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 Governing Equations

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

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

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:

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

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

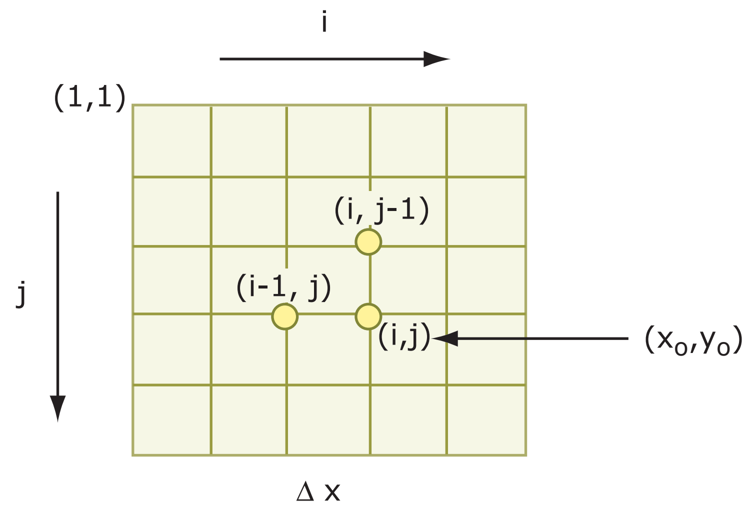
Additional equations for radiative transfer, conservation of water (atmosphere) and salinity (ocean), etc.

Numerical solution of PDEs

- Finite difference method, e.g.

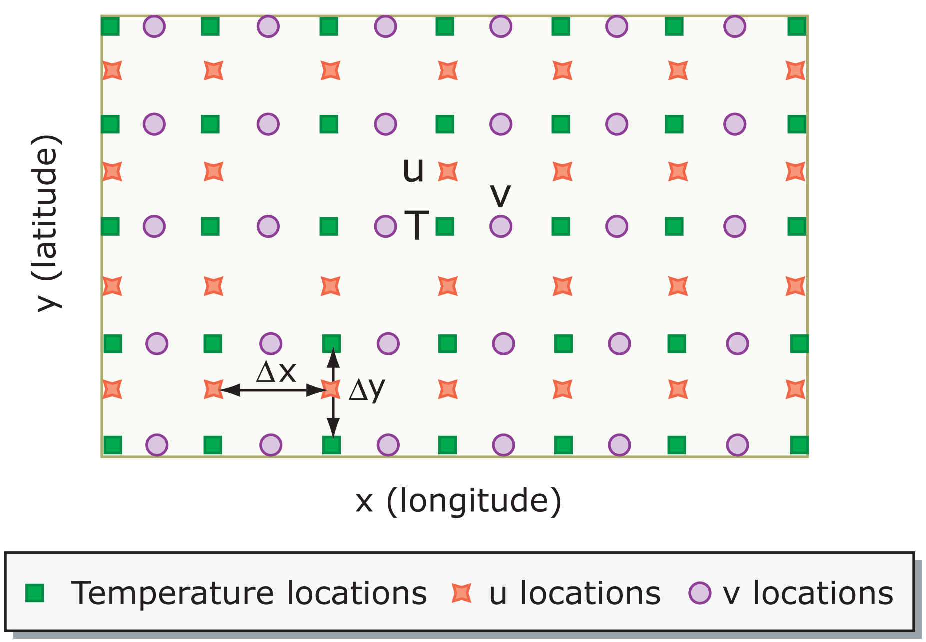
$$\frac{\partial u}{\partial t} = -c\frac{\partial u}{\partial x} \rightarrow$$

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



General finite difference grid showing index conventions.

"C" Grid



Vertical Layers

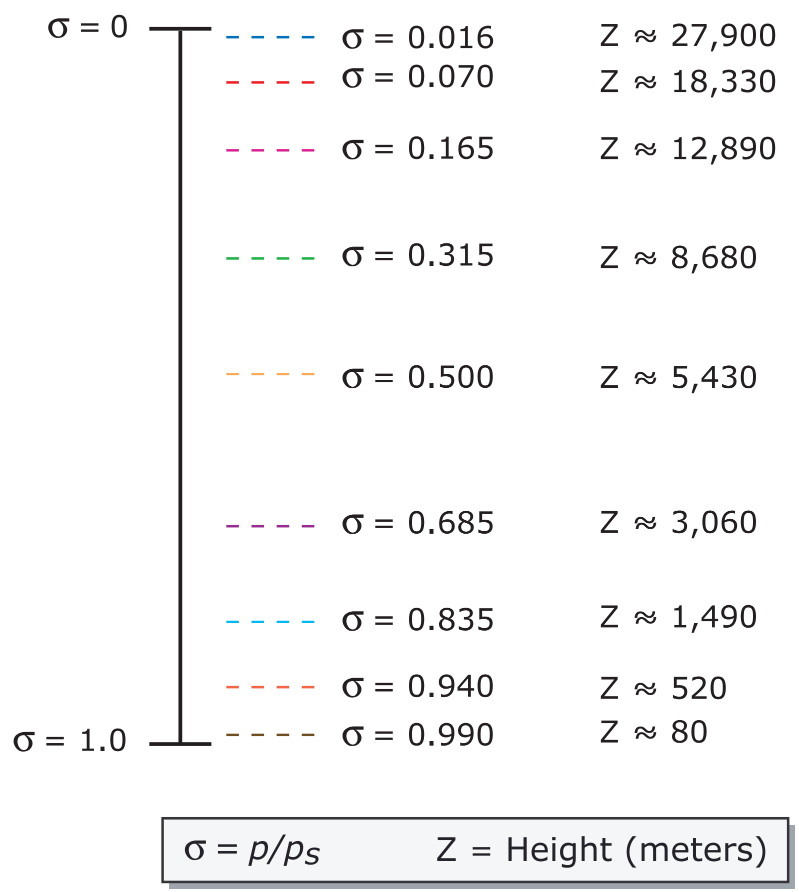
- Climate models usually have less vertical slices than typical weather forecast models
- Not equally spaced
  - More levels closer to ground and near the tropopause (things change quickly at those points
- Sigma Coordinate is typically used as the vertical coordinate

$$\sigma = \frac{p}{p_s}$$

Actual pressure

Surface pressure

Vertical Layers



Example of the vertical grid spacing in sigma coordinates, and the corresponding average altitudes of the levels in a nine-level atmospheric general circulation model employed by Manabe *et al*. (1970).

