A Brief History of Climate Modeling and its Connection to HPC

Warren M. Washington
National Center for Atmospheric Research

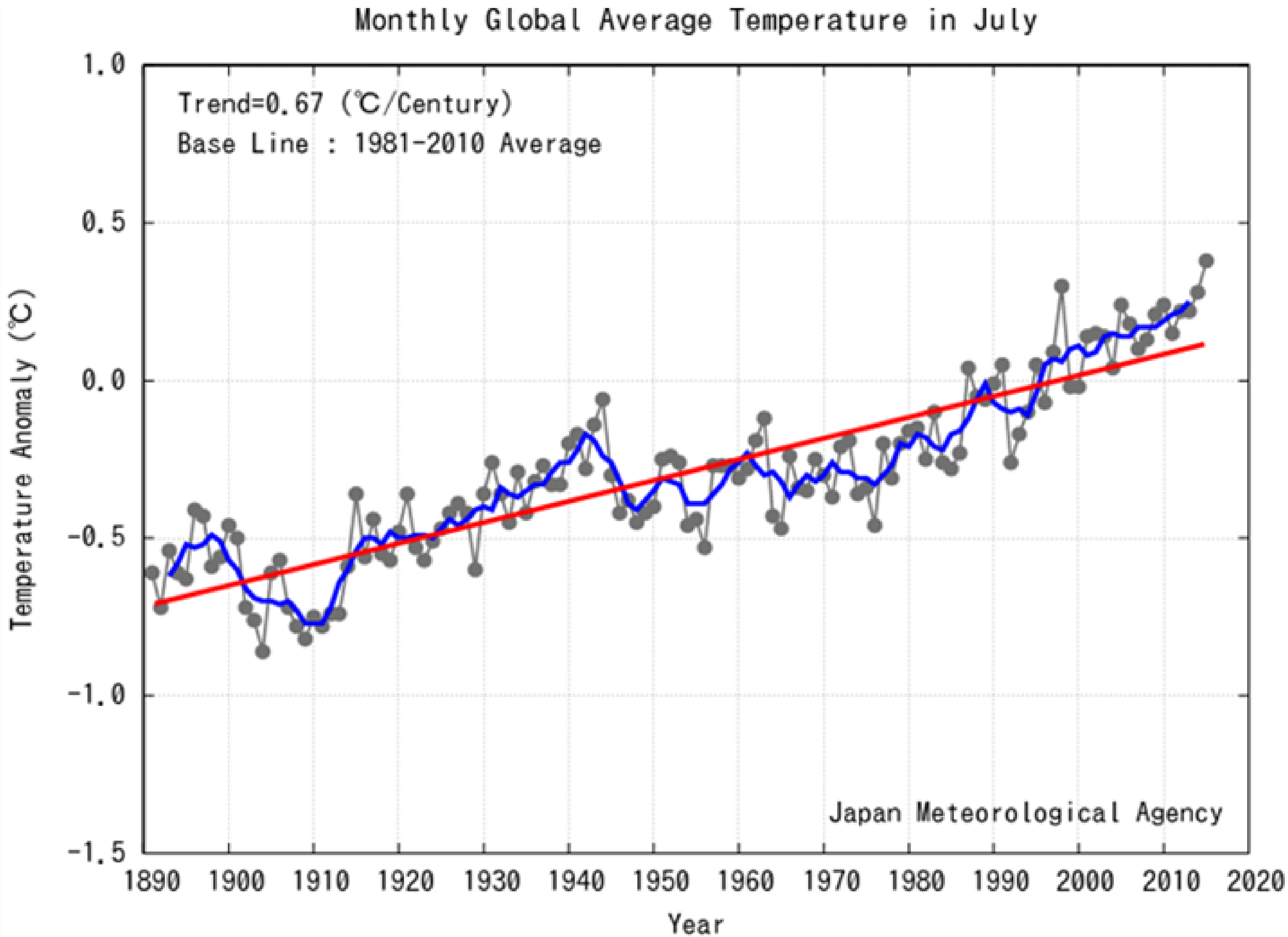
International HPC Summer School 2017

June 29, 2017

NCAR

U.S. DEPARTMENT OF ENERGY
Office of Science

The History of Climate Modeling



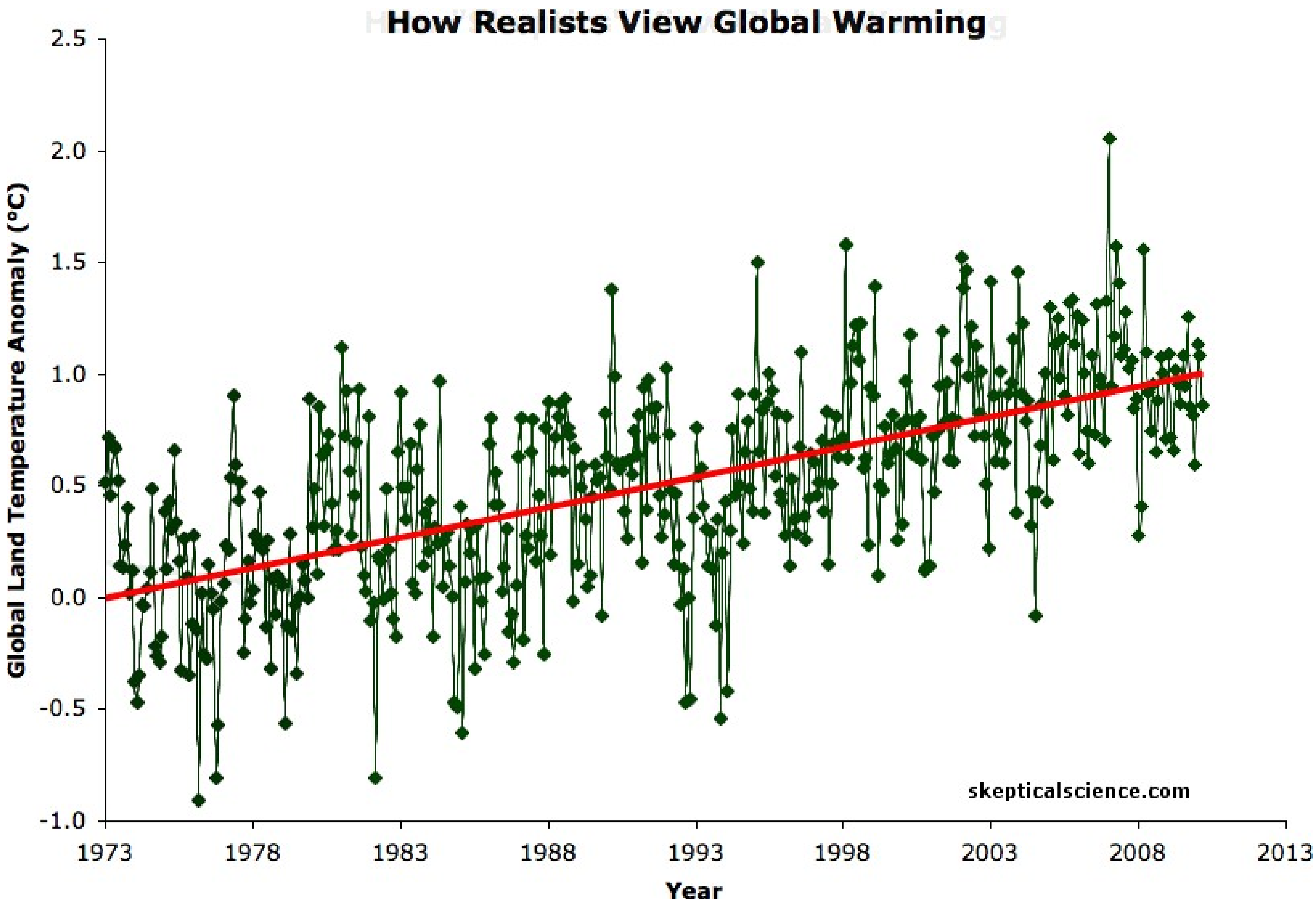
Anomalies are deviation from baseline (1981-2010 Average).

The black thin line indicates surface temperature anomaly of each year.

The blue line indicates their 5-year running mean.

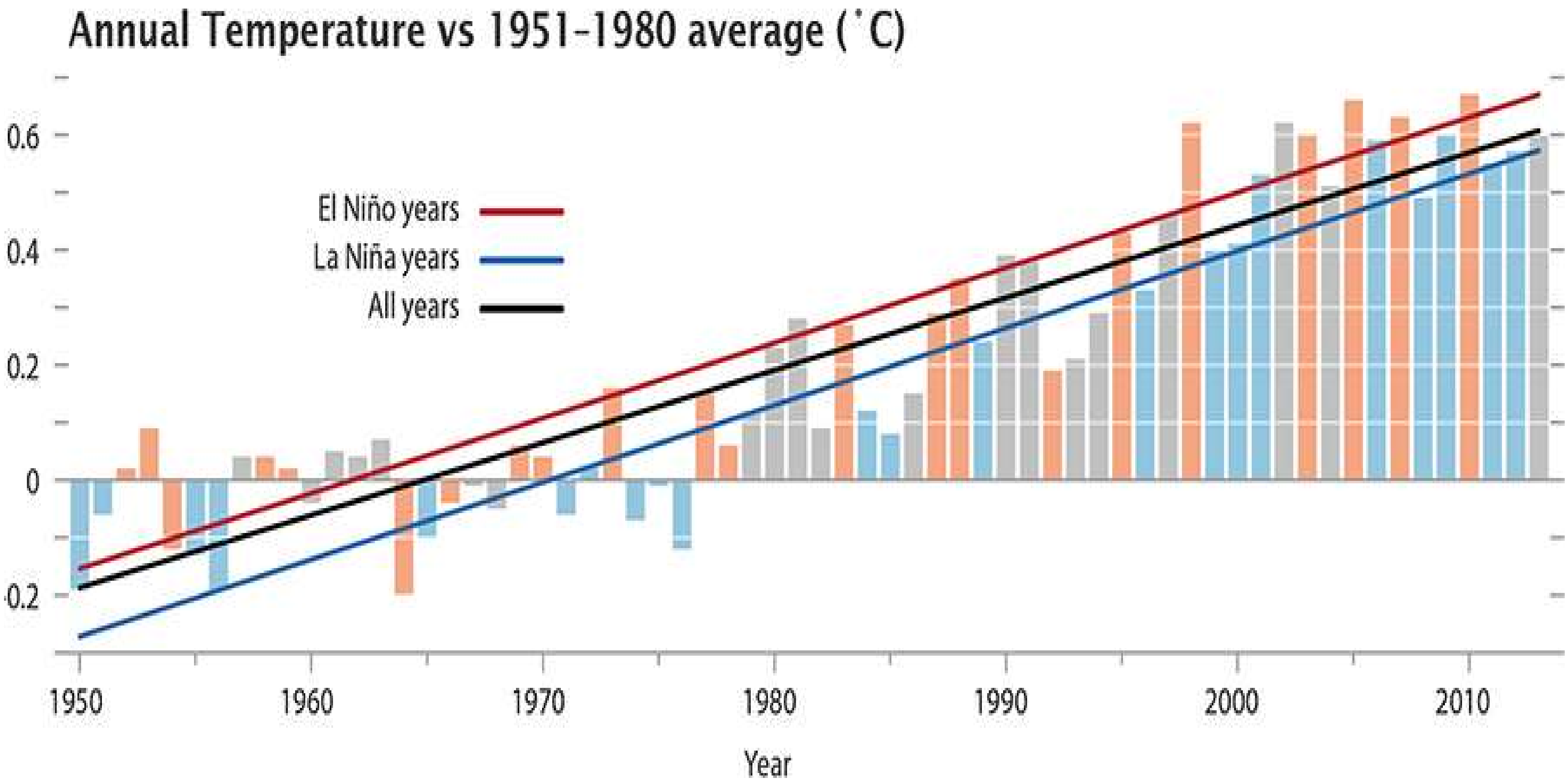
The red line indicates the long-term linear trend.

Two Views on Global Warming: Climate Scientists and Skeptics



The reasons for "hiatus periods" are unclear, some research indicates that heat goes into the deeper ocean or caused by smaller volcanic eruptions that adds aerosols to the atmosphere.

