Global Climate Models and Downscaling

What (the Heck) Are They and Why Should I Care?

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The Path Ahead...

- Describe what climate models are, what their strengths and limitations are, & why they are useful
- Discuss some ways to correctly (& incorrectly) interpret global climate models
- Describe what downscaling is, what some methods are, what their strengths and limitations are, & why downscaling is useful

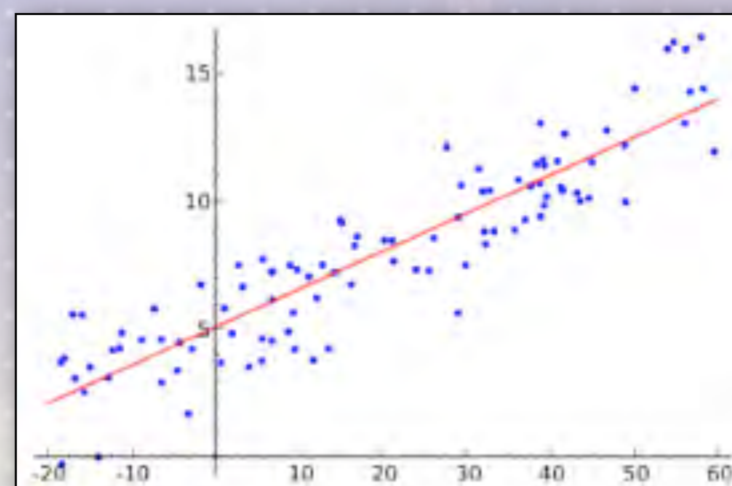
What is a “Model”?

- A model is a representation of an object, concept, system, etc. that is used by us to better understand that object, concept, system, etc.

Physical Model

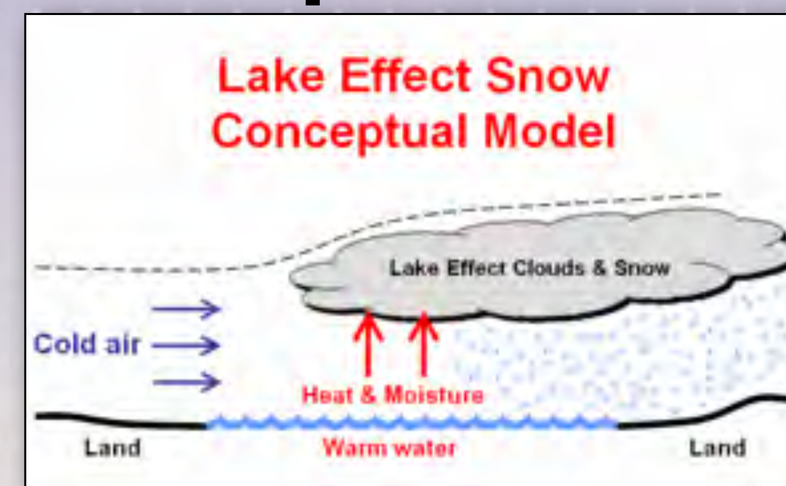
Sean Gallup/Getty Images

Statistical Model



Wikimedia

Conceptual Model



NOAA

Analytical Model

$$\frac{\mathrm{d}P}{\mathrm{d}t} = kP$$

Numerical Model

$$Population\ growth\ rate = \frac{P(t_2) - P(t_1)}{P(t_1)(t_2 - t_1)}$$

Why Do We Model the Climate?

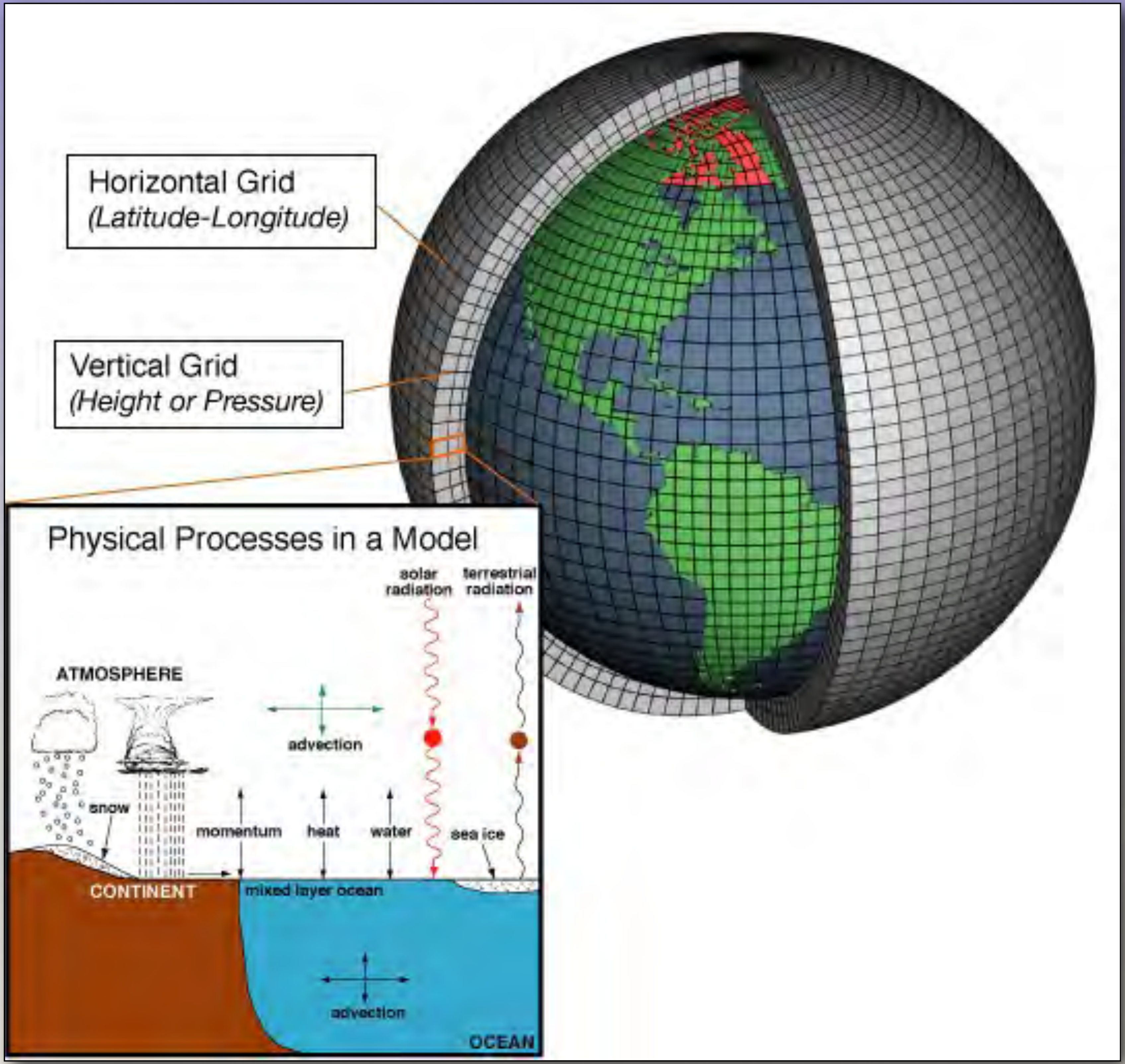
- To understand **how the processes & feedbacks impact** our contemporary climate & our paleoclimate, especially in areas/times with few measurements
- To project **what our future climate may be**
- To **experiment on our climate** over & over again to learn about what could happen if we change something in our system
- To **measure the influence of humans** by running models with & without manmade emissions ("fingerprint studies")

Numerical Modeling of Climate

- Numerical modeling uses computers and numerical methods to solve mathematical equations

- Basic steps:
  - Gather appropriate equations (i.e., algebraic & differential equations, parameterizations, statistical relationships) that adequately describe physical system
  - Simplify equations, as necessary, & use numerical/ computational methods to program equations for computers
  - Validate & calibrate the model
  - Run simulations
  - Analyze results

Global Climate Model (GCM)



"Essentially, all models are wrong, but some are useful"
– George E.P. Box

Governing Prognostic Equations for the Atmosphere

Conservation of momentum, energy, mass and moisture:

$$\frac{\partial \vec{V}}{\partial t} = -(\vec{V}\cdot\nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega}\times\vec{V} + \nabla\cdot(k_\omega \nabla\vec{V}) - \vec{F}_d$$

$$\rho c_p \frac{\partial T}{\partial t} = -\rho c_p(\vec{V}\cdot\nabla)T - \nabla\cdot\vec{R} + \nabla\cdot(k_\tau \nabla T) + C + S$$

$$\frac{\partial \rho}{\partial t} = -(\vec{V}\cdot\nabla)\rho - \rho(\nabla\cdot\vec{V})$$

$$\frac{\partial q}{\partial t} = -(\vec{V}\cdot\nabla)q + \nabla\cdot(k_q\nabla q) + S_q + E$$

Equation of state:

$$p = \rho R_d T$$

$V = velocity$

$T = temperature$

$p = pressure$

$\rho = density$

$q = specific\ humidity$

$g = gravity$

$\Omega = rotation\ of\ Earth$

$F_d = drag\ force\ of\ Earth$

$R = radiation\ vector$

$C = conductive\ heating$

$c_p = heat\ capacity, constant\ p$

$E = evaporation$

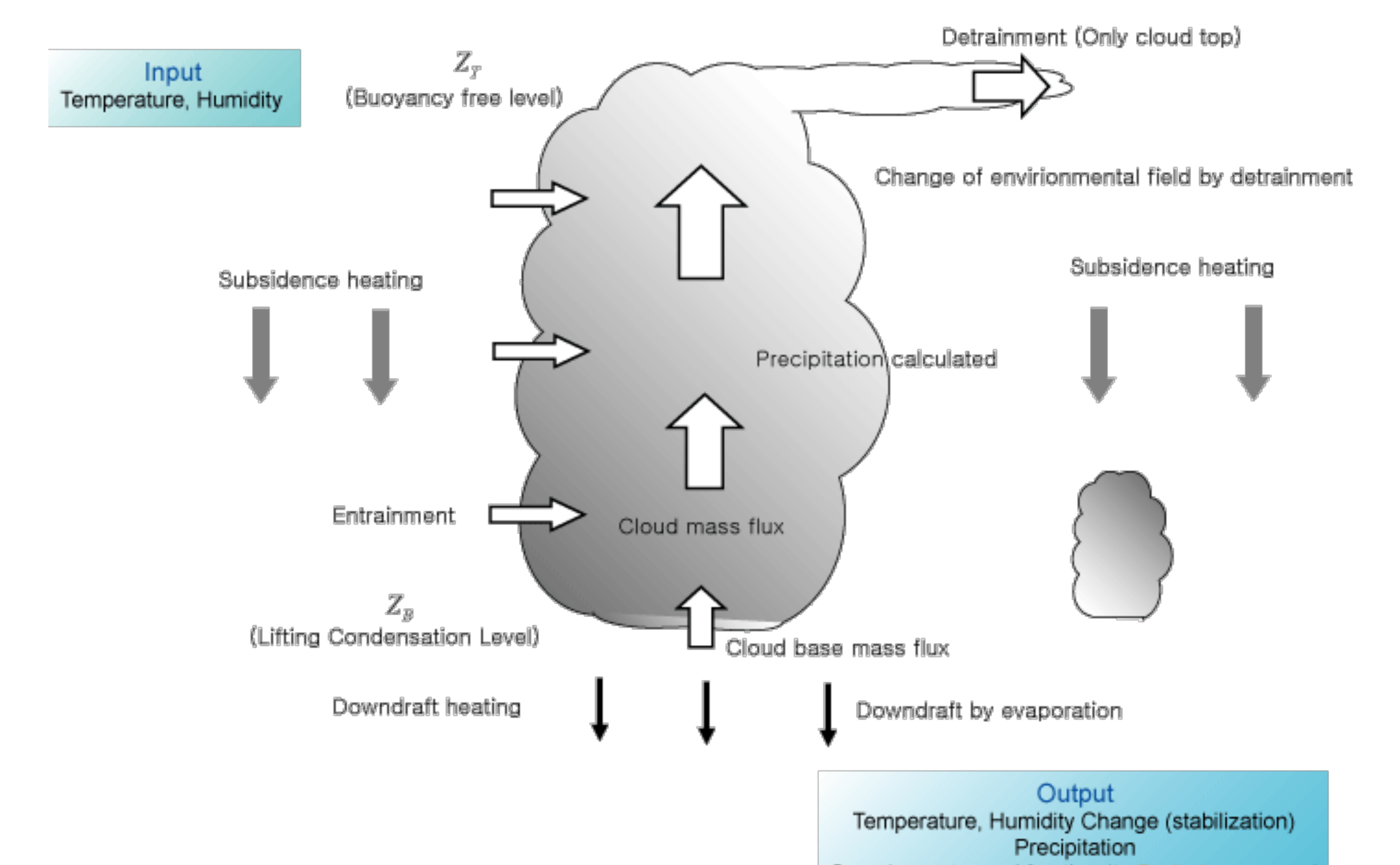
$S = latent\ heating$

$S_q = phase\ change\ source$

$k = diffusion\ coefficients$

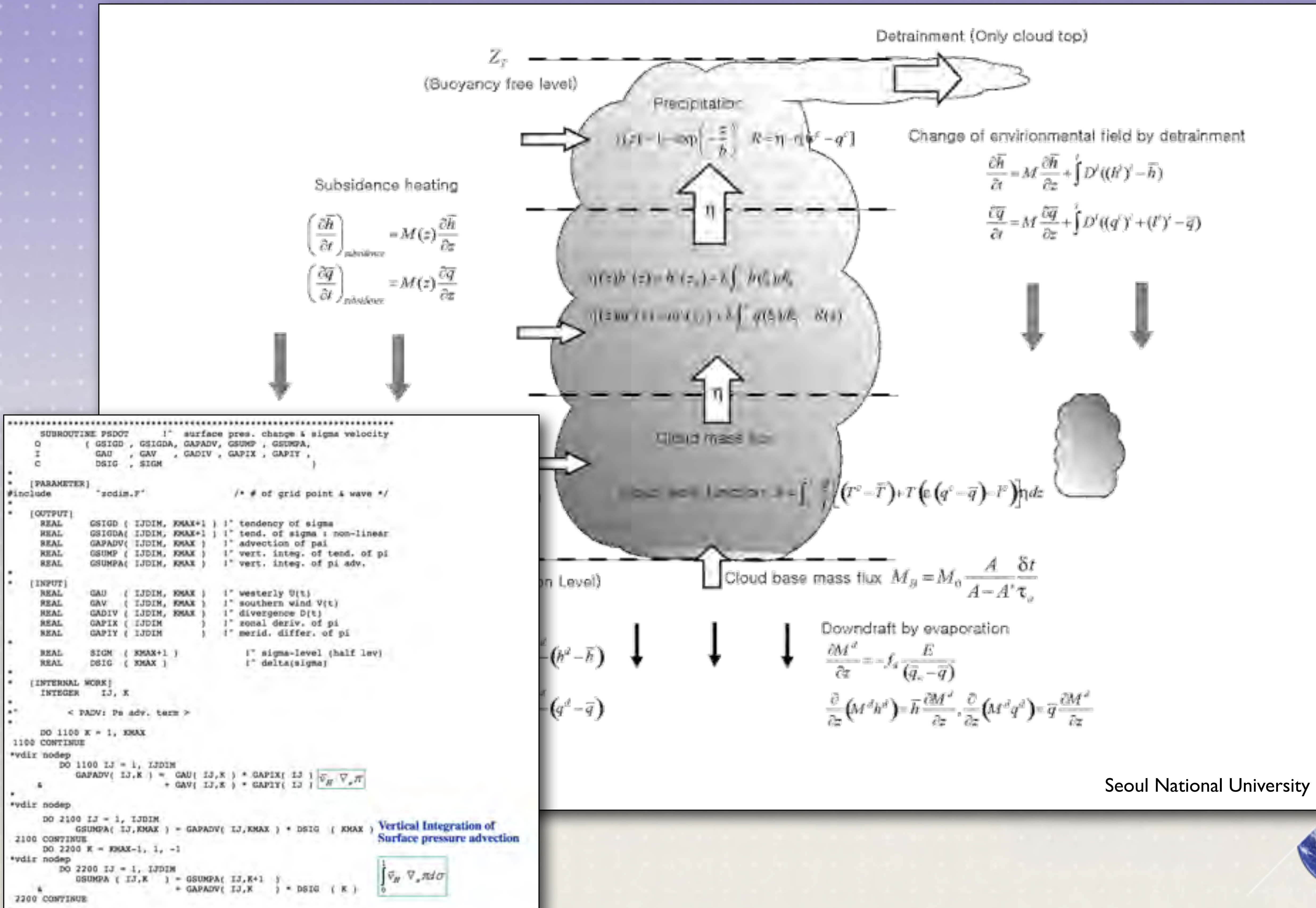
$R_d = dry\ air\ gas\ constant$

Parameterizations



Seoul National University

Parameterizations




```
***************************************************************************
      SUBROUTINE PSDOT      !" surface pres. change & sigma velocity
     O         ( GSIGD , GSIGDA, GAPADV, GSUMP , GSUMPA,
     I           GAU   , GAV   , GADIV , GAPIX , GAPIY ,
     C           DSIG  , SIGM                          )
*
*   [PARAMETER]
#include        "zcdim.F"                /* # of grid point & wave */
*
*   [OUTPUT]
      REAL     GSIGD ( IJDIM, KMAX+1 ) !" tendency of sigma
      REAL     GSIGDA( IJDIM, KMAX+1 ) !" tend. of sigma : non-linear
      REAL     GAPADV( IJDIM, KMAX )   !" advection of pai
      REAL     GSUMP ( IJDIM, KMAX )   !" vert. integ. of tend. of pi
      REAL     GSUMPA( IJDIM, KMAX )   !" vert. integ. of pi adv.
*
*   [INPUT]
      REAL     GAU   ( IJDIM, KMAX )   !" westerly U(t)
      REAL     GAV   ( IJDIM, KMAX )   !" southern wind V(t)
      REAL     GADIV ( IJDIM, KMAX )   !" divergence D(t)
      REAL     GAPIX ( IJDIM       )   !" zonal deriv. of pi
      REAL     GAPIY ( IJDIM       )   !" merid. differ. of pi
*
      REAL     SIGM  ( KMAX+1 )            !" sigma-level (half lev)
      REAL     DSIG  ( KMAX )              !" delta(sigma)
*
*   [INTERNAL WORK]
      INTEGER    IJ, K
*
*"         < PADV: Ps adv. term >
*
      DO 1100 K = 1, KMAX
 1100 CONTINUE
*vdir nodep
         DO 1100 IJ = 1, IJDIM
            GAPADV( IJ,K ) =  GAU( IJ,K ) * GAPIX( IJ )
     &                      + GAV( IJ,K ) * GAPIY( IJ )
*
*vdir nodep
      DO 2100 IJ = 1, IJDIM
            GSUMPA( IJ,KMAX ) = GAPADV( IJ,KMAX ) * DSIG  ( KMAX )
 2100 CONTINUE
      DO 2200 K = KMAX-1, 1, -1
*vdir nodep
         DO 2200 IJ = 1, IJDIM
            GSUMPA ( IJ,K   ) = GSUMPA( IJ,K+1  )
     &                        + GAPADV( IJ,K    ) * DSIG  ( K )
 2200 CONTINUE
*
```

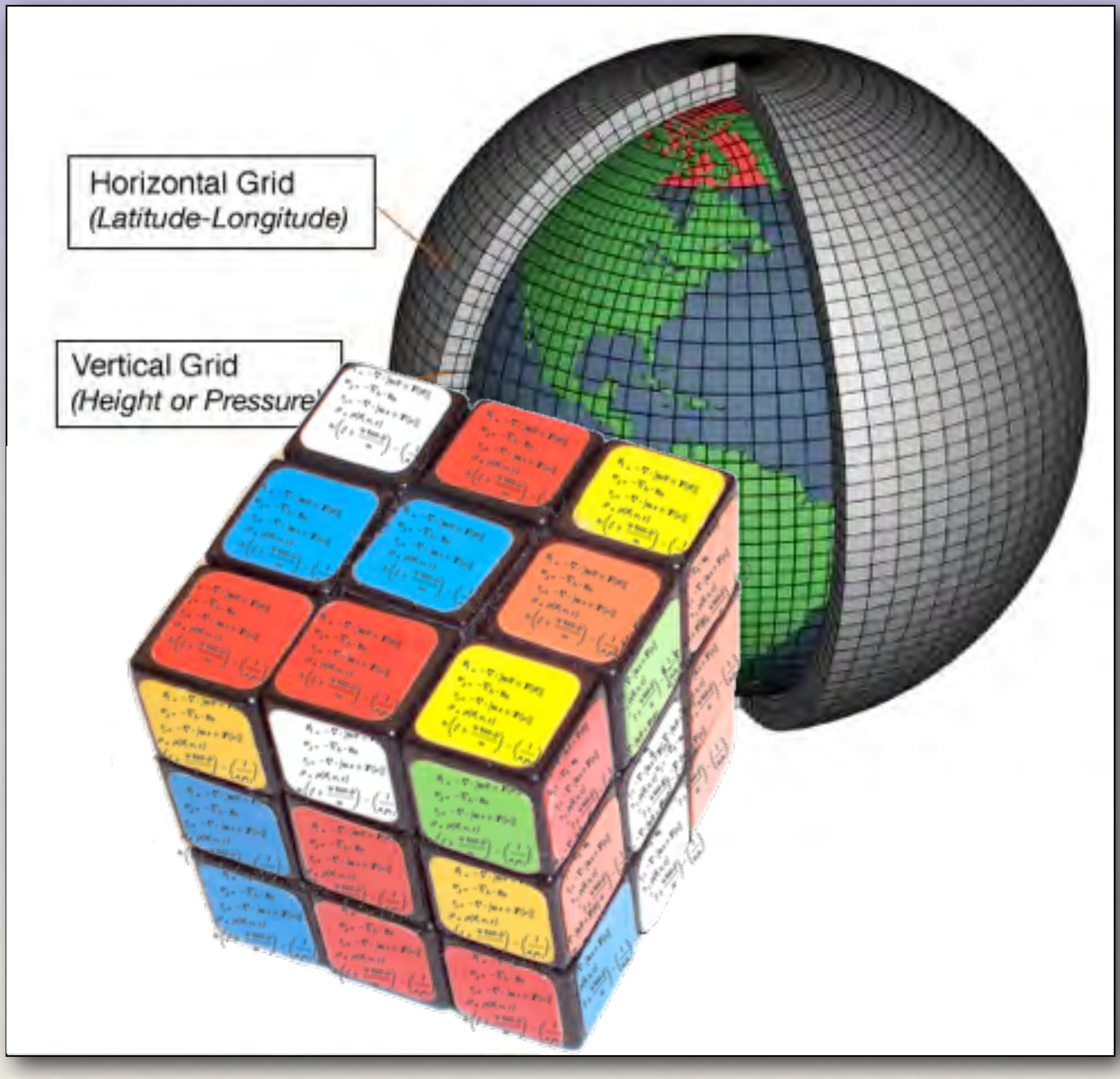
$\vec{v}_H \cdot \nabla_\sigma \pi$

Vertical Integration of Surface pressure advection

$\int_0^1 \vec{v}_H \cdot \nabla_\sigma \pi d\sigma$

Global Climate Model (GCM)

