The Community Earth System Model (CESM)

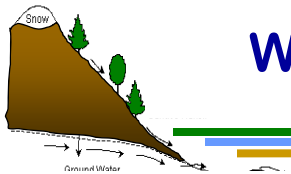
David Lawrence

with thanks to Jim Hurrell and Peter Gent

current and former chairs of CESM

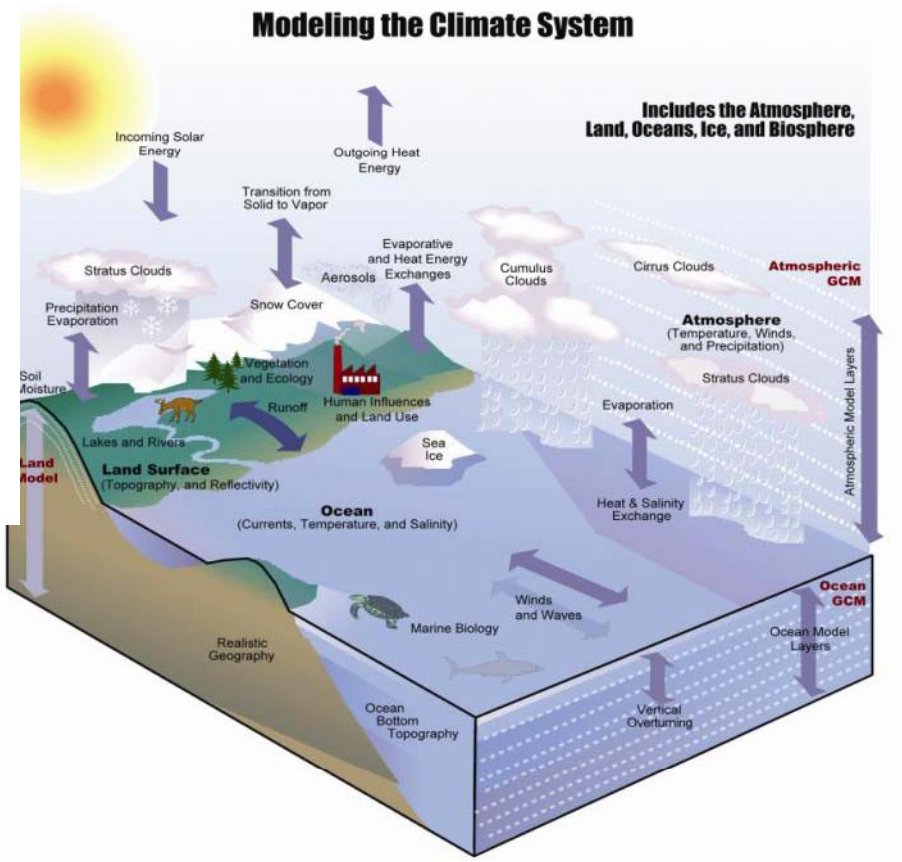
Climate and Global Dynamics Division

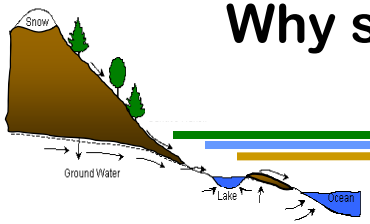
NCAR Earth System Laboratory



What is the Community Earth System Model (CESM) Project?

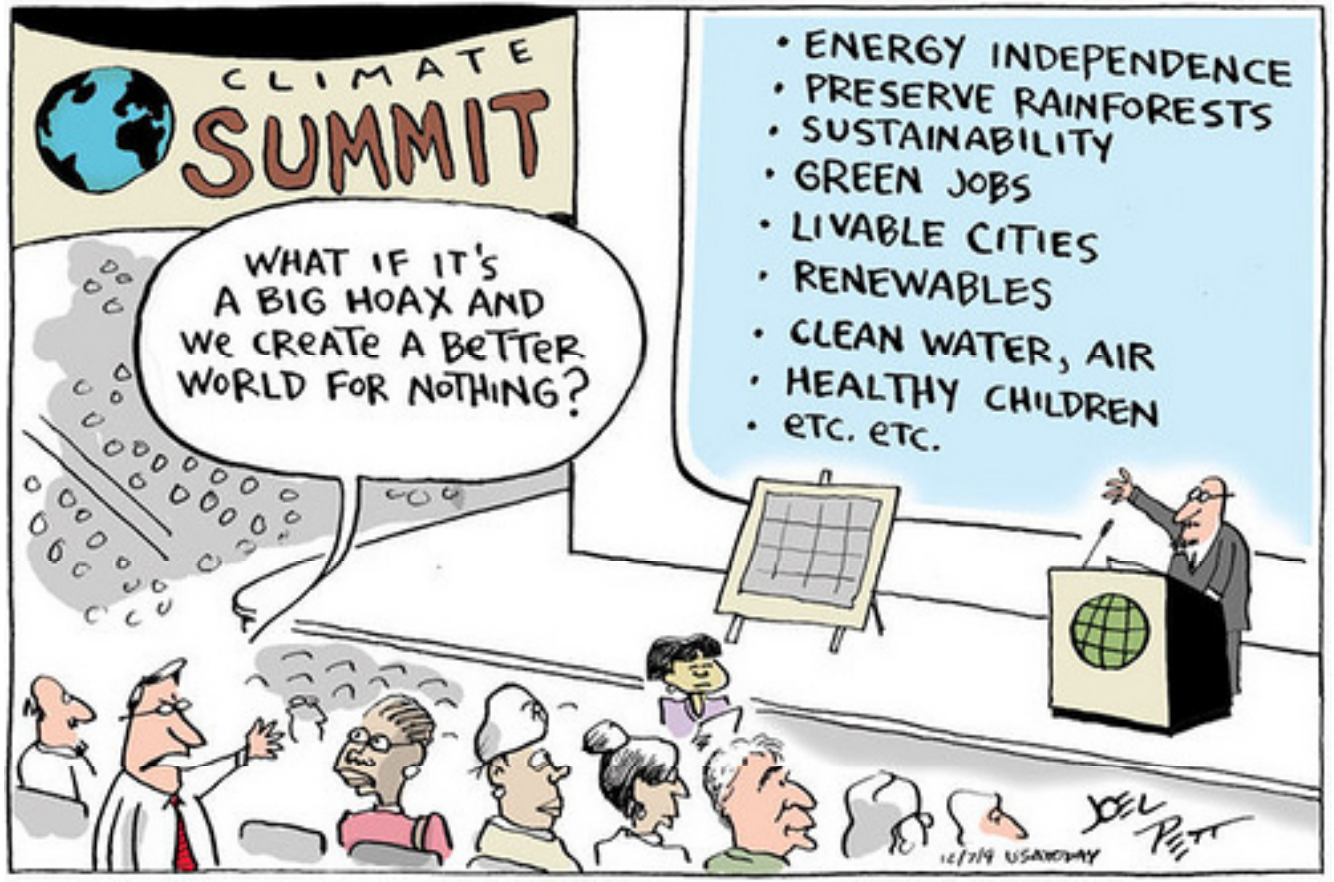
- Project to develop and utilize a comprehensive model to:
  - Investigate and predict seasonal and interannual variability in the climate
  - Explore the history of Earth's climate
  - Estimate future of environment for policy formulation
- Collaborations are critical:
  - Developed jointly by NCAR, National Labs and Universities
- Provide support for climate modeling:
  - fully documented and freely available model (portable)
  - model data
  - training





Why so much effort to keep improving our collective ability to model Earth's climate?

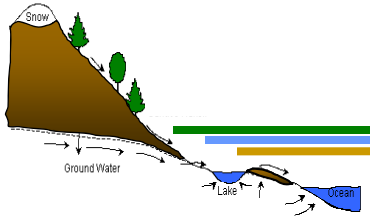
"Prediction is [very] difficult, especially of the future" (Niels Bohr)



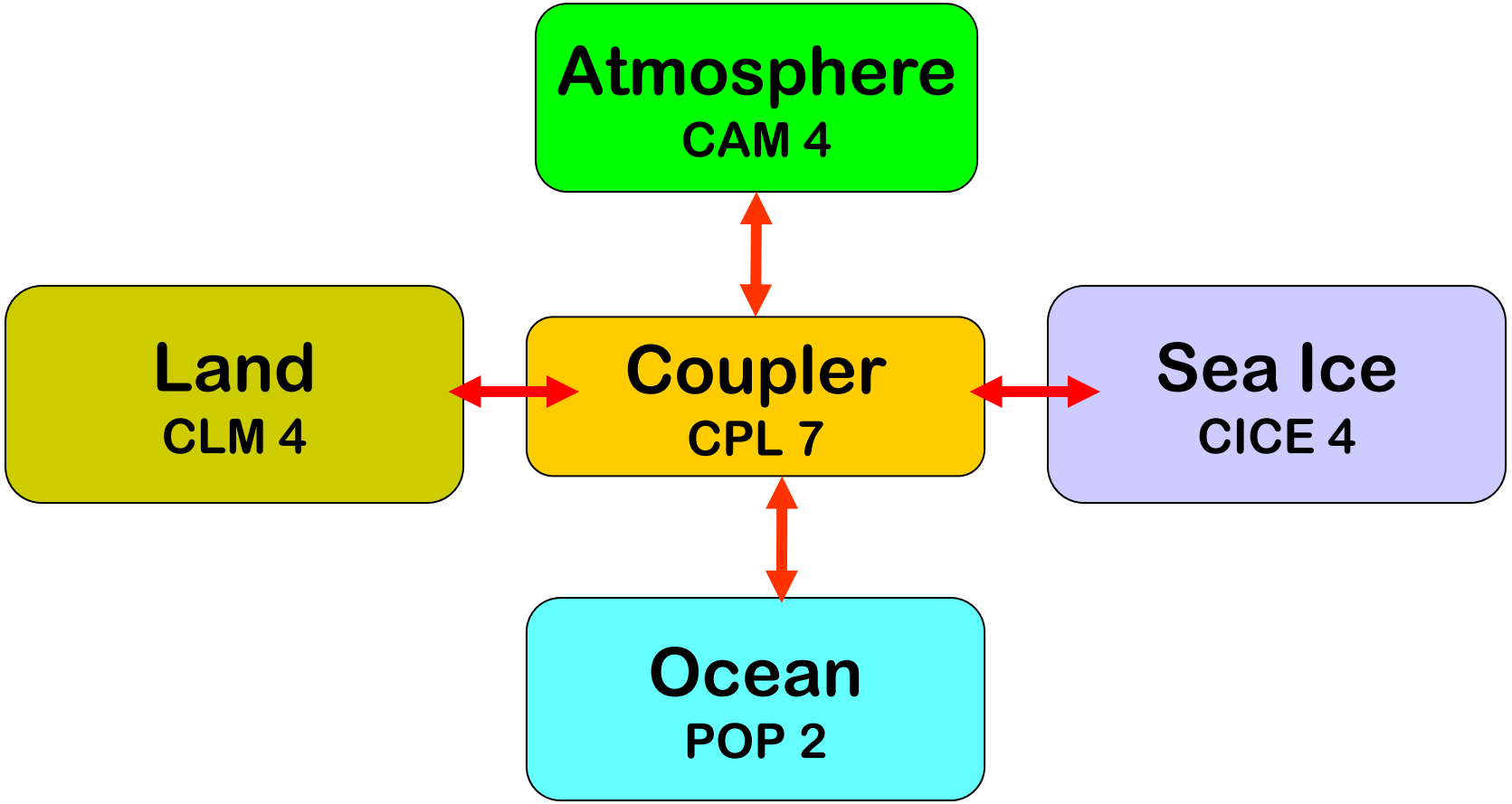
Community Earth System Model (CESM1)

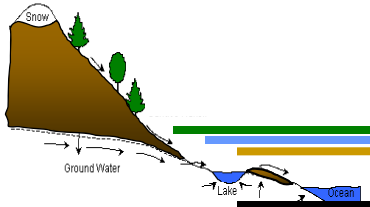
Core is a Coupled Ocean-Atmosphere-Land- Sea Ice model (CCSM4)

- 0.5º, 1º , 2º, T31 resolutions
- 30 minute time step
- 26 atmosphere levels
- 60 ocean levels
- 15 ground layers
- ~5 million grid boxes at 1º
- ~1.5 million lines of computer code
- Archive data (monthly, daily, hourly) for hundreds of geophysical fields (over 250 in land model alone)



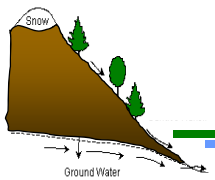
Configuration of CCSM4



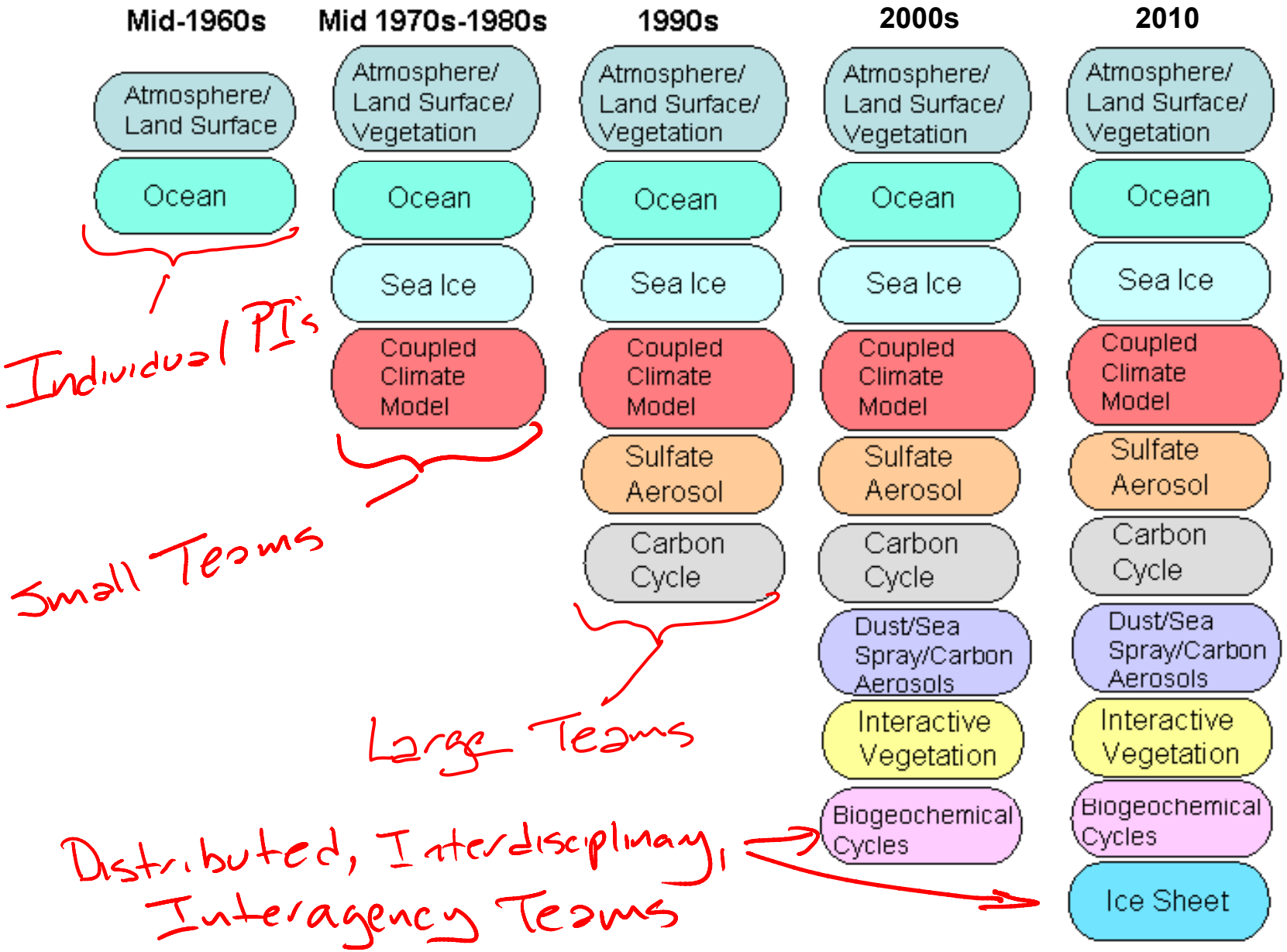


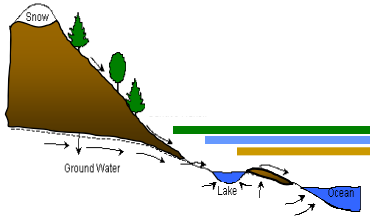
CCSM4: 1° resolution; T_{surf}, clouds, P

animation courtesy ETH Zurich



History of Climate Model to Earth System Model Development
http://www.aip.org/history/climate/GCM.htm





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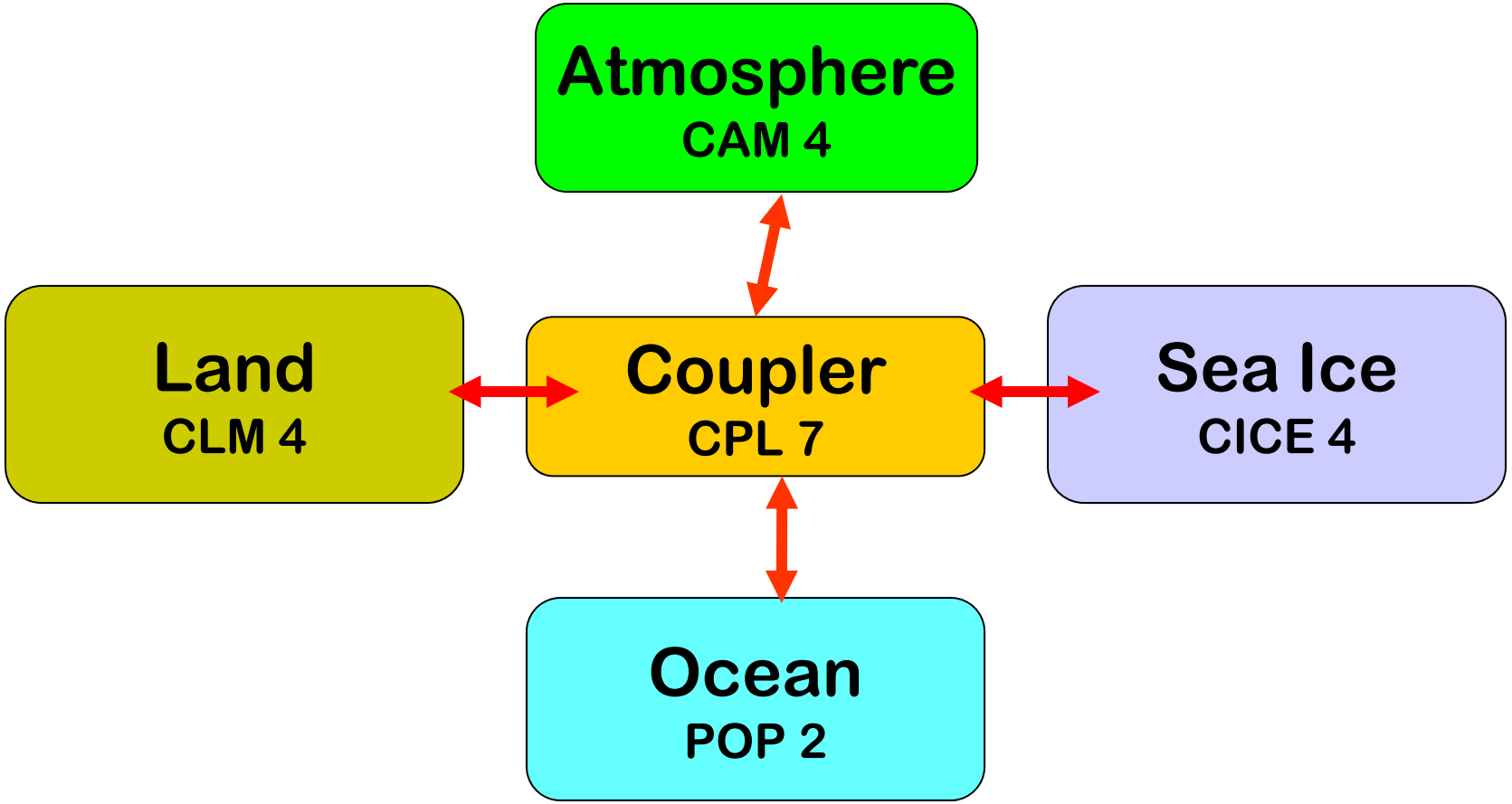
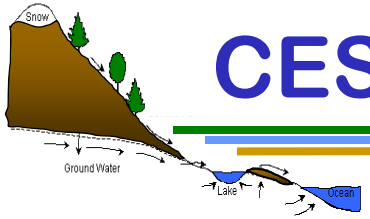




CESM1 (Coupled modeling framework)

Atmosphere
CAM 4, CAM5, WACCM,
Fast Chem, Full Chem

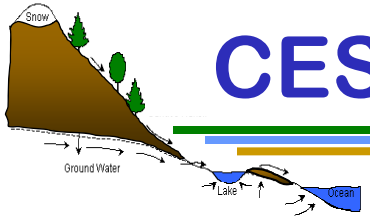
Land
CLM 4
SP, CN, CNDV

Coupler
CPL 7

Sea Ice
CICE 4

Land ice
CISM

Ocean
POP 2
Ecosys



CESM1 (Coupled modeling framework)

