Climate-Ocean Interactions in the Northeast Region – Current Understandings, Key Science Challenges

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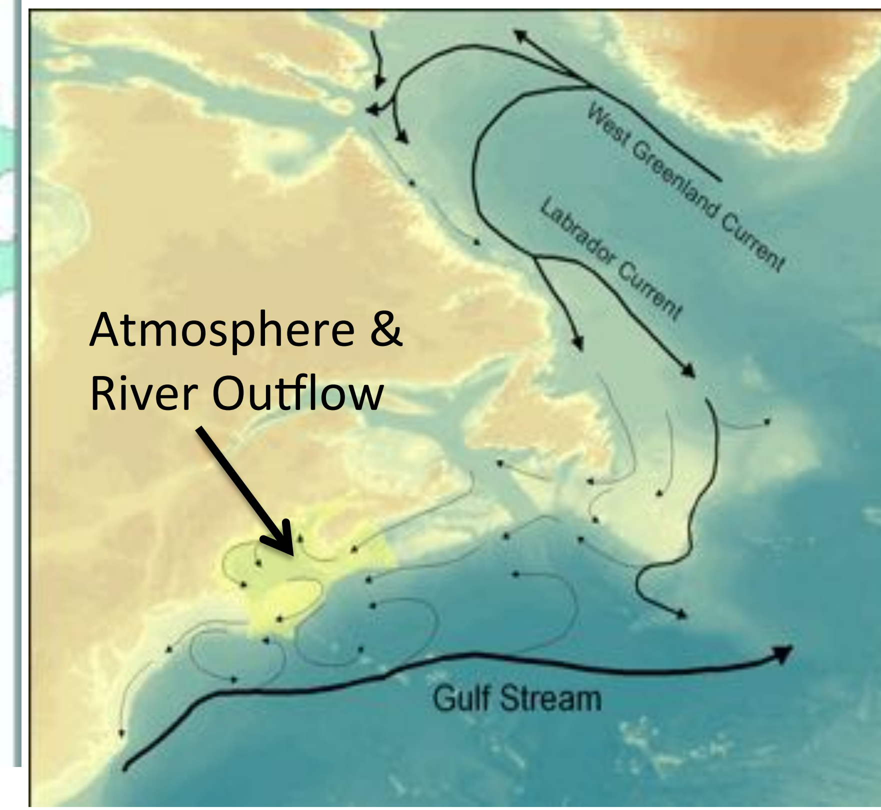
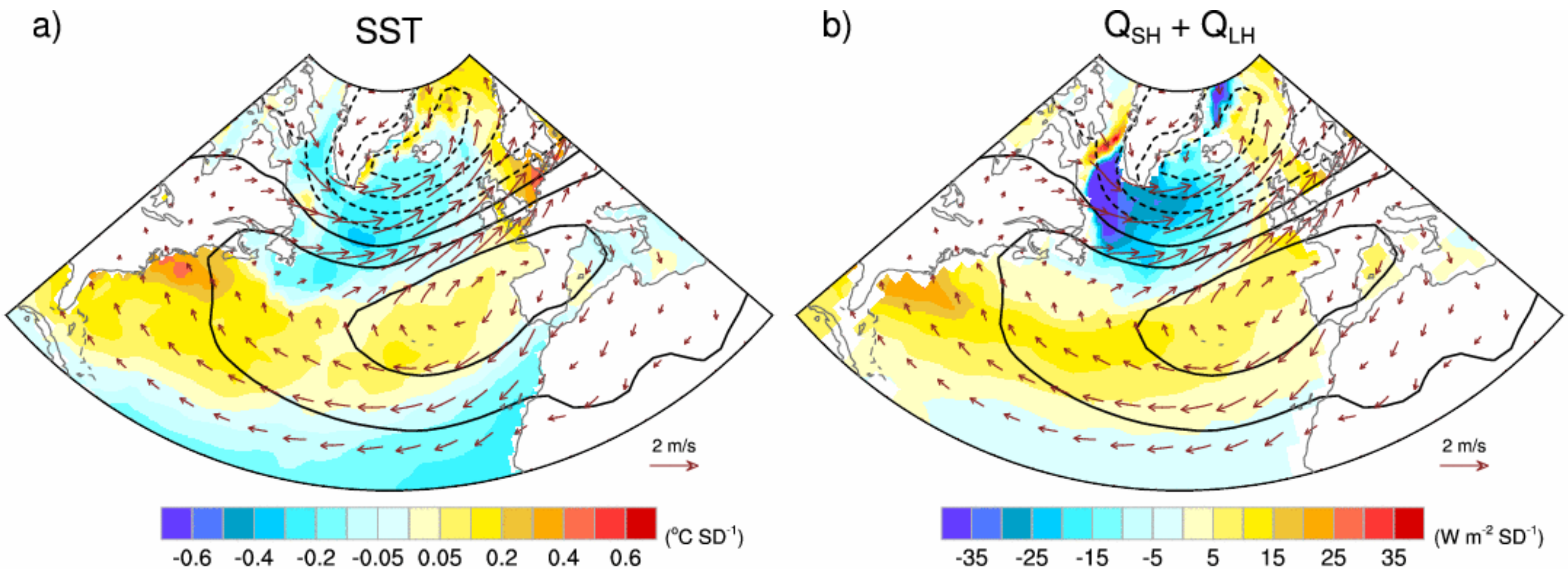
With input from Enrique Curchitser, John Hare, Vincent Saba, Charlie Stock

North Atlantic Circulation



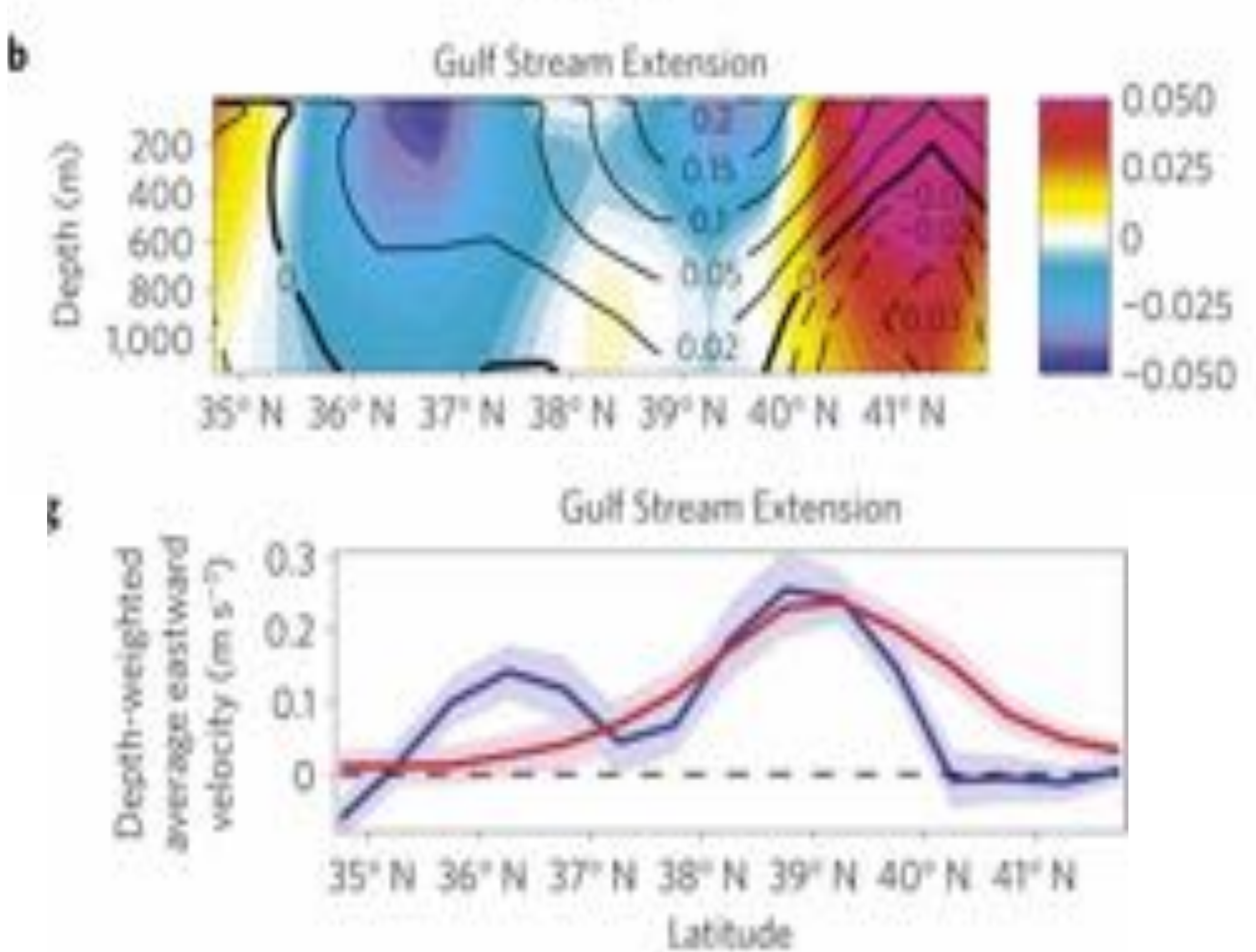
North Atlantic Oscillation
Patterns of Surface Fluxes and SSTs



Contours are sea level pressure (SLP); vectors - winds
Shading left is SST anomalies, on right is the Flux anomalies
NAO north-south SLP anomaly pattern over the Atlantic

Deser et al. 2010, Annual Reviews of Marine Science

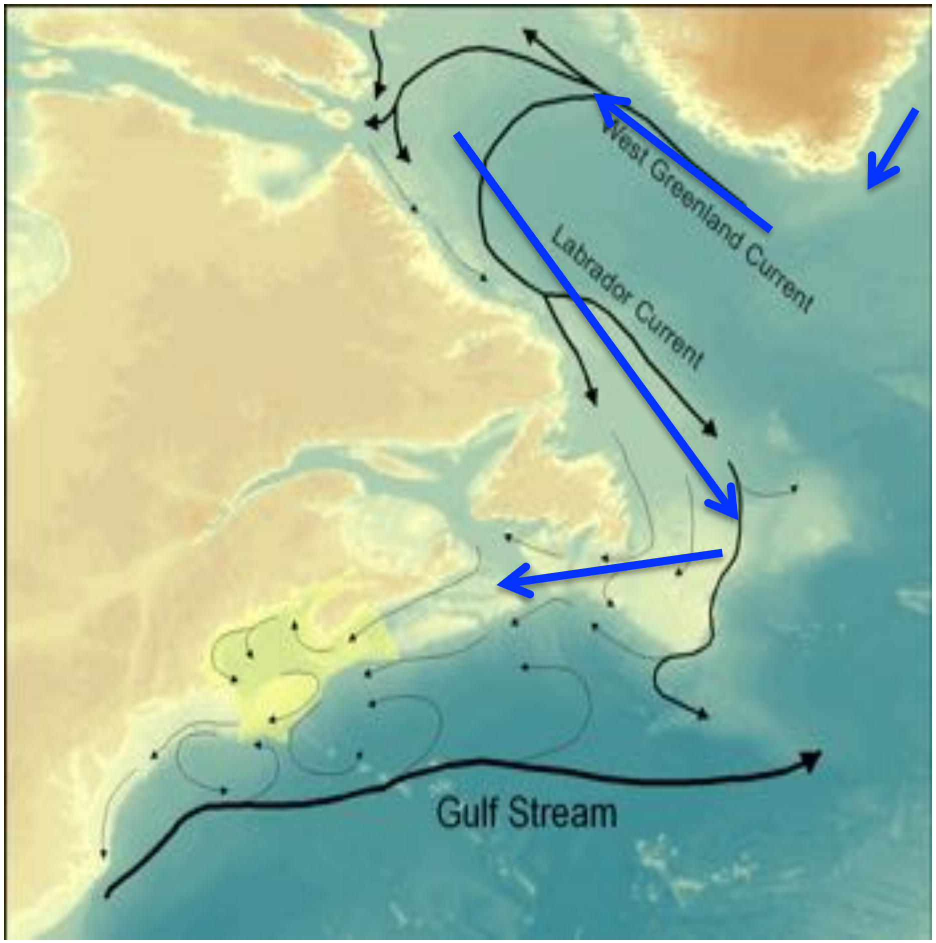
Observed Changes in Gulf Stream Position



Depth–latitudinal profile of mean (contours) and trend (1900–2008, colour). Units for mean and trend are m s^{-1} and m s^{-1} per century, respectively.

Wu et al. 2012, Nature Climate Change

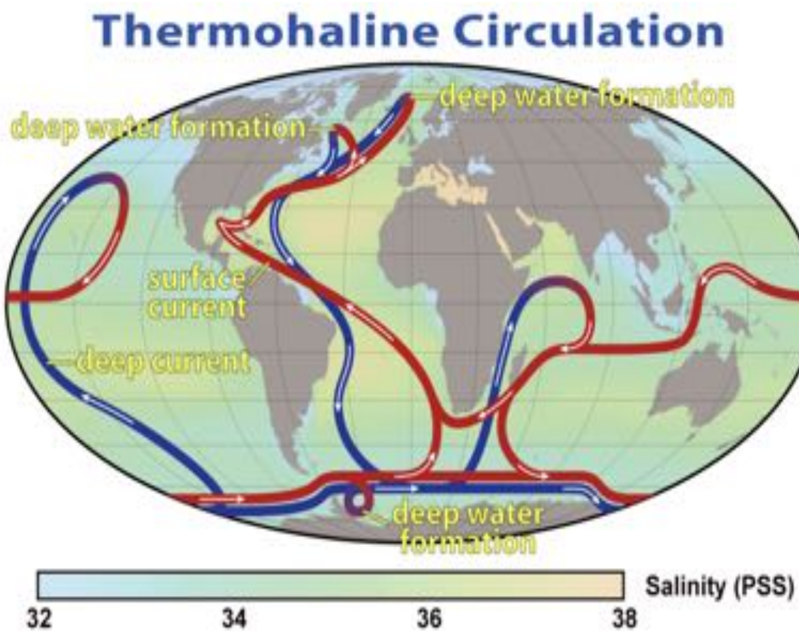
Transport of Artic Water onto the NE Shelf

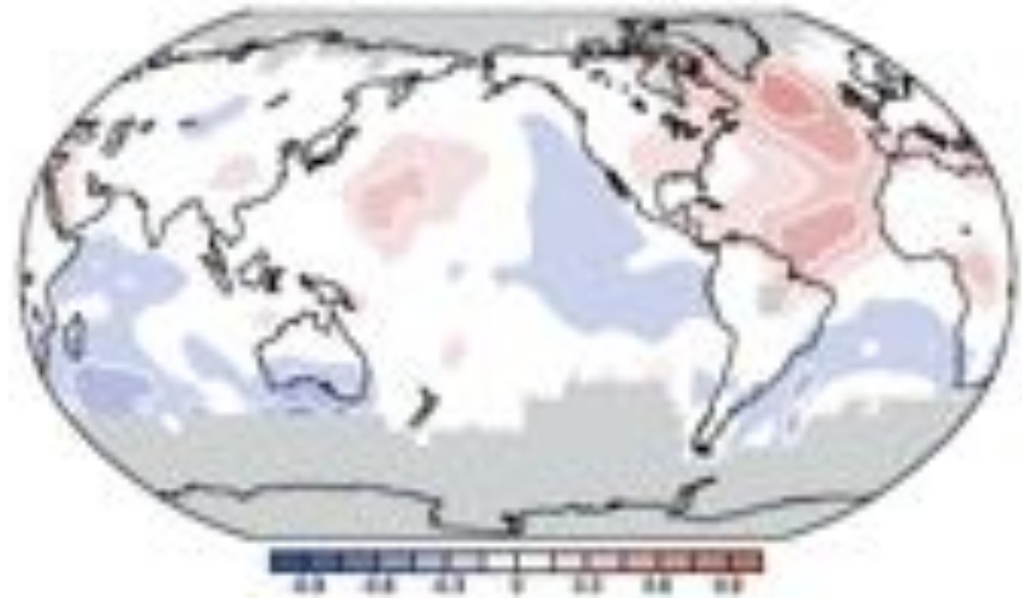


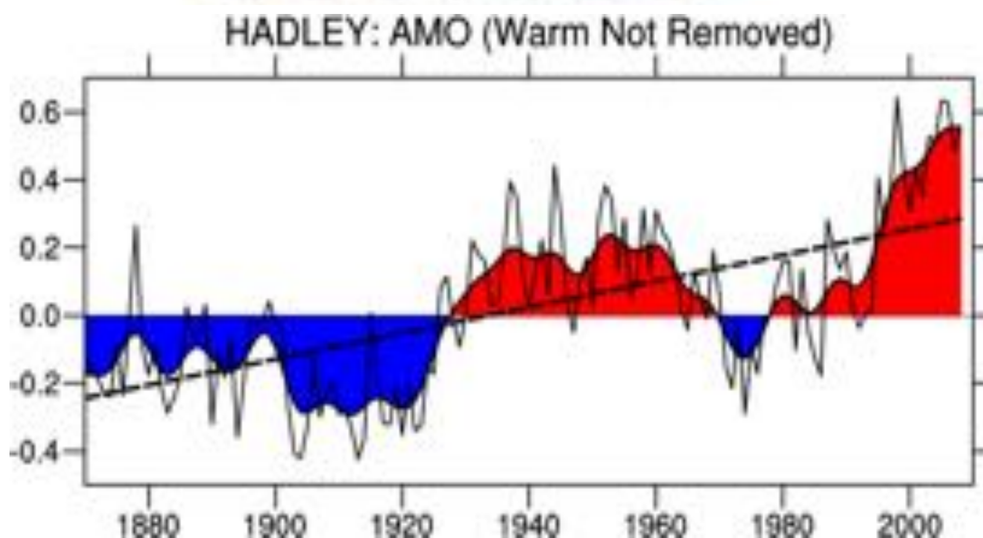
- Cold Fresh Artic water
  - From the east side of Greenland
  - From Labrador Sea
  - Natural Variability: Low frequency Oscillations
  - Melting of Sea Ice & Enhanced high latitude precipitation
    - Alters stratification and nutrient transport GoM & Georges Bank

Papers by: *Greene, Pershing and Townsend*

Atlantic Multidecadal Oscillation (AMO)



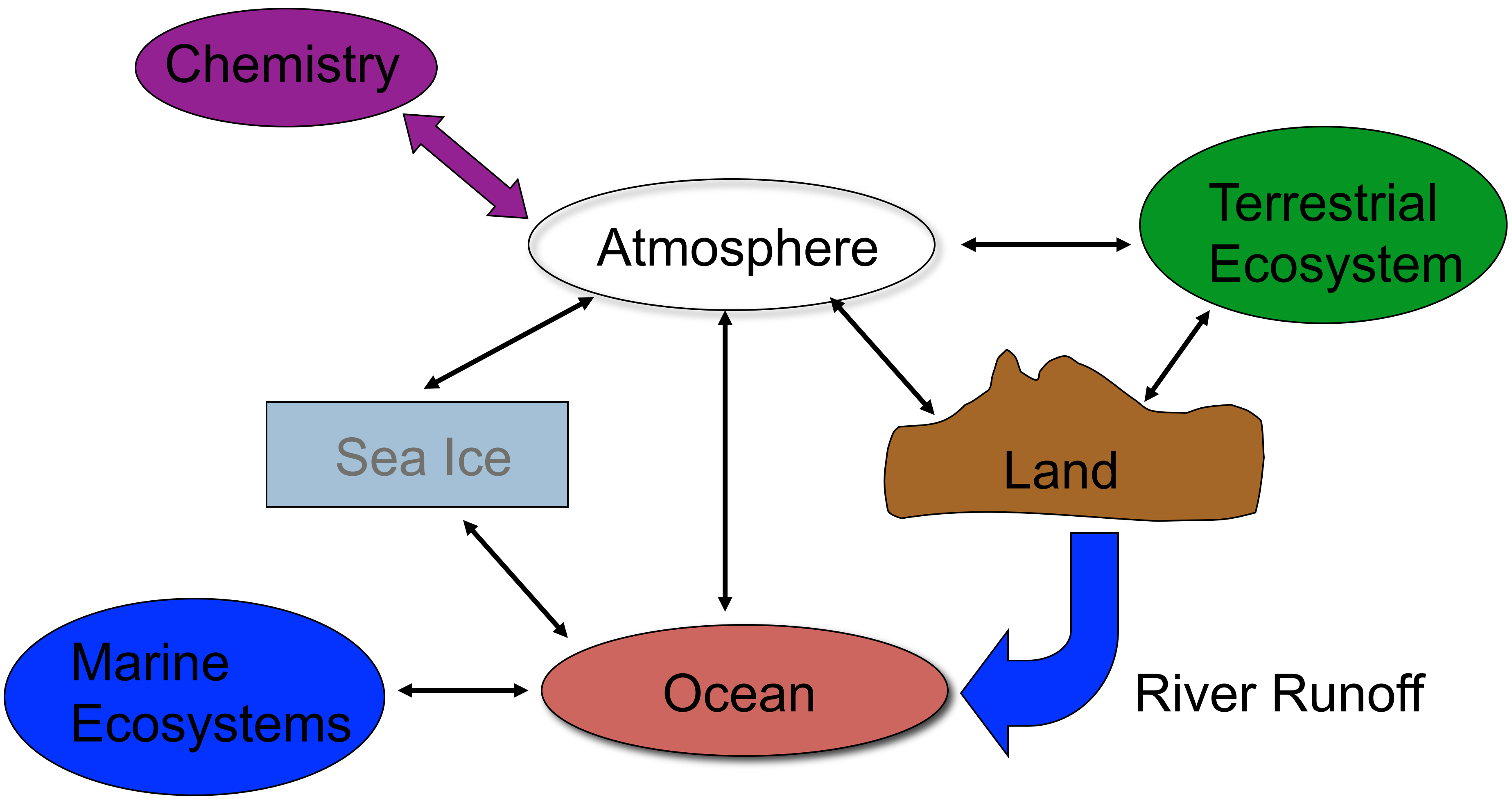




AMO: detrended SST anomalies
Averaged over the North Atlantic

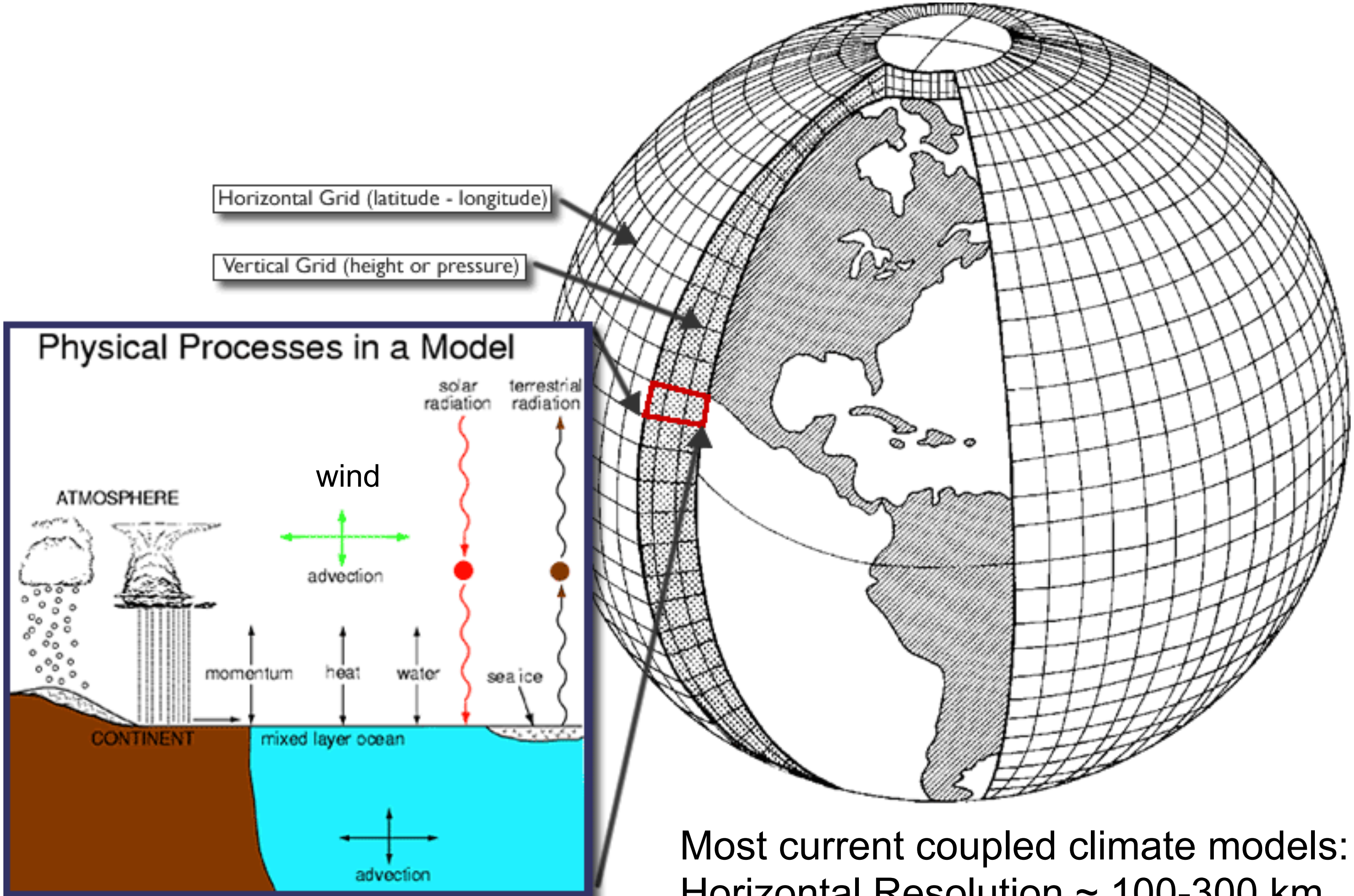
Trenberth and Shea (Geophys. Res. Let., 2002)

