Climate Change Projections: Opportunities and Challenges for Marine Ecosystem Applications

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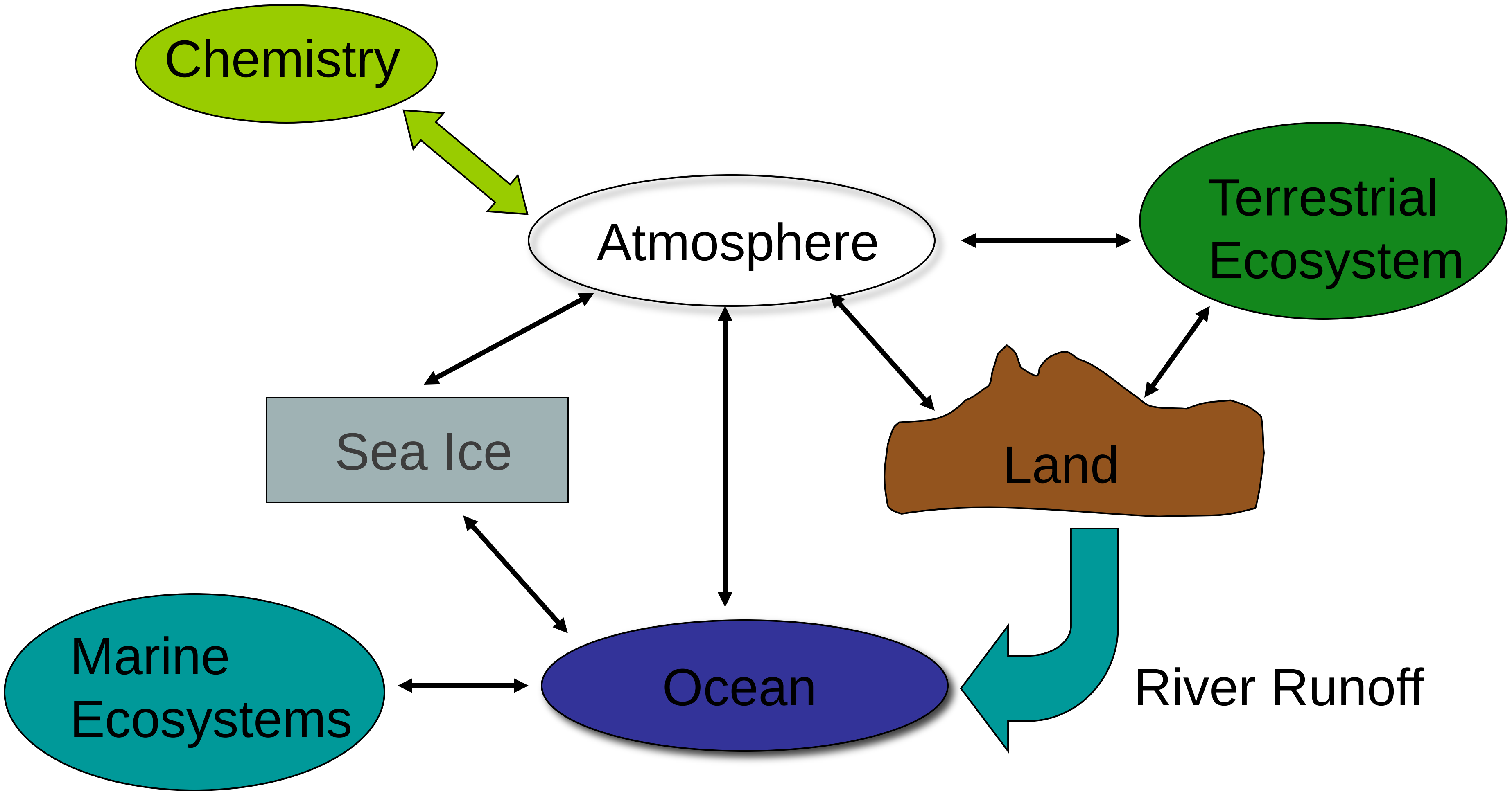
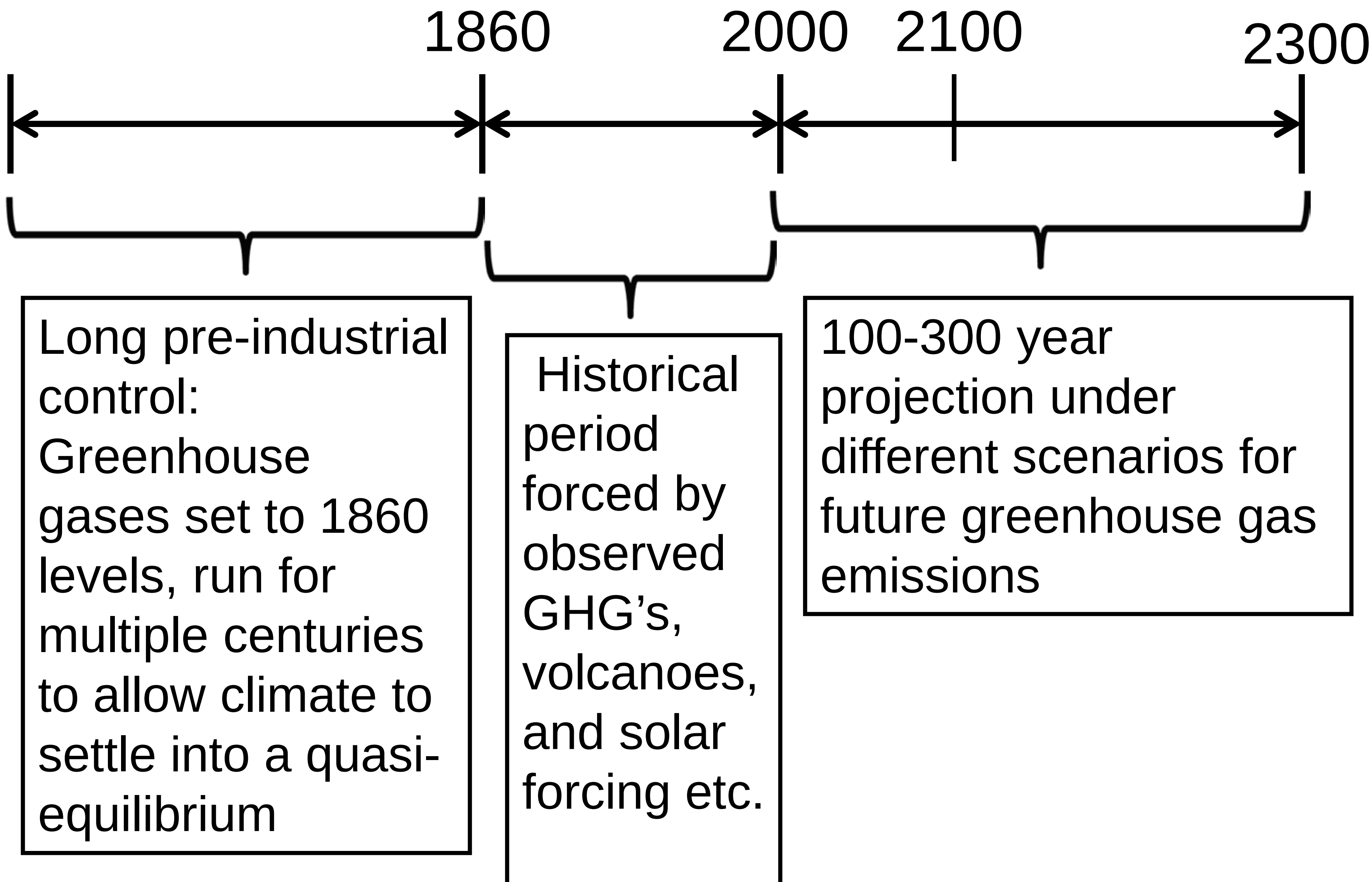
National Adaptation Forum April 2013

Components of Climate Models



Model Resolution – varies but roughly 50 – 200 km in the Ocean

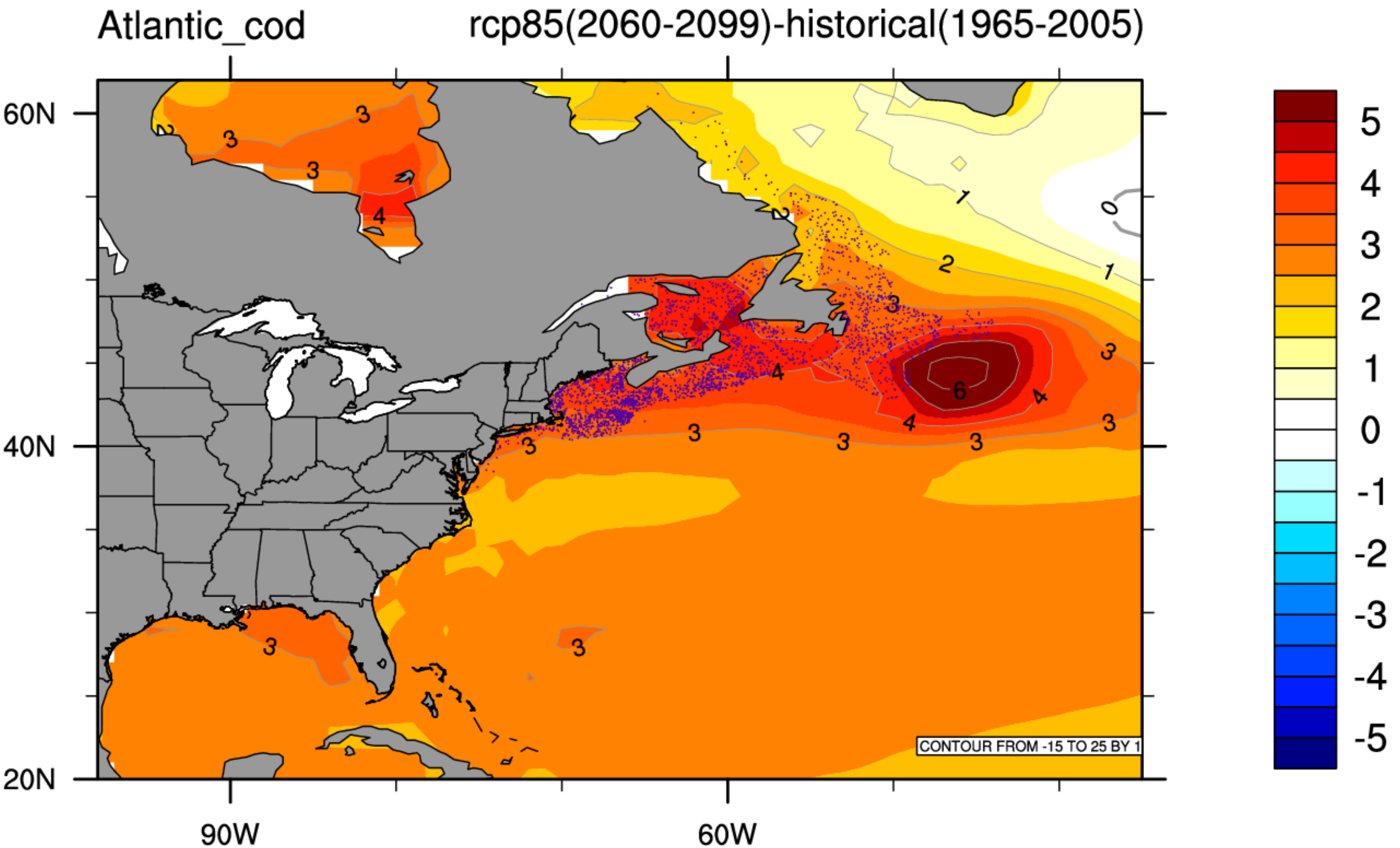
Century-scale climate model projections



Opportunities

- Some examples from the Atlantic using the new Climate Model Intercomparison Project version 5 (CMIP5)

4 Model average ΔSST (° C) & Cod locations



Impact of temperature change on:

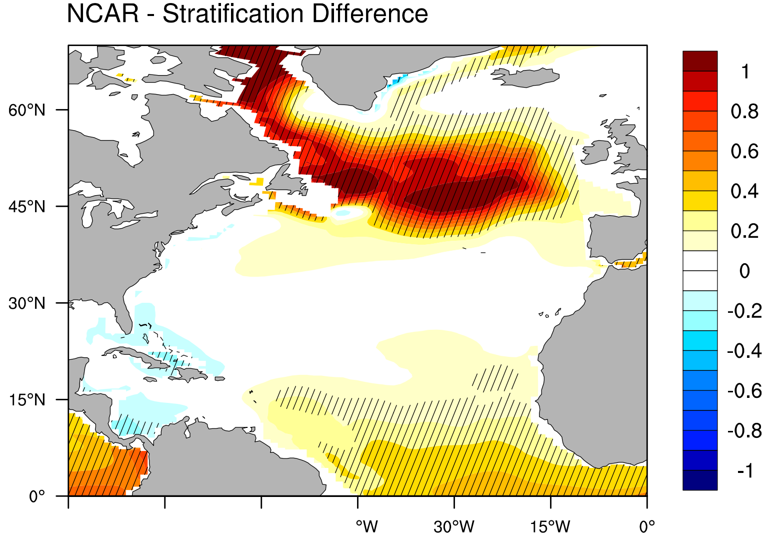
Atlantic Croaker (Hare et. al.,2010 *Ecological Applications*)

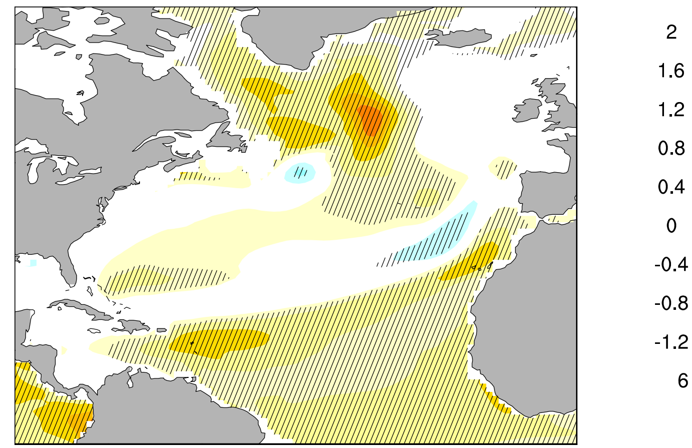
Cusk (Hare et al., 2013, J, of Marine Systems, in press)

Stratification changes

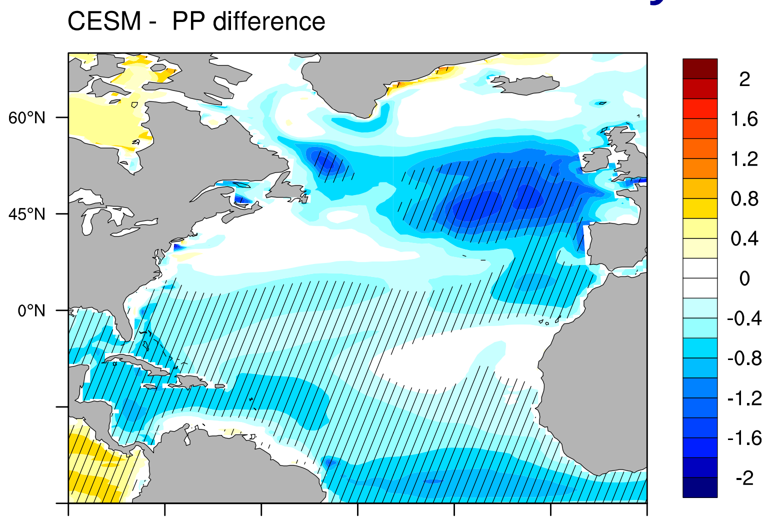
NCAR-CESM

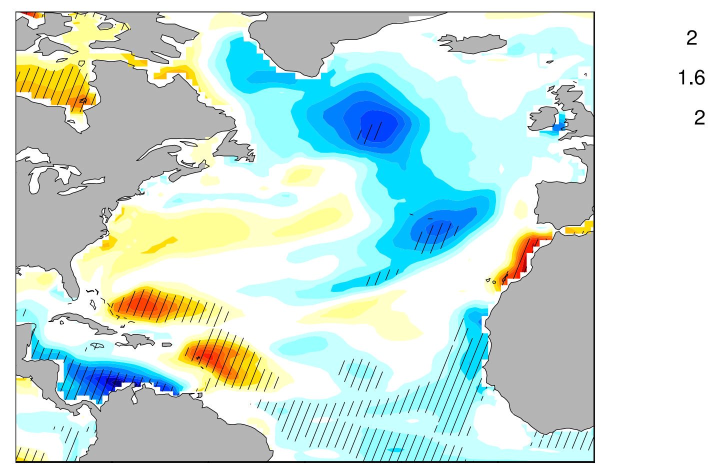
GFDL





Primary Production





Challenges

- Complexity – can be difficult to obtain, process and understand output
- Scale – climate models often at coarser resolution then some physical & ecological processes of interest

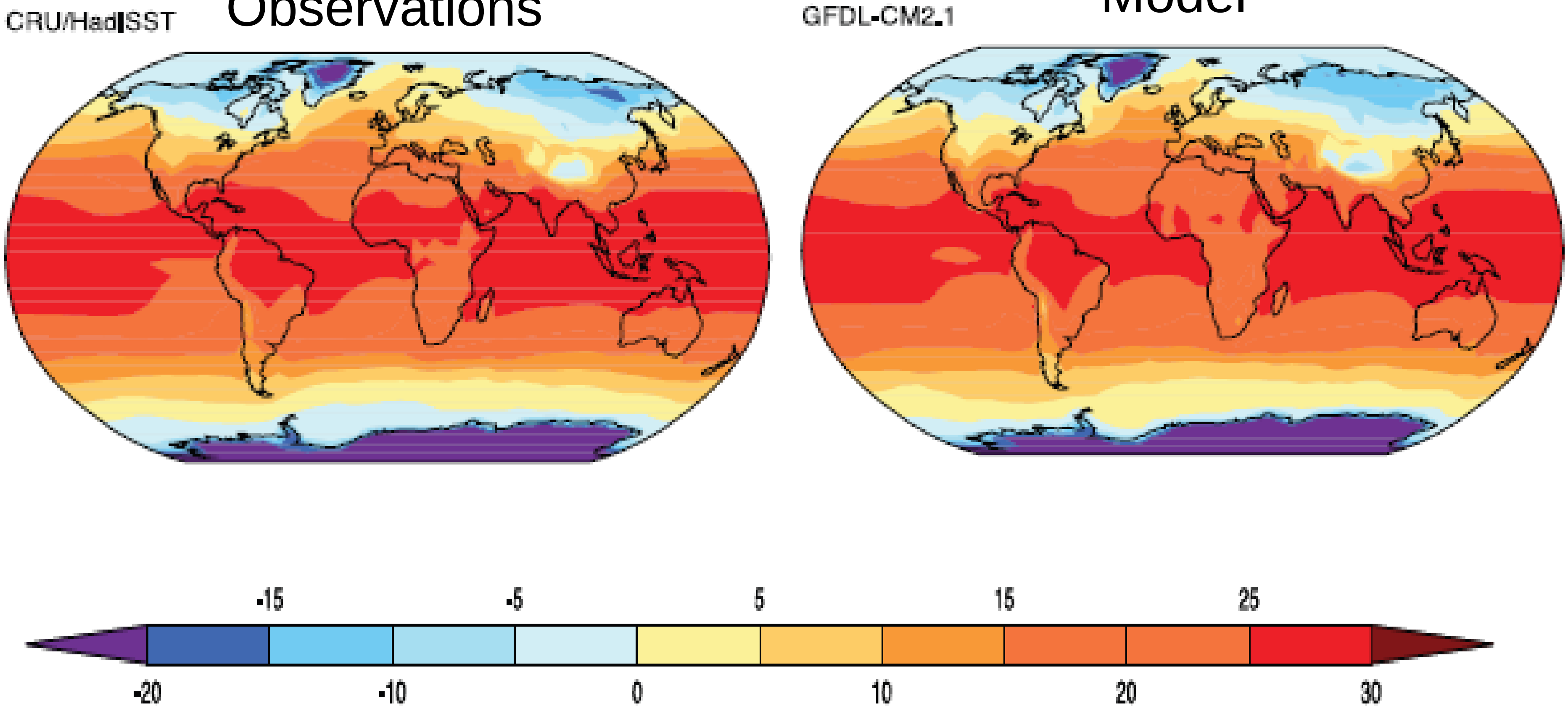
✓ Model bias

✓ Uncertainty: several sources

Large-scale distributions of many variables reproduced in climate models

Observations

Model



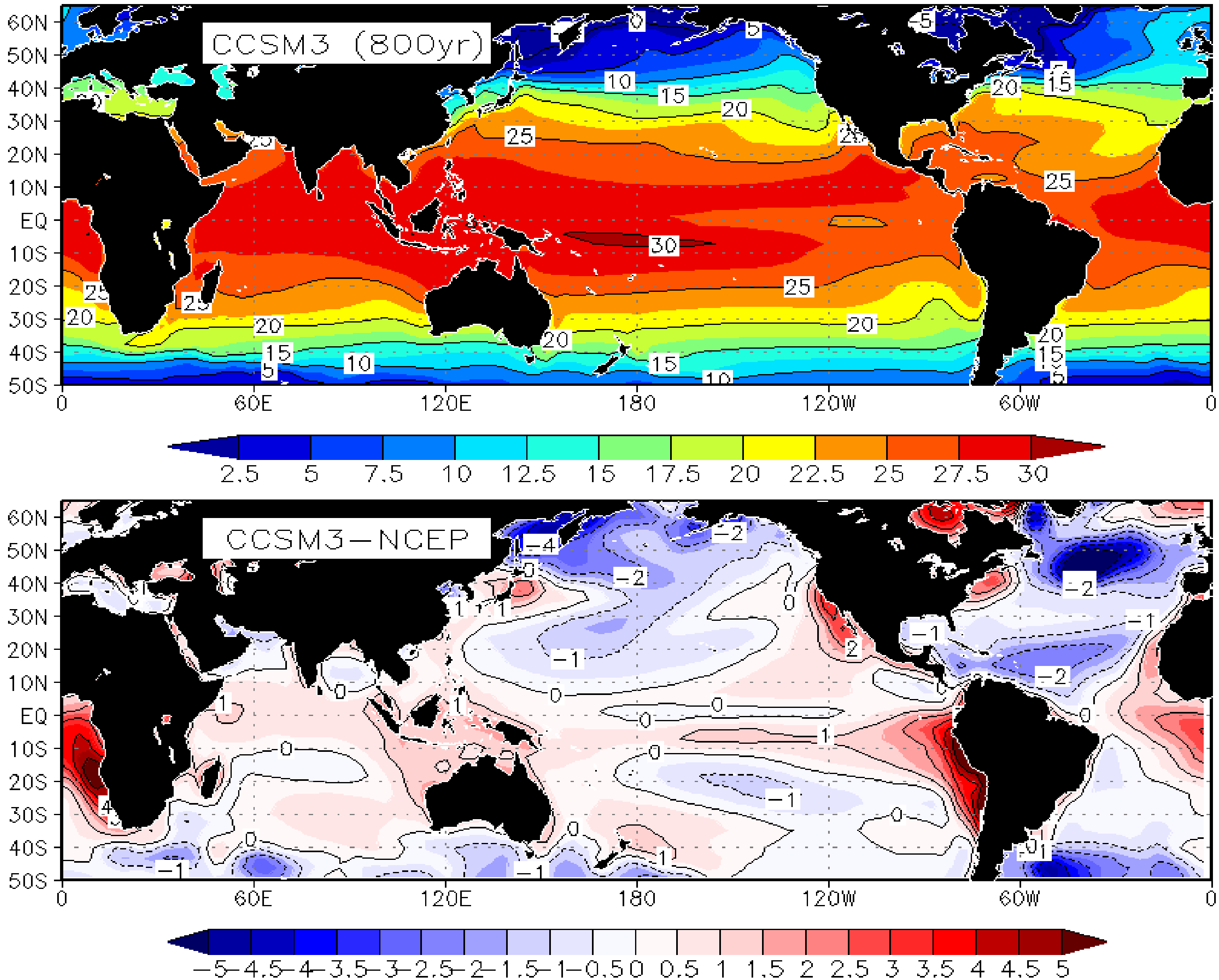
-20 C

Surface Air Temperature

30 C

Source: IPCC AR4 WG1 report, chapter 8

Annual Mean SST (ºC)



Climate Change: Sources of Uncertainty

- Forcing

  Greenhouse Gases (CO_2, Methane, etc.)

