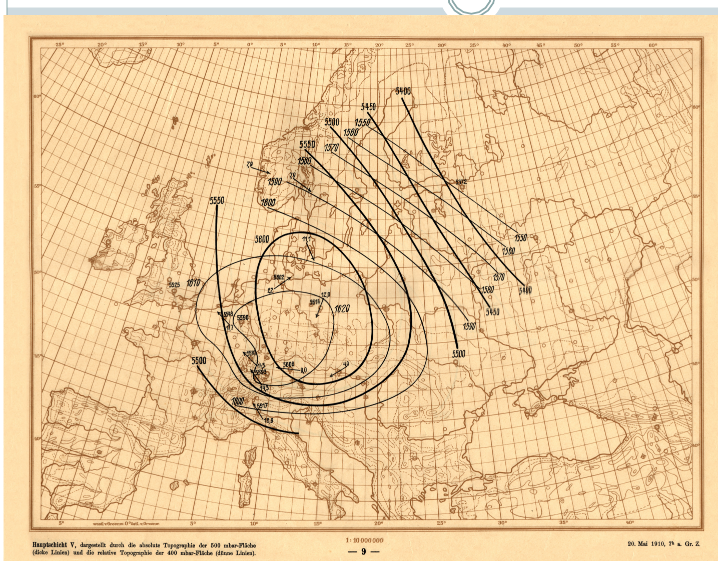
Richardson's Experiment



Used data from May 20, 1910

SLP and surface temperature

Richardson's Experiment

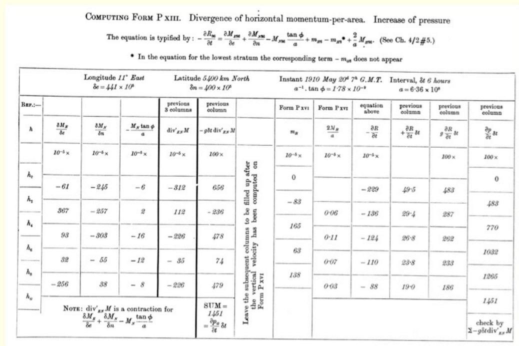


Tabulated values from these charts by hand!

500 mbar heights and 500-400 mbar thickness

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

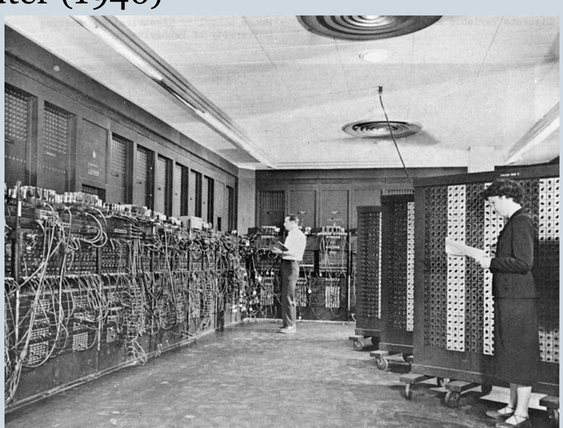
Longitude *11° East* $\delta e = 441 \times 10^5$ — Latitude *5400 km North* $\delta n = 400 \times 10^5$ — Instant *1910 May 20d 7h G.M.T.* $a^{-1}.\tan\phi = 1{\cdot}78 \times 10^{-9}$ — Interval, δt *6 hours* $a = 6{\cdot}36 \times 10^8$

Ref.:—				previous 3 columns	previous column		Form P XVI	Form P XVI	equation above	previous column	previous column	previous column
h	$\frac{\delta M_E}{\delta e}$	$\frac{\delta M_N}{\delta n}$	$-\frac{M_N \tan\phi}{a}$	$div'_{EN}M$	$-g\delta t\, div'_{EN}M$	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: $div'_{EN}M$ 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 $\Sigma - g\delta t\, div'_{EN}M$

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!