Components of Climate Models



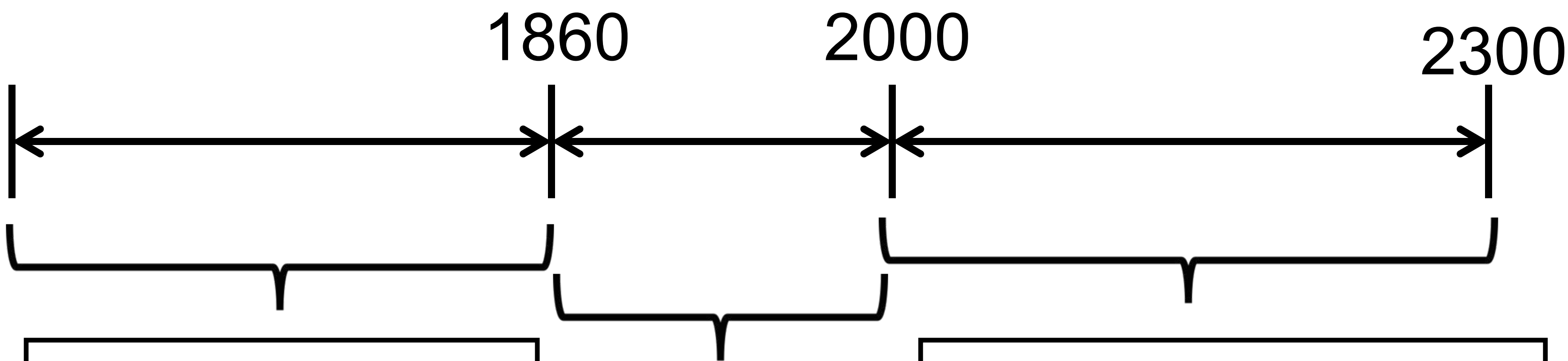
Components can be run independently or as subsets

Climate Models



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

Century-scale climate model projections

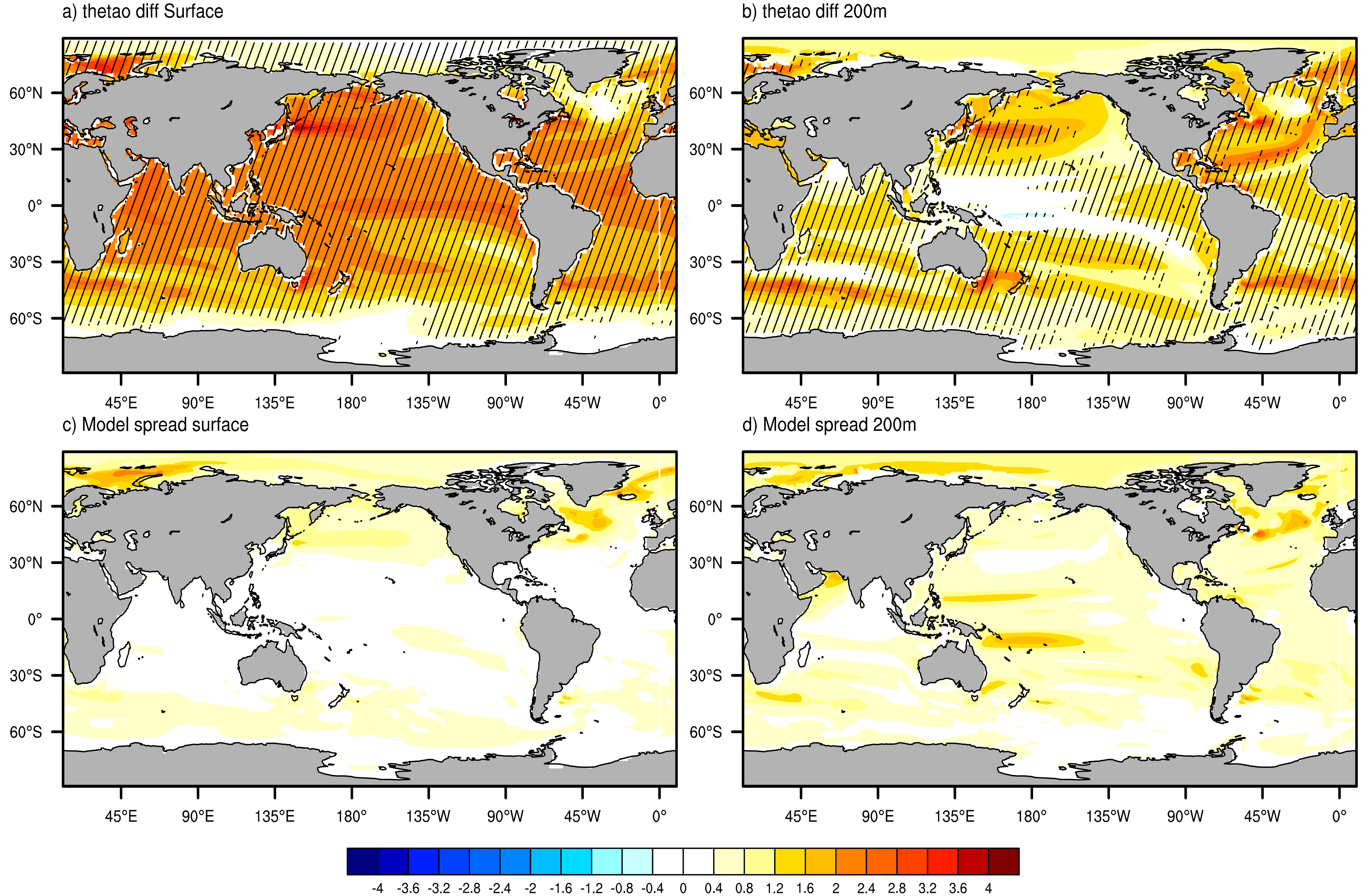


Long pre-industrial control: Greenhouse gases set to 1860 levels, run for multiple centuries to allow climate to settle into a quasi-equilibrium

Historical period forced by observed GHG's, volcanoes, and solar forcing etc.

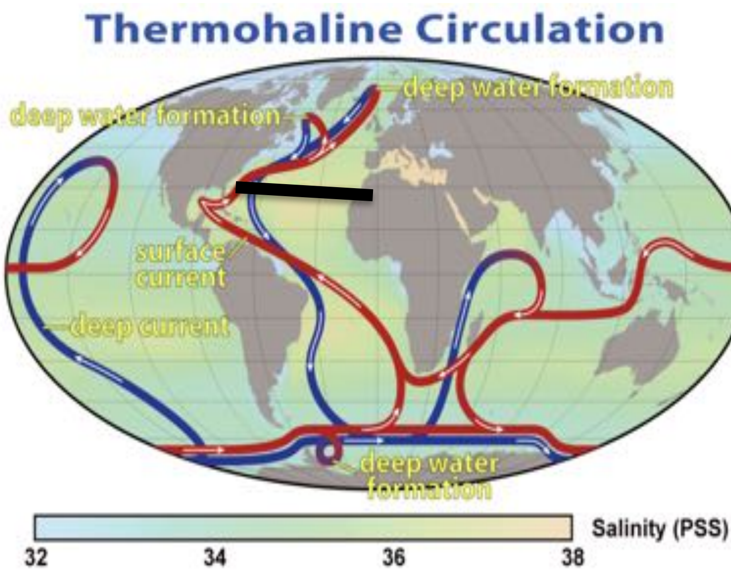
100-300 year projection under different scenarios for future greenhouse gas emissions

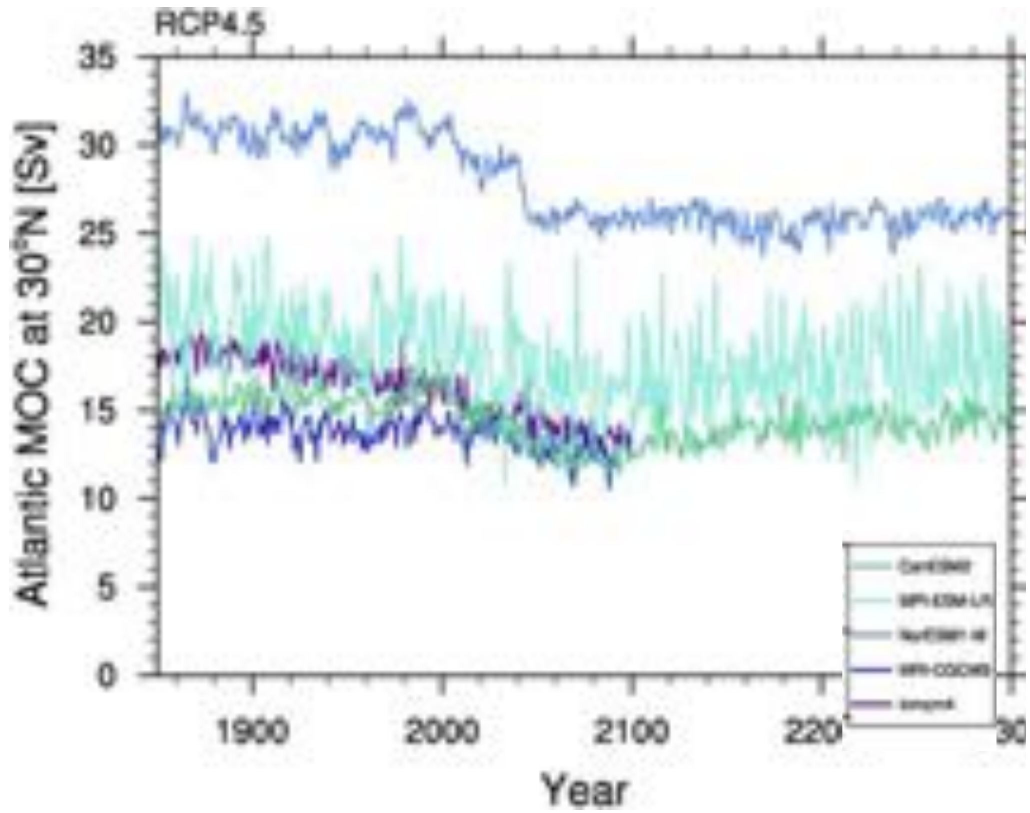
2051-2100 – 1951-2000 SST & 200 m ocean temperature from A2 simulations



Capotondi et al. 2012 JGR

Changes in Atlantic Meridional Overturning Circulation (AMOC)



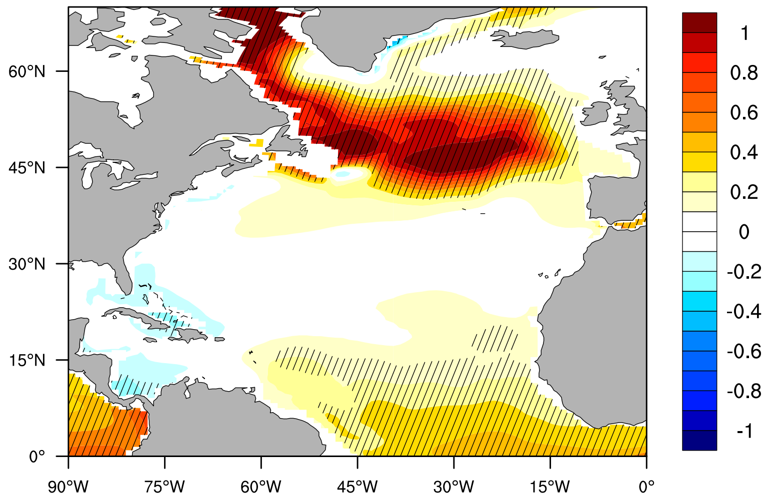


Freshening and warming at high latitudes reduces density and sinking thereby slowing the thermohaline circulation/AMOC

Stratification changes

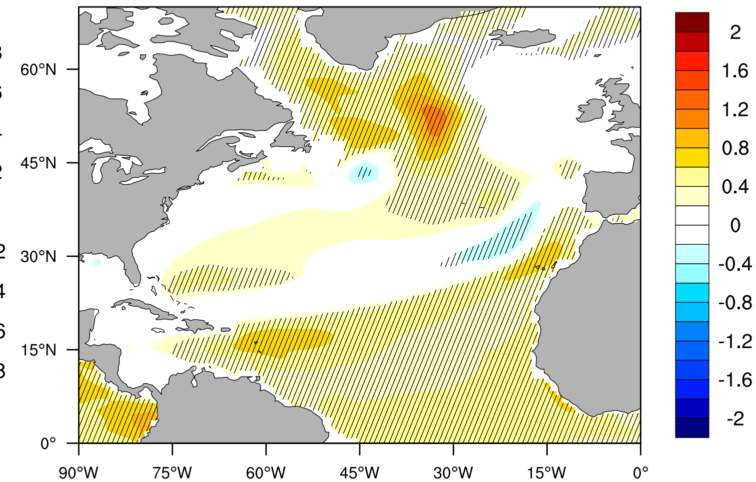
NCAR-CESM

NCAR - Stratification Difference



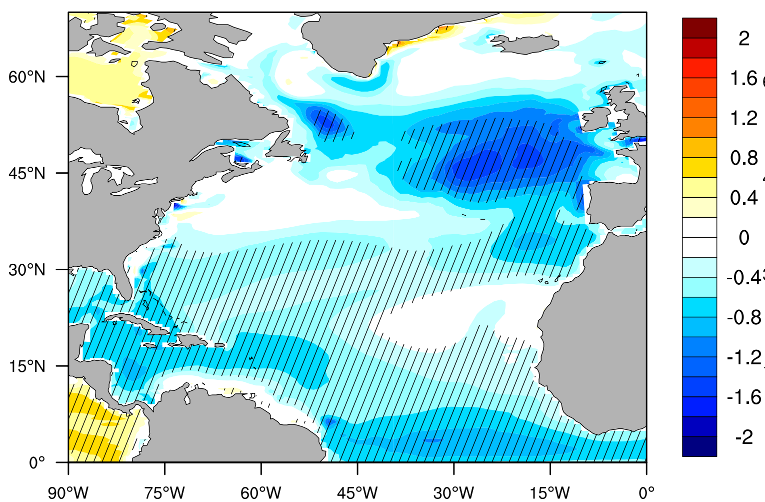
GFDL

GFDL - Surface Density difference

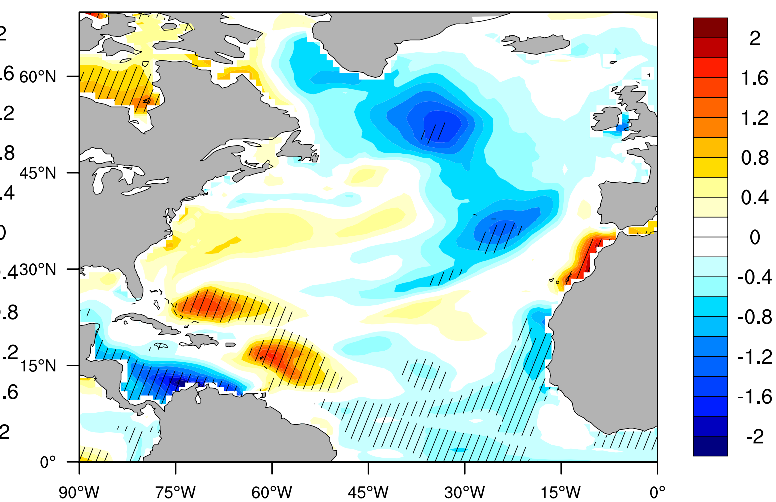


Primary Production

CESM - PP difference



GFDL - PP difference



Additional Issues

- Sea Level Rise
  - (inundation of estuaries)
  - Circulation-driven changes especially large in NE Shelf
- Changes in River runoff
  - Warmer water in rivers earlier peak flows
  - Enhanced runoff - more precip over Northeast States
    - Although precipitation changes more uncertain than temperature
- Changes in Extremes and storminess
  - Northward position of storm track
  - Fewer but stronger hurricanes
- Ocean Acidification

Climate Change: Sources of Uncertainty

- Forcing

  Greenhouse Gases (CO_2, Methane, etc.)

  Aerosols, land use, black carbon …

  Sunlight at the top of the Atmosphere

  How will these change in the future?

  "Scenarios", "what if questions"

  Answer depends on economics, sociology, etc.

- Model Response

  Model sensitivity – respond differently to forcing

  (different physics, parameterizations, resolution …)

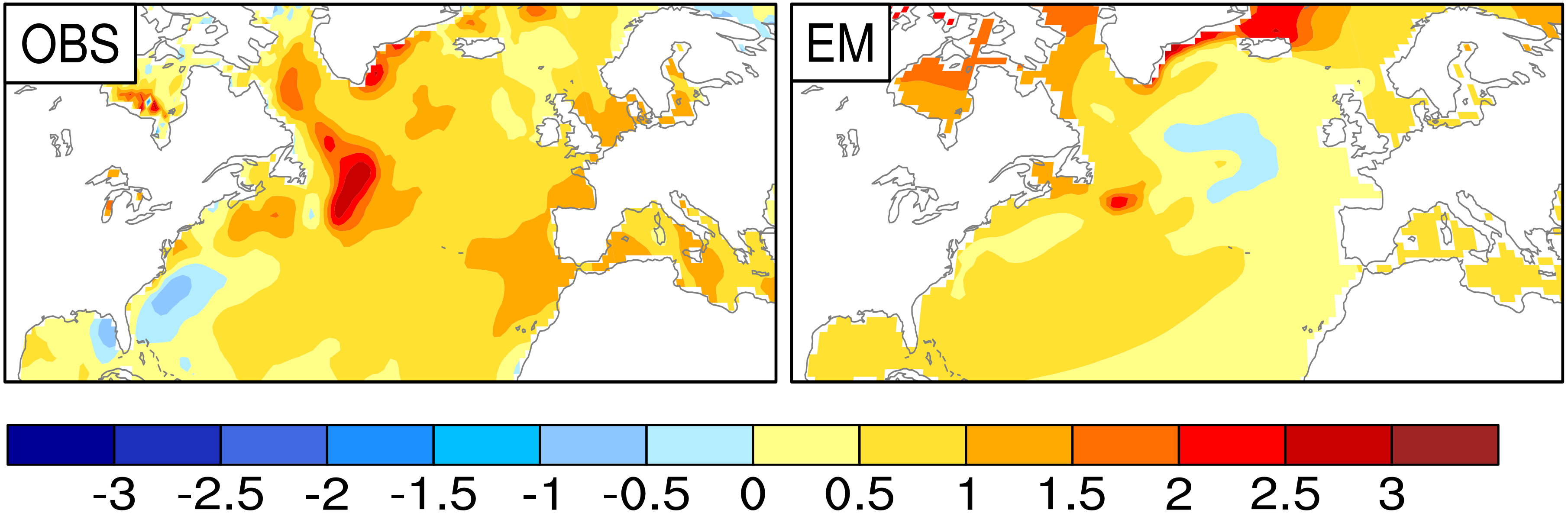
- Internal (Natural) Variability
  - coupled atmosphere-ocean-ice-land interactions

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 a few 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