Sigma Coordinate

- **Advantages**
  - **Conforms to natural terrain (mountains are represented in models)**
  - **Will never intersect the ground like a height coordinate**
  - **Simplifies mathematical equations in model**
- **Limitations**
  - **Complicates certain computations (pressure gradient force in sloped regions**
  - **Sometimes land points extend into oceans due to smoothing near mountainous terrain**

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

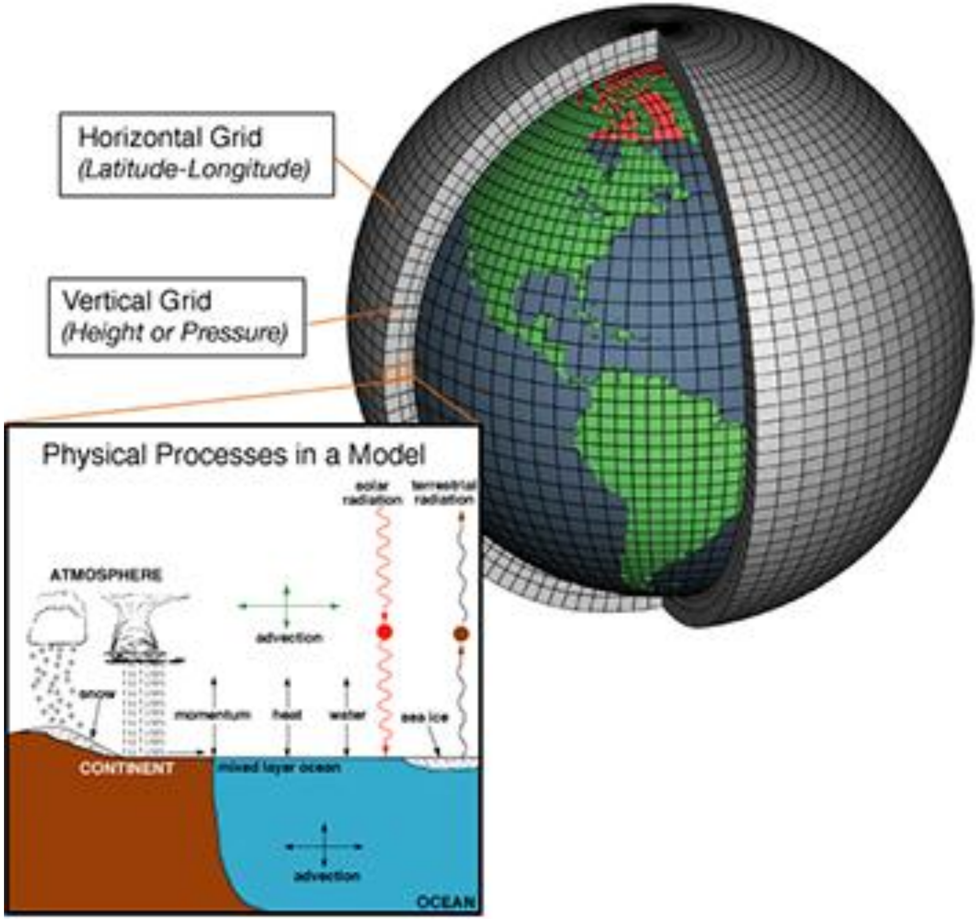


Image courtesy of NOAA.

Alternative Grids:

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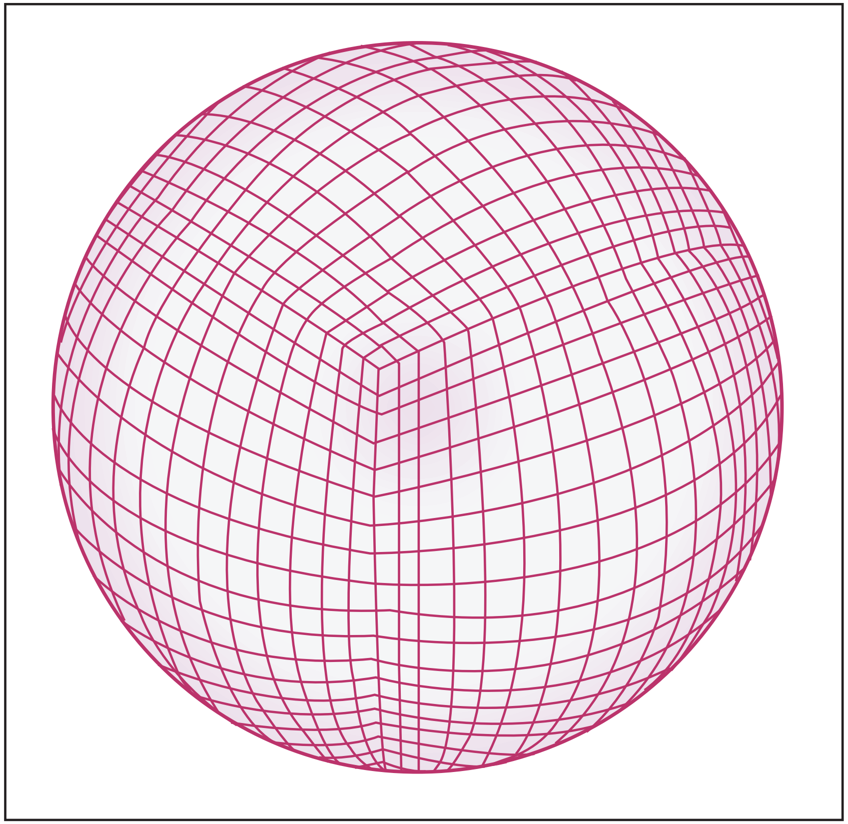
Classical spherical coordinates



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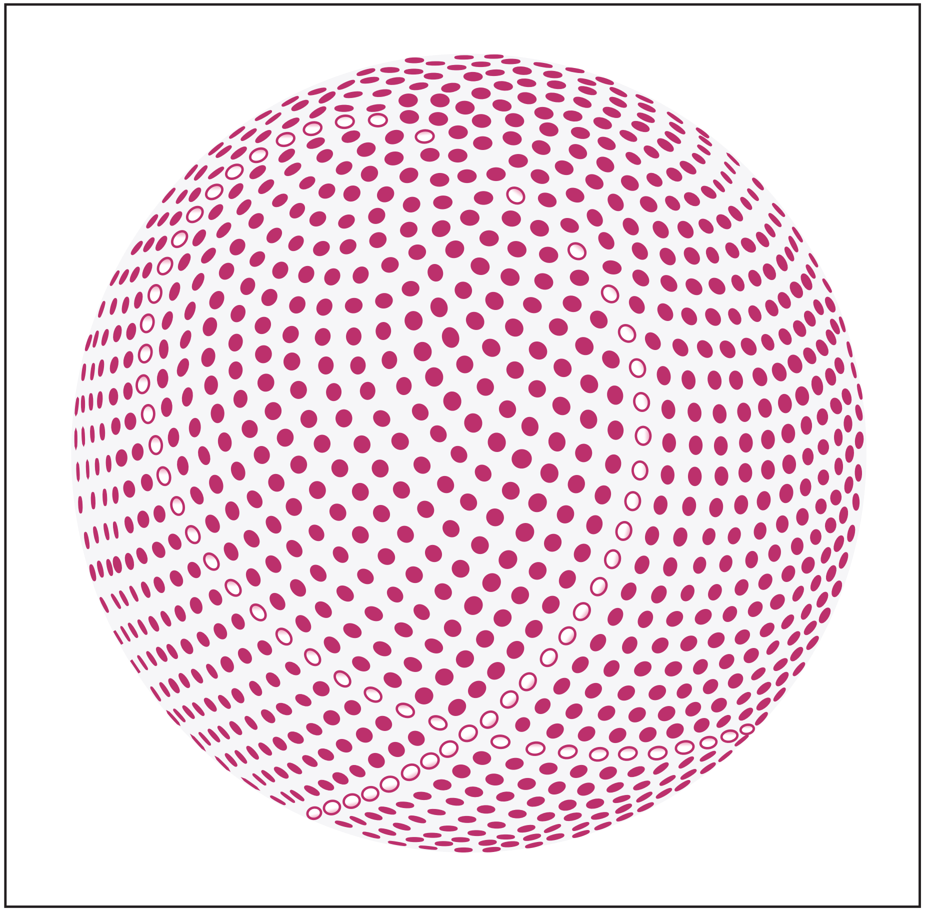
Conformal mapping of cube onto sphere