Global Surface Temperature
El Niño vs. La Niña years



Laws of Physics, Chemistry, and Biology

- Equations govern the dynamics of atmosphere, ocean, vegetation, and sea ice
- Equations put into a form that can be solved on modern multi-processor computer systems
- Physical processes such as precipitation, radiation (solar and terrestrial), vegetation, boundary transfers of heat, momentum, and moisture at earth's surface are included
- Forcings: GHGs, Volcanic, Solar variations

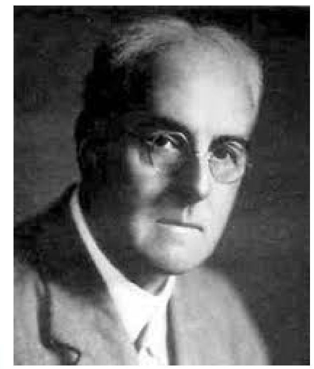
Mathematical Equations (known since 1904)

V. Bjerknes

Eqs. of Momentum

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right) v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial\lambda} + F_\lambda$$

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right) u = -\frac{1}{\rho a}\frac{\partial p}{\partial\phi} + F_\phi$$



L. F. Richardson

Hydrostatic

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

Conservation of mass

$$\frac{\partial\rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(\rho u) + \frac{\partial}{\partial\phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

First law of thermodynamics

$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

Gas law

$$p = \rho R T$$

$(u, v, w, \rho, p, \text{and } T)$,

J. Charney

N. Phillips

Late 1950s and Early 1960s Climate Modeling groups

GFDL

S. Manabe
J. Smagorinsky

UCLA

Y. Mintz
A. Arakawa

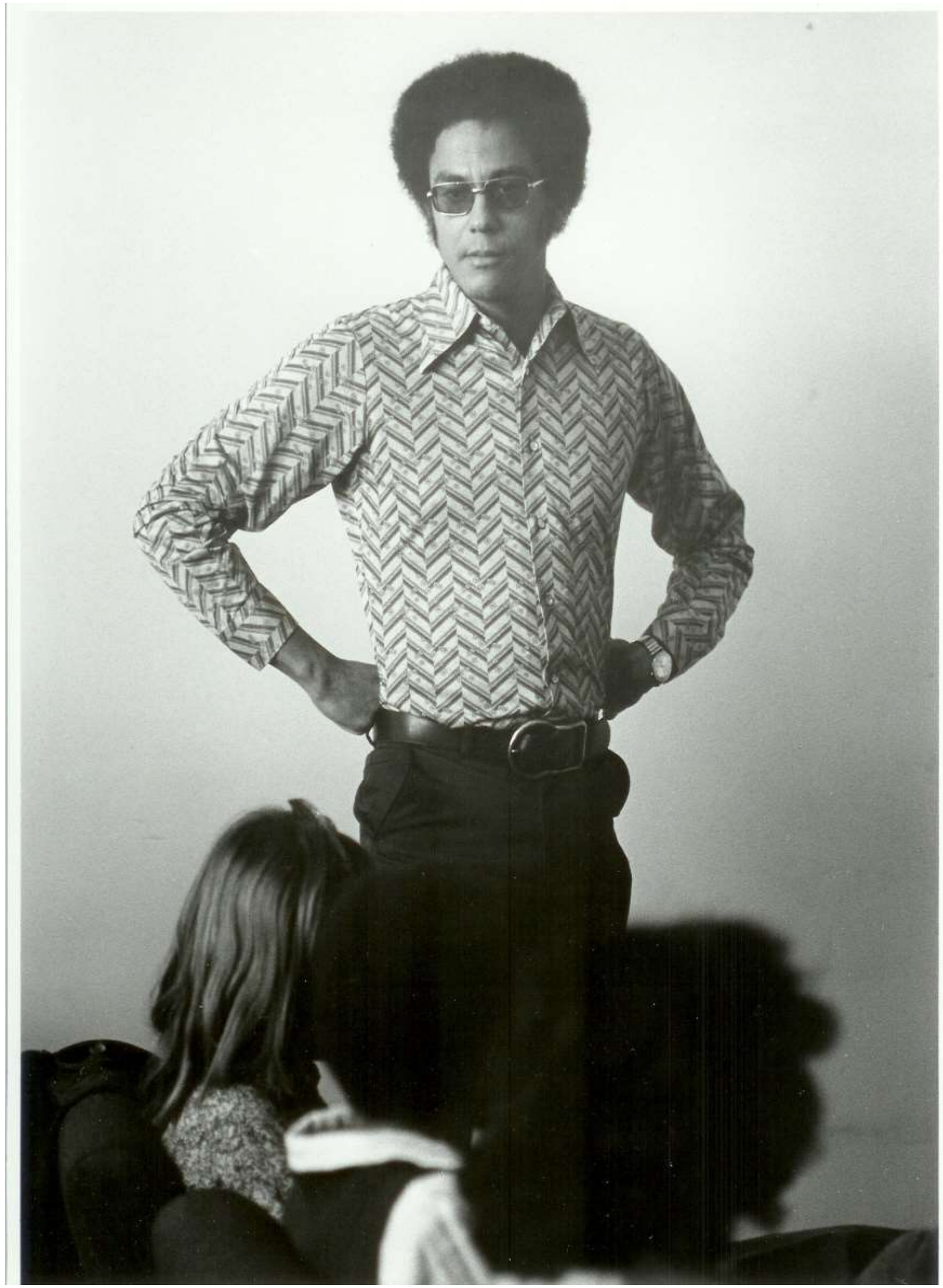
LLNL
& NCAR

C. Leith

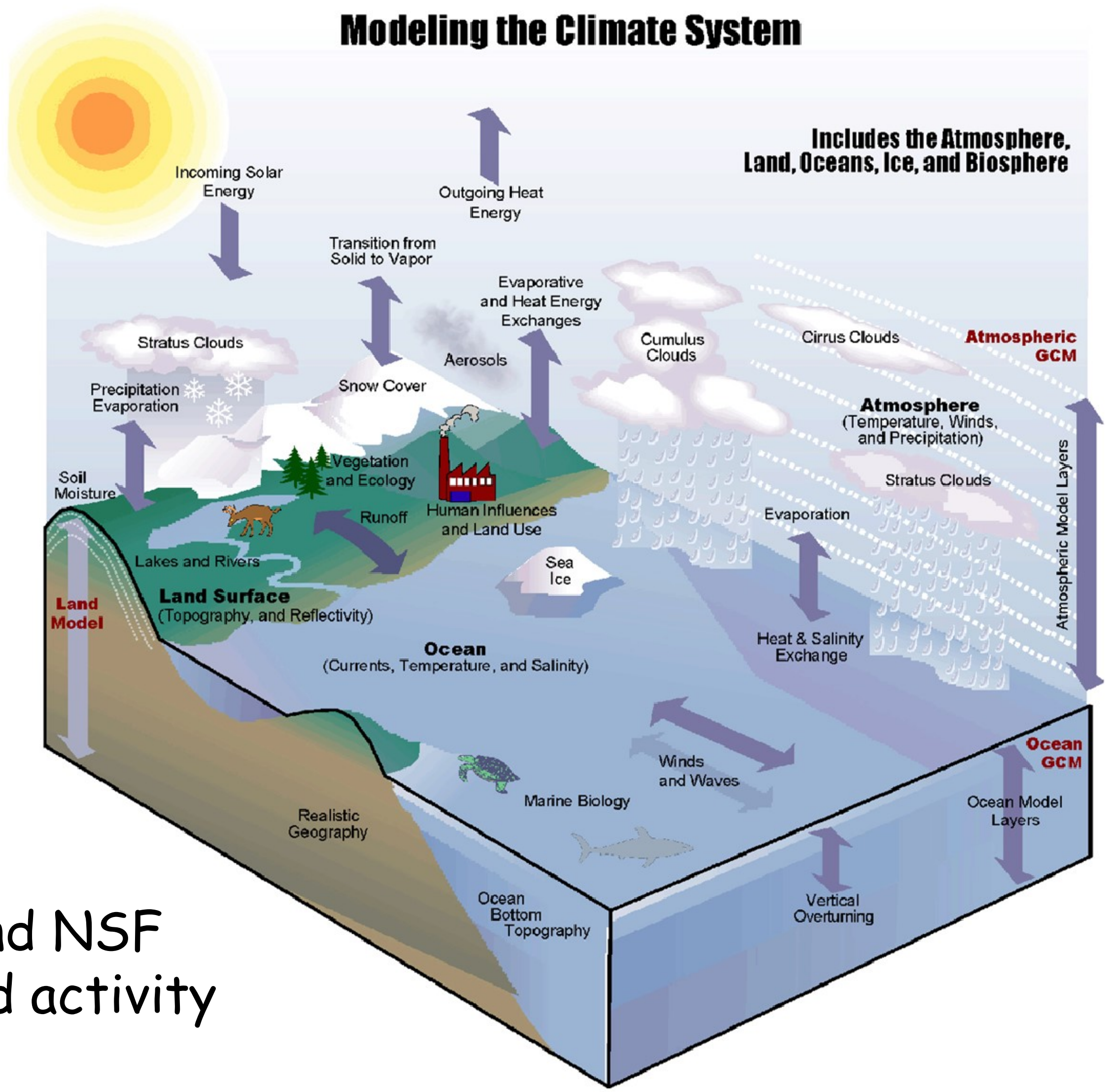
A. Kasahara
W. Washington

From Dave Randall

A young climate modeler!

