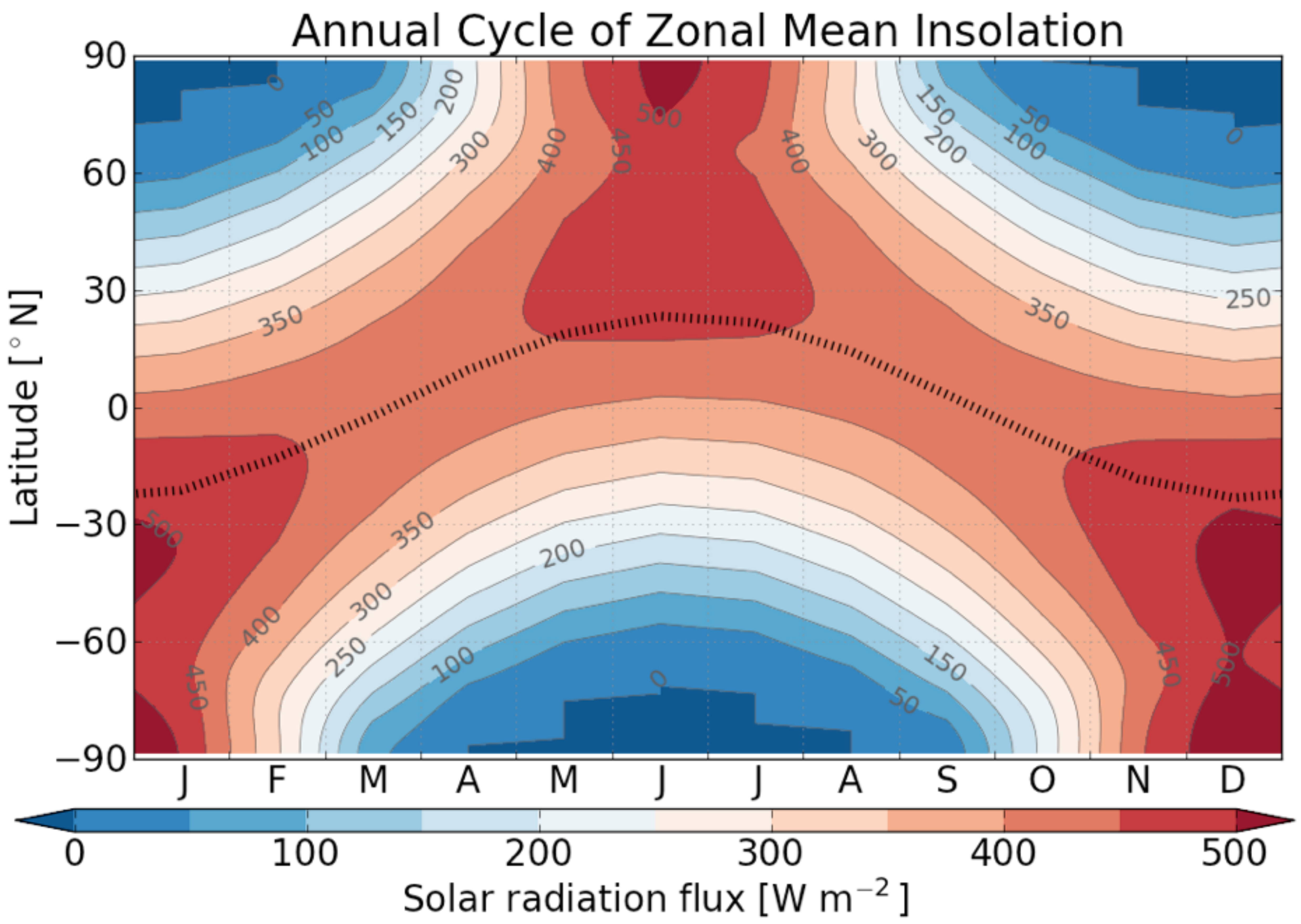
Atmosphere–Ocean Interactions

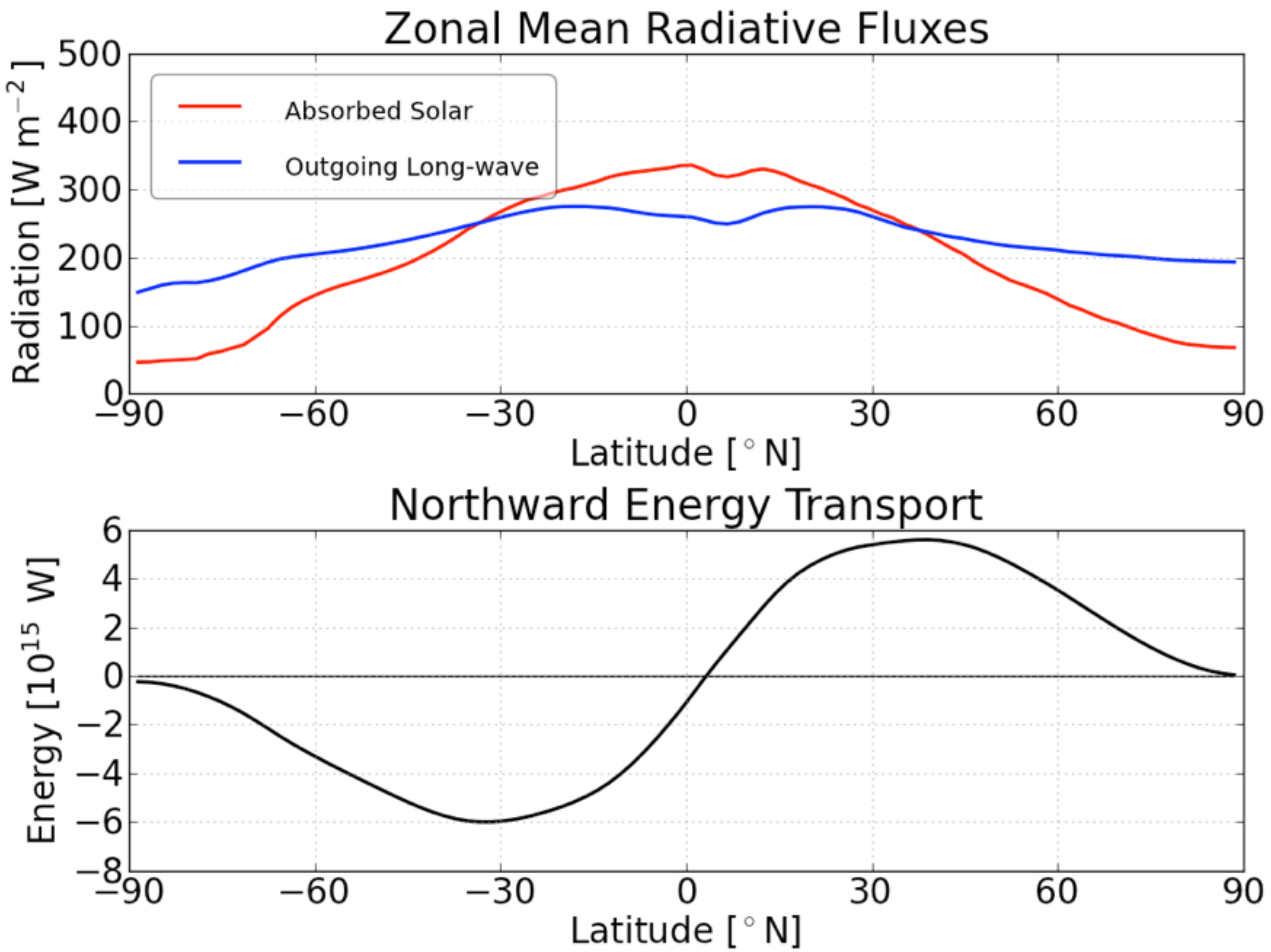
14. Climate Modeling and Climate Change

- A review of atmosphere–ocean interactions
- Coupling the atmosphere–ocean system in GCMs
- The global warming “hiatus”

The Climate System

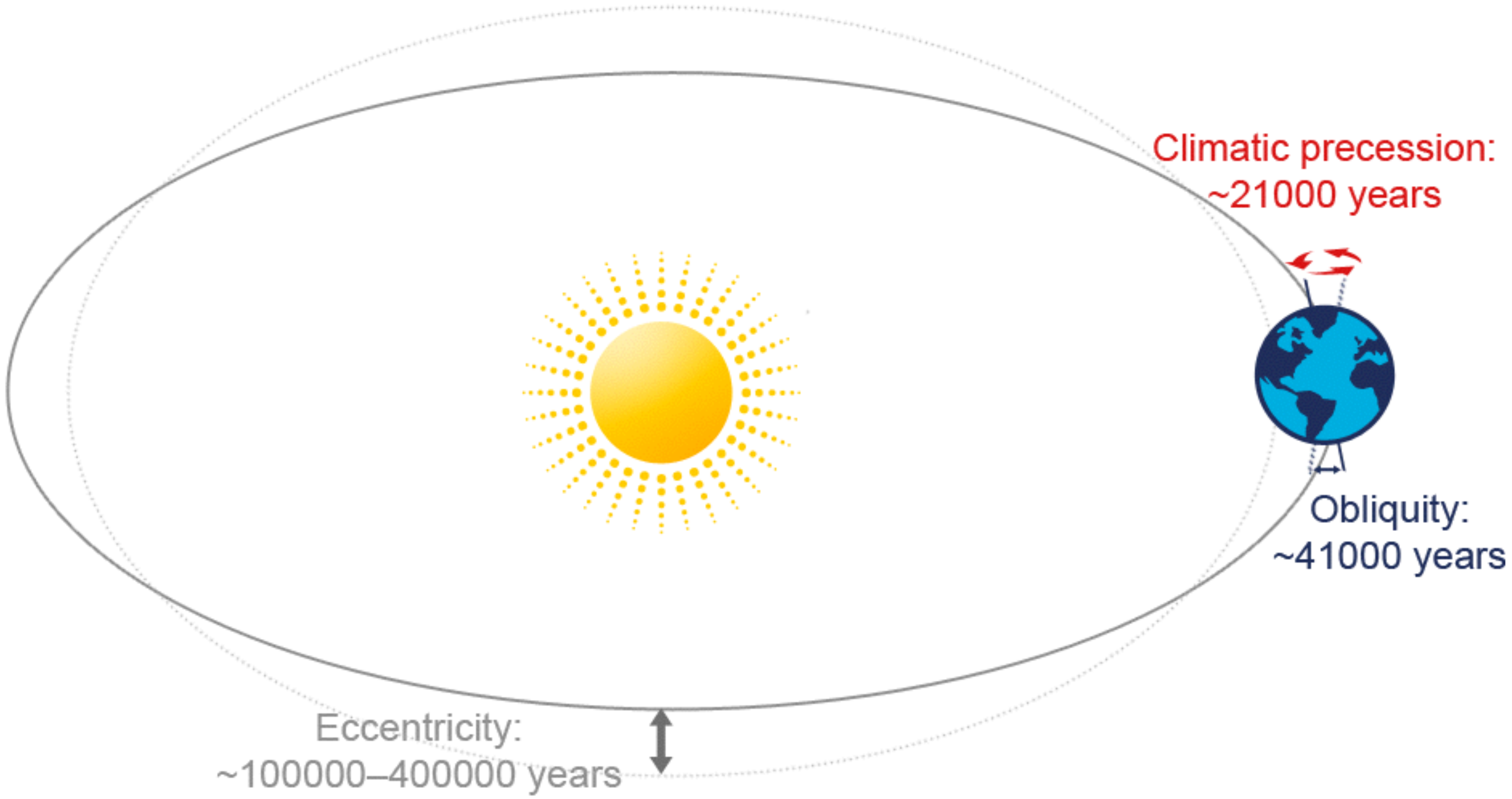
Solar radiation is the ultimate driving force behind motion in the atmosphere and ocean, and has regular diurnal and seasonal cycles



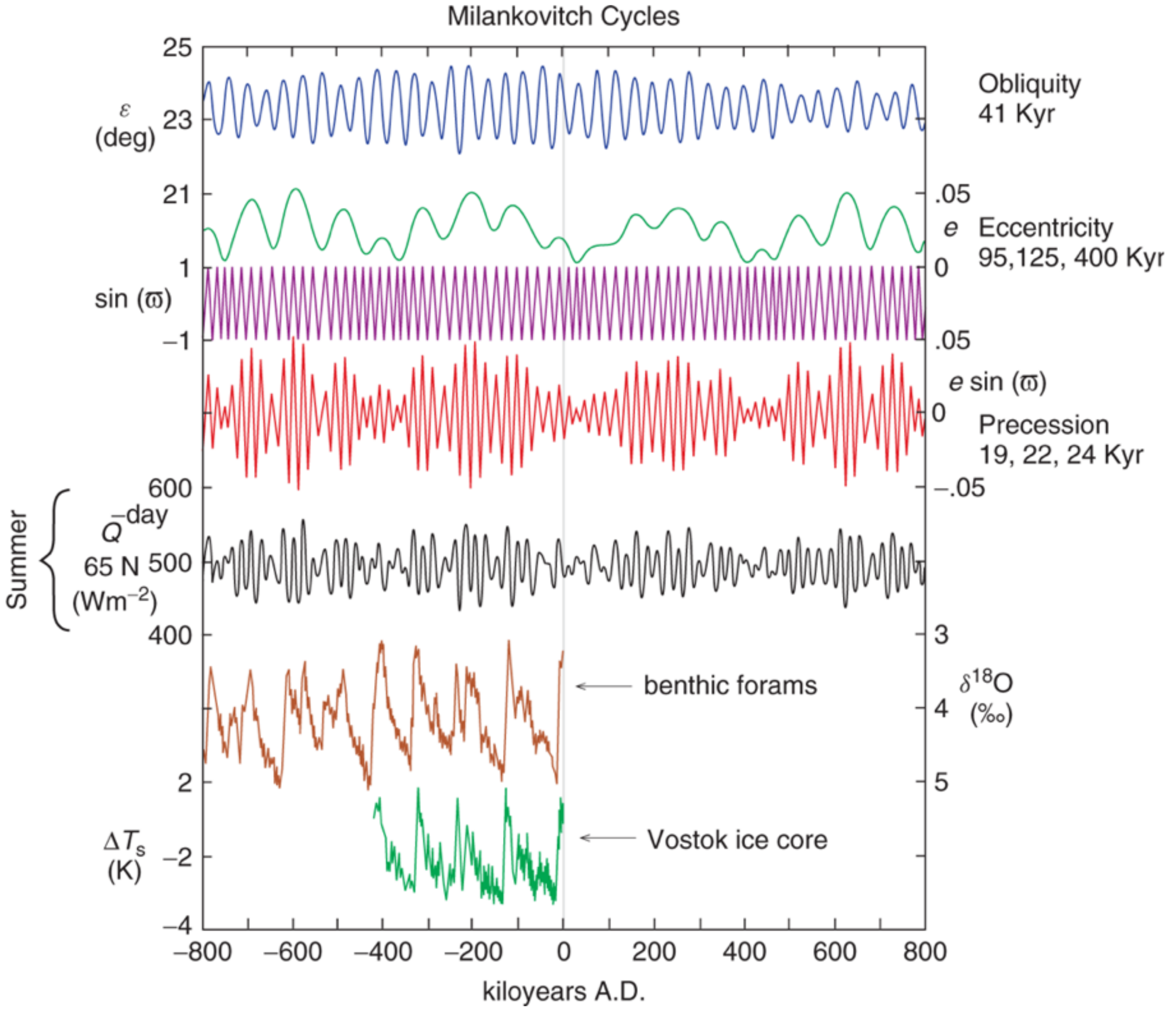


Data: Climate Forecast System Reanalysis

The Climate System



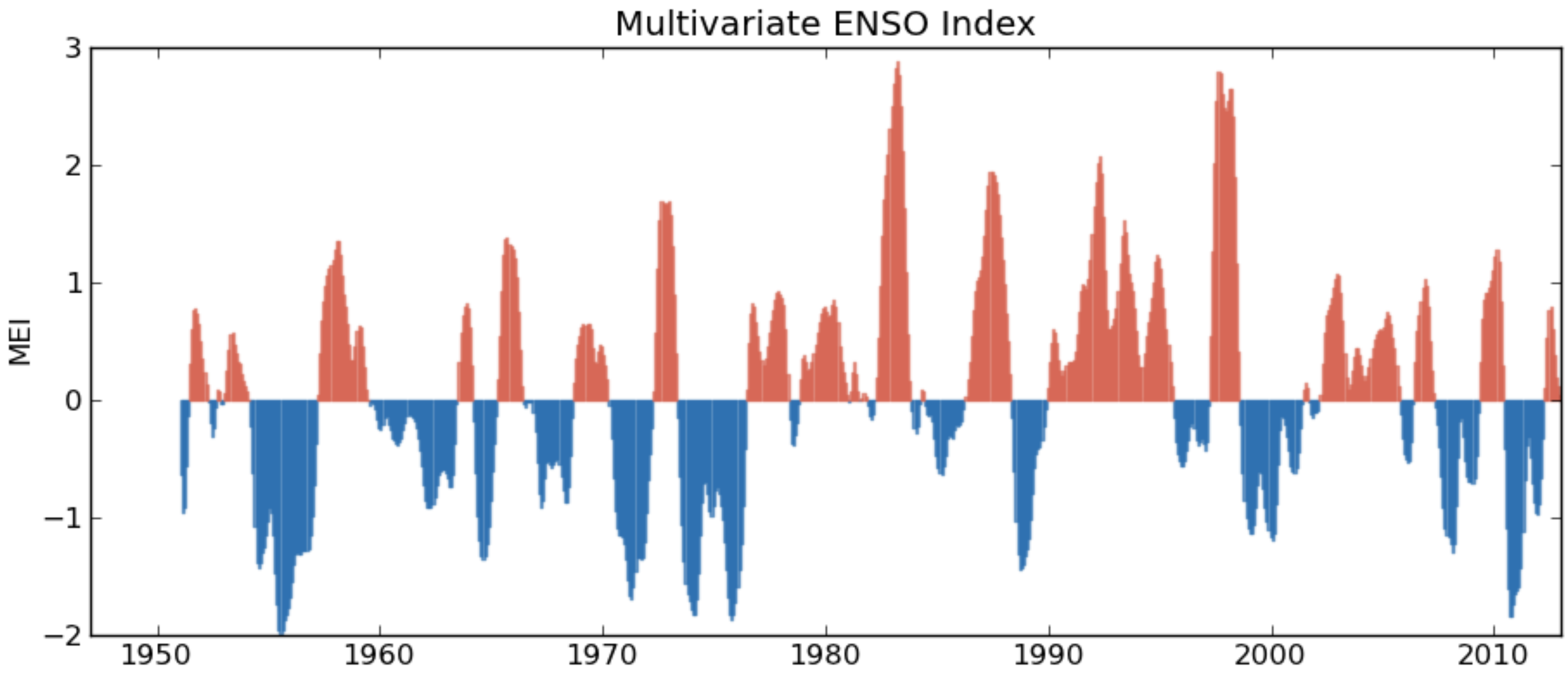
As well as orbital variations with longer timescales



Wells, 2012

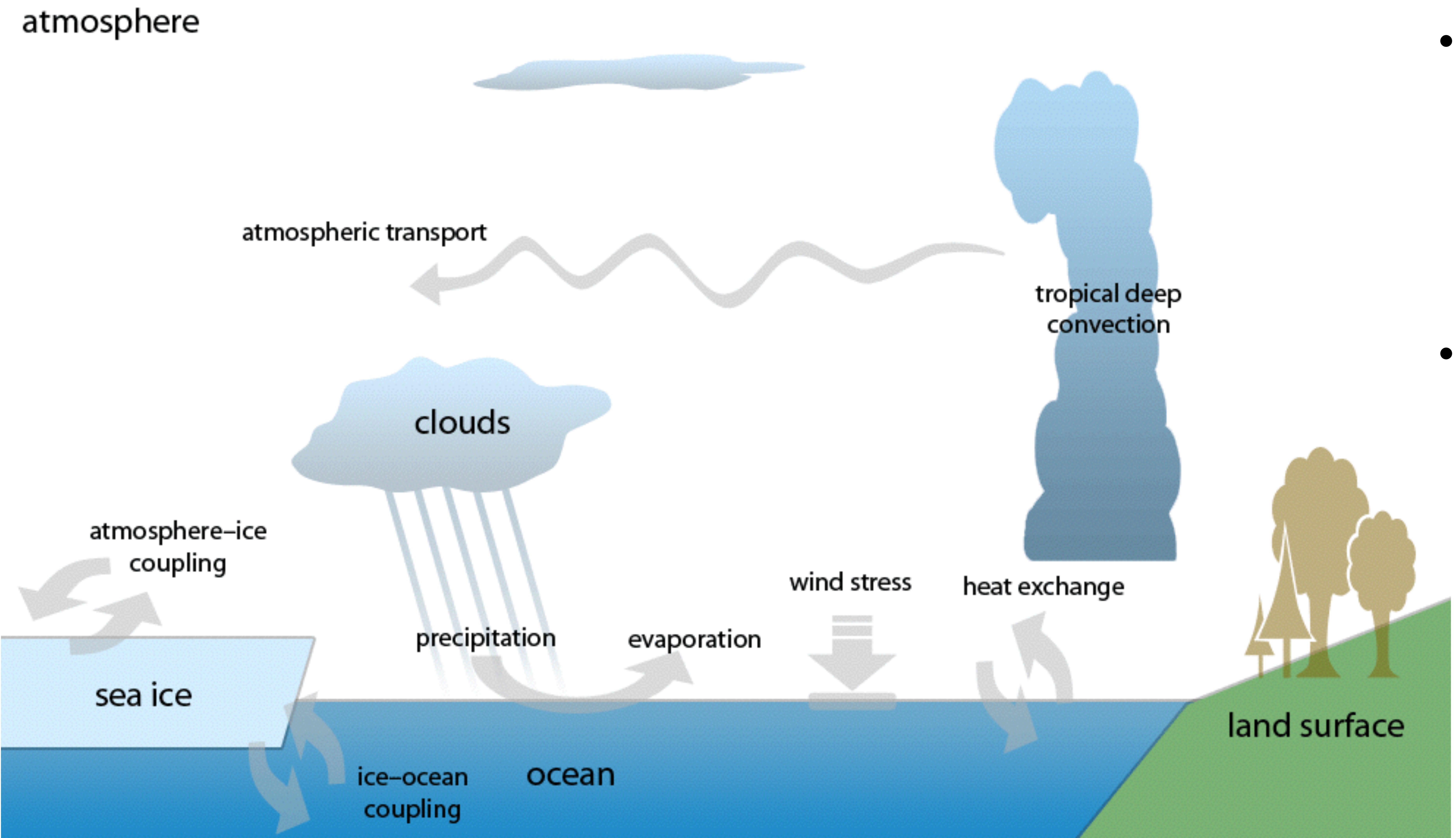
The Climate System

Climate variations are not solely due to regular repeating cycles of solar radiation, but also show internal variability (such as ENSO)



Data: NOAA Climate Prediction Center

The Climate System

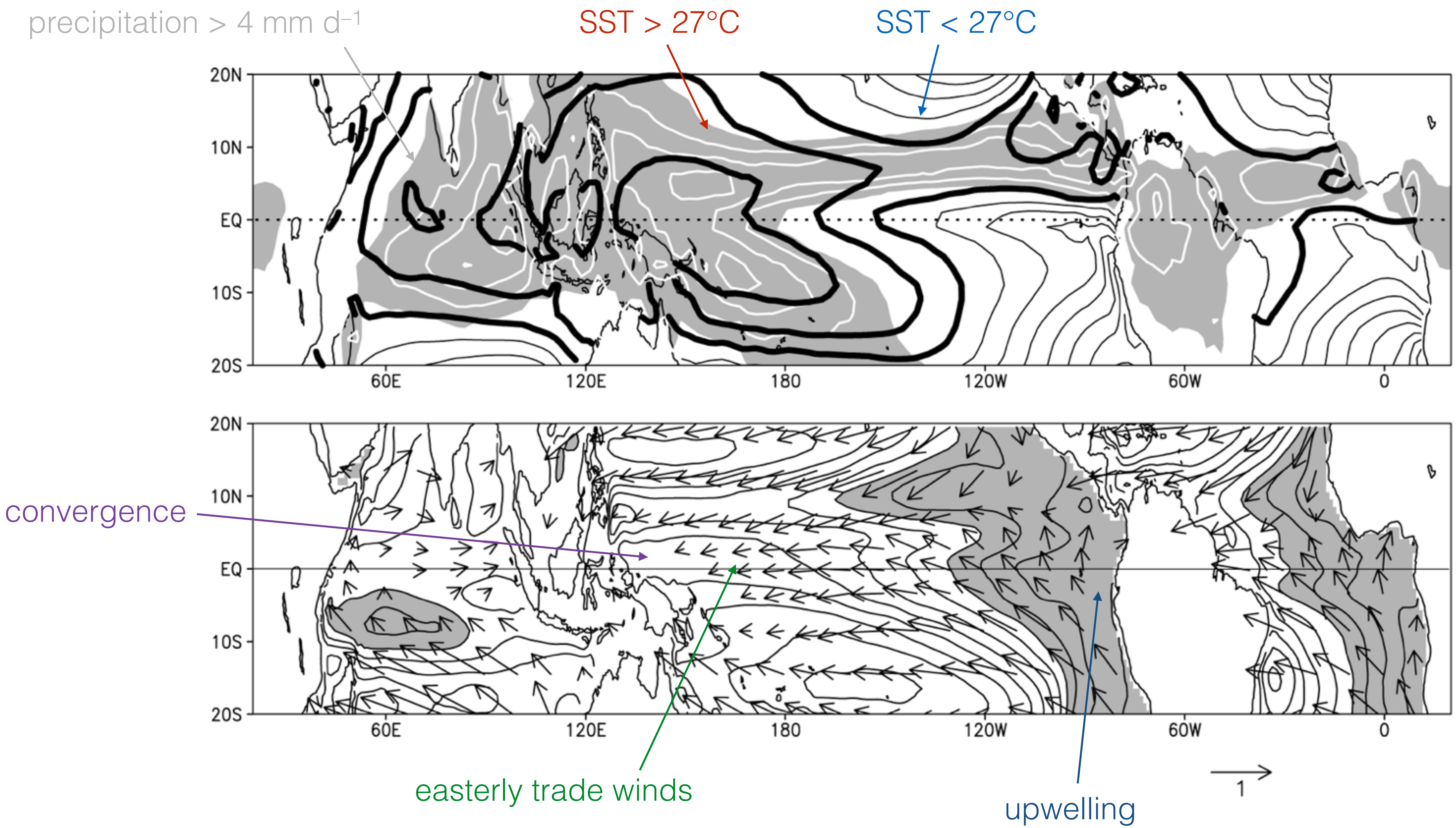


- The atmosphere, ocean, cryosphere (ice sheets, glaciers, and sea ice), biosphere, and land surface comprise the climate system
- All of these components interact in complex ways on a wide variety of time scales

Coupling in the Tropics

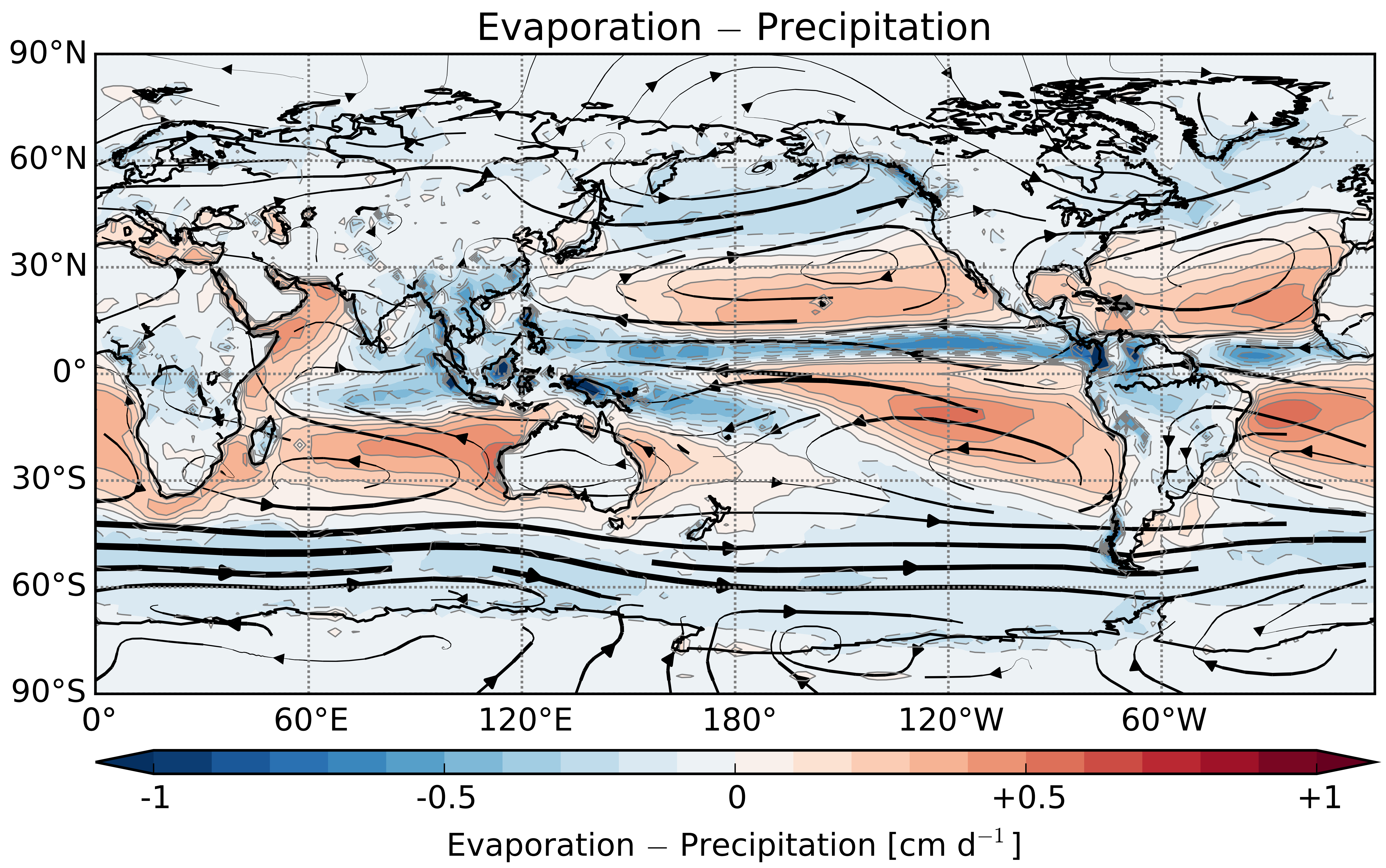
Easterly trade winds lead to a zonal tilt of the thermocline in the tropical oceans, with upwelling, a shallower thermocline, and colder SSTs in the east

Coupling in the Tropics



Wang et al., 2004

Coupling in the Tropics



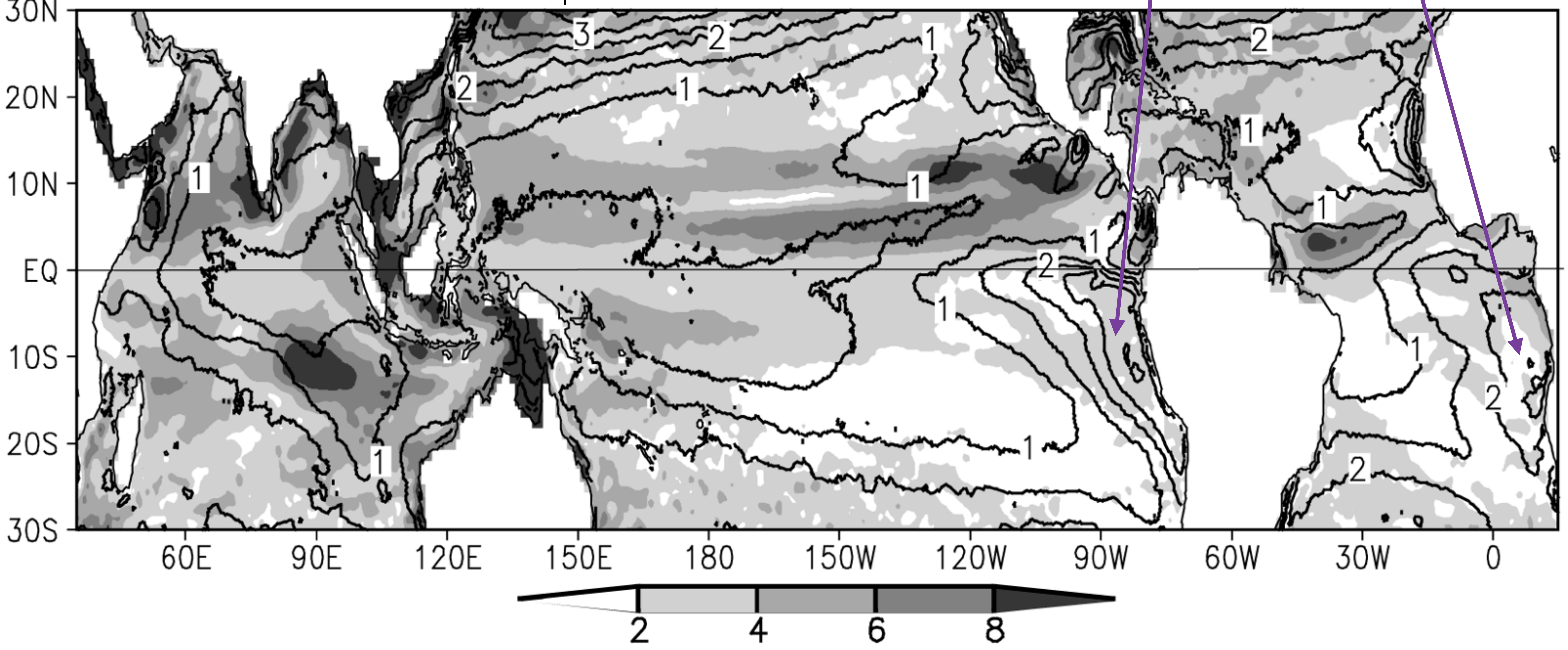
Convection and precipitation are shifted north of the equator in the eastern tropical oceans due to upwelling along the eastern boundary

Data: Climate Forecast System Reanalysis

Coupling in the Tropics

Cross-equatorial surface winds weaken and strengthen in response to the seasonal cycle of sunlight, resulting in strong seasonal cycles in upwelling regions

root mean square seasonal variance in SST and SSH

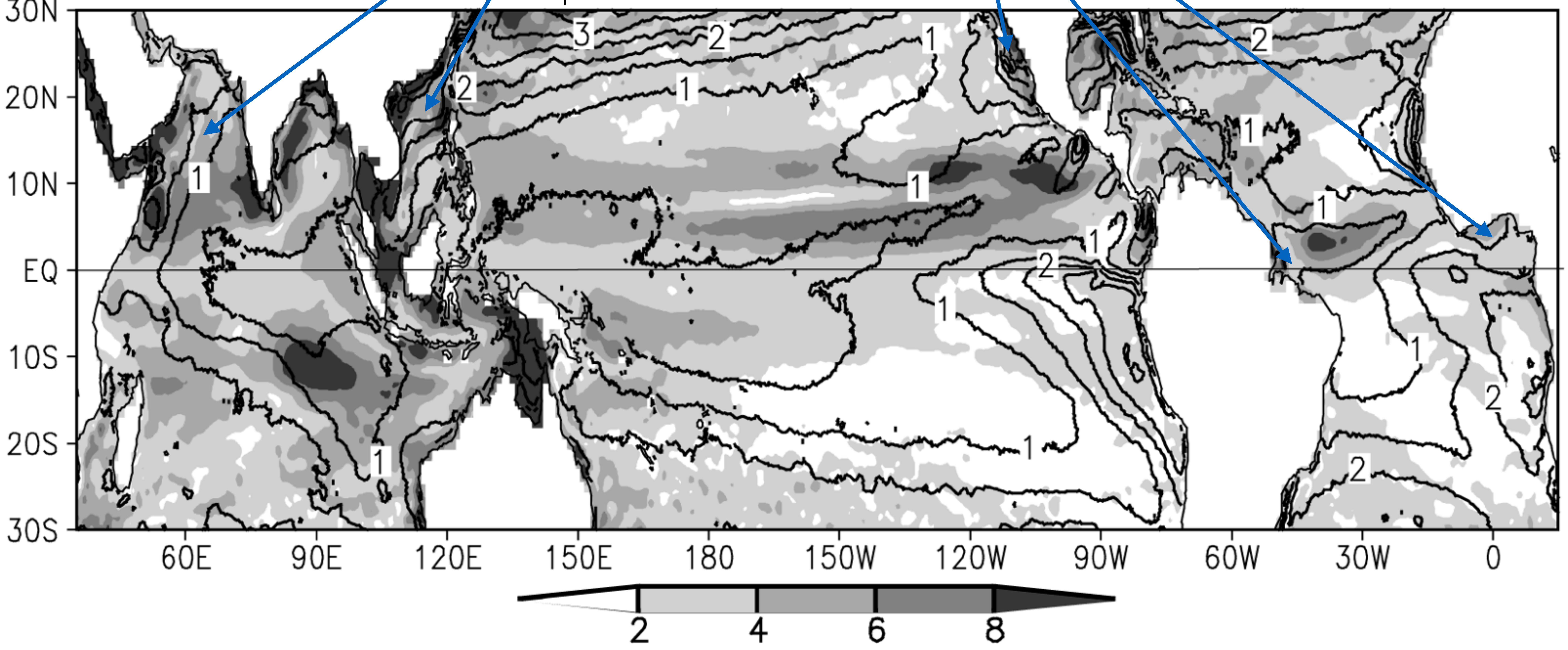


Wang et al., 2004

Coupling in the Tropics

Monsoons also play a key role in increasing seasonal ocean variability, especially in the Arabian and South China Seas