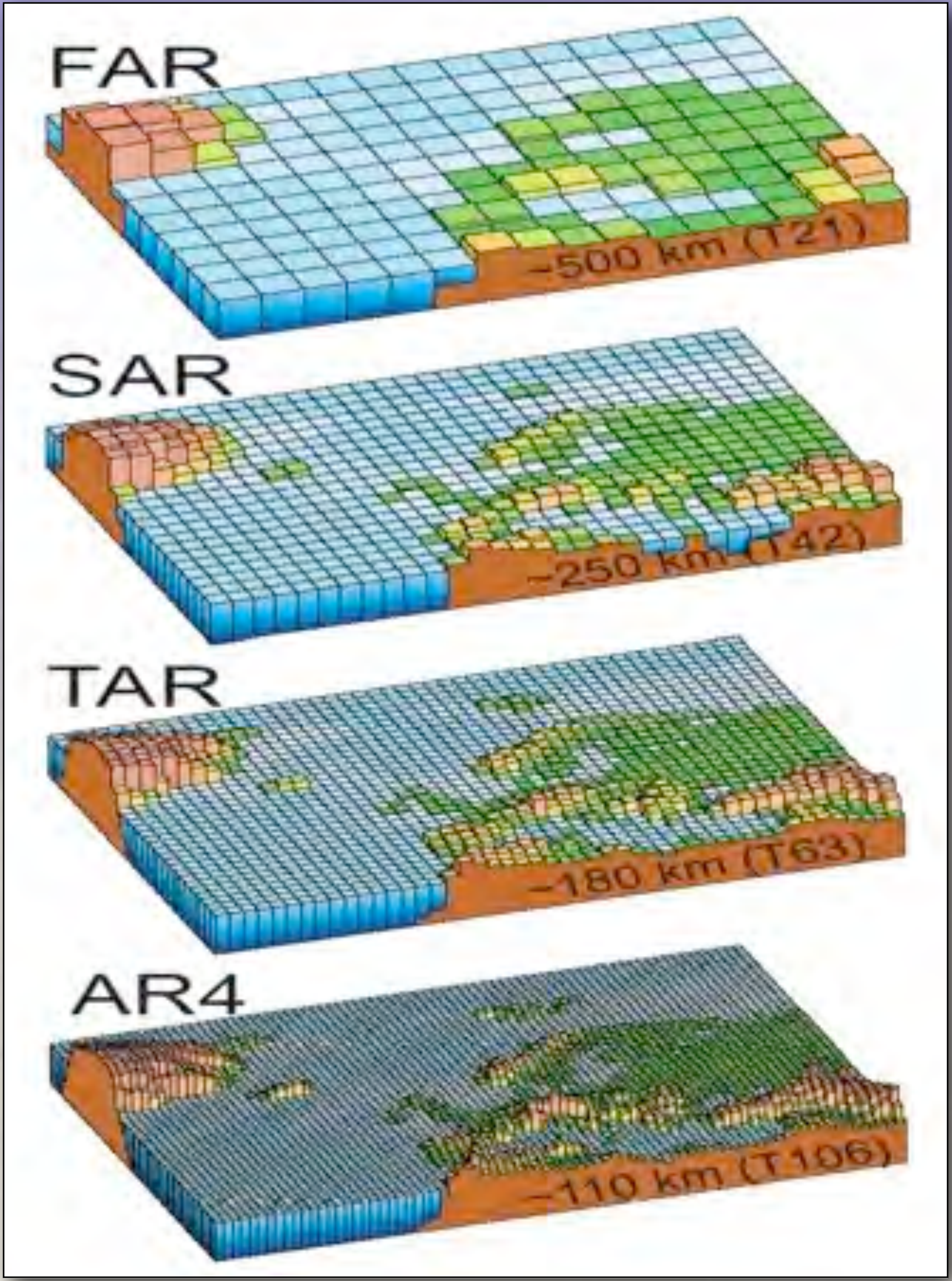
- Calculates temperature, moisture, wind, pressure, etc. at all of the "grid points" for every time step (10-20 minutes) over hundreds of years

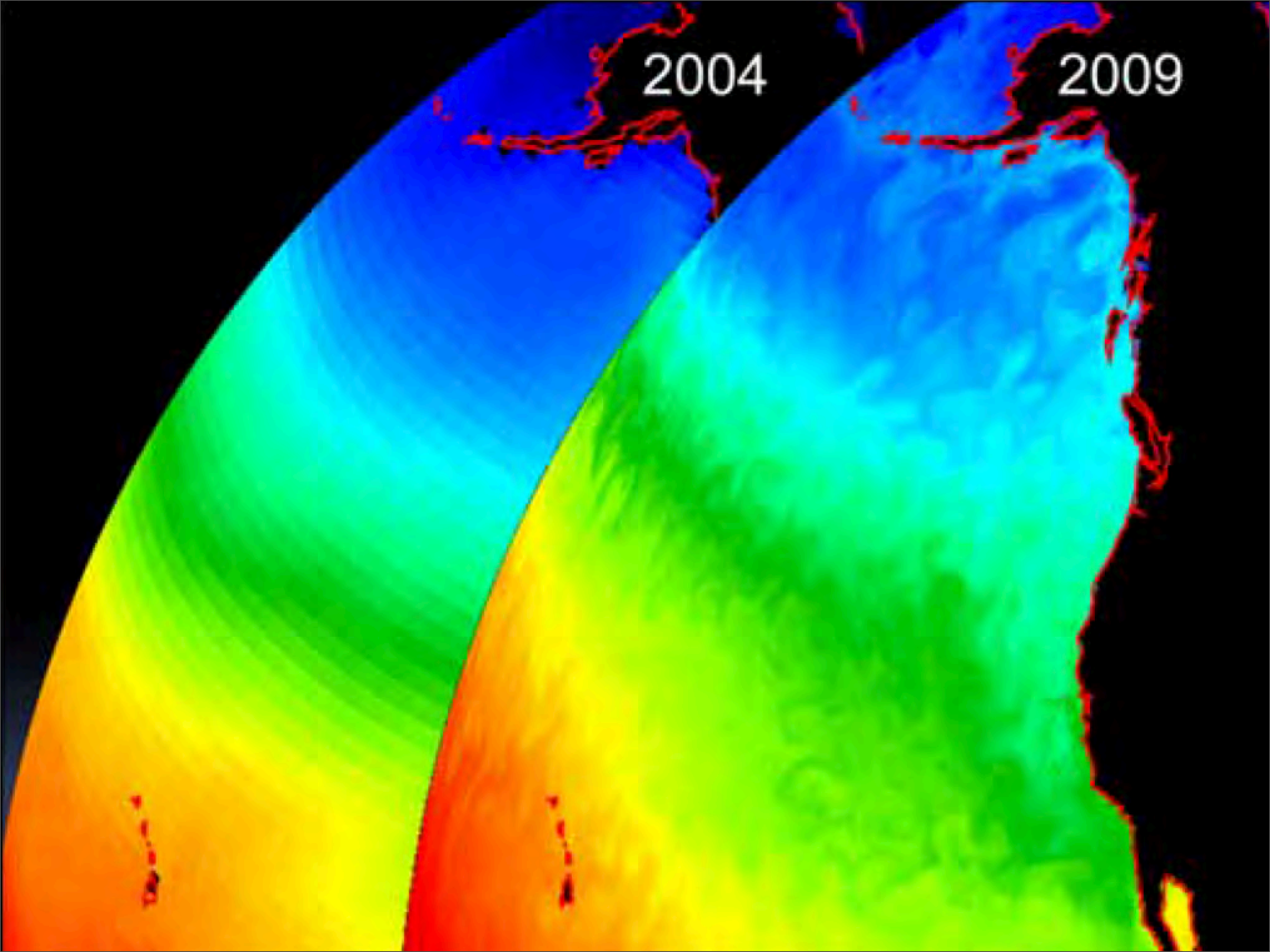


- Current GCMs calculate at ~70 million points, which would be as many grid points as more than 2½ million Rubik's cubes

Evolution of Model Resolution

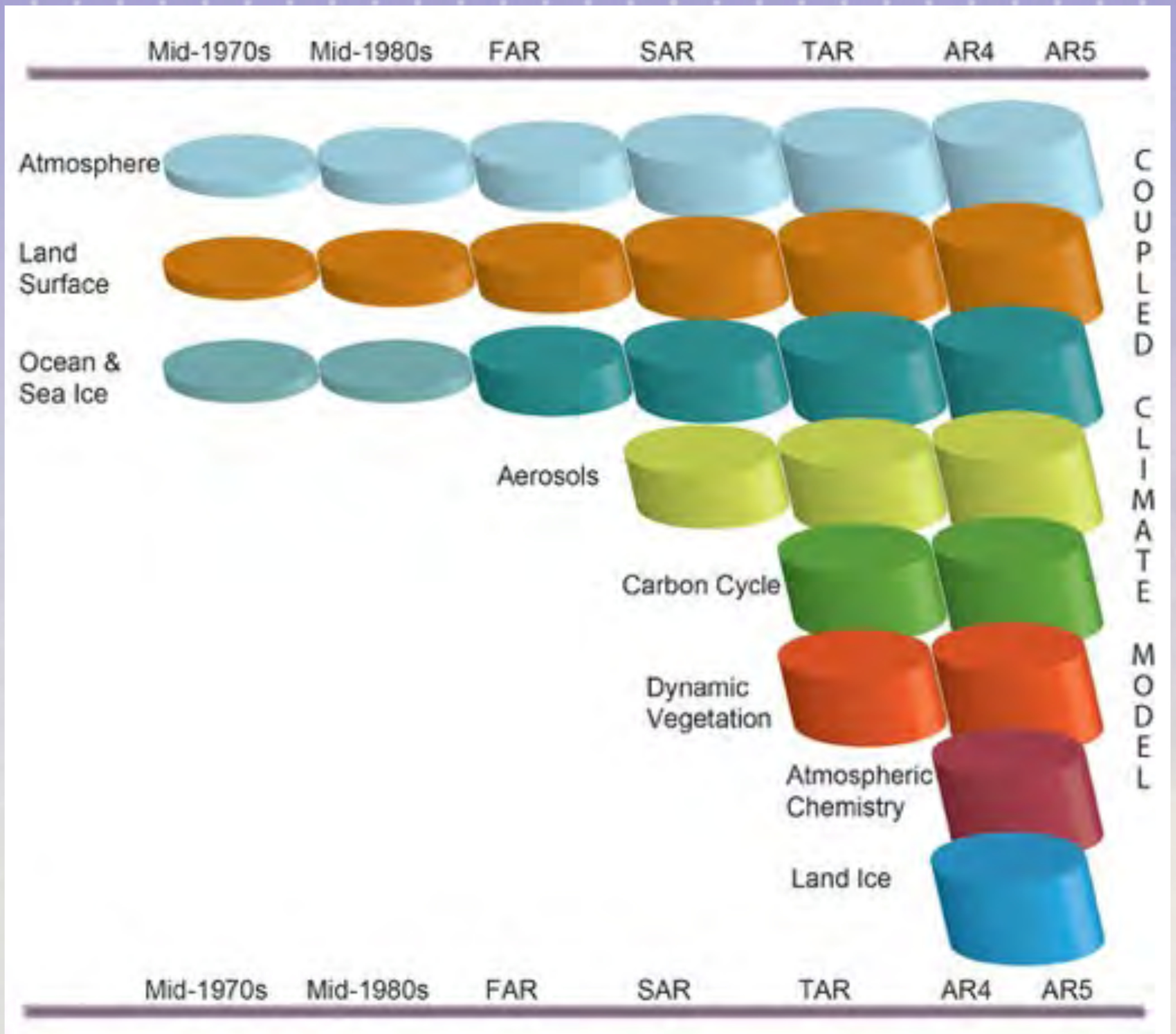
- FAR = First Assessment Report (IPCC; 1990)
- SAR = Second Assessment Report (1996)
- TAR = Third Assessment Report (2001)
- AR4 = Fourth Assessment Report (2007)
- AR5 = Fifth Assessment Report (2014)

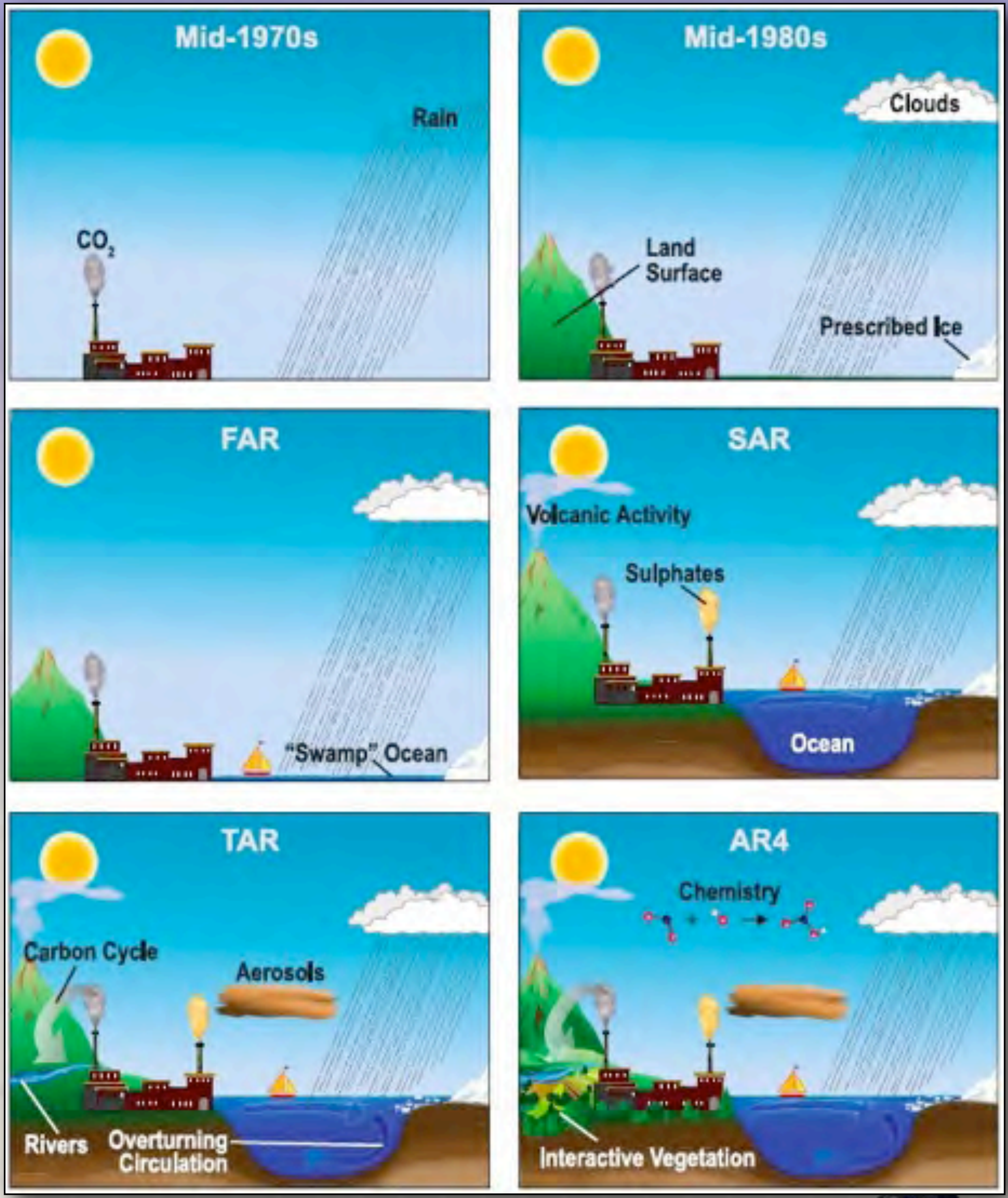




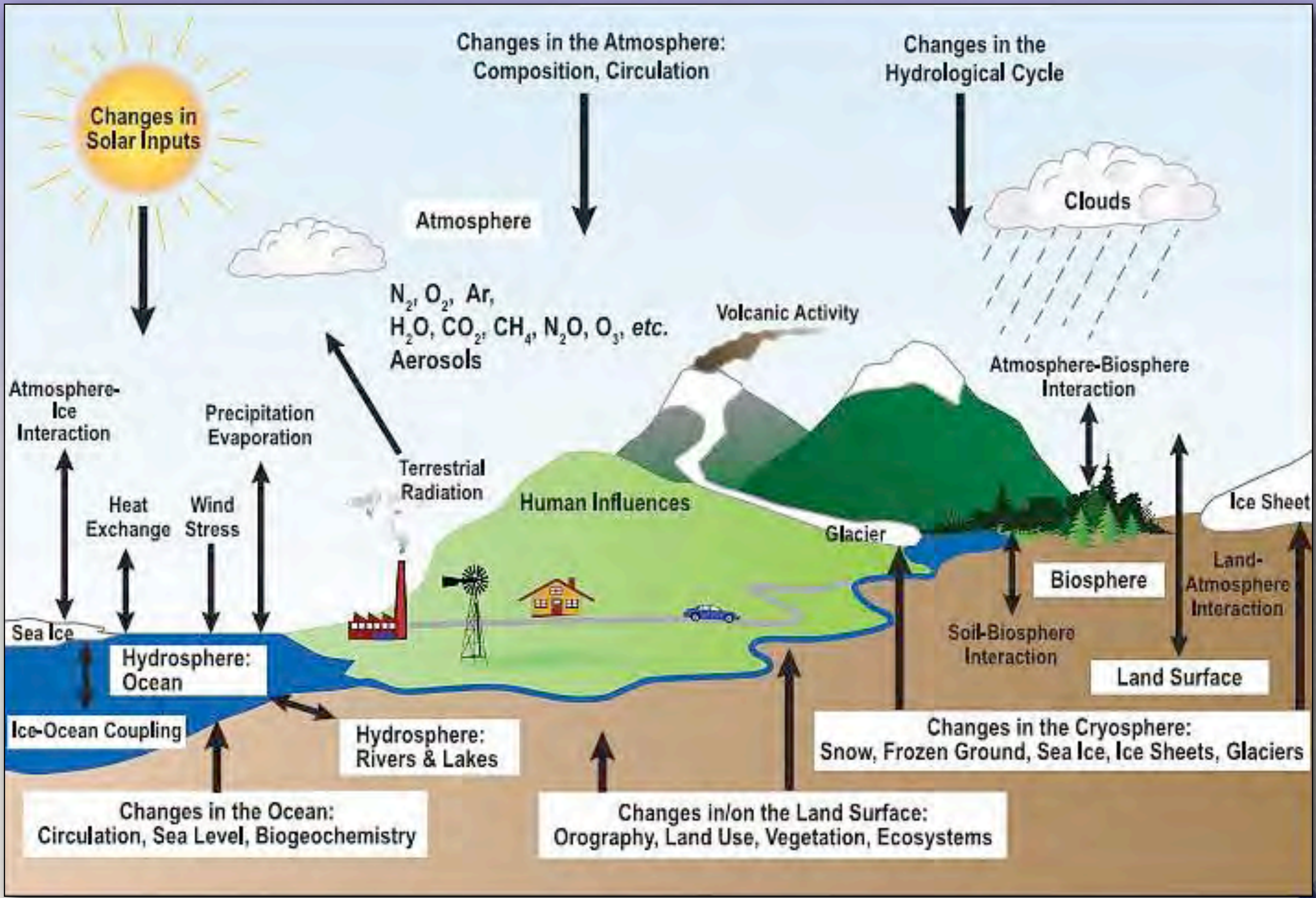
2004
2009

Evolution of Model Complexity

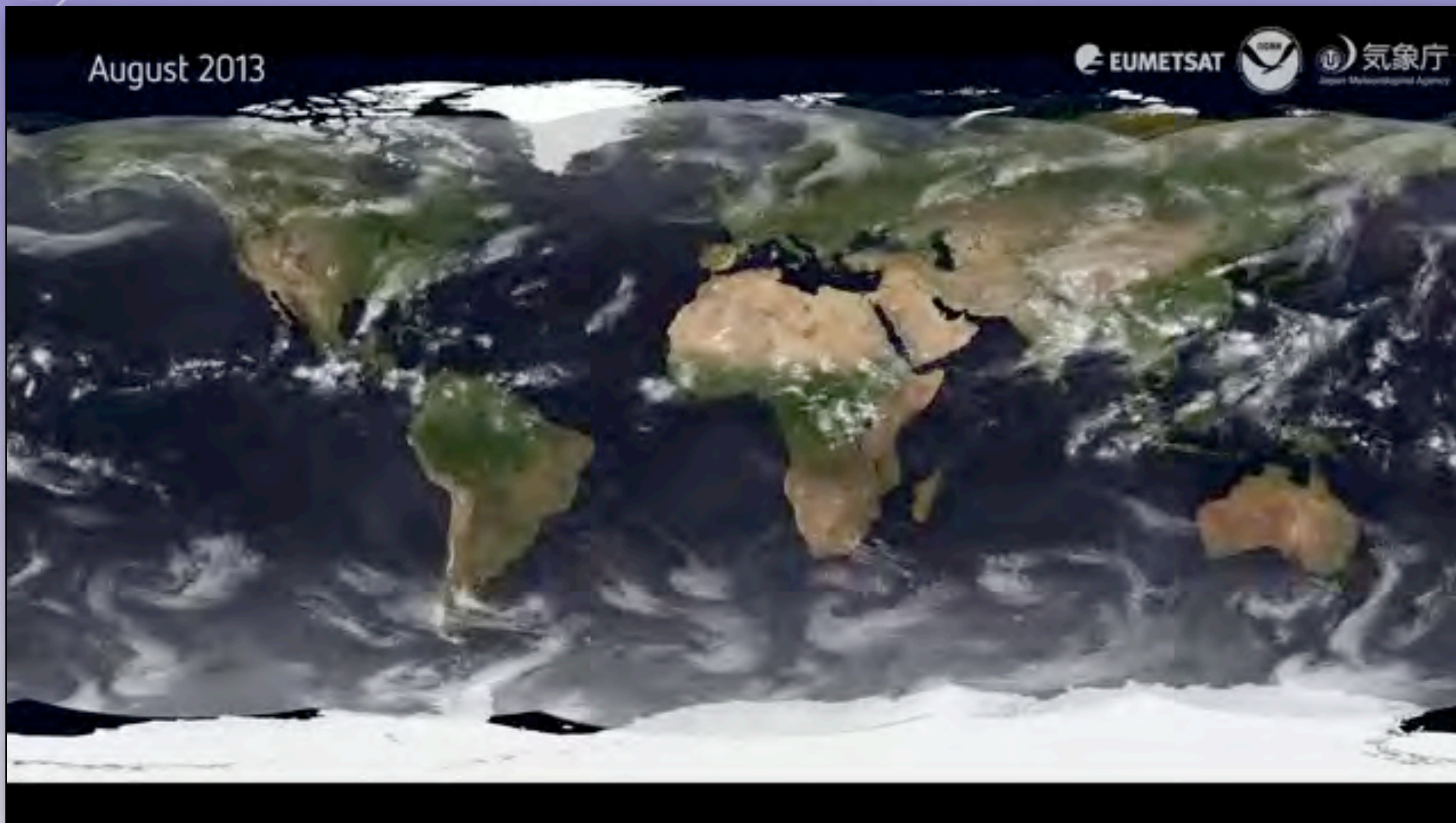




Physics in Current Generation of Climate Models



Model or Observations?