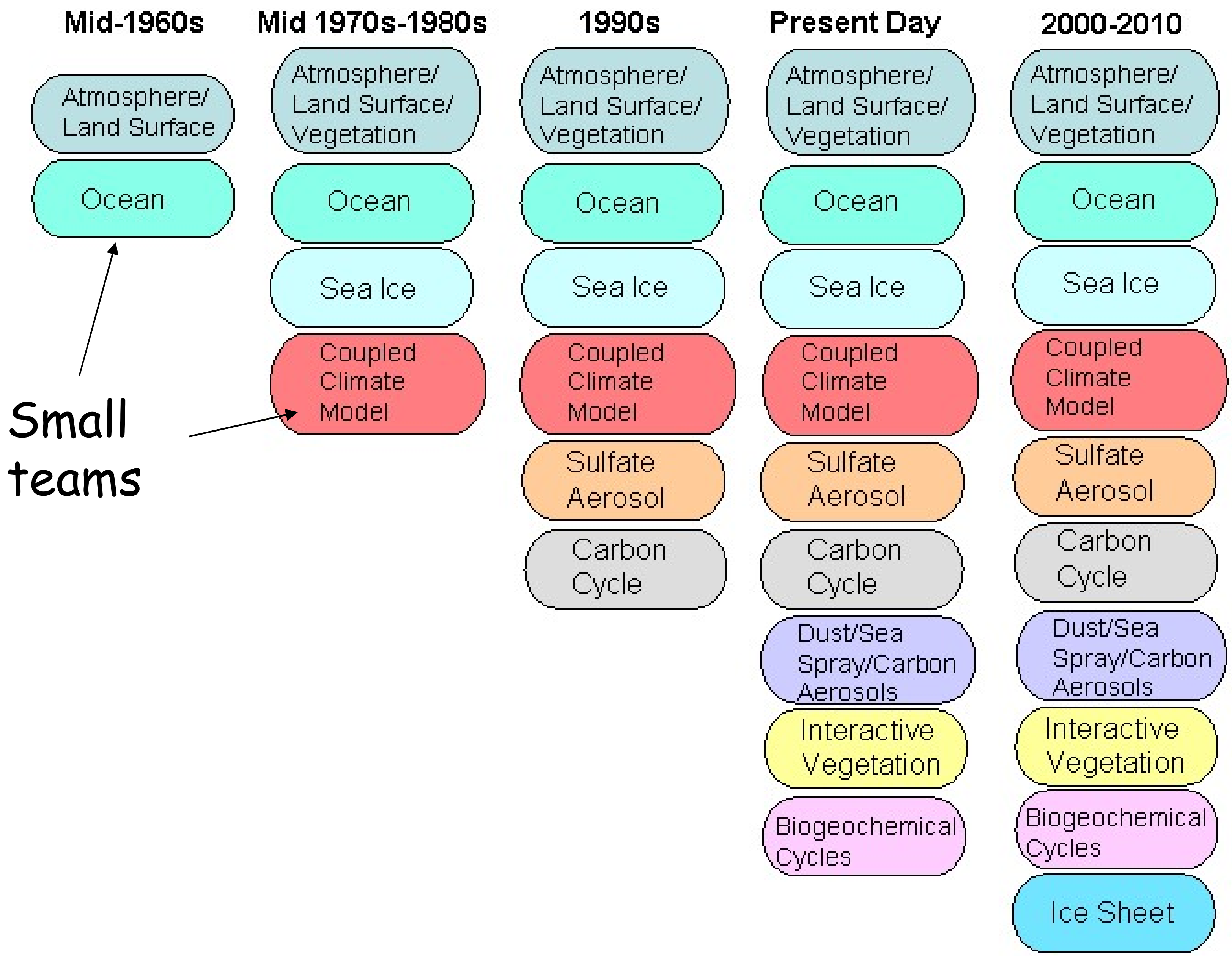


The Community Earth System Model (CESM) is becoming more complete

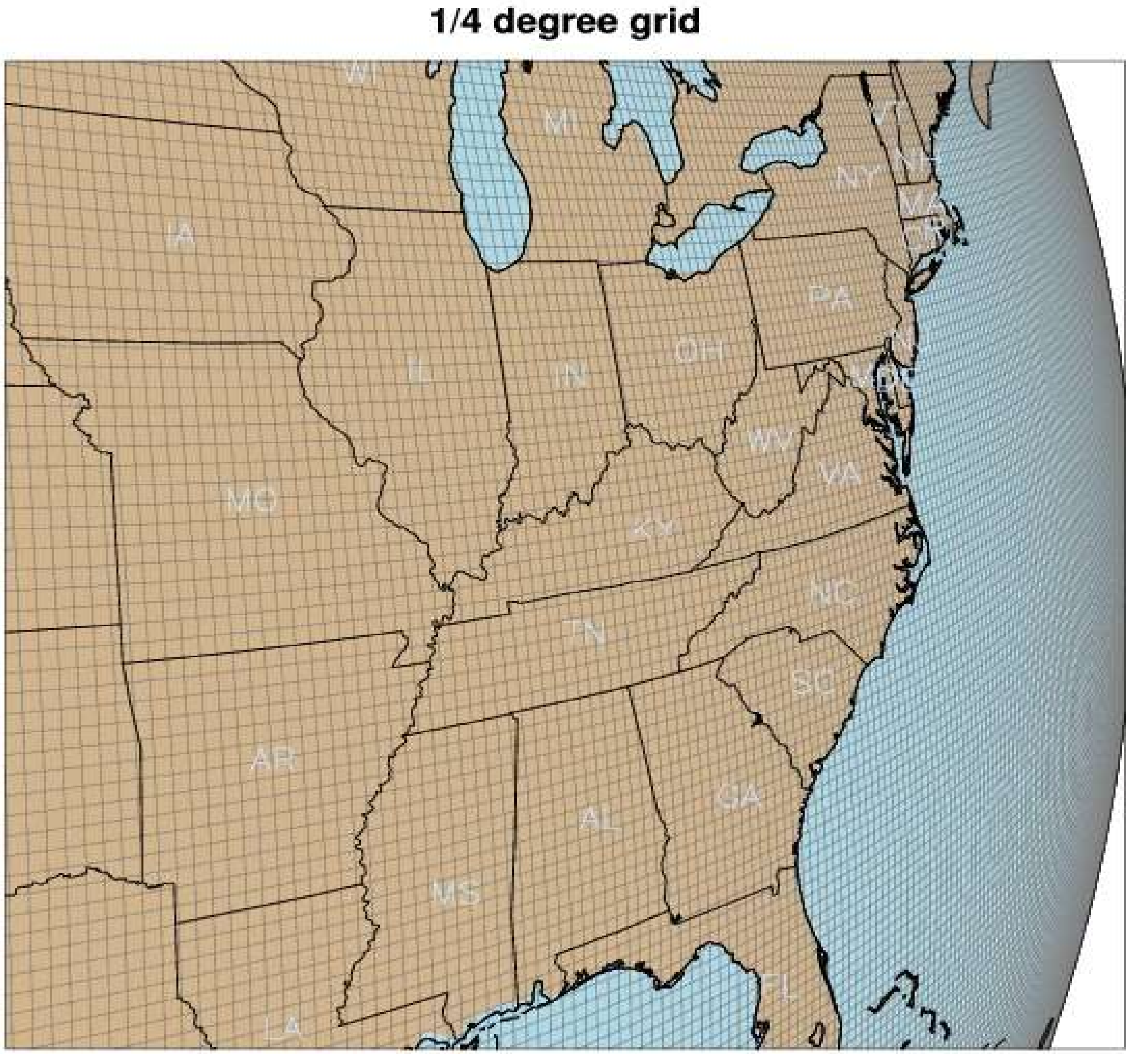


A DOE and NSF supported activity

Timeline of Climate Model Development



Part of the global grid (25 km) for the next IPCC simulations

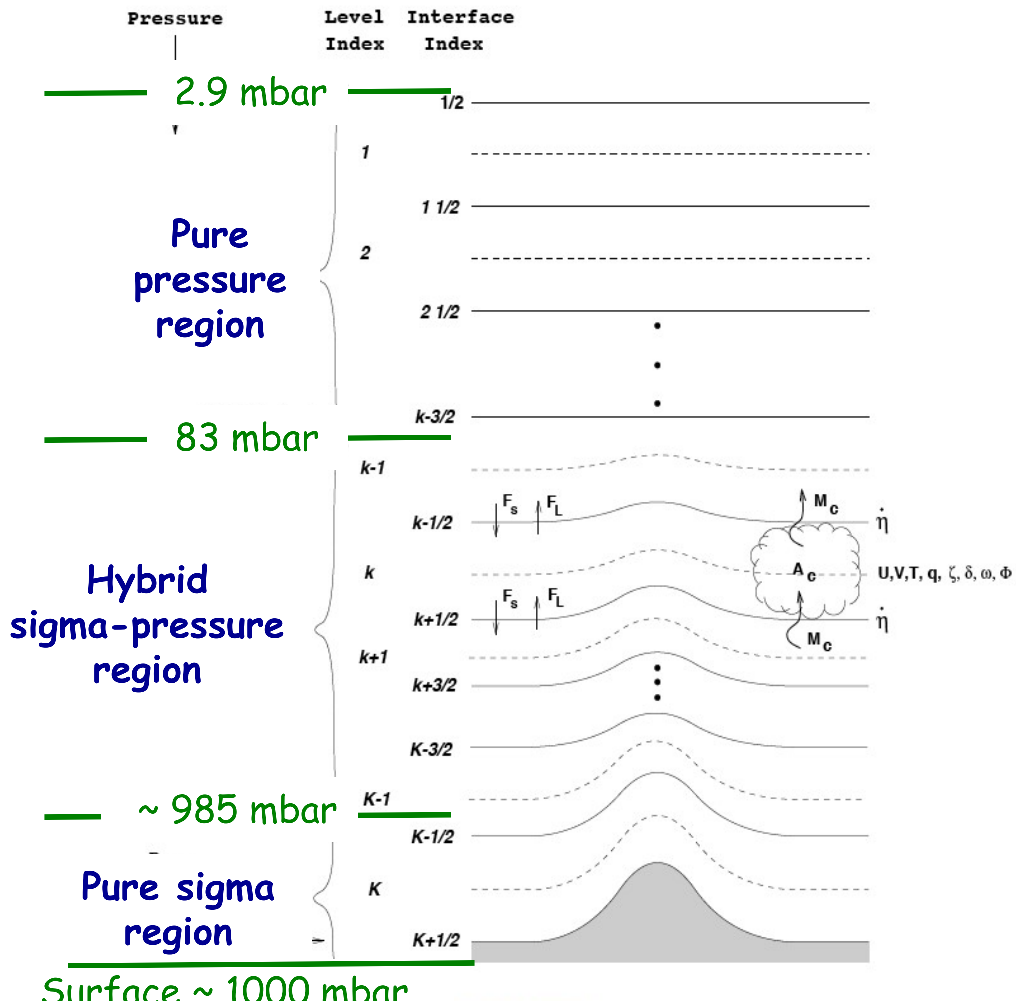


Vertical Grid

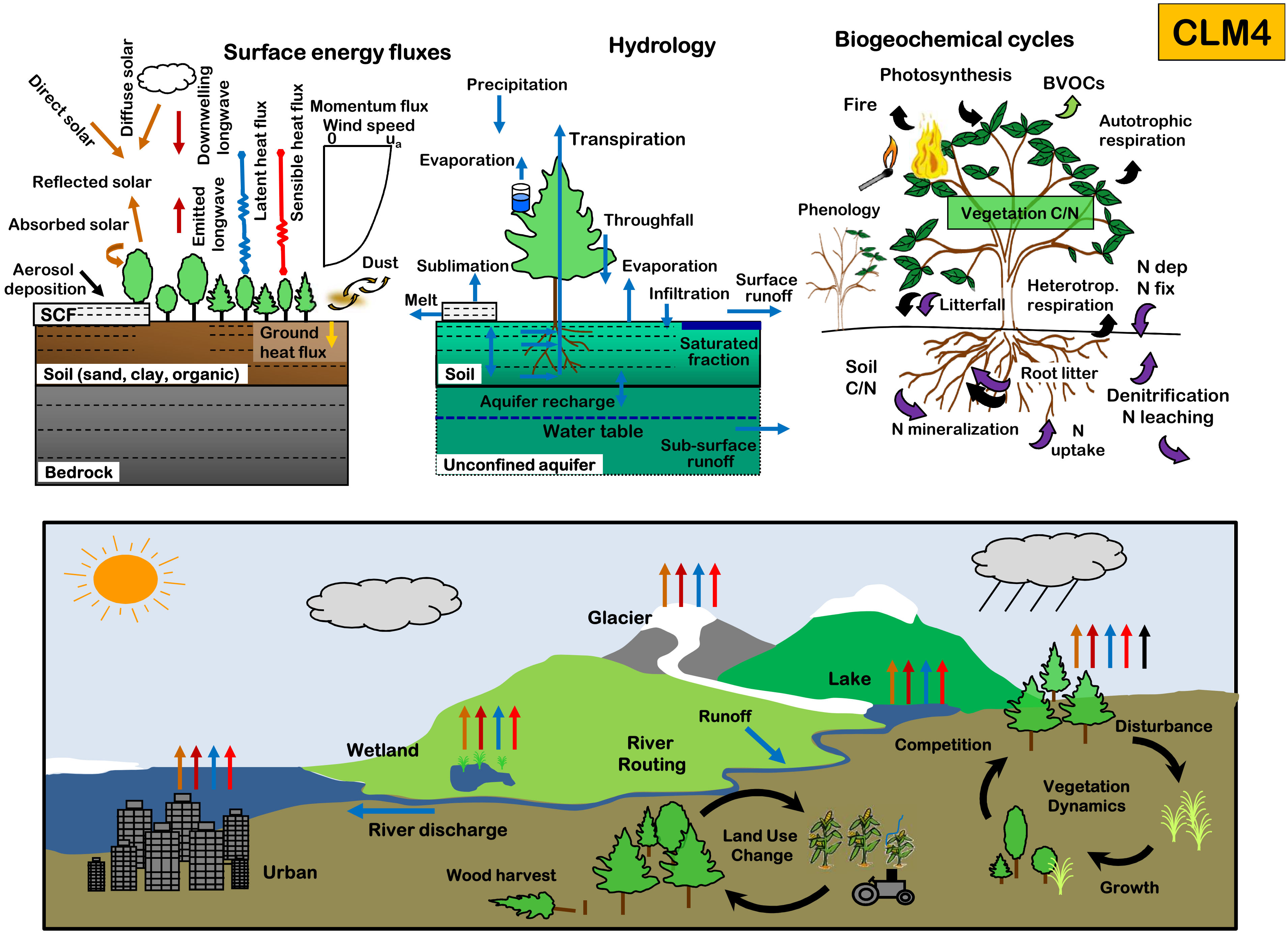
- Vertical resolution is also important for quality of simulations

- Levels are not equally spaced (levels are closer near surface and near tropopause where rapid changes occurs)

- In CAM: "hybrid" coordinate
  - bottom: sigma coordinate (follows topography)
  - top: pressure coordinate
  - middle: hybrid sigma-pressure



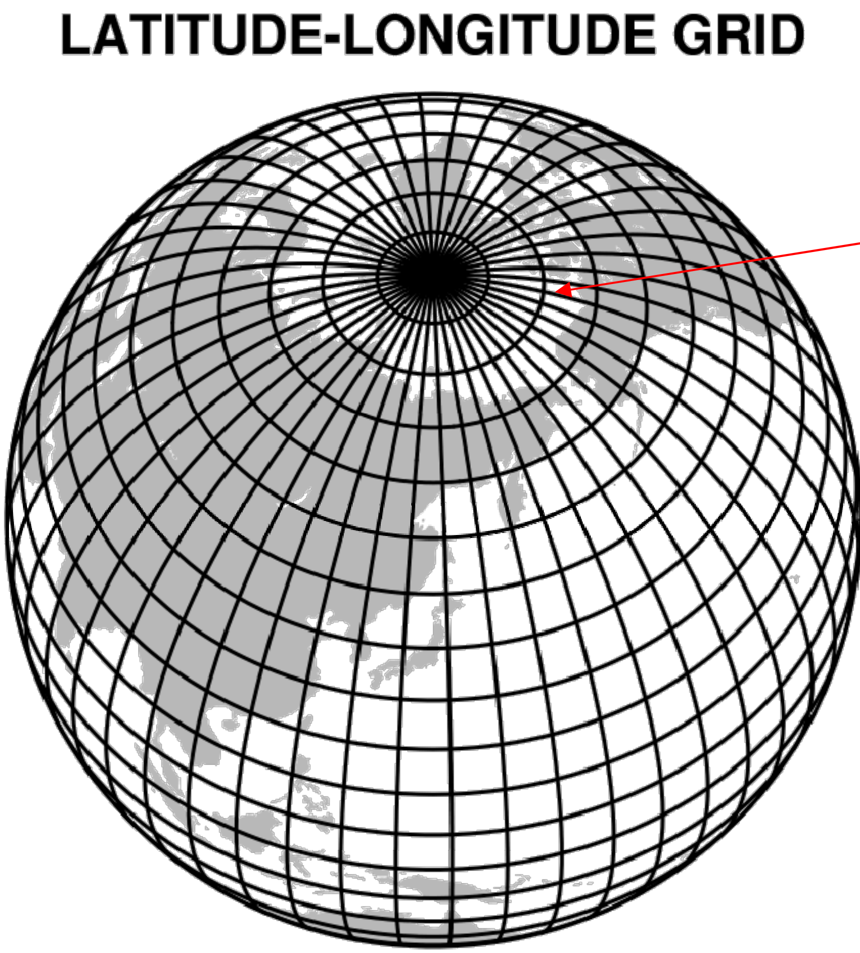
ertical level structure of CAM 4.0



CLM4
Surface energy fluxes
Hydrology
Biogeochemical cycles
Direct solar
Diffuse solar
Downwelling longwave
Latent heat flux
Sensible heat flux
Momentum flux
Wind speed
0
u_a
Reflected solar
Absorbed solar
Emitted longwave
Aerosol deposition
Dust
SCF
Ground heat flux
Soil (sand, clay, organic)
Bedrock
Precipitation
Transpiration
Evaporation
Throughfall
Sublimation
Evaporation
Melt
Infiltration
Surface runoff
Saturated fraction
Soil
Aquifer recharge
Water table
Sub-surface runoff
Unconfined aquifer
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Phenology
Vegetation C/N
N dep
N fix
Heterotrop. respiration
Litterfall
Soil C/N
Root litter
Denitrification
N leaching
N mineralization
N uptake
Glacier
Lake
Wetland
Runoff
River Routing
Competition
Disturbance
River discharge
Land Use Change
Vegetation Dynamics
Urban
Wood harvest
Growth