  Aerosols, land use, black carbon …

  How will these change in the future?

  "Emission Scenarios", "what if questions"

  Answer depends on economics, sociology, etc.

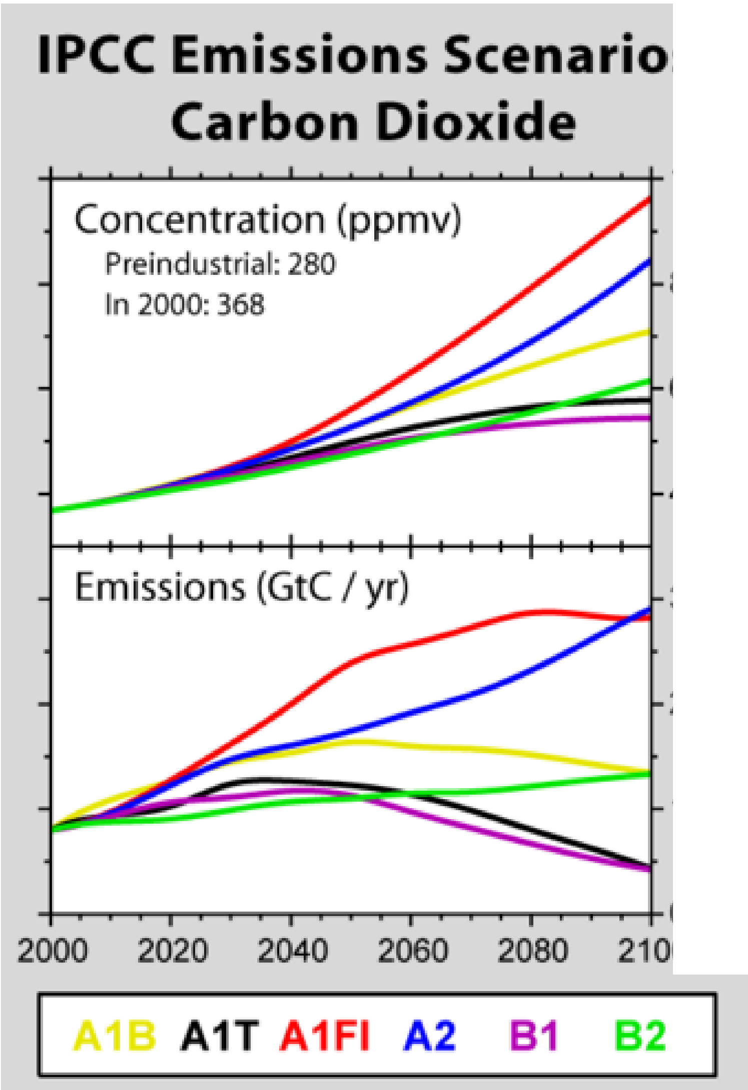
- Model Response

  Model sensitivity – respond differently to forcing

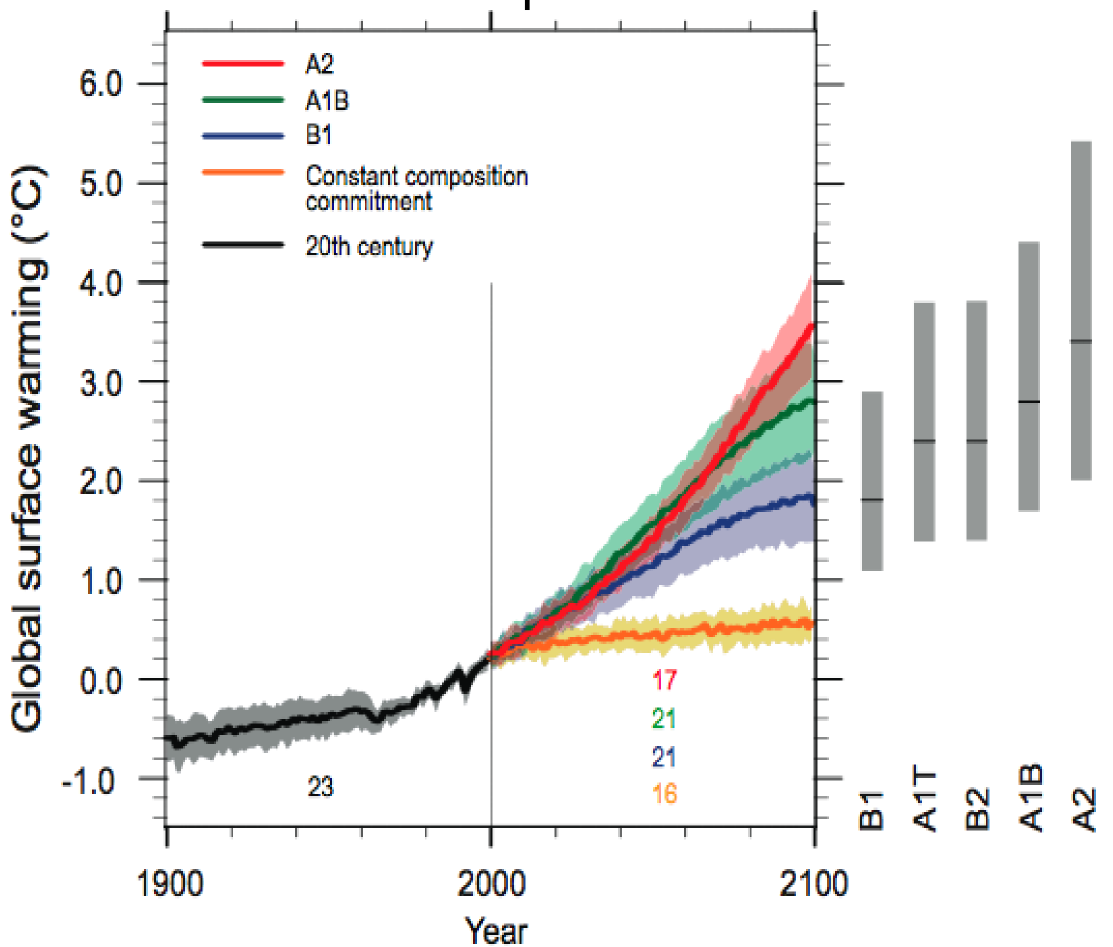
  (different physics, parameterizations, resolution …)

- Internal (Natural) Variability
  - coupled atmosphere-ocean-ice-land interactions

IPCC Projections of Climate Change
4th assessment report (AR4, 2007)

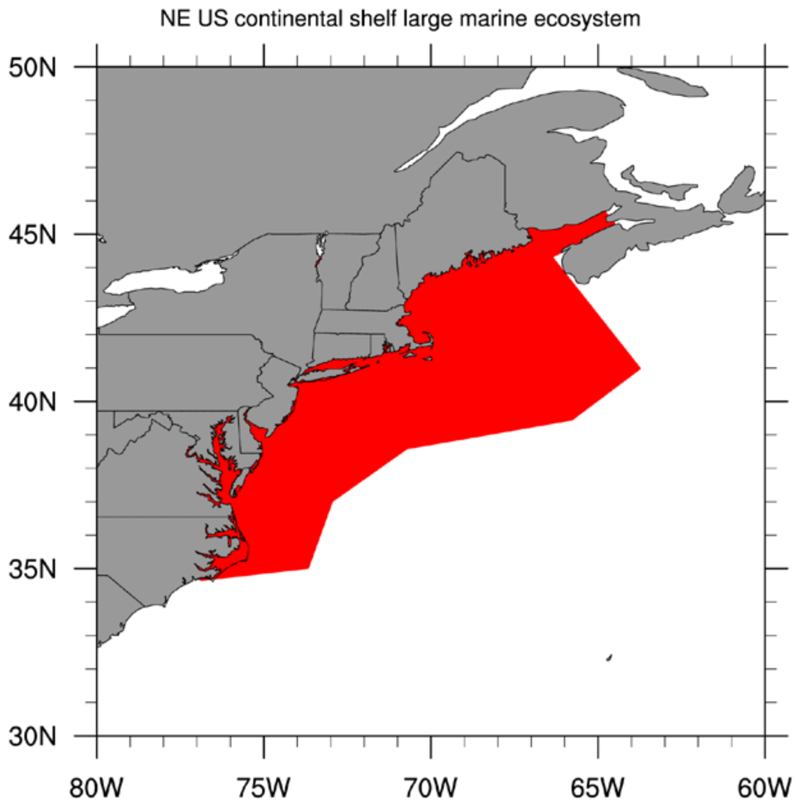


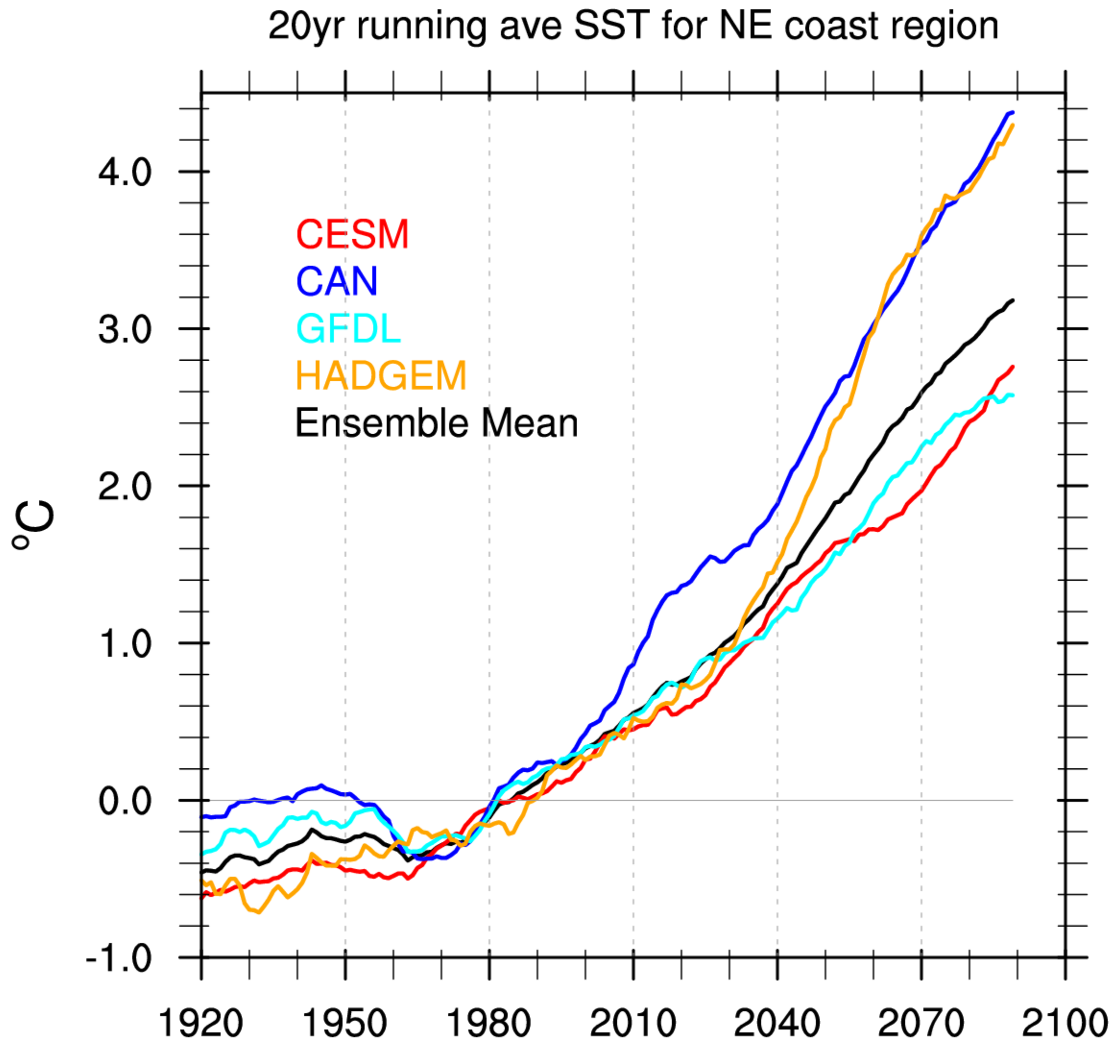
Global Temperature



Special Report on Emissions Scenarios (SRES)

SST averaged over NE US continental shelf. SST anomalies relative to the 1965-2005 climate in each model.





Future North Atlantic SST changes across GFDL CM2.1 Ensemble of simulations

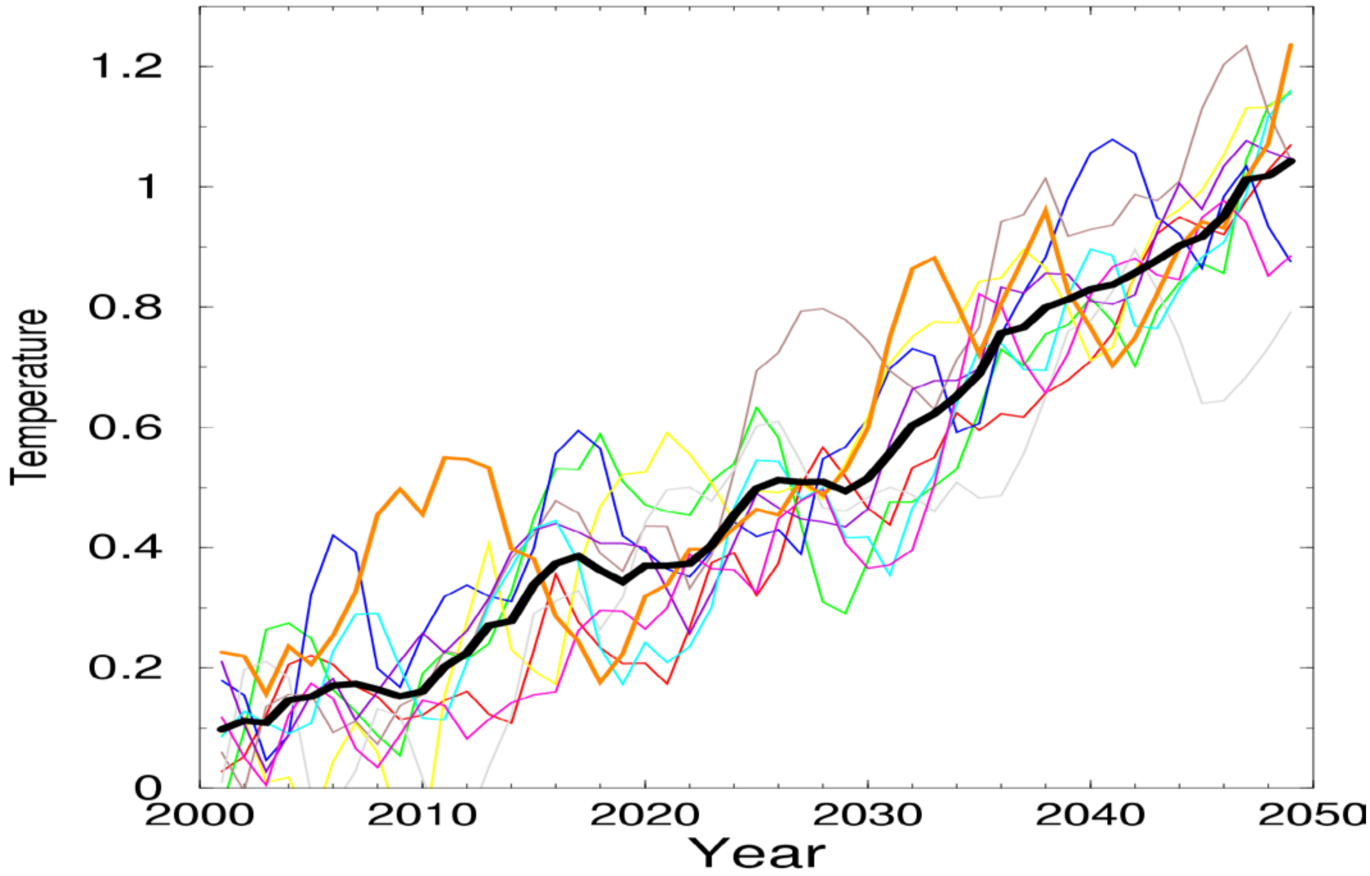
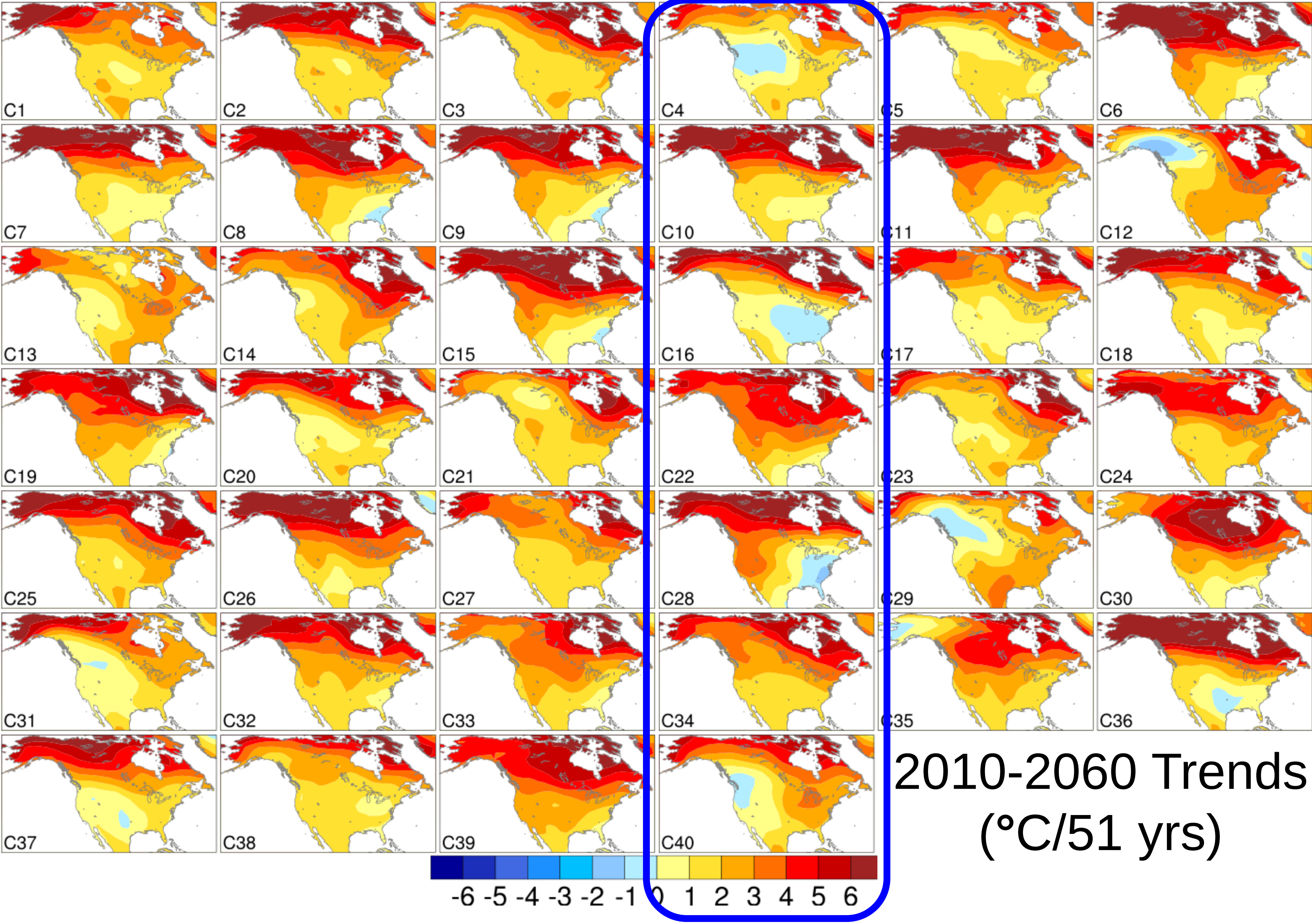
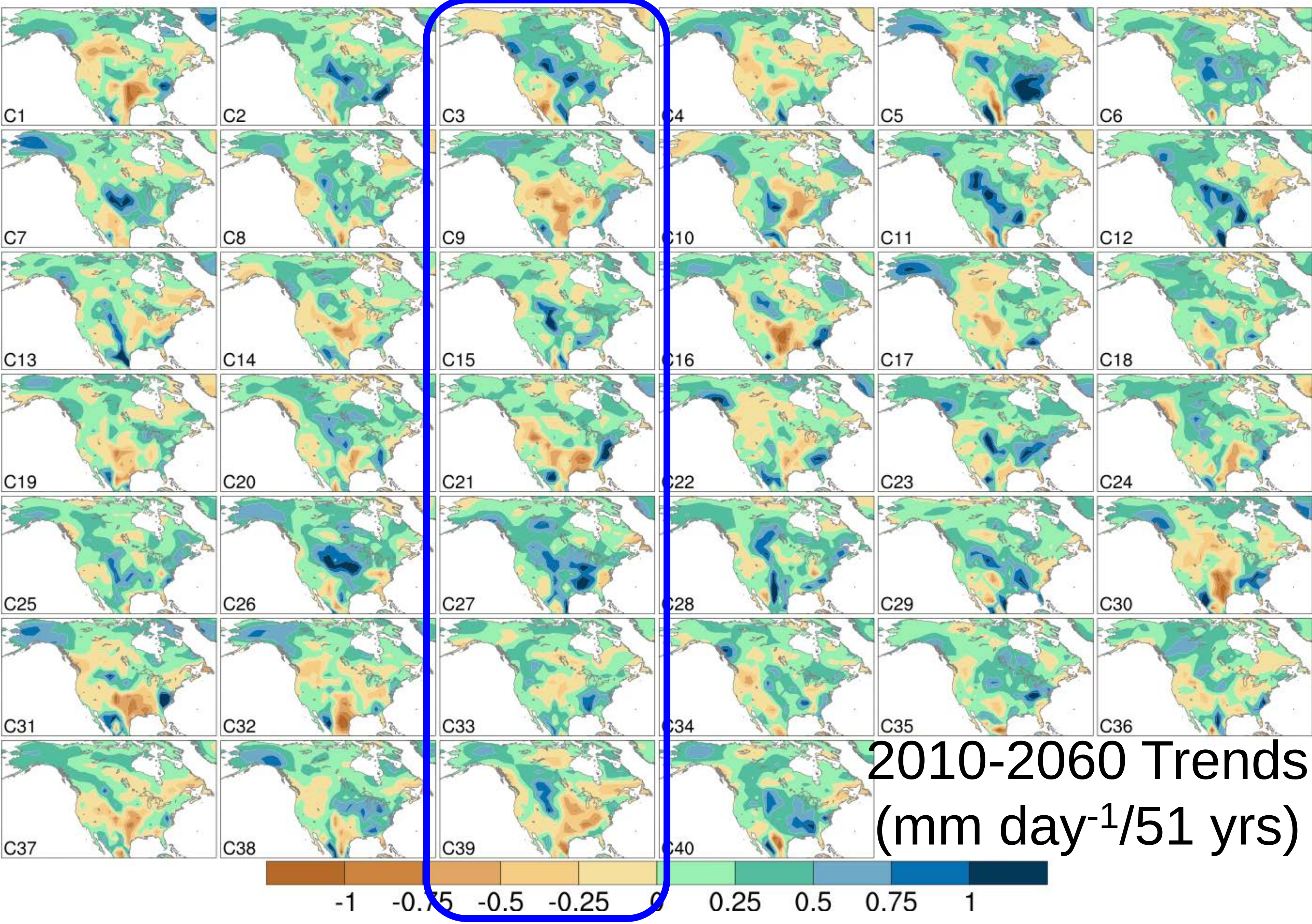