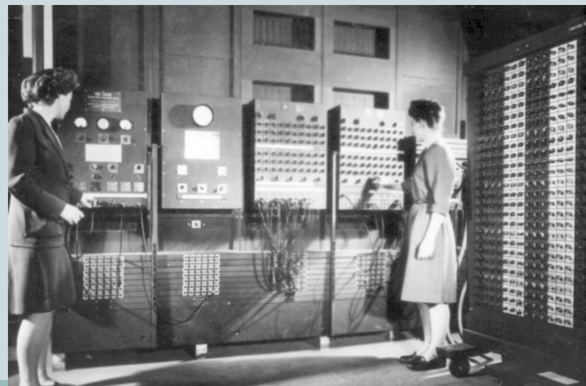
The First Computer

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



The First Computer!

- ENIAC: The Electronic Numerical Integrator and Computer



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

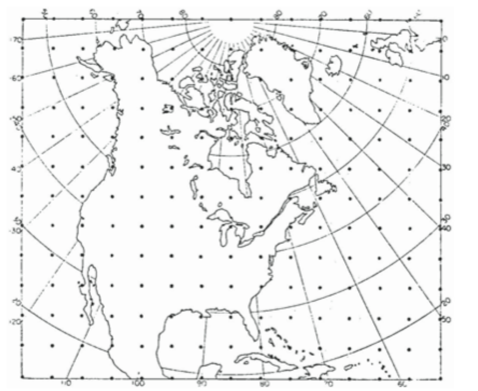


FIG. 2. Computation grid used for the ENIAC forecasts. One line is omitted from the southern edge and two lines from the remaining edges (from CFvN).

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?

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

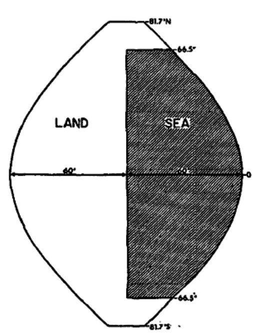


Fig. 1. Ocean-continent configuration of the model

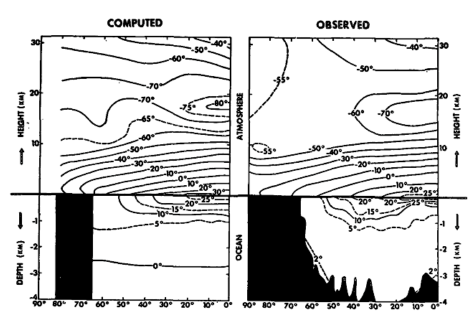


Fig. 2. Zonal mean temperature of the joint ocean-atmosphere system, left-hand side. This distribution, which is the average of two hemispheres, represents the time mean over two-sevenths of the period of the final stage of the time integration. The right-hand side shows the observed distribution in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

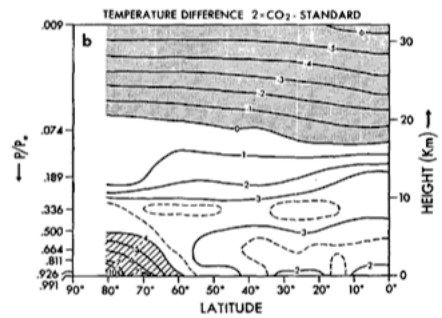


FIG. 4. Latitude-height distribution of the zonal mean temperature (K) for the standard case (a) and of the increase in zonal mean temperature (K) resulting from the doubling of CO_2 concentration (b). Stippling indicates a decrease in temperature.

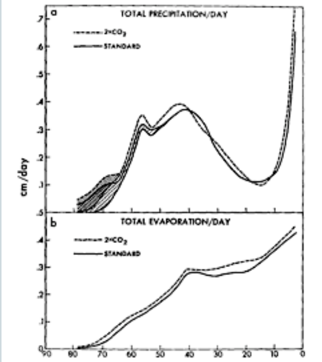


FIG. 7. Zonal mean rates of total precipitation, where shaded areas denote the rates of snowfall (a), and zonal mean rates of evaporation (b).

