Climate models: General concept, history, design, testing and sensitivity

Global Climate Modeling

- **General philosophy**:
  - Simulate large-scale motions of atmosphere, oceans, ice
  - Solve approximations to full radiative transfer equations
  - Parameterize processes too small to resolve
  - Some models also try to simulate biogeochemical processes
  - First GCMs developed in 1960s

Model Partial Differential Equations

- Conservation of momentum
- Conservation of mass
- Conservation of water
- Conservation of certain chemical species
- First law of Thermodynamics
- Equation of state
- Radiative transfer equations

The Conservation Equations

Mass: $\frac{D\rho}{Dt} + \rho\nabla\cdot\vec{u} = 0$ (ρ = density, $\vec{u}$ = velocity vector)

Total vs. local time derivative: $\frac{d}{dt} = \frac{\partial}{\partial t} + \vec{u}\bullet\nabla$

Momentum: $\rho\frac{D\vec{u}}{Dt} = -\nabla p - \nabla\cdot\vec{\tau} + \rho\vec{g}$

(p = pressure; $\vec{\tau}$ = stress; g=gravity)

$$\tau = -\mu\left(\nabla\vec{u} + \nabla\vec{u}^T - \frac{2}{3}\nabla\cdot\vec{u}\right)$$

Thermodynamics (atmosphere):

$$c_p \frac{dT}{dt} - \alpha \frac{dp}{dt} = \dot{Q} \qquad (\alpha \text{ = specific volume, } \dot{Q} \text{ = heating})$$

Equation of State:

$$\alpha p = RT \qquad \text{(atmosphere)}$$

$$\alpha = \alpha(p, s, T) \quad (\text{ocean; } s \text{ = salinity})$$

Additional equations for radiative transfer, conservation of water (atmosphere) and salinity (ocean), etc.

Numerical solution of PDEs

- Finite difference method, e.g.

$$\frac{\partial u}{\partial t} = -c\frac{\partial u}{\partial x} \rightarrow$$

$$u_2^i = u_1^i - c\Delta t\left(\frac{u_1^{i+1} - u_1^{i-1}}{2\Delta x}\right)$$

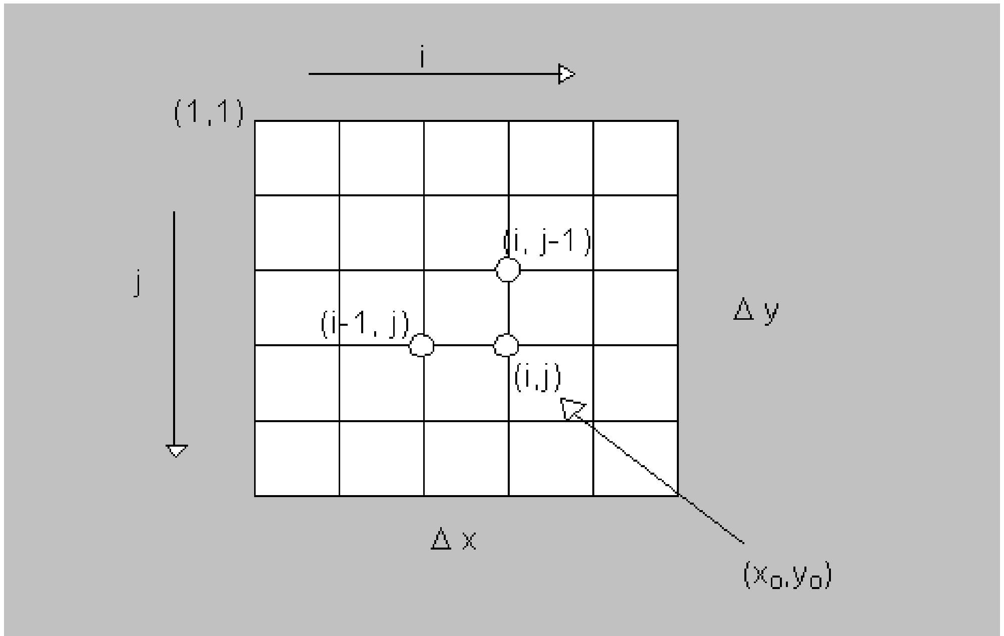
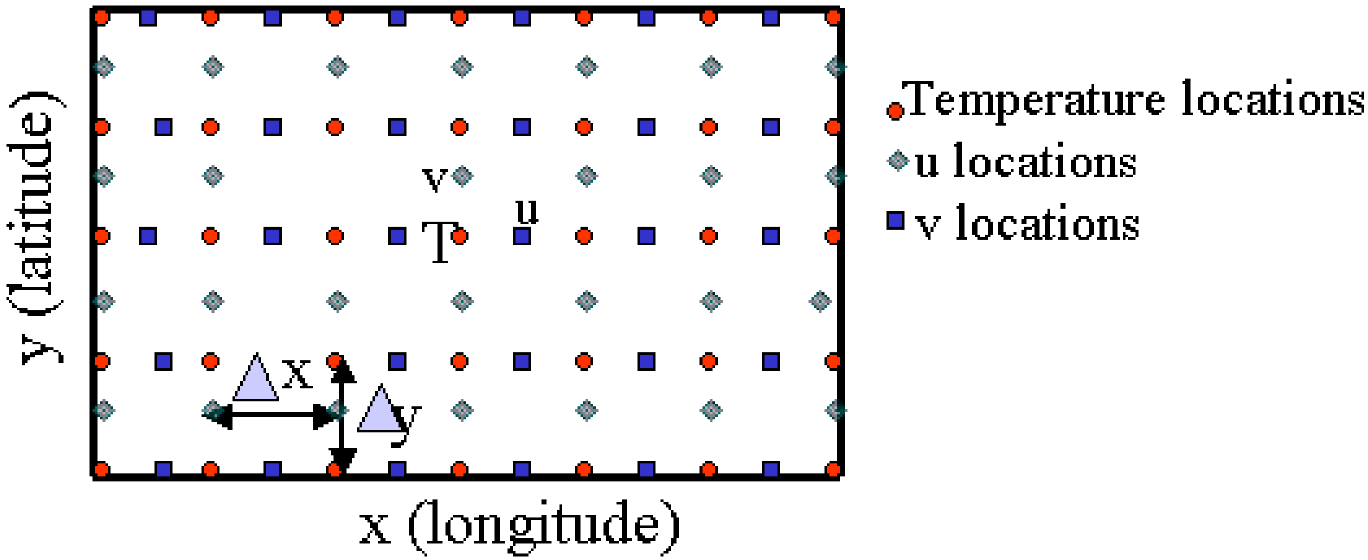
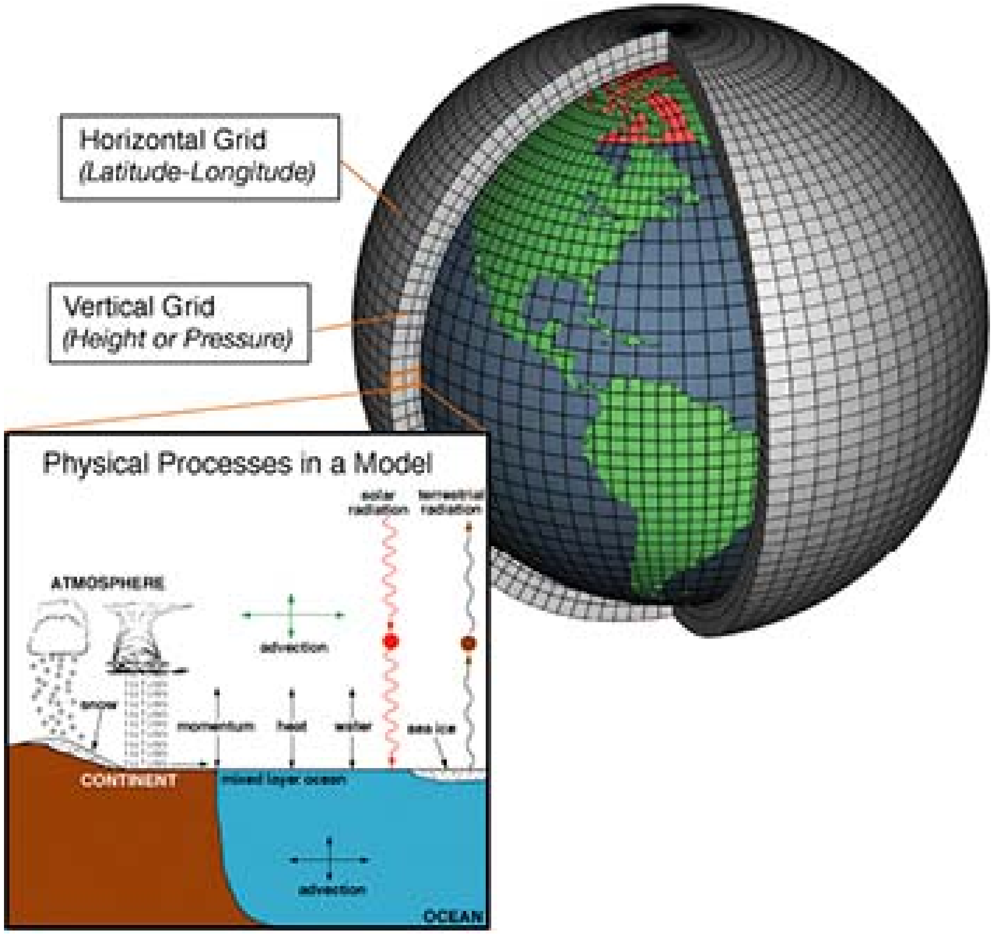


Figure 5-1. General finite difference grid showing index conventions.

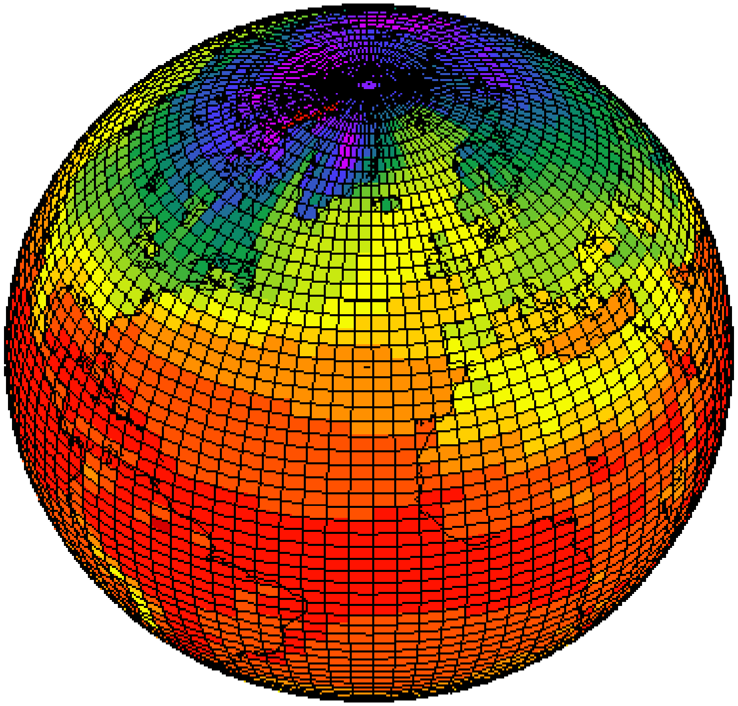
“C” Grid



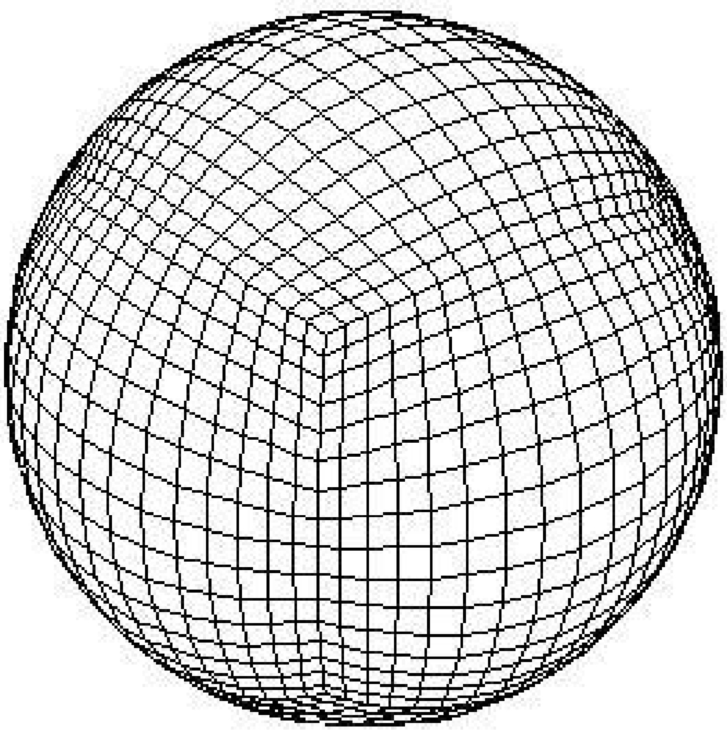
PDE’s written as finite difference equations, or phrased in finite elements, or spectrally decomposed