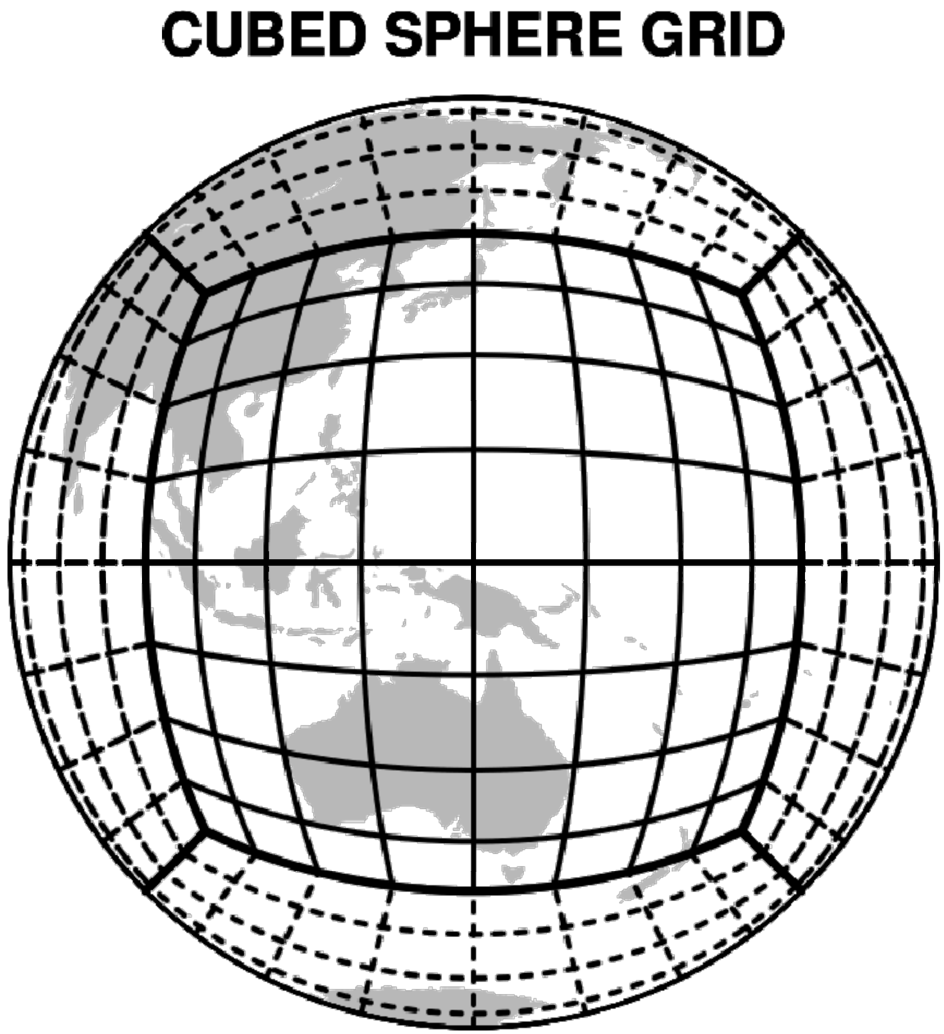
The Pole Problem!

Atmospheric Grid Structure in the 1960s and 1970s

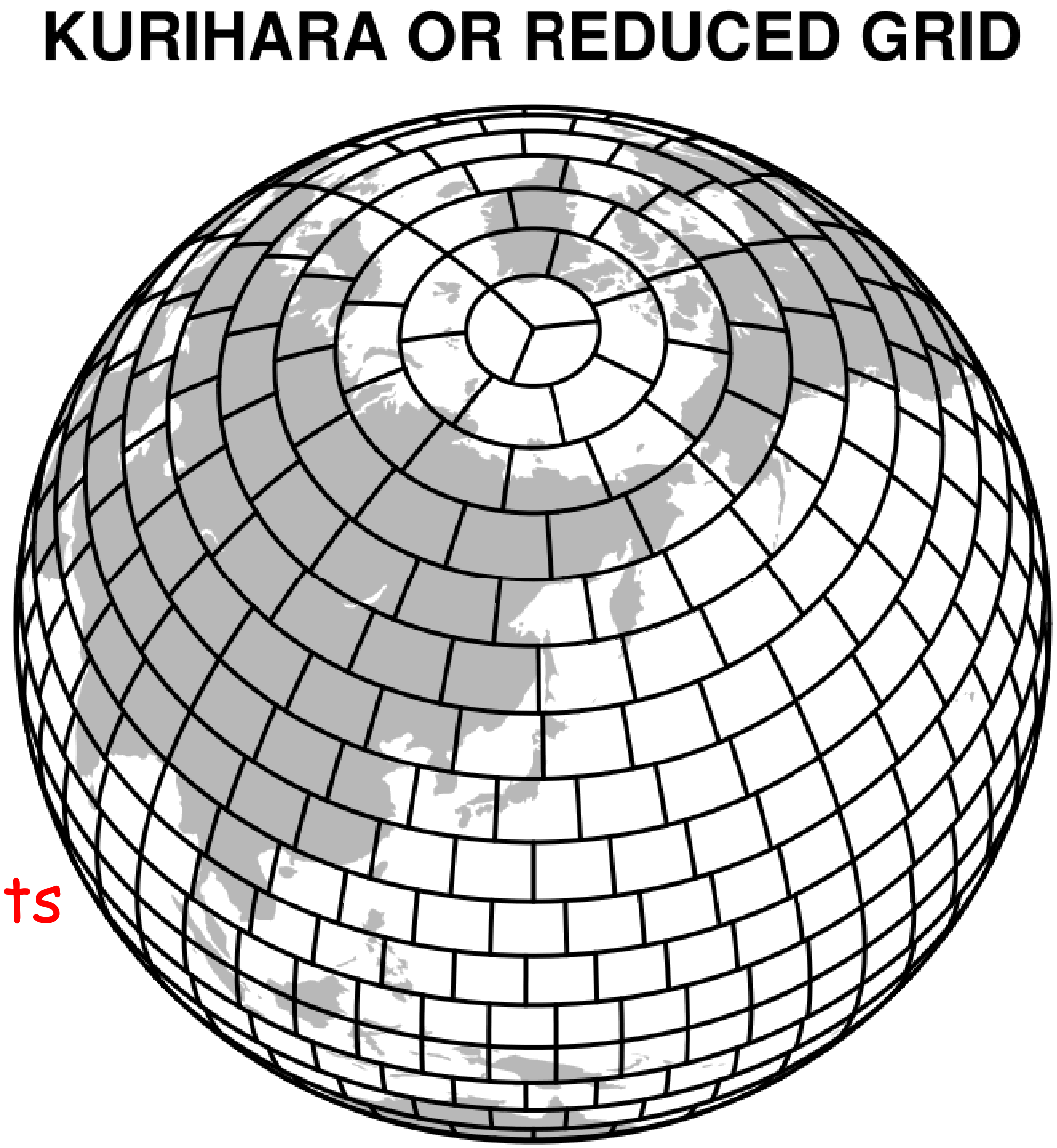


Problem near the poles where longitudes converge

Novel Solution to the Pole Problem by Sadourny (1972)



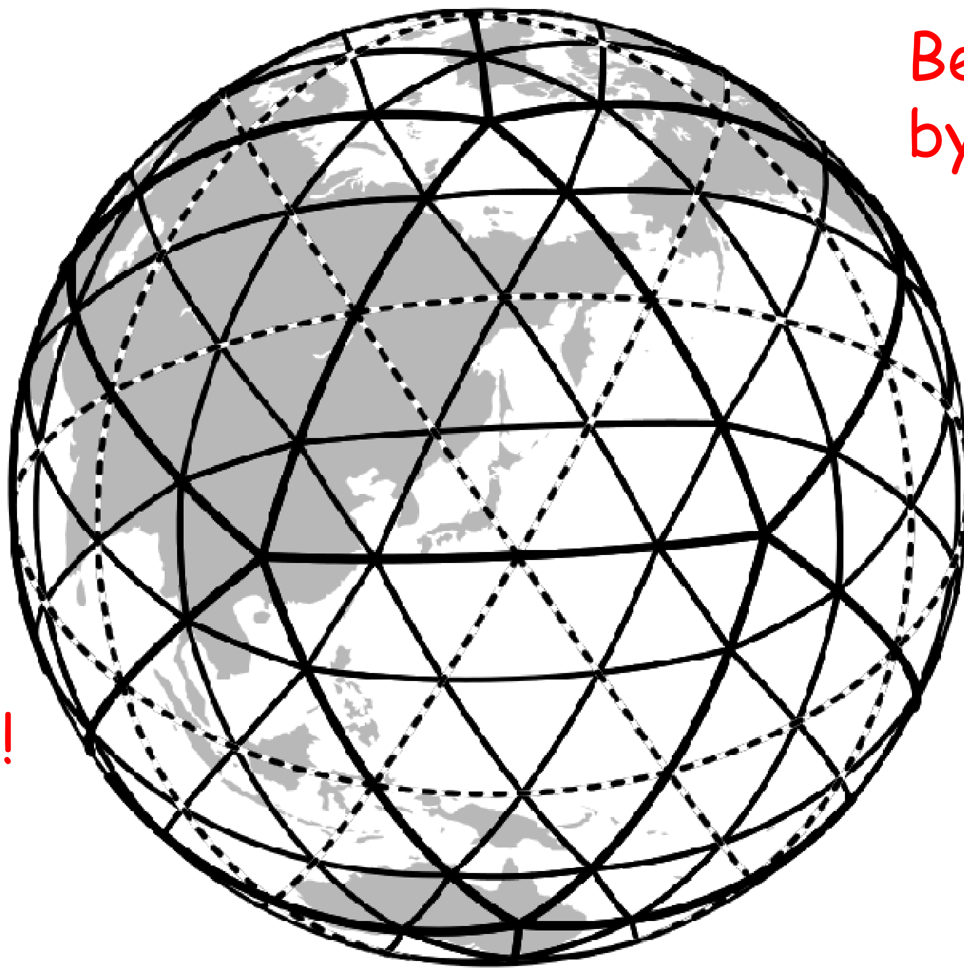
Kurihara or Reduced Grid



Many variants of this by others.

The Icosahedral Solution

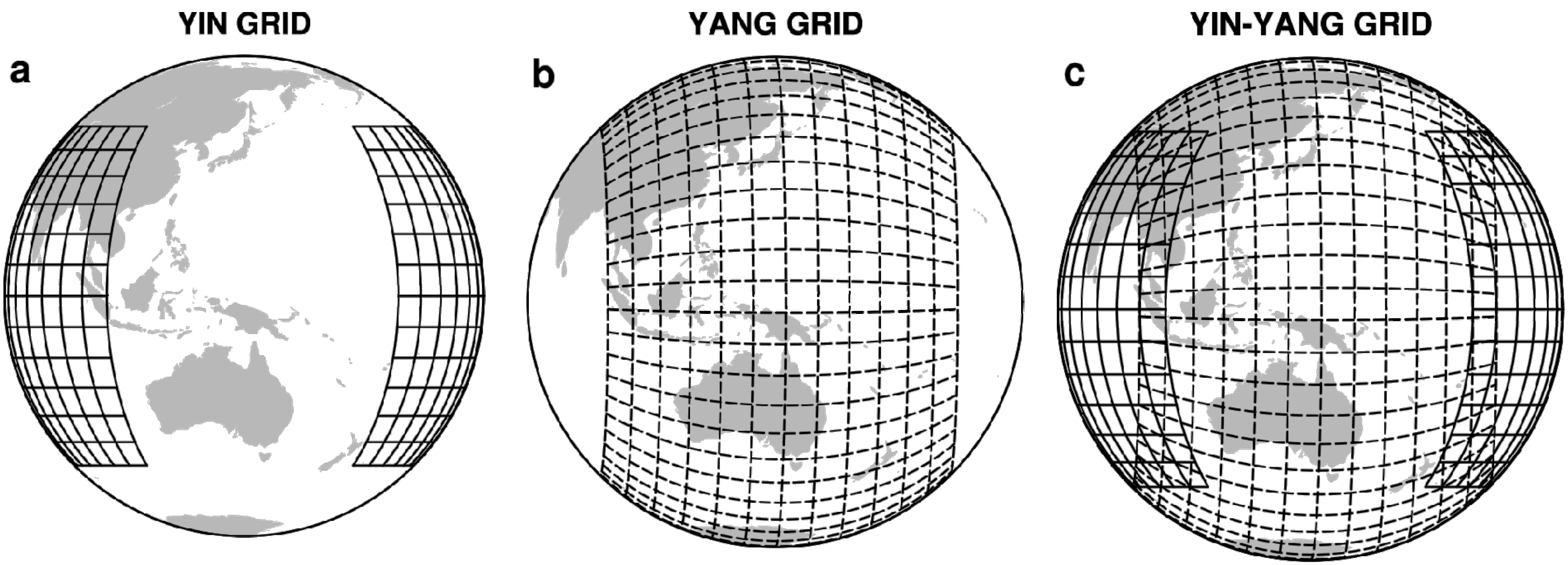
SPHERICAL GEODESIC
OR ICOSAHEDRAL GRID



Being tested
by Dave Randall

Still to be
Investigated!