Figure courtesy of Tom Delworth/GFDL Climate Change Variability and Prediction Group



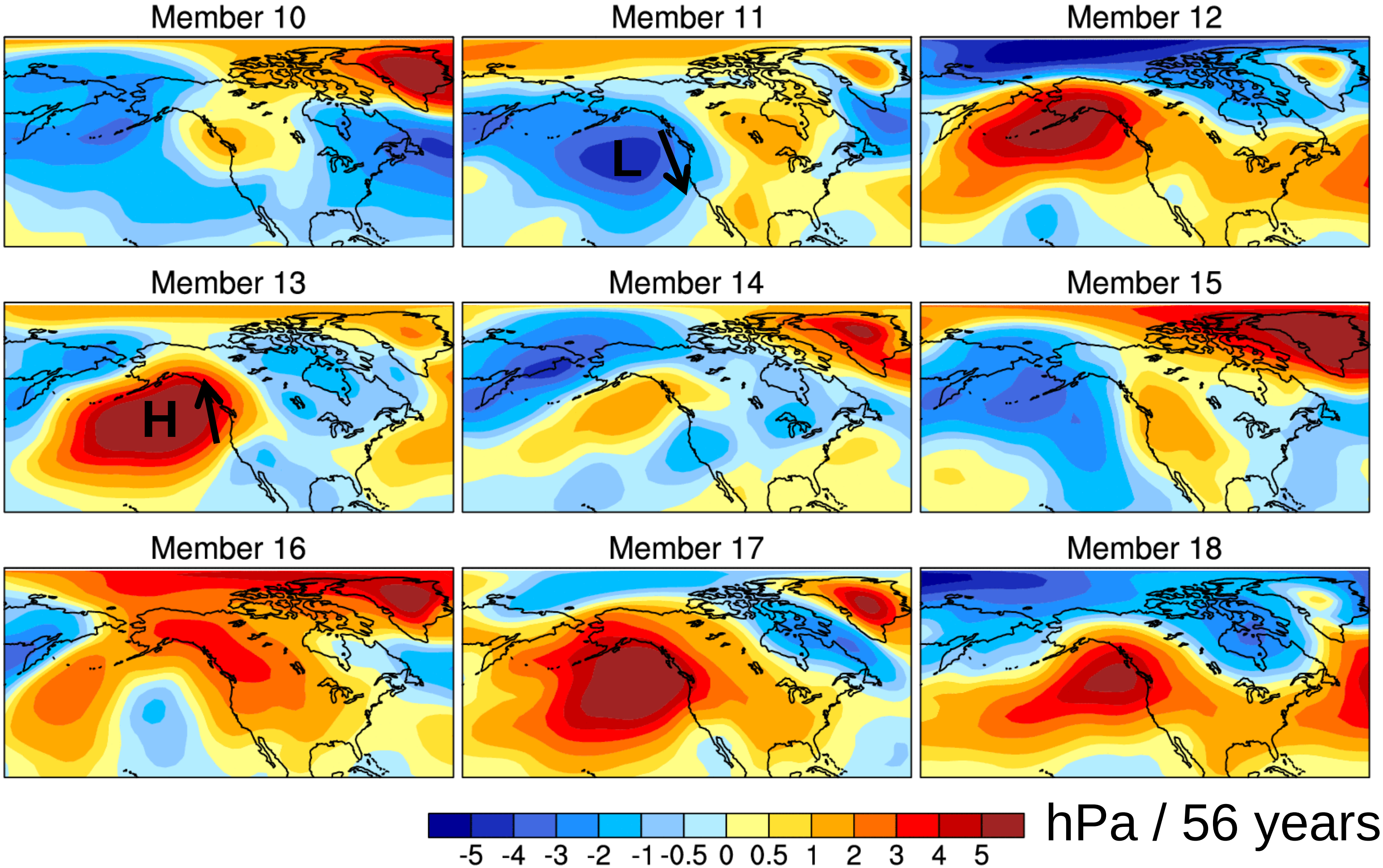
Each simulation is forced with the identical GHG increase



Each simulation is forced with the identical GHG

CCSM3 Large Ensemble

SLP Trends 2005-2060



Internal Variability (in one model)

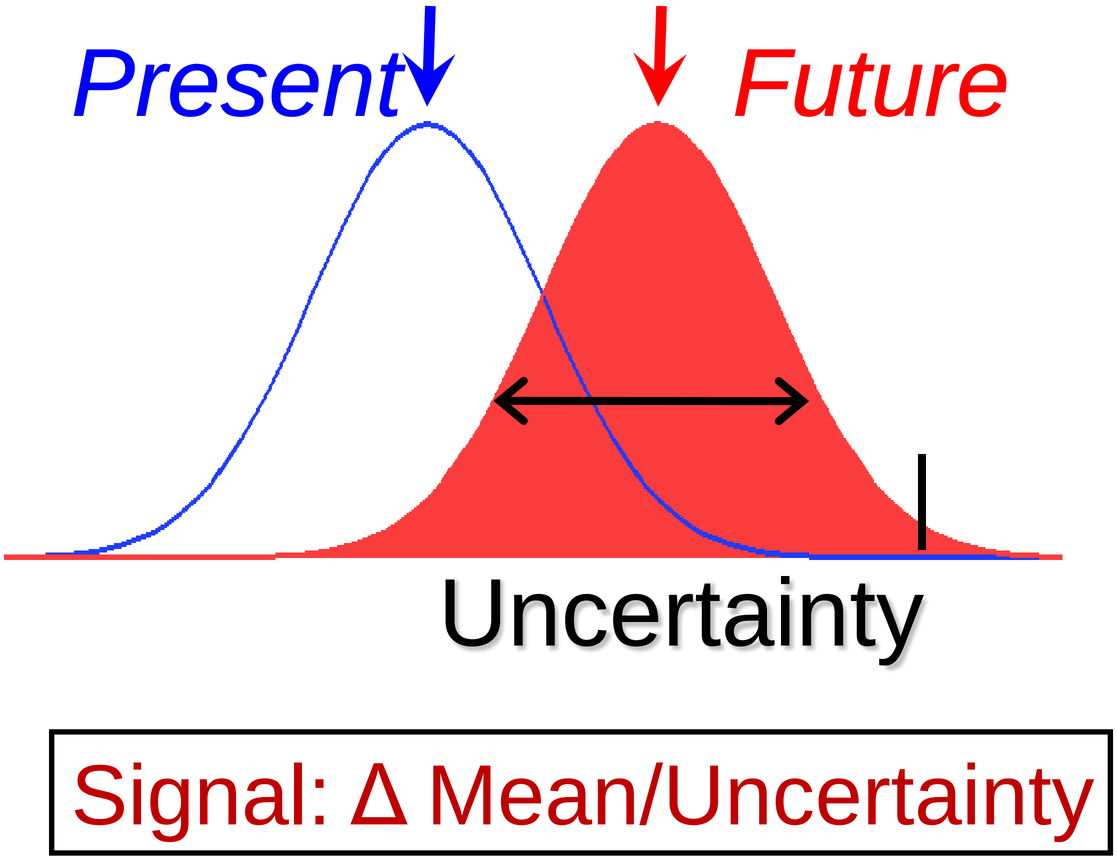
Summary

- Climate models provide guidance on how climate may change.
- Difference will arise due to how people use fossil fuels in the future
- Due to different parameterizations models will give different results
  - Unclear if weighting models is a good idea, (not clear how to determine good and bad models, e.g. good mean climate doesn’t mean good response to climate change)
- Expect a range of climate change outcomes due to natural variability of the atmospheric circulation even for long-term trends.
  - Any one realization is possible
- Over US and adjacent oceans: GHG driven temperature changes are more robust than those for dynamic quantities such as atmospheric circulation or currents

Adaptation

Plan for a range of climate changes

Decisions shaped by vulnerability & risk



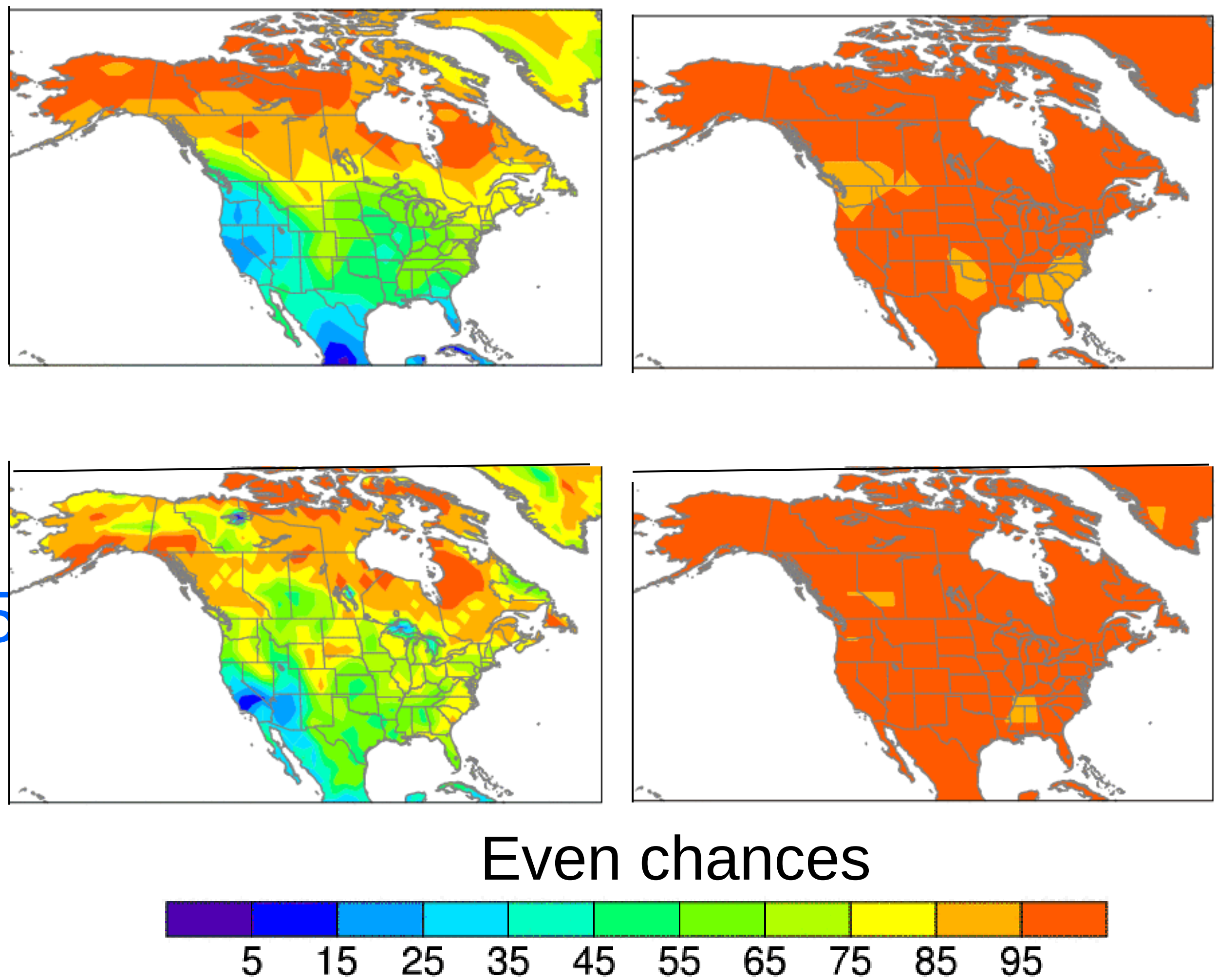
Chance of a Positive Trend in the Next 50 Years

Winter

Precipitation Temperature

CCSM3

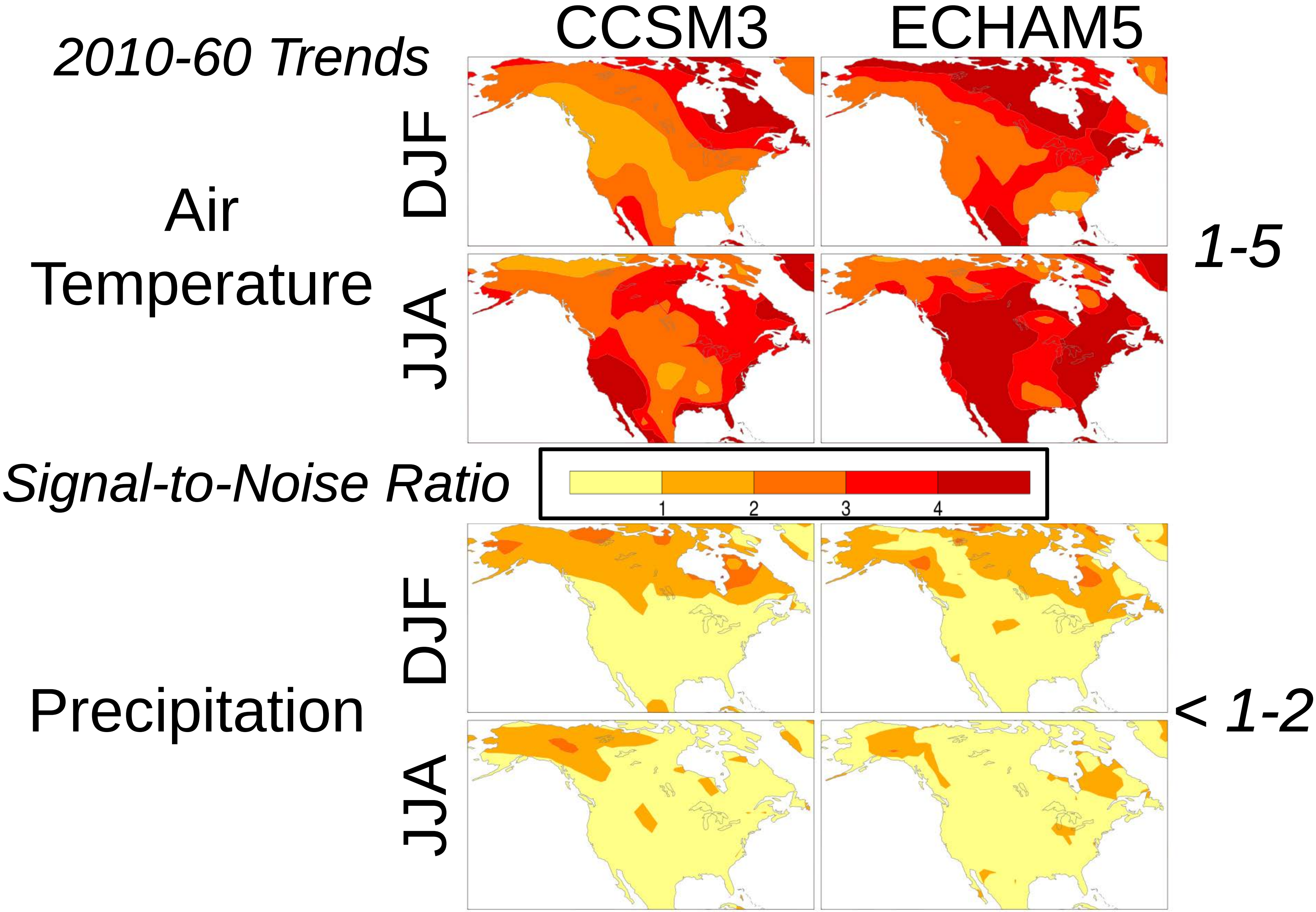
ECHAM5



Even chances

High chance of negative trend

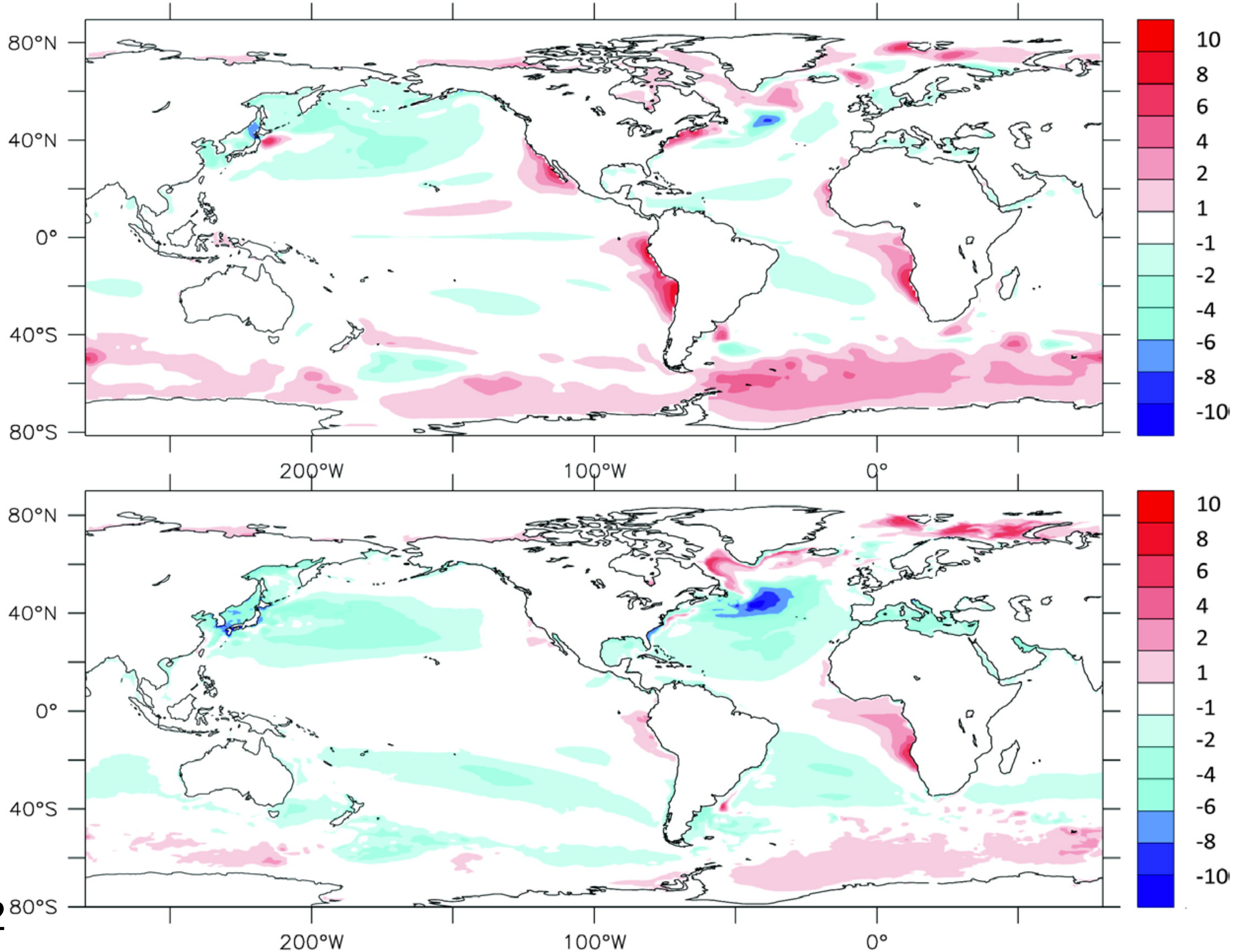
High chance of positive trend


2010-60 Trends
CCSM3
ECHAM5
Air Temperature
DJF
JJA
1-5
Signal-to-Noise Ratio
1
2
3
4
Precipitation
DJF
JJA
< 1-2