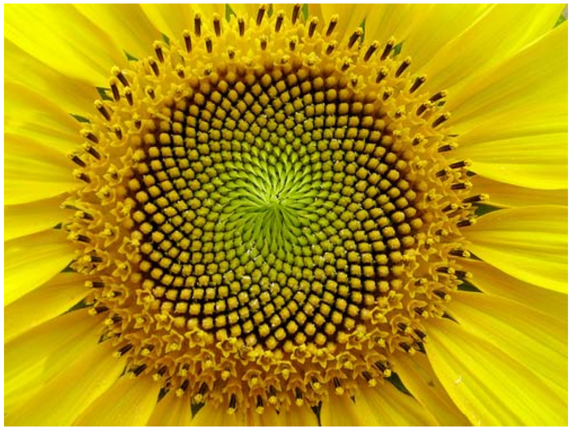
Alternative Grids:

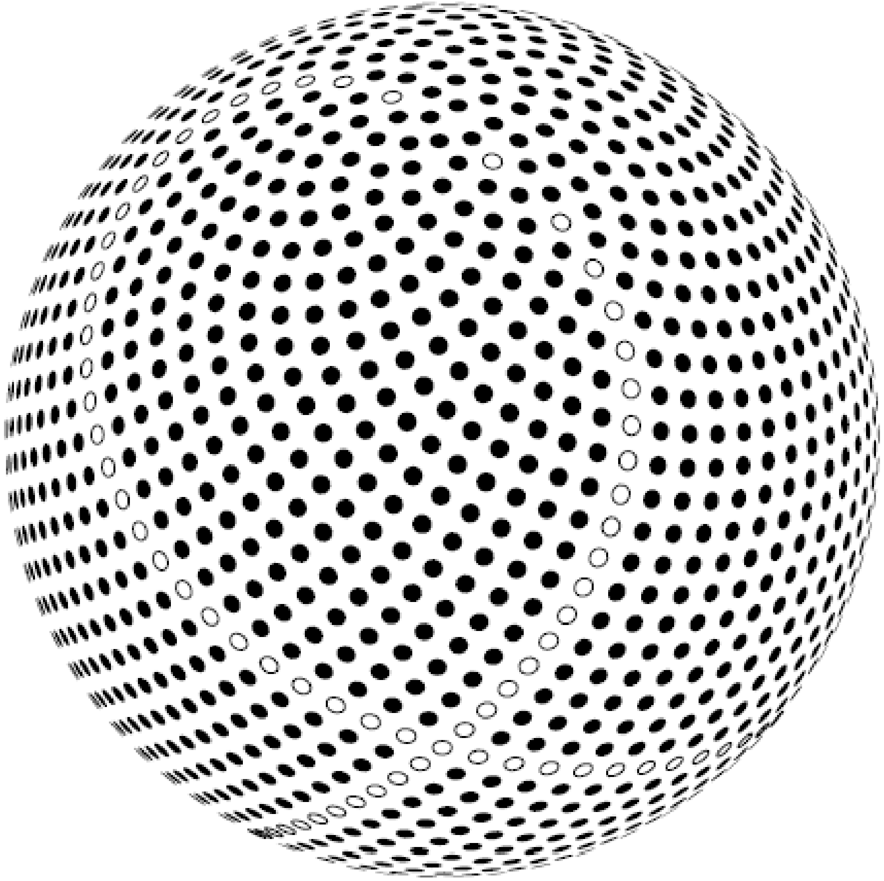


Classical spherical coordinates



Conformal mapping of cube onto sphere





A spherical grid based on the Fibonacci sequence. The grid is highly uniform and isotropic.

- Spectral methods, e.g.

$$\frac{\partial u}{\partial t} = -c\frac{\partial u}{\partial x} \rightarrow$$

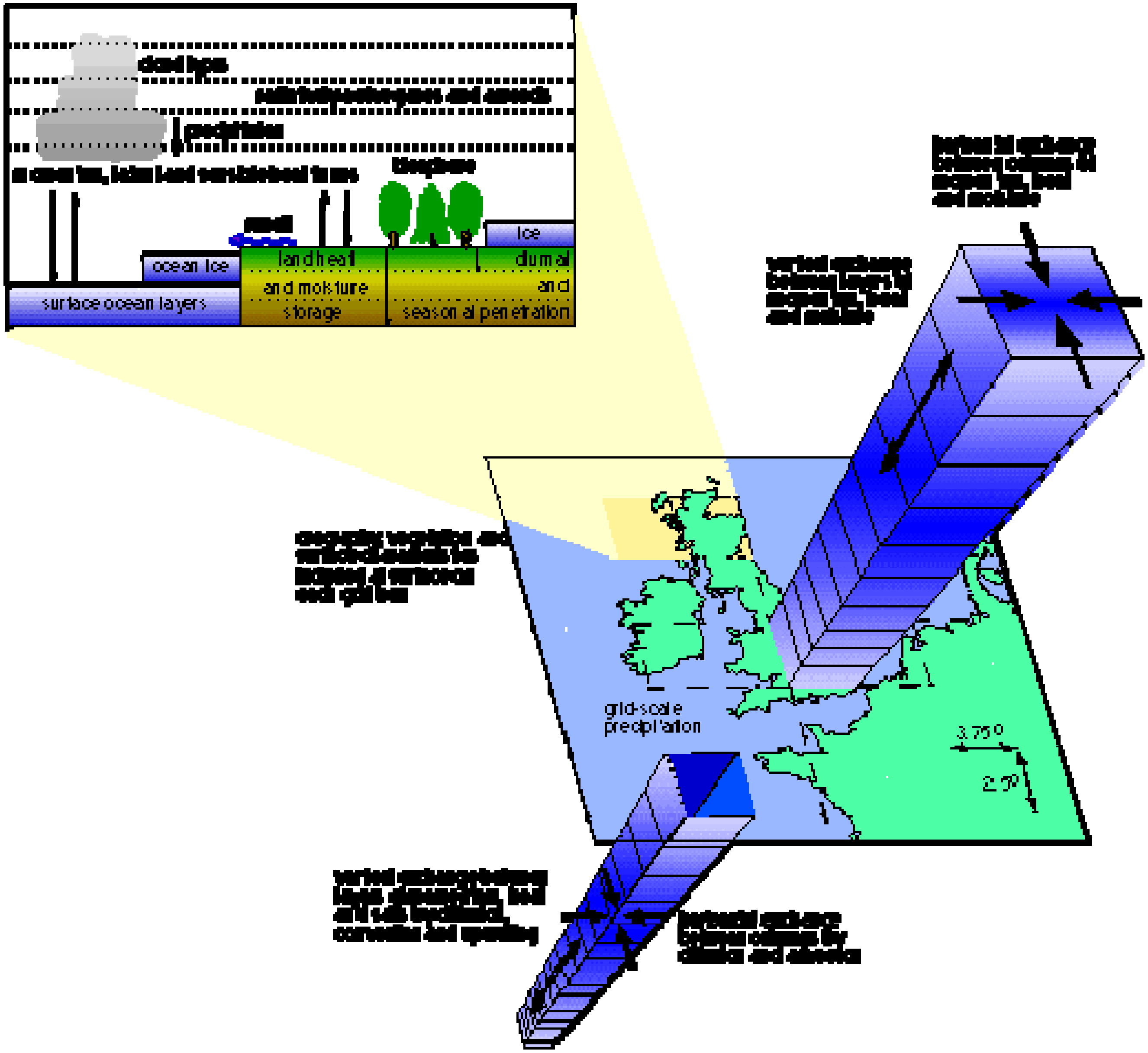
$$u = \sum_n a_n \sin\left(\frac{n\pi x}{L}\right) + b_n \cos\left(\frac{n\pi x}{L}\right) \rightarrow$$

$$\frac{\partial a_n}{\partial t} = c\frac{n\pi}{L}b_n,$$

$$\frac{\partial b_n}{\partial t} = -c\frac{n\pi}{L}a_n$$

Must use spherical harmonics for equations on a sphere

Note: Spectral method not used for vertical differences



Some Fundamental Numerical Constraints

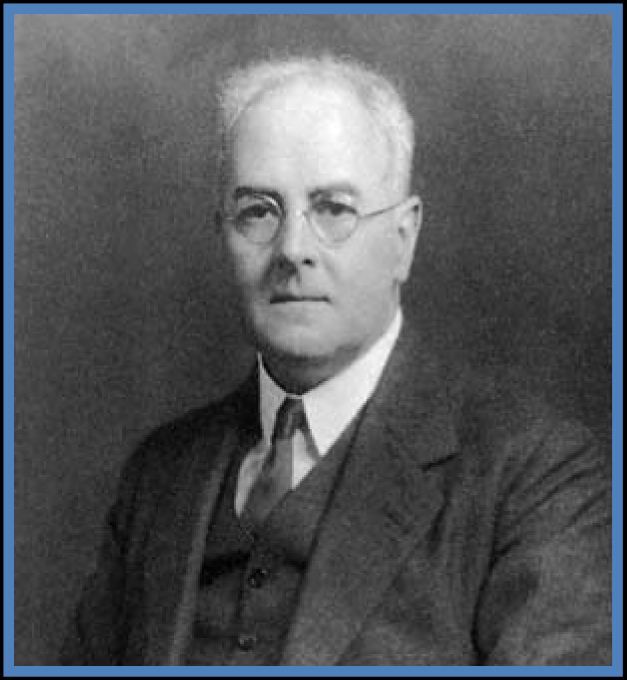
Courant-Friedrichs-Lewy (CFL) condition:

$$\frac{c\Delta t}{\Delta x} < 1,$$

where c is the phase speed of the fastest wave in the system, Δt is the time step used by the model, and Δx is a characteristic spacing between grid points.

Typical size of model: 20 levels, grid points spaced ~120 km apart, 10-15 variables to defines state of atmosphere or ocean at each grid point: ~1,000,000-5,000,000 variables. Typical time step: 20 minutes. Thus 70,000,000 -350,000,000 variables calculated per simulated day.