Multi-Satellite Image Animation

https://www.youtube.com/watch?v=m2Gy8V0Dv78

Global Climate Model Simulation

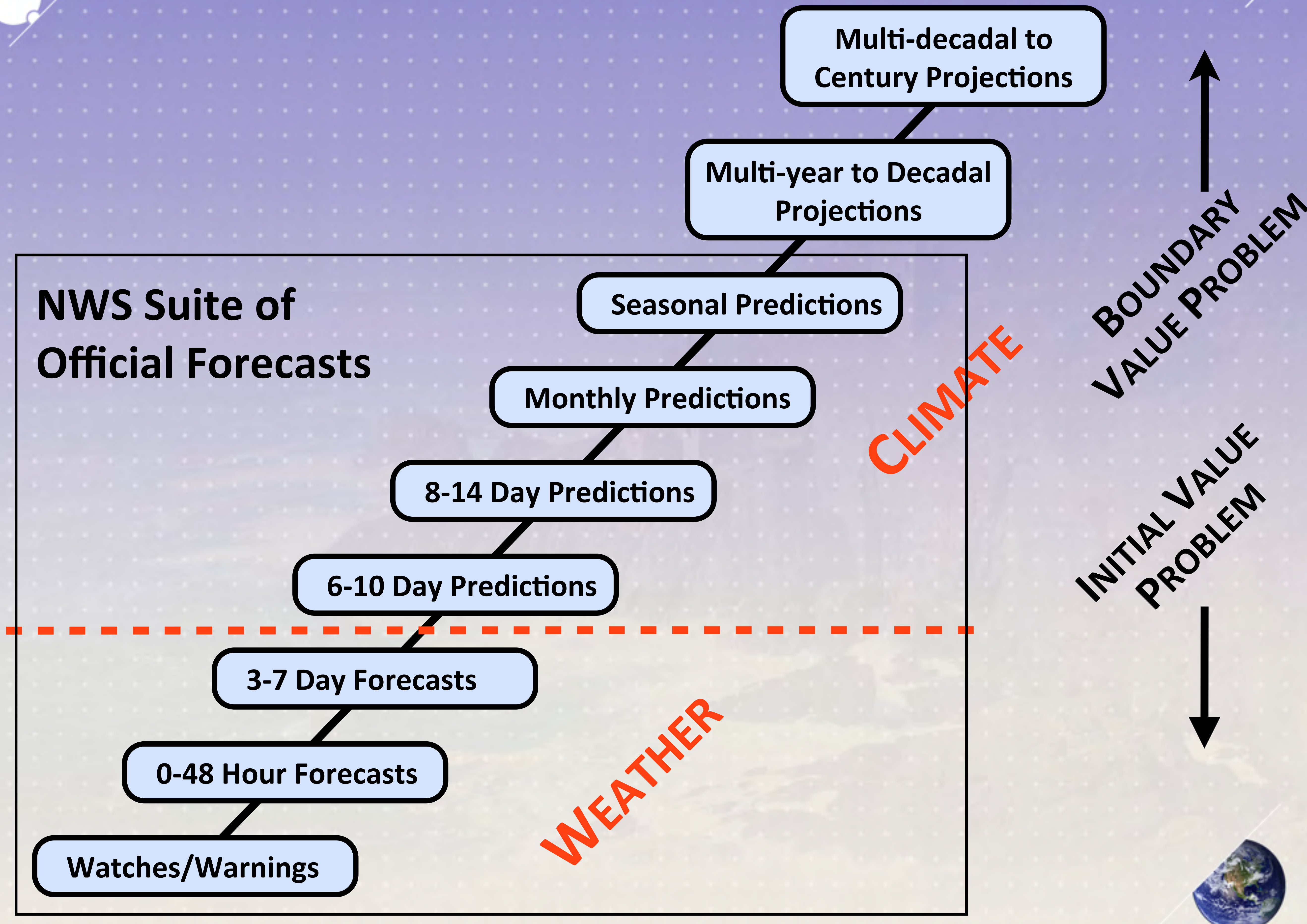
http://www.vets.ucar.edu/vg/T341/index.shtml

Limitations of GCMs

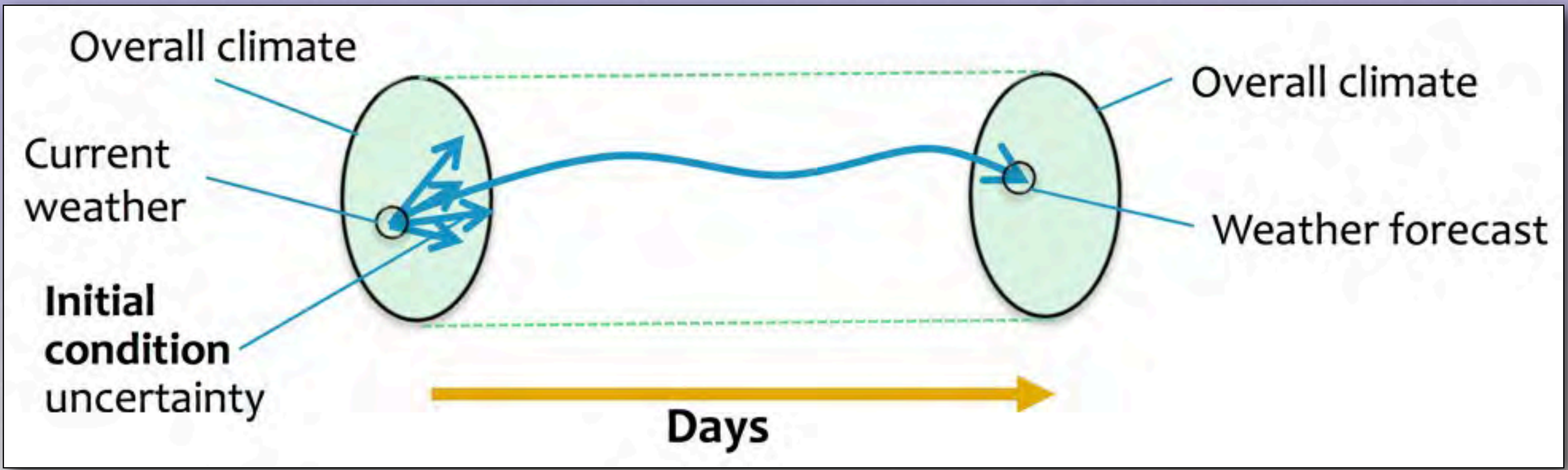
- They can't calculate every variable everywhere at all times.
- Some physical processes, interactions, and feedbacks are not known (or not known well) and aren't included (or not fully included) in the model.
- Sensitivity of models to the same increase in radiative forcing (e.g., doubling of CO_2) is different between models.

Weather vs. Climate

- Common question: "If we can't predict the weather beyond 2 weeks, how can we predict the climate in 100 years?"
- Reminder: There is a difference between weather and climate! ("The climate is what you expect. The weather is what you get.")
  - **Weather – timing and location of specific weather phenomena** (e.g., cold front passage, tornadic thunderstorm) are important to **<u>forecast</u>**
  - **Climate – statistics of the overall diurnal/ monthly/seasonal cycles and spatial patterns** (e.g., El Niño, sea ice extent) are important to **<u>project</u>**


NWS Suite of Official Forecasts
Multi-decadal to Century Projections
Multi-year to Decadal Projections
Seasonal Predictions
Monthly Predictions
8-14 Day Predictions
6-10 Day Predictions
3-7 Day Forecasts
0-48 Hour Forecasts
Watches/Warnings
CLIMATE
WEATHER
BOUNDARY VALUE PROBLEM
INITIAL VALUE PROBLEM

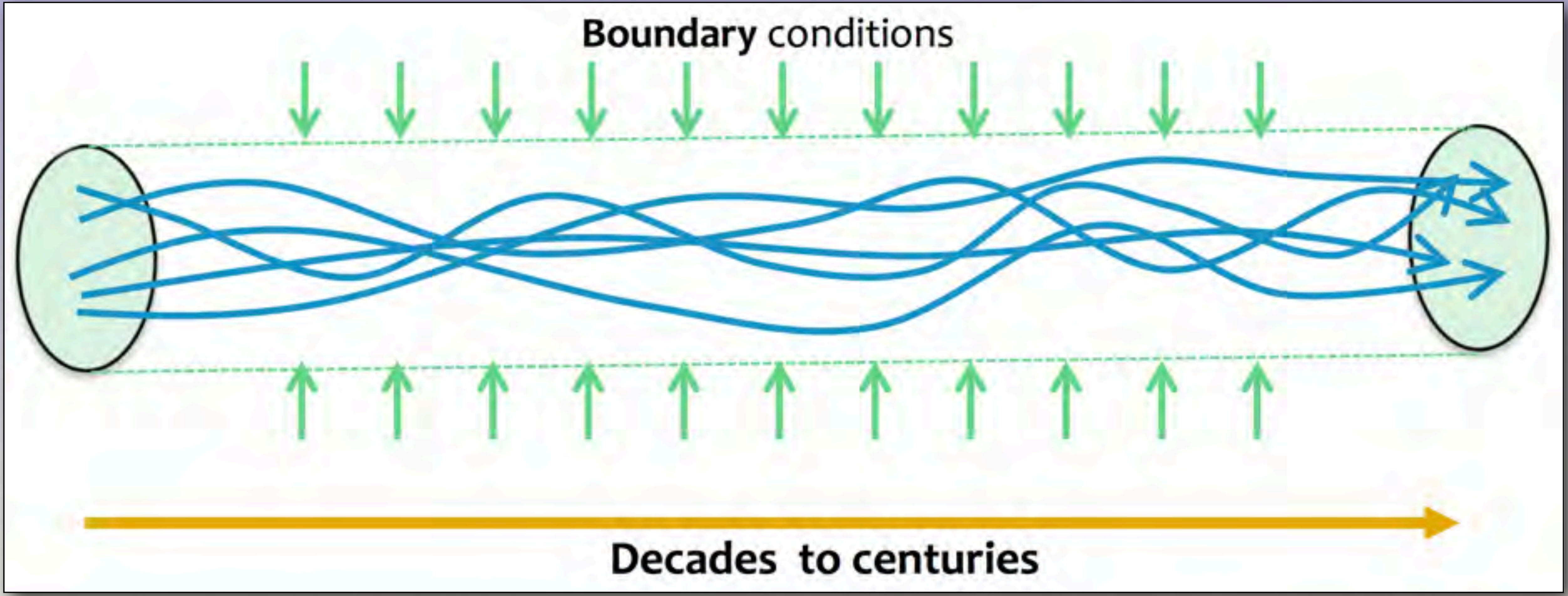
Initial Value Problem – Weather Forecasting or Seasonal Climate Prediction



Steve Easterbrook

Chaos theory: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas? – Ed Lorenz

Boundary Value Problem – Climate Projections in a Stationary Climate



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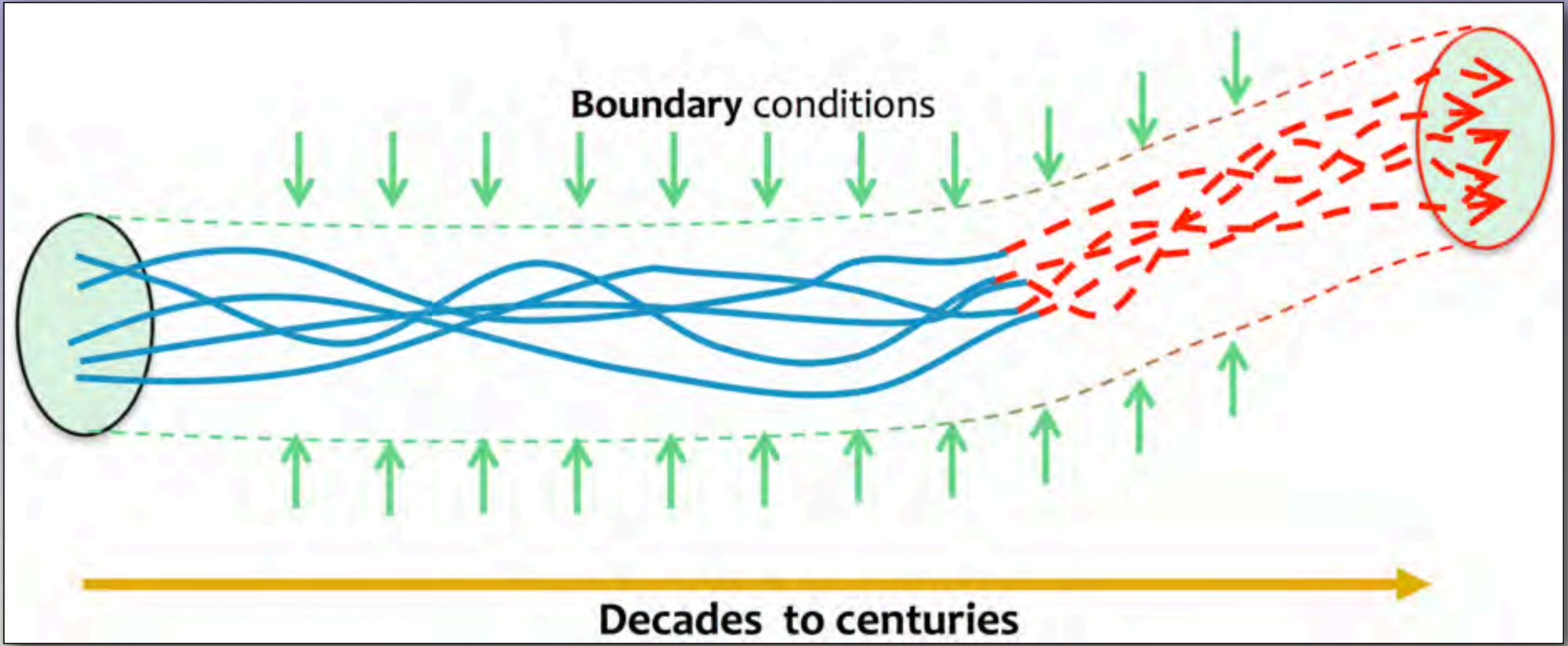
Boundary Value Problem – Climate Projections in a <u>Changing</u> Climate



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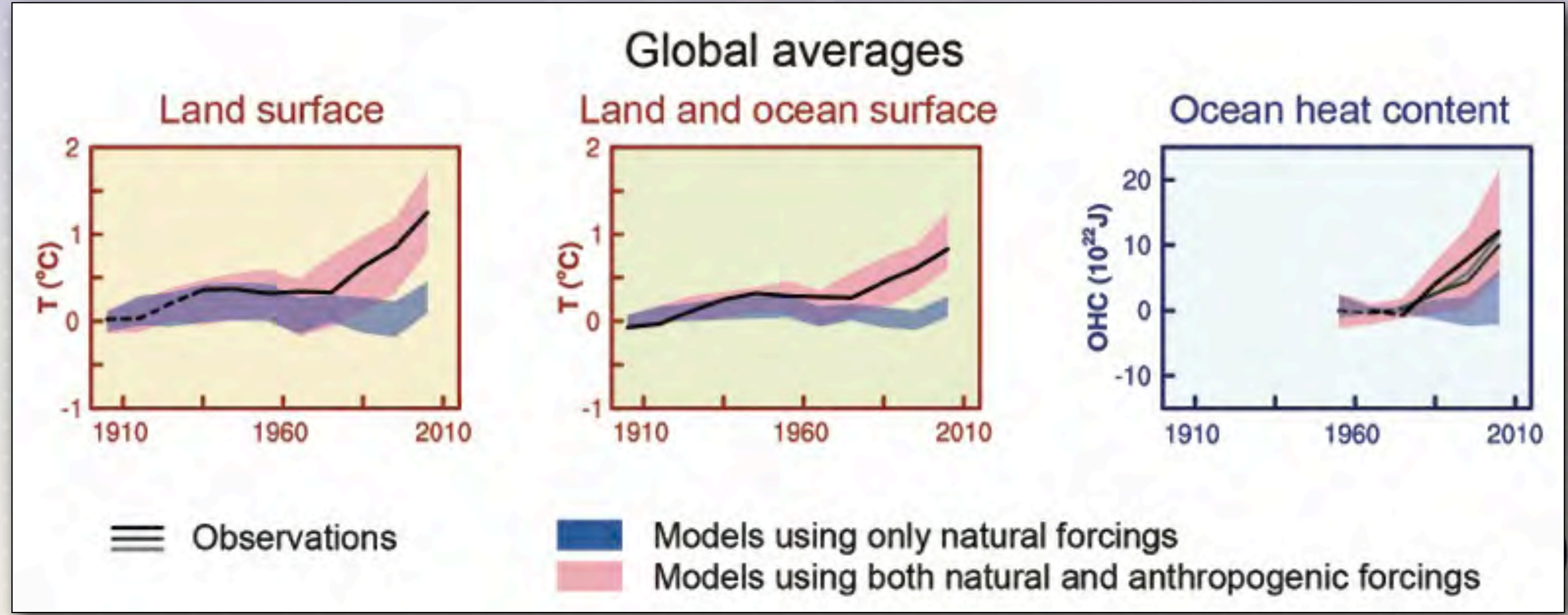
GCMs and the IPCC Process

- Projections using an "ensemble" of models from 20 climate modeling groups worldwide
- Models that include <u>both</u> natural forcing and forcing from human activities best relate to the actual observations



IPCC AR5

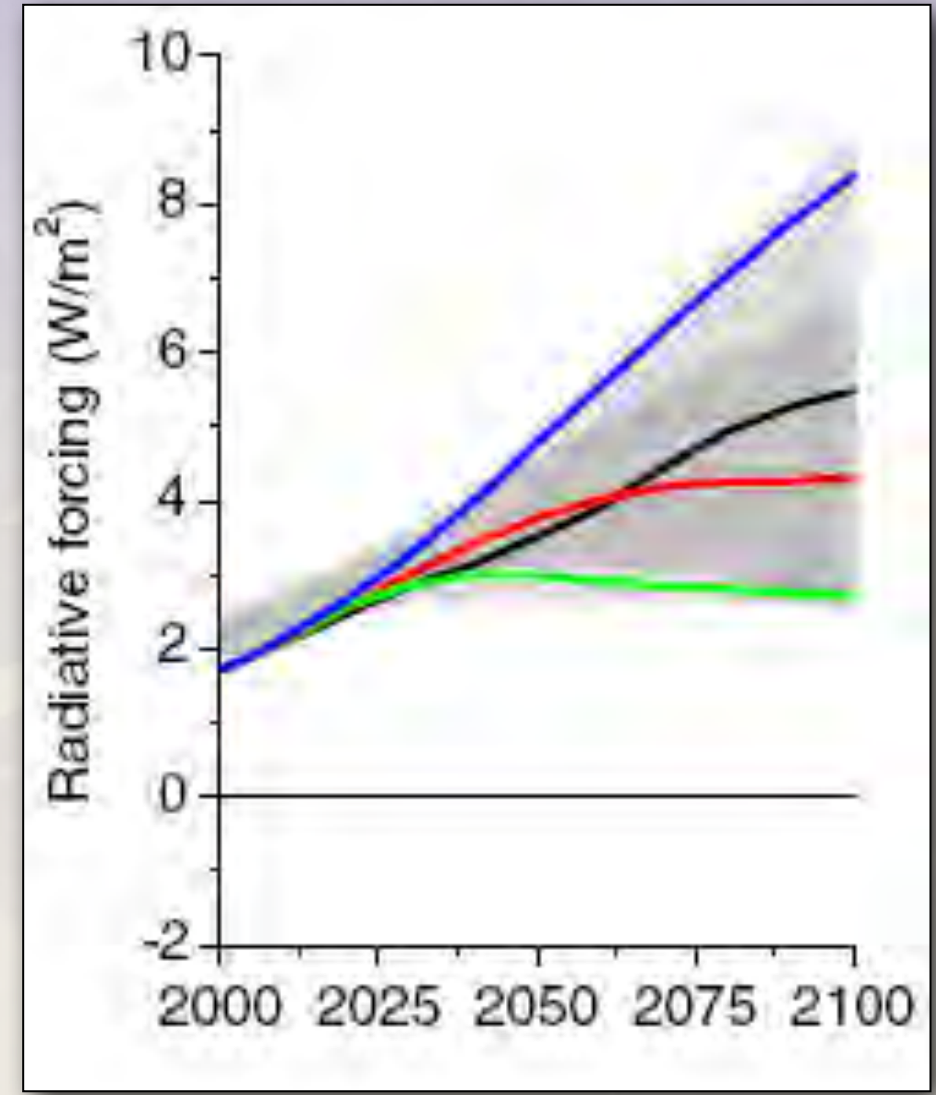
What are the Boundary Values?

- **Emission scenario** – a plausible time sequence of anthropogenic and natural forcings (e.g., manmade GHGs, volcanoes, sunspot cycle) that drive changes in radiative forcing on the climate system; based on assumptions about patterns of economic and population growth, technology development, & other driving factors; used in IPCC Assessment Reports 3 & 4 (TAR & AR4)

- **Representative concentration pathway (RCP)** – a plausible time sequence of changing radiative forcing on the climate system; used in IPCC Assessment Report 5 (AR5)

Radiative Forcing Scenarios for AR5

- RCP 8.5 – GHG emissions increase until forcing difference reaches 8.5 Watts per square meter
- RCP 6 – radiative forcing stabilized around 2100 using a variety of technologies & strategies to reduce GHGs
- RCP 4.5 – similar to RCP 6 but with a lower stabilization target
- RCP 2.6 – a "peak-and-decline" scenario where GHG emissions are reduced significantly over time



How “Good” Are GCMs?

- Two ways to examine representativeness of GCMs

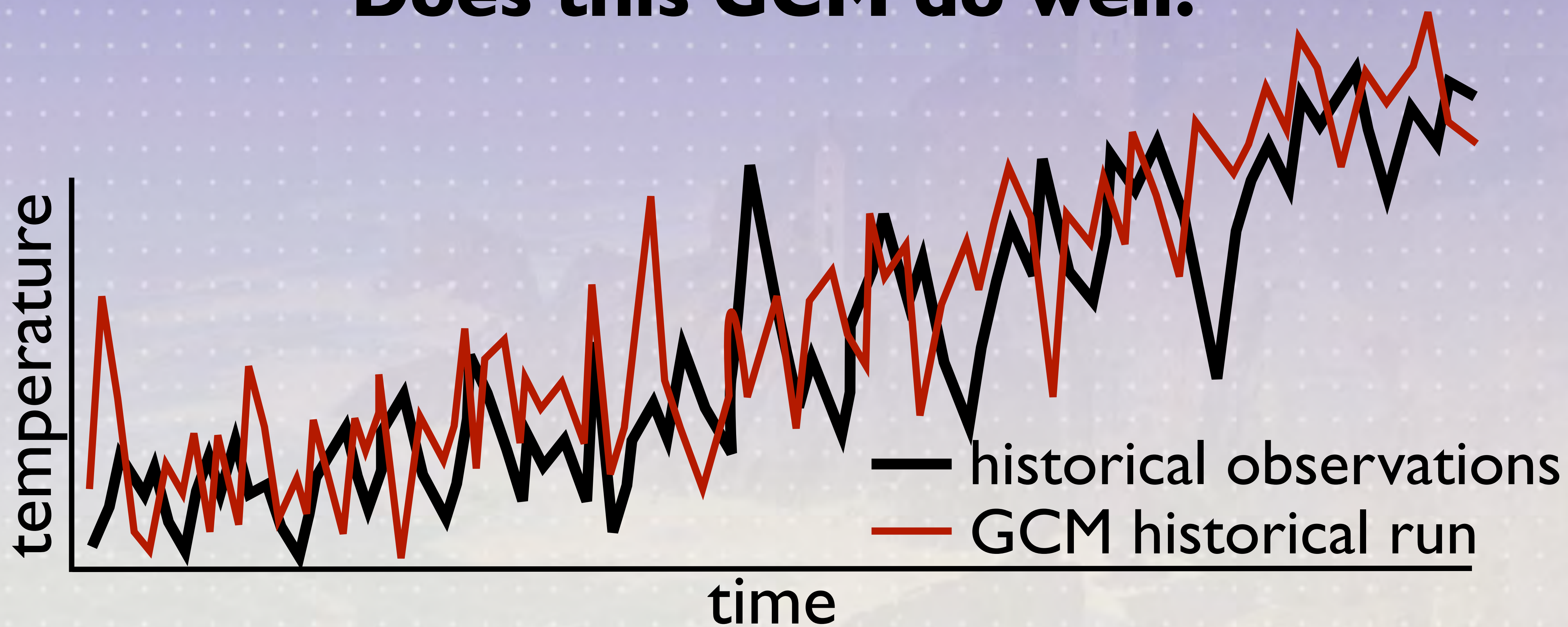
  1) How well does it do historically?

  2) How well does it represent the main processes of the atmosphere, ocean, land, and ice?

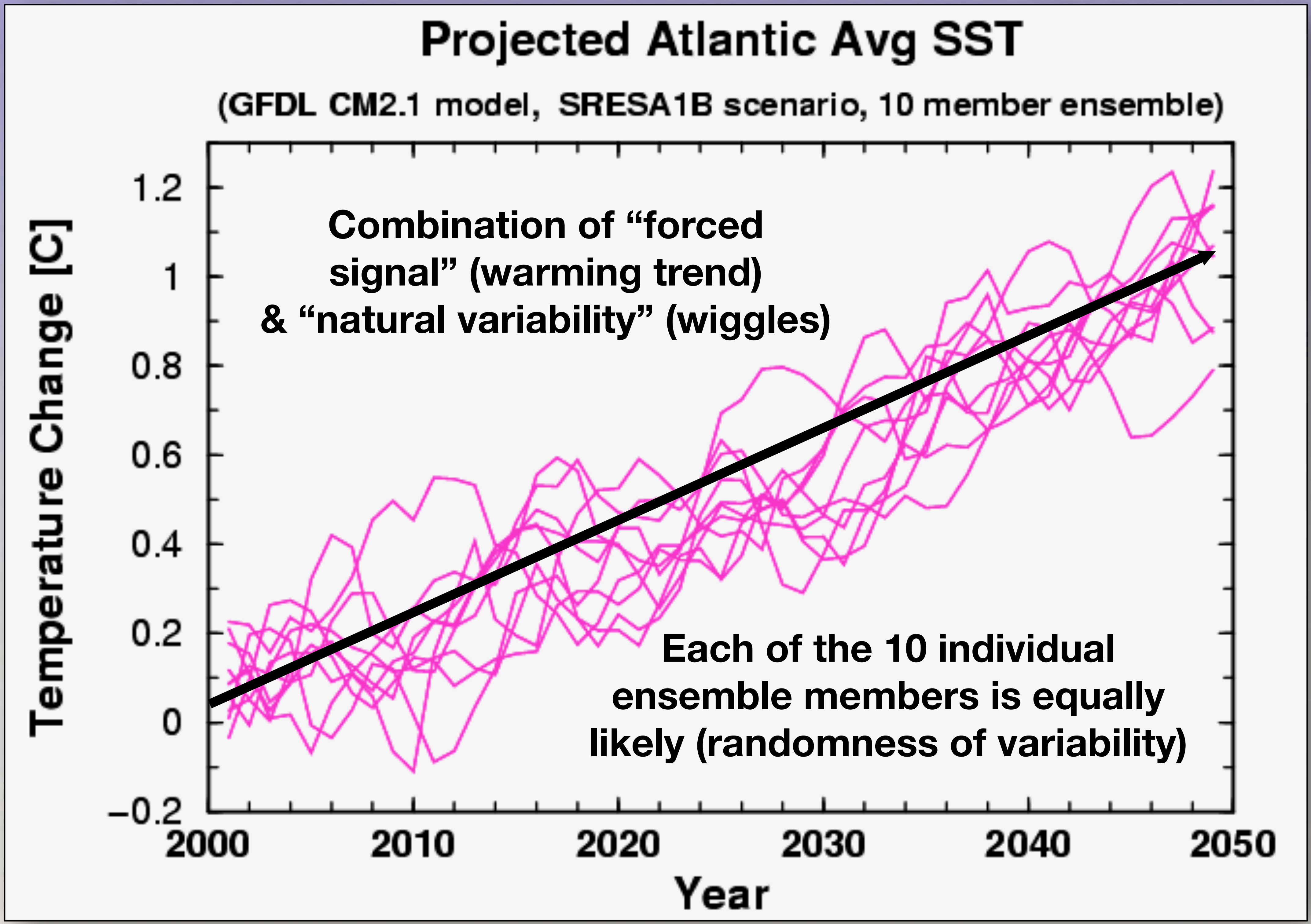
- If we only focus on #1, we run the risk of getting the right answers for the wrong reasons.