Other Early Manabe Studies

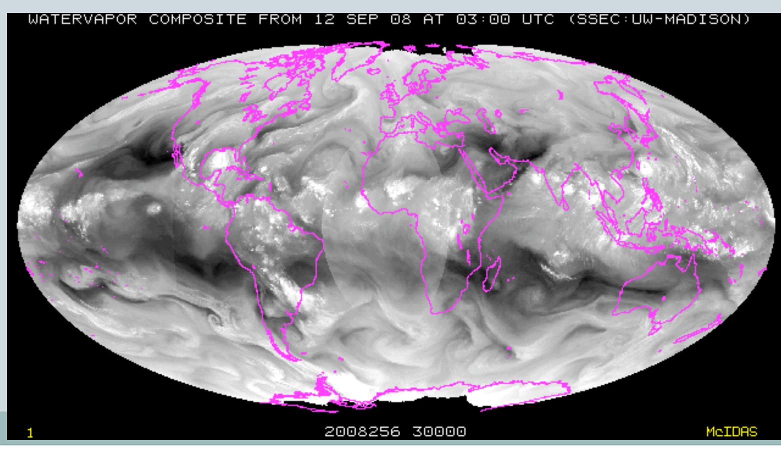
- I find these early modeling papers still really fascinating…
- Effect of ocean circulation on climate:
  - Turn off ocean model
- Effect of moisture:
  - Turn off latent heating
- Effect of mountains:
  - Bulldoze all topography
- Effect of changing **solar radiation**, doubling **CO2**, **ice sheets**, **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

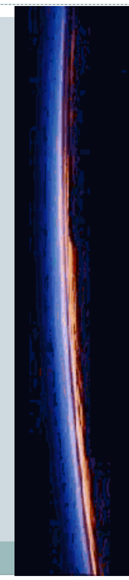
Dynamical Core of AGCMs

- 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

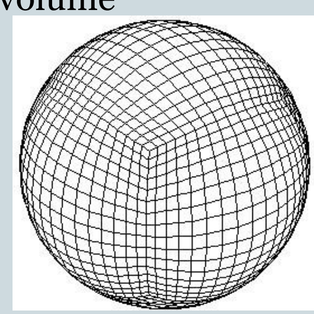
- Momentum equations:
  - Coriolis terms: due to rotation of Earth (*not sphericity*)
  - "Metric terms": to account for sphericity
- Energy equation:
  - Energy balance is in the standard fluid equations
  - Goes into the GCM without approximation

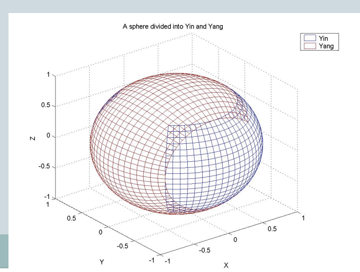
Numerical Methods

- 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"





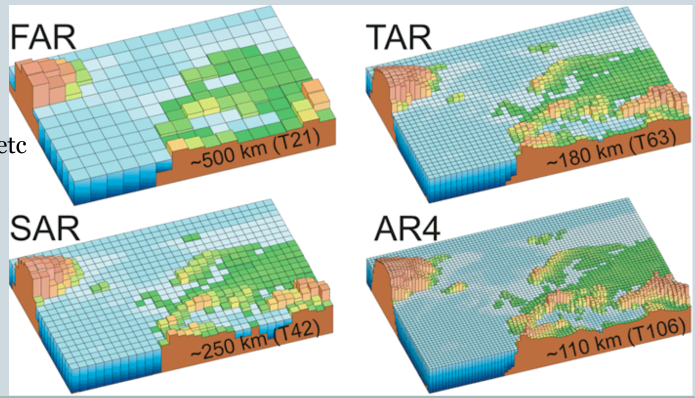
Model Resolution Evolution

- Changes in resolution over time:

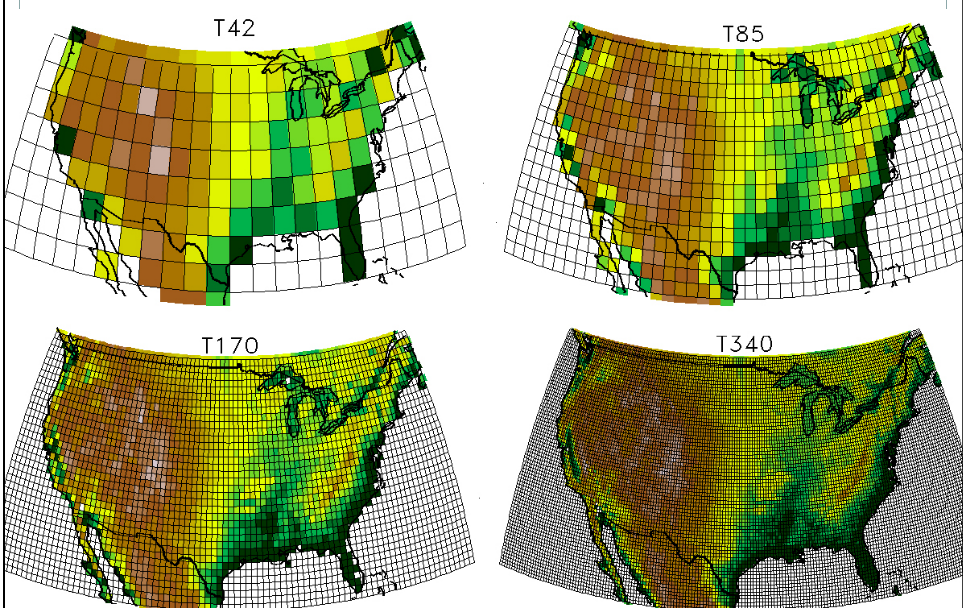
AR = "assessment report"

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

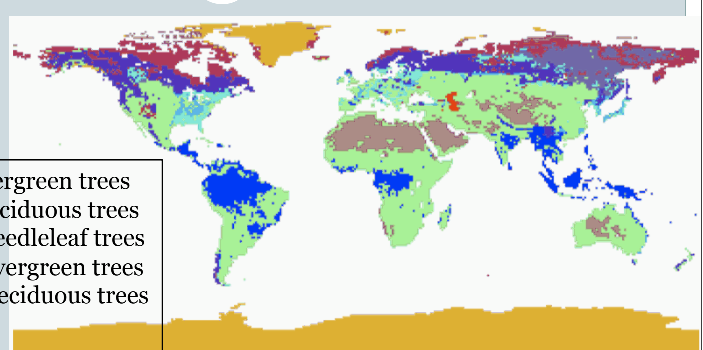
- Climate models have some very complex parameterizations of physical processes
  - Radiative transfer
  - Clouds
  - Convection
  - Surface fluxes/boundary layer schemes
- We'll describe general ideas of how these are parameterized
- And the history of some of the parameterizations

What Models Don't Parameterize (yet)

- But first, a list of things the AR4 GCMs don'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 AR4 GCMs don't even try to do:
  - Carbon cycle
    - Prescribed CO2 distributions (well-mixed)
  - 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 considered

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
    - Distributions 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!
  - ~50% of the total CPU usage is running the radiation code
  - Often not called every time step
  - Faster implementations such as neural networks are being 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

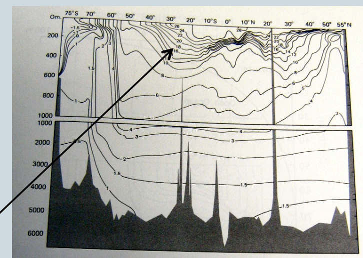


Figure 1.3 Temperature along approximately 160° W in the Pacific from the Antarctic to Alaska. Vertical exaggeration is 5.5×10^3 in the upper 1000 m and 1.11×10^3 below 1000 m. (After Reid, *Intermediate Waters of the Pacific Ocean*, The John Hopkins Oceanography Studies, The John Hopkins Press, 1965.)

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

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

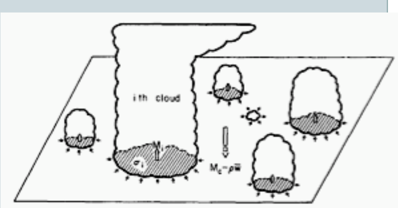


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

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

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

Surface roughness values for different surfaces

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

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
- Now only 4 of 24 models have flux adjustment
  - They tend to be the models from newer/less funded groups

AR4 GCM Summary

- Of 24 models in the AR4 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
- There will be big changes with these for AR5
  - Especially in terms of chemistry and aerosol indirect effects
  - Also there will be *other models* used in AR5 with dynamic vegetation, carbon cycle, etc