History of Climate Modeling

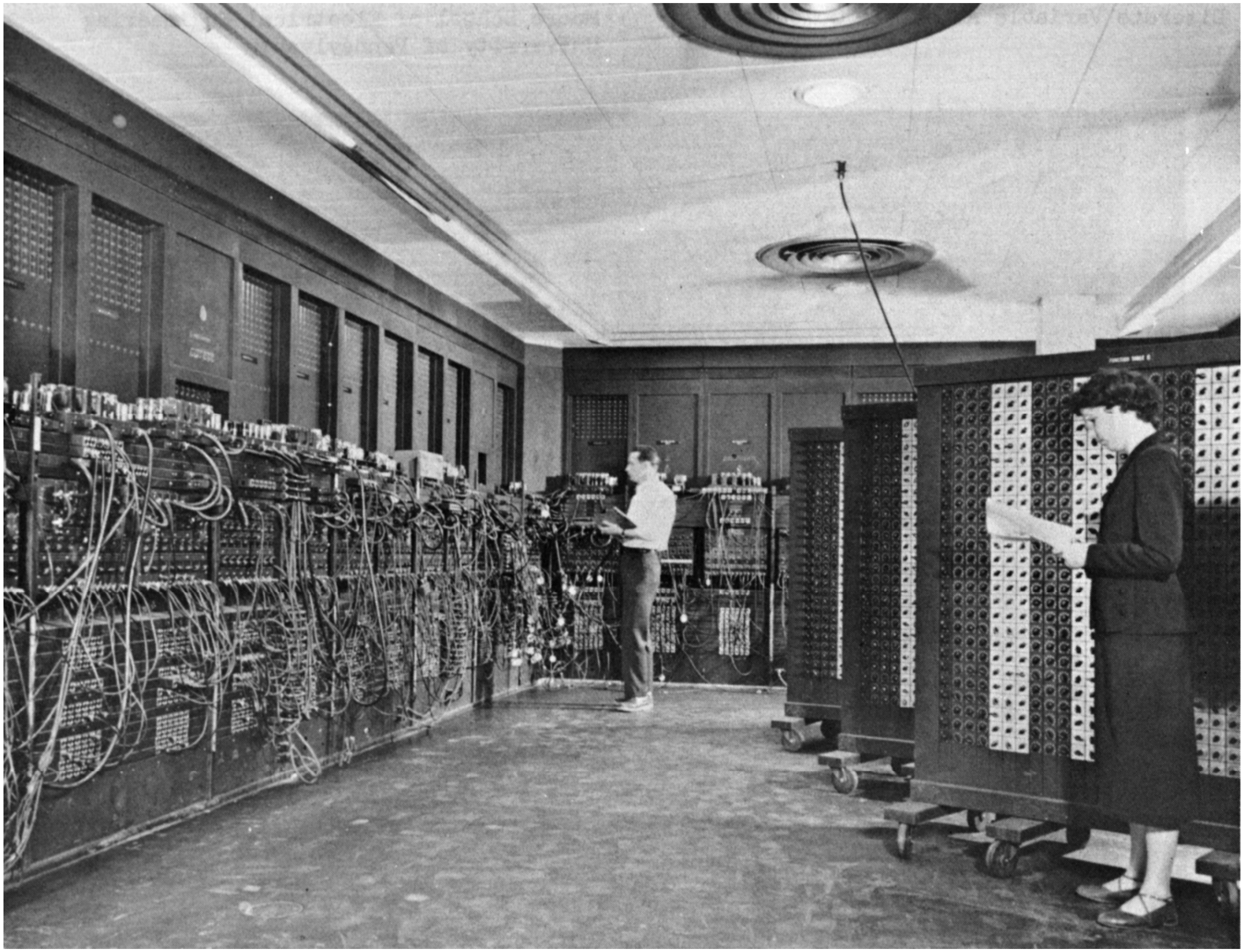


Numerical Weather Prediction: Lewis Fry Richardson, 1922

Richardson's "Forecast Factory"

"Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream."

The ENIAC: Electronic Numerical Integrator And Computer (1946)



17,468 vacuum tubes, 7,200 crystal diodes, 1,500 relays, 70,000 resistors, 10,000 capacitors and around 5 million hand-soldered joints. Weight: 30 short tons. 350 floating point operations per second (flops). (This PC: 21 Gigaflops!)

First Successful Numerical Weather Forecast in April, 1950: Jule Gregory Charney, (1917-1981)

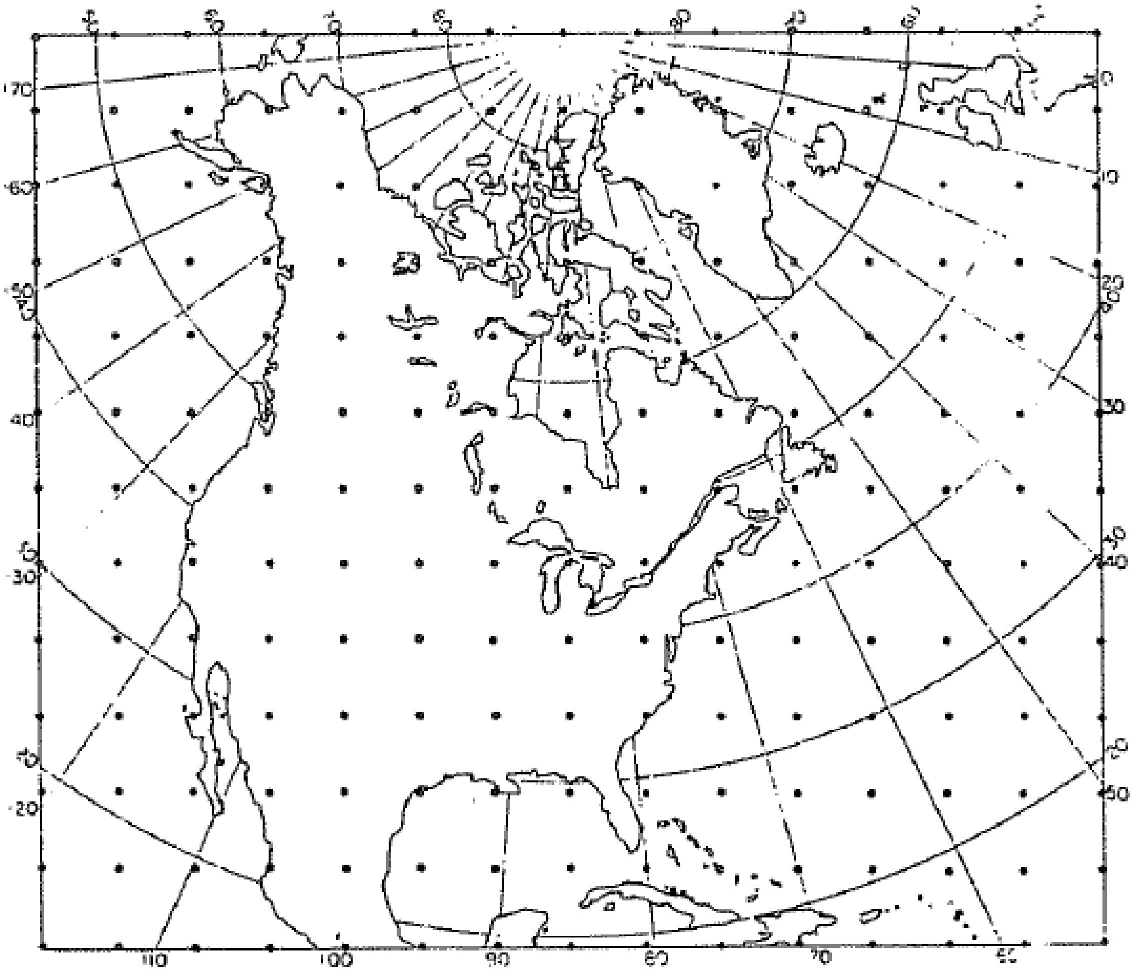
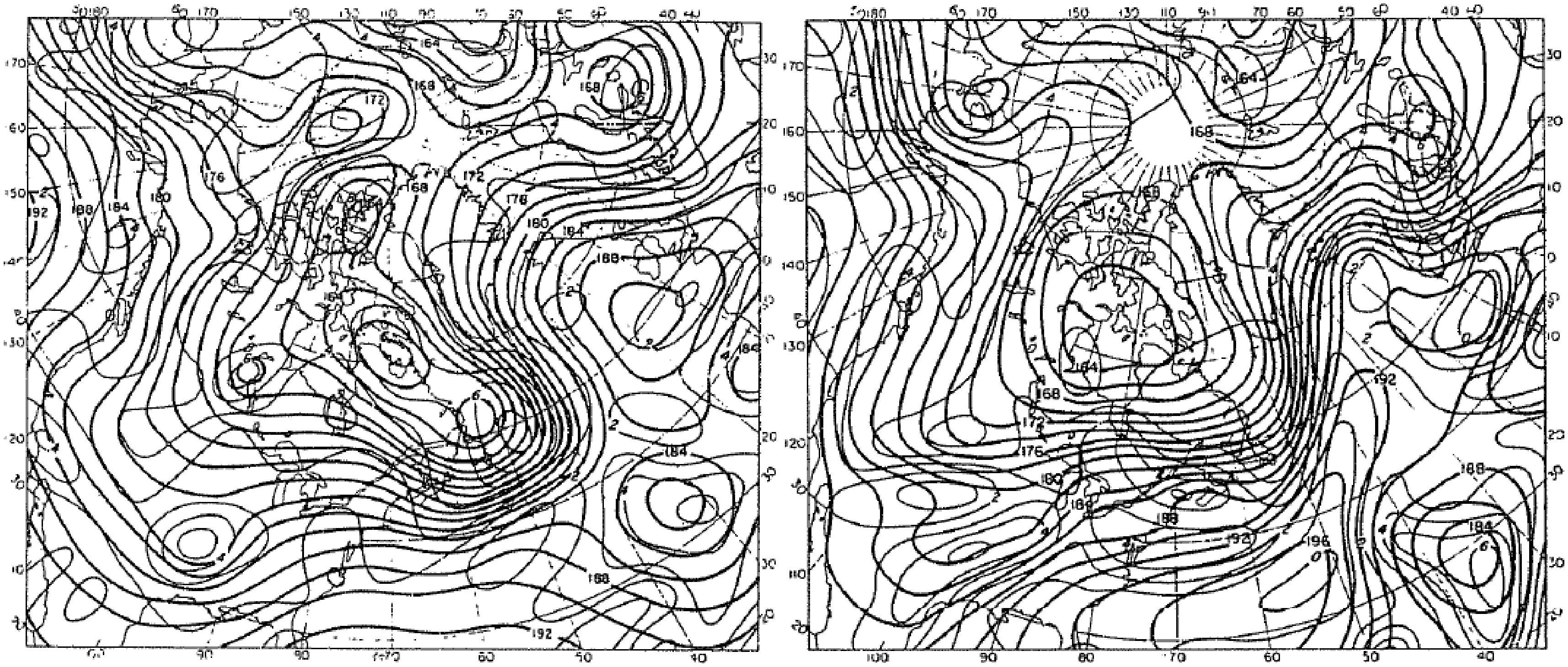


Fig. 1. A typical finite-difference grid used in the computations. A strip two grid intervals in width at the top and side borders and one grid interval in width at the lower border is not shown.