Atmosphere
CAM 4, CAM5, WACCM,
Fast Chem, Full Chem

Land
CLM 4
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Sea Ice
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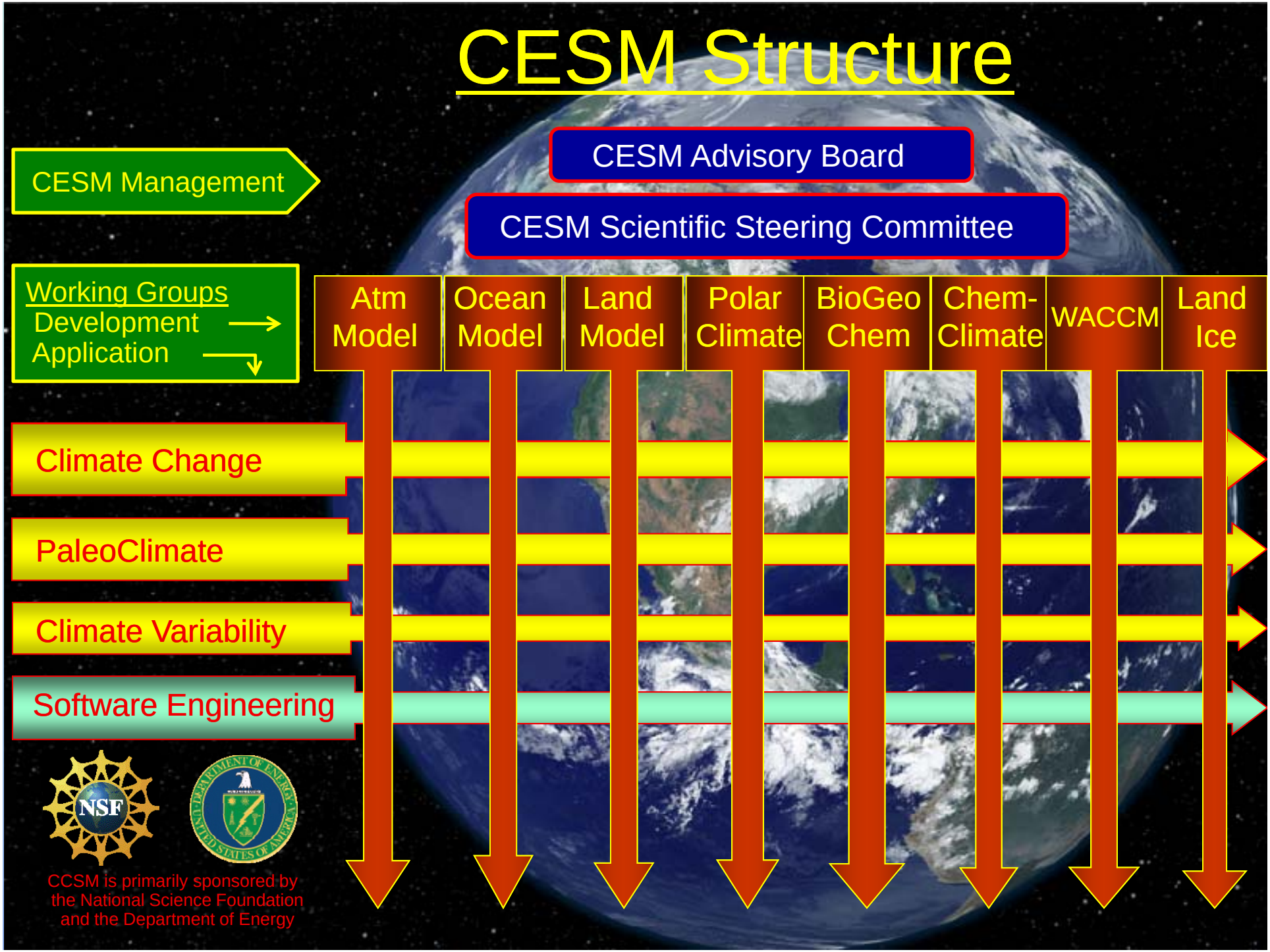
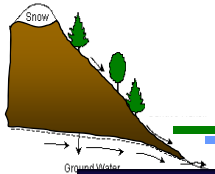
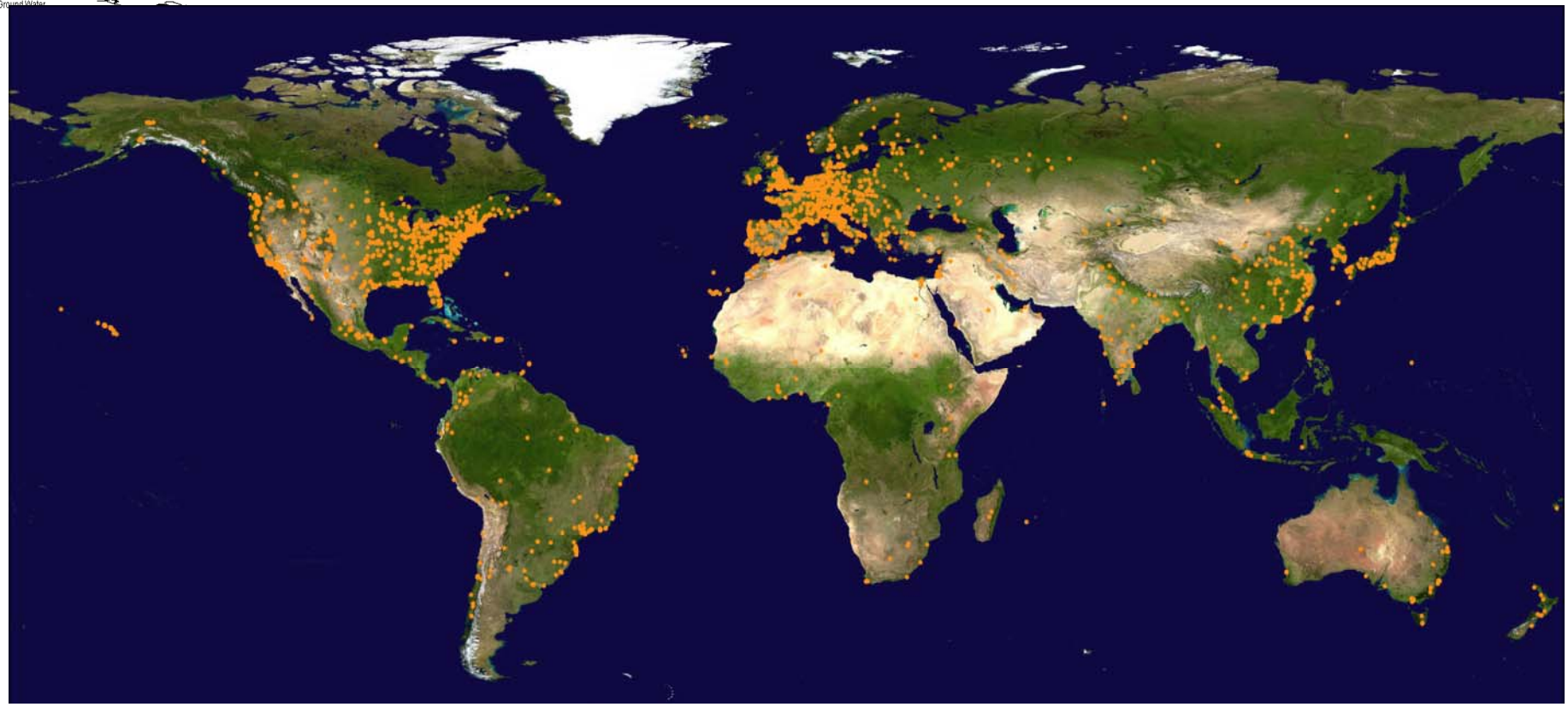
Ocean
POP 2
Ecosys

CESM Structure



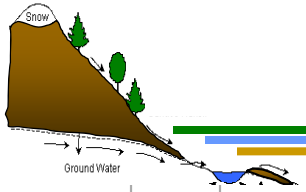


CESM: A Community Resource

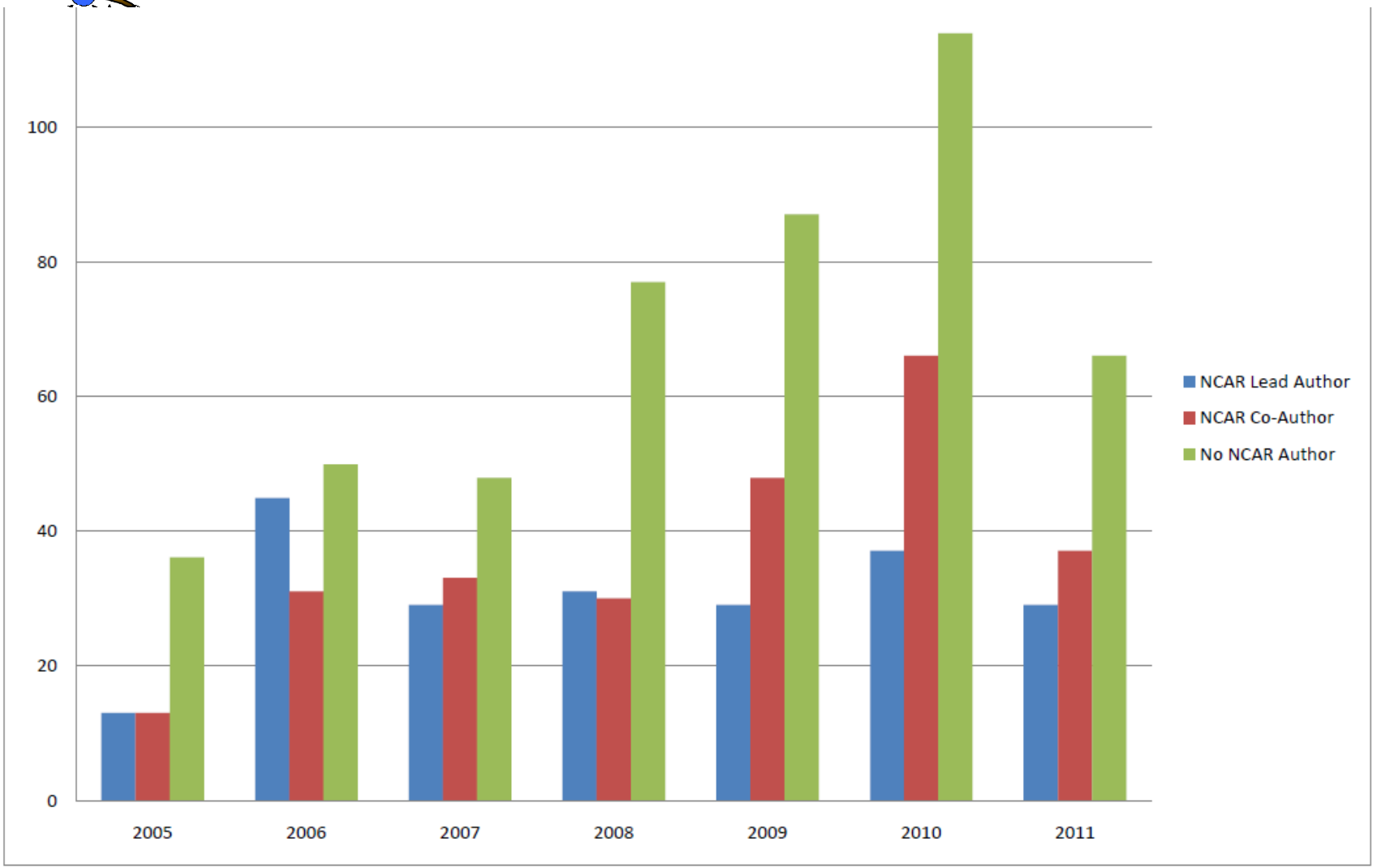


Model data: Over 3,000 sites from 130+ countries
> 230 Tb since 2005
Model code: Over 1100 downloads since April 2010

Courtesy Gary Strand



CCSM / CESM Publications



CMIP-5 Simulations

- CESM and partners will make a major contribution to IPCC AR5 through simulations performed with CCSM4.0 and CESM1.0

- CMIP-5 Experimental Design (Taylor et al. 2009):

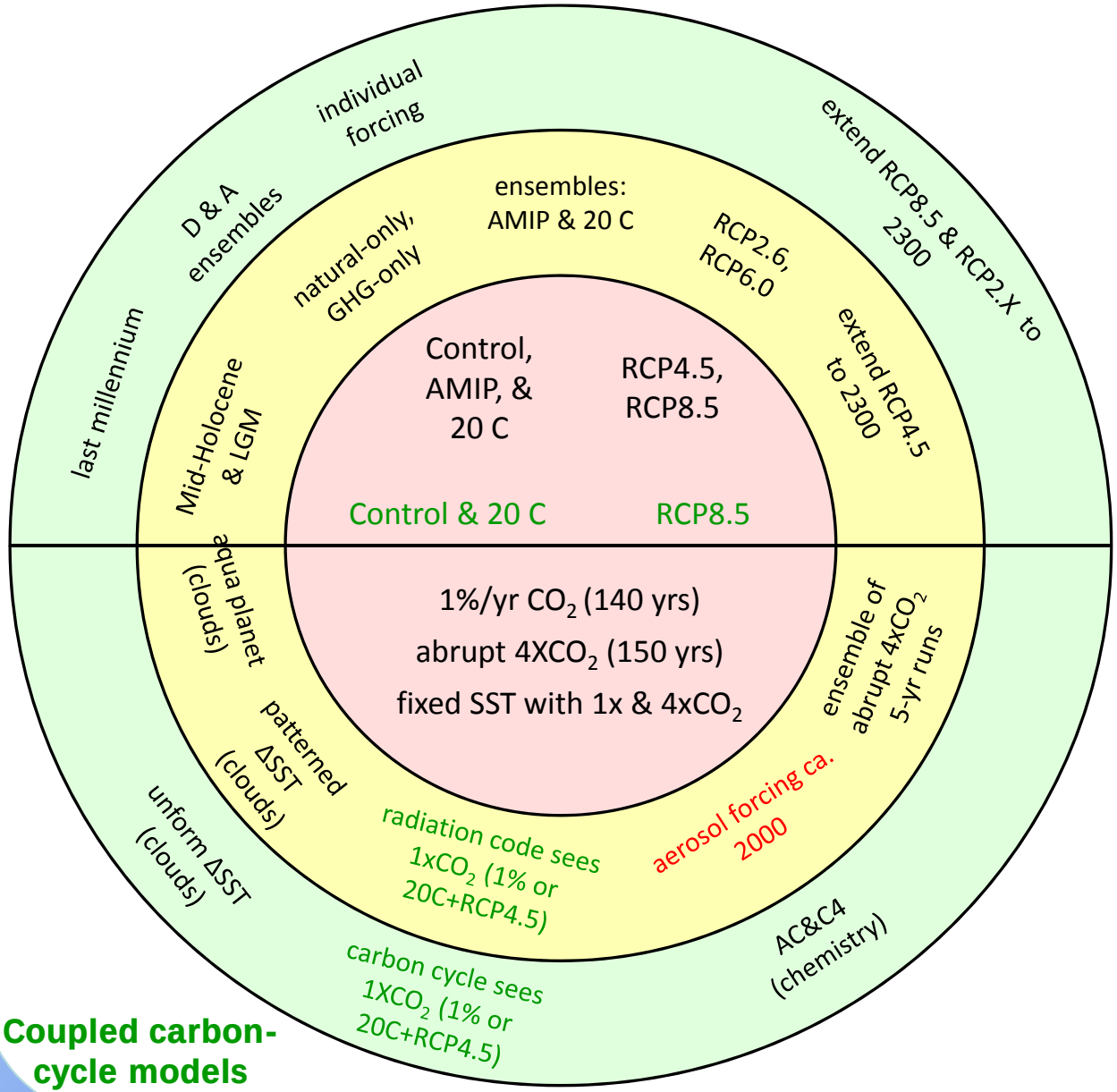
  A set of coordinated climate model experiments to:

  - ✓ address outstanding scientific questions from AR4
  - ✓ improve understanding of climate variability/change
  - ✓ provide estimates of future climate change useful to those considering its possible consequences

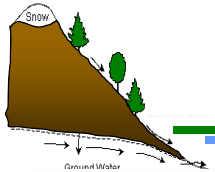
- CMIP-5 is a 5-year experimental design, but a significant fraction of the experiments will be done in time to be included in AR5

  - ✓ Initialized decadal prediction and long-term climate change
  - ✓ Includes carbon cycle, paleoclimate, whole atmosphere, and land ice

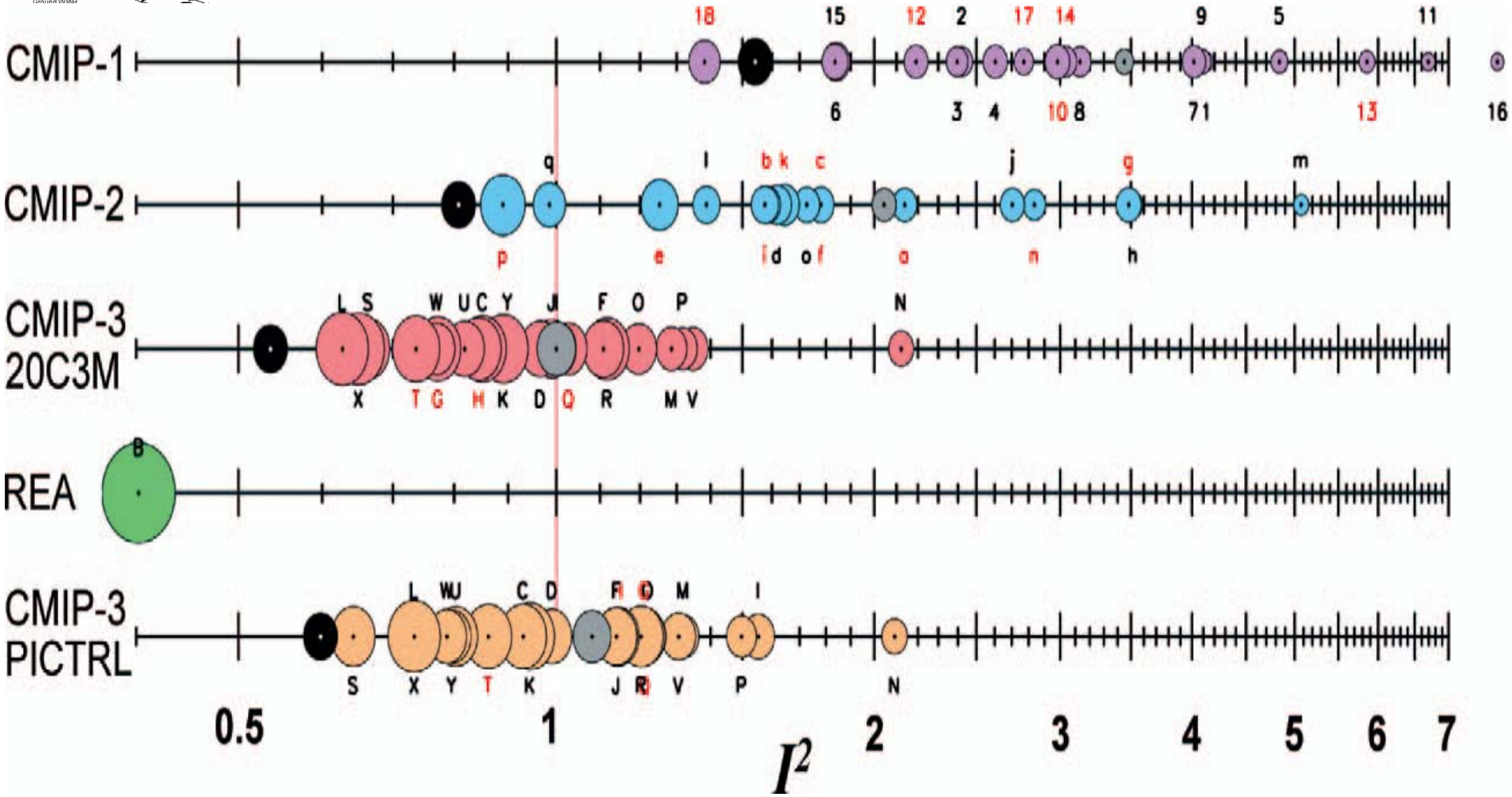
CMIP5 Long-term Climate Change Experiments



- All Core + Most Tier completed at NCAR (> 11M GAU used) (~500 Tb history output)
- Began in Sept 2009
- Experiments with:
  - o CAM4
  - o CAM5
  - o CAM-CHEM
  - o WACCM
- 1,000 yr controls
- Ensembles:
  - o Historical
  - o RCPs
- High-frequency output
  - o Control
  - o Historical
  - o RCPs



Have GCMs actually been getting any better?



Reichler et al., 2008, BAMS

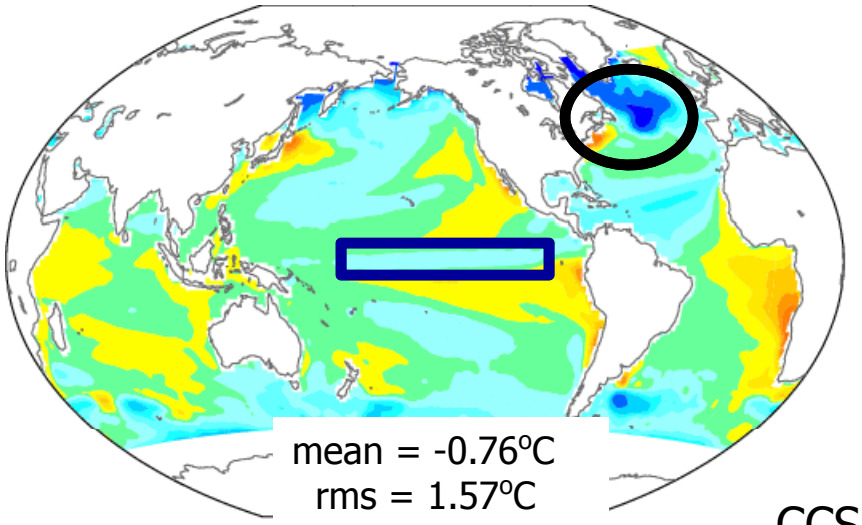
Selected Results

- **Pre-industrial controls (CCSM4 and CESM1)**
  - ✓1850 conditions, multi-century, mostly 1º resolution
  - ✓ some comparisons to 1870 CCSM3 (T85)
- **20th century transient simulations**
  - ✓ 1850-2005, some ensembles, mostly 1º resolution
  - ✓ some comparisons to CCSM3 (1870-1999; T85)
- **Observations (best available, common periods)**
- **Mean and Variability**
- **Good and Bad**
- **Details and more results in CCSM4 and CESM1 Journal of Climate Special Collections (~65 papers)**

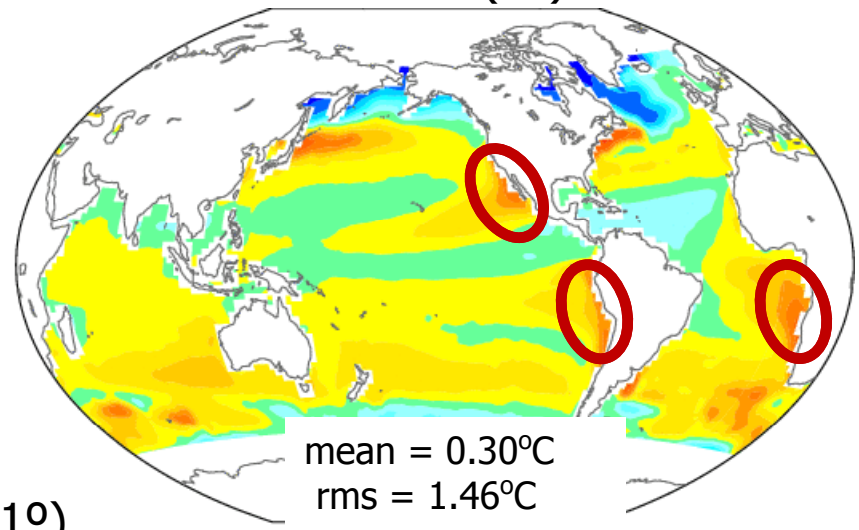
SST Biases

(Pre-Industrial)

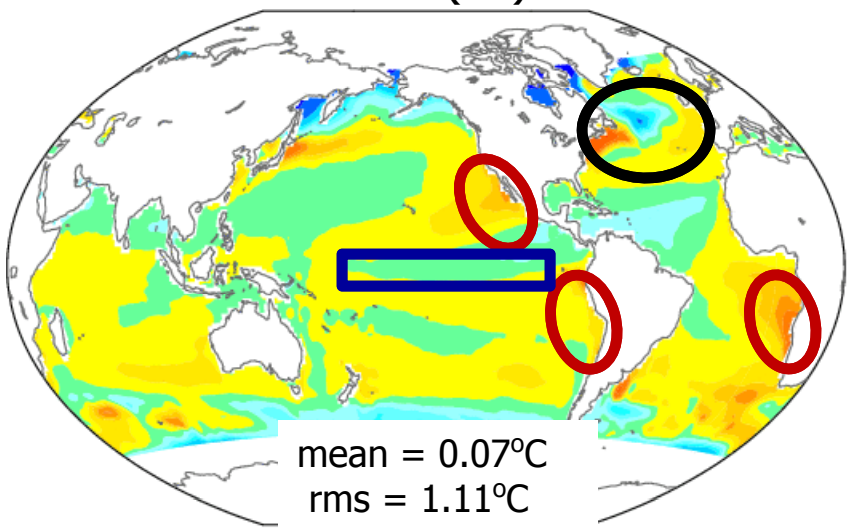
CCSM3

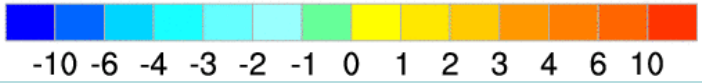


CCSM4 (2°)



CCSM4 (1°)

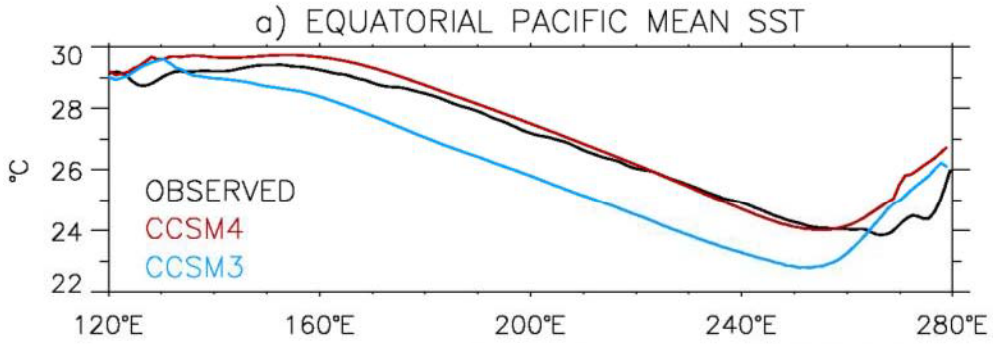




Overall reduction
SST bias, all basins

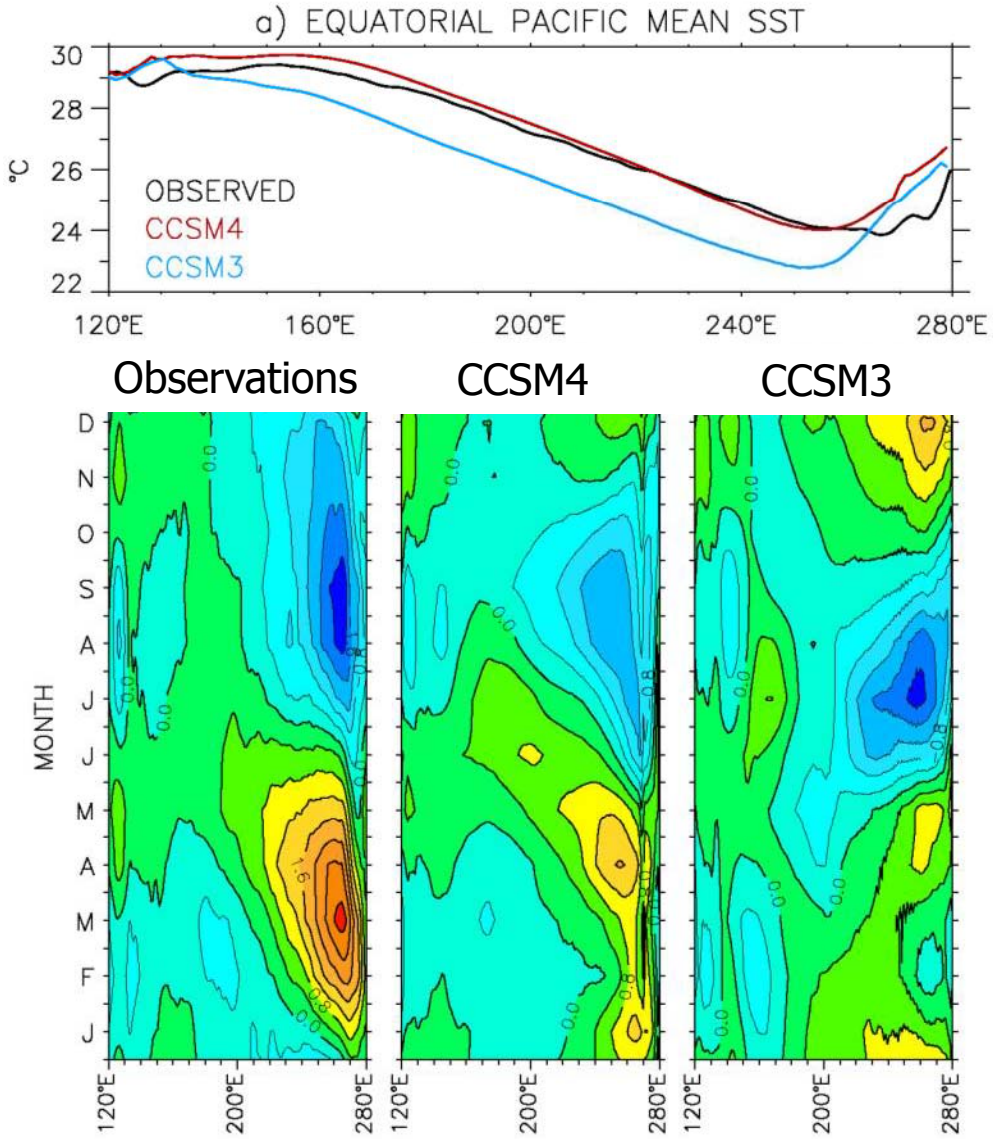
Equatorial Pacific SST

(Late 20th Century)