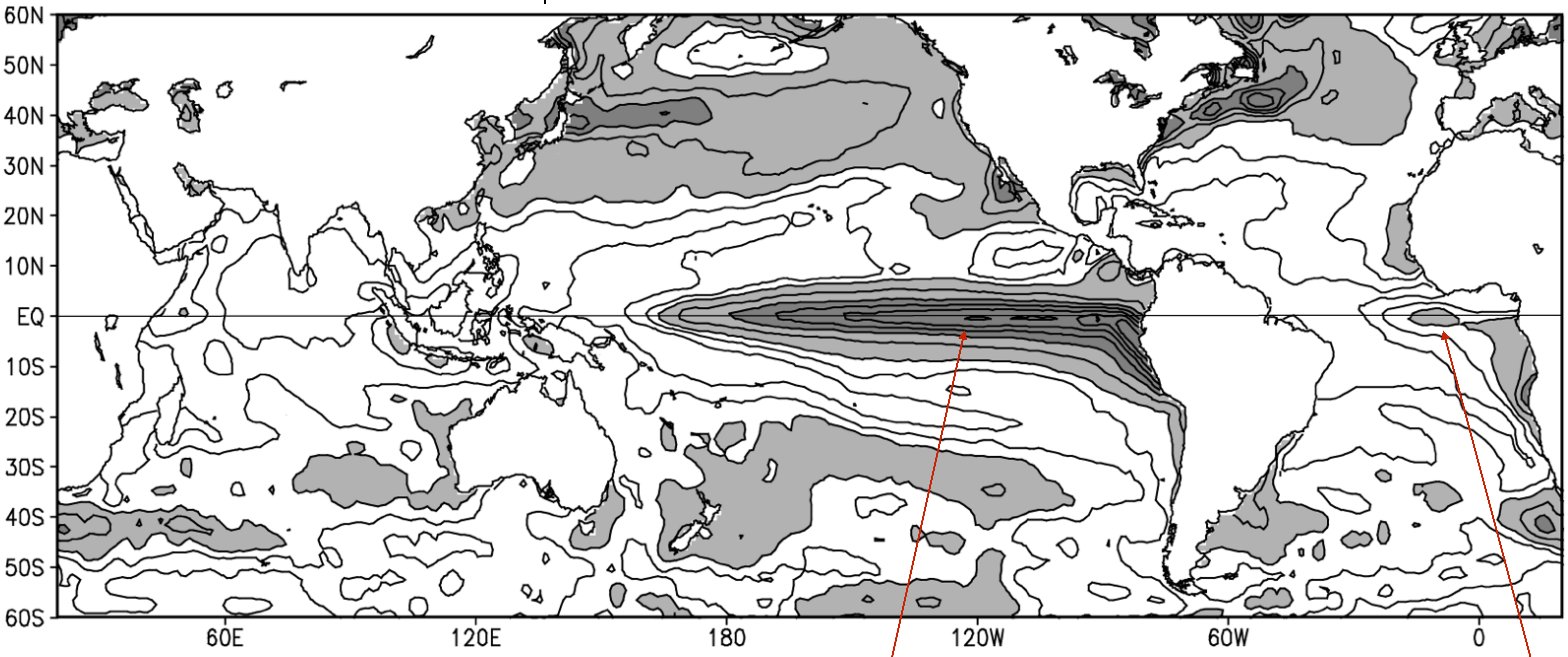
root mean square seasonal variance in SST and SSH



Wang et al., 2004

Coupling in the Tropics

root mean square variance of interannual SST anomalies



Interannual variability in the tropical oceans is dominated by the ENSO signal in the tropical Pacific

“Atlantic Niño”

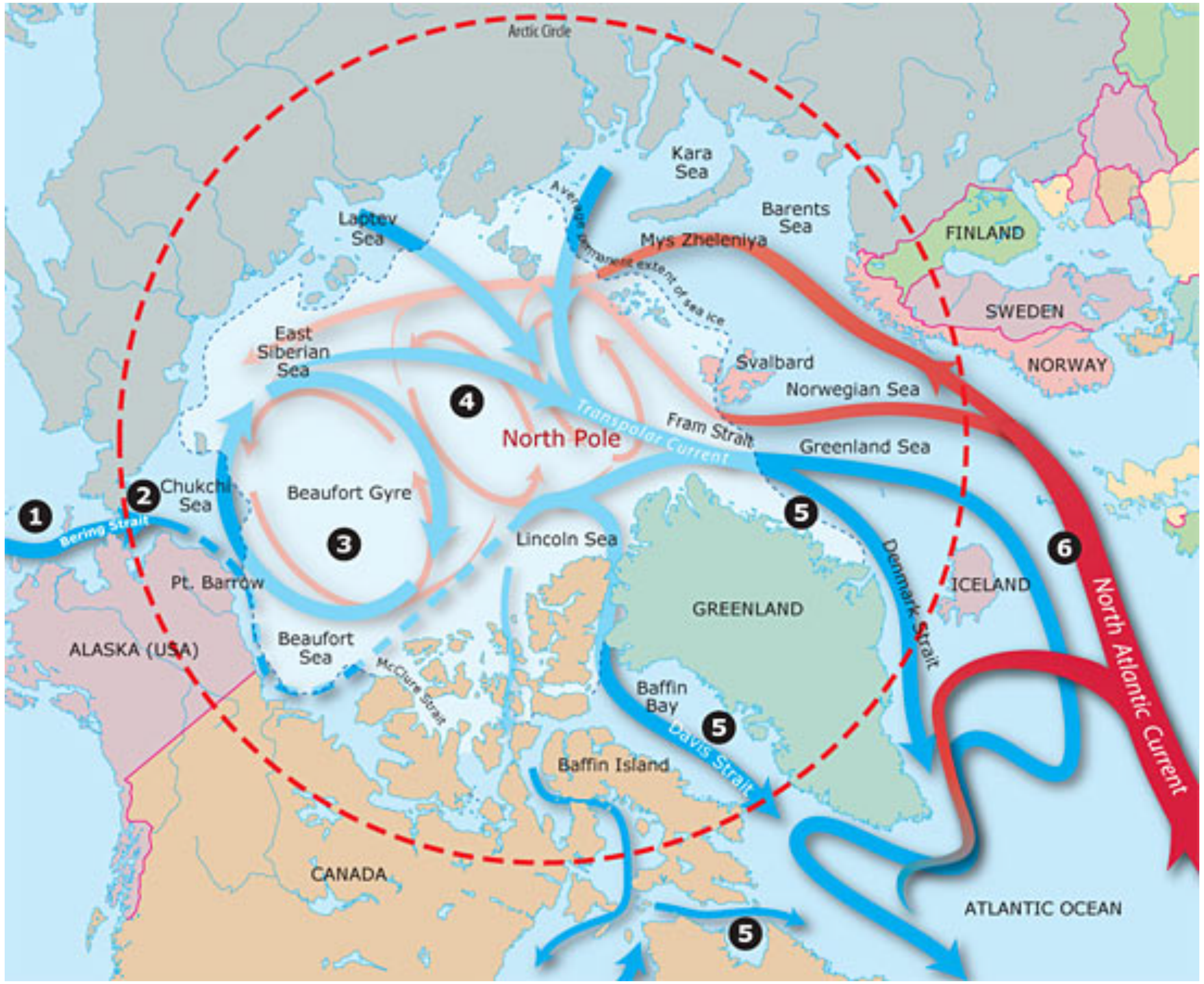
Wang et al., 2004

Coupling in Mid-Latitudes

- More difficult to identify for several reasons:
  - meteorology is more complex, with weaker links between SST anomalies and surface winds
  - SSTs are cooler and the mixed layer is generally deeper — the ocean responds more slowly to changes in atmospheric conditions
  - the Coriolis term is larger and places stronger constraints on momentum
- Coupled variability still arises (e.g., the Pacific Decadal Oscillation)
- Three categories of midlatitude atmosphere–ocean interaction theories:
  - arise from interactions between the tropics and midlatitudes
  - occur in subtropics/midlatitudes and involve changes in the gyre circulations
  - occur in midlatitudes and involve changes in the thermohaline circulation
- The ocean appears to integrate stochastic weather events (white noise) into longer-term variability (red noise) in midlatitudes

Coupling in High Latitudes

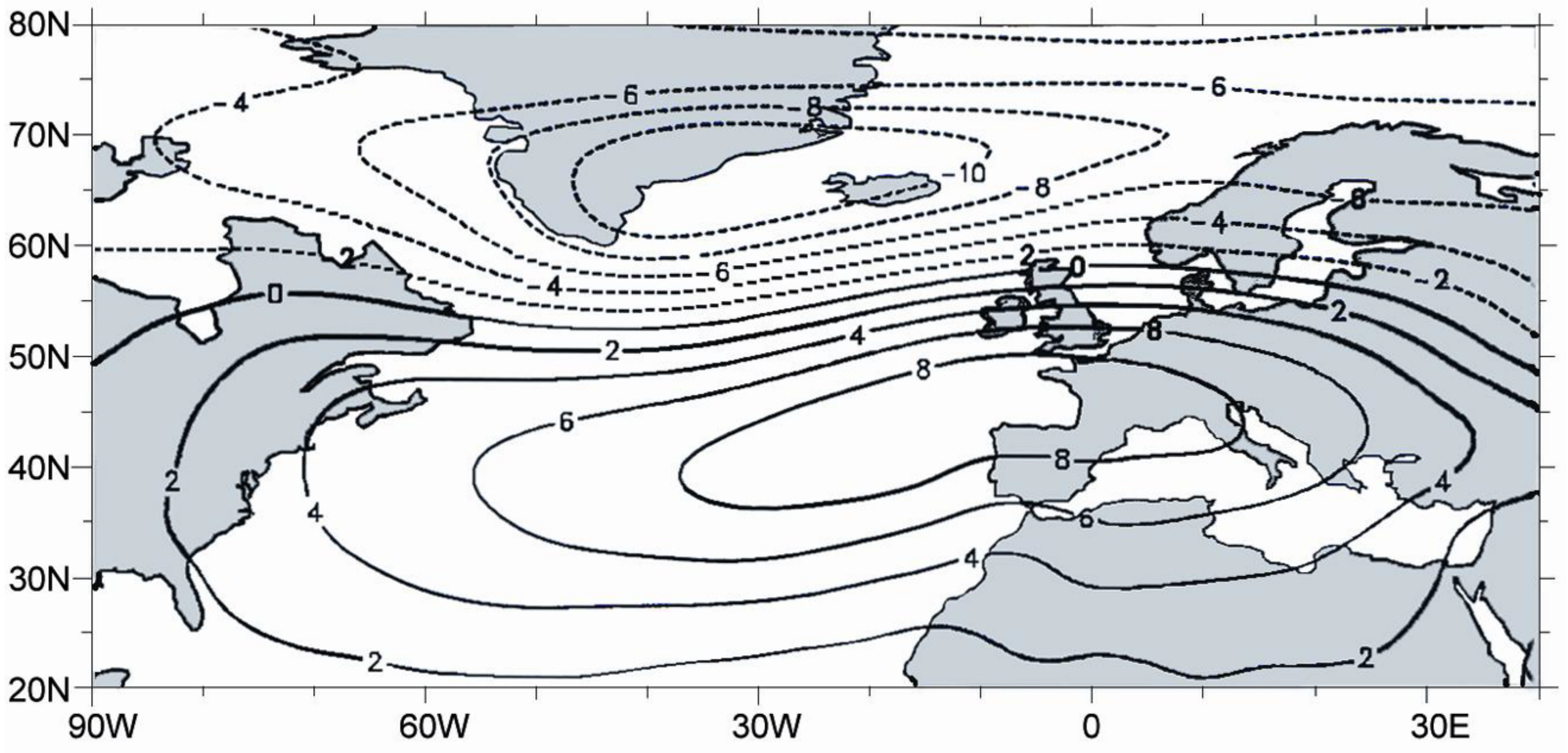
- Low thermal energy state
- Intimate and complex coupling between atmosphere, ocean and sea ice
- Arctic Ocean occupies most area north of 70°N, and serves as the northern link between the Pacific and Atlantic
- Atmosphere–ocean exchange of heat and momentum heavily influenced by sea ice cover, especially sea ice extent
- Fractions of thick, multi-year sea ice are declining, along with albedo
- Surface heat fluxes upward during winter, downward during summer
- Very cloudy with low-level inversions
- Co-varying signals among atmosphere, ocean and ice in Southern Ocean



Serreze and Barry, 2014

North Atlantic Oscillation

- First EOF of winter sea level pressure for North Atlantic
- Covariability in strength of Icelandic Low and Azores High (shifts in mass)
- Causes substantial shifts in jet location, storminess, and energy transport

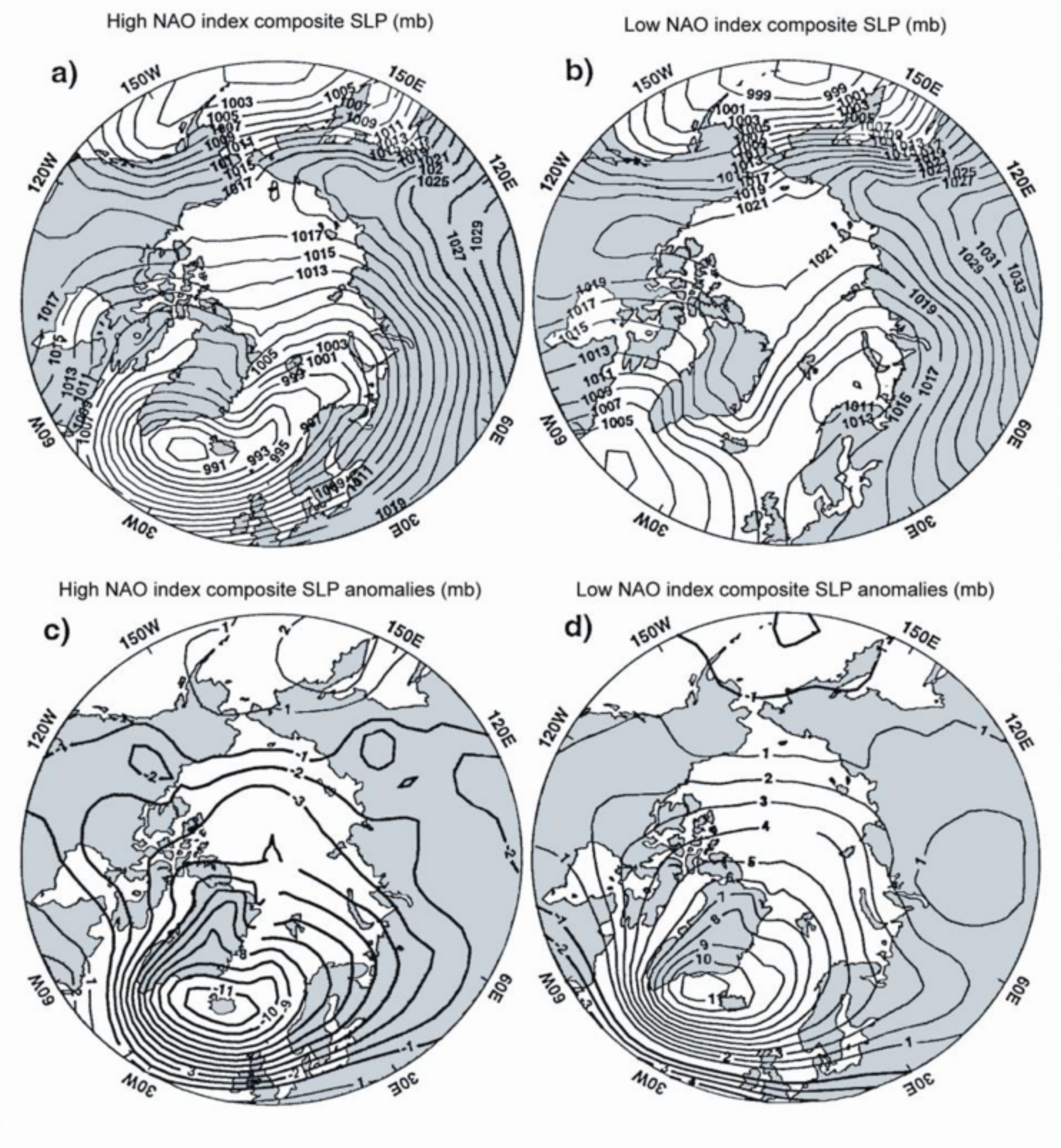


Serreze and Barry, 2014

Coupling in High Latitudes

North Atlantic Oscillation

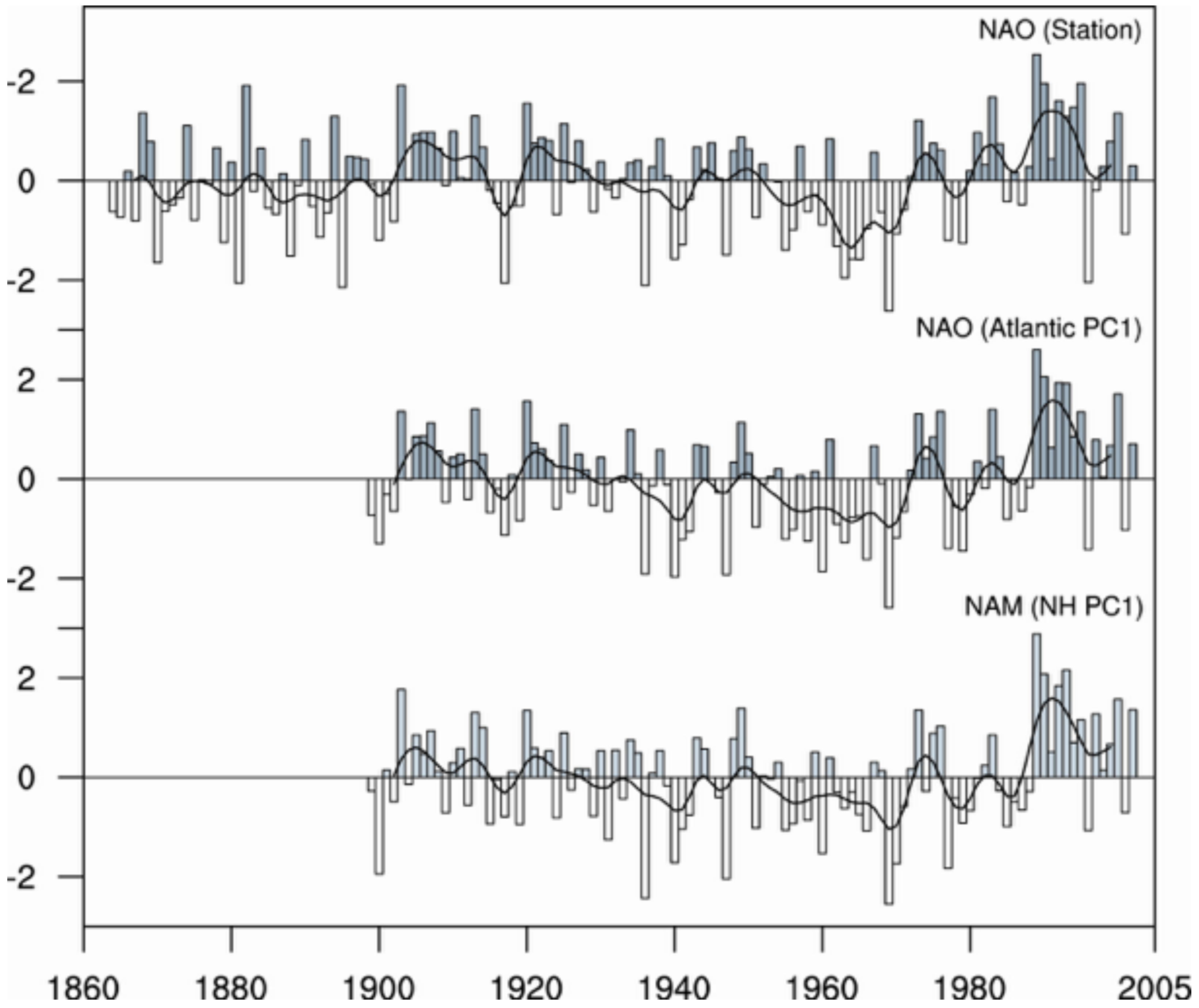
- Positive NAO: lower pressure in North Atlantic means greater cyclone activity, greater heat transport, and warm and wet conditions in Nordic Seas / Western Europe
- Negative NAO: higher pressure in North Atlantic means fewer cyclones and reduced heat transport, with cold and dry conditions over Nordic Seas / Western Europe

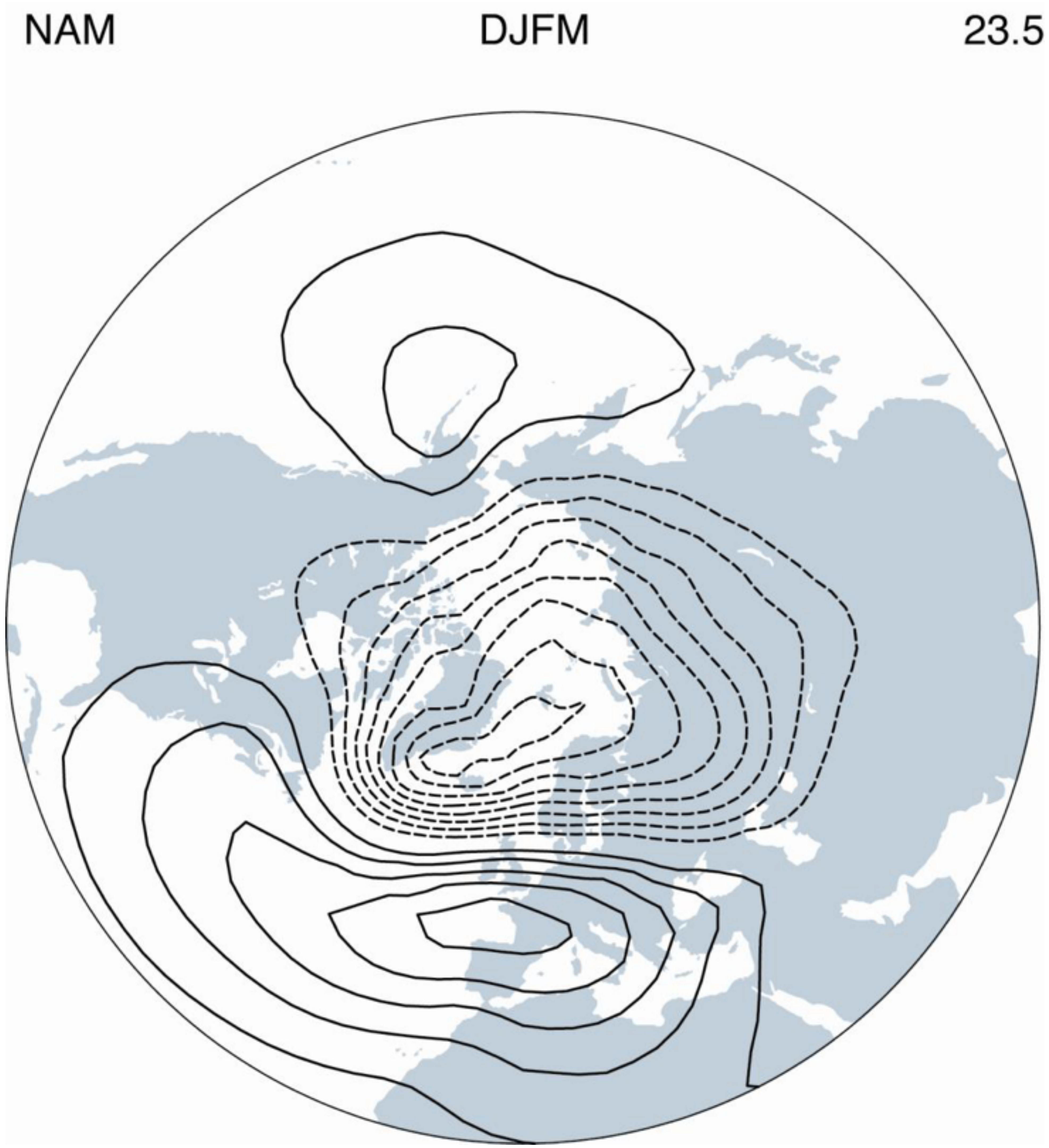


Serreze and Barry, 2014

Arctic Oscillation / Northern Annular Mode

- The “big brother” of the NAO — the NAO is the North Atlantic component of the AO
- Instead of Icelandic low and Azores high, focus is on see-saw of pressure (mass) between midlatitudes and Arctic
- Also a Southern Annular Mode

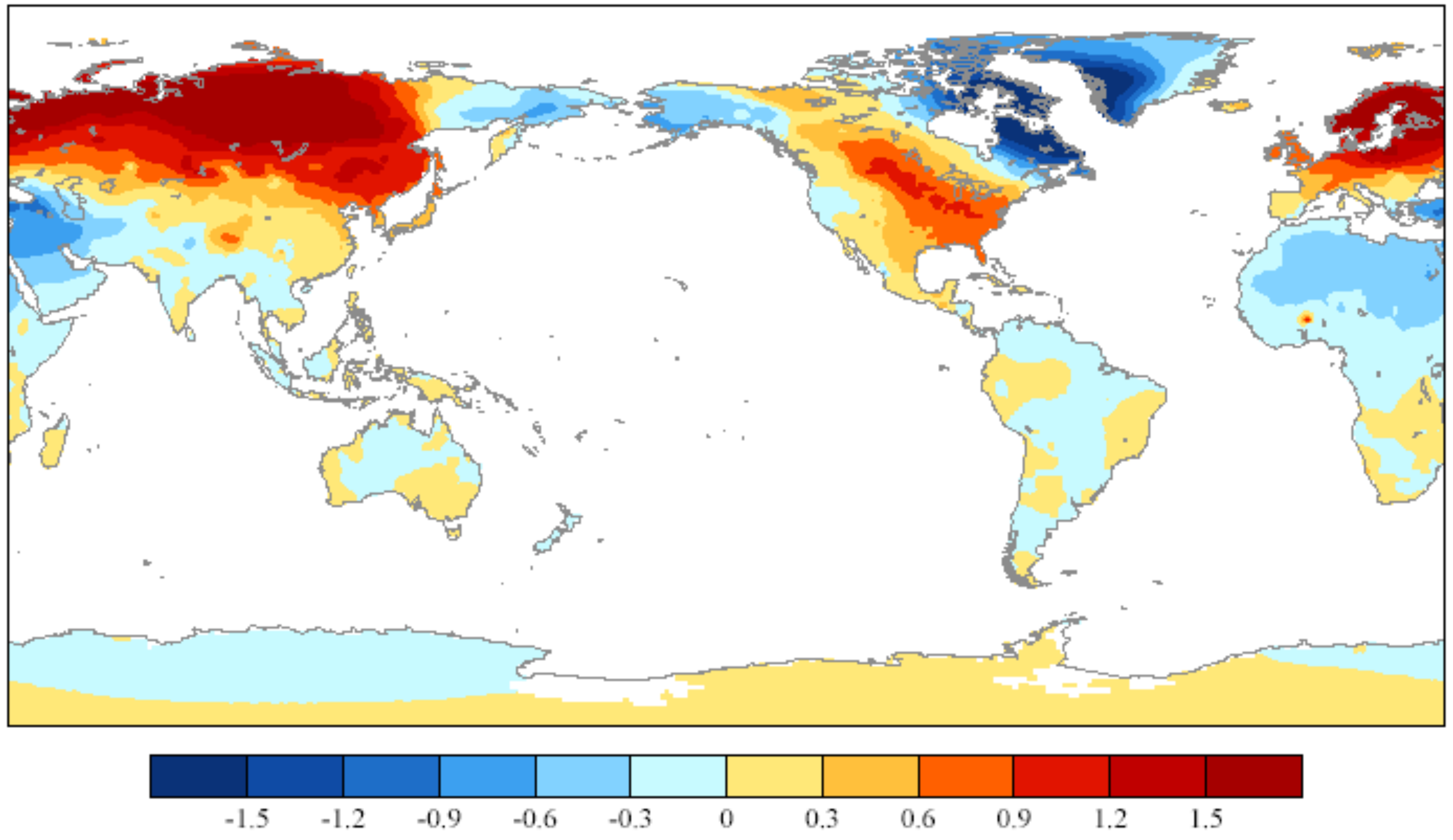


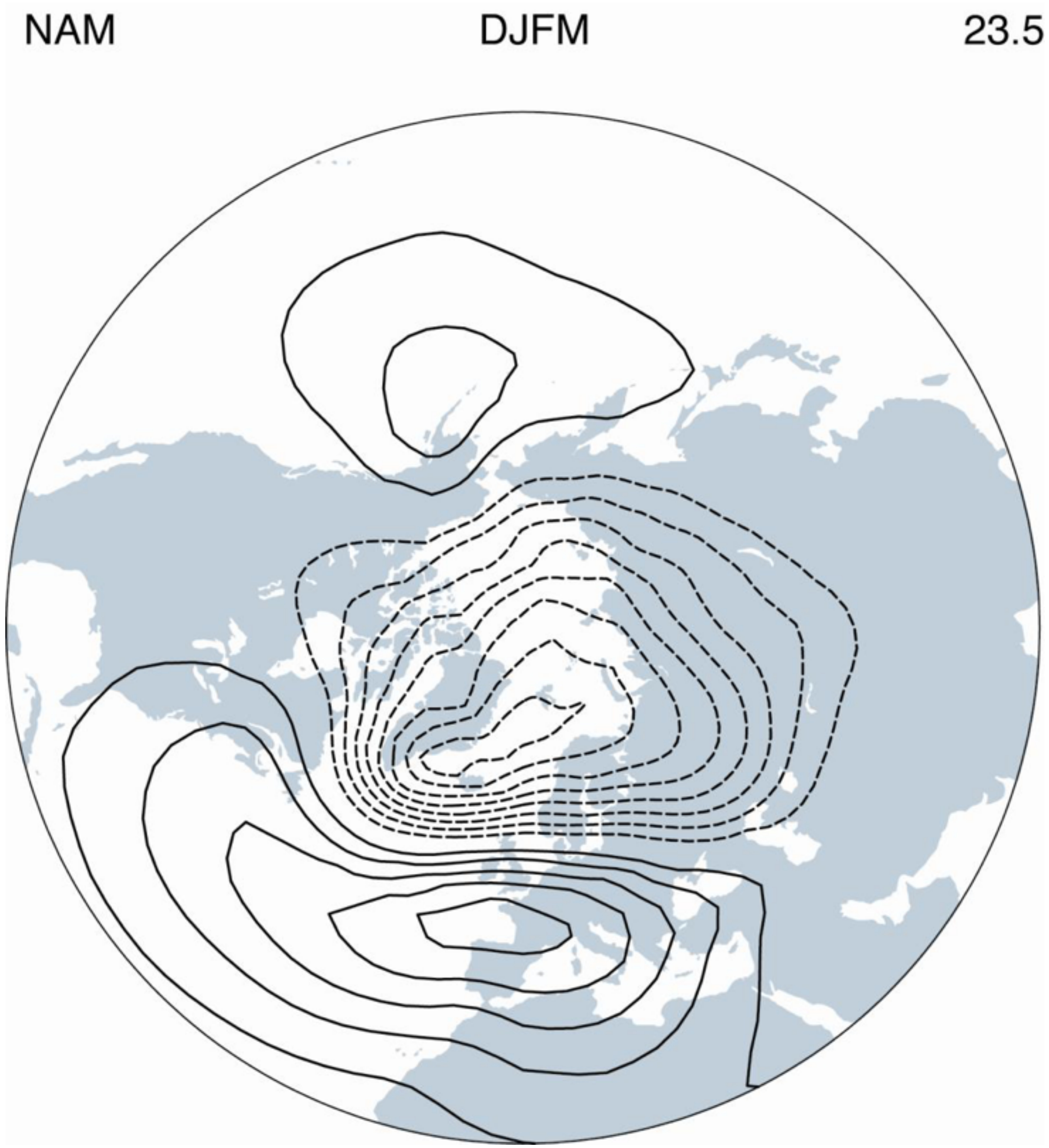


Serreze and Barry, 2014

Arctic Oscillation

- Also called the Northern Annular Mode
- The “big brother” of the NAO — the NAO is the North Atlantic component of the AO
- Instead of Icelandic low and Azores high, focus is on see-saw of pressure (mass) between midlatitudes and Arctic
- Changes in AO affect surface air temperature

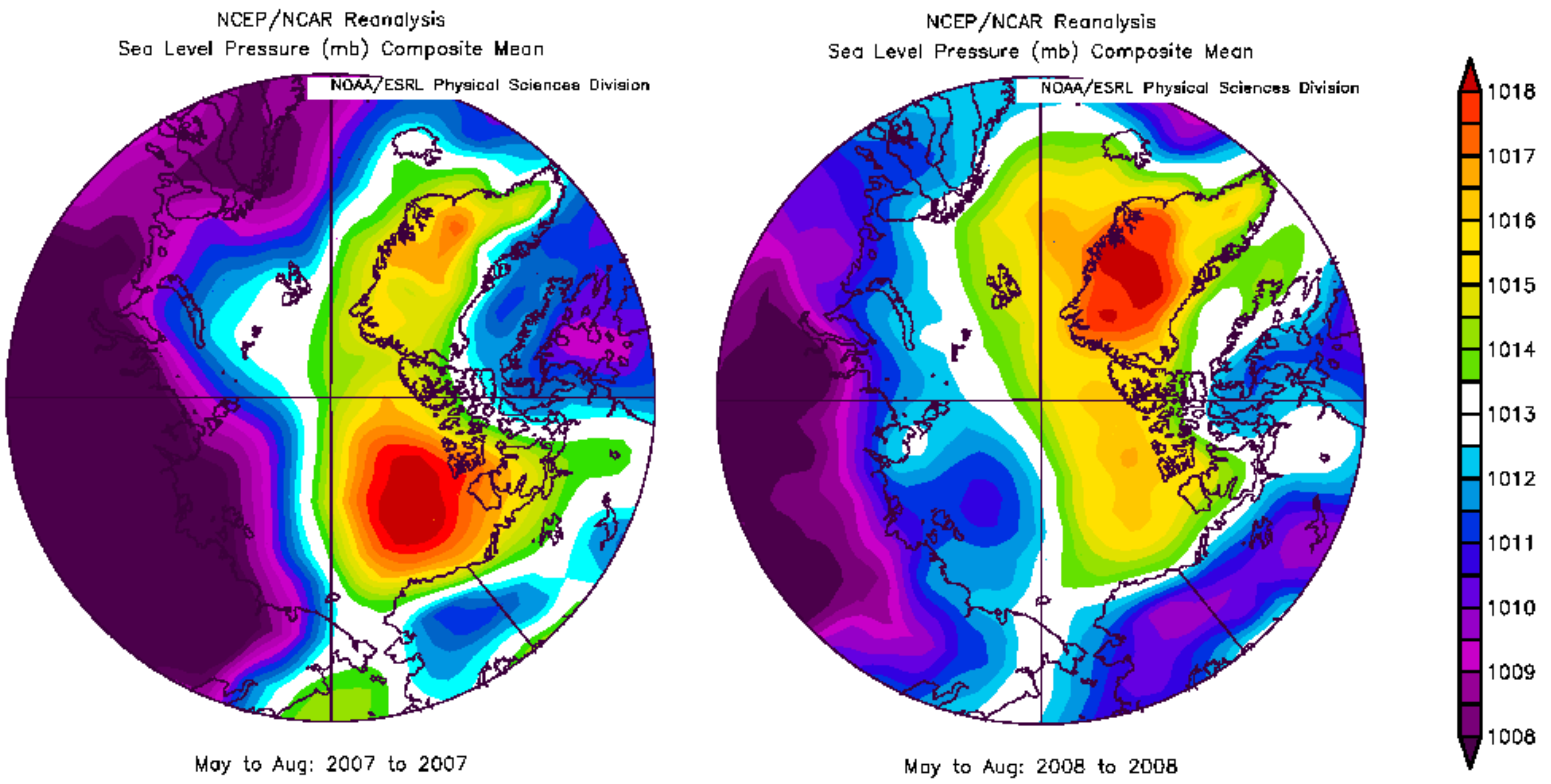




Serreze and Barry, 2014

Arctic Dipole Anomaly

- Summertime positive SLP anomalies on North Atlantic side; negative on Eurasian side
- Favors southerly winds and ice melt in Eurasian seas — record low in September 2007