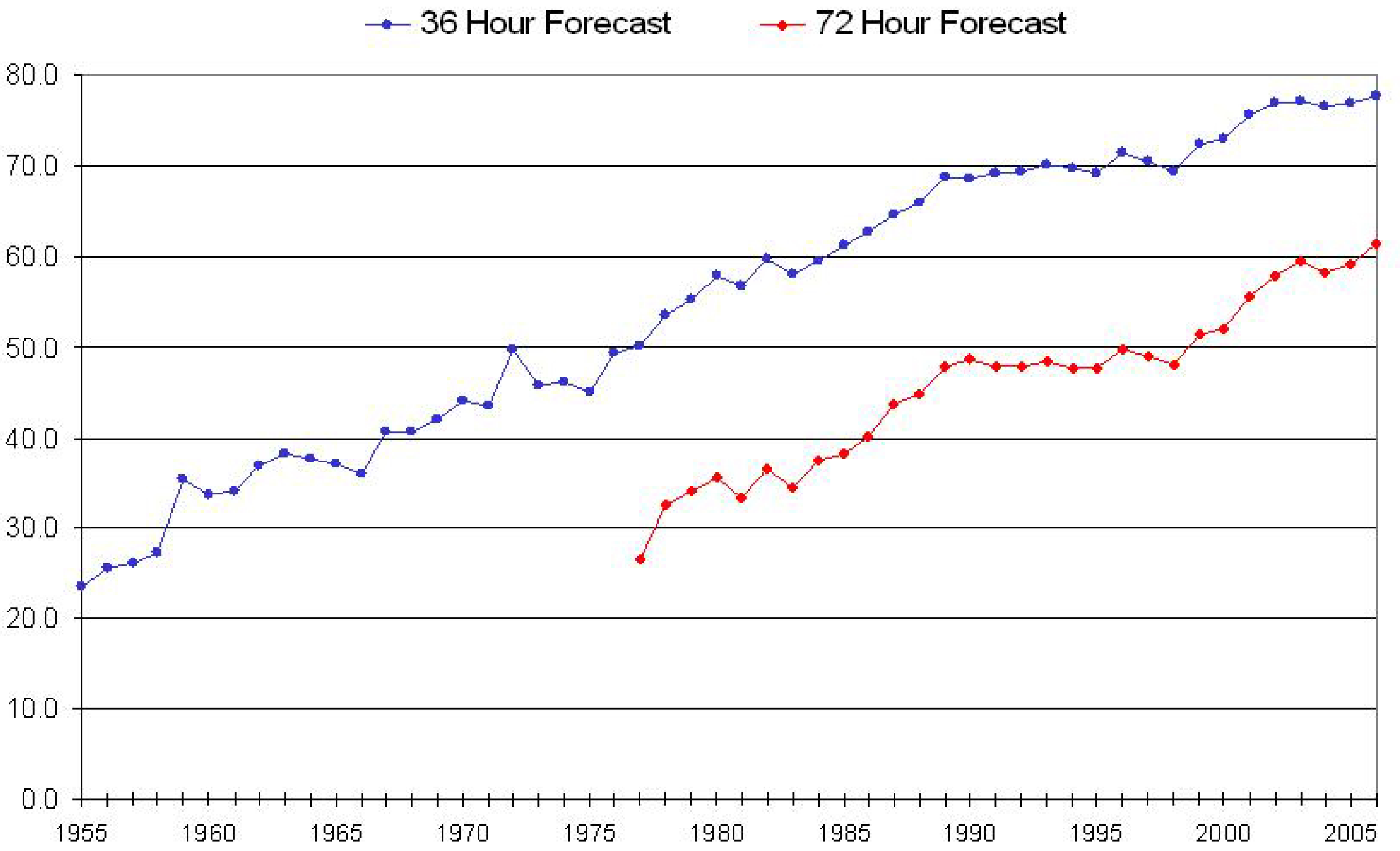


Observed (left) and 24-hour forecast (right) of 500 hPa geopotential heights (thick) and vorticity (thin) for 0300 GMT 31 January 1949

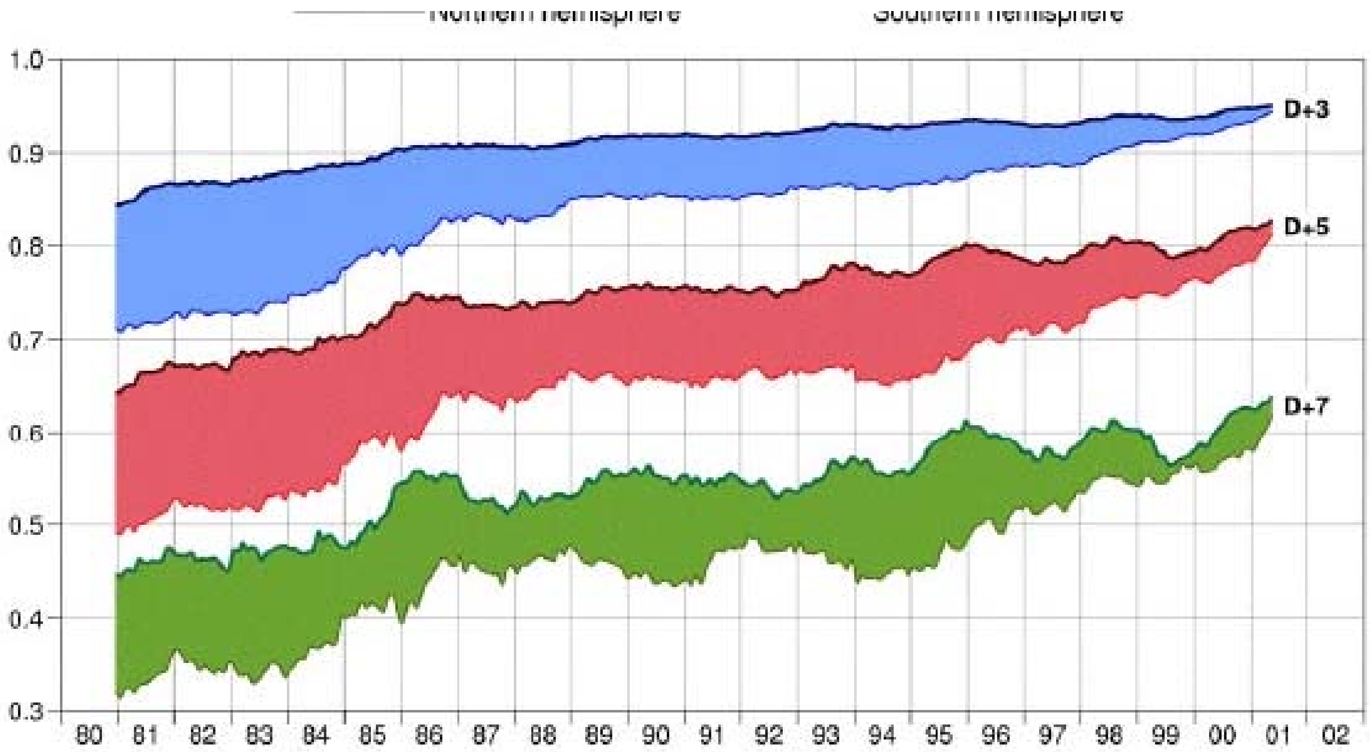
NCEP Operational Forecast Skill

36 and 72 Hour Forecasts @ 500 MB over North America

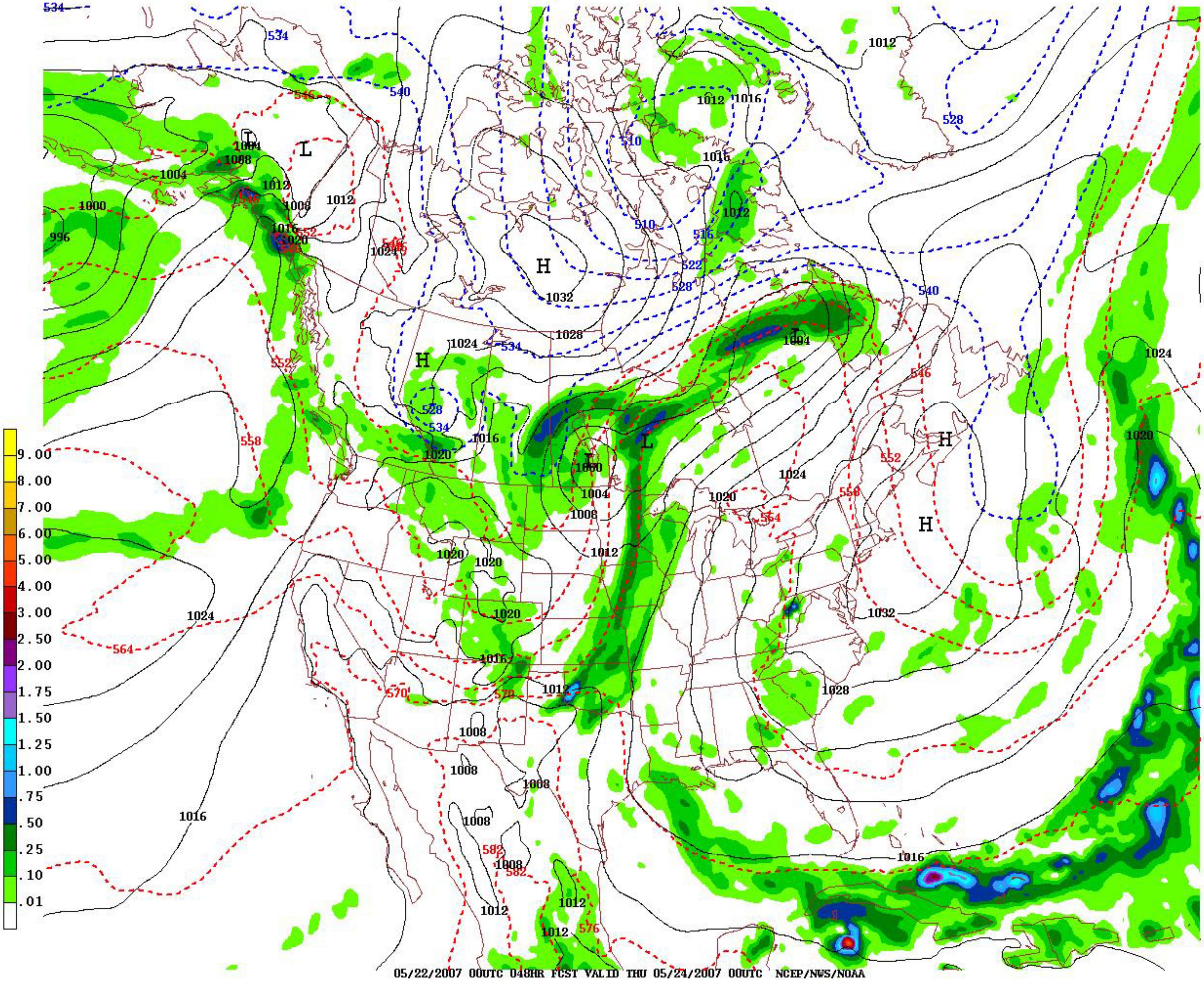
[100 * (1-S1/70) Method]



NCEP Central Operations January 2007


Northern hemisphere
Southern hemisphere
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
00
01
02
D+3
D+5
D+7