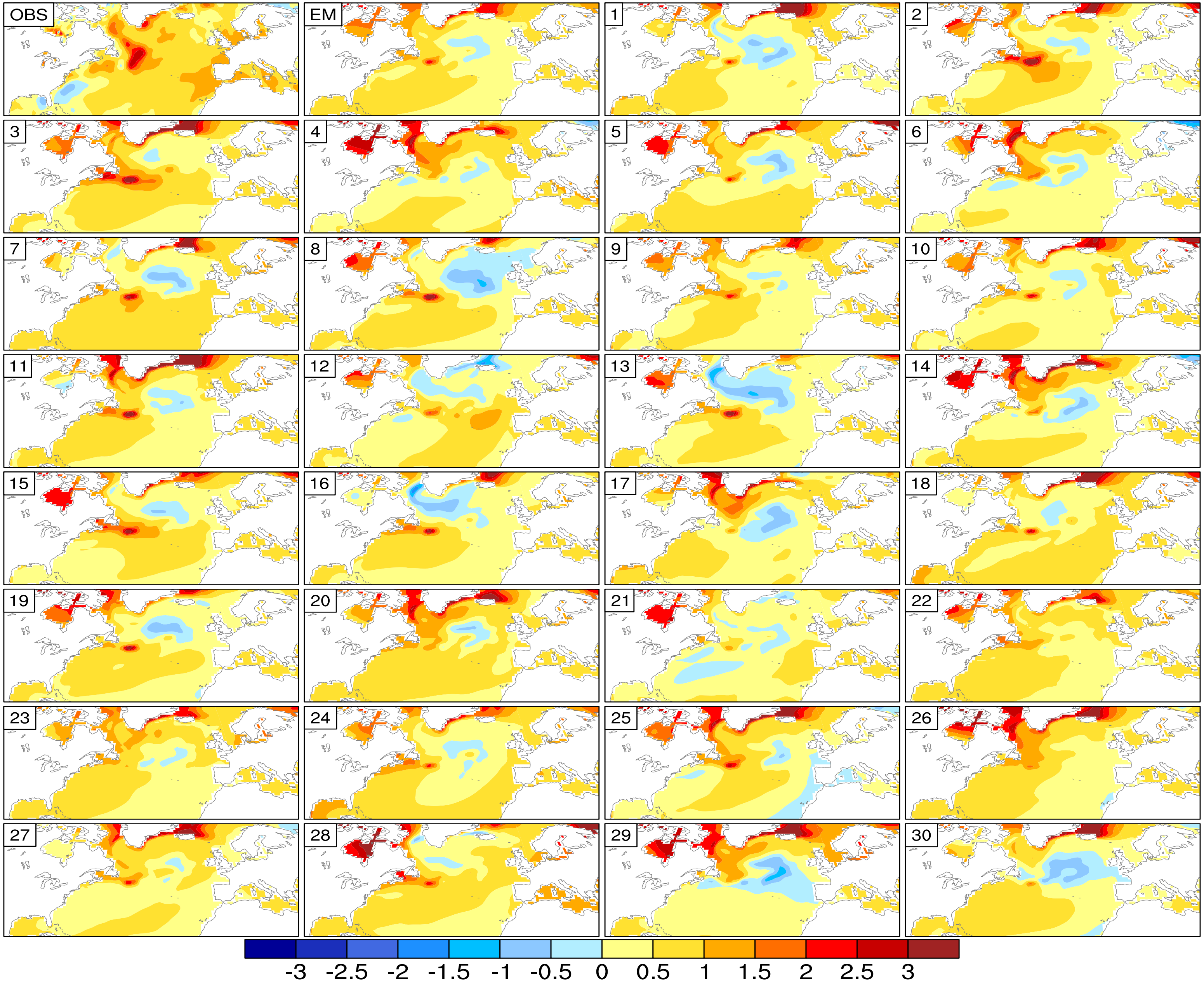
SST trend (°C/36 years) 1970-2005

all months of the year

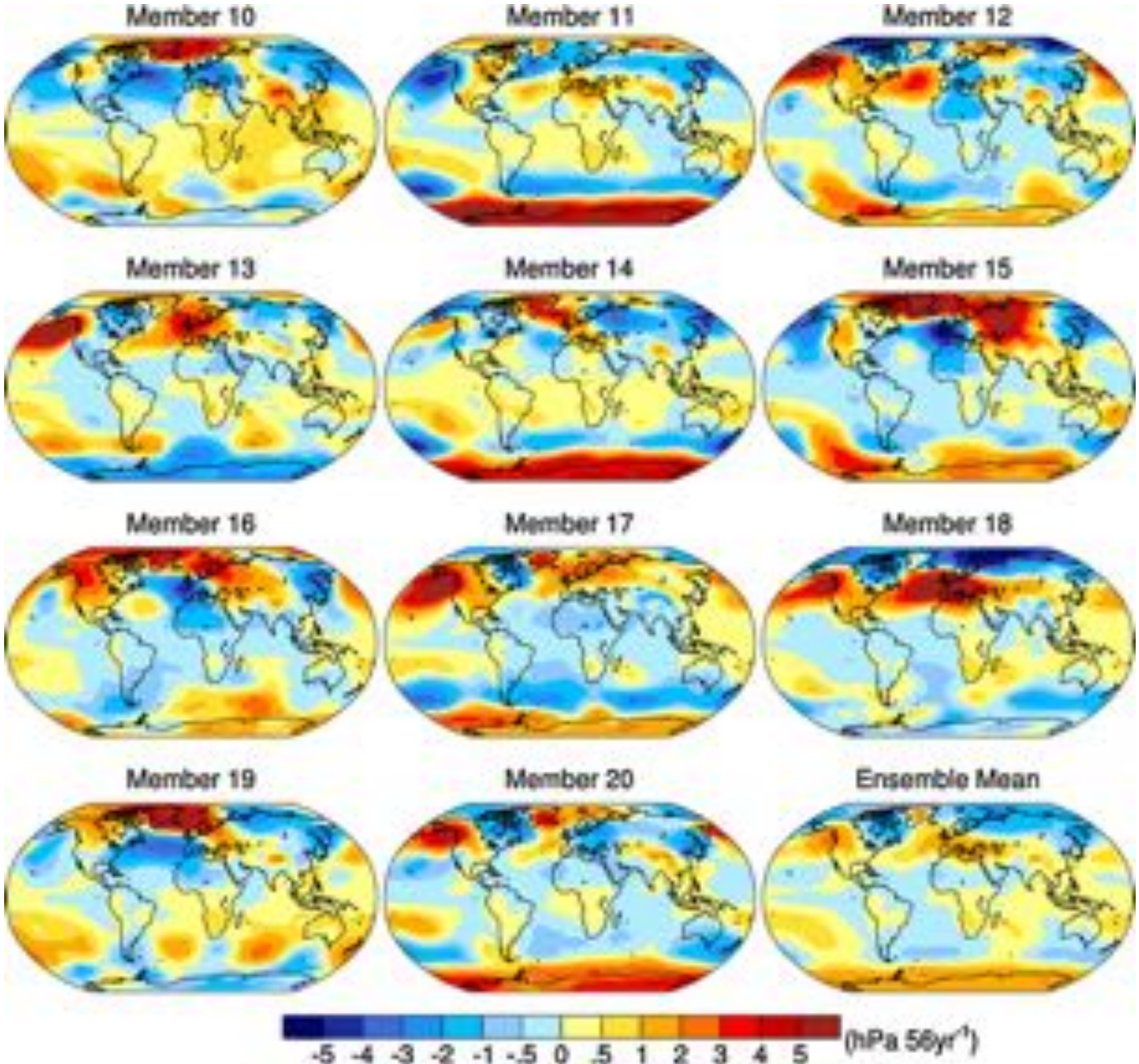


Right Ensemble Mean (EM) – of 30 CCSM4 (NCAR model) started with minute differences in the initial conditions of air temperature (10^{-15} °C)

SST trend (°C/36 years) 1970-2005



DJF SLP trends for 10 ensemble 2005–2060 in CCSM3



Decadal Predictions

- Decadal predictions are being conducted as part of the IPCC AR5
- climate models are initialized using observations and integrated 10-30 years into the future, including estimates of the change in greenhouse gasses.
- In addition to climate change, parts of the climate system that evolve slowly, e.g. AMOC are potentially predictable on decadal timescales
- Given the chaotic nature of the climate system, predictions will need to be given in a broad probabilistic sense.
- For example, it might be possible to provide some skillful estimates of multi-year North Atlantic SSTs in a 10-year forecast (Smith et al. 2007, Branstator and Teng 2010, Muller et al. 2012, Yeager et al. 2012).
- Predictability of air temperature and precipitation changes in these model runs appears to be limited to a few years (Branstator and Teng, 2011).
- Even as climate models improve there will be due uncertainty in emissions and natural variability in the climate system will lead to spread in climate prediction and projections.

Downscaling (resolve finer scales)

Statistical

- Prior to downscaling nearly always need to bias correct
  - Delta method: Take difference between past and future period add to observed climate (removes mean bias)
  - (John's talk)
- Can "correct" other aspects of the distribution (e.g. variance)
- Can interpolate to finer resolution (not using relationship between coarse and fine scale)
  - "NDSM"
  - *Non-downscaling Statistical Method* ☺

Dynamical

- Use numerical models to downscale
- Finer resolution global models
  - Already 10-25 km ocean models
- Regional Ocean Models
  - Driven by Climate models along boundaries
  - Embedded within climate model
- Models with variable grids
  - (FV-COM)
- May still need to bias correct or statistically down scale
- Computationally expensive
  - Generally with a small subset of forcing

Statistical Downscaling II

- Use observed statistical relationships between resolved, larger-scale features and unresolved finer-scale features.
  - e.g. Can take into account how circulation features or bottom boundary effects temperature

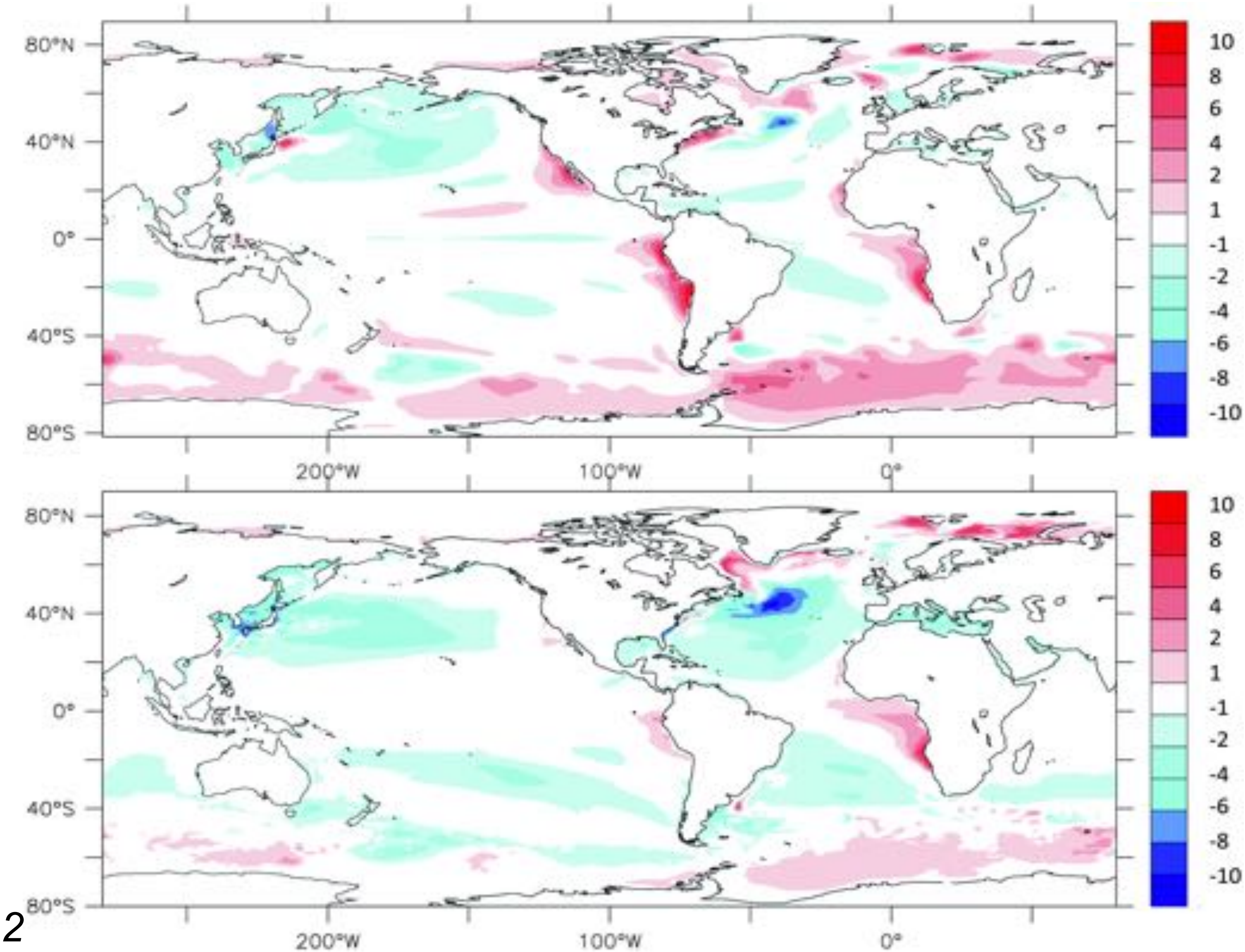
Upsides
- Relatively low computational cost
- Can apply to multiple models.

Downsides
- Assume stationarity in the statistical relationship
- If climate model projected change in correct downscaled will be as well.
- Requires long observational time series to establish relationships
  - Difficult in the ocean
  - NE Shelf may be a good candidate

SST Bias (°C) GFDL GCM

CM2.1
Low
Res

CM2.5
High
Res



Delworth et al. 2012

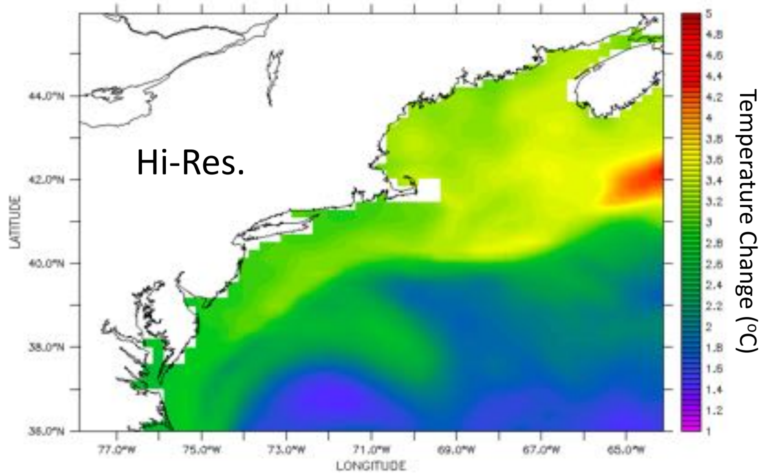
Projected impacts of climate change on the physical environment of the U.S. NES using a <u>high-resolution</u> climate model

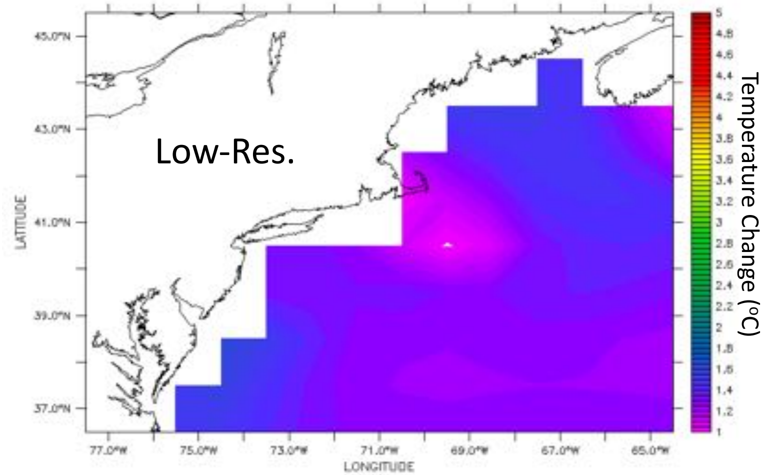
V. Saba, J. Hare, et al.

GFDL CM2.5 2xCO_2 simulations

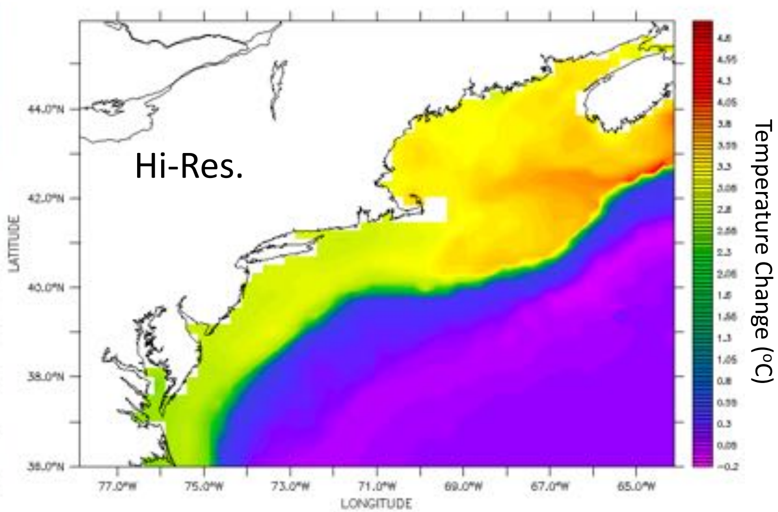
GFDL CM2.1 2xCO_2 simulations

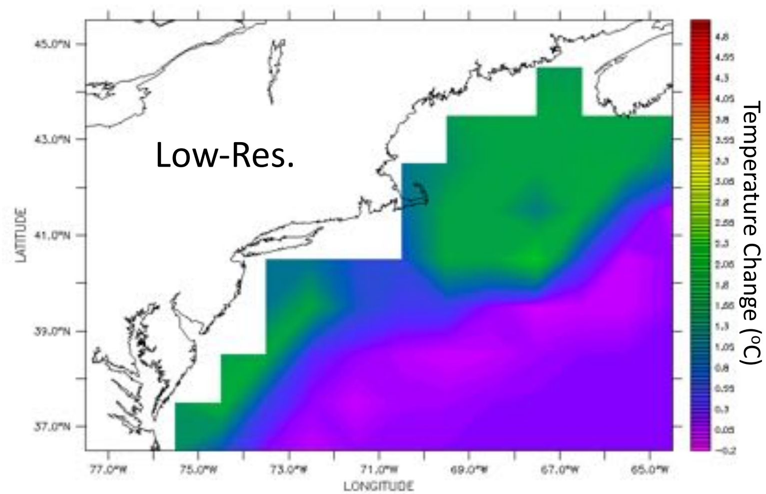
SST Change (2075-2100) minus (1990-2015)



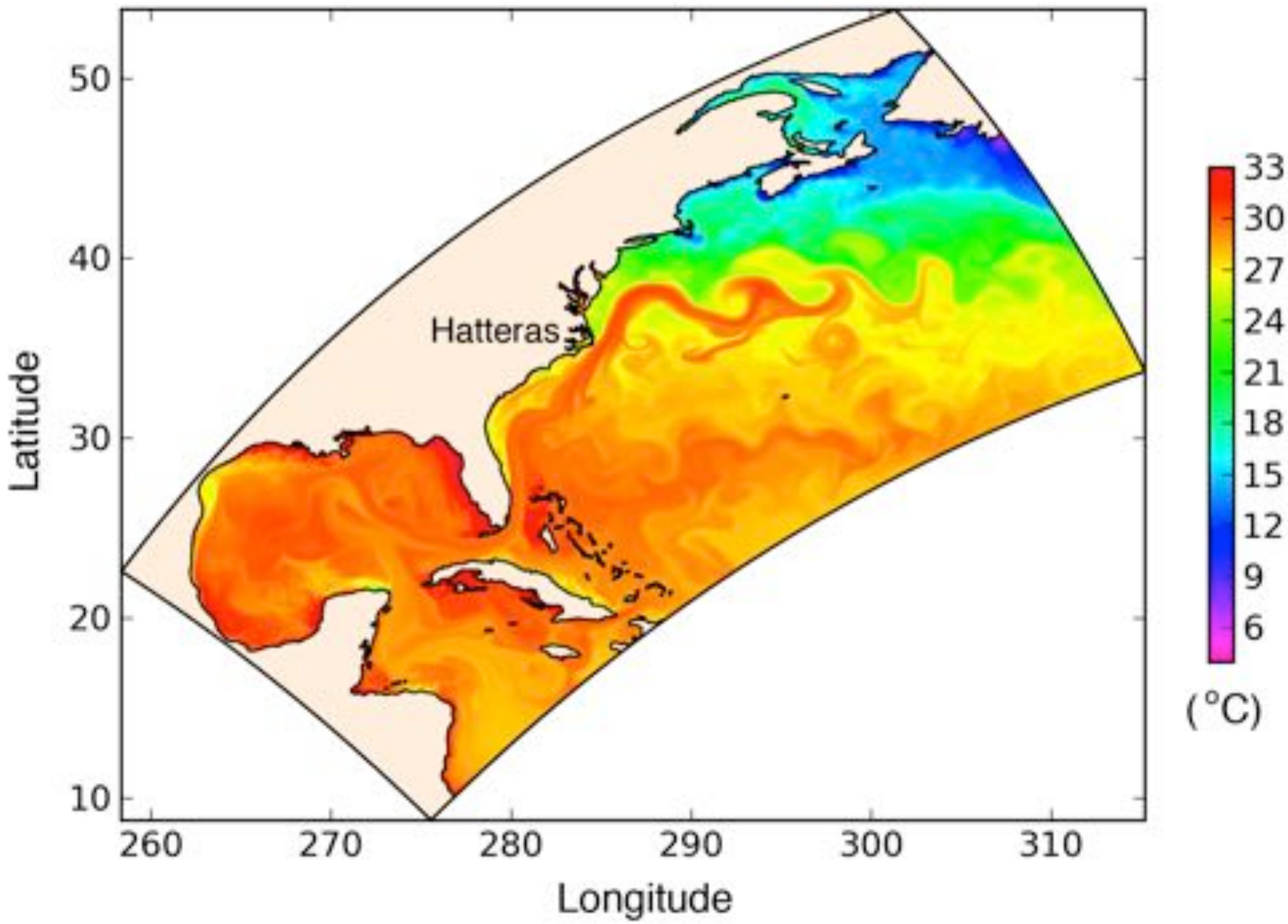


Bottom temp. Change (2075-2100) minus (1990-2015)





SST snapshot 7-km ROMs simulation



Key Issues/Opportunities (short term)

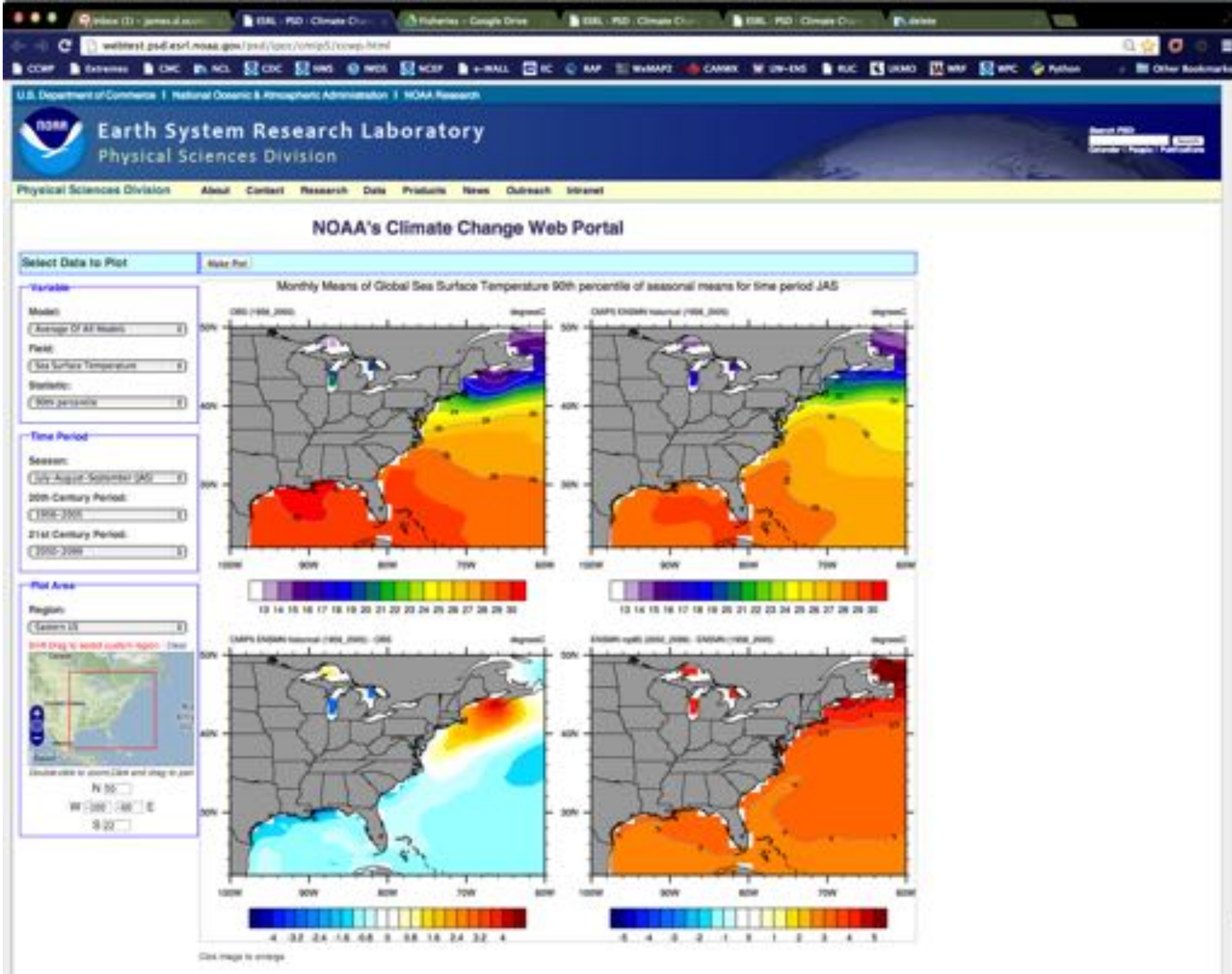
- How to best process large volumes of data from the CMIP/IPCC archives?
  - Web-based Tools
- How can we best use information coming from Earth System Models In CMIP5?
  - Verification and Analysis of Biogeochemistry – useful for coastal applications?
- Climate change "Signal" relative to natural climate variability (Noise)
  - Can we get useful information from variables in which S>N?
    - Temperature
  - Examine large ensemble of simulations, as being conduct at NCAR

