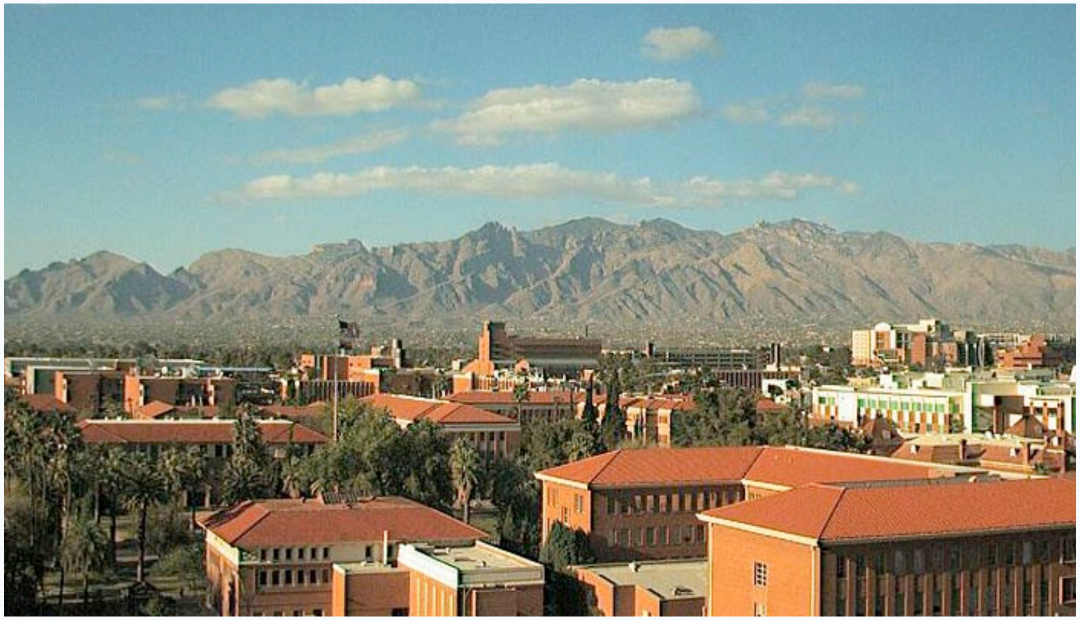
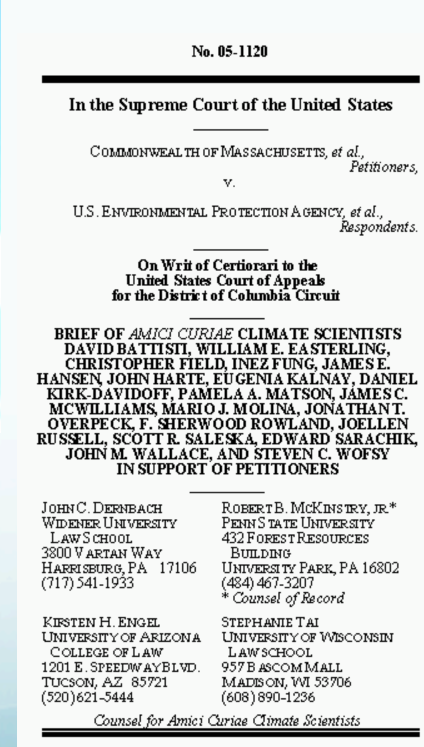
Southwest Climate:
The Westerly Winds and Climate Model Projections



Prof. Joellen L. Russell

Dept. of Geosciences, University of Arizona

SANTA FE INSTITUTE



No. 05-1120

In the Supreme Court of the United States

COMMONWEALTH OF MASSACHUSETTS, *et al.*,
Petitioners,
v.
U.S. ENVIRONMENTAL PROTECTION AGENCY, *et al.*,
Respondents.

On Writ of Certiorari to the United States Court of Appeals for the District of Columbia Circuit

BRIEF OF *AMICI CURIAE* CLIMATE SCIENTISTS DAVID BATTISTI, WILLIAM E. EASTERLING, CHRISTOPHER FIELD, INEZ FUNG, JAMES E. HANSEN, JOHN HARTE, EUGENIA KALNAY, DANIEL KIRK-DAVIDOFF, PAMELA A. MATSON, JAMES C. MCWILLIAMS, MARIO J. MOLINA, JONATHAN T. OVERPECK, F. SHERWOOD ROWLAND, JOELLEN RUSSELL, SCOTT R. SALESKA, EDWARD SARACHIK, JOHN M. WALLACE, AND STEVEN C. WOFSY IN SUPPORT OF PETITIONERS

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Counsel for Amici Curiae Climate Scientists

Climate Model Projections for the Southwest

- Climate change overview - heat and water
- What is a climate model?
- Trends in the Westerlies
- The Westerlies and changes in precipitation patterns
- Conclusions and speculation

Climate Model Projections for the Southwest

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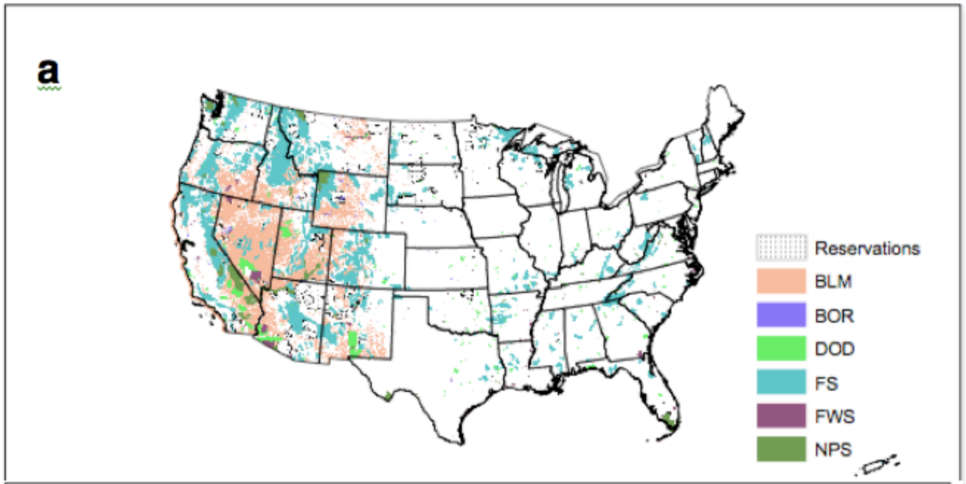
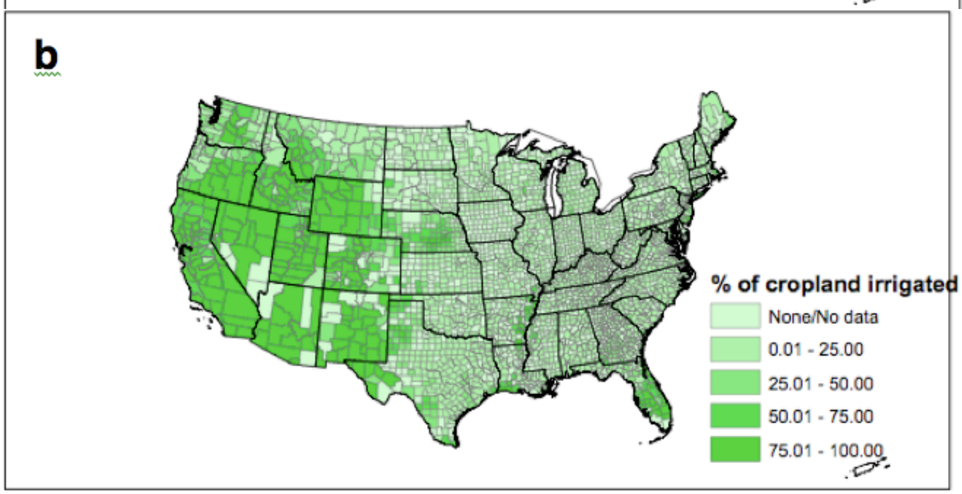
- The Westerlies and changes in precipitation patterns
- Conclusions and speculation

Growing rapidly …. And vulnerable to climate change





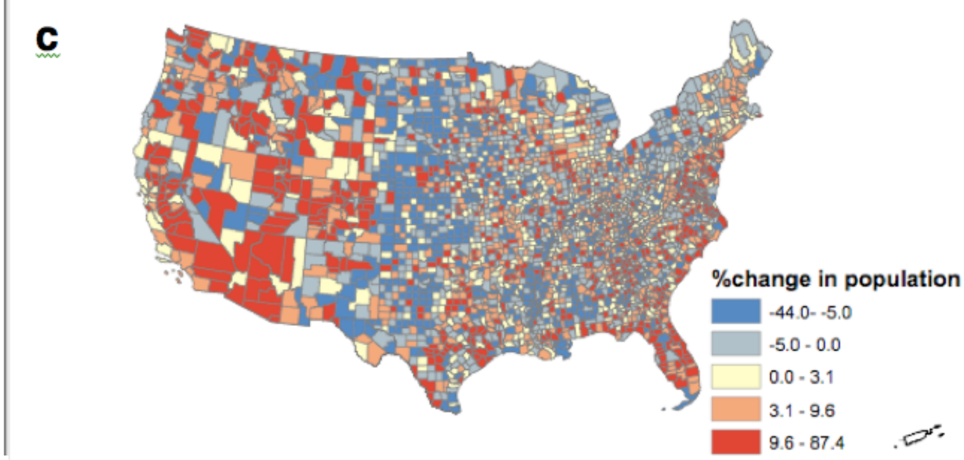
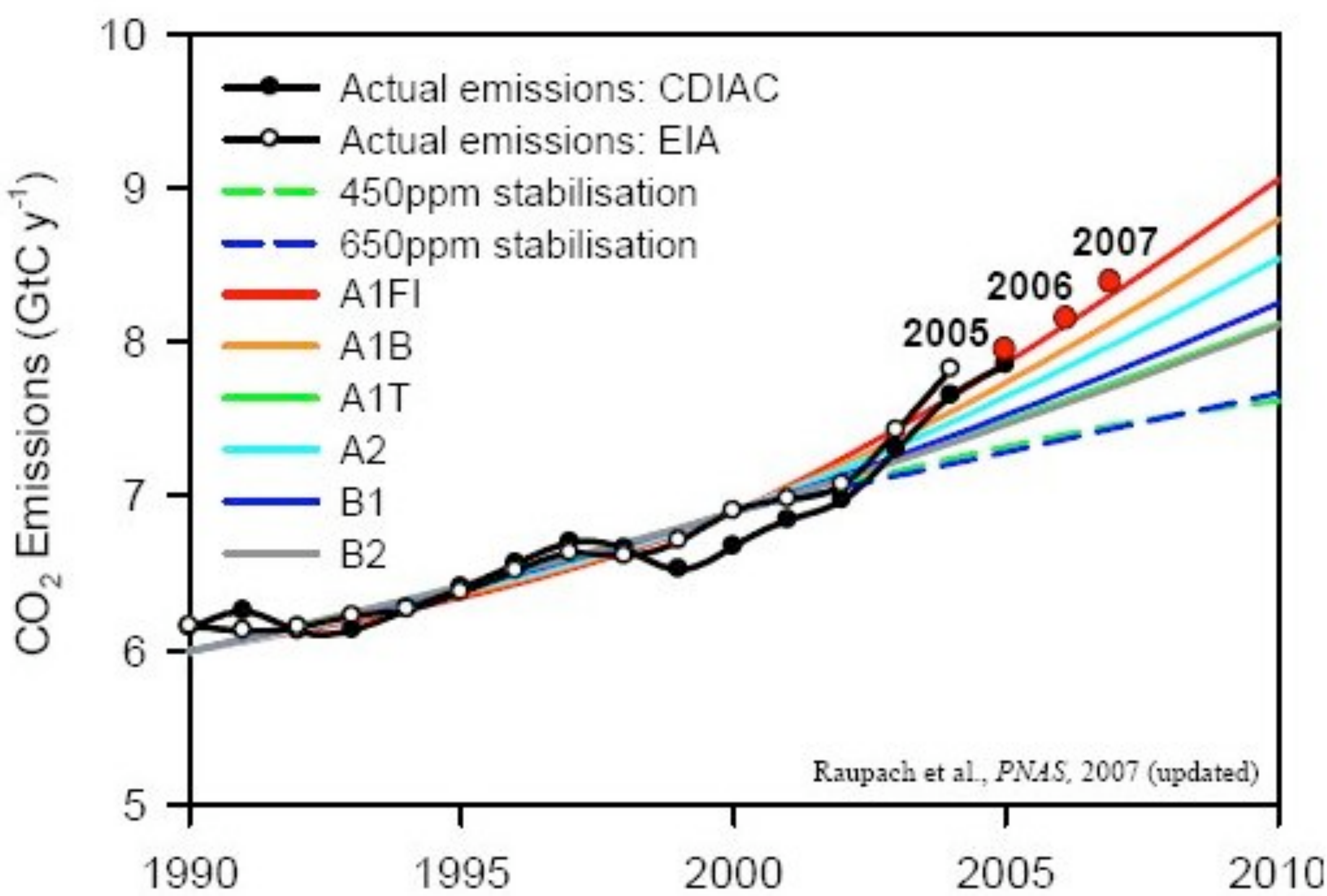


Figure F.2. Maps of federal lands and American Indian reservations (a), the percent of cropland irrigated (b), and the percent change in population from 2000 to 2008 (c). Data from the National Atlas and the U.S. Census Bureau.

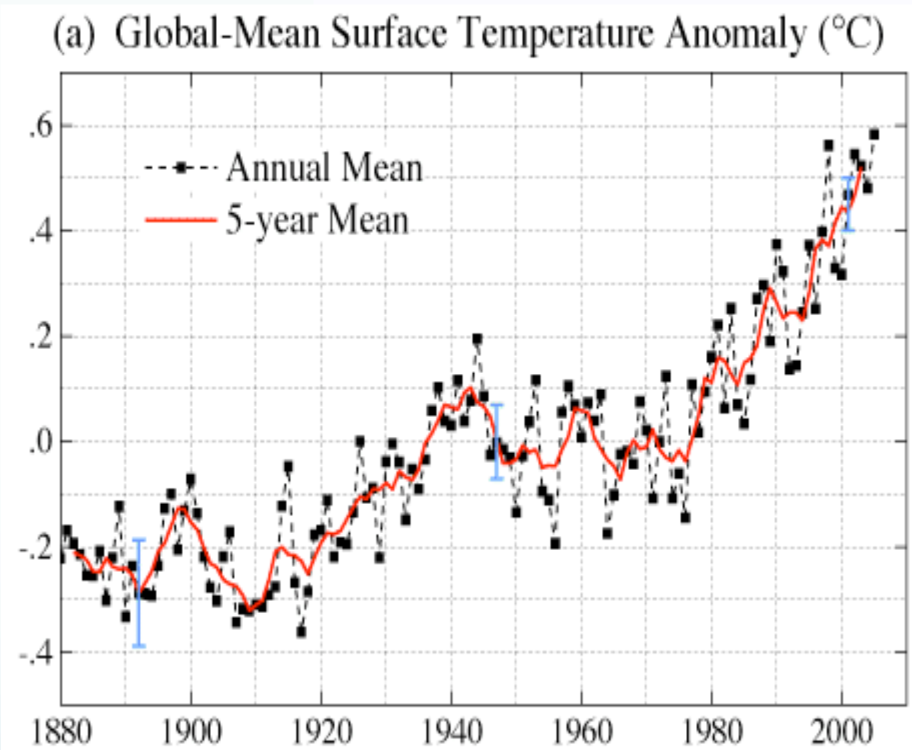
From S. McAfee

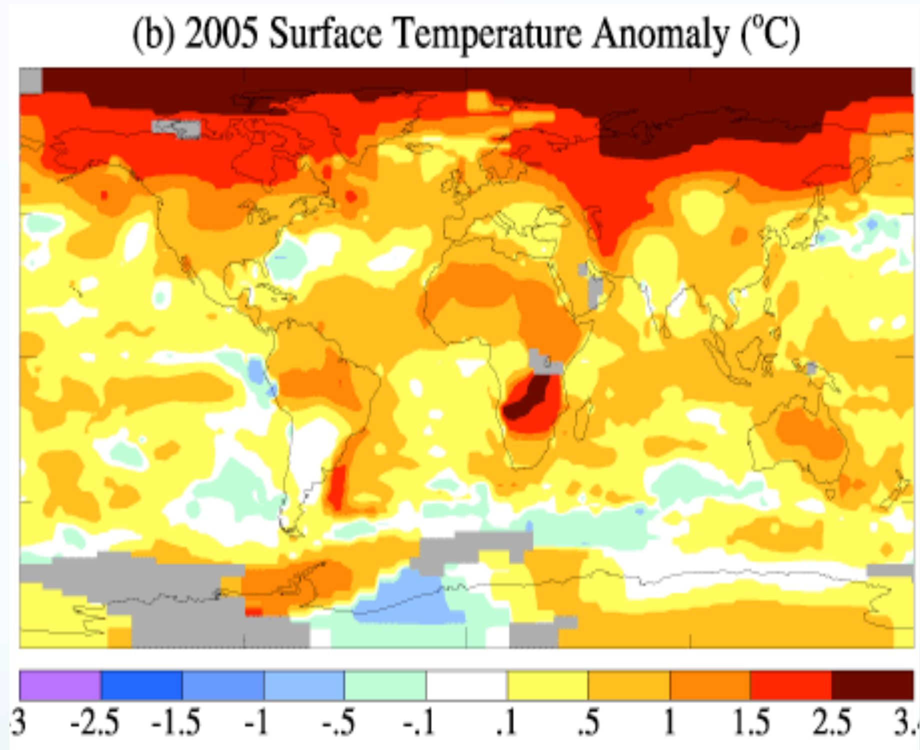
Trajectory of Global Fossil Fuel Emissions



Temperature Records

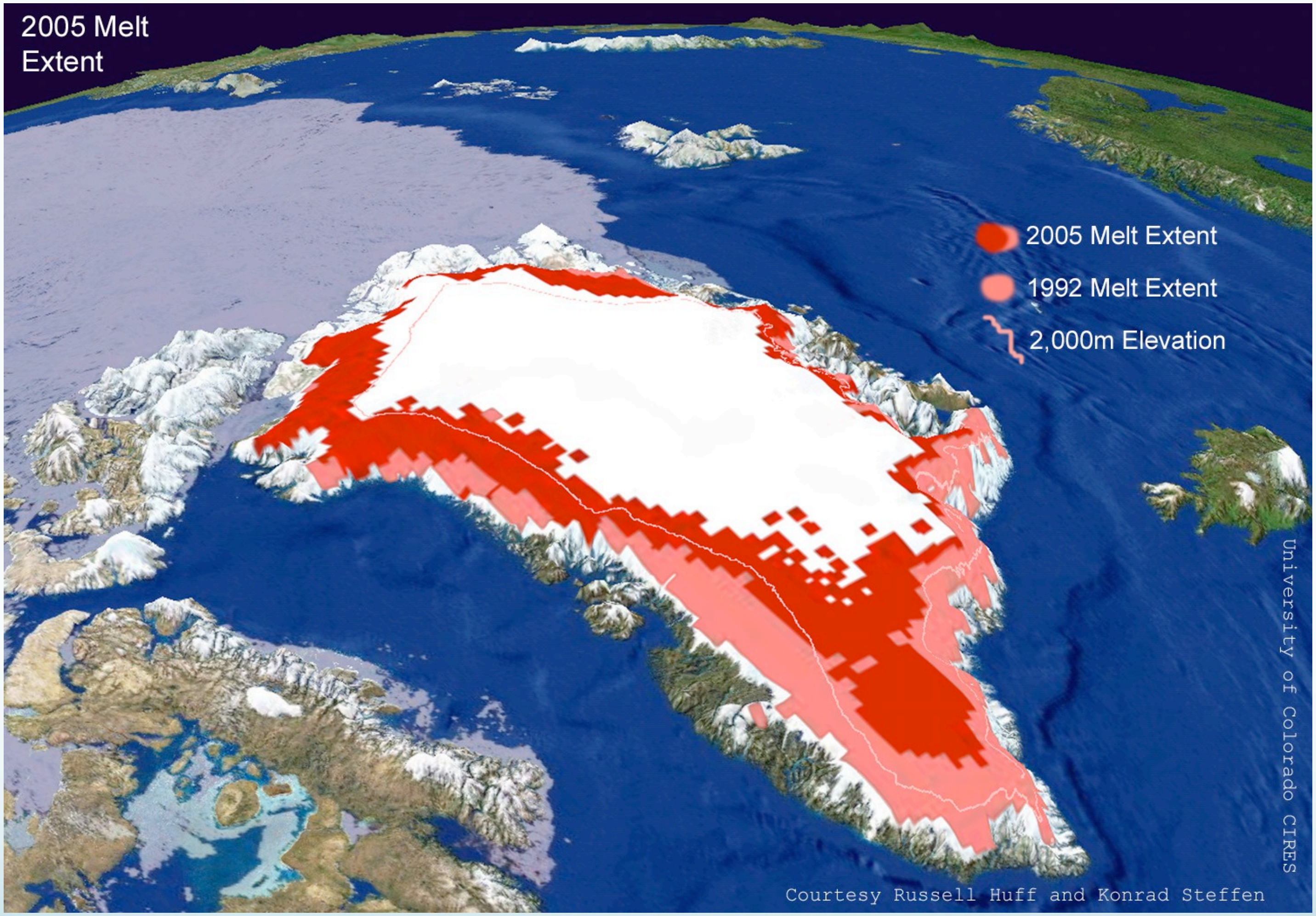
(Deviation from 1951- 1980 mean)





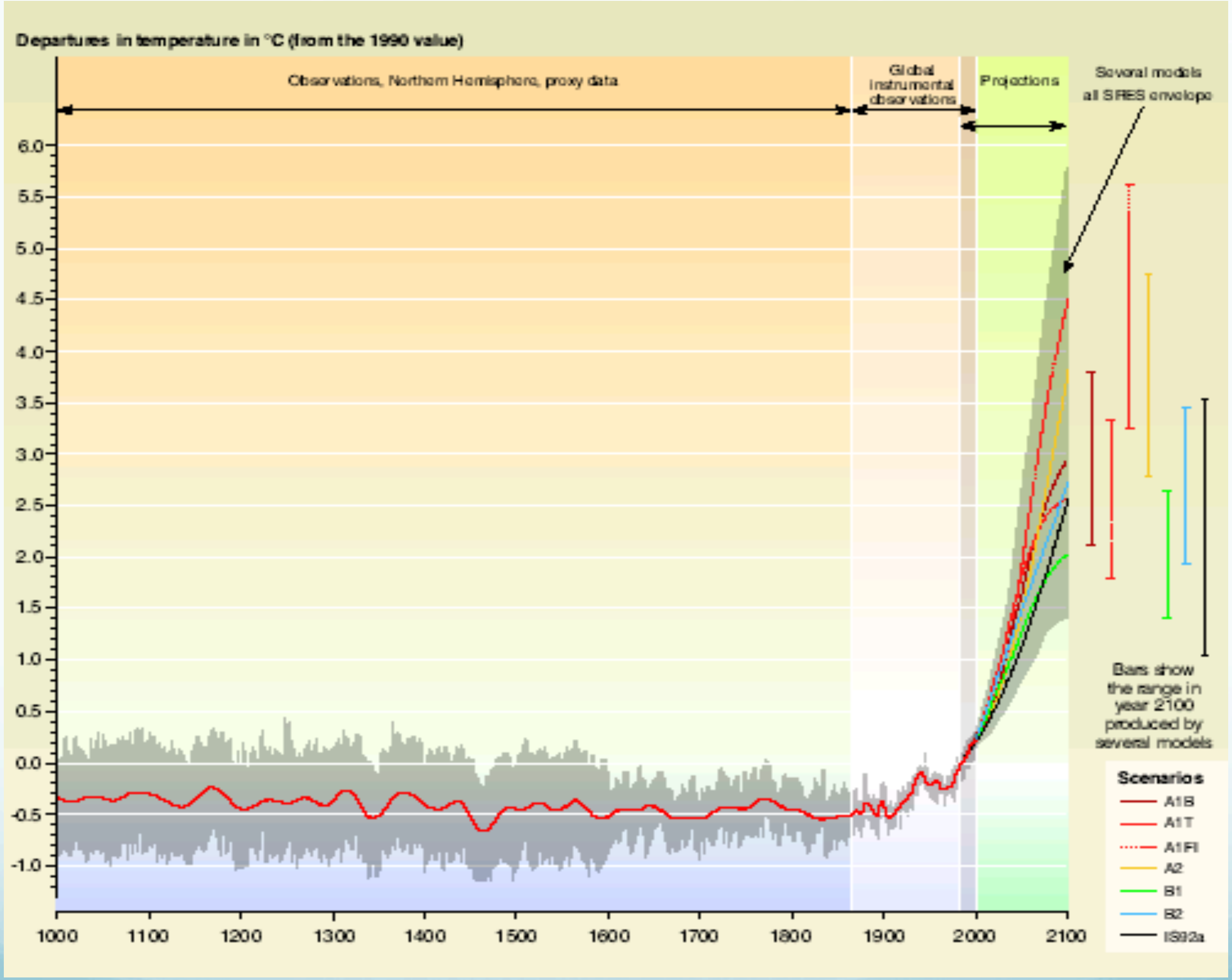
Source: NASA Goddard Institute for Space Studies Surface Temperature Analysis at [*data.giss.nasa.gov/gistemp/*](data.giss.nasa.gov/gistemp/)

Ice Melt in Greenland



Source: http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/

Temperature (Past and Projected)



Source: IPCC, Climate Change, 2001

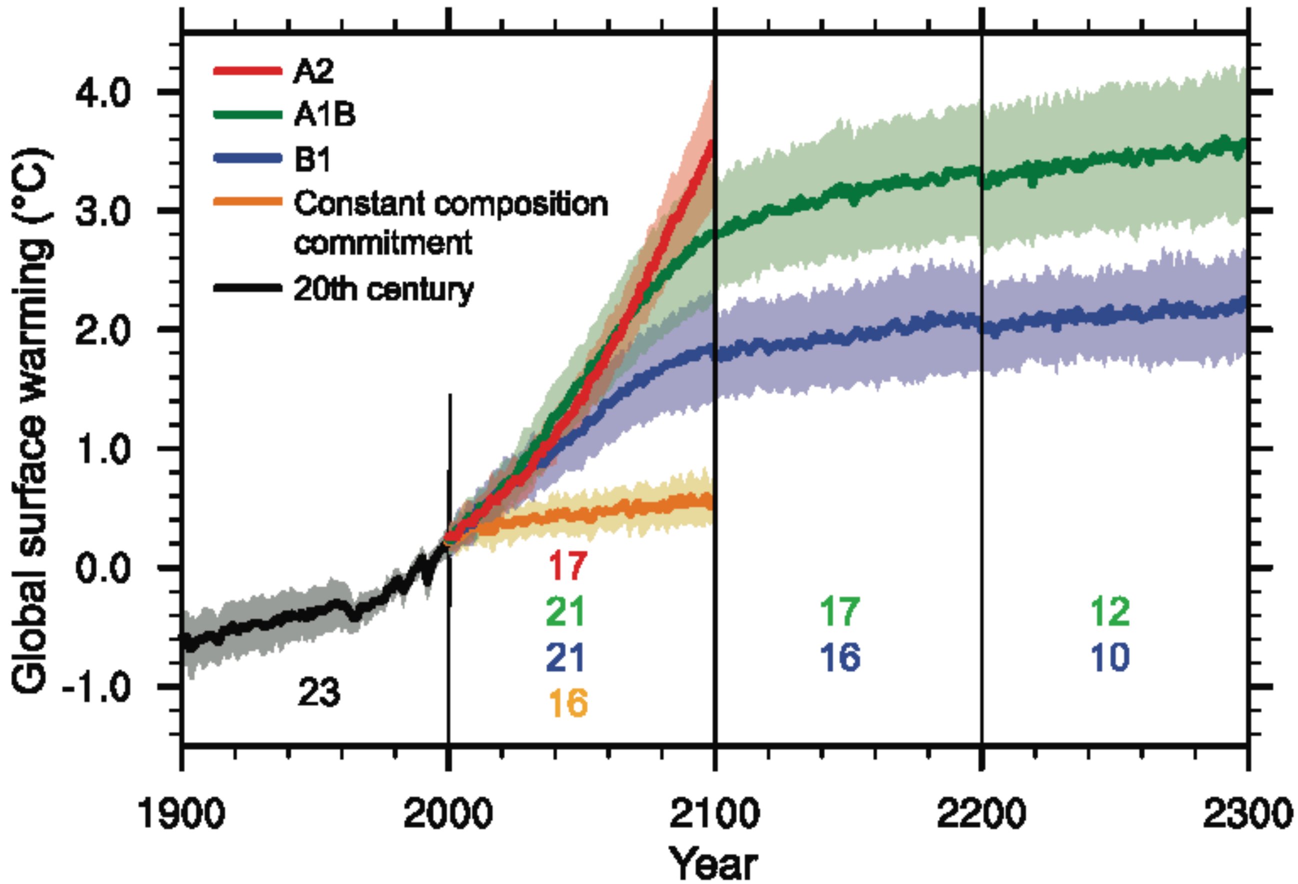
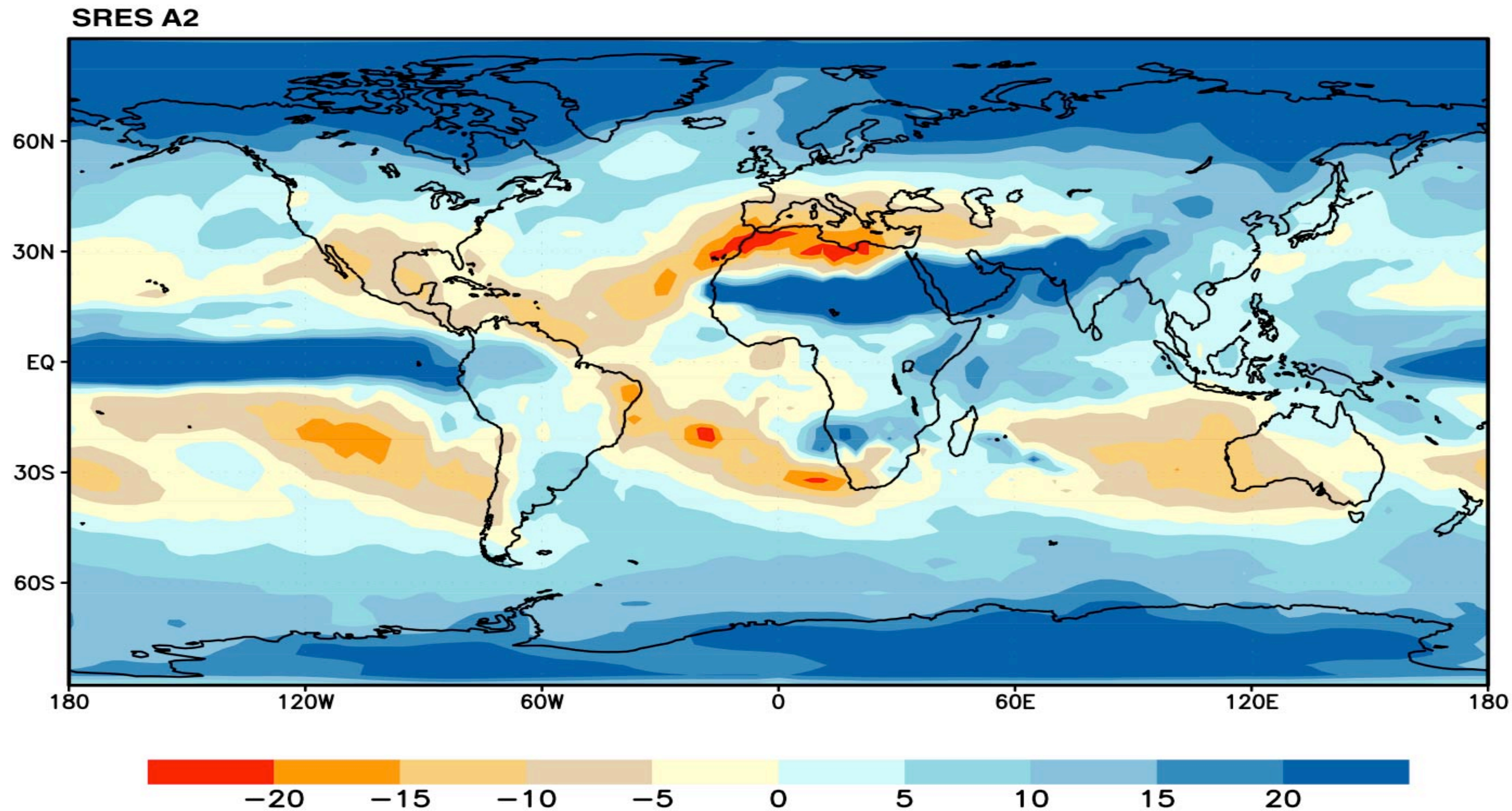