070524/0000V048 NAM MSLP, 06-HR TOTAL PCPN, 1000-500 MB THICKNESS



05/22/2007 00UTC 048HR FCST VALID THU 05/24/2007 00UTC NCEP/NWS/NOAA

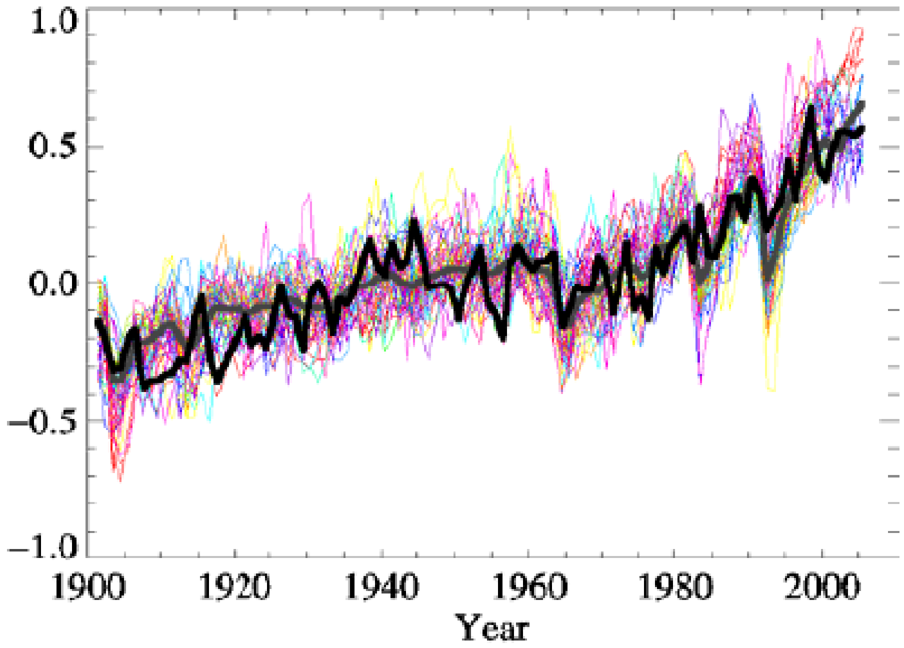
Unresolved physical processes must be handled parametrically

- Convection
- Thin and/or broken clouds
- Cloud microphysics
- Aerosols and chemistry (e.g. photochemical processes, ozone)
- Turbulence, including surface fluxes
- Sea ice
- Land ice
- Land surface processes

How Do We Know If We Have It Right?

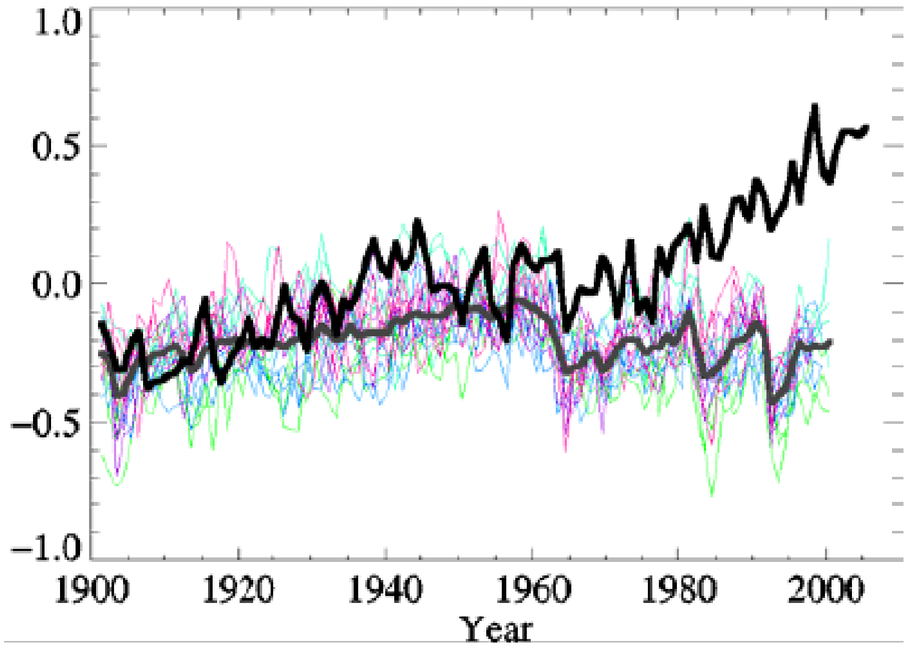
- Very few tests of model as whole: annual and diurnal cycles, weather forecasts, 20th century climate, response to orbital variations
- Fundamentally ill-posed: More free parameters than tests
- Alternative: Rigorous, off-line tests of model subcomponents. Arduous, unpopular: Necessary but not sufficient for model robustness: Model as whole may not work even though subcomponents are robust

Global mean temperature (black) and simulations using many different global models (colors) including all forcings

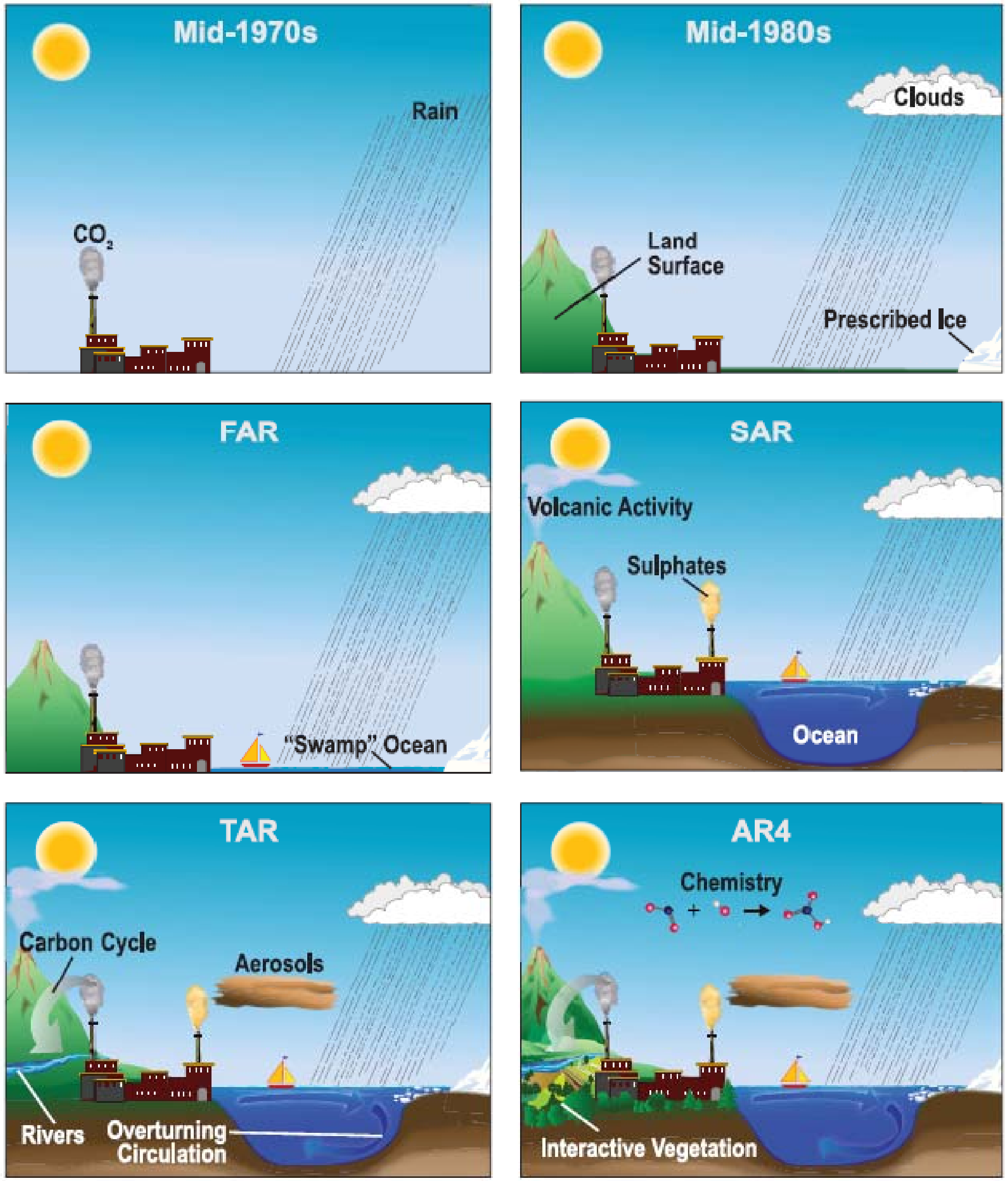


To some extent, “success” of 20th century simulations is a result of model curve fitting

Same as above, but models run with only natural forcings



Progress in Climate Modeling



IPCC Terminology:

FAR=First Assessment Report

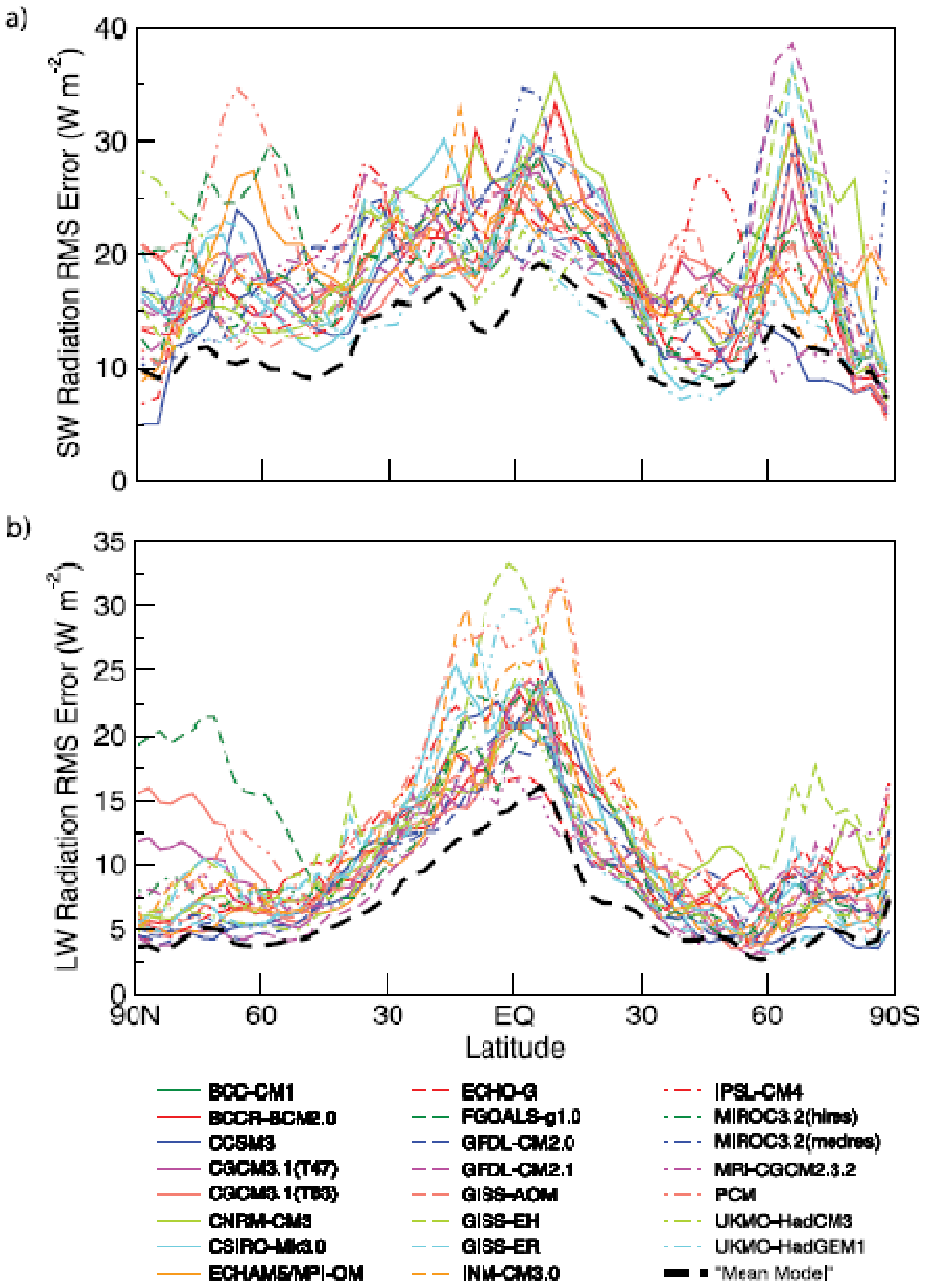
SAR=Second " "