Image courtesy of lucapost. http://www.flickr.com/photos/lucapost/694780262.



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

- Spectral methods, e.g.

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

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

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

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

Must use spherical harmonics for equations on a sphere

Note: Spectral method not used for vertical differences

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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

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Norwegian physicist and meteorologist Vilhelm Bjerkes

"Father of modern meteorology"

Numerical Weather Prediction: Lewis Fry Richardson, 1922

“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.”

Richardson’s “Forecast Factory”

Image courtesy of Flickr. http://farm3.static.flickr.com/2350/1732900095_5bb3d6b1b4_o.jpg.

Weather Prediction by Numerical Process

Lewis Fry Richardson 1922

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- **Grid over domain**
- **Predict pressure, temperature, wind**

Temperature
-->density
→ Pressure

Pressure gradient
→Wind
→ temperature

Weather Prediction by Numerical Process

Lewis Fry Richardson 1922

$$\frac{\partial p_s}{\partial t}$$

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- **Predicted:**
  145 mb/ 6 hrs

- **Observed:**
  -1.0 mb / 6 hs

The ENIAC: Electronic Numerical Integrator And Computer (1946)

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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)

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- **Mid-late 1950s**
  - **First routine numerical weather forecasts by U.S. Joint Numerical Weather Prediction Unit**
  - **First efforts to regularly collect weather data at surface and upper atmosphere**
  - **Major general circulation modeling effort evolved into the Geophysical Fluid Dynamics Laboratory at Princeton University**

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Joseph Smagorinsky, Former GFDL Director

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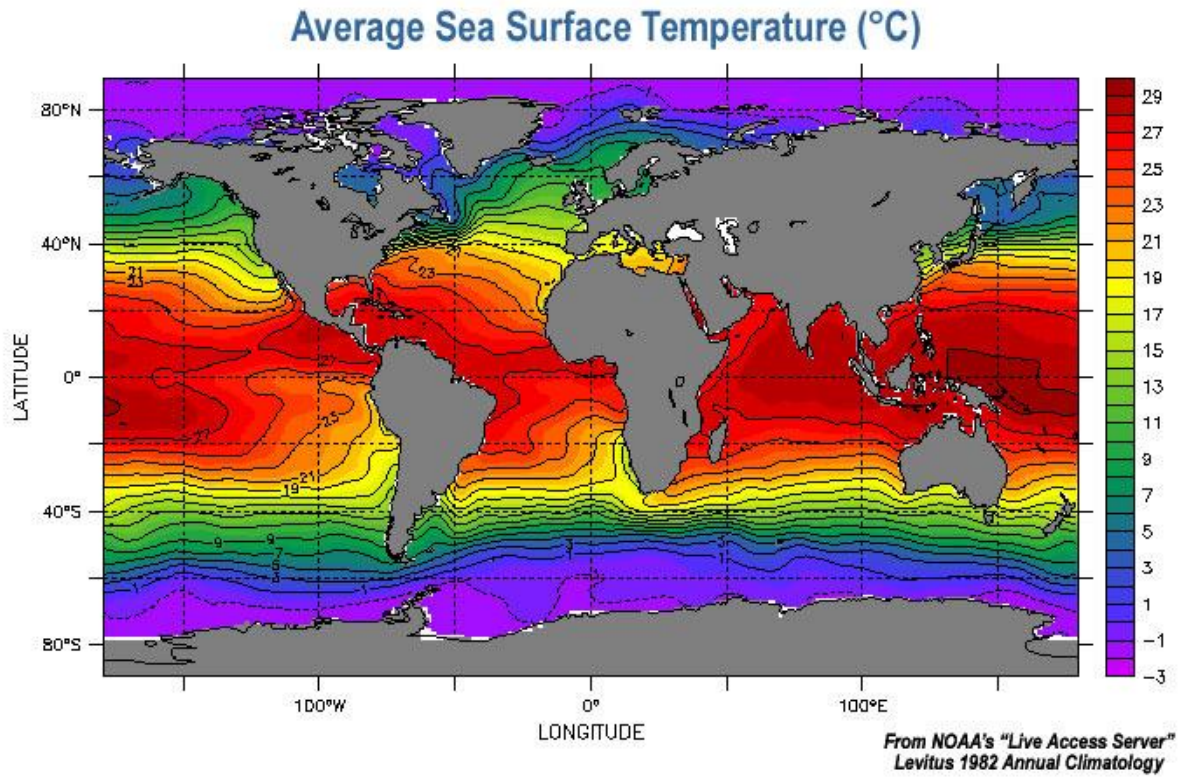
Observed (left) and 24-hour forecast (right) of 500 hPa geopotential heights (thick) and vorticity (thin) for 0300 GMT 31 January 1949

- **Early to mid 1960s**
  - **Ocean models developed**
  - **Roles of sea ice, snow, land processes, and biosphere begin to be incorporated into general circulation models (GCMs)**