Evaluation Via “Hindcasting”

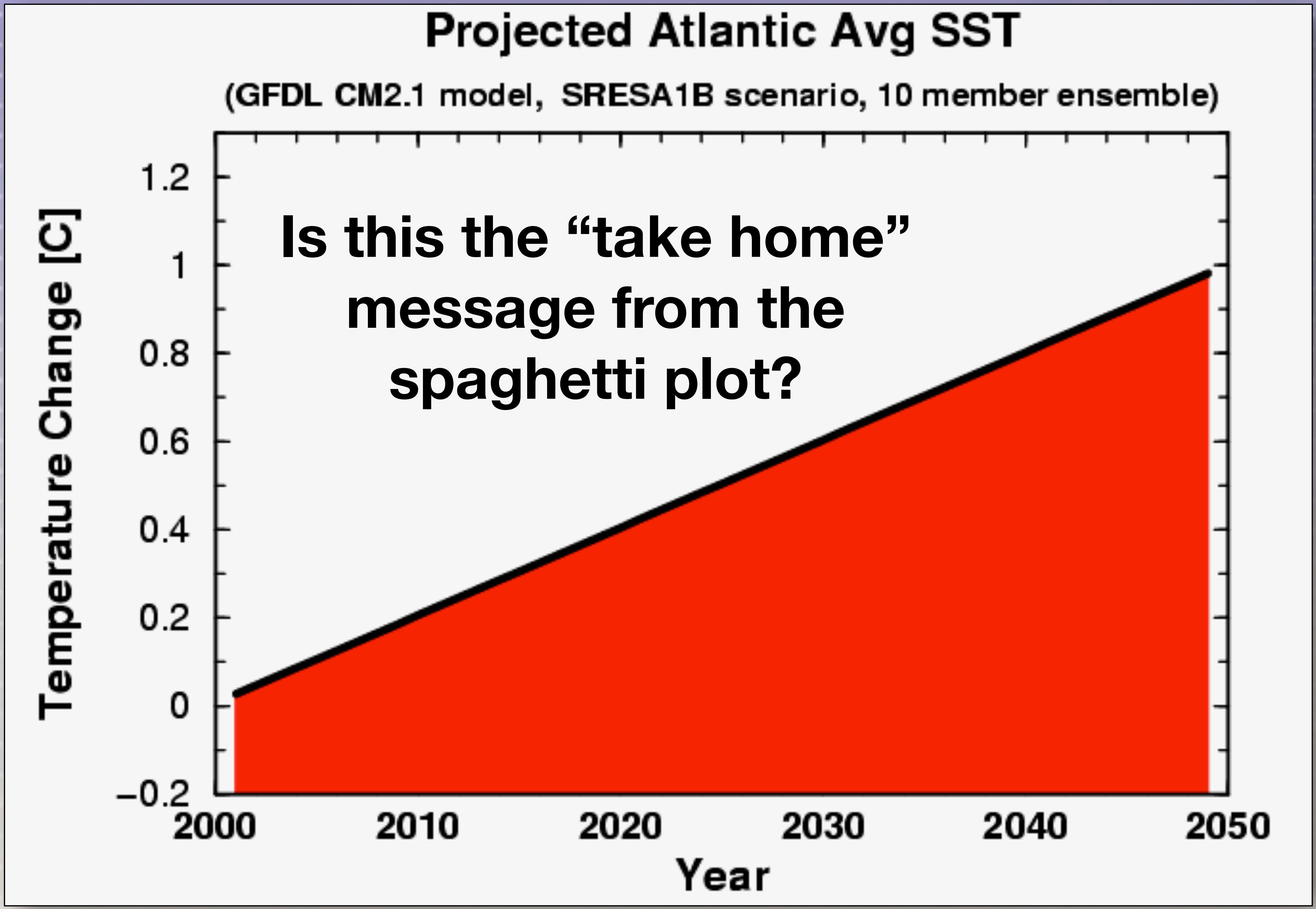
Does this GCM do well?