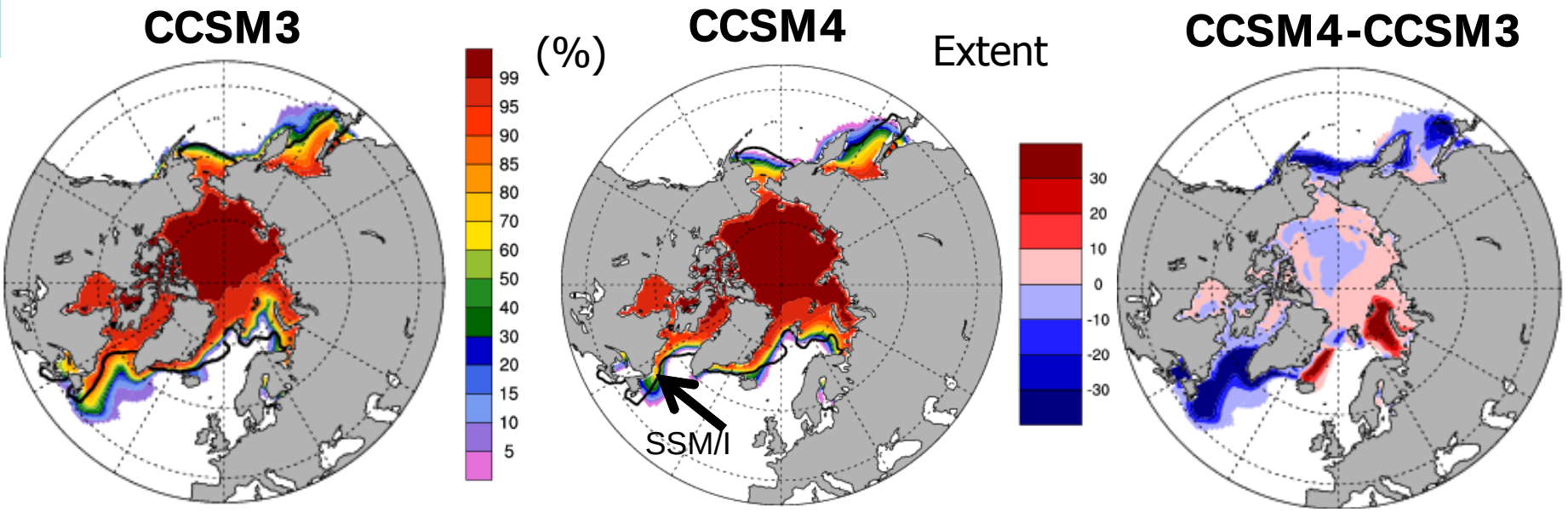
Equatorial Pacific SST

(Late 20th Century)



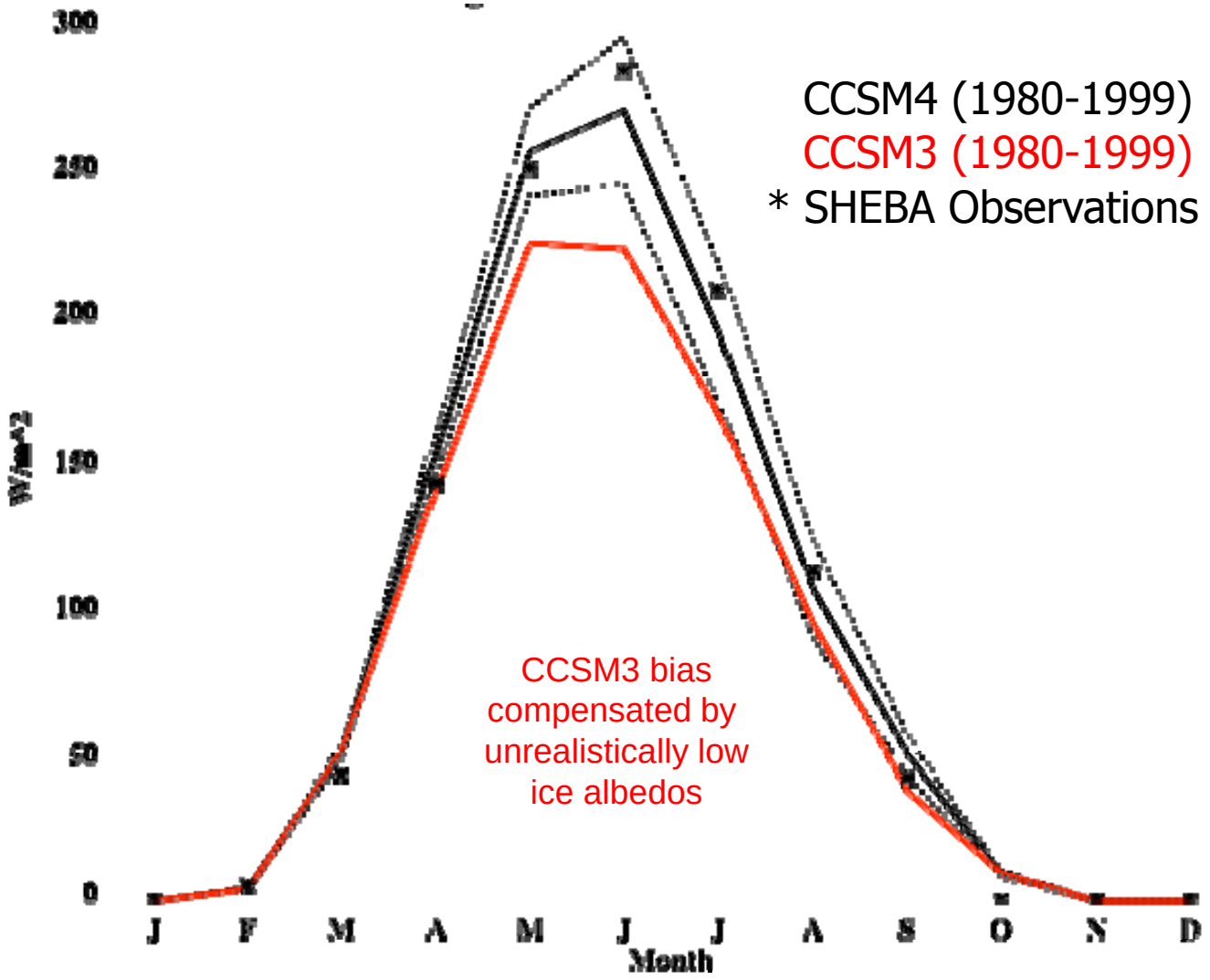
JFM Arctic Sea Ice

(Late 20th Century)



Incoming Shortwave Radiation

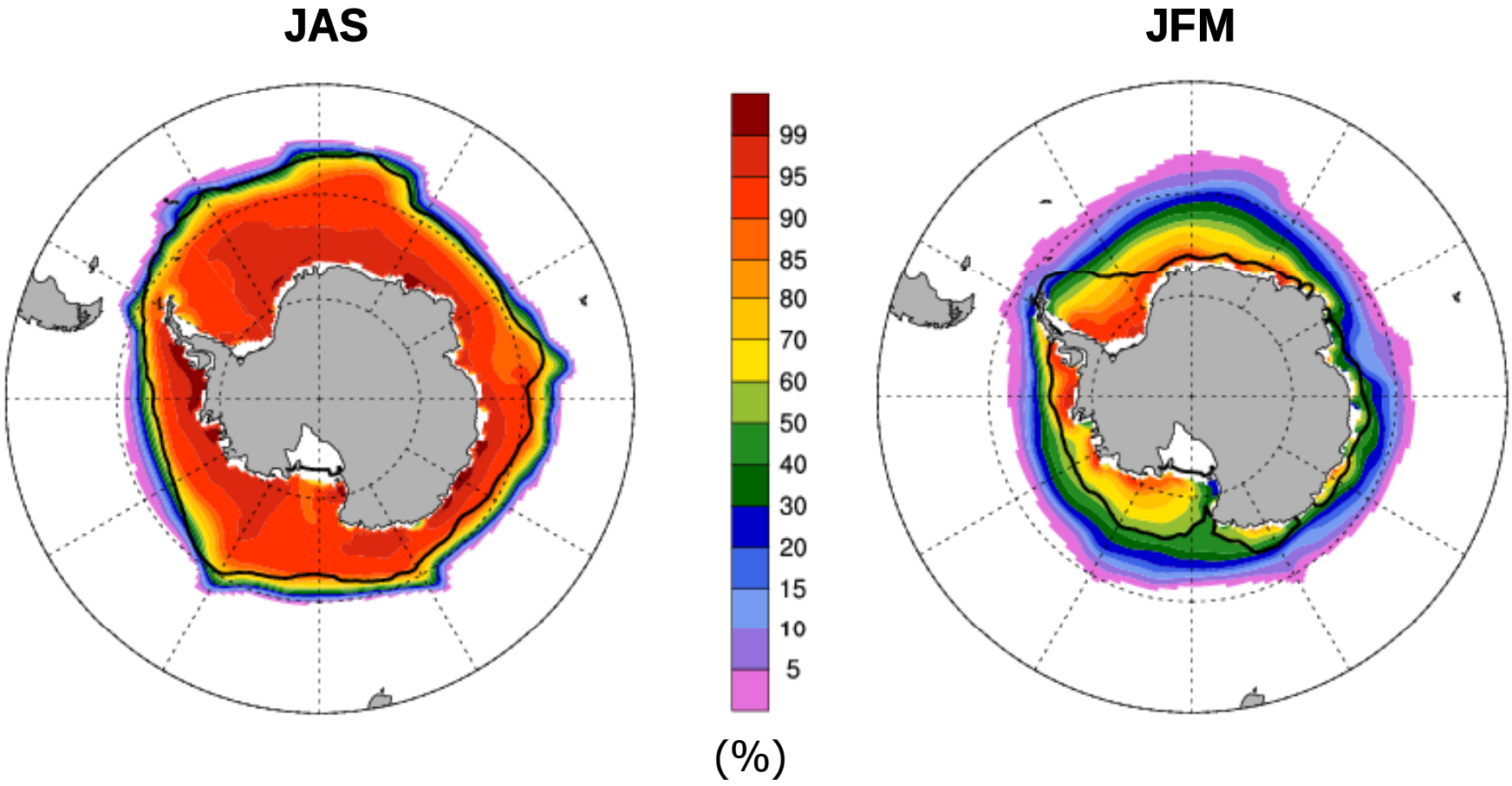
(Differences from SHEBA Observations)



Antarctic sea ice cover

(Late 20th Century)

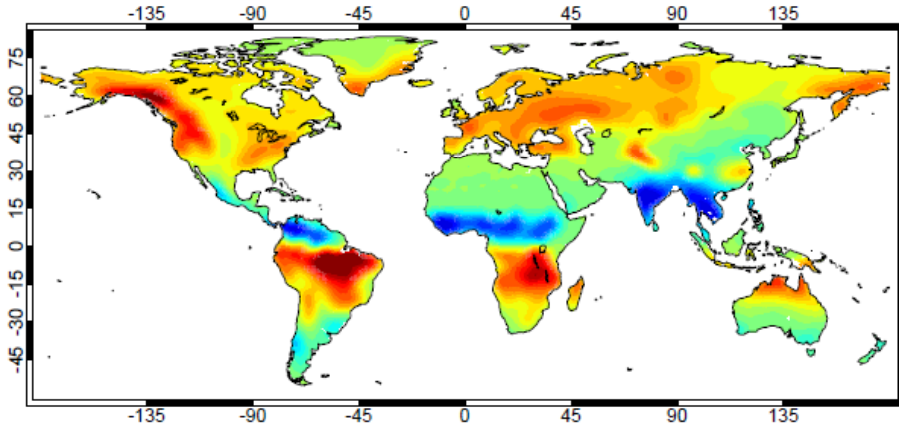
CCSM4



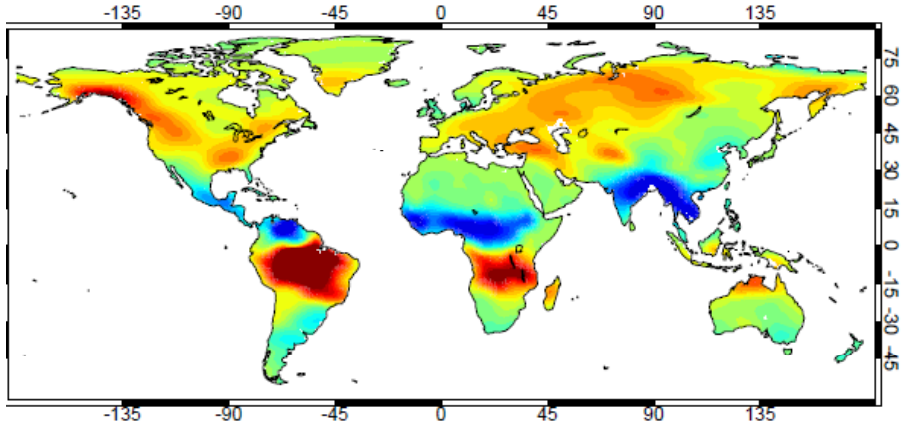
Too extensive, similar to CCSM3

Land water storage (MAM-SON)

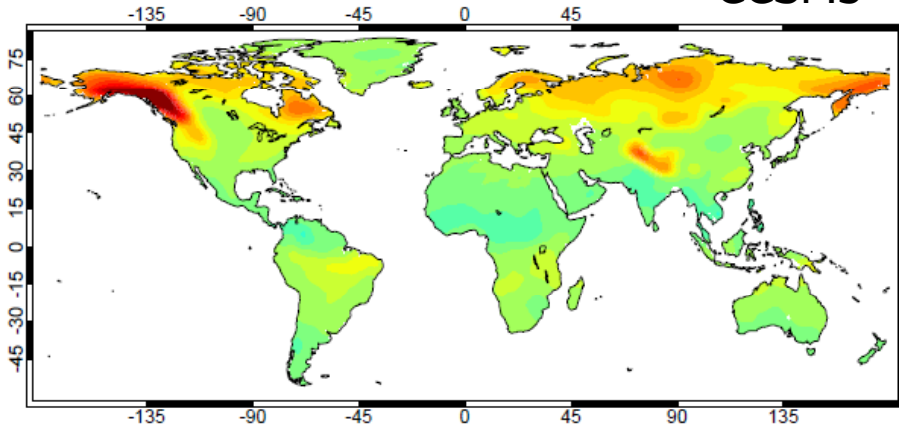
CCSM4



GRACE



CCSM3



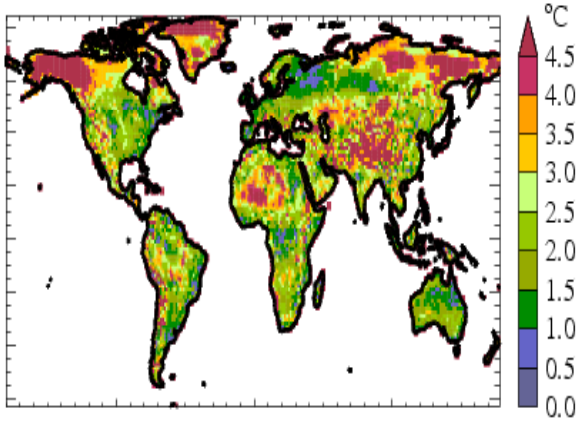
300 200 100 0 -100 -200 -300 (mm)

GRACE satellite measures small changes in gravity which on seasonal timescales are due to variations in mean soil and snow water content. CLM4 has improved capacity to store water from one season to the next

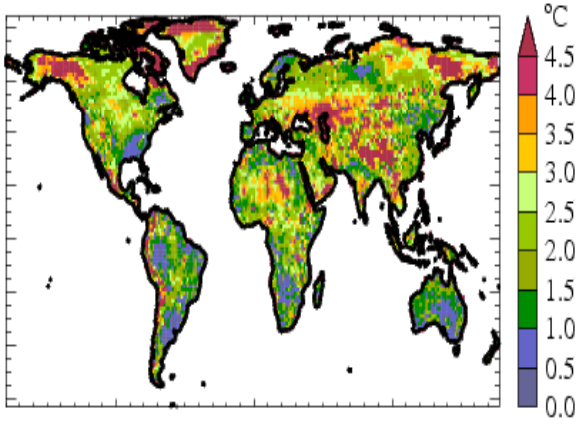
Land surface temperature (annual)

(Differences from Observations: 1950-99)

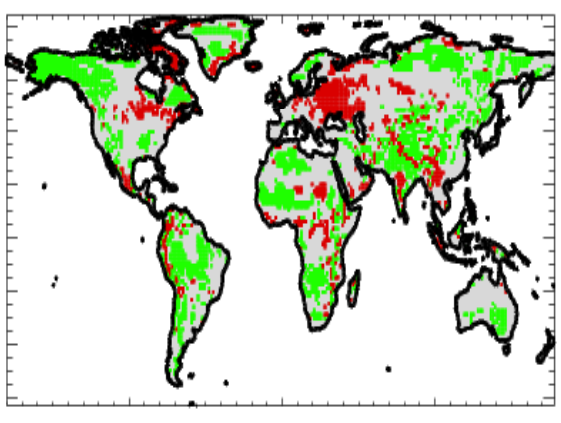
T_{air} RMSE: CCSM3
3.01°C



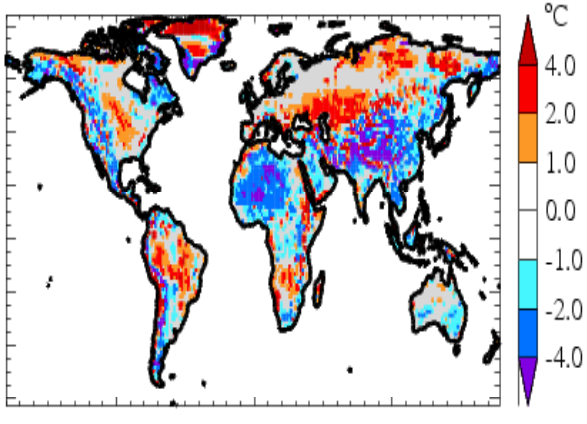
T_{air} RMSE: CCSM4
2.71°C



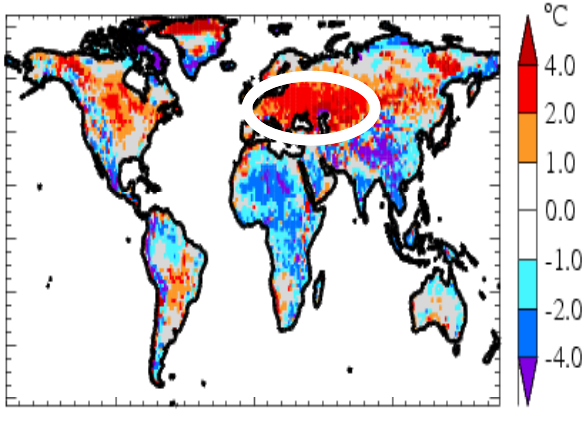
T_{air} RMSE: CCSM4 vs CCSM3
27.1%(+) 12.9%(−)