Serreze and Barry, 2014

Coupling in High Latitudes

Arctic Dipole Anomaly

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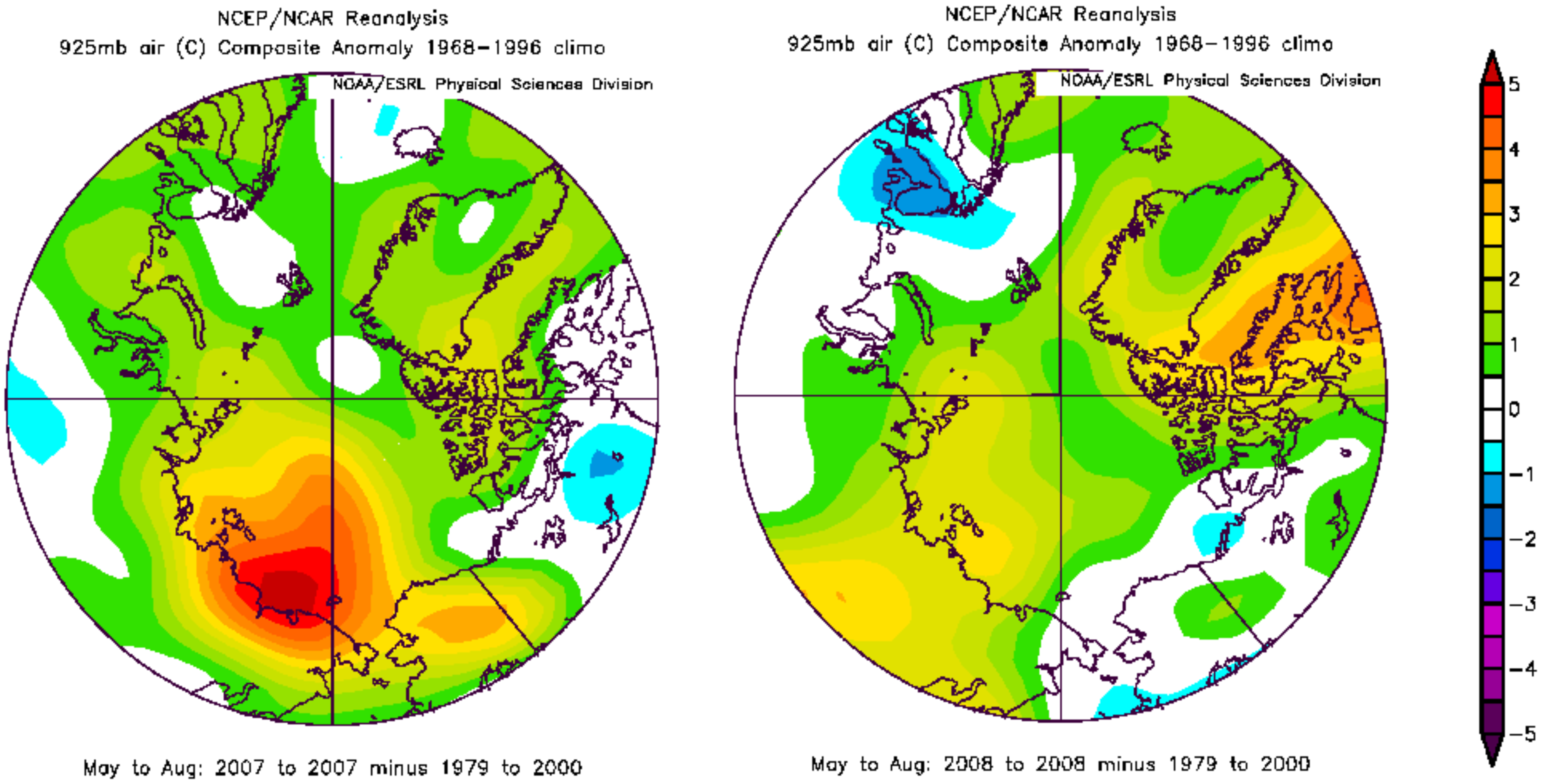
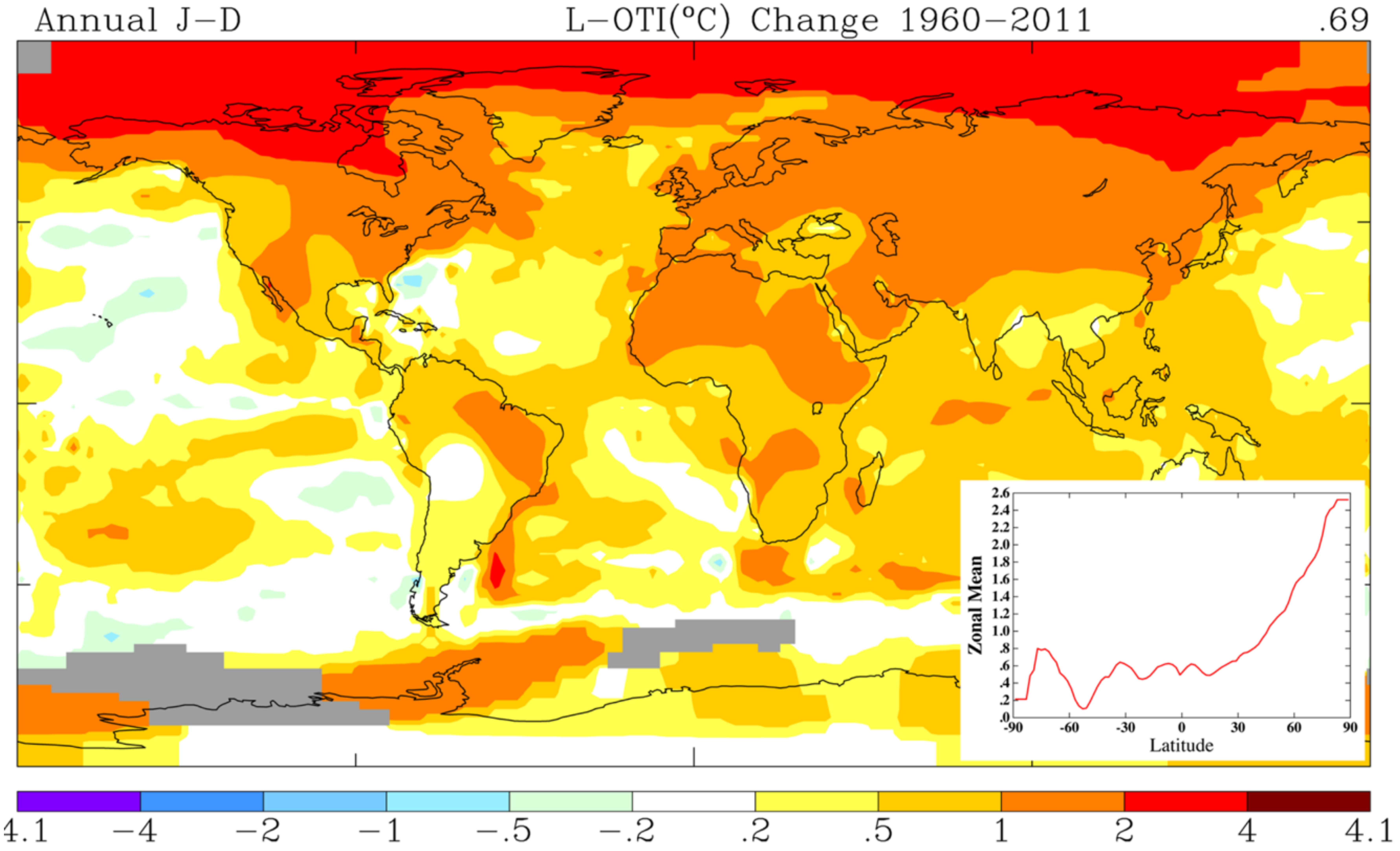


Serreze and Barry, 2014

Coupling in High Latitudes

Changes in temperature: Arctic amplification

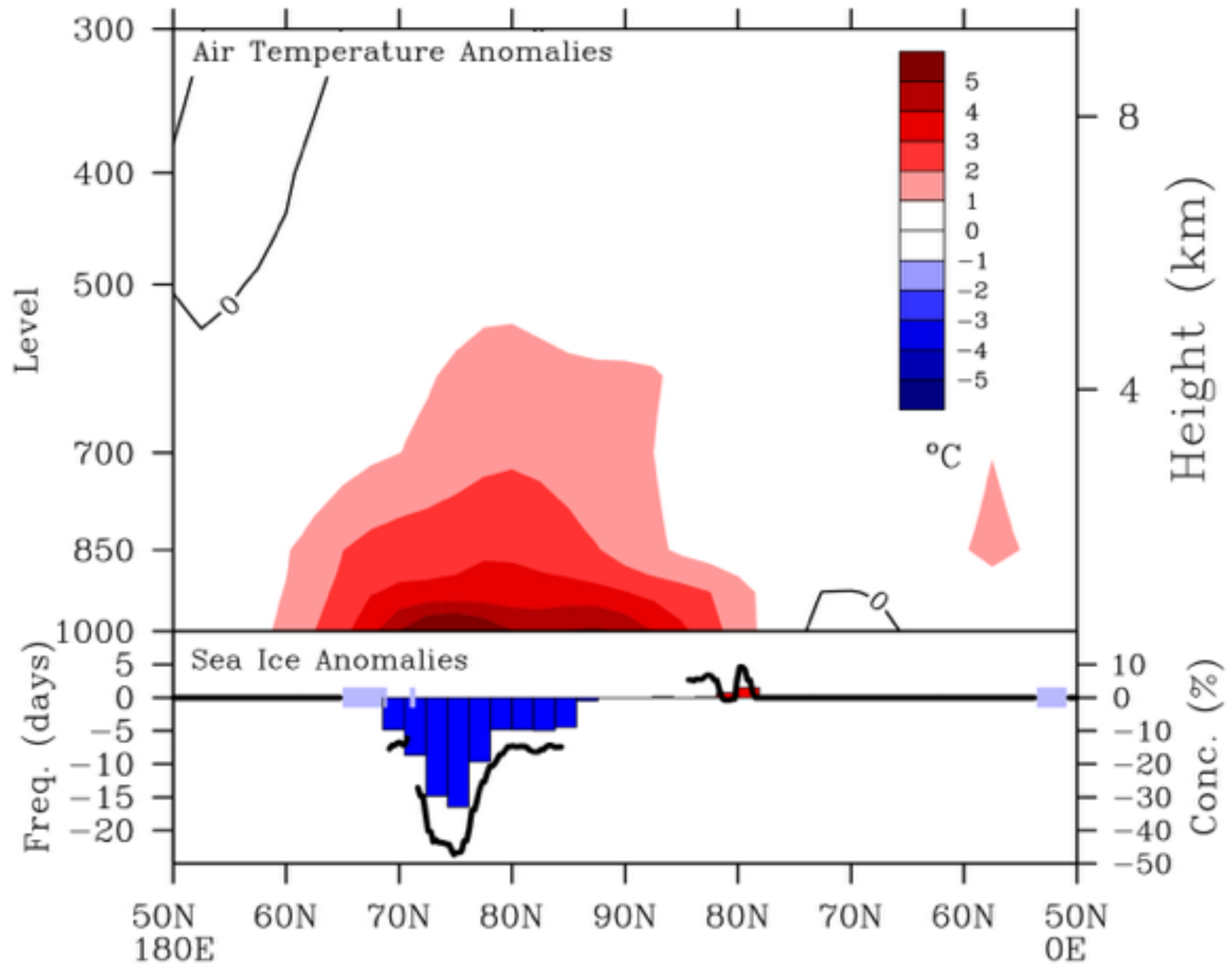


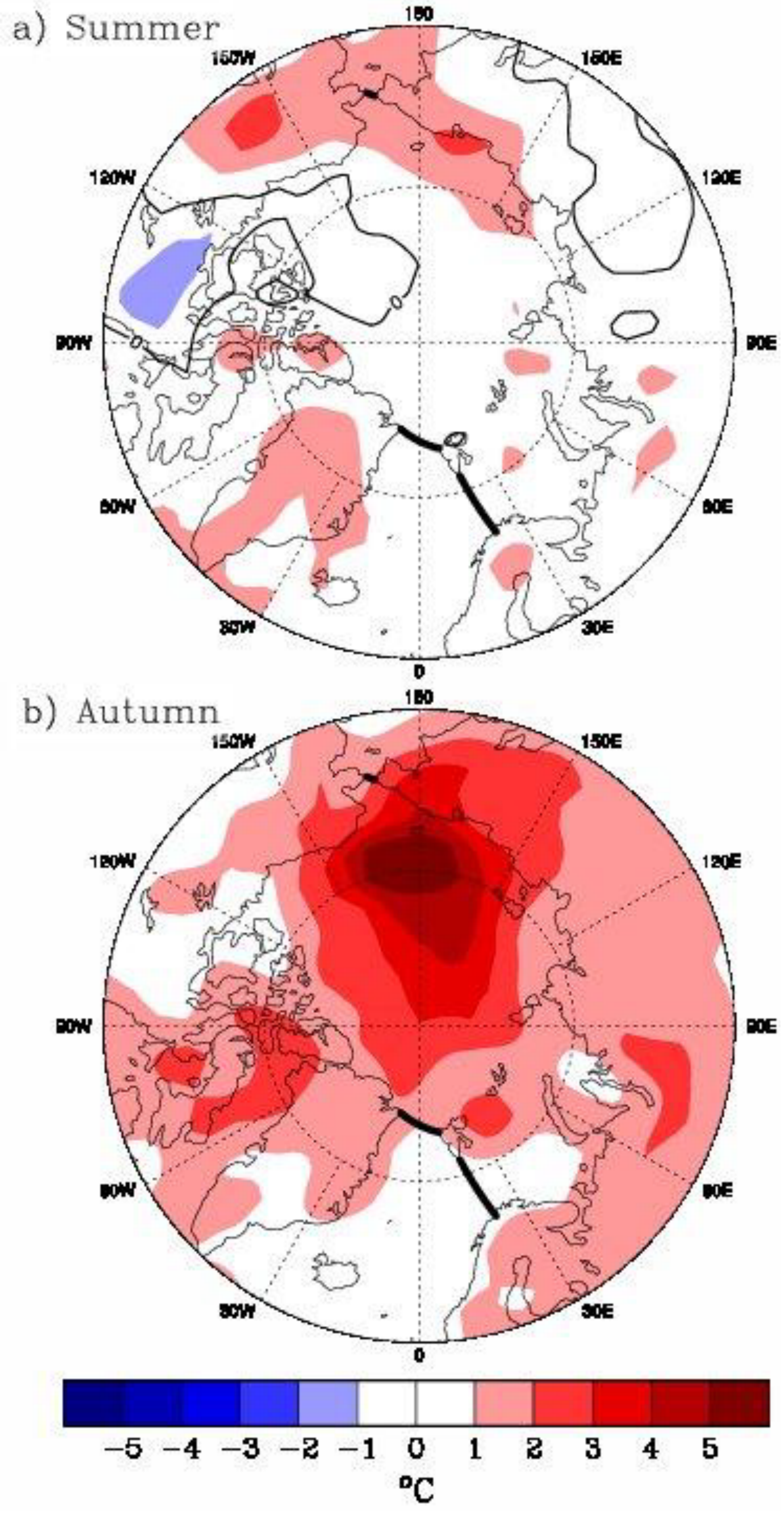
Serreze and Barry, 2014

Coupling in High Latitudes

Changes in temperature: Arctic amplification

- Arctic warming is particularly pronounced in autumn
- Loss of sea ice allows for large heat transfer between the ocean and atmosphere
- Temperature anomalies are weaker during summer, when melting ice keeps the surface air temperature closer to freezing



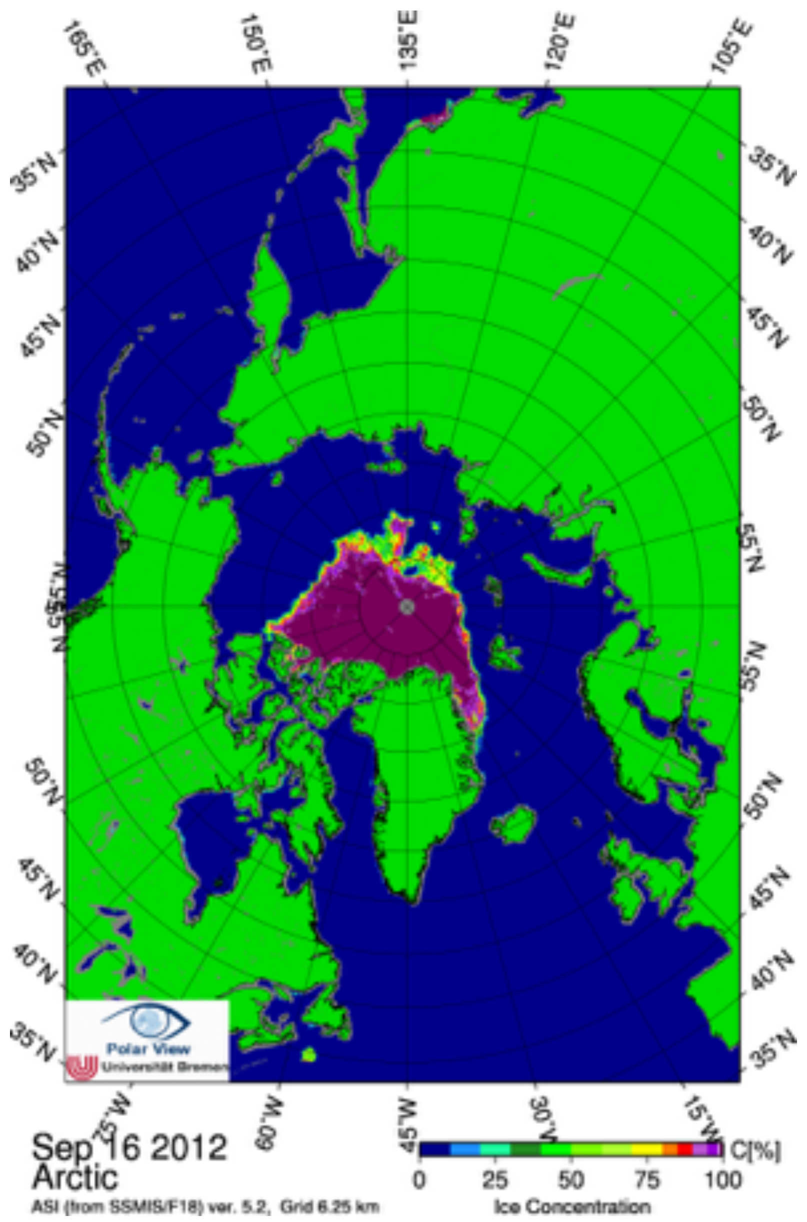


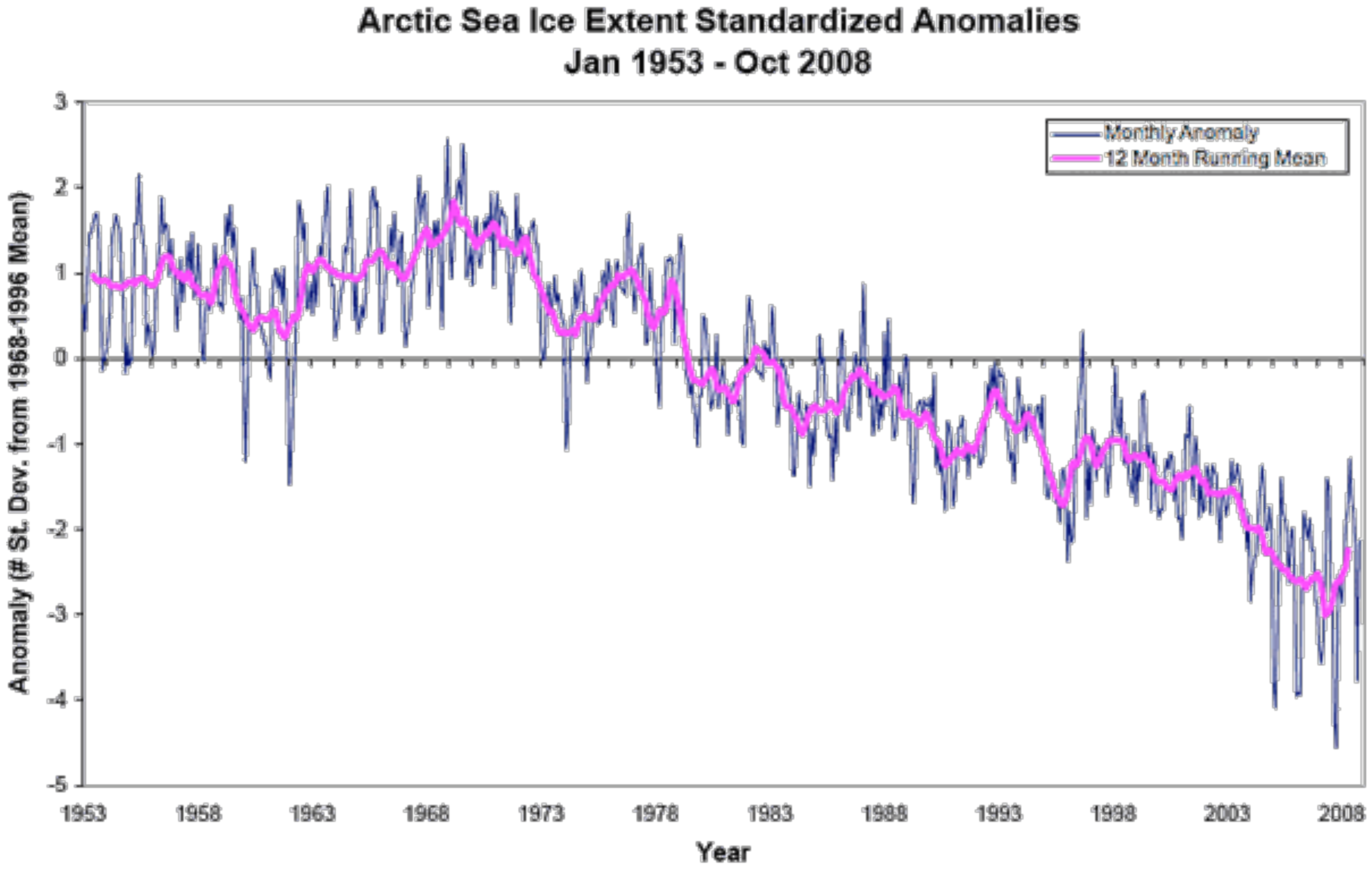
Serreze and Barry, 2014

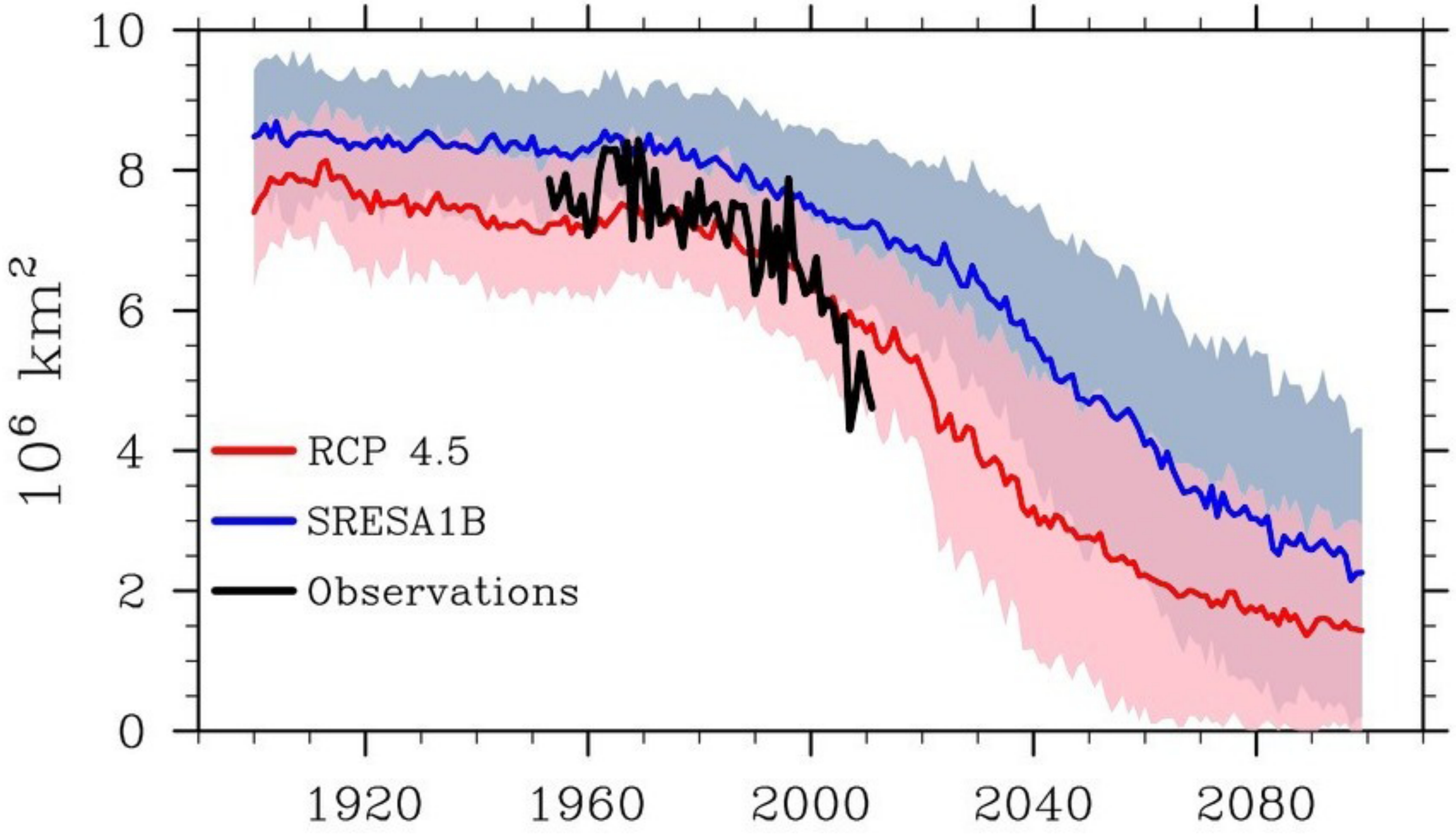
Coupling in High Latitudes

Changes in sea ice

- Trends toward less ice in recent years (especially in September)
- Increased destabilization after 2000 — “new Arctic”?
- Decreasing trends stronger than those predicted by climate models
- Climate models project continued decreases into the future
- A summertime ice-free Arctic within decades?





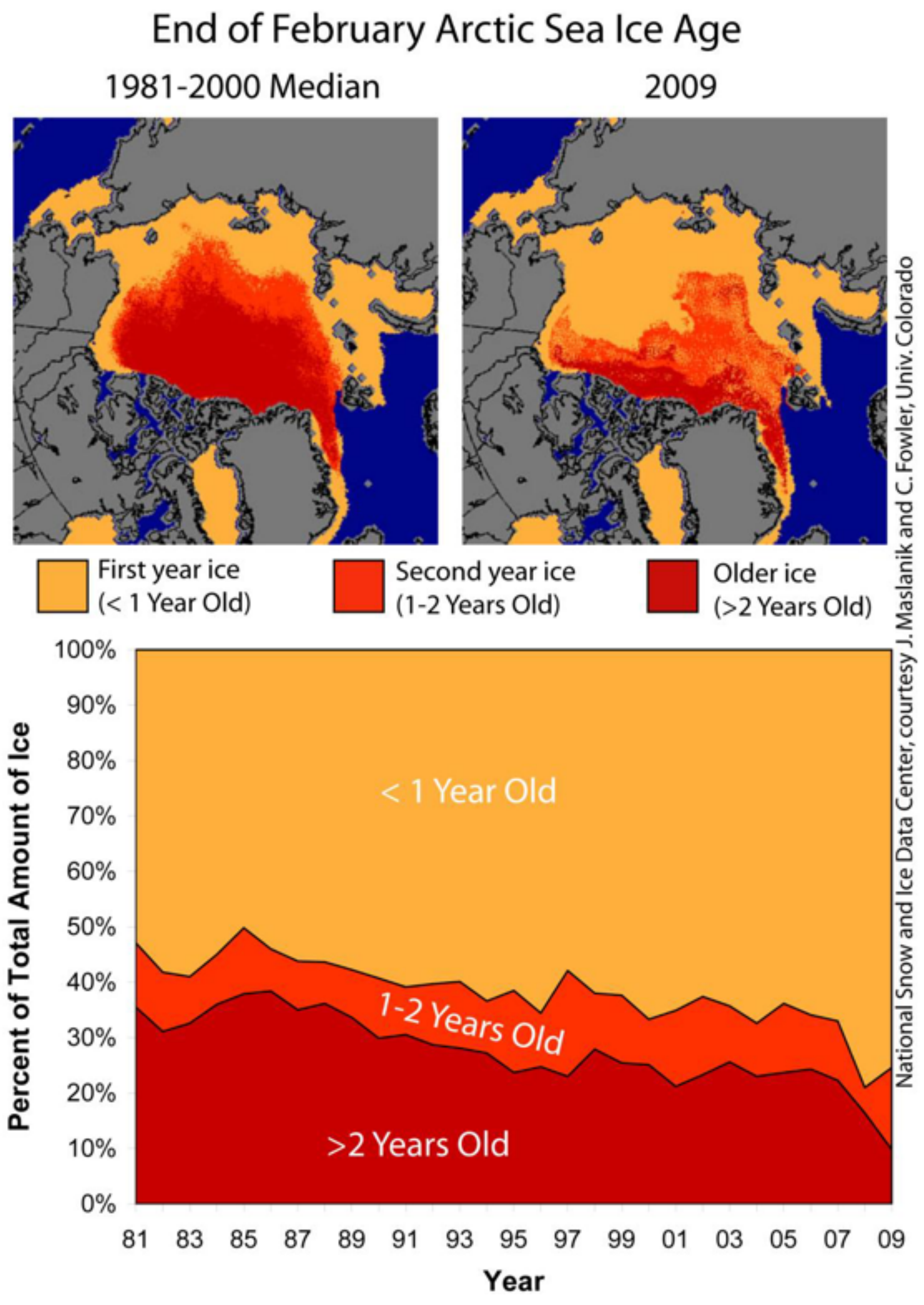


Serreze and Barry, 2014

Coupling in High Latitudes

Changes in sea ice

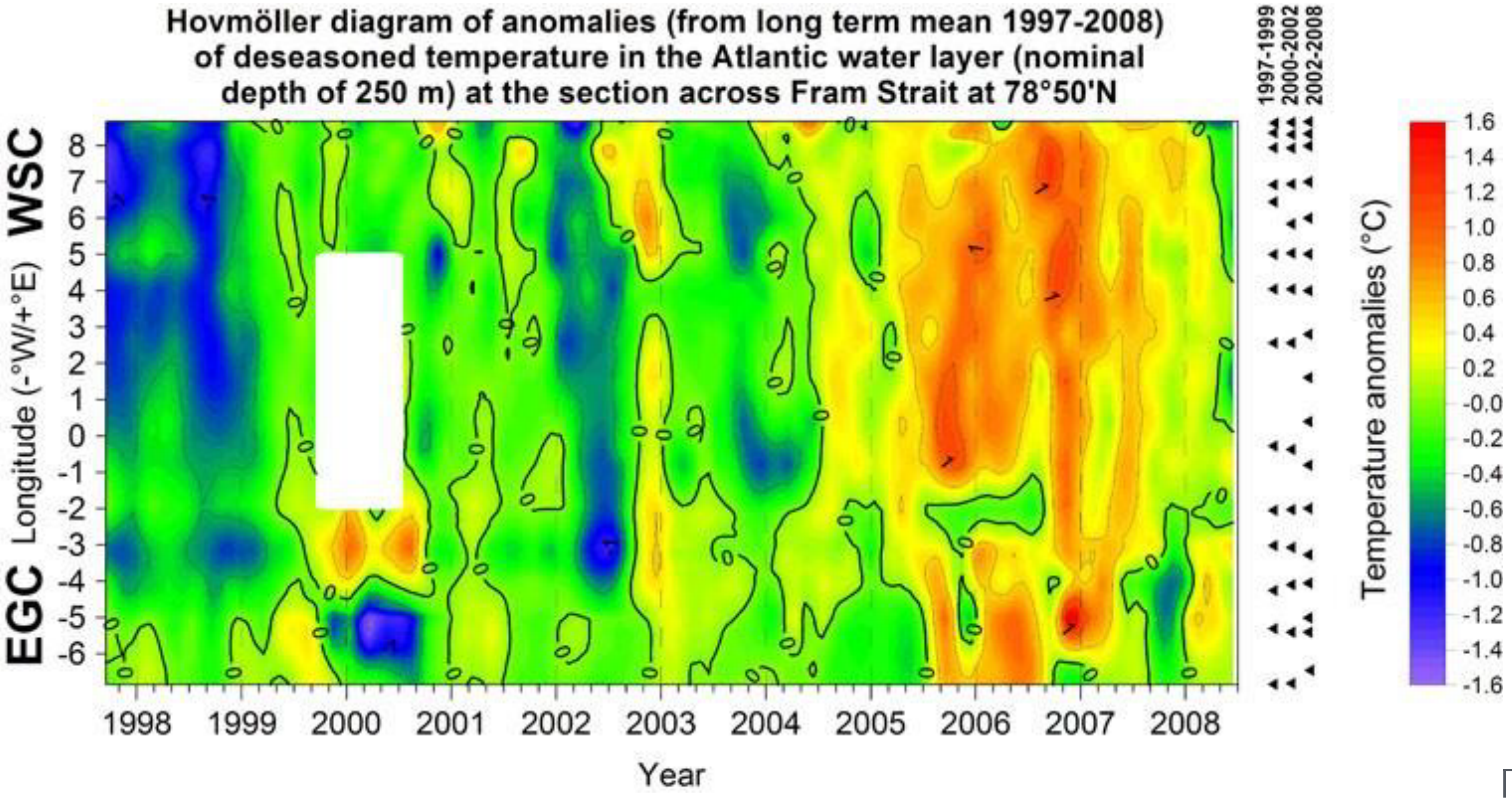
- Strong indications of a decrease in ice thickness, from a mean of 3.78 m in 1980 to a mean of 2.53 m in 2000
- Satellite data indicate further decreases to 1.89 m through 2008, with accelerated loss after 2000
- Although uncertainties are large, best estimates of volume loss indicate that the decreasing trend is greater than that for extent, ranging from about 900 km^3 per year (late winter / spring) to about 1500 km^3 per year (late summer / fall)
- The most extensive loss is for older ice, with the estimated fraction of multi-year ice decreasing from 75% in the 1980s to 45% in 2011 — accelerated bottom melt of deep ridges?
- Relationships among ice growth, ice strength, and ice motion may impact the formation of leads, feeding back to ice growth, with partial recoveries after each collapse
- Implications for atmosphere–ocean coupling and climate and weather in mid-latitudes



Serreze and Barry, 2014

Coupling in High Latitudes — Changes in ocean circulation

- Warmer inflow of Atlantic Water in Nordic Seas
- Marine species are moving northward

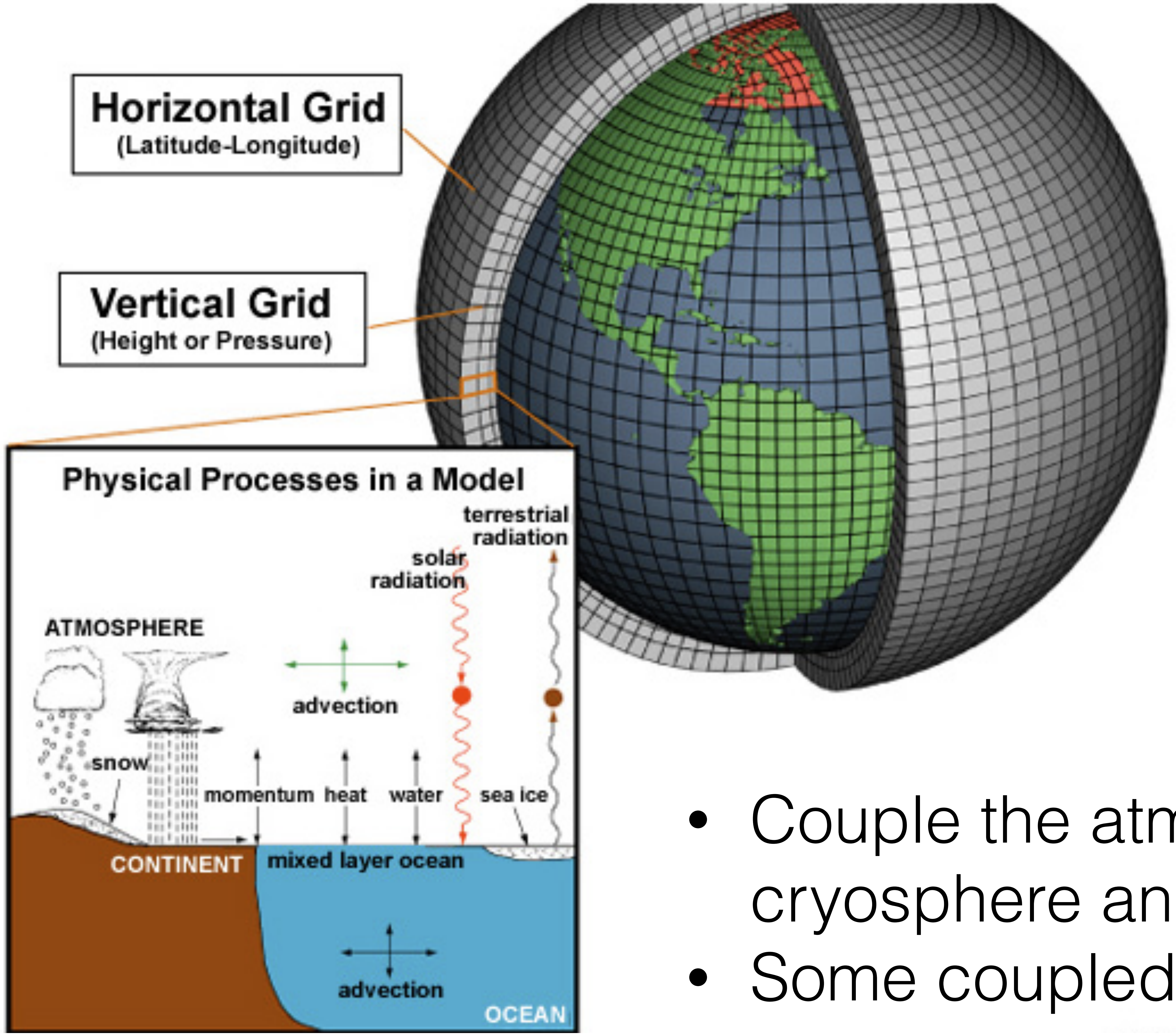


Talley et al., 2011

Outlook

- The Arctic is a major player in climate, and climate prediction requires an accurate understanding of drivers and feedbacks in the Arctic
- Understanding the role of the Arctic requires untangling complex and intricate interactions among atmosphere, ocean, sea ice, and land processes
- Surface observations, remote sensing data, and models will all be important
- Focused study has led to significant advances in understanding the Arctic climate system and projected changes, but quantitative attribution is still lacking
- Despite rapid improvements in parameterization of small-scale physical processes in atmosphere, ocean and ice, significant problems remain
- Southern hemisphere changes also important — greenhouse gas increases and ozone depletion both enhance the occurrence of the positive phase of the southern annular mode
- Ekman pumping associated with SAM changes enhances upwelling of warm water with high dissolved inorganic carbon, reducing sea ice year-round and reducing the Southern Ocean carbon sink