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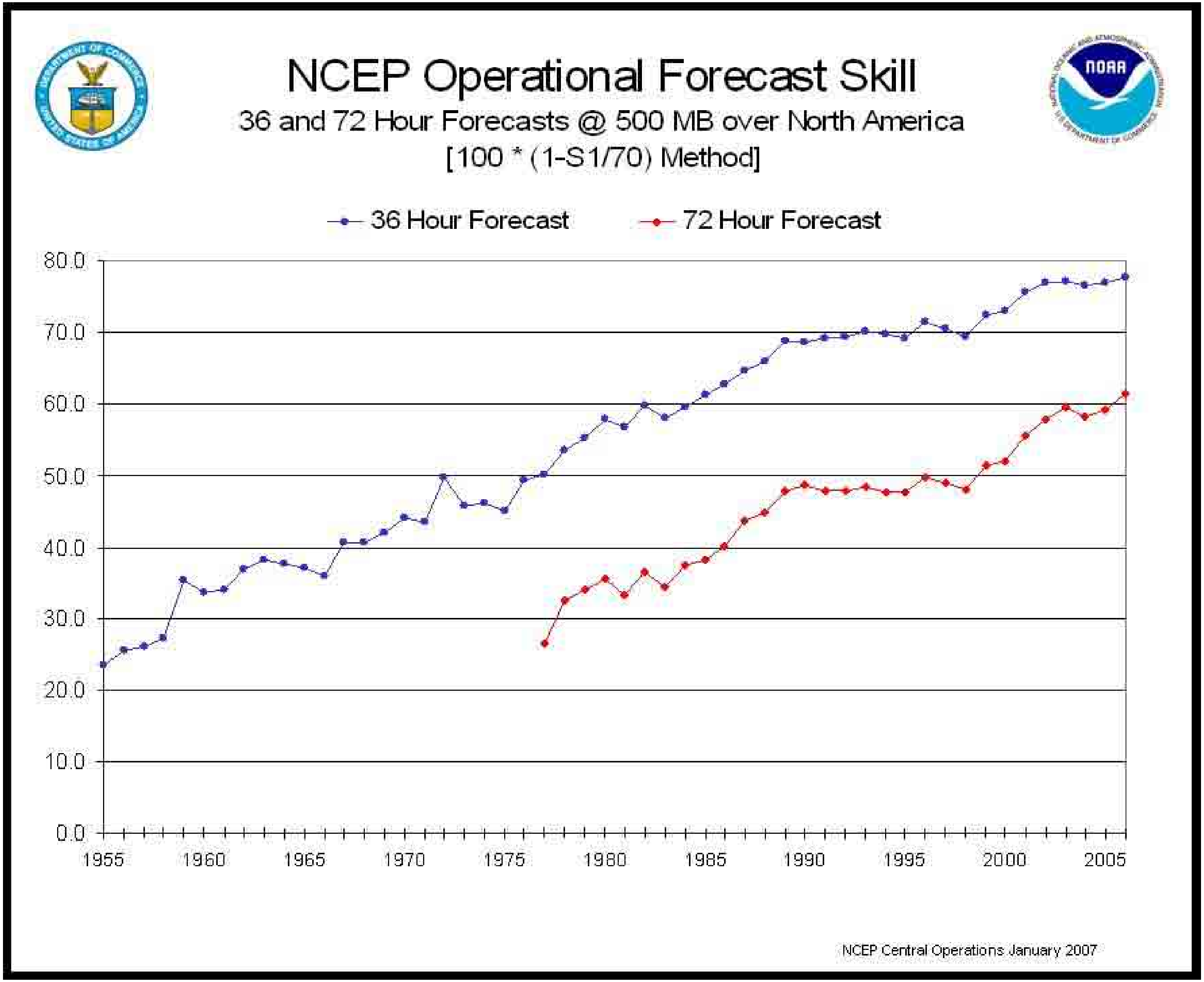

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500 hPa anomaly correlations

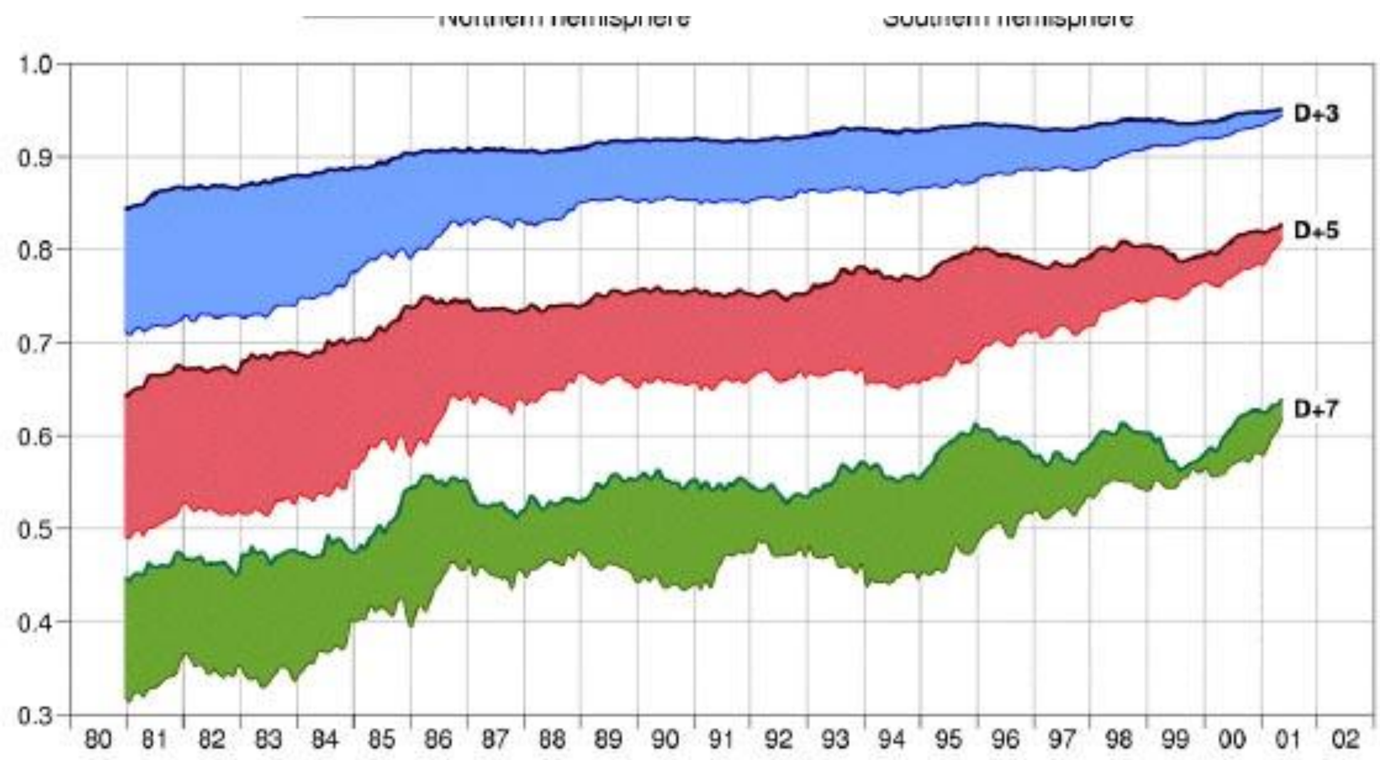

Image courtesy of European Centre for Medium-Range Weather Forecasts (ECMWF). Used with permission.