Figure 10.4. *Multi-model means of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th-century simulation. Values beyond 2100 are for the stabilisation scenarios (see Section 10.7). Linear trends from the corresponding control runs have been removed from these time series. Lines show the multi-model means, shading denotes the ±1 standard deviation range of individual model annual means. Discontinuities between different periods have no physical meaning and are caused by the fact that the number of models that have run a given scenario is different for each period and scenario, as indicated by the coloured numbers given for each period and scenario at the bottom of the panel. For the same reason, uncertainty across scenarios should not be interpreted from this figure (see Section 10.5.4.6 for uncertainty estimates).*

Some Areas are Projected to Become Wetter, Others Drier



Annual Mean Precipitation Change: 2071 - 2100 Relative to 1990

Temperature & Precipitation (Projected)

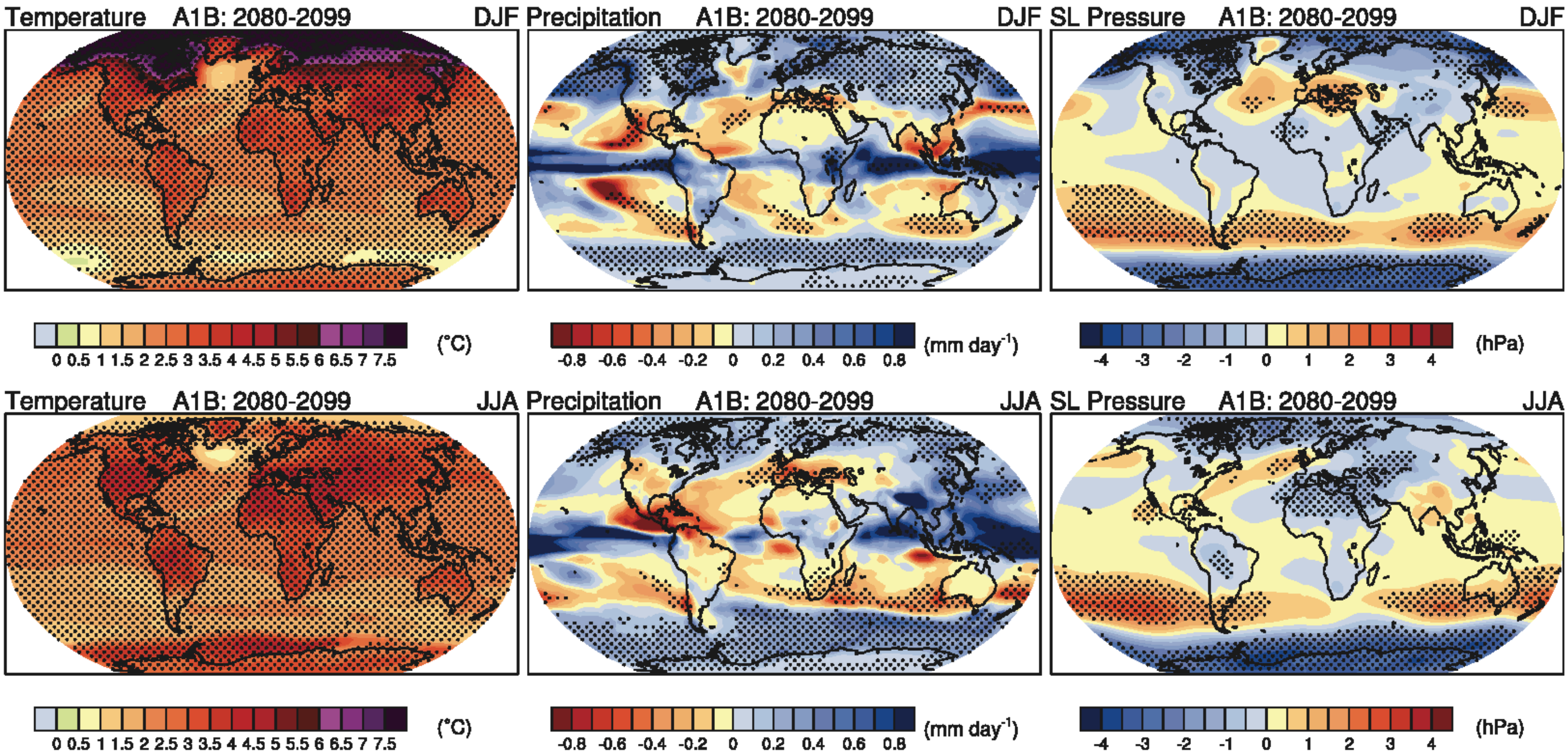
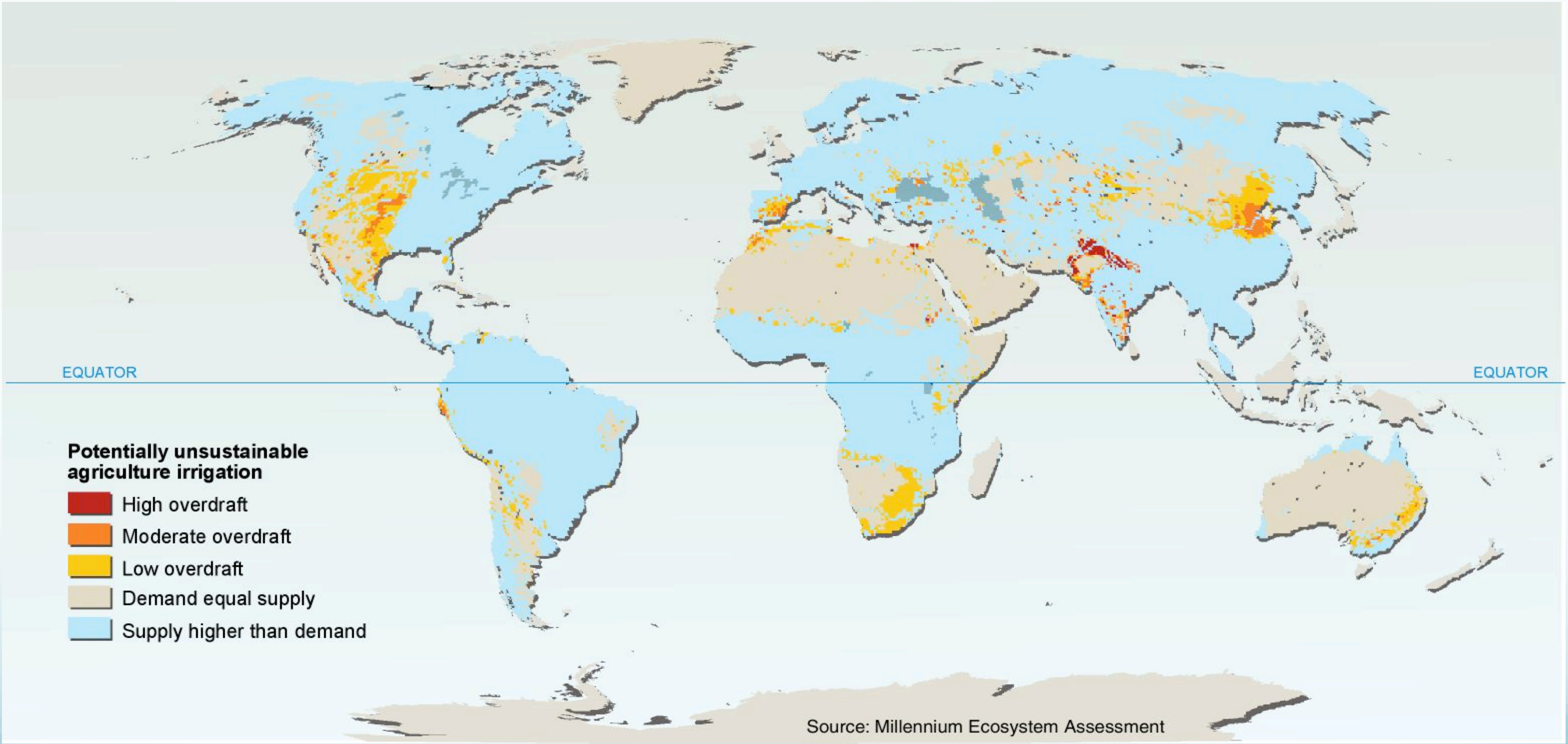


Figure 10.9. *Multi-model mean changes in surface air temperature (°C, left), precipitation (mm day^{-1}, middle) and sea level pressure (hPa, right) for boreal winter (DJF, top) and summer (JJA, bottom). Changes are given for the SRES A1B scenario, for the period 2080 to 2099 relative to 1980 to 1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. Results for individual models can be seen in the Supplementary Material for this chapter.*

Source: IPCC, Climate Change, 2007

Water

- 5 to possibly 25% of global freshwater use exceeds long-term accessible supplies (*low to medium certainty)*
- 15 - 35% of irrigation withdrawals exceed supply rates and are therefore unsustainable (*low to medium certainty)*



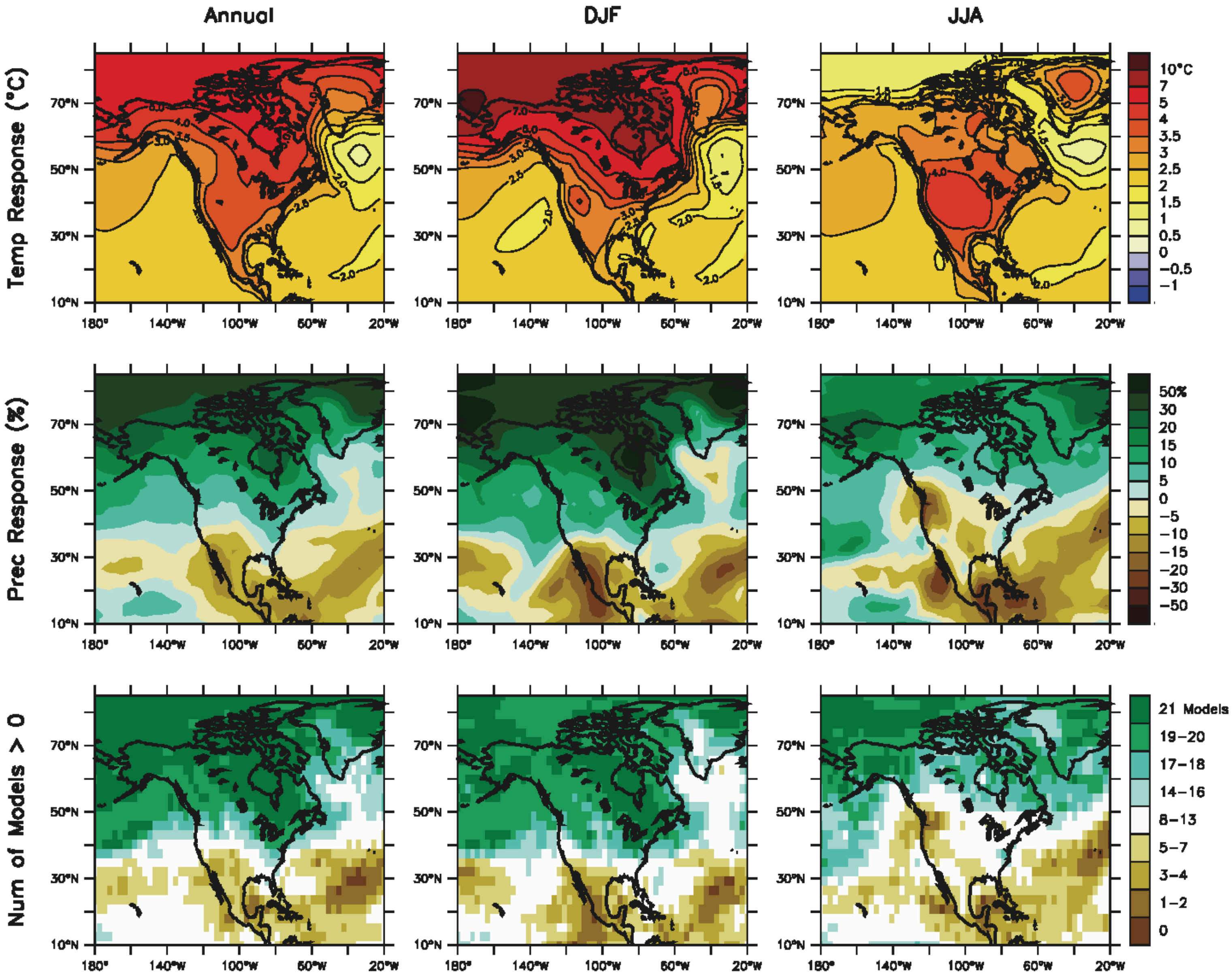
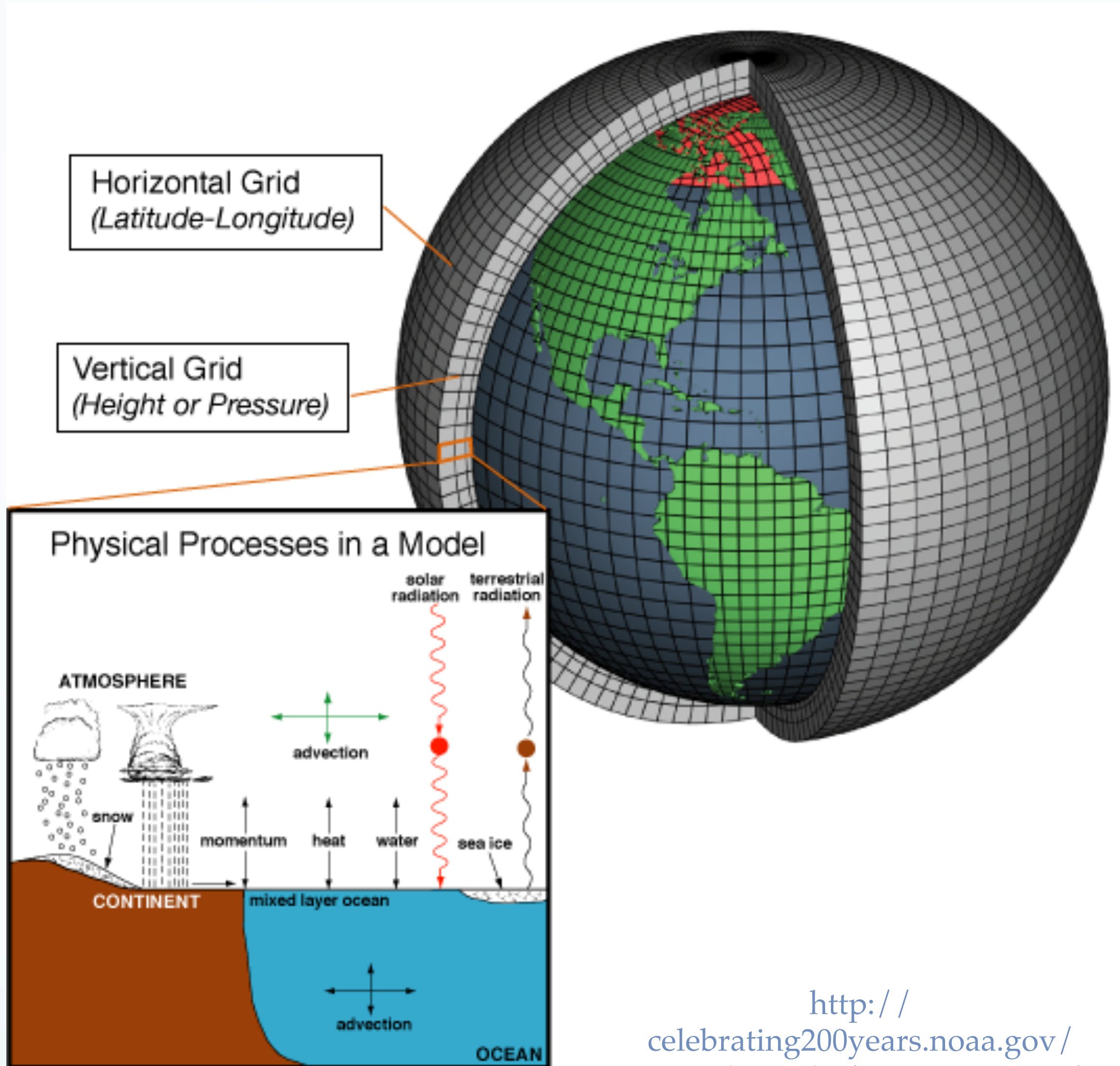


Figure 11.12. *Temperature and precipitation changes over North America from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation.*

What is a climate model?

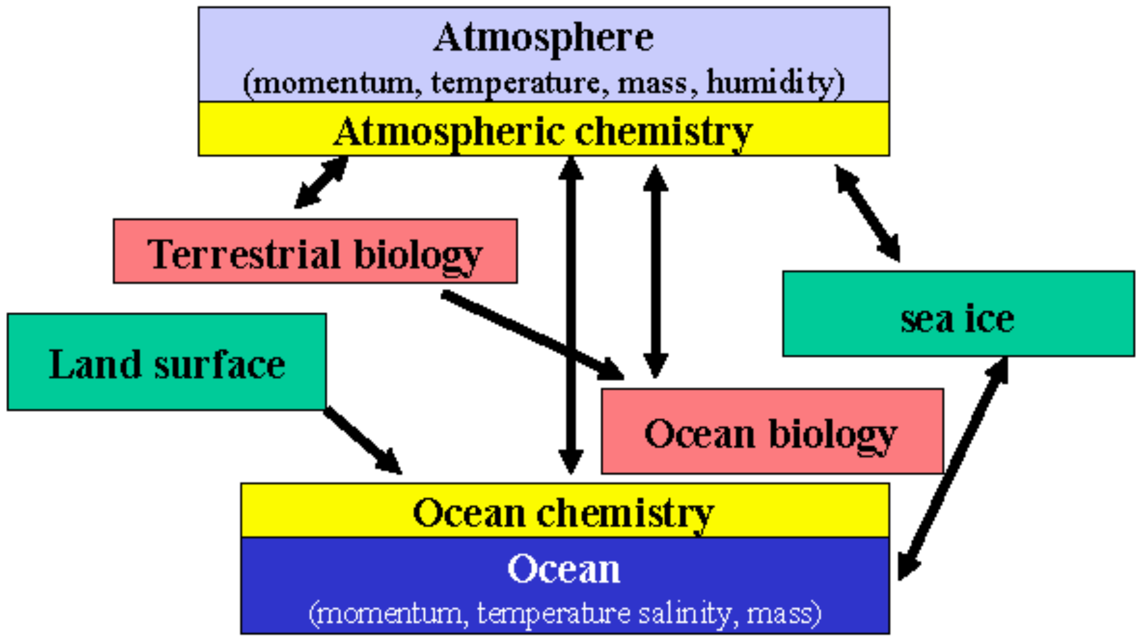
Atmospheric Models



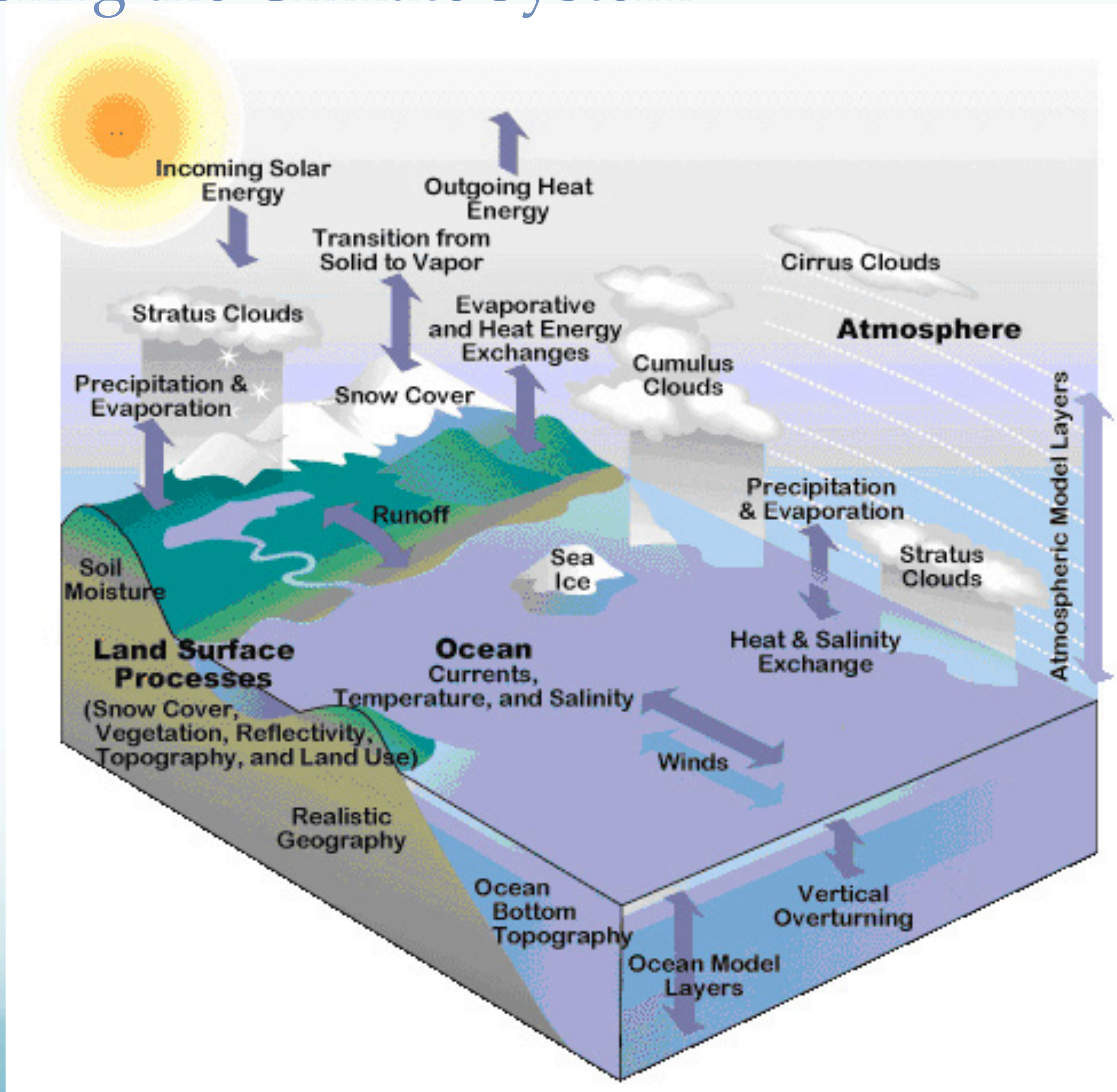
http://celebrating200years.noaa.gov/breakthroughs/climate_model/

Computer code that solves differential equations of air motion and thermodynamics to obtain time and space dependent values for temperature, wind speed, moisture and pressure in the atmosphere.

Climate system models



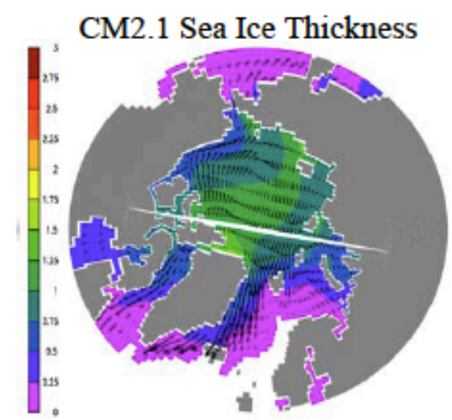
Modeling the Climate System



Simulating the future….

NOAA/GFDL's CM2.1 Coupled Climate Model

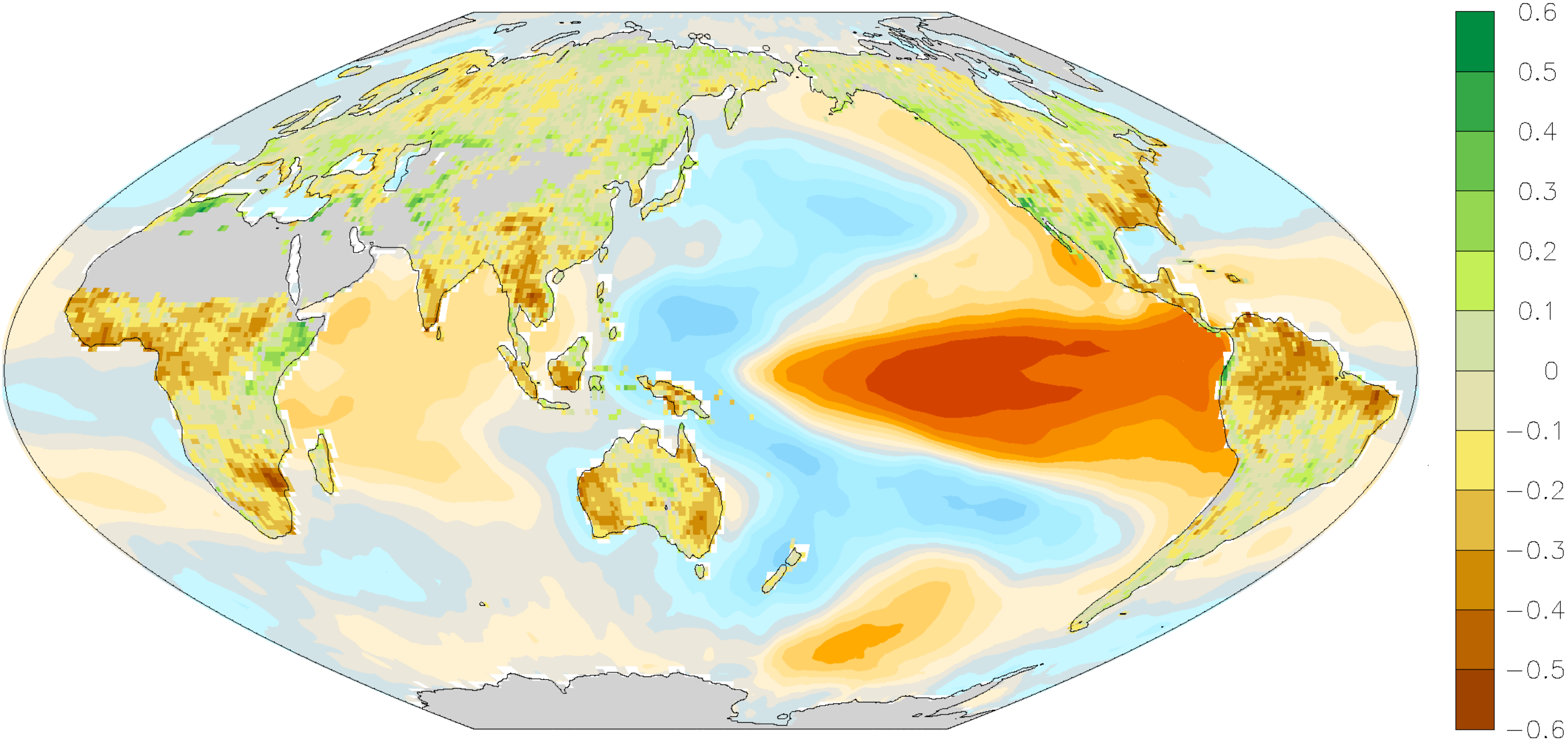
- **Atmosphere based on S.J. Lin's Finite-Volume Dynamical Core**
  - 2.5°x2° horizontal resolution, 24-levels
  - ALE formalism, hybrid sigma-pressure vertical coordinates
  - Reduced Arakawa-Schubert convection ; Prescribed aerosols
- **Ocean built from MOM4.0**
  - 1° horizontal resolution on tripolar B-grid, 50 z-coordinate levels
  - KPP + Bryan-Lewis diapycnal mixing ; Neutral physics
- **SIS dynamical/thermodynamical sea-ice model**
  - 5 ice thickness categories + leads ; 3 vertical levels
  - B-grid discretization on ocean model grid
  - Elastic-viscous-plastic ice internal forces (rheology)



- **Land Model**
  - Multi-layer soil and vegetation thermodynamics
  - Elaborate water storage & routing schemes
  - Prescribed vegetation (Fully interactive ESMs are available as ESM2.1.)
- **All coupled fluxes calculated on the "exchange grid", defined by the union of ocean/ice and atmosphere grid cell boundaries**
  - No flux corrections are used in coupling.
  - The land/ocean boundary is defined by the ocean grid.