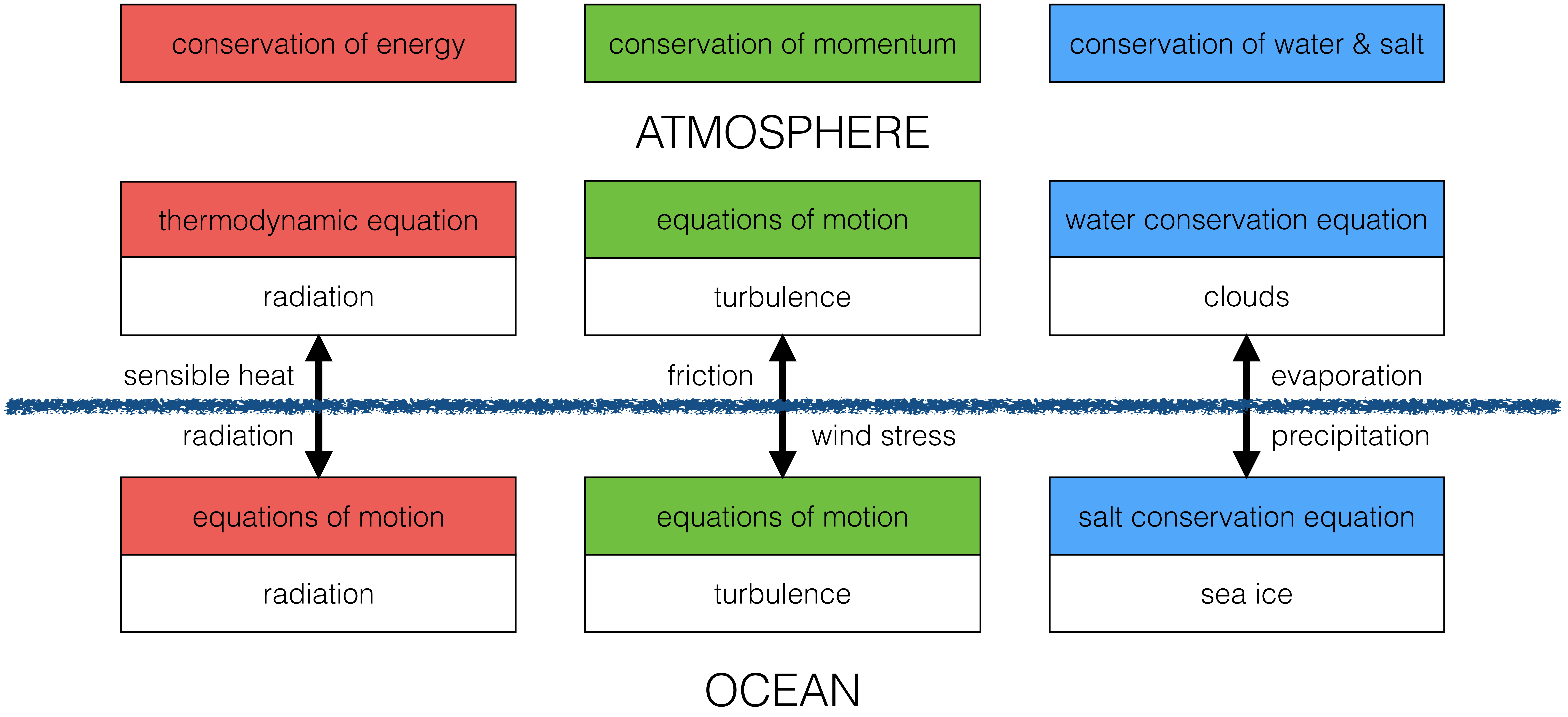
Coupled Climate Models



- Couple the atmosphere and ocean together with the cryosphere and land surface
- Some coupled models also include the biosphere

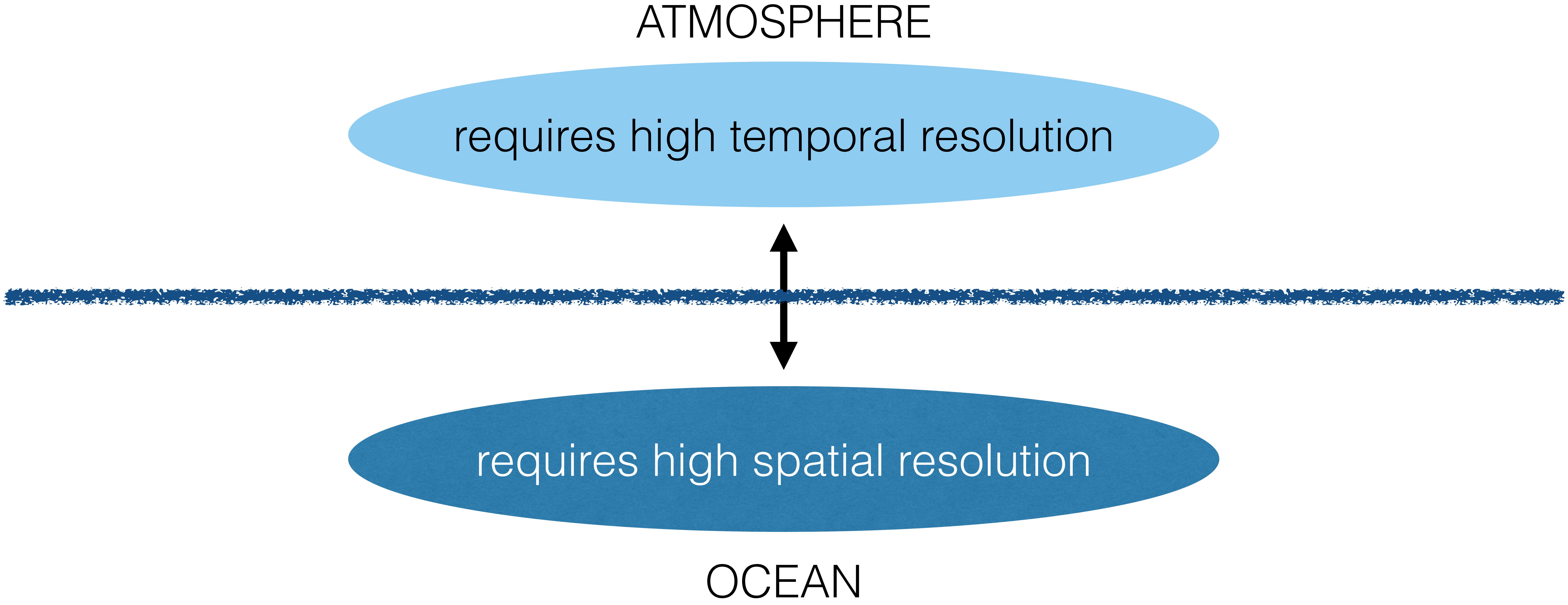
noaa.gov

Coupled Climate Models



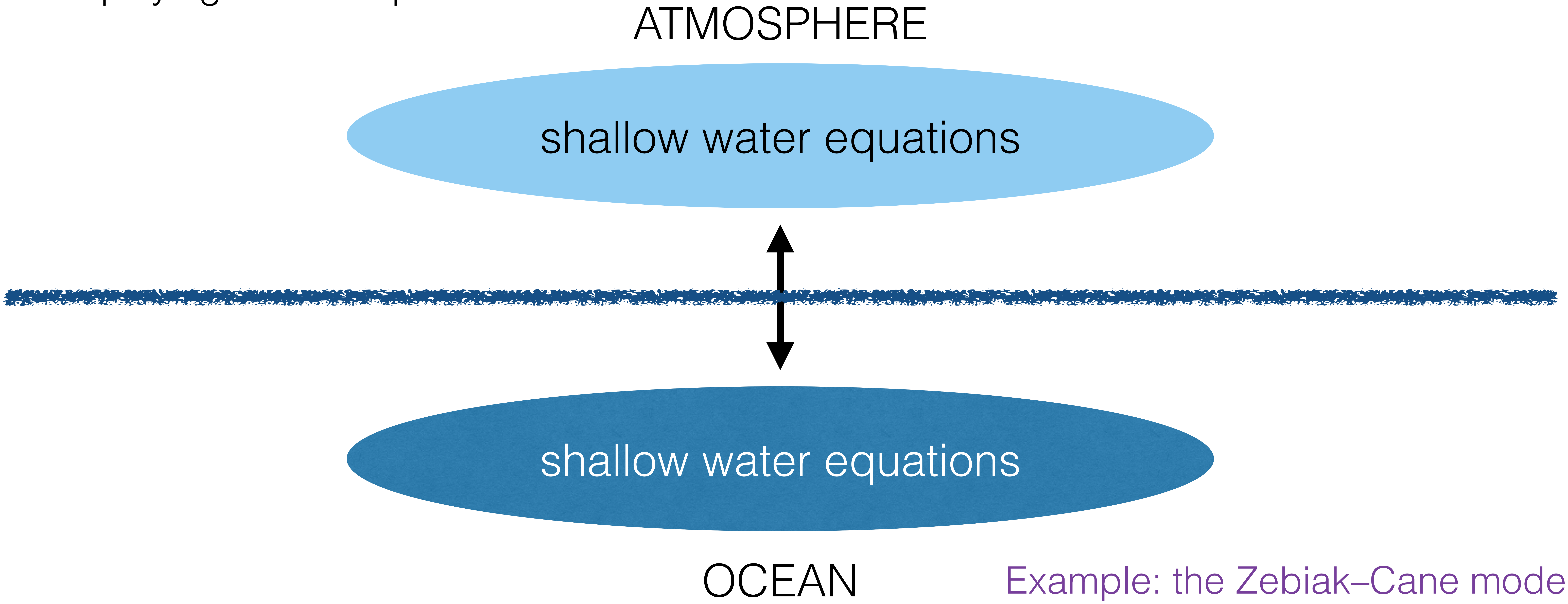
Coupled Climate Models

The atmosphere and ocean have different requirements…



Coupled Climate Models

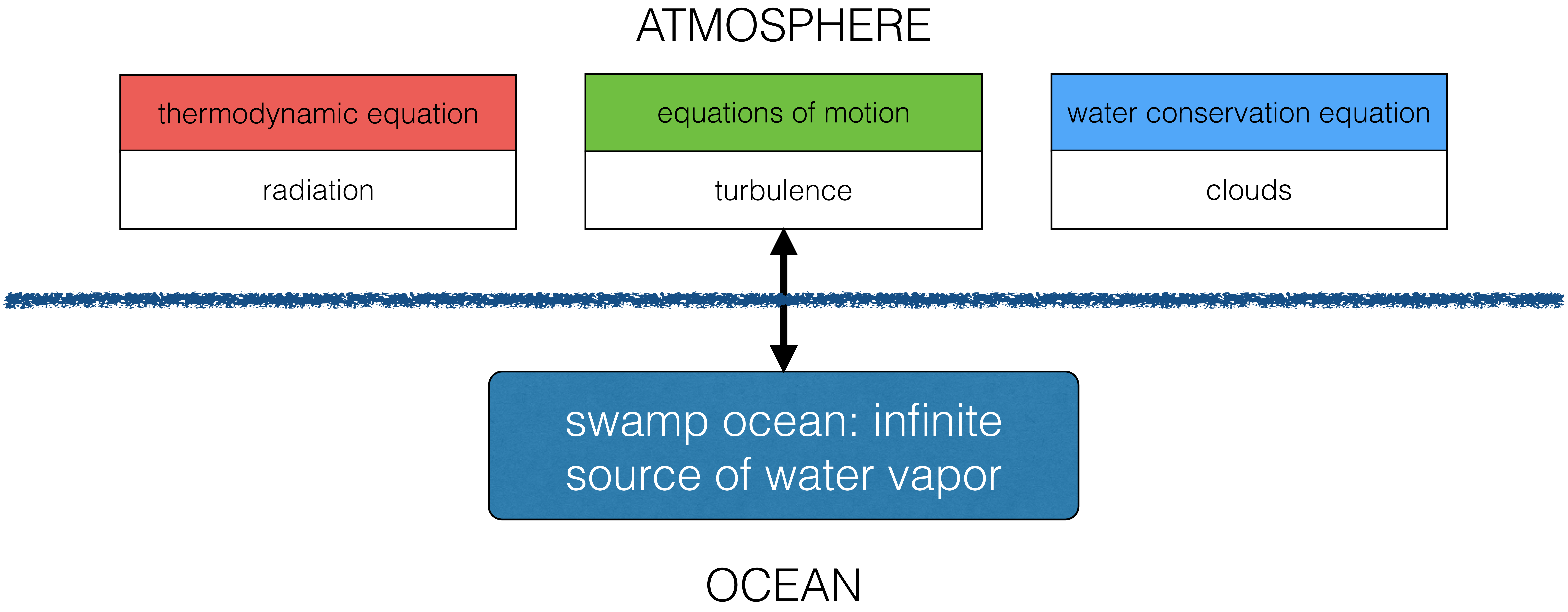
We can reduce complexity by simplifying both components…



Example: the Zebiak–Cane model

Coupled Climate Models

We can also simplify one component
and focus on the other…



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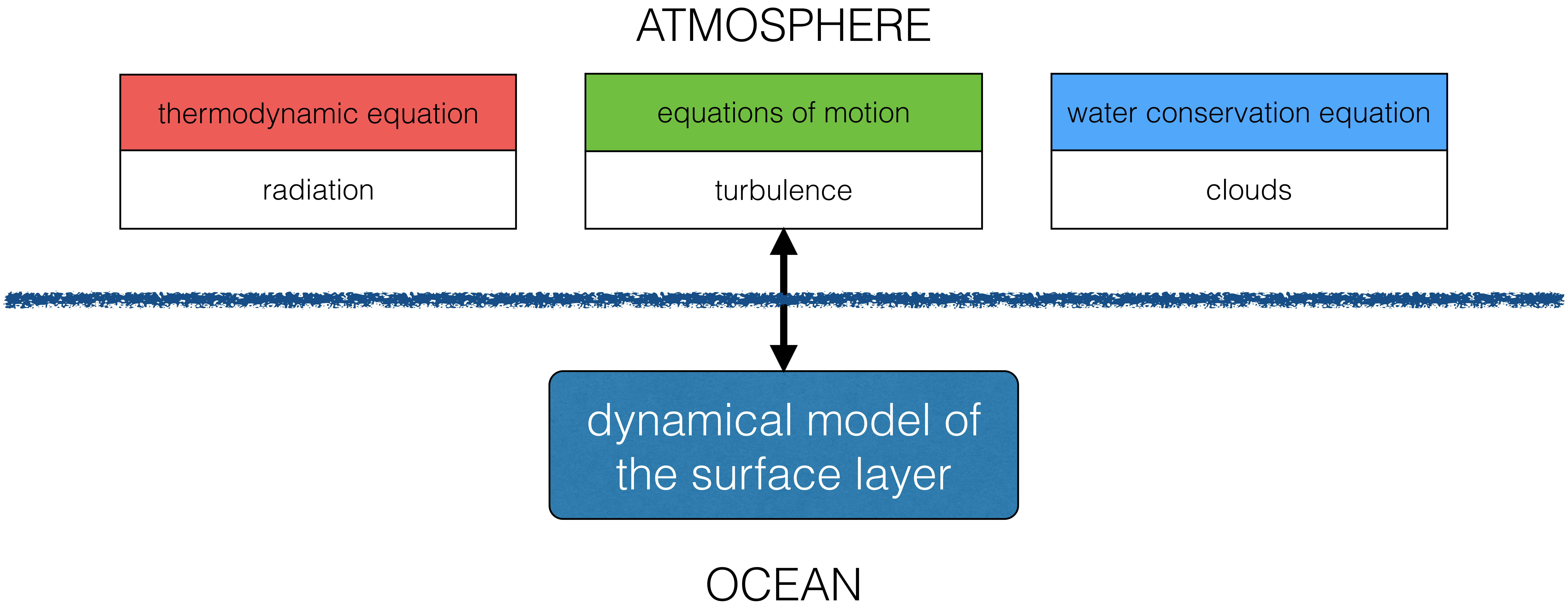
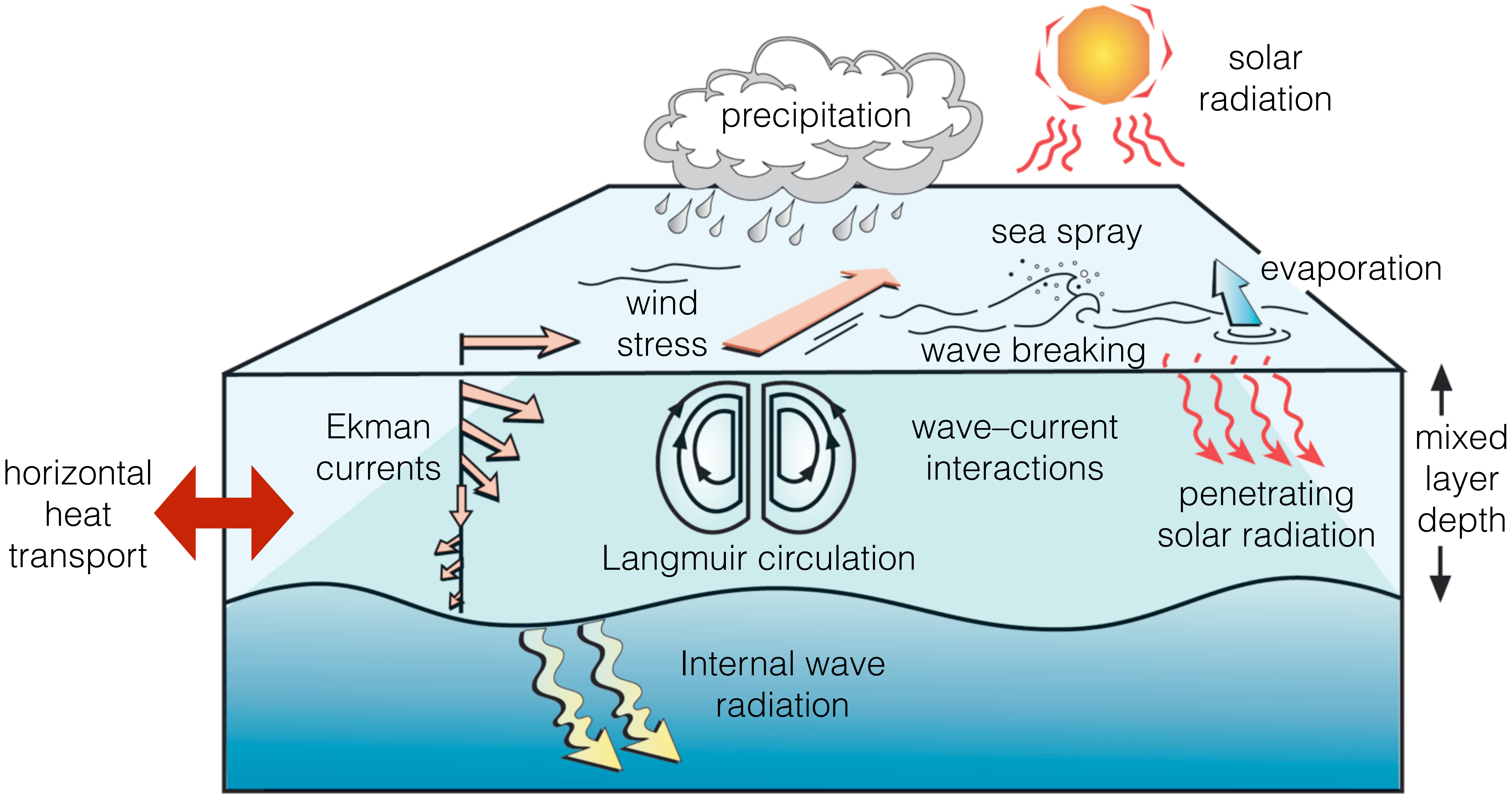


Coupled Climate Models

Dynamical model of the ocean surface layer



Wells, 2012

Coupled Climate Models

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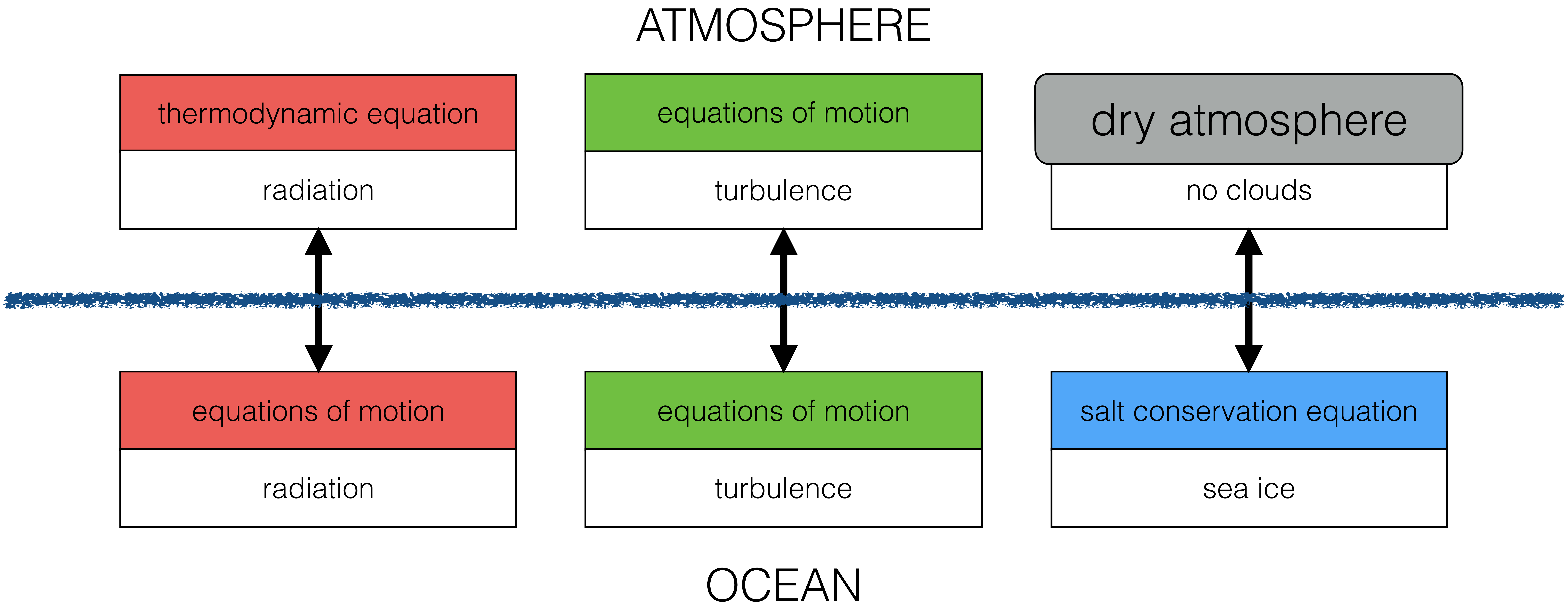

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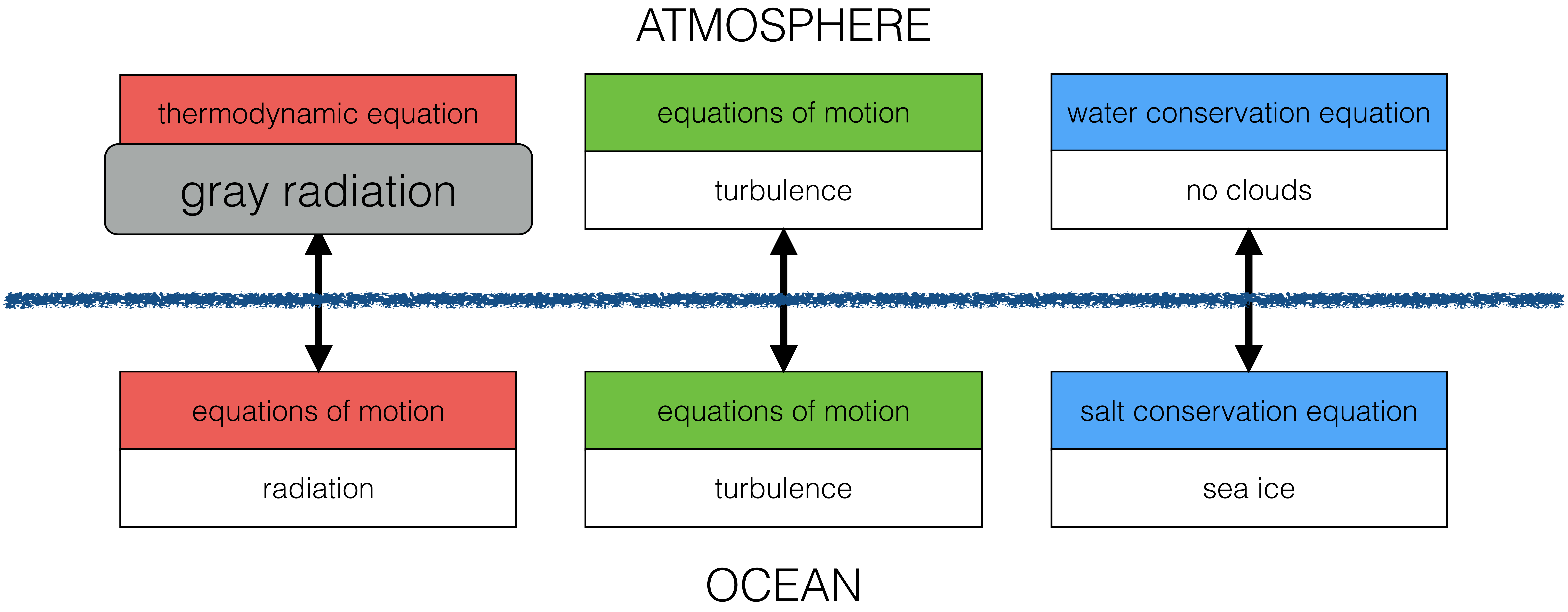

Coupled Climate Models

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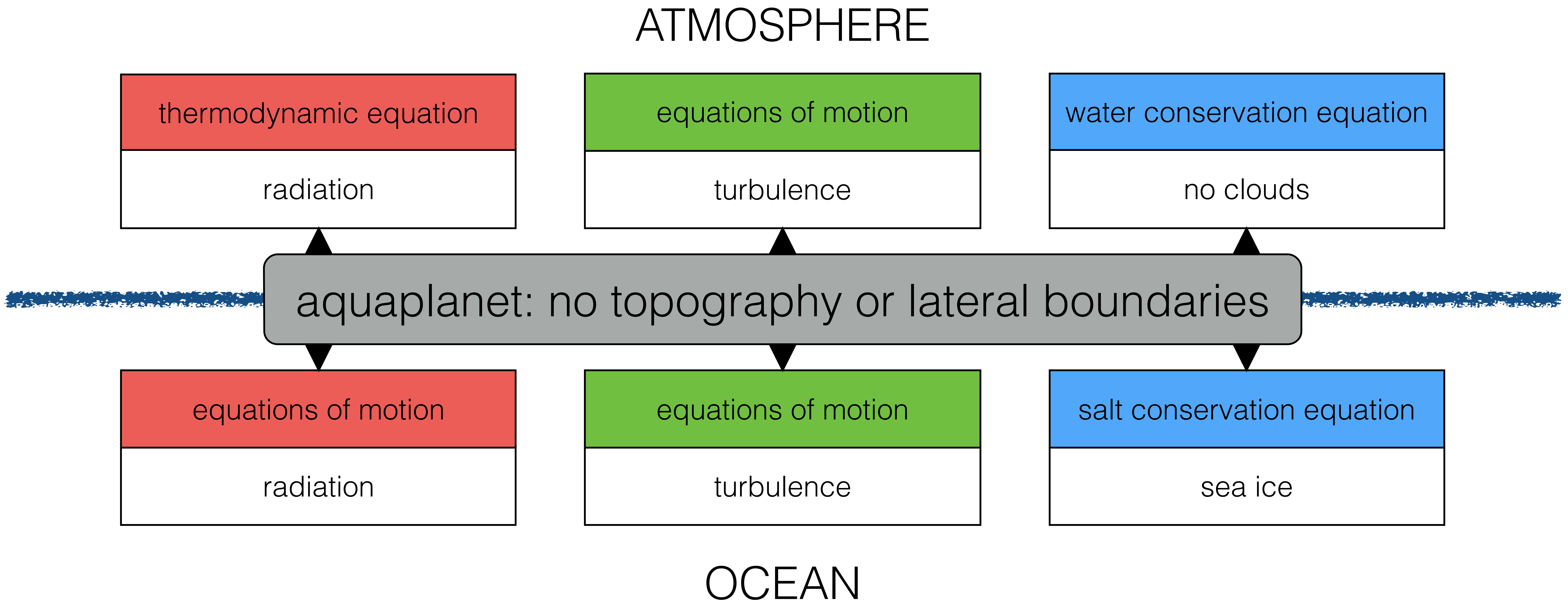

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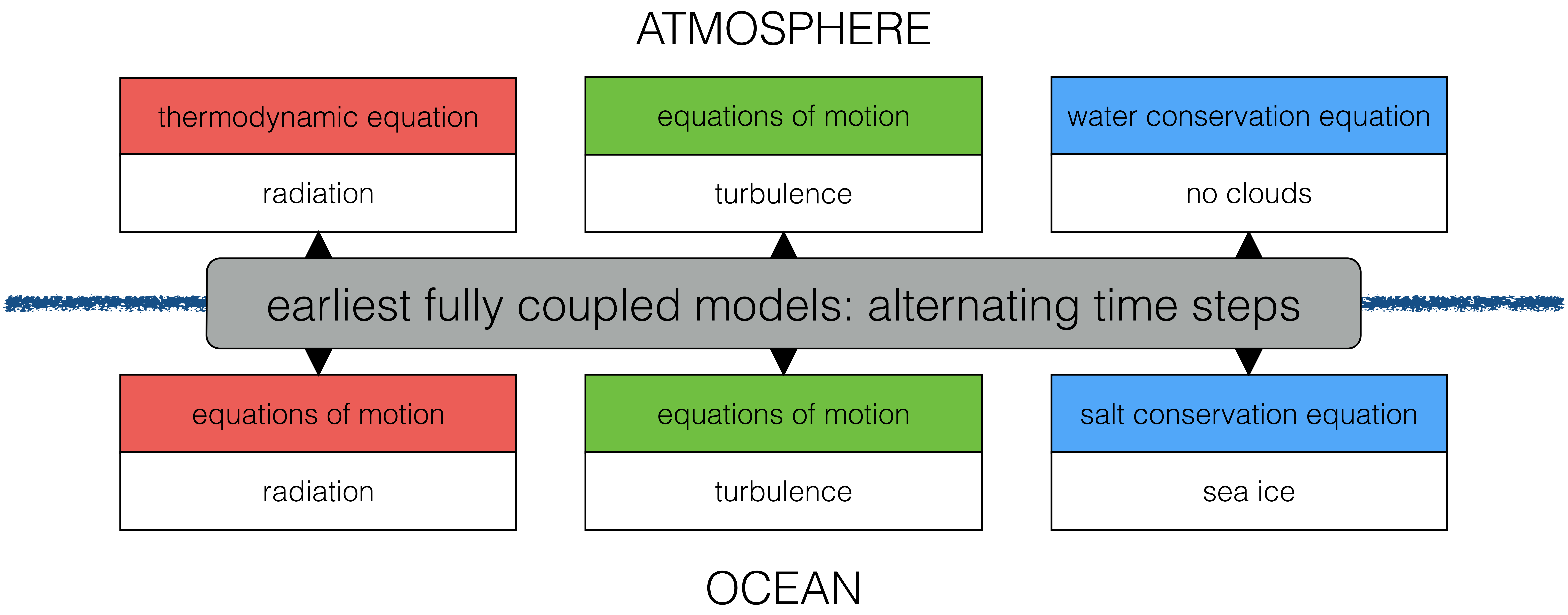


Coupled Climate Models

Coupling climate models requires sophisticated (and efficient) interpolation techniques

ATMOSPHERE

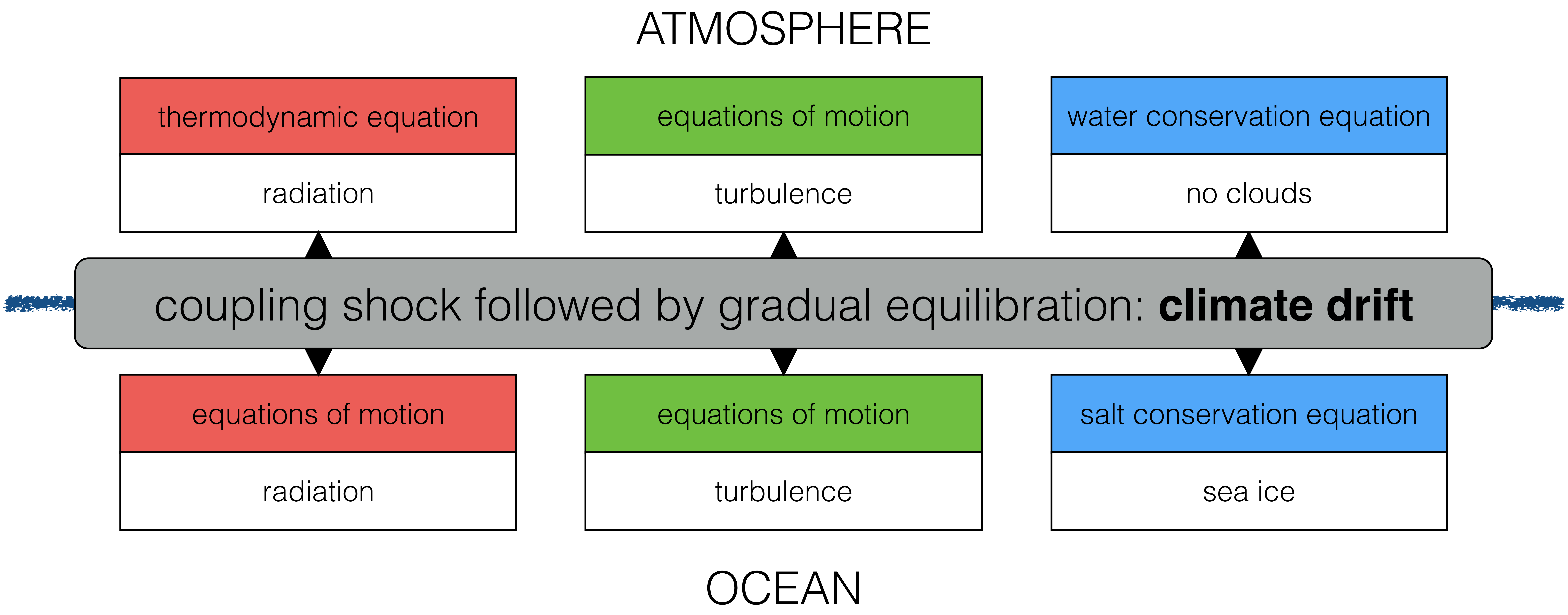
Δx = 100~300 km

Fluxes of heat, momentum, and water at the surface

Δx = 30~100 km

OCEAN

Coupled Climate Models

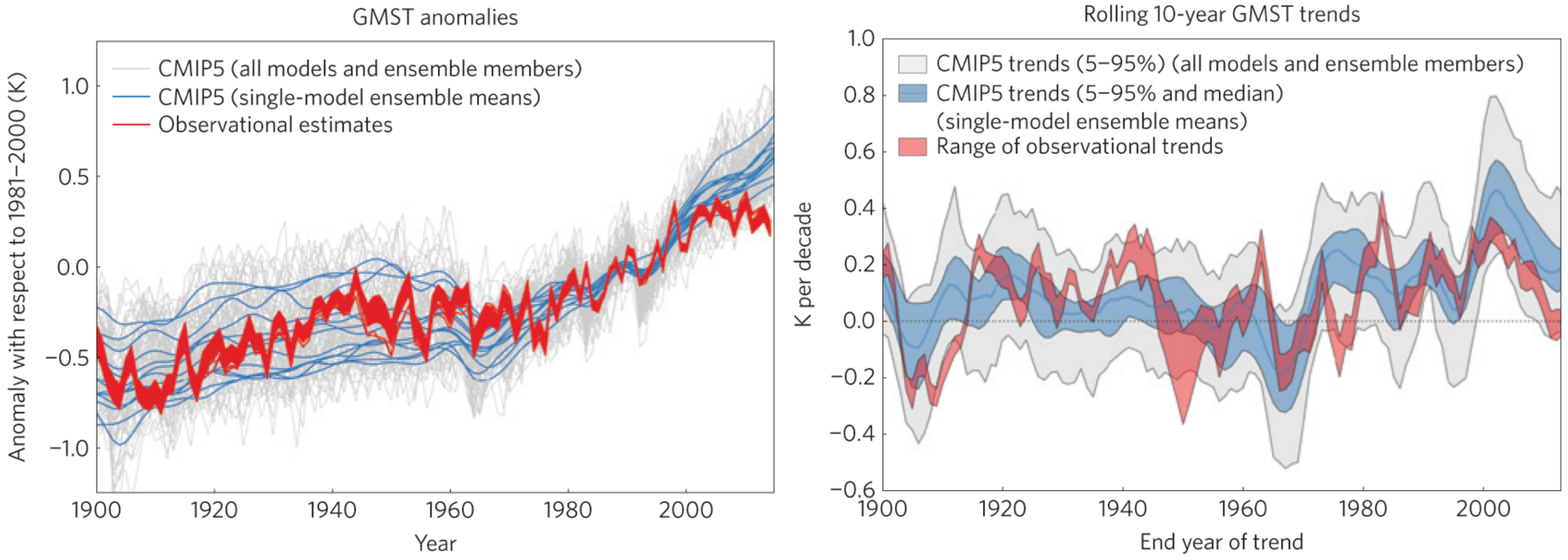


Coupled Climate Models

- Coupling-related climate drift can complicate studies of climate change signals
- Careful initialization is crucial for coupled climate models:
  - Run each component model several times
  - Observationally constrain variables at the air–sea interface
- Empirical “flux corrections”
  - Calibration of coupled models with surface variables (temperature, salinity, momentum, etc.) constrained to observed climatologies
  - Apply calculated “corrections” as artificial fluxes during coupled simulations to prevent drift away from a realistic climate state
  - Requires very long (~1000 years) initialization runs of the ocean component
  - Gradually being replaced by direct flux coupling techniques