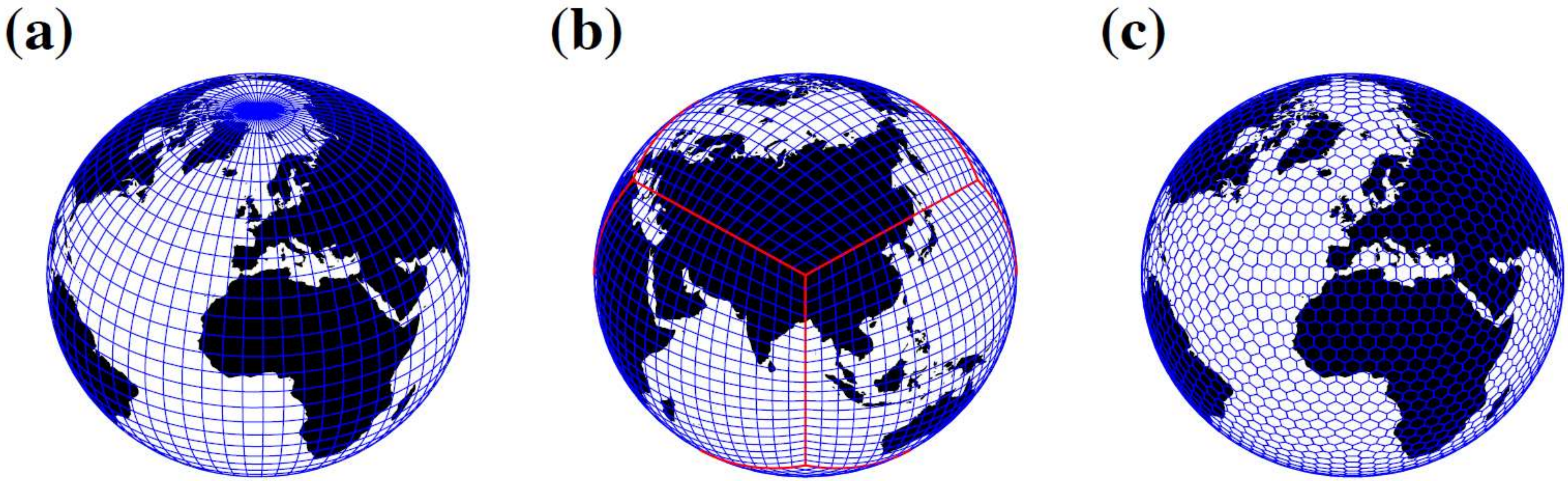
Yin-Yang Grids



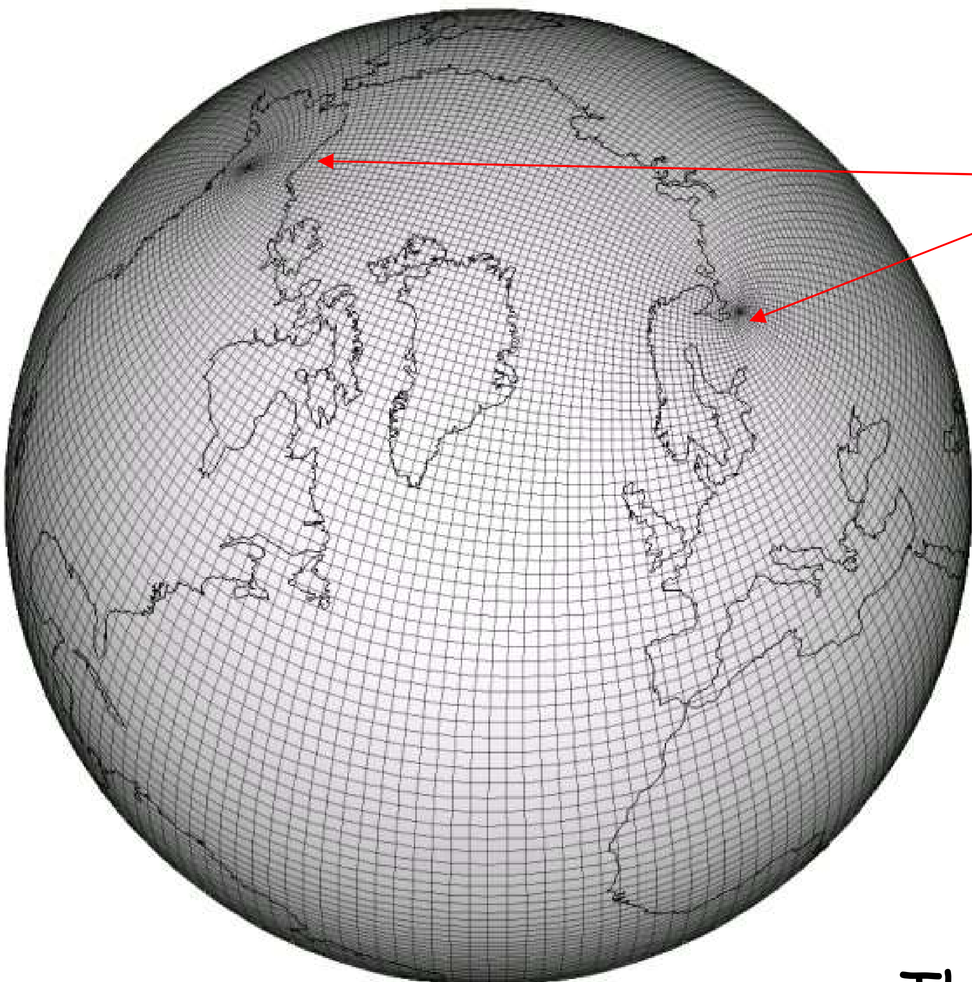
Note…no pole problem but lots of interpolation!

Kameyama et al. (2004)

Grids: Latitude-longitude, Cubed-Sphere, icosahedral (hexagons and pentagons)



Ocean Parallel Ocean Program (POP)