TAR=Third " "

AR4=Assessment Report 4

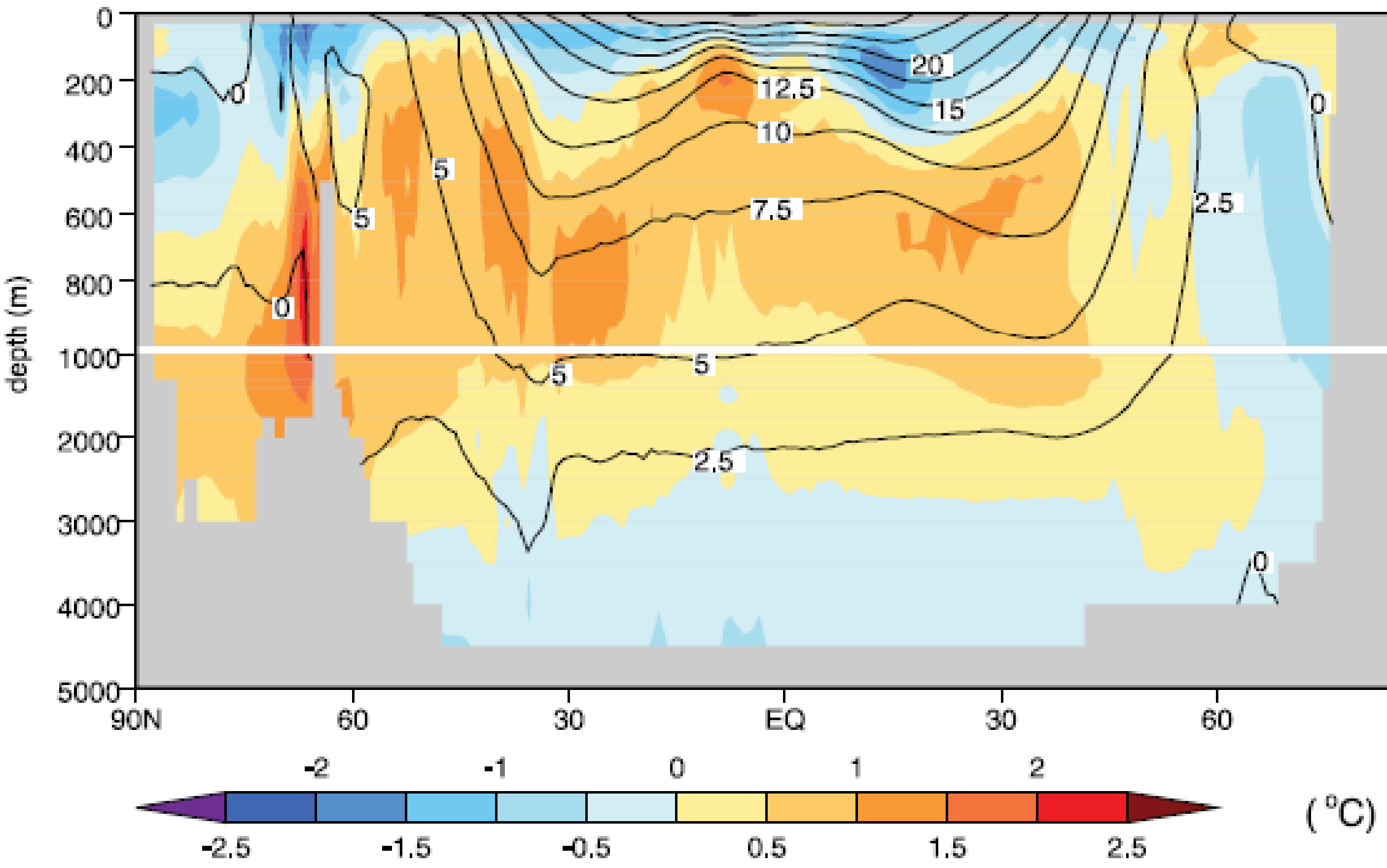
Selected Features of Some Climate Models, AR4

Model ID, Vintage	Sponsor(s), Country	Atmosphere Top Resolution[a] References	Ocean Resolution[b] Z Coord., Top BC References	Sea Ice Dynamics, Leads References	Coupling Flux Adjustments References	Land Soil, Plants, Routing References
1: BCC-CM1, 2005	Beijing Climate Center, China	top = 25 hPa T63 (1.9° x 1.9°) L16 Dong et al., 2000; CSMD, 2005; Xu et al., 2005	1.9° x 1.9° L30 depth, free surface Jin et al., 1999	no rheology or leads Xu et al., 2005	heat, momentum Yu and Zhang, 2000; CSMD, 2005	layers, canopy, routing CSMD, 2005
2: BCCR-BCM2.0, 2005	Bjerknes Centre for Climate Research, Norway	top = 10 hPa T63 (1.9° x 1.9°) L31 Déqué et al., 1994	0.5°–1.5° x 1.5° L35 density, free surface Bleck et al., 1992	rheology, leads Hibler, 1979; Harder, 1996	no adjustments Furevik et al., 2003	Layers, canopy, routing Mahfouf et al., 1995; Douville et al., 1995; Oki and Sud, 1998
3: CCSM3, 2005	National Center for Atmospheric Research, USA	top = 2.2 hPa T85 (1.4° x 1.4°) L26 Collins et al., 2004	0.3°–1° x 1° L40 depth, free surface Smith and Gent, 2002	rheology, leads Briegleb et al., 2004	no adjustments Collins et al., 2006	layers, canopy, routing Oleson et al., 2004; Branstetter, 2001
4: CGCM3.1(T47), 2005	Canadian Centre for Climate Modelling and Analysis, Canada	top = 1 hPa T47 (~2.8° x 2.8°) L31 McFarlane et al., 1992; Flato, 2005	1.9° x 1.9° L29 depth, rigid lid Pacanowski et al., 1993	rheology, leads Hibler, 1979; Flato and Hibler, 1992	heat, freshwater Flato, 2005	layers, canopy, routing Verseghy et al., 1993
5: CGCM3.1(T63), 2005		top = 1 hPa T63 (~1.9° x 1.9°) L31 McFarlane et al., 1992; Flato 2005	0.9° x 1.4° L29 depth, rigid lid Flato and Boer, 2001; Kim et al., 2002	rheology, leads Hibler, 1979; Flato and Hibler, 1992	heat, freshwater Flato, 2005	layers, canopy, routing Verseghy et al., 1993
6: CNRM-CM3, 2004	Météo-France/Centre National de Recherches Météorologiques, France	top = 0.05 hPa T63 (~1.9° x 1.9°) L45 Déqué et al., 1994	0.5°–2° x 2° L31 depth, rigid lid Madec et al., 1998	rheology, leads Hunke-Dukowicz, 1997; Salas-Mélia, 2002	no adjustments Terray et al., 1998	layers, canopy,routing Mahfouf et al., 1995; Douville et al., 1995; Oki and Sud, 1998
7: CSIRO-MK3.0, 2001	Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atmospheric Research, Australia	top = 4.5 hPa T63 (~1.9° x 1.9°) L18 Gordon et al., 2002	0.8° x 1.9° L31 depth, rigid lid Gordon et al., 2002	rheology, leads O'Farrell, 1998	no adjustments Gordon et al., 2002	layers, canopy Gordon et al., 2002
8: ECHAM5/MPI-OM, 2005	Max Planck Institute for Meteorology, Germany	top = 10 hPa T63 (~1.9° x 1.9°) L31 Roeckner et al., 2003	1.5° x 1.5° L40 depth, free surface Marsland et al., 2003	rheology, leads Hibler, 1979; Semtner, 1976	no adjustments Jungclaus et al., 2005	bucket, canopy, routing Hagemann, 2002; Hagemann and Dümenil-Gates, 2001
9: ECHO-G, 1999	Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group, Germany/Korea	top = 10 hPa T30 (~3.9° x 3.9°) L19 Roeckner et al., 1996	0.5°–2.8° x 2.8° L20 depth, free surface Wolff et al., 1997	rheology, leads Wolff et al., 1997	heat, freshwater Min et al., 2005	bucket, canopy, routing Roeckner et al., 1996; Dümenil and Todini, 1992

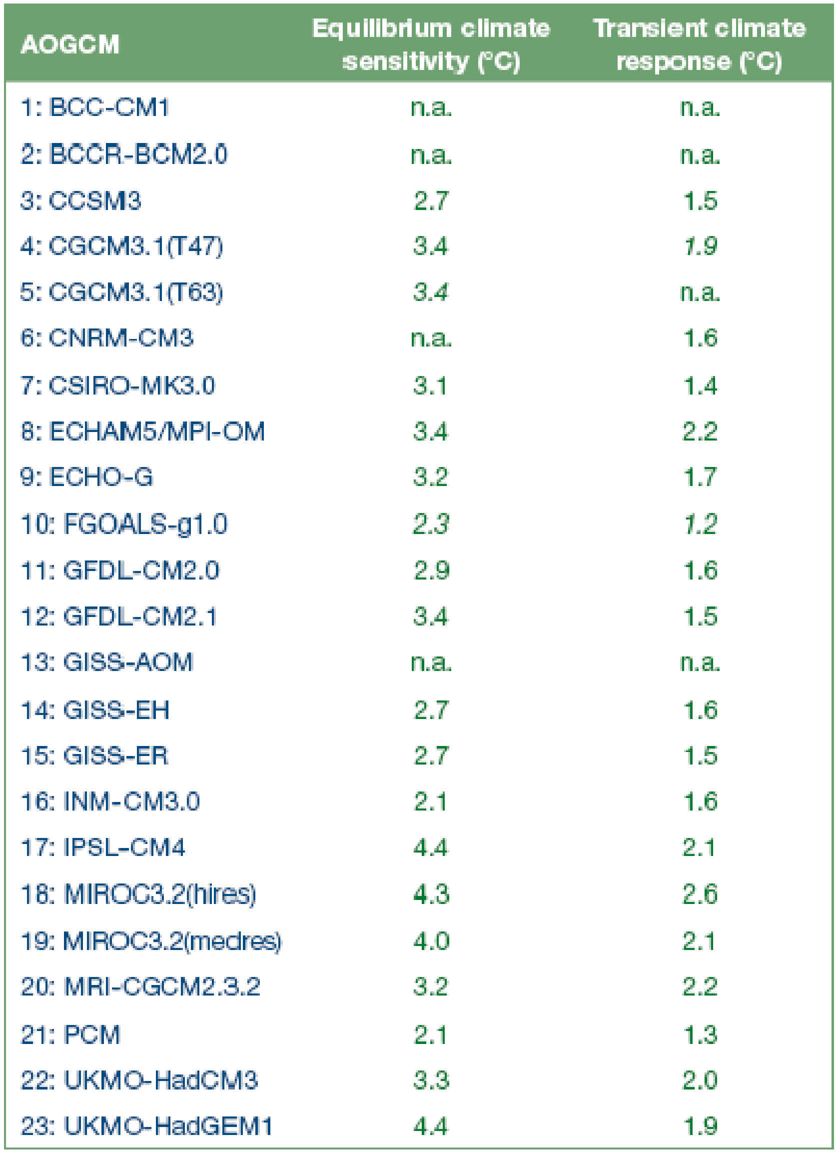


Root-mean-square error in zonally and annually averaged SW radiation (top) and LW radiation (bottom) for individual AR4 models (colors) and for ensemble mean (black dashed)