The Global Warming "Hiatus"

Since 1998, global mean surface temperature has remained roughly constant even as greenhouse gas concentrations have continued to increase



Roberts et al., 2015

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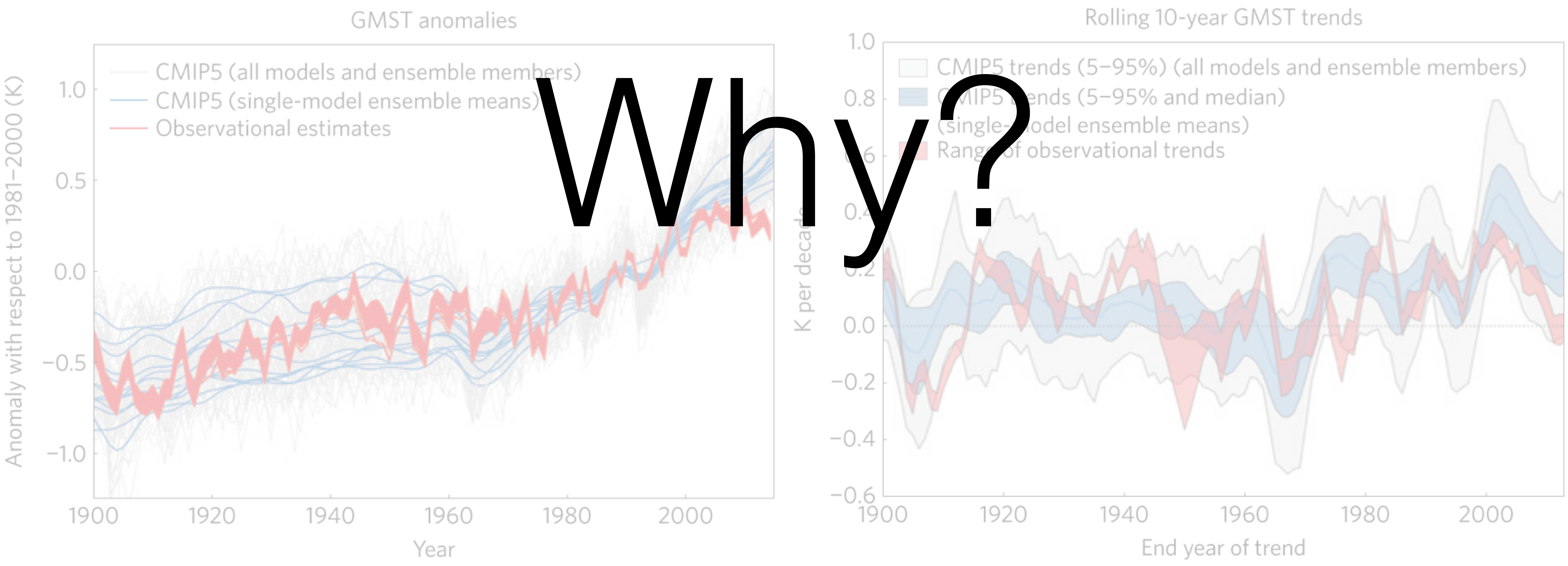
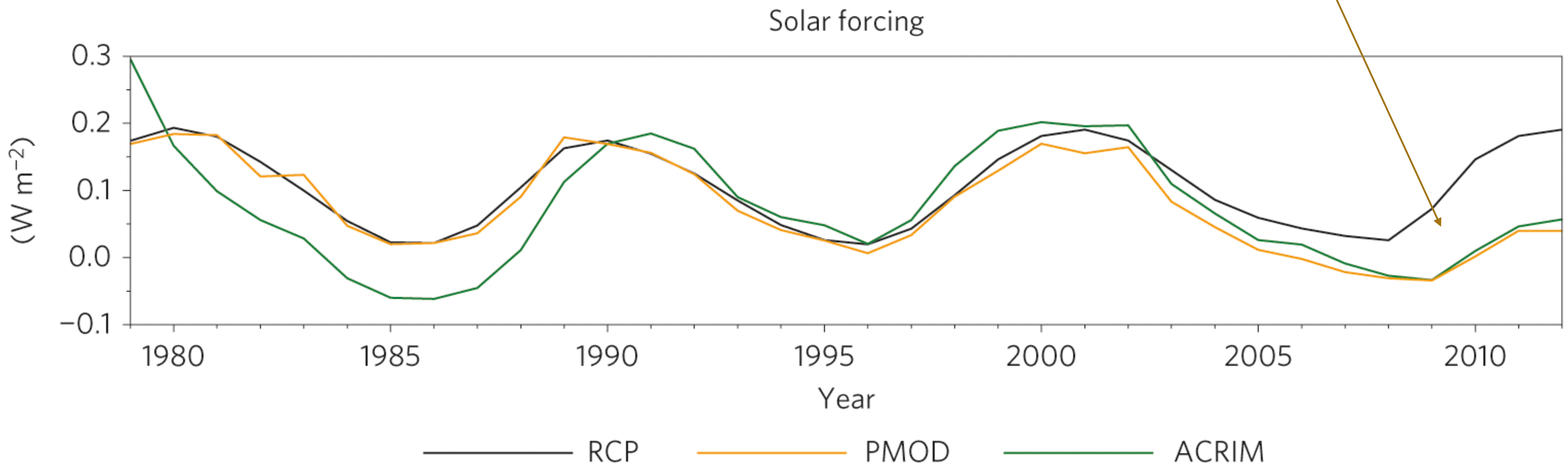


Roberts et al., 2015

Reduced Solar Radiation?

The hiatus period has coincided with a prolonged solar minimum, so that insolation was overestimated in model projections

Inaccurate projection of solar cycle evolution caused CMIP5 models to warm more than they should have during the early 2000s

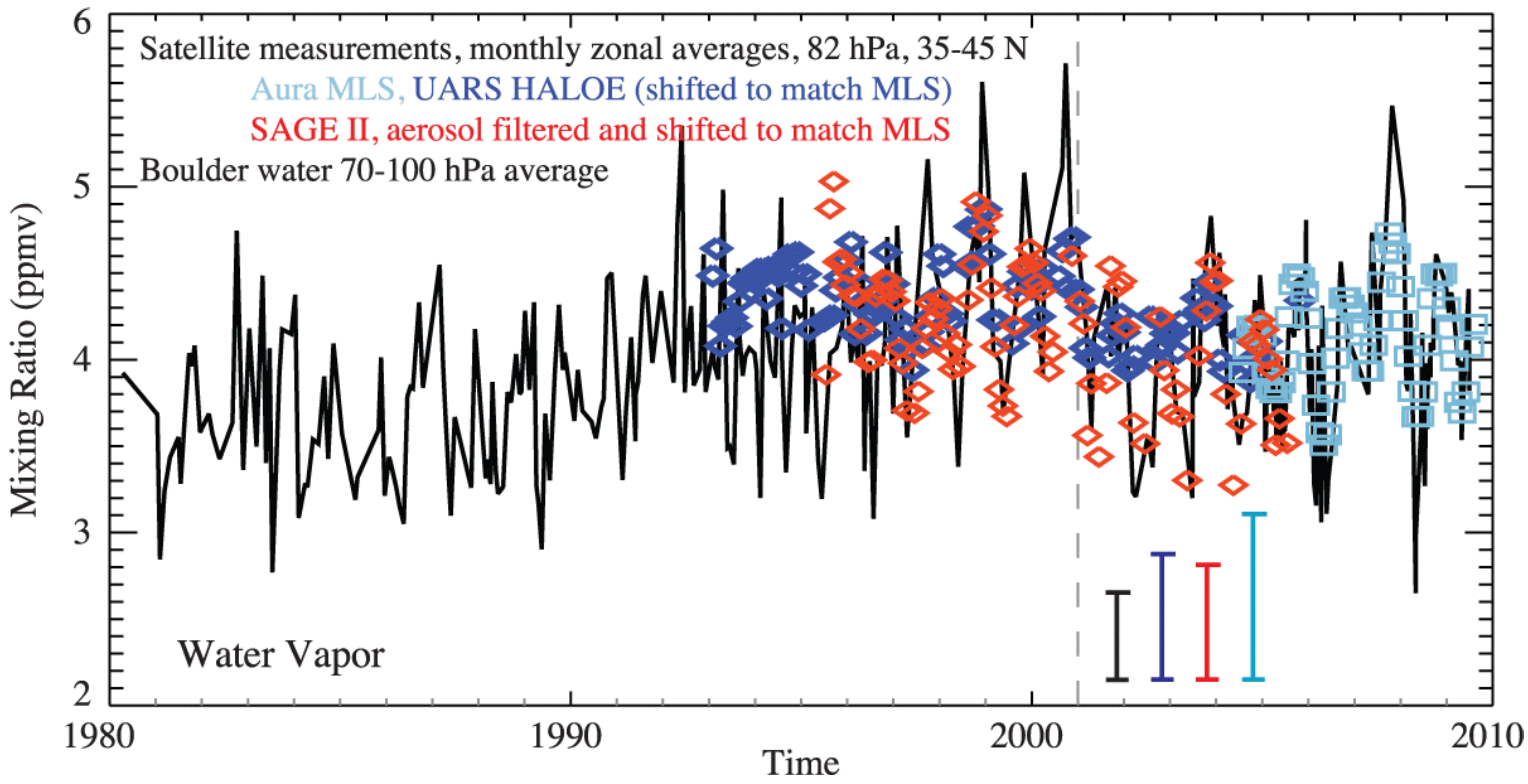


ACRIM and PMOD are two different observational estimates of total solar irradiance (TSI)

Huber & Knutti, 2014

Stratospheric Water Vapor?

Stratospheric water vapor, which has a strong greenhouse effect, decreased abruptly in 2000



The decrease in radiative forcing due to this change is also missing from climate model simulations

Solomon et al., 2010

Stratospheric Water Vapor?

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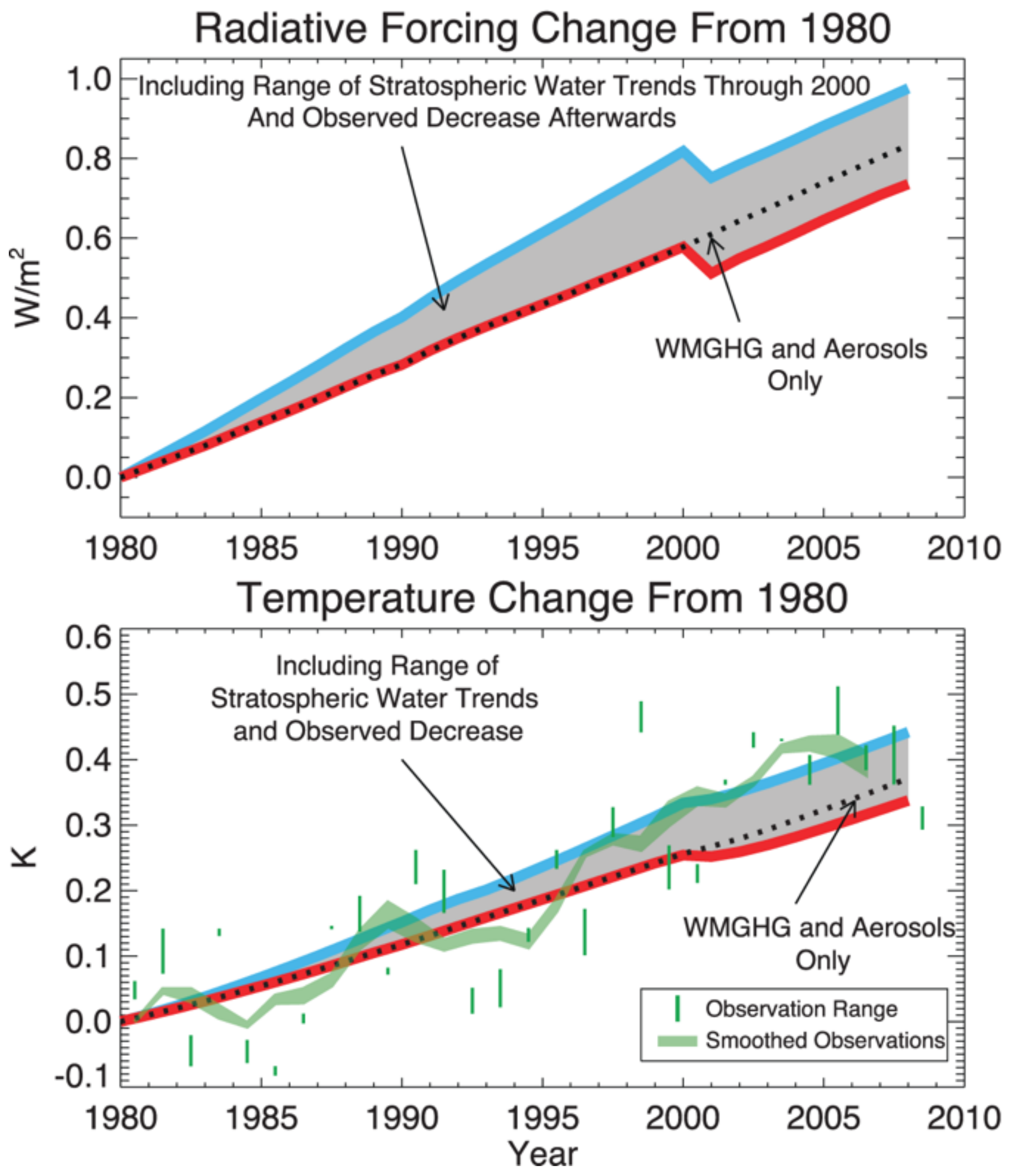
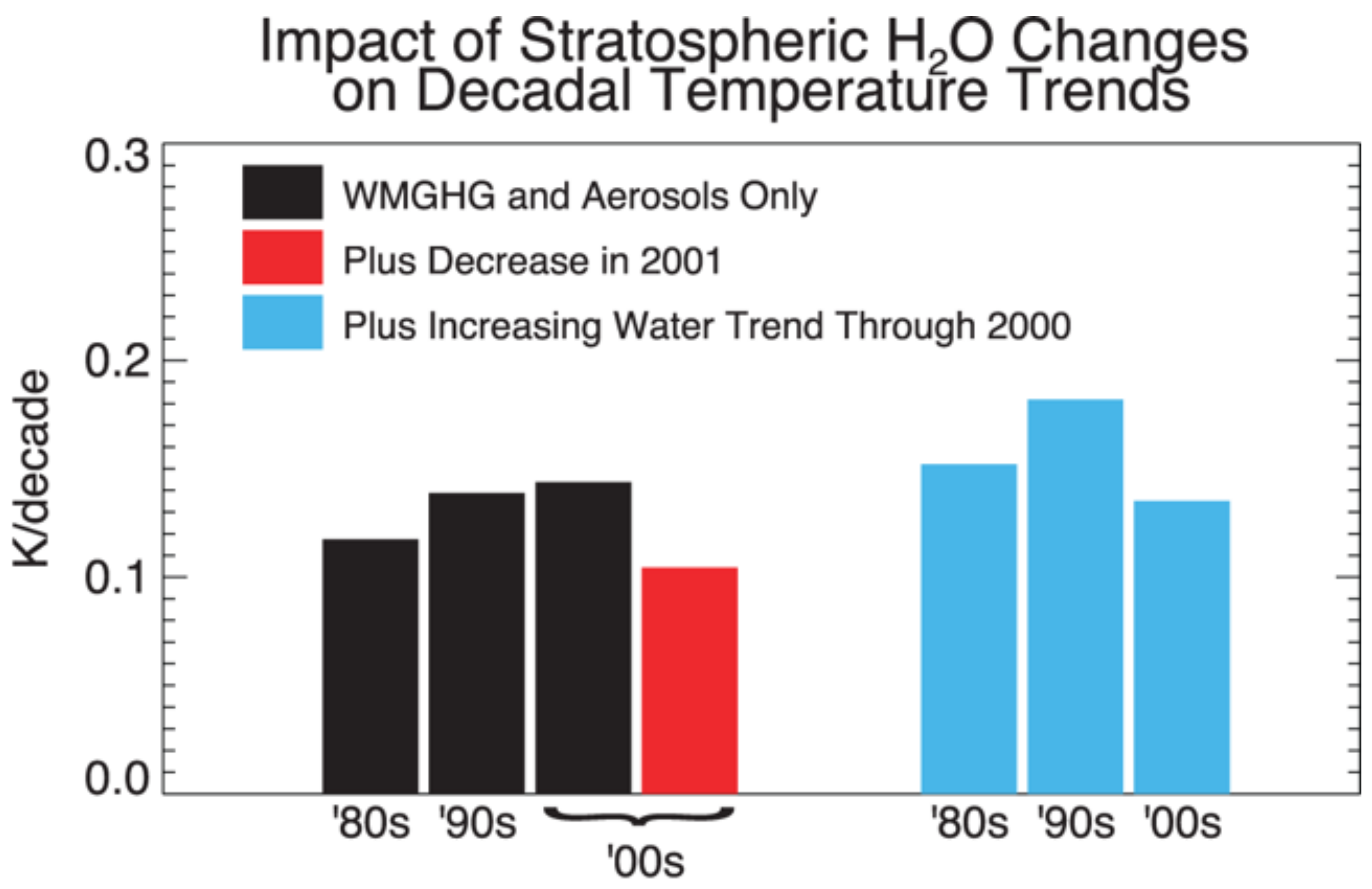


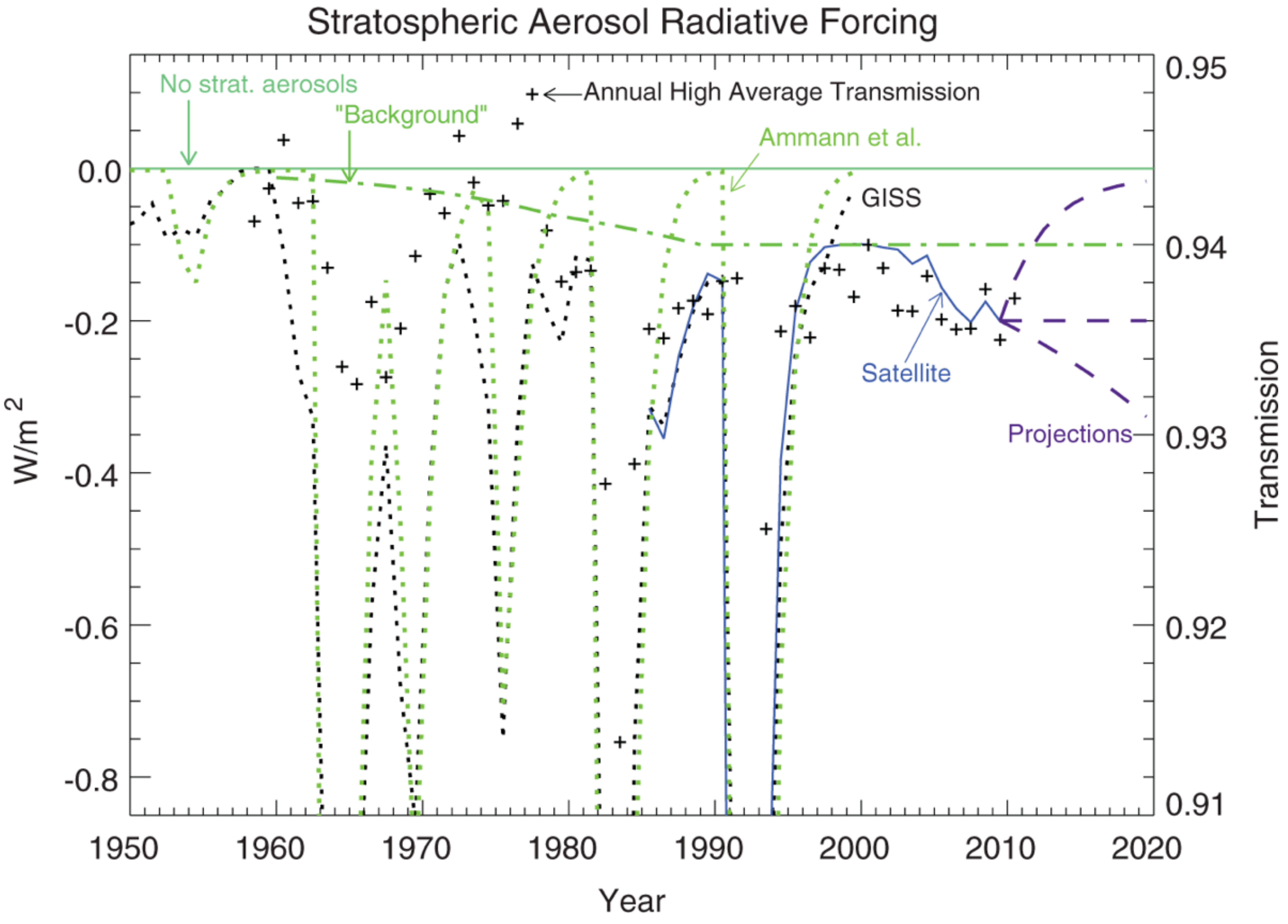


The drop in stratospheric water vapor may have contributed to the reduction in warming during the early 2000s, but scale (and subsequent increases) mean it is unable to fully explain the hiatus

Solomon et al., 2010

Volcanic Aerosols?

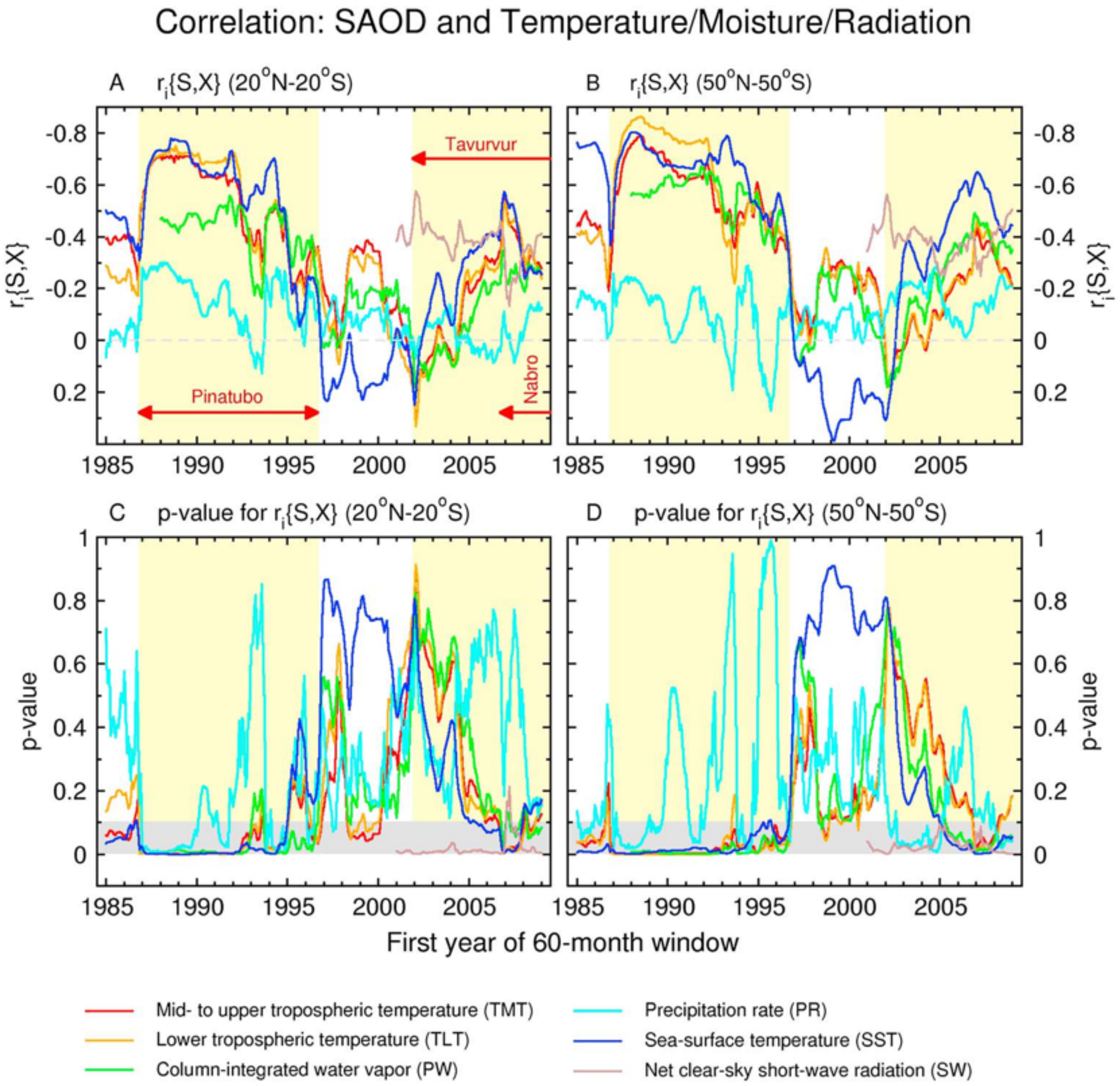
Many models assume zero forcing from volcanic aerosols after 2000, but this neglects several recent “small” eruptions

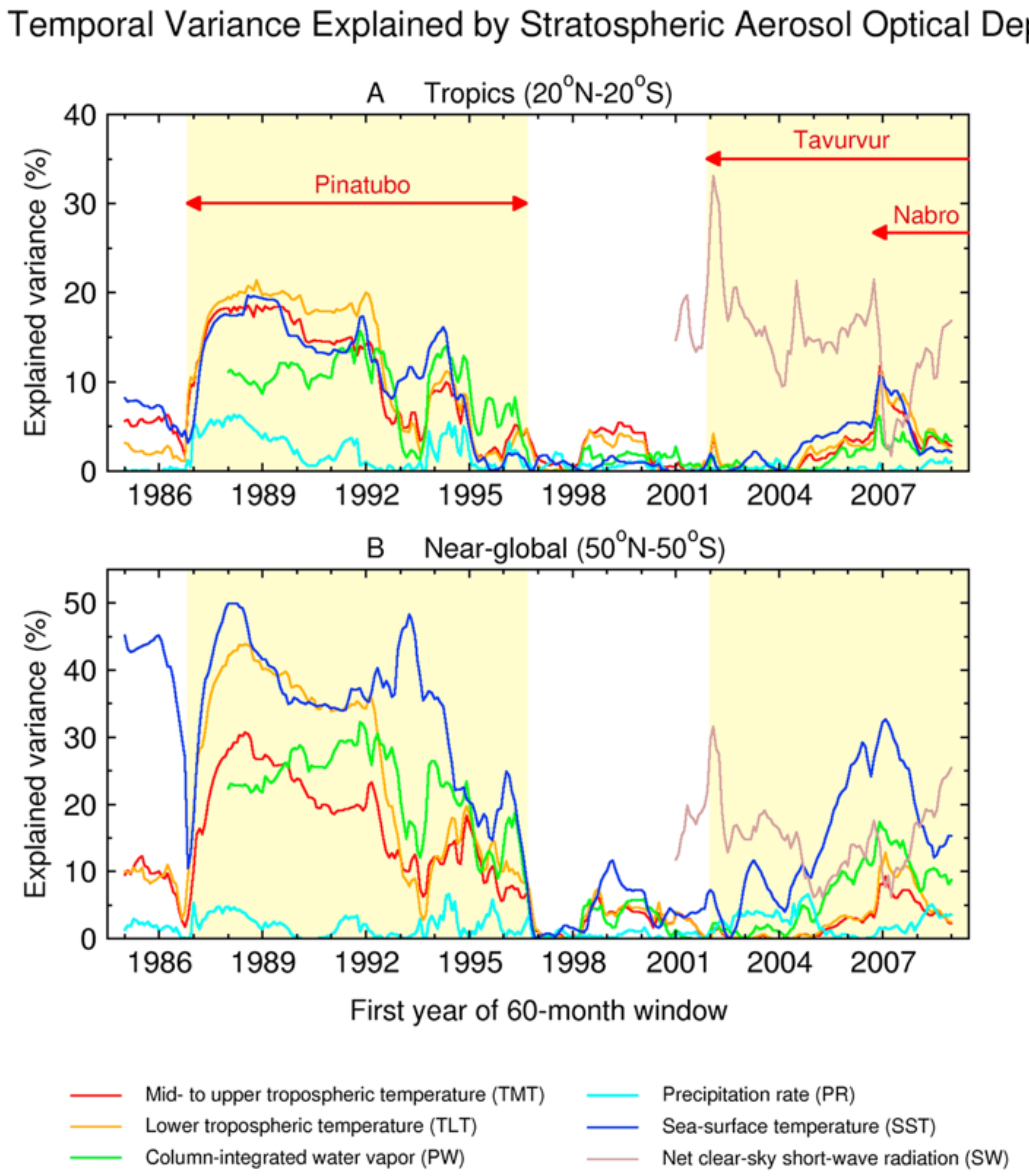


Solomon et al., 2011

Volcanic Aerosols?

Tropical and global mean SST appear to have a connection with stratospheric aerosol variability during the early 2000s

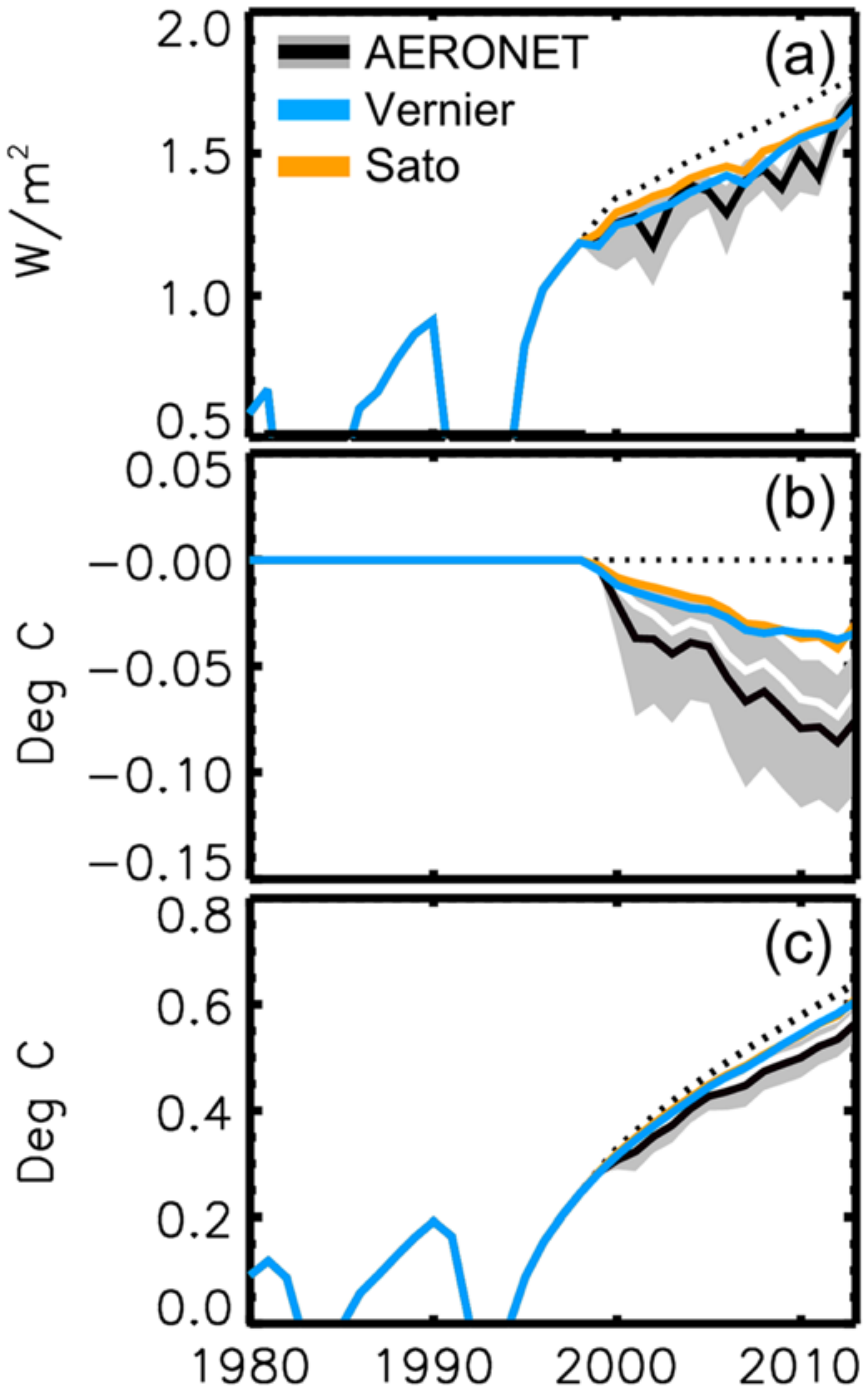




Santer et al., 2015

Volcanic Aerosols?