Independently considered among the more credible models in the IPCC/AR4.

El Niño in the Model



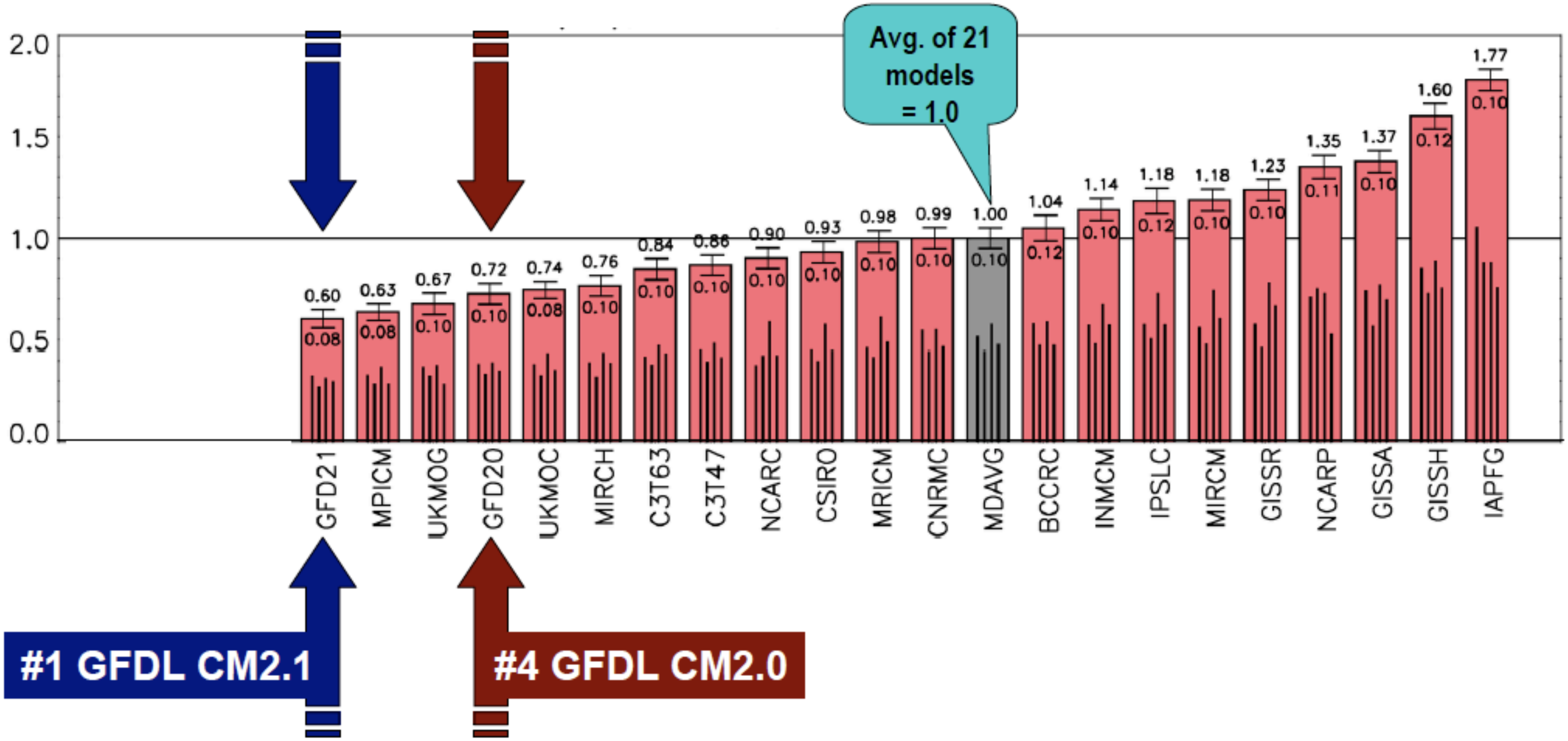
SST contour interval is 0.1°C

Overall Performance Index $\overline{\overline{I_m^2}}^{v,s}$

courtesy Thomas Reichler & Junsu Kim, Univ. of Utah

A combined measure of how well 21 different global climate models simulate 35 different observed climate features (time averaged, large scale quantities).

Normalized so that the average model score = 1.0; Values less than 1.0 are better.
Lower Values = Smaller Errors (i.e., greater agreement btwn the model simulation & observations)



Overall Performance Index $\overline{\overline{I_m^2}}^{v,s}$

courtesy Thomas Reichler & Junsu Kim, Univ. of Utah

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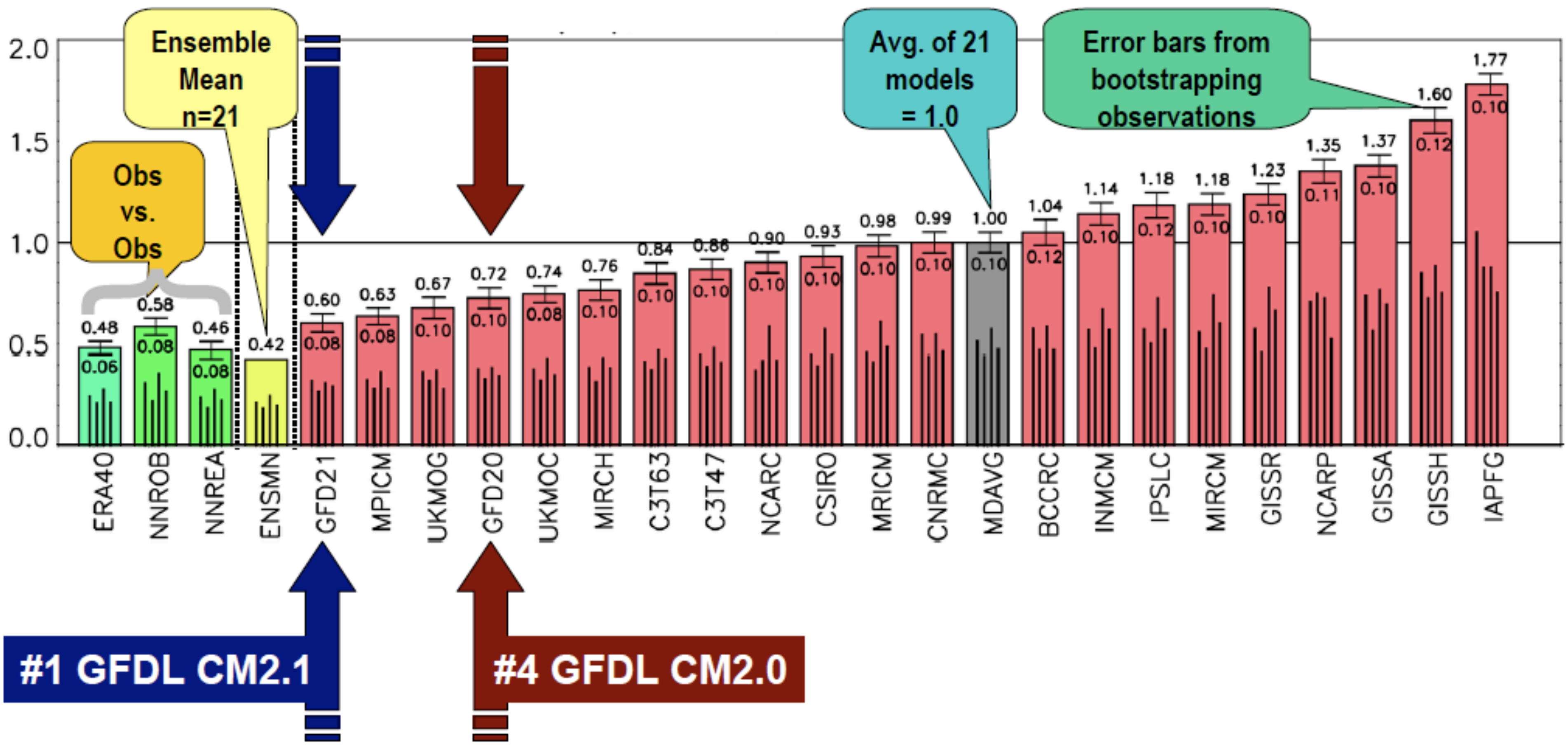
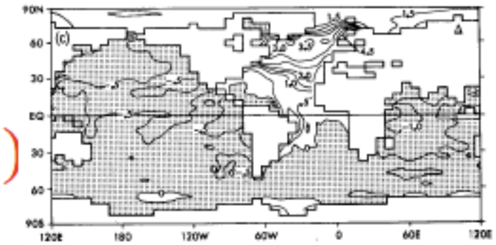


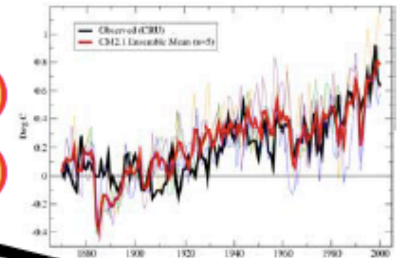
Manabe-Bryan (~1970)

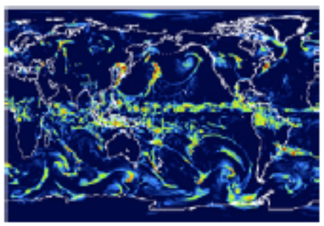
Manabe Climate Model (~1984)



CM2.0 (~2002)

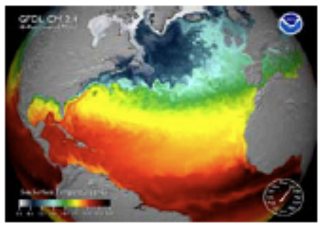
CM2.1 (~2004)





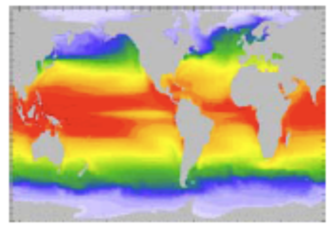
Atmos. only

(25 or 50 km Atm.)



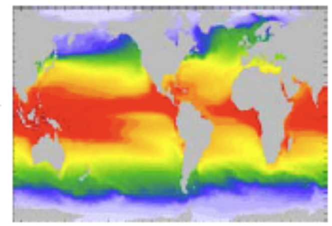
CM2.4

(1°Atm ¼° Ocn)



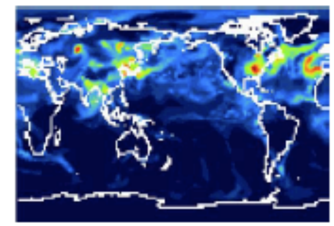
CM2M

(p* ocean)



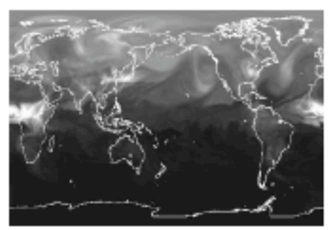
CM2G

(ρ ocean)



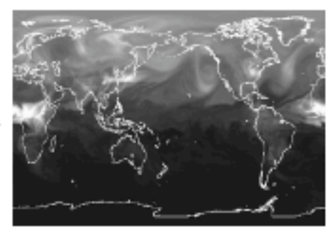
AM3/CM3x

(Atmos. chem.)



ESM2M

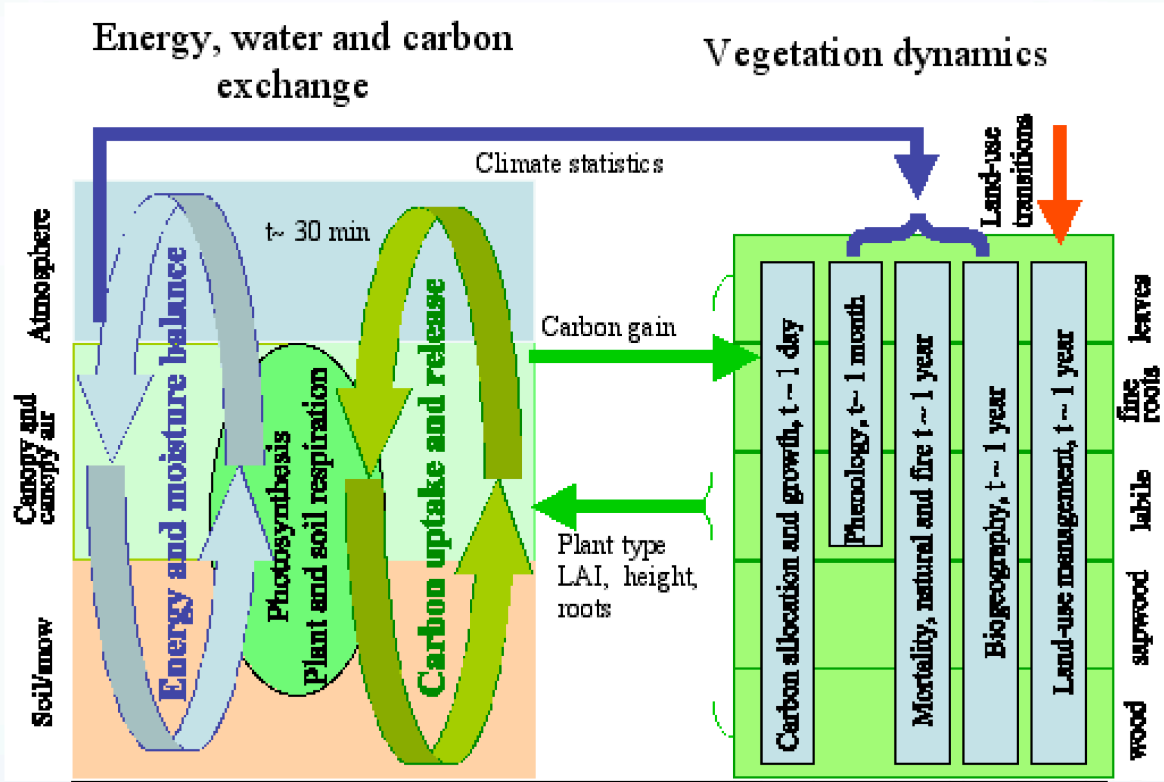
(Biosphere)



ESM2G

(Biosphere)

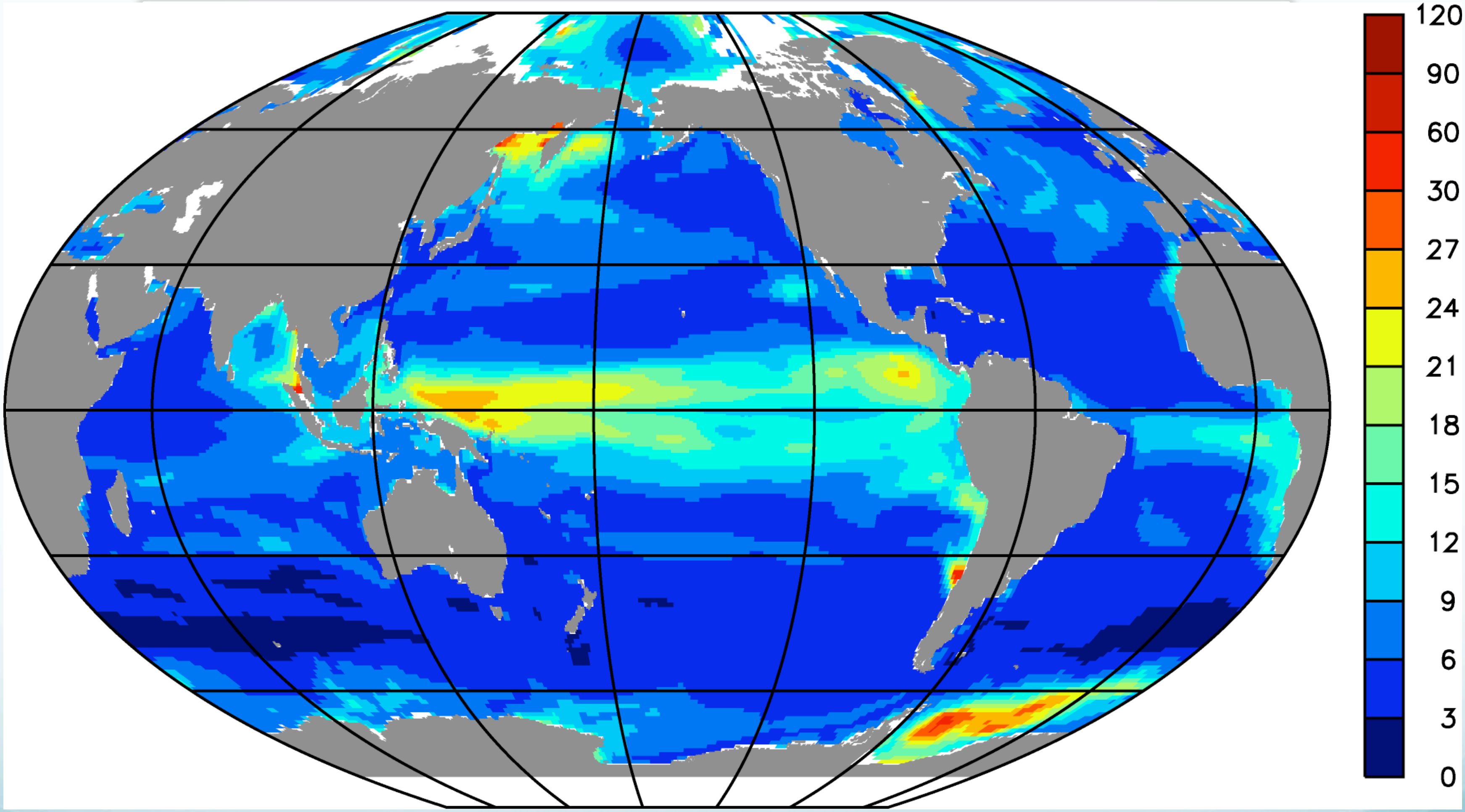
Schematic of the NOAA Dynamic Vegetation Land Model



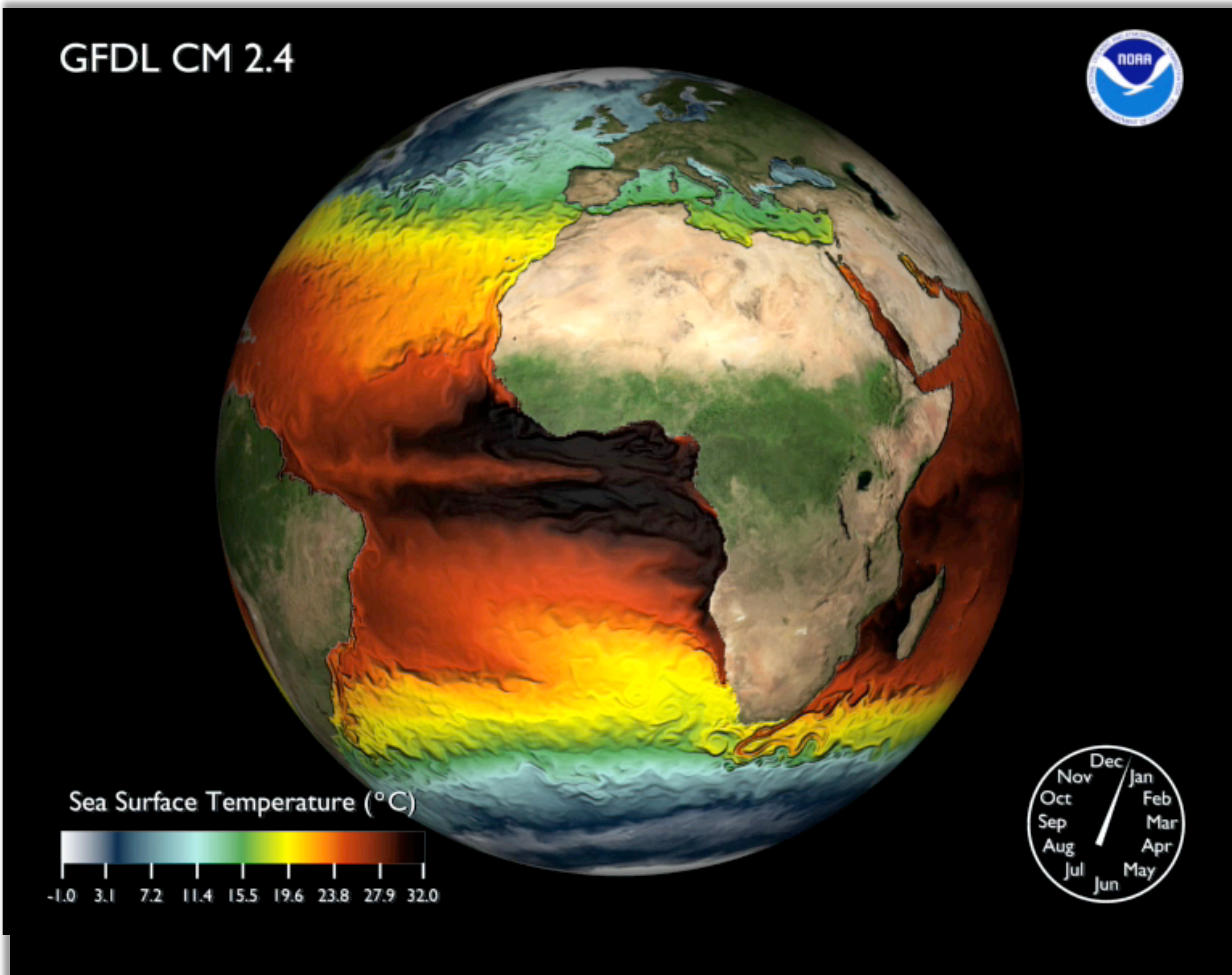
Dynamic Land Model LM3V

Courtesy Elena Shevliakova

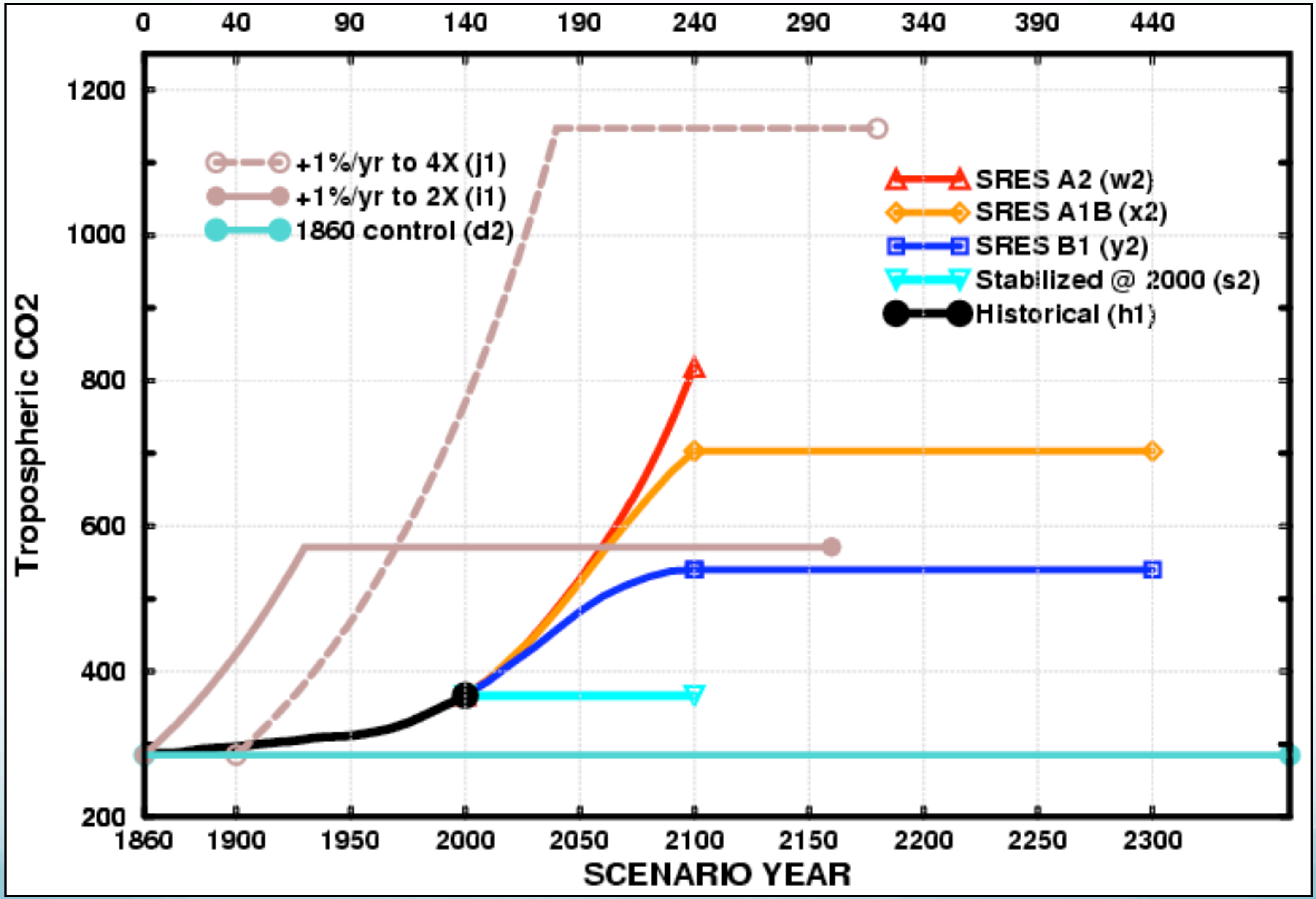
New Earth System Model: A carbon-atmosphere-ocean-land-ice model



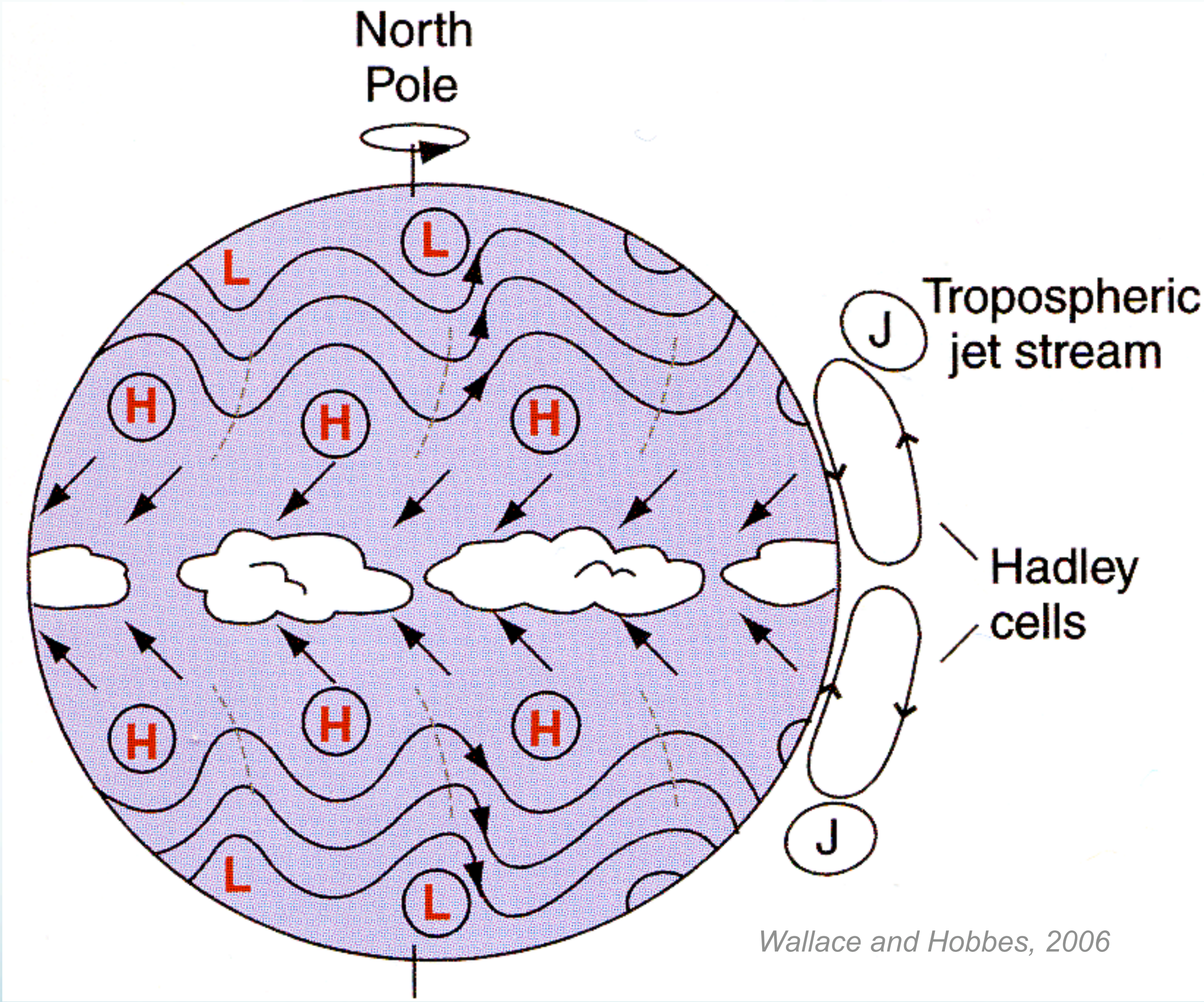
Annual average of monthly standard deviations of the surface carbon flux data as simulated by the GFDL ESM (averaged over model years 101-120).