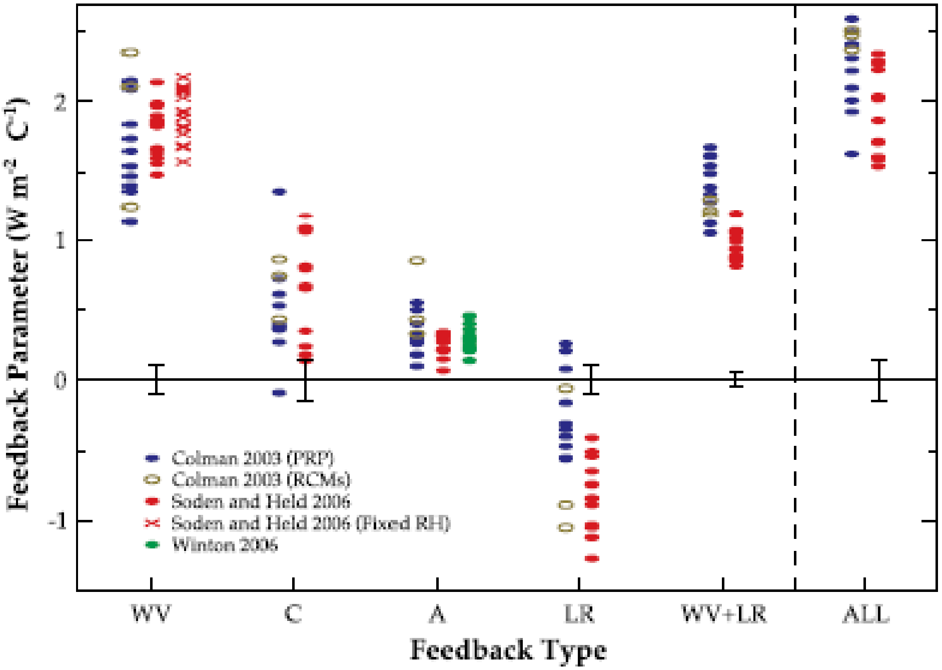
Observed time mean, zonally averaged ocean temperature (black contours), and model-mean minus observed temperature (colors) for the period 1957-1990



Model Climate Sensitivity



AOGCM	Equilibrium climate sensitivity (°C)	Transient climate response (°C)
1: BCC-CM1	n.a.	n.a.
2: BCCR-BCM2.0	n.a.	n.a.
3: CCSM3	2.7	1.5
4: CGCM3.1(T47)	3.4	*1.9*
5: CGCM3.1(T63)	*3.4*	n.a.
6: CNRM-CM3	n.a.	1.6
7: CSIRO-MK3.0	3.1	1.4
8: ECHAM5/MPI-OM	3.4	2.2
9: ECHO-G	3.2	1.7
10: FGOALS-g1.0	*2.3*	*1.2*
11: GFDL-CM2.0	2.9	1.6
12: GFDL-CM2.1	3.4	1.5
13: GISS-AOM	n.a.	n.a.
14: GISS-EH	2.7	1.6
15: GISS-ER	2.7	1.5
16: INM-CM3.0	2.1	1.6
17: IPSL-CM4	4.4	2.1
18: MIROC3.2(hires)	4.3	2.6
19: MIROC3.2(medres)	4.0	2.1
20: MRI-CGCM2.3.2	3.2	2.2
21: PCM	2.1	1.3
22: UKMO-HadCM3	3.3	2.0
23: UKMO-HadGEM1	4.4	1.9