Volcanic forcing likely reduced warming over the hiatus period, but appears unable to explain all of the difference



Total radiative forcing with/without volcanic aerosols

Temperature anomaly relative to baseline model

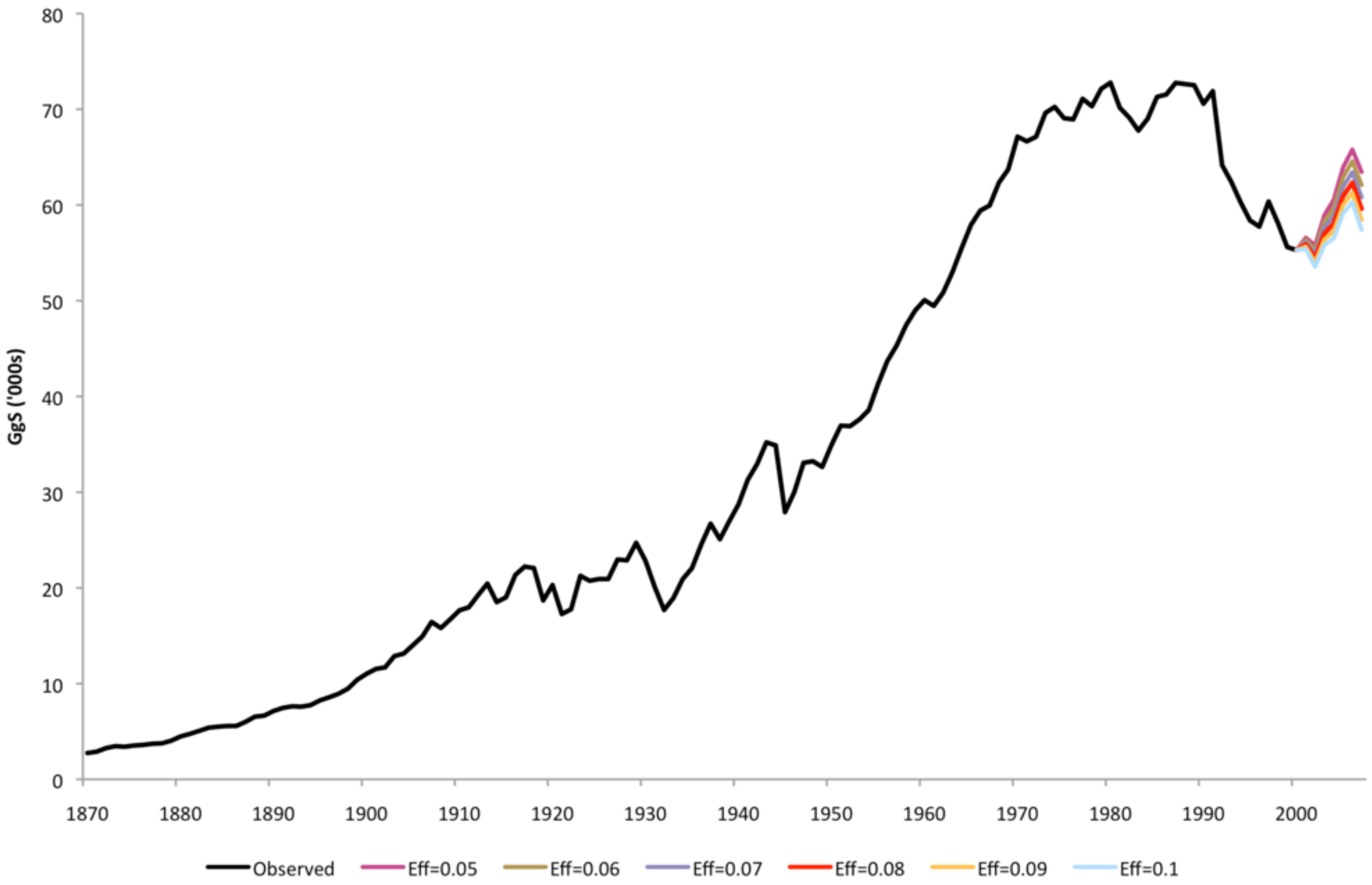
Temperature anomaly (anthropogenic + volcanic forcings) in a “climate model of intermediate complexity”

Ridley et al., 2014

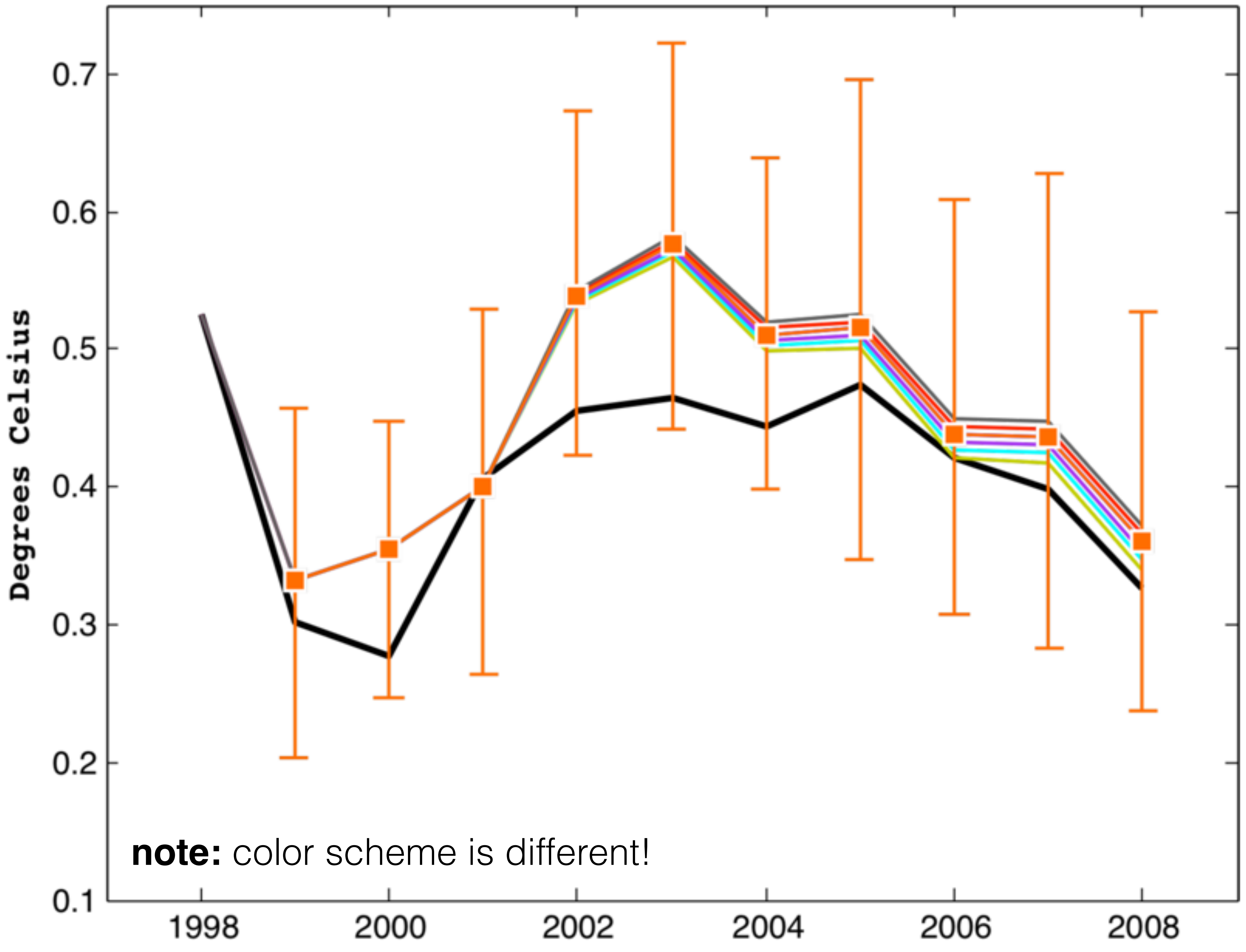
Anthropogenic Aerosols?

Sulphate emissions from coal combustion in China have grown rapidly in recent years — did these contribute to the hiatus?

sulphate emission estimates under different assumptions



forecasts of global mean temperature anomaly

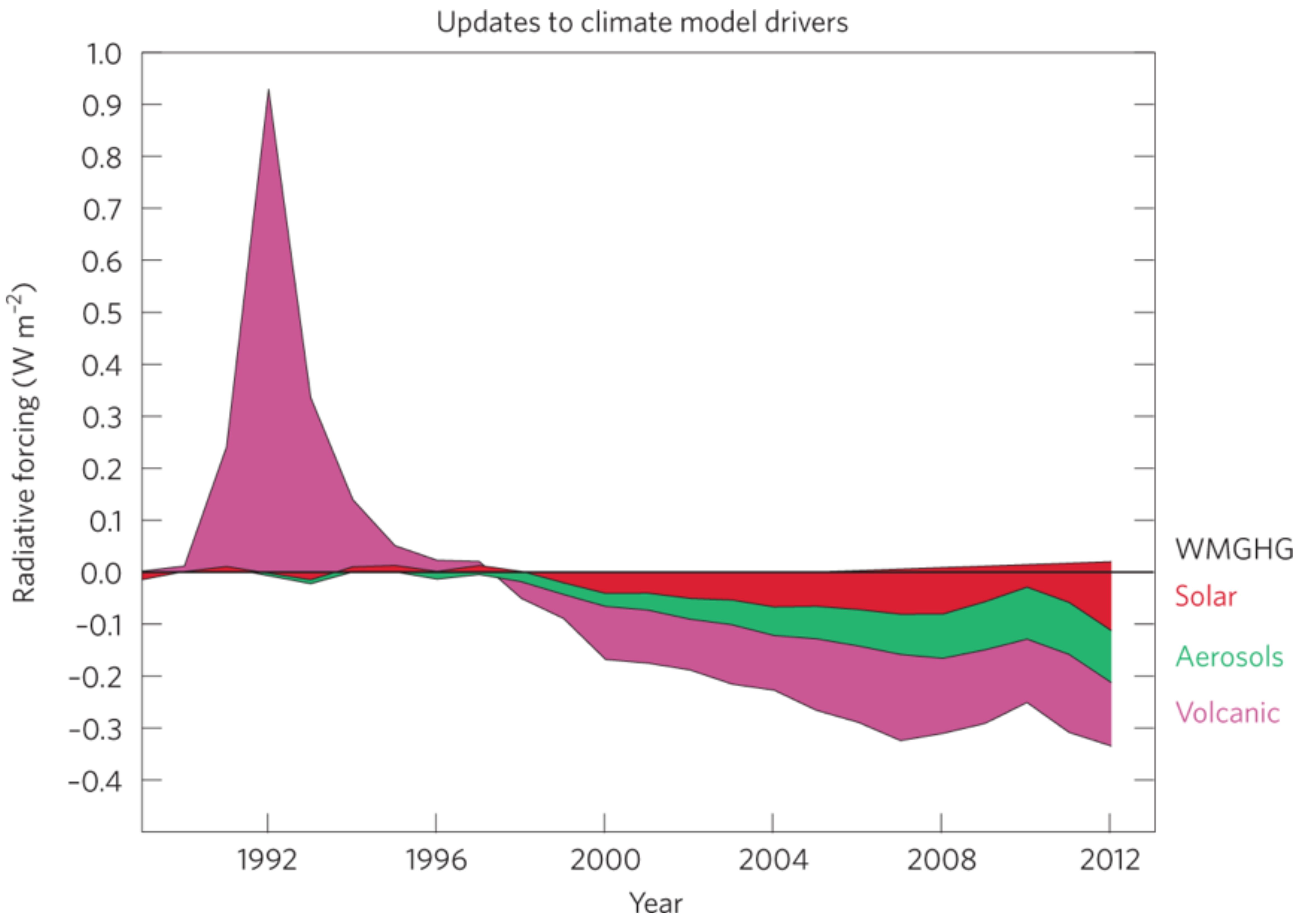


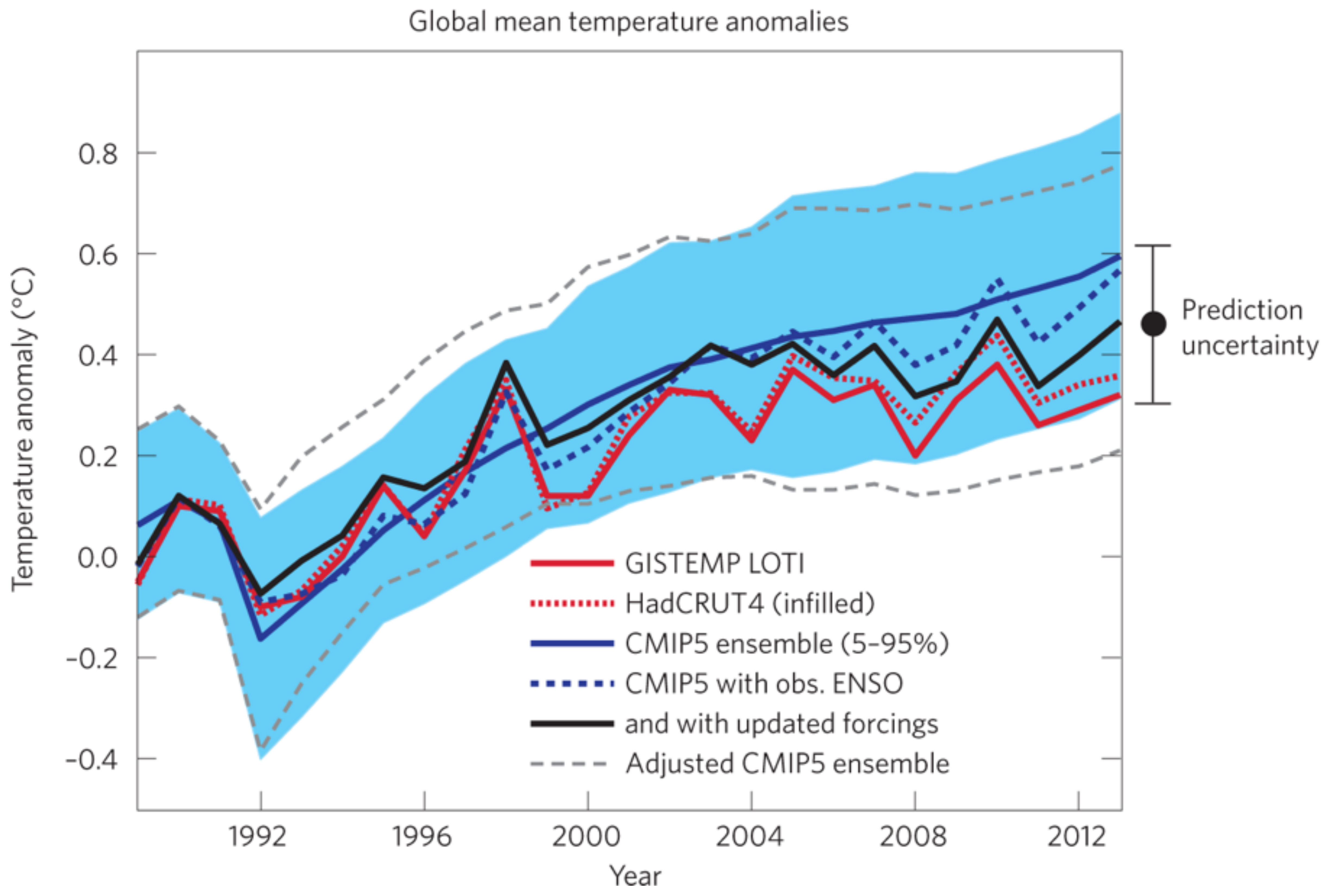
Volcanic and anthropogenic aerosol changes together can explain 50~75% of the hiatus

Kaufmann et al., 2011

A Combination of Forcings?

Adjusting solar, volcanic and anthropogenic aerosol forcings to better match observations can eliminate most of the model bias



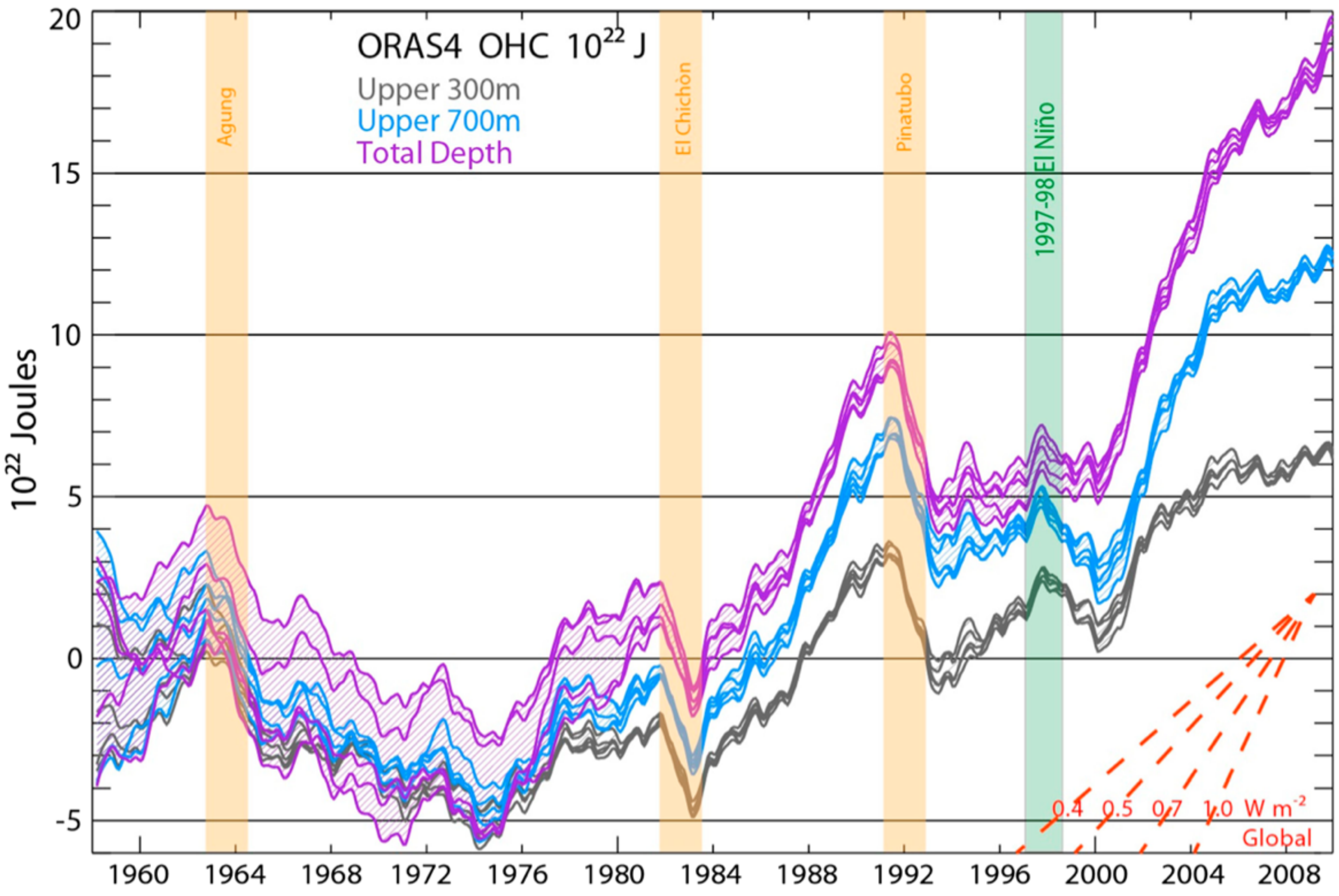


- **Volcanic**: ~30%
- **Solar**: ~15%
- **Anthropogenic aerosols**: ~25%

Schmidt et al., 2014

Ocean Heat Uptake?

More than 90% of global warming is entering the oceans — could the hiatus indicate redistribution of OHC with depth?



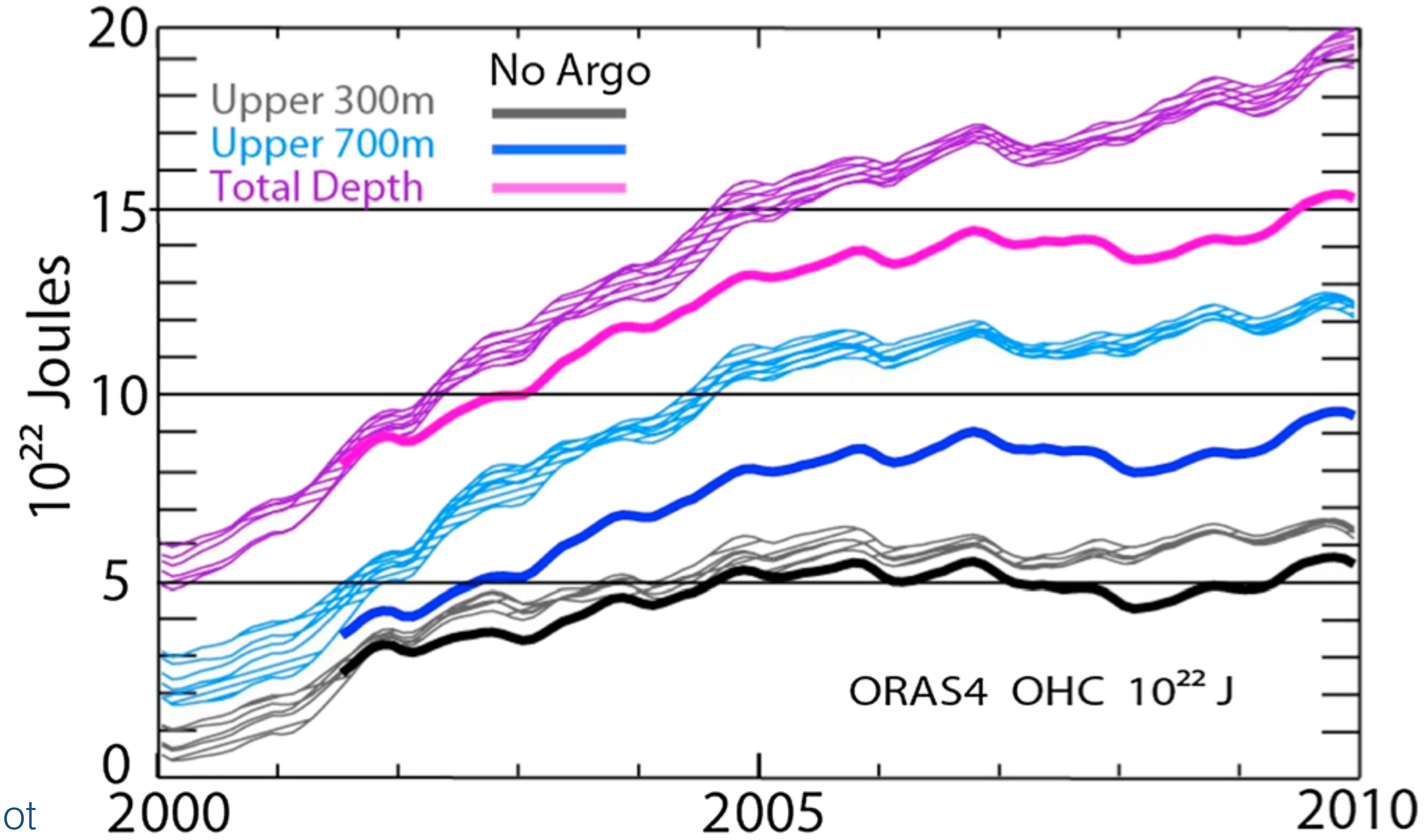
Deep ocean heat content appears to have increased faster than upper ocean heat content in recent years

Balmaseda et al., 2013

Ocean Heat Uptake?

Could the deployment and inclusion of new observations bias time series of estimated ocean heat content?

The picture depends strongly on which data are used



Argo floats were not available before 2000

Balmaseda et al., 2013

Ocean Heat Uptake?

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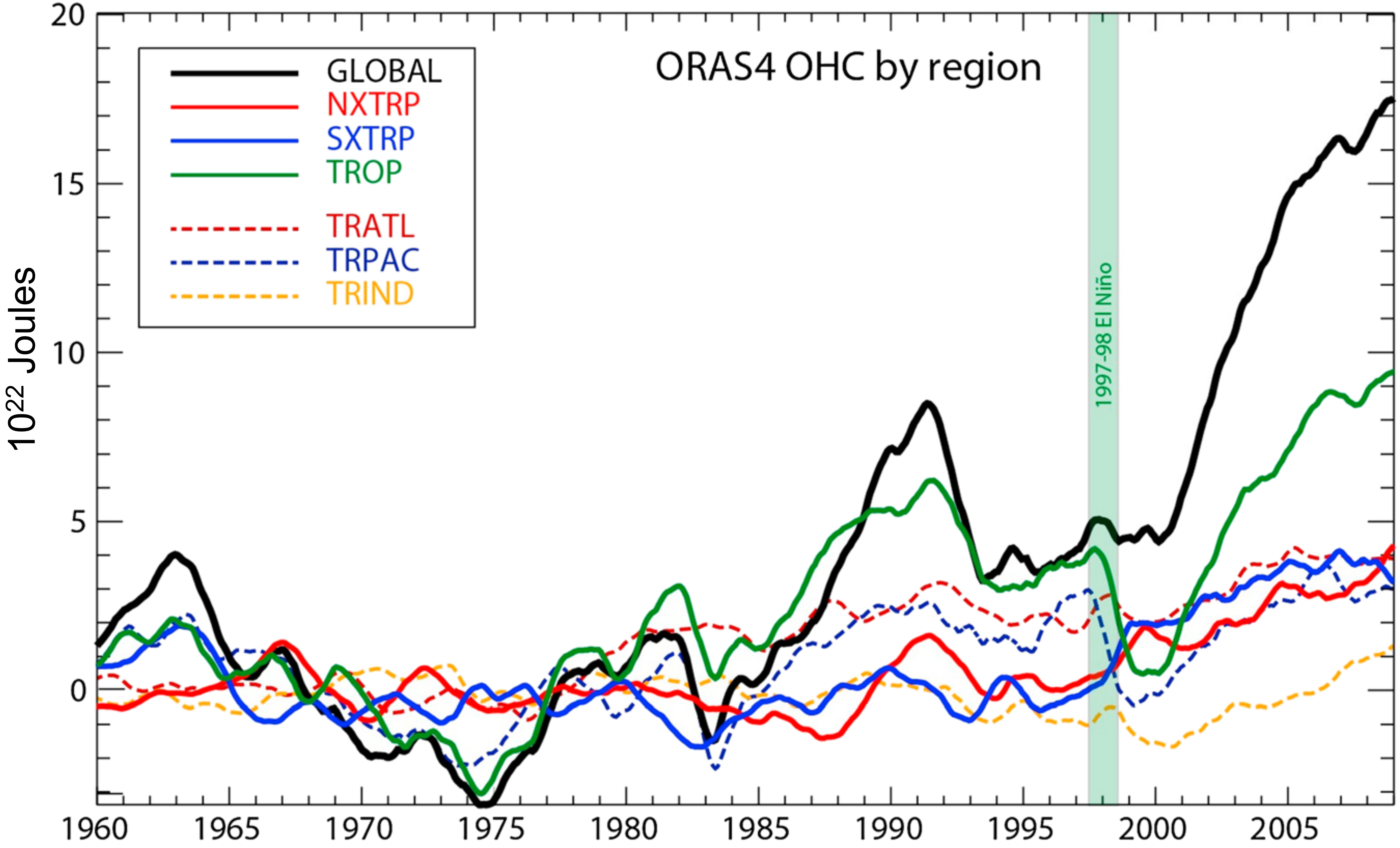

Reanalysis indicates rapid increases in tropical OHC during hiatus period

Balmaseda et al., 2013

Ocean Heat Uptake?

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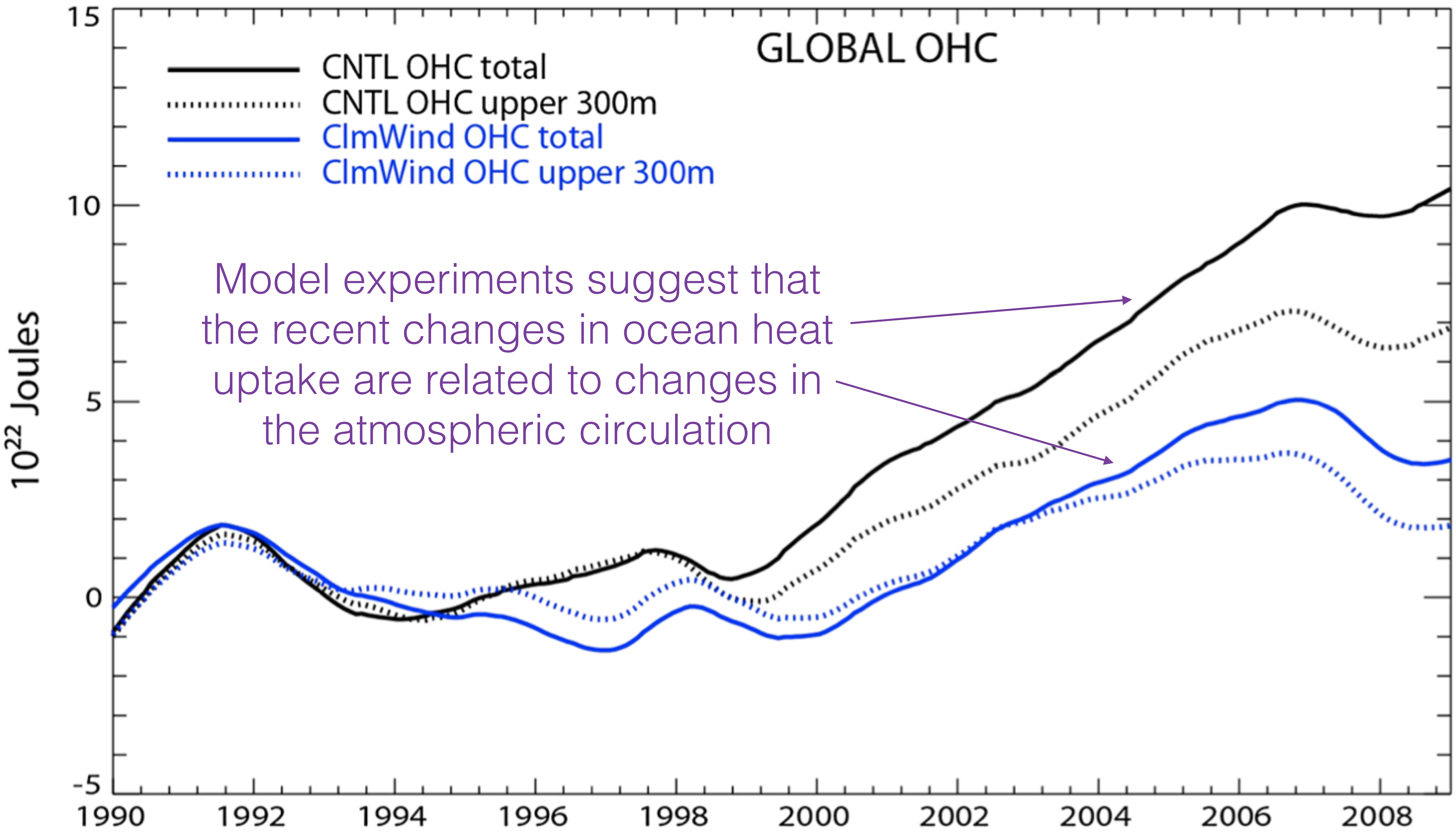
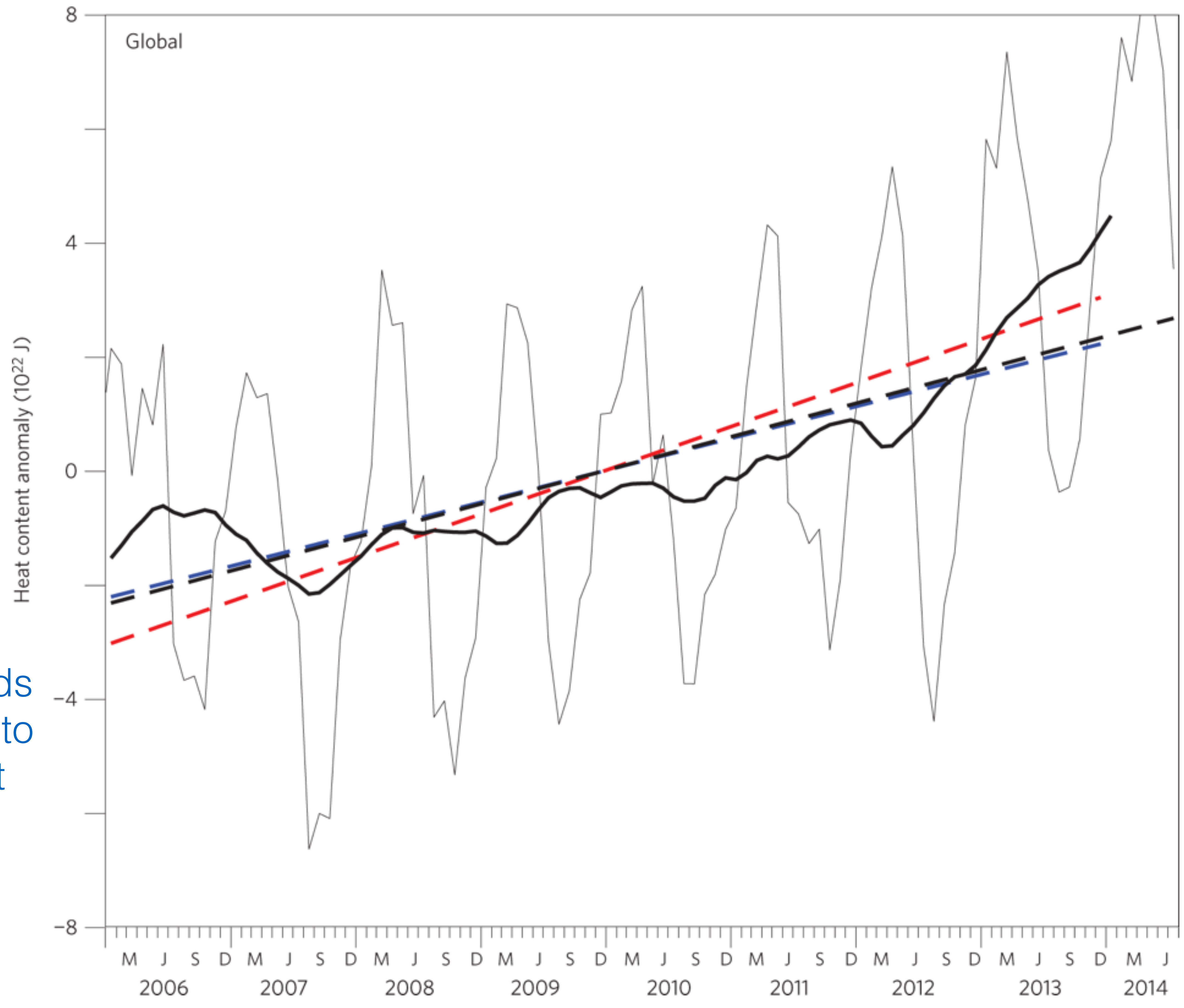


Balmaseda et al., 2013

Ocean Heat Uptake?