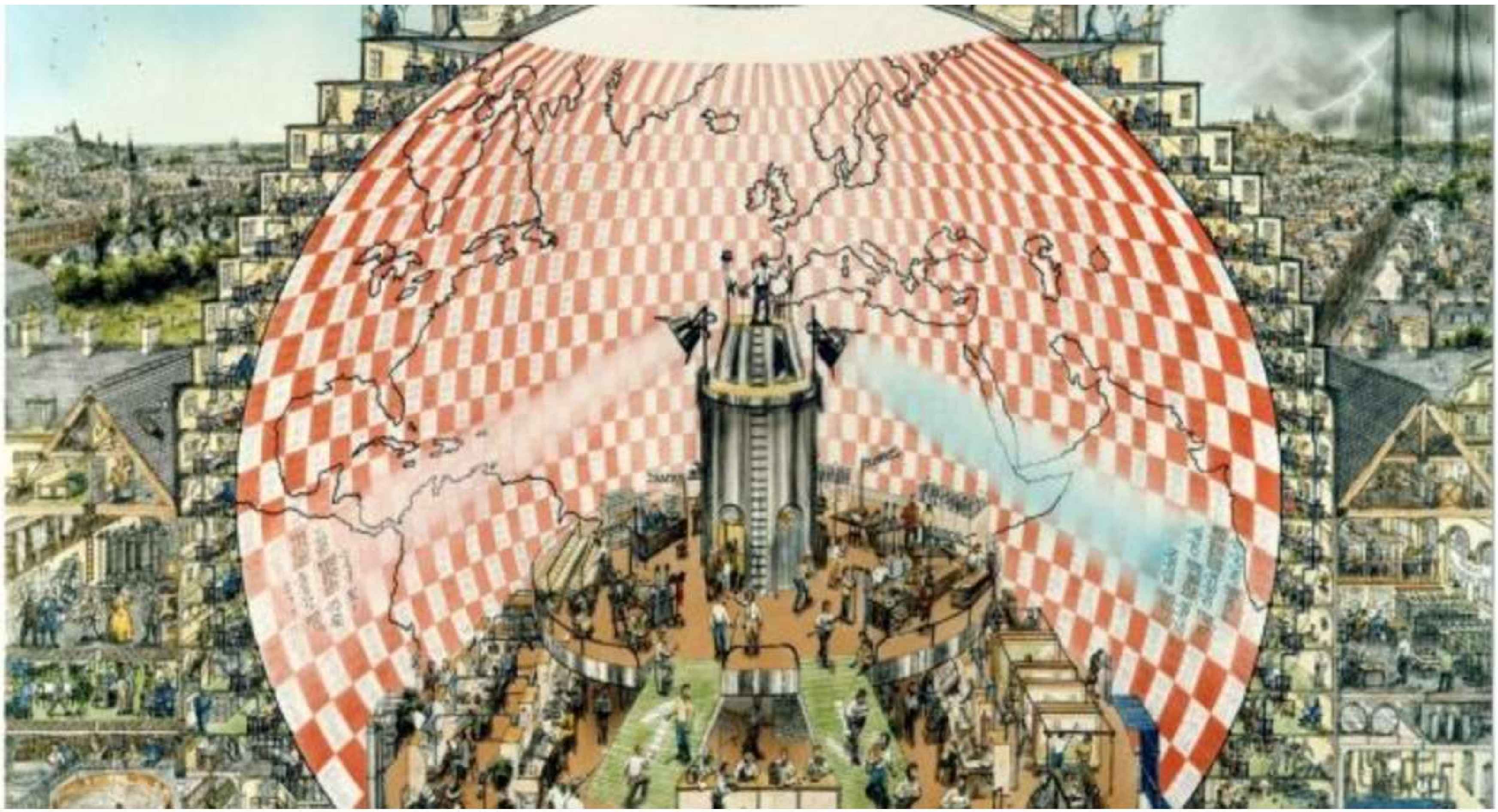


Tripole grid

Third pole at South Pole

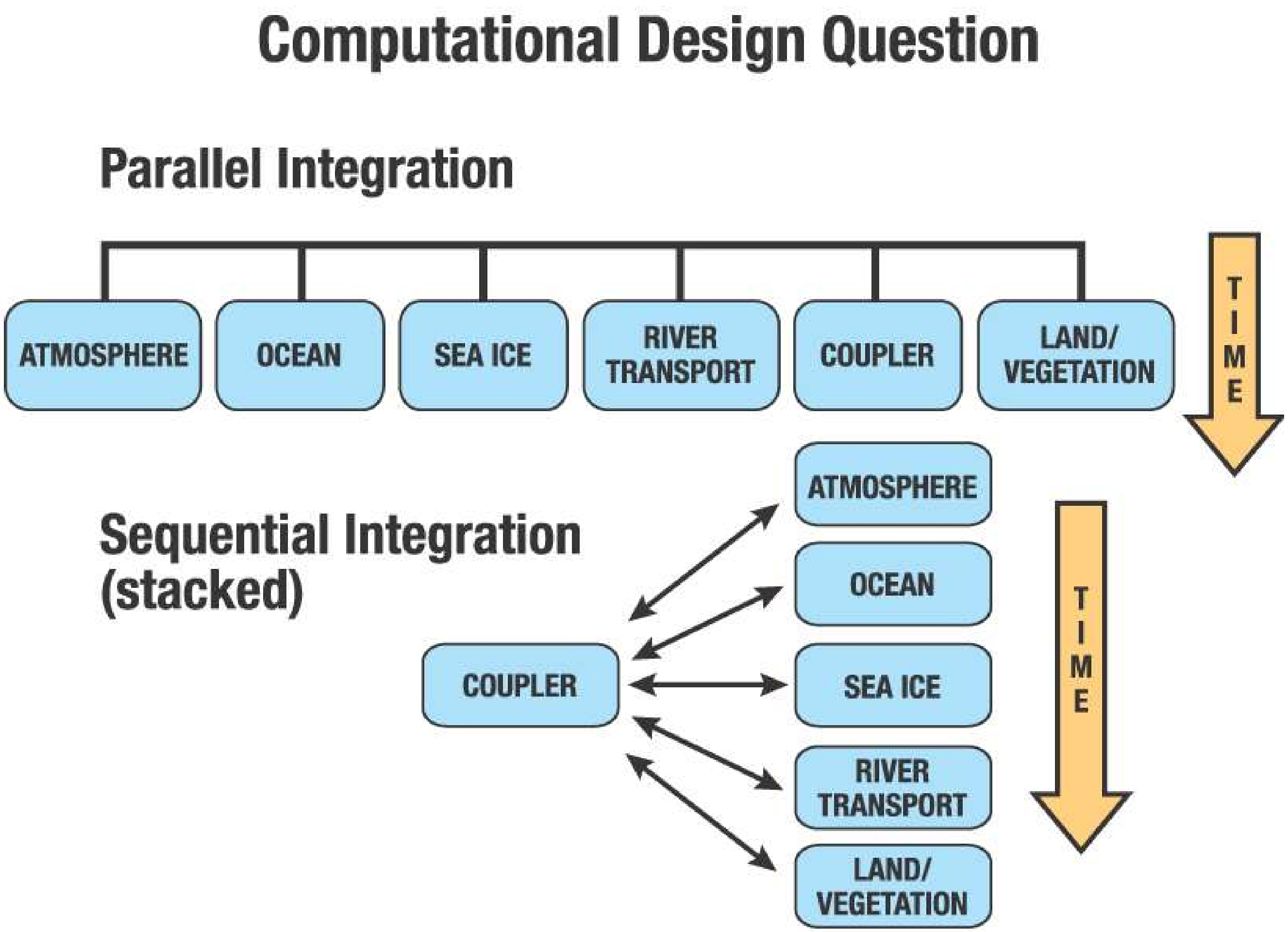
L. F. Richard HPC Scheme in 1920s

Peter Lynch

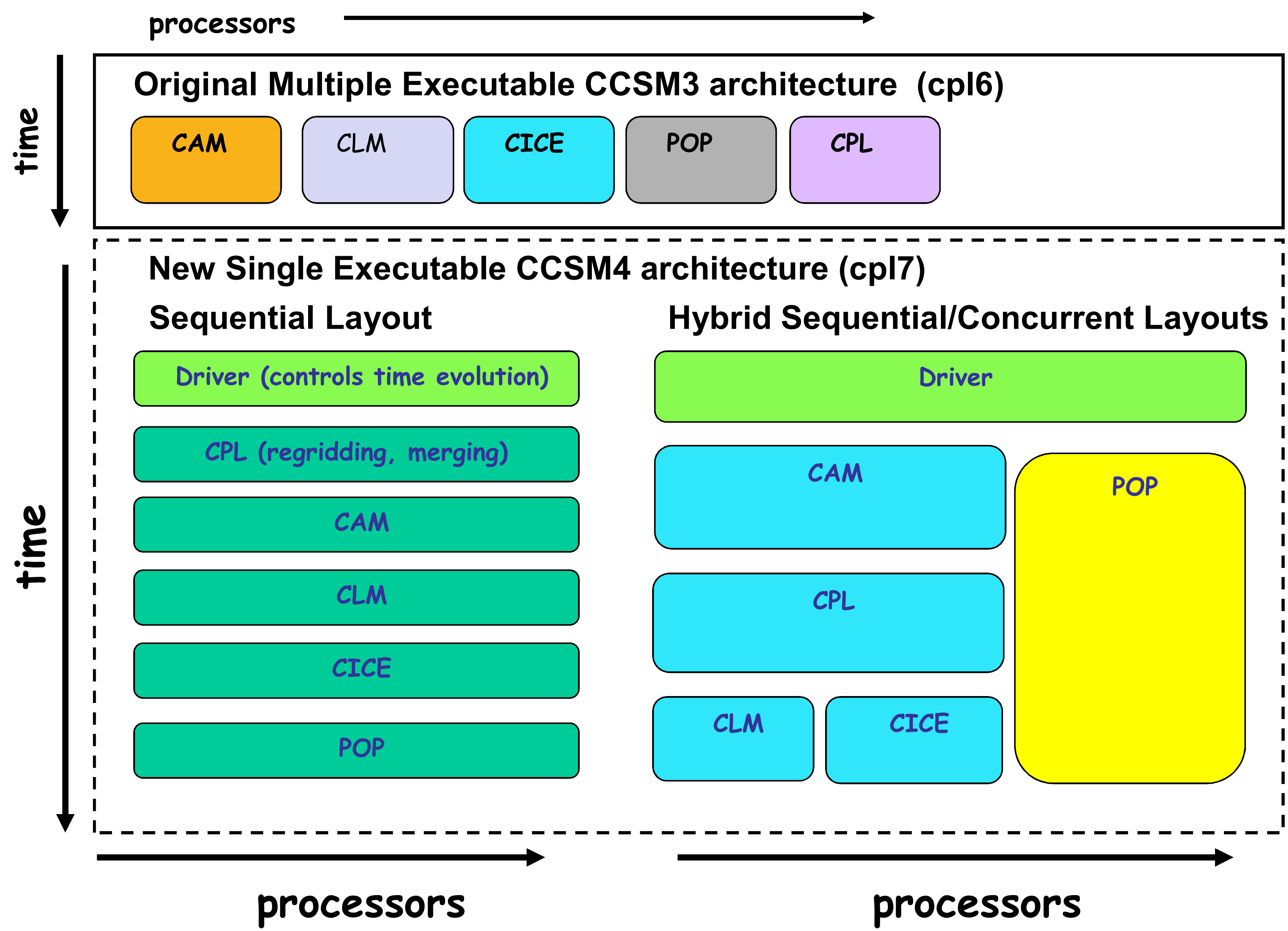


The Weather Forecasting Factory by Stephen Conlin.The working of the forecast factory is co-ordinated by a director of operations. Standing on a central dais, he synchronises the computations

Parallel and Sequential Integration HPC



CCSM4/CPL7 Architecture



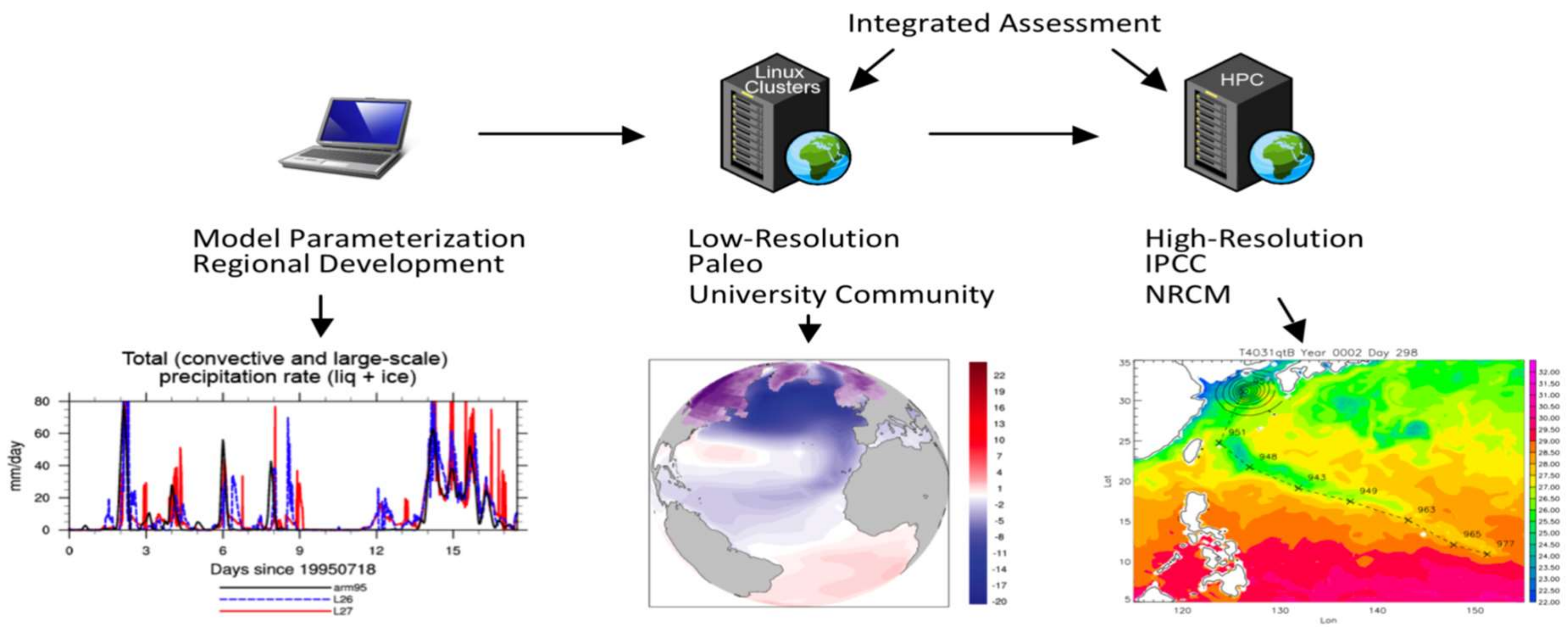
Advantages of CLP7 Design

- New flexible coupling strategy
  - Design targets a wide range of architectures - massively parallel peta-scale hardware, smaller linux clusters, and *even* single laptop computers
  - Provides efficient support of varying levels of parallelism via simple run-time configuration for processor layout
    - Simple xml file specifies processor layout of entire system
- **Scientific unification**
  - *ALL* model development done with one code base - elimination of separate stand-alone component code bases (CAM, CLM)
- **Code Reuse and Maintainability**
  - Lowers cost of support/maintenance

More CPL7 advantages…

- **Simplicity**
  - Easier to debug - much easier to understand time flow
  - Easier to port - ported to
    - IBM p6 (NCAR)
    - Cray XT4/XT5 (NICS,ORNL,NERSC)
    - BGP (Argonne), BGL (LLNL)
    - Linux Clusters (NCAR, NERSC)
  - Easier to run - new xml-based scripts permit user-friendly capability to create "out-of-box" experiments
- Performance (throughput and efficiency)
  - Much greater flexibility to achieve optimal load balance for different choices of
    - Resolution, Component combinations, Component physics
  - Automatically generated timing tables provide users with immediate feedback on both performance and efficiency

CCSM4 Provides a Seamless End-to-End Cycle of Model Development, Integration and Prediction with One Unified Model Code Base

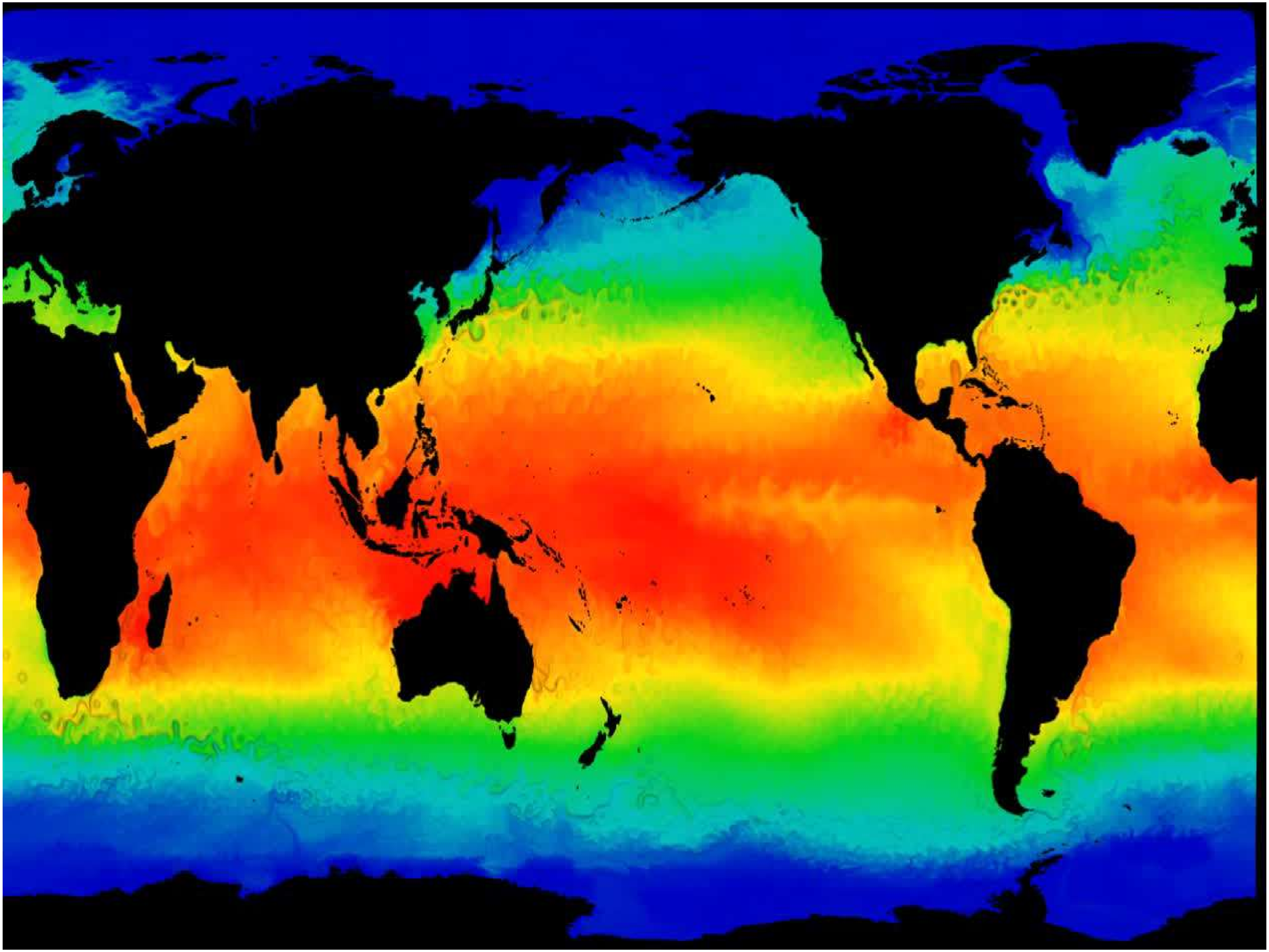


Left panel is the total precipitation rate in the Single Column Model (SCM). Middle panel is sea surface temperature change (°C) for 17,000 years ago as simulated by low-resolution version of CCSM3 when meltwater off the North American and European ice sheets (purple) is added to the North Atlantic Ocean. Right panel is sea surface temperature in the Pacific Ocean south of Japan in an ultra-high-resolution coupled simulation that uses a 0.25° atmosphere and land coupled to a 0.1° ocean and sea ice model. Note the reduction in sea surface temperature to the right of the category 4 typhoon storm track.