Upper curves: Northern Hemisphere; Lower curves: Southern Hemisphere

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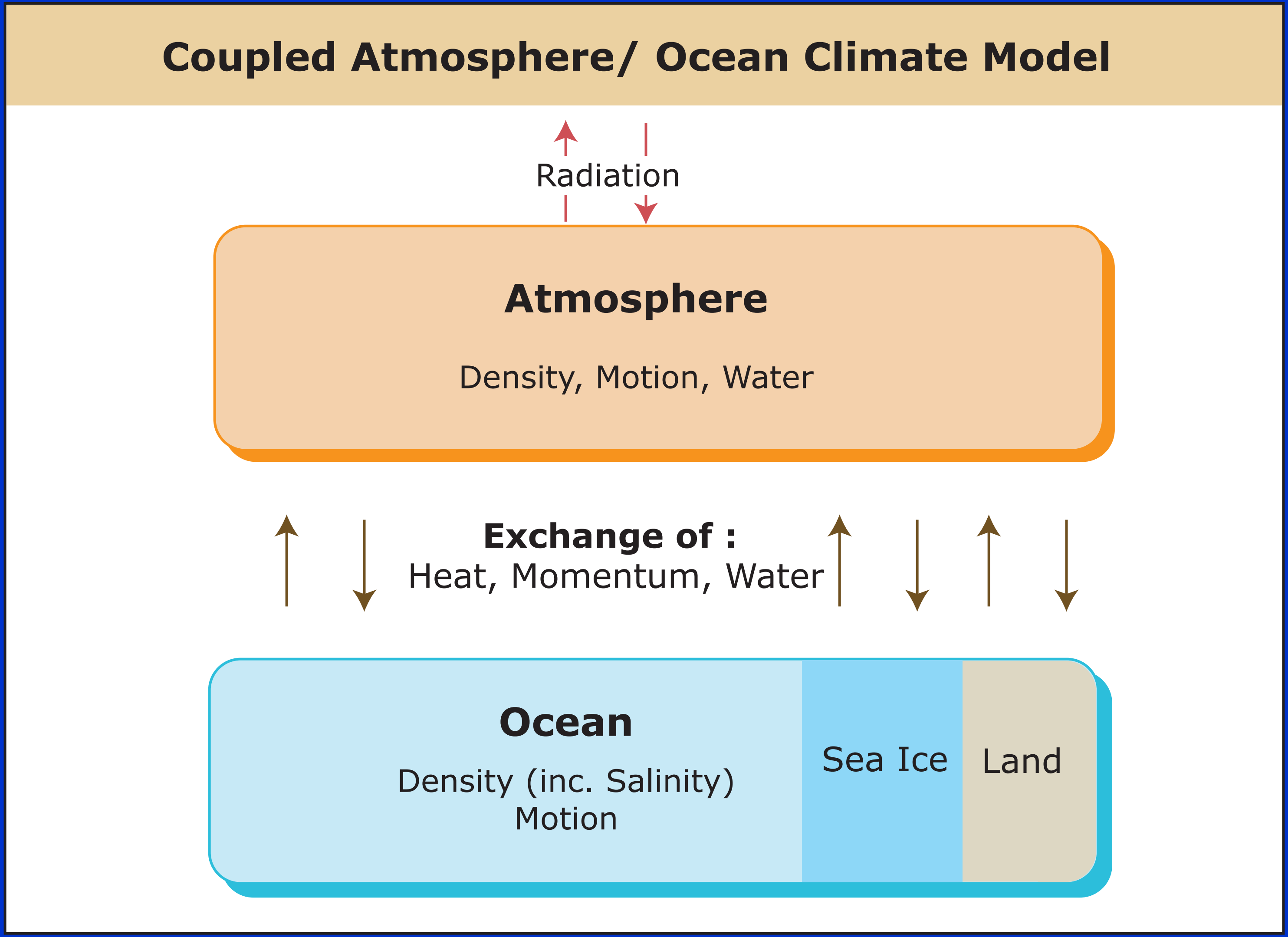
What is in a climate model?

- Atmospheric general circulation model
  - Dynamics
  - Sub-grid scale parameterized physics processes
    - Turbulence, solar/infrared radiation transport, clouds.
- Oceanic general circulation model
  - Dynamics (mostly)
- Sea ice model
  - Viscous elastic plastic dynamics
  - Thermodynamics
- Land Model
  - Energy and moisture budgets
  - Biology
- Chemistry
  - Tracer advection, possibly stiff rate equations.



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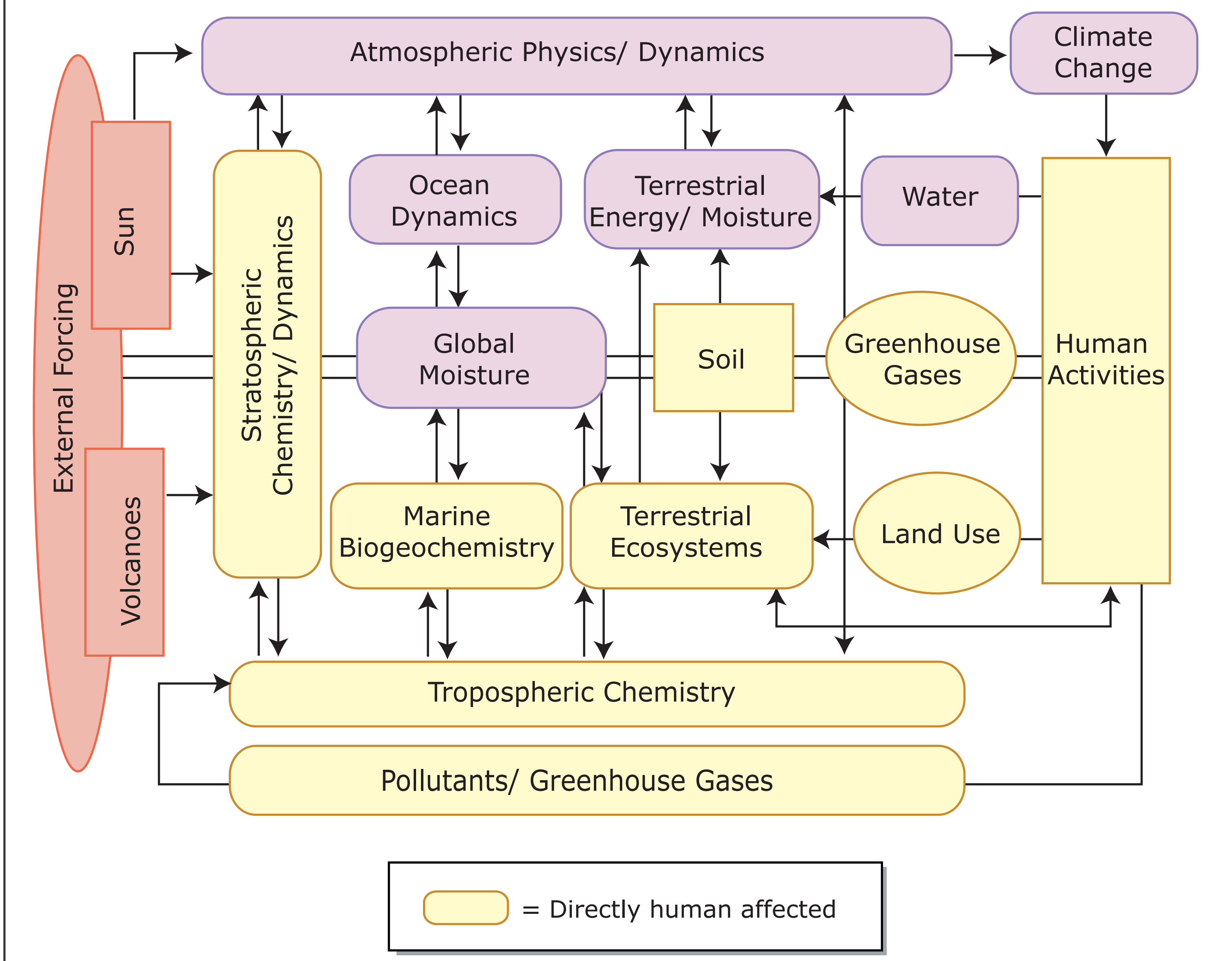
Physical Climate System