SST Bias (° C) GFDL GCM

CM2.1
Low
Res

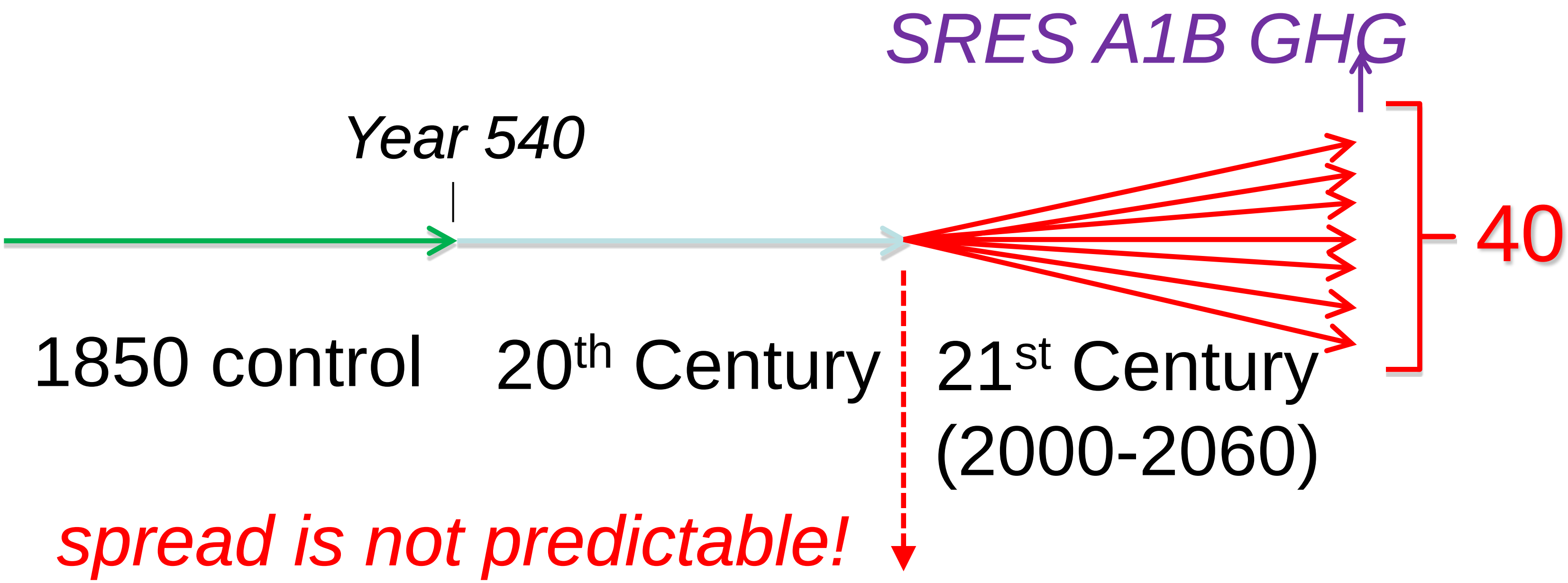
CM2.5
High
Res



Delworth
et al. 2012

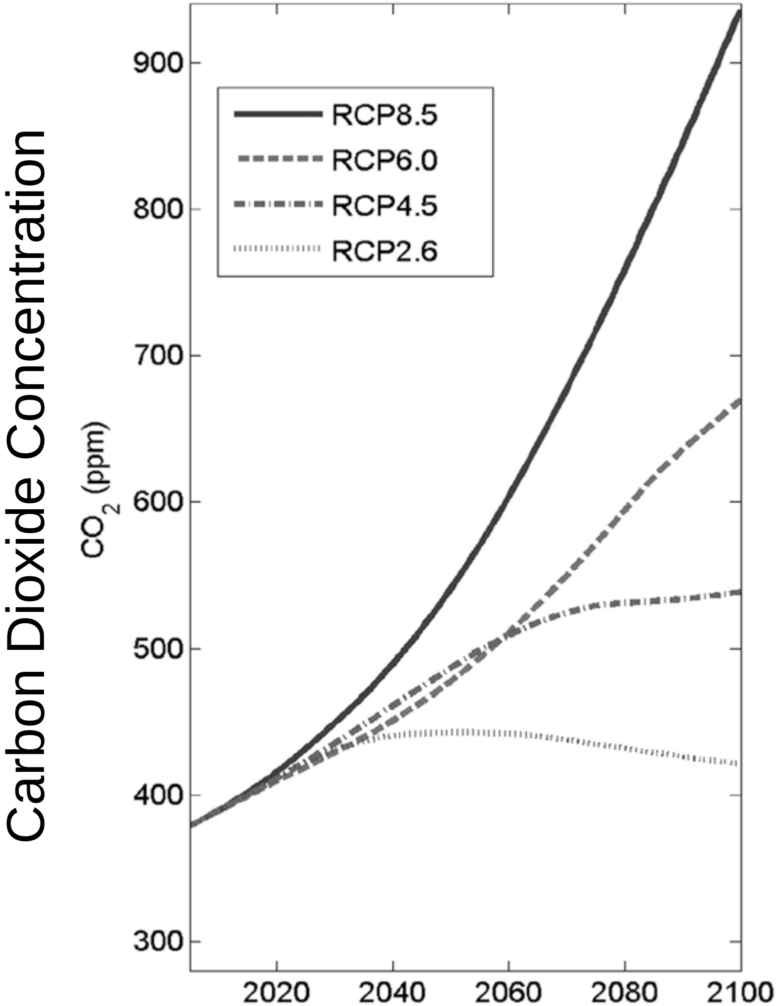
Assessing Climate Change in the Presence of Unforced Multi-decadal Variability: The CCSM Large Ensemble Project

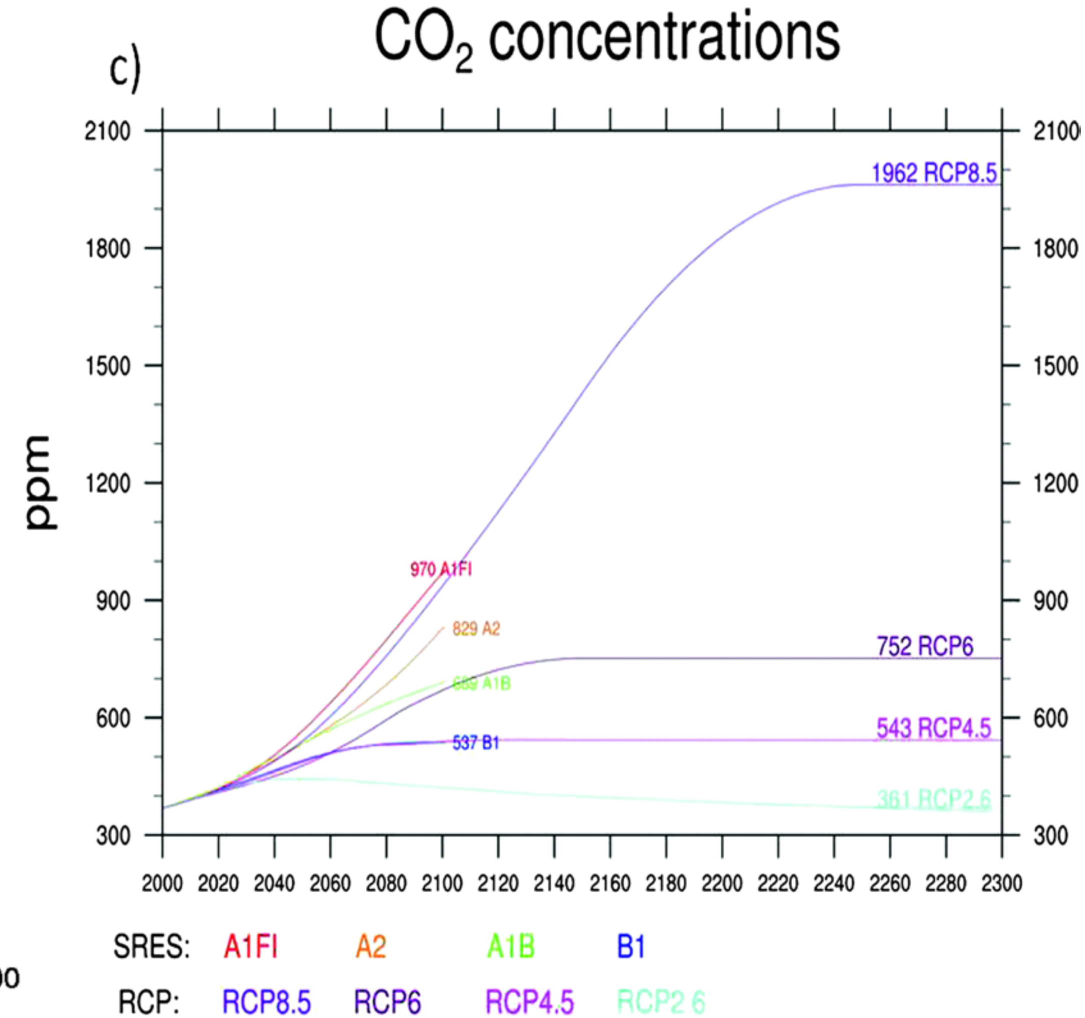
Community Climate System Model v3 (CCSM3 T42)



Different atmospheric initial states (Dec 1999, Jan 2000)
Same ocean, ice, land initial states (Jan 1, 2000)

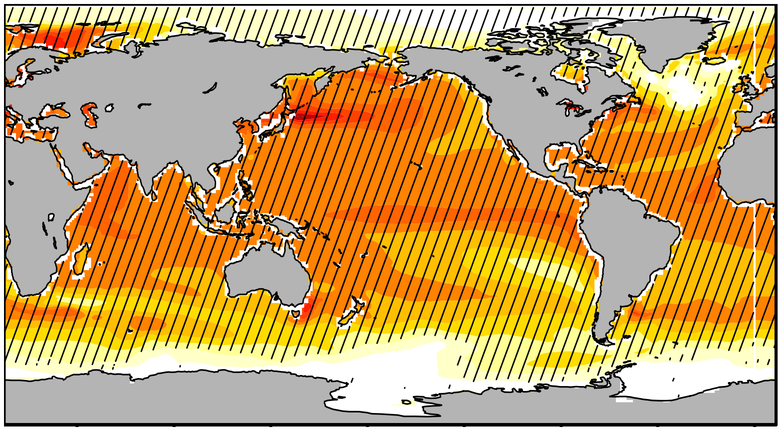
IPCC (AR5) Scenarios (Different)

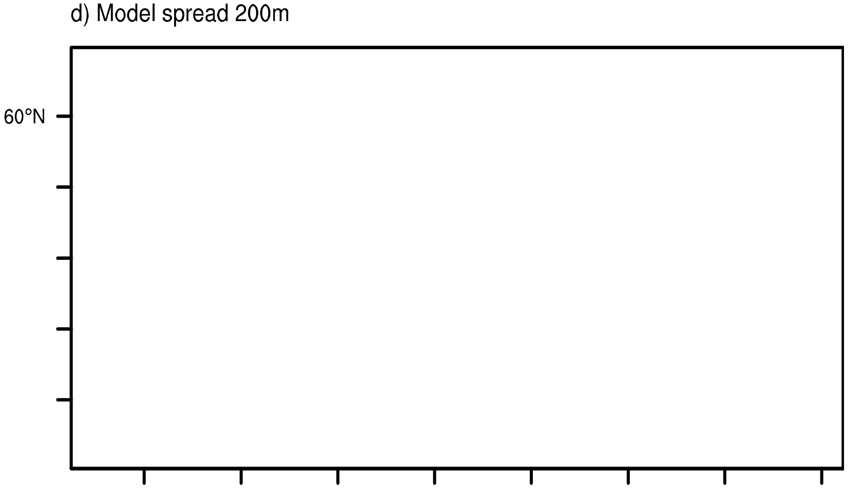


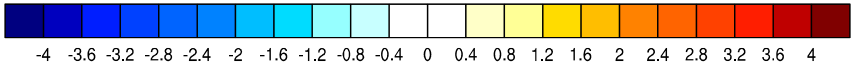


RCP – Radiation Concentration Pathway

2051-2100 – 1951-2000 SST & 200 m ocean temperature from A2 simulations

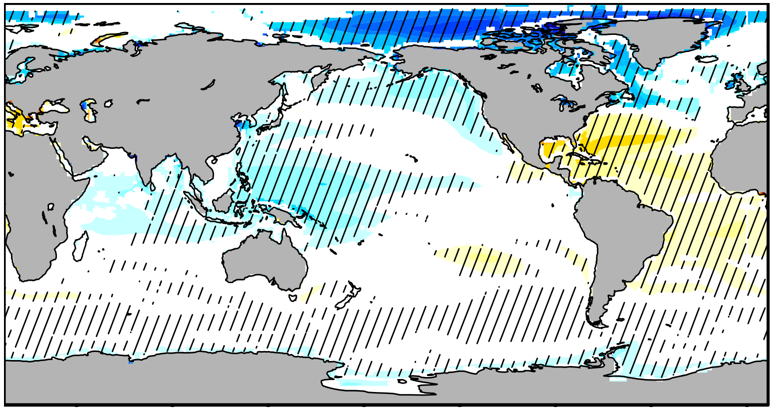






Capotondi et al. 2012 JGR

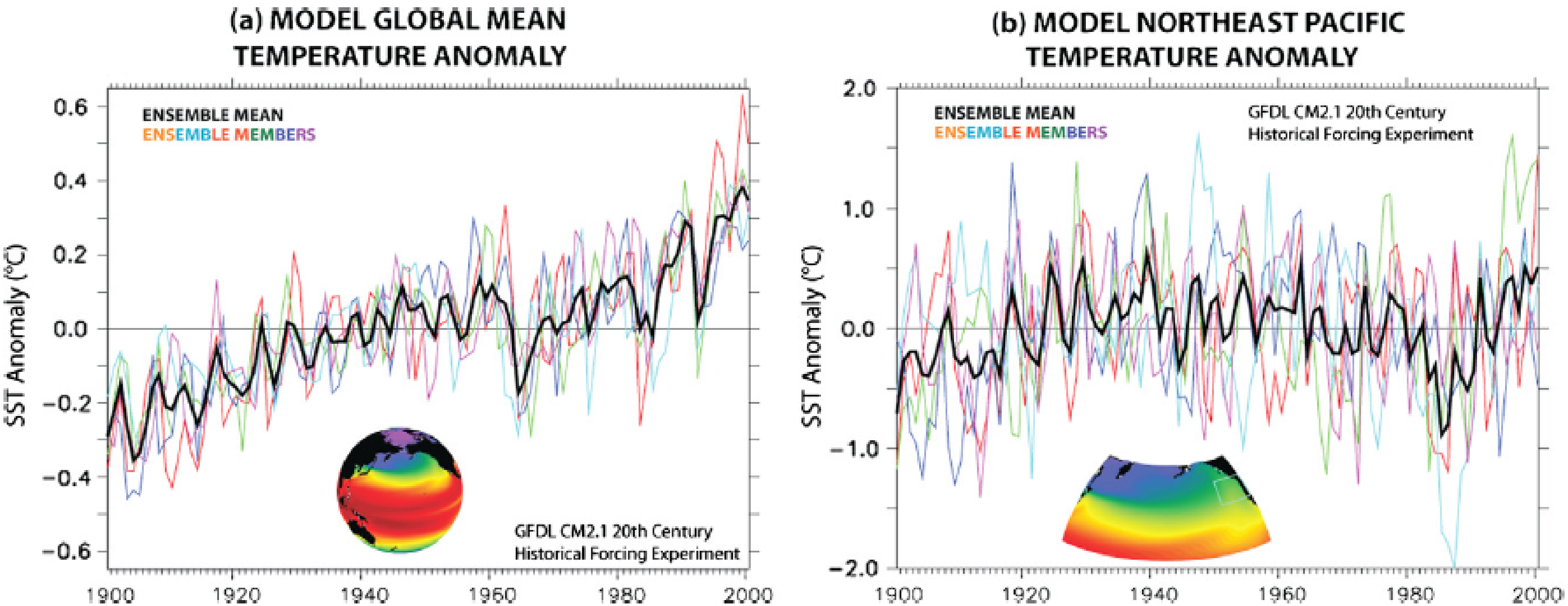
2051-2100 – 1951-2000 0 & 200 m ocean Salinity from A2 simulations



2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

Capotondi et al. 2012 JGR

Variability is generally more prominent at regional scales



Stock et al., 2011, Prog. Oceanogr. 88, 1-27

Natural Climate Variability

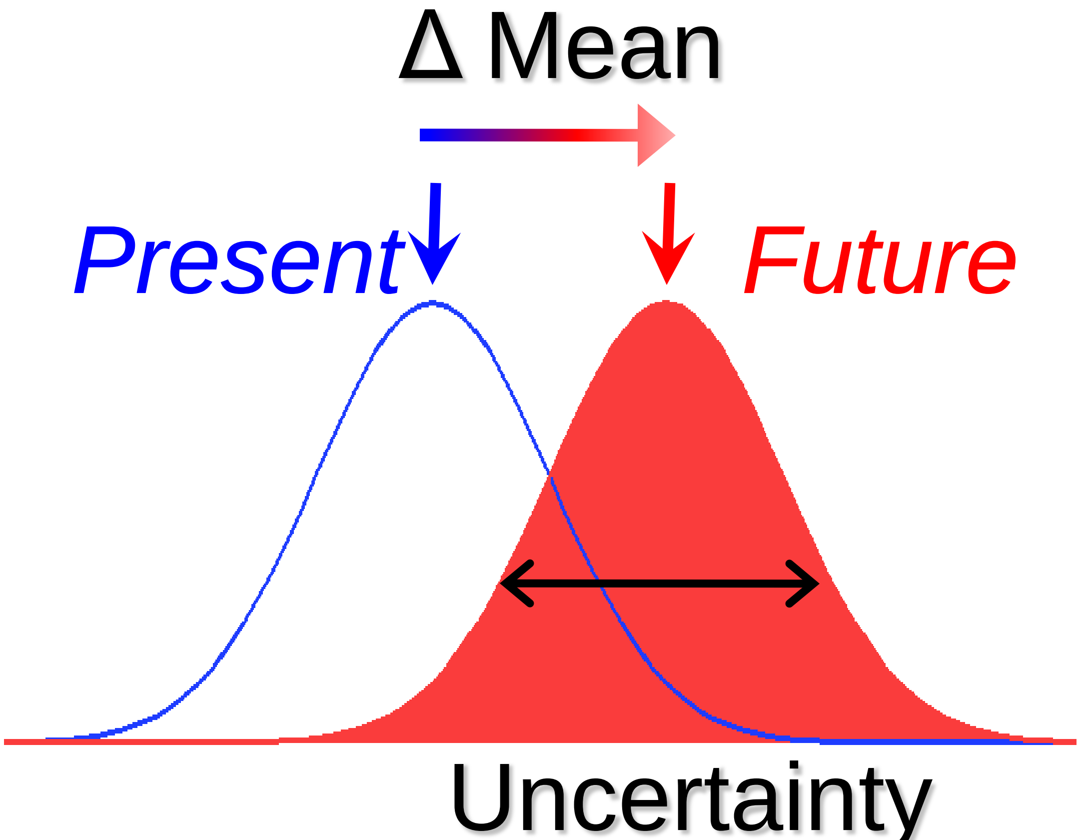
- Given the nonlinear nature of the climate system very small changes can result in a very different state of the atmosphere ("butterfly effect") after just a few weeks. Extends to the climate system as a whole by ~5-10 years.
- This has surprising consequences
- Won't have skillful (deterministic) forecasts of the atmosphere after ~2-3 weeks
  - Can't forecast the NAO beyond 2 weeks
- Still have lots of natural variability at decadal and longer time scales frequency; e.g
  - Can have 50 year trends in a given location In a "20th century simulation" where climate model is initialized in the 19th century) a given time in the model will NOT match nature
  - Can't directly compare time series from model to nature. Can compare average over a period

Implications of Experimental Design

- The statistical properties of climate variability may be captured by a model, but it will not be "in phase" with the historical record.