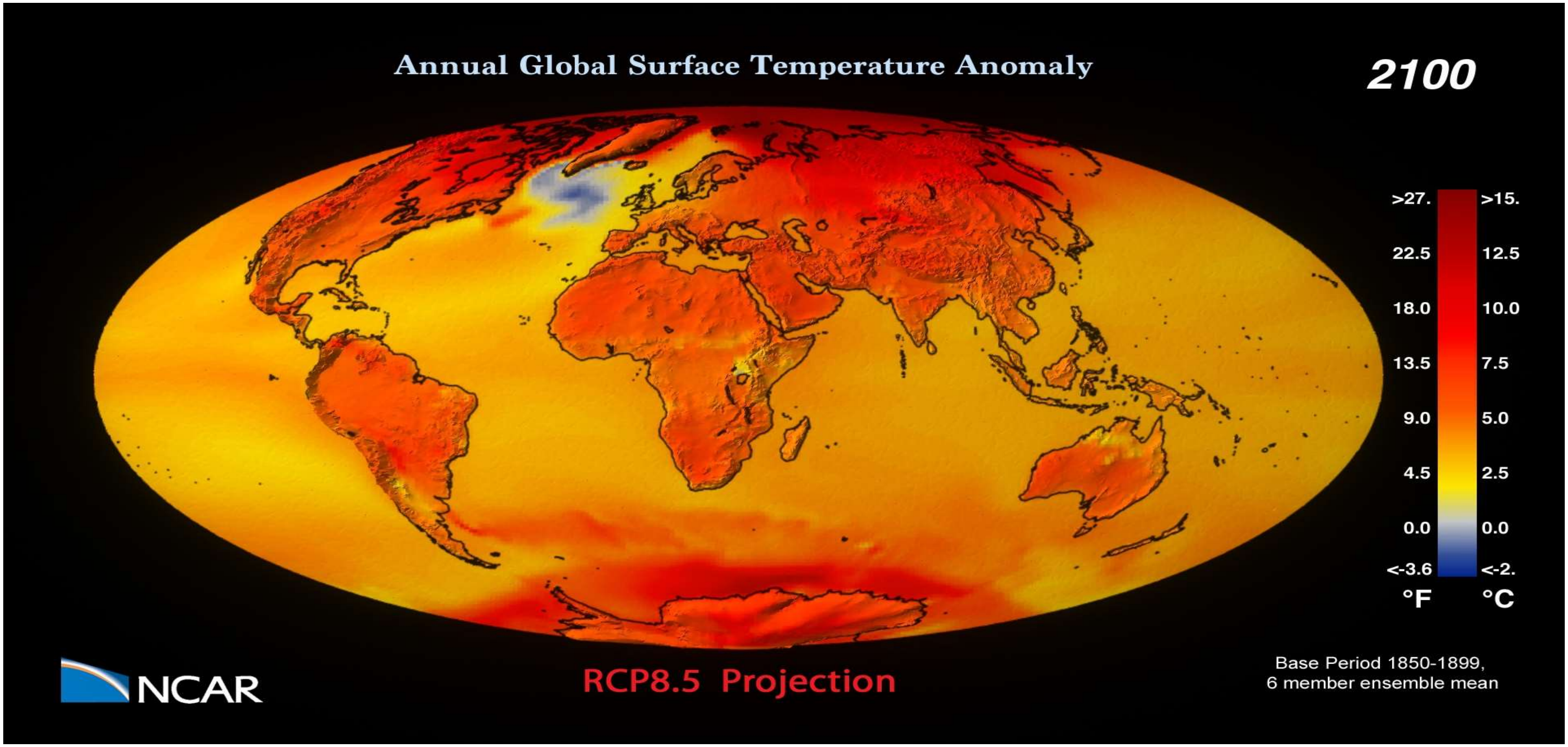
CPL7 permits new extensions of coupling capability

Implementation of interactive ensembles provides a great example!

Examples of Simulations

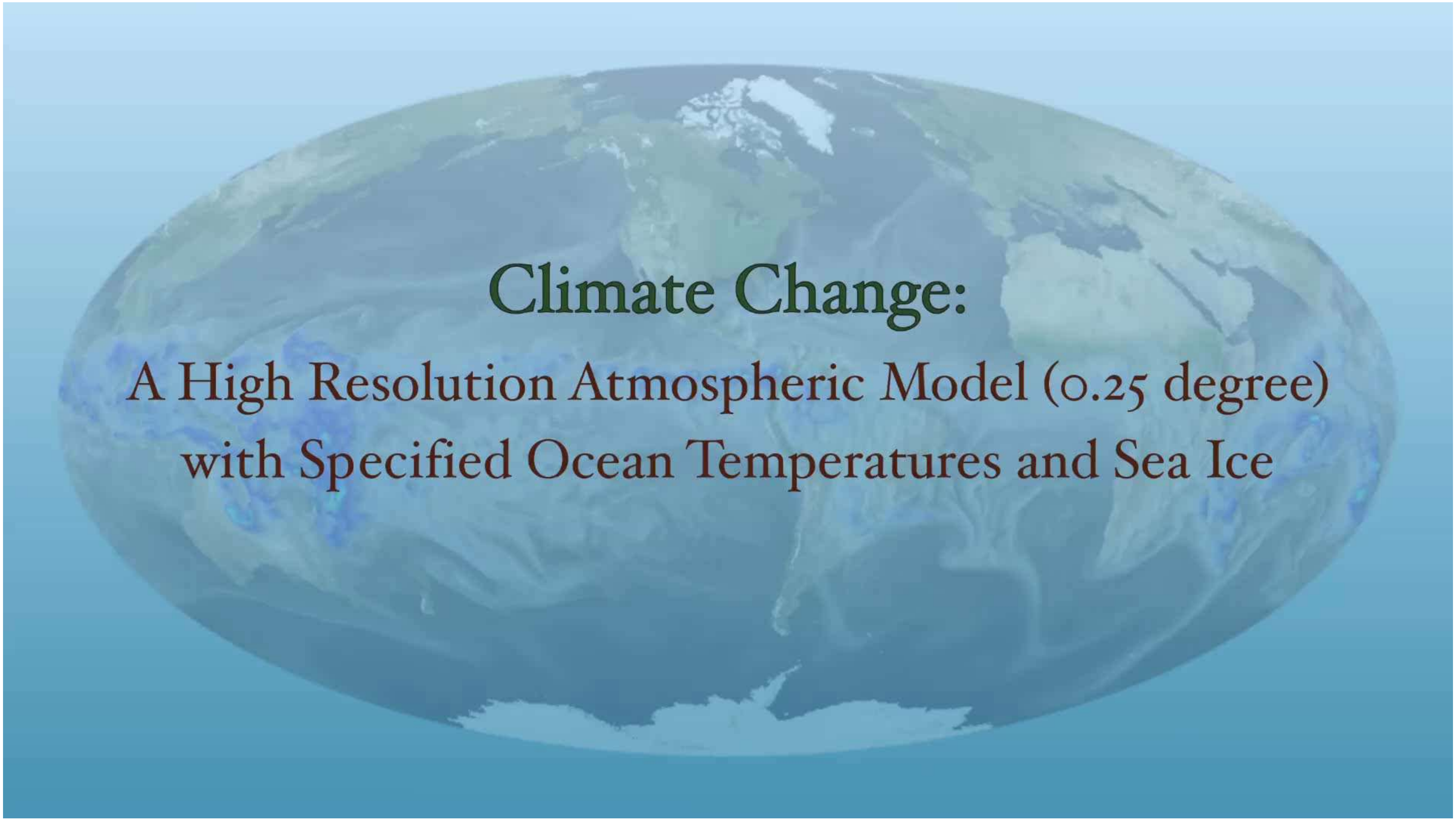


Geographical Pattern of 8.5 RCP at year 2100



Climate Change:

Using A High Resolution Atmospheric Model (25 km)


Climate Change:
A High Resolution Atmospheric Model (0.25 degree)
with Specified Ocean Temperatures and Sea Ice


Climate and Earth System models have and continue to contribute to understanding and predicting the climate system. They allow the science community to determine objectively the possible impacts of climate change on food production, flooding, drought, sea level rise, and health as well as decision support. Higher resolution and more complete models will help.
From Istockphoto.com

National Medal of Science

The End

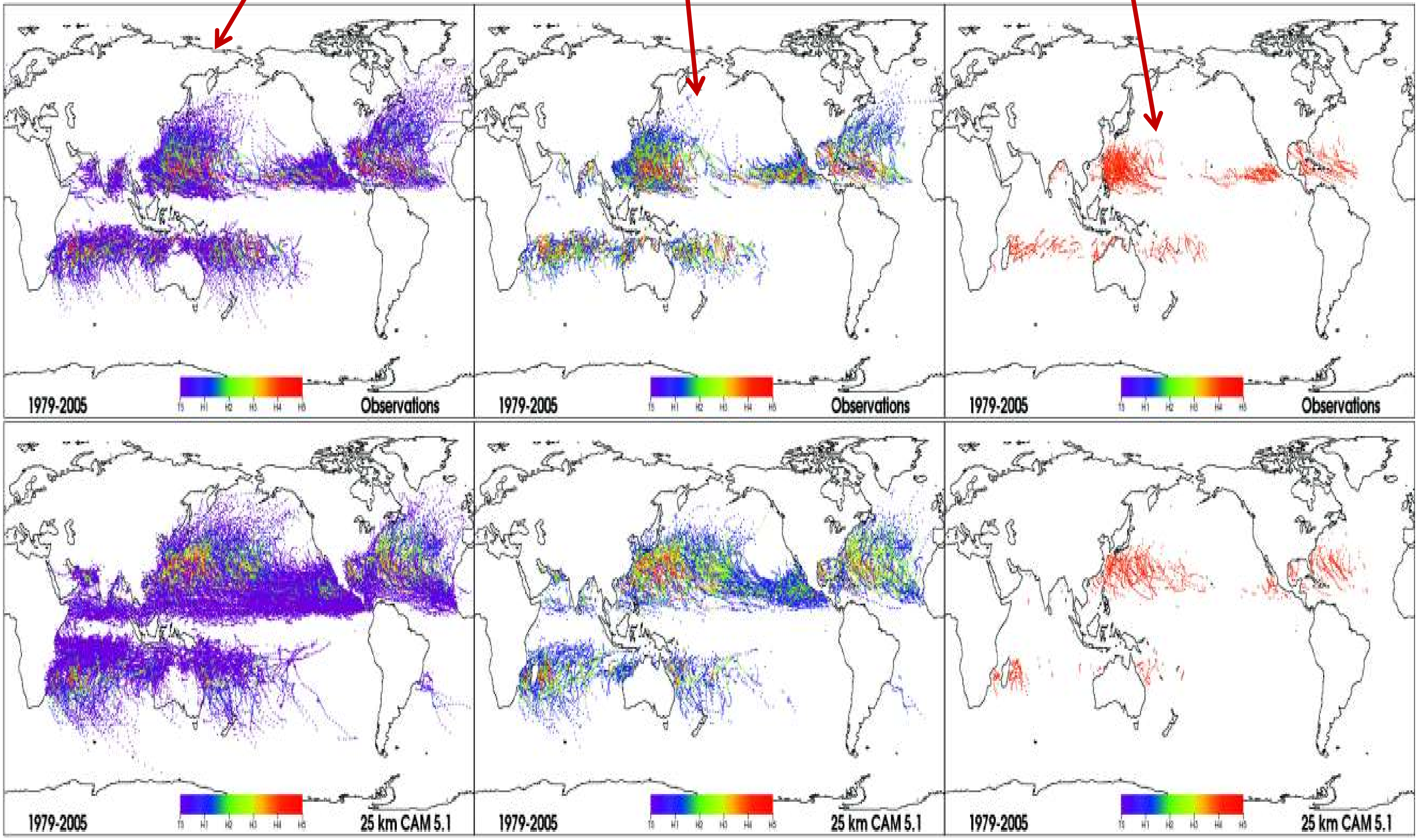
Animations provided by Los Alamos National Laboratory (LANL), NASA and NCAR