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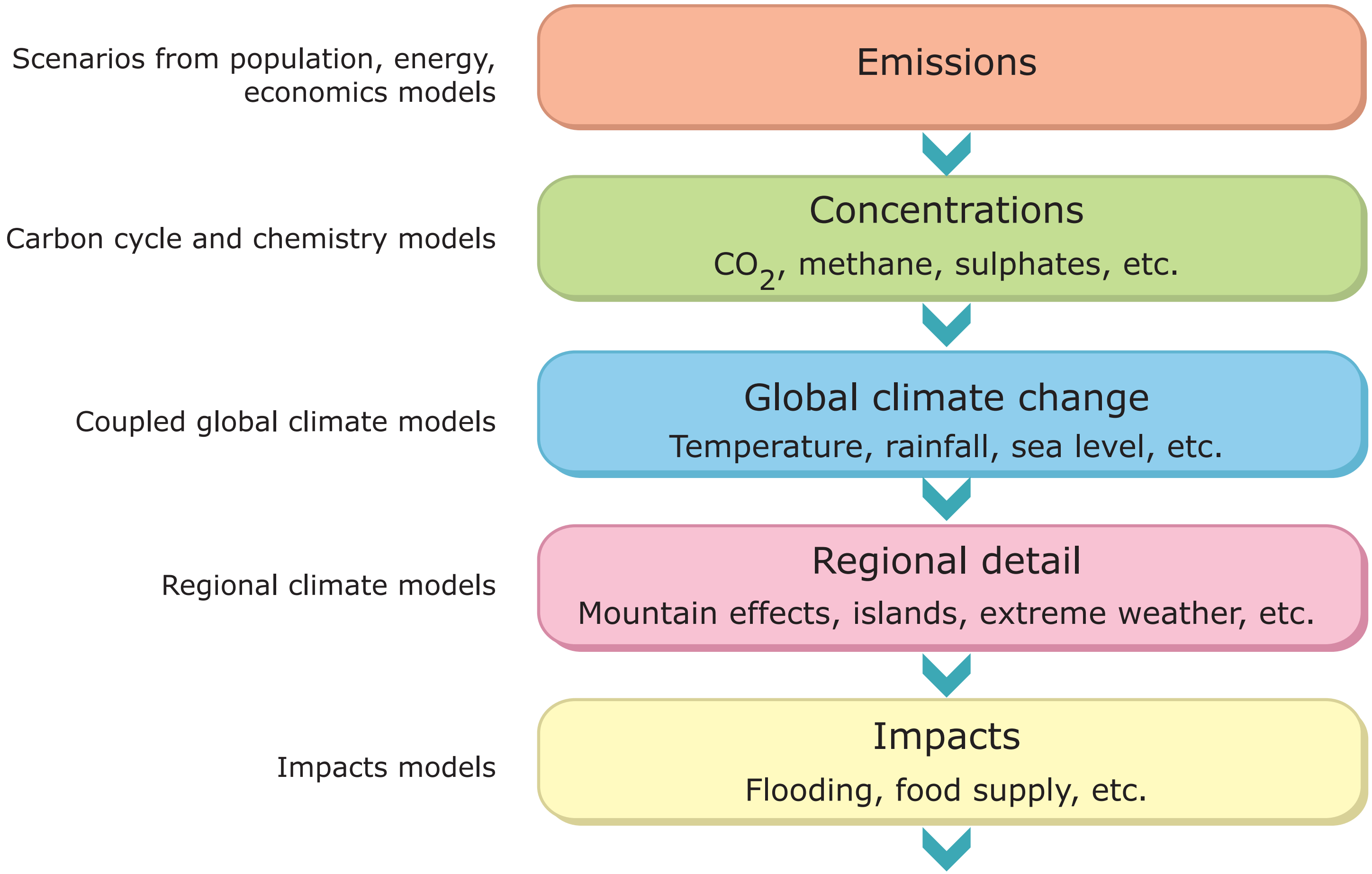
Predicting impacts of climate change



The main stages required to provide climate change scenarios for assessing the impacts of climate change.

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Hadley Centre - PRECIS brochure

Modern climate models

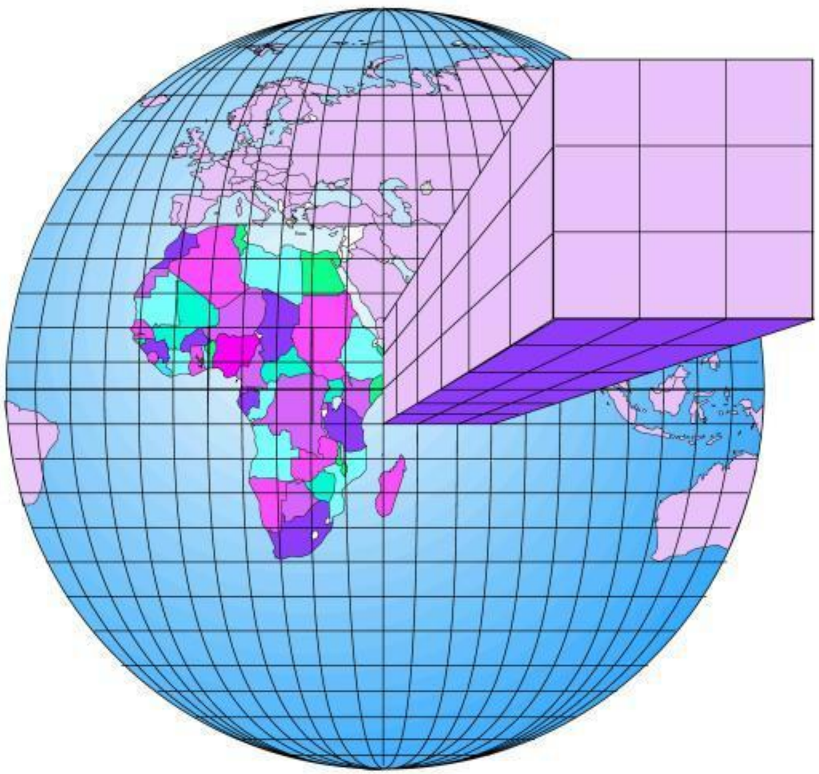


Image courtesy of NASA.