Using observations along also indicates increases in OHC over recent years, regardless of the fitting technique used



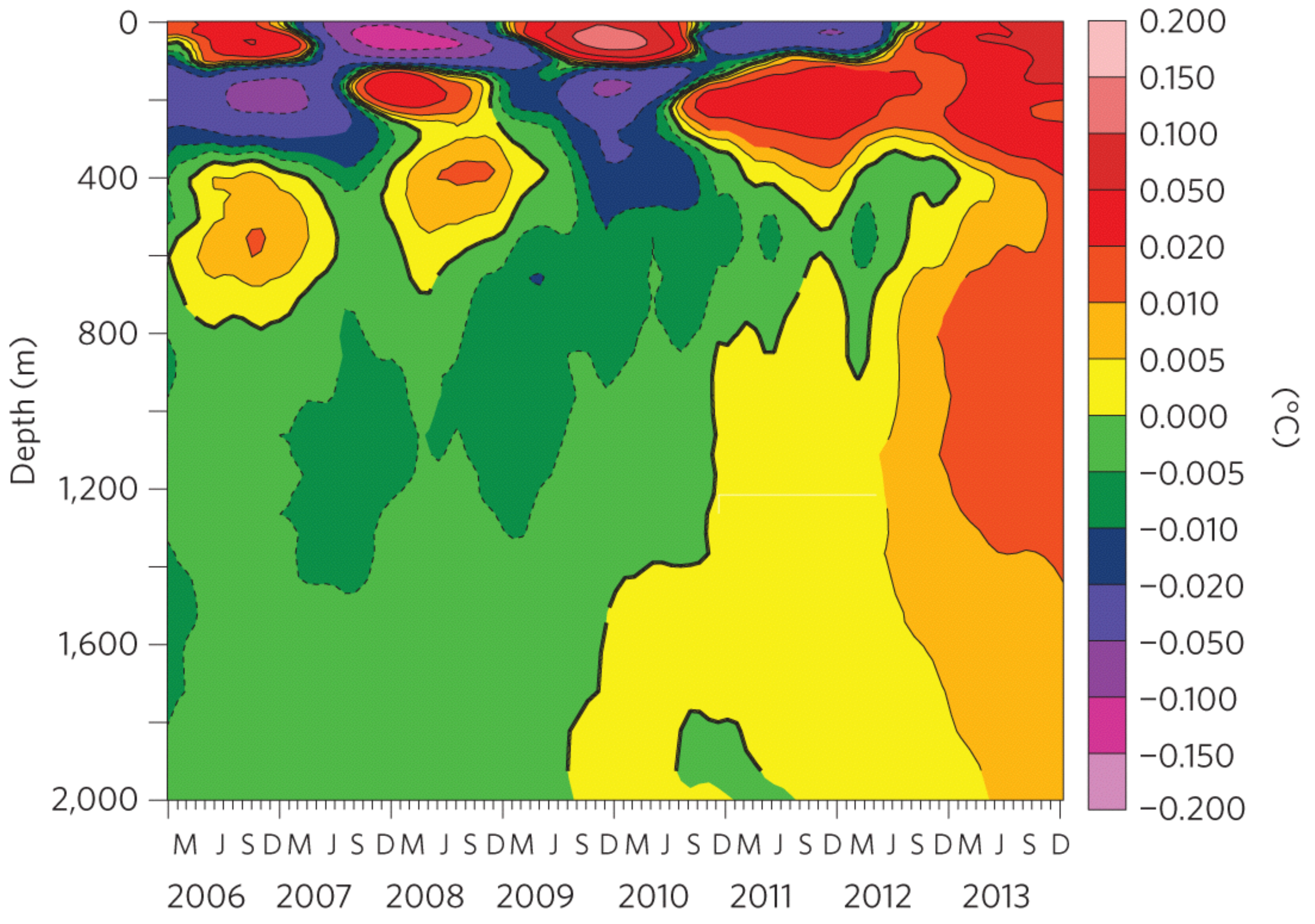
time series is limited but largely consistent with reanalysis estimates

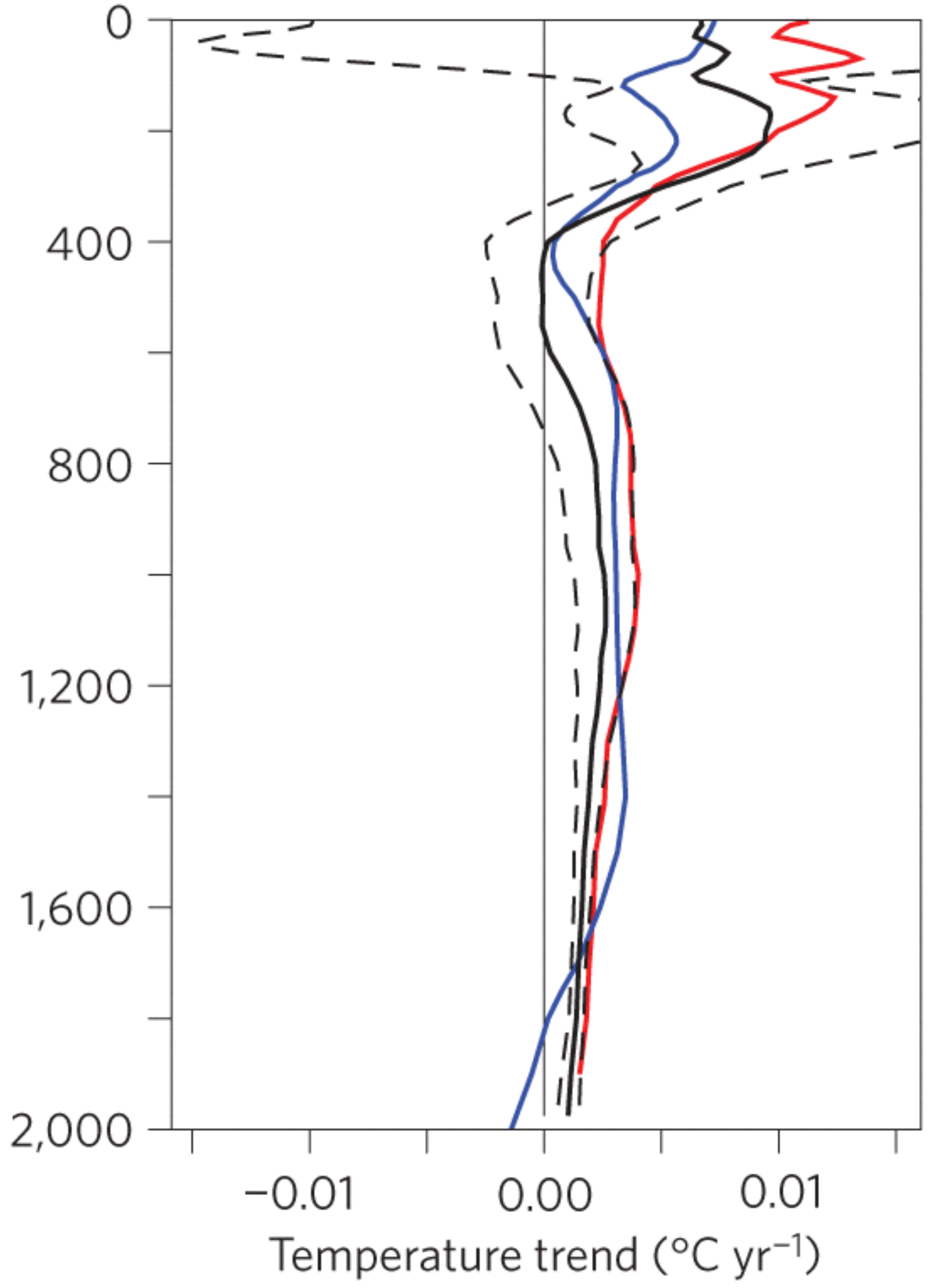
dashed lines indicate trends using different techniques to create a "global" product from the best Argo floats

Roemmich et al., 2015

Ocean Heat Uptake?

Surface changes largely reflect ENSO-related variations in the Pacific thermocline; but warming at depth has been steady

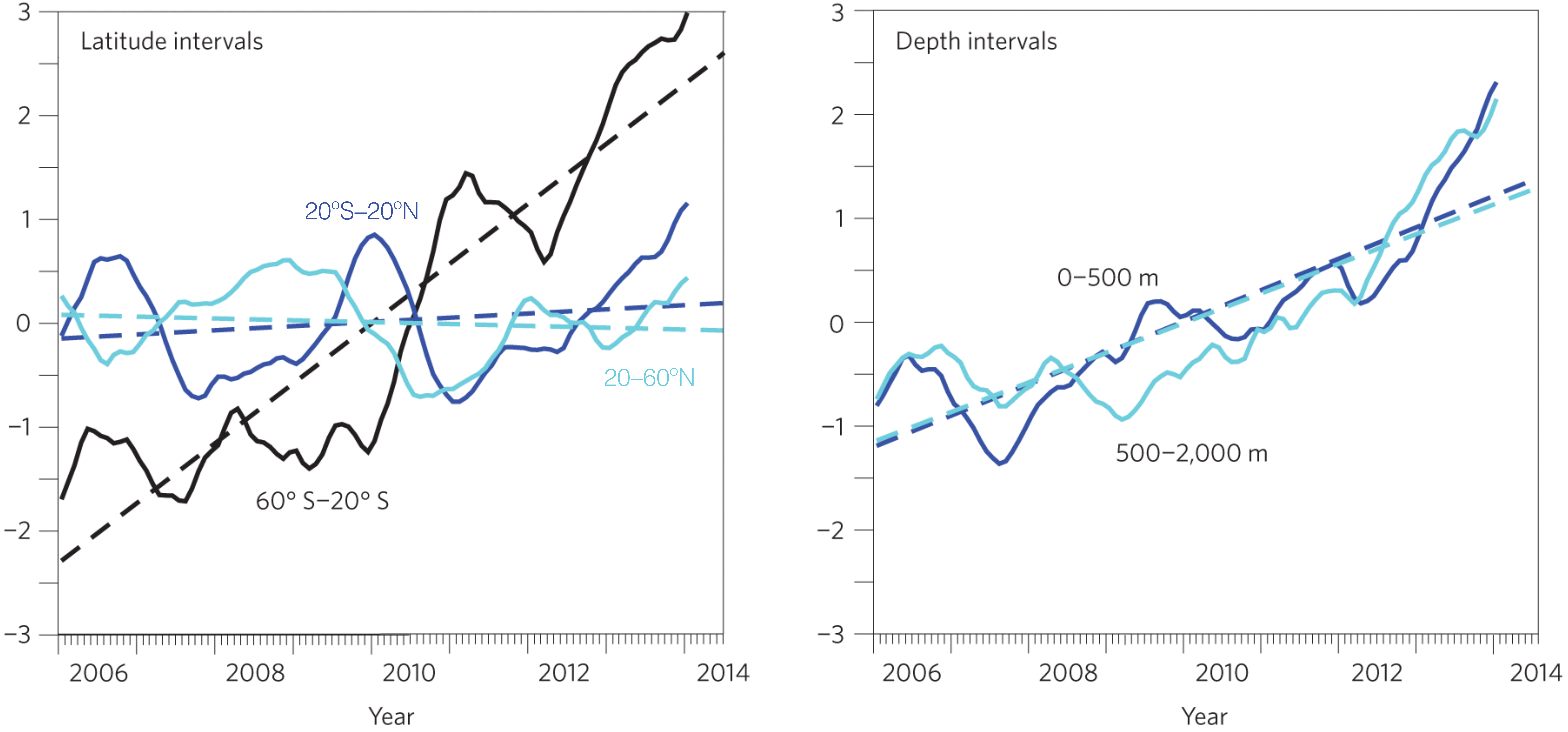




Roemmich et al., 2015

Ocean Heat Uptake?

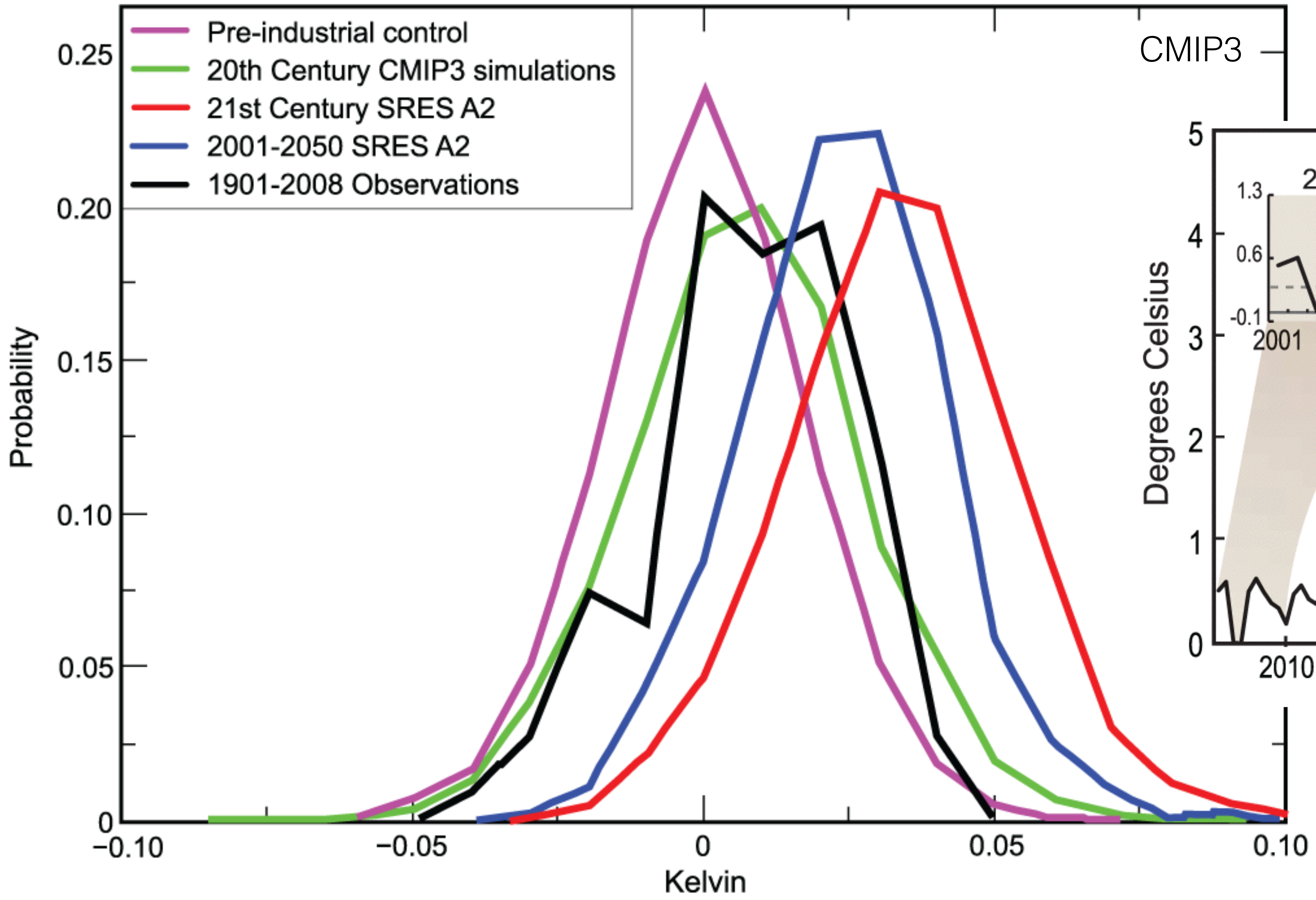
Argo observations indicate that most of the increase in OHC over the past 8 years has been in the Southern Ocean

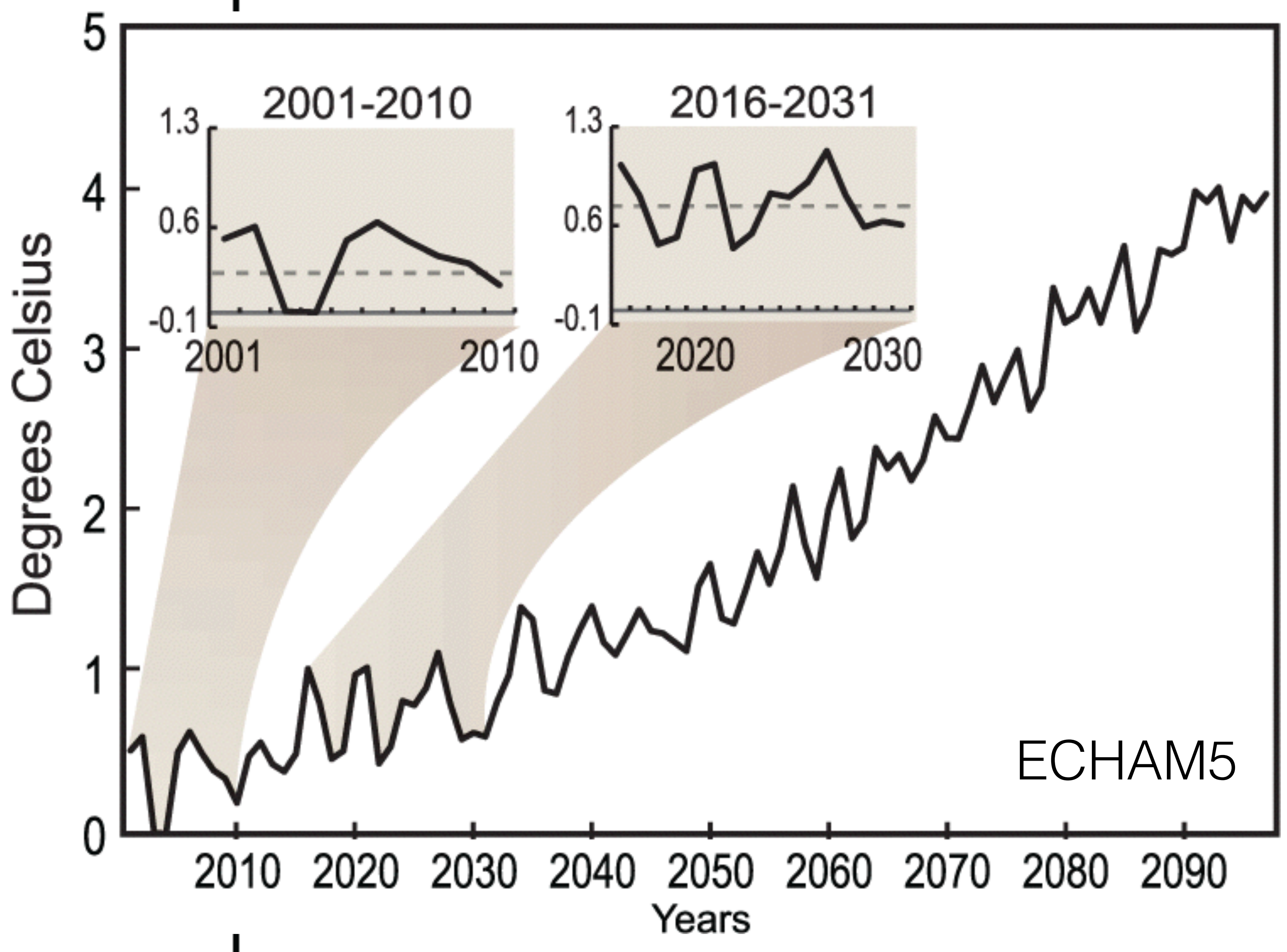


Roemmich et al., 2015

Natural Variability?

Coupled model experiments indicate that periods of cooling are still possible, even in a strongly warming world





Easterling and Wehner, 2009

Natural Variability?

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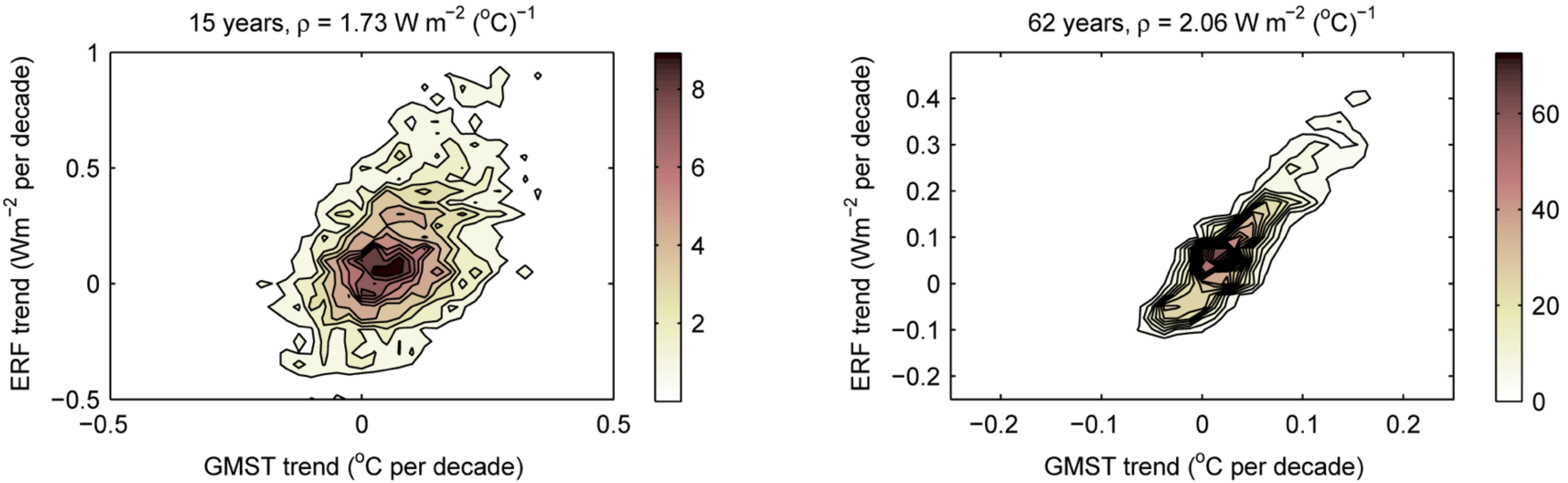
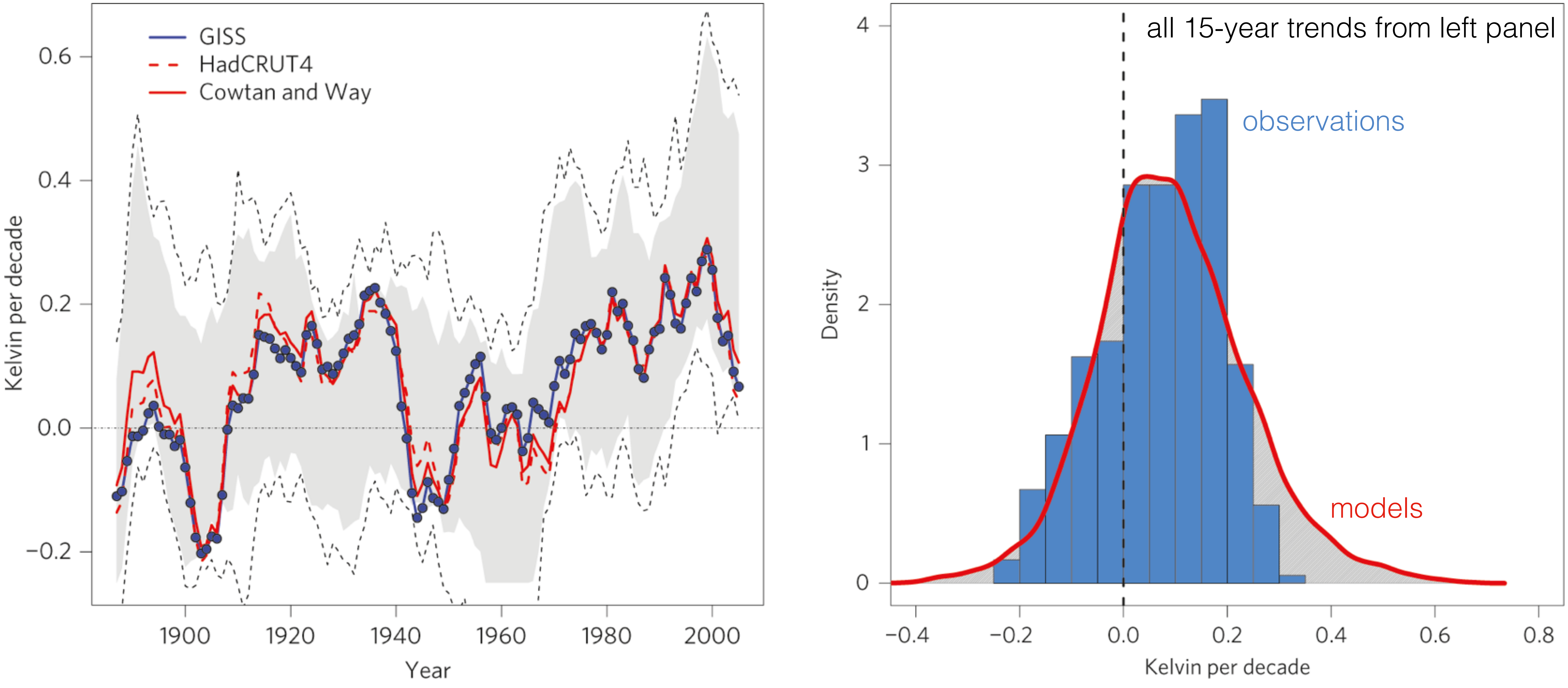


Changes in radiative forcing tightly constrain simulated surface temperature trends over longer time periods (decades), but not necessarily over shorter time periods (~15 years)

Marotzke & Forster, 2015

Natural Variability?

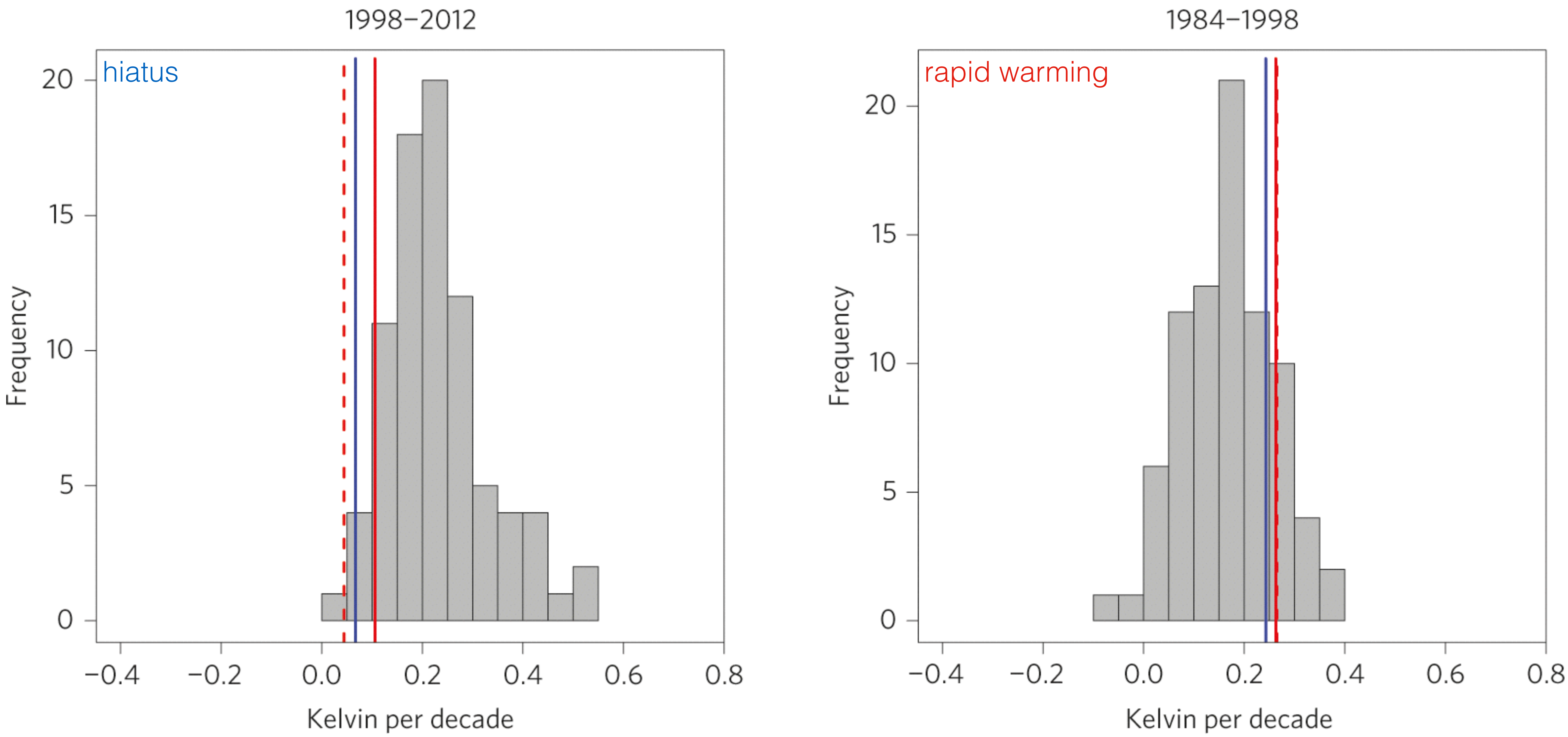
The distribution of model trends over the historical period was not that different from the distribution of observed trends



Risbey et al., 2014

Natural Variability?

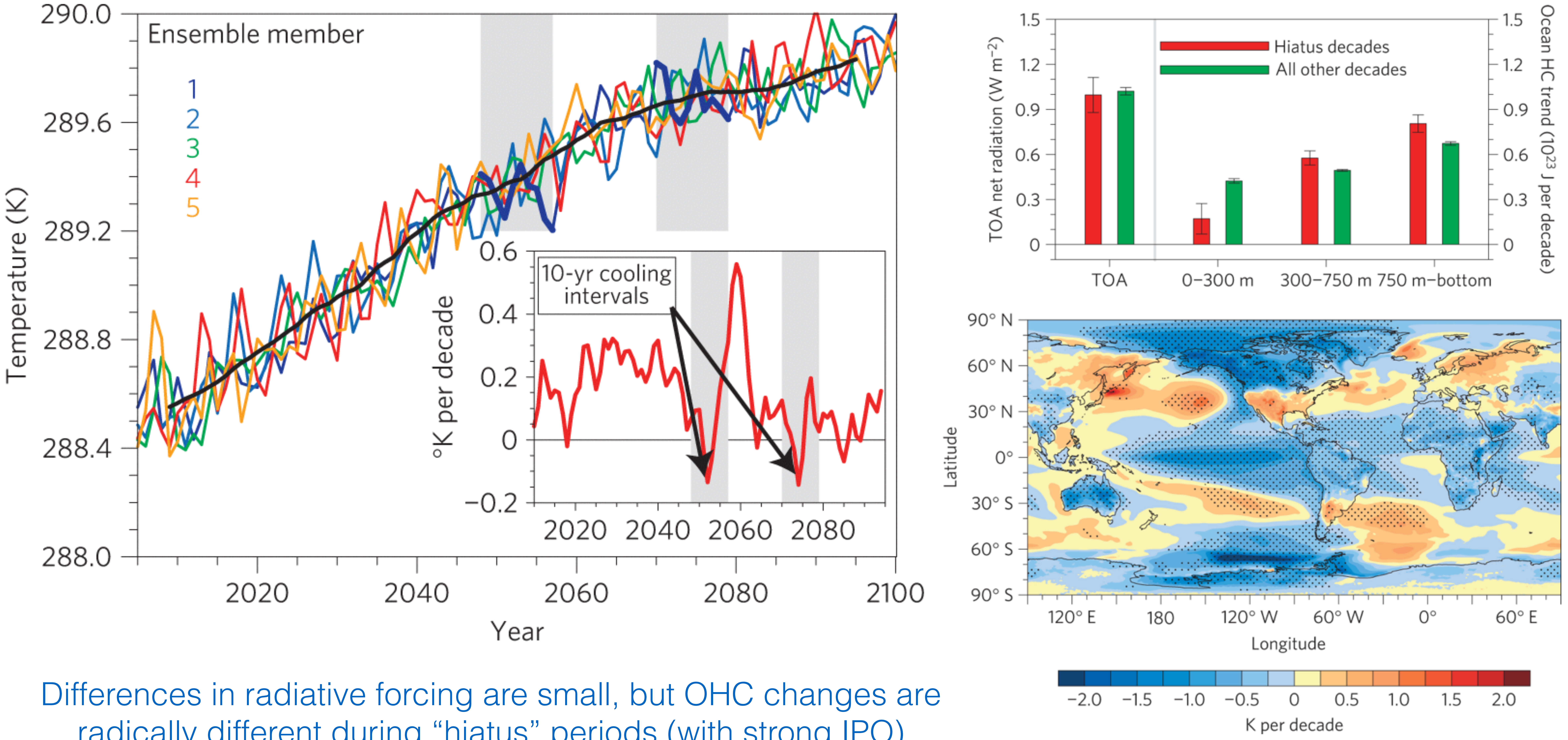
Moreover, models overestimate trends during the hiatus period, but underestimate trends during the rapid warming period



Risbey et al., 2014

Natural Variability?

We can gain insight into the mechanisms that could cause such a hiatus by examining hiatus periods in coupled models



Differences in radiative forcing are small, but OHC changes are radically different during "hiatus" periods (with strong IPO)

Meehl et al., 2011

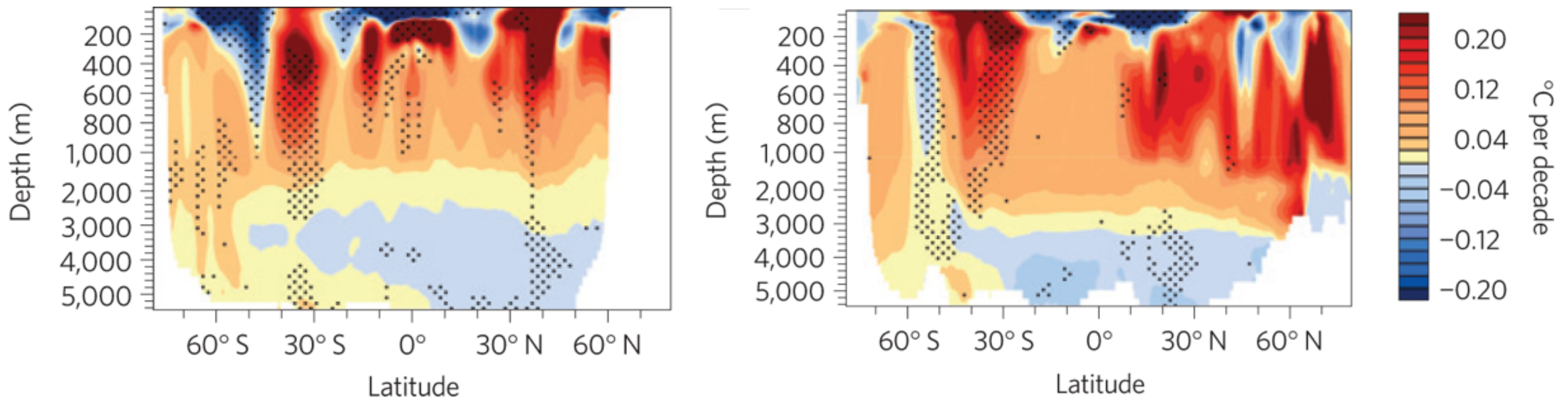
Natural Variability?

Such periods are characterized by strong increases in ocean heat content at intermediate depths in CCSM4

Note different depth scale!

Composite trends over hiatus periods:

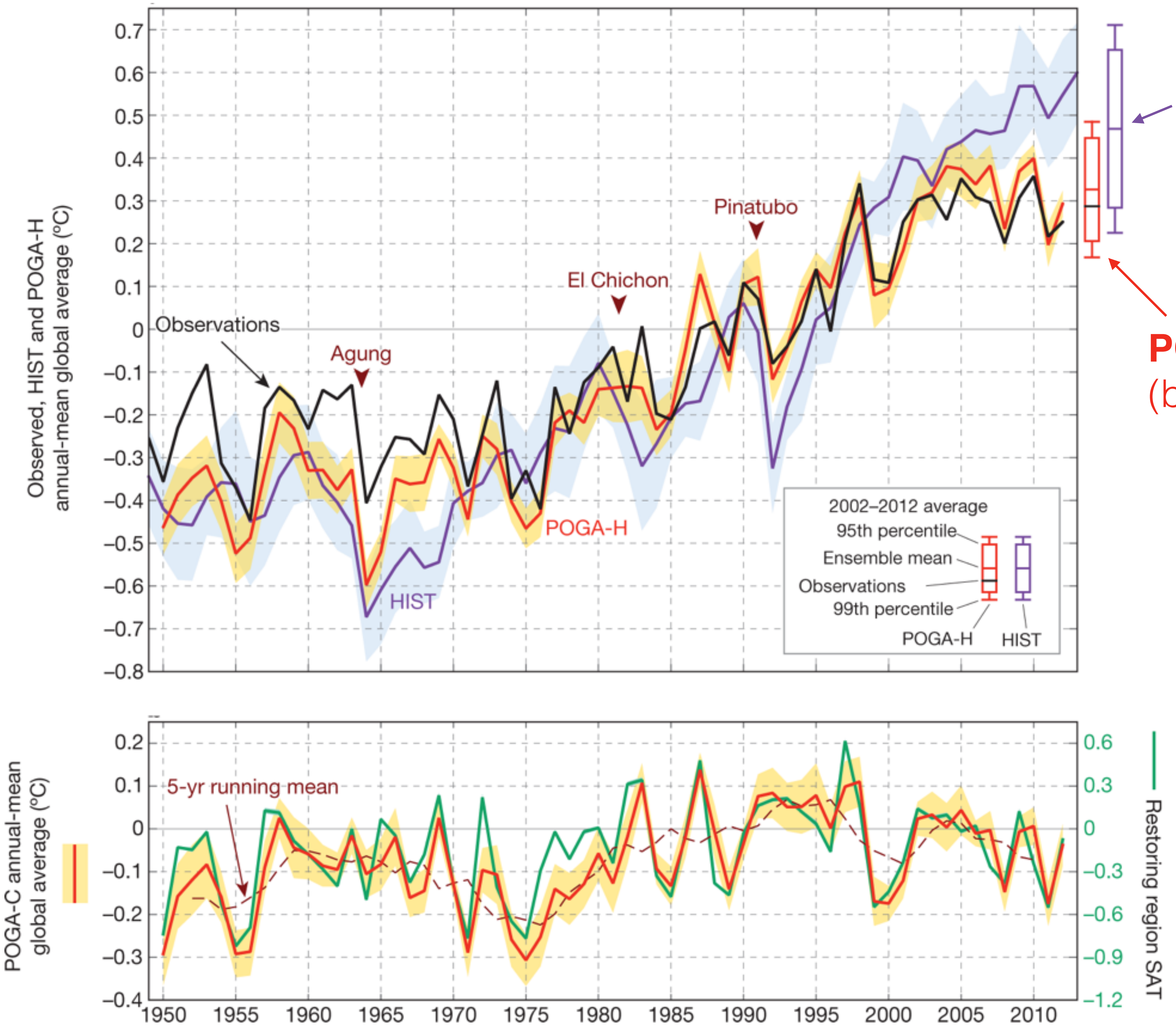
- Stronger subtropical cells, especially in Pacific
- Weaker deep water formation in North Atlantic
- Strong simulated increases in OHC at depth in both Pacific and Atlantic



Meehl et al., 2011

Natural Variability?