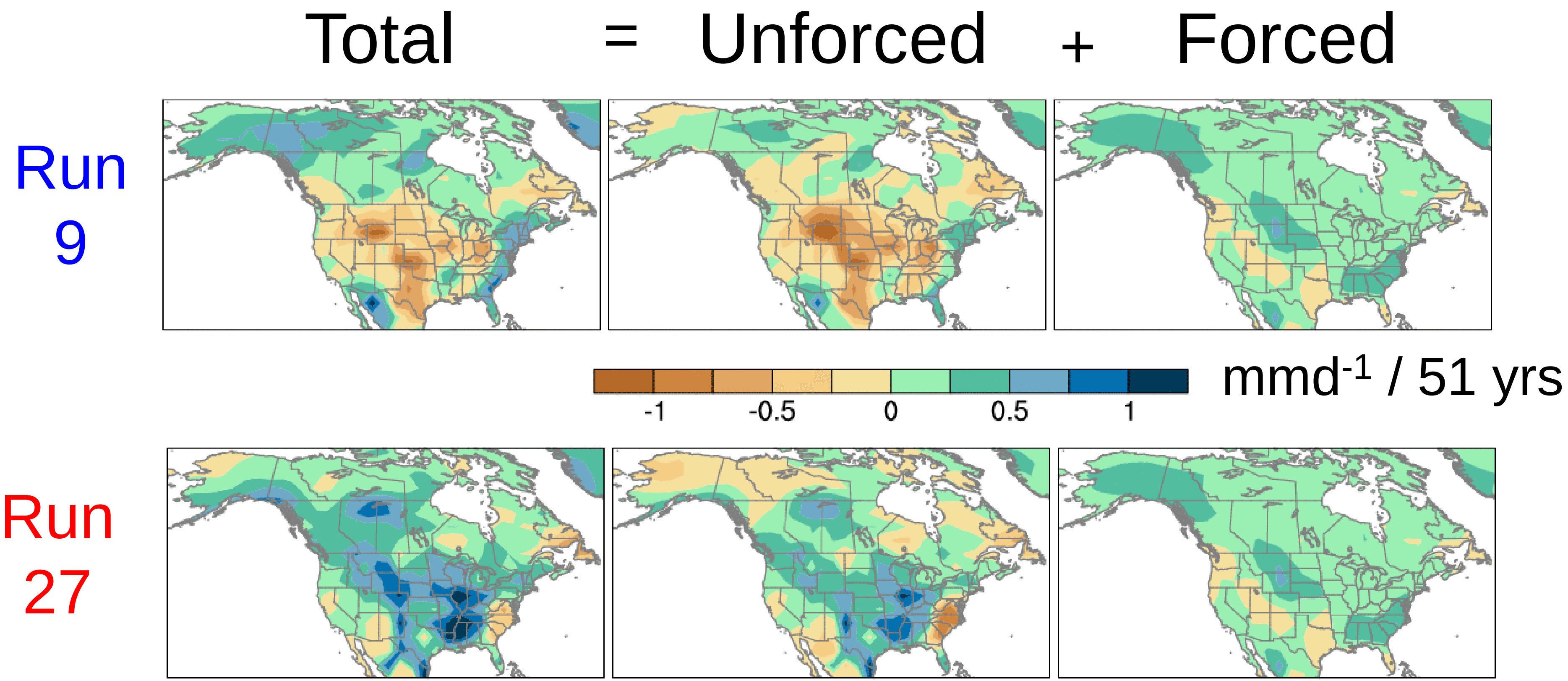
- Often use "ensembles" a set of simulations with the same forcings that only differ by their initial conditions
  - Spread of ensemble members measure of natural variability)
  - Each ensemble member is equally likely

Climate Change



Signal: Δ Mean/Uncertainty

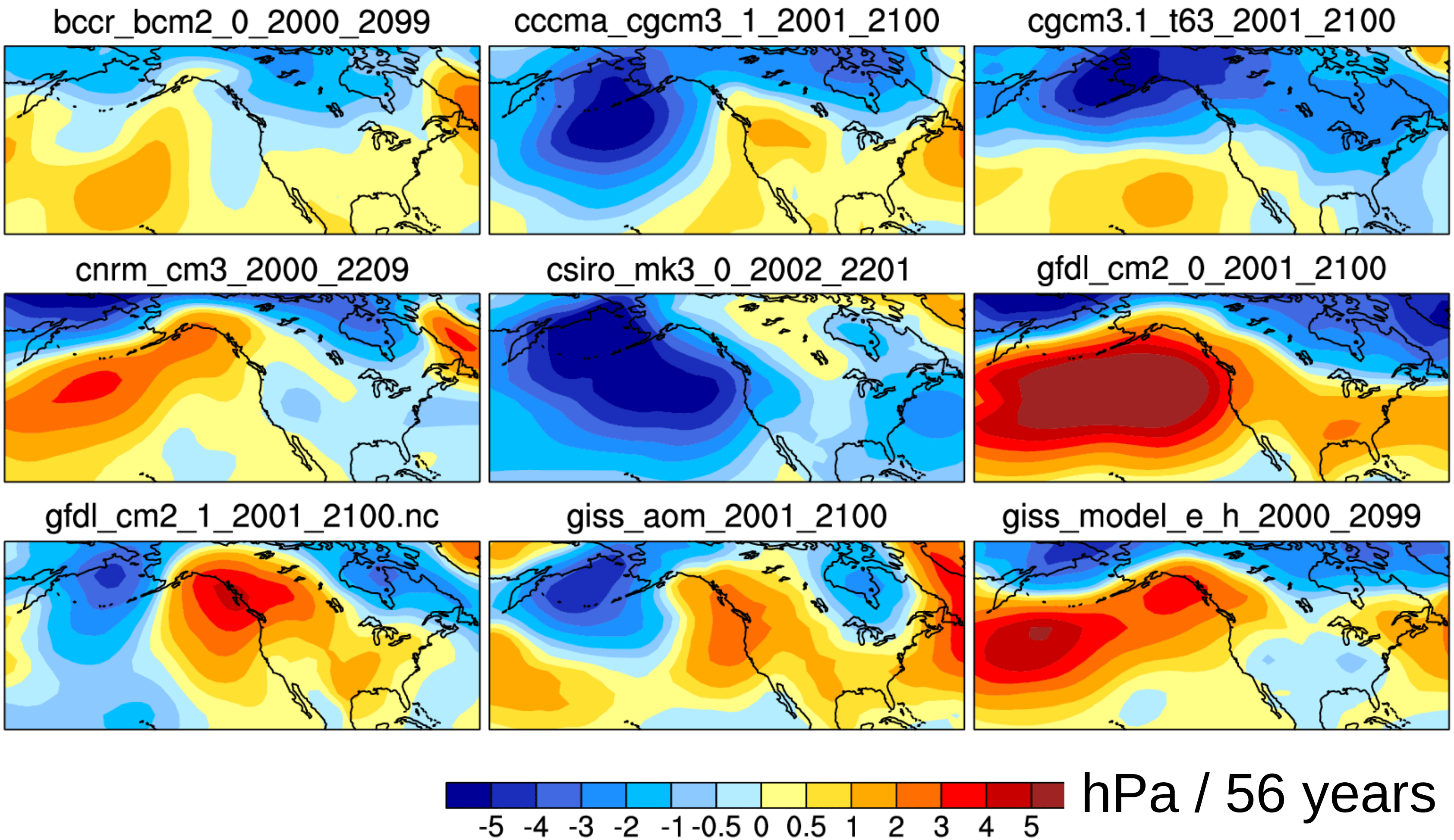
Summer Precipitation Trends 2010-2060



- Unforced component can be larger than forced
- Unforced component has large spatial scales

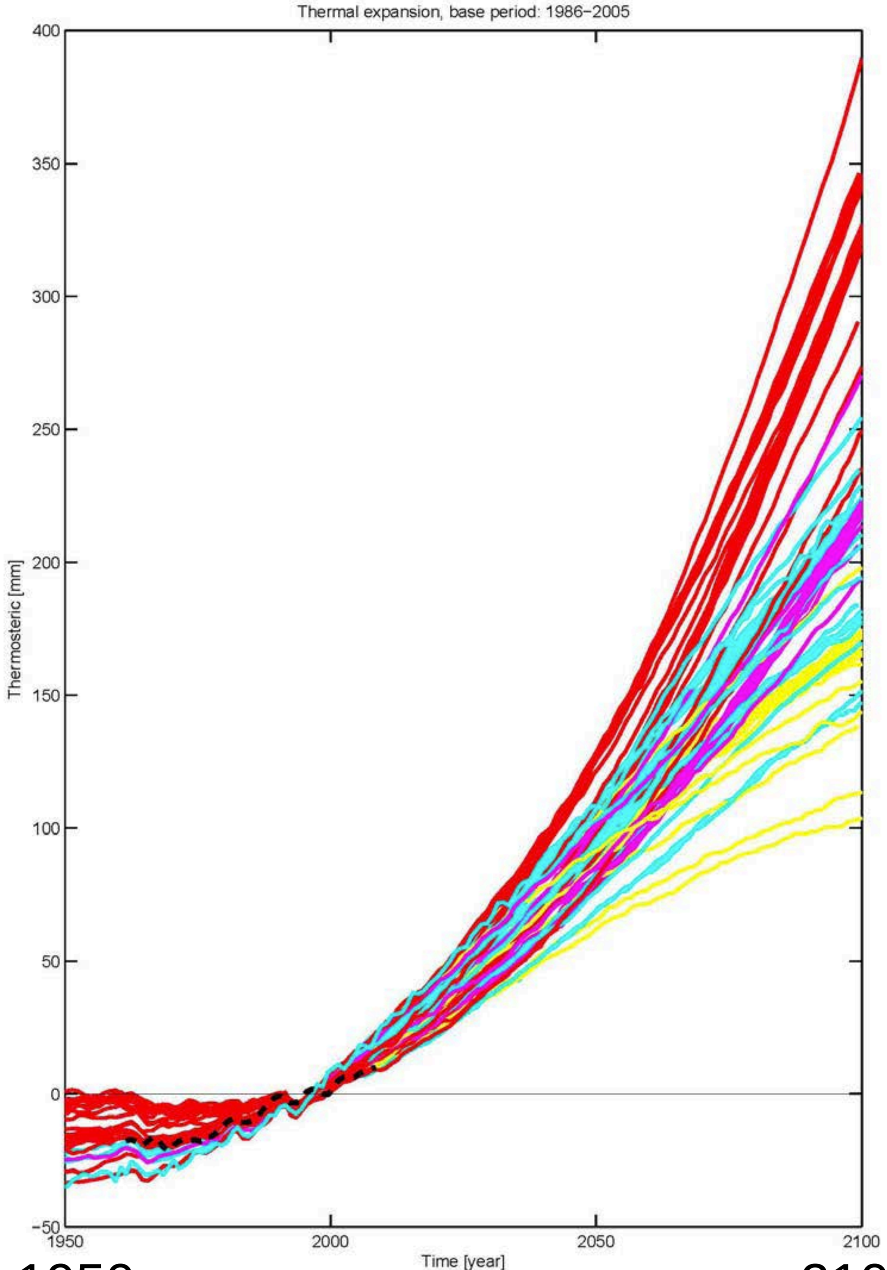
IPCC AR4 (CMIP3) Model Archive

SLP Trends 2005-2060



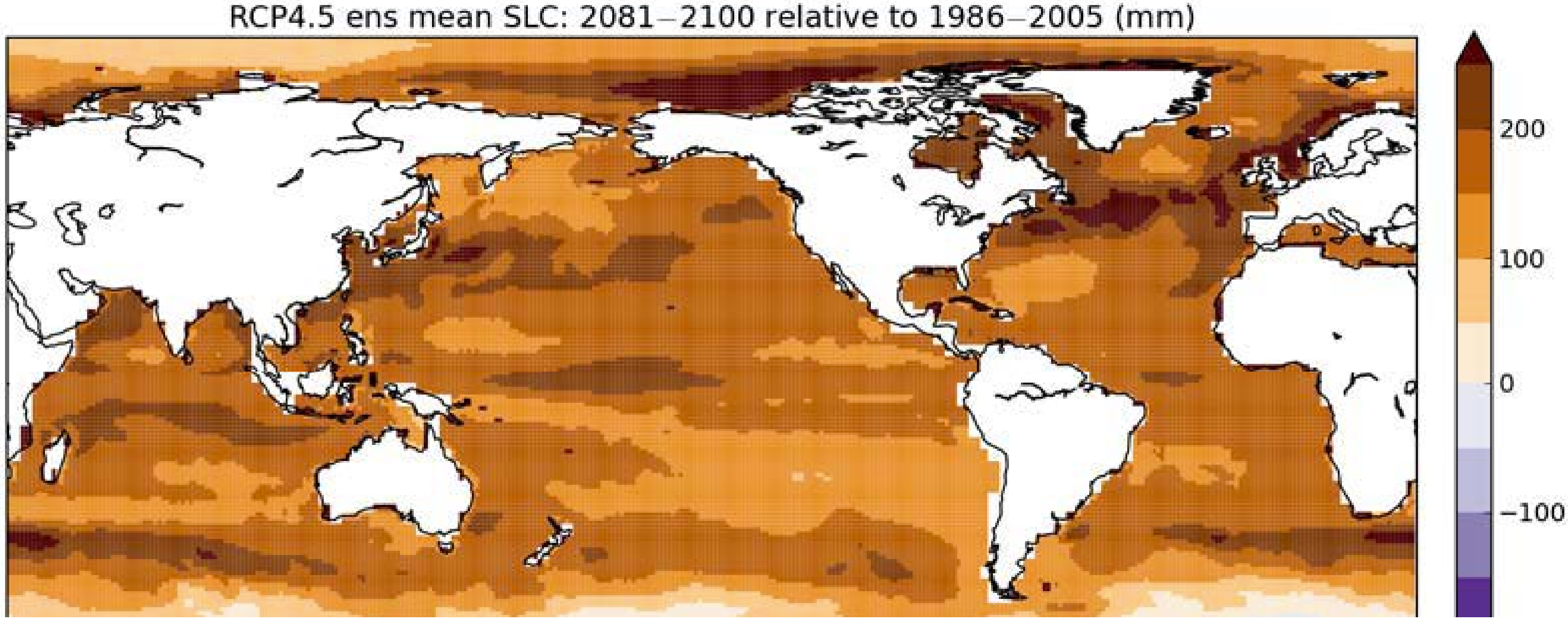
Model Sensitivity or Internal Variability?

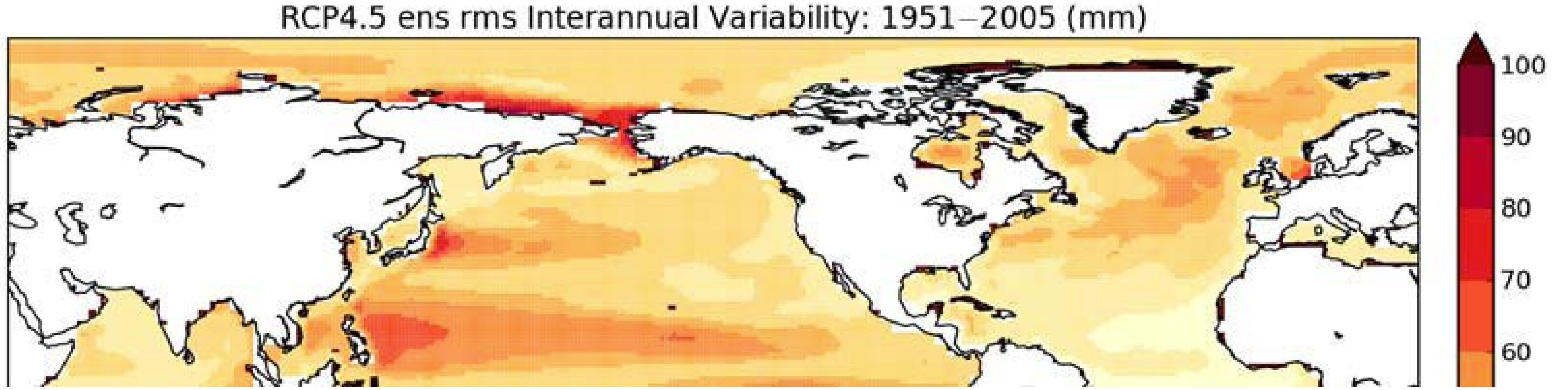
Observed & Projected Global Sea Level change (thermal expansion) AR5



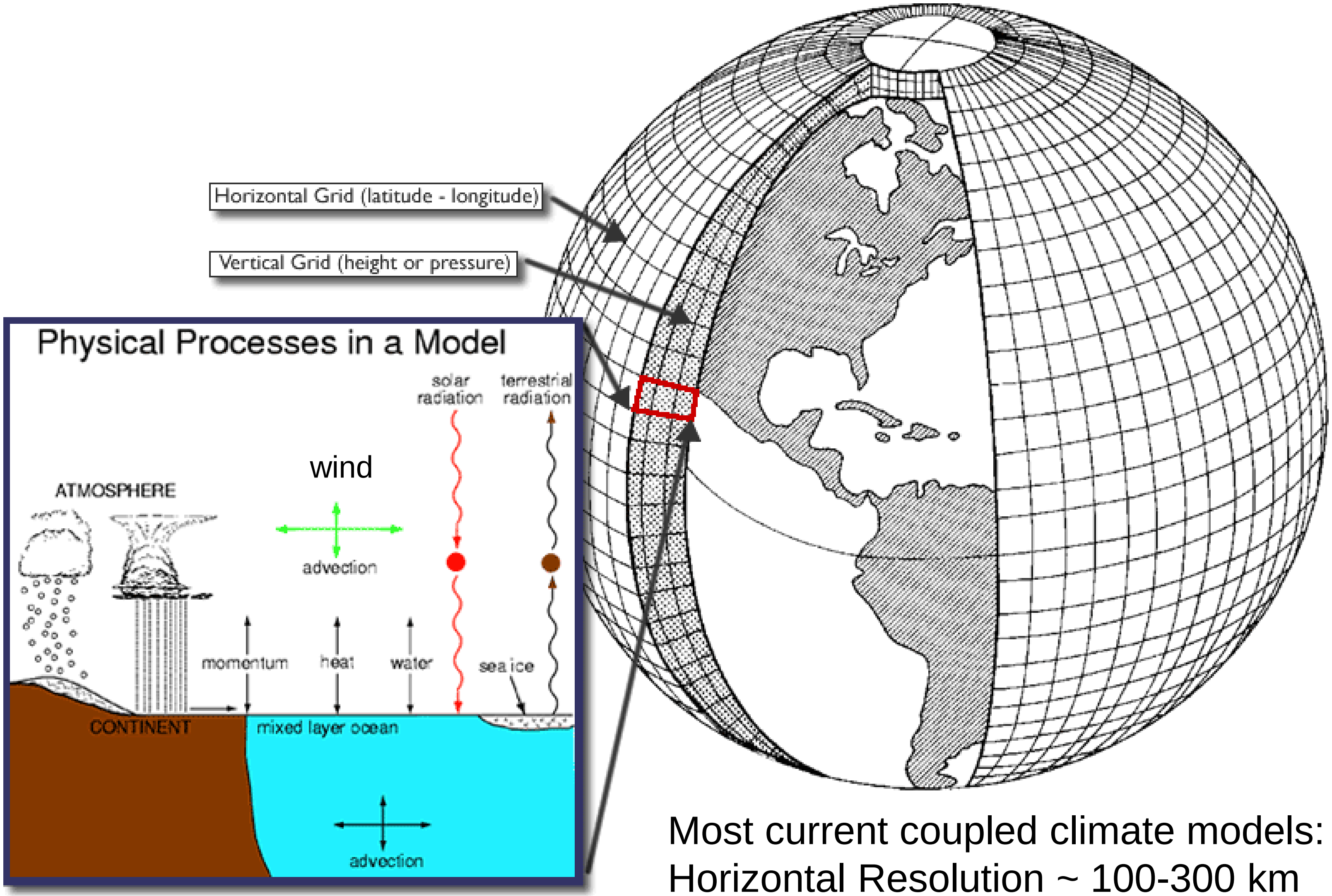
1950 2100

Sea Level Change (mm)