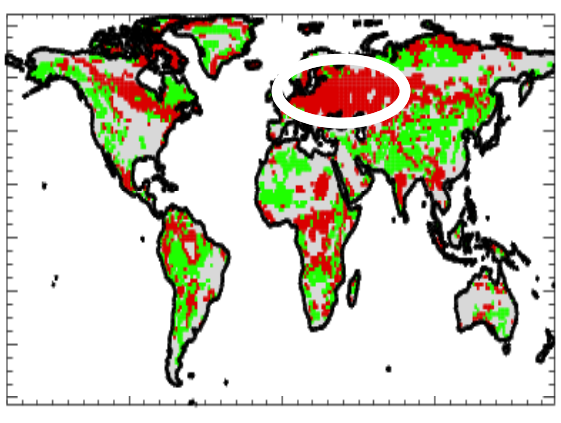
T_{air} ANN Mean Bias: CCSM3
-0.28°C



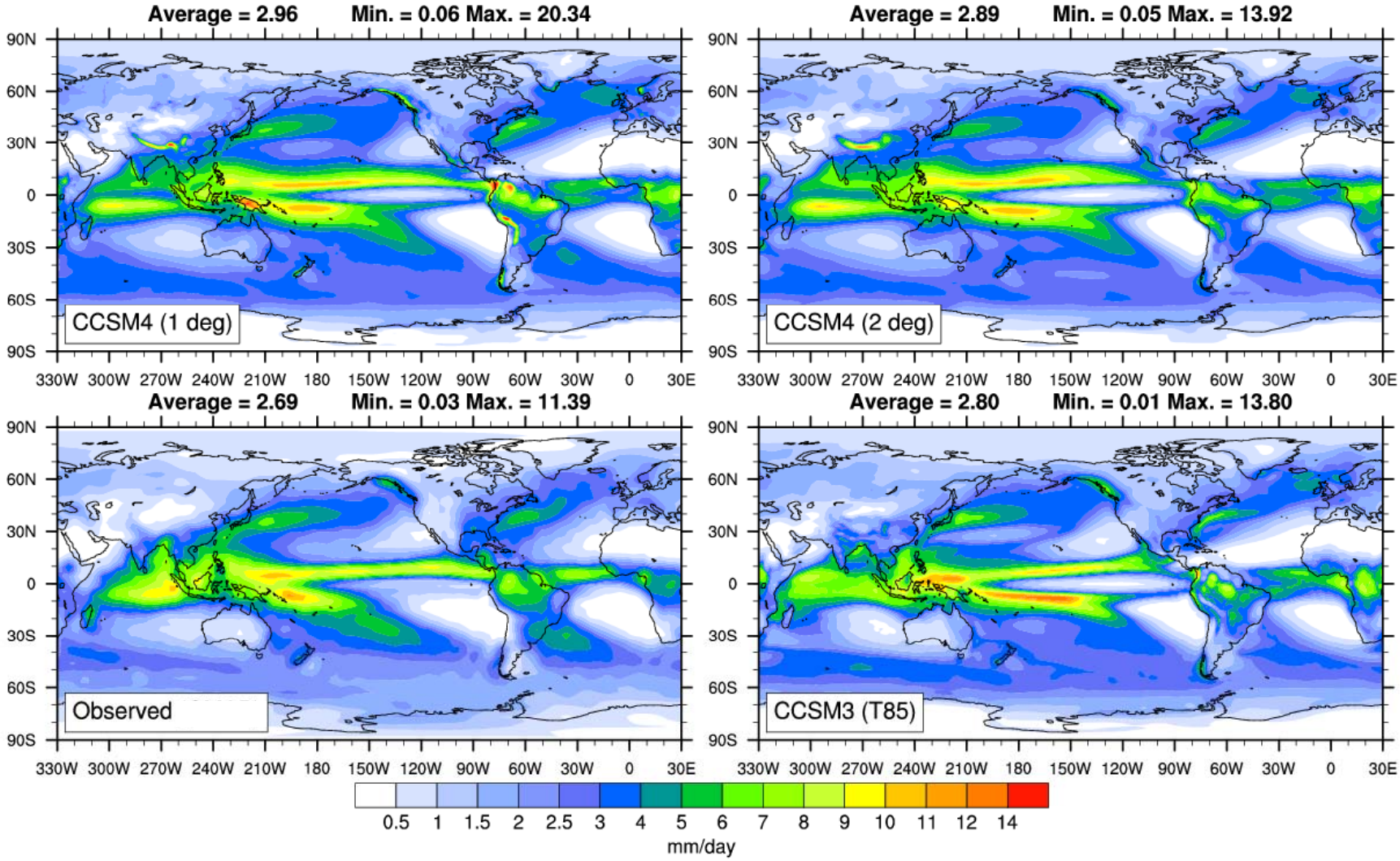
T_{air} ANN Mean Bias: CCSM4
-0.17°C



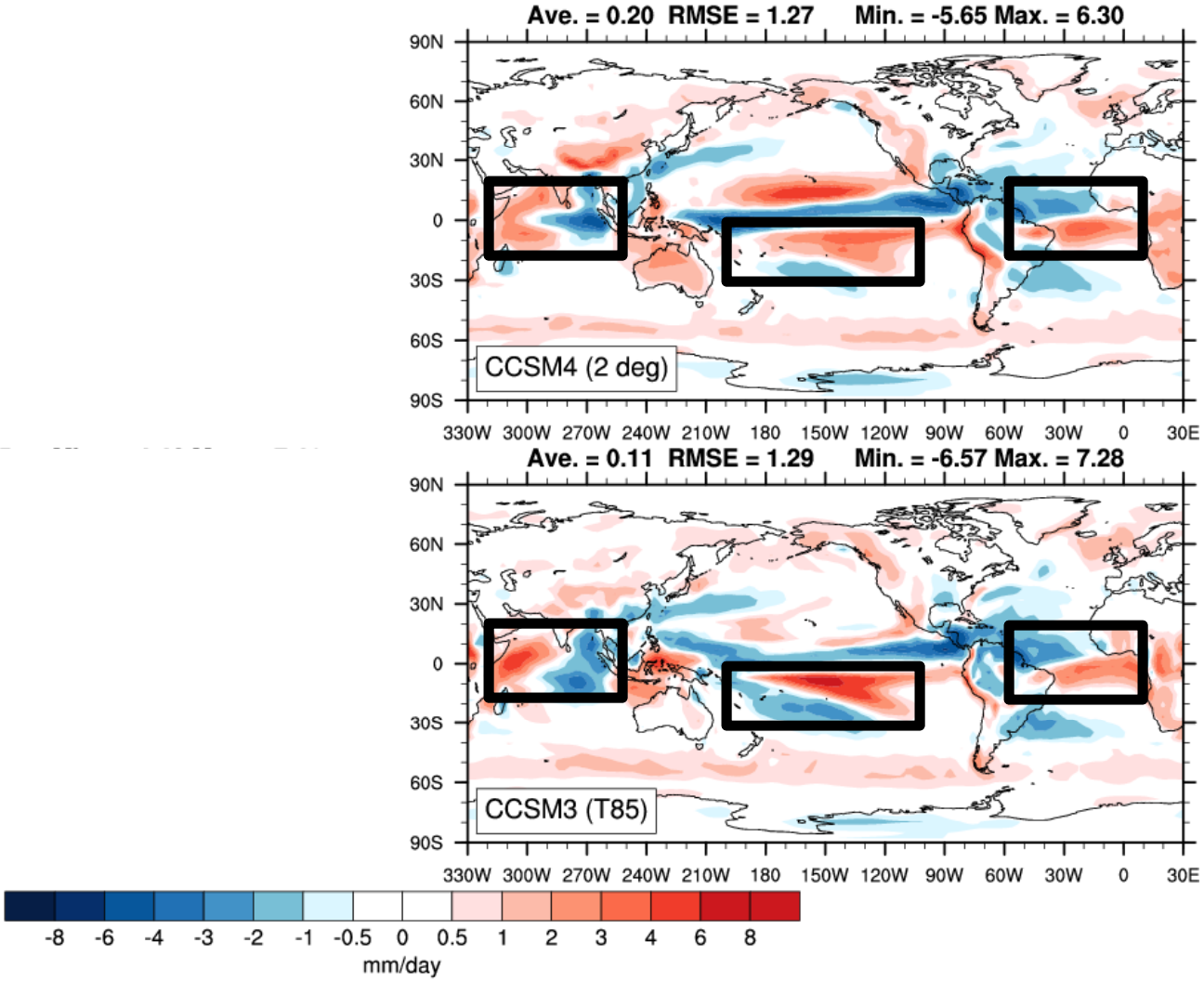
T_{air} ANN Mean Bias: CCSM4 vs CCSM3
27.7%(+) 28.3%(−)



Total Precipitation
(Annual)



Total Precipitation Difference
(Annual)



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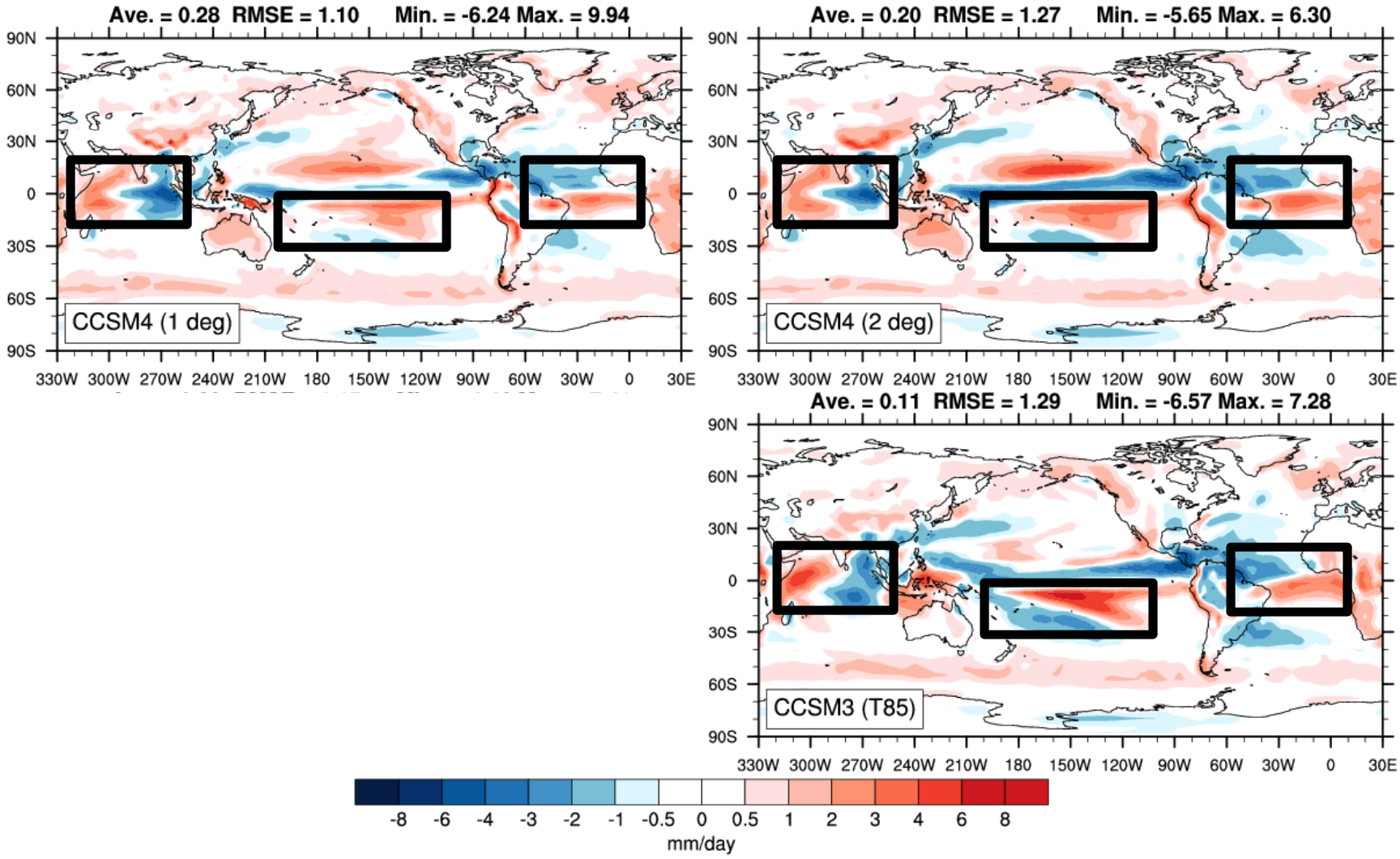
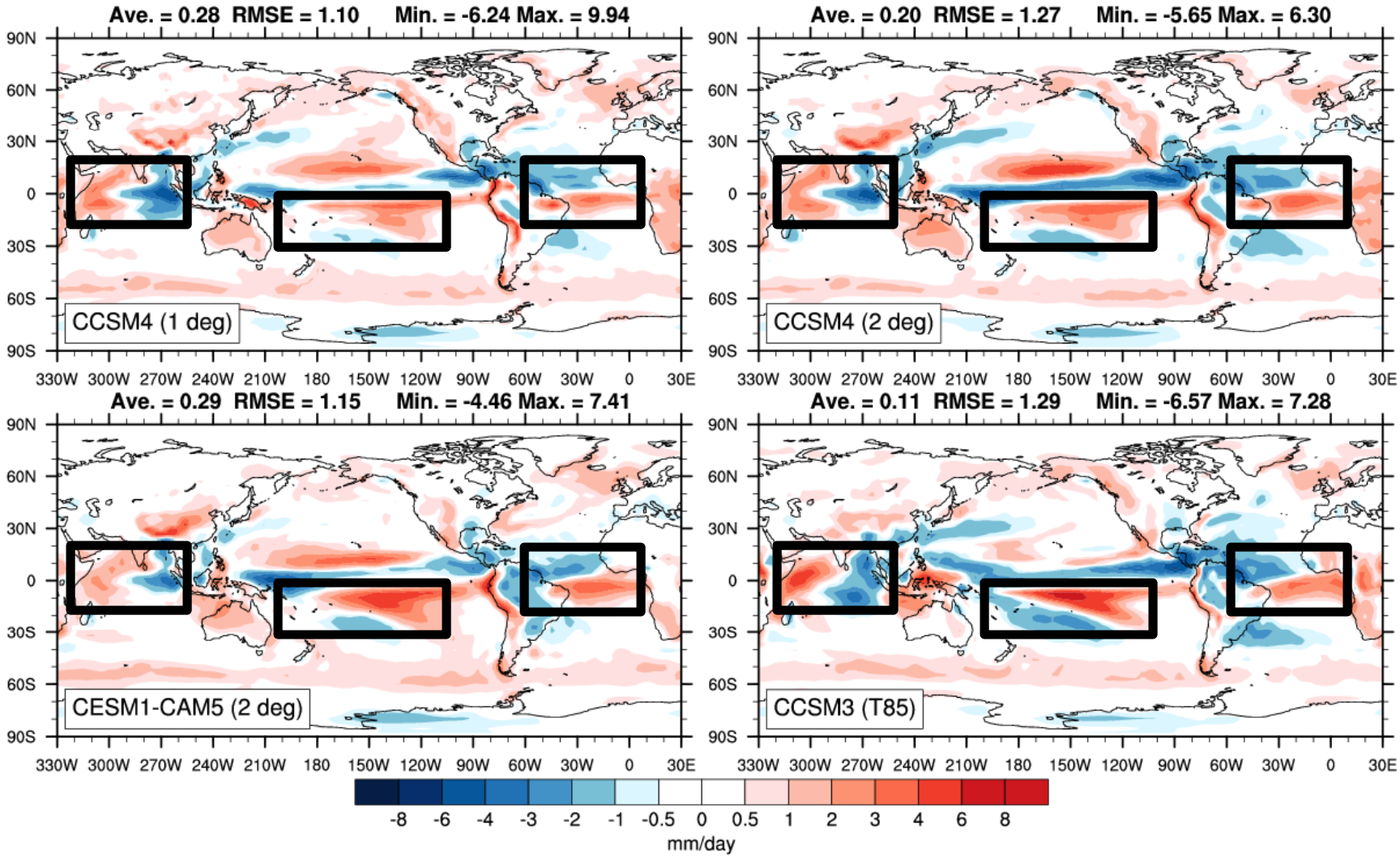
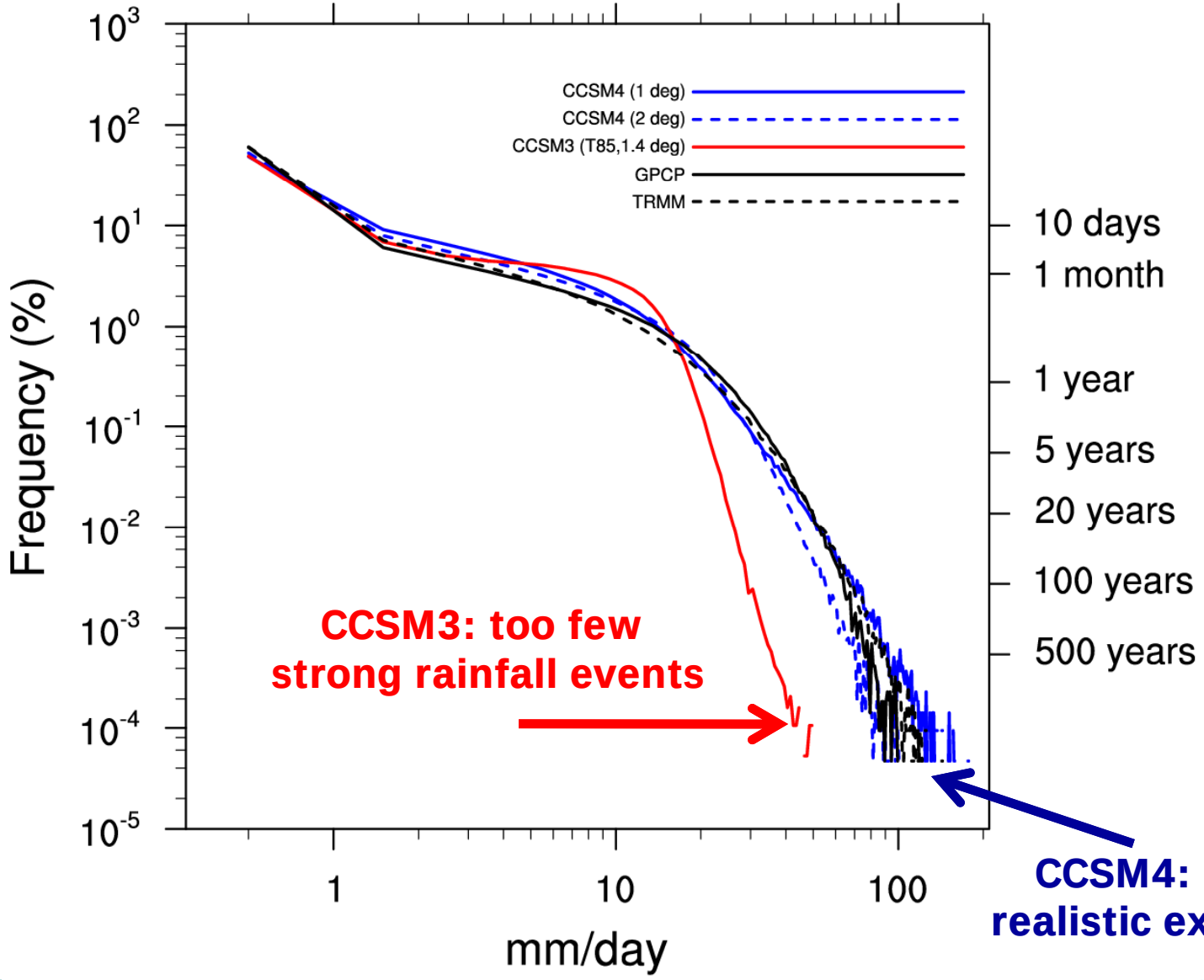


Total Precipitation Difference
(Annual)

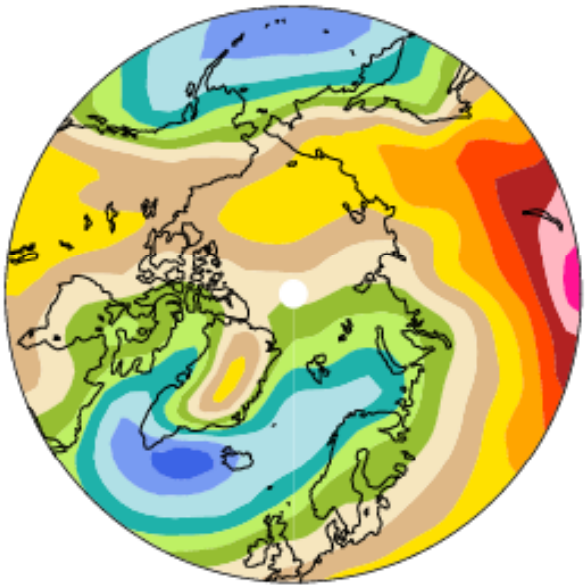


Tropical Land Precipitation

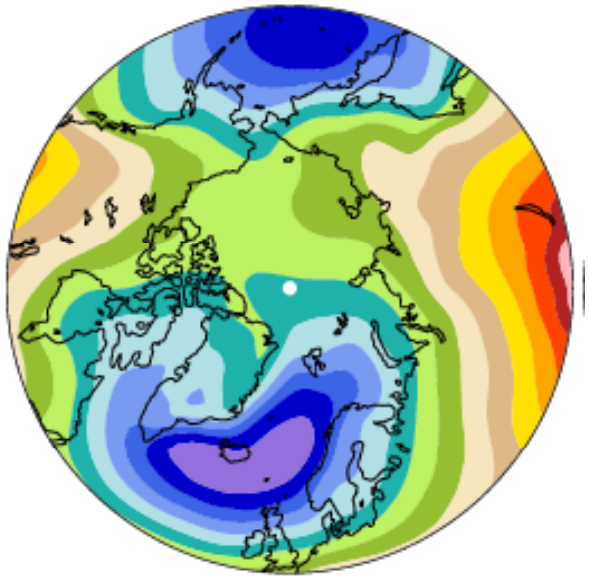
(Frequency of Daily Rate)



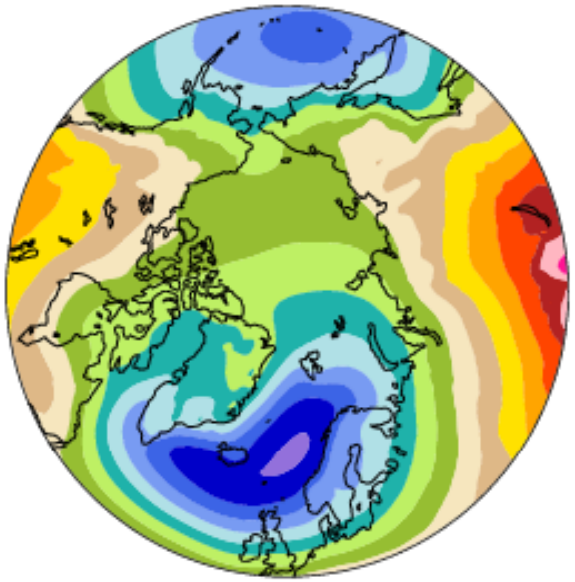
High Latitude SLP (DJF)



Observed



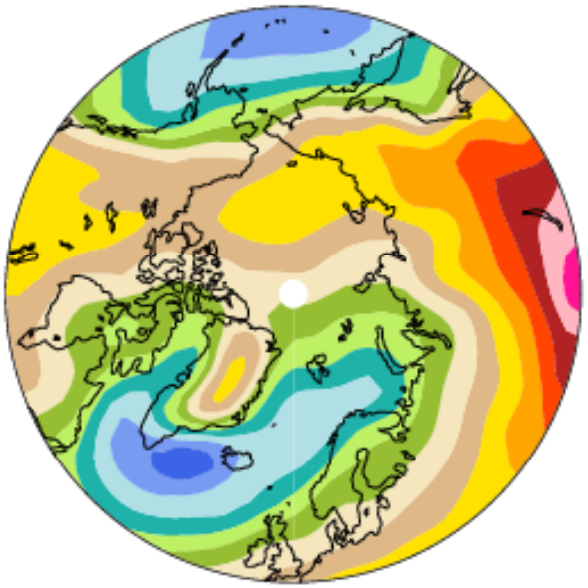
CCSM3



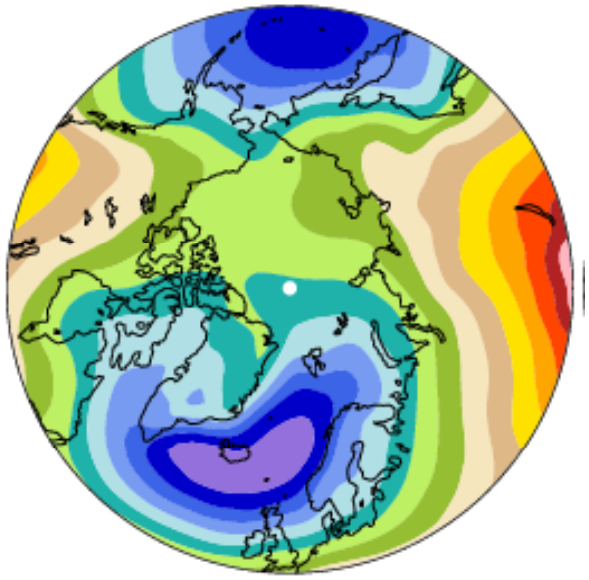
CCSM4

Systematic Reduction in North Atlantic and North Pacific biases

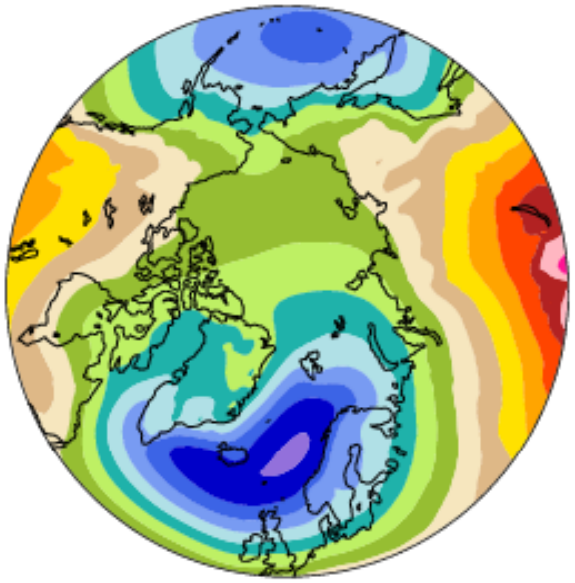
High Latitude SLP (DJF)



Observed

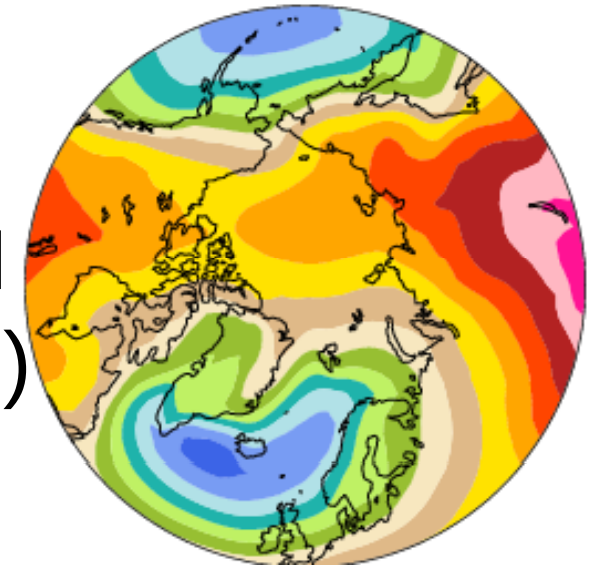


CCSM3



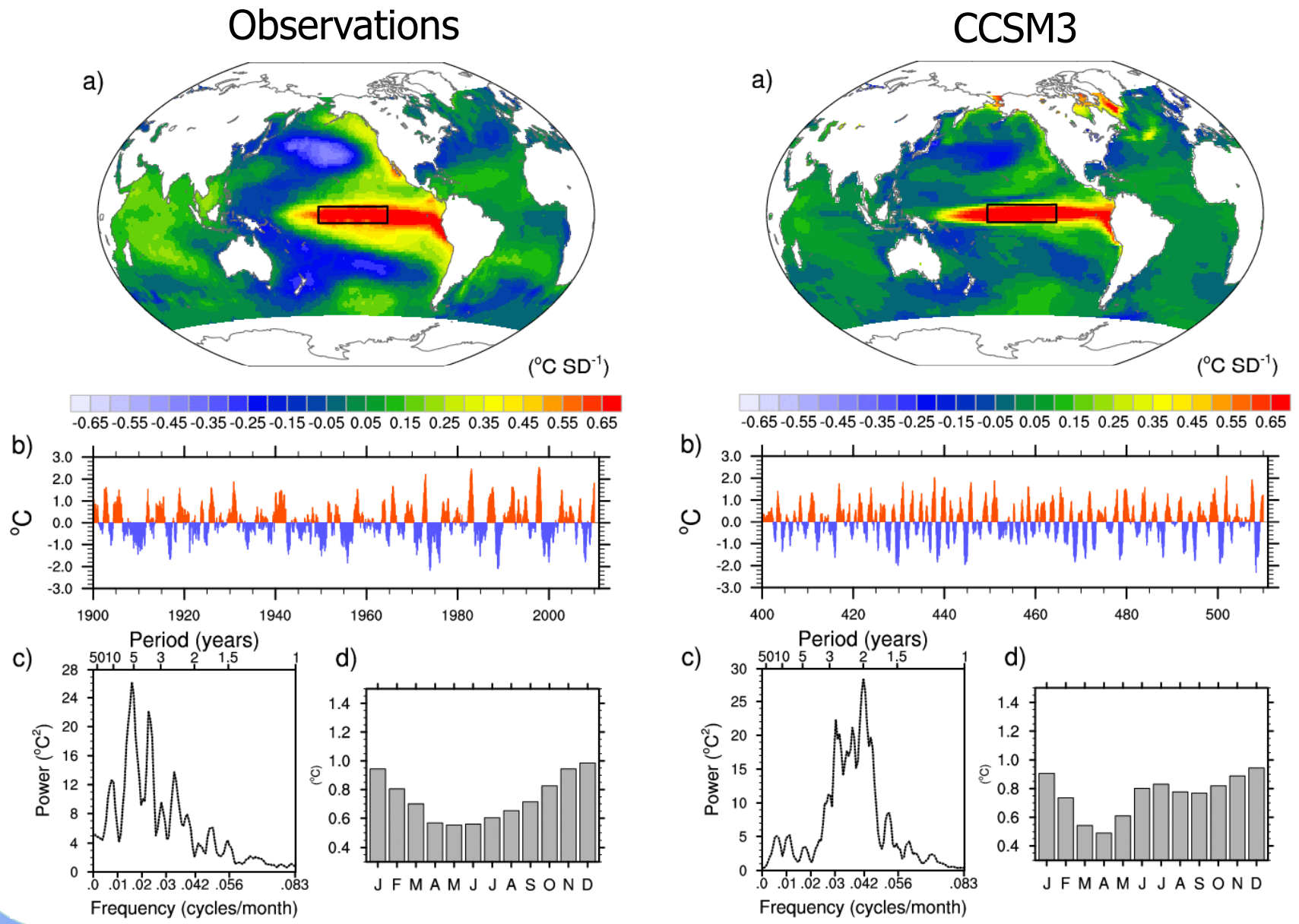
Systematic Reduction in North Atlantic and North Pacific biases