Having learned of the potential relationship with La Niña / IPO, we can make a model match observations in the ENSO region



Historical run (fully-coupled, with only radiative forcing specified)

POGA-H: Pacific Ocean Global Atmosphere-Historical (both forcing and tropical eastern Pacific SST specified)

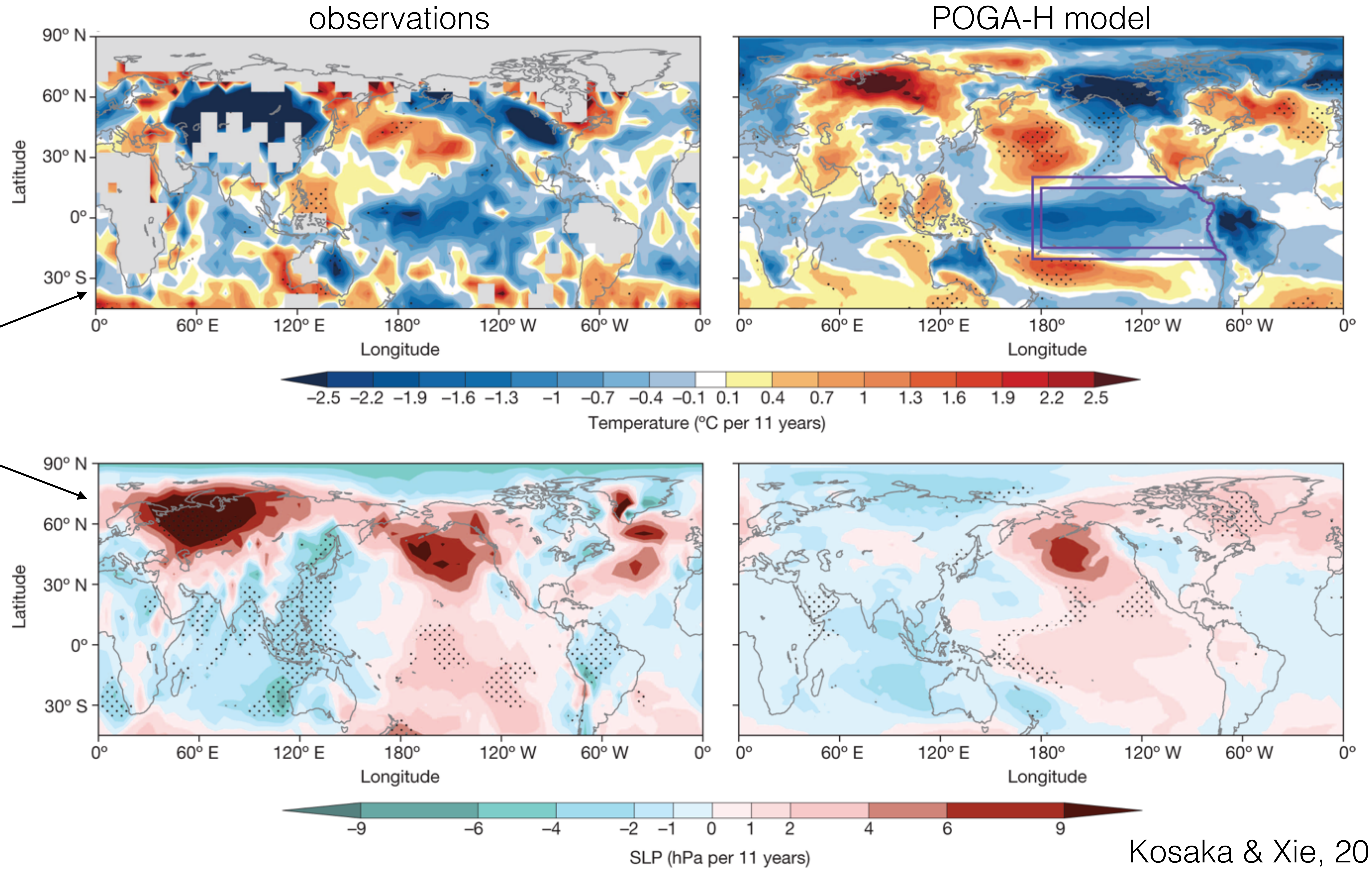
POGA-C: Pacific Ocean Global Atmosphere (forcing fixed; tropical eastern Pacific SST specified)

Kosaka & Xie, 2013

Natural Variability?

We can gain insight into the mechanisms that could cause such a hiatus by examining hiatus periods in coupled models

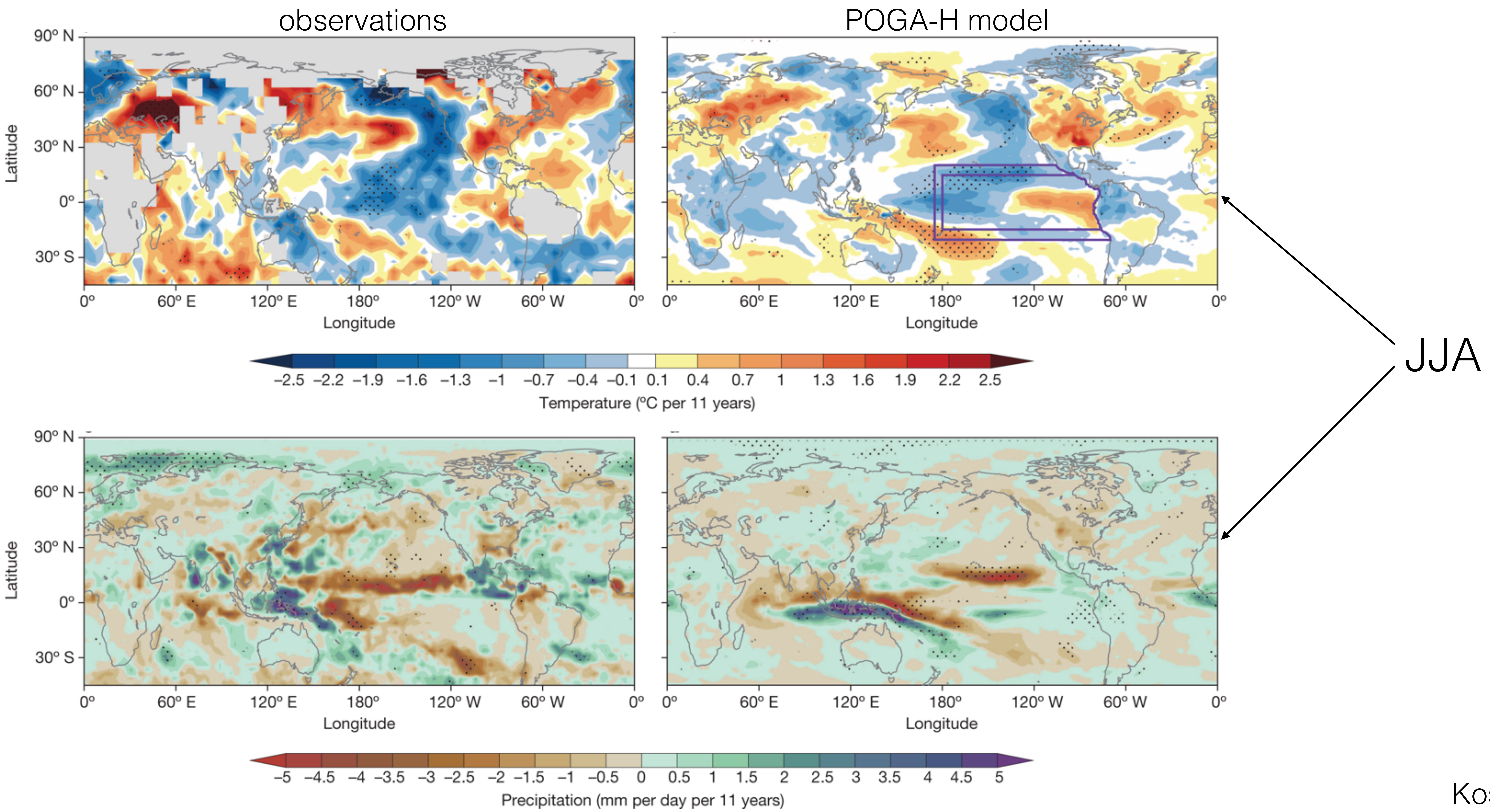
DJF



Kosaka & Xie, 2013

Natural Variability?

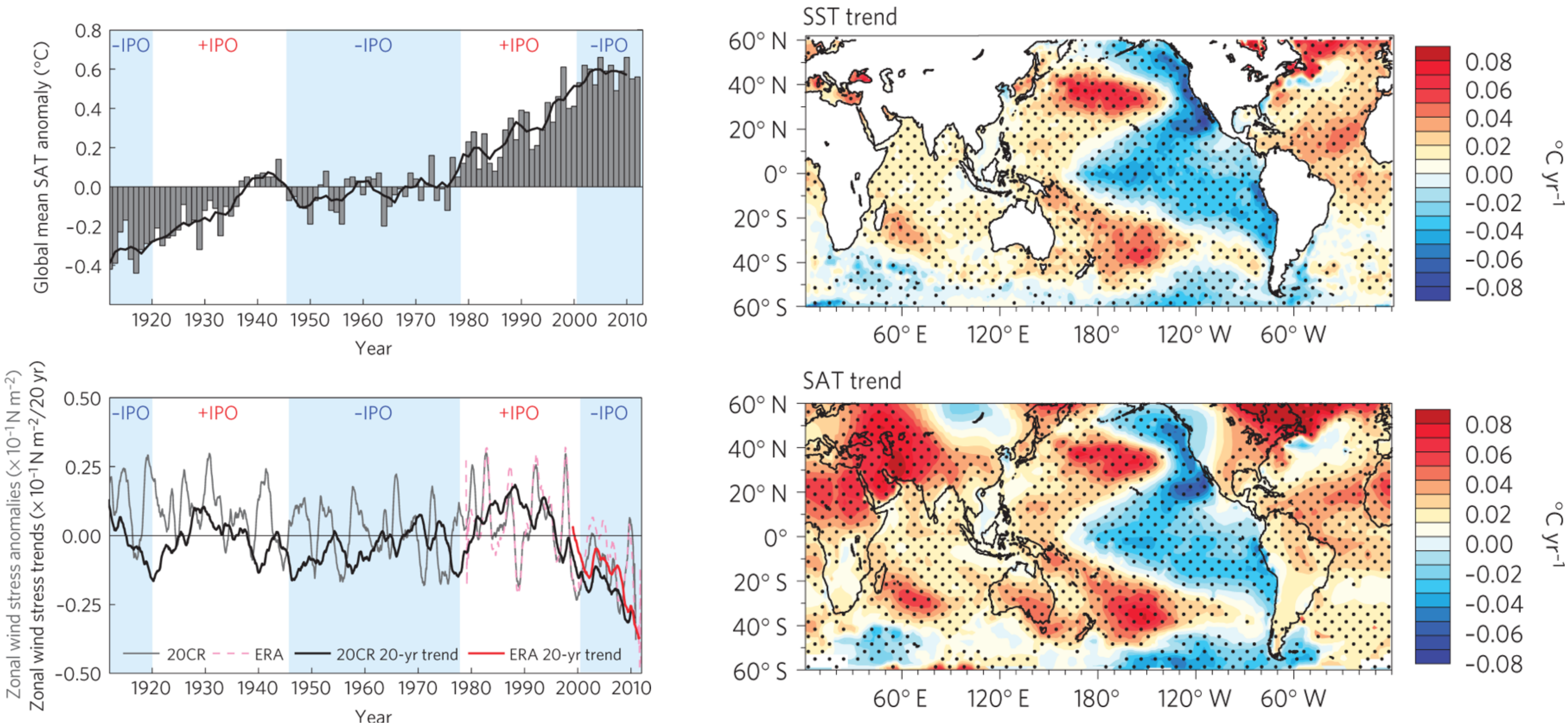
The POGA-H simulation is also able to capture key regional changes and their seasonality



Kosaka & Xie, 2013

Natural Variability?

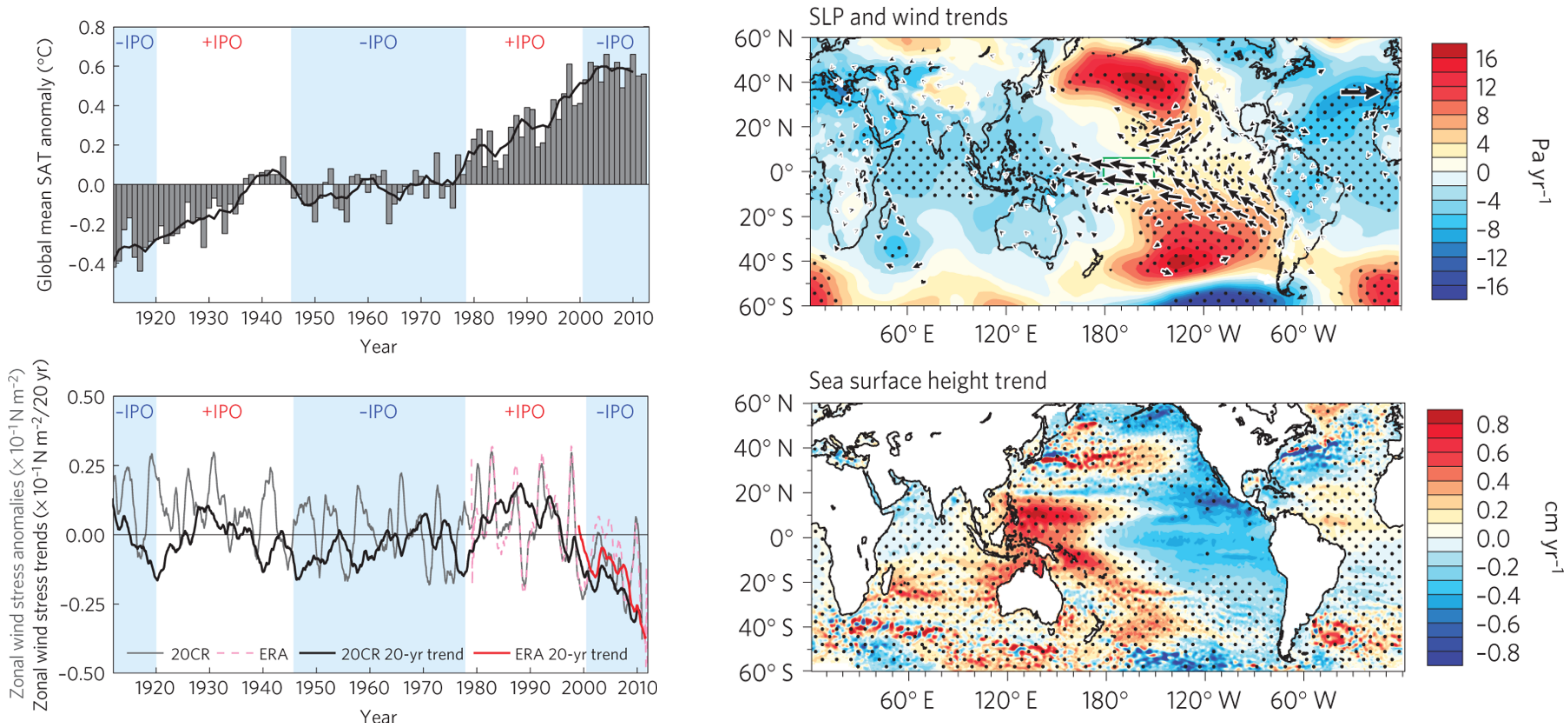
The negative IPO pattern that characterizes hiatus periods in models has also been observed over recent years (1992–2011)



England et al., 2014

Natural Variability?

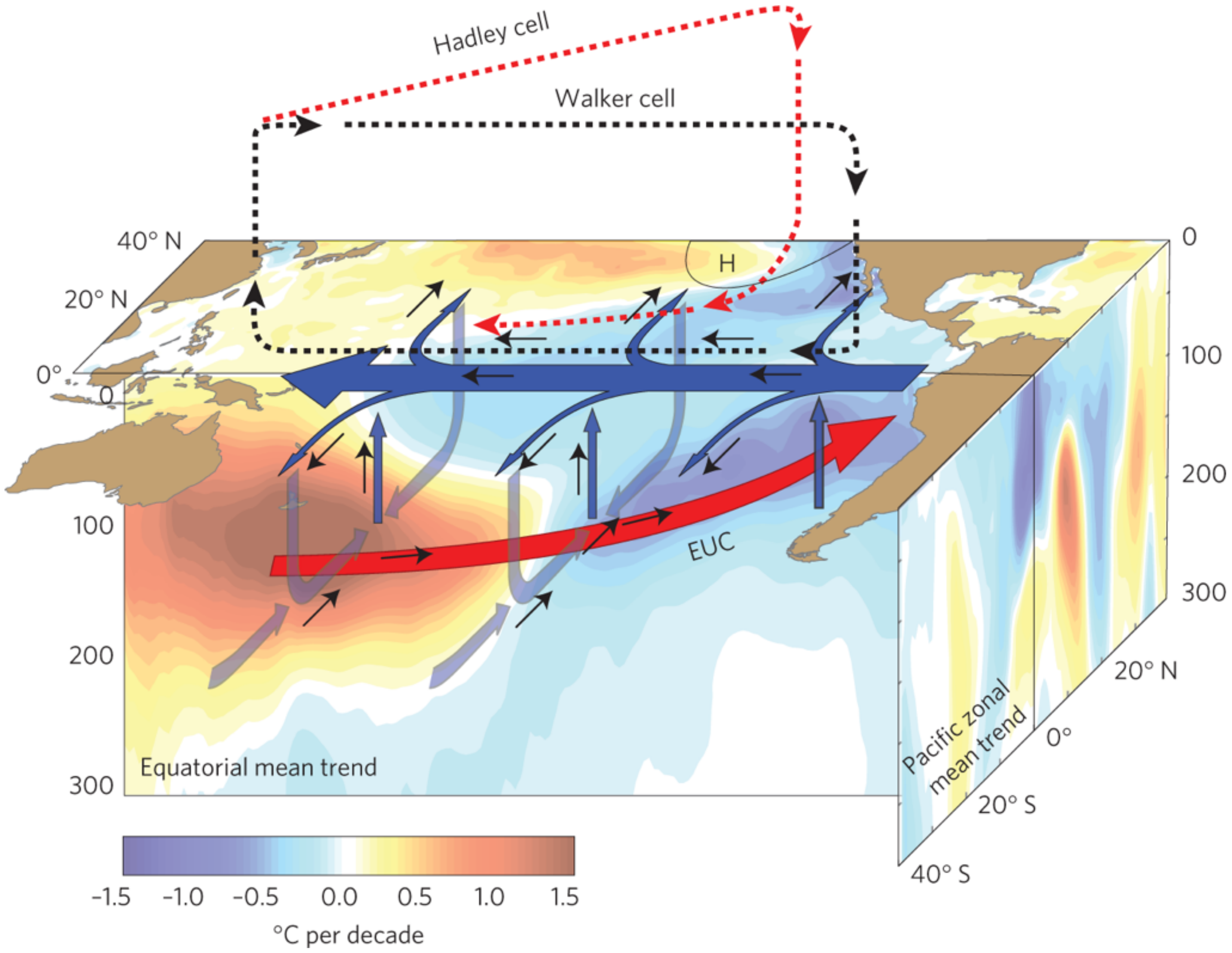
This pattern enhances the Walker circulation and subtropical highs in the Pacific, leading to increased easterly trade winds

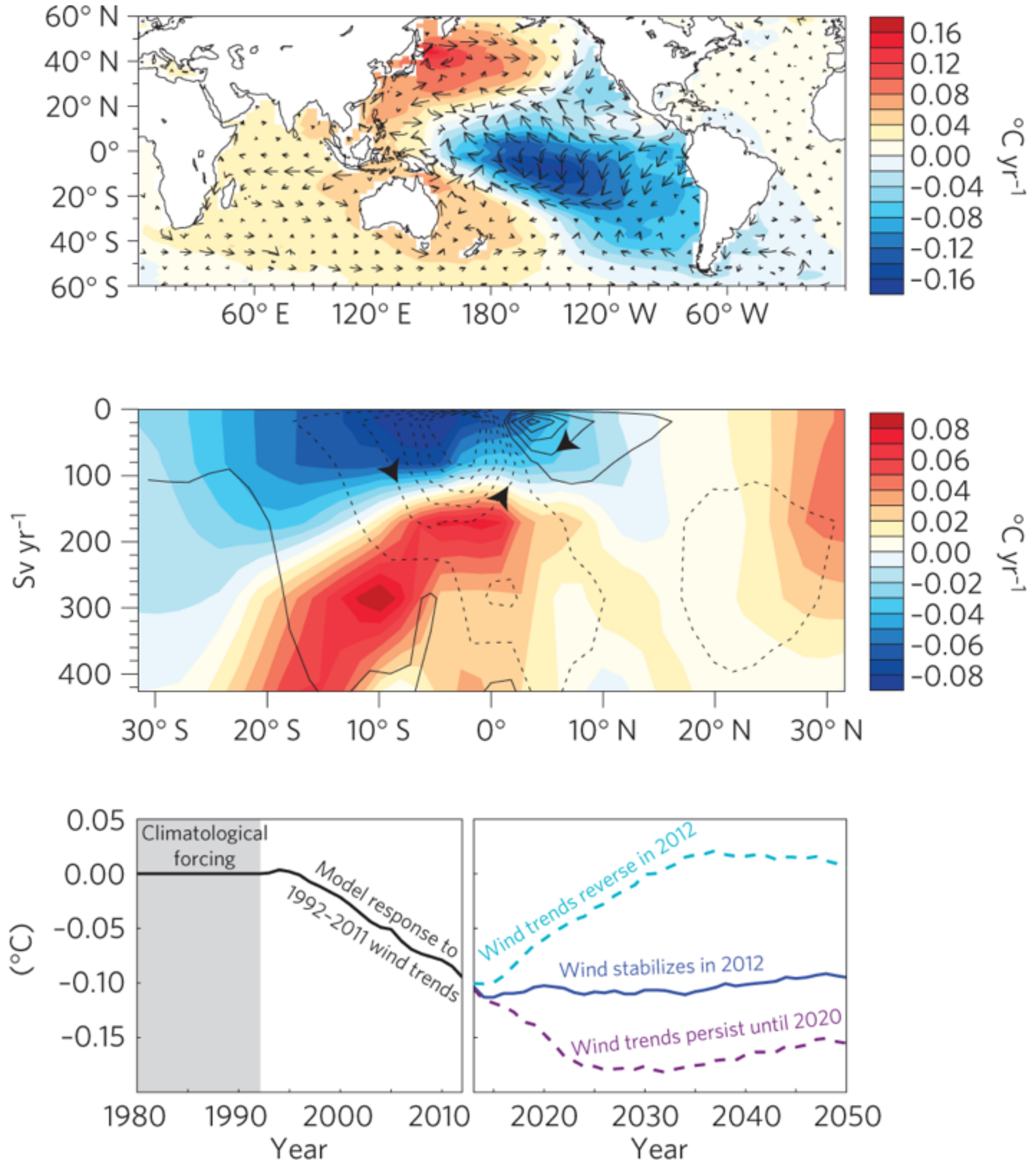


England et al., 2014

Natural Variability?

The atmosphere and ocean response resemble the Bjerknes feedback, with trade winds leading to stronger STCs

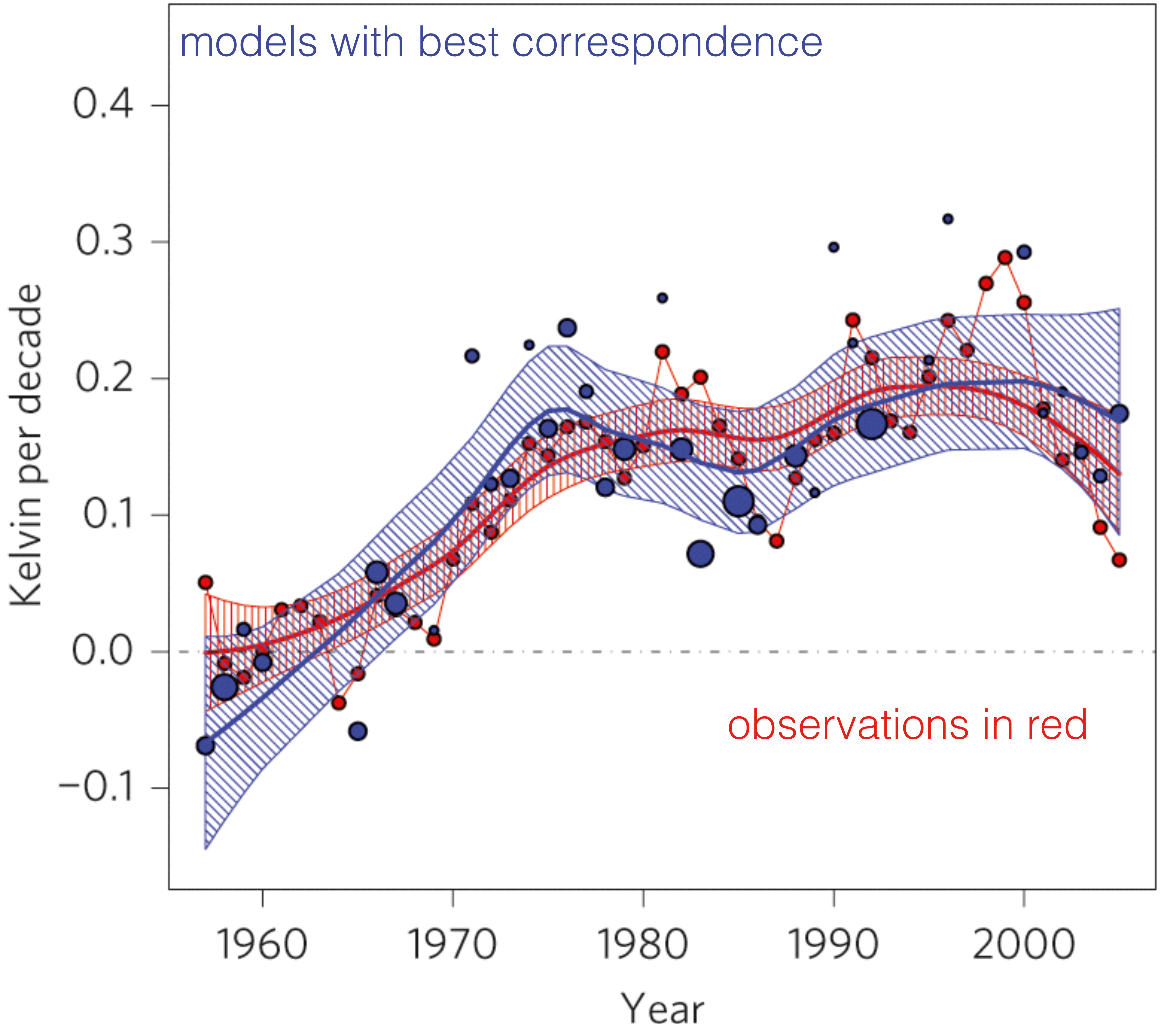


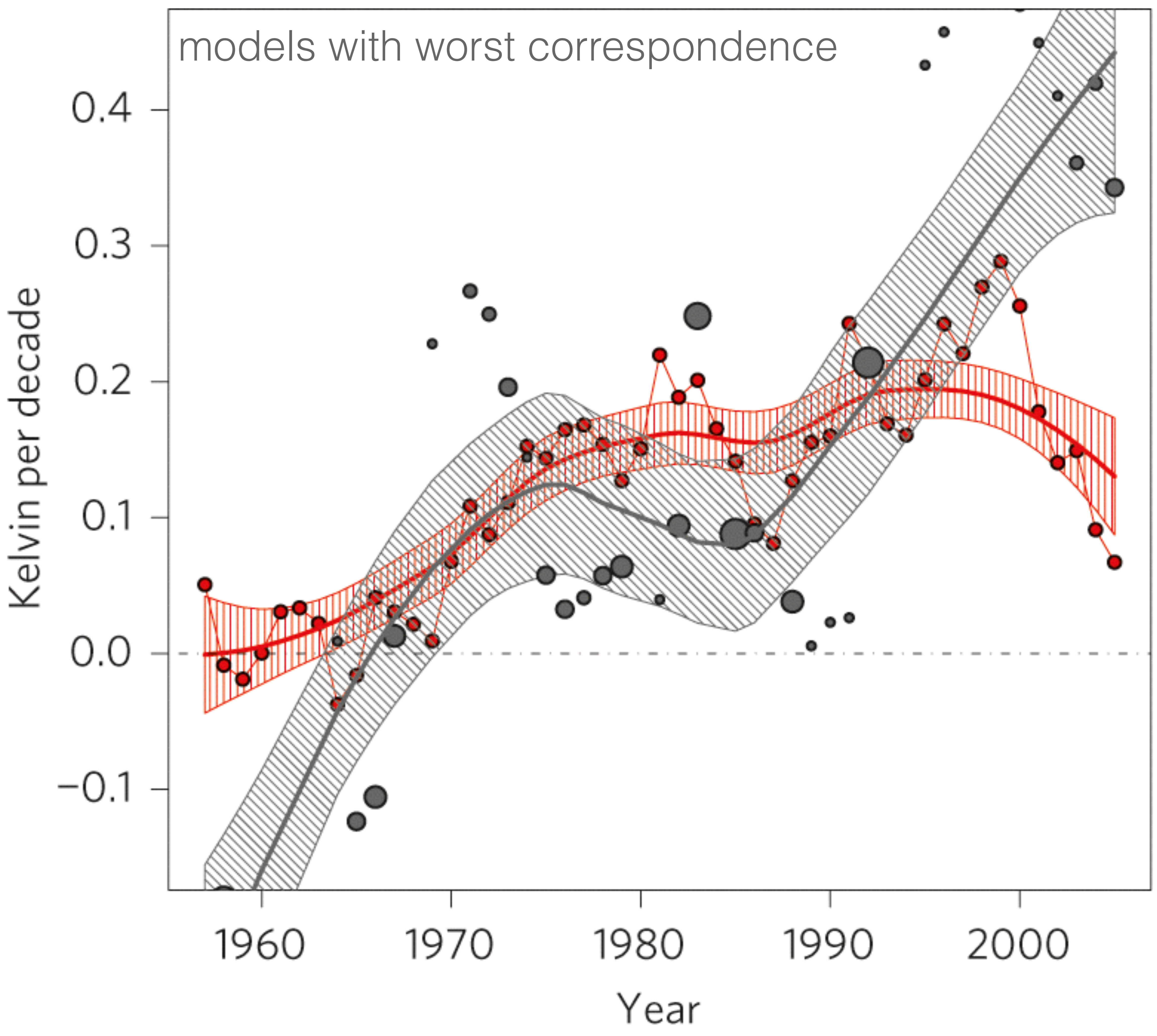


England et al., 2014

Natural Variability?

We can select models based on whether their simulated ENSO phase matches the observed ENSO phase for a given year

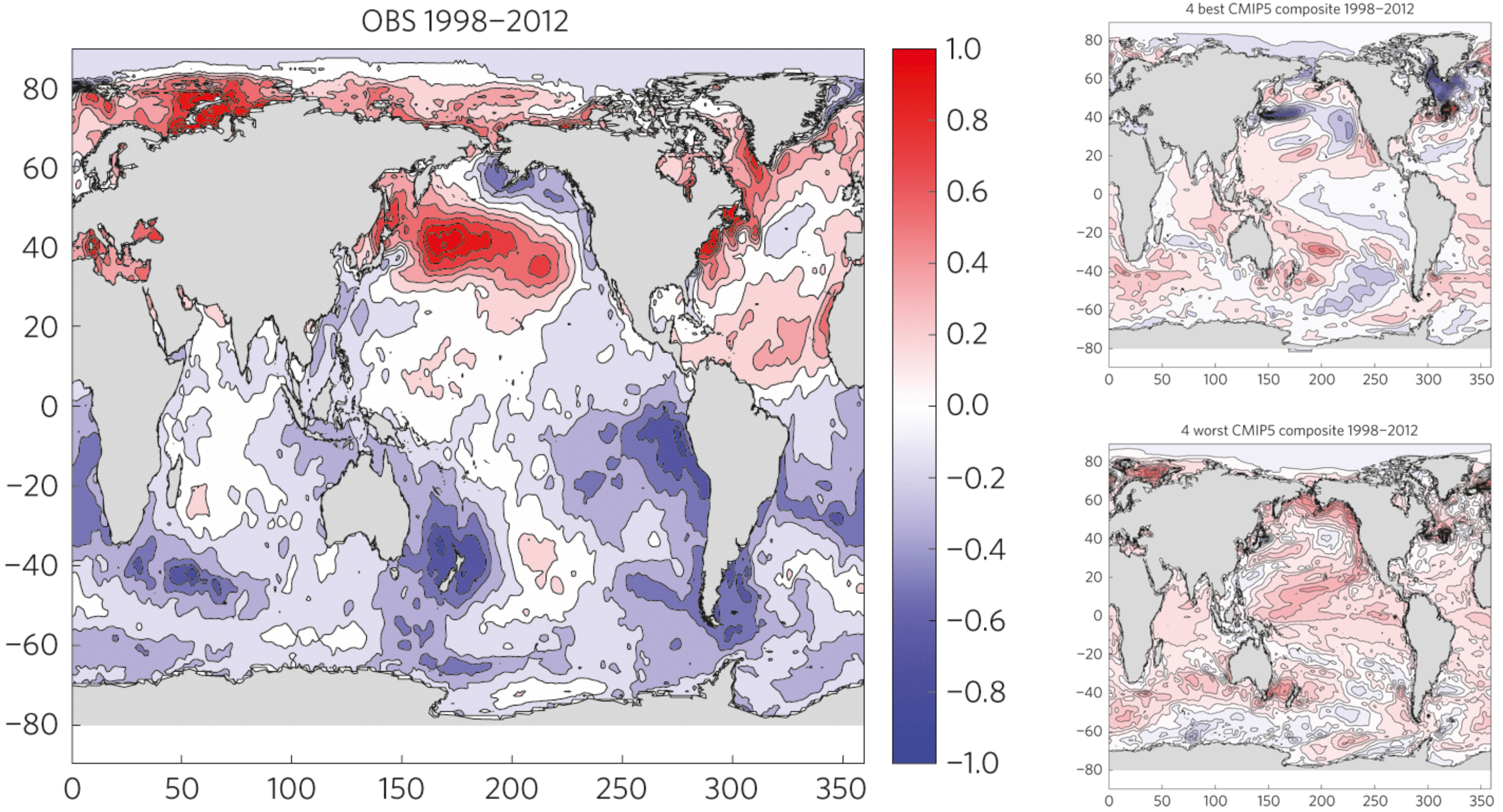




Risbey et al., 2014

Natural Variability?

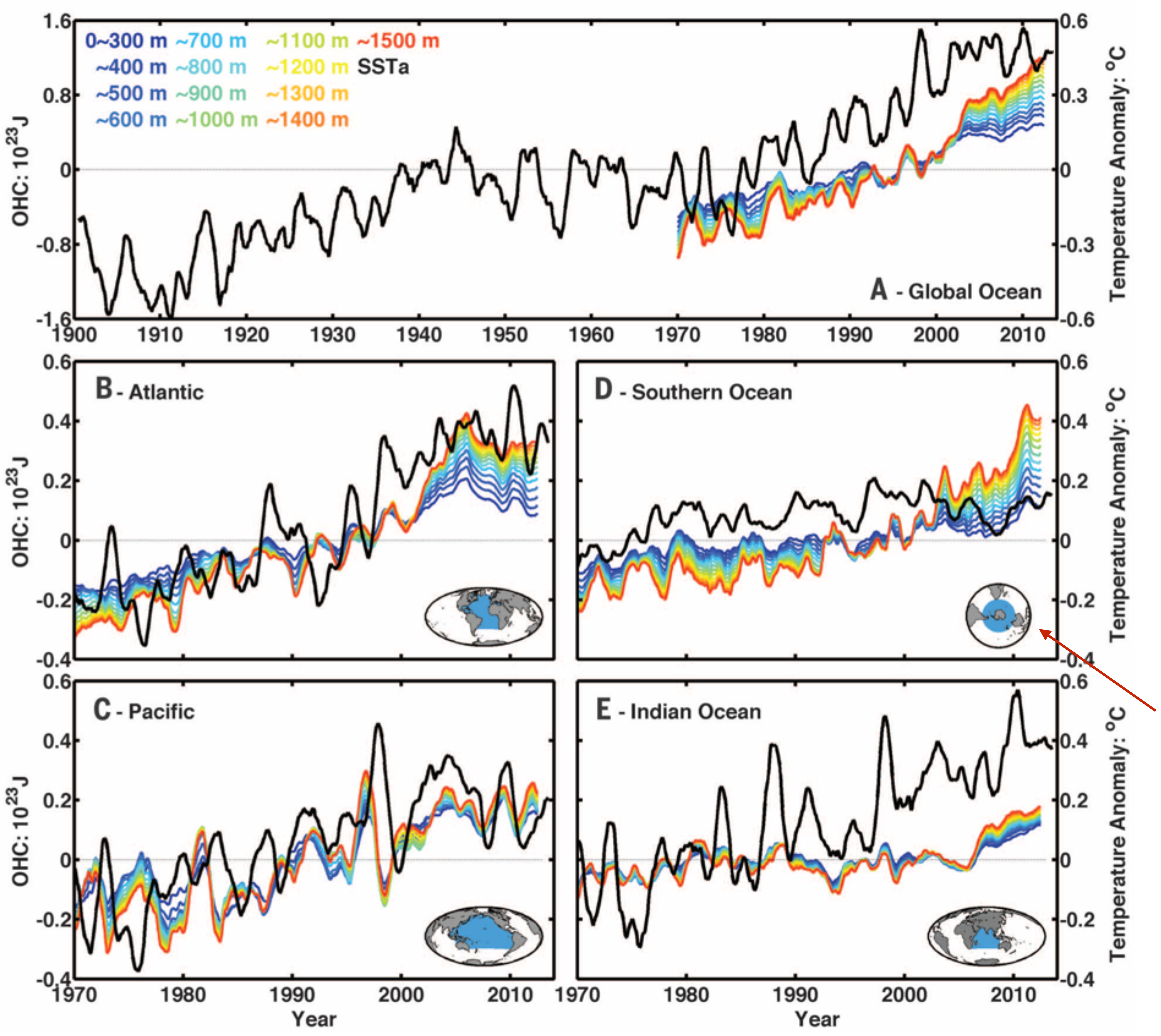
The best matches to the observed temperature record are for models with a negative IPO



Risbey et al., 2014

Natural Variability?

Models implicate the Pacific, but observations show increases of OHC at deeper layers in the Atlantic and Southern Oceans