GFDL CM 2.4
NOAA
Sea Surface Temperature (°C)
-1.0 3.1 7.2 11.4 15.5 19.6 23.8 27.9 32.0
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov

Climate Forcing Scenarios



Trends in the Westerlies


North
Pole
L
L
H
H
H
H
H
H
L
L
J
Tropospheric
jet stream
Hadley
cells
J
Wallace and Hobbes, 2006

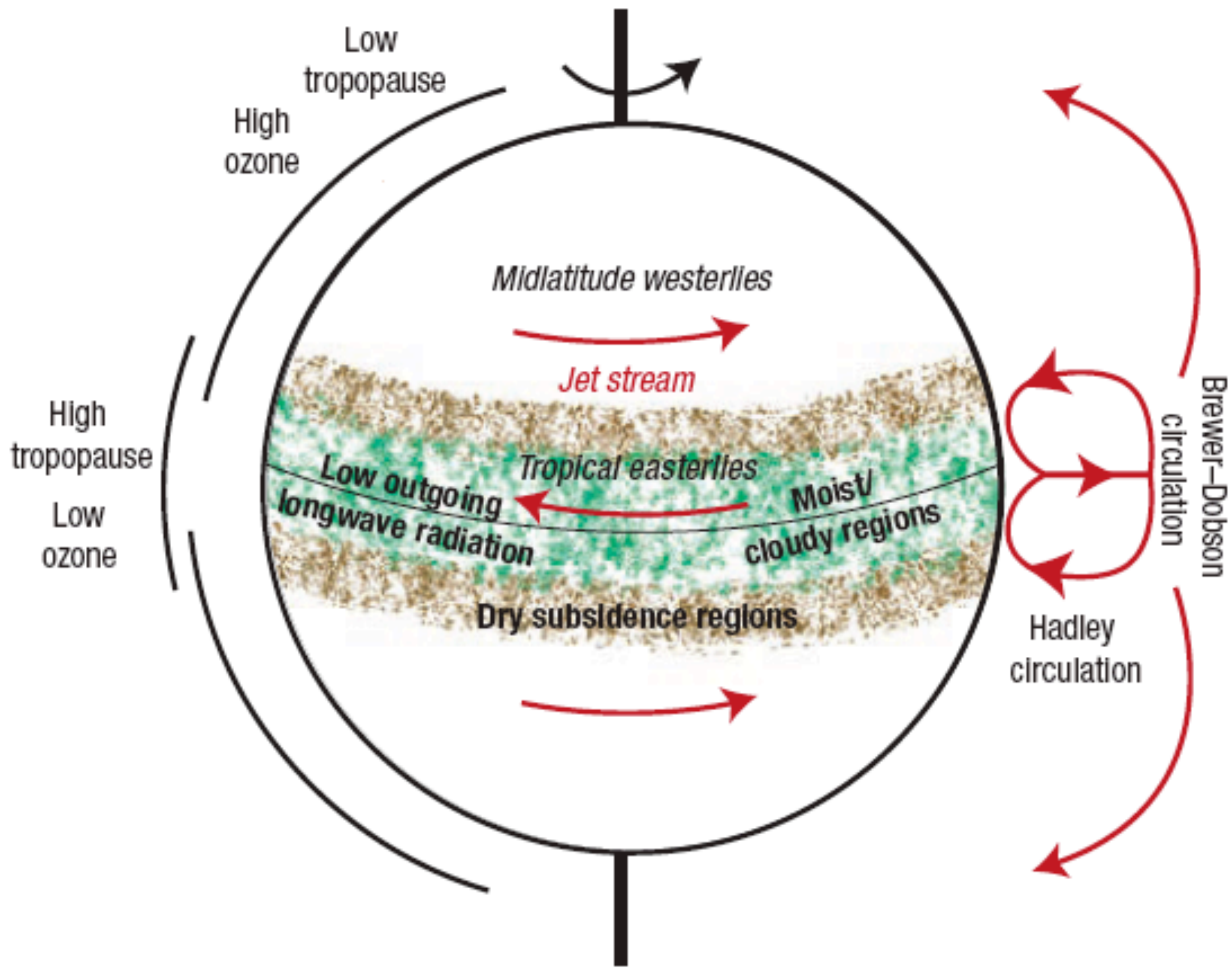


Figure 1 What climatological features distinguish the tropics? Some of the atmospheric structure, circulation, and hydrological features shown in this schematic diagram of the Earth have moved poleward in recent decades, indicating a widening of the tropical belt and the Hadley circulation. *Seidel et al., 2007*

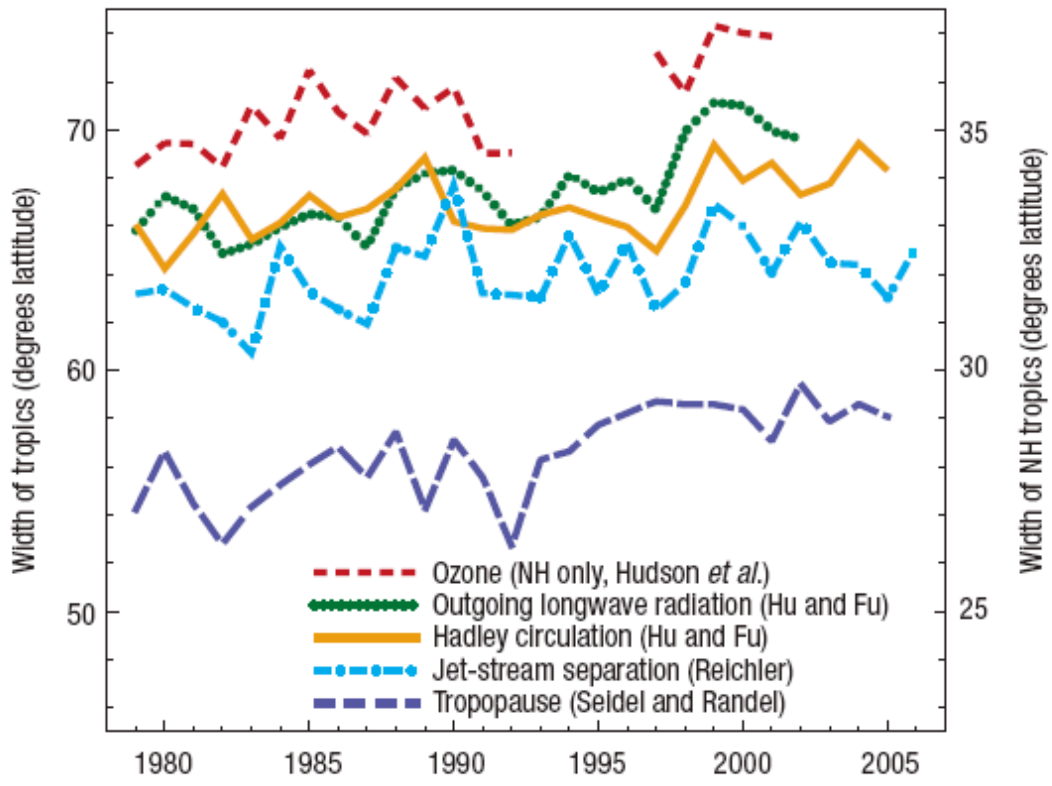
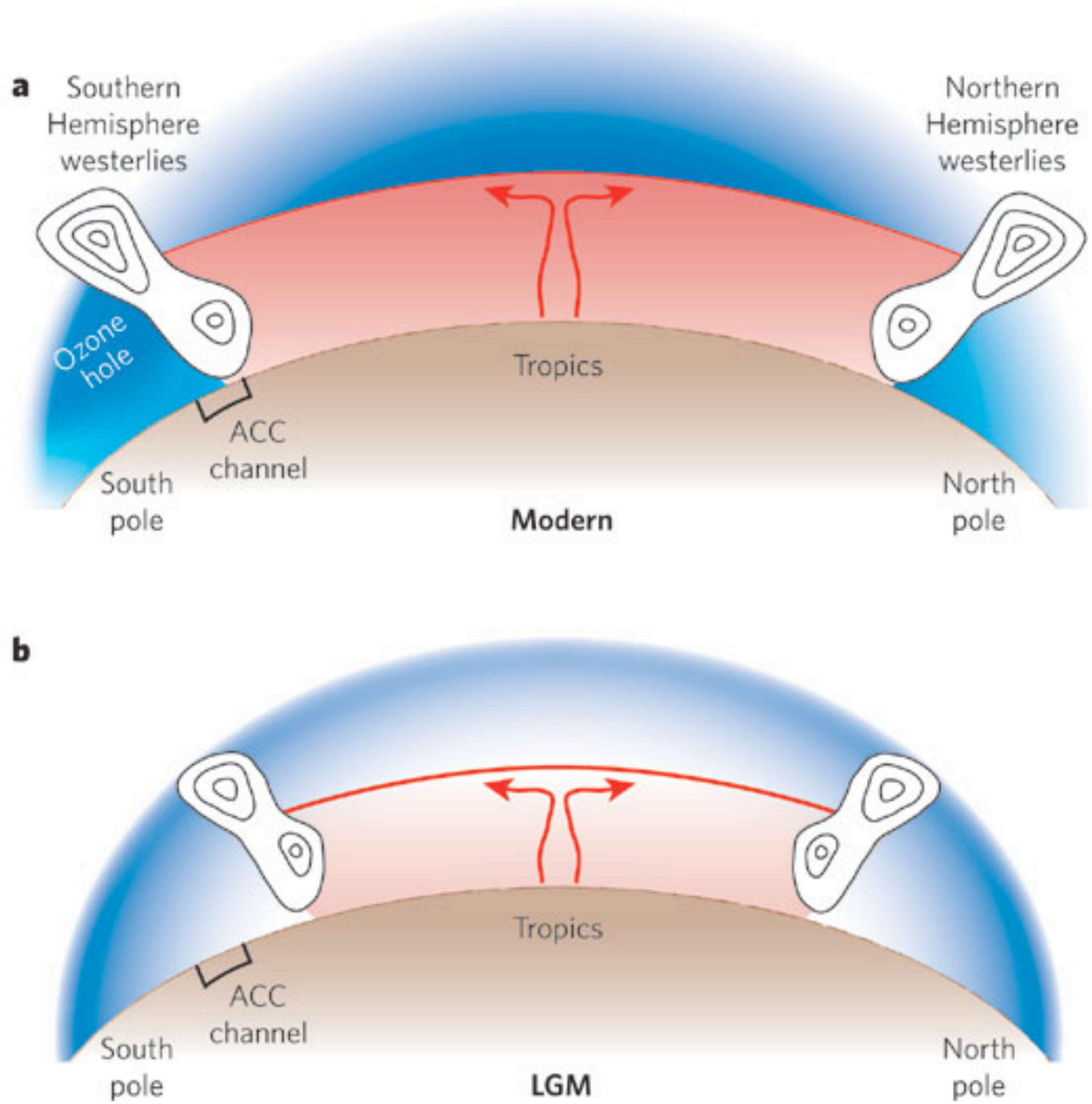
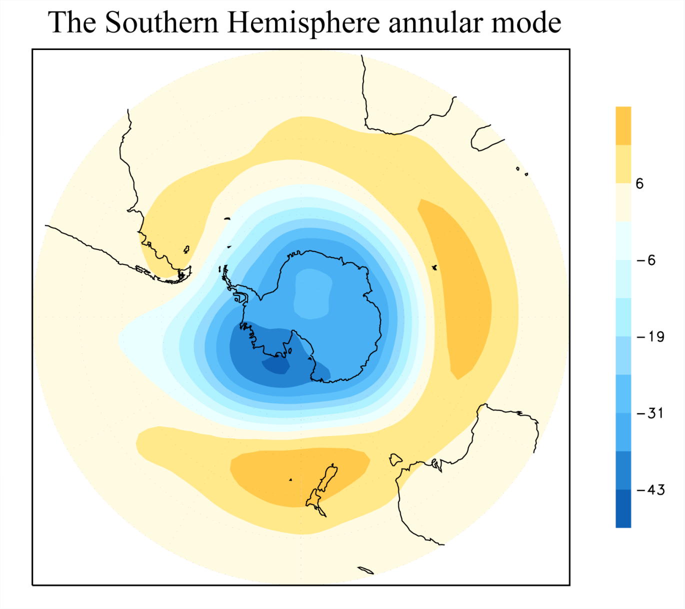


Figure 2 Changes in several estimates of the width of the tropical belt since 1979. These include: the width of the Hadley circulation, based on both outgoing longwave radiation and horizontal winds streamfunction[10]; the separation of the Northern and Southern Hemisphere subtropical jet-stream cores; the width of the region of frequent high tropopause levels[8]; and the width of the region with tropical column ozone levels (Northern Hemisphere only, right axis, ref. 6). Although each shows an increase since 1979, the rates vary from 2.0 to 4.8 degrees latitude per 25 years, with an even larger range when considering the entire spread of trend estimates in each individual study.

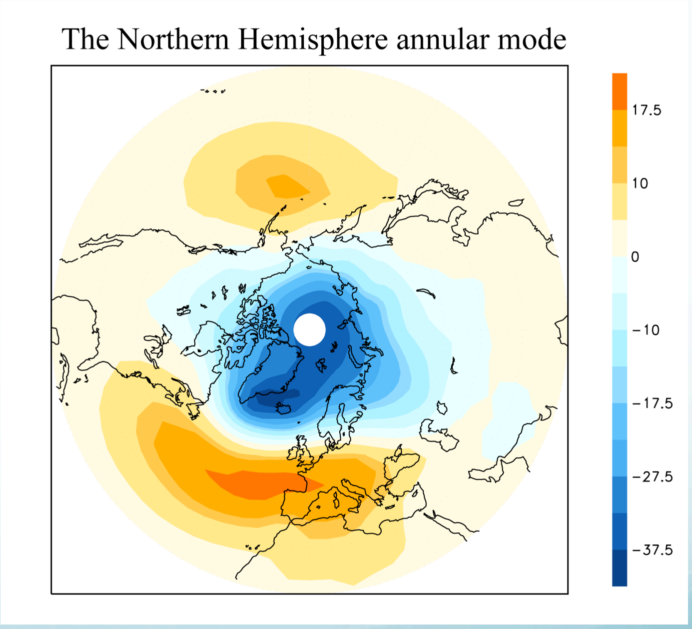
Seidel et al., 2007


a
Southern Hemisphere westerlies
Northern Hemisphere westerlies
Ozone hole
Tropics
ACC channel
South pole
North pole
Modern
b
Tropics
ACC channel
South pole
North pole
LGM

- Poleward shift of the Southern Hemisphere Westerlies

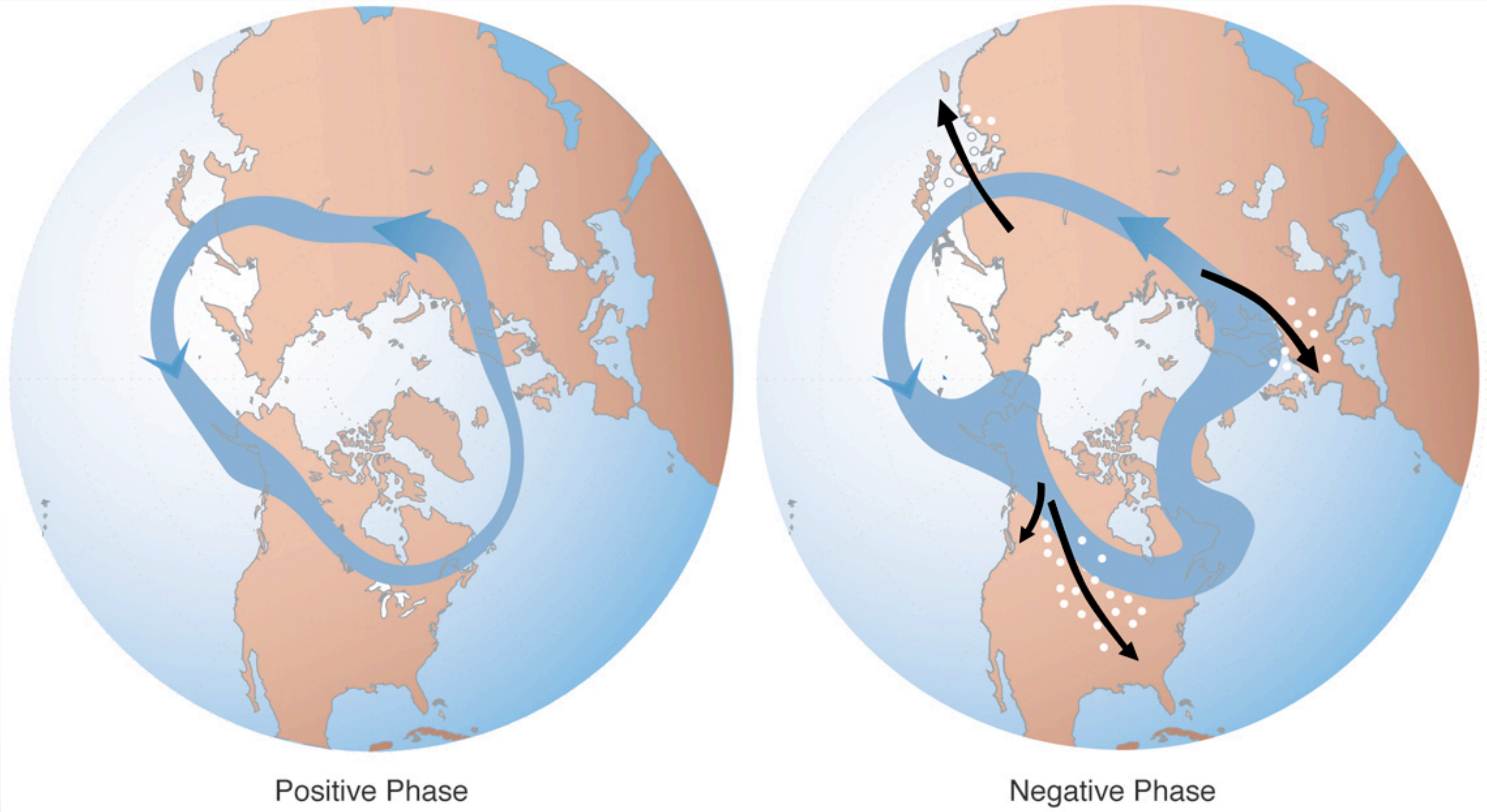


- Poleward shift of the Northern Hemisphere Westerlies



D. Thompson

The Northern Annular Mode



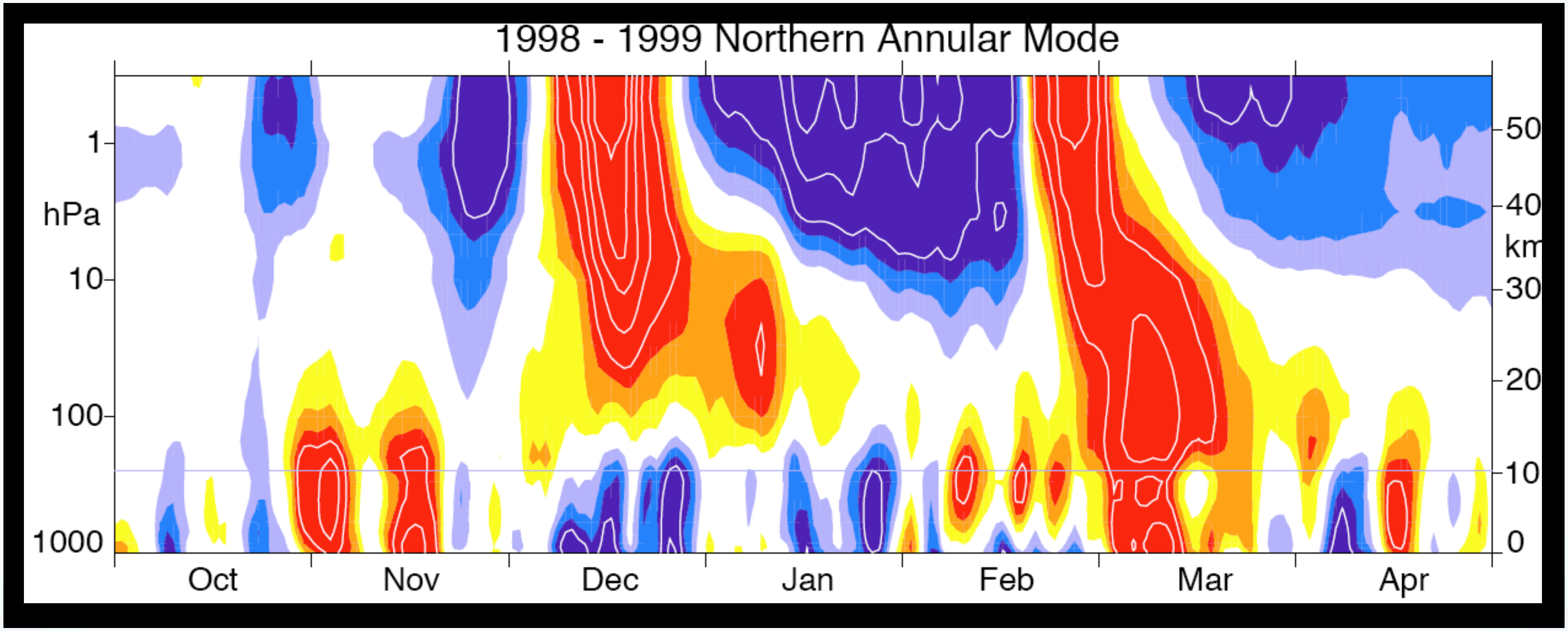
High Index

Low Index

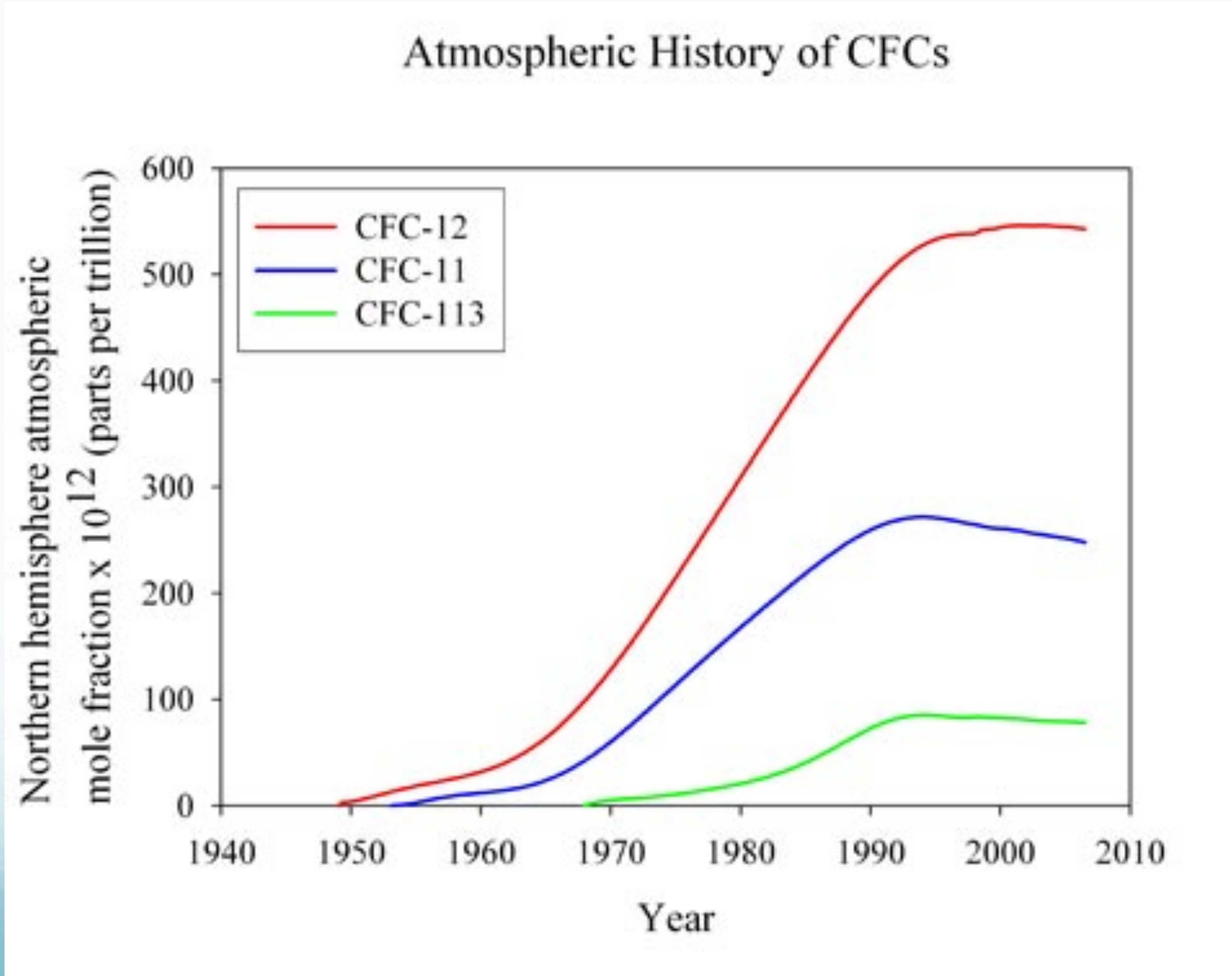
The history of the NAO (or AO or NAM) is quite long….