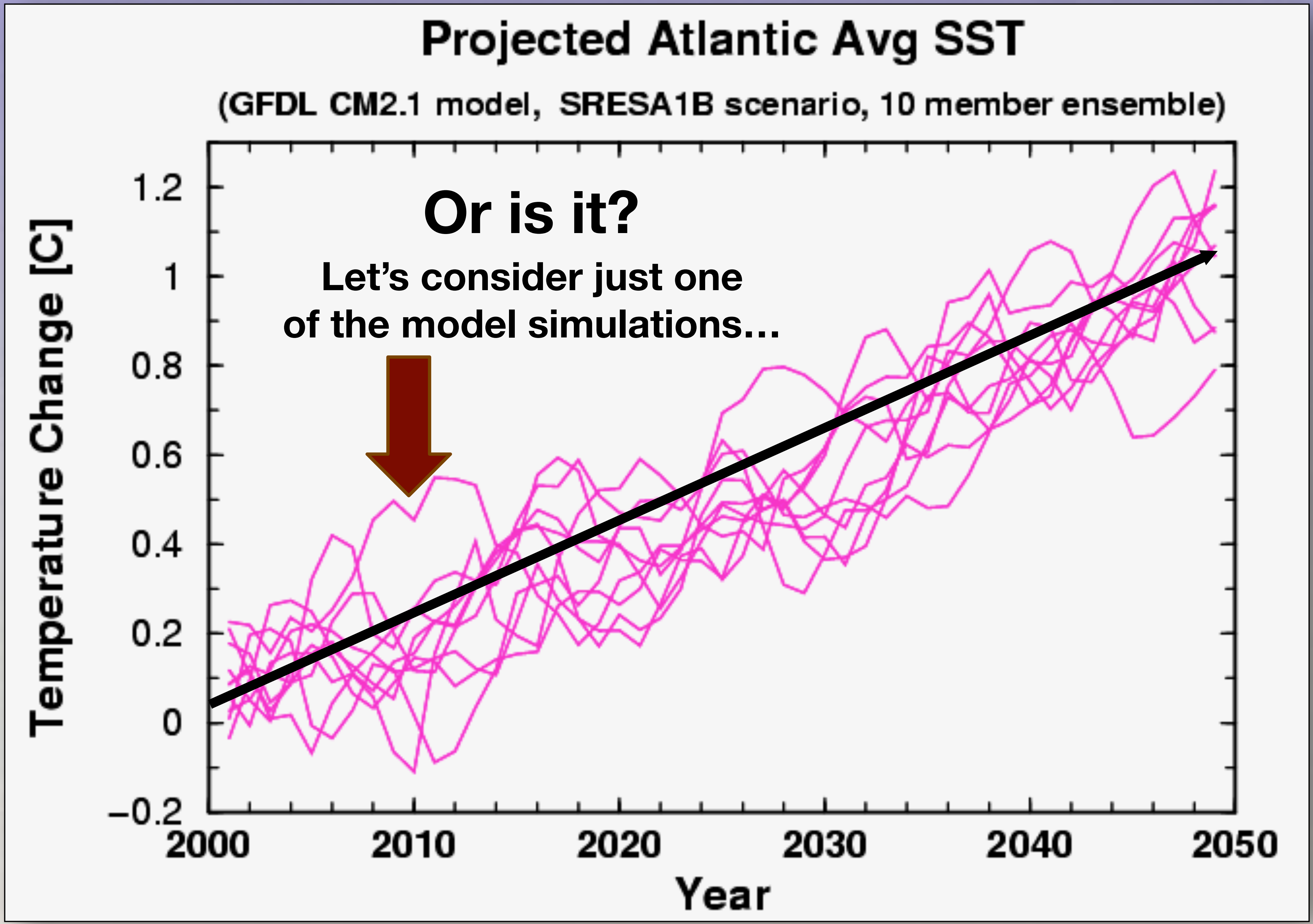
Poor Interpretation & Use of GCM Output



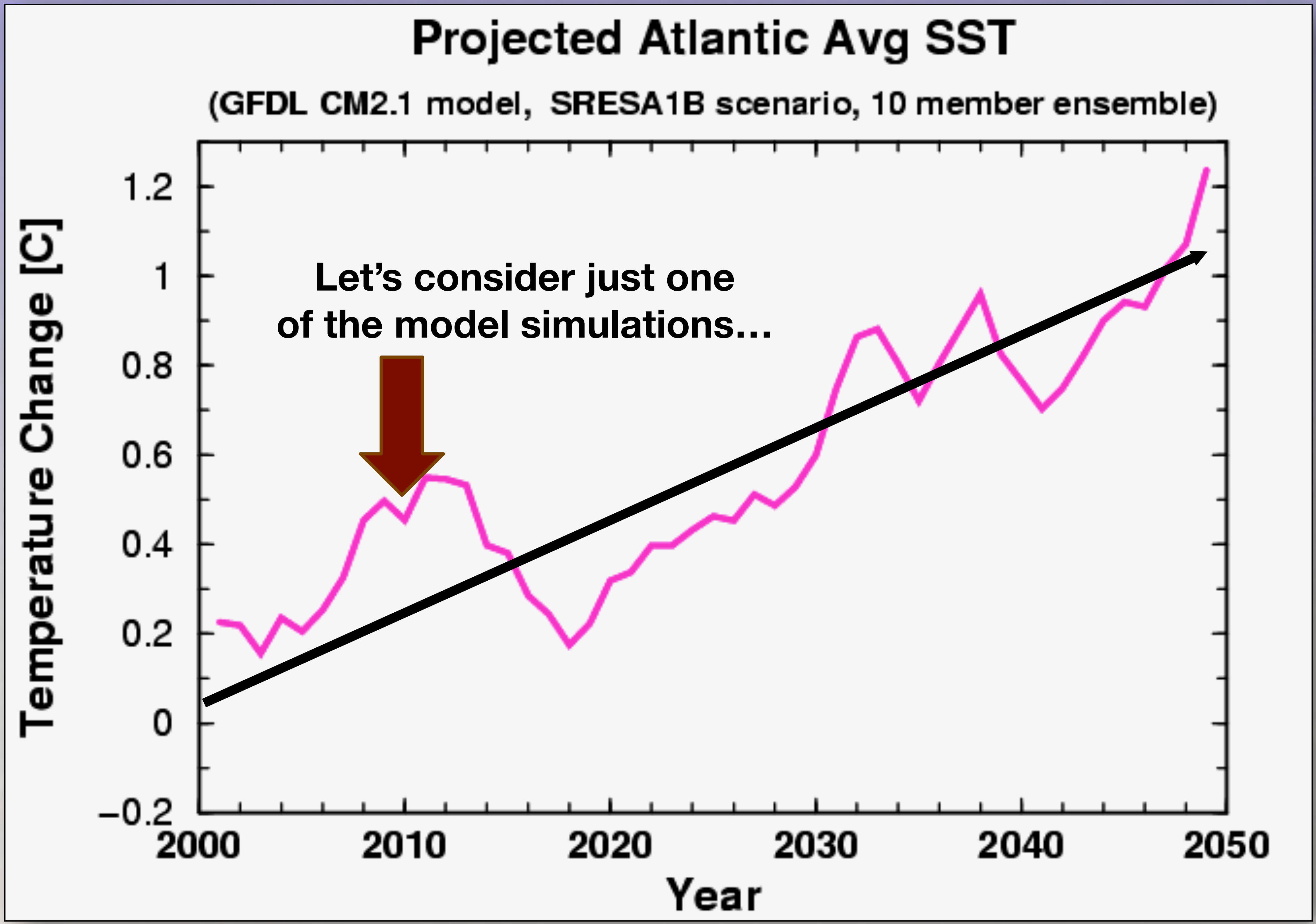
Poor Interpretation & Use of GCM Output



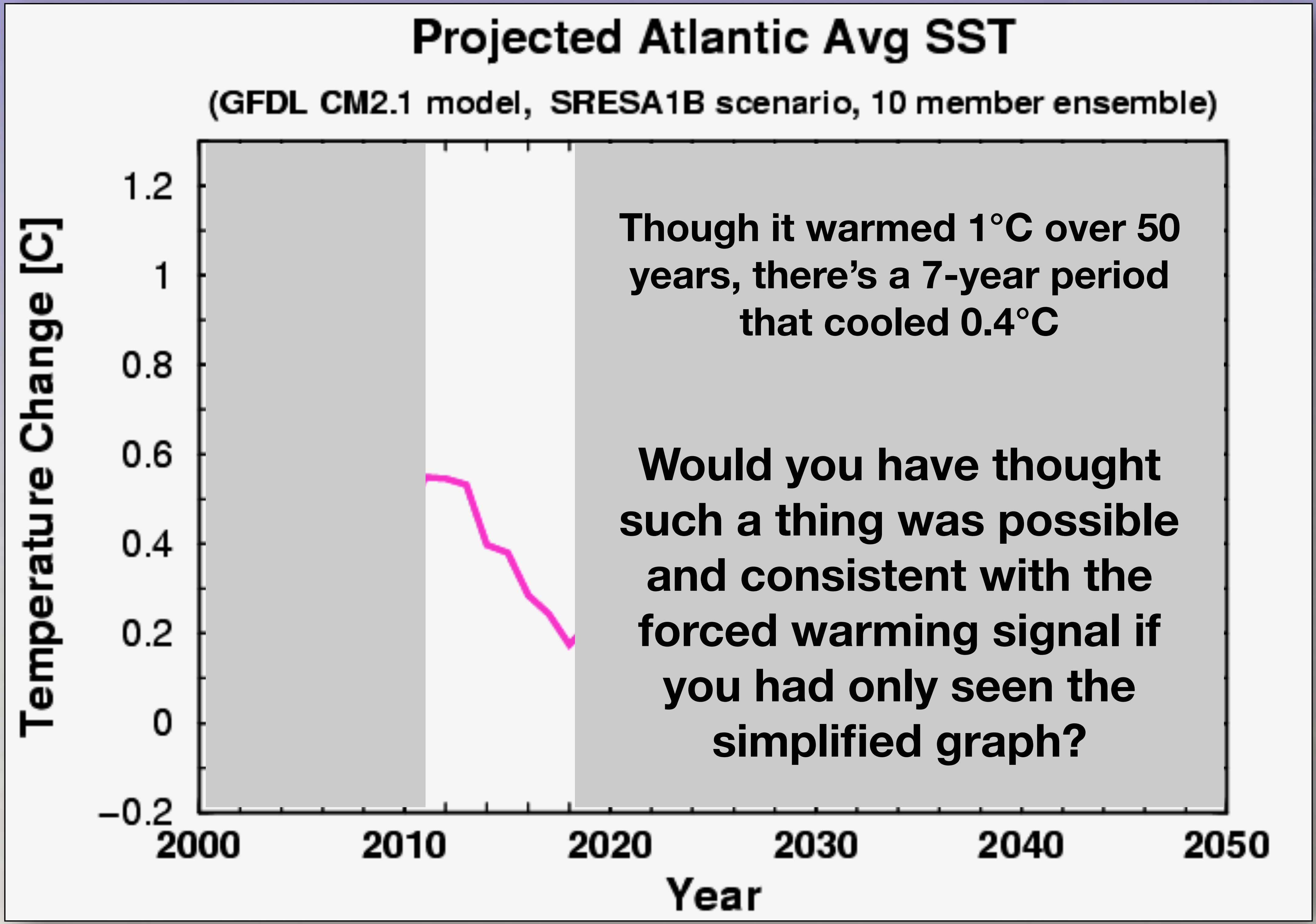
Poor Interpretation & Use of GCM Output



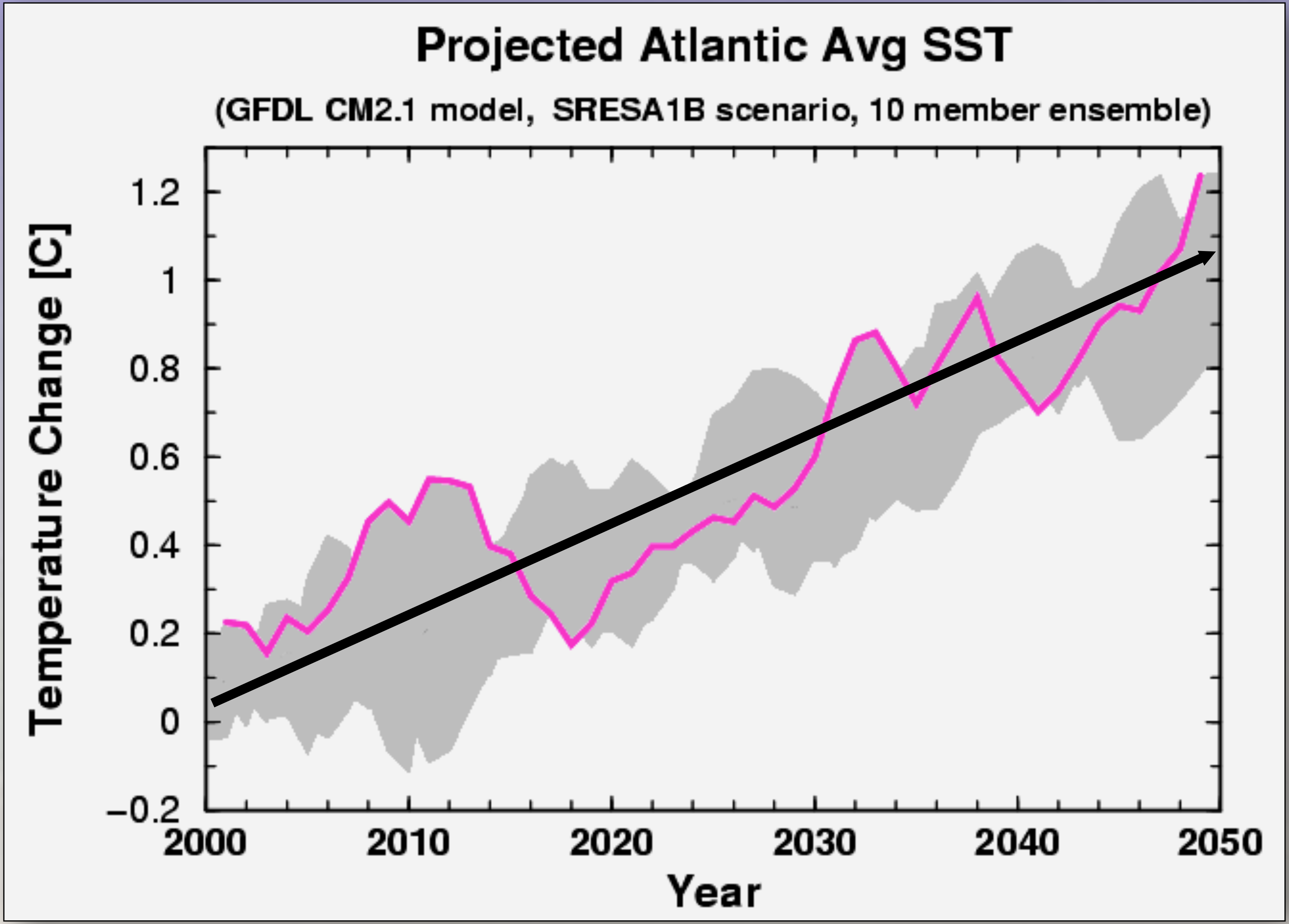
Poor Interpretation & Use of GCM Output



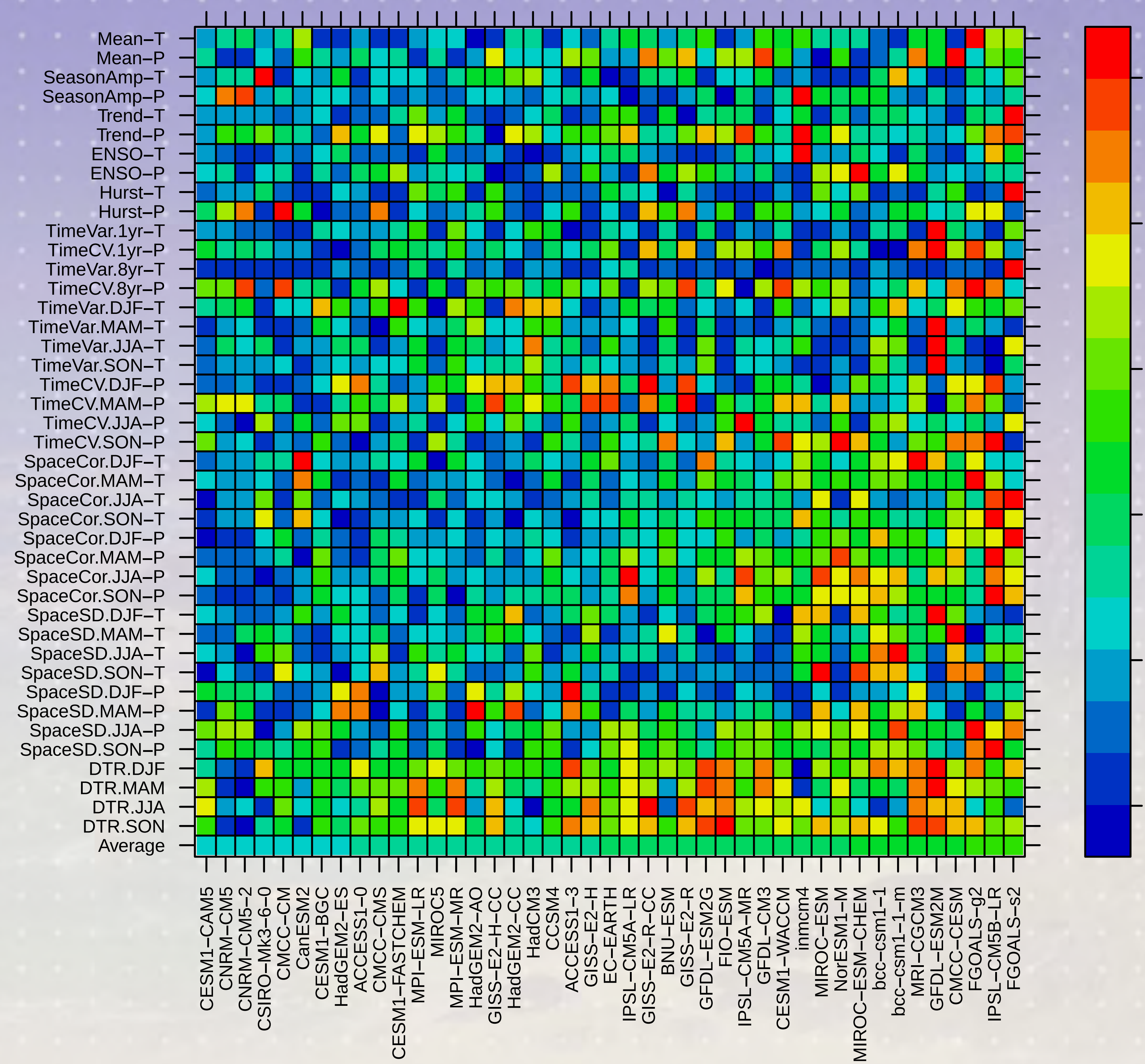
Poor Interpretation & Use of GCM Output



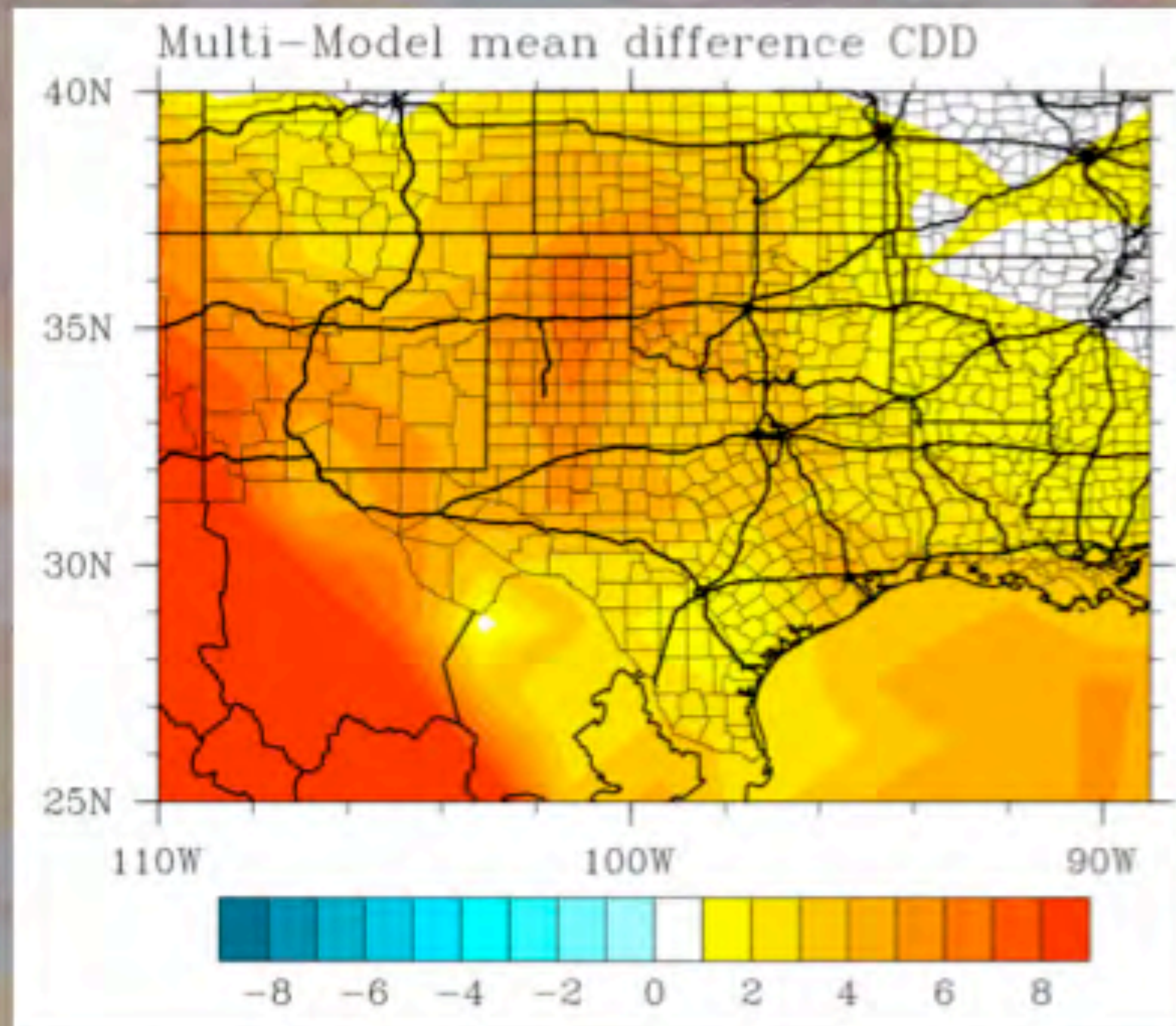
Think About Interpretation of GCM Output



How “Good” Are GCMs?



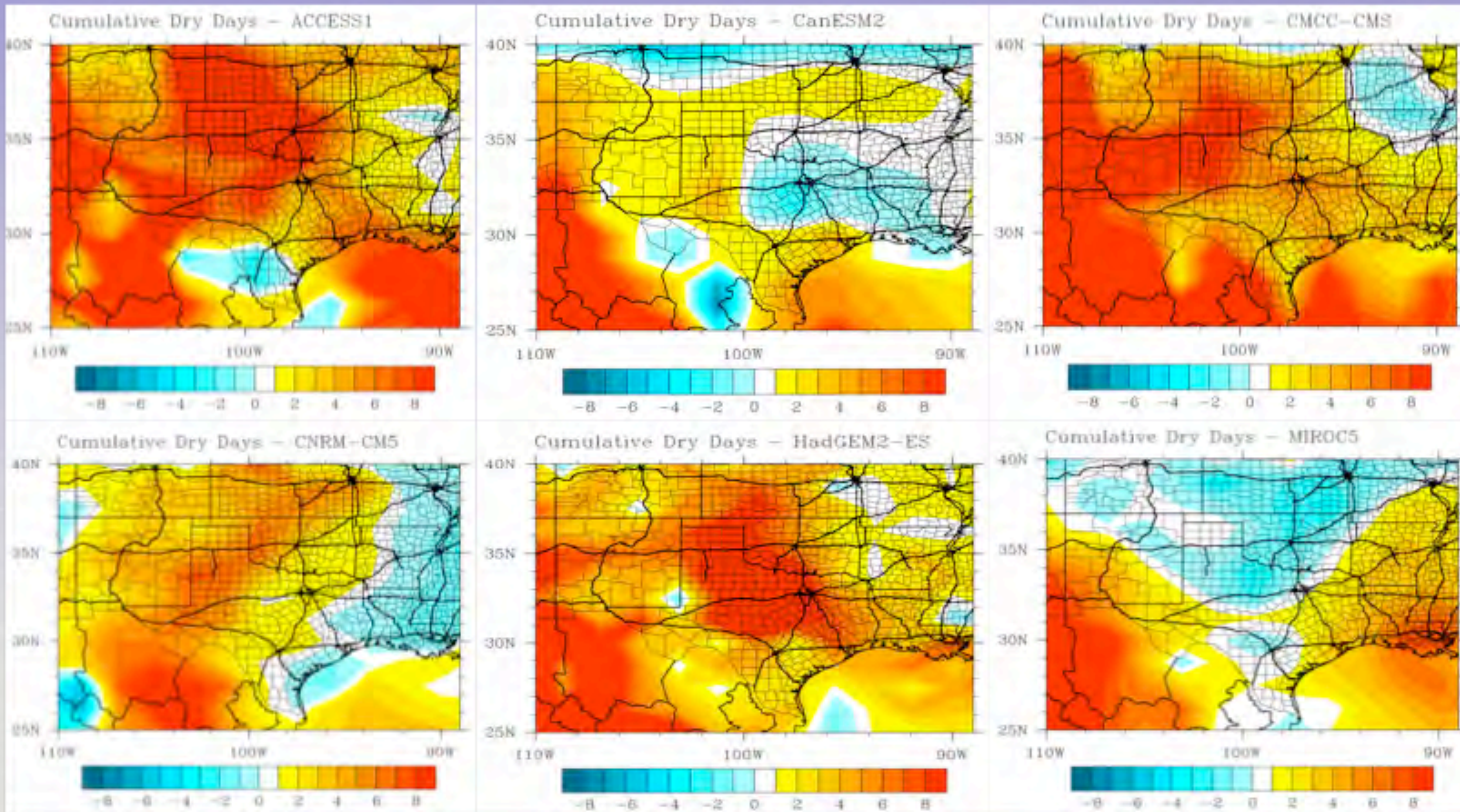
Multi-Model Mean



Consecutive dry days, difference 2050-70 relative to 1980-2000

CLIMDEX Climate Extremes Indices, obtained from Environment Canada

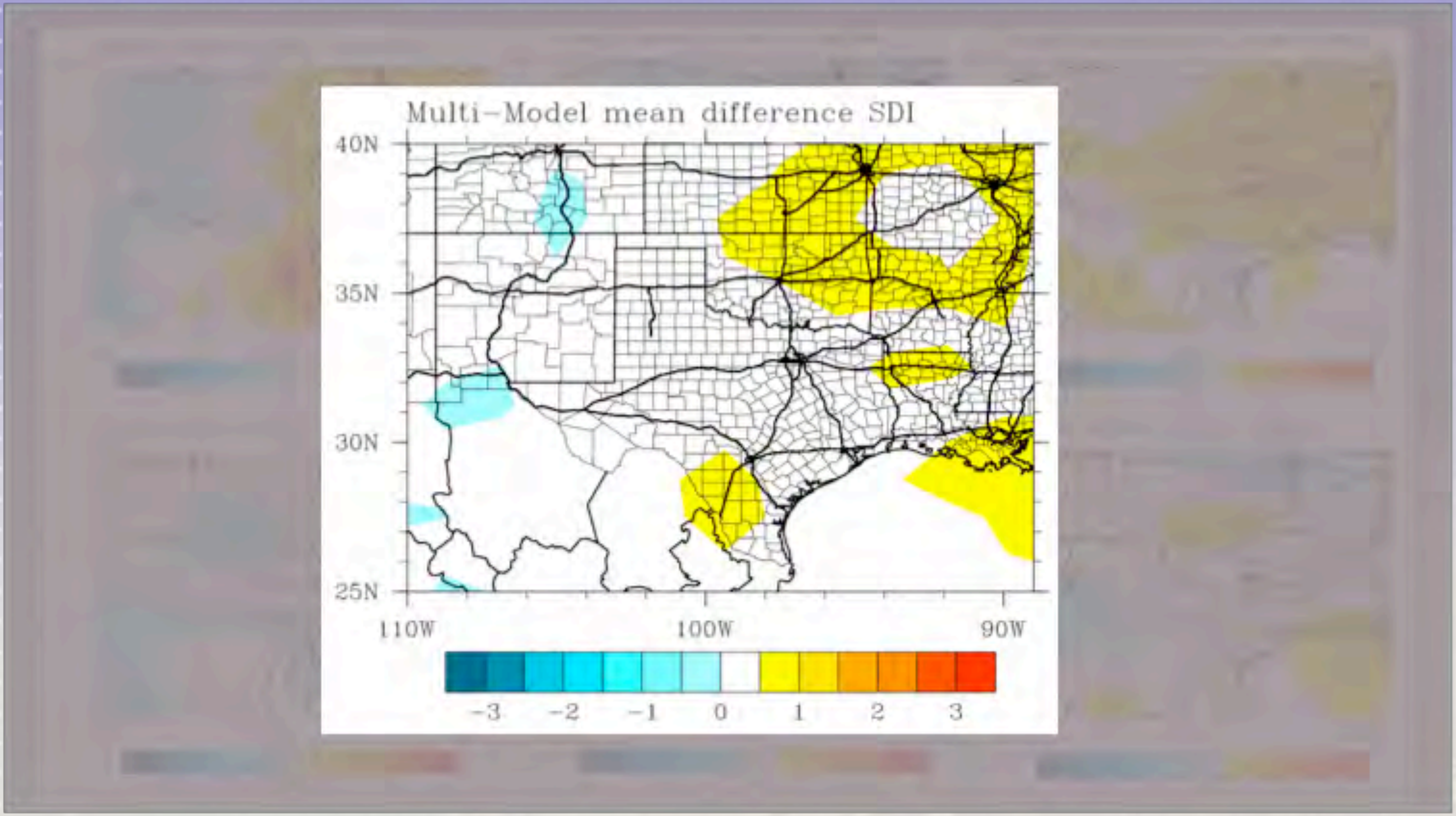
Individual GCMs with Same Forcings



Consecutive dry days, difference 2050-70 relative to 1980-2000 (RCP8.5)

CLIMDEX Climate Extremes Indices, obtained from Environment Canada

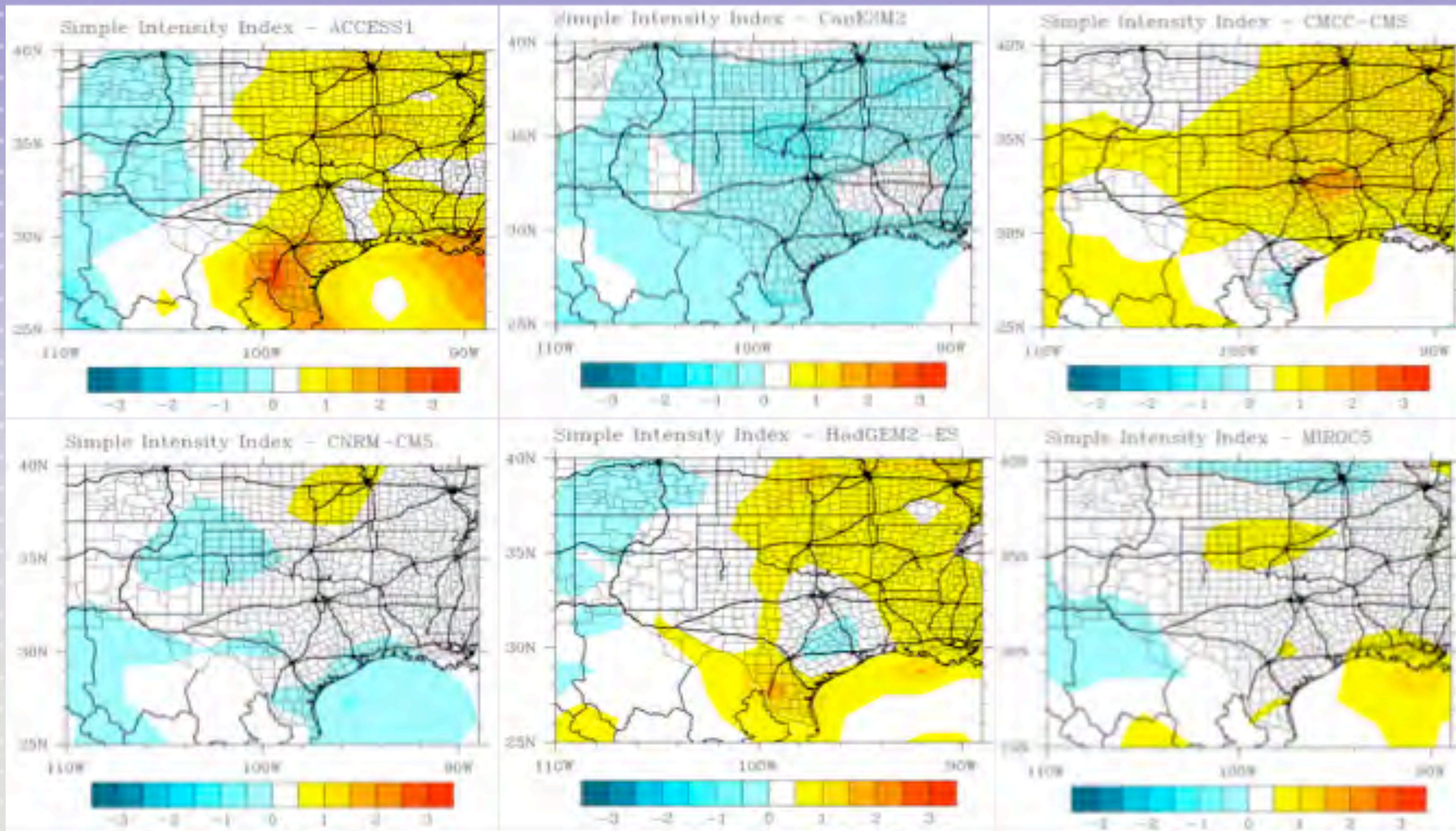
Individual GCMs with Same Forcings



'Simple intensity index' for precipitation

CLIMDEX Climate Extremes Indices, obtained from Environment Canada

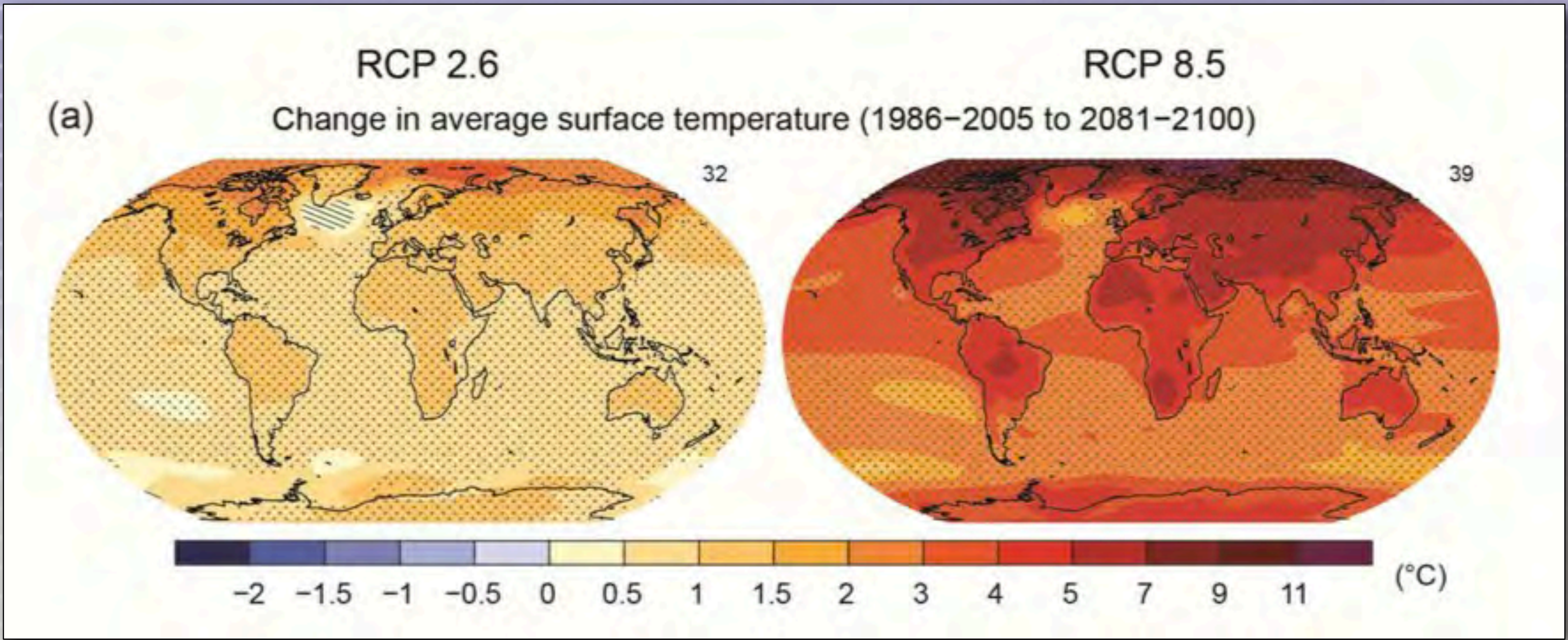
Individual GCMs with Same Forcings



'Simple intensity index' for precipitation (2050-70 difference from 1980-2000, RCP8.5)

IPCC AR5 Multi-model Projections

Projections for the late 21st century relative to 1986–2005

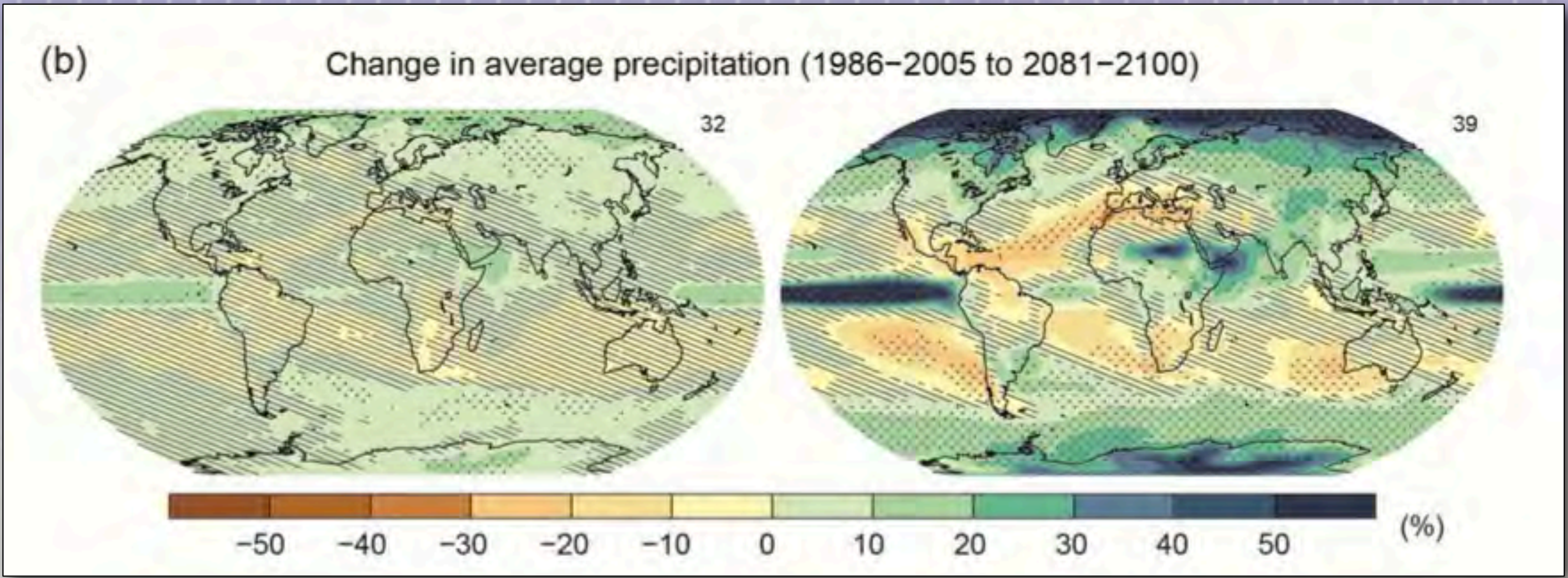


lowest radiative forcing

highest radiative forcing

IPCC AR5 Multi-model Projections

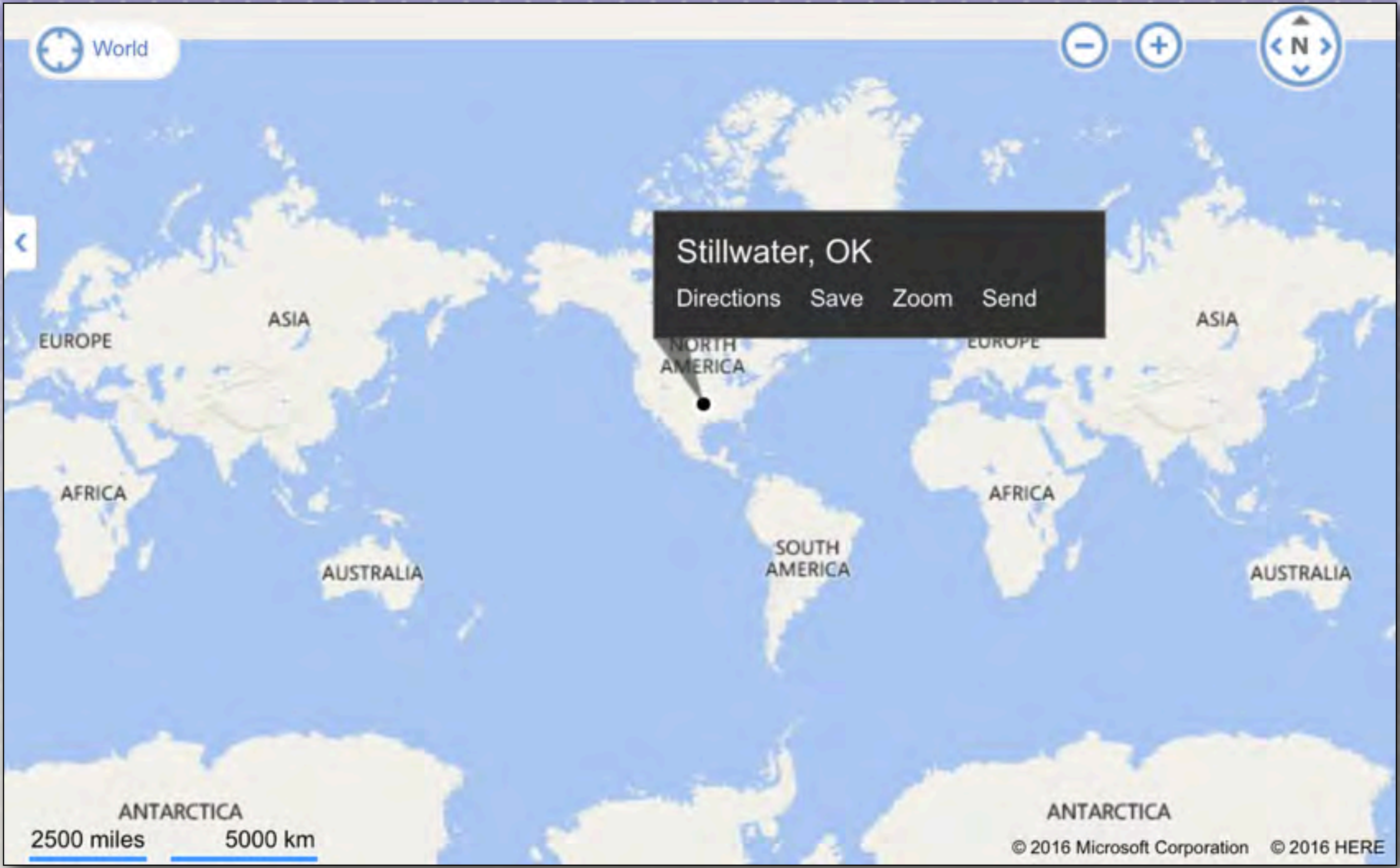
Projections for the late 21st century relative to 1986–2005