    New methods for estimating change

    e.g. probability of exceeding a key biological threshold
- Consider Ocean Extremes
  - e.g. a few weeks were the temperature is above a critical threshold for given organism

Key Issues/Opportunities (Longer Term)

- New data sources needed open ocean => shelf?
  - e.g. Transport of nutrients from Scotian shelf into the GOM
- Downscaling
  - Is it always necessary?
  - Vulnerability assessment first (large-scale fields may be adequate)
  - Tied to mechanism/vulnerability
- Dynamical Downscaling
  - Experiment design / Boundary conditions
  - Probably advisable to use multiple approaches
- Statistical Downscaling*
  - Apply advanced ("actual") statistical downscaling (as developed for land)
  - need historical data base (or perhaps ocean reanalyses) to develop statistical relationship
  - what to do about non-stationarity?
- How can we best use decadal forecasts?
- End-to-End model/forecast system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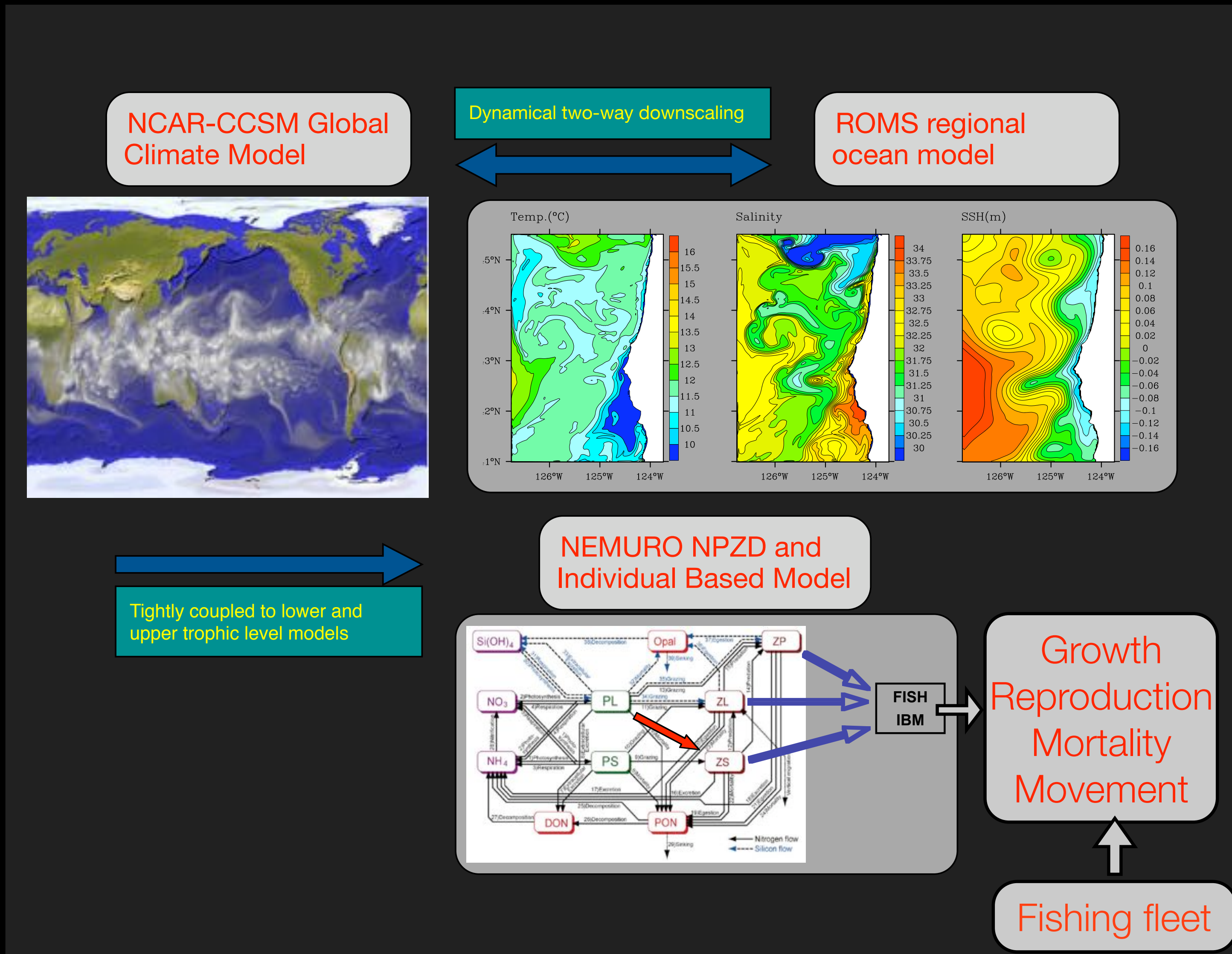
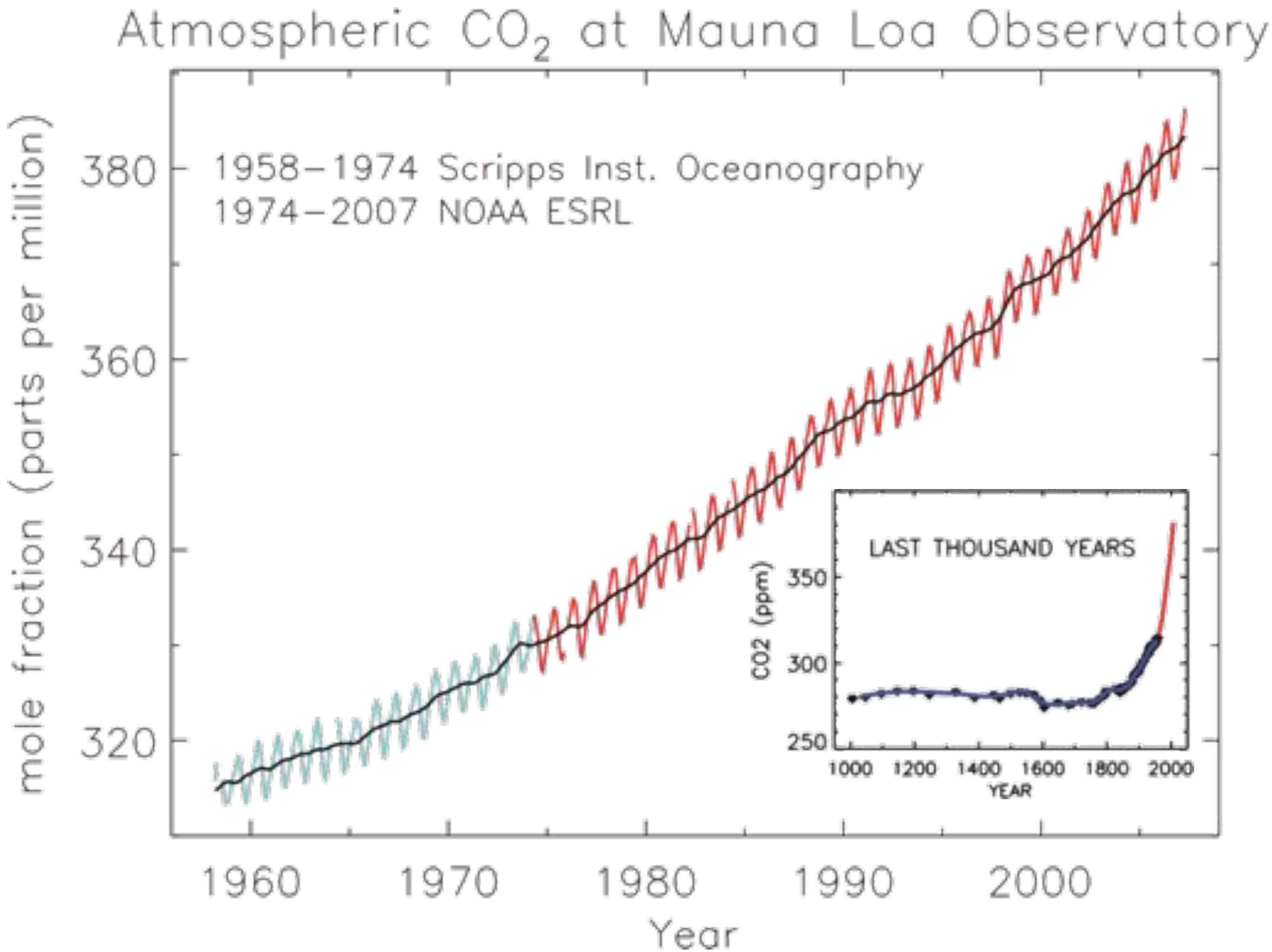
Make Plot
Monthly Means of Global Sea Surface Temperature 90th percentile of seasonal means for time period JAS
Variable
Model:
Field:
Statistic:
Time Period
Season:
20th Century Period:
21st Century Period:
Plot Area
Region:
13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Example “End-to-End” Forecast System

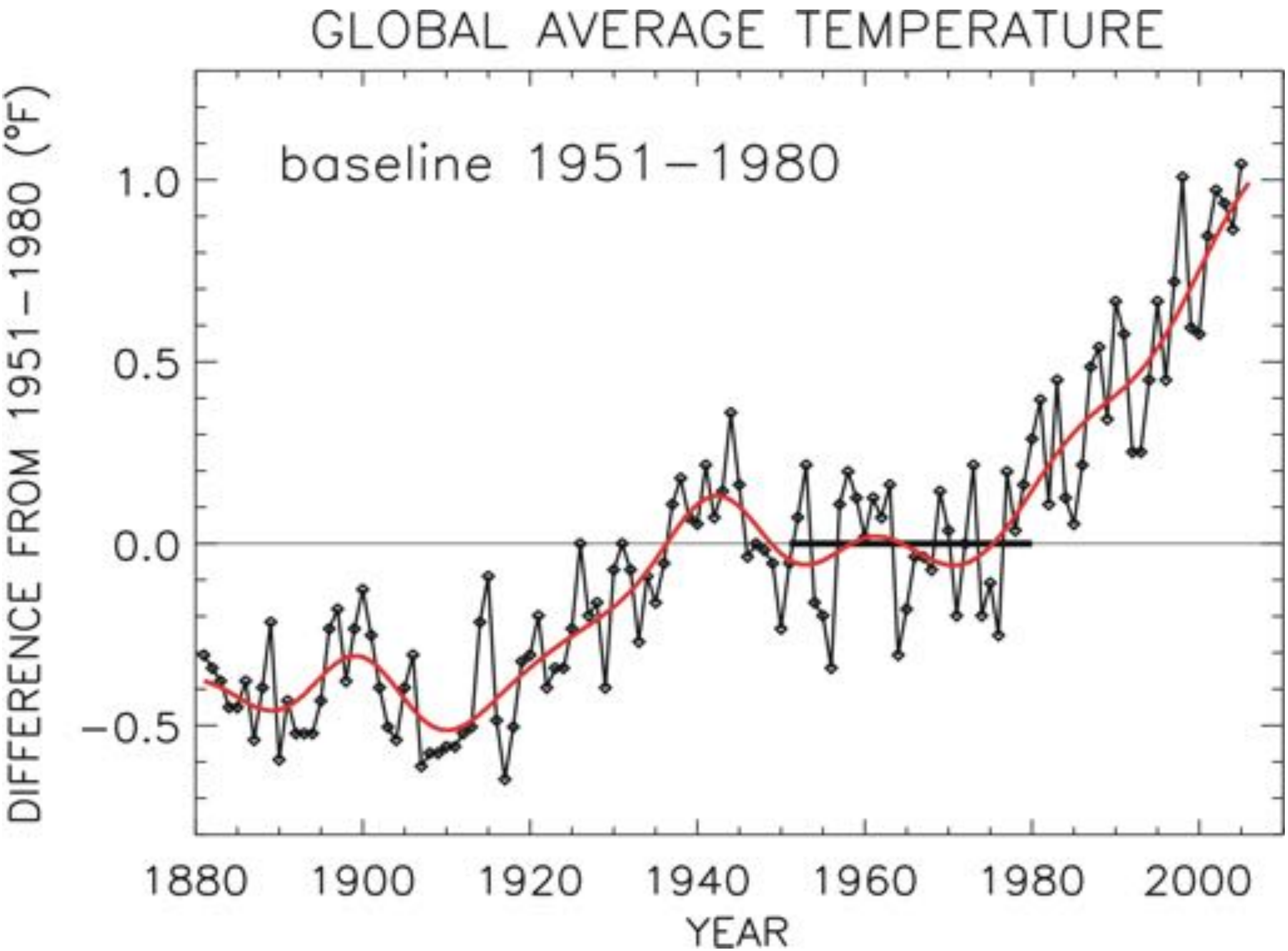


Curchitser

OBSERVED INCREASES IN GREENHOUSE GASES

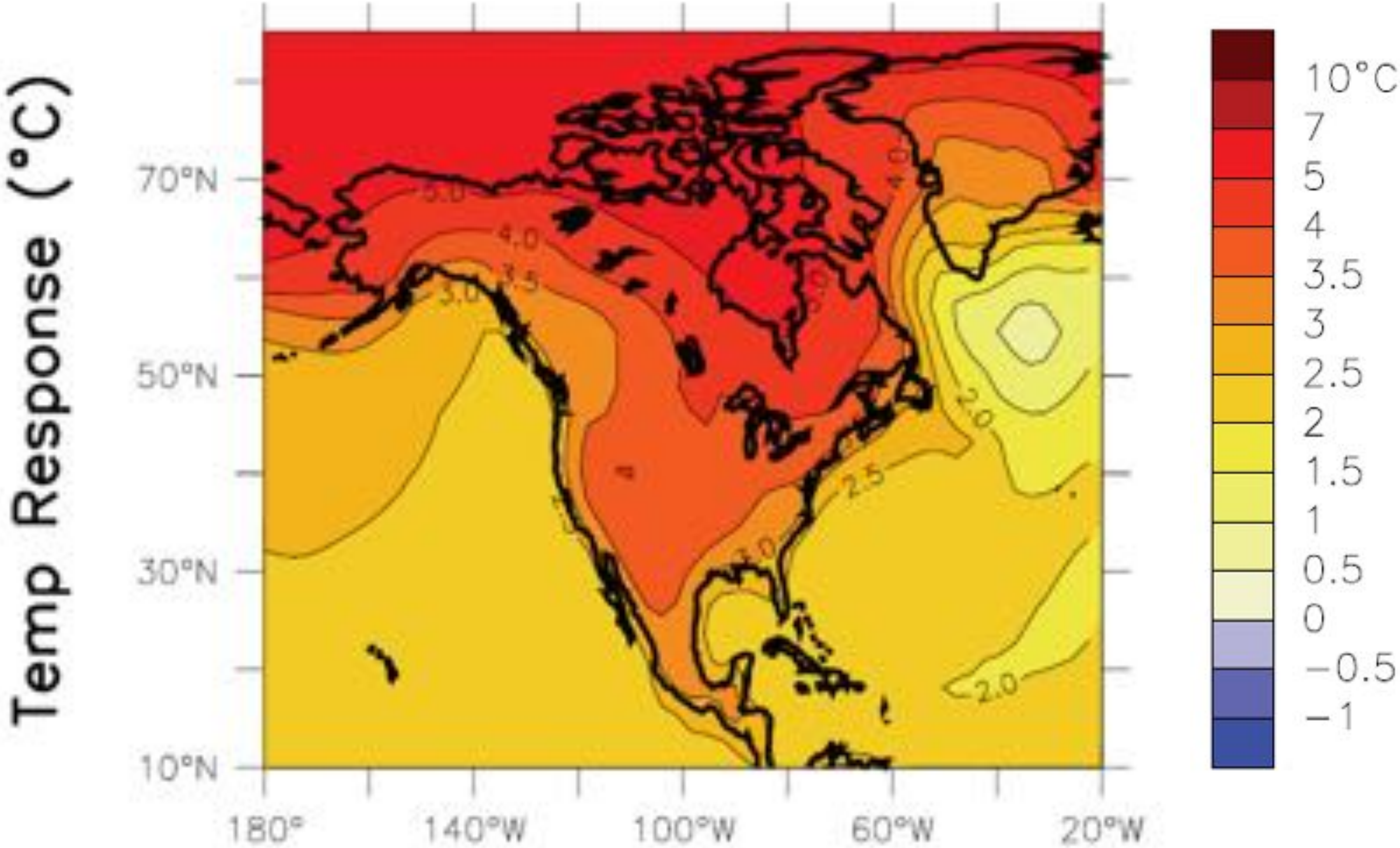


SOME OBSERVED CHANGES IN CLIMATE



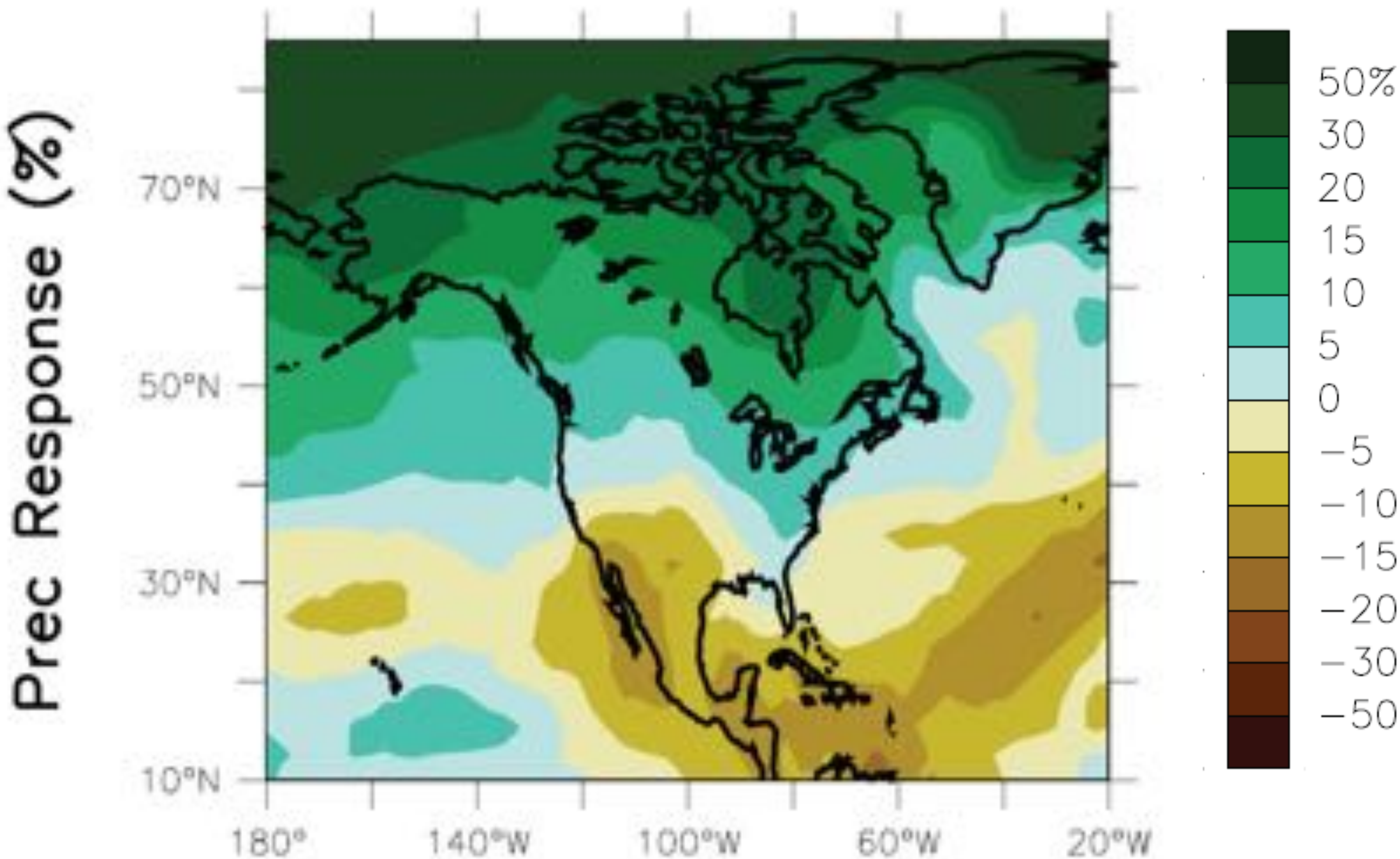
Source: Goddard Inst. Space Studies, NASA

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

What are Climate models?

- Very sophisticated models of the atmosphere, ocean, land, sea ice
  - hundreds of thousands of lines of code
- Systems of differential equations derived from the basic laws of physics and fluid dynamics
- Equations are discretized and solved numerically on a 3-D grid
- At each grid point, the equations for heat, motion (winds, currents), and surface fluxes are calculated
  - Considering each grid volume updating millions of variables (lat, lon, height/depth), multiple variables, every time step (~15 minutes)
- The computations are stepped forward in time from seasons to centuries depending on the study.