Feedbacks in Various Models

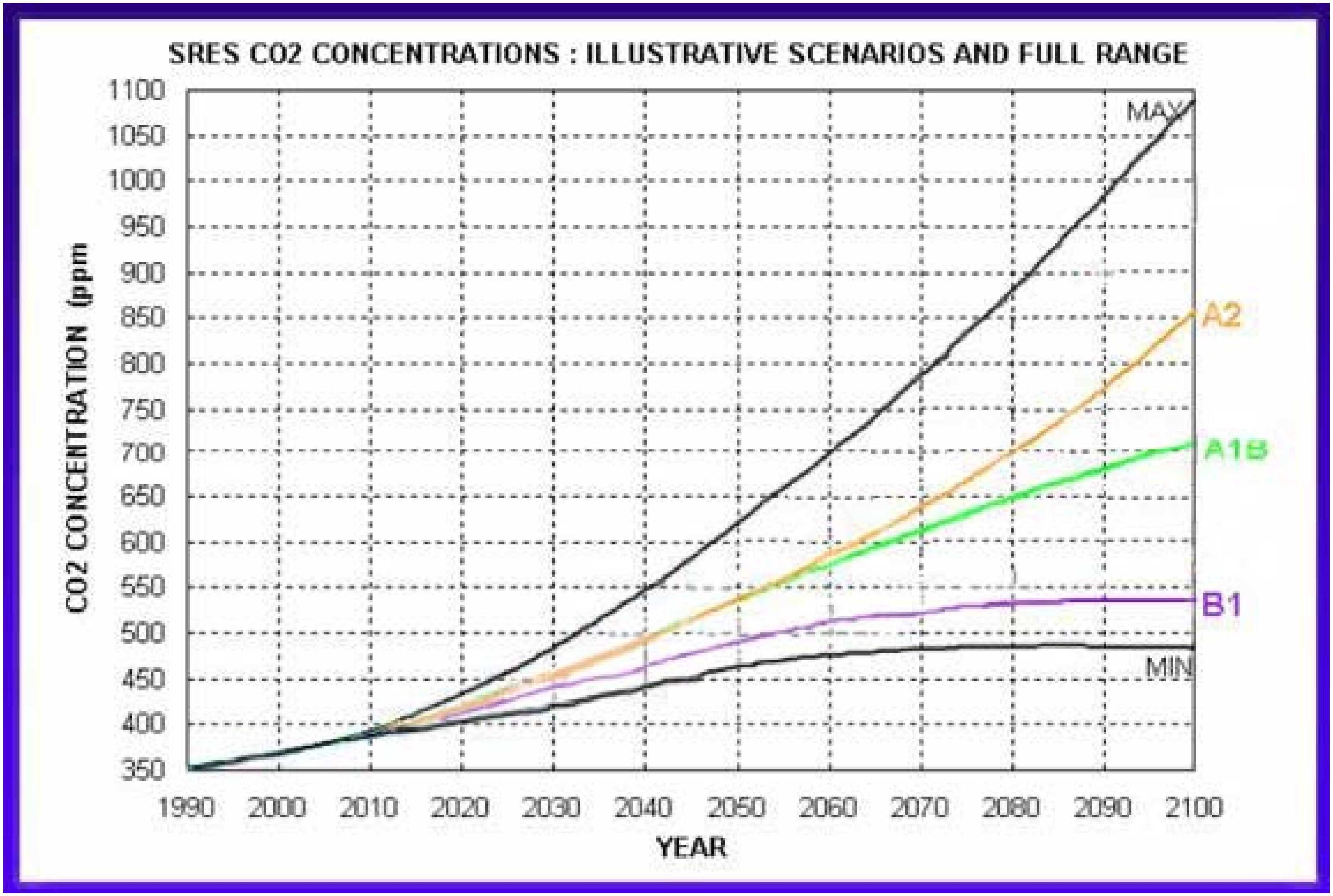
WV=water vapor

C=Cloud

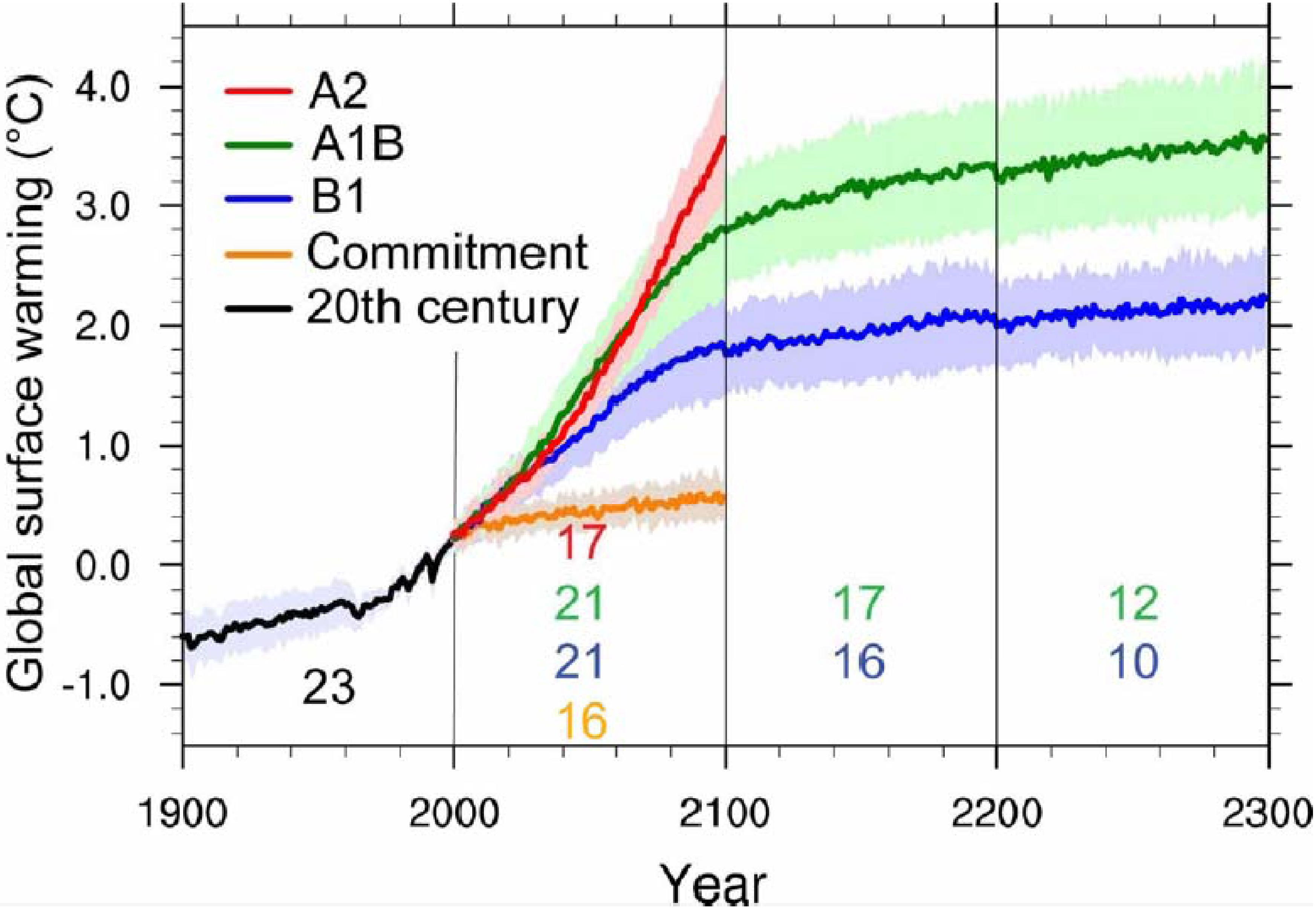
A=Albedo

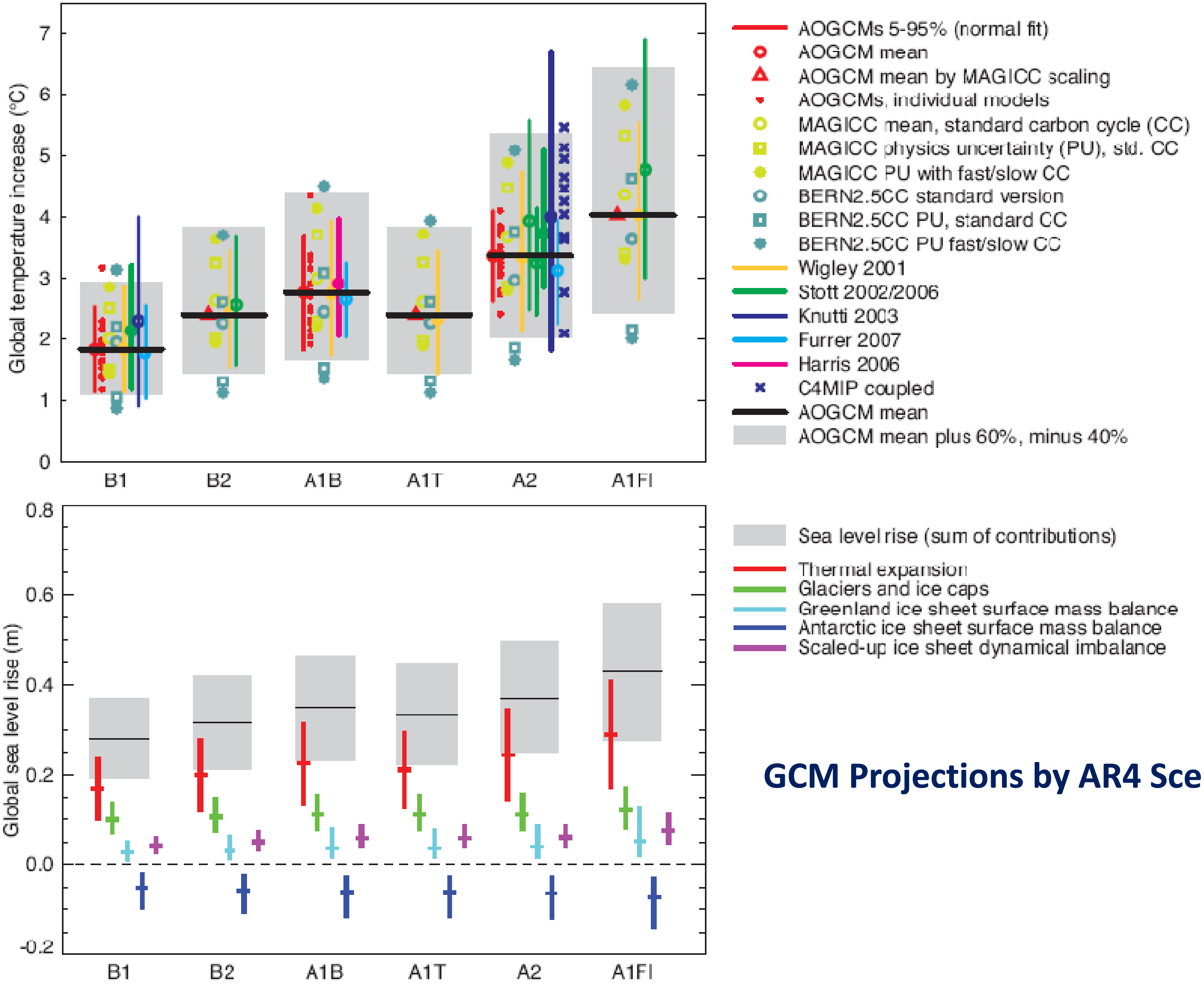
LR=Lapse Rate

IPCC Emissions Scenarios



Projected Warming:

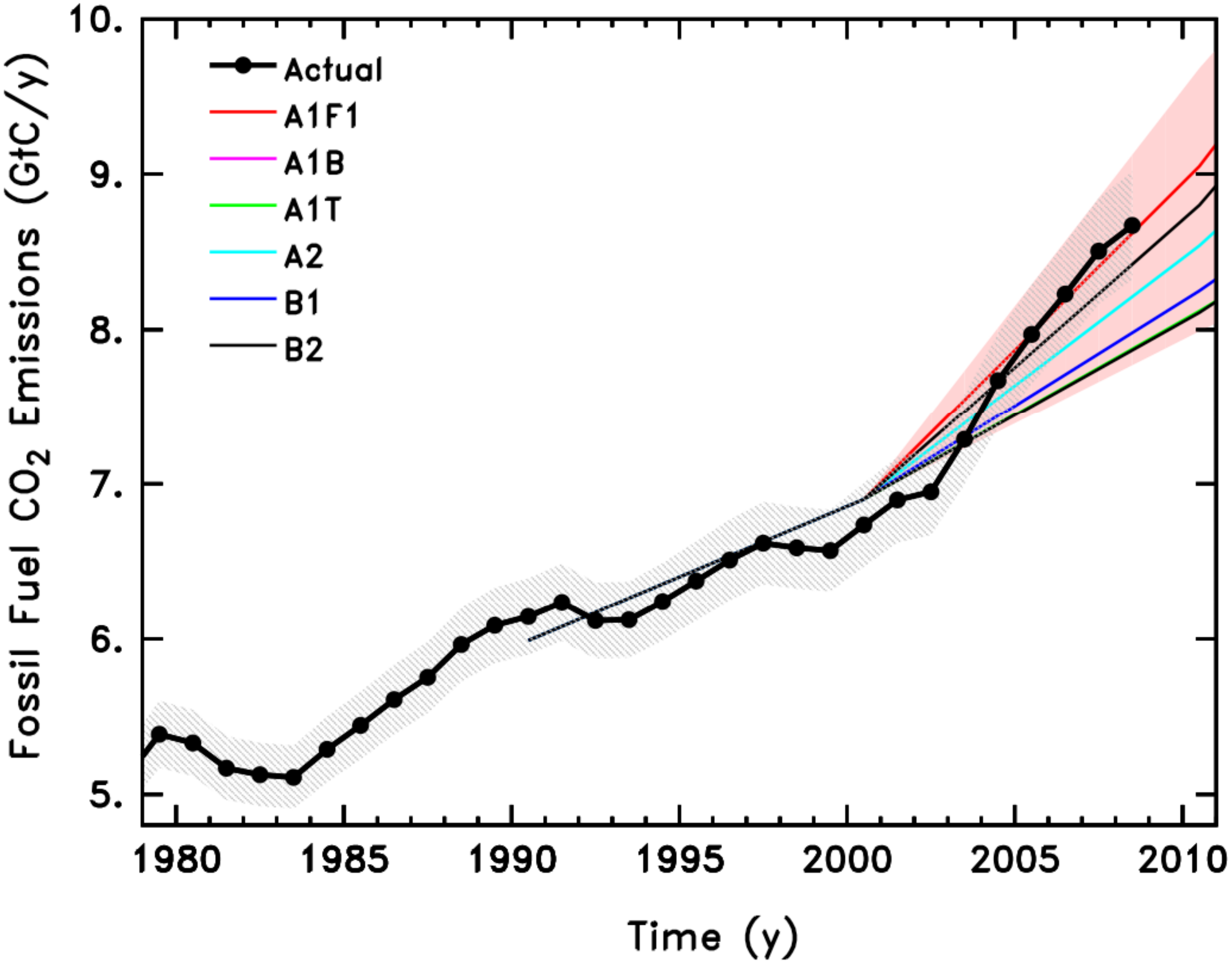




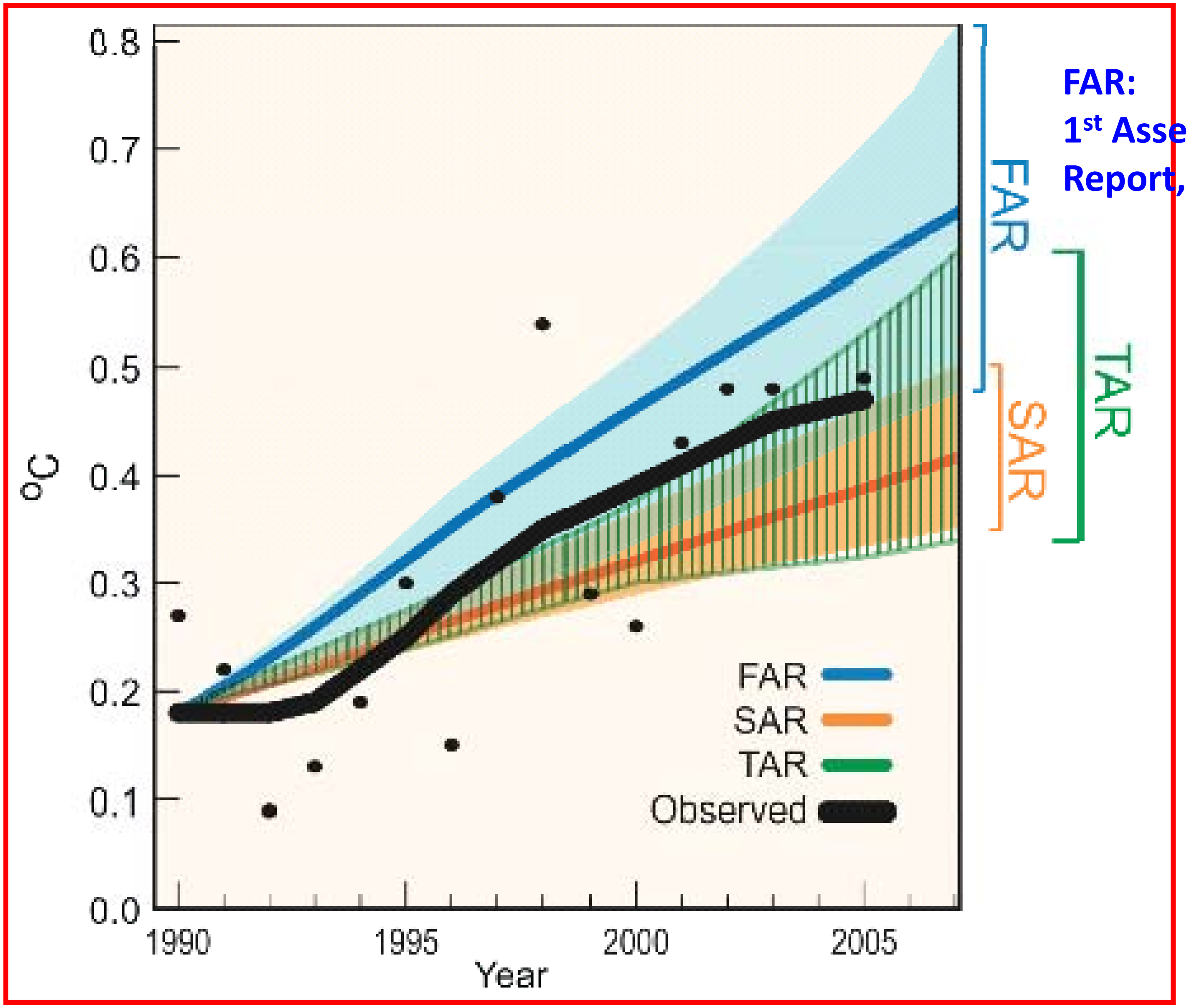
GCM Projections by AR4 Scenario

How Are Projections Doing So Far?

Global CO_2 Emissions from Fossil Fuels



A genuine out-of-sample prediction



FAR:
1st Assessment Report, 1990

Observed and modeled Arctic sea-ice extent