lowest radiative forcing

highest radiative forcing

But What About Us? – Downscaling to Regions



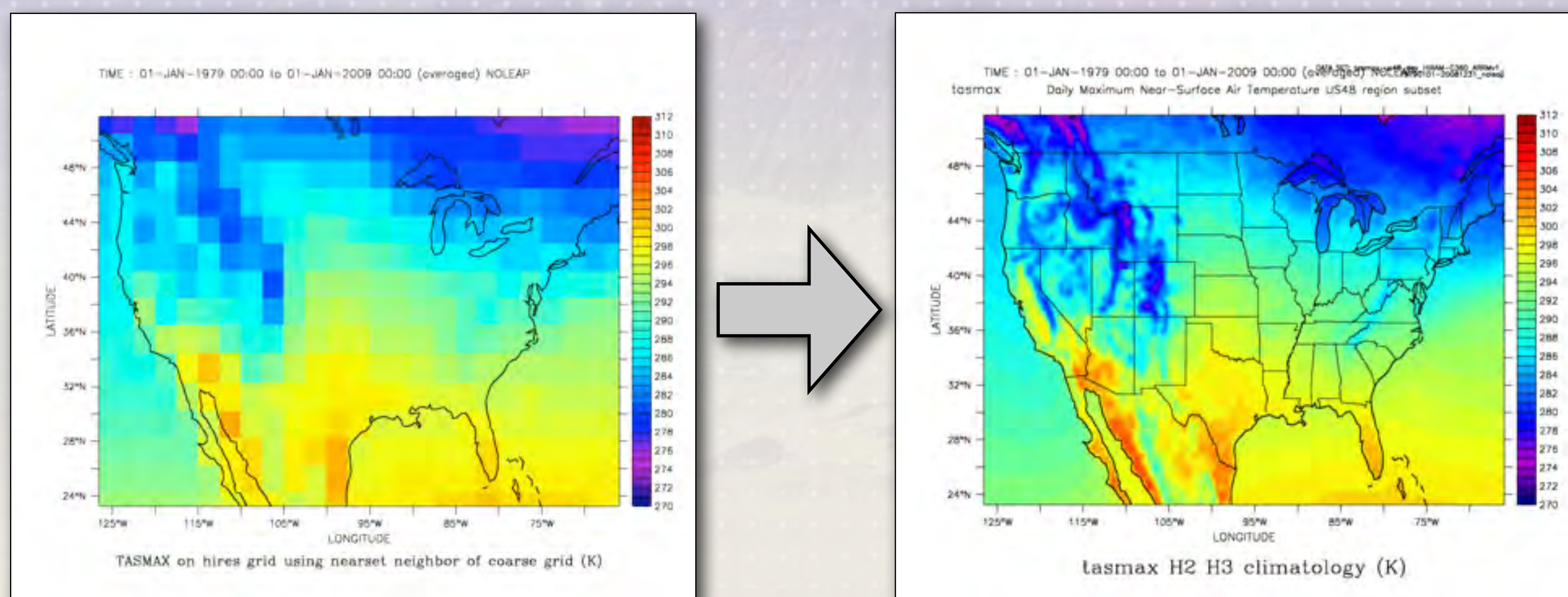
But What About Us?

- How will climate change affect our water?
- How will it change the price of fuel?
- Can we still grow watermelons?
- Will our favorite beach resort be flooded?
- How do we have to change our behavior?
- How will our values and priorities change?
- Etc., etc.

What is Downscaling?

- Method to use coarse (low) resolution output (e.g., 100-500 km grid) from global climate models and obtain fine (high) resolution datasets (e.g., 10-50 km grid) for regional to local decision making

- A "value-added" process



Why Downscale?

- To help answer stakeholders' questions about how the climate will change in their location (i.e., impact assessments) & better represent local climates

Mountain climates

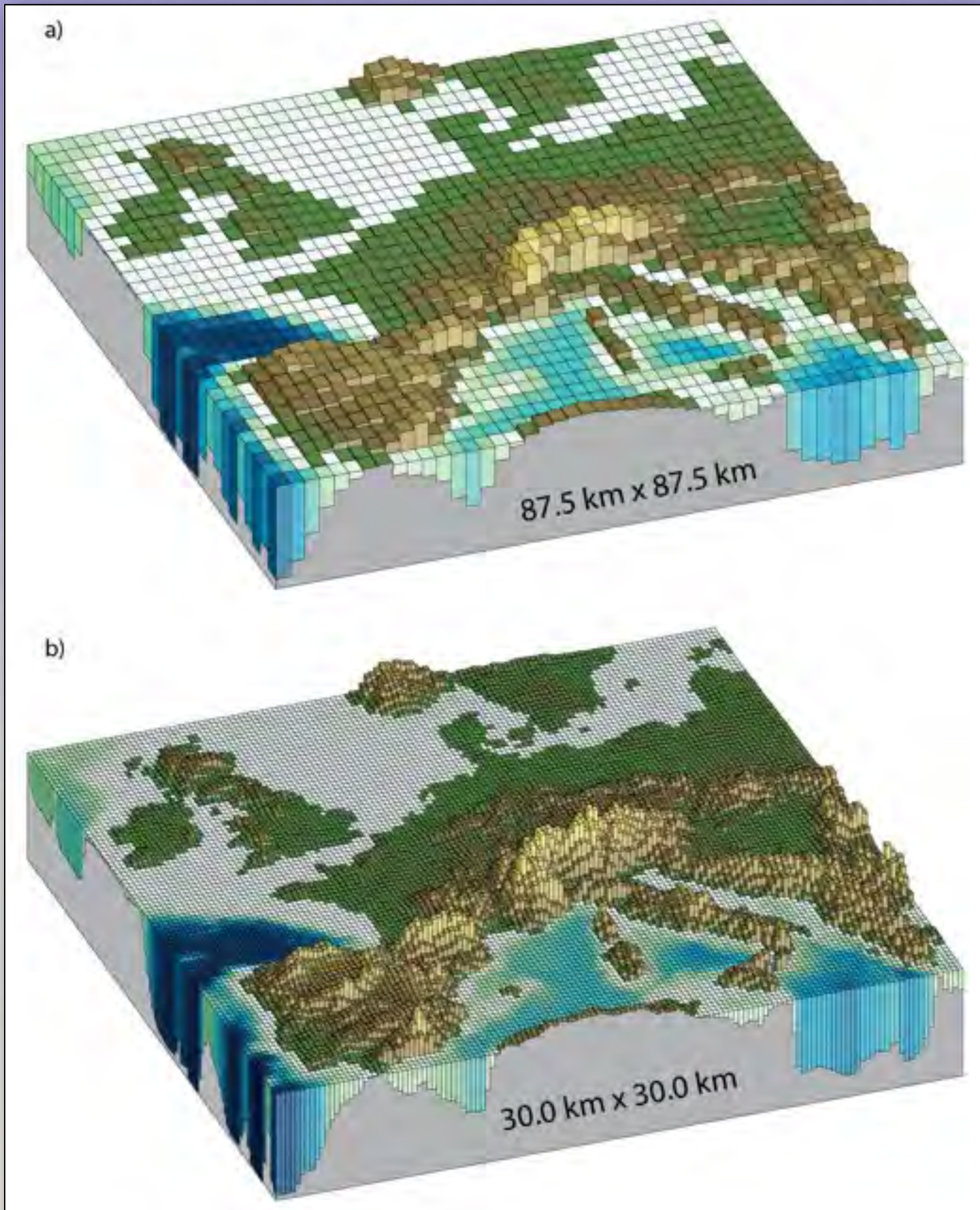
Urban climates

Coastal climates

Main Downscaling Methods

- **Dynamical downscaling** – uses high-resolution numerical models (i.e., **regional climate models**) to produce high-resolution, three-dimensional fields
- **Statistical downscaling** – uses **statistical relationships** to relate the value of the large-scale grid box to site-specific values at the surface (two-dimensional fields); different methods include: (1) transfer functions, (2) weather typing, and (3) weather generators

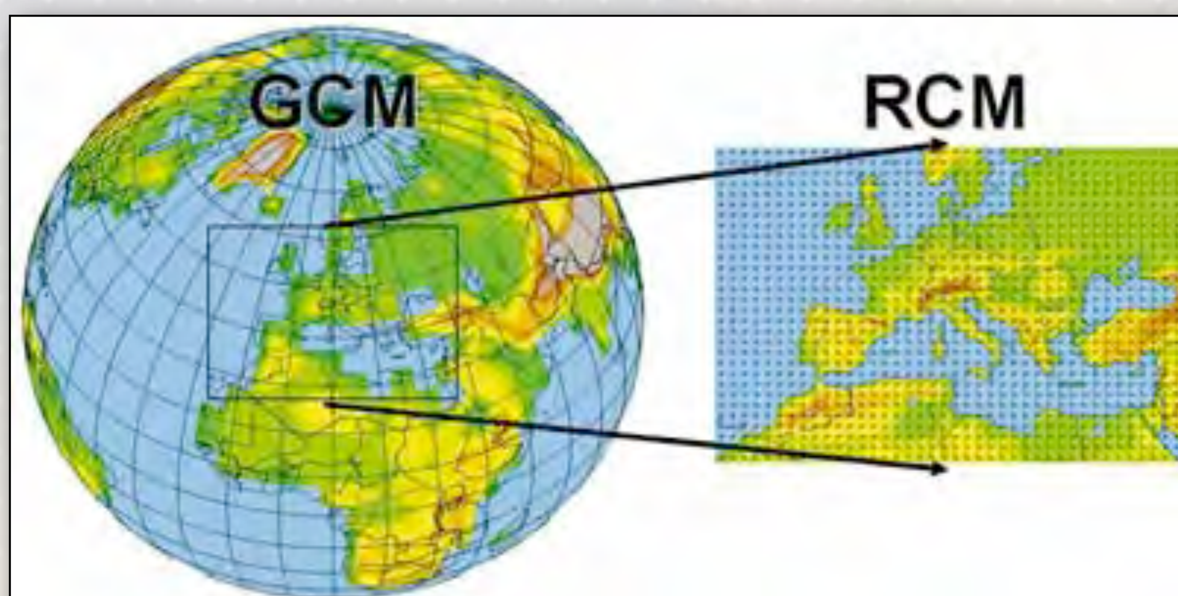
Model Resolution of GCMs vs. RCMs

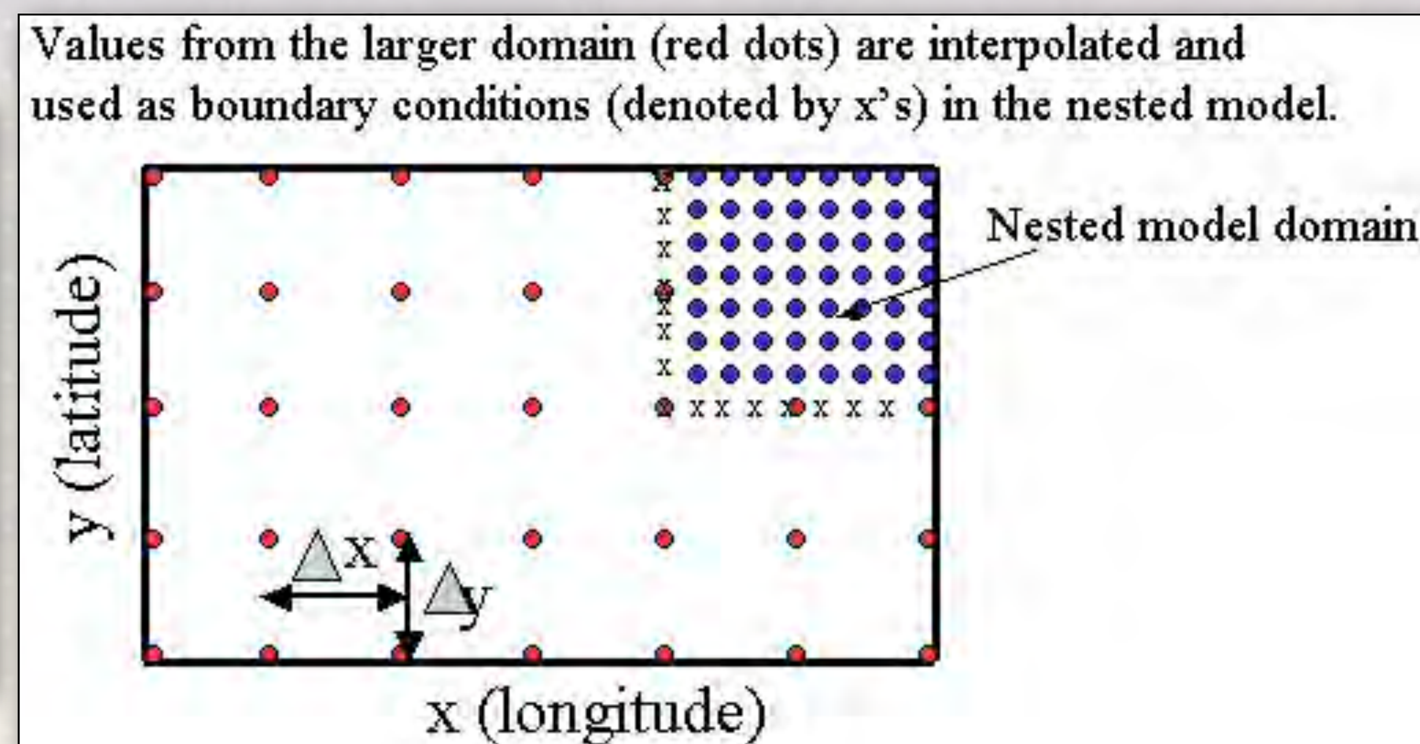


- Regional climate models (RCMs) are used for dynamical downscaling
- RCM resolutions range from about 4–50 km
- Depending on the resolution, RCMs may include explicit representations of processes rather than use parameterizations

Roles of GCM vs. RCM

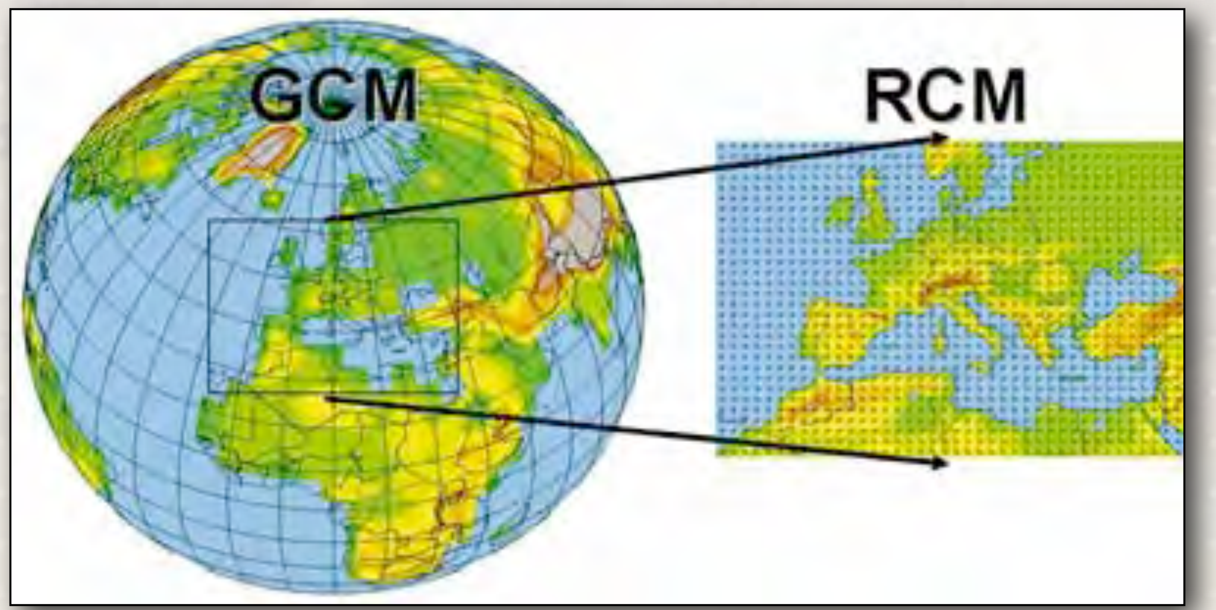
- GCM simulates large-scale circulations responding to large-scale forcings (e.g., GHG concentrations)
- RCM is "nested" within GCM domain & simulates sub-GCM-grid-scale forcings (e.g., complex topography, land cover inhomogeneities) using physically based equations; can couple to ocean, sea-ice, hydrology, chemistry, & land-biosphere models





Dynamical Downscaling using RCMs

- **Historical simulations** – large-scale forcing provided by either GCM or "reanalysis" datasets
  - Output of historical GCM simulations that are not forced by observations is used as input for a limited-area domain simulation using a high-resolution RCM
  - Output of dynamically consistent gridded dataset that has been forced by assimilating all available observations (i.e., a reanalysis dataset) is used as input to the RCM
- **Future projections** – large-scale forcing provided by GCM projections; output of GCM projection used as input to RCM

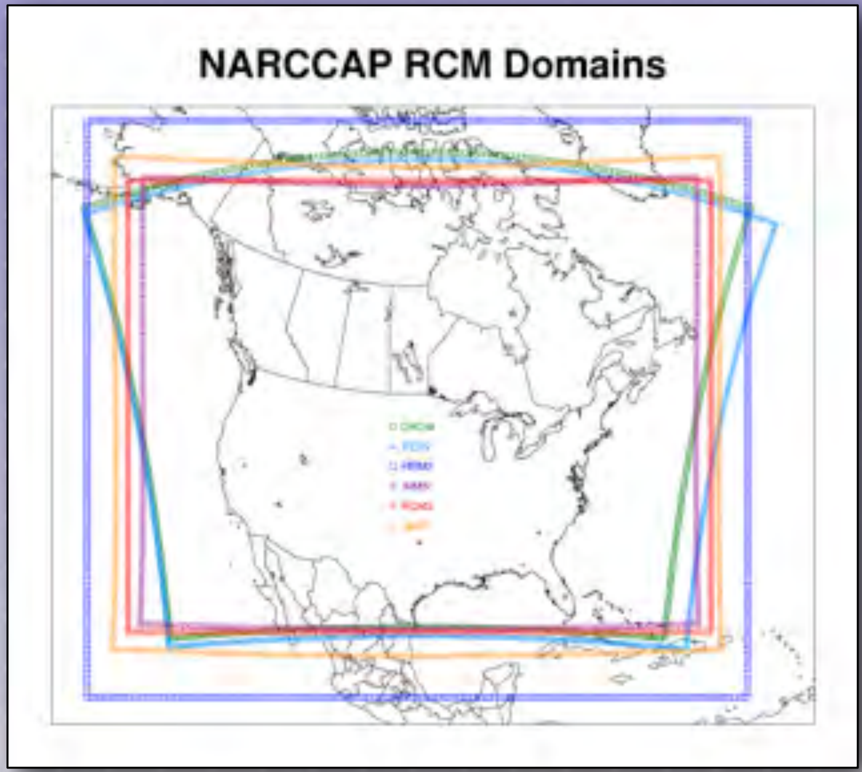


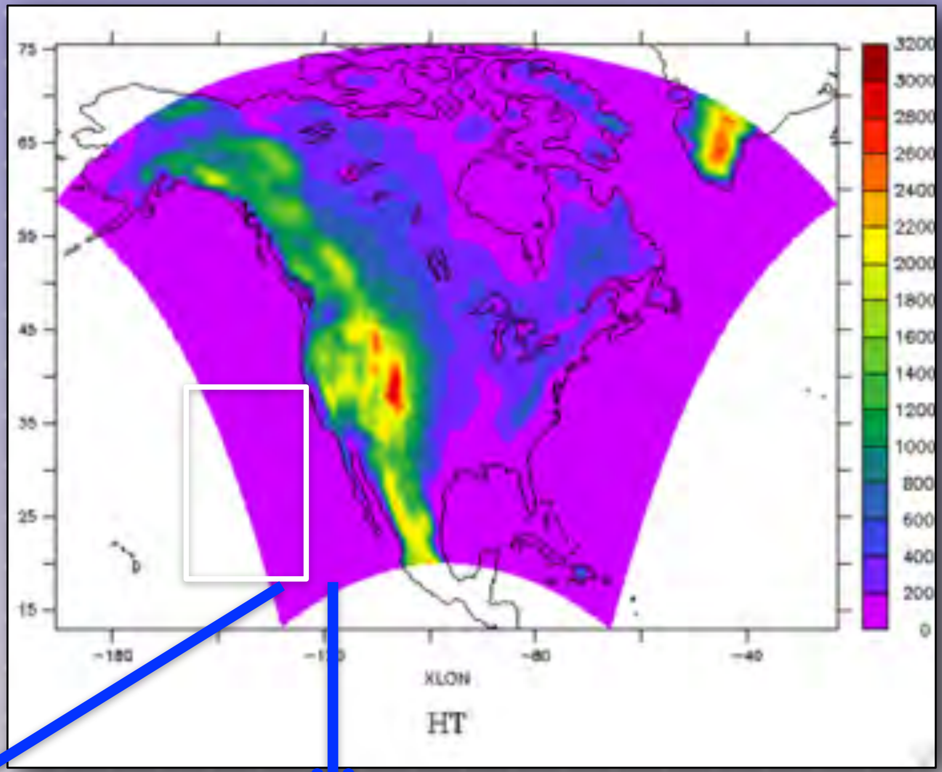
Benefits & Limitations of RCMs

- **Benefits**
  - **Physically representative** of how atmosphere works
  - **Can capture "new extremes"**, as it considers dynamics, feedbacks, interactions, & physical processes
  - **Does not require observations** (which may not exist in poorer countries or over expanses of ocean/sea waters)
- **Limitations**
  - Needs **huge computational resources** (i.e., super-computer) & storage capacity, so only certain variables may be output, only selected "time slices" may be examined (e.g., 2050-2060), no ensembles may be available, or only a couple of scenarios may be used (e.g., RCP 2.6 & RCP 8.5)
  - RCMs inherit biases from driving GCMs & are biased themselves, so **bias correction must be applied**