Climate Models

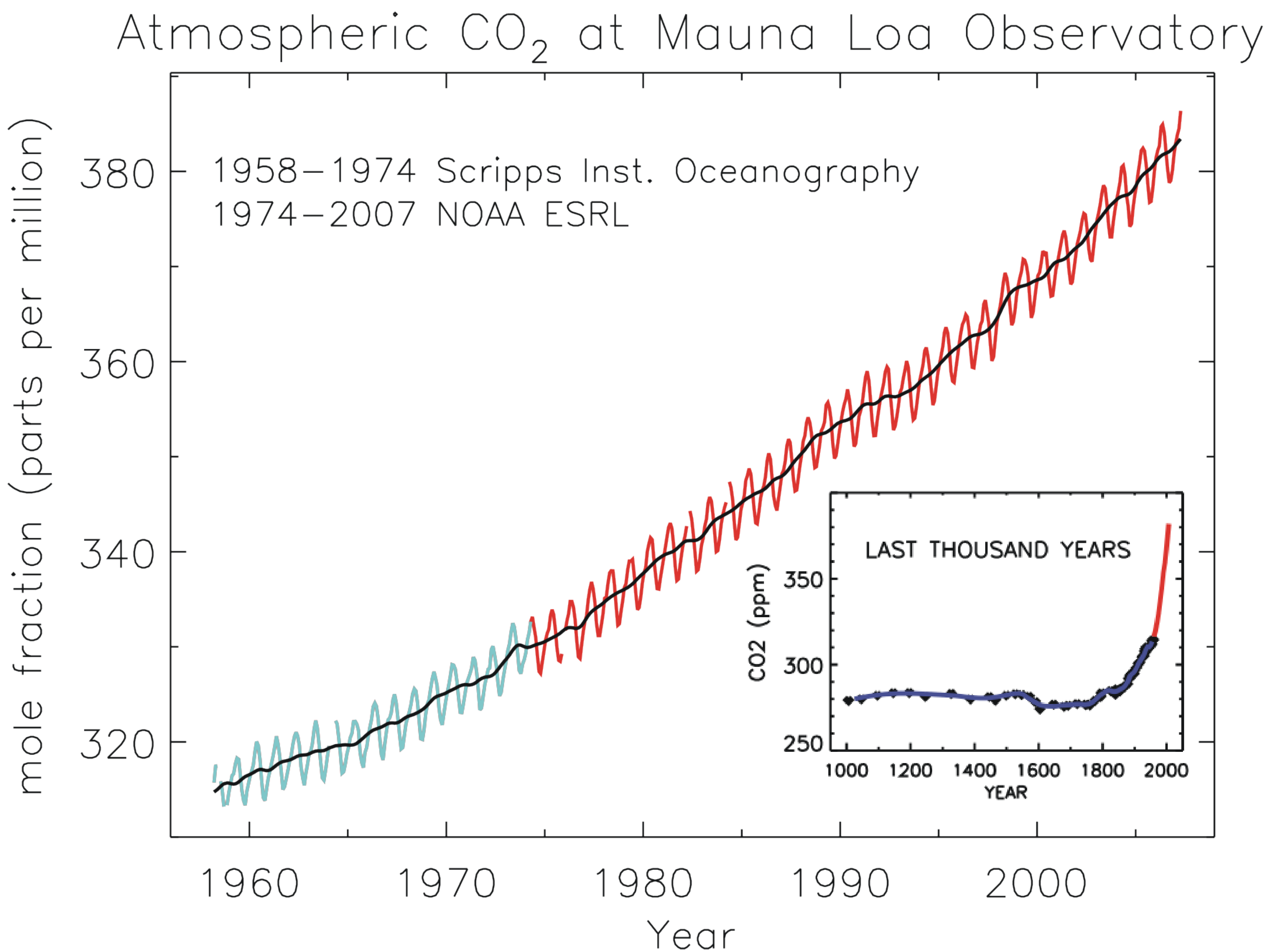


Most current coupled climate models:
Horizontal Resolution ~ 100-300 km
Vertical ~30 layers

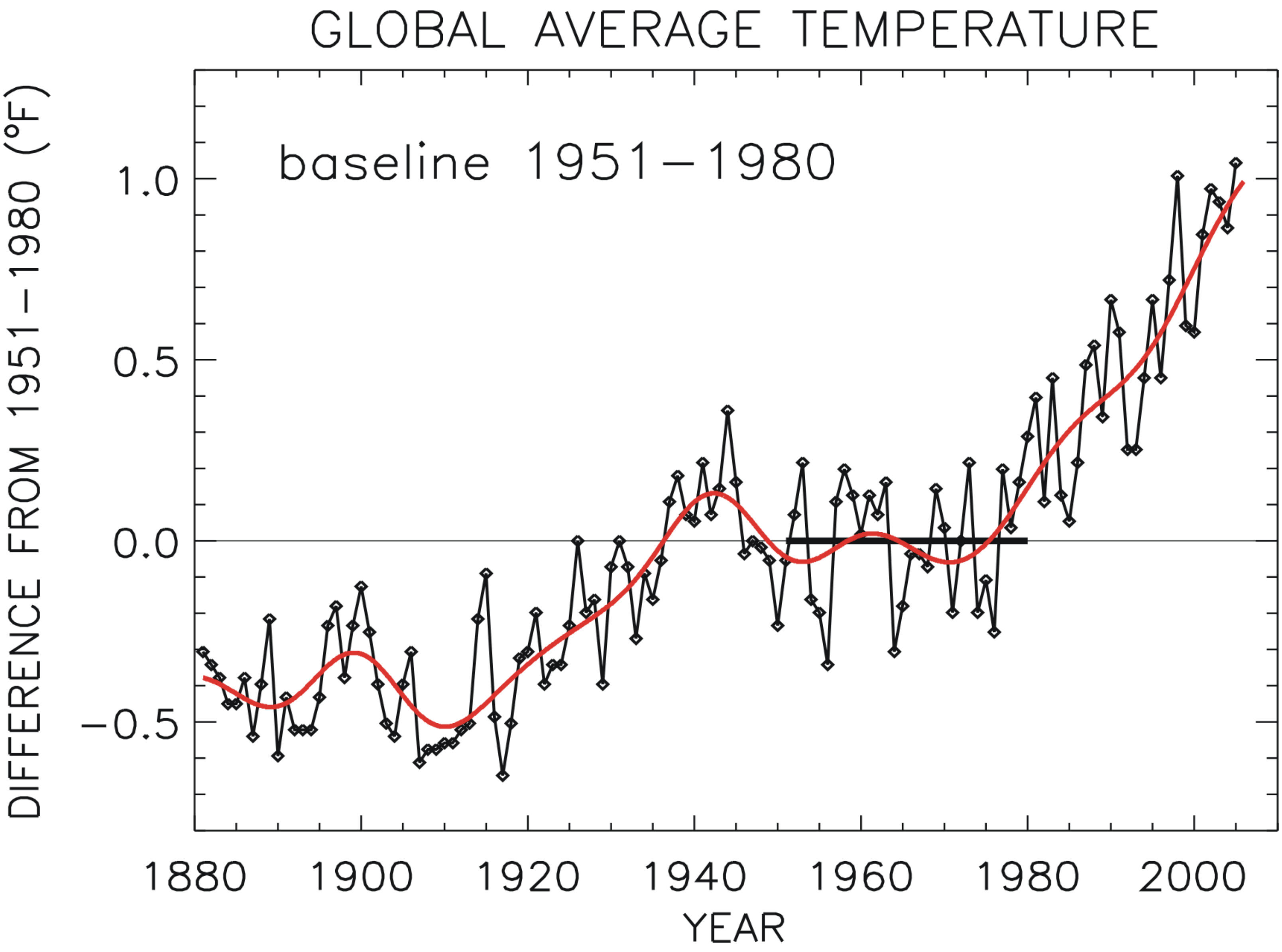
Parameterizations for the Physics

- Most of the physical process are at scales smaller than the grid spacing
  - Need to represent these sub-gridscale processes by mean variables within the gridbox
  - e.g. clouds function (T,q,convergent winds)
- Atmosphere
  - clouds:
    - precipitation & radiation
  - boundary layers
    - Surface fluxes
- Ocean
  - Mixing by eddies
  - Vertical mixing in upper ocean
  - Flow over sills => deep water formation
- Based on theory and observations (art)
- Parameters "tuned" to get reasonable climate

OBSERVED INCREASES IN GREENHOUSE GASES

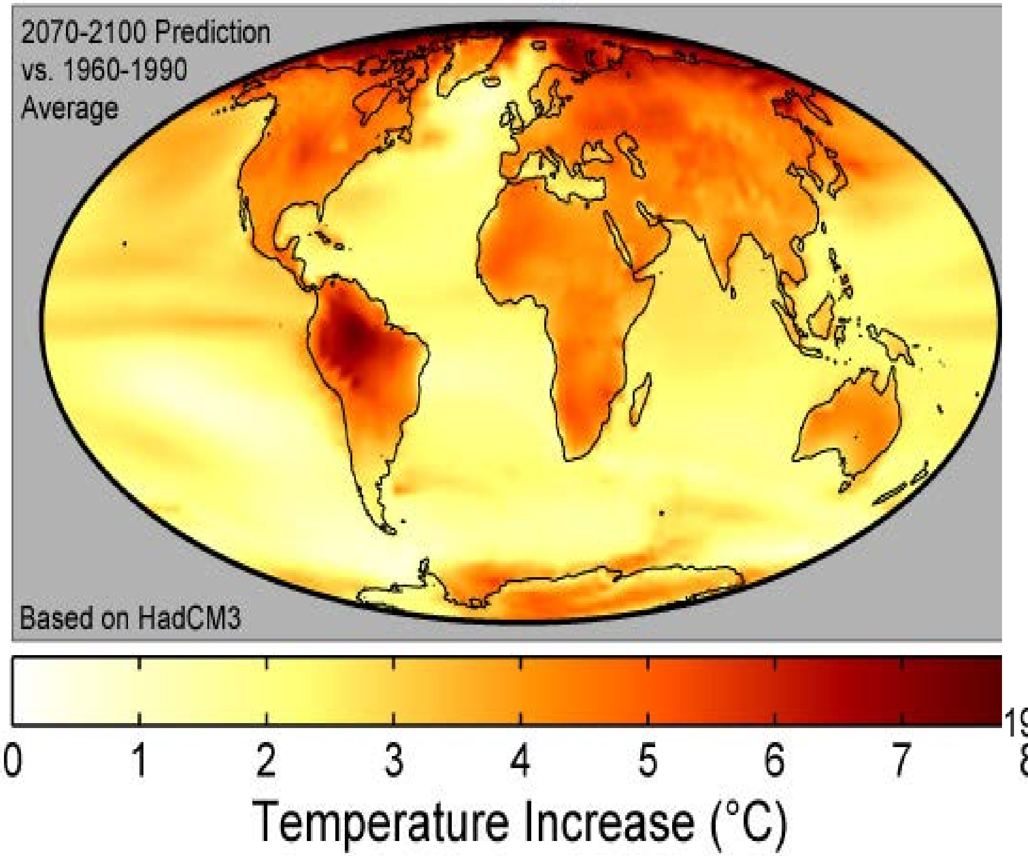


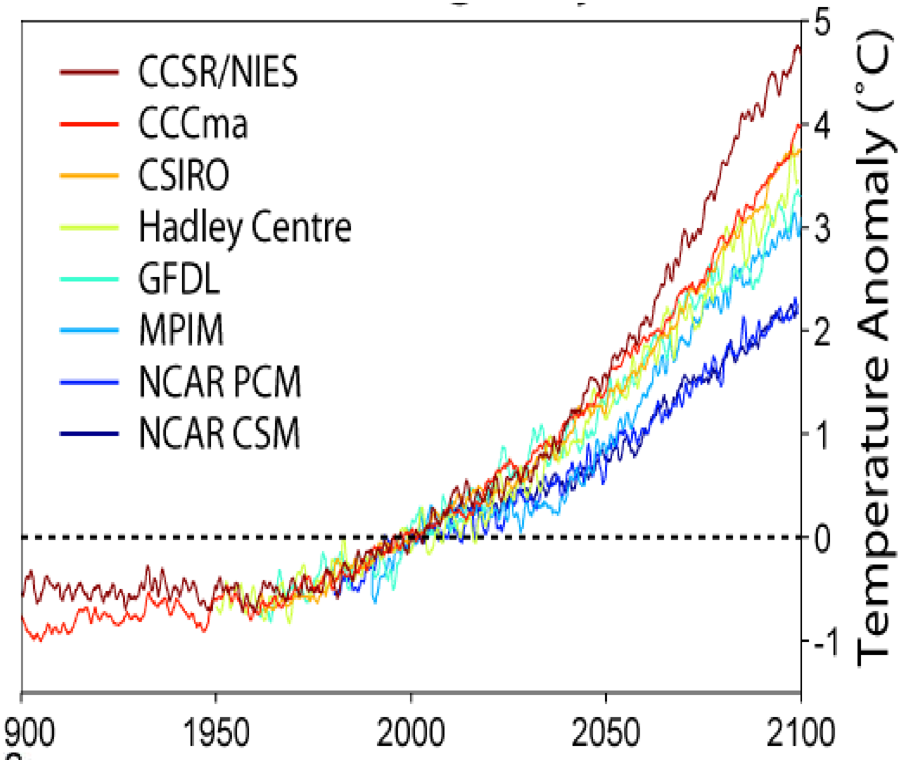
SOME OBSERVED CHANGES IN CLIMATE



Source: Goddard Inst. Space Studies, NASA

Global Warming Projections From different Models

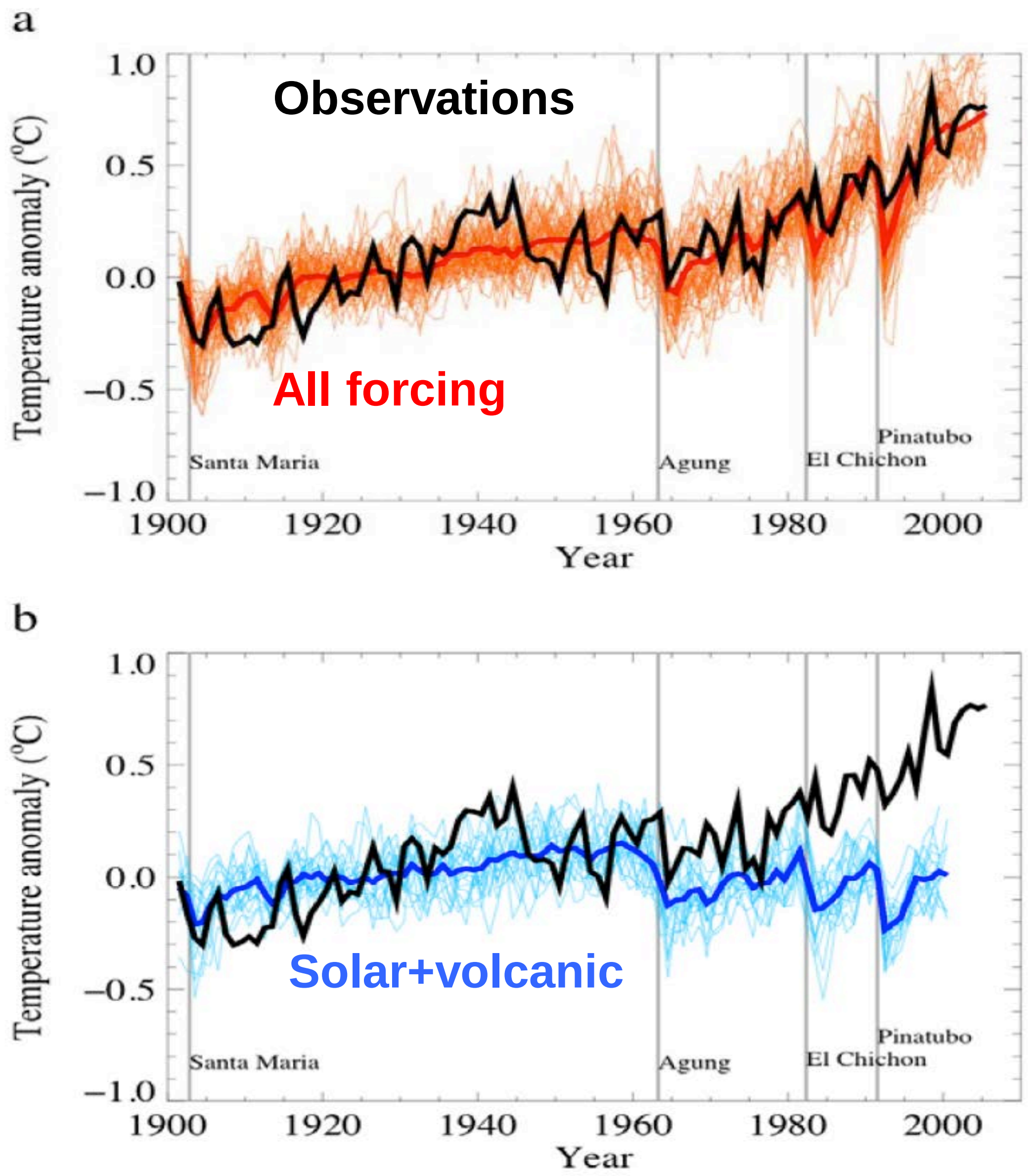




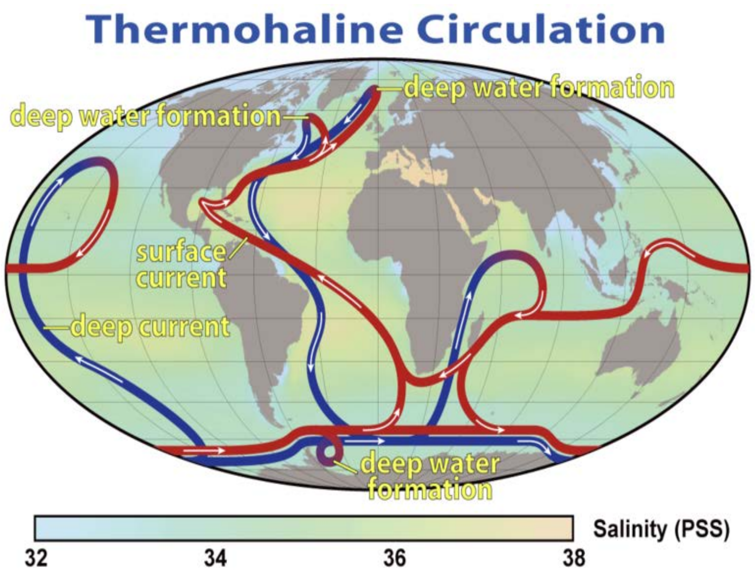
Climate Change in the 20th Century

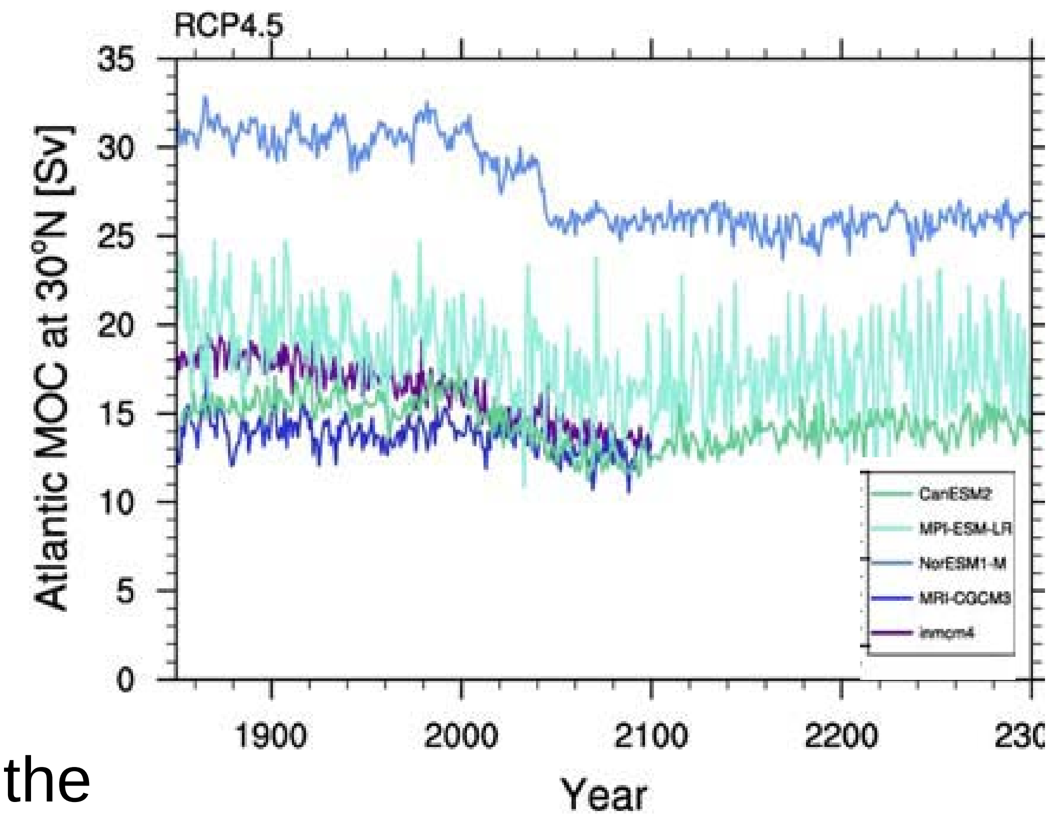
- **Global temperature model with all forcing & observations**

- ***Very unlikely* due to known natural causes alone**



Atlantic Meridional Overturning Circulation (AMOC)





AMOC – Atlantic portion of the Thermohaline Circulation

Should I weight models based on skill metrics?