Hans Egede observed in the 1700's

"When the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely"

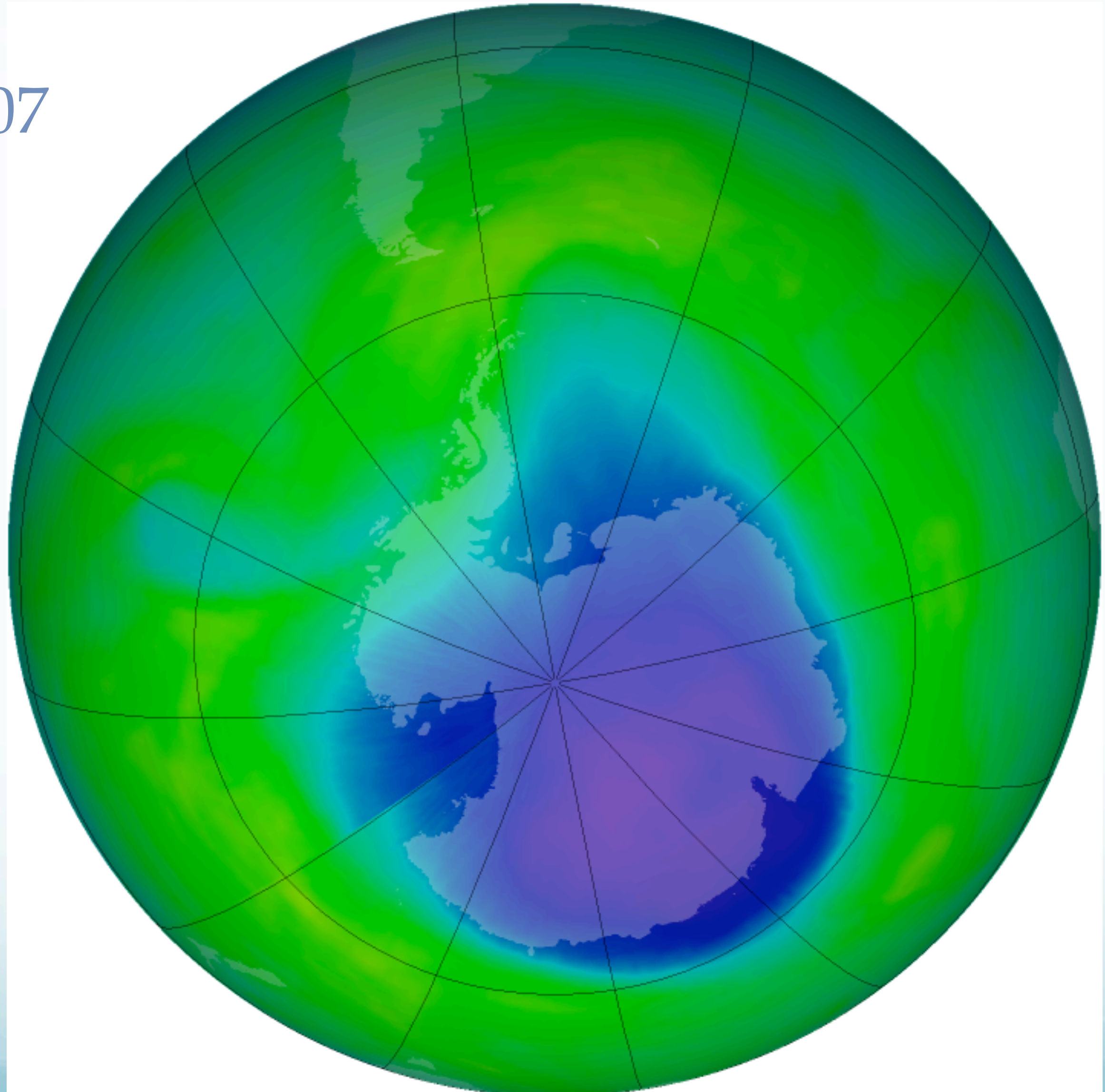


Baldwin and Dunkerton 2001

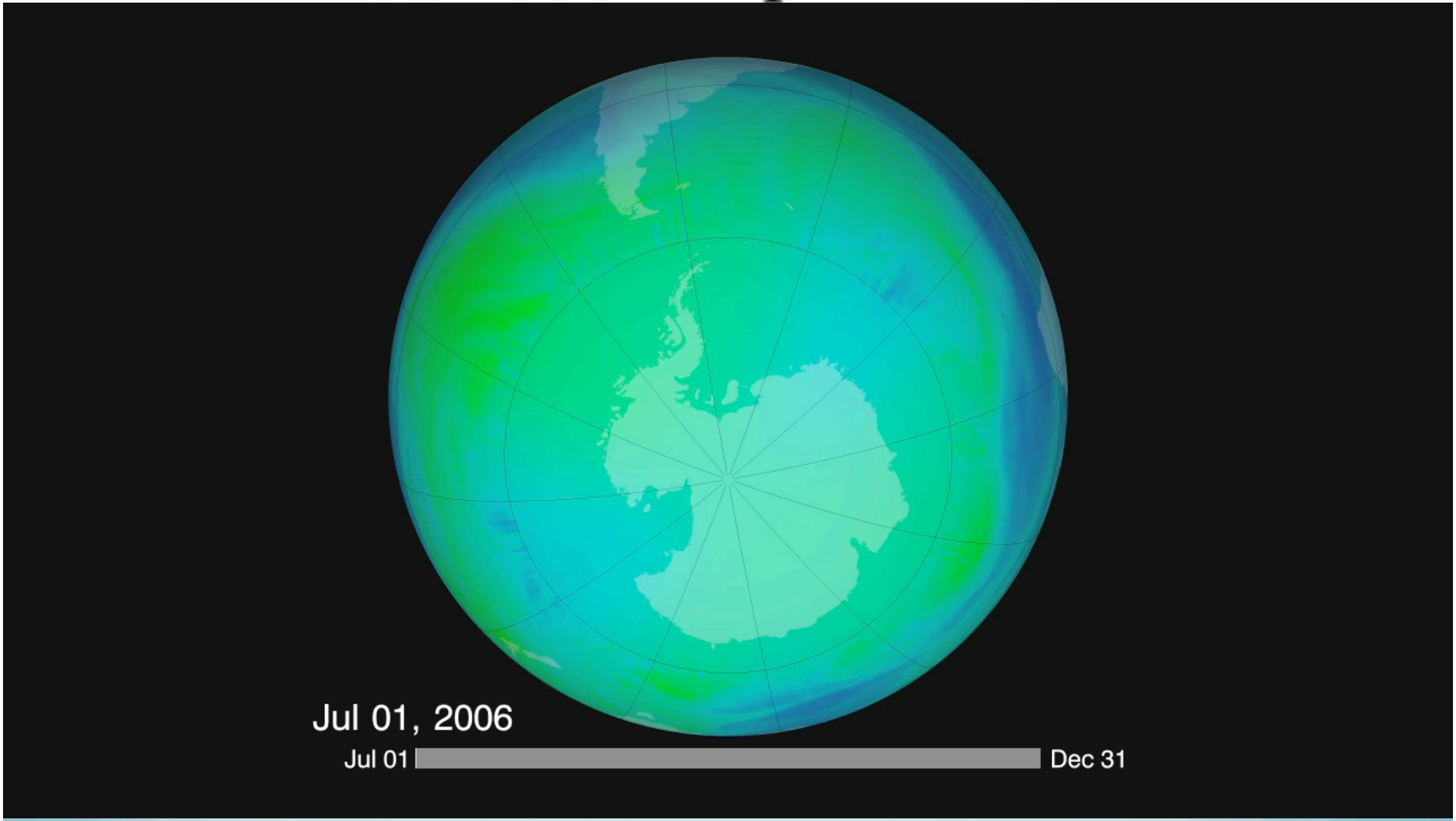

Atmospheric History of CFCs
Northern hemisphere atmospheric mole fraction x 10^12 (parts per trillion)
600
500
400
300
200
100
0
CFC-12
CFC-11
CFC-113
1940
1950
1960
1970
1980
1990
2000
2010
Year

The Southern Hemisphere Ozone Hole

Nov 2, 2007

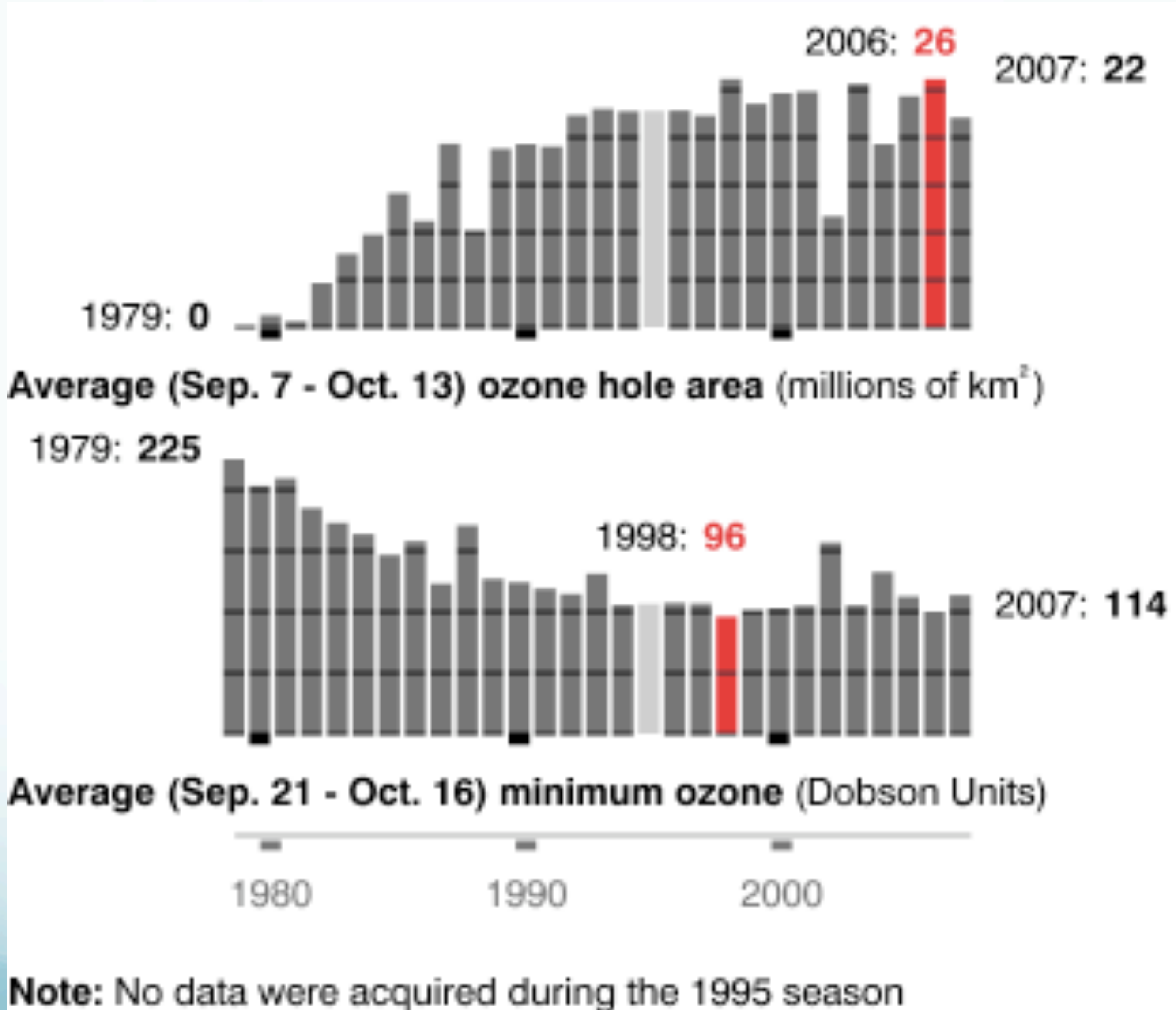


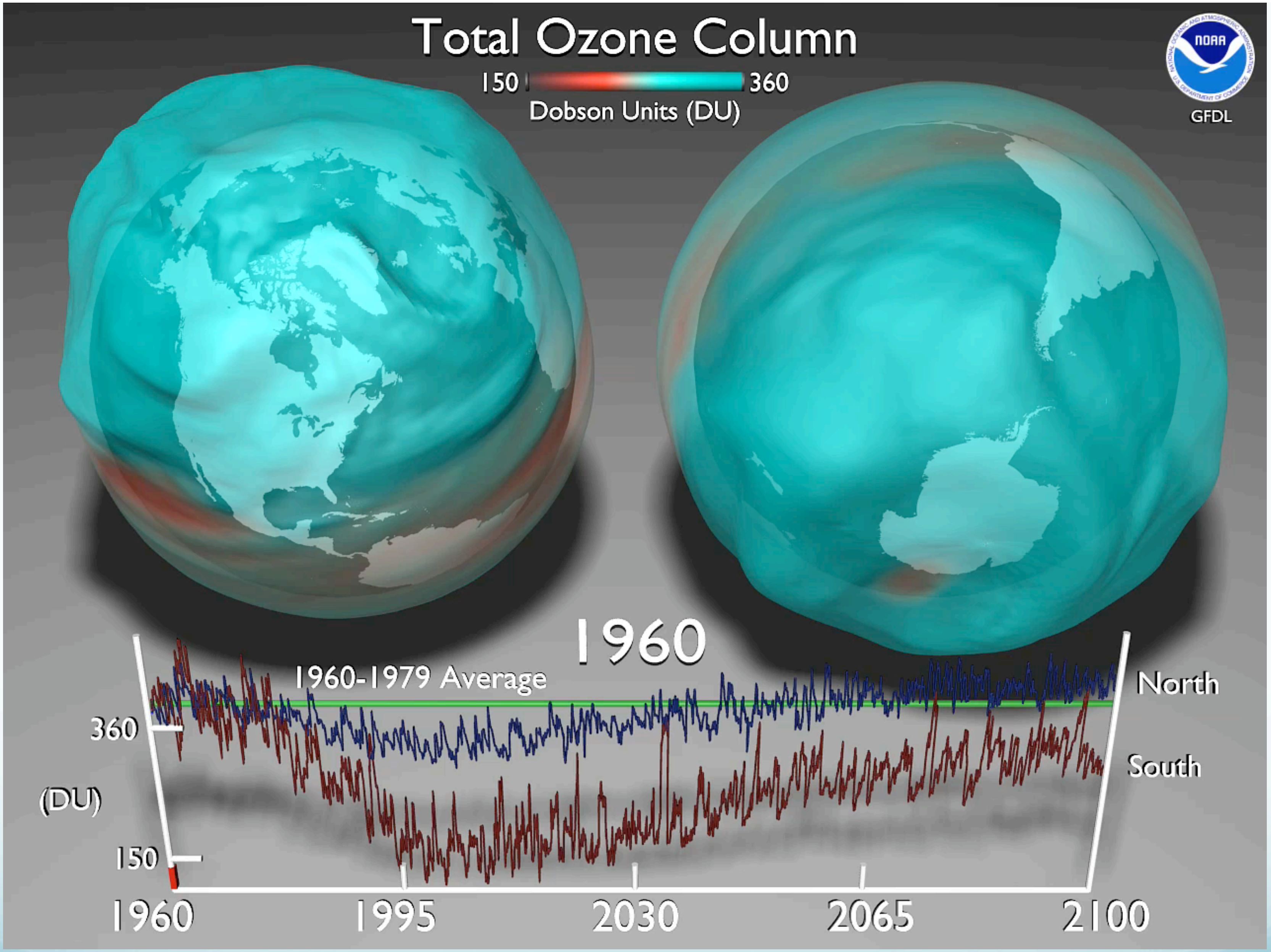
The Southern Hemisphere Ozone Hole



From NASA

The Southern Hemisphere Ozone Hole





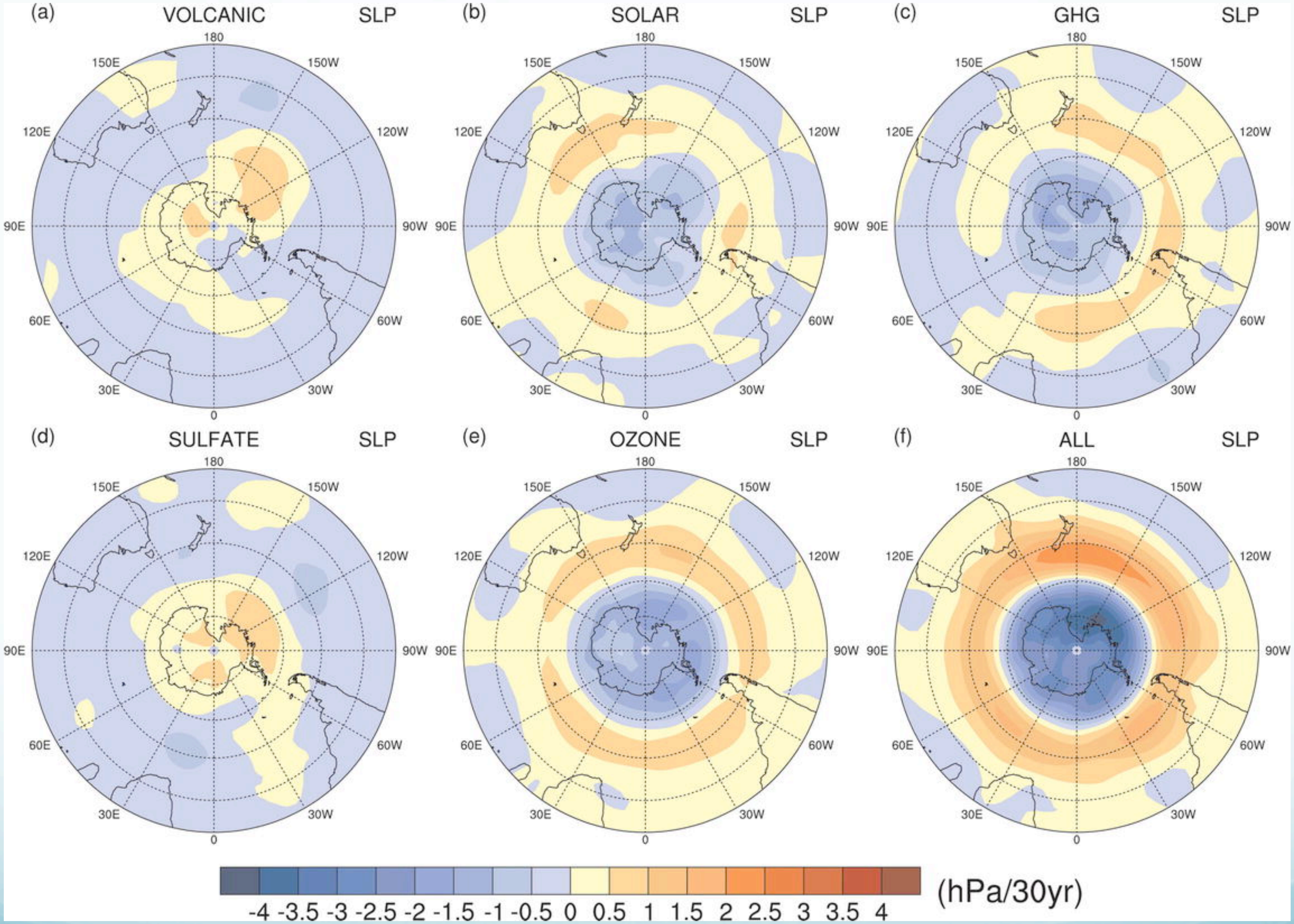
John Austin: The animation shows the evolution of northern and southern hemisphere ozone as simulated in the GFDL coupled chemistry-climate model.

"Despite the apparent robustness of the above evidence, the principal mechanisms whereby stratospheric variability may influence the tropospheric circulation remain unclear. A complete explanation of the observed coupling likely lies in one or more of the following physical processes:

1) Geostrophic and hydrostatic adjustment of the tropospheric flow to anomalous wave drag (Haynes et al.,1991; Thompson et al., 2006) and anomalous diabatic heating at stratospheric levels (Thompson et al., 2006);
2) The impact of anomalous shear in the lower stratospheric zonal flow on the momentum flux by baroclinic eddies (Shepherd, 2002; Kushner and Polvani, 2004; Wittman et al., 2004);
3) Amplification due to internal tropospheric dynamics (Song and Robinson, 2004);
4) The impact of anomalous shear at the tropopause level on vertically propagating waves (Chen and Robinson,1992; Shindell et al., 1999; Limpasuvan and Hartmann, 2000);
5) The reflection of planetary waves (Hartmann et al.,2000; Perlwitz and Harnik, 2004)."

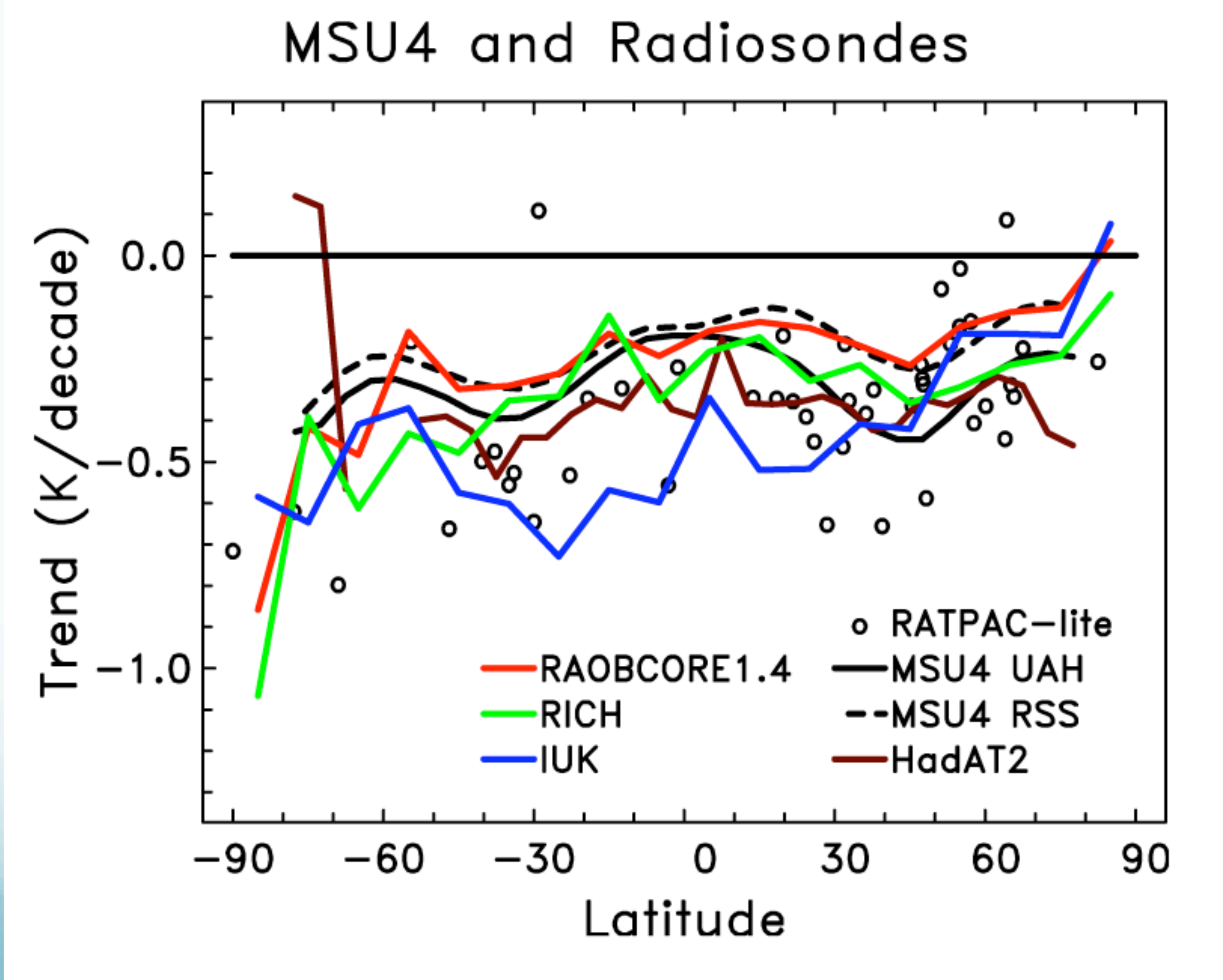
Baldwin et al., 2007

Attribution of Jet Forcing (Model Results)



Arblaster & Meehl, 2006

Stratospheric Temperature Trends



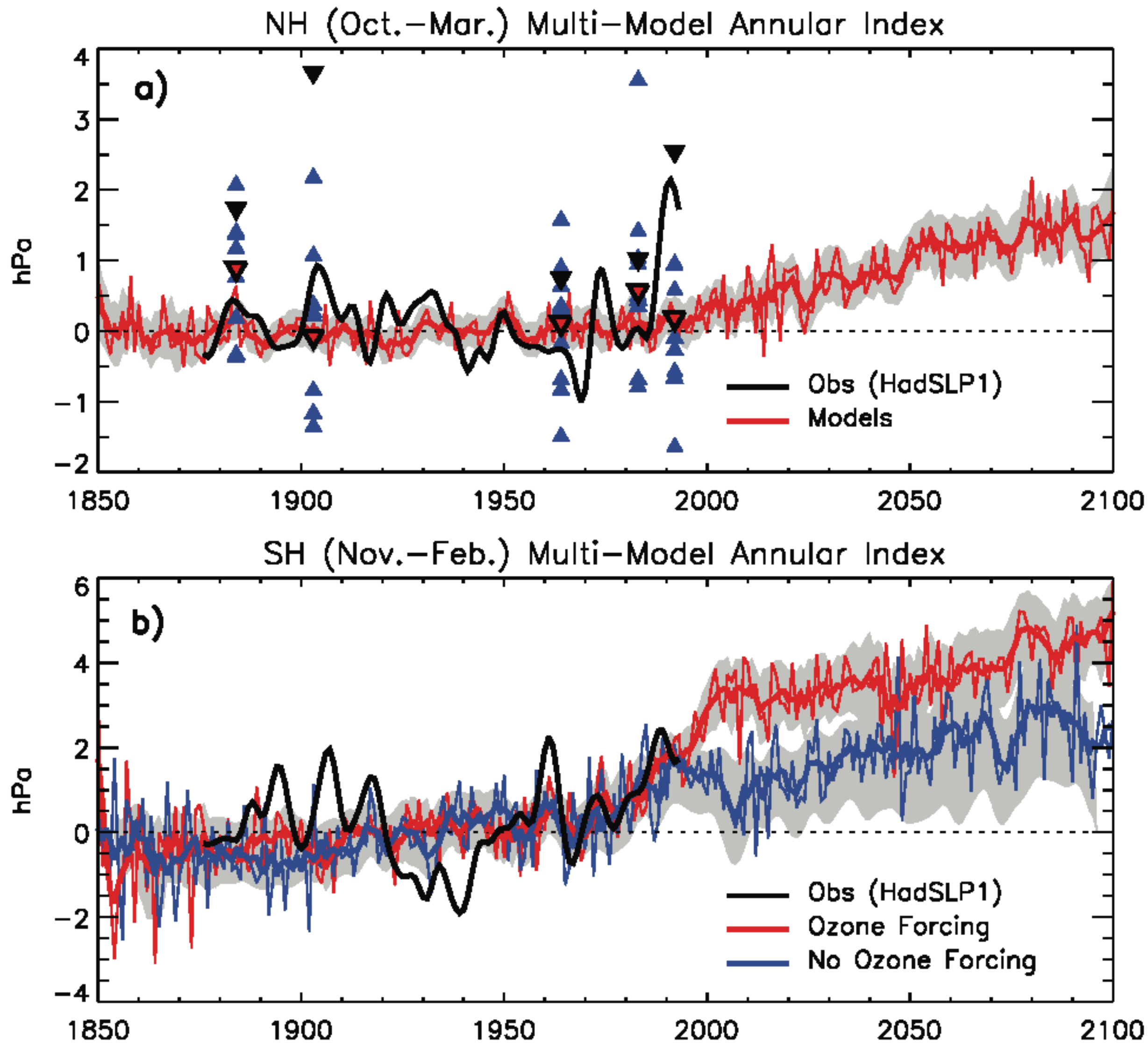
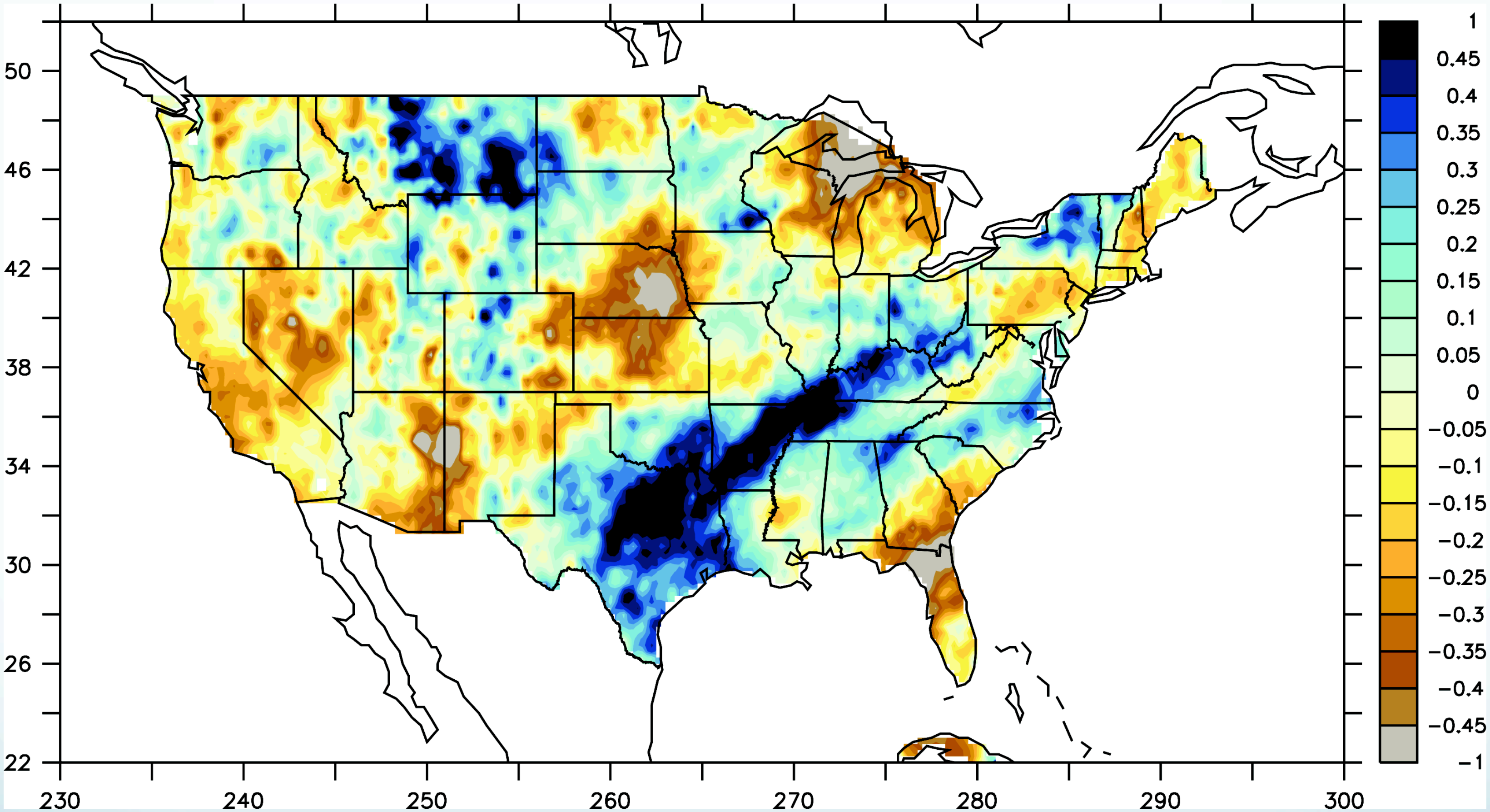