CESM (CAM5)

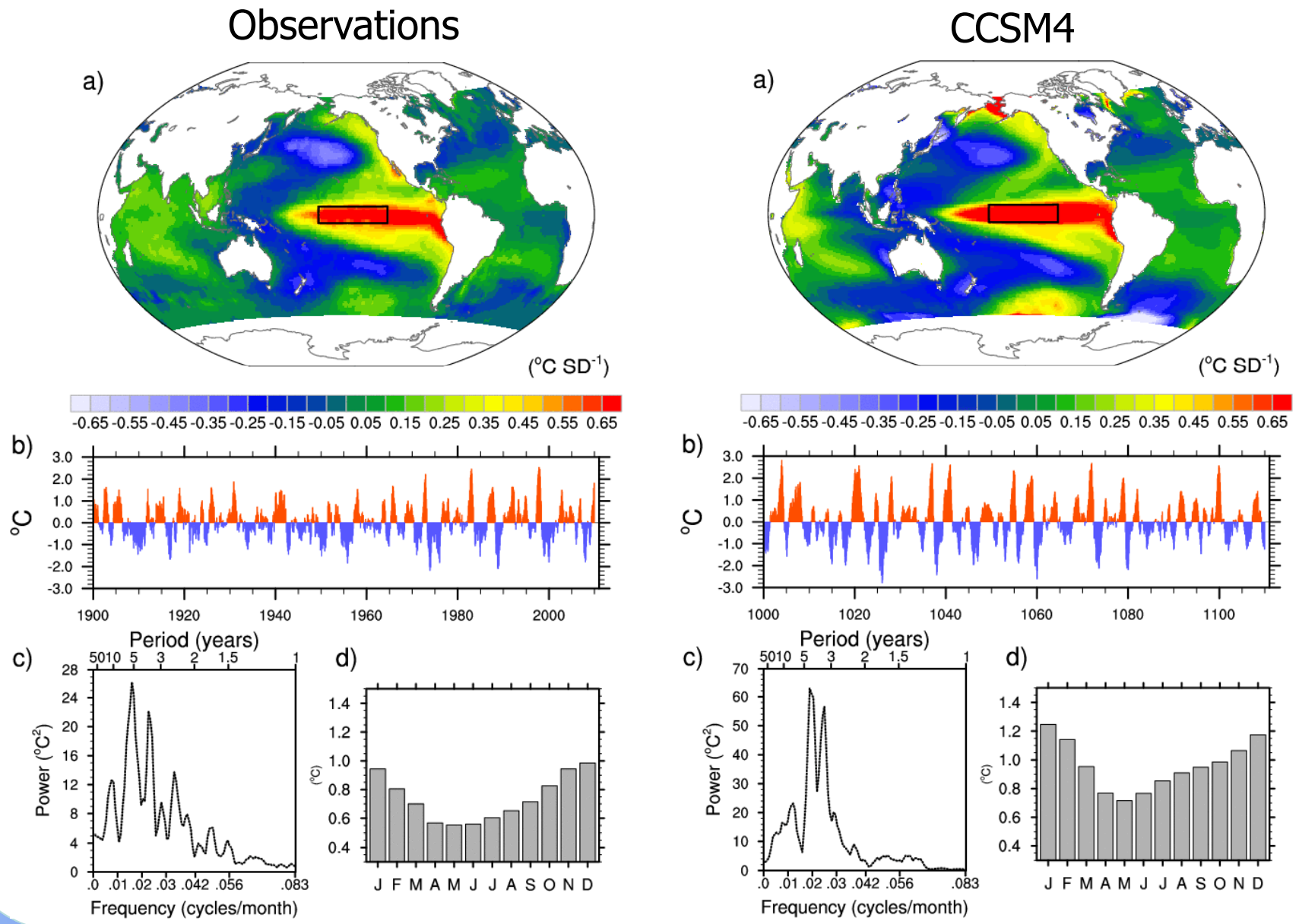


Variability

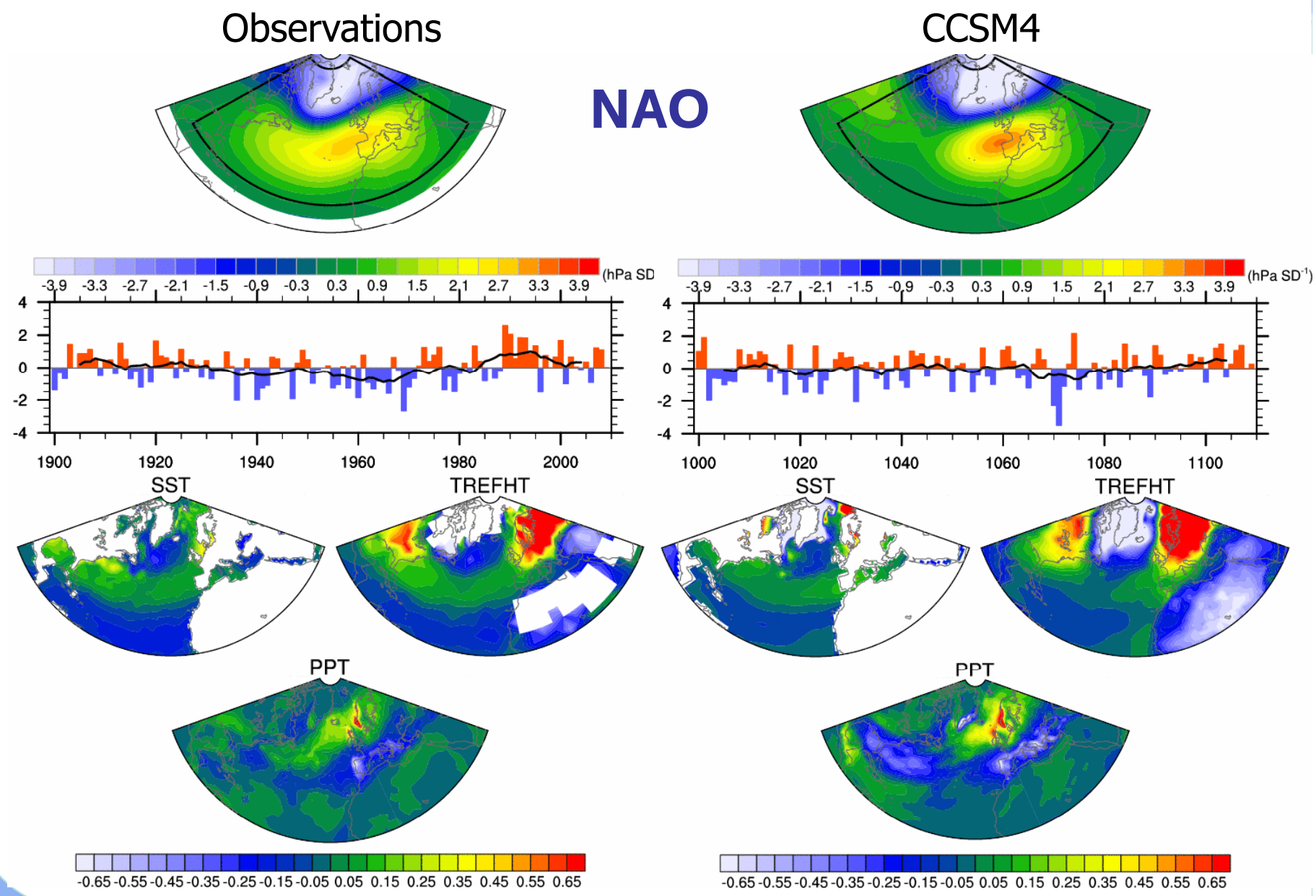
Leading Mode of Global SST Variability



Leading Mode of Global SST Variability

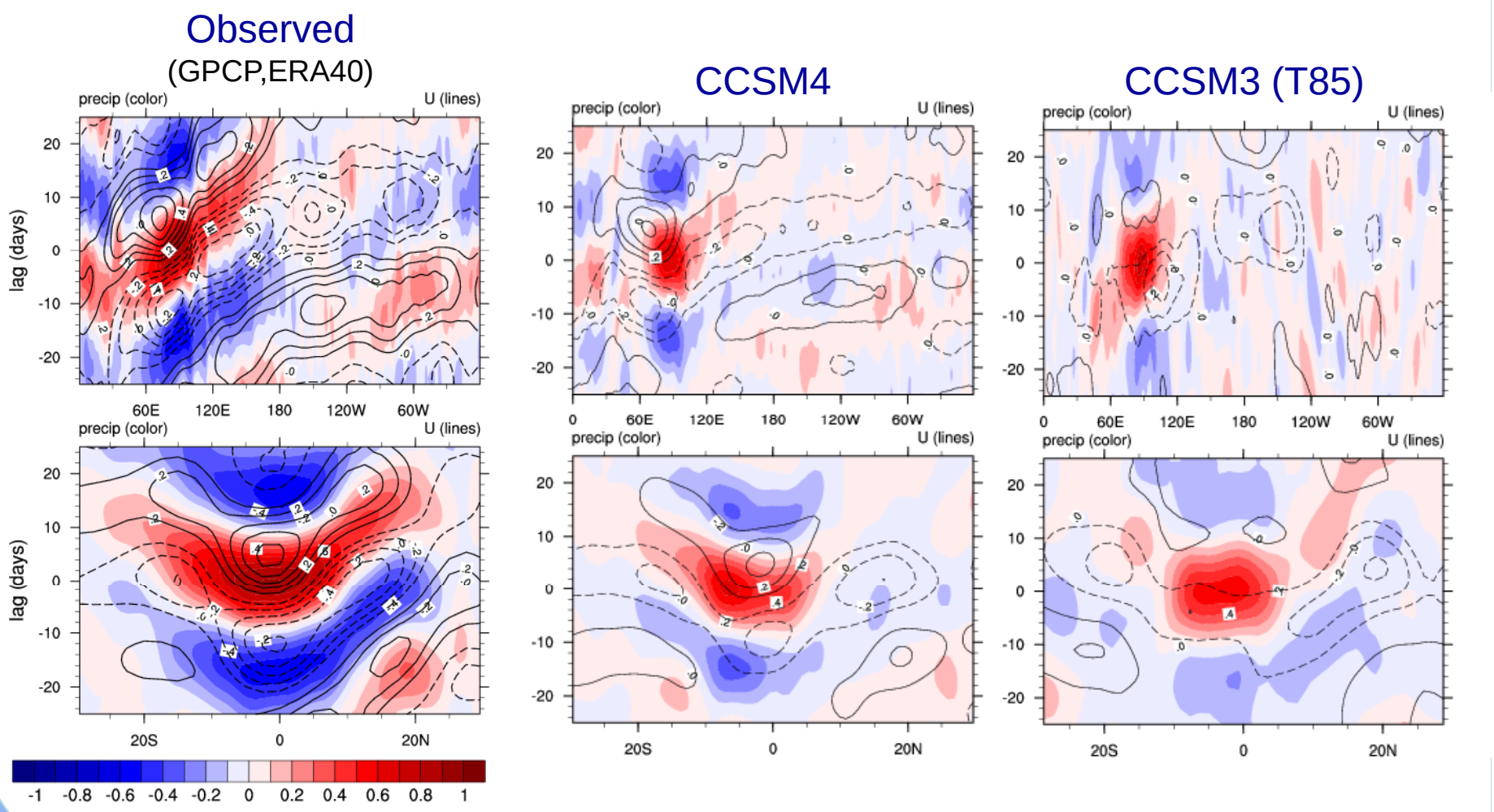


North Atlantic Variability



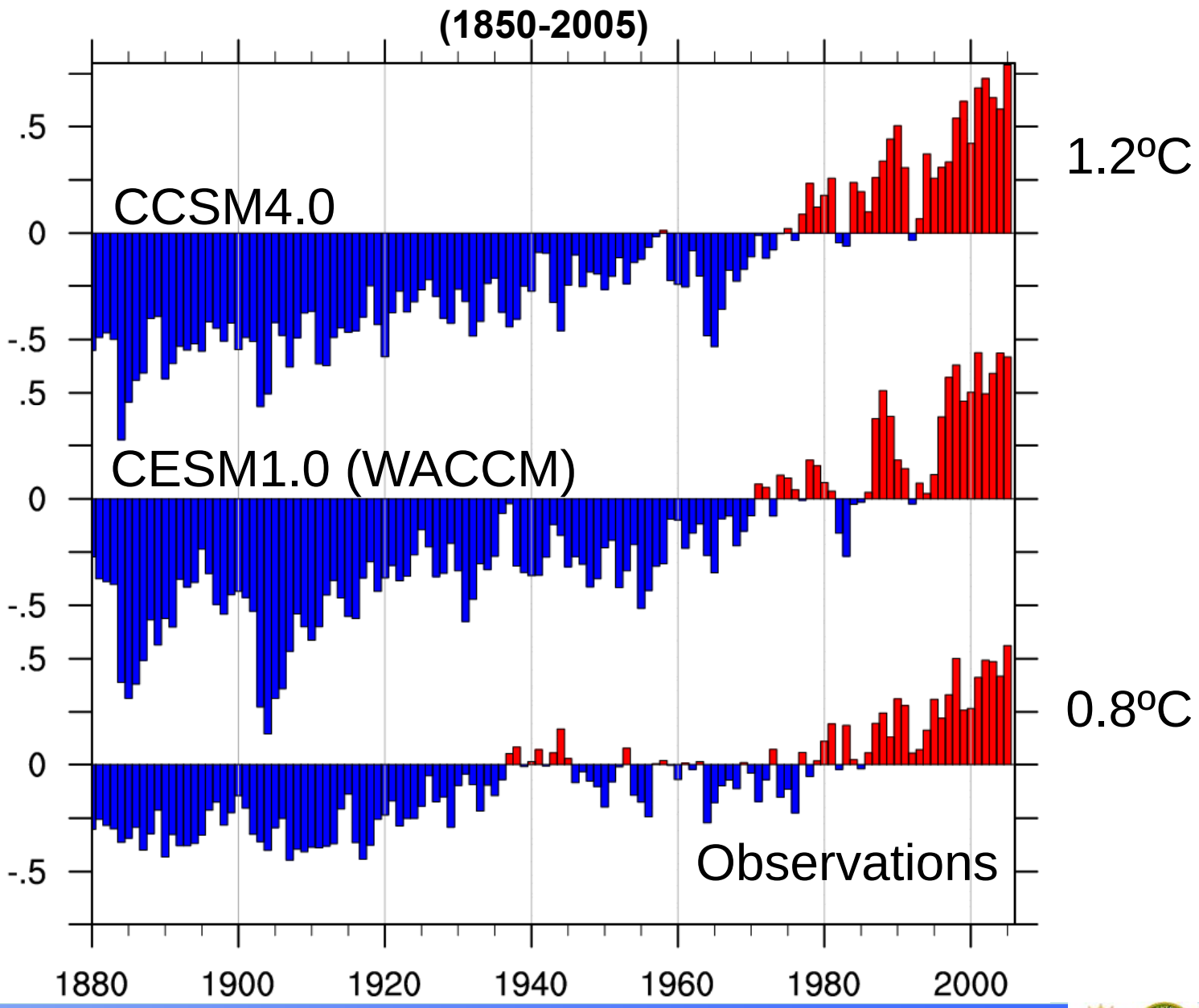
Intraseasonal Variability

Lag correlation of 20-100 day band pass filtered precipitation and 850-mb zonal wind



20th Century and Future Climate

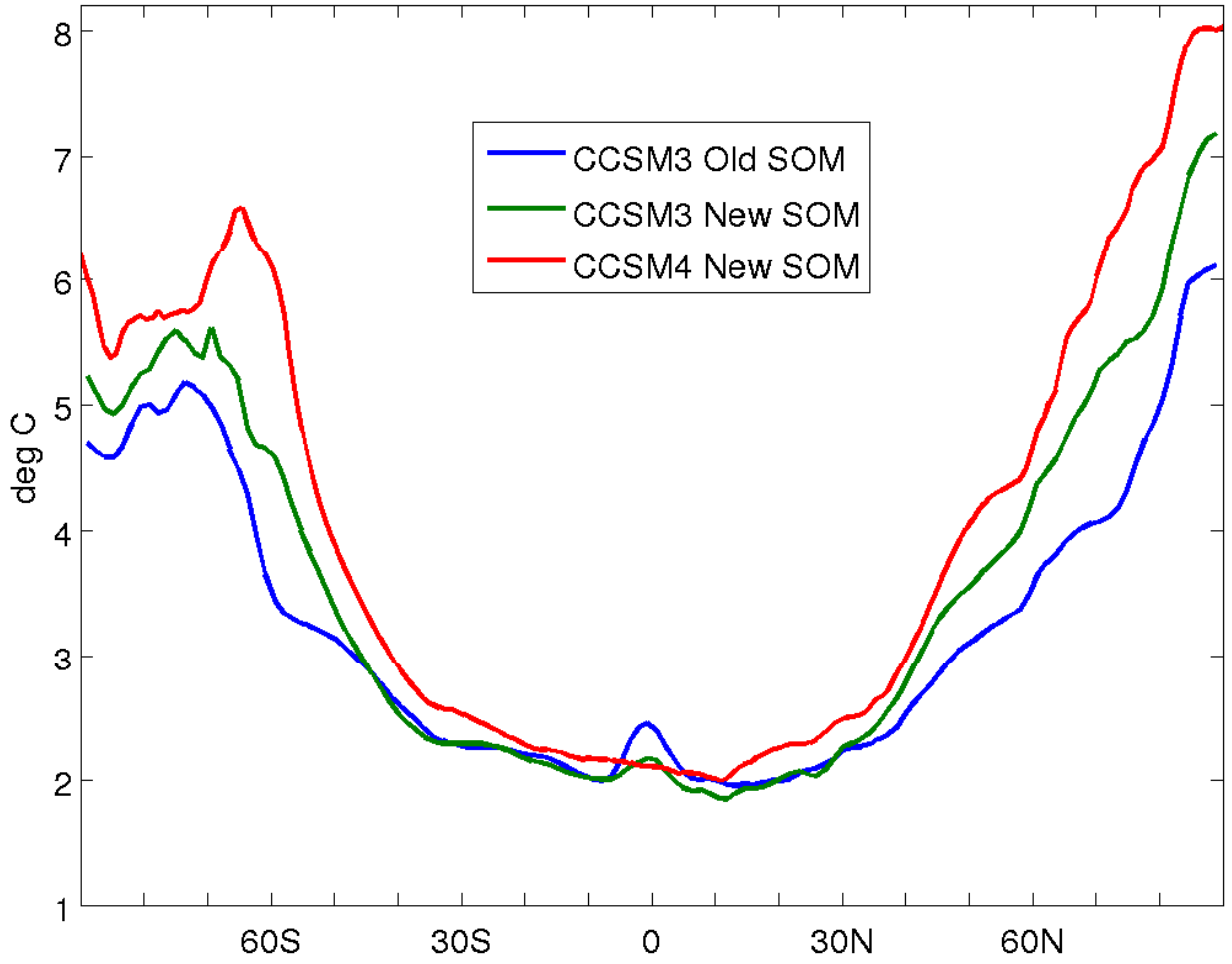
Global Temperature



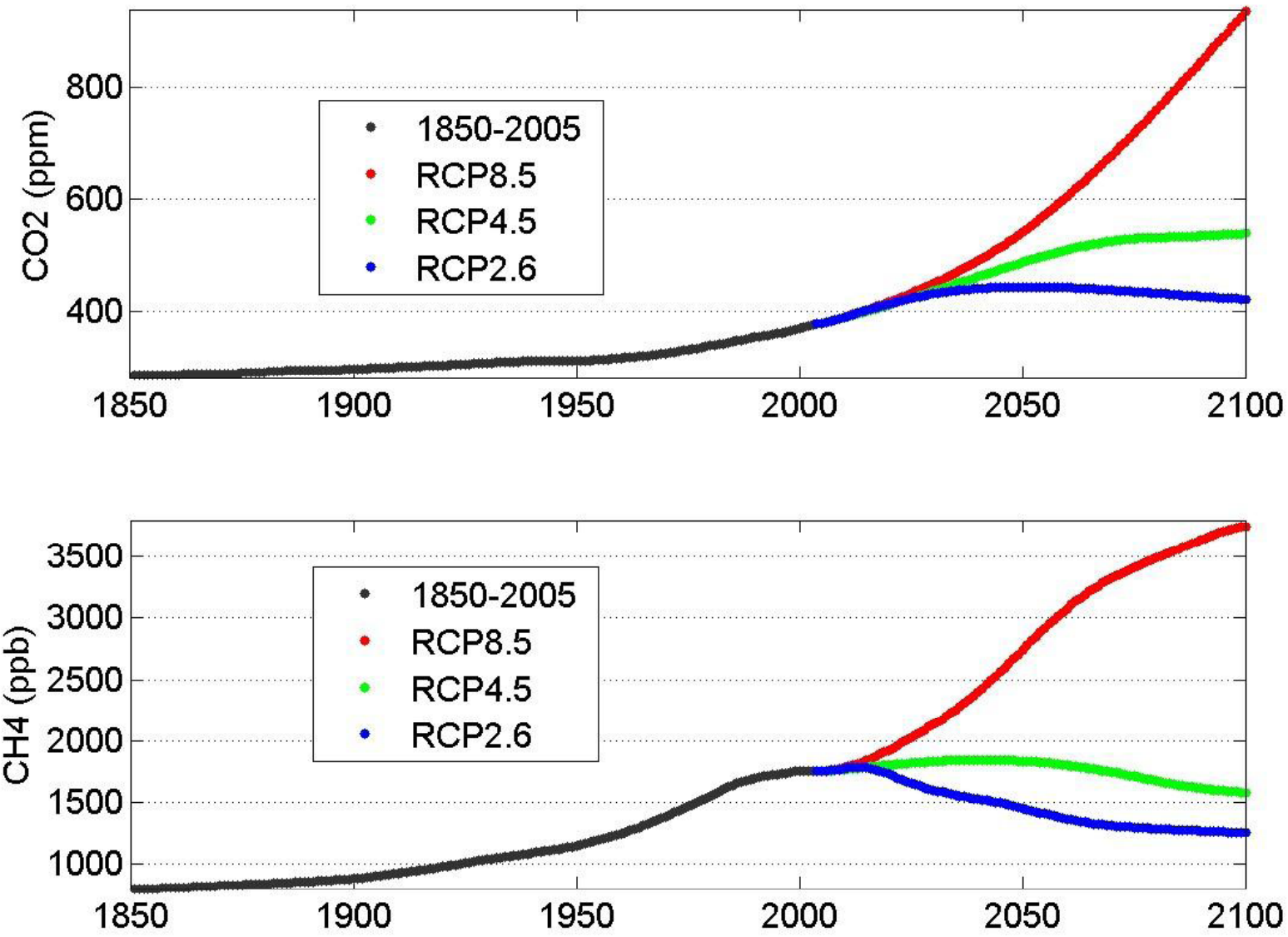
Equilibrium Climate Sensitivity

3.20°C in CCSM4 at 1°; 2.86°C in CCSM3 at T85

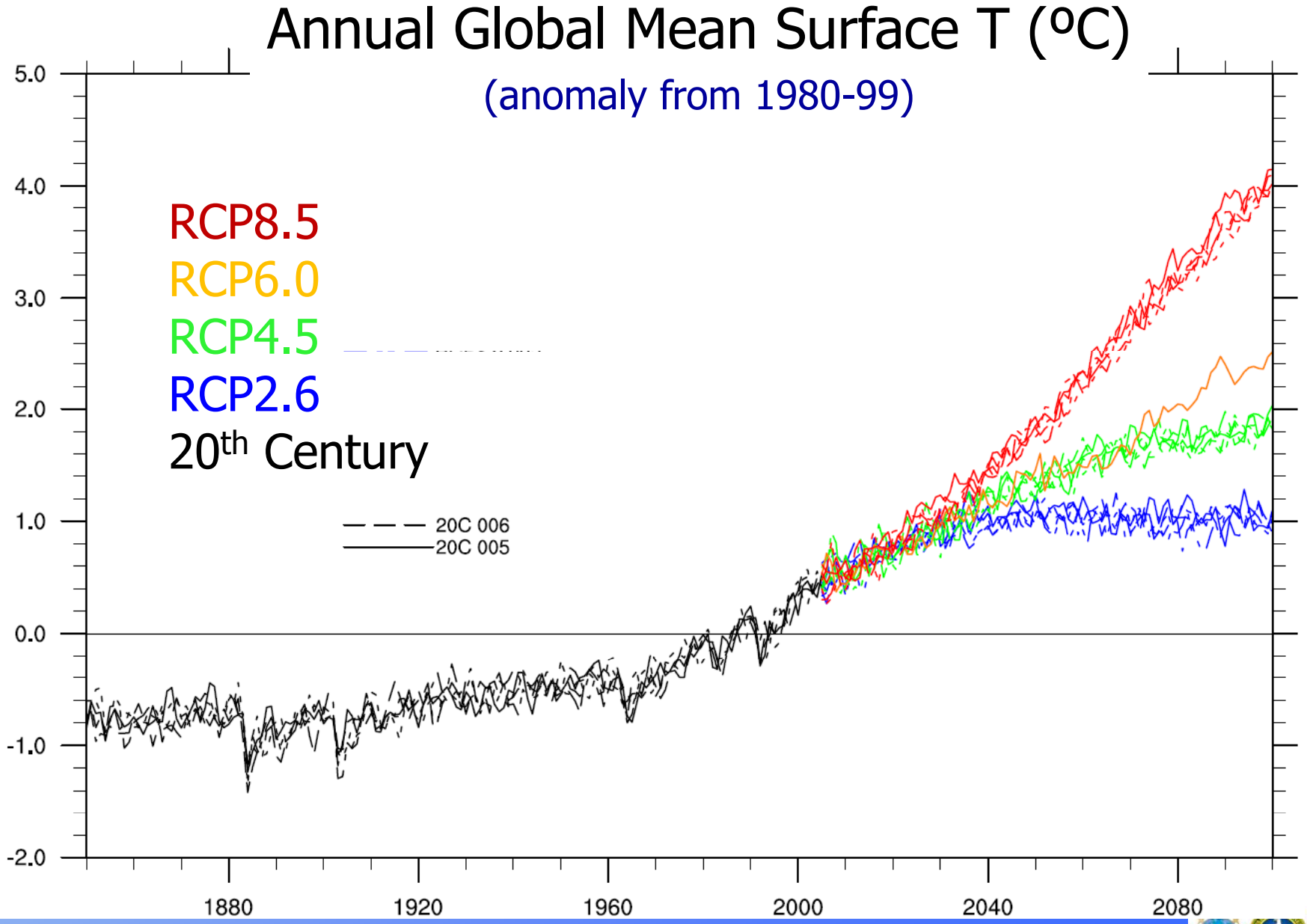
Due primarily to decline in negative lapse-rate feedback and an increase in positive shortwave cloud feedback



