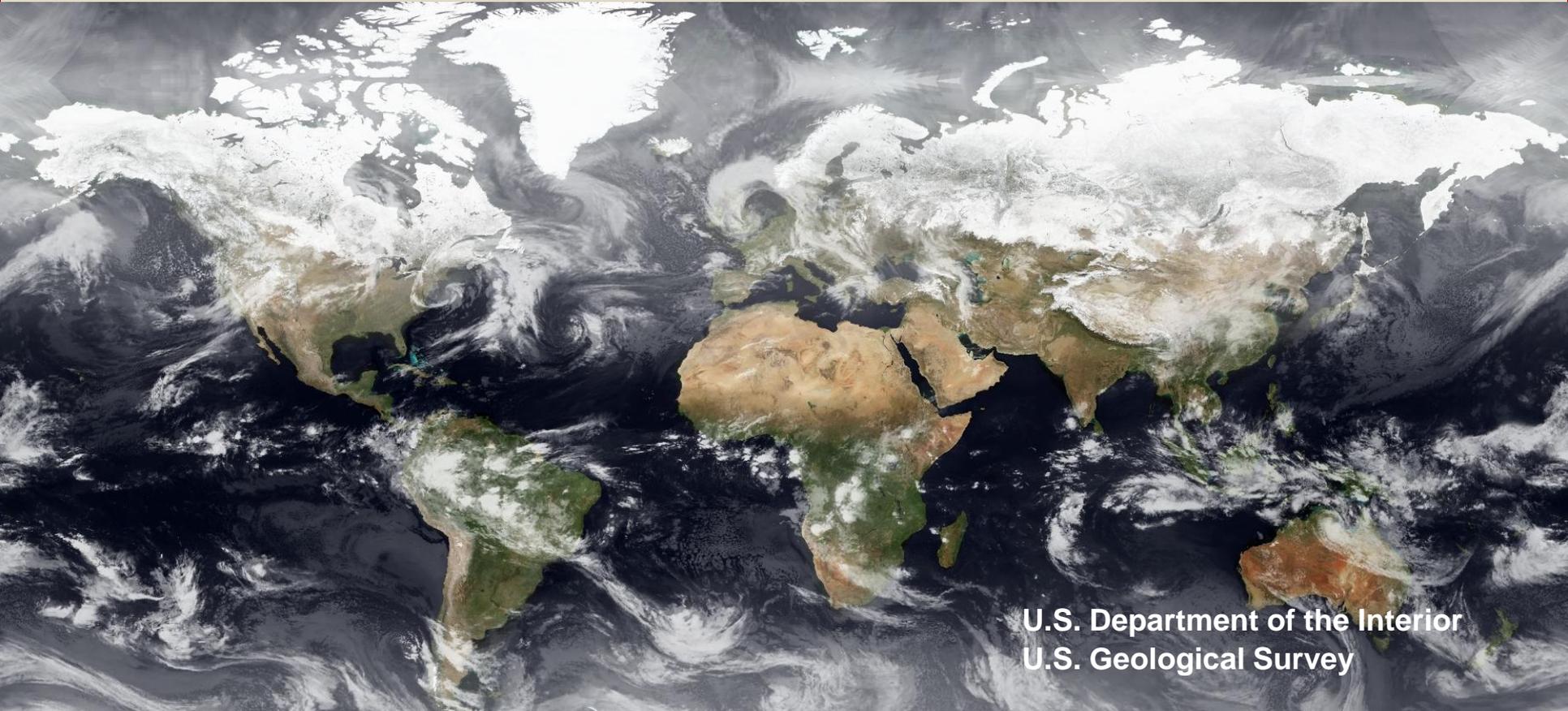




Climate Change – Past, Present, and **Future**

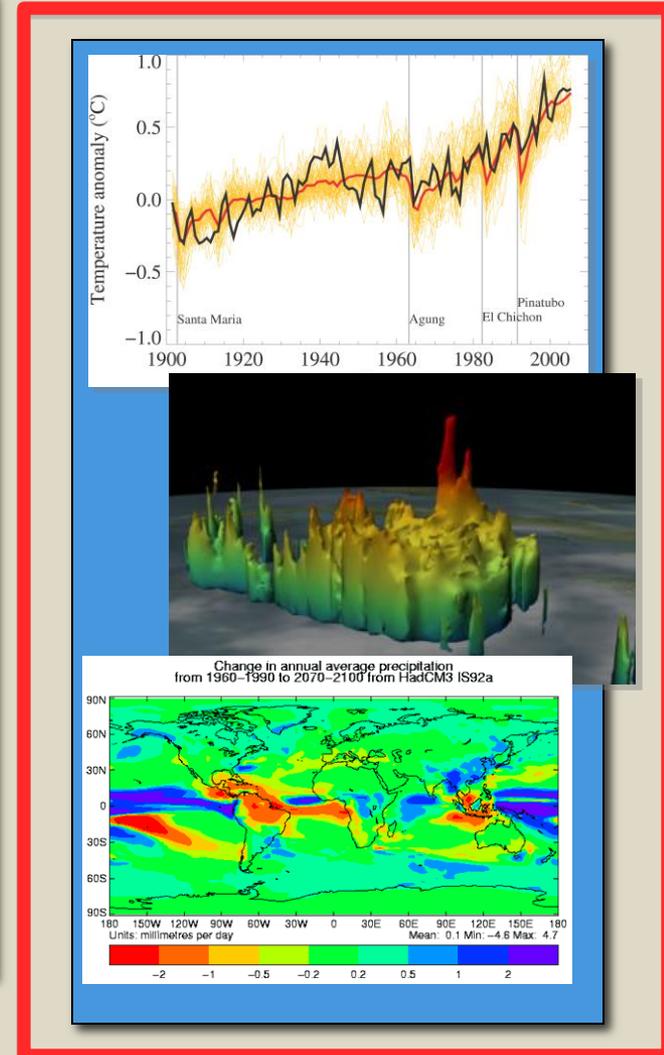
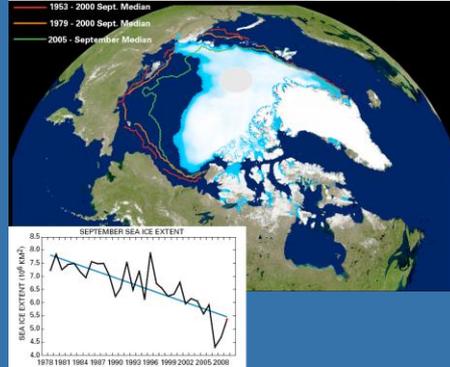
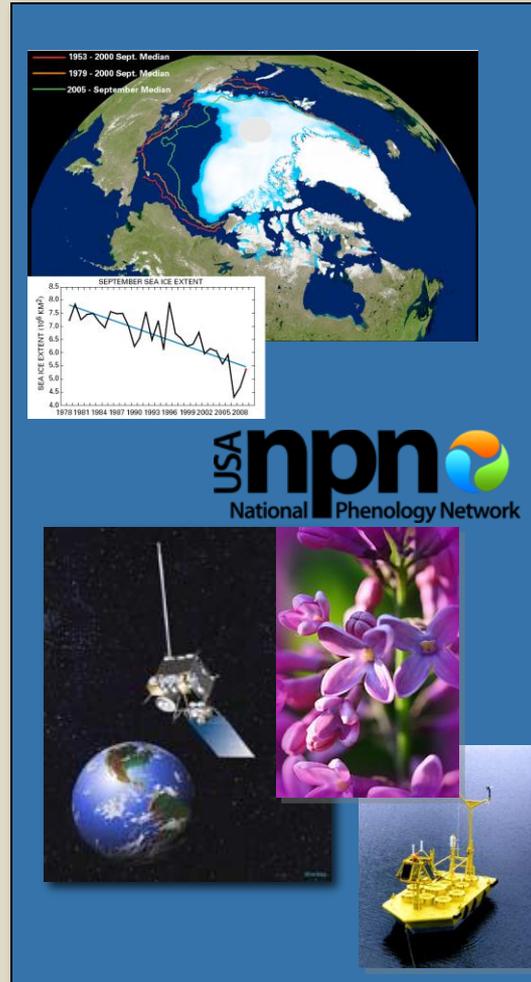
Gary Clow

Geology and Environmental Change Science Center



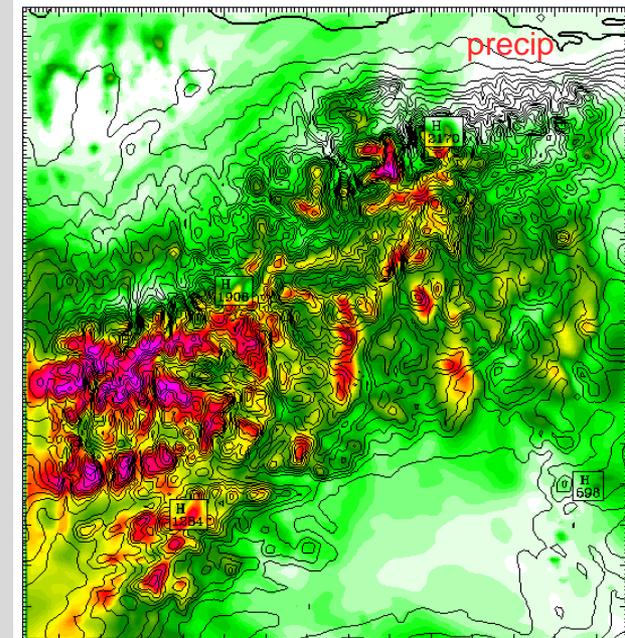
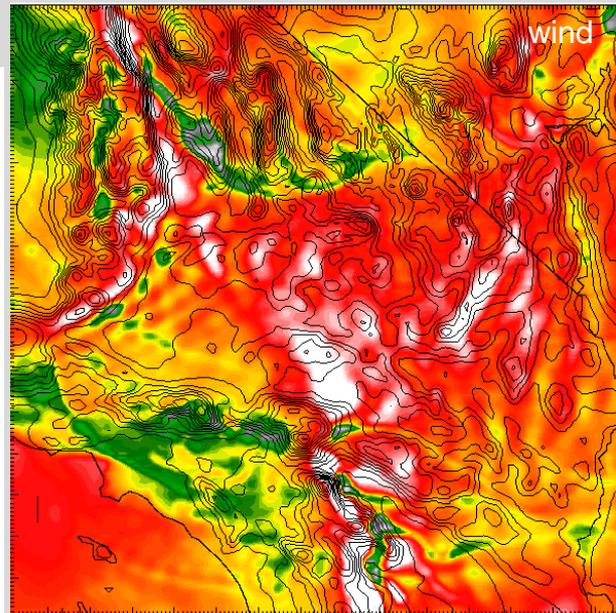
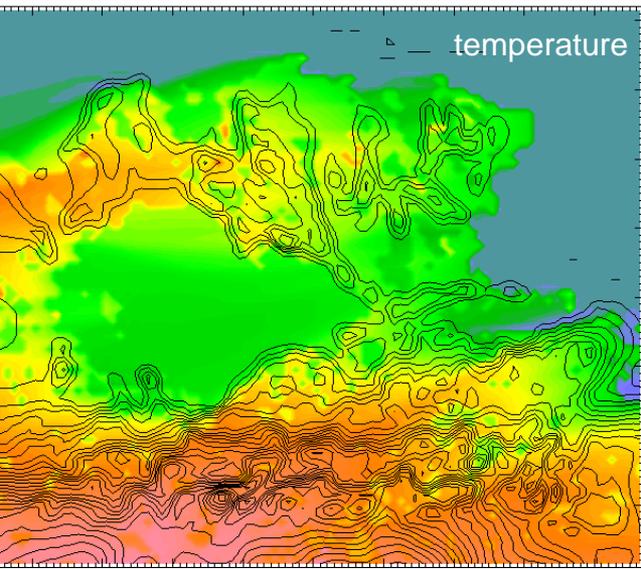
U.S. Department of the Interior
U.S. Geological Survey

Climate – The Future



Outline

- 1) Tools – How do we Project what will Happen in the Future?
- 2) AOGCM (Global) Climate Projections for the 21st Century
- 3) Regional Climate Projections



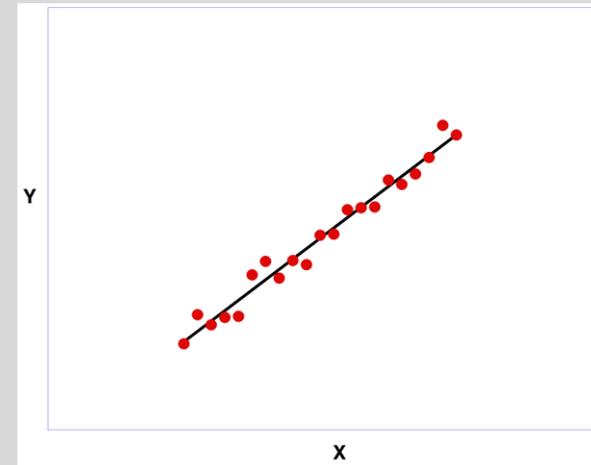
1) Tools,

How do we Project what will Happen in the Future?

Climate Models – Two Basic Categories:

- **Statistical or Empirical Models**

- based on an observed relationship between 2 or more quantities



- **Physically-Based Models**

- based on laws of physics

Flux-Form Equations in Mass Coordinate

Introduce the perturbation variables: $\phi = \bar{\phi}(z) + \phi'$, $\mu = \bar{\mu}(z) + \mu'$;
 $p = \bar{p}(z) + p'$, $\alpha = \bar{\alpha}(z) + \alpha'$

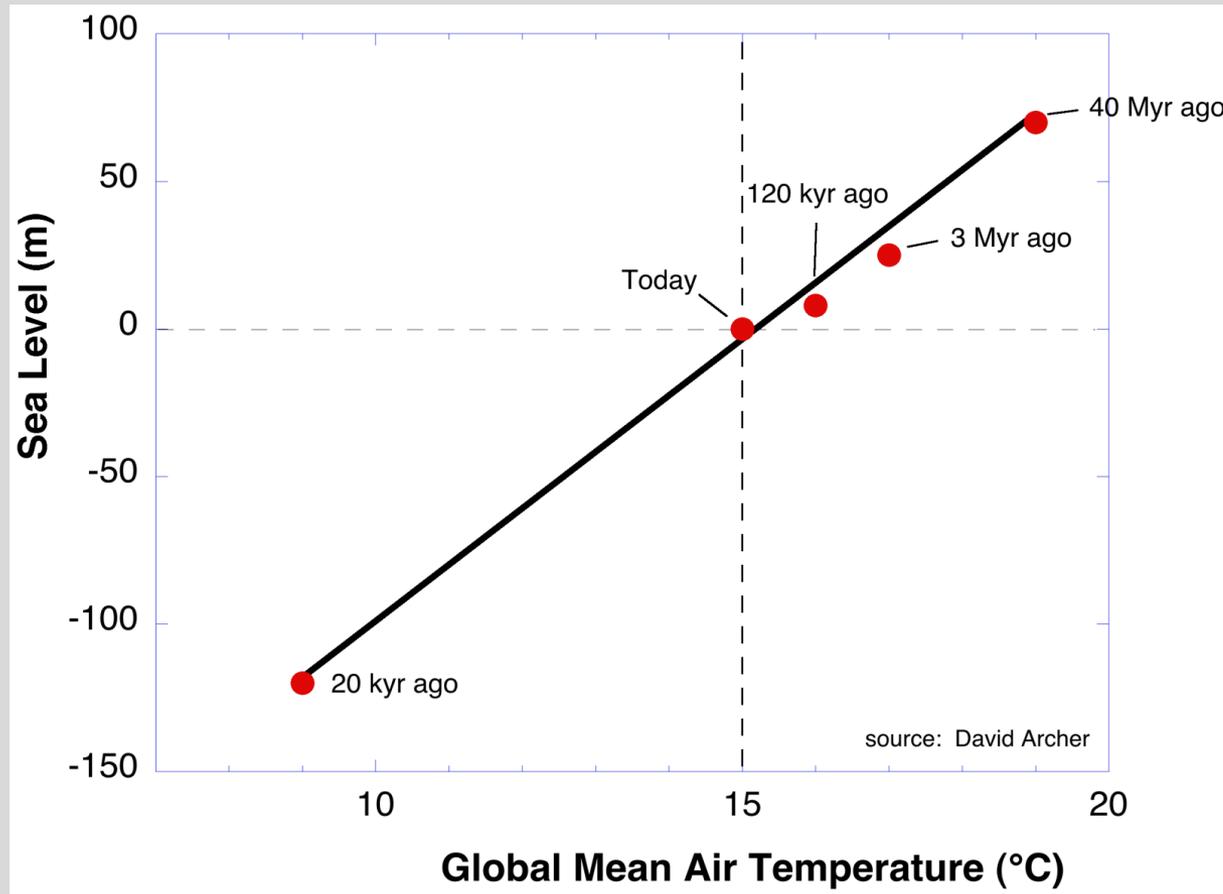
Note – $\phi = \bar{\phi}(z) = \bar{\phi}(x, y, \eta)$,
likewise $\bar{p}(x, y, \eta)$, $\bar{\alpha}(x, y, \eta)$

Momentum and hydrostatic equations become:

$$\frac{\partial U}{\partial t} + \mu \alpha \frac{\partial p'}{\partial x} + \eta \mu \alpha \frac{\partial \bar{\mu}}{\partial x} + \mu \frac{\partial \phi'}{\partial x} + \frac{\partial \phi'}{\partial x} \left(\frac{\partial p}{\partial \eta} - \mu' \right) = - \frac{\partial U u}{\partial x} - \frac{\partial \Sigma u}{\partial \eta}$$
$$\frac{\partial W}{\partial t} + g \left(\mu' - \frac{\partial p'}{\partial \eta} \right) = - \frac{\partial U w}{\partial x} - \frac{\partial \Sigma w}{\partial \eta}$$
$$\frac{\partial \phi'}{\partial \eta} = - \bar{\mu} \alpha' - \bar{\alpha} \mu'$$

Tools: Statistical or Empirical Models

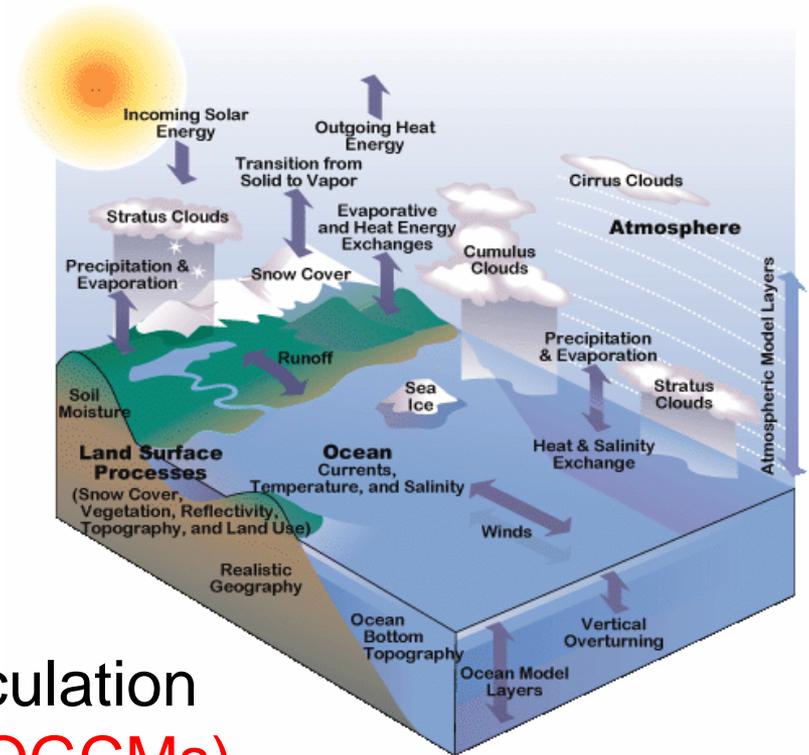
A Simple Example,



Tools: Physically-Based Models

Categories:

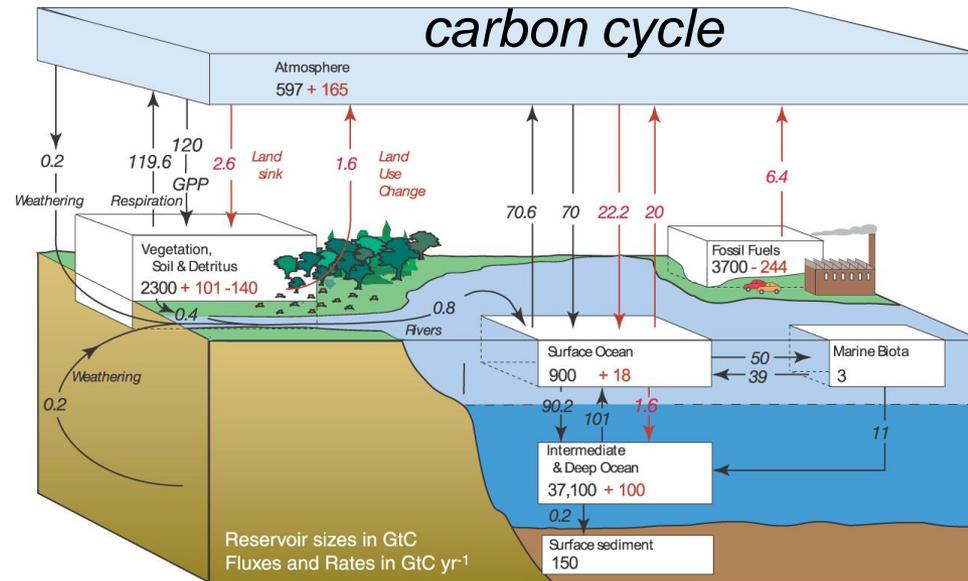
- Simple Climate Models
- Earth System Models of Intermediate Complexity
- Atmosphere/Ocean General Circulation Models (AGCMs, OGCMs, AOGCMs)
- Regional Climate Models (RCMs)



Tools: Physically-Based Models

Sources of Uncertainty in Future Climate Projections:

- Incomplete understanding of Earth System processes

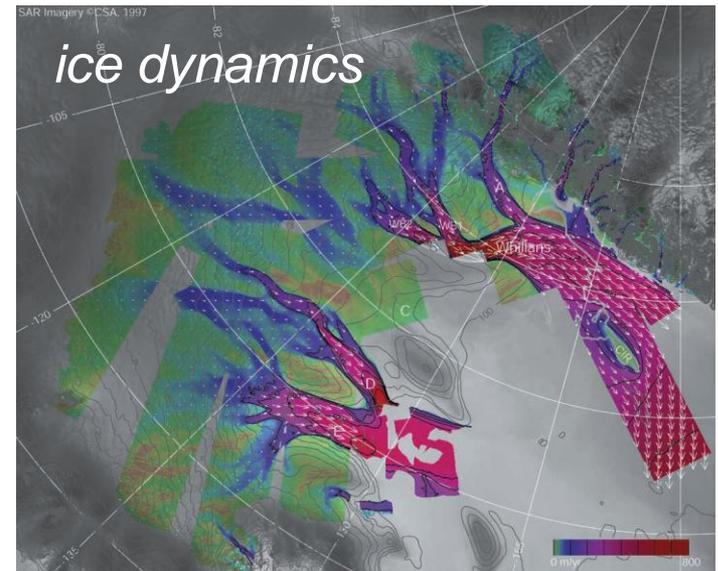


Tools: Physically-Based Models

Sources of Uncertainty in Future Climate Projections:

- Incomplete understanding of Earth System processes
- Missing processes & feedbacks

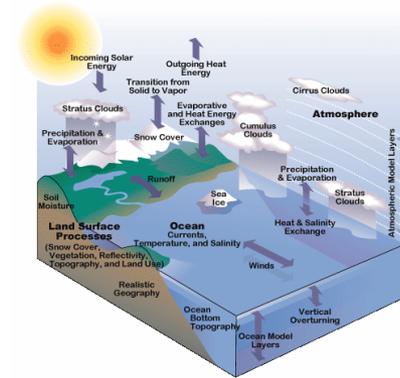
future volcanic activity
future solar variability
ice sheet dynamics
carbon cycle feedbacks



Tools: Physically-Based Models

Sources of Uncertainty in Future Climate Projections:

- Incomplete understanding of Earth System processes
- Missing processes
- Uncertainties in the parameters



Physics

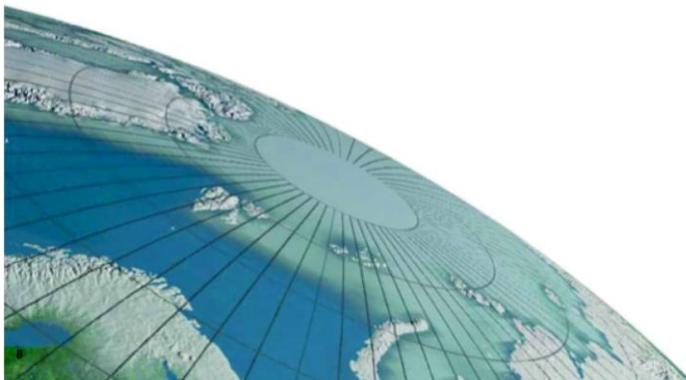
$$\text{Evaporation Rate} = C_R \left[\frac{\kappa^{1/2} u_*^{3/4} \rho_o (q_o - q_d)}{(\nu z_o)^{1/4}} \right]$$

What's this?

Tools: Physically-Based Models

Sources of Uncertainty in Future Climate Projections:

- Incomplete understanding of Earth System processes
- Missing processes
- Uncertainties in the parameters
- Numerical Representation of Processes



Advection in the Height/Mass Coordinate Model

2nd, 3rd, 4th, 5th and 6th order centered and upwind-biased schemes are available in the WRF model.

Example: 5th order scheme

$$\frac{\partial(U\phi)}{\partial x} = \frac{1}{\Delta x} \left(F_{i+\frac{1}{2}}(U\phi) - F_{i-\frac{1}{2}}(U\phi) \right)$$

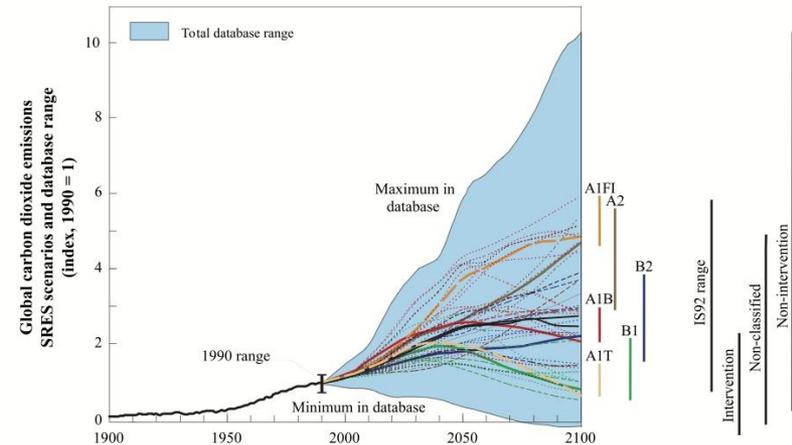
where

$$F_{i-\frac{1}{2}}(U\phi) = U_{i-\frac{1}{2}} \left\{ \frac{37}{60}(\phi_i + \phi_{i-1}) - \frac{2}{15}(\phi_{i+1} + \phi_{i-2}) + \frac{1}{60}(\phi_{i+2} + \phi_{i-3}) \right\} \\ - \text{sign}(1, U) \frac{1}{60} \{ (\phi_{i+2} - \phi_{i-3}) - 5(\phi_{i+1} - \phi_{i-2}) + 10(\phi_i - \phi_{i-1}) \}$$

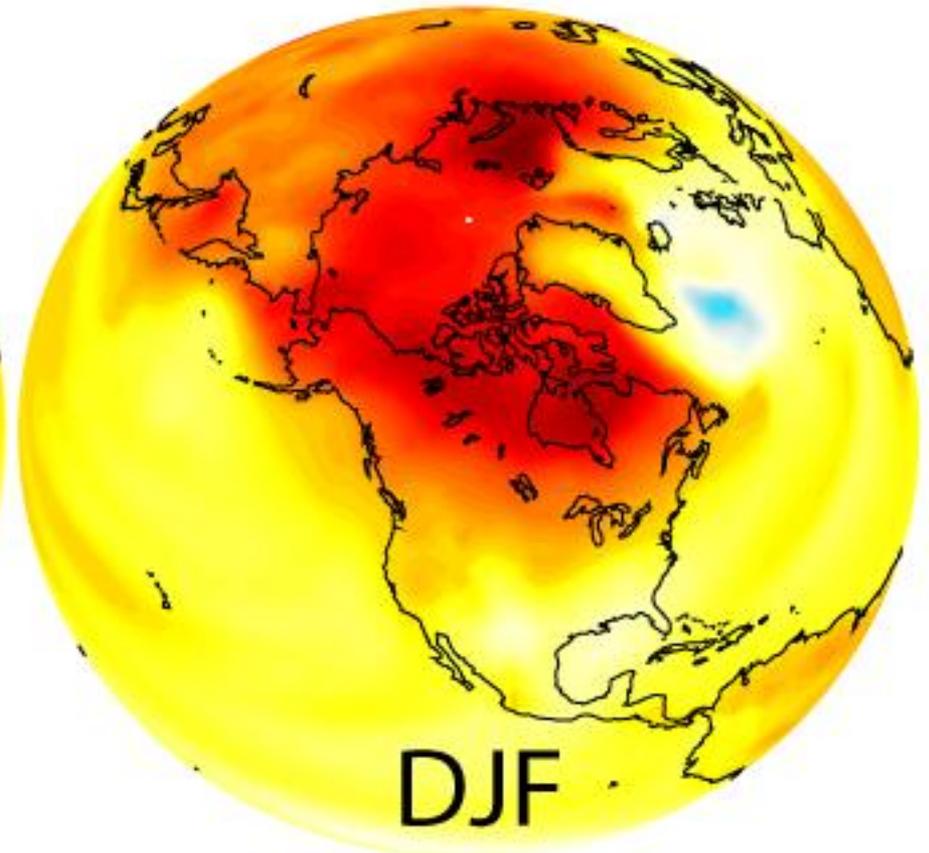
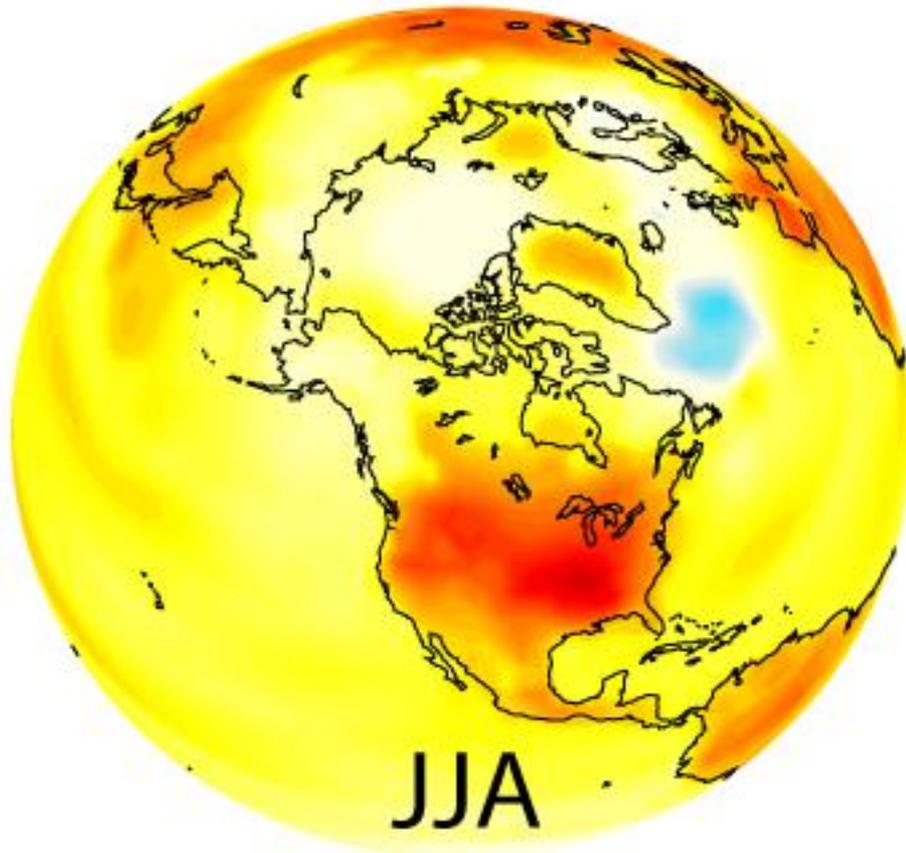
Tools: Physically-Based Models

Sources of Uncertainty in Future Climate Projections:

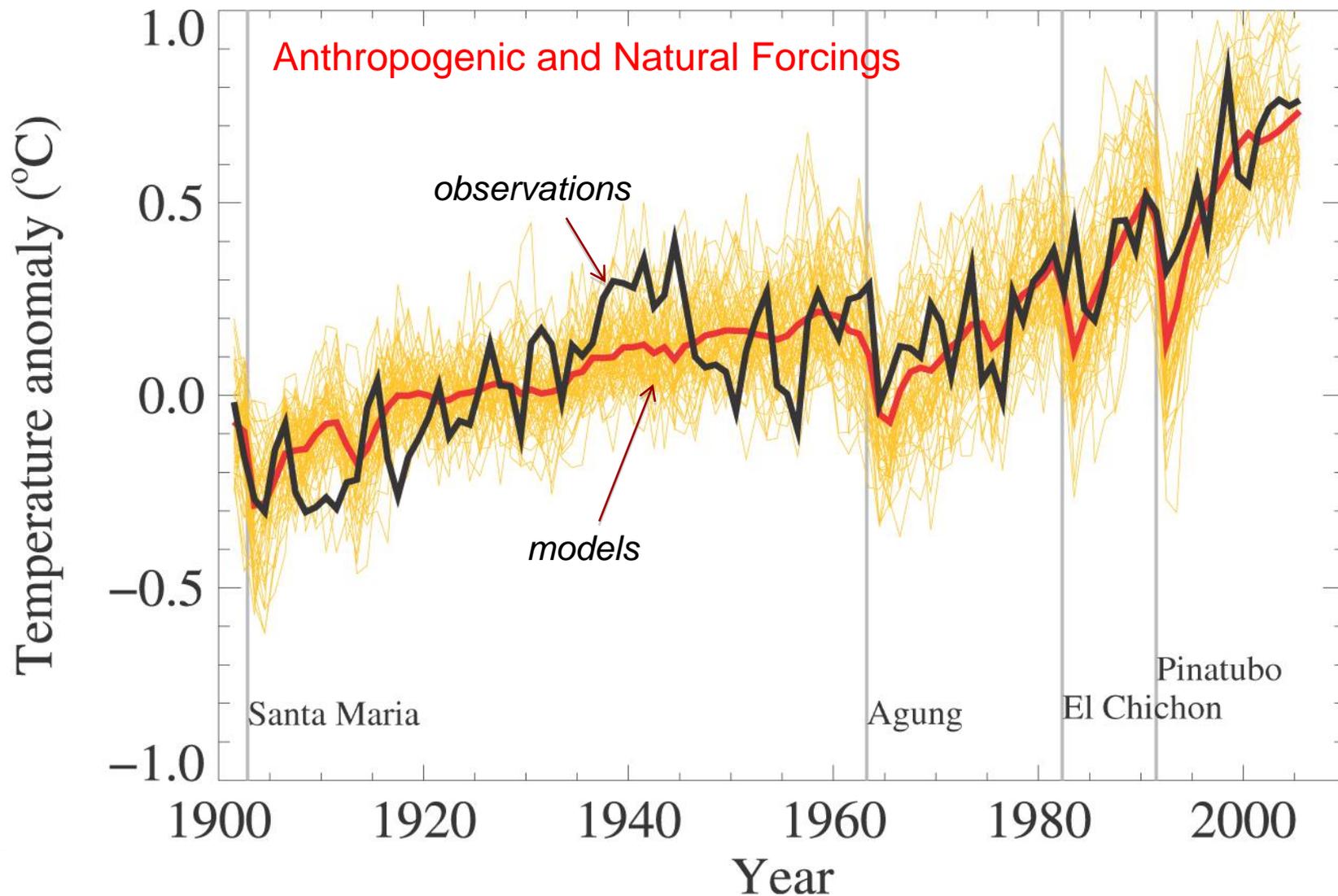
- Incomplete understanding of Earth System processes
- Missing processes
- Uncertainties in the parameters
- Numerical Representation
- Humans (GHG emissions, aerosols, landuse change ...)



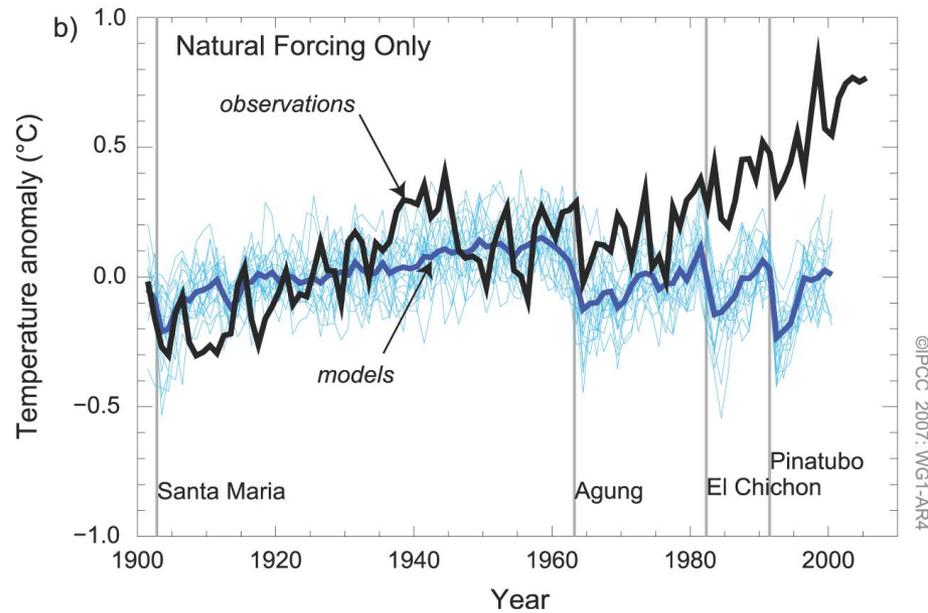
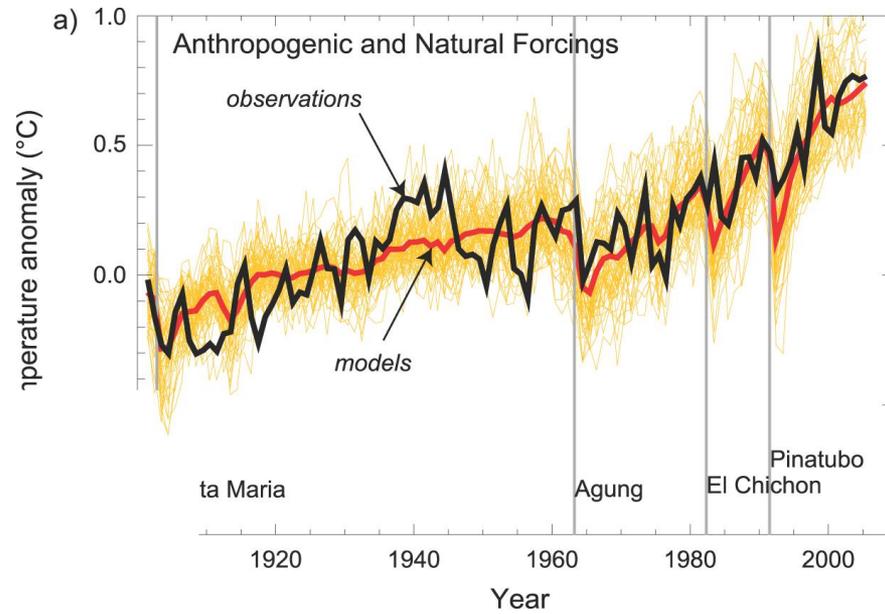
AOGCM Performance – 20th Century Tests



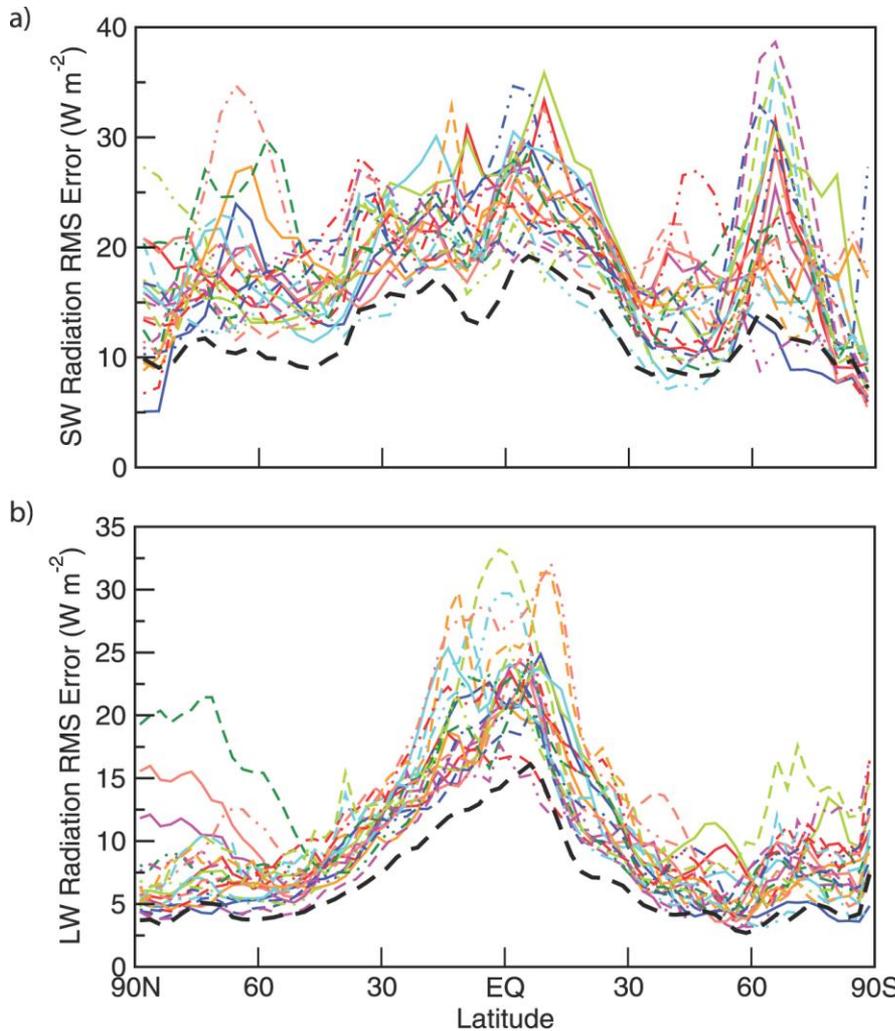
Observed and Simulated 20th-century Global Temperature Change



Observed and Simulated 20th-century Global Temperature Change



Errors in Shortwave and Longwave Radiation Fluxes (TOA)



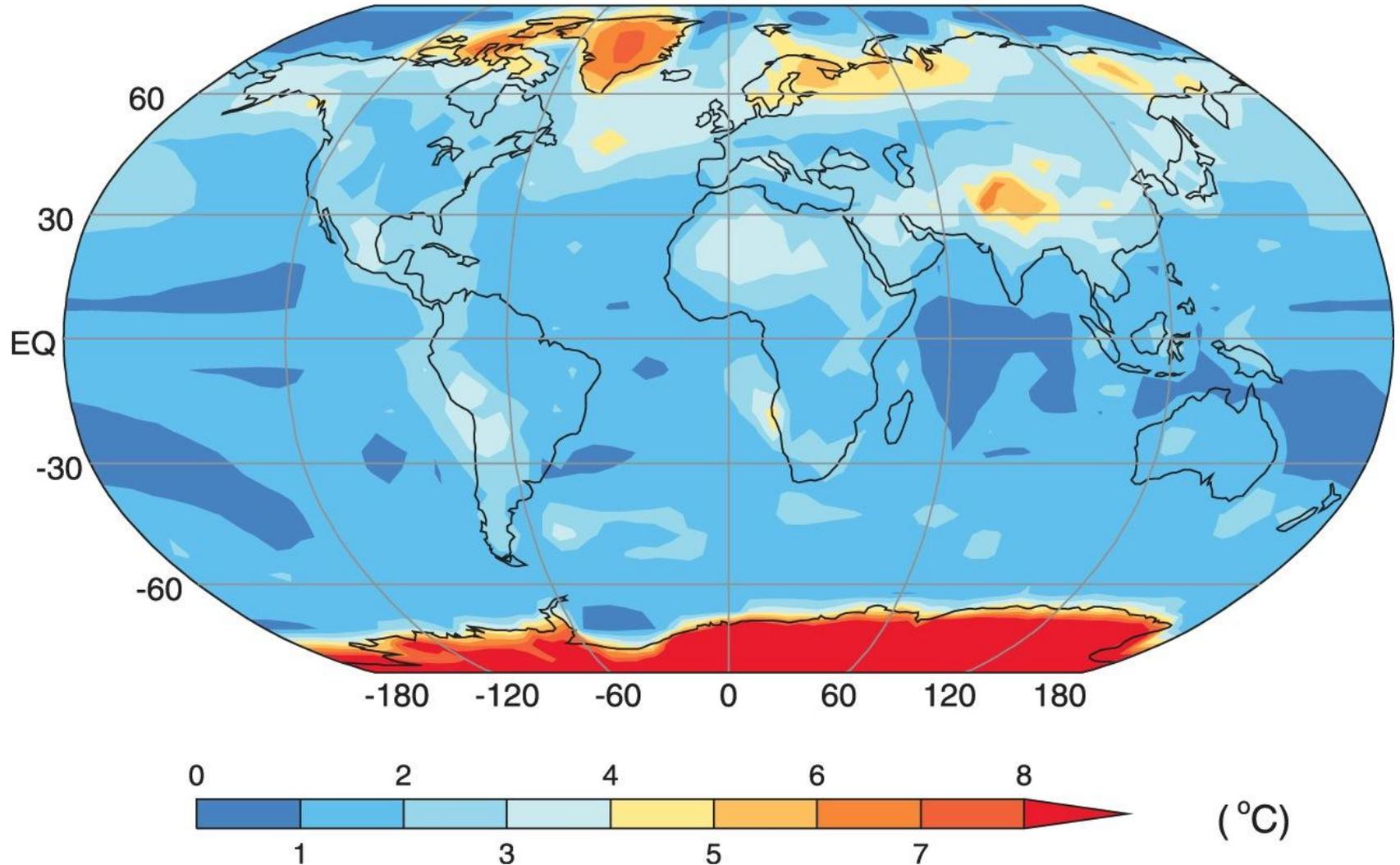
“Ensemble Mean”
is better than any
individual model

- | | | |
|-----------------|---------------|--------------------|
| — BCC-CM1 | — ECHO-G | — IPSL-CM4 |
| — BCCR-BCM2.0 | — FGOALS-g1.0 | — MIROC3.2(hires) |
| — CCSM3 | — GFDL-CM2.0 | — MIROC3.2(medres) |
| — CGCM3.1(T47) | — GFDL-CM2.1 | — MRI-CGCM2.3.2 |
| — CGCM3.1(T63) | — GISS-AOM | — PCM |
| — CNRM-CM3 | — GISS-EH | — UKMO-HadCM3 |
| — CSIRO-Mk3.0 | — GISS-ER | — UKMO-HadGEM1 |
| — ECHAM5/MPI-OM | — INM-CM3.0 | — “Mean Model” |

23 AOGCMs

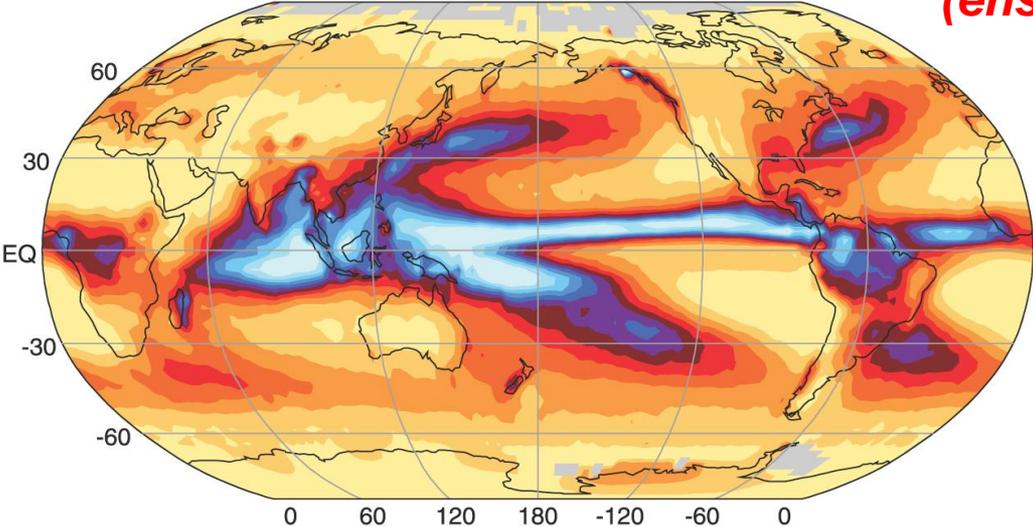
Error in Simulating Contemporary Surface-Temperature Pattern

(ensemble mean)

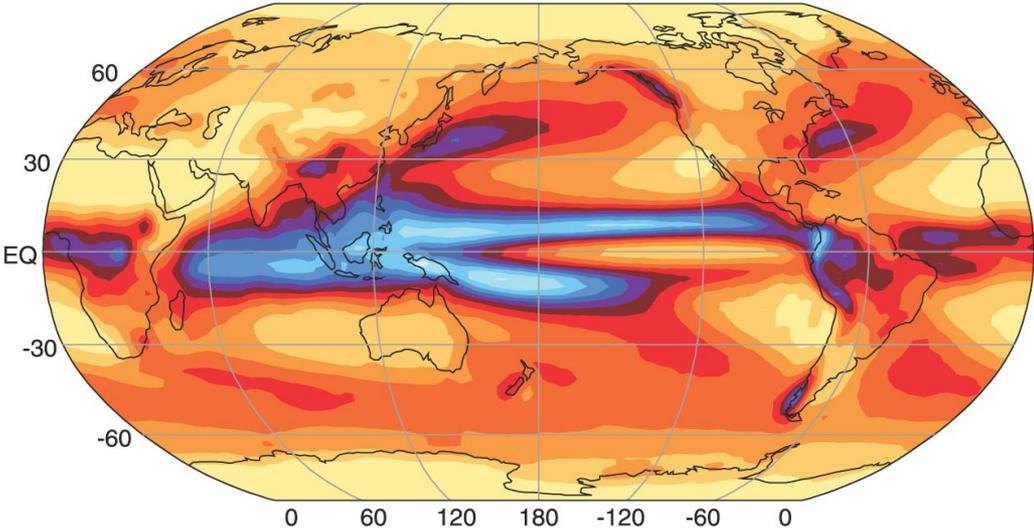


Observed and Simulated Mean-Annual Precipitation Pattern

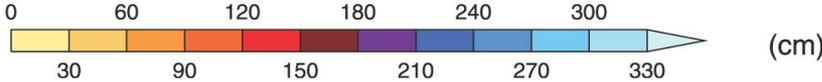
(ensemble mean)

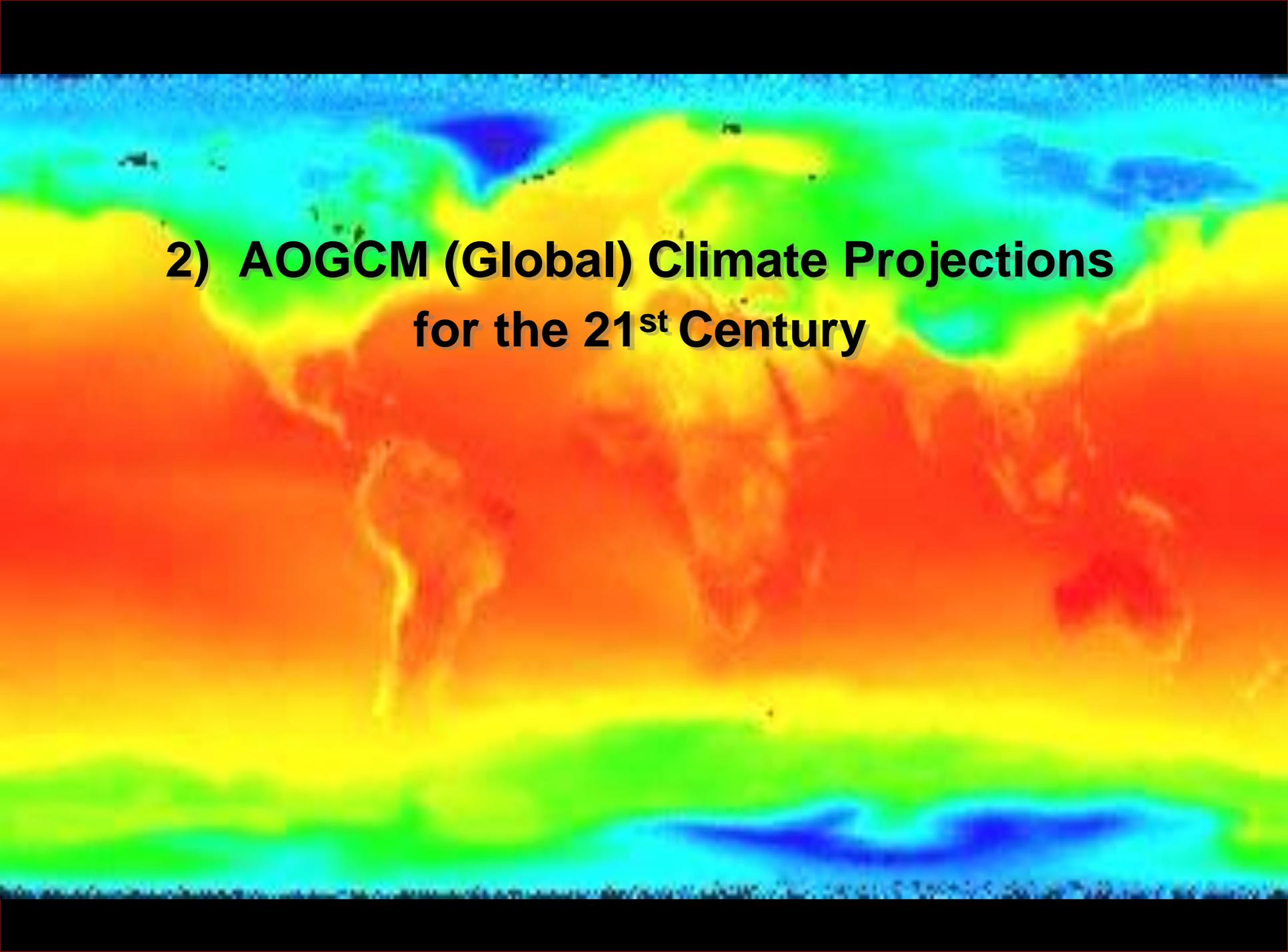


observed



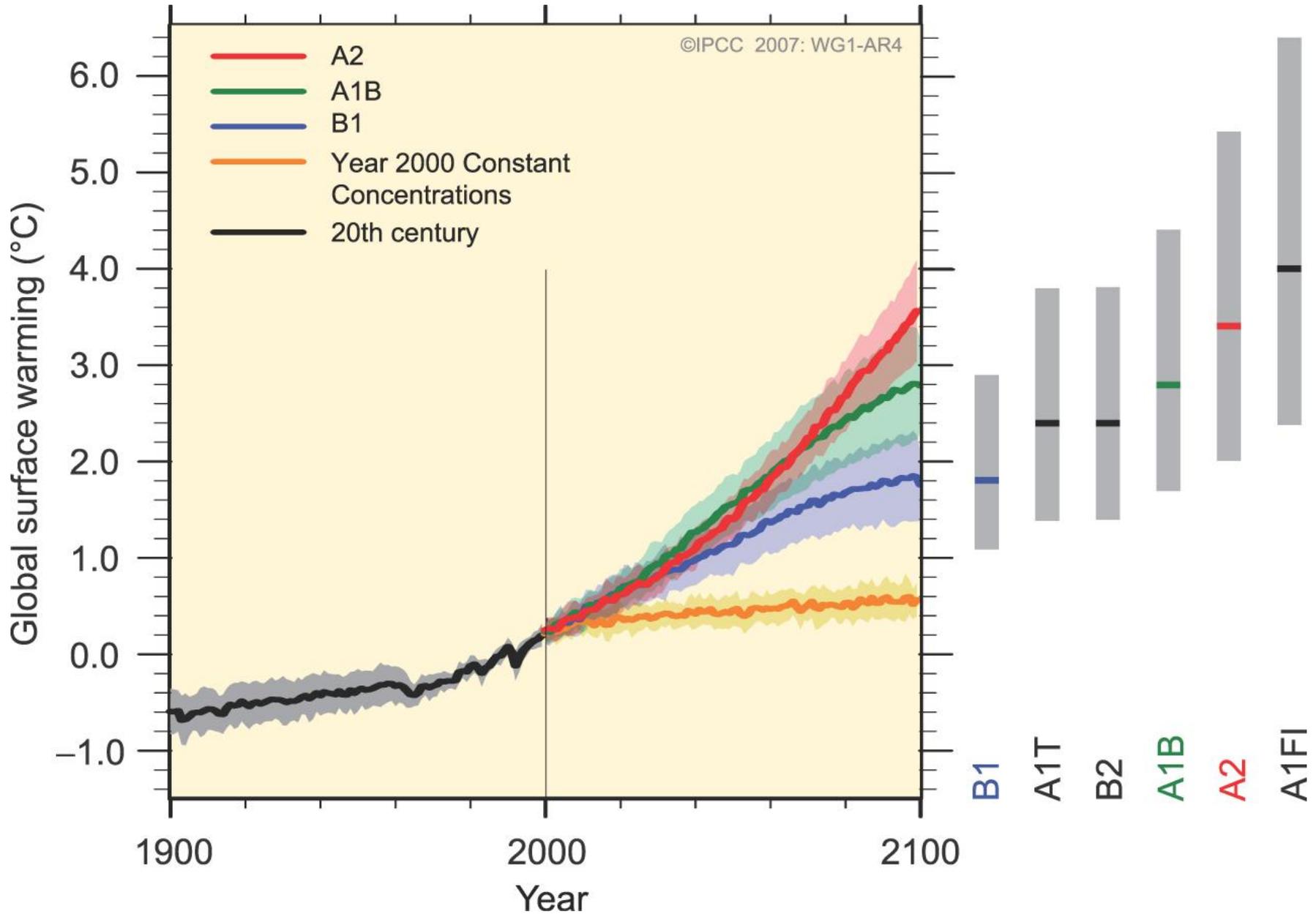
simulated



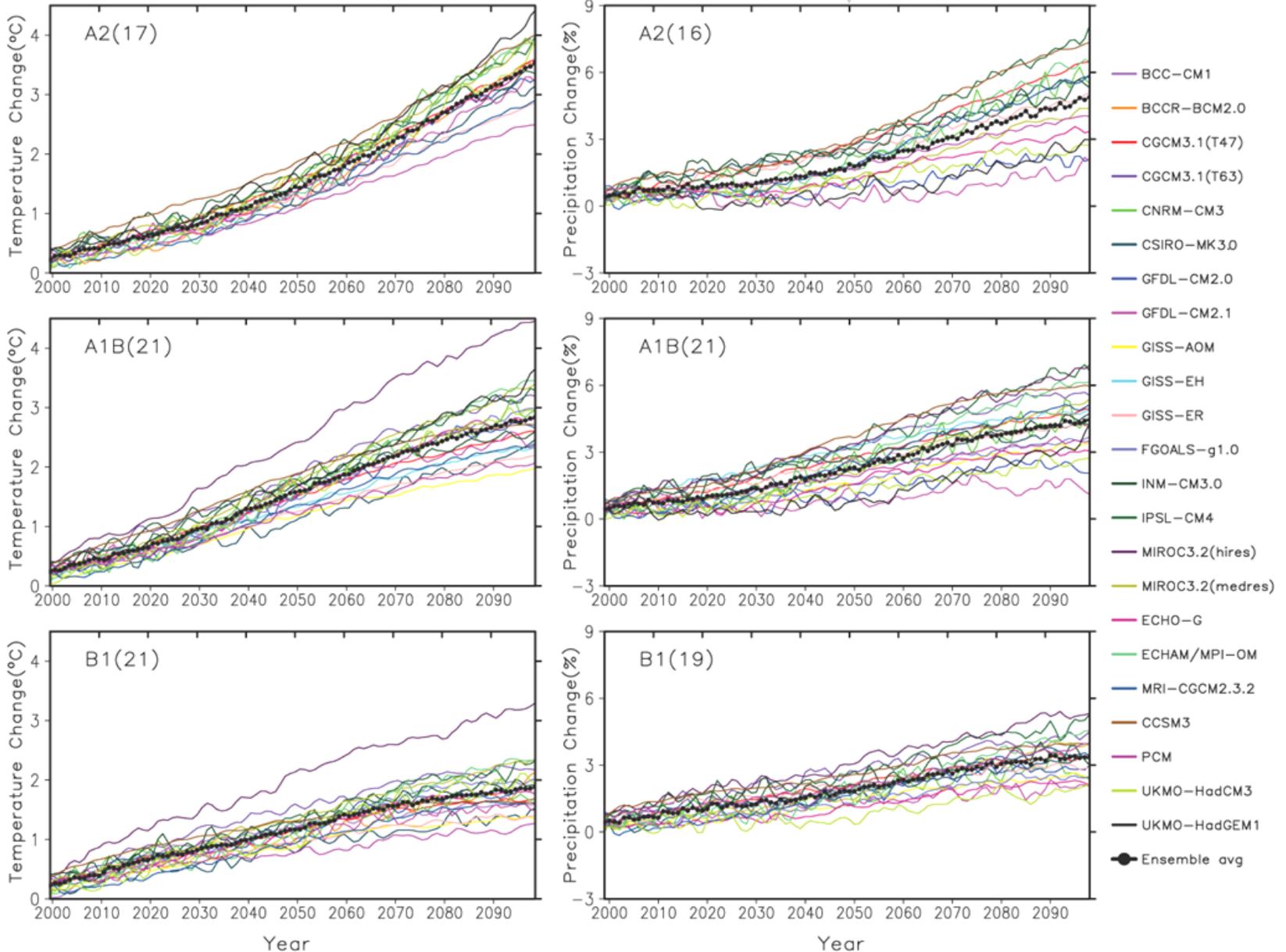
A world map showing climate projections for the 21st century. The map uses a color scale from blue (cooler) to red (warmer). The most significant feature is a large, intense red area covering the tropical and subtropical regions, indicating significant warming. Cooler areas (blue and green) are visible in the high northern and southern latitudes. The text is overlaid on the map.

**2) AOGCM (Global) Climate Projections
for the 21st Century**

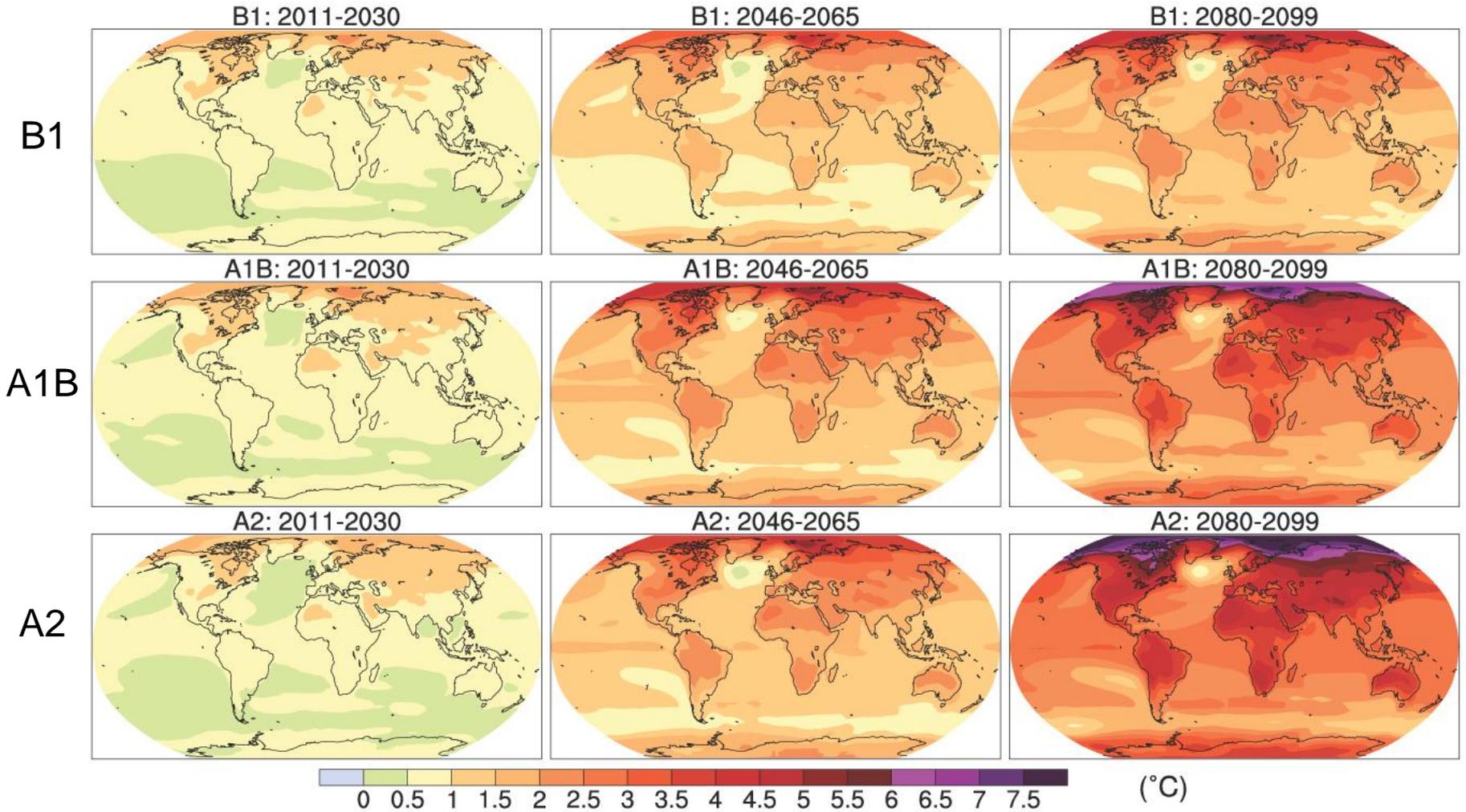
Global Surface-Temperature Projections to 2100



Projected 21st-Century Global Precipitation Changes

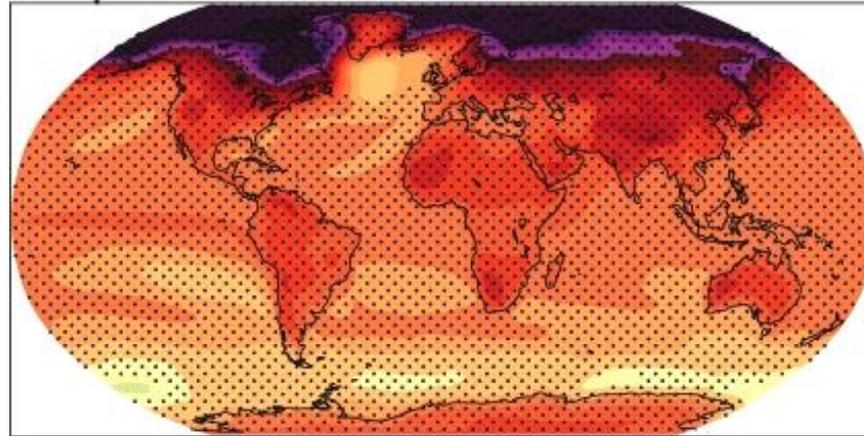


Projected Pattern of Mean-Annual Temperature Change

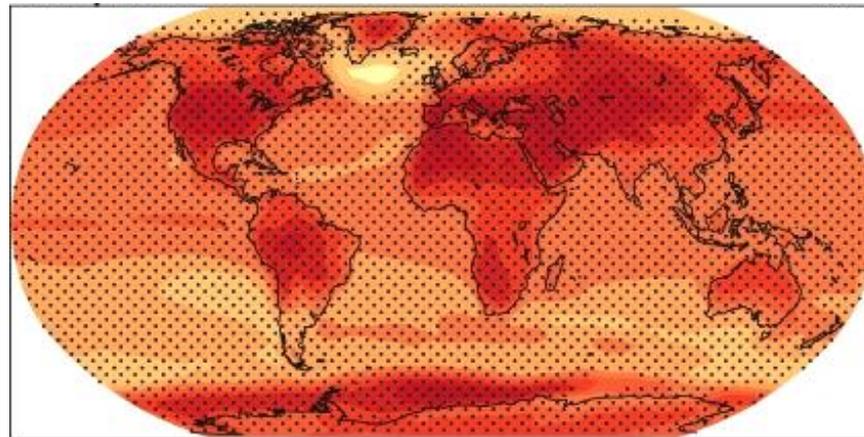


Projected Pattern of Seasonal Temperature Change

(A1B, 2080-2099)



winter

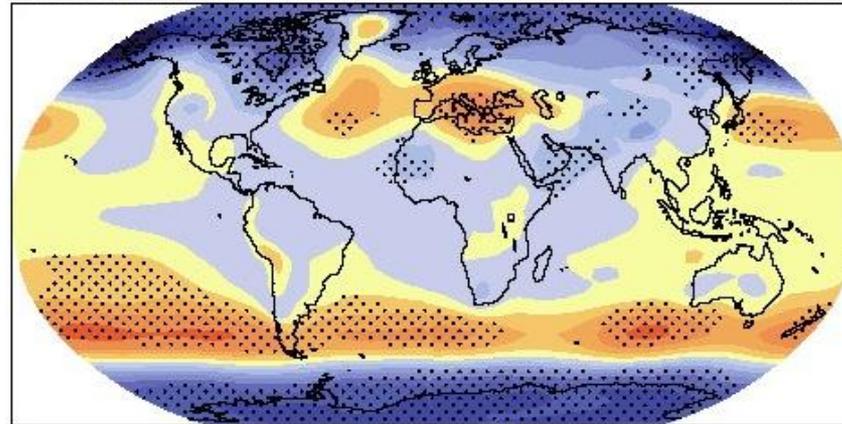


summer

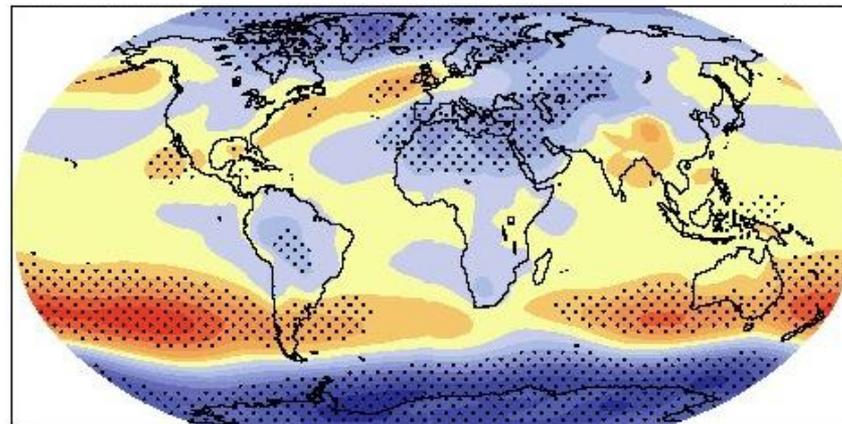
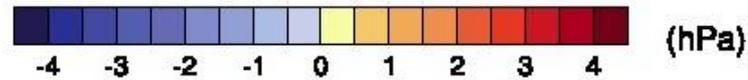


Projected Pattern of Atmospheric Pressure Change

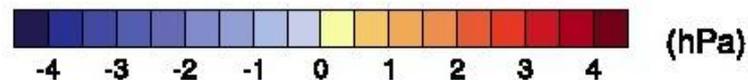
(A1B, 2080-2099)



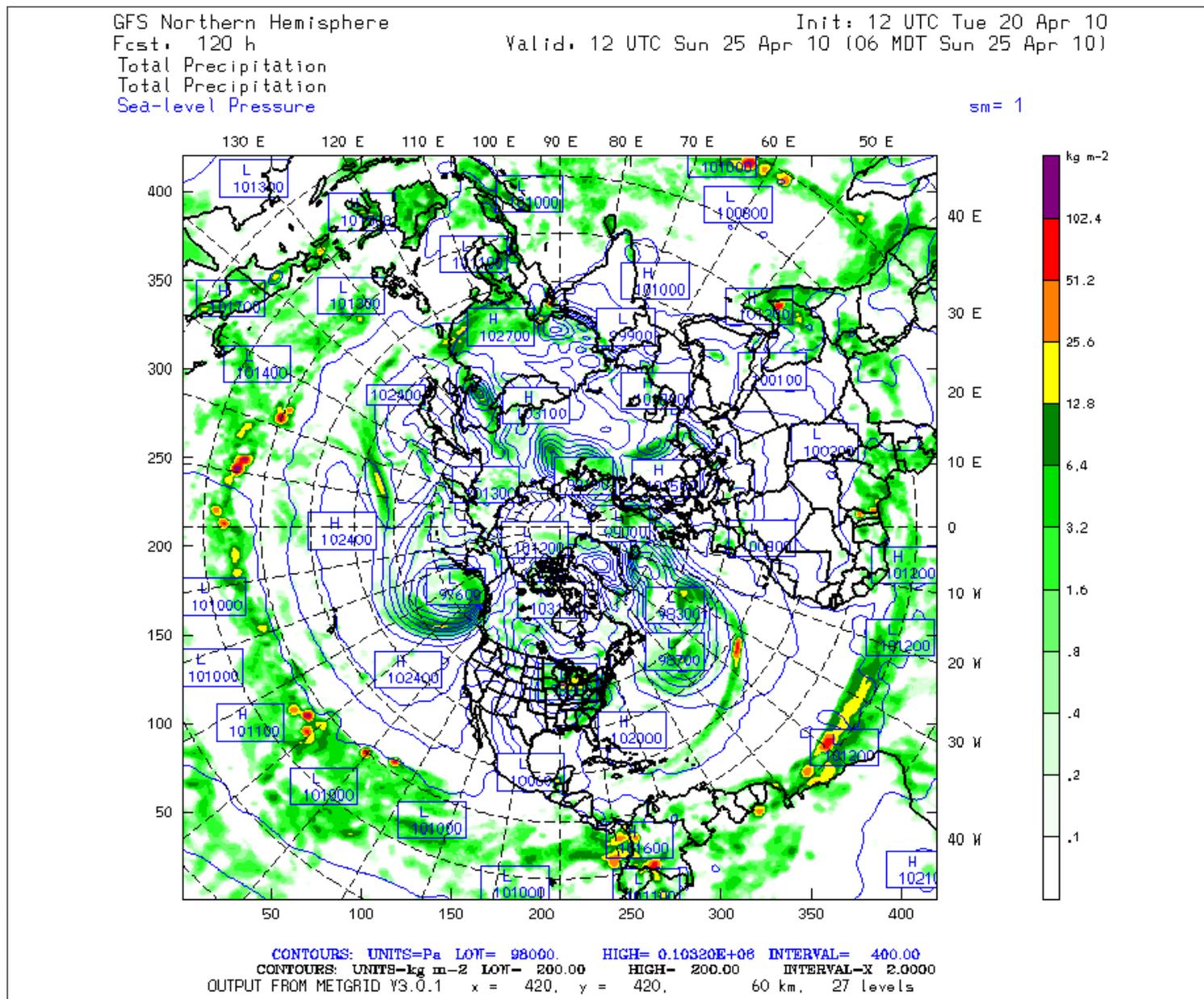
winter



summer

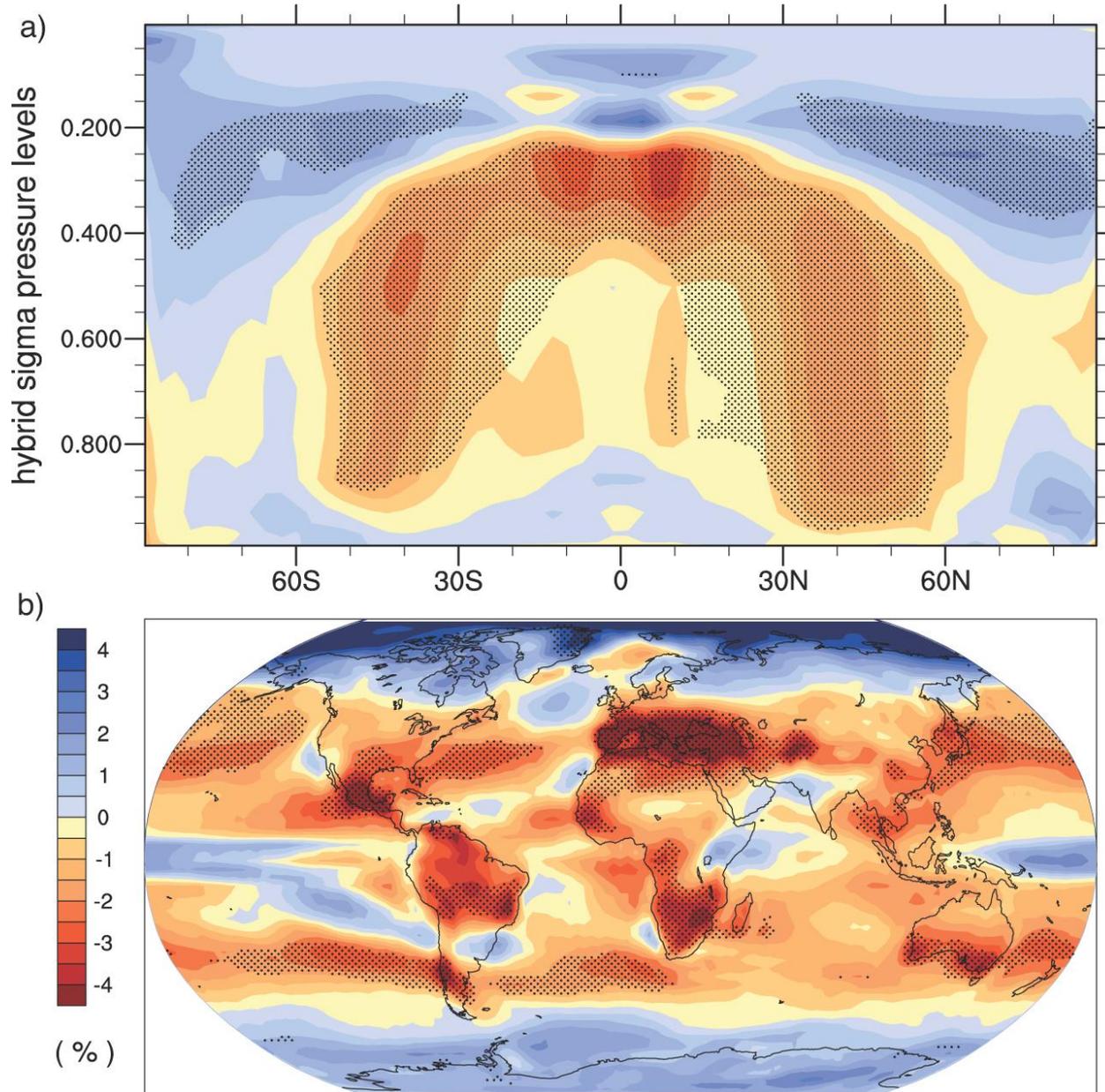


Example: Storms in Northern Hemisphere 2 Days Ago (25 April, 2010)



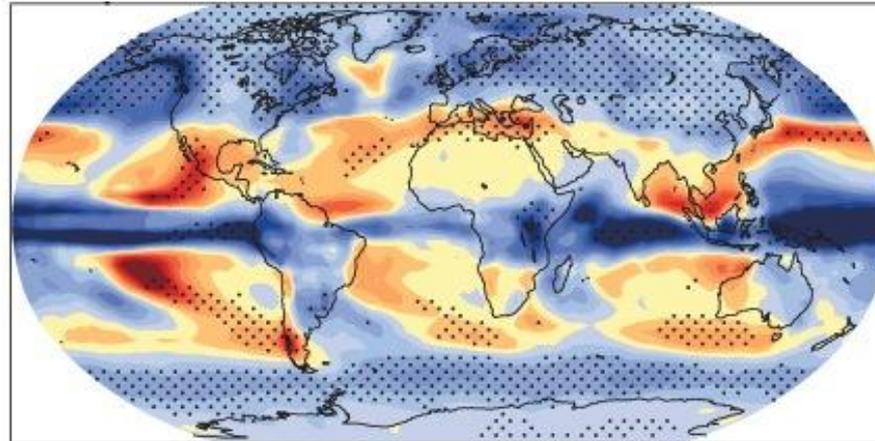
Projected Pattern of Cloud Cover Change

(A1B, 2080-2099)

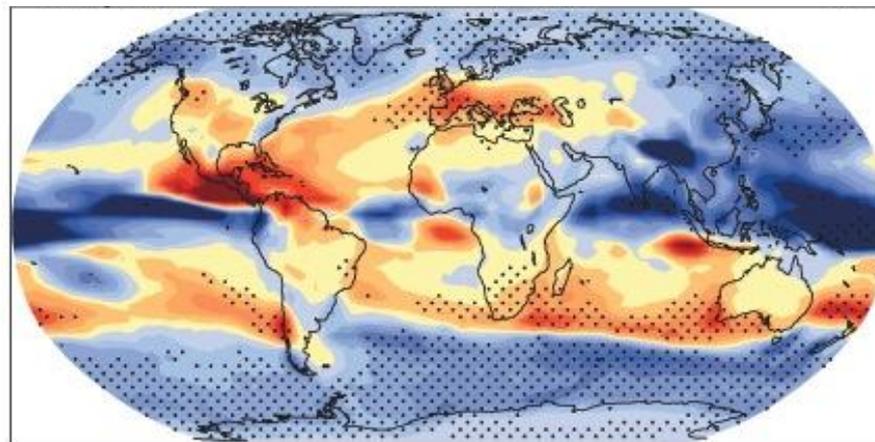
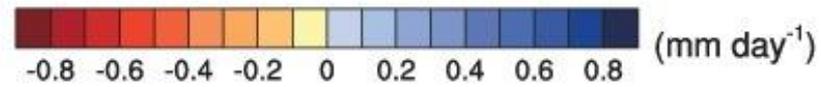


Projected Pattern of Precipitation Change

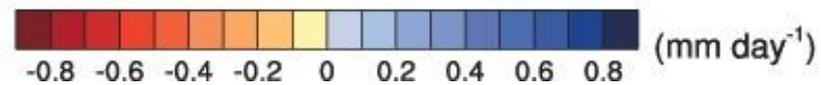
(A1B, 2080-2099)



winter

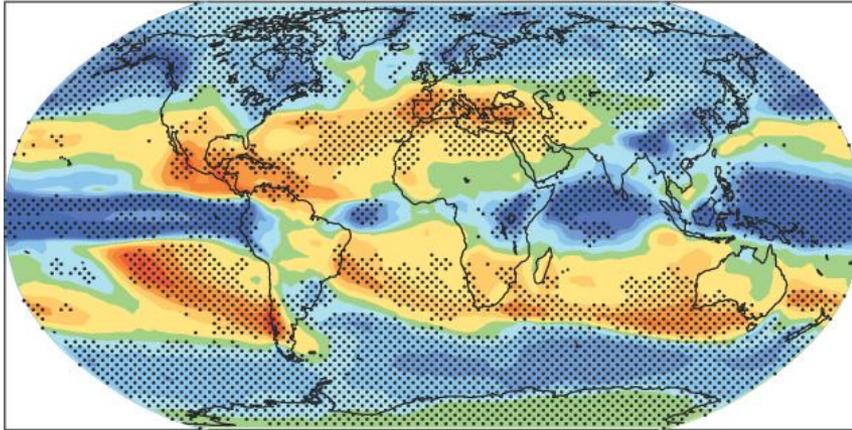


summer

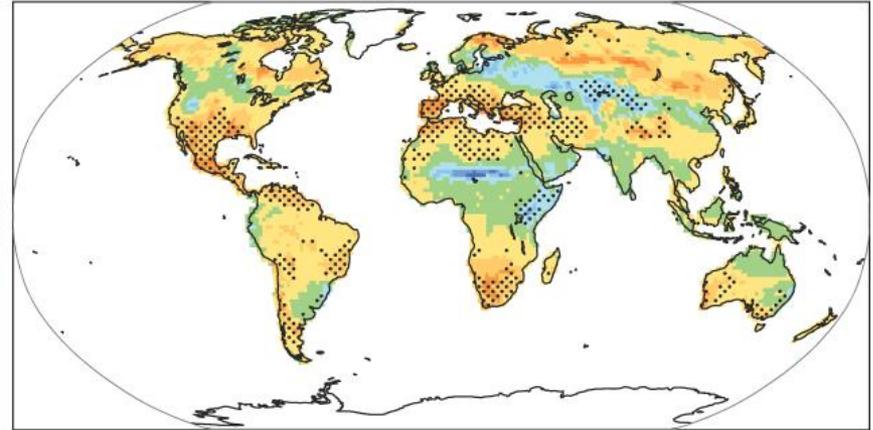


Projected Pattern of Soil Moisture, Runoff, Evaporation Changes

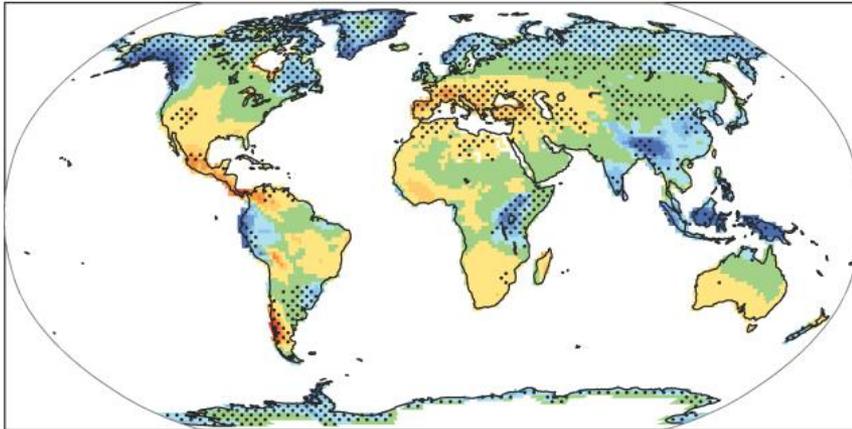
a) Precipitation



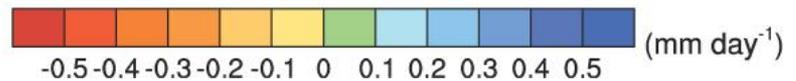
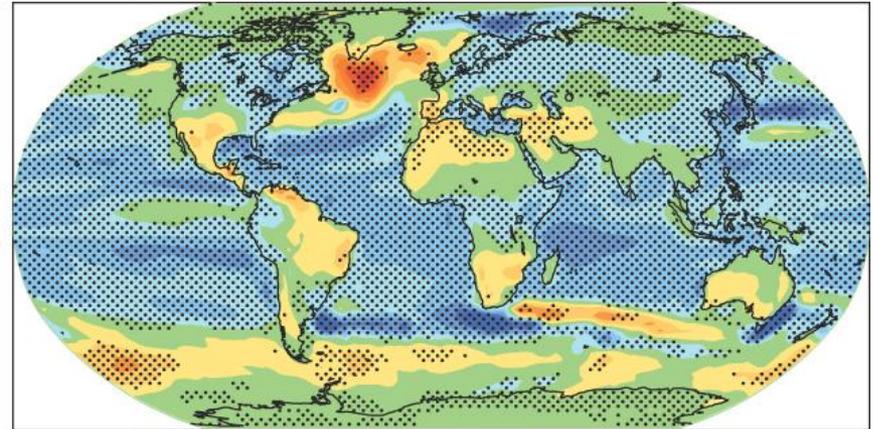
b) Soil moisture



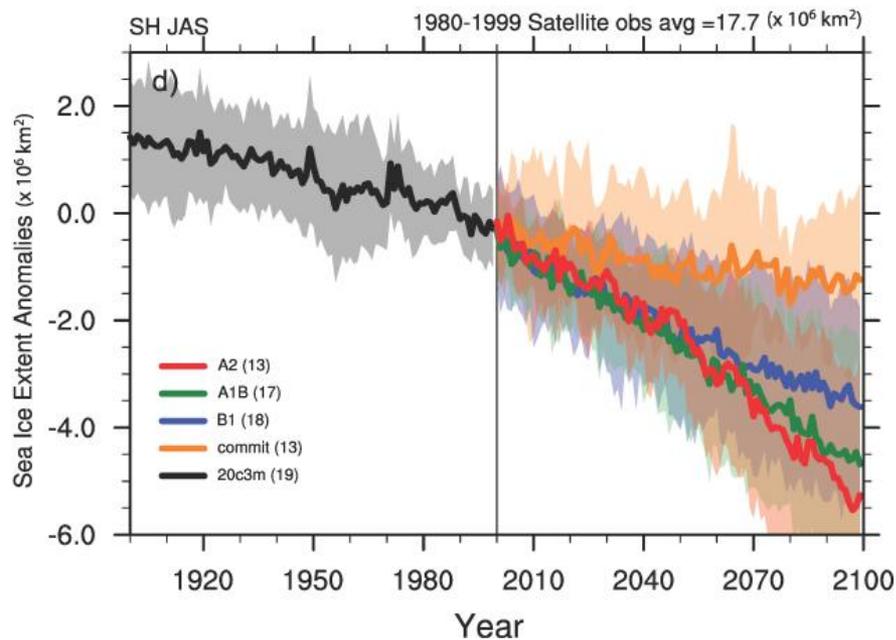
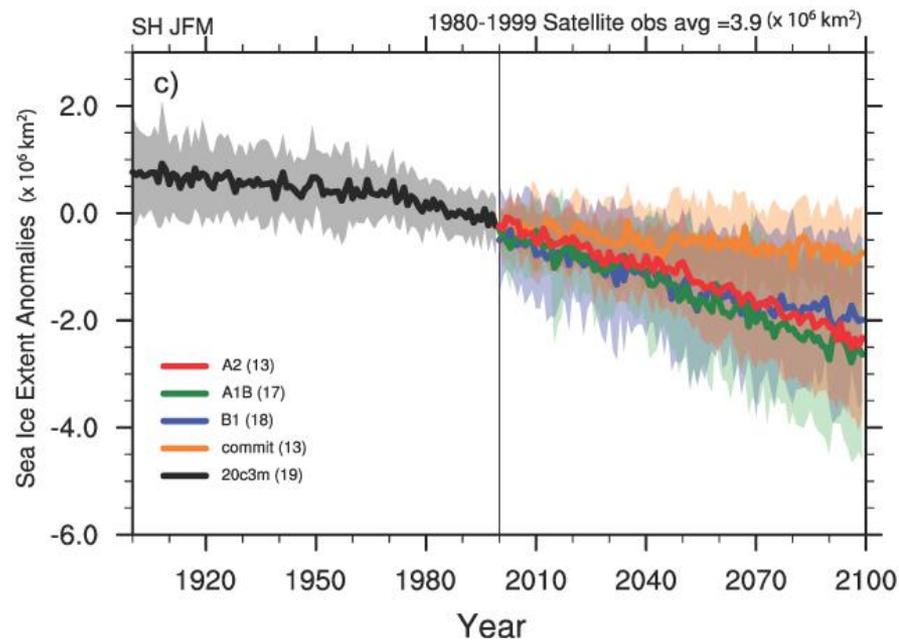
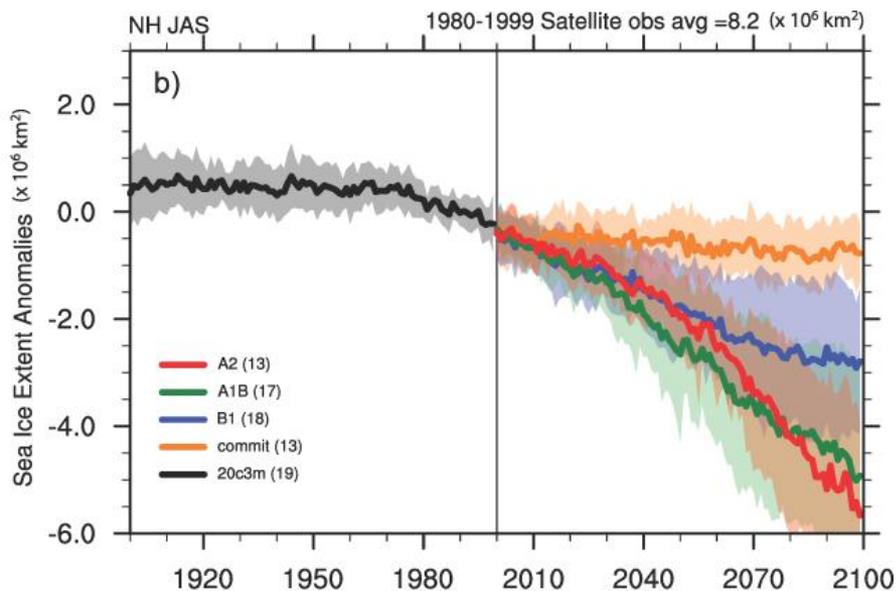
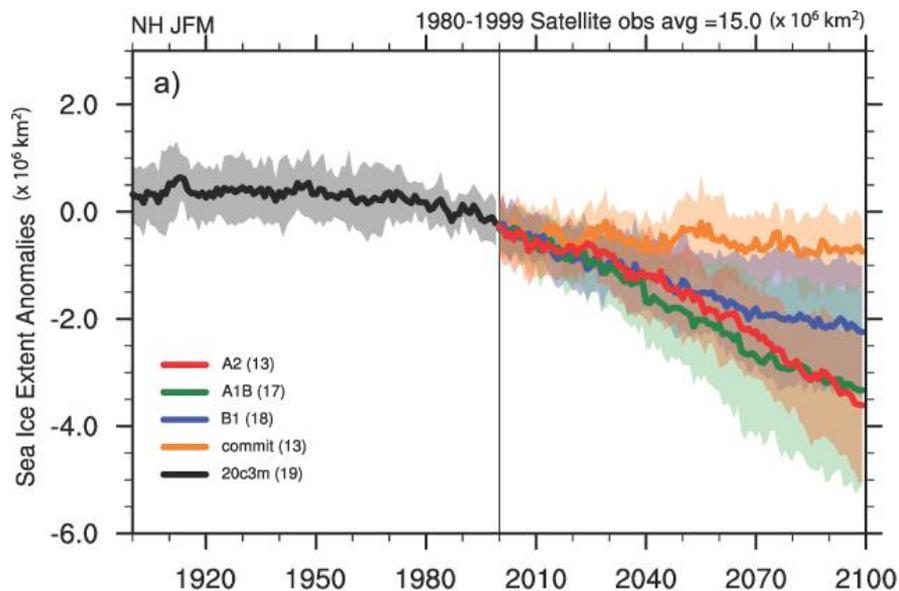
c) Runoff



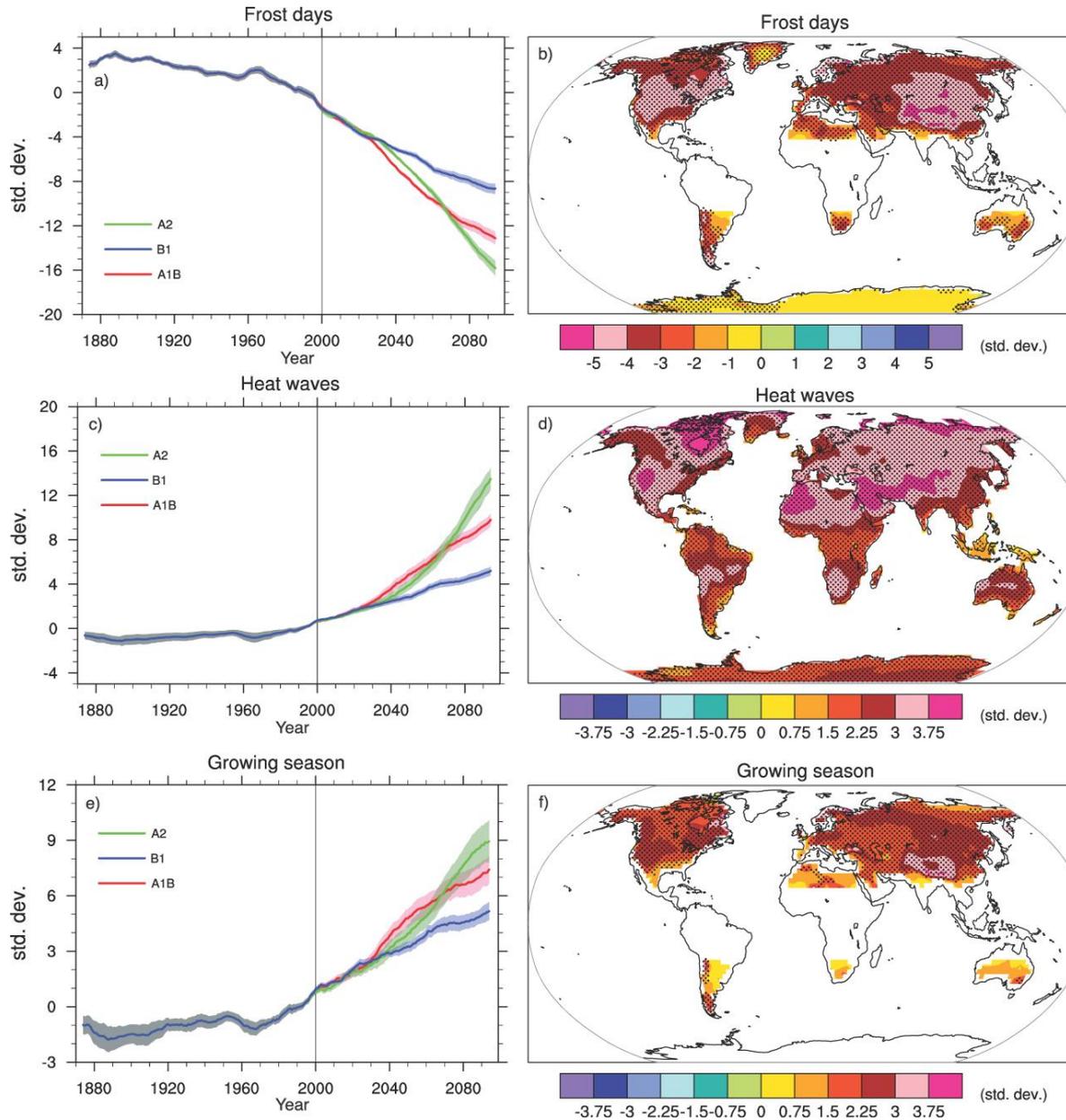
d) Evaporation



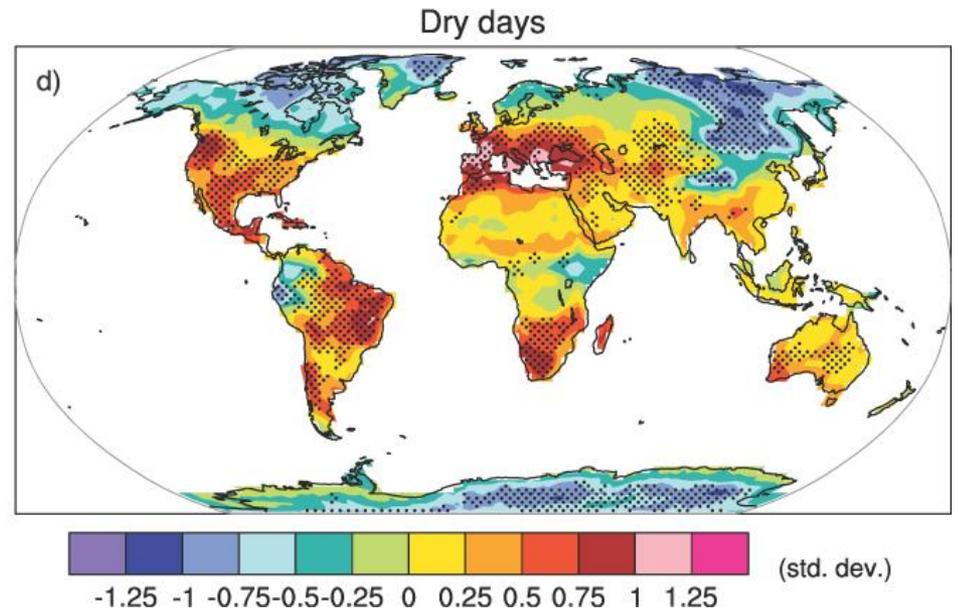
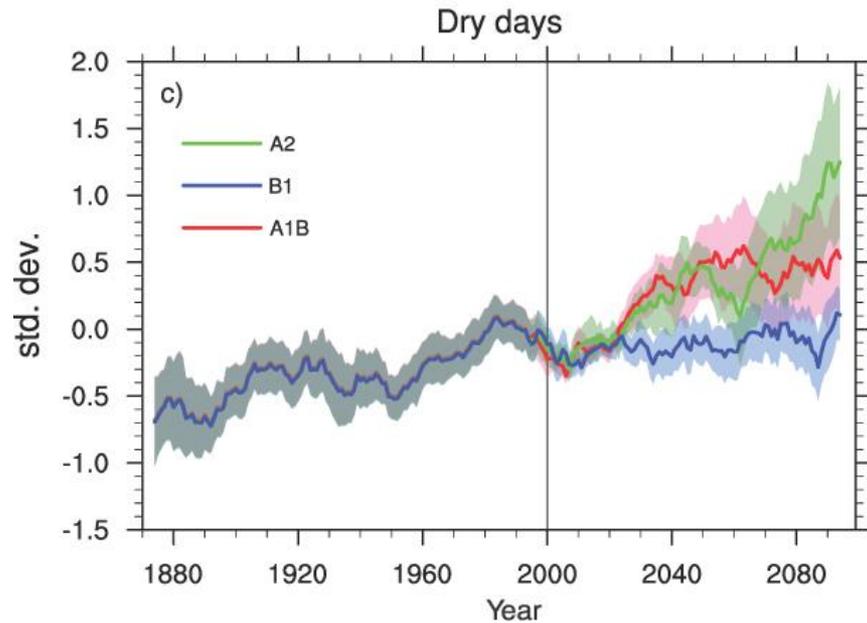
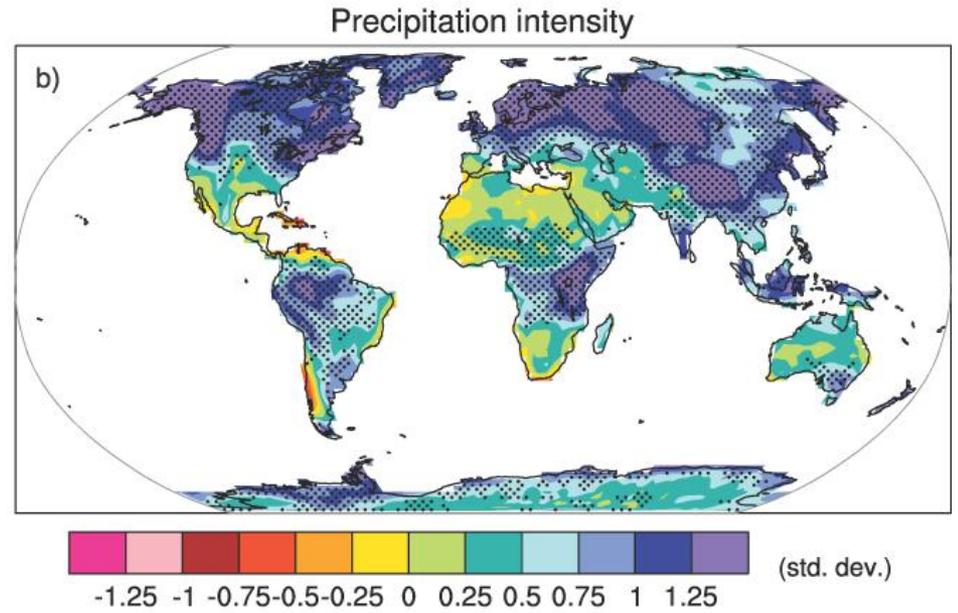
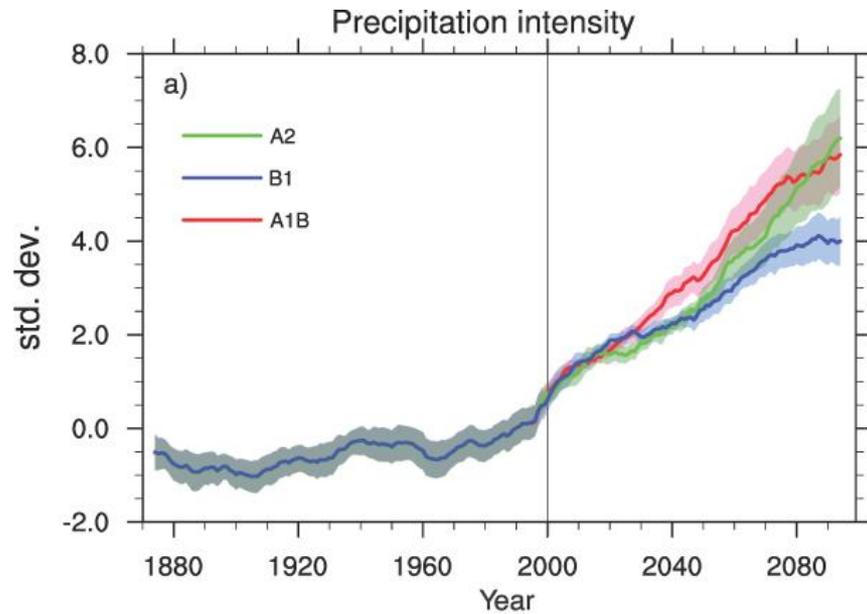
Projected Sea-Ice Extent



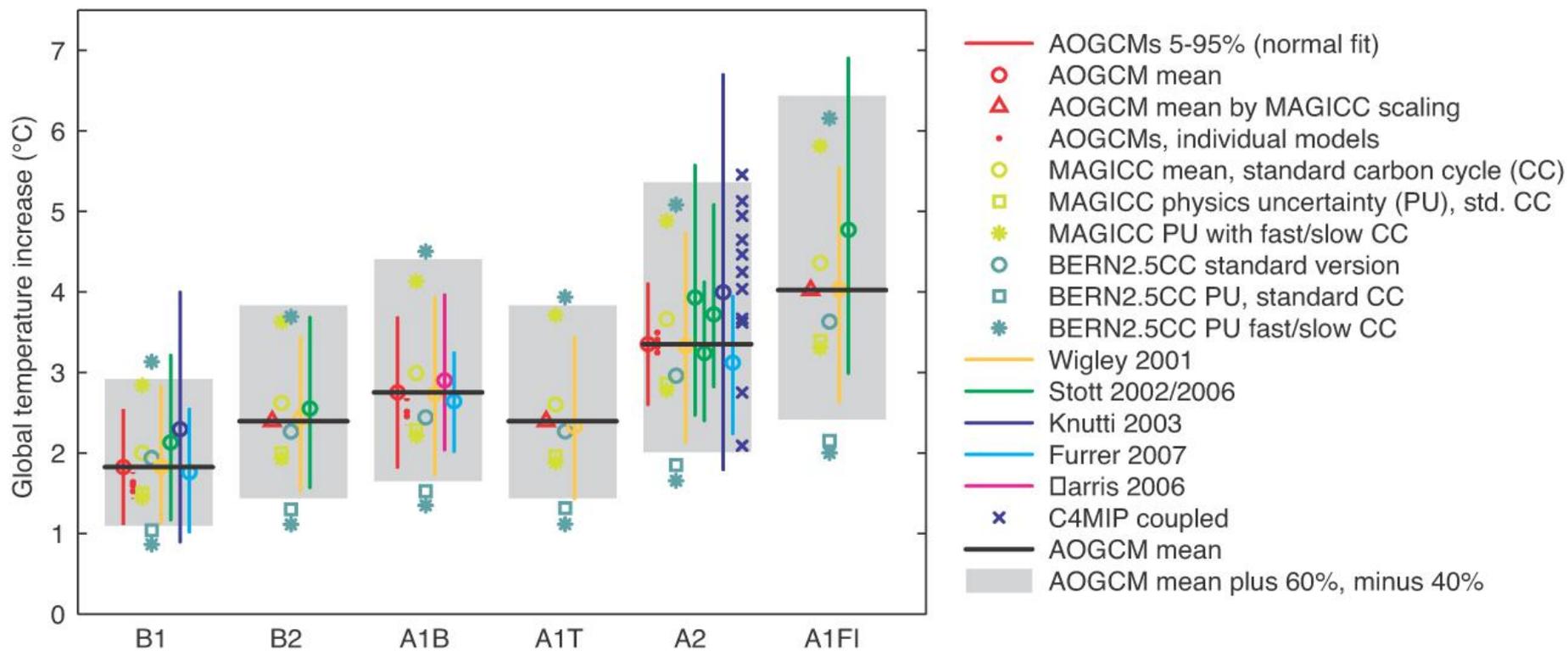
Extremes: Projected Frost Days, Heat Waves, Growing Season Changes



Extremes: Projected Precipitation Intensity, Dry Period Changes

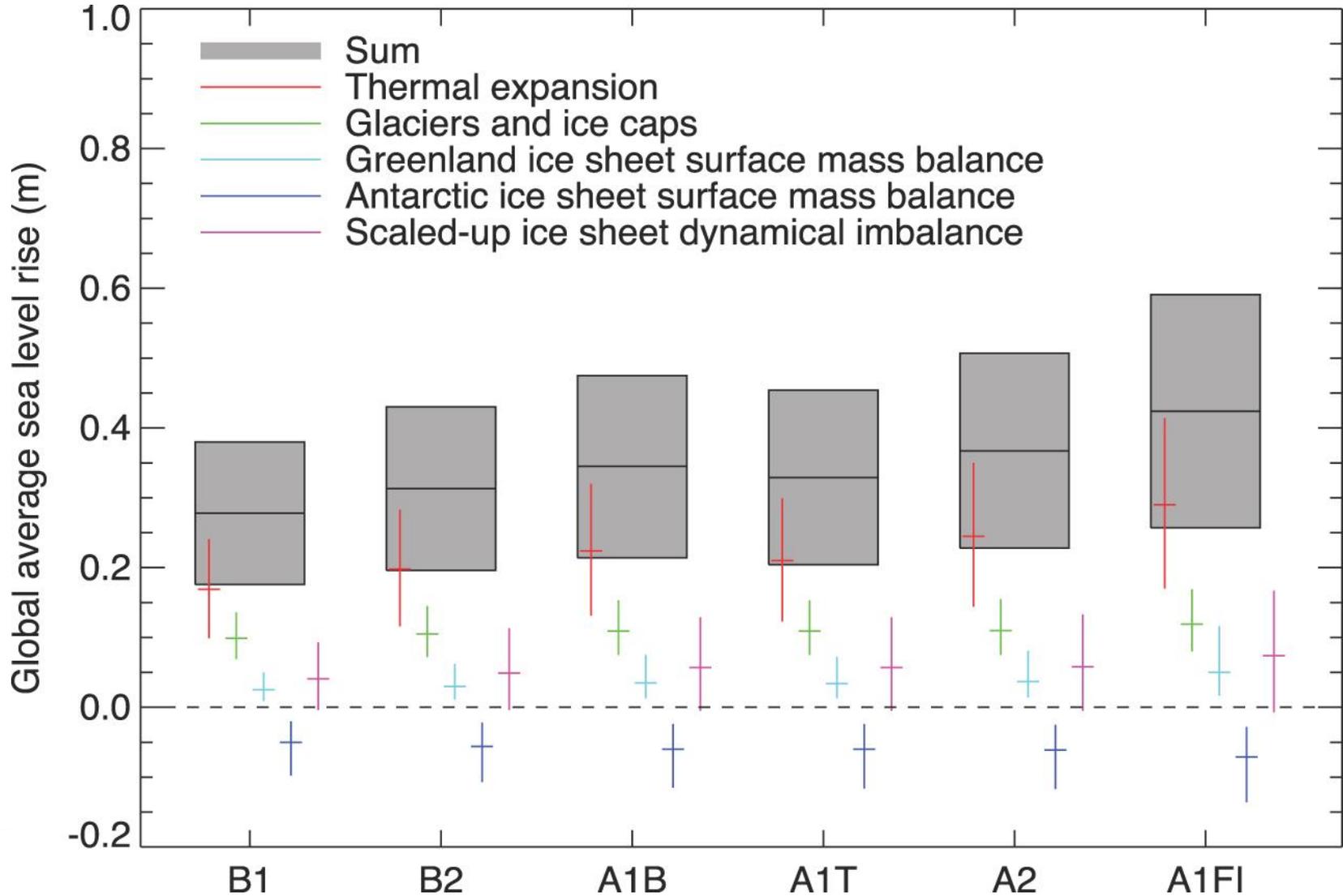


Projections and Uncertainties for Global Mean Temperature Increase by 2090-2099



Projected Sea-Level Changes for 2100,

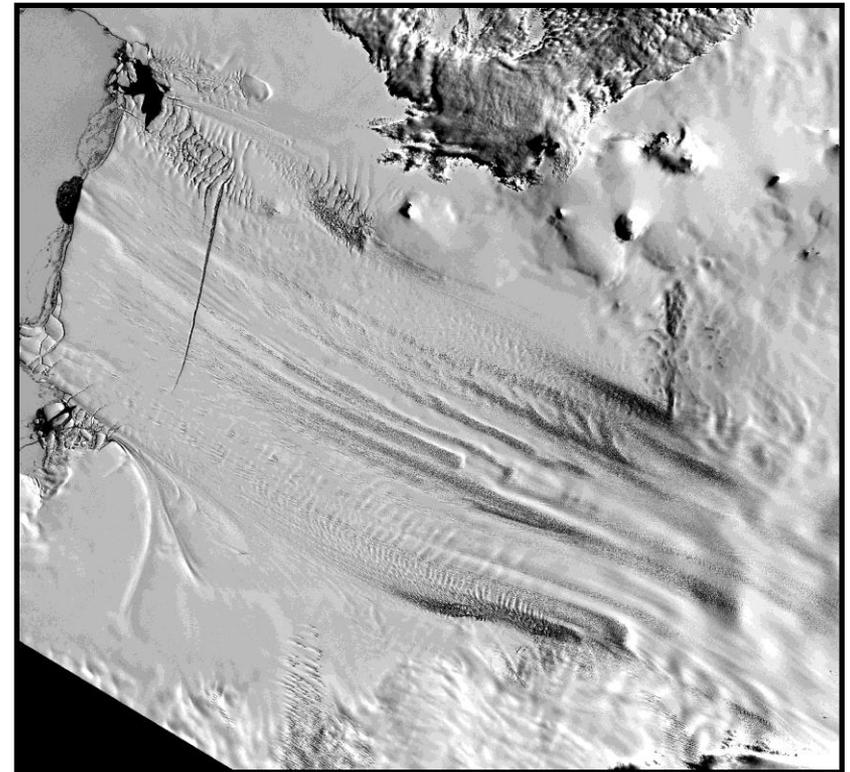
Excluding future rapid dynamic response of the Ice Sheets



New Evidence indicates a Rapid Dynamic Response of the Ice Sheets to Climate Change May be Possible

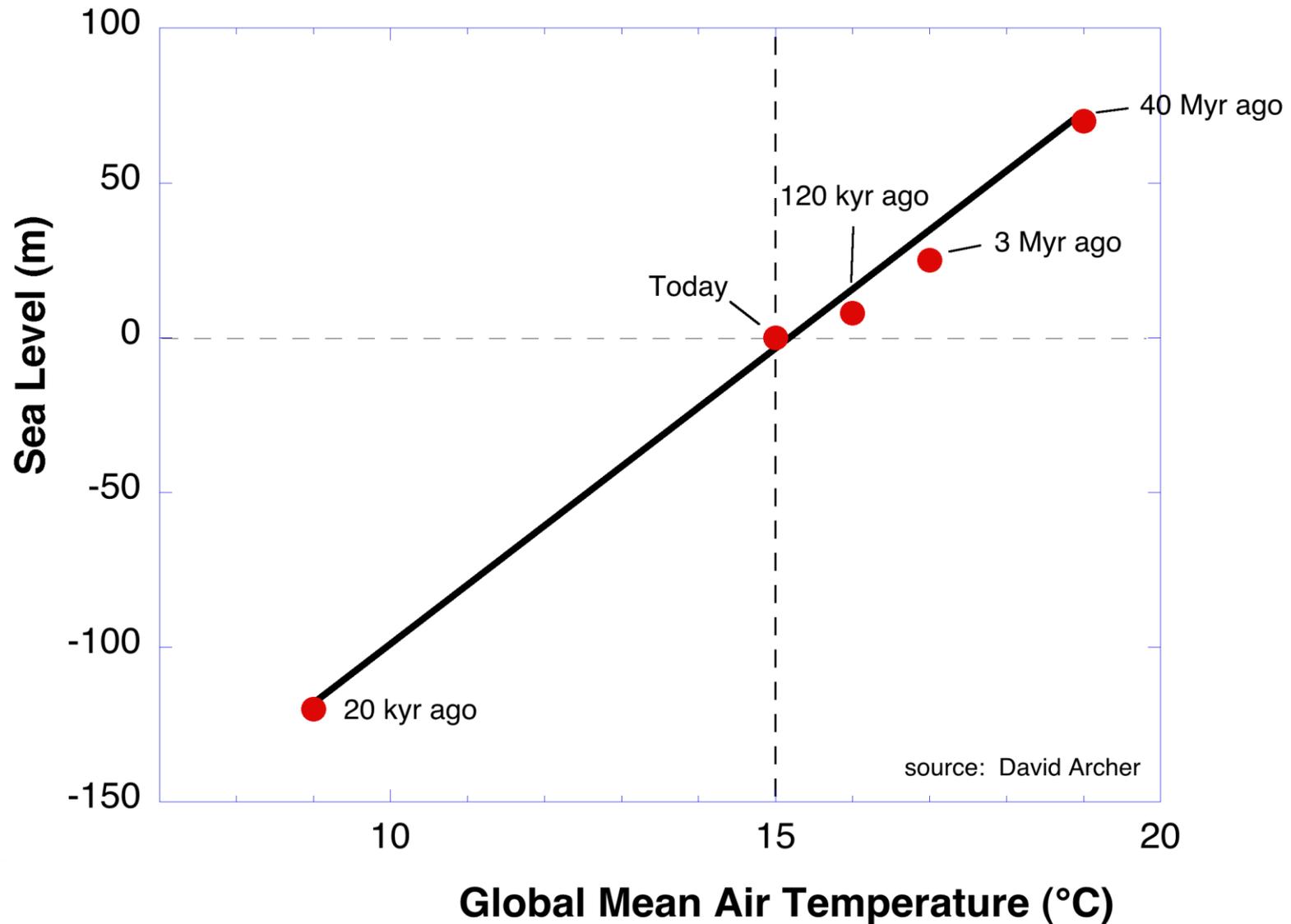


Disintegration of Larsen B Ice Shelf, 2002

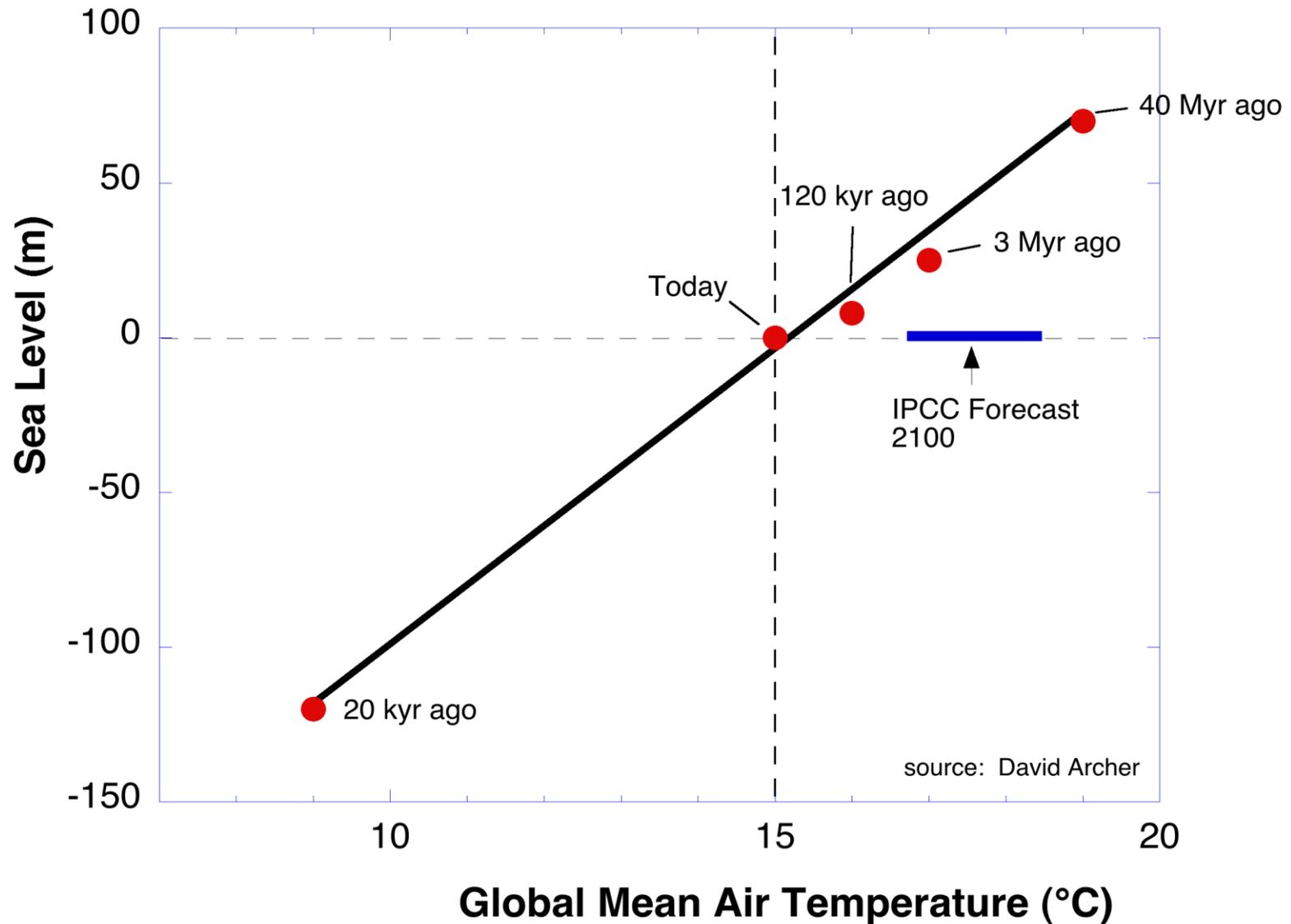


Pine Island Glacier, West Antarctica

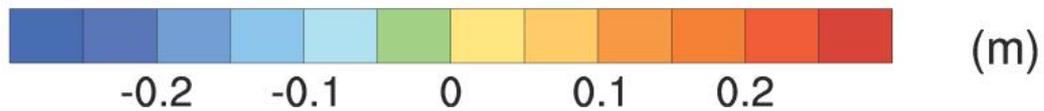
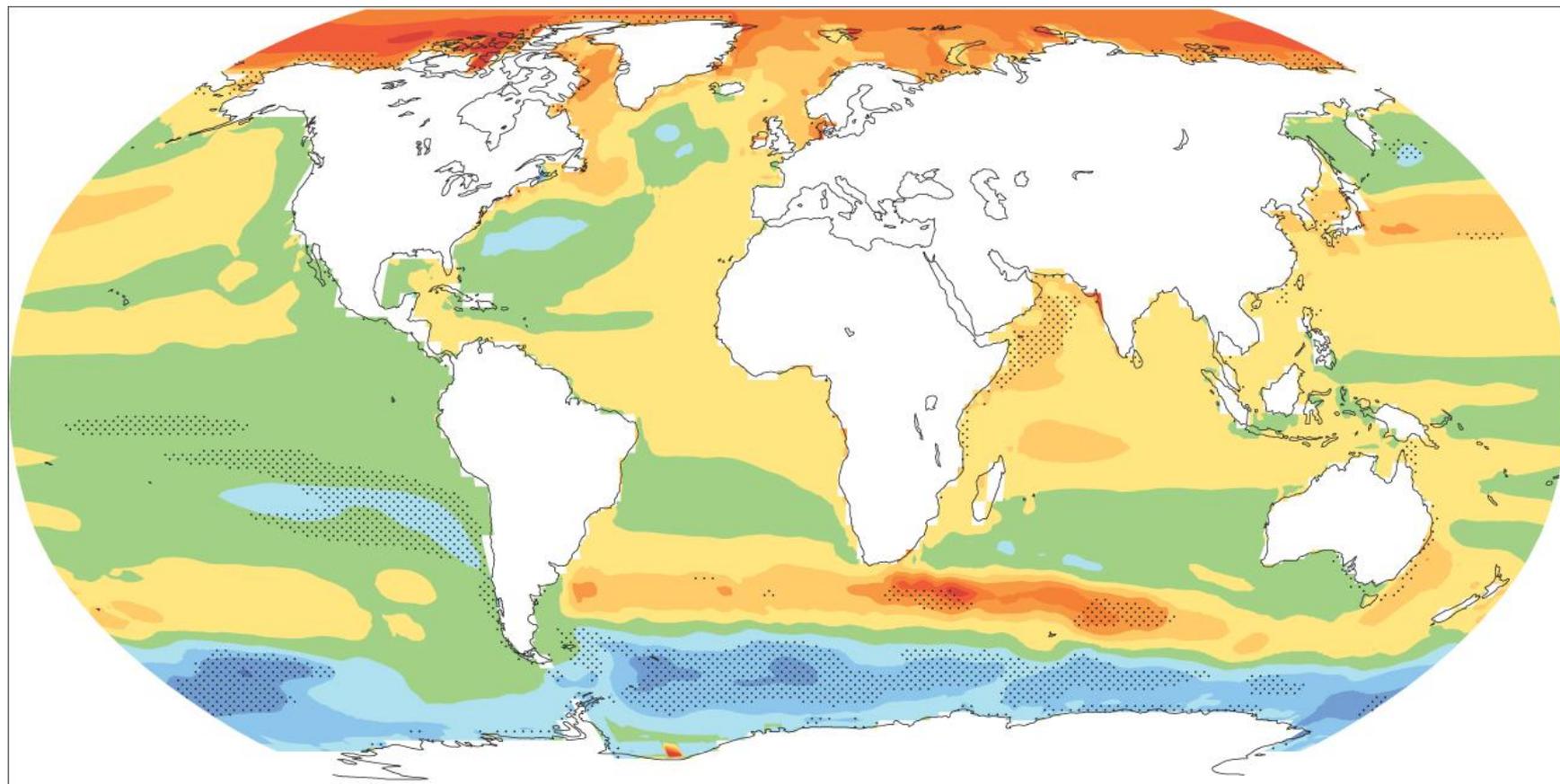
How has Sea-Level Responded in the Past to the Projected 21st Century Temperatures?



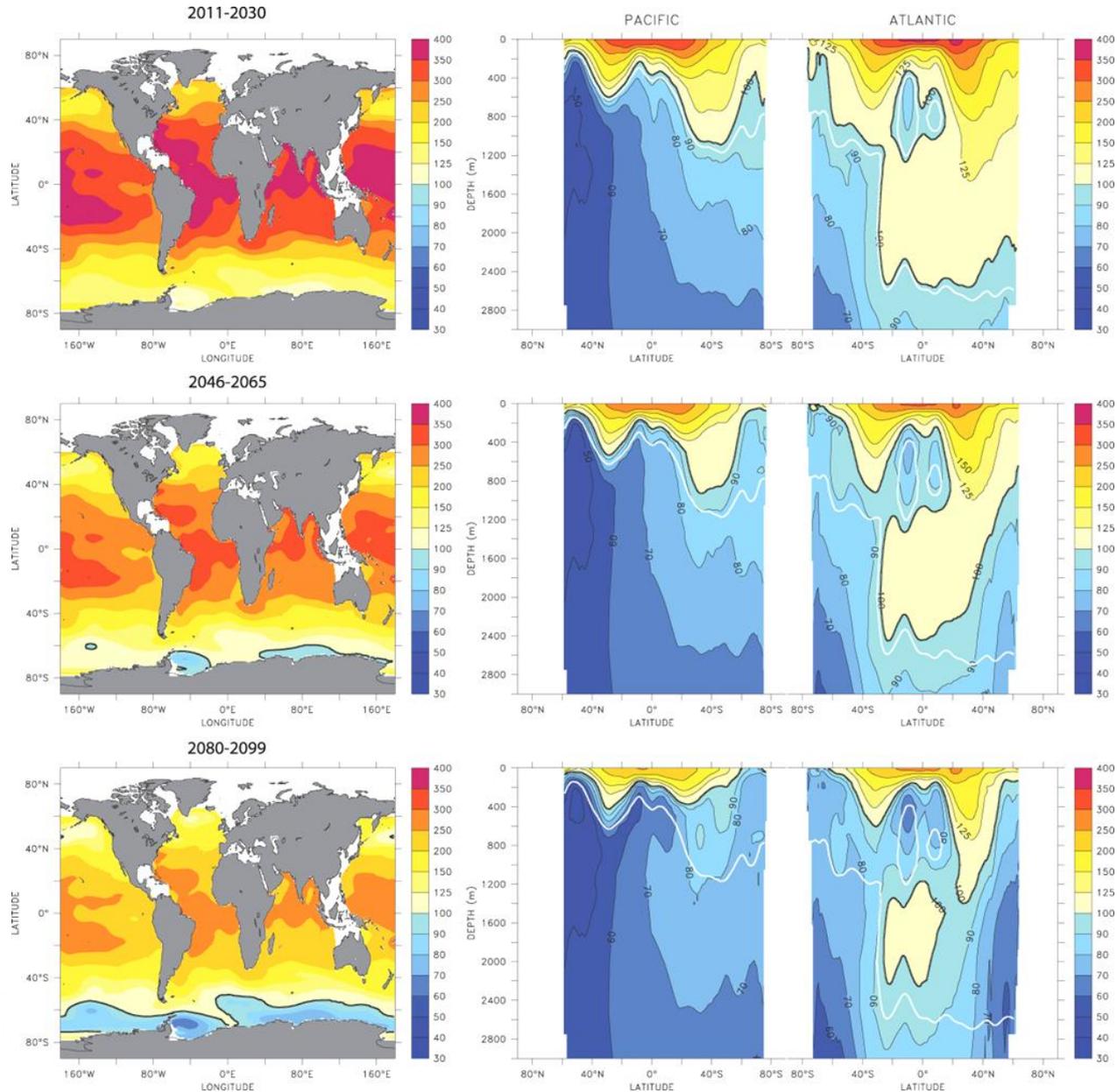
How has Sea-Level Responded in the Past to the Projected 21st Century Temperatures?



Sea-Level Rise **Won't be the Same Everywhere**



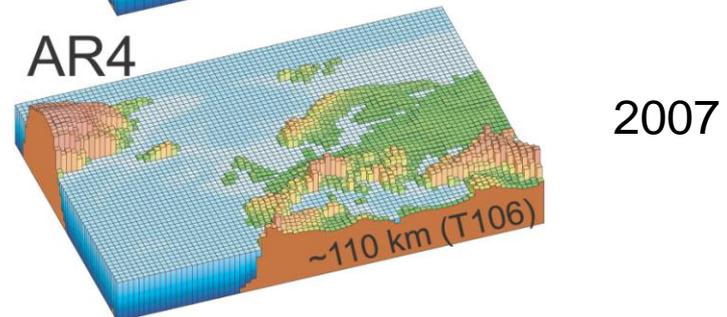
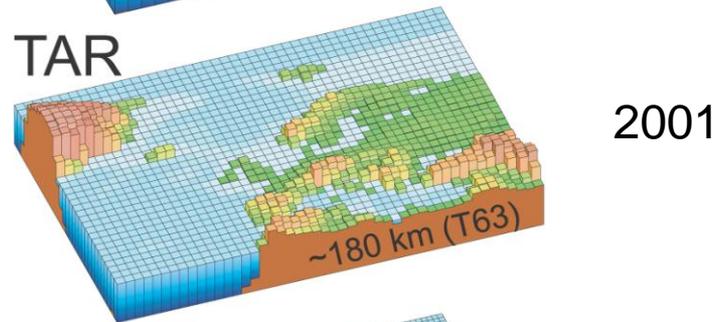
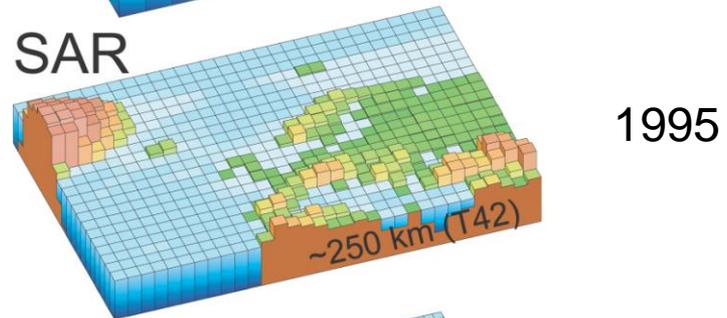
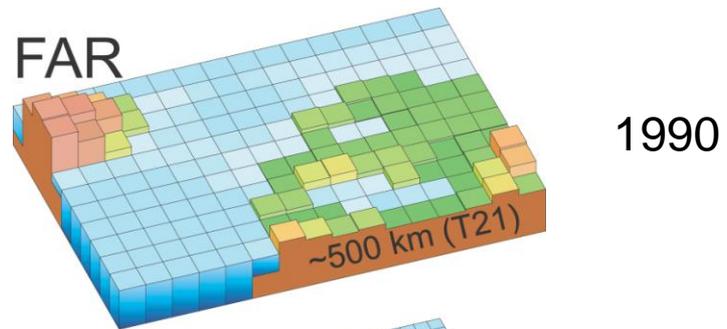
Changes in Ocean Acidification Due to Increasing Atmospheric CO₂





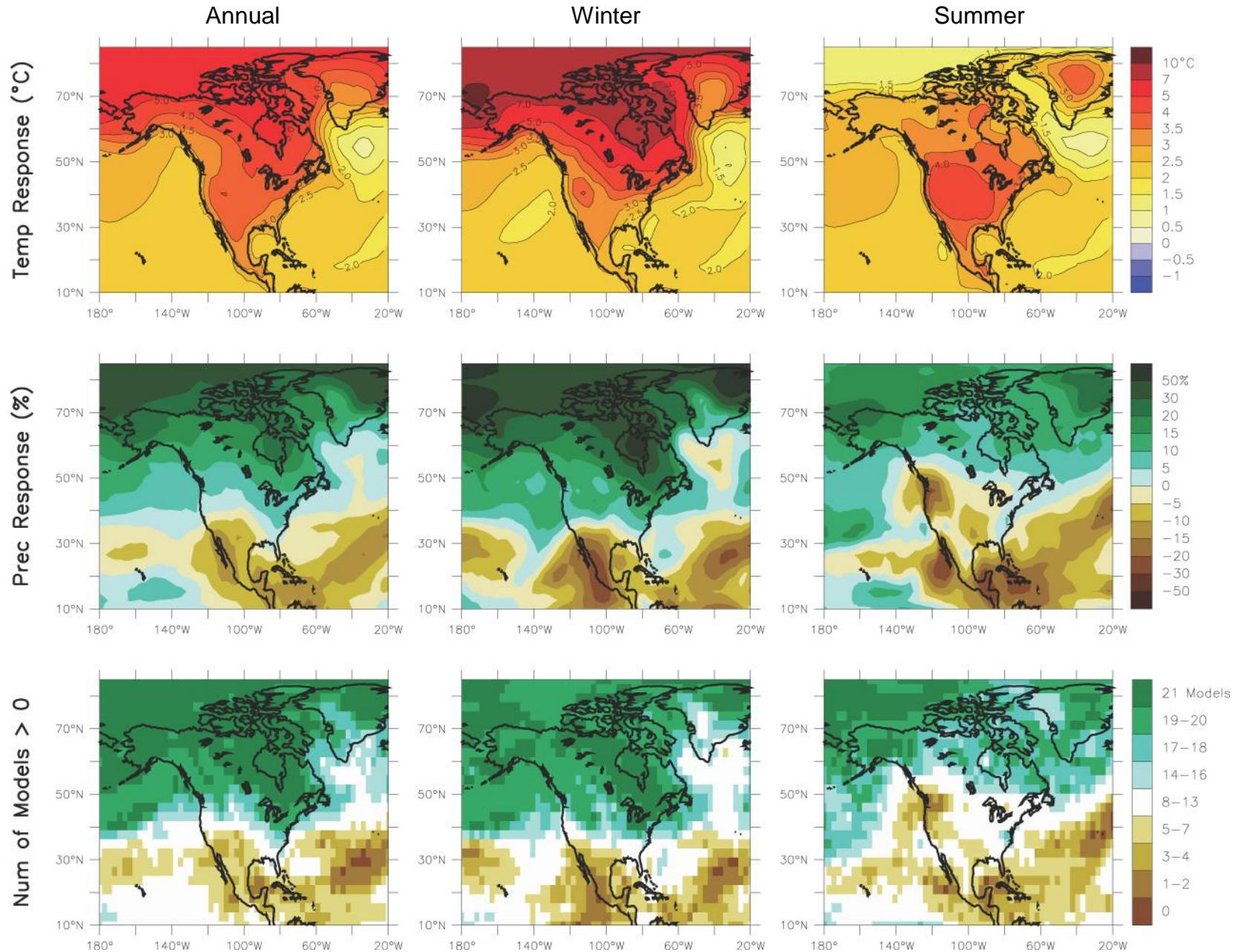
**3) Regional Climate Projections
for the 21st Century**

Evolution of AOGCM Resolution



The horizontal scale at which AOGCMs provide useful information is about 4-5 times the horizontal resolution.

Temperature and Precipitation Changes, North America

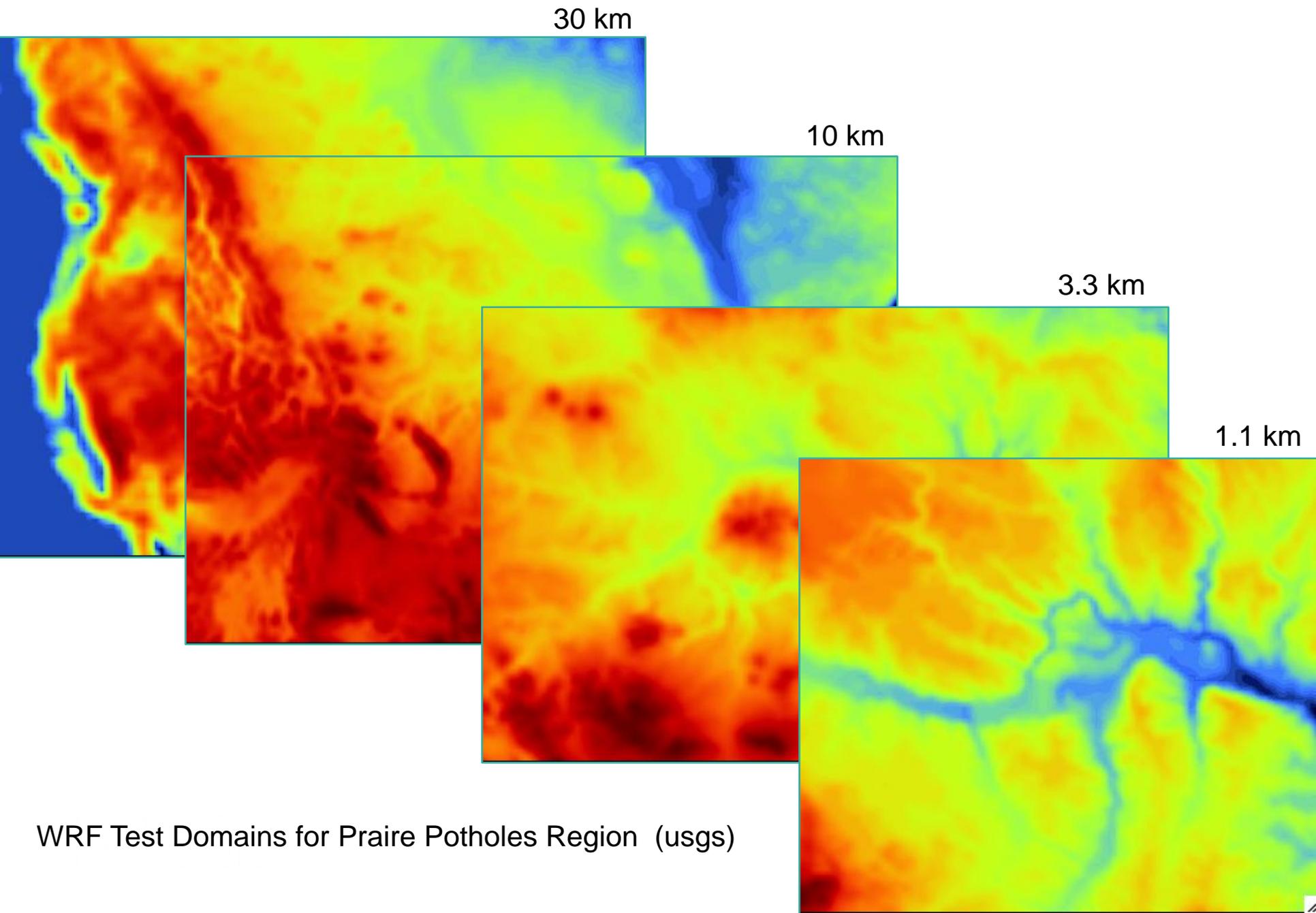


Other Regional/Local Results:

- Compared to the previous figure, **warming is likely to be larger in winter over elevated areas** due to snow-albedo feedback which is poorly simulated by AOGCMs.
- Compared to the previous figure, **precipitation is likely to be greater on the windward slopes of mountains** in the west with orographic precipitation.
- The northward displacement and strengthening of the **westerly flow will be enhanced during the autumn and winter**.
- The East Pacific subtropical high will intensify during the summer, particularly off the coast of California and Baja California (with **possible impacts on the North Pacific eastern boundary current, offshore Ekman transport, marine stratus clouds, North American Monsoon System**).



Downscaling to Achieve Higher Resolution

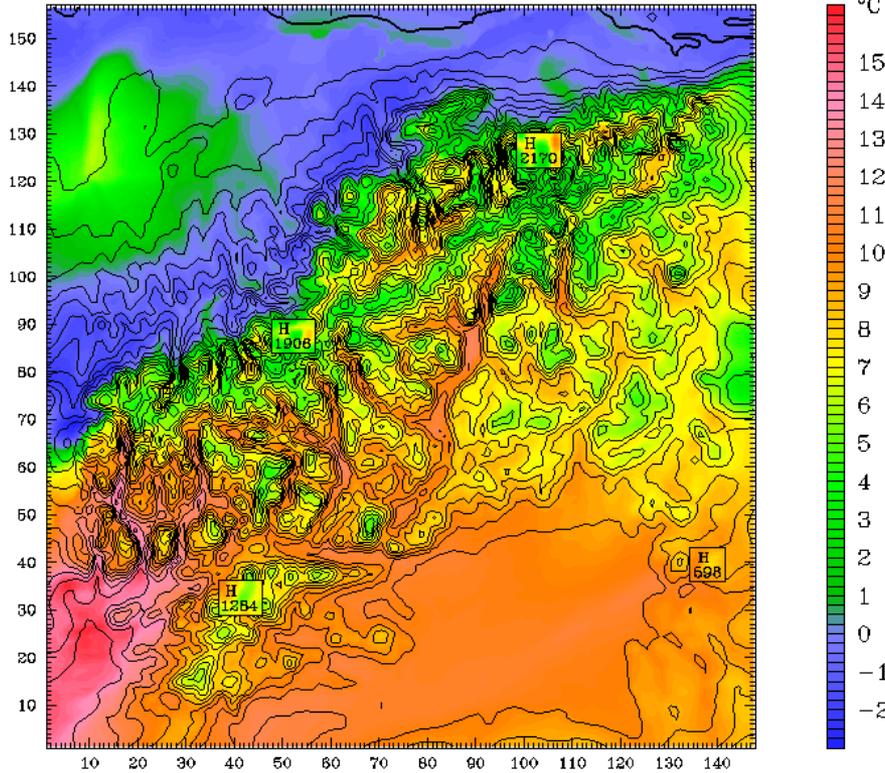


WRF Test Domains for Praire Potholes Region (usgs)

Dynamical Downscaling, Arctic NWR – 3 km Resolution

Temperature

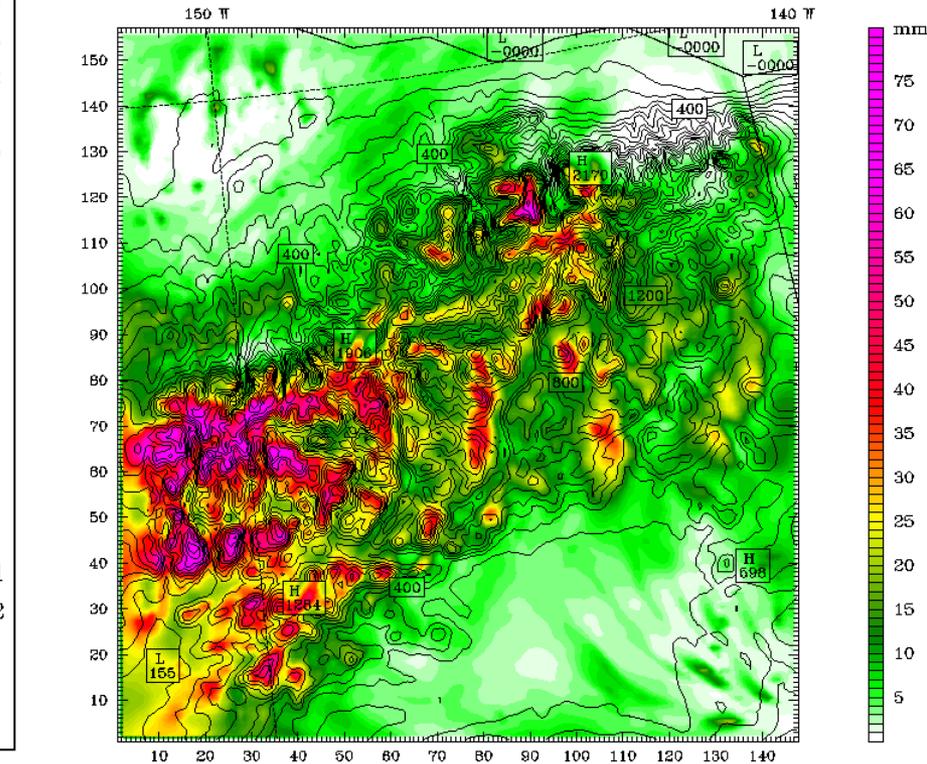
WRF nest, 3-km resolution (Western Arctic AK) Init: 1800 UTC Wed 07 Jun 06
 Fcst: 229.00 h Valid: 0700 UTC Sat 17 Jun 06 (2300 LDT Fri 16 Jun 06)
 Surface air temperature
 Terrain height AMSL
 Terrain height AMSL



Model Info: V2.2 M No Cu YSU PBL WSM 6class Ther-Diff 3.0 km, 27 levels, 17 sec
 LW: RRTM SW: Dudhia DIFF: simple KM: 2D Smagor

Precipitation

Model Nest – 3 km Resolution Init: 1800 UTC Wed 07 Jun 06
 Fcst: 320.00 h Valid: 0200 UTC Wed 21 Jun 06 (1800 LDT Tue 20 Jun 06)
 Total precip. since h 0
 Rain height AMSL

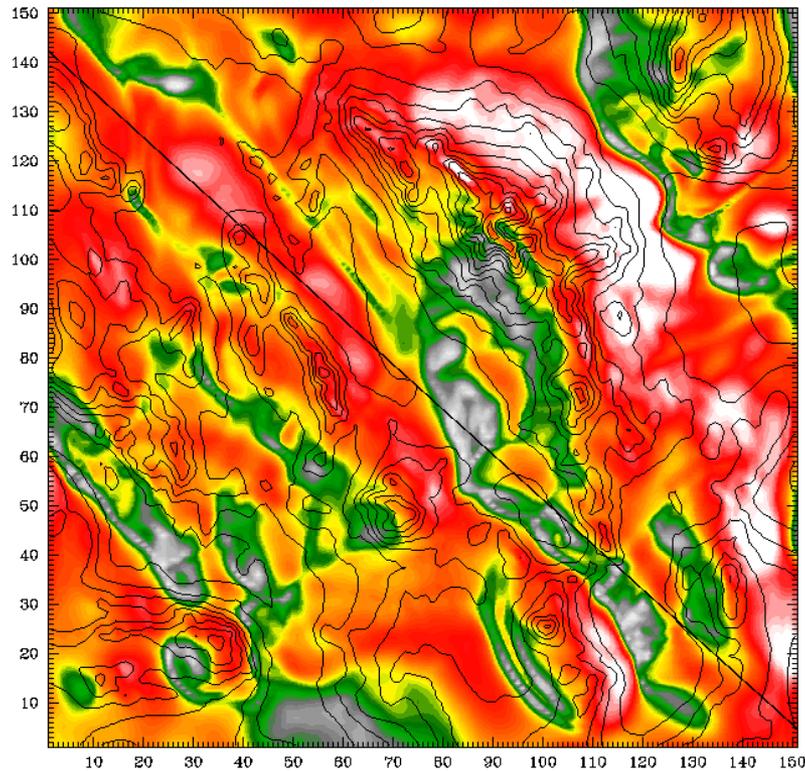


CONTOURS: UNITS=m LOW= 0.0000 HIGH= 2100.0 INTERVAL= 100.00
 Model Info: V2.2 M No Cu YSU PBL WSM 6class Ther-Diff 3.0 km, 27 levels, 17 sec
 LW: RRTM SW: Dudhia DIFF: simple KM: 2D Smagor

Dynamical Downscaling, Mojave Desert – 1 km Resolution

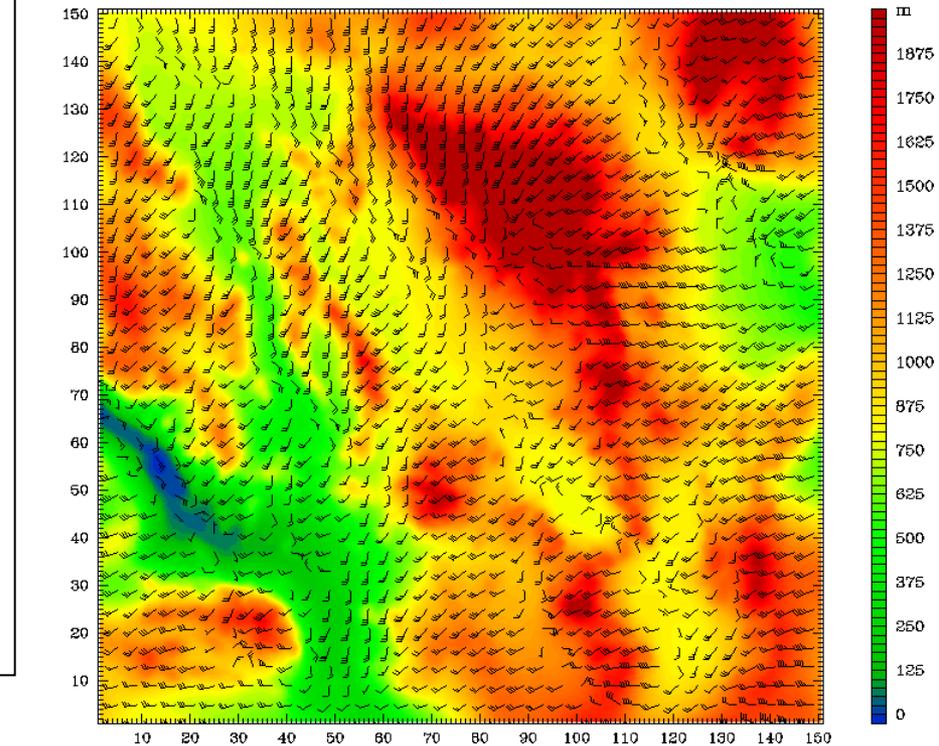
Wind Speed

WRF 1-km Resolution (Mojave) Init: 1800 UTC Sat 21 Mar 09
Fest: 14.00 h Valid: 0800 UTC Sun 22 Mar 09 (0000 PST Sun 22 Mar 09)
Horizontal wind speed at k-index = 27
Terrain height AMSL



Wind Direction

WRF 1-km resolution (Mojave) Init: 1800 UTC Sat 21 Mar 09
Fest: 14.00 h Valid: 0800 UTC Sun 22 Mar 09 (0000 PST Sun 22 Mar 09)
Terrain height AMSL
Horizontal wind vectors at k-index = 27



BARB VECTORS: FULL BARB = 5 m s^{-1}
Model Info: V3.1.1 No Cu YSU PBL WSM 3class Noah LSM 1.0 km, 27 levels, 6 sec
LW: RRTM SW: Dudhia DIFF: simple KM: 2D Smagor