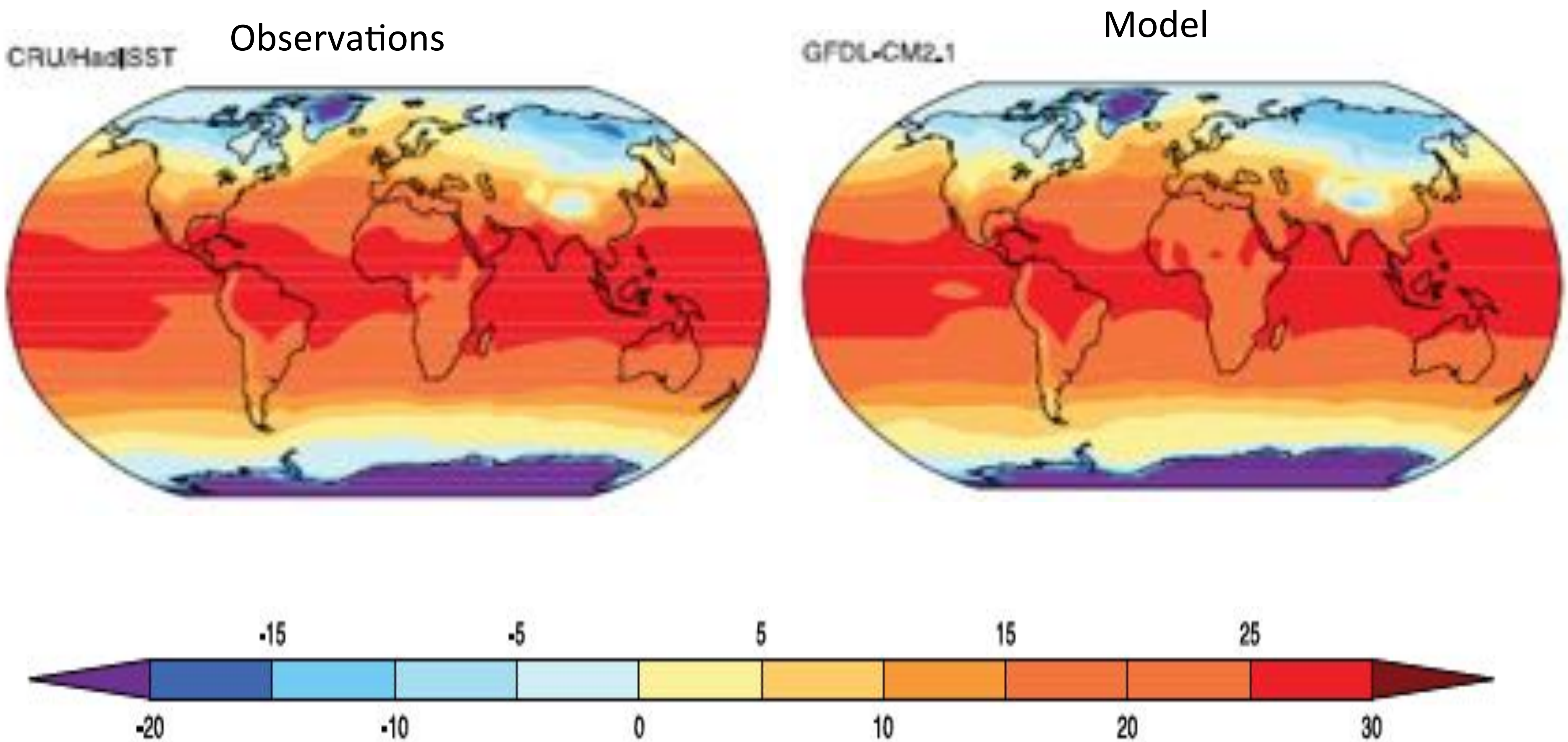
Parameterizations for the Physics

- 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

The Value of Climate Models

- Like a laboratory
  - Conduct experiments that can not be done in the real world
- Generate very long “data sets”
  - E.g. Examine ENSO, decadal varaibility in a 1000-yr simulation
  - or large ensembles (many simulations of the same process) better identify signal-to-noise ratio
- No missing data
- Data are dynamically consistent
  - Can close budgets
- Make forecasts (e.g. predict El Nino events)

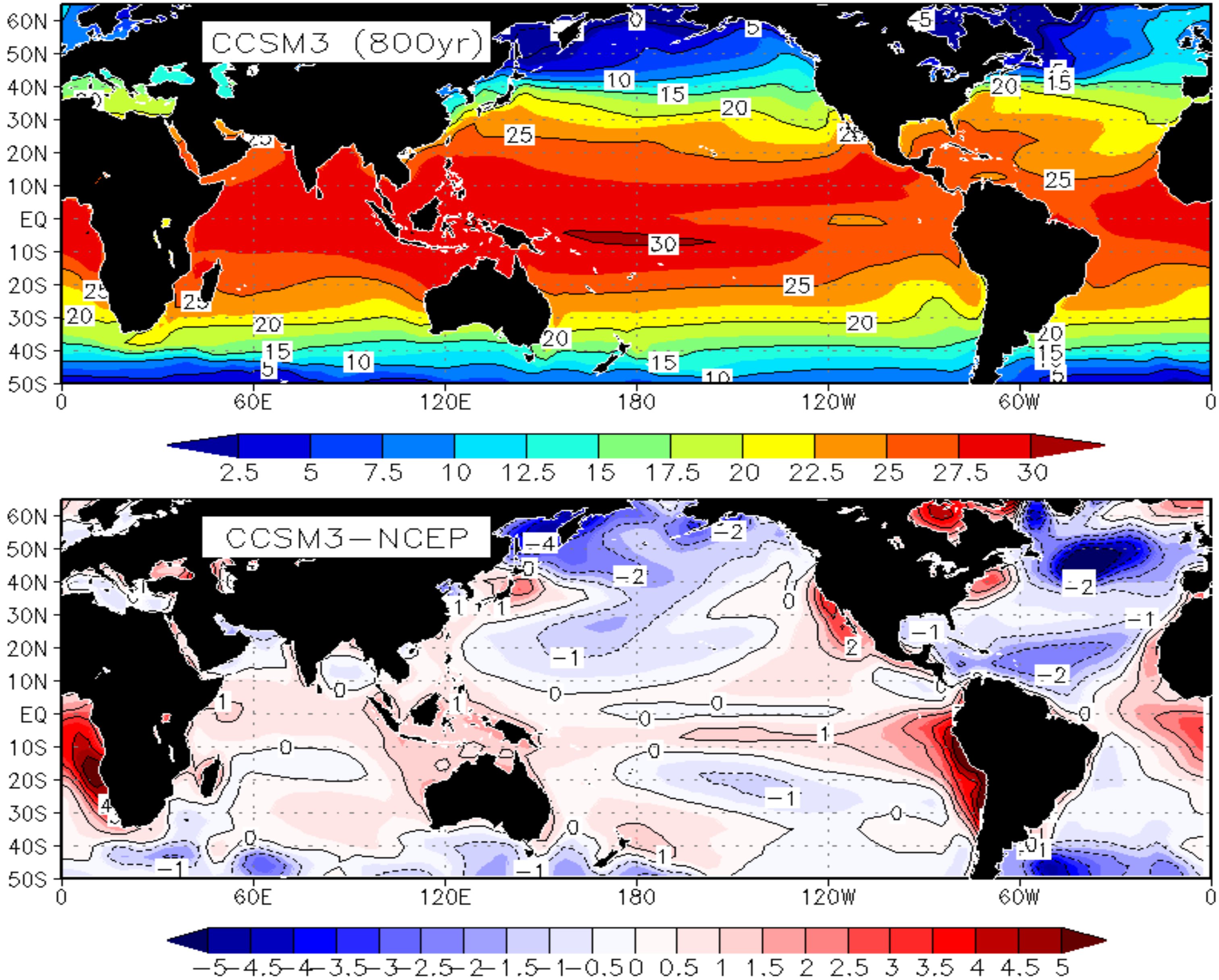
Large-scale distributions of many variables reproduced in climate models



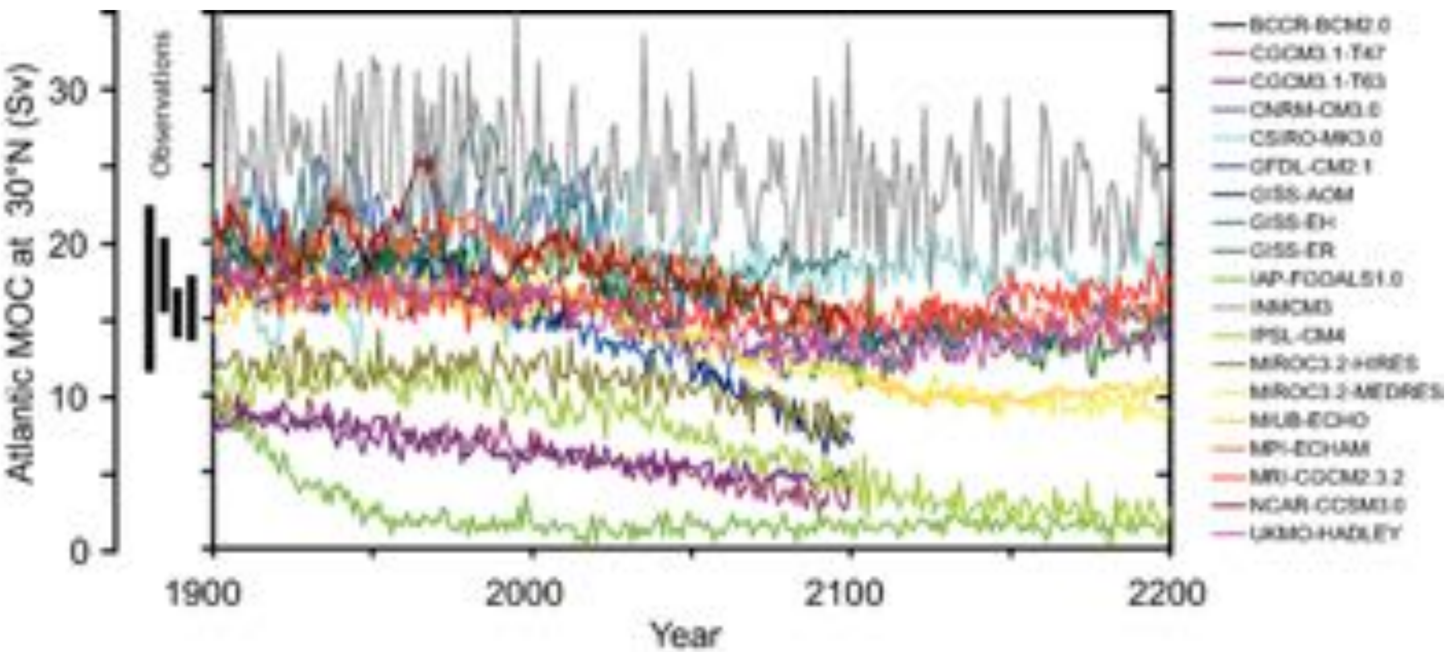
-20 C Surface Air Temperature 30 C

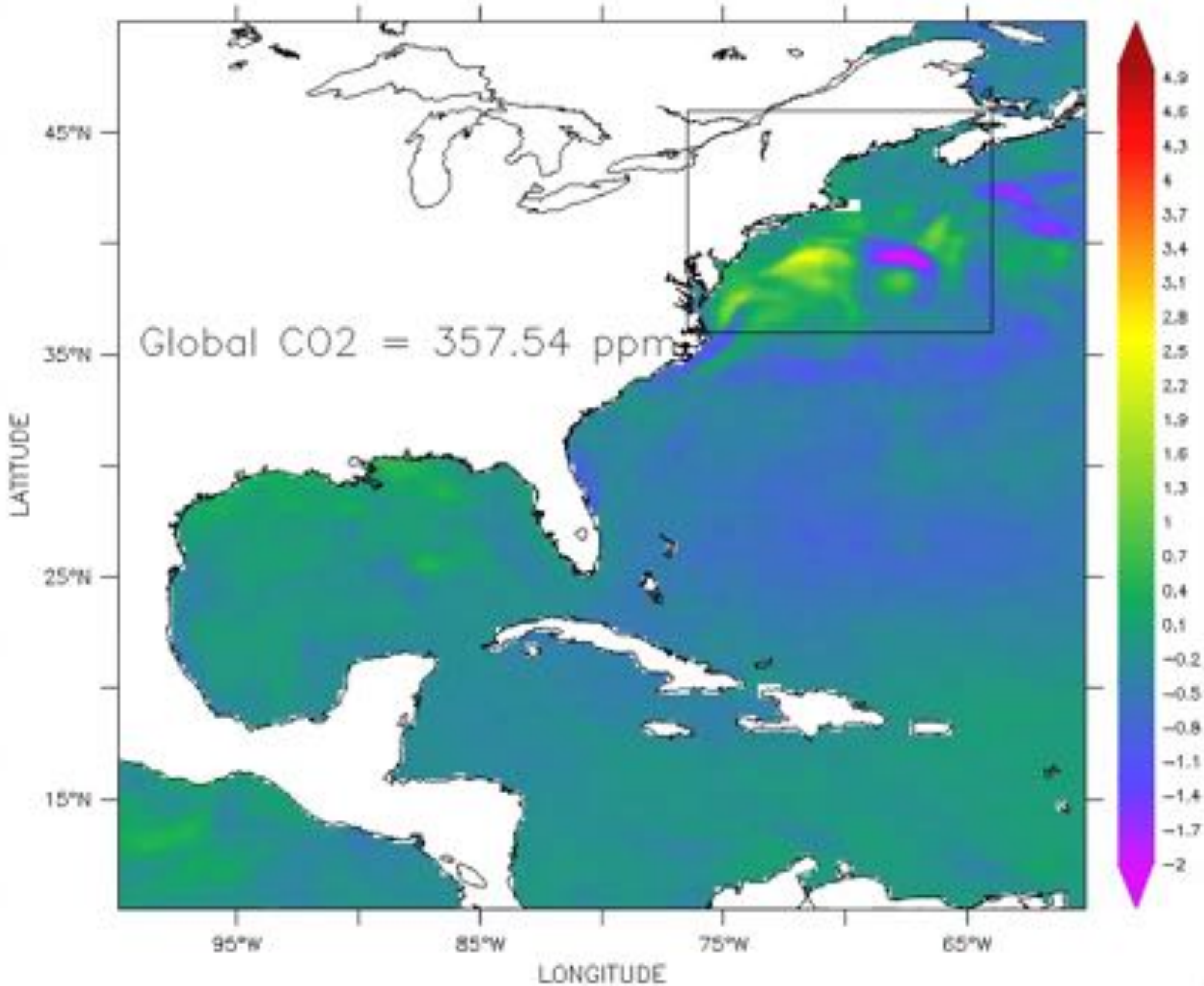
Source: IPCC AR4 WG1 report, chapter 8

Annual Mean SST (ºC)



Climate Change

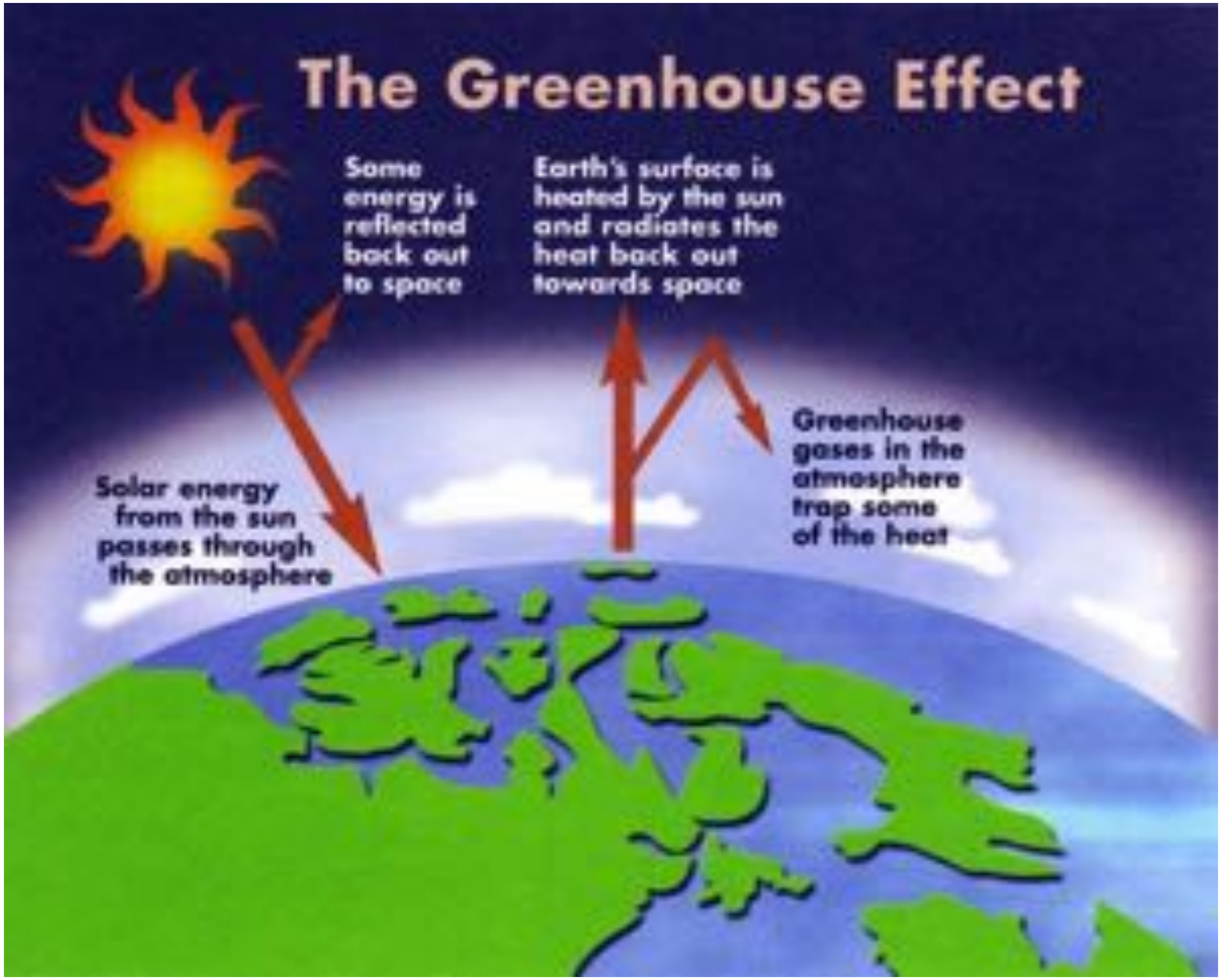

Atlantic MOC at 30°N (Sv)
Observations
0
10
20
30
1900
2000
2100
2200
Year
BCCR-BCM2.0
CGCM3.1-T47
CGCM3.1-T63
CNRM-CM3.0
CSIRO-MK3.0
GFDL-CM2.1
GISS-AOM
GISS-EH
GISS-ER
IAP-FGOALS1.0
INMCM3
IPSL-CM4
MIROC3.2-HIRES
MIROC3.2-MEDRES
MIUB-ECHO
MPI-ECHAM
MRI-CGCM2.3.2
NCAR-CCSM3.0
UKMO-HADLEY



High-resolution, global climate model projection of annual SST change under a 1% per year increase in global atmospheric carbon dioxide (CO_2). CO_2 levels begin with 1990 observations and then increase by 1% per year for 70 years until CO_2 doubles and then stabilizes for an additional 70 years. This projection is from NOAA GFDL's CM 2.5 [Delworth et al. (2012); average ocean resolution = 25 km x 25 km]. Color scale units are in degrees Celsius.

Greenhouse Effect: Natural + Human

Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties alter the energy balance of the climate system.