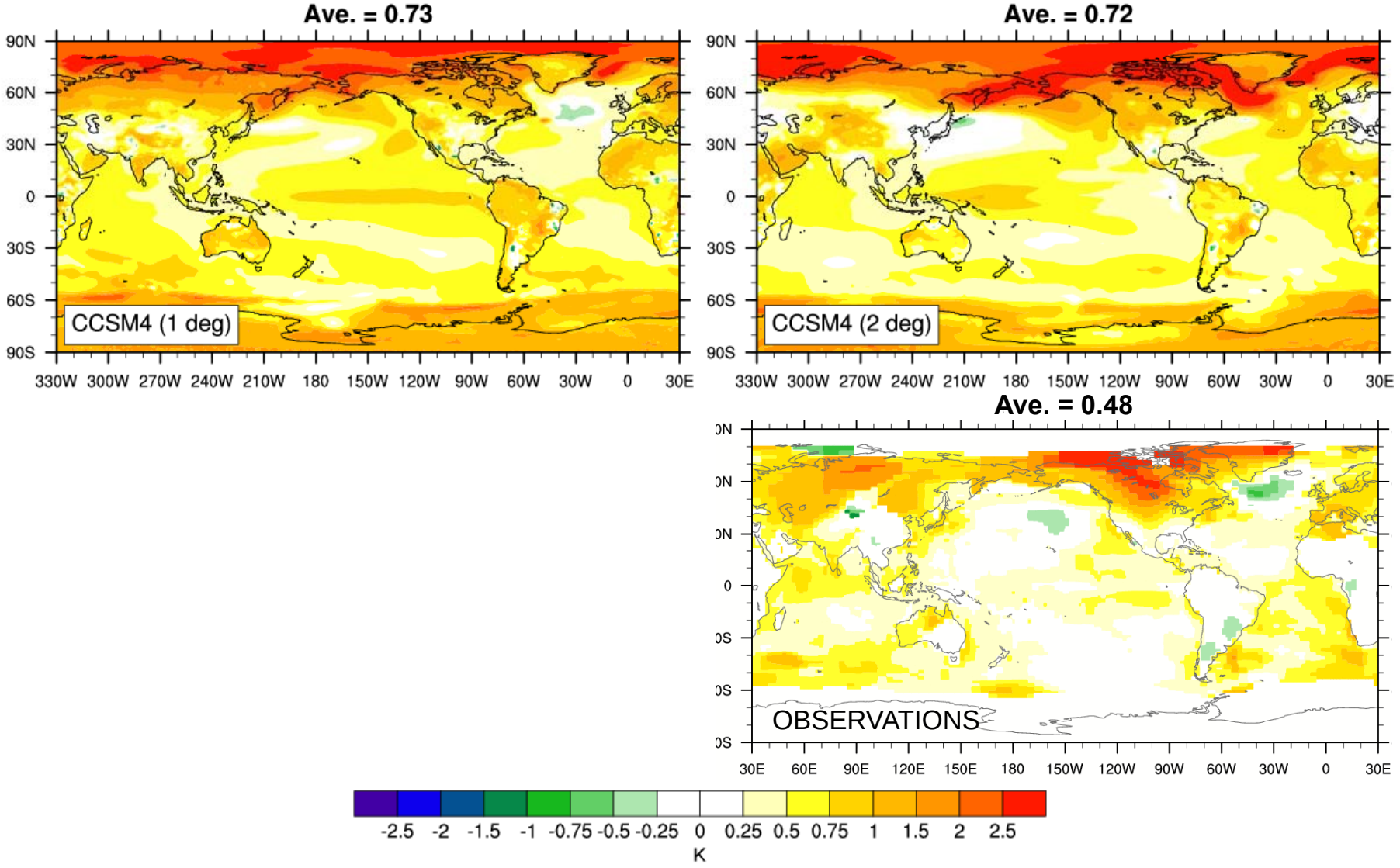
Representative Concentration Pathways (RCP)



Simulation of the 20th and 21st Centuries

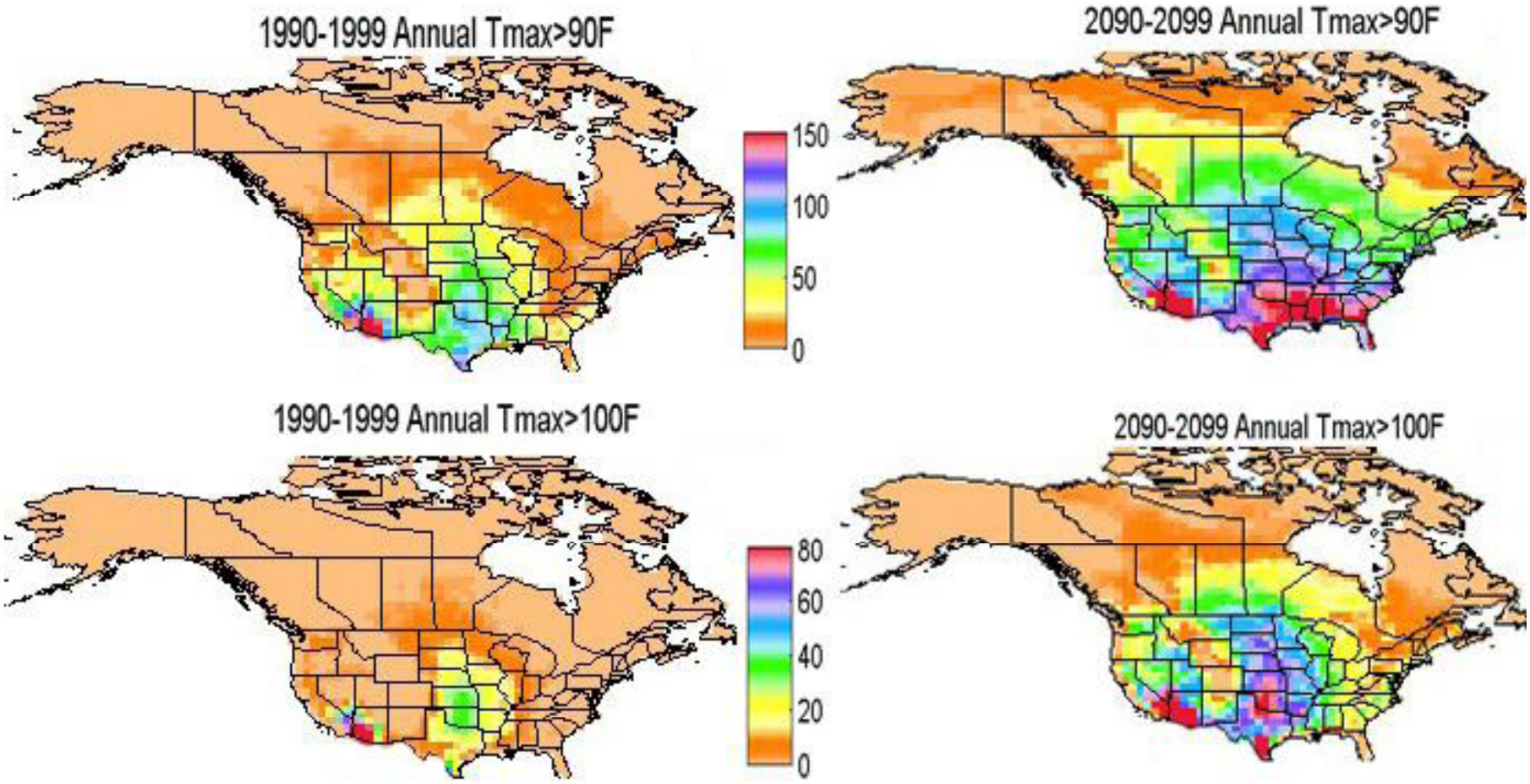


20th Century Surface Temperature Change



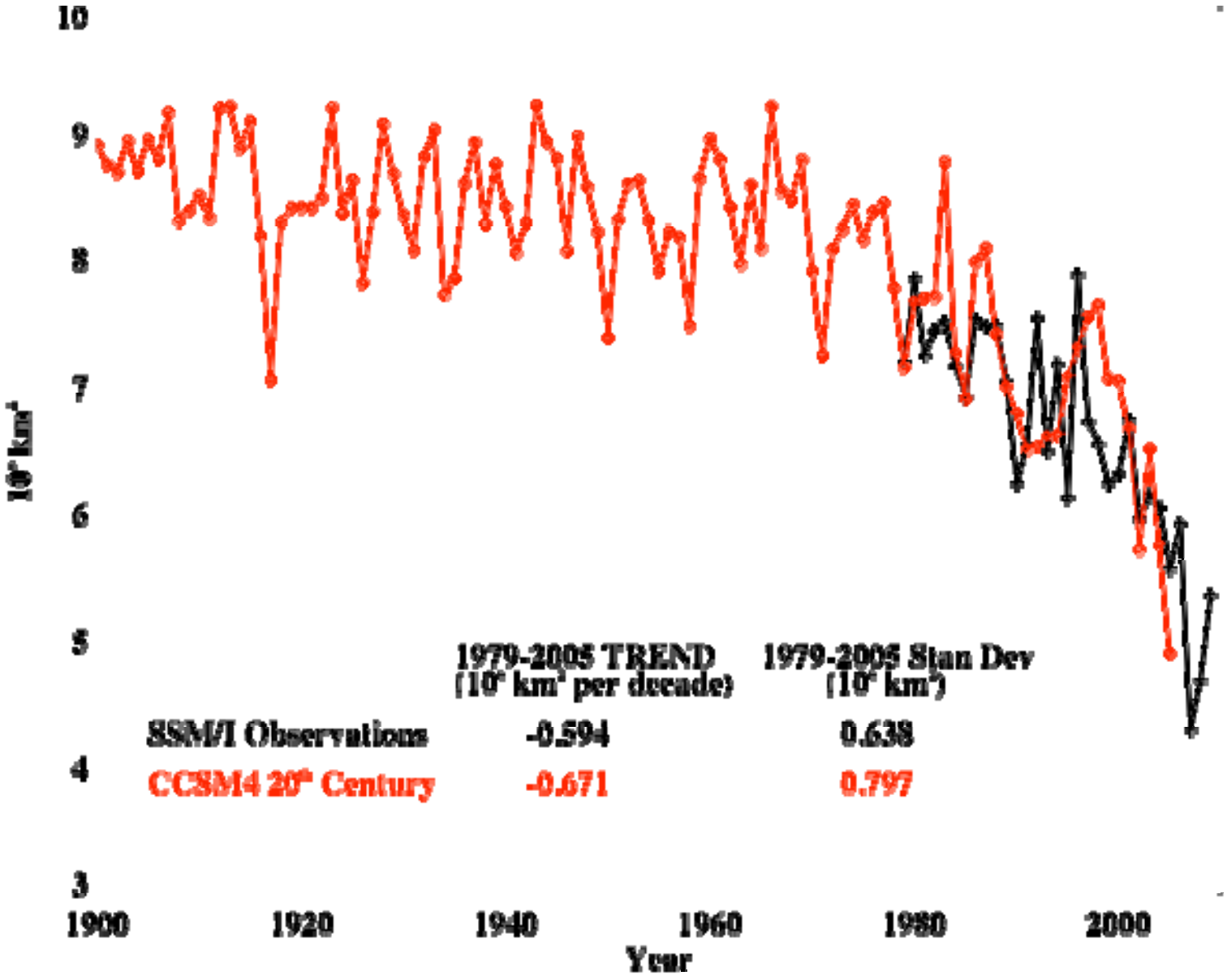
Warming too strong in CCSM4.0

Projected # of Days of Extreme Heat (RCP8.5)



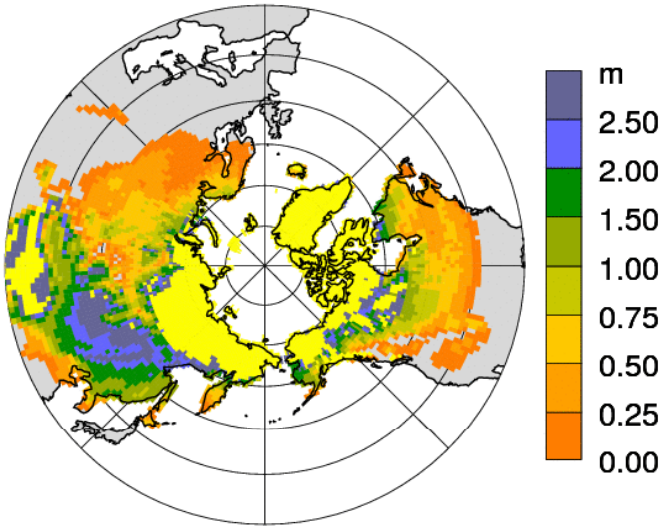
Peacock, 2011

September Arctic Sea Ice Extent

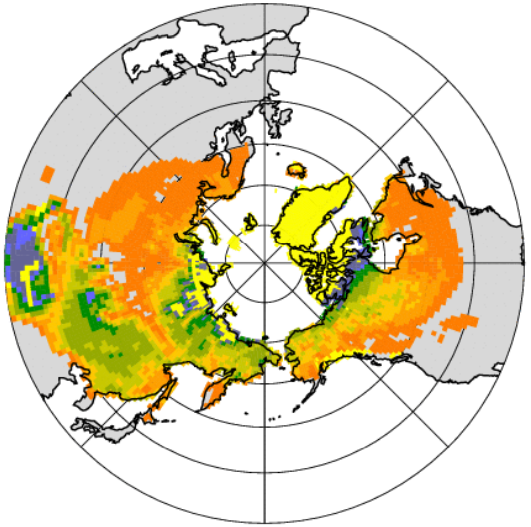


Seasonally Frozen Ground

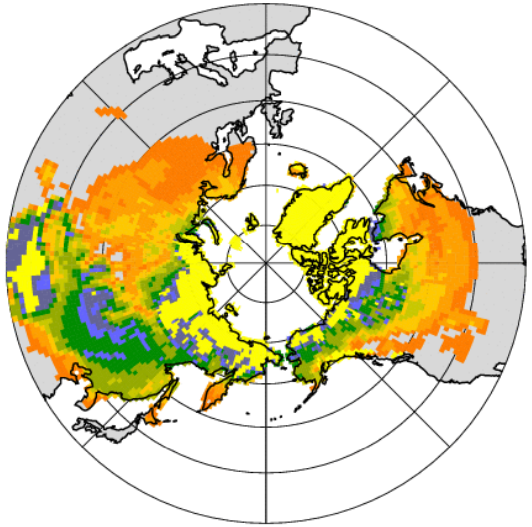
CCSM4 (1980-1999)



CCSM4_RCP8.5 (2080-2099)



CCSM4_RCP2.6 (2080-2099)

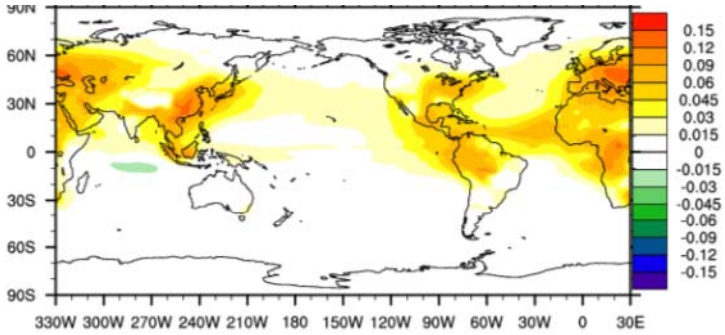


Earth System Model Features of CESM1

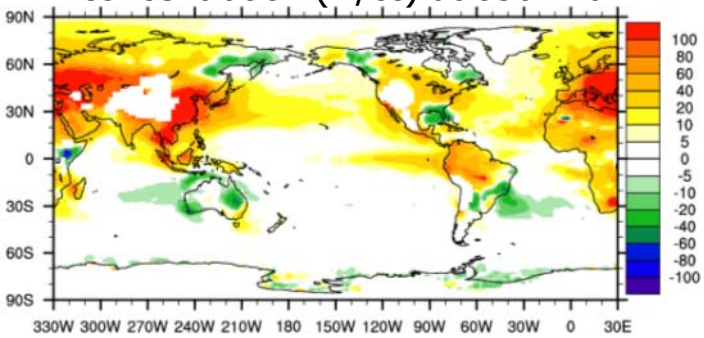
Anthropogenic Aerosol Affects: CESM1 (CAM5)

(late 20th century relative to pre-industrial climate)

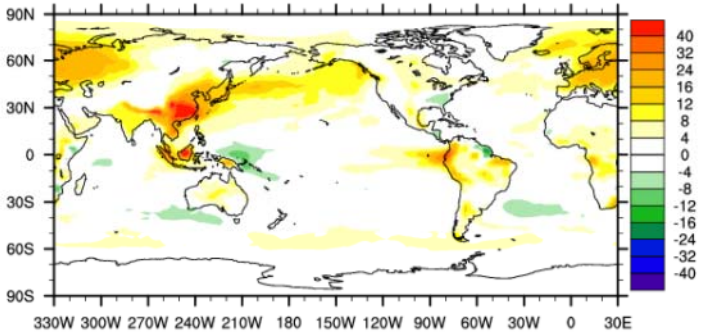
Total aerosol change (optical depth)



Cloud water droplet number concentration (#/cc) at 850 hPa



Liquid water path (g/m^2)

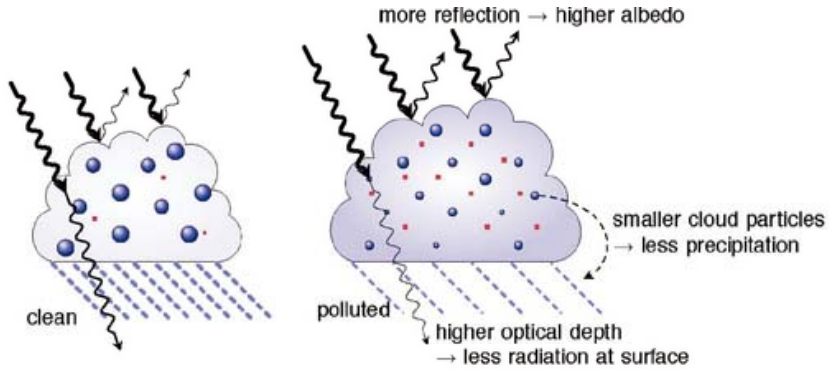


✓Increased aerosol burdens in SE Asia, Europe, NE North America, Brazil

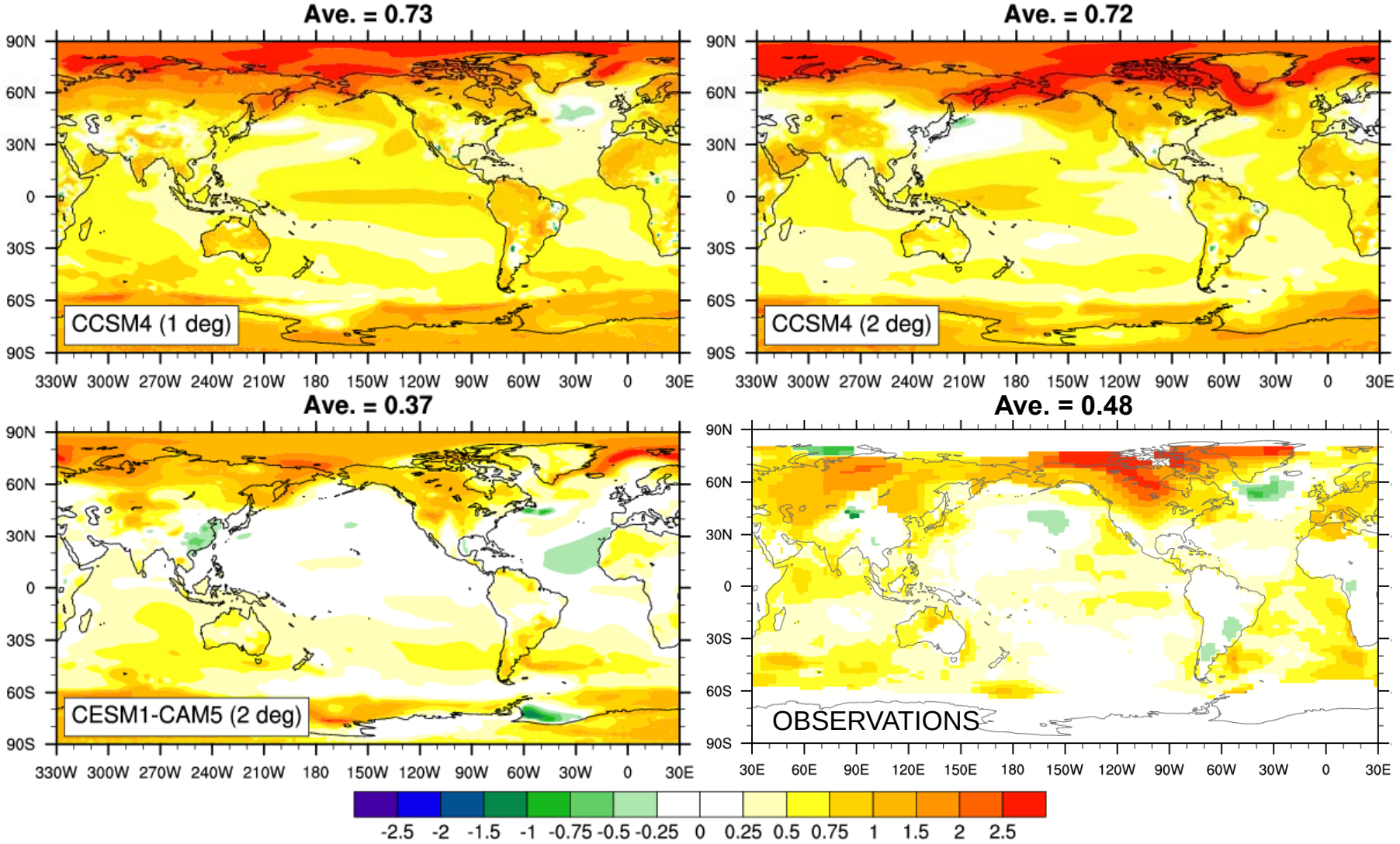
✓Increased cloud droplet number concentration; strongest over land