- Forcing: solar irradiance, volcanic aerosols, greenhouse gases, …

- Predict: T, p, wind, clouds, water vapor, soil moisture, ocean current, salinity, sea ice, …

- Very high spatial resolution:
    <1 deg lat/lon resolution
    ~50 atm, ~30 ocn, ~10 soil layers

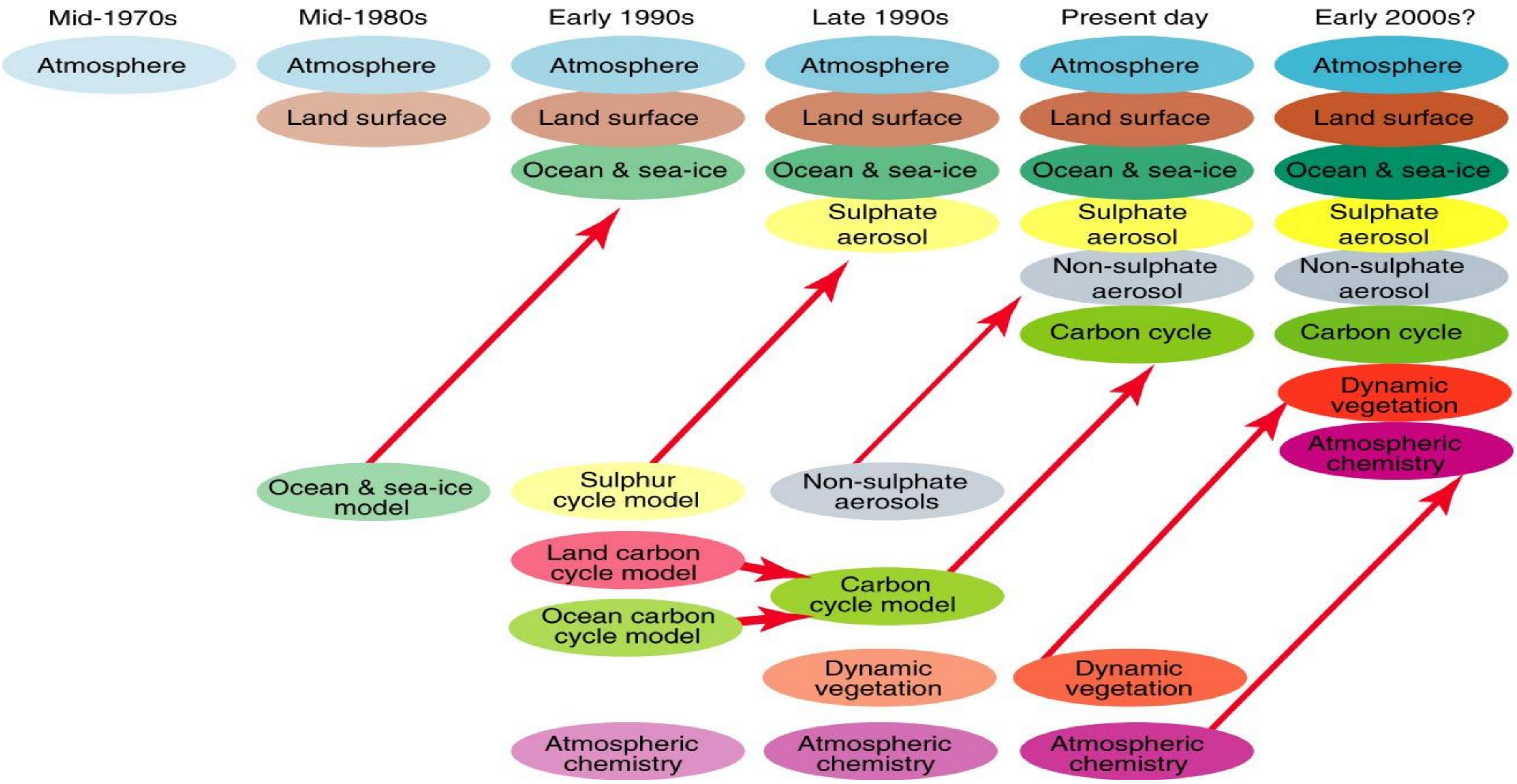
==> 6.5 million grid boxes

- Very small time steps (~minutes)