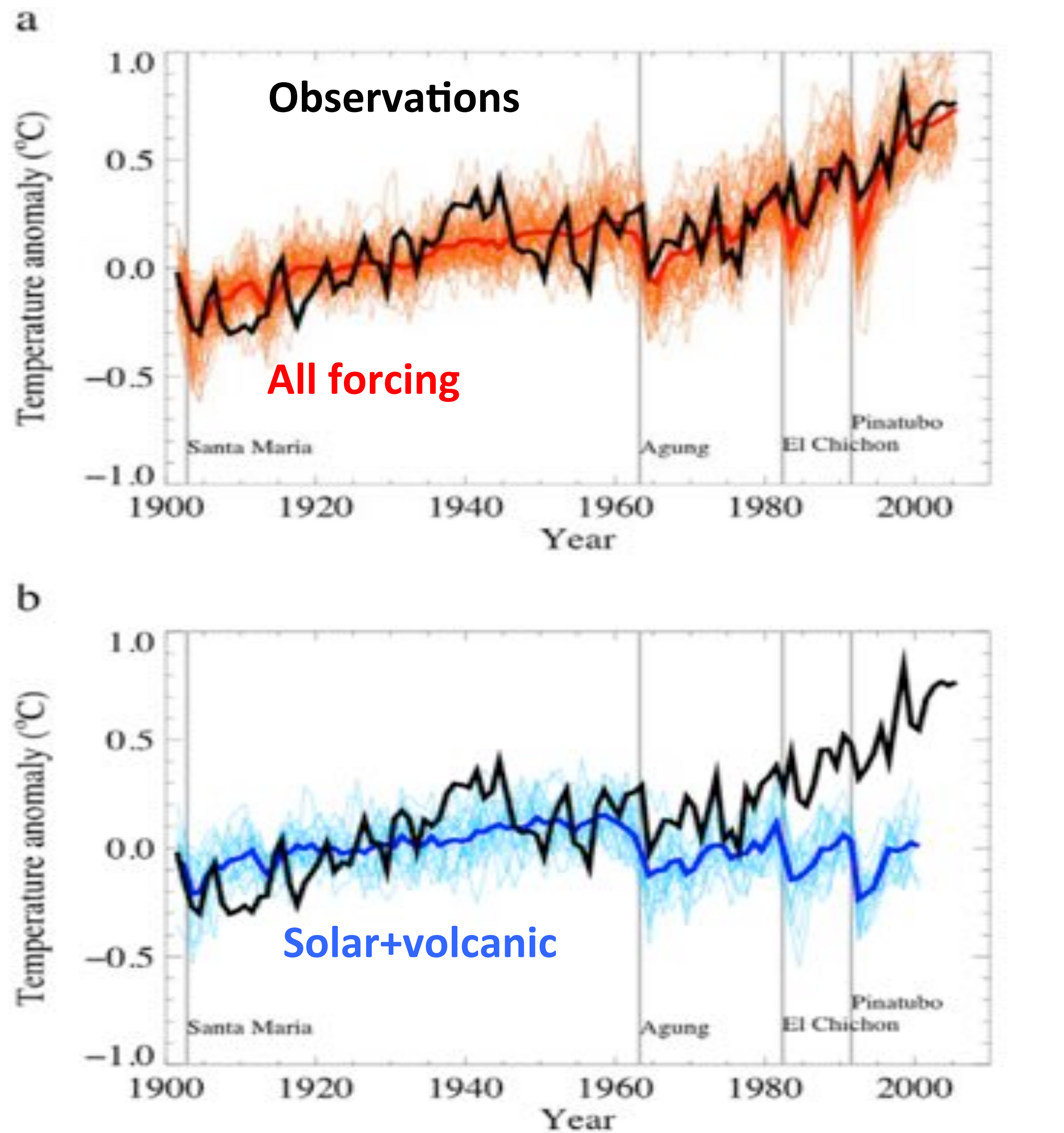


Greenhouse gases include carbon dioxide (CO_2), water vapor, ozone, methane

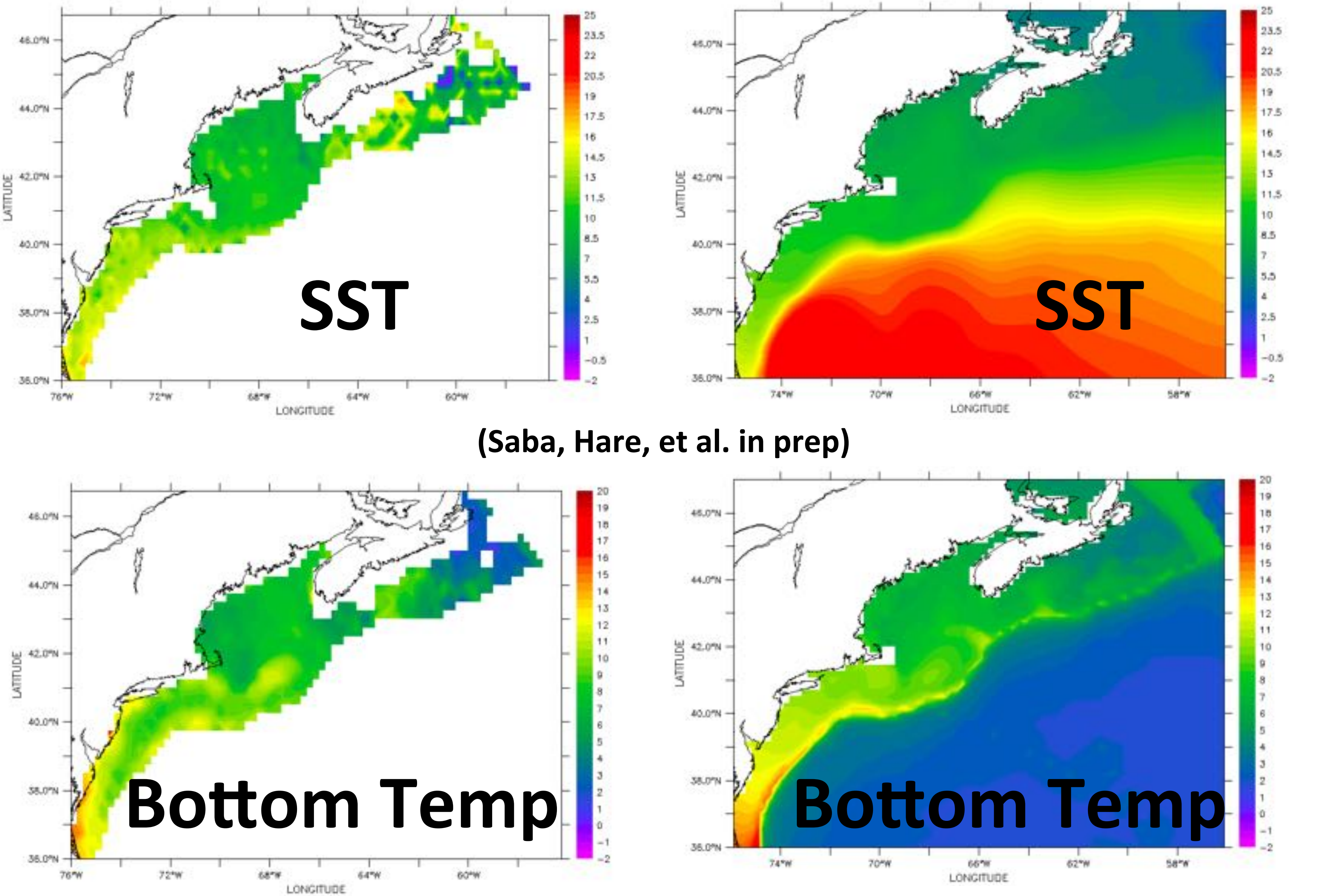
Climate Change in the 20th Century

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

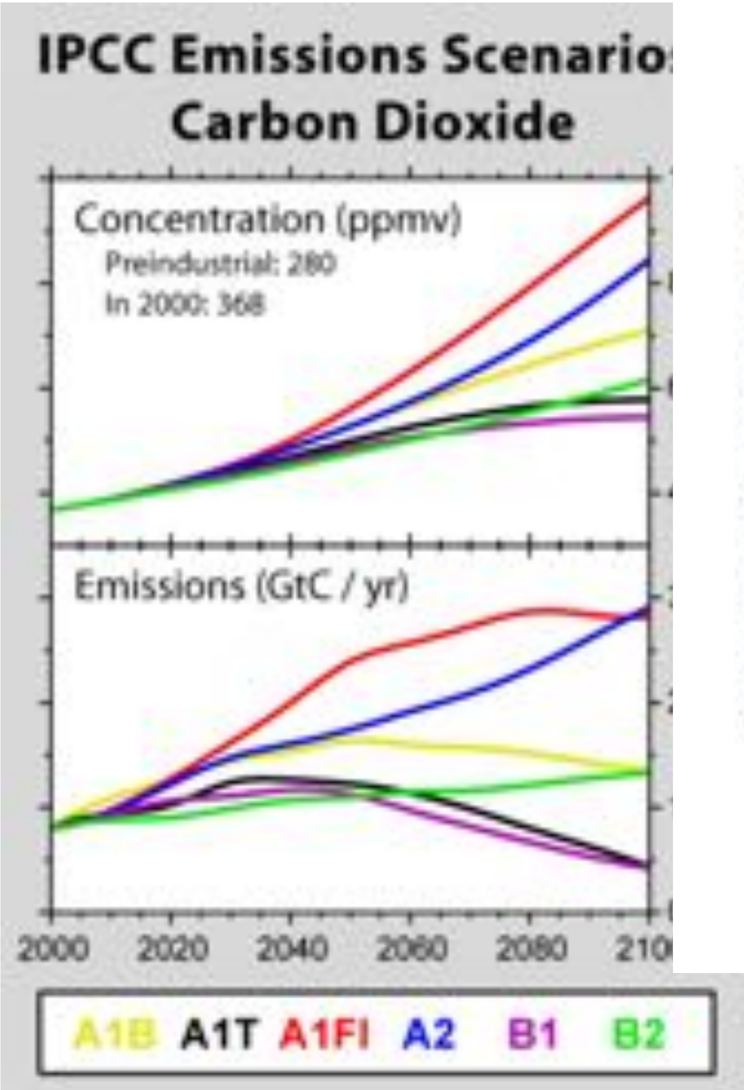
- ***Very unlikely* due to known natural causes alone**



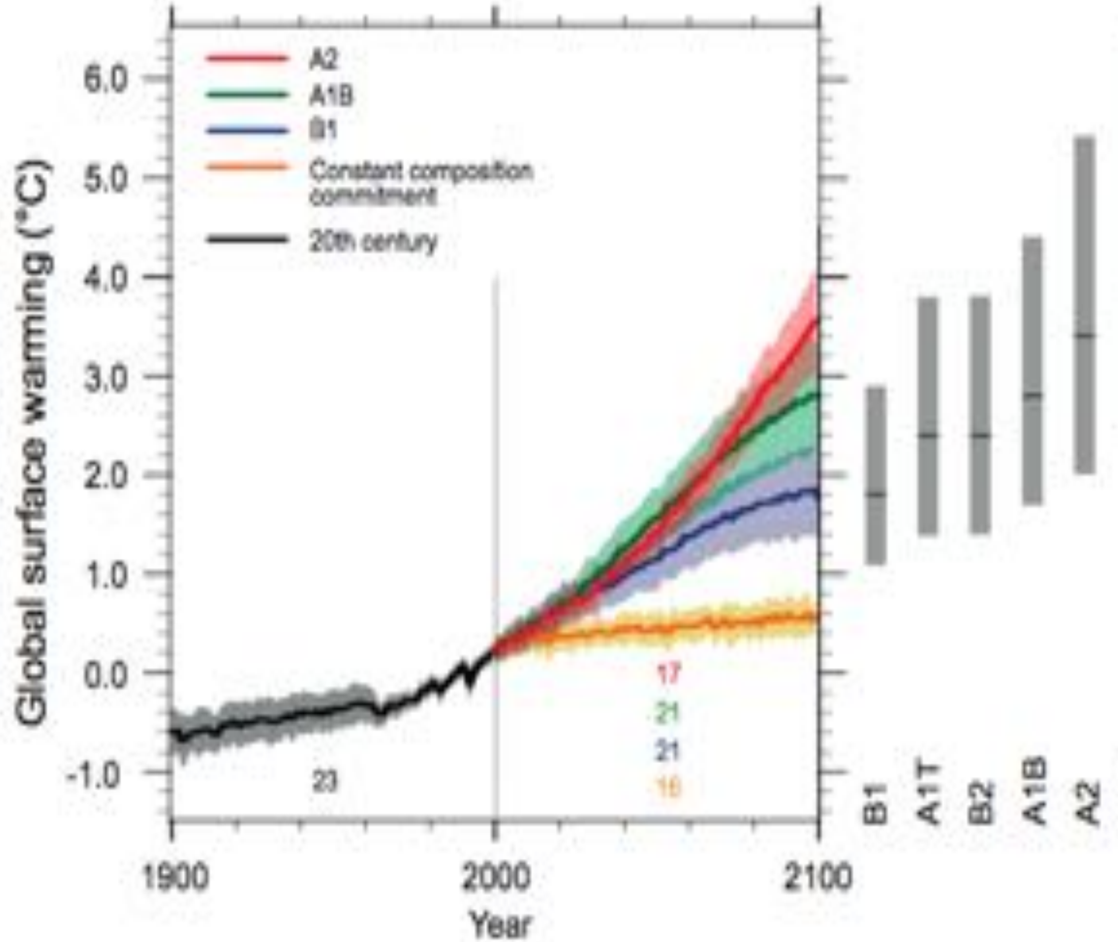
NES Annual Climatology 1977-2009 | **GFDL CM2.5 1990 Control Run**



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



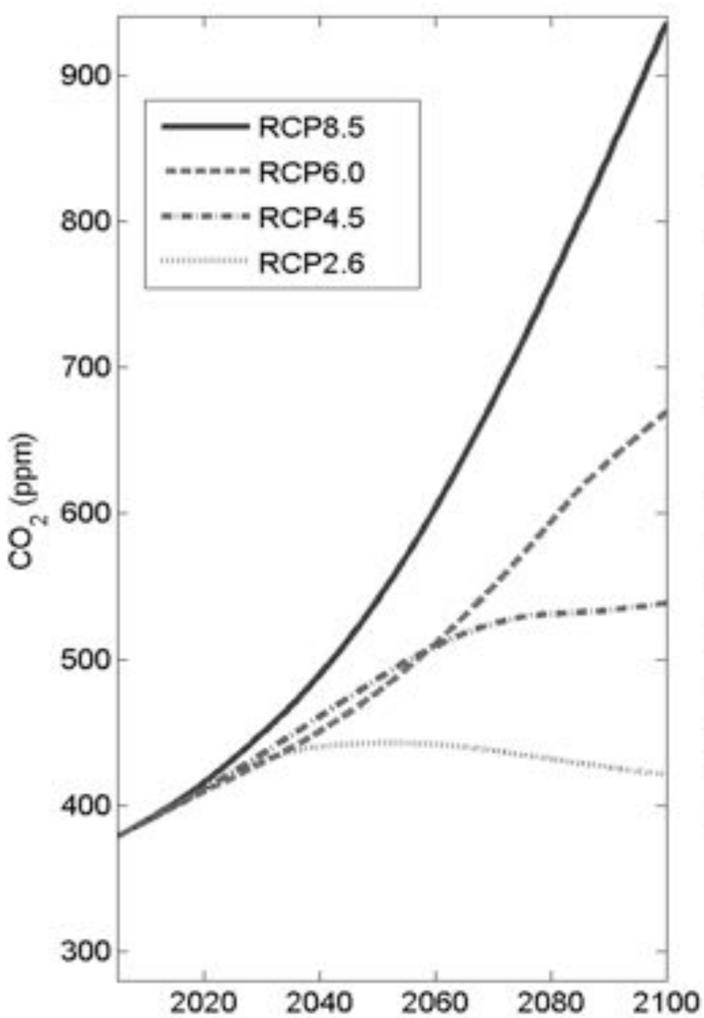
Temperature

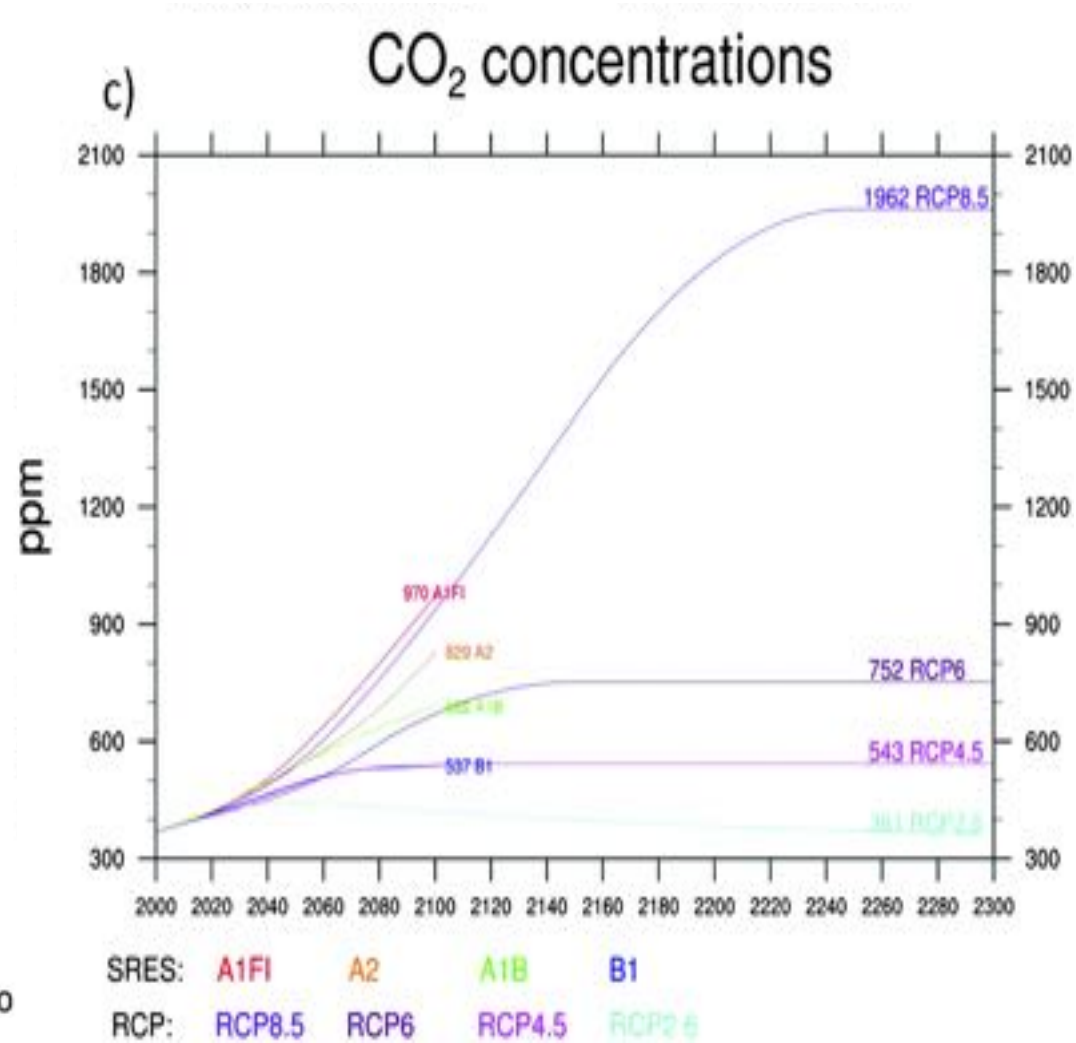


Special Report on
Emissions Scenarios (SRES)

IPCC (AR5) Scenarios (Different)