NCAR

U.S. DEPARTMENT OF ENERGY

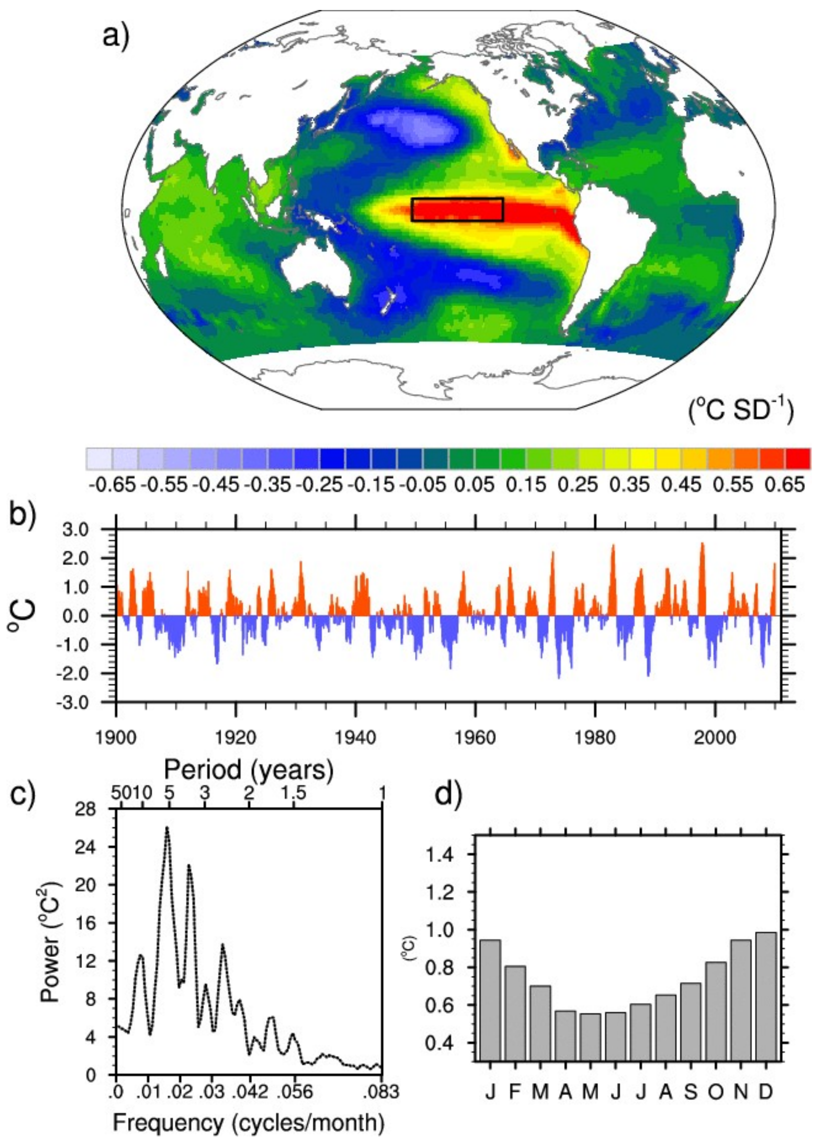
Office of Science

Tropical storms, hurricanes, and intense hurricanes for high resolution (25 km) atmospheric model(CAM5) M. Wehner, DOE LBL

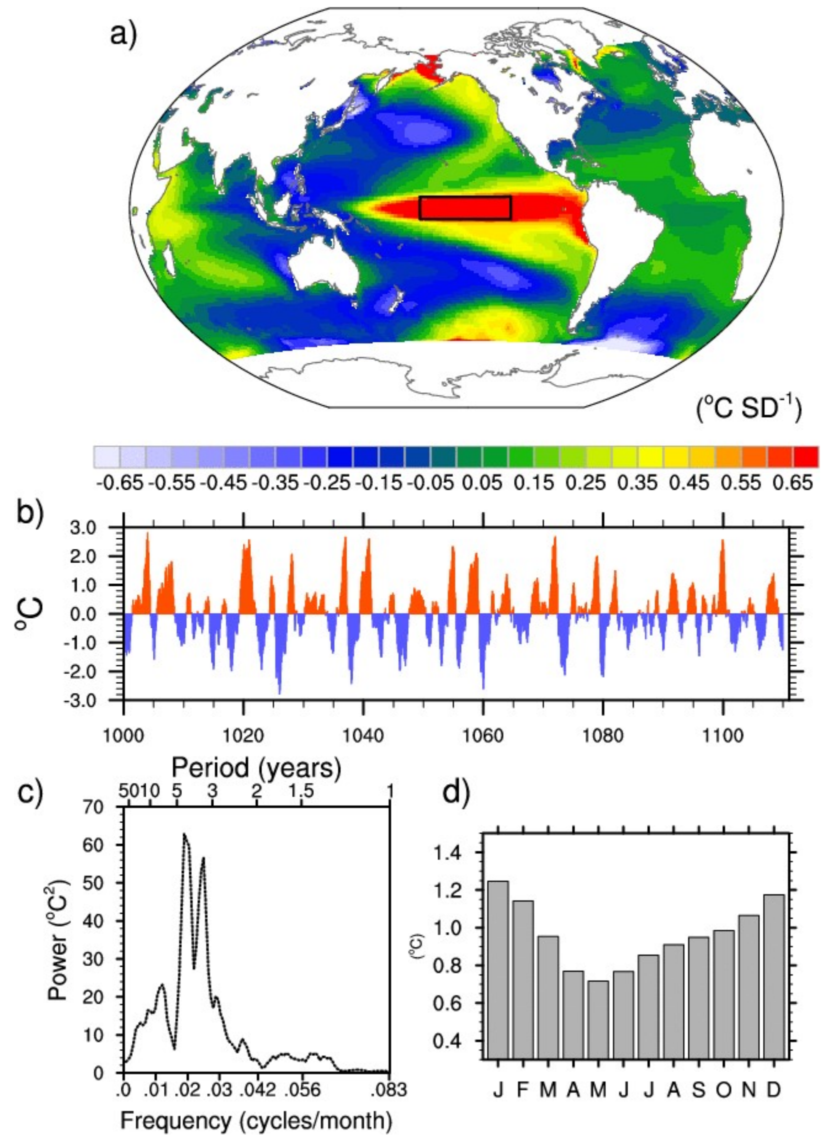


Leading Mode of Global SST Variability
Seasonal Capability (Neale, NCAR)

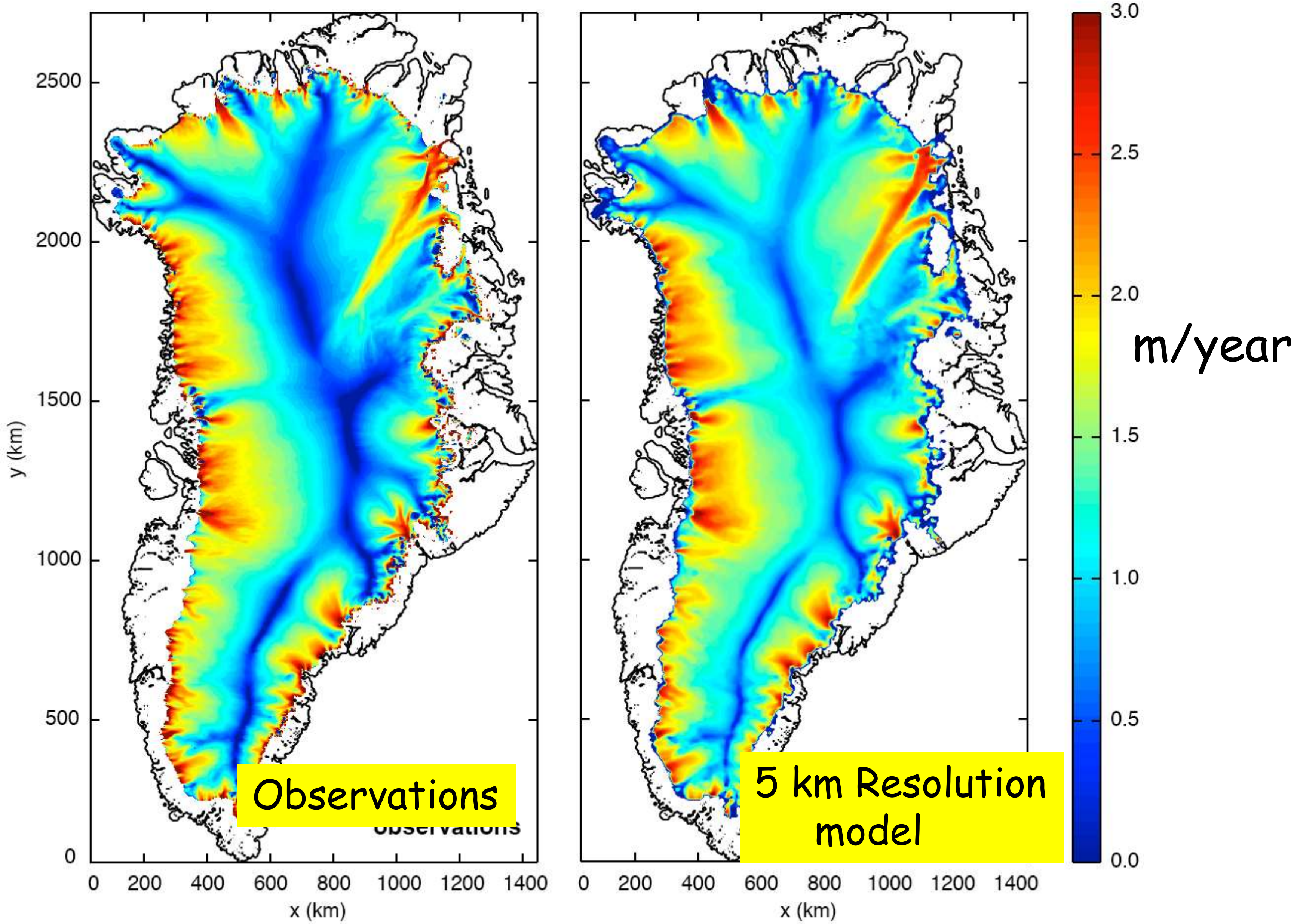
Observations



CCSM4

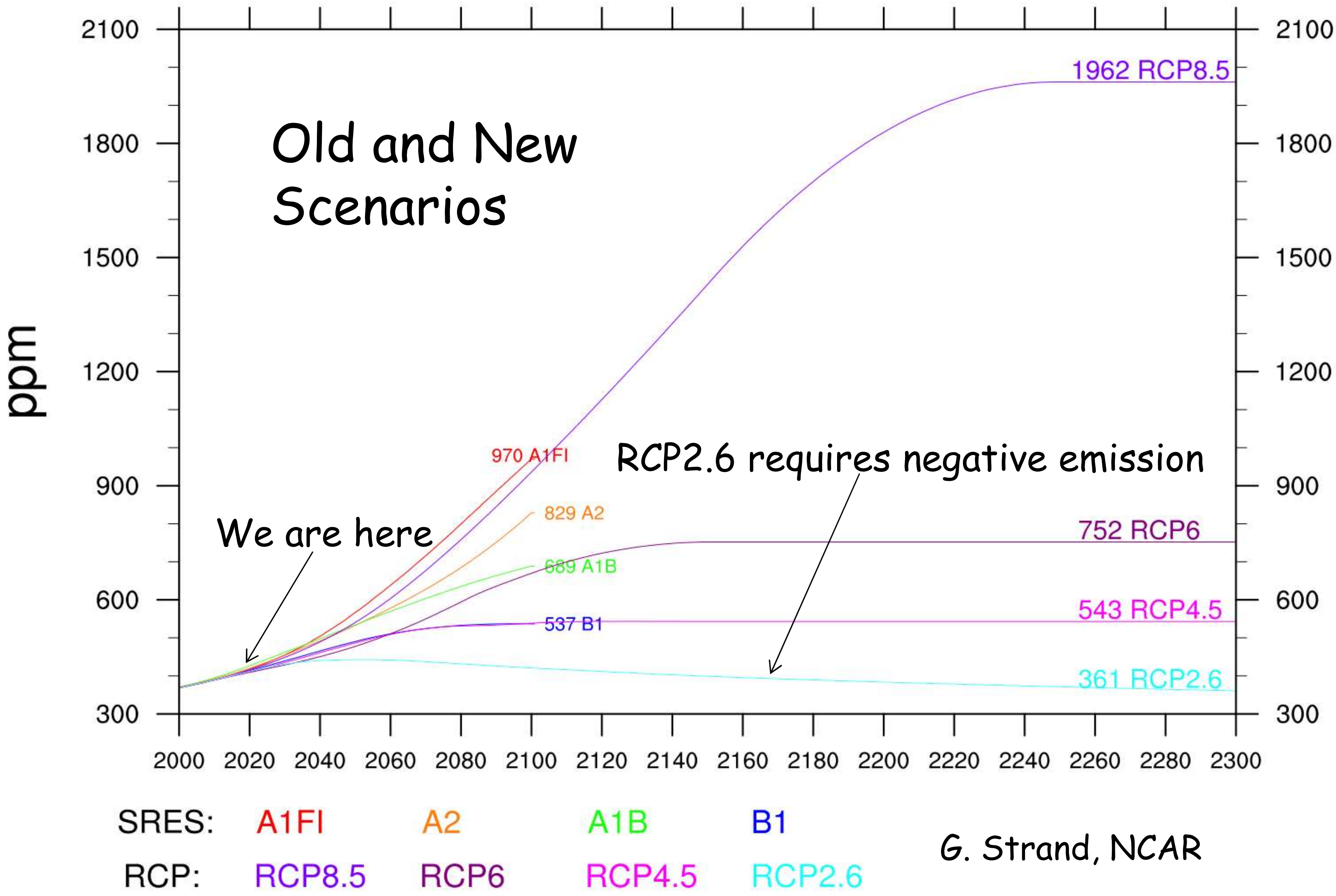


Velocities



Price, Lipscomb et al, DOE/LANL, 2010

CO_2 concentrations



G. Strand, NCAR

Each Country's Share of 2011 Total Carbon Dioxide Emissions from the Consumption of Energy

have signed an Agreement to Cut emissions