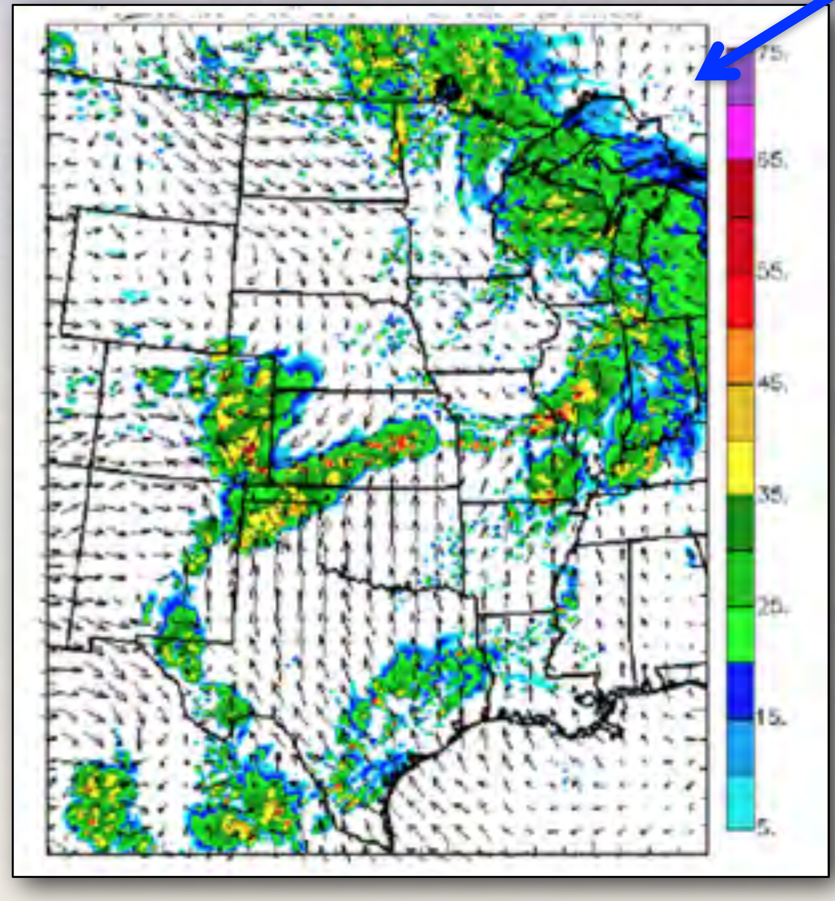
High-resolution Modeling at OU

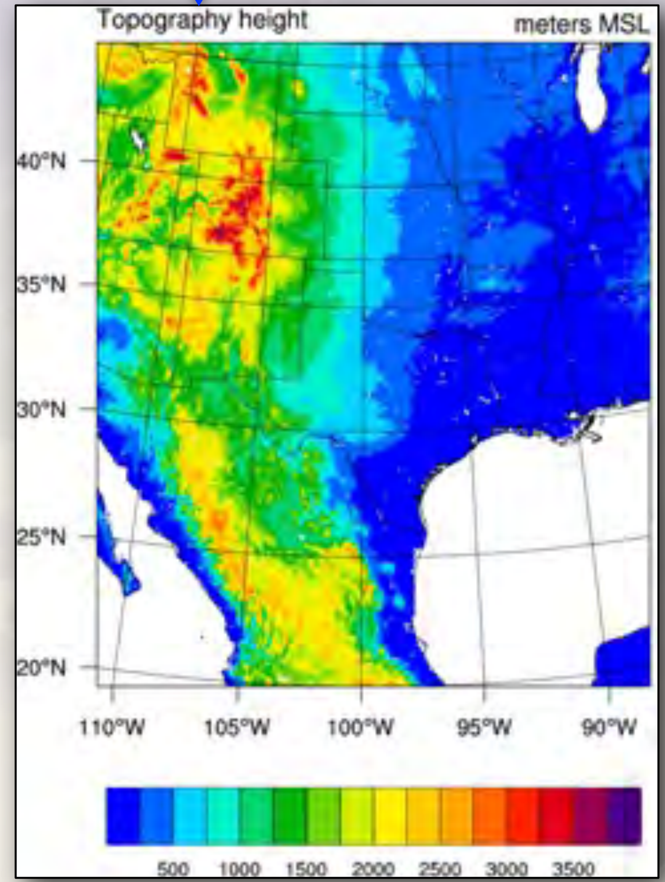
North American Regional Climate Change Assessment Program



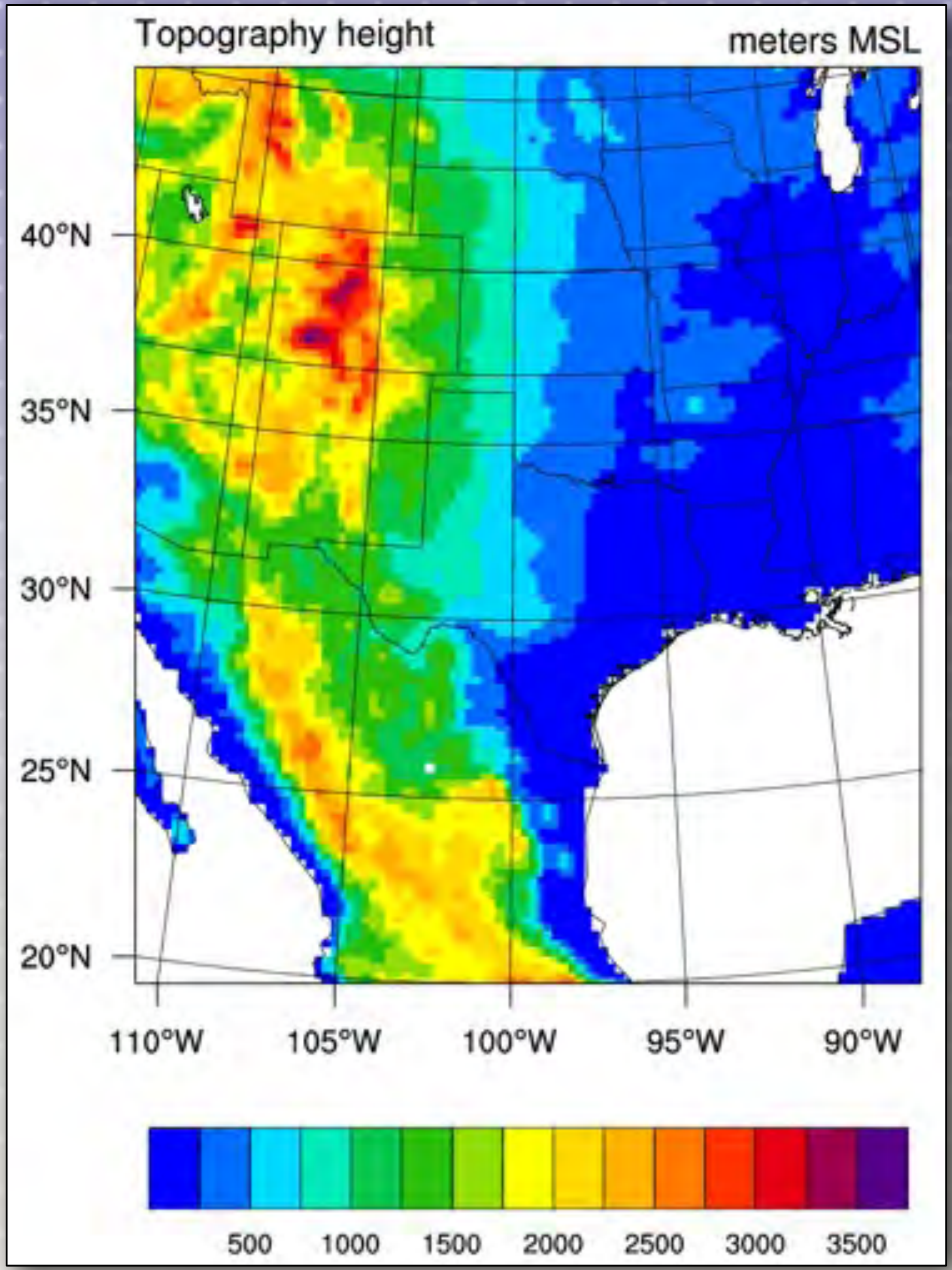


High-Resolution Weather Research and Forecasting (WRF) Model

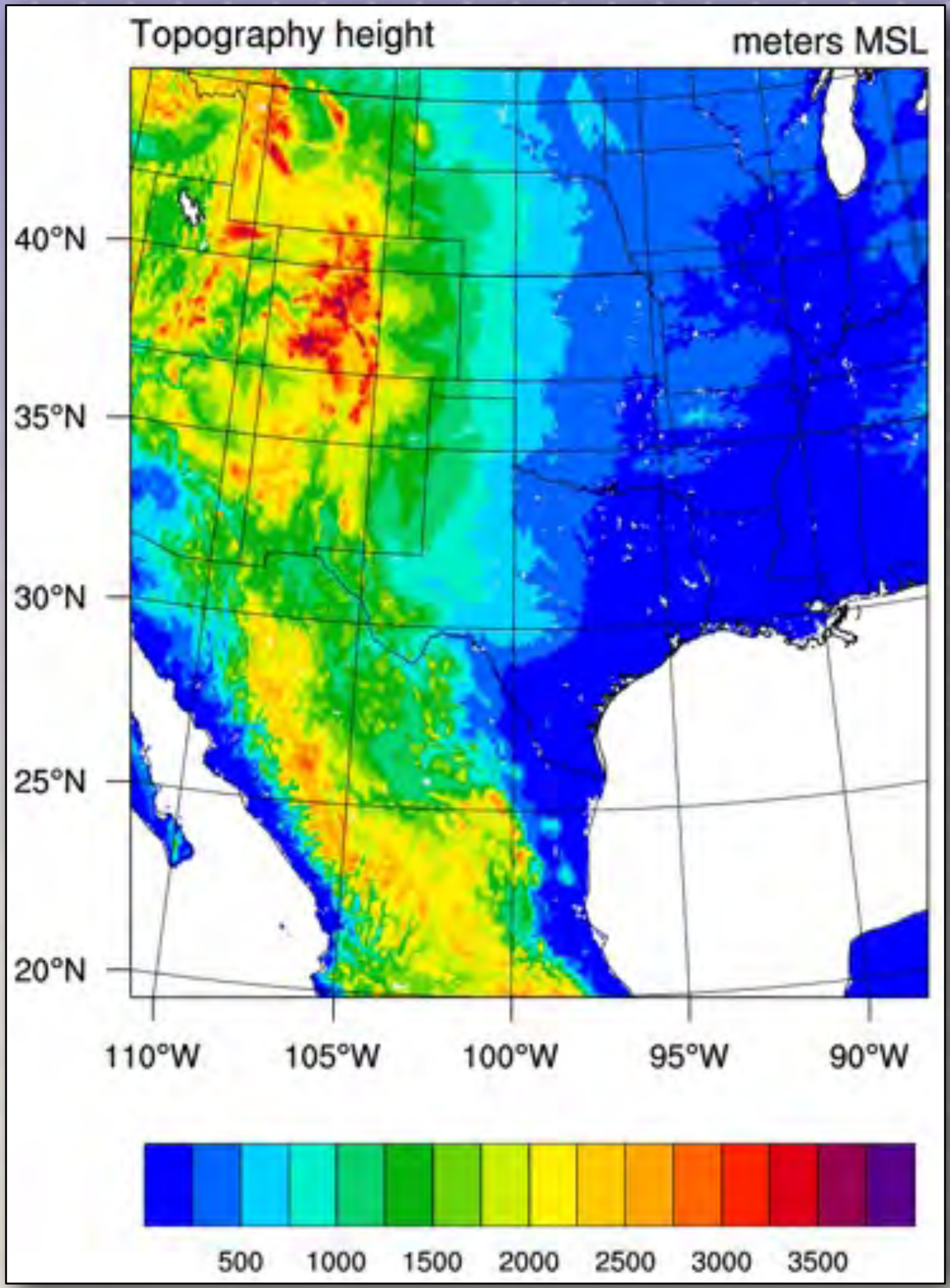




WRF Domains for Low (25km) and High (4km) Resolutions



25-km resolution topography



4-km resolution topography

Interpretation Questions to Ask

- Has the model been compared to historical observations?
- Are the results bias corrected? (Were the model biases in temperature, precipitation, etc. removed?)
- How many scenarios were used? How many GCMs were used to force the RCM? How many RCMs were used? (Is there a sufficient ensemble of models to capture the possibilities of the future?)
- If only one RCM was used, did they run it multiple times using perturbations in the physics?

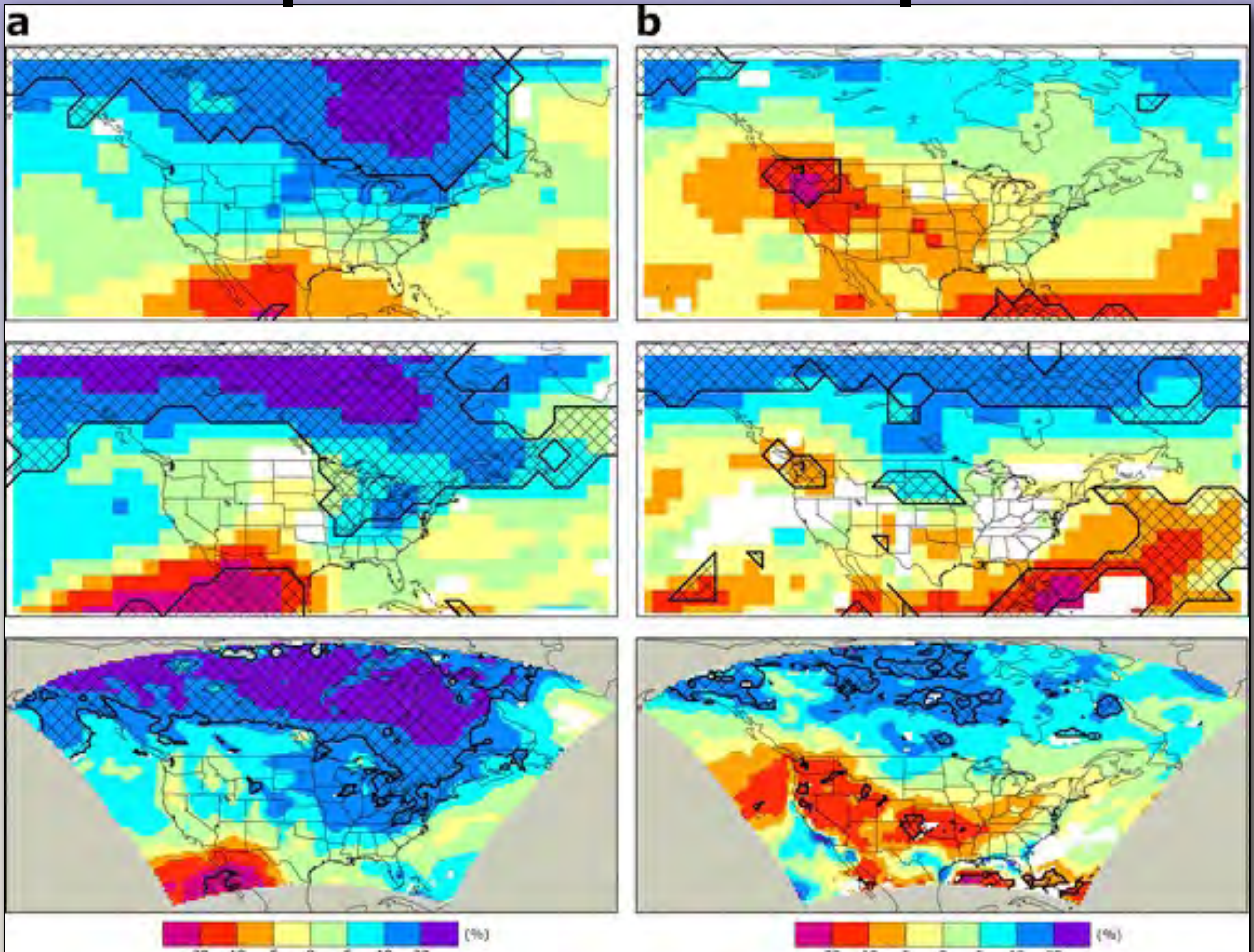
Coordinated Modeling Efforts

- **North American Regional Climate Change Assessment Program (NARCCAP)** – an "international program that serves the high resolution climate scenario needs of the United States, Canada, and northern Mexico"
- Uses several AOGCMs that force several RCMs to produce an ensemble of projections for SRES A2 emissions scenario

RCMs	Driving AOGCMs				
	NCEP	CCSM	CGCM3	GFDL	HadCM3
CRCM		x		x	x
ECP2	x		x		x
HRM3	x		x		x
MM5I			x	x	x
RCM3	x	x			x
WRFG		x		x	x
ECPC					x
WRFP					x

NARCCAP vs. GCM Ensembles

Winter Precipitation | **Summer Precipitation**



17 CMIP3 GCMs

4 CMIP3 GCMs used below

11 GCM-RCM pairs

Mearns et al. (2013)

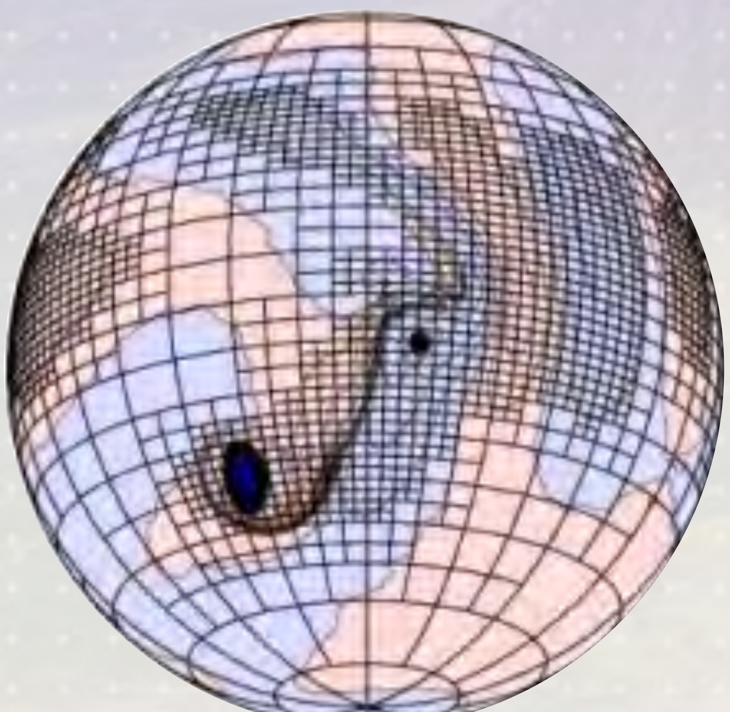
Coordinated Modeling Efforts

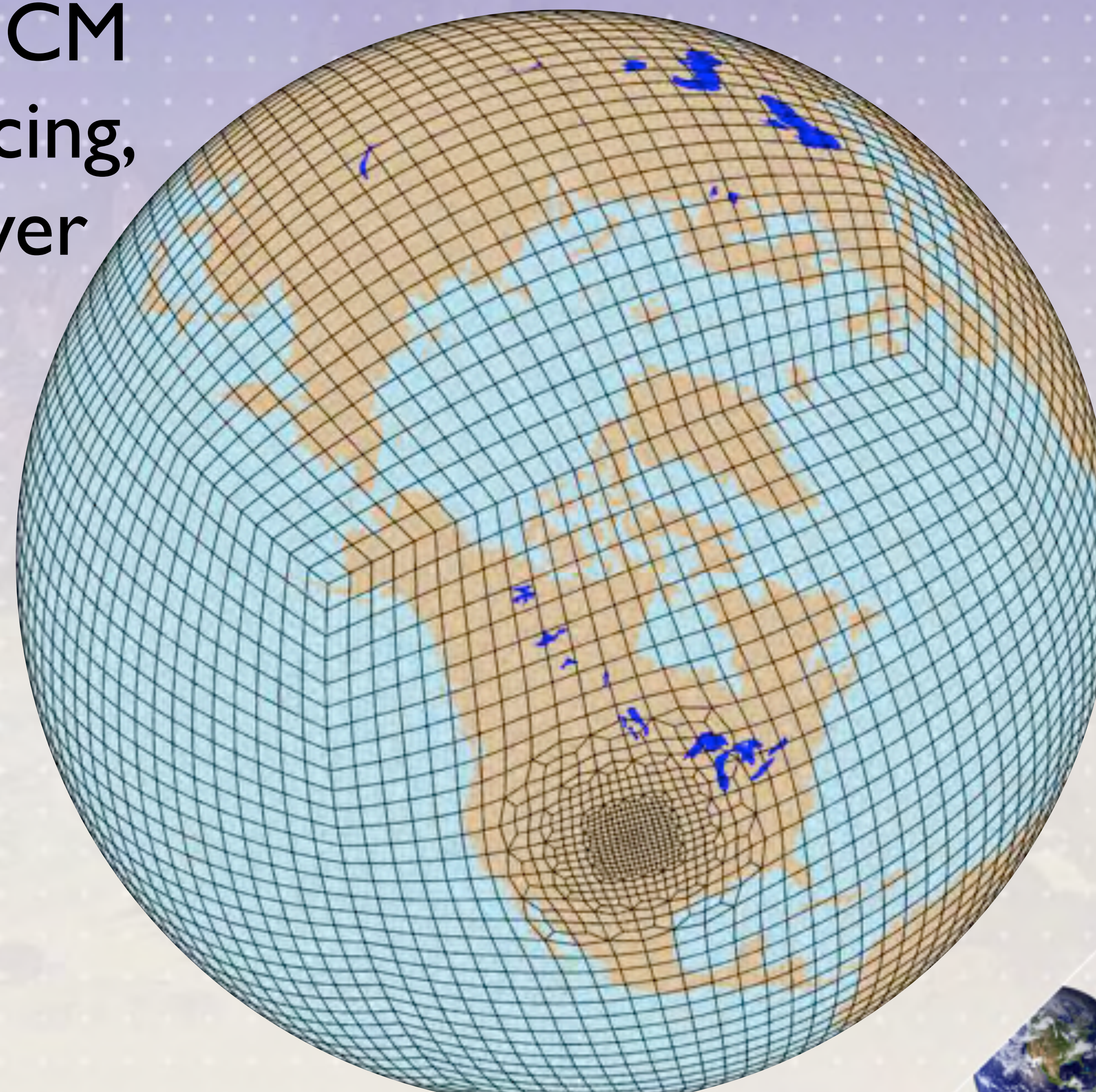
- **CORDEX (Coordinated Regional Climate Downscaling Experiment)** – to "advance and coordinate the science and application of regional climate downscaling through global partnerships;" sponsored by the World Climate Research Programme (WCRP)

WCRP CORDEX

Future of Dynamical Downscaling

- **Variable resolution GCM (adaptive mesh refinement)** – run GCM with adaptable grid spacing, increasing resolution over region of interest

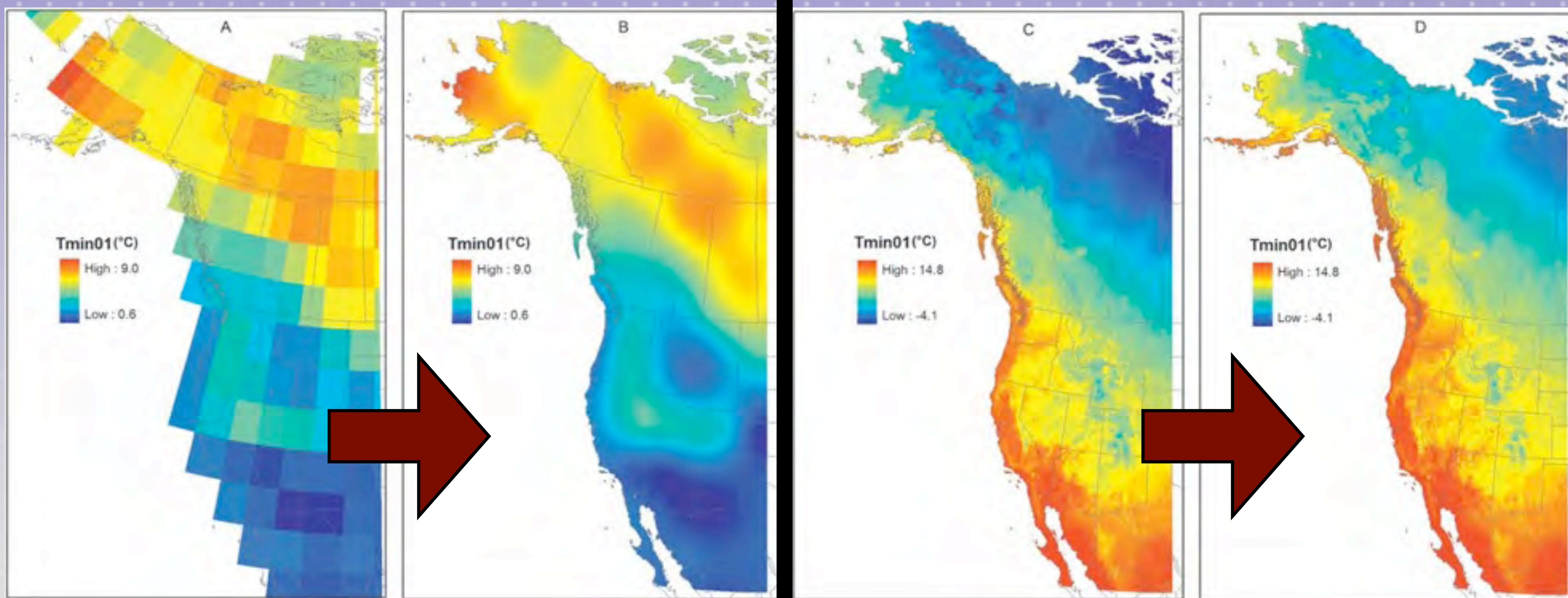




Statistical Downscaling Methods

- **Scaling/delta** methods – spatially interpolate GCM output; more for "bias correction" of GCMs
- **Transfer function** methods – use a function to relate predictors & predictands; includes linear & non-linear regression, artificial neural network, & machine learning techniques
- **Weather pattern** (typing) methods – use pattern recognition techniques to classify historical patterns & relate them to future patterns
- **Stochastic weather generator** methods – use random number generators to simulate daily time series of variables

Statistical Downscaling using Delta Method



GCM output (historical & future) is interpolated to...