- Active area of research that could reduce uncertainty due to inter-model spread
- No accepted method - many cases where a model's ability to match contemporary regional features was unrelated to a model's ability to match the warming trend (don't like draft a "good hitting" pitcher in the American league)
- Present default is not to weight, though some "culling" of highly aberrant simulations may be necessary (e.g., Overland et al., J. Climate, 24 2011)

Stock et al., 2011, Prog. Oceanogr. 88, 1-27

Climate Model Metrics

- Ability to simulate mean climate features
- Ability to simulate natural variability
  - Statistics (e.g 30-year mean), teleconnections;
  - NOT the observed temporal evolution
- Model response to observed forcing
  - Volcanic eruptions
  - Seasonal cycle
  - Paleoclimate information/events (e.g. glacial-interglacial variations; 6.2 ka event; etc.)
  - Observed 20th century climate response (need to be careful because of mix of natural & forced change)
- Difficult to design a single set of metrics.
- Whether a model is "good enough" can often depend on problem of interest.

Why do we trust climate model projections?

"There is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above. This confidence comes from the foundation of the models in accepted physical principles and from their ability to reproduce observed features of the current and past climate changes."

Randall et al., 2007 (Chapter 8 of IPCC WG1 Report)

Regional Climate Change

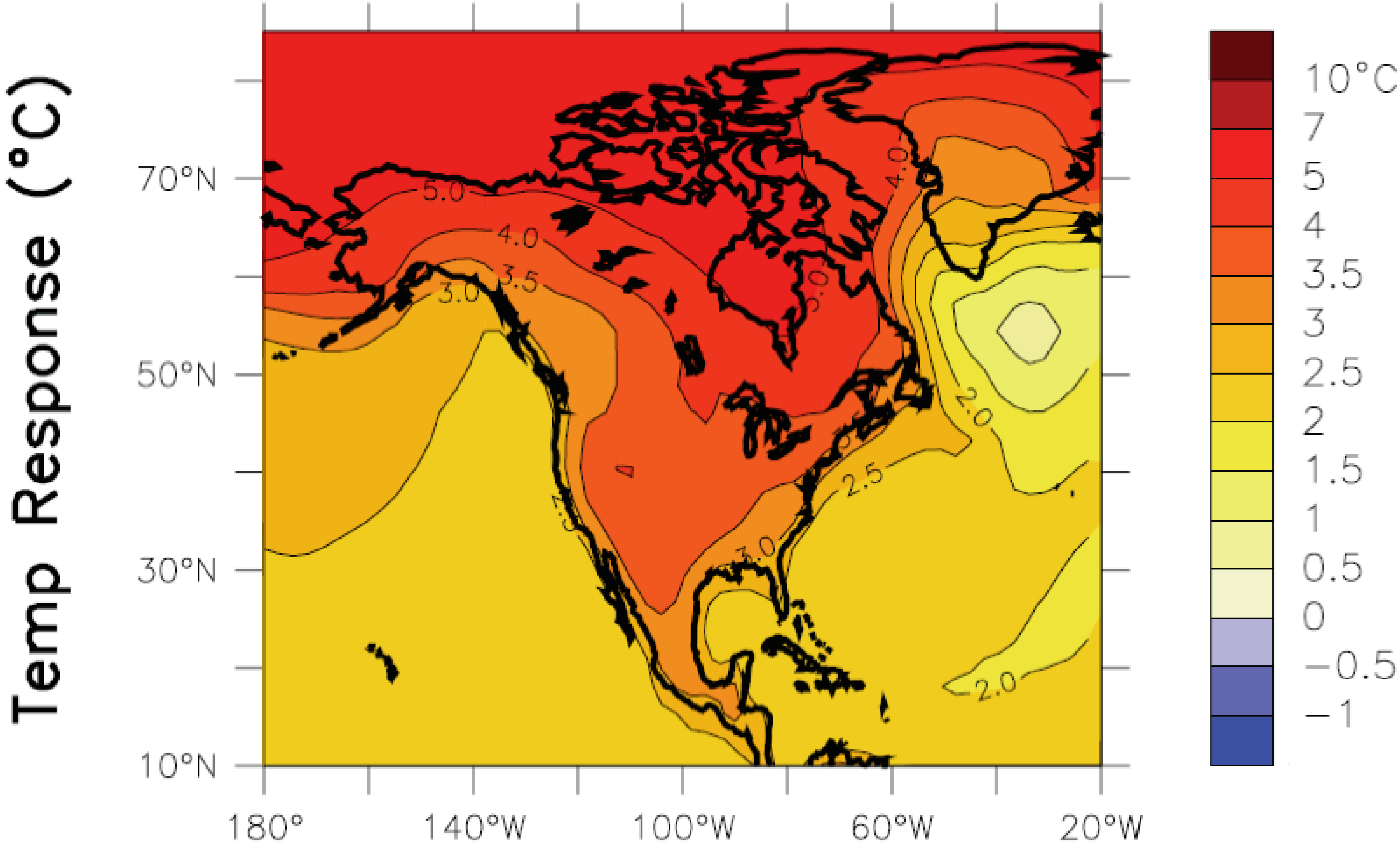
- Regardless of scale can bias correct
  - Simplest is the Delta method
    - Assumes Change not influenced by model bias

- Use current GCMS
  - Lack key features
    - ~2 grid points in gulf of Maine
- Increase resolution of GCMs
    - Starting to happen but very computationally intensive
    - Not all biases improve
- Dynamical Downscaling
  - Use finer scale physical models in a region where boundary conditions are provided by GCMs

Regional Climate Change II

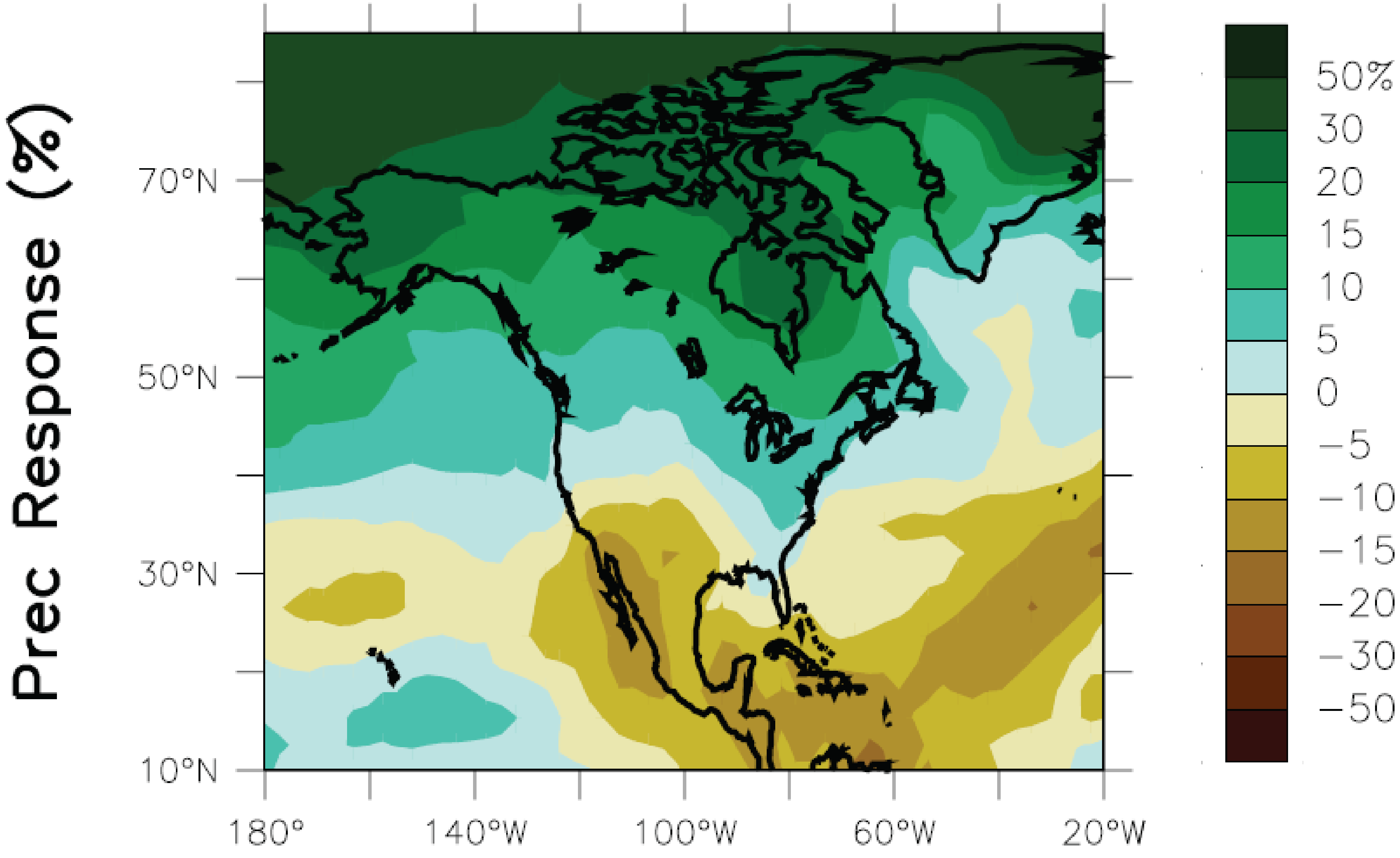
- Statistical downscaling
  - Use statistical relationships between resolved, larger-scale features and unresolved finer-scale features.
  - Relatively low computational cost but:
  - Assume stationarity in the statistical relationship
  - Selecting relevant predictors can be difficult Requires long observational time series to establish relationships
  - If climate model projected change in correct downscaled will be as well.

Annual Temperature: End of 21st Century



IPCC 4th Assessment: Working Group I, Chapter 11, Regional Projections

Annual Precipitation: End of 21st Century



IPCC 4th Assessment: Working Group I, Chapter 11, Regional Projections

Projected Changes in Weather Extremes

Table 1: Estimates of confidence in observed and projected changes in extreme weather and climate events.

Confidence in observed changes (latter half of the 20th century)	Changes in Phenomenon	Confidence in projected changes (during the 21st century)
Likely[7]	**Higher maximum temperatures and more hot days over nearly all land areas**	Very likely[7]
Very likely[7]	**Higher minimum temperatures, fewer cold days and frost days over nearly all land areas**	Very likely[7]
Very likely[7]	**Reduced diurnal temperature range over most land areas**	Very likely[7]
Likely[7], over many areas	**Increase of heat index[12] over land areas**	Very likely[7], over most areas
Likely[7], over many Northern Hemisphere mid- to high latitude land areas	**More intense precipitation events[b]**	Very likely[7], over many areas
Likely[7], in a few areas	**Increased summer continental drying and associated risk of drought**	Likely[7], over most mid-latitude continental interiors. (Lack of consistent projections in other areas)
Not observed in the few analyses available	**Increase in tropical cyclone peak wind intensities[c]**	Likely[7], over some areas
Insufficient data for assessment	**Increase in tropical cyclone mean and peak precipitation intensities[c]**	Likely[7], over some areas

Internal Variability in Relation to Forcing and Model Sensitivity

Time Scale:

- Forcing - long timescales
- Model Sensitivity – all time scales
- Internal (Natural) Variability – short (< 10-20 years?)
  - Increases as the spatial scale decreases
  - Will differ by variable
    - Larger for precipitation than temperature in most areas

Model Experiments:

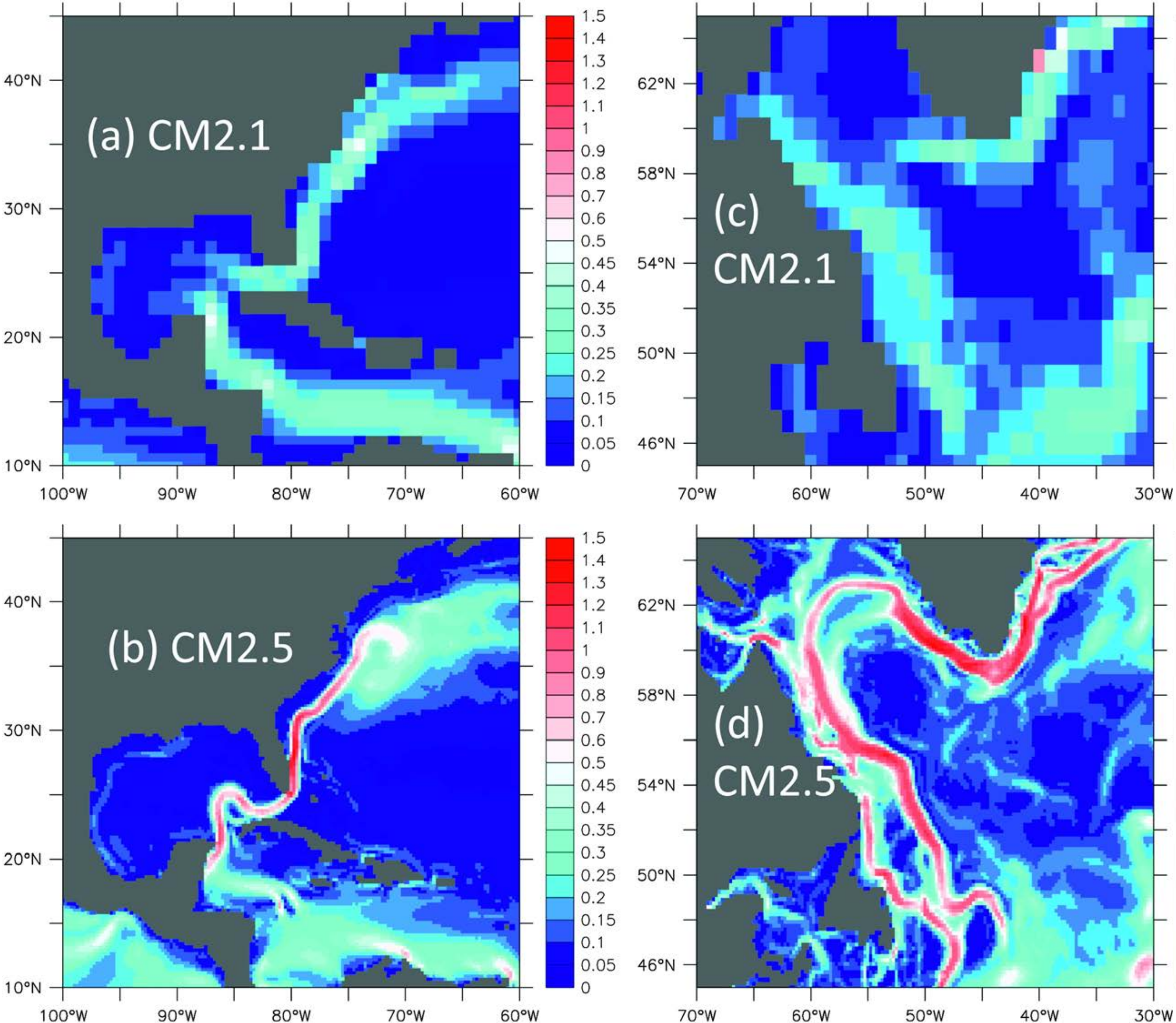
- Examine internal variability by using more than one run, i.e. an ensemble of simulations
- Nearly all climate change studies have used one or a very small number of ensemble members

Refined resolution AOGCMs

- Could fundamentally improve the resolution of shelf-scale processes and basin-shelf interactions in climate models
- Computational costs increase with the cube of horizontal grid refinement
- Processes that were once sub-grid scale are now resolved: parameterizations must be reformulated; some large-scale features may look worse.
- May address some biases, but not all biases rooted in resolution.

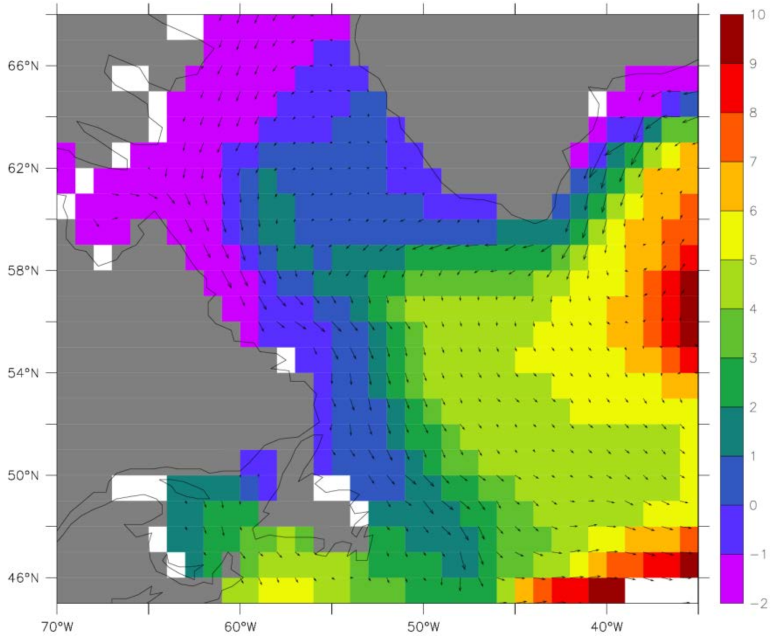
While more refined-resolution simulations (~1/8-1/4 degree) will be available in IPCC AR5, most will have resolutions similar to those in IPCC AR4.

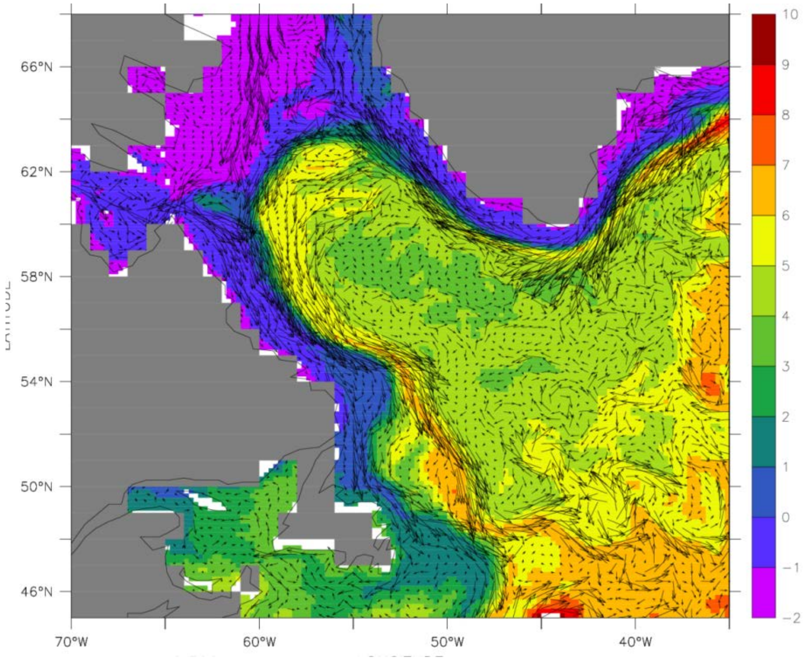
Stock et al., 2011, Prog. Oceanogr. 88, 1-27



(a) CM2.1
(b) CM2.5
(c) CM2.1
(d) CM2.5
40°N
30°N
20°N
10°N
100°W
90°W
80°W
70°W
60°W
62°N
58°N
54°N
50°N
46°N
70°W
60°W
50°W
40°W
30°W
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.375
0.35
0.325
0.3
0.275
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0

Refined resolution Climate models





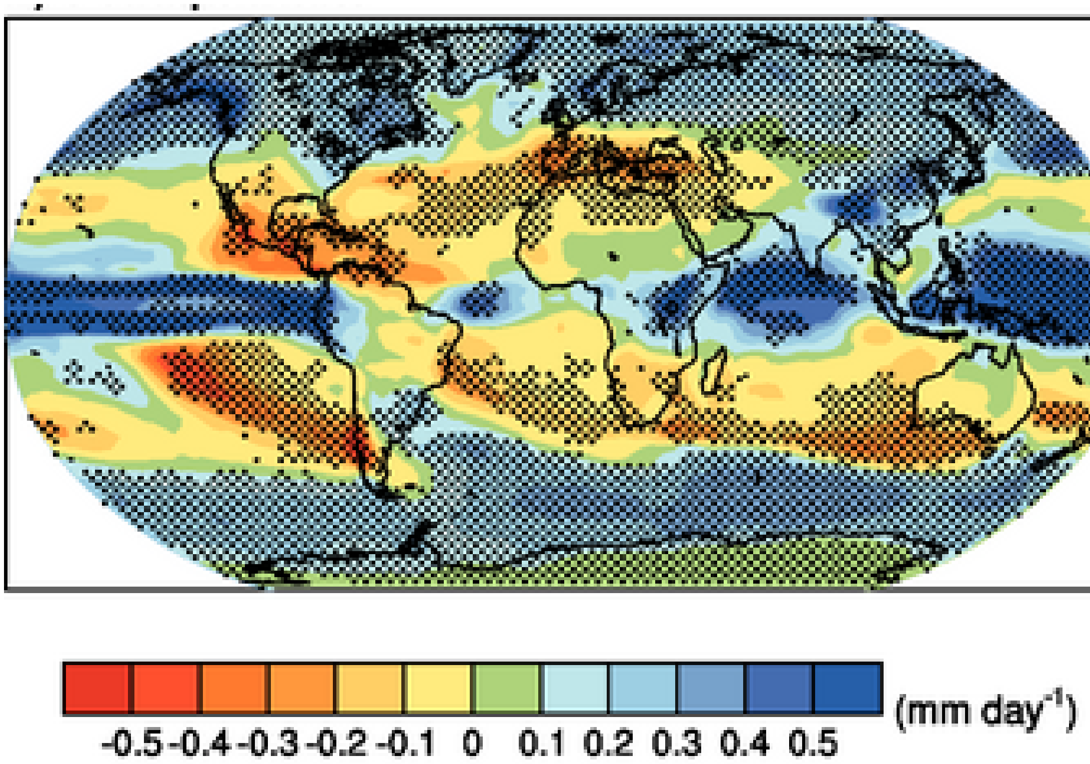
It is becoming increasingly feasible to run long time-scale climate simulations at resolutions ~0.25 deg. In the ocean or higher