Figure 10.17. *(a) Multi-model mean of the regression of the leading EOF of ensemble mean Northern Hemisphere sea level pressure (NH SLP, thin red line). The time series of regression coefficients has zero mean between year 1900 and 1970. The thick red line is a 10-year low-pass filtered version of the mean. The grey shading represents the inter-model spread at the 95% confidence level and is filtered. A filtered version of the observed SLP from the Hadley Centre (HadSLP1) is shown in black. The regression coefficient for the winter following a major tropical eruption is marked by red, blue and black triangles for the multi-model mean, the individual model mean and observations, respectively. (b) As in (a) for Southern Hemisphere SLP for models with (red) and without (blue) ozone forcing. Adapted from Miller et al. (2006).*

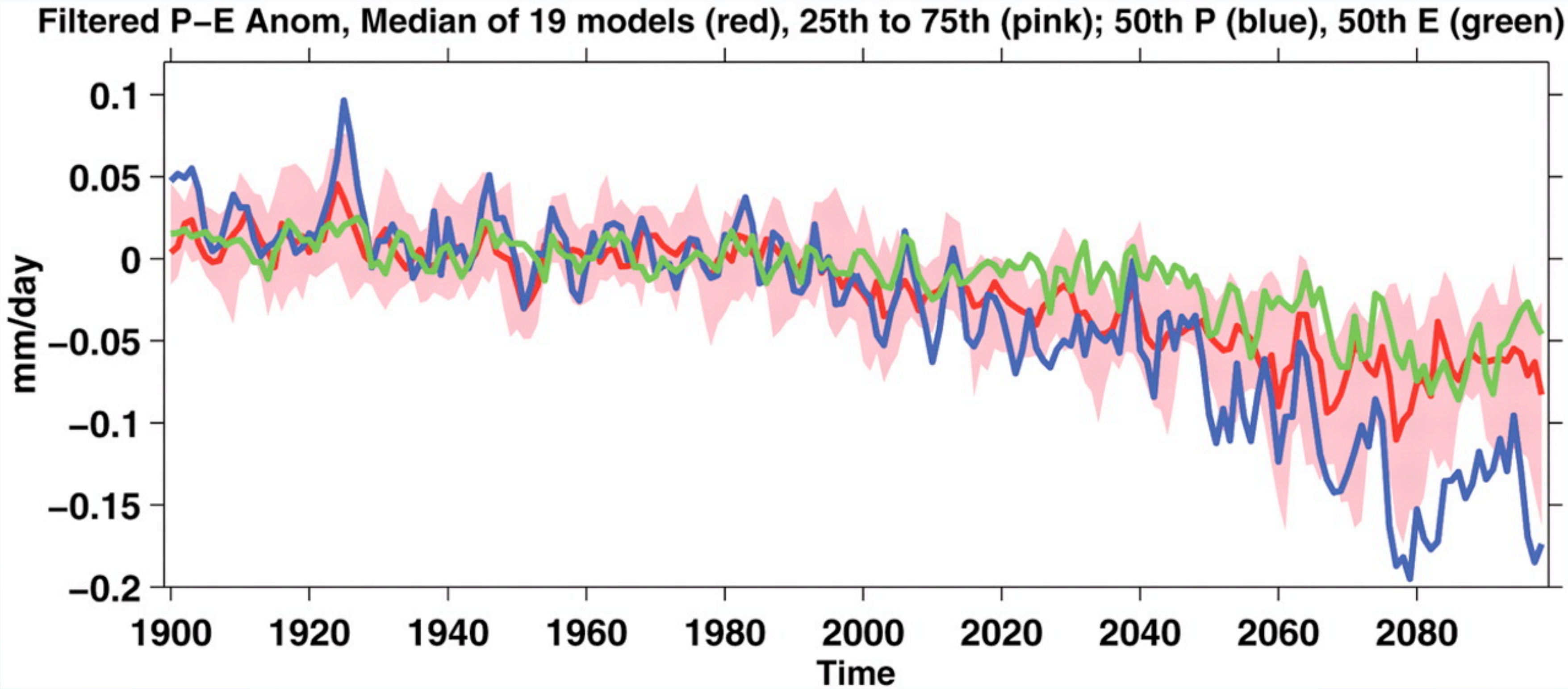
Climate Model Projections for the Southwest

Correlation of monthly precipitation anomalies (FMA) with the JFM Northern Annular Mode (NAM) Index

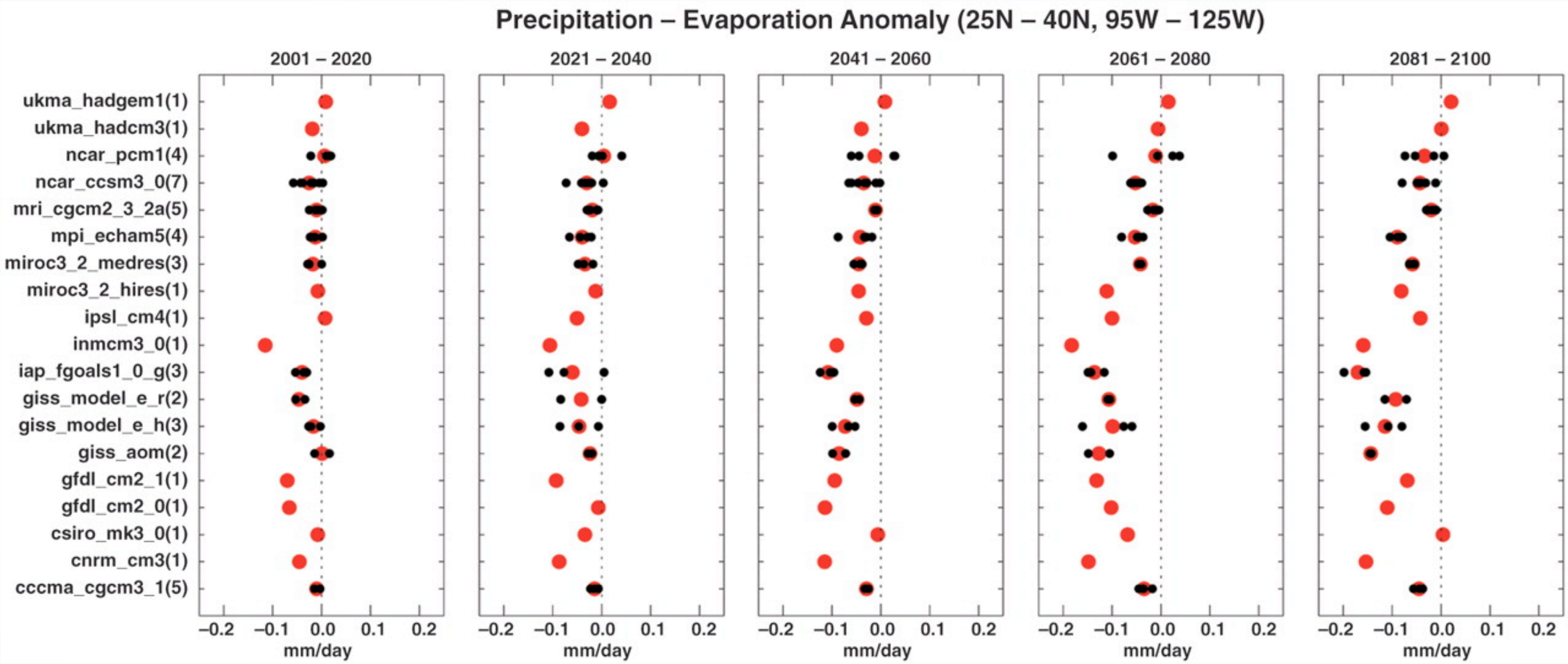


Courtesy of Stephanie McAfee

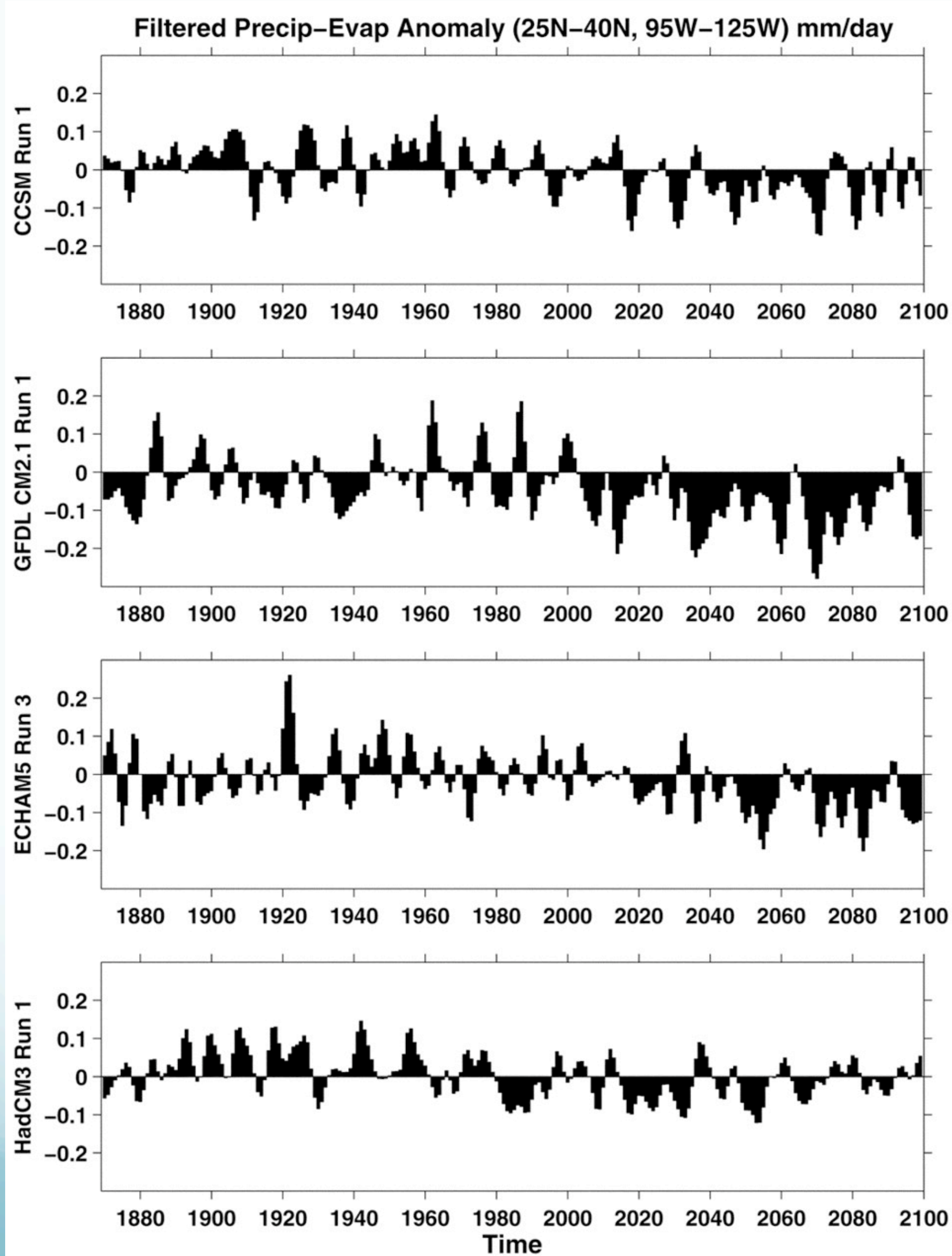
Filtered P-E Anomalies



Seager et al, 2007

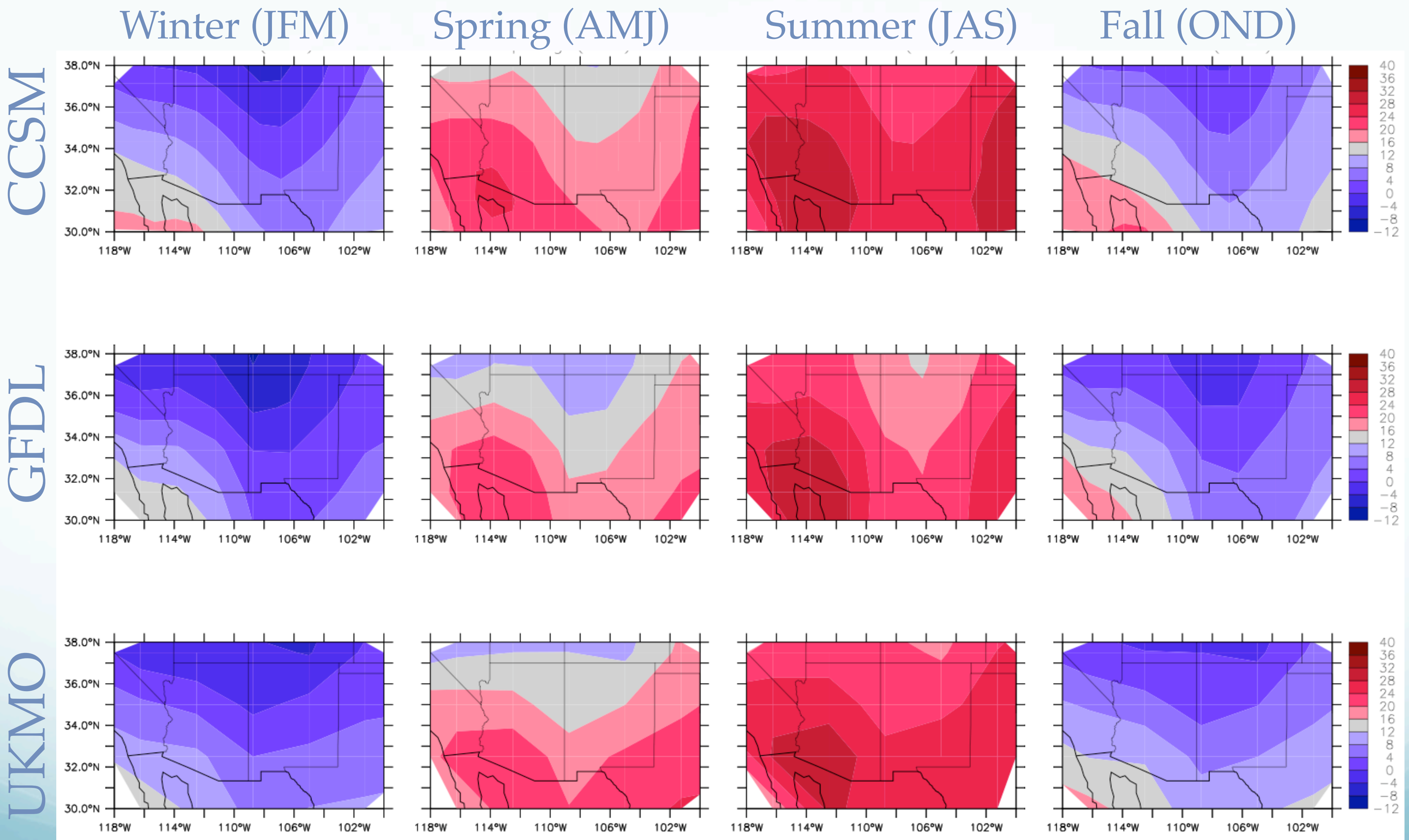


Seager et al, 2007

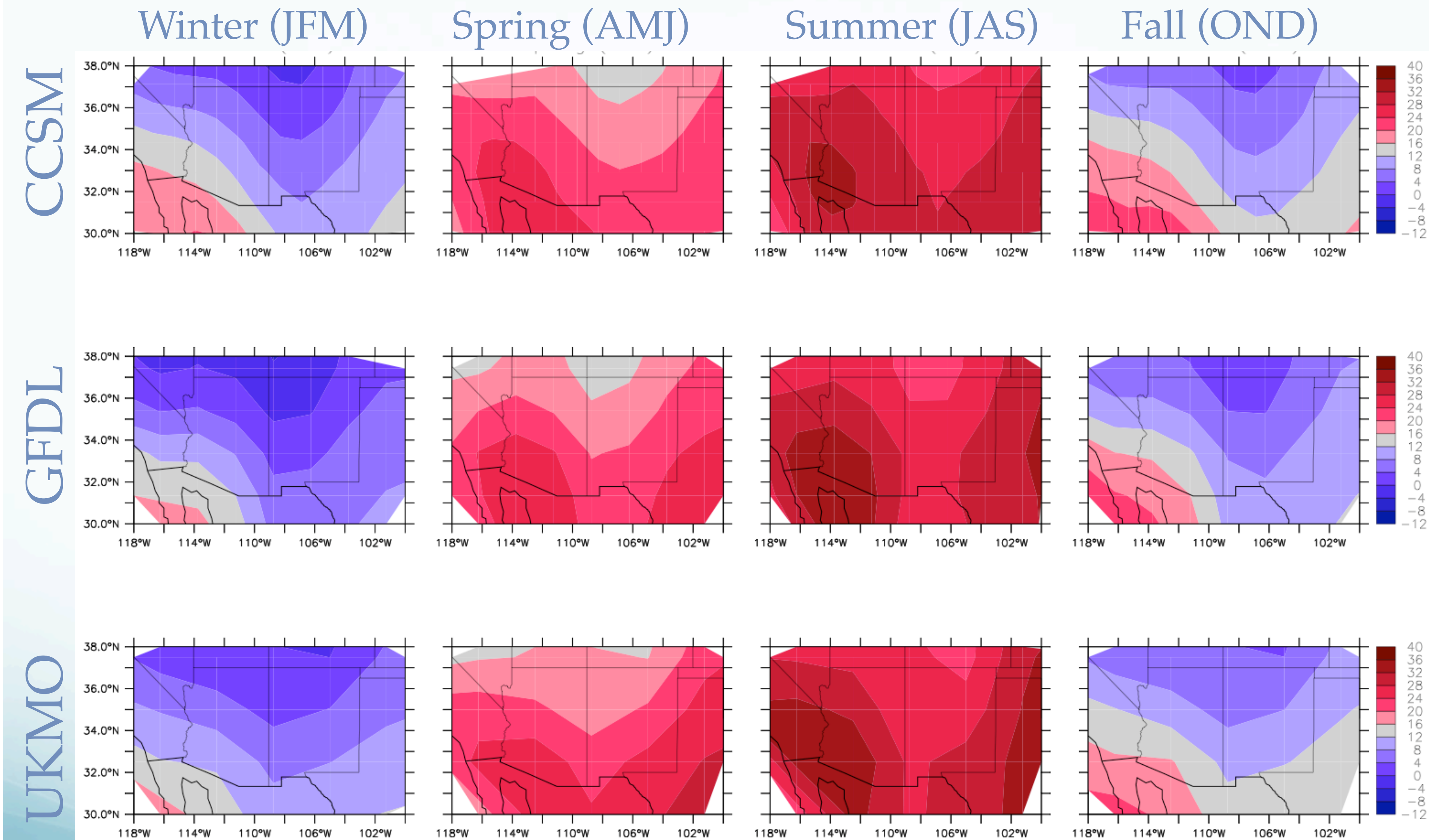


Seager et al, 2007

Modeled Mean Surface Air Temperature (°C, 2001-2005, A1B)

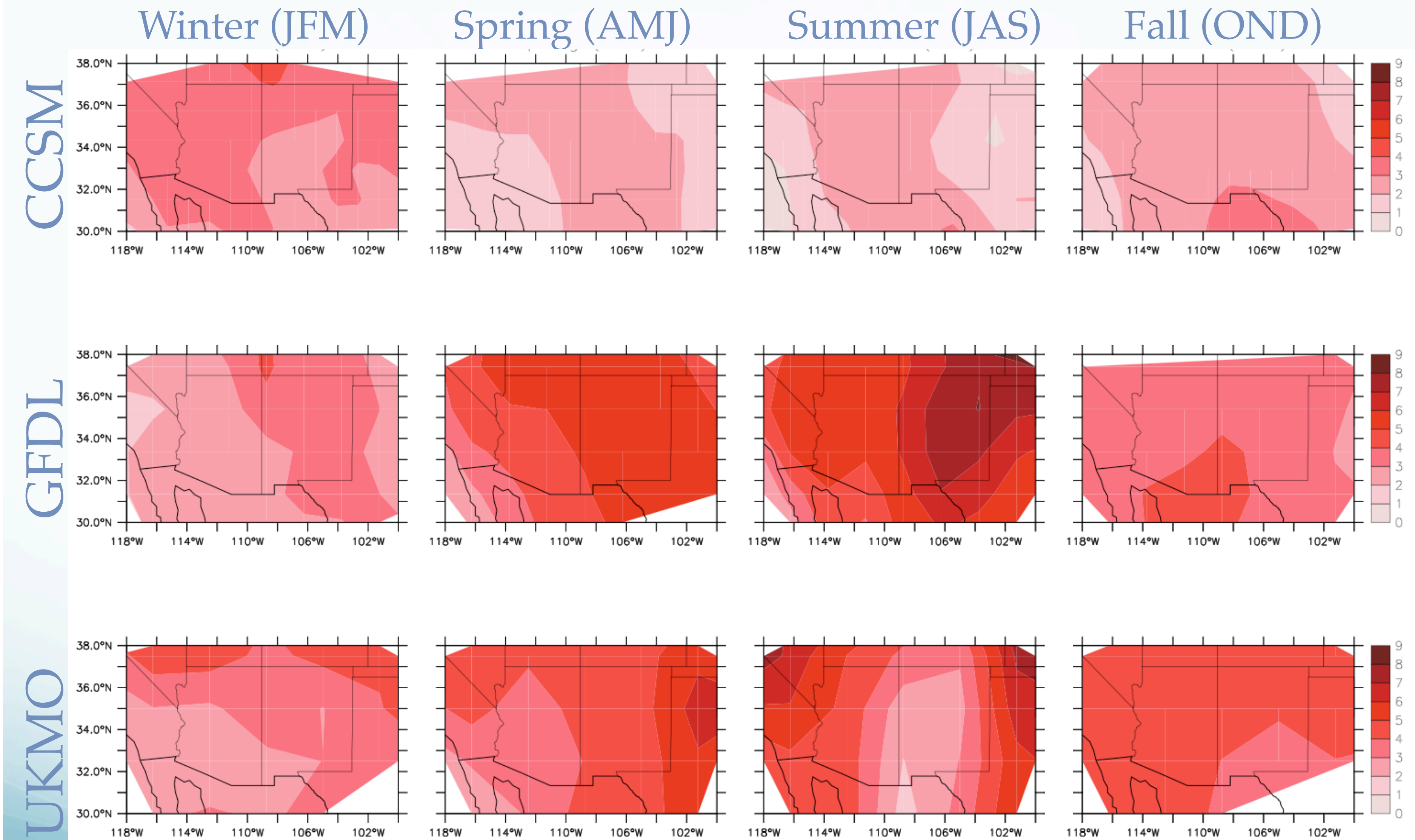


Modeled Mean Surface Air Temperature (°C, 2096-2100, A1B)

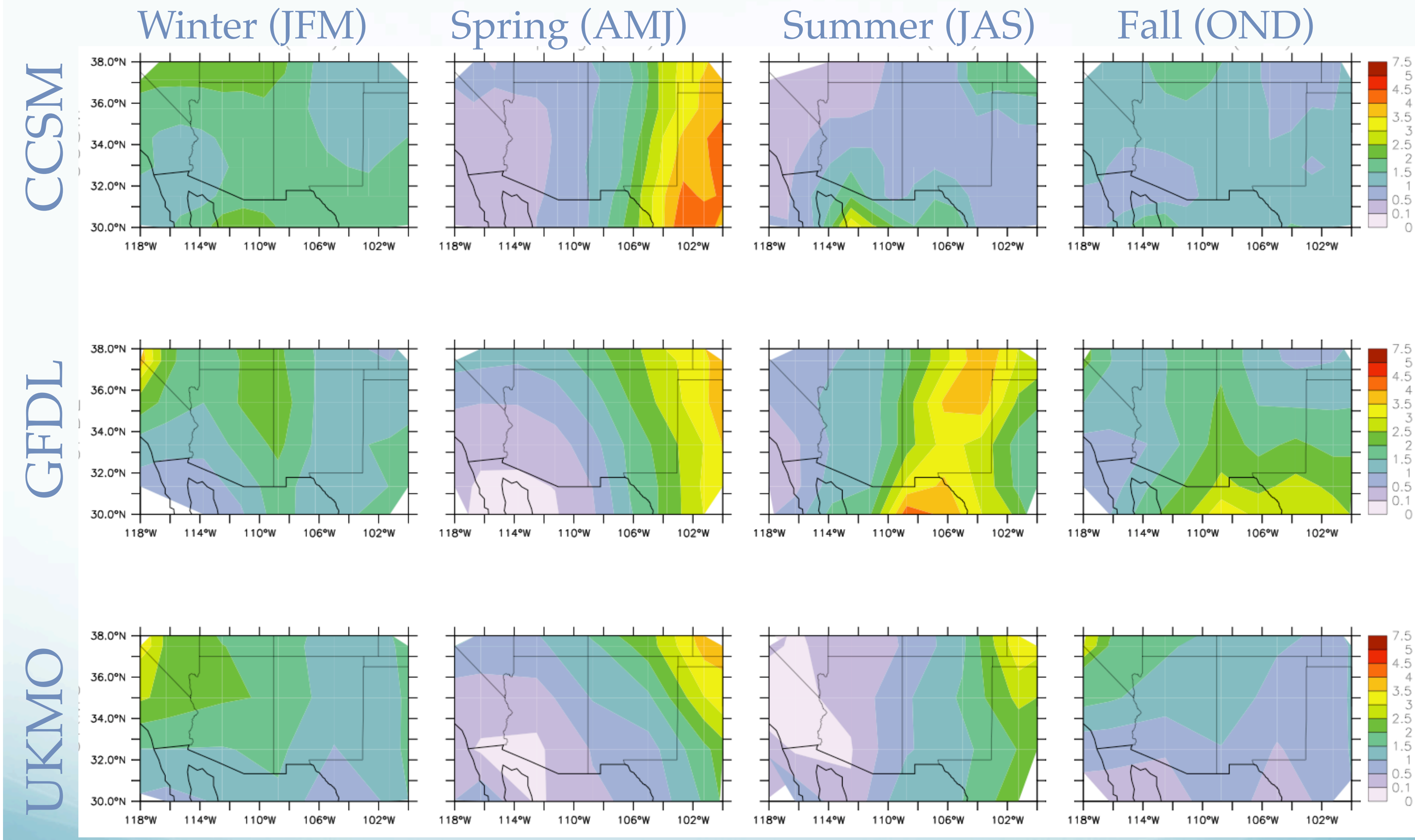


Modeled Surface Air Temperature Difference

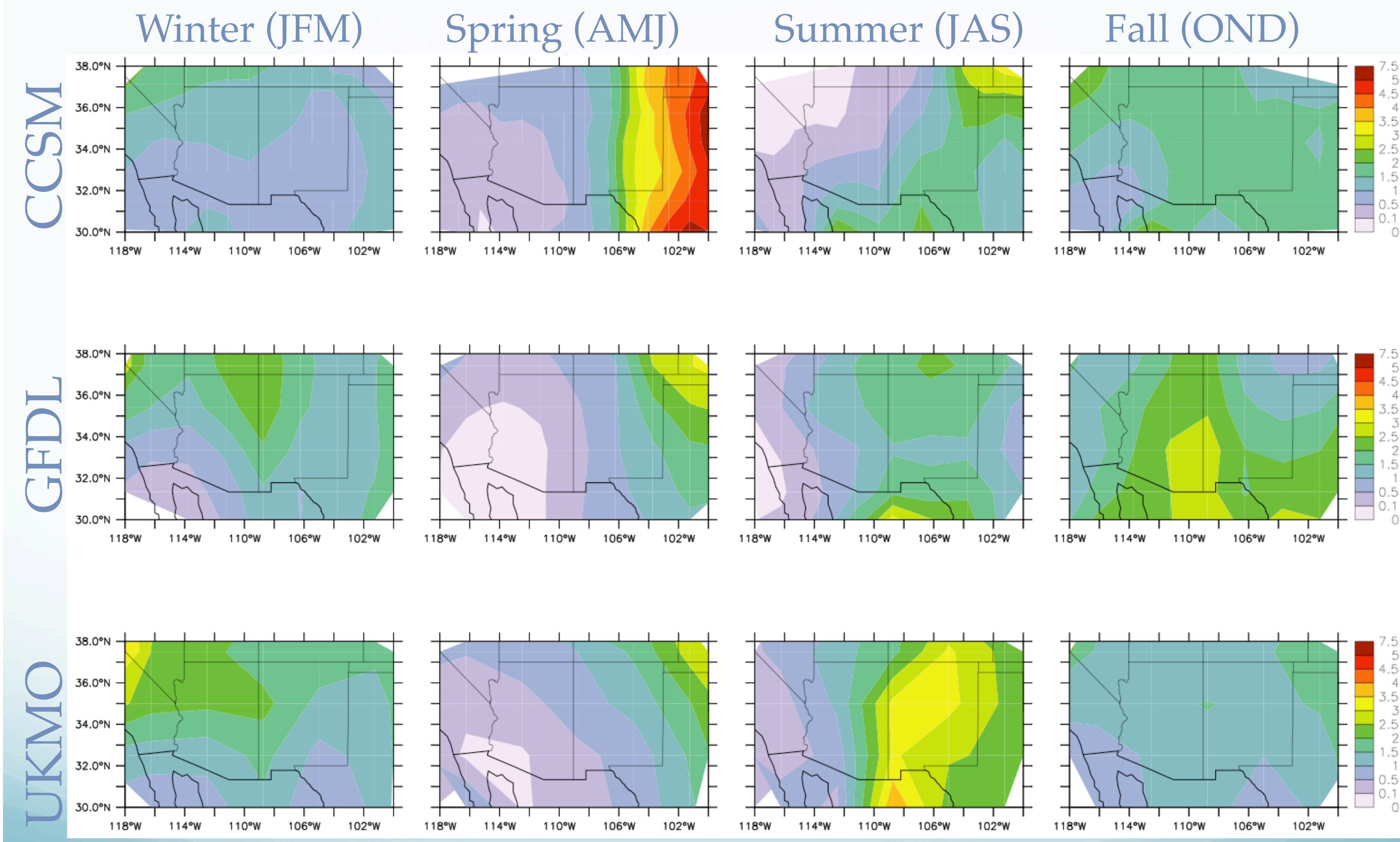
(°C, 2100-2000, A1B)