...higher resolution, then relative change (delta) between historical & future GCM output is computed.

Delta is applied spatially to high-resolution, historical observations...

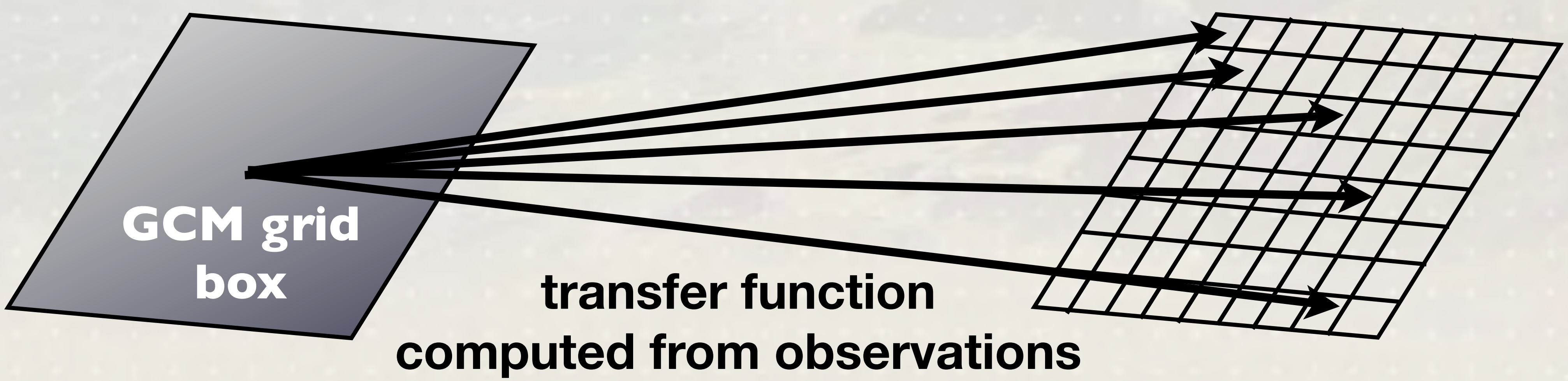
... to yield downscaled projection for future.

Statistical Downscaling using Delta Method

- **Benefits** – very **simple computationally**; straightforward to implement; **time sequence of events matches the historic record** in the gridded data sets; **bias from GCMs is not passed on**; & easily interpreted
- **Limitations** – **can not resolve regional-local scale processes & relationships**; assumes changes only in the means (i.e., no changes in higher statistical moments); **does not allow for changes in variability and/or extremes** (i.e., can underestimate low-frequency, high-impact events)

Statistical Downscaling using Transfer Functions

- **Predictor** – values of a climate variable (e.g., air temperature, precipitation) at the GCM grid box
- **Predictand** – site-specific variable (e.g., max. temperature at the surface) that is predicted, usually on a daily time scale, from the predictors
- **Transfer function** – a statistical model that relates the predictor to the predictand using an appropriate technique & actual observations for calibration & validation



Statistical Downscaling using Transfer Functions

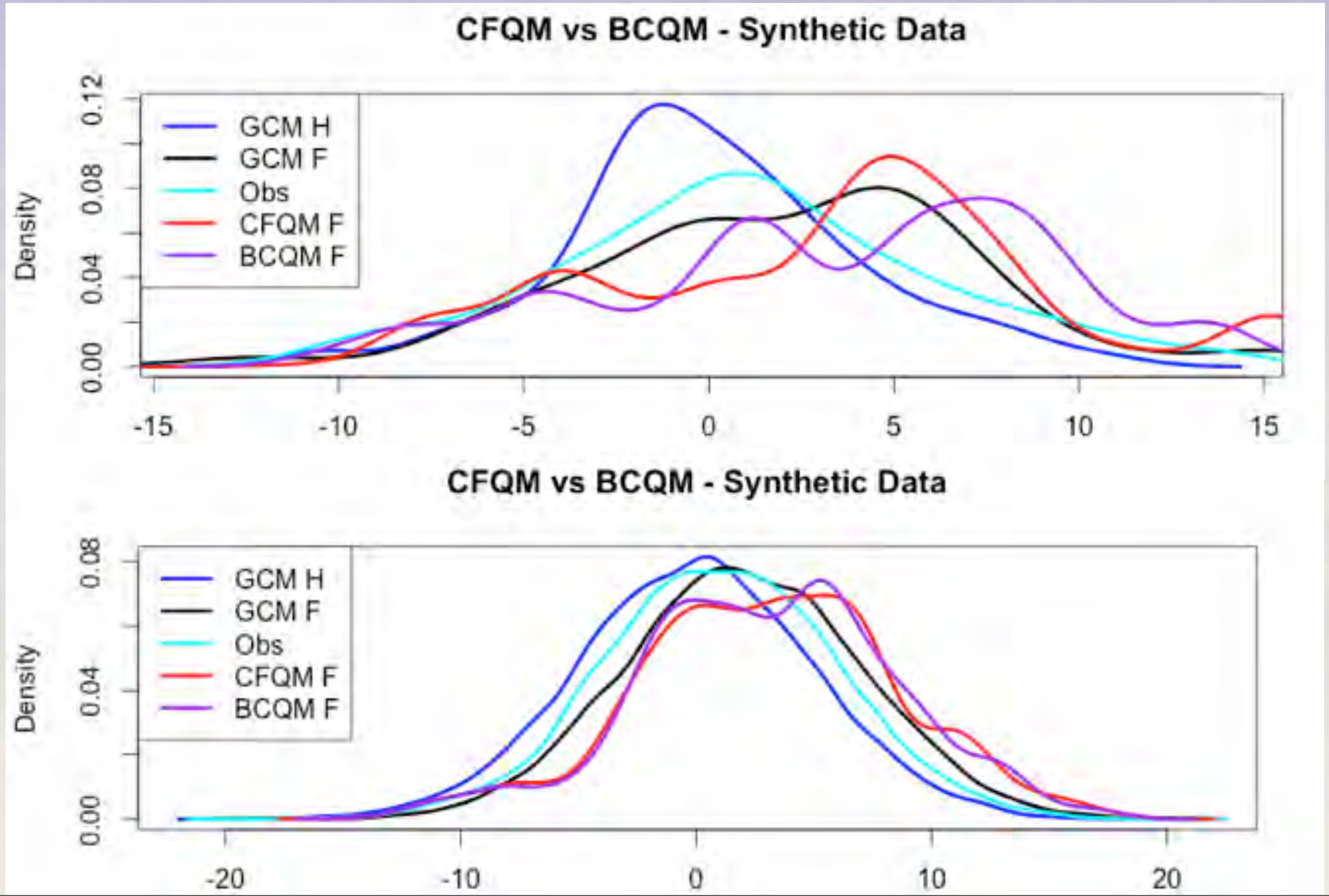
- **Main assumption of stationarity** – statistical relationship between large-scale predictors & small-scale predictands (i.e., transfer function) that was computed using historical observations is valid in the future
- **Benefits** – relatively **simple computationally**; easy to produce; **can provide point estimates**; can produce ensembles of high-resolution climate projections for long time periods; reduces biases from GCM output
- **Limitations** – requires long time series of quality observations of predictand variable for calibration & validation; **may not be a relationship between large & small scales for some predictands**; relationships only valid for range of observational data at location; does not consider dynamics, feedbacks, interactions, & physical processes

Predictors

- Common predictors – daily/monthly maximum/ minimum/average temperature; daily/monthly precipitation; sea-level pressure; humidity; winds
- **Predictors require a long time series of observations** to calibrate the statistical model
- May relate multiple predictors to a single predictand to obtain between statistical relationships; may also relate a predictor across multiple grid boxes to a predictand in a single grid box
- **Decisions are subjective** on how to implement the transfer function

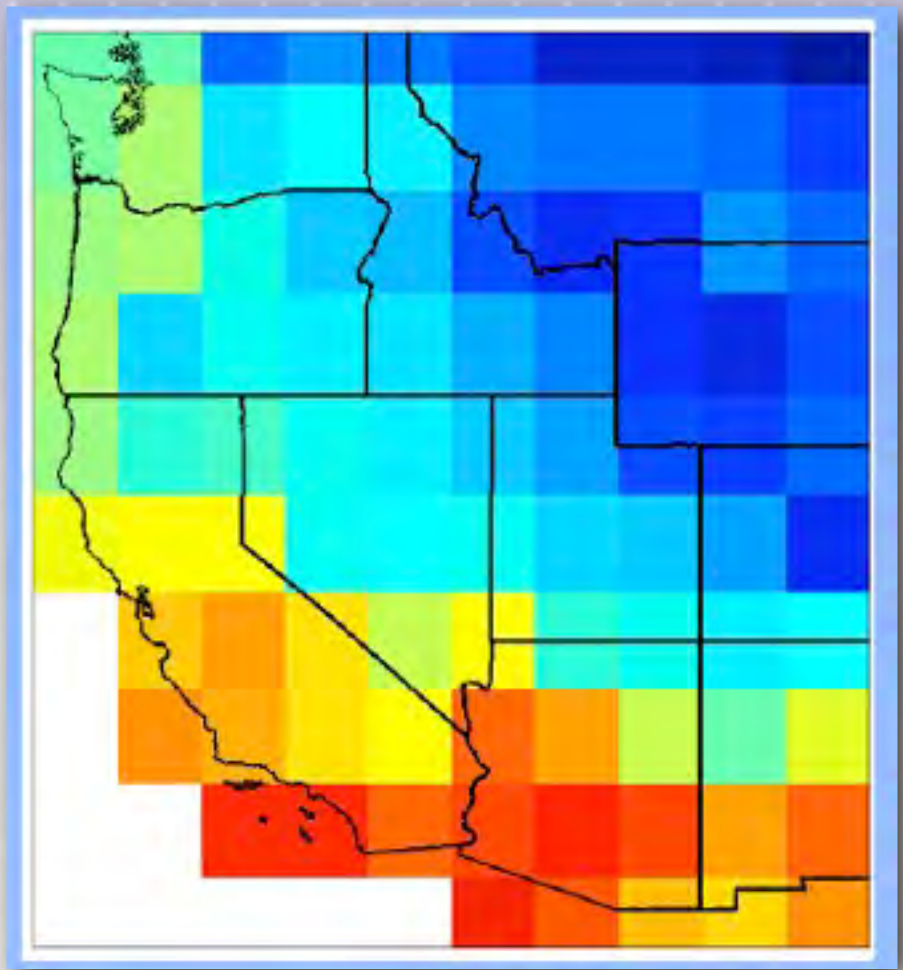
Empirical Statistical Downscaling Cautions

- Statistical methods rely on the amount of available data, so results using fewer observations (top) can be significantly different from results using more observations (bottom)

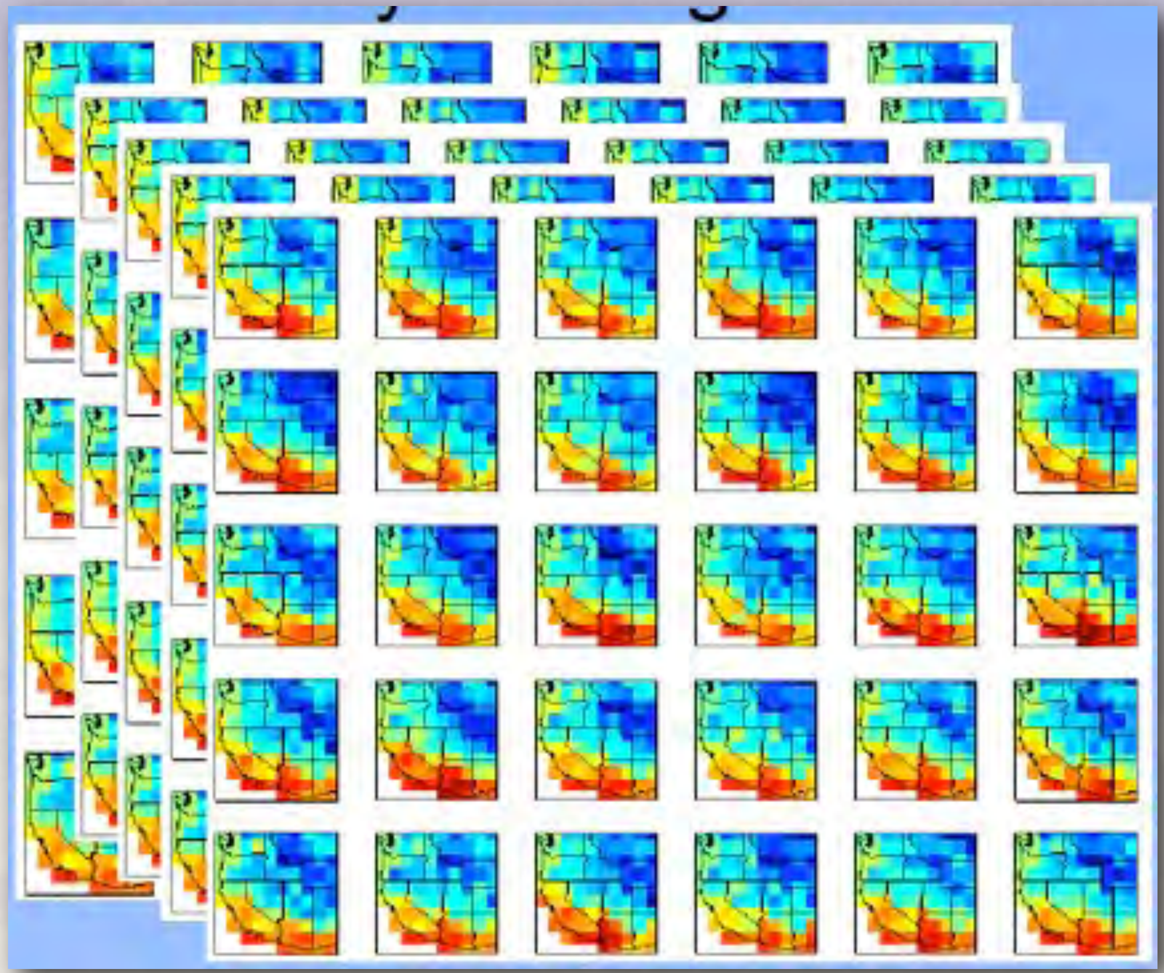


Statistical Downscaling using Weather Typing

- Statistically relate large-scale, GCM output to regional spatial patterns, classify patterns either objectively or subjectively, & create conditional probability distributions from local observations



GCM output



potential analogues

Statistical Downscaling using Weather Typing

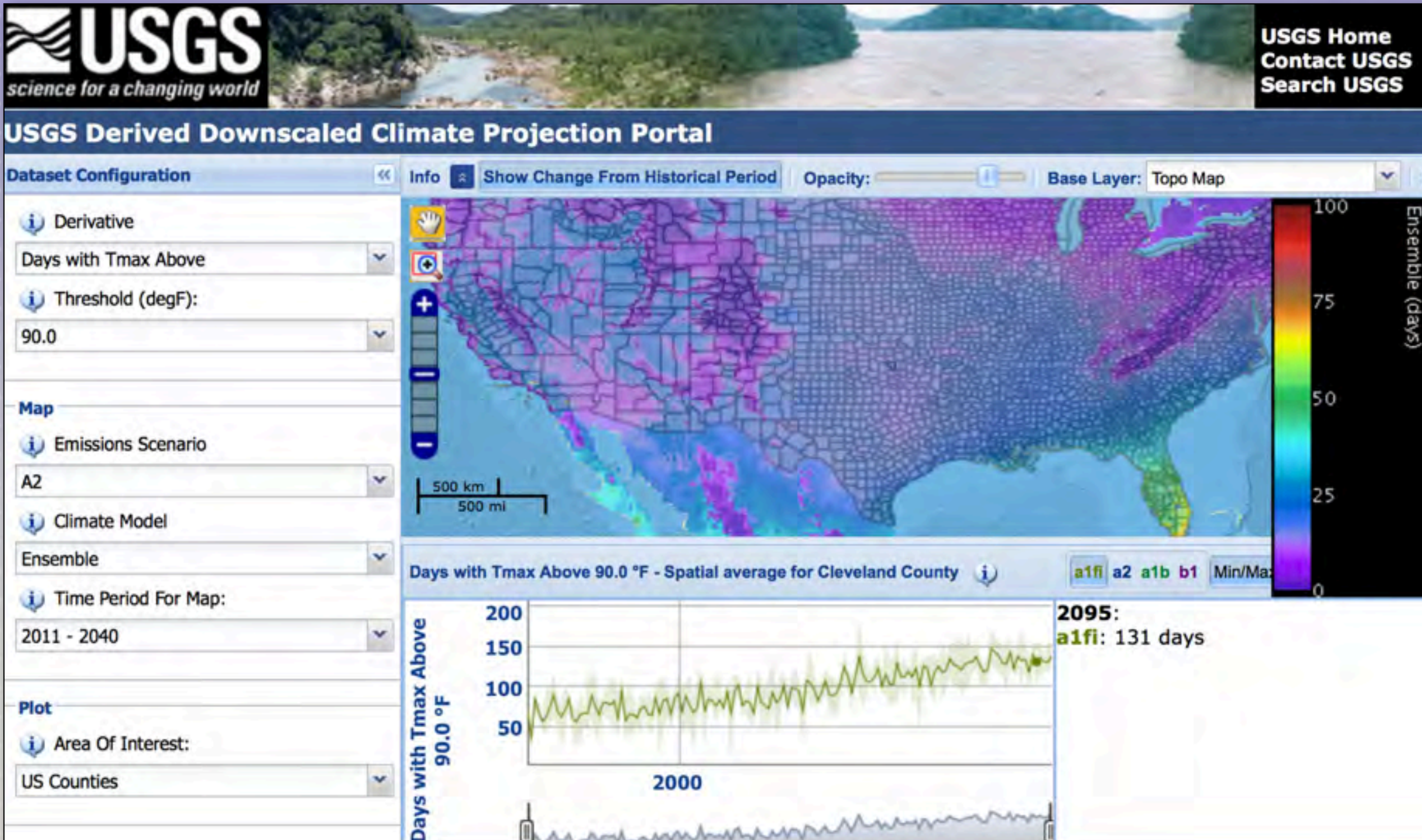
- **Advantages** – **represents daily extremes better** than transfer functions; founded on **physical linkages between large and small scales**; can produce high-resolution climate projections

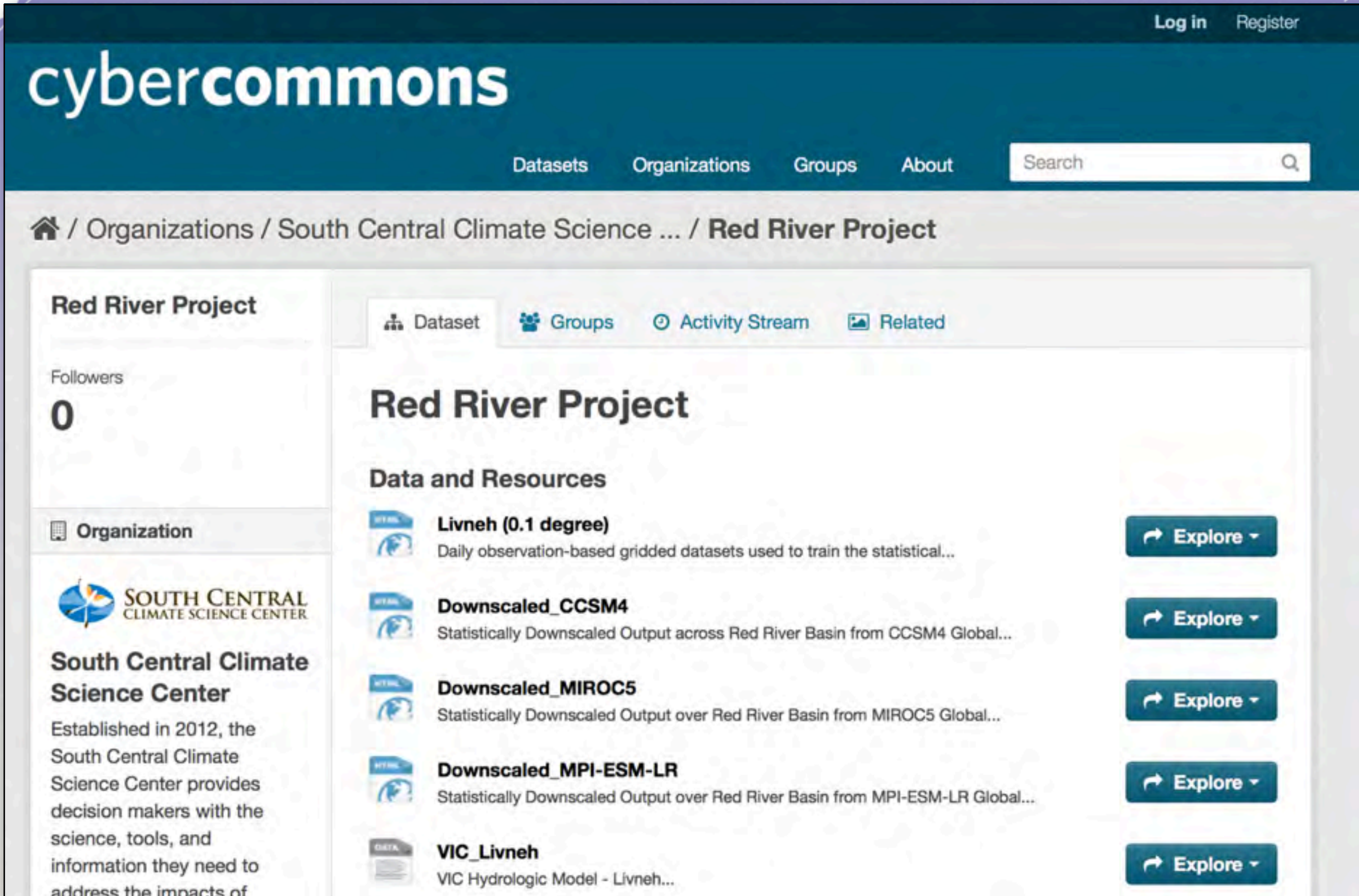
- **Disadvantages** – also **assumes stationarity**; requires long-term spatial observations across region of interest; does not account for biases in the GCM output; pattern matching dependent on the domain extent & location; **no analogs for future climates**

Statistical Downscaling using Weather Generators

- **Stochastic weather generator** – creates artificial time series of weather data at a given site based on its statistical characteristics of observed weather; usually precipitation is estimated for wet days based on precip. frequency distribution from observations, then other variables (e.g., daily max. & min. temperature) are conditionally based on precipitation occurrence (i.e., different relationships whether it's a wet or dry day)
- **Advantages** – can produce projections in data sparse areas; **can produce hourly time series**
- **Disadvantages** – **does not represent extremes**, rare events, or spatial correlation well; also **assumes stationarity**

Downscaled Projections Portals





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URL: http://data.southcentralclimate.org/RedRiver/Downscaled/CCSM4/

Statistically Downscaled Output across Red River Basin from CCSM4 Global Climate Model

Website

</> Embed

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rcp85/	20-Aug-2015 21:19	-

Getting the Data

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- http://data.cybercommons.org/organization/south-central-climate-science-center

… the End of the Path

- Global climate models are not intended to replicate the weather of the past or to forecast the weather of the future. Treat their results as "representative" of the past and future climate.
- Downscaling methods have their limitations. Be sure you understand those before you apply them.
- It's best to use "ensemble" results that include multiple scenarios, multiple GCMs, & multiple downscaling methods. There is no "best" one of each.
- If you care about extremes, don't just use the means.
- Understand your application & choose wisely.

Questions?

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