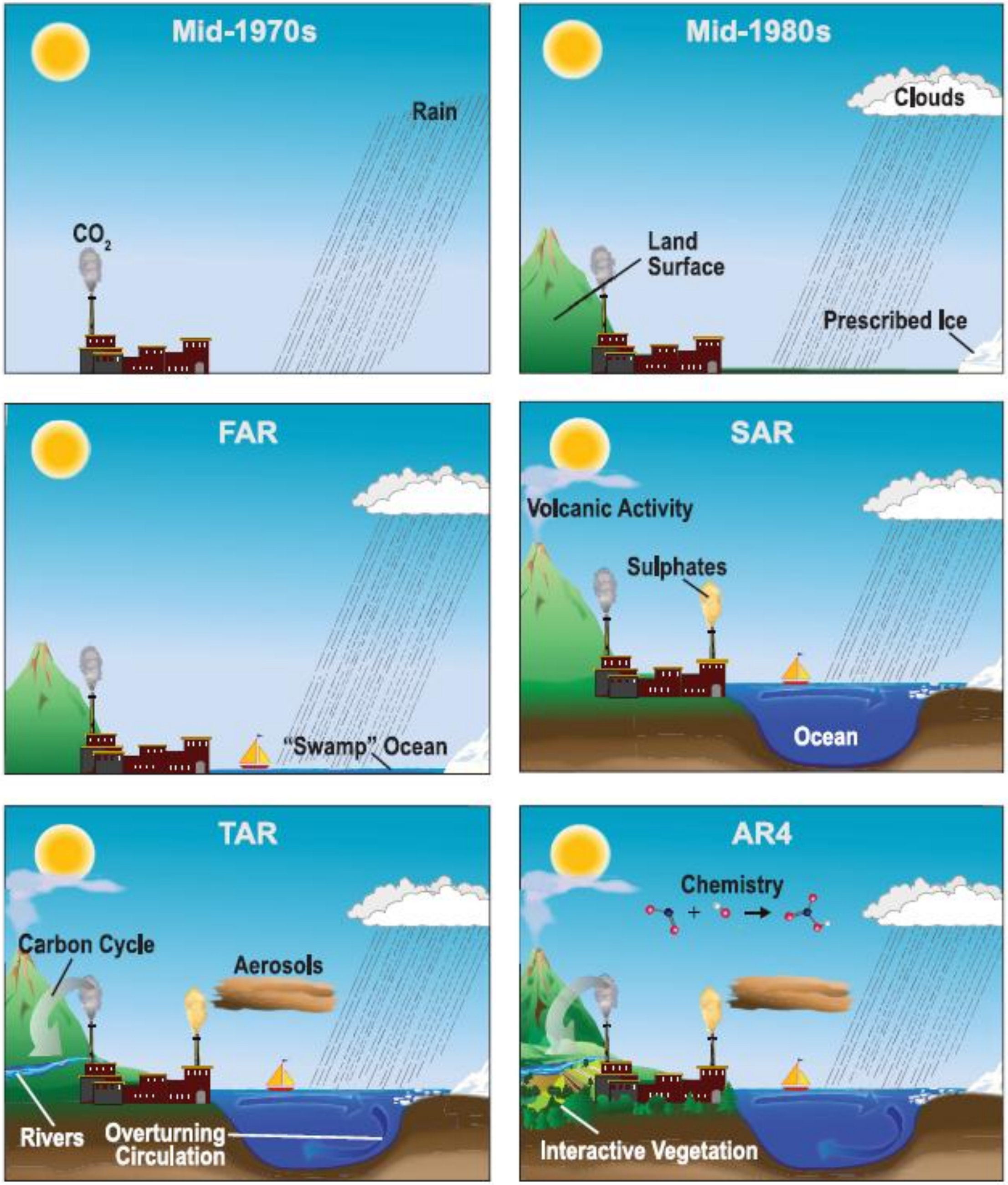
- Ensemble runs multiple experiments)

Model experiments (e.g. 1800-2100) take weeks to months on supercomputers

The Development of Climate models, Past, Present and Future



Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Box 3, Figure 1. Cambridge University Press. Used with permission.



Progress in Climate Modeling

IPCC Terminology:

FAR=First Assessment Report

SAR=Second " "

TAR=Third " "

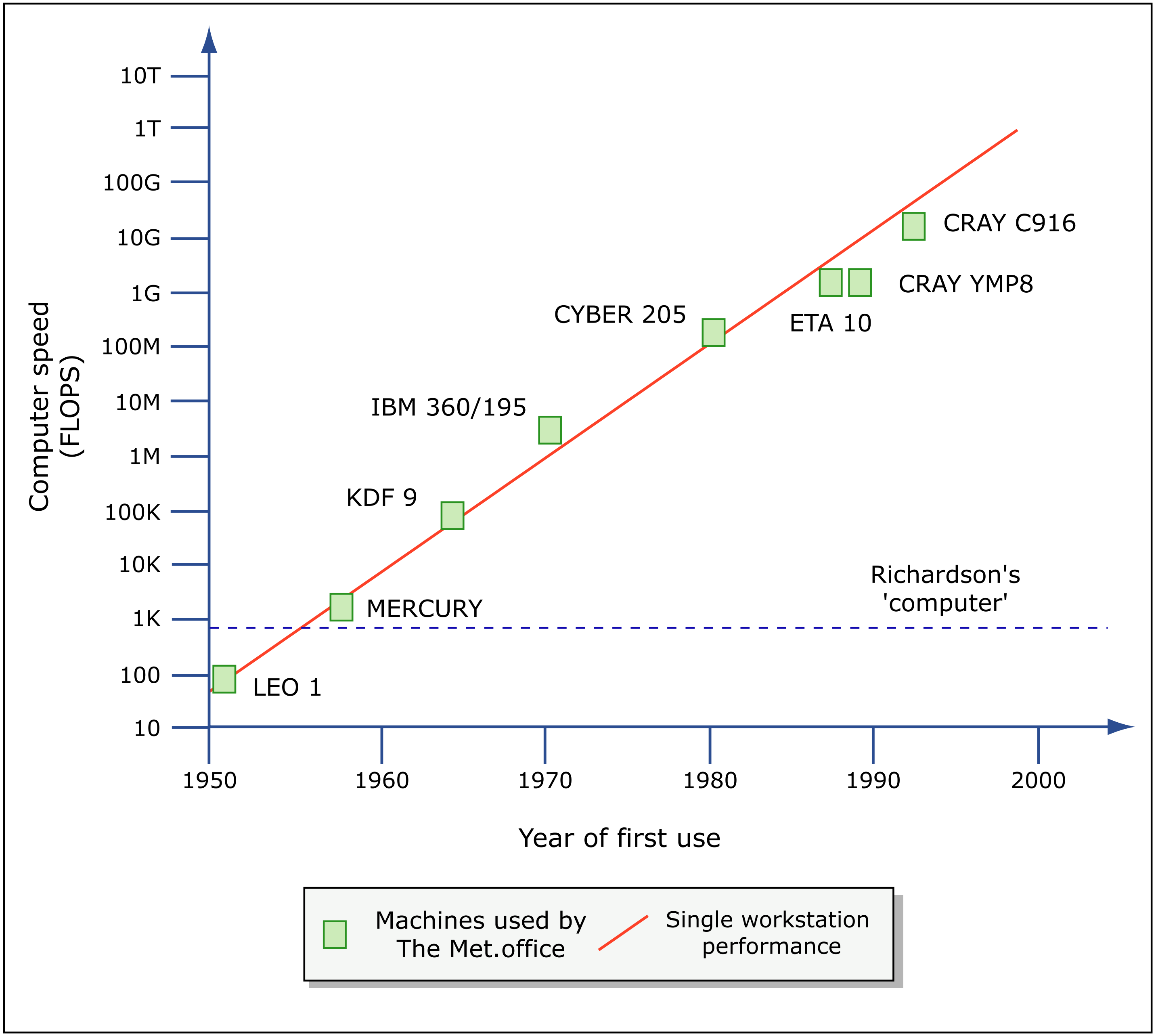
AR4=Assessment Report 4

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 1.2. Cambridge University Press. Used with permission.

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

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Table 8.1. Cambridge University Press. Used with permission.



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BlueGene/L

- IBM
- MPP (massively parallel processing)
- #1 on top500 as of November 2004
- 32,768 processors (700Mhz)
- 70.72 Teraflops (trillions of FLOPS)
- Runs linux
- DNA, climate simulation, financial risk
- Cost more than $100 million

Earth Simulator

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