Modeled Mean Seasonal Precipitation (mm / day, 2001-2005, A1B)

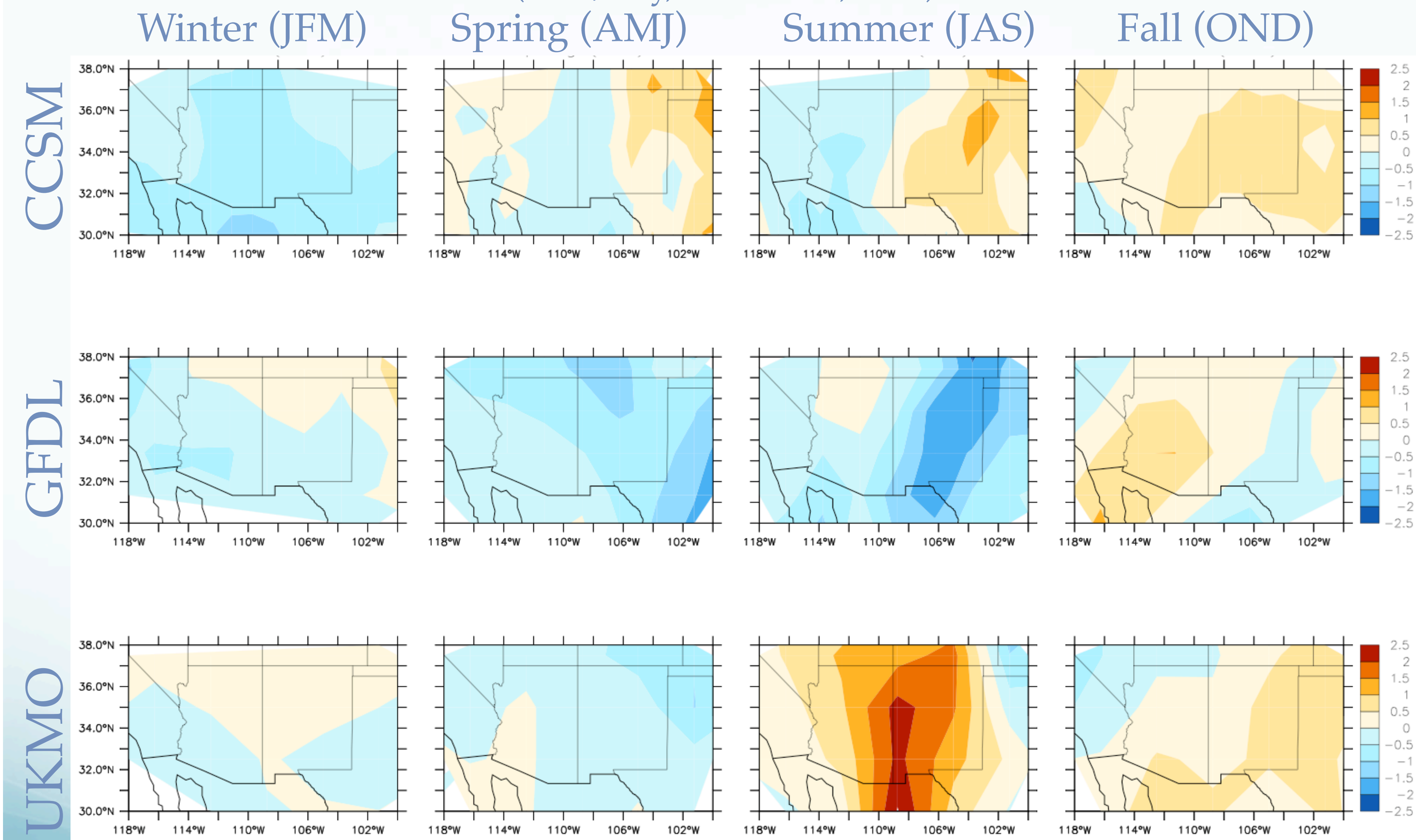


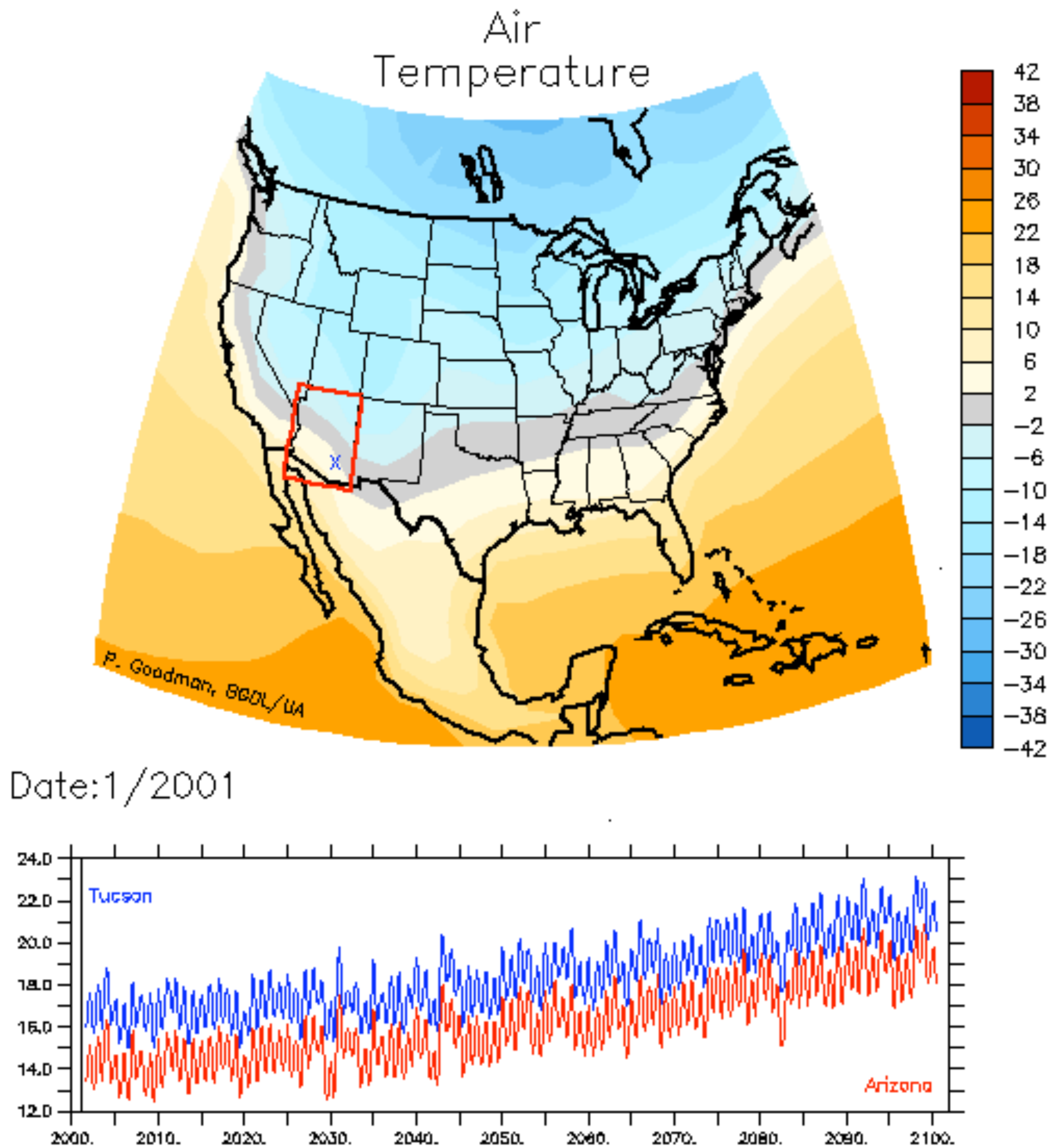
Modeled Mean Seasonal Precipitation (mm/day, 2096-2100, A1B)



Modeled Precipitation Change

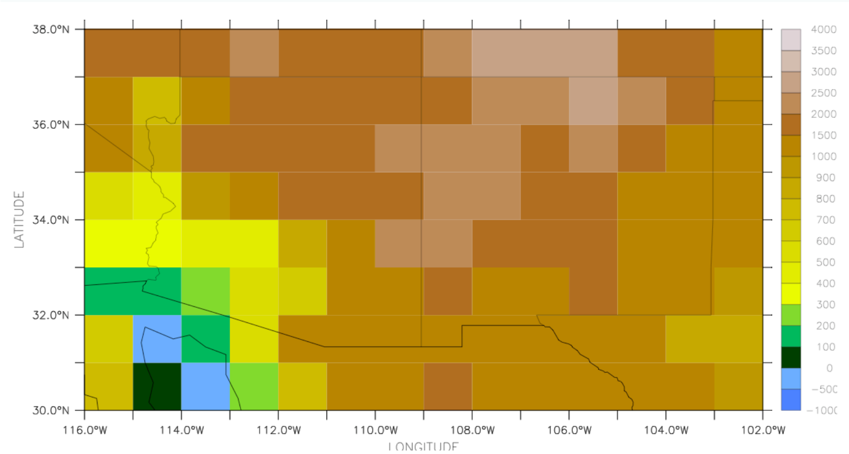
(mm/day, 2100-2000, A1B)



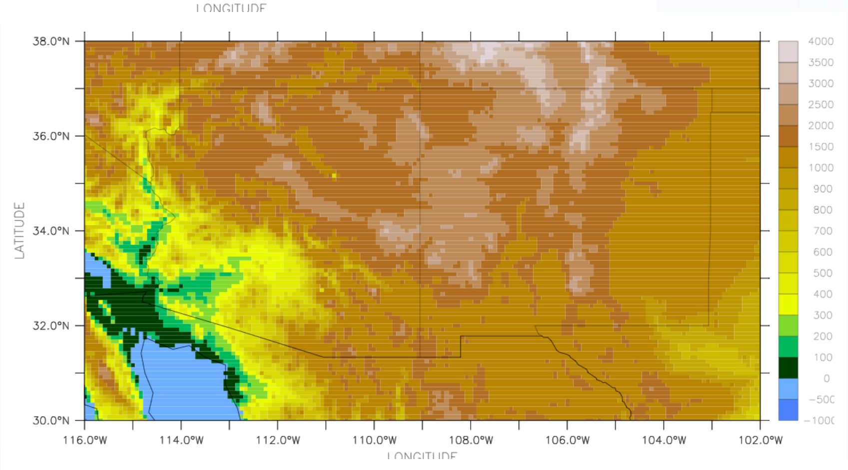


GFDL CM2.1 – SRES A1B

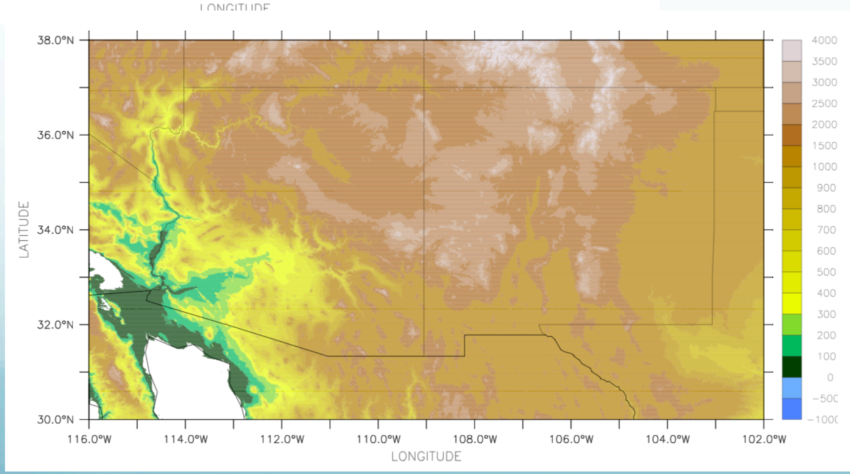
Resolution



1°x1°
(~111 km)



1/12°x1/12°
(~10 km)



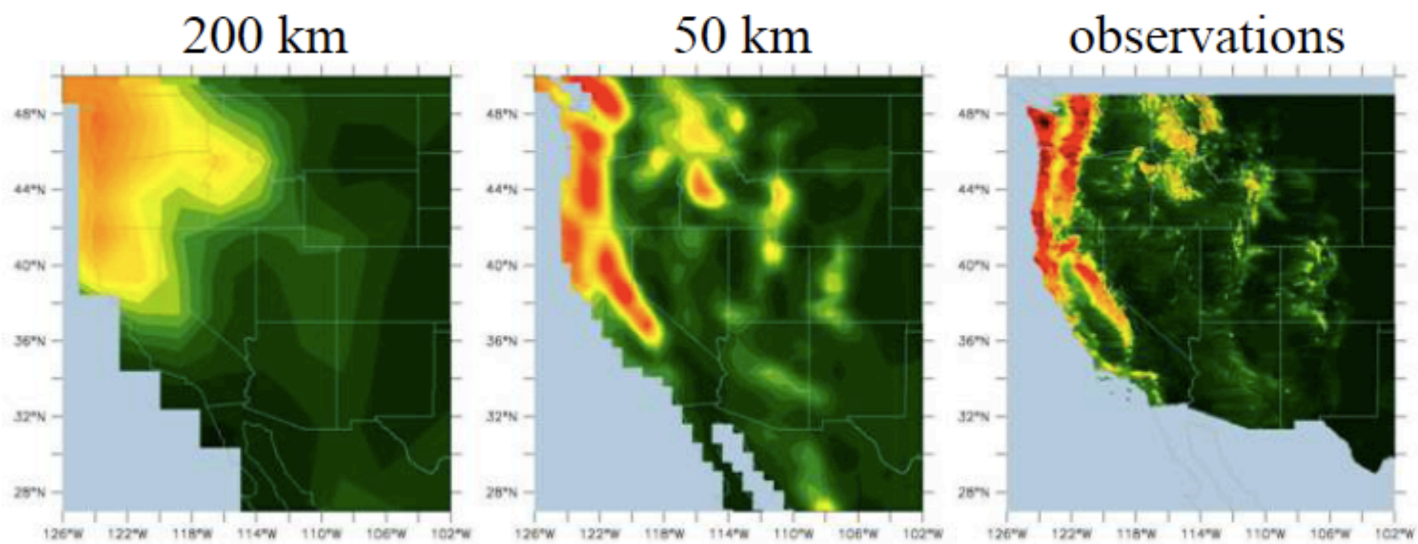
1/120°x1/120°
(~1 km)

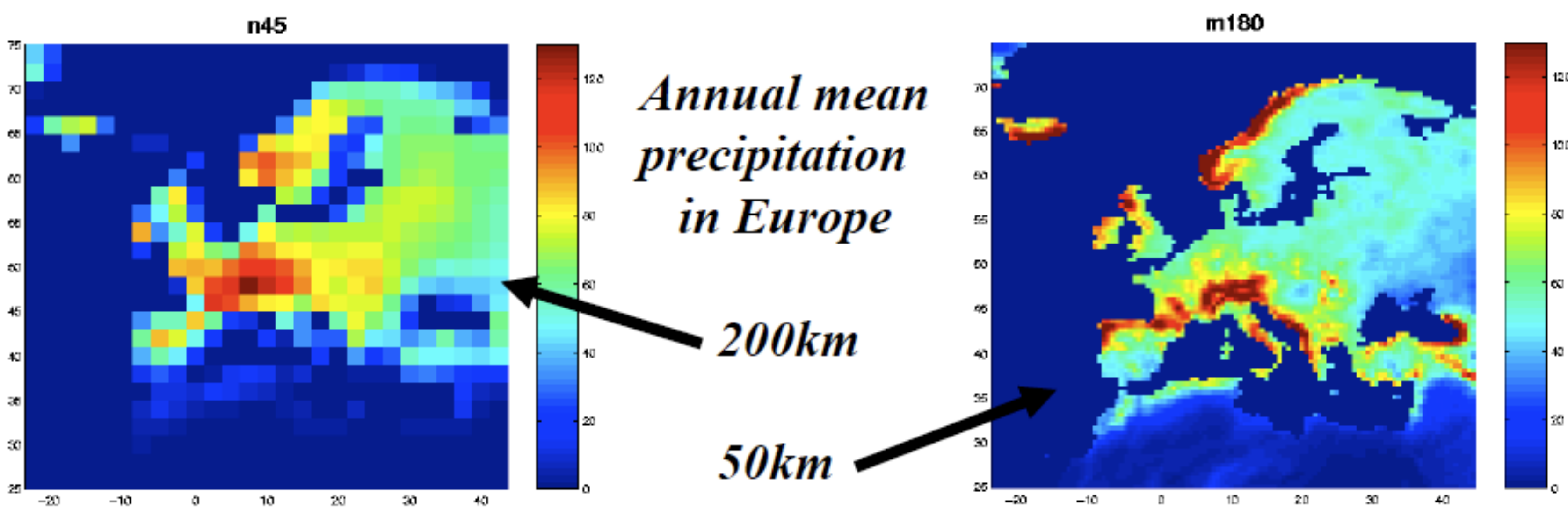
High-res atmosphere example #1:
Regional precipitation in AR4 global models compared to 50 km atmospheric models.

Winter mean precipitation in Western U.S. in GFDL models

Held and Wyman,
In prep, 2008

Lau et al , submitted on Indian monsoon simulation at 50km JAS, 2008





Regional Model Projections for the Southwest

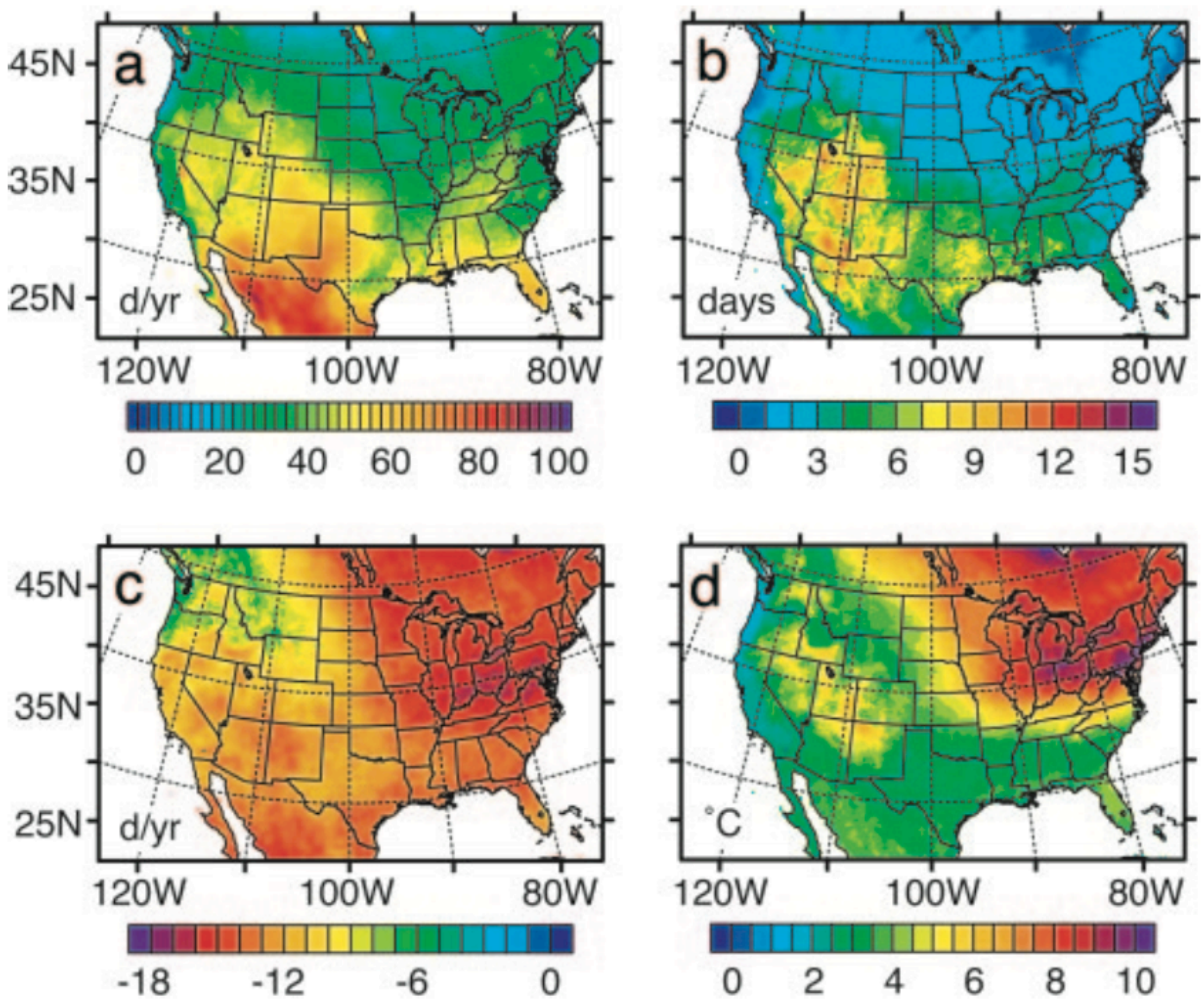


Fig. 1. Anomalies (*A2 − RF*) in T_{95} event frequency (days/year) (*a*), T_{95} mean heat-wave length (days/event) (*b*), T_{05} event frequency (days/year) (*c*), and 95th-percentile cold-event value (°C) (*d*). Only values for land and lake grid points that are statistically significant at the 95% confidence level are shown.

Diffenbaugh et al., 2005

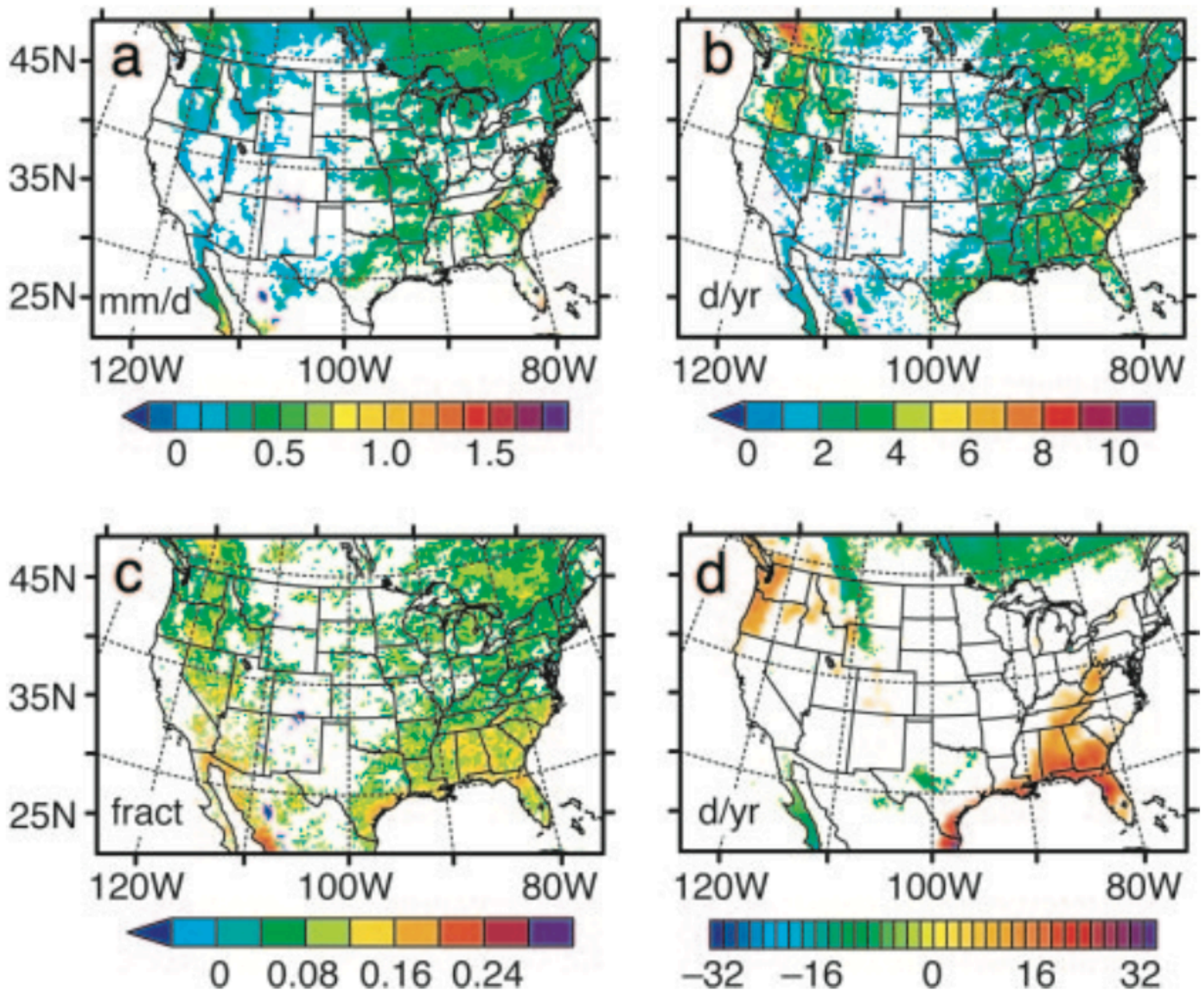
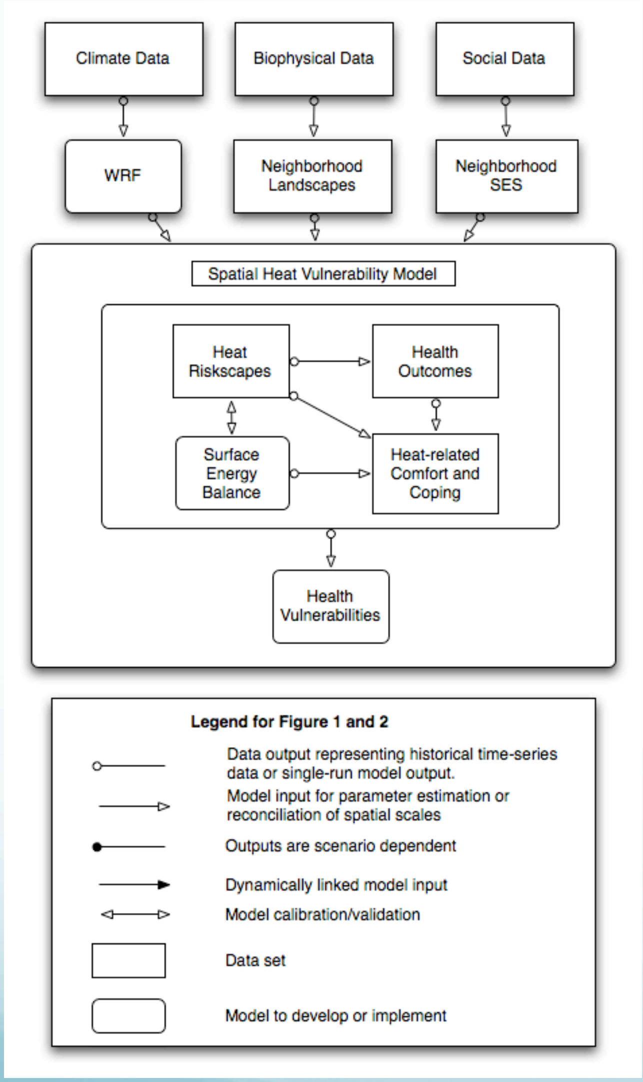
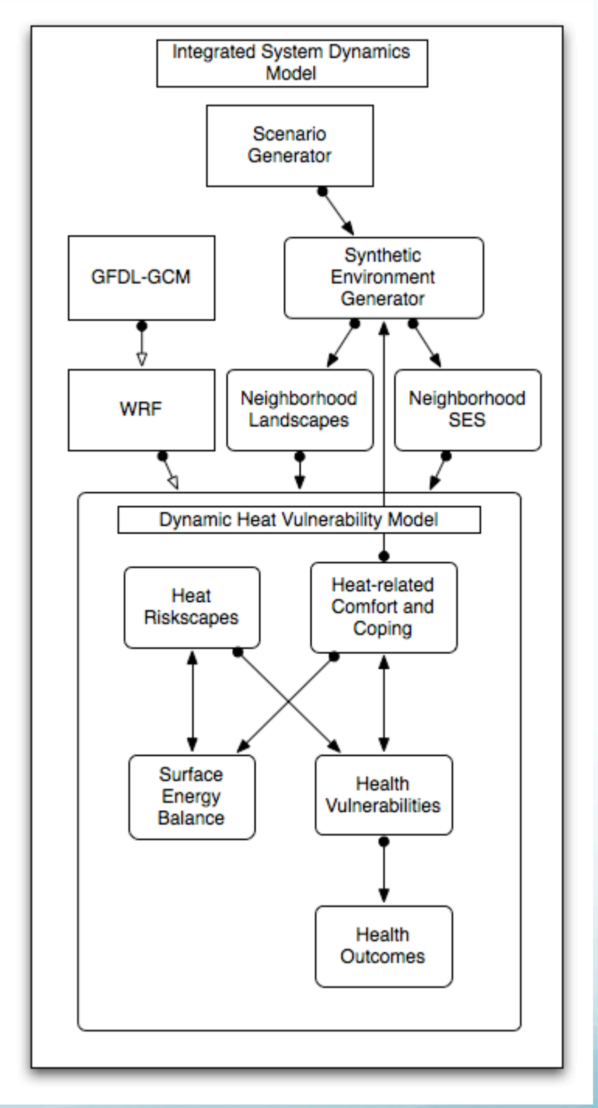


Fig. 3. Anomalies ($A2 - RF$) in mean annual precipitation (mm/day) (*a*), P_{95} event frequency (days/year) (*b*), extreme-precipitation fraction (fraction) (*c*), and dry-day frequency (days/year) (*d*). Only values for land and lake grid points that are statistically significant at the 95% confidence level are shown.