✓ Increased numbers of smaller drops; thus brighter low clouds with more liquid

Low cloud affects: net cooling over 20th century



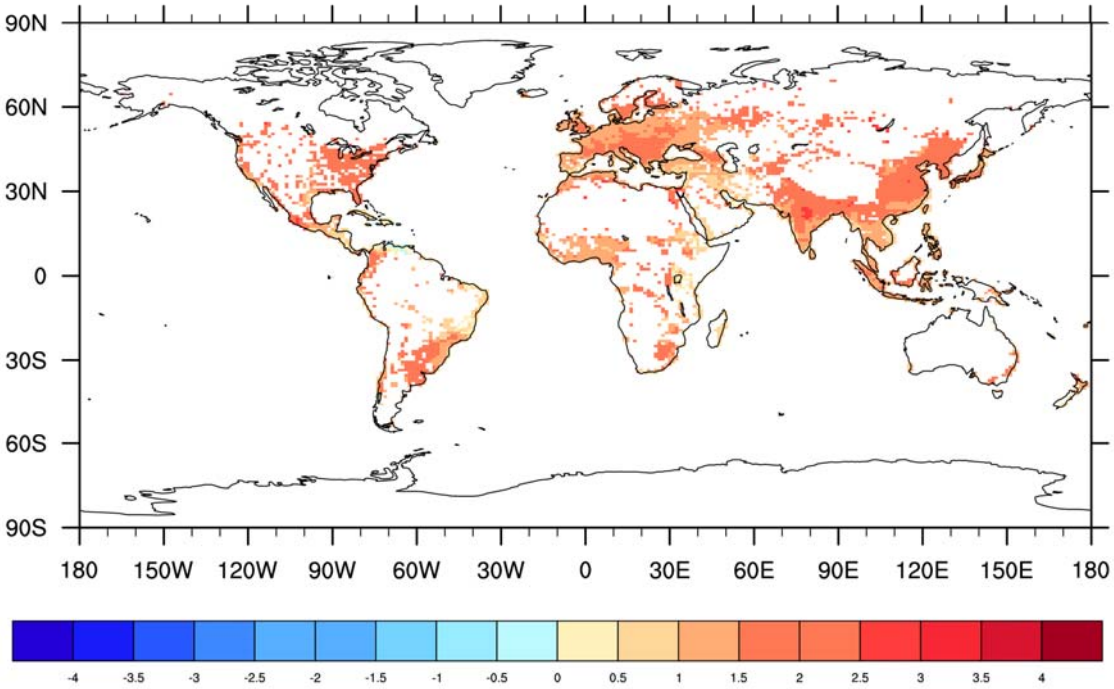
20th Century Surface Temperature Change



Weaker warming in CESM1.0 (CAM5) –
Note preliminary version of CAM5

New Capability: Urban Modeling

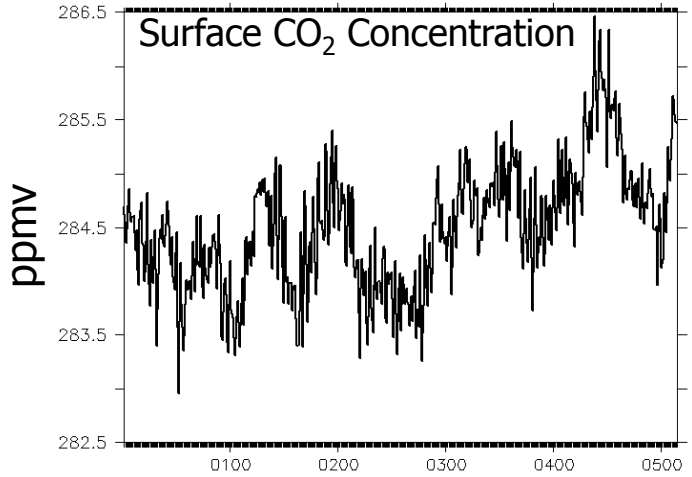
Present day Urban Heat Island (UHI) simulated by Community Land Model Urban (CLMU) (°C)



- CLM4 includes a representation of urban processes; global simulation of urban environments incl. T of cities.
- The UHI describes the fact that urban areas are generally warmer than surrounding rural areas.
- More directly evaluate projected changes in urban heat stress

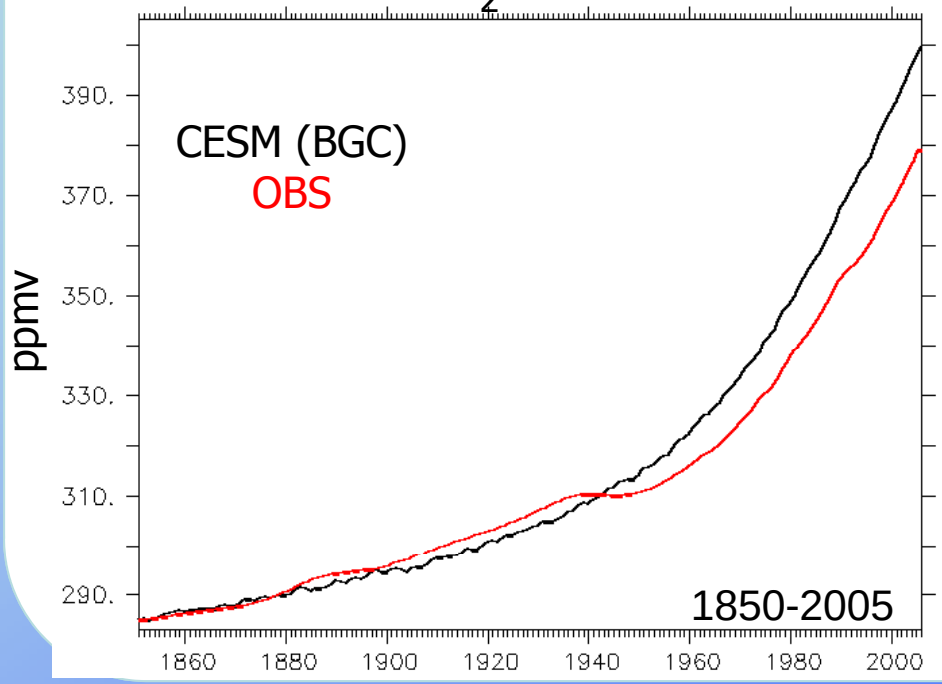
Oleson, K.W., G.B. Bonan, J. Feddema, M. Vertenstein, C.S.B. Grimmond, 2008a, *J. Appl. Meteor. Climatol.*
Oleson, K.W., G.B. Bonan, J. Feddema, M. Vertenstein, 2008b, *J. Appl. Meteor. Climatol.*

CESM1.0 (BGC) Simulations

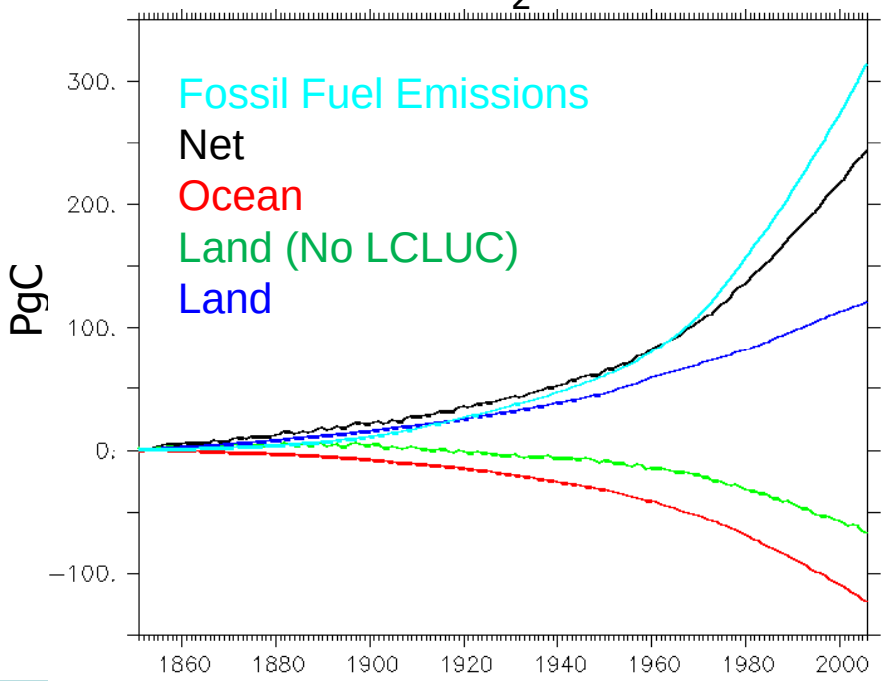


500+ yr Pre-industrial Control

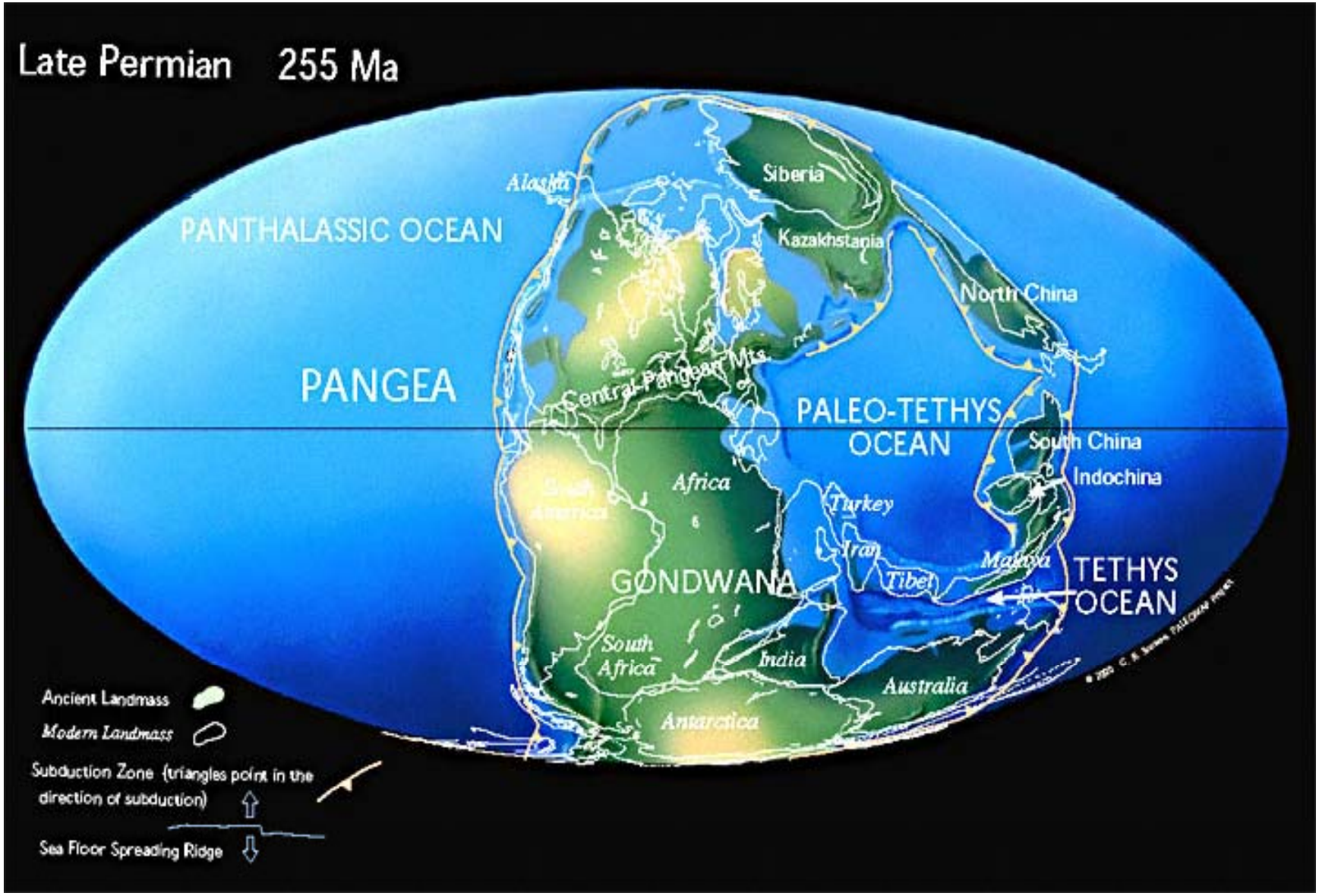
Surface CO_2 Concentration



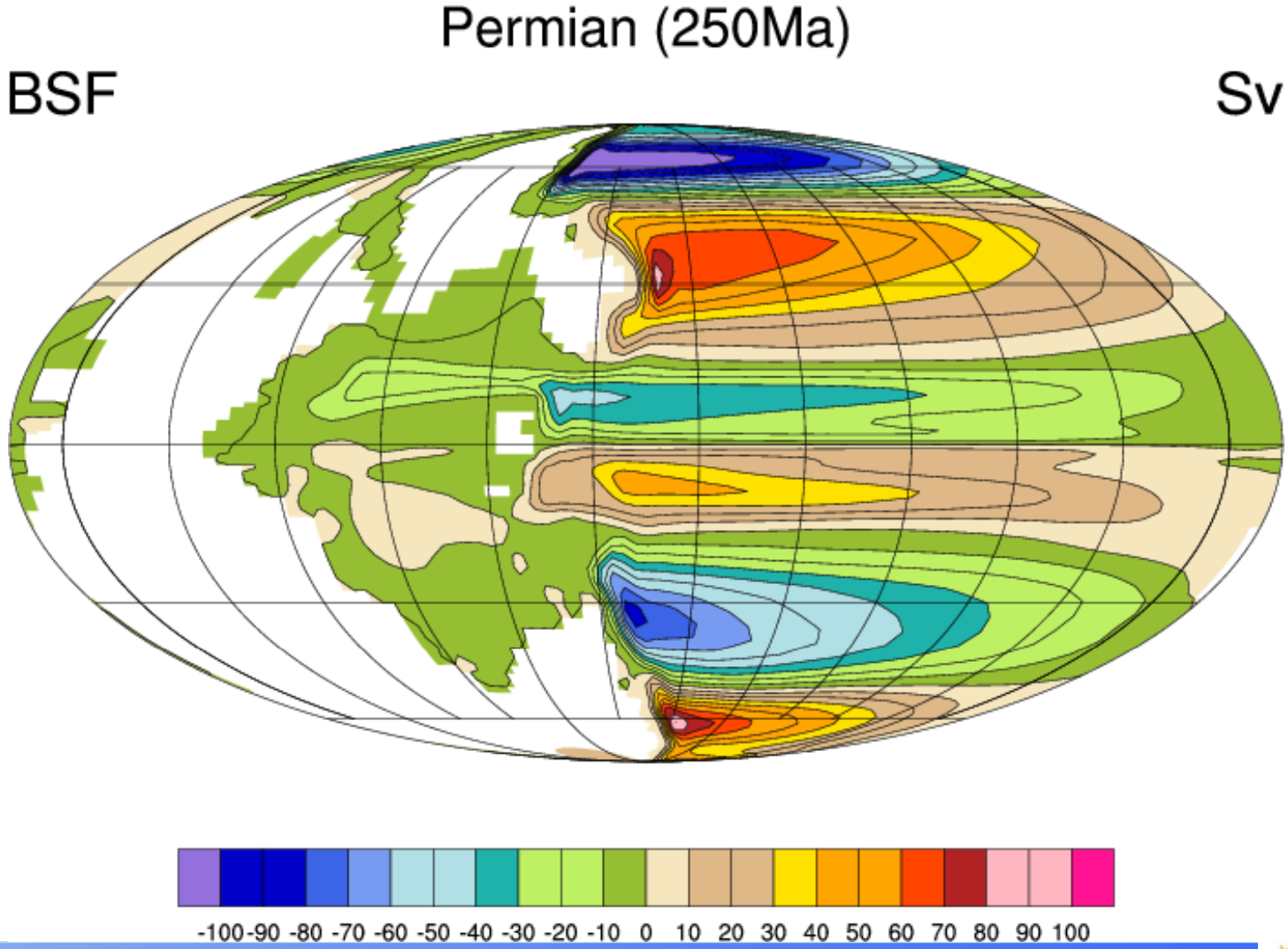
Cumulative CO_2 Surface Flux



Paleoclimate: Late Permian continents



Simulation with CCSM3: Ocean barotropic streamfunction (Kiehl and Shields, 2005)



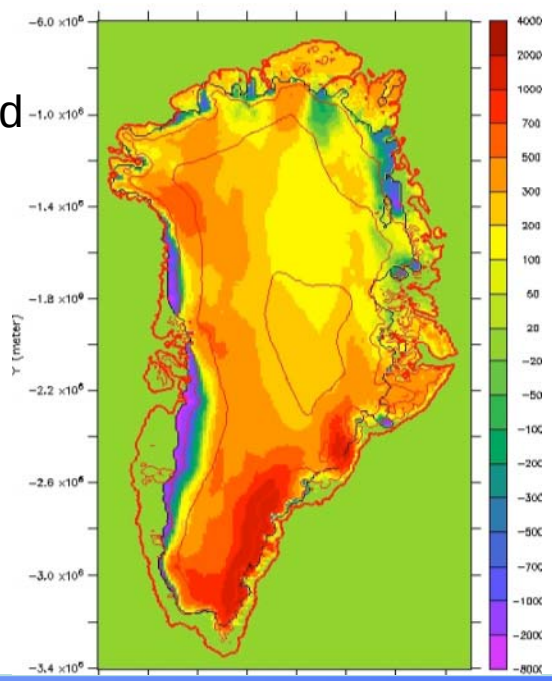
An ice sheet model in CESM

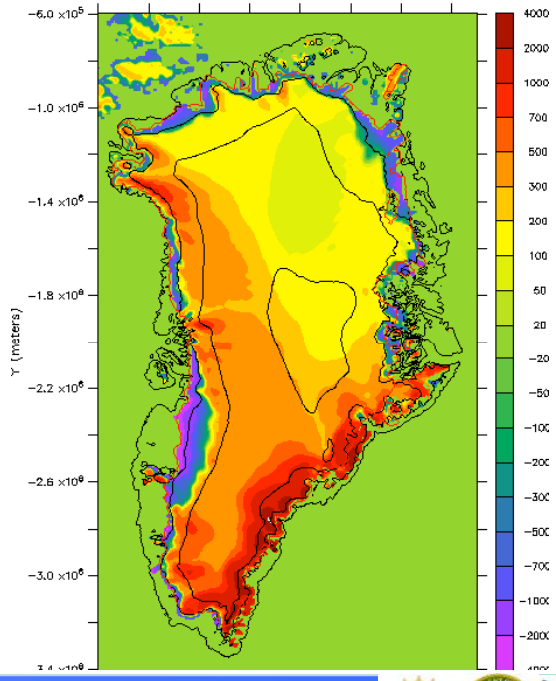
- Community Ice Sheet Model (Glimmer-CISM)
  - Currently Glimmer-CISM 1.6 (shallow-ice dynamics)
  - Glimmer-CISM 2.0 (higher-order dynamics) to be added soon
  - Greenland grids at 5, 10, and 20 km are supported.
- CESM also includes a new surface mass balance scheme for ice sheets in CLM.
  - The surface mass balance is computed on the global land grid, then sent to Glimmer-CISM and downscaled to the local ice sheet grid.

Left: Greenland SMB from CESM: CLM on 1º grid forced by CAM output, downscaled to 10-km ice sheet grid

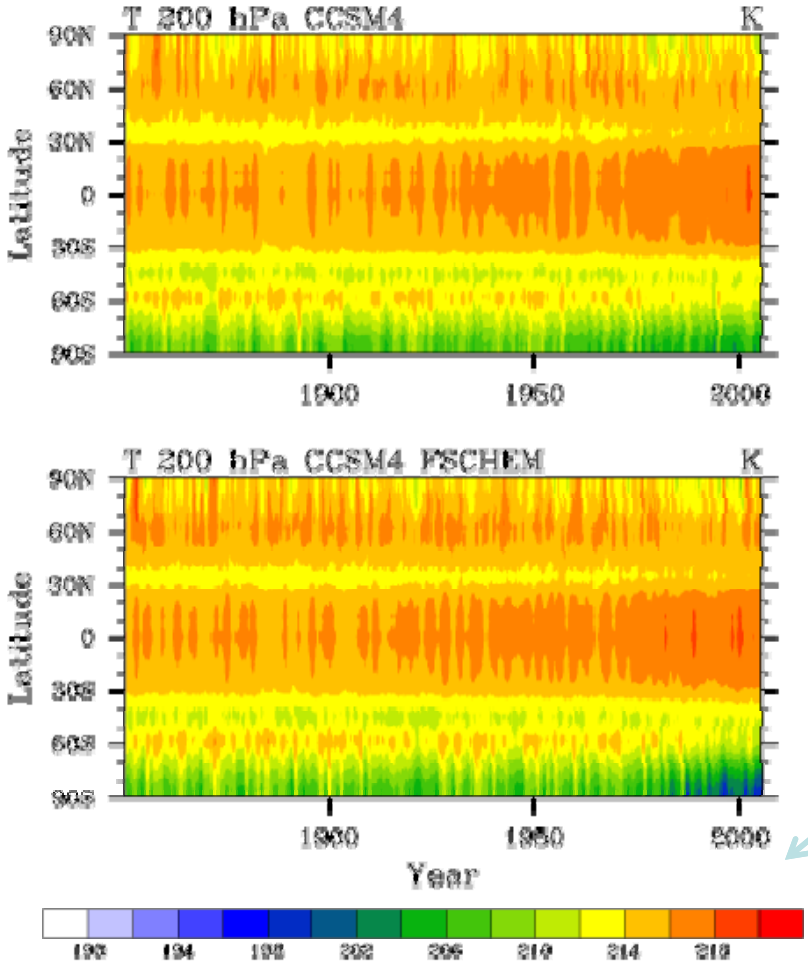
Right: Greenland SMB from high-resolution regional climate model (RACMO; Ettema et al. 2009)

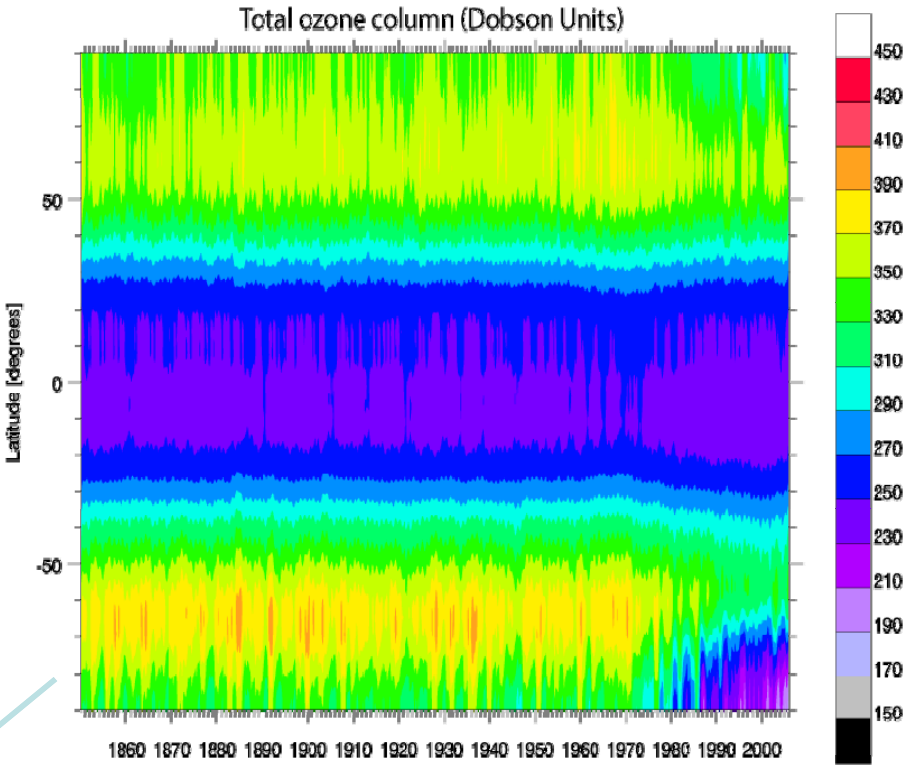
Red = net accumulation
Blue = net ablation