Climate variability in century-scale physical climate models

- Many climate models produce realistic representations of prominent modes of climate variability
- Can use climate change projections to study climate variability, but don’t expect to be “in phase” with observed variability
- Ensemble means and focusing on differences between multi-decadal averages across century time-scales helps isolate the climate change trend

Climate models agree on many broad-scale climate changes over the next century

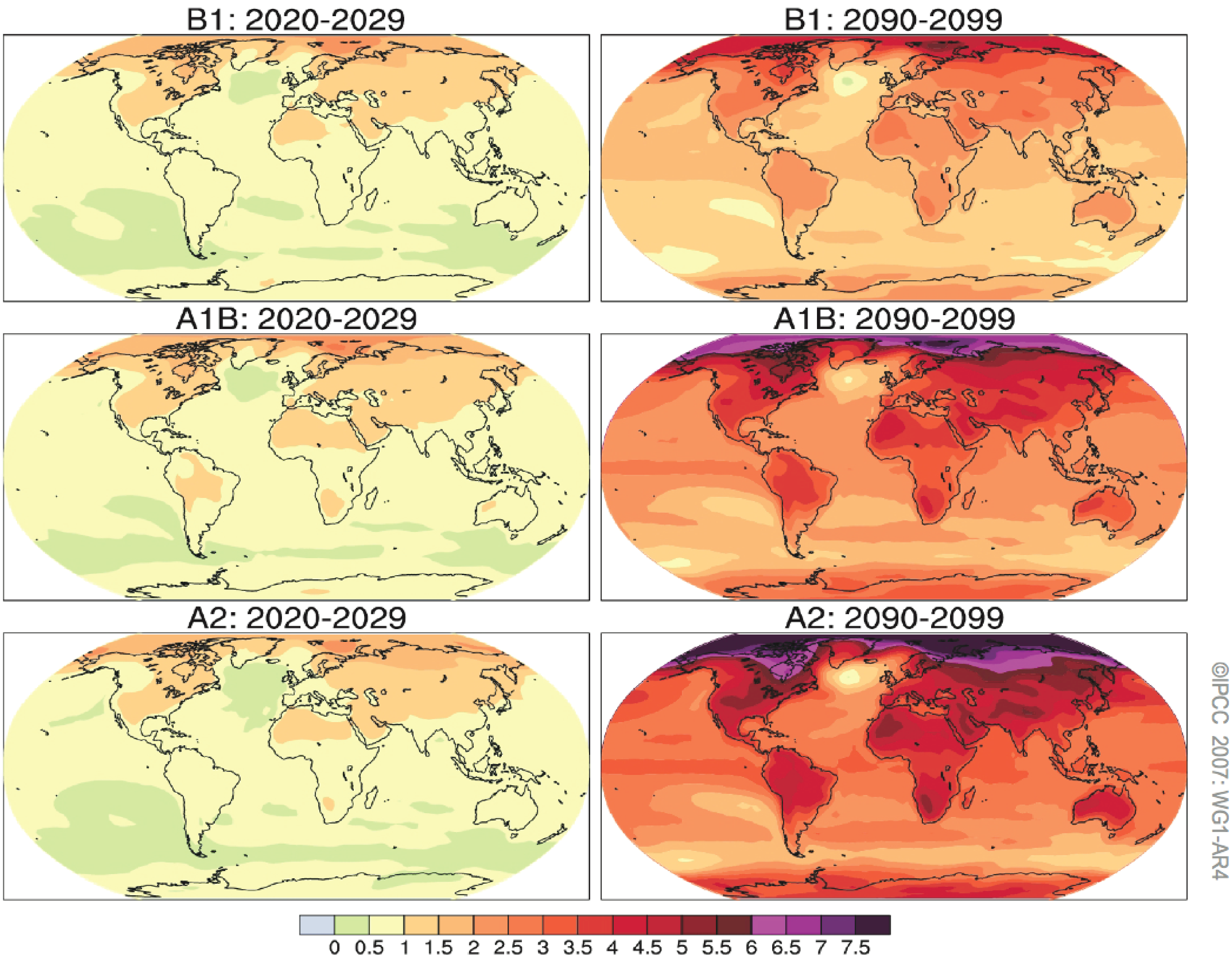
Precipitation change, A1B, 2080-2099 – 1980-1999



Stippling in places where at least 80% of models agree on sign of change

Meehl et al., Chapter 10, IPCC AR4 WG1 Report

Projections of Future Temperatures



Sea Level Rise

- Global average sea level rise for the 20th century was 4.4-8.8 inches
- Global average sea level estimated to rise between 0.6 and 2 feet over 21st century

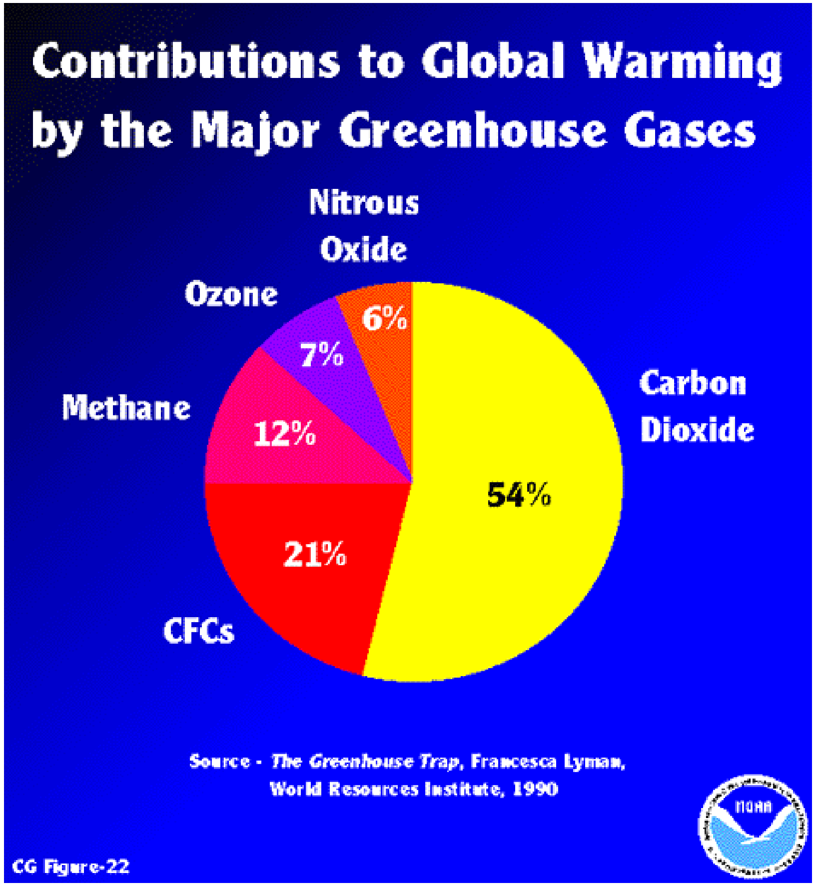
Why?

- Salt water expands as it warms
- Melting of mountain glaciers and portions of Greenland and the Antarctic ice sheets

Anthropogenic (Human) Sources of Greenhouse Gases

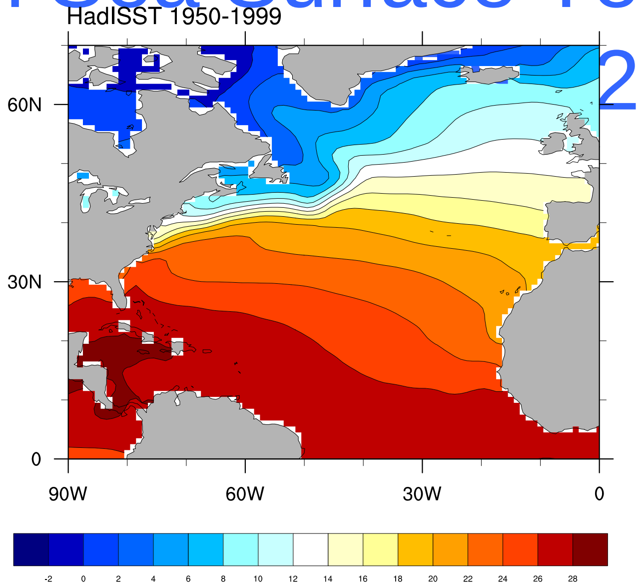
- Annual emissions of CO_2 from fossil fuel burning increased from an average of 6.4 GtCper year in the 1990s, to 7.2 GtC per year in 2000-2005

- Other GHGs have also increased: Global atmospheric concentration of nitrous oxide increased from pre-industrial value of about 170 parts per billion to 319 ppb in 2005.

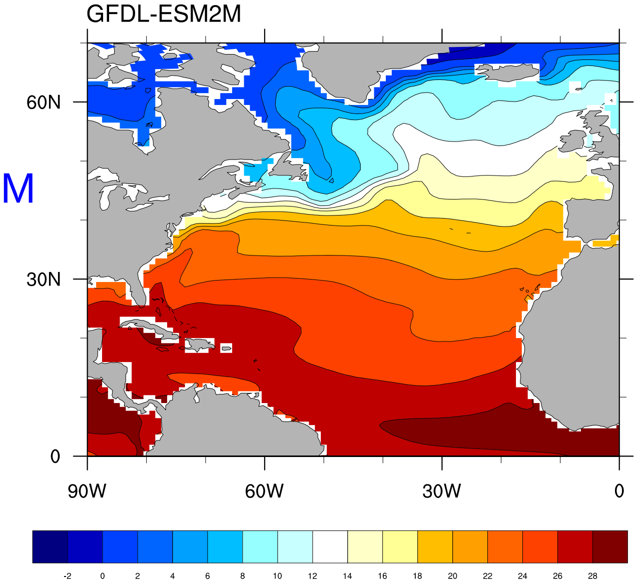


Mean Sea Surface Temperature (GFDL-ESM2M)

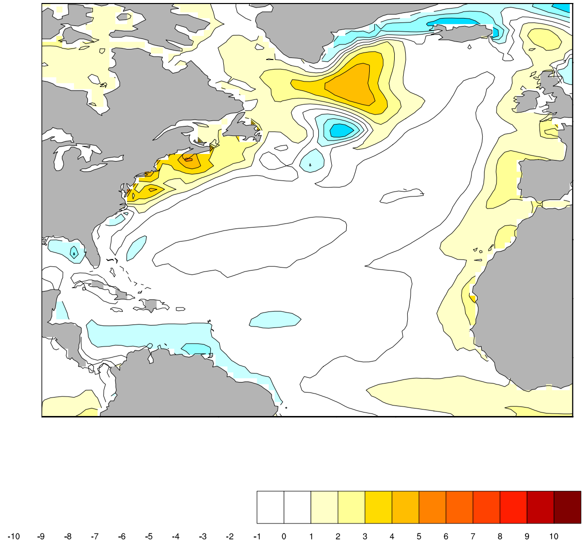
Observations HadISST (1950-1999)



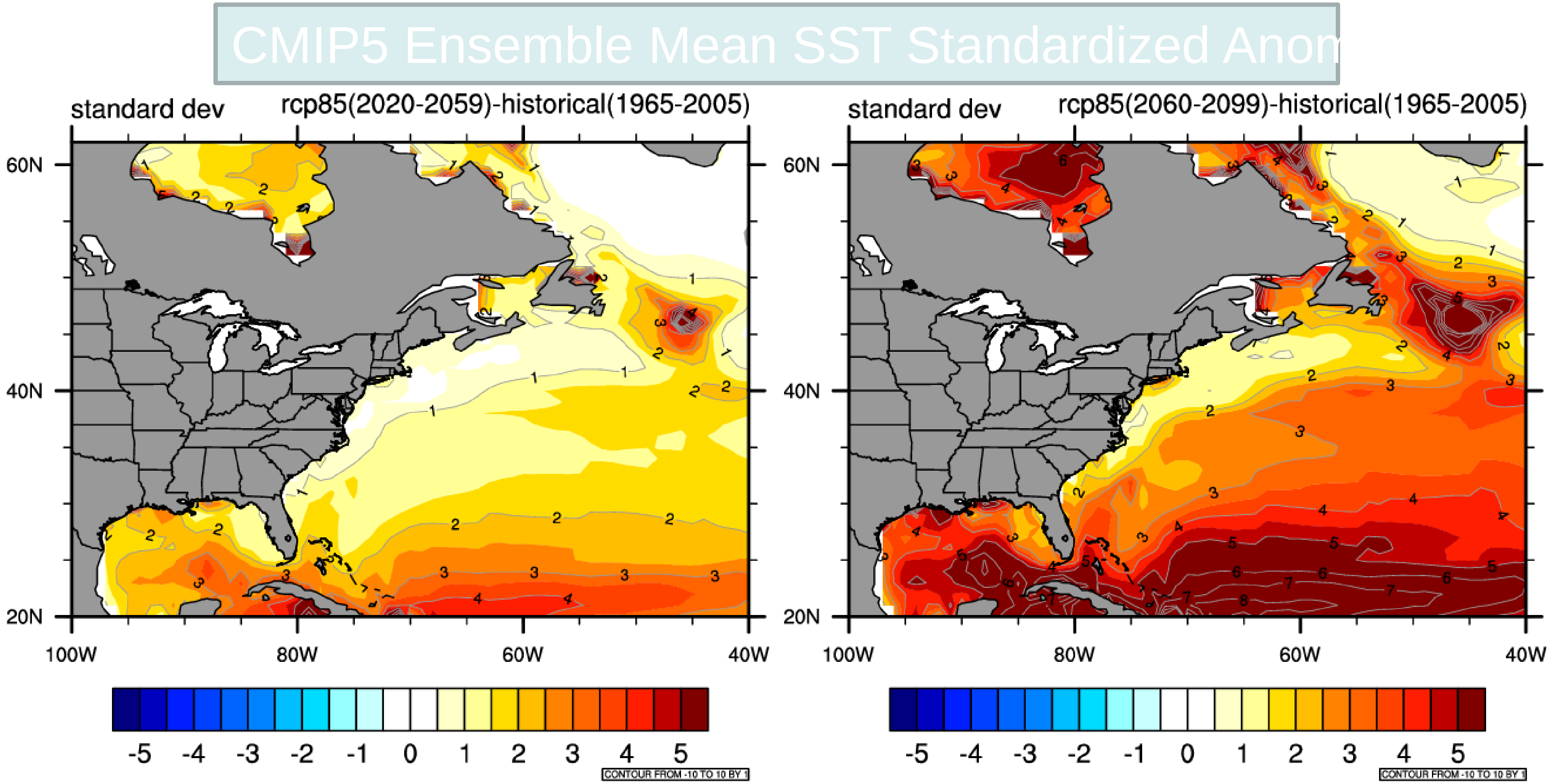
GFDL-ESM2M



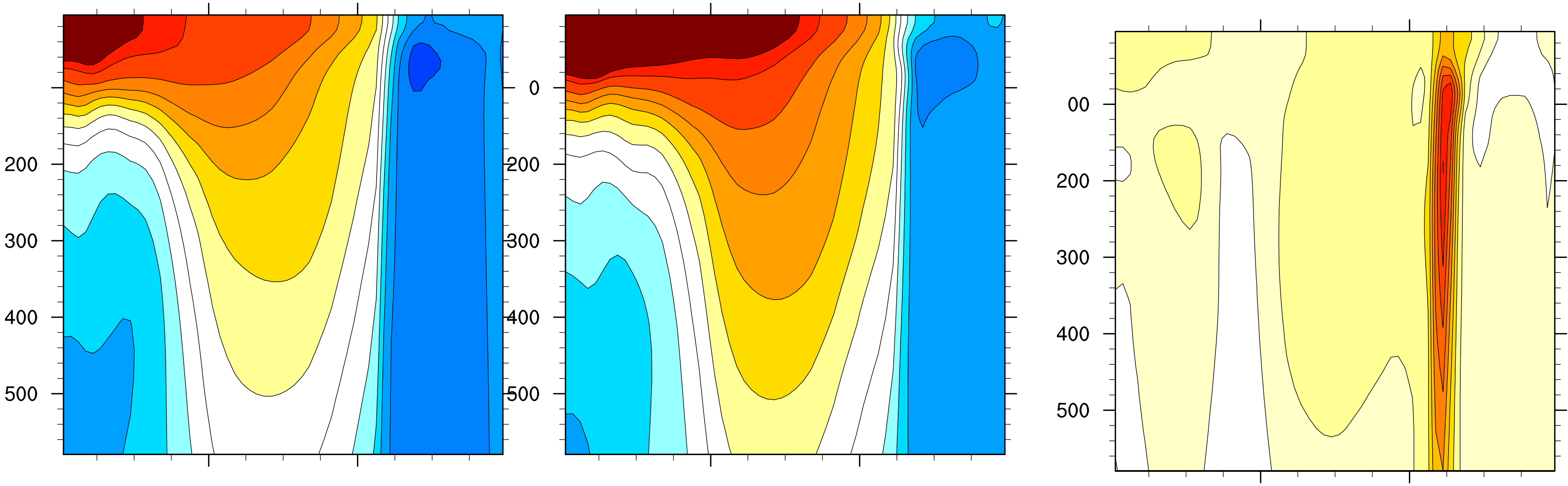
GFDL-ESM2M minus HadISST



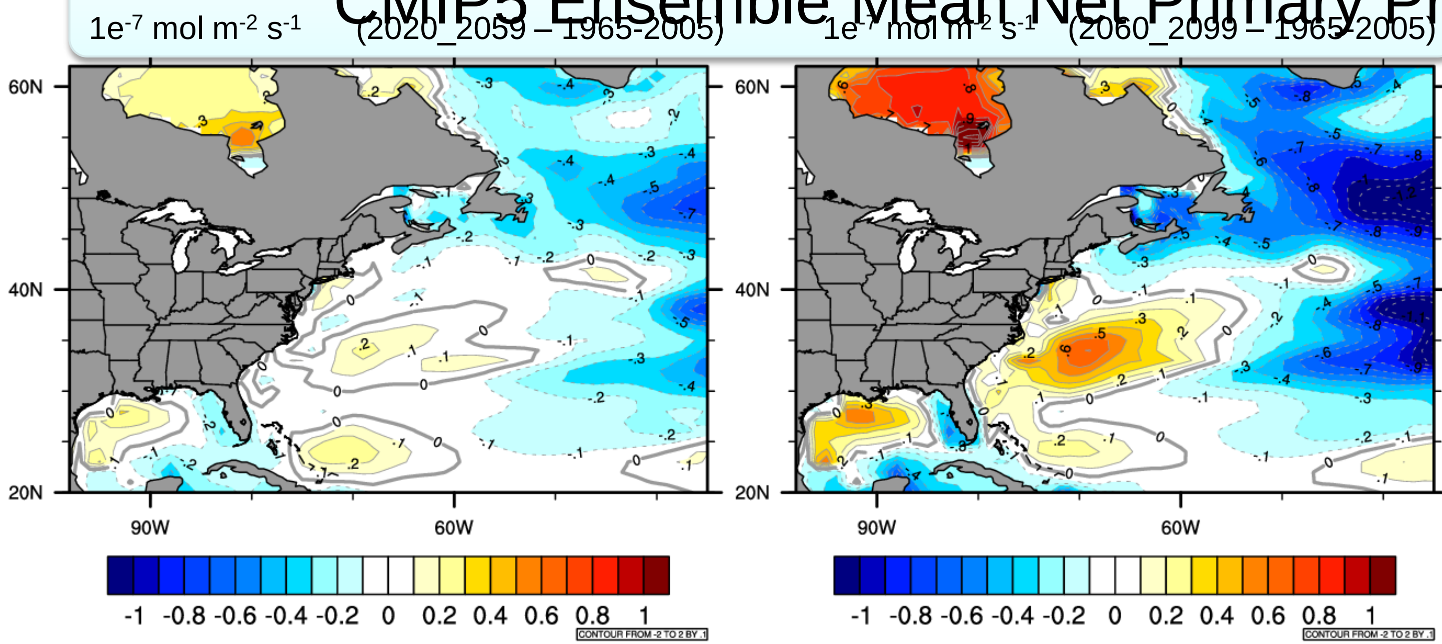
Ensemble mean SST anomalies normalized by the ensemble standard deviation of the historical (1965-2005) climate mean from 4 models represents confidence in climate change signal.



Potential temperature (CESM)
45° W



CMIP5 Ensemble Mean Net Primary Prod Anom



CMIP5 Ensemble Mean Net Primary Prod Standardized