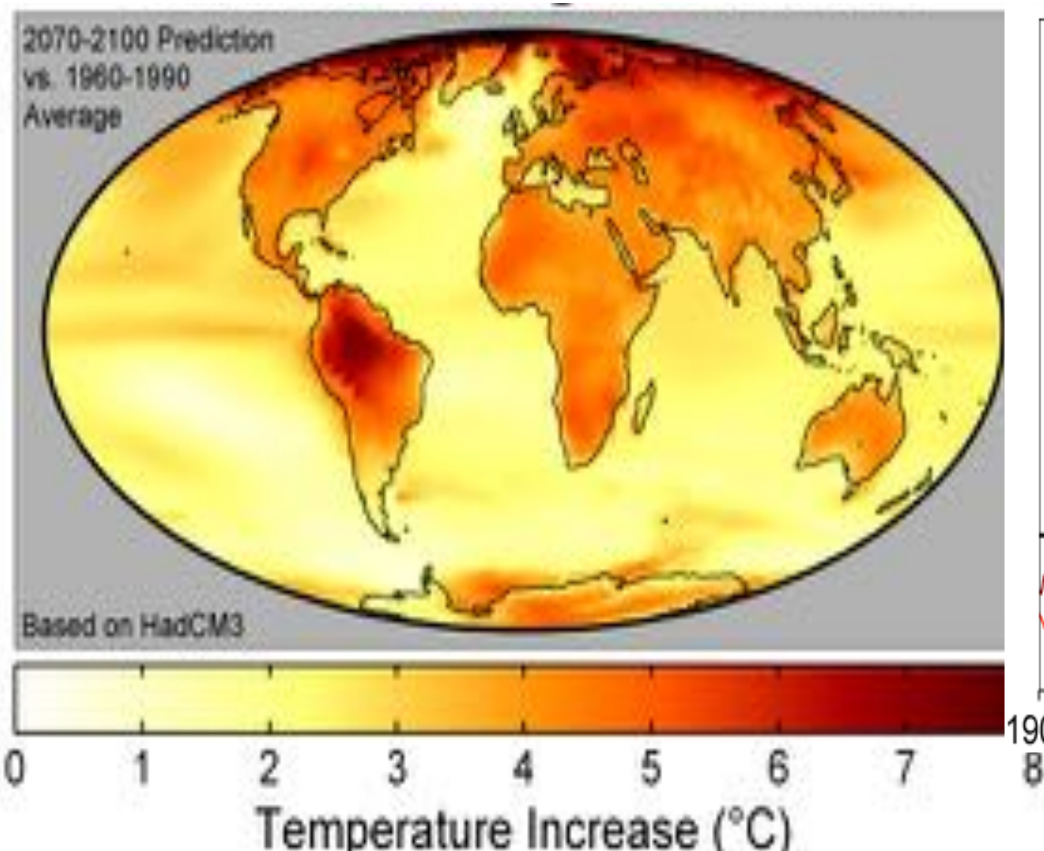
Carbon Dioxide Concentration

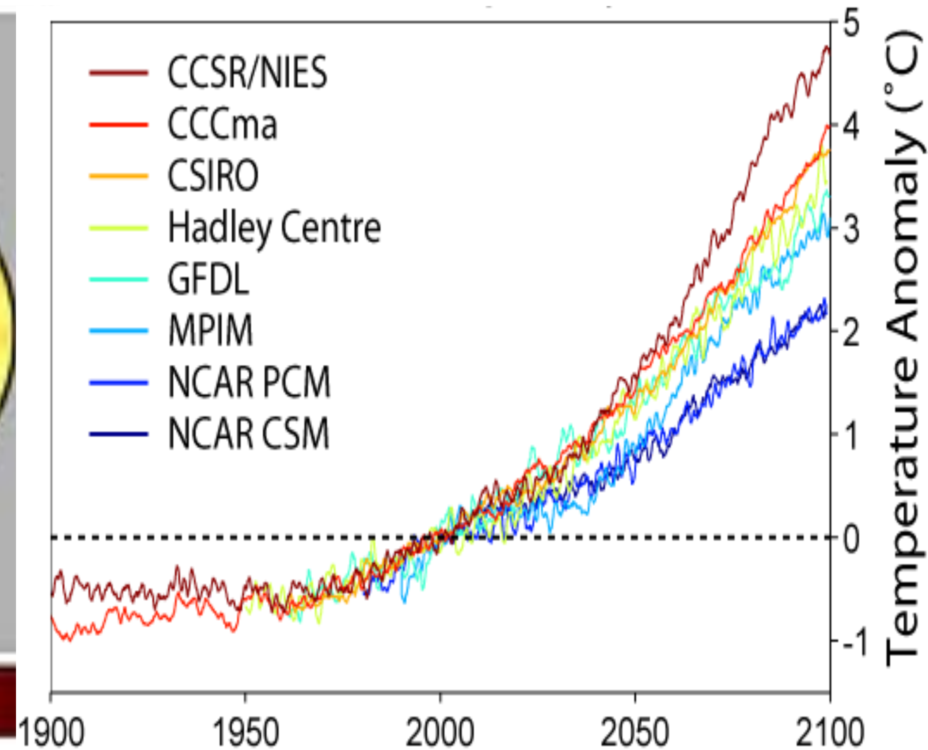




RCP – Radiation Concentration Pathway

Global Warming Projections From different Models





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

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

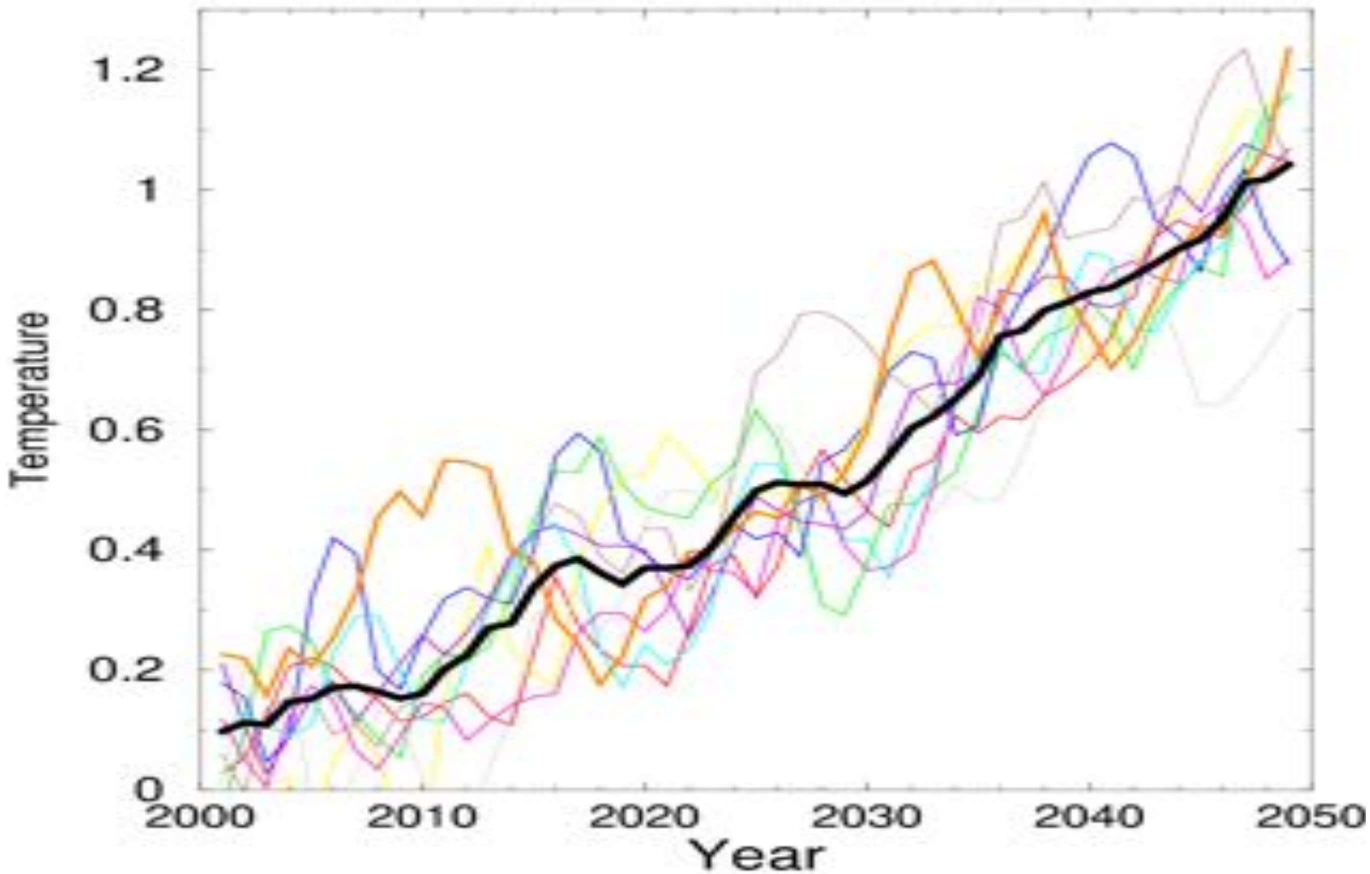
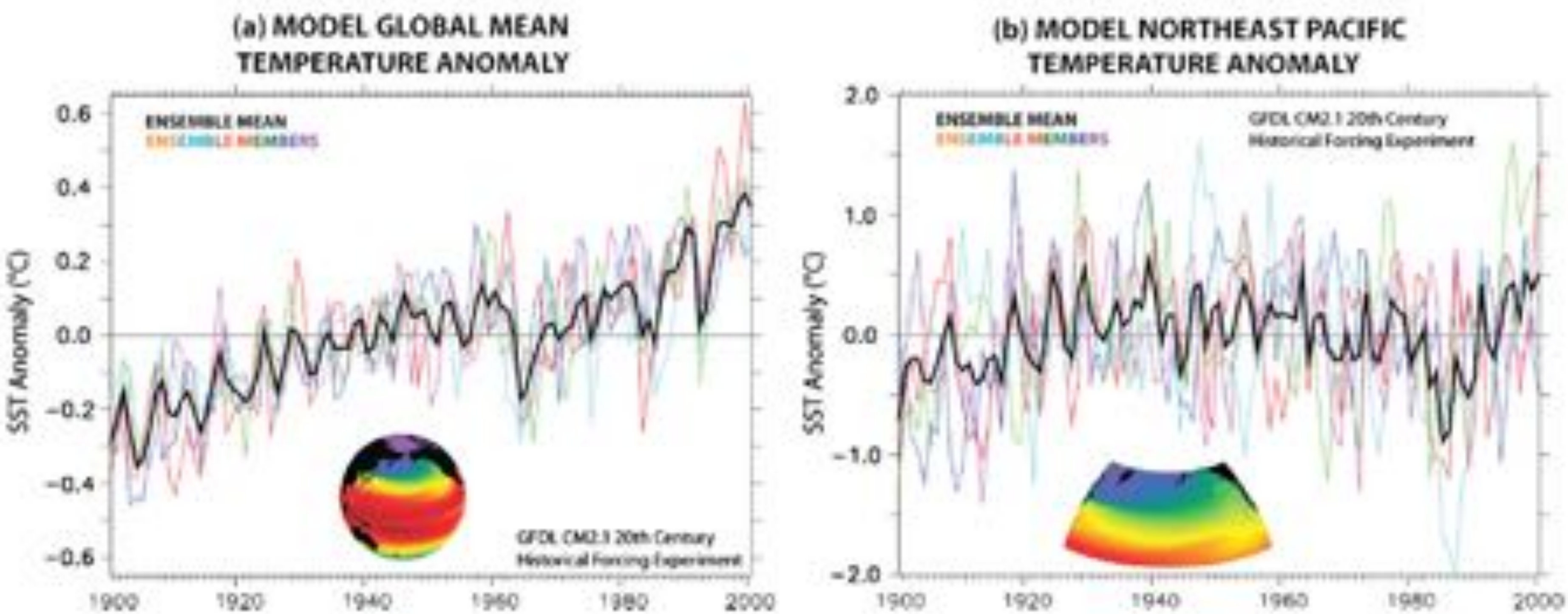


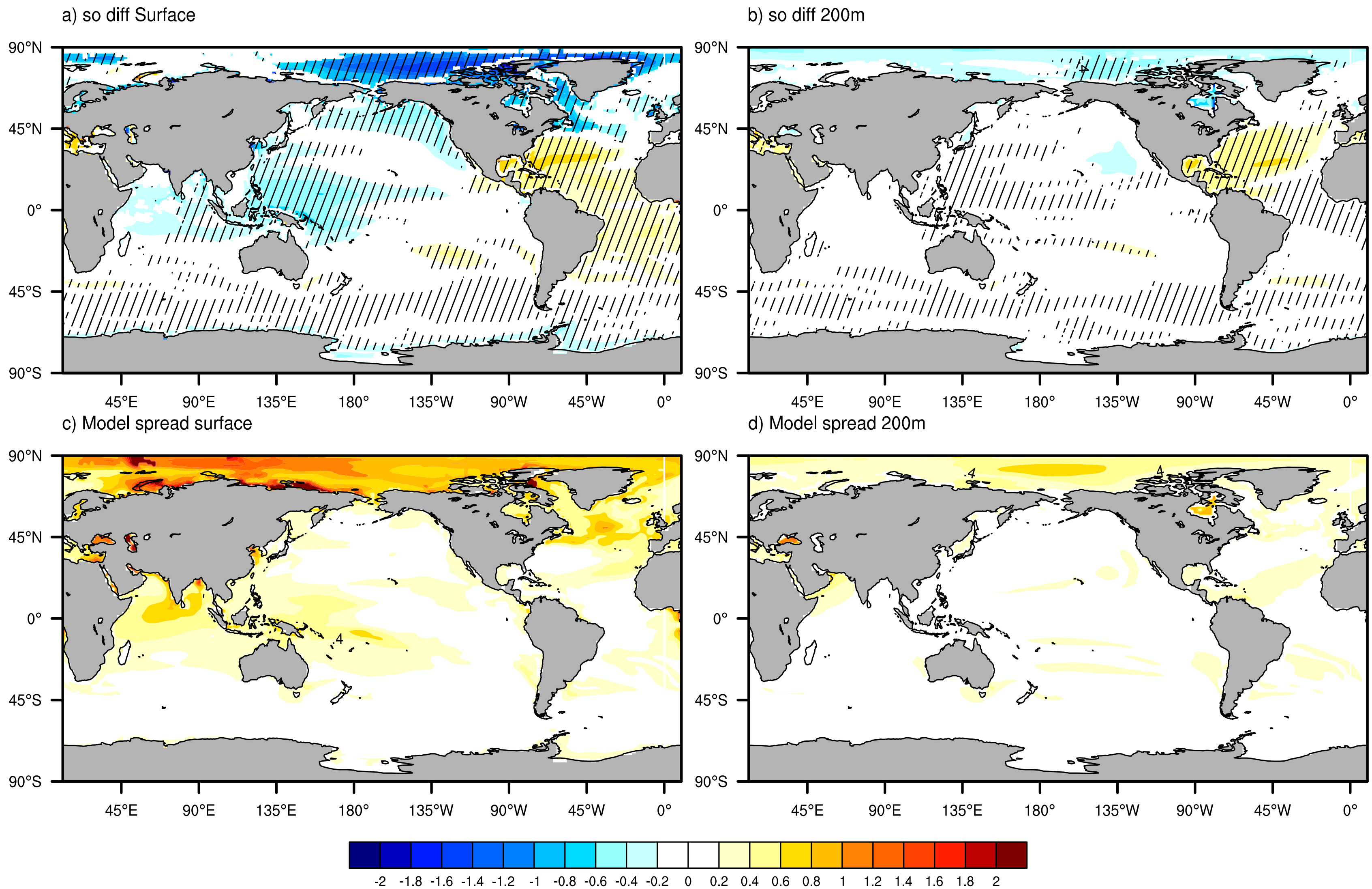
Figure courtesy of Tom Delworth/GFDL Climate Change Variability and Prediction Group

Variability is generally more prominent at regional scales



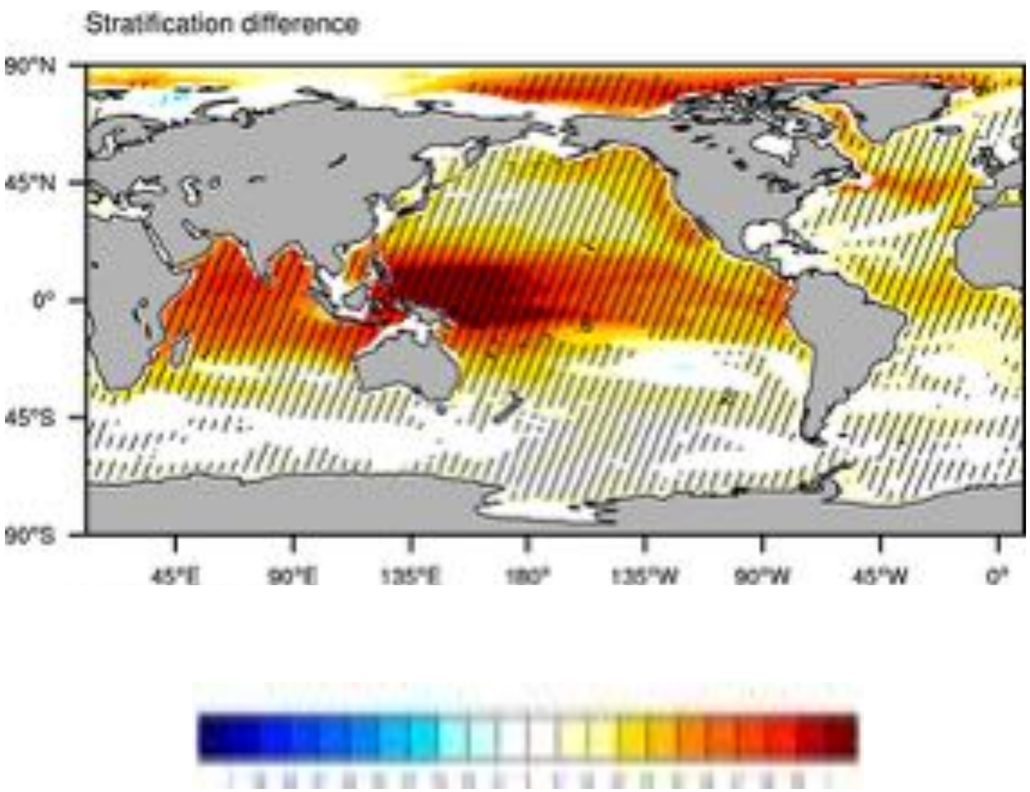
Stock et al., 2011, Prog. Oceanogr. 88, 1-27

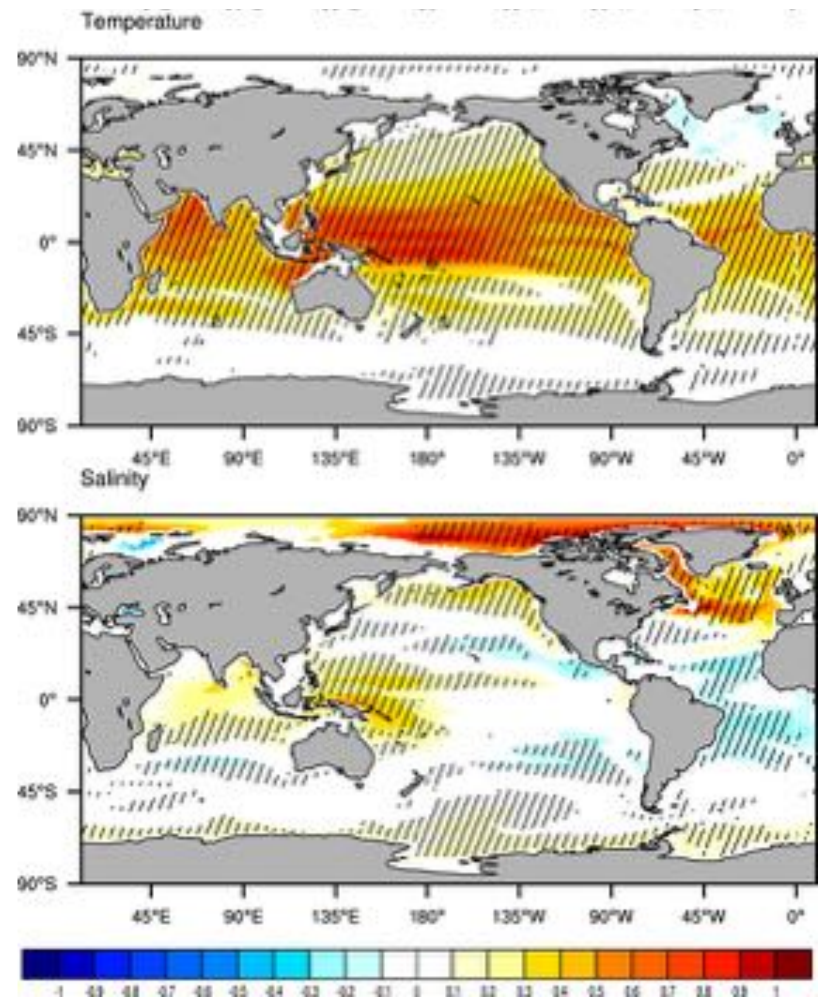
2051-2100 – 1951-2000 0 & 200 m ocean Salinity from A2 simulations



Capotondi et al. 2012 JGR

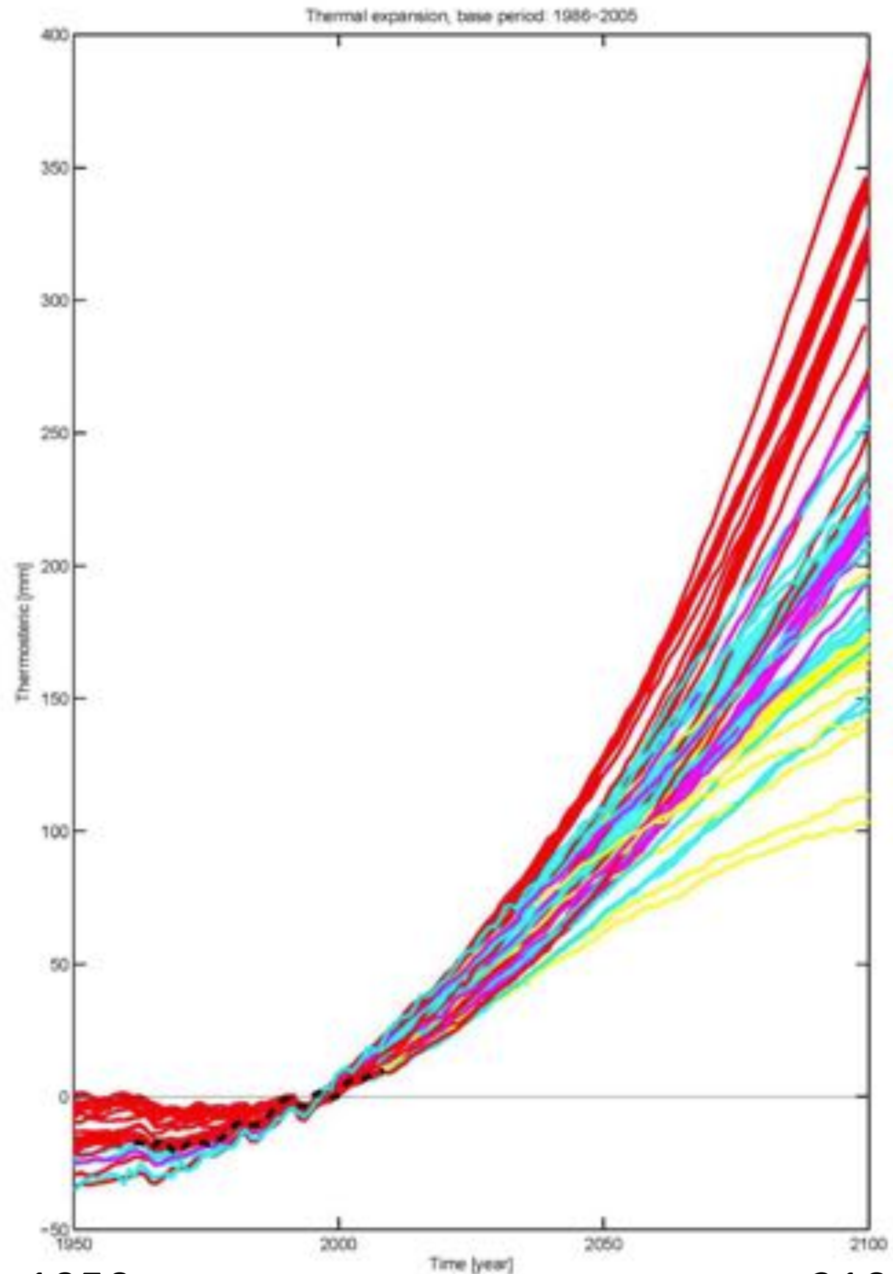
2051-2100 – 1951-2000 Stratification
Δ density 200m – density at 5m





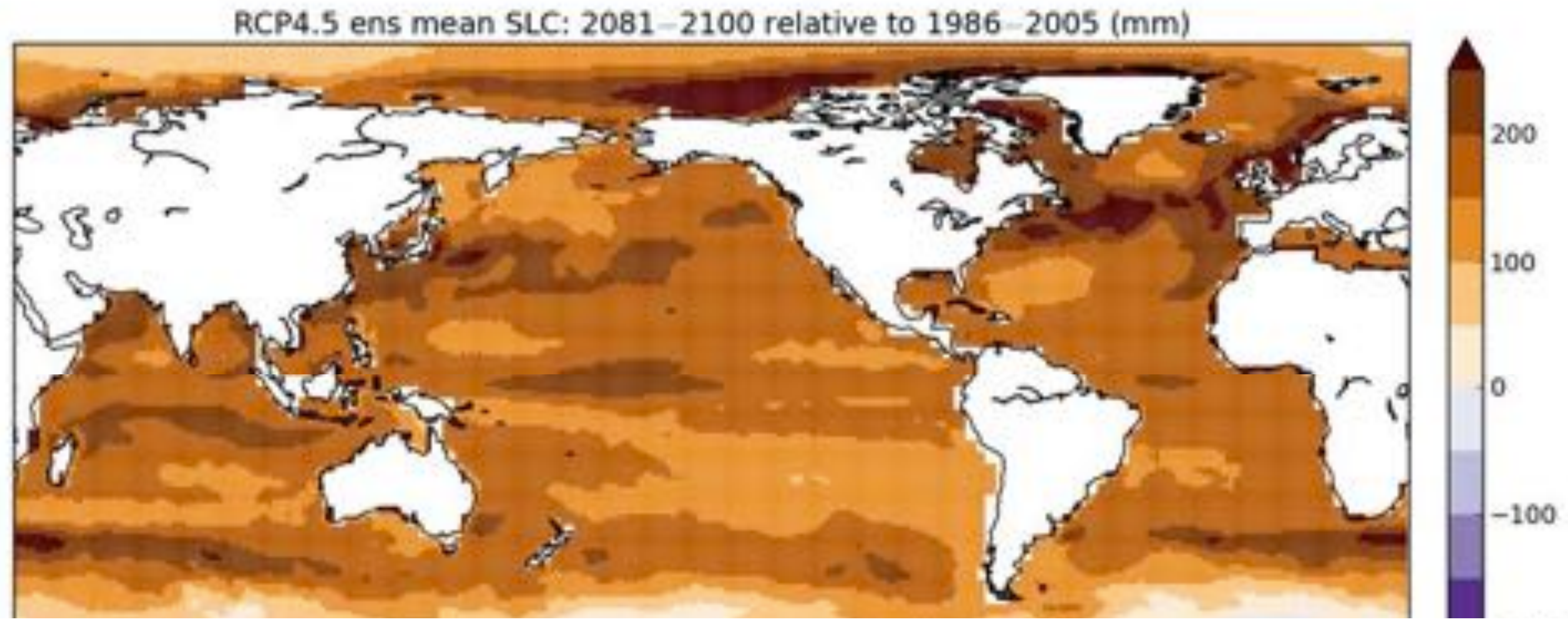
Capotondi et al. 2012, JGR- Oceans

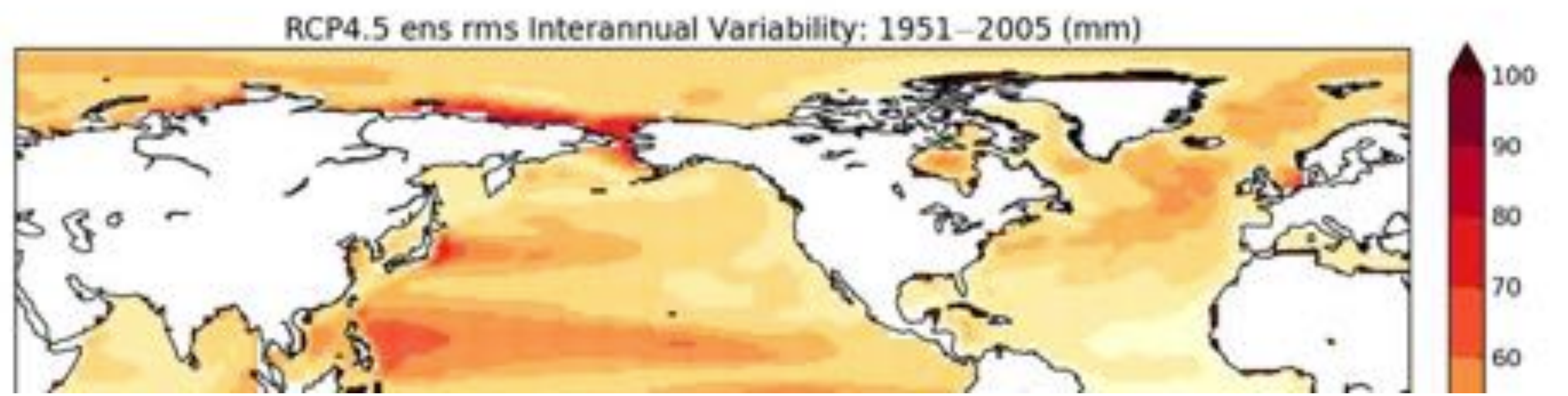
Observed & Projected Global Sea Level change (thermal expansion) AR5



1950 2100

Sea Level Change (mm)





Summary and Outlook

- 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, although may exclude models if bias influences sensitivity (e.g. sea ice in wrong place)
- 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
- Some of the differences between climate models based on single or a small number realization may actually be due to natural variability

Summary of response to greenhouse

- North Atlantic
  - SST will warm (not as much as land)
  - Surface-intensified ocean warming
    - Increased stratification in most areas
  - Enhanced Salinity in subtropics
  - Global Sea-level height will rise
    - Less clear about regional changes but maybe greater along the northeast US coast.
    - as of now model only see thermal/salinity effect

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

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

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:

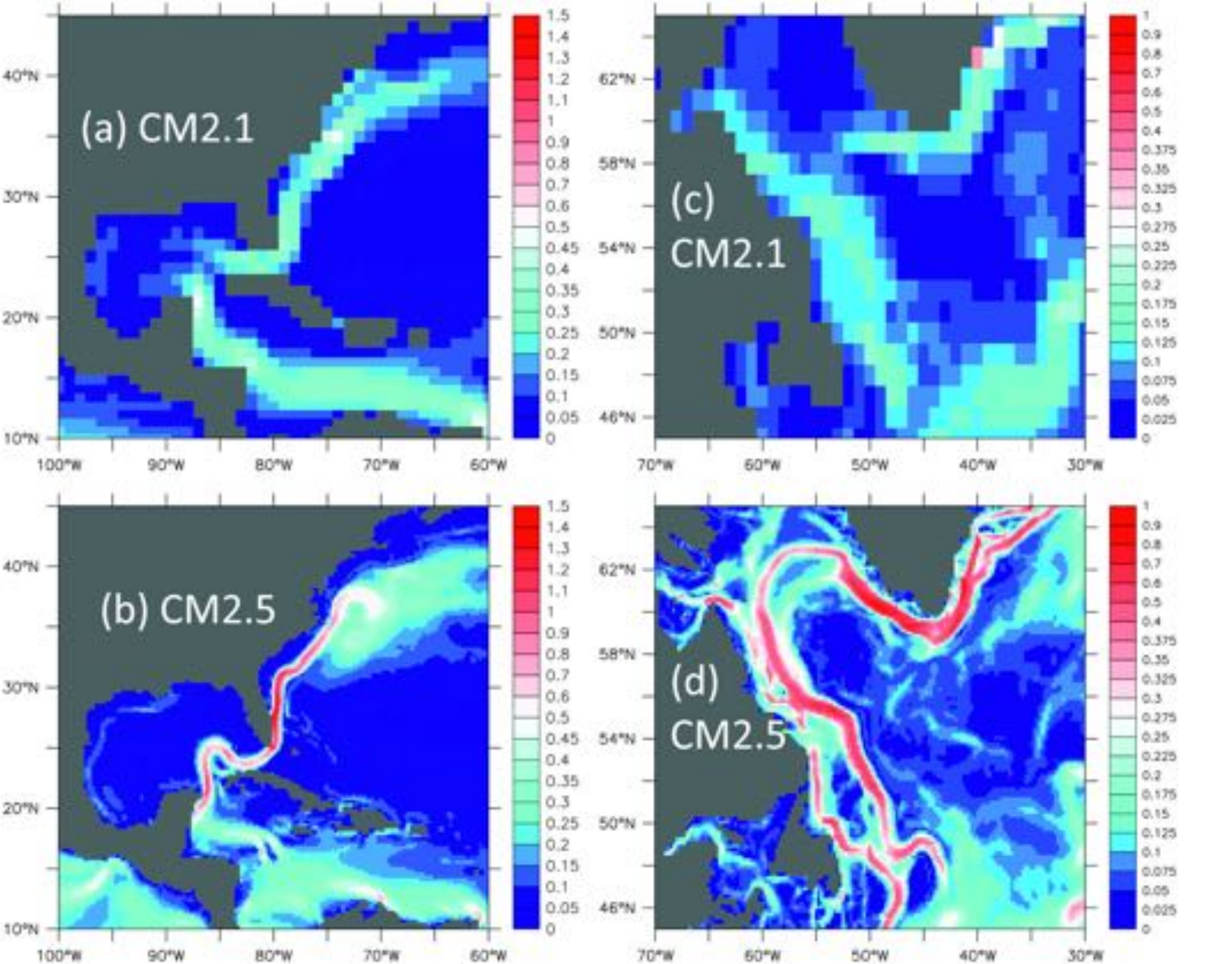
- Examine internal variability by using more than one run, i.e. an ensemble of simulations
- Nearly all climate change studies have used one or a very small number of ensemble members

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
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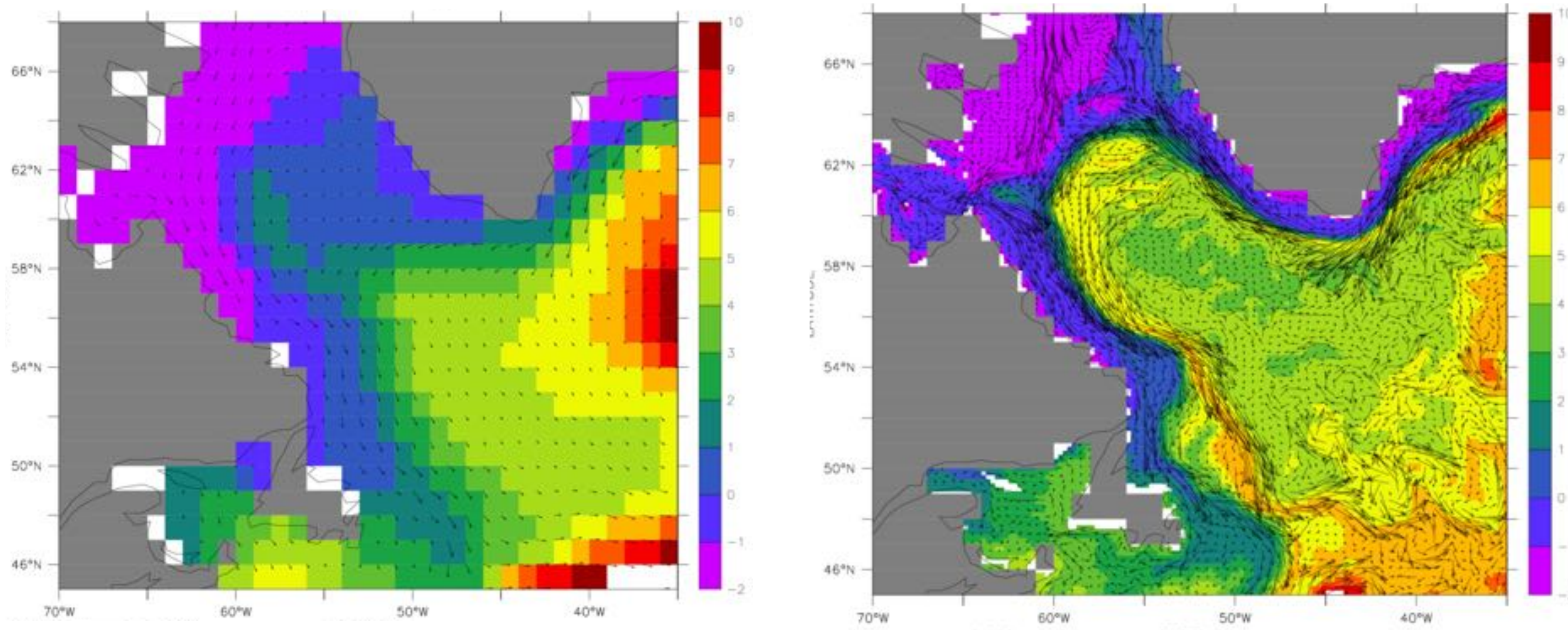
Refined resolution Climate models

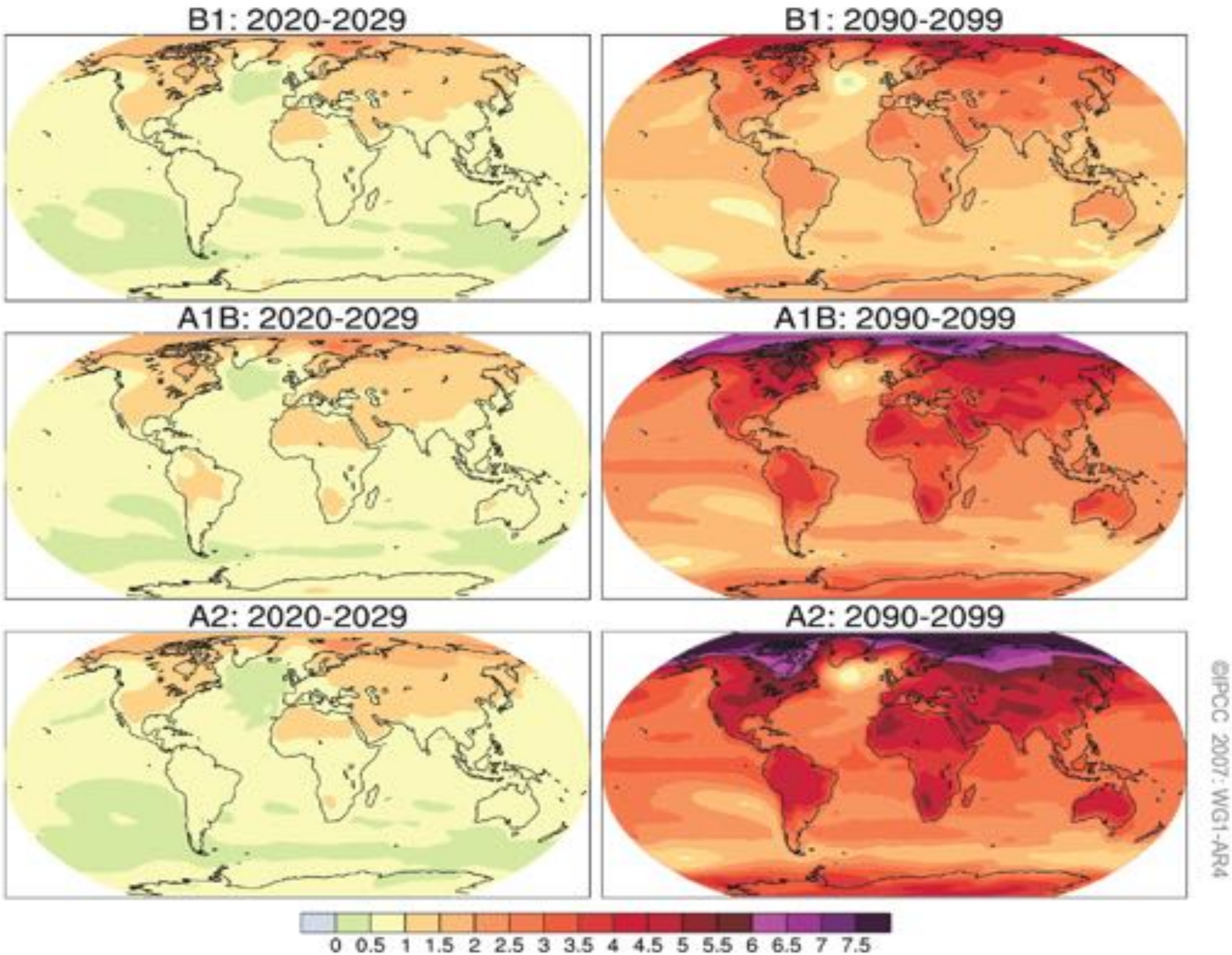


It is becoming increasingly feasible to run long time-scale climate simulations at resolutions ~0.25 deg. In the ocean or higher

Climate variability in century-scale physical climate models

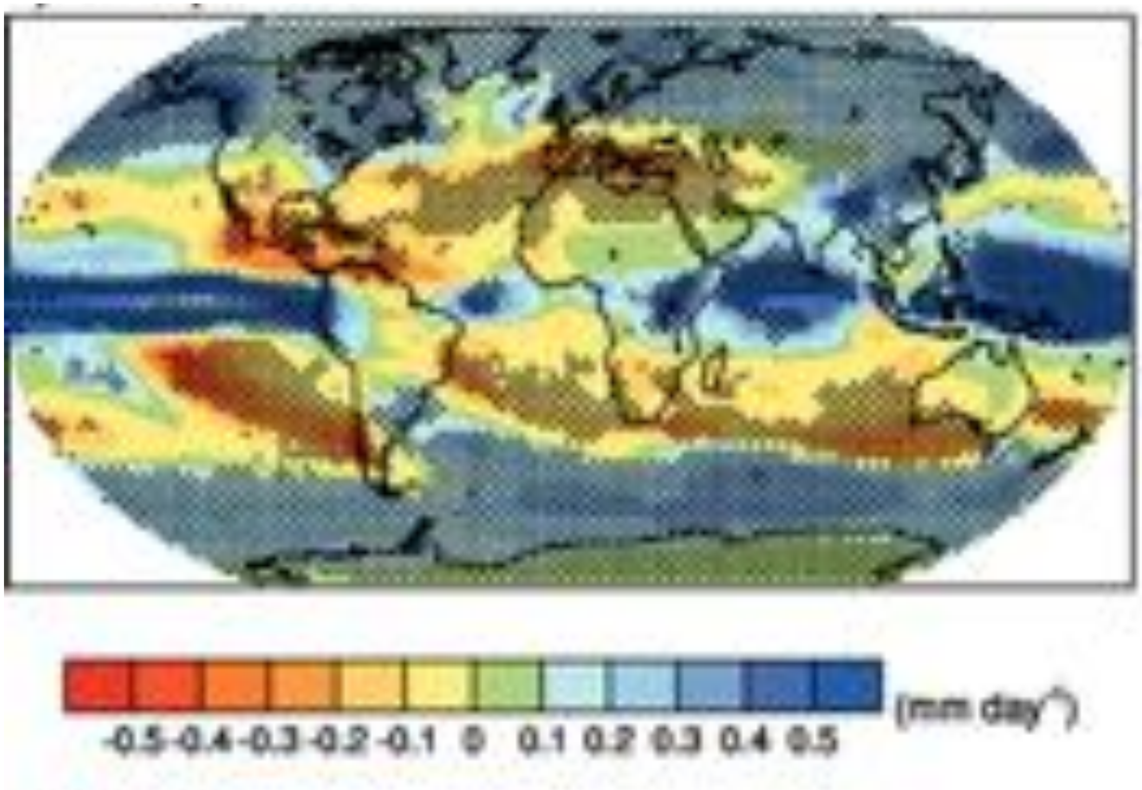
- Many climate models produce realistic representations of prominent modes of climate variability
- Can use climate change projections to study climate variability, but don't expect to be "in phase" with observed variability
- Ensemble means and focusing on differences between multi-decadal averages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

Projections of Future Temperatures



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

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



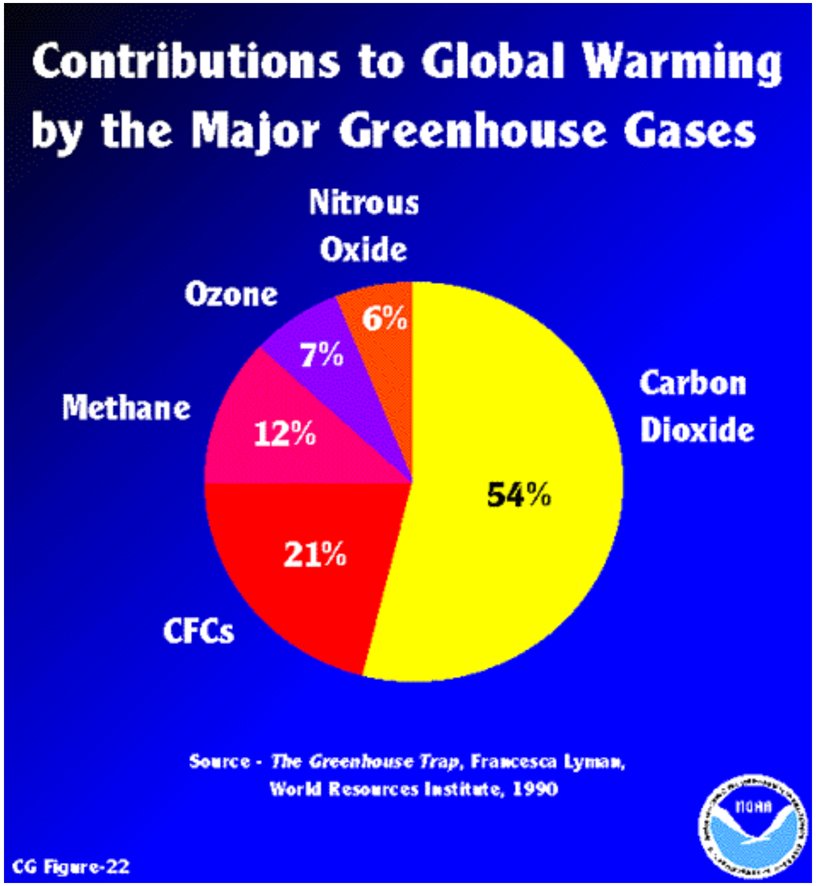
Stippling in places where at least 80% of models agree on sign of change

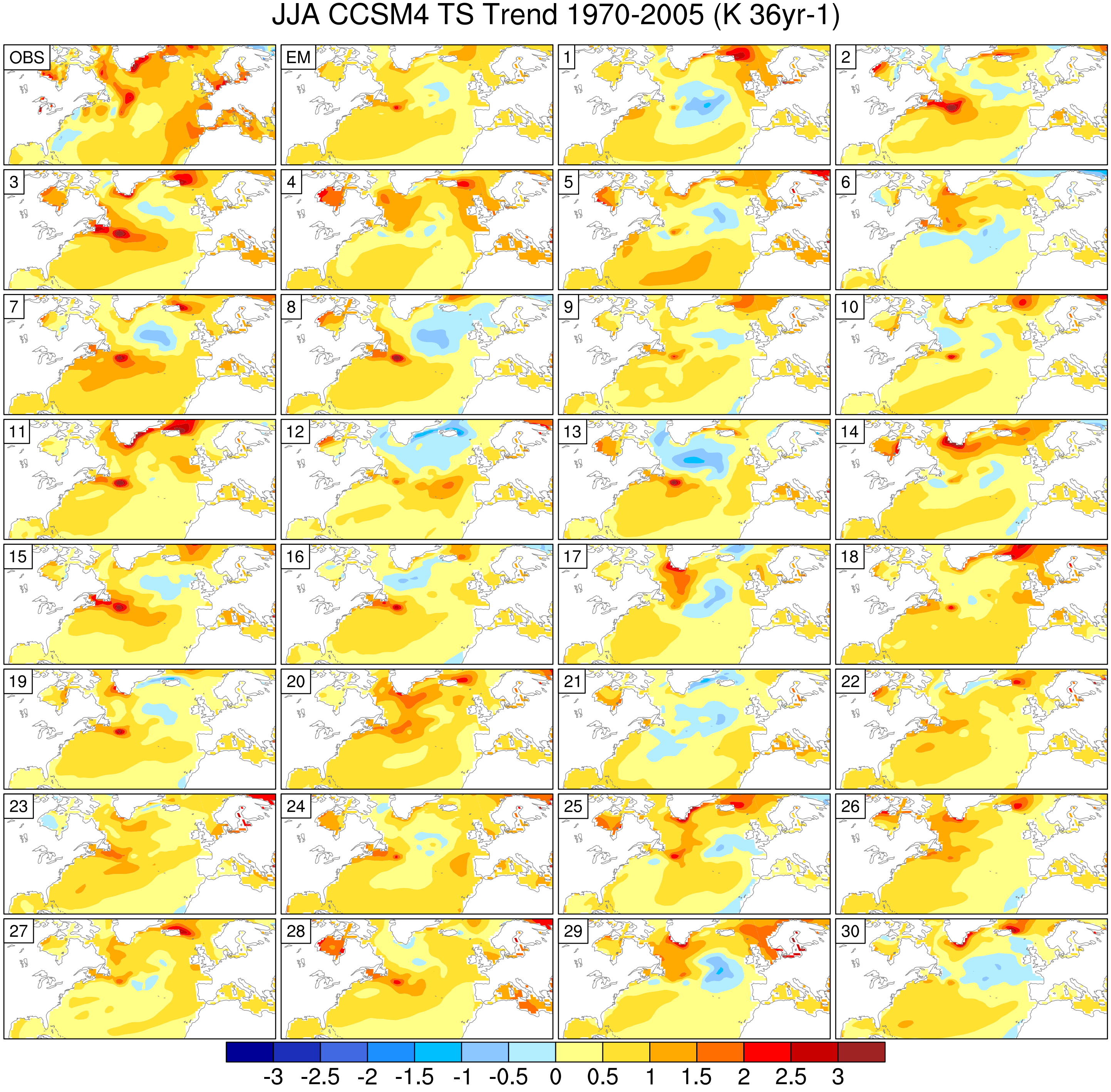
Meehl et al., Chapter 10, IPCC AR4 WG1 Report

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.




JJA CCSM4 TS Trend 1970-2005 (K 36yr-1)
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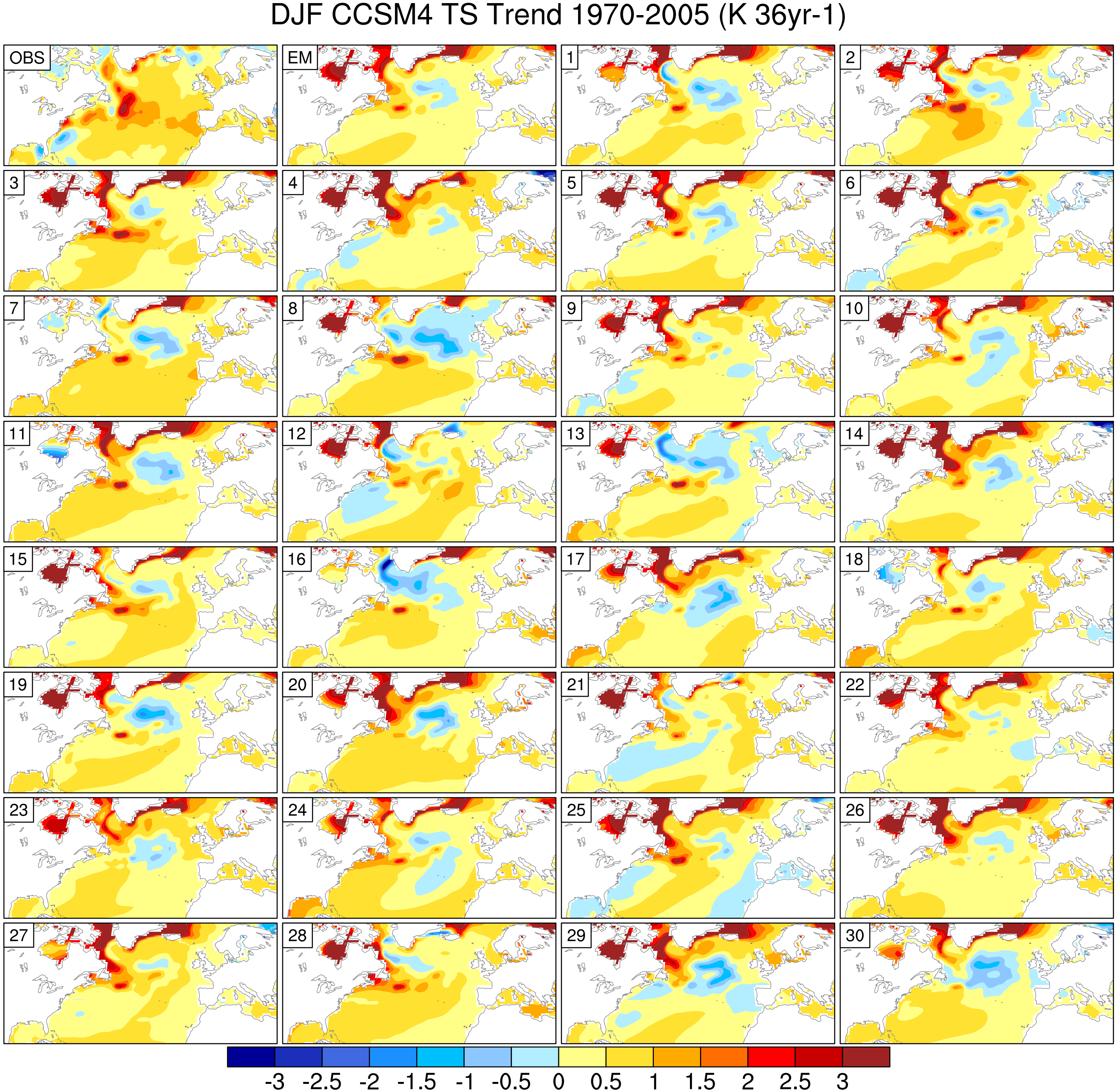

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