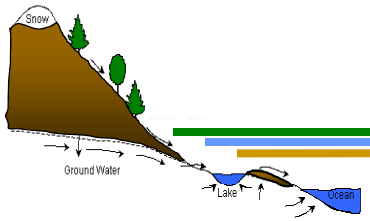




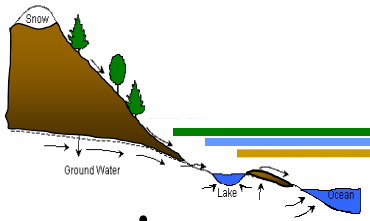
Superfast Chemistry in CESM





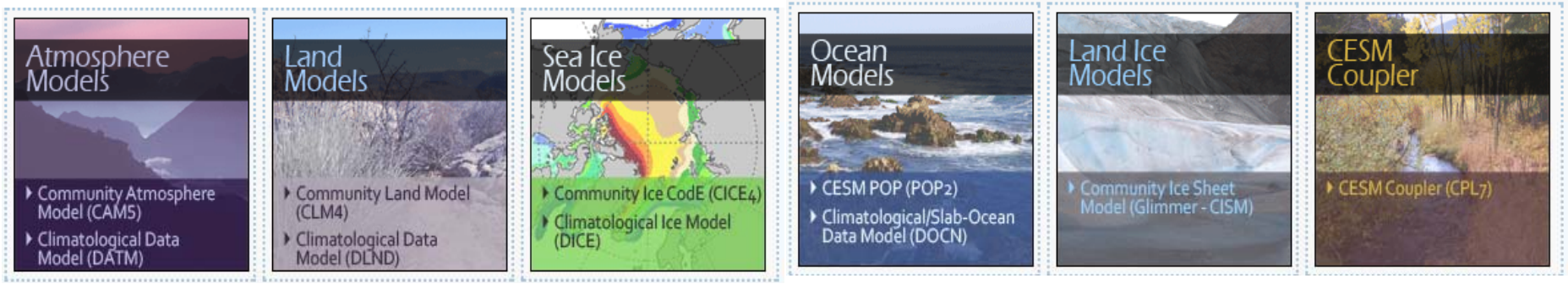


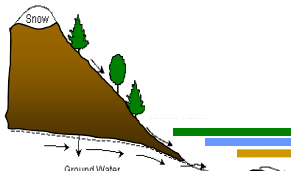
Final Thoughts



Some Upcoming Challenges

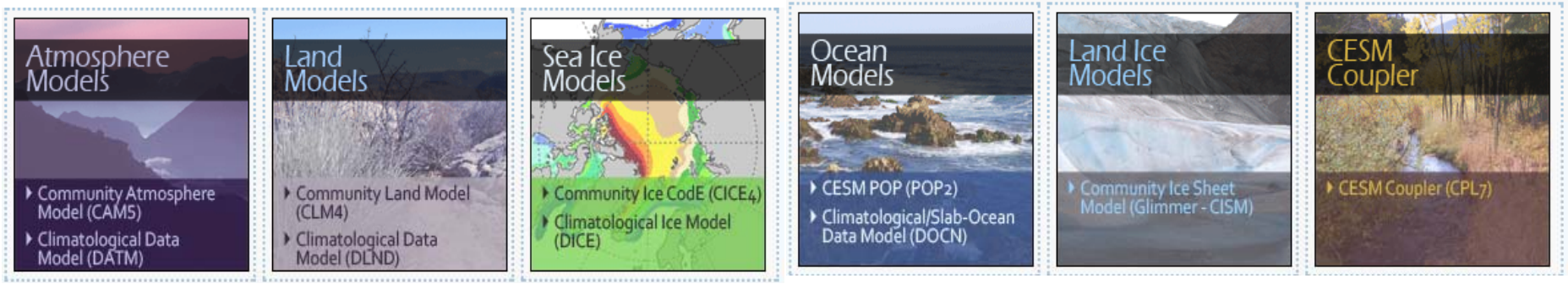
- Incorporation of vast array of new capabilities and parameterizations provided by the community (e.g., isotopes, super-parameterization – embedded cloud resolving model, global methane cycle, …)
- Regional refined grids (NRCM and static regionally refined meshes)
- Extending data assimilation capability
- Incorporation of hooks for human dimensions
- Improved validation metrics, benchmarking
- Post-processing – data management





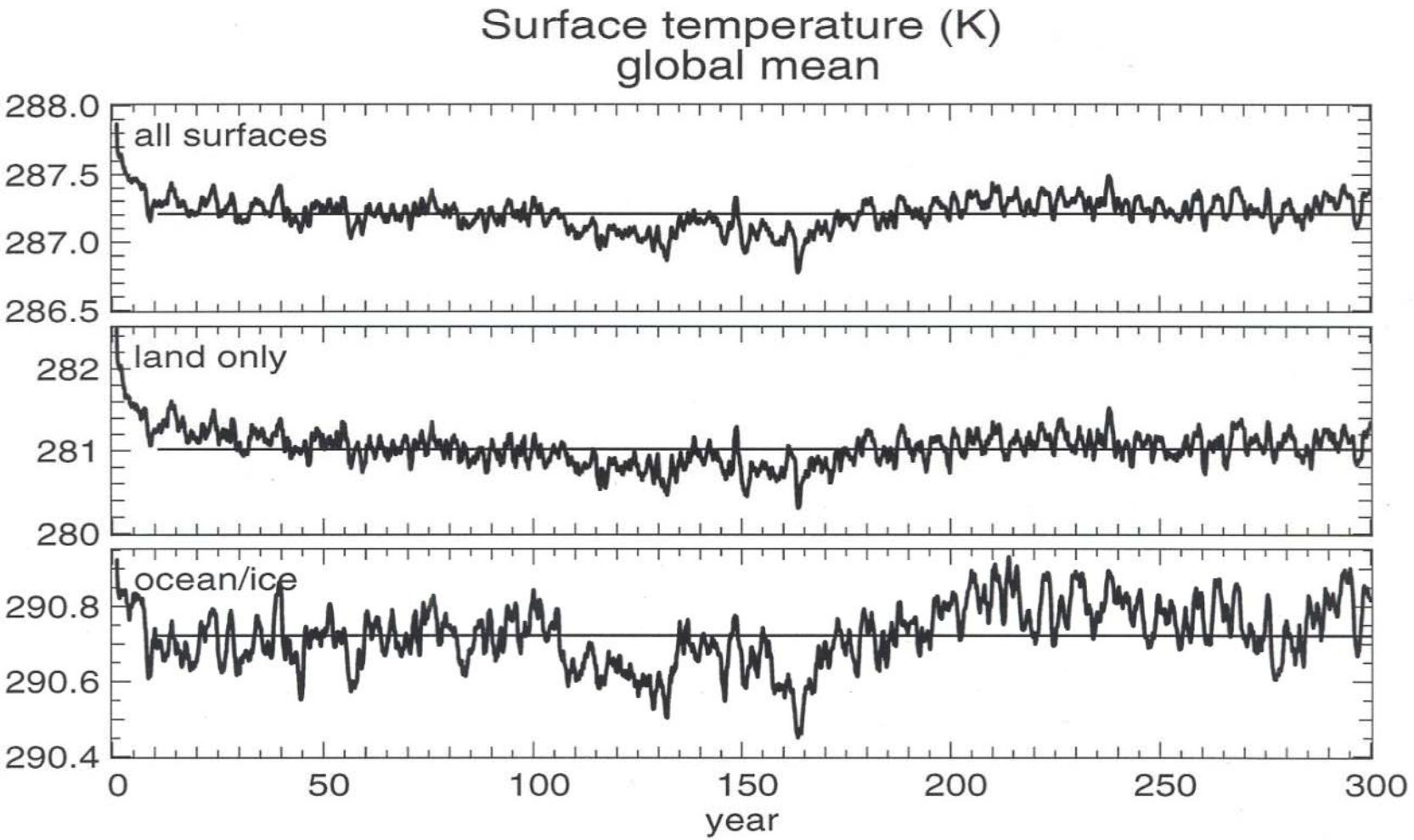
Thanks and Get Involved!

- CESM Workshop every June in Breckenridge
- Working group meetings in Winter every year
  - Model development discussions
- Download and analyze CESM output
  - CCSM4 CMIP5 data will be posted to Earth System Grid ~May 25
- Download and run the model and do great science with it!
- Sign up for CESM and/or Working group email lists (see www.cesm.ucar.edu)



CSM 1 was the first climate model to produce a non-drifting control run without “flux corrections”

FIG 8



Decadal Forecasts

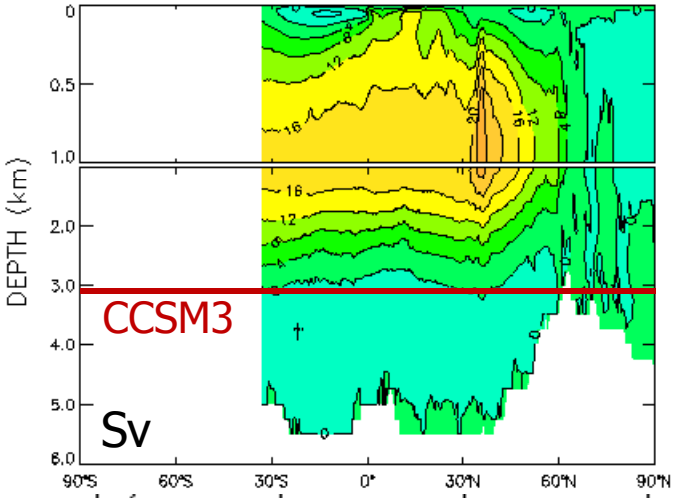
- **For forecasts need to initialize the ocean component.**
- **Use an ocean and sea ice hindcast from 1950 – 2005 forced by best estimate of atm forcing from reanalysis.**
- **Run ocean component alone forced by atm reanalysis, but assimilating ocean temp and salinity observations.**
- **This is new, and more deep ocean obs after ~2003 from ARGO floats trying to initialize N Atlantic MOC.**

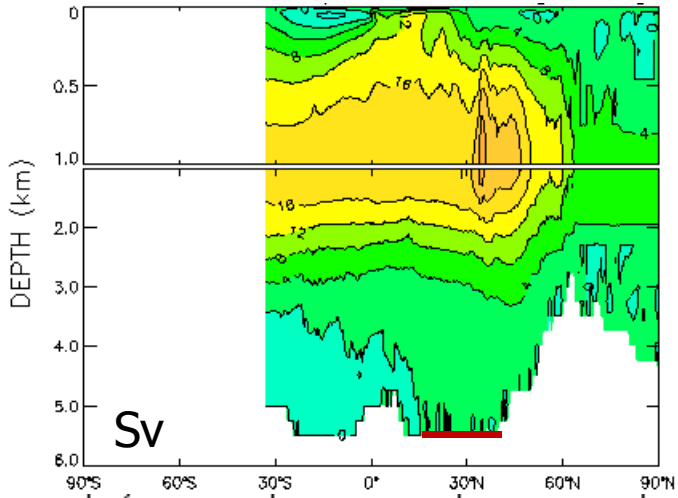
Atlantic MOC in CCSM4

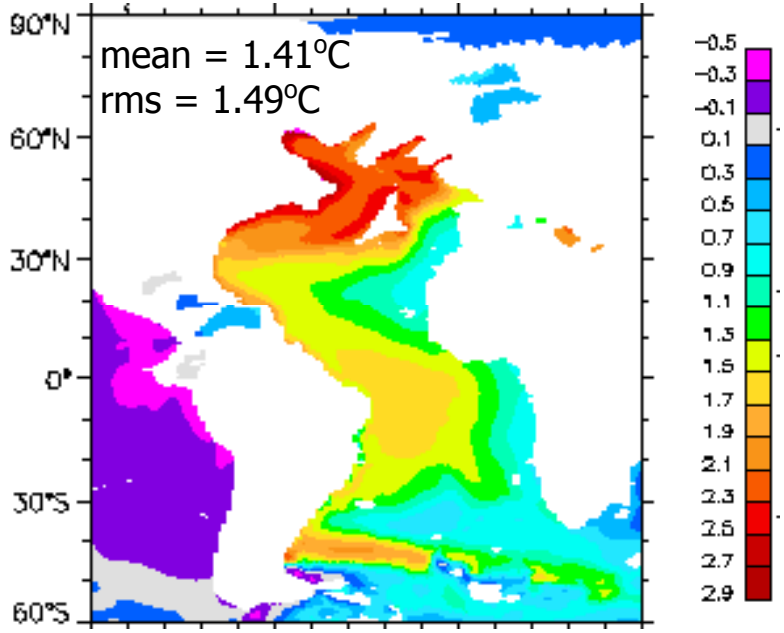
(Late 20th Century)

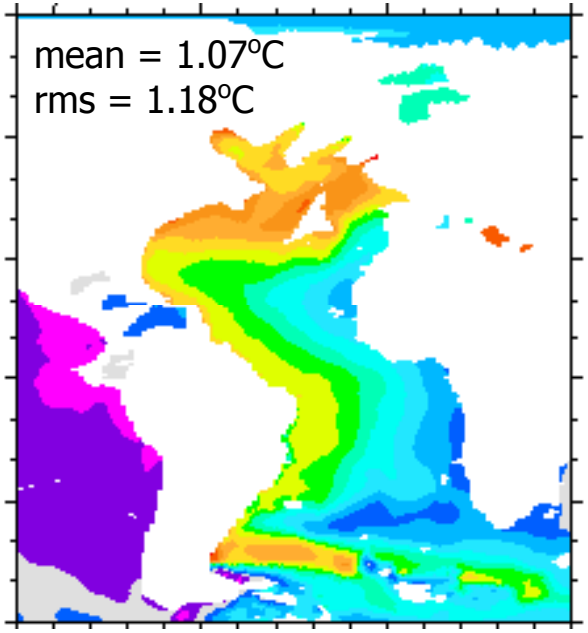
No Overflows

With Overflows









T (2649 m)

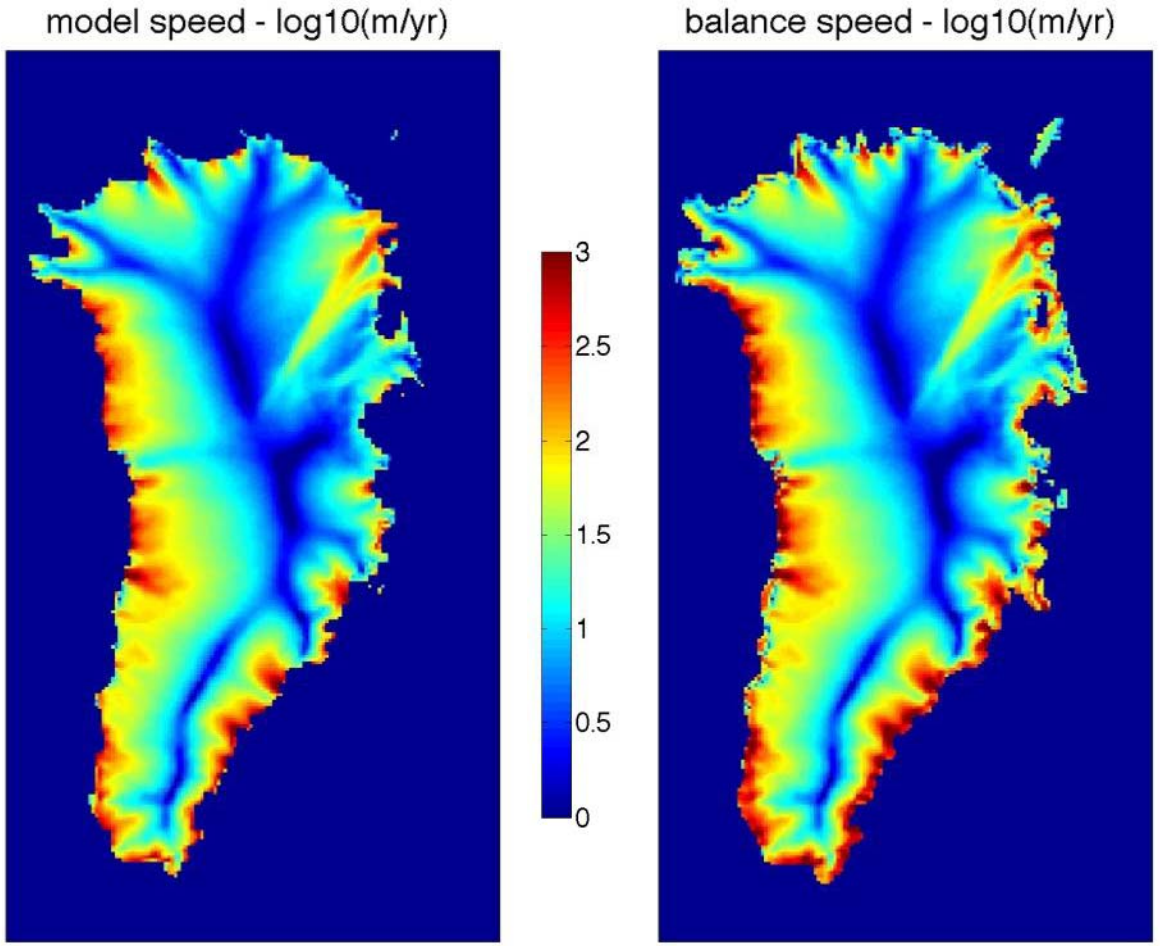
Land ice sheet model development

A CESM release later in 2010 will include Glimmer-CISM 2.0, with “higher-order” ice dynamics valid in all parts of an ice sheet (including ice streams, ice shelves)

Left: Greenland surface velocities (on a log scale) from a higher-order version of Glimmer-CISM

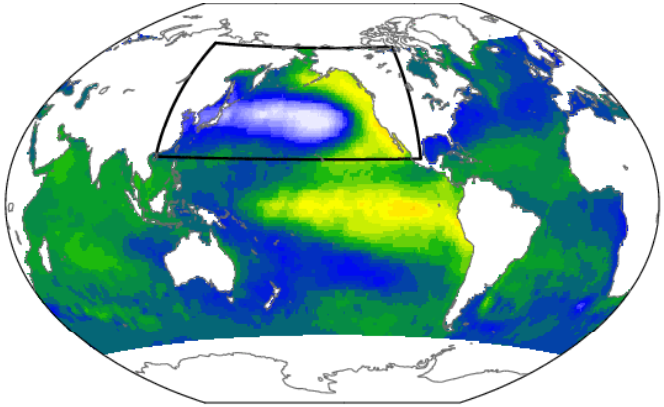
Right: Target velocities based on observations

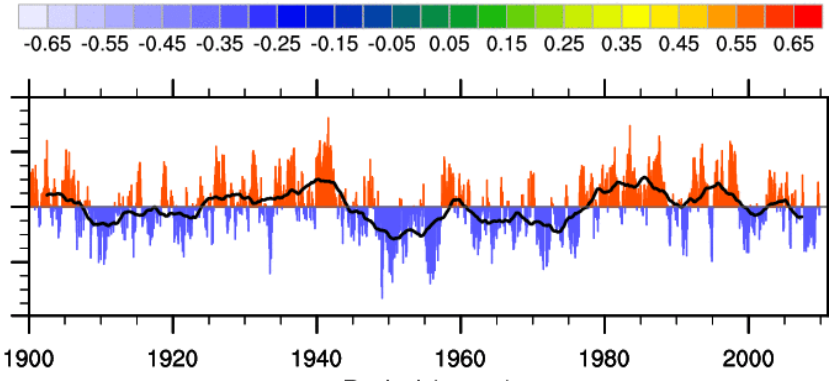
Red = fast (~3 km/yr)
Blue = slow (~30 m/yr)



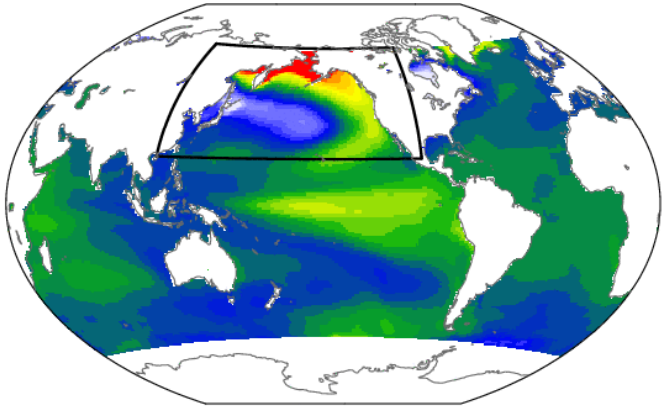
North Pacific Decadal Variability

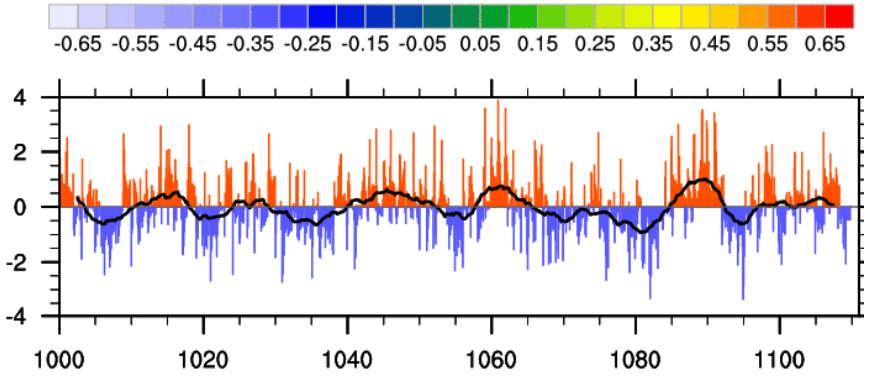
Observations



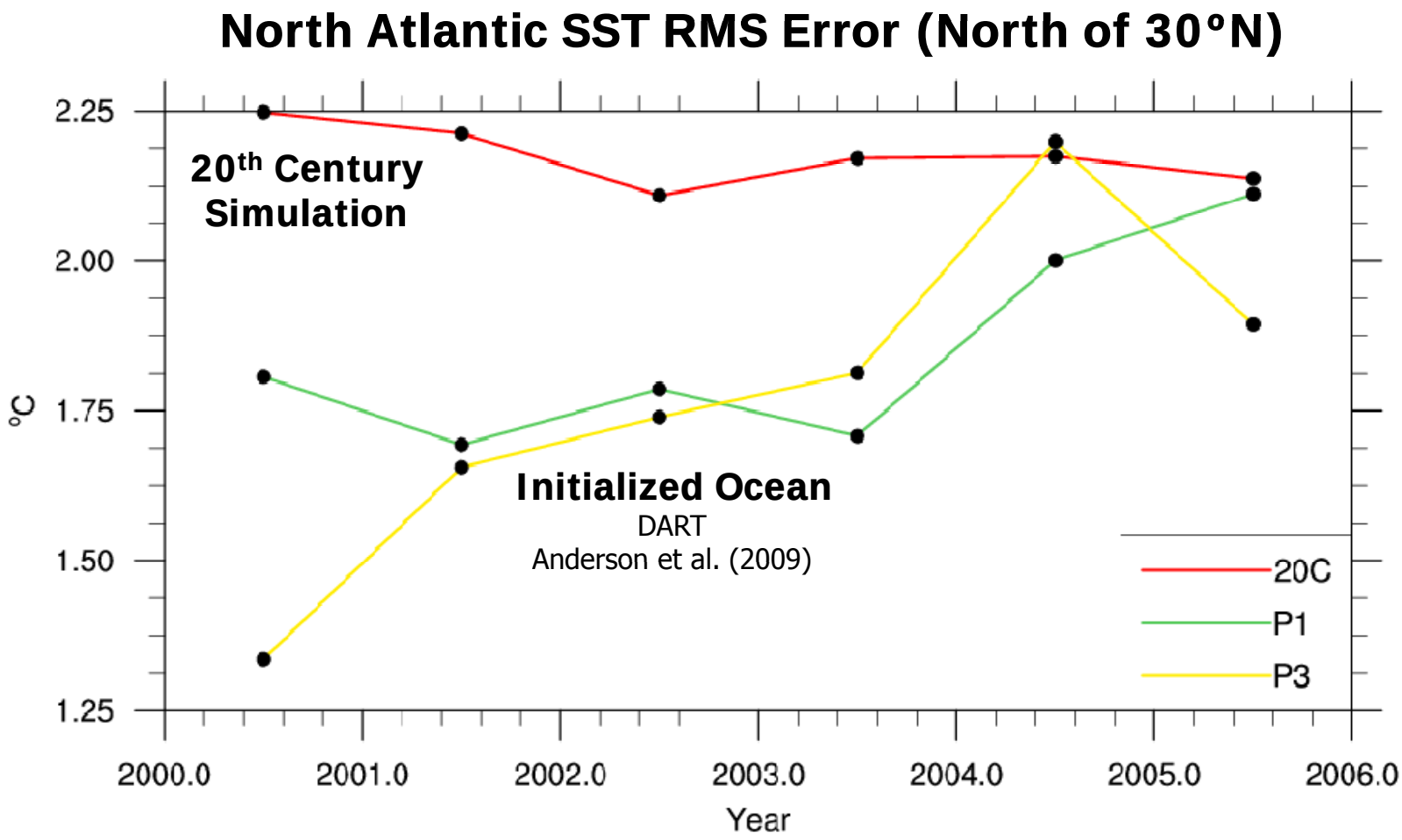


CCSM4





Initialized (Decadal) Predictions with CCSM4



Persistence of large-scale SST bias reduction

Steve Yeager et al. (2010)