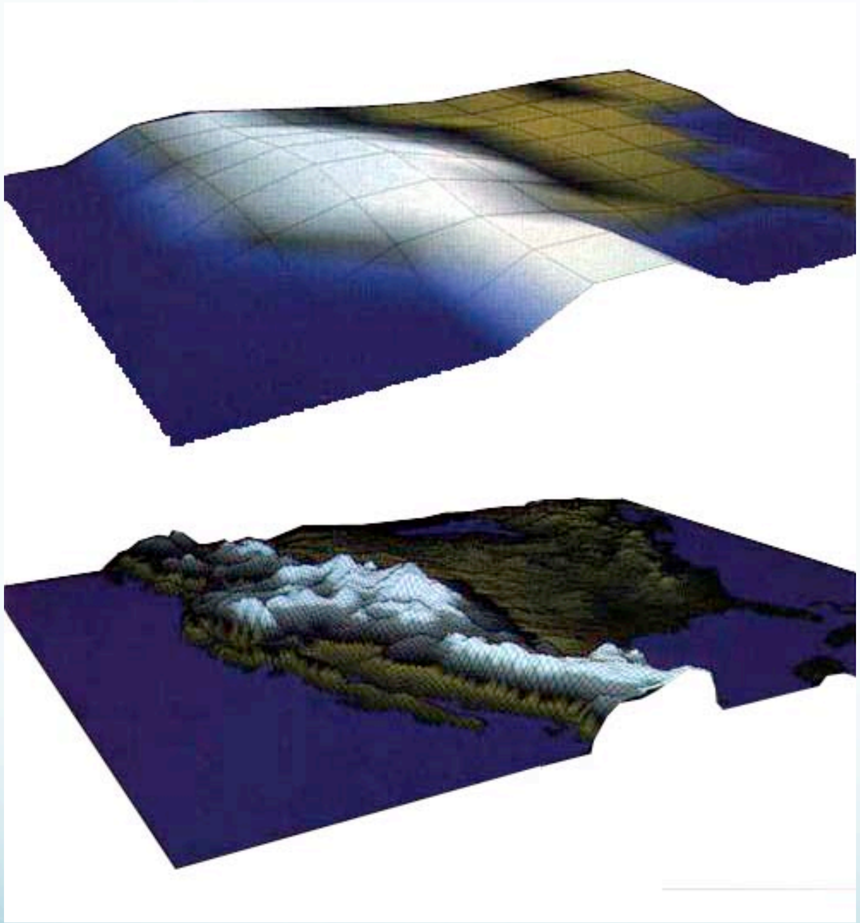
Diffenbaugh et al., 2005

System Dynamics Approach





Dynamic Downscaling of Global Climate Model Output using Regional Climate Models

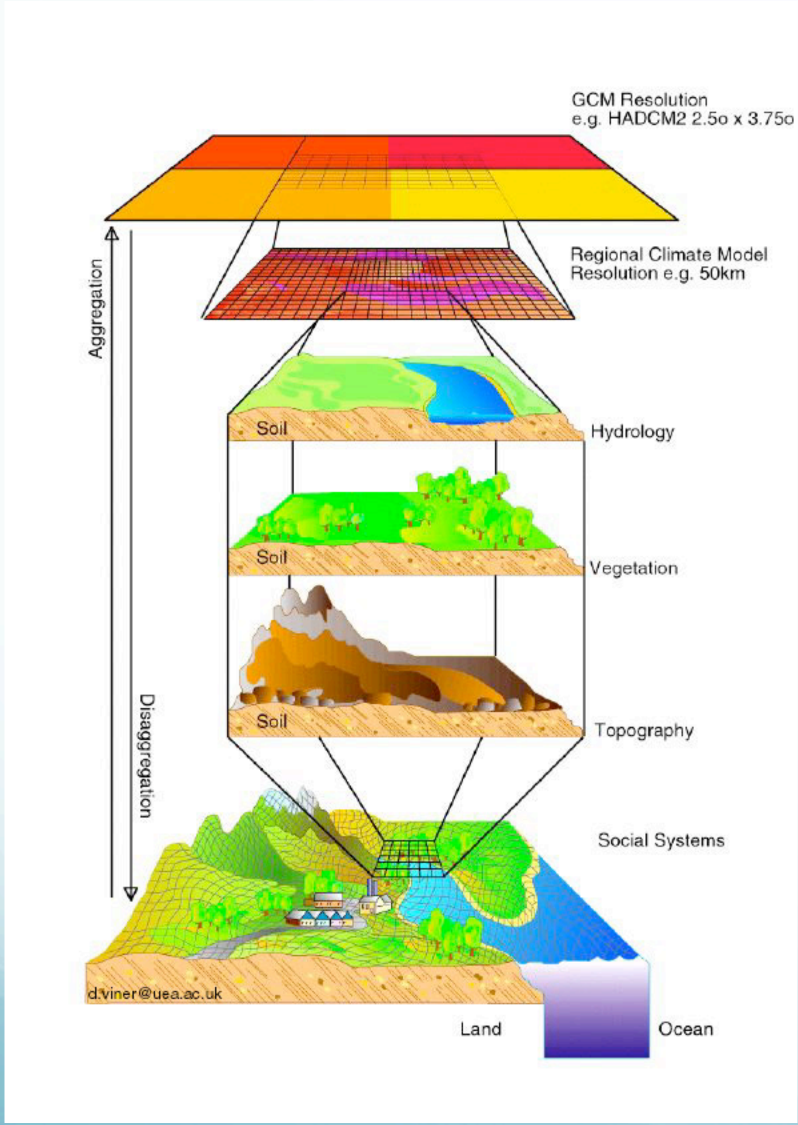


www.co2science.org/

Global Climate Model simulates large scale circulations. Spatial resolution is too low for capturing local effects.

Regional Climate Model receives initial and boundary conditions from Global Climate Model.

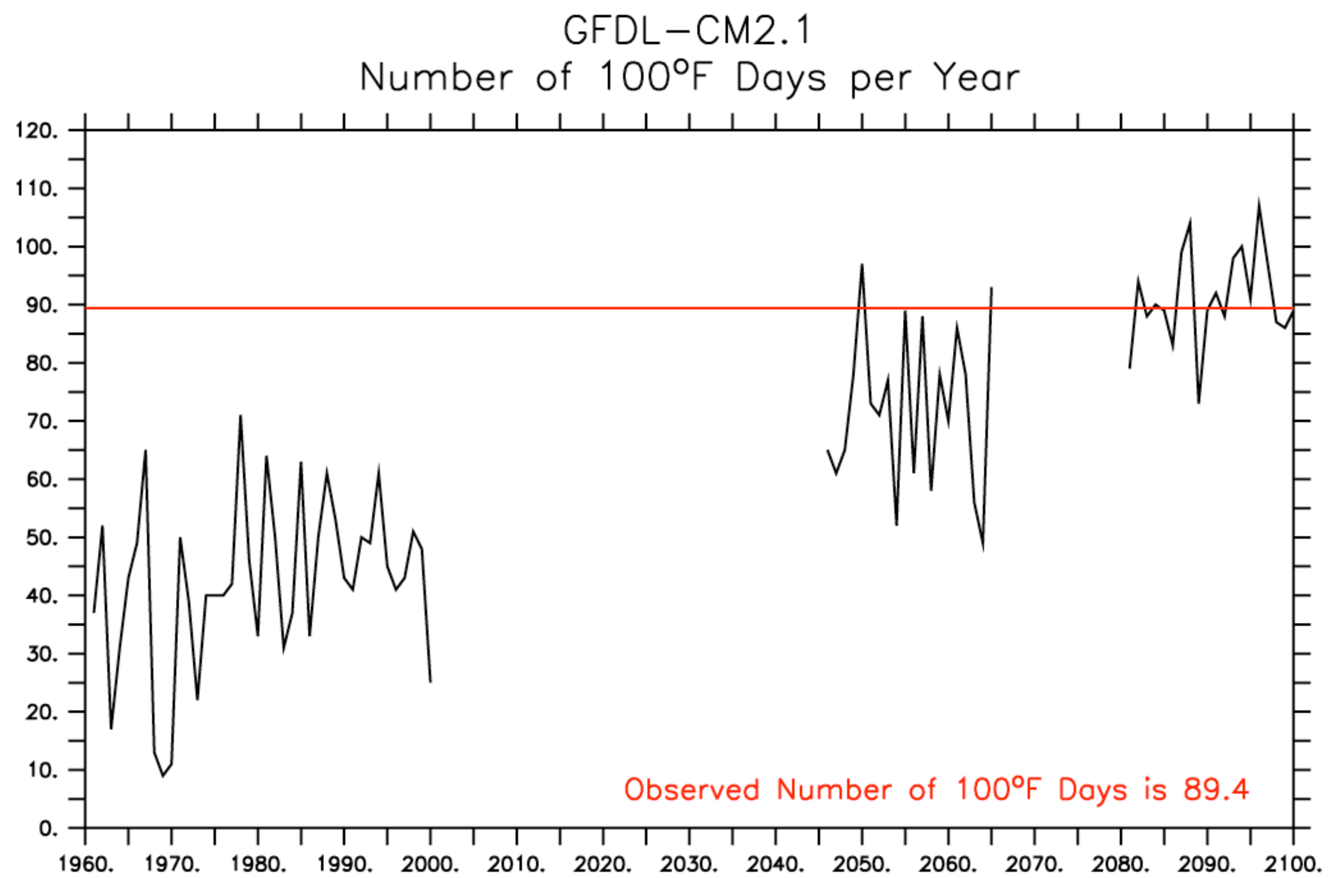
Dynamic Downscaling of Global Climate Model Output using Regional Climate Model



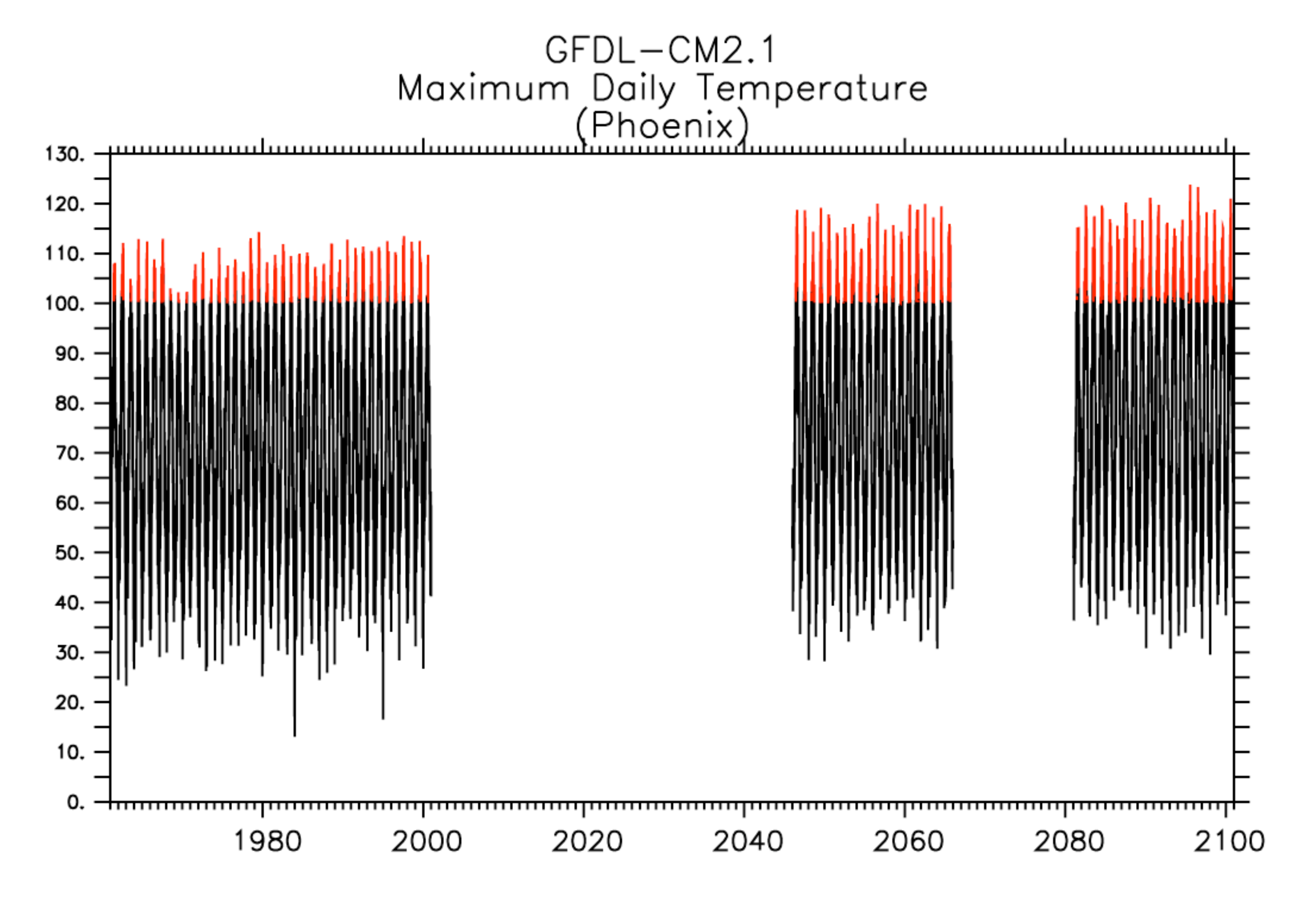
www.cccsn.ca/Help_and_Contact/_Downscaling-e.html

Regional climate model can consider effects of local terrain, land use/ cover, soil moisture on the atmosphere and therefore simulate variability of state of the atmosphere in a Global Climate Model grid cell.

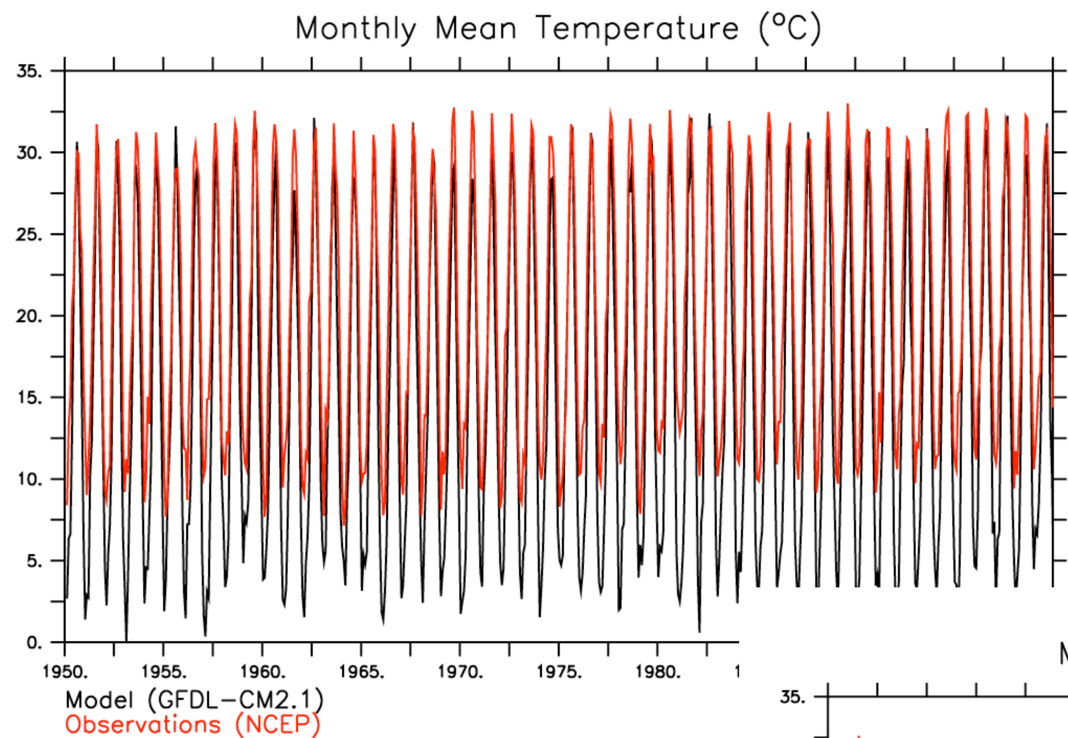
Ensemble simulations
Resolution
Domain position
Nested runs
Spectral nudging
One-way and two way nesting,
Restarts and long-term simulations



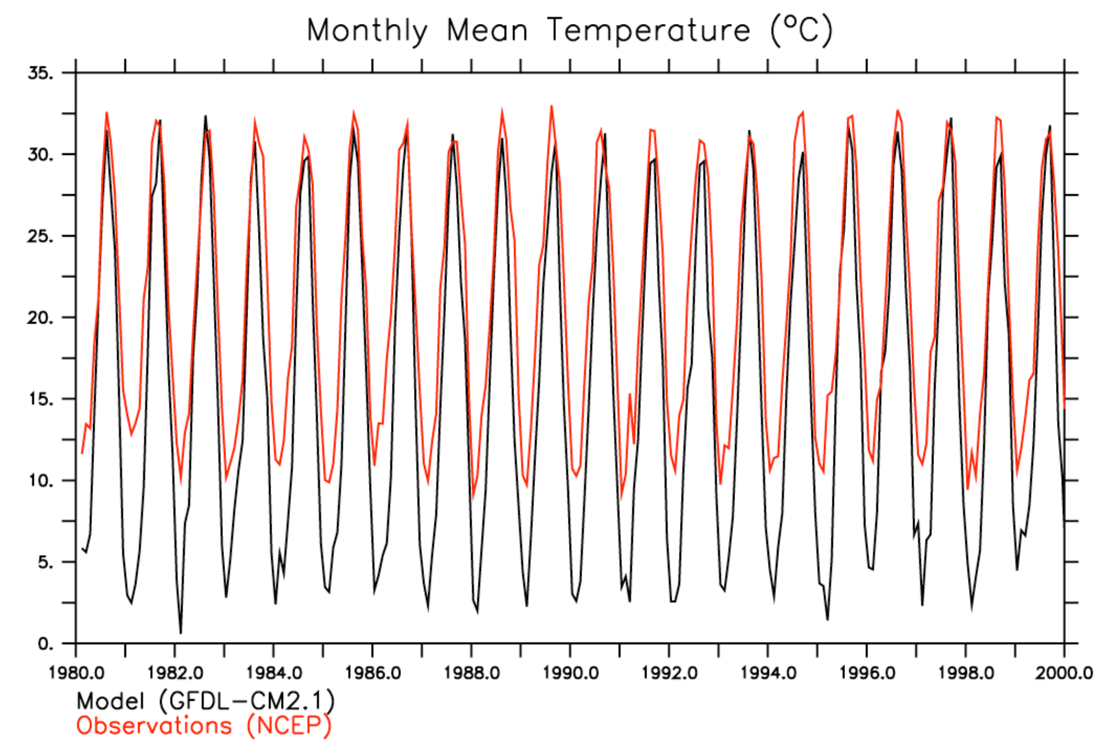
Phoenix is defined as (33.5°N, 112°W)



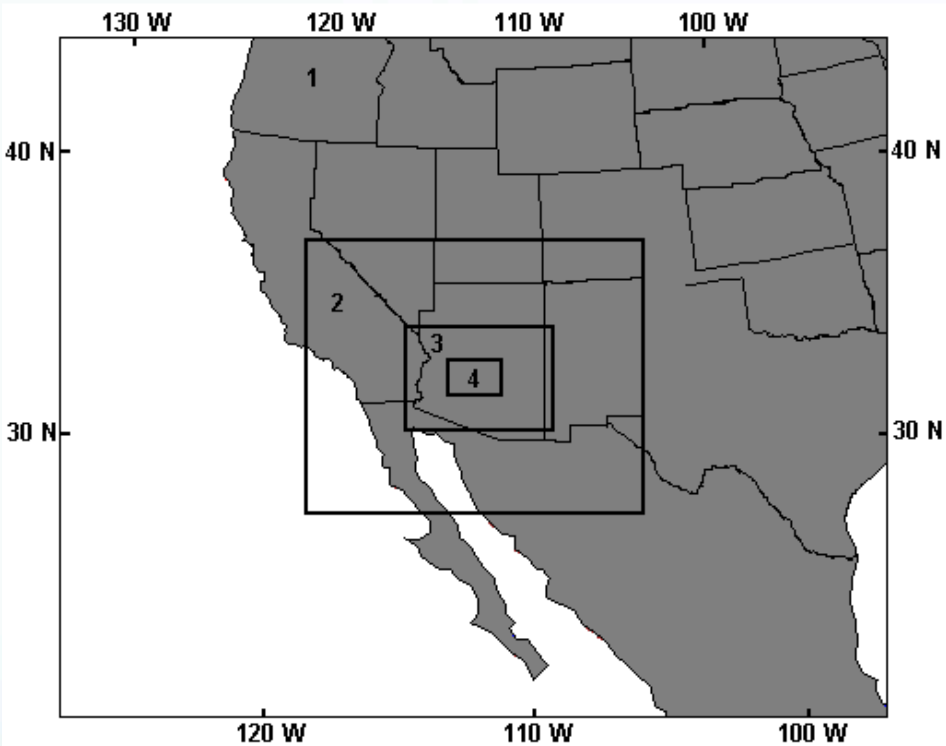
Phoenix is defined as (33.5°N, 112°W)



Phoenix is defined as (33.5°N, 112°W)



WRF Model Output



Simulations:

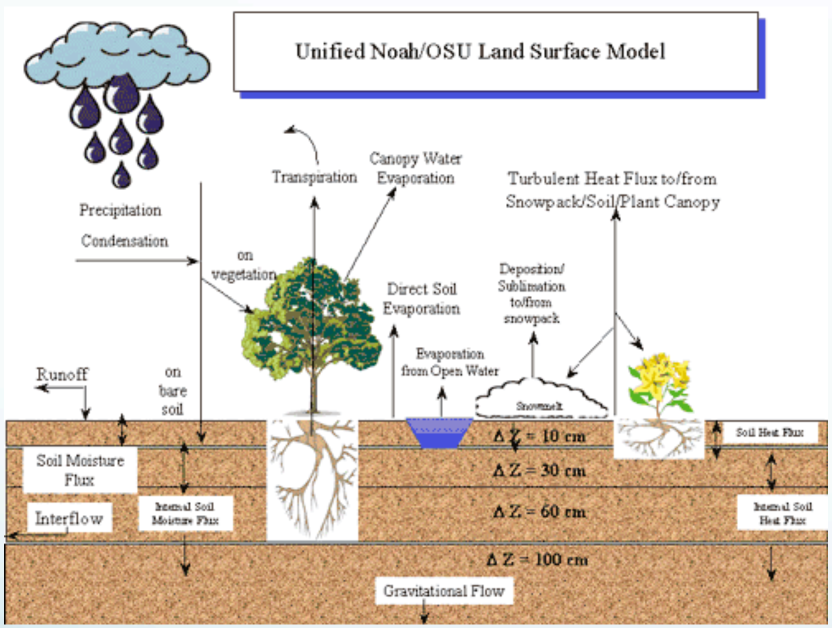
- **Hourly air temperature, humidity, wind speed for:**
  - **Past typical summer for model validation.**
  - **At least one future wet and dry summer.**

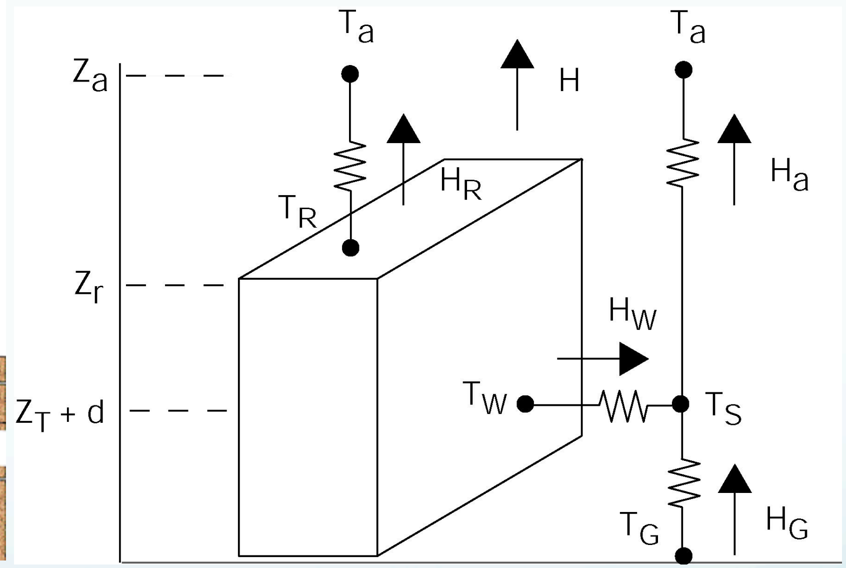
Computational Effort:

- **Simulations for 180 days per summer: ~ 540 days.**
- **1 day simulation needs ~ 3 CPU hours on IBM supercomputer or linux cluster -> 1620 CPU hours ~ 70 days.**

WRF Land Surface Model for Calculation of Urban Surface Energy Balance

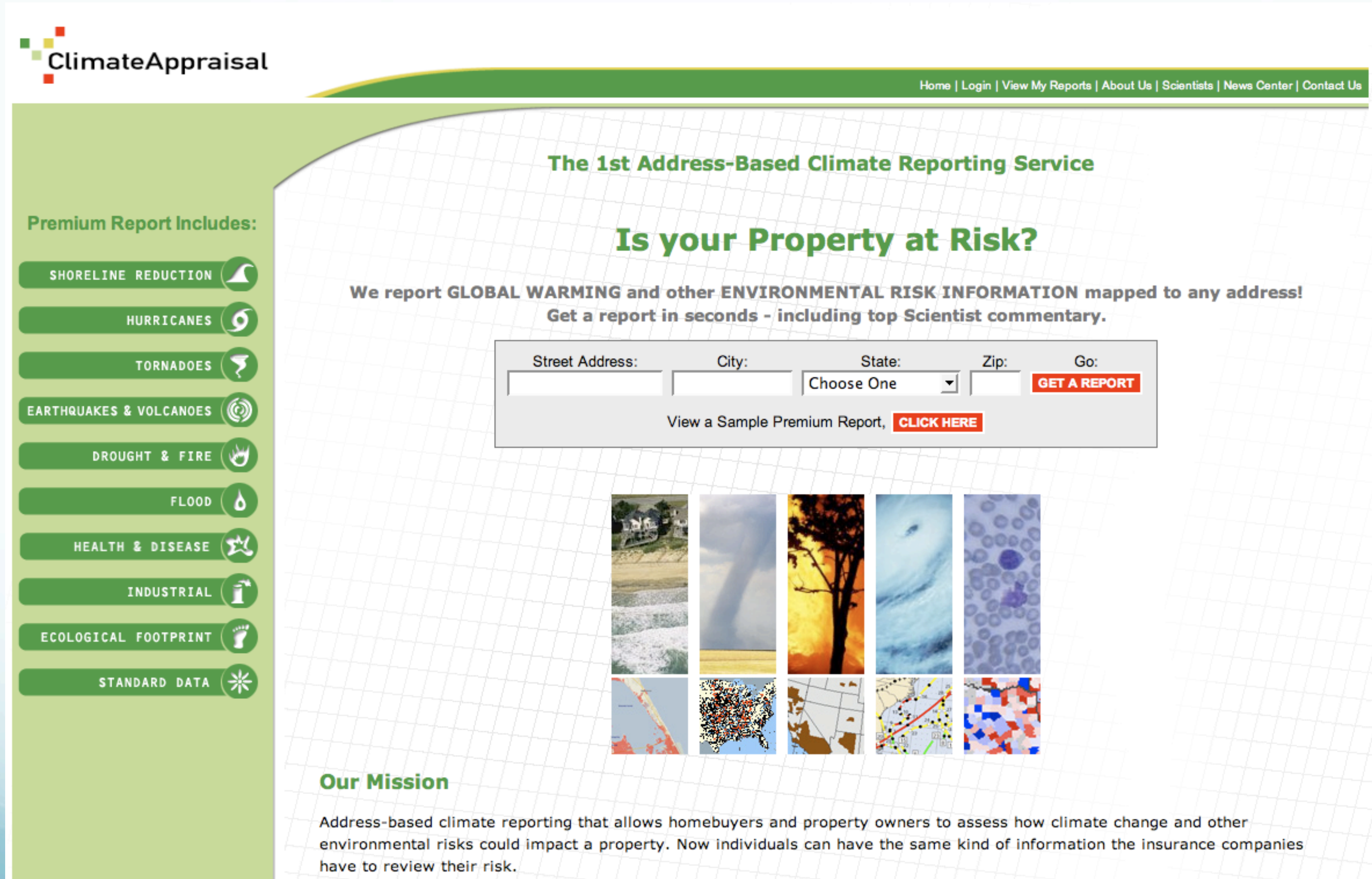
Noah Land Surface Model





Applied to fraction cover of natural surfaces vs. building/road surfaces in a model grid cell.

Bringing Climate Change to your House



Conclusions

While the current models have many challenges to overcome, the shift of the Westerlies is likely to contribute to:

- warming and drying in the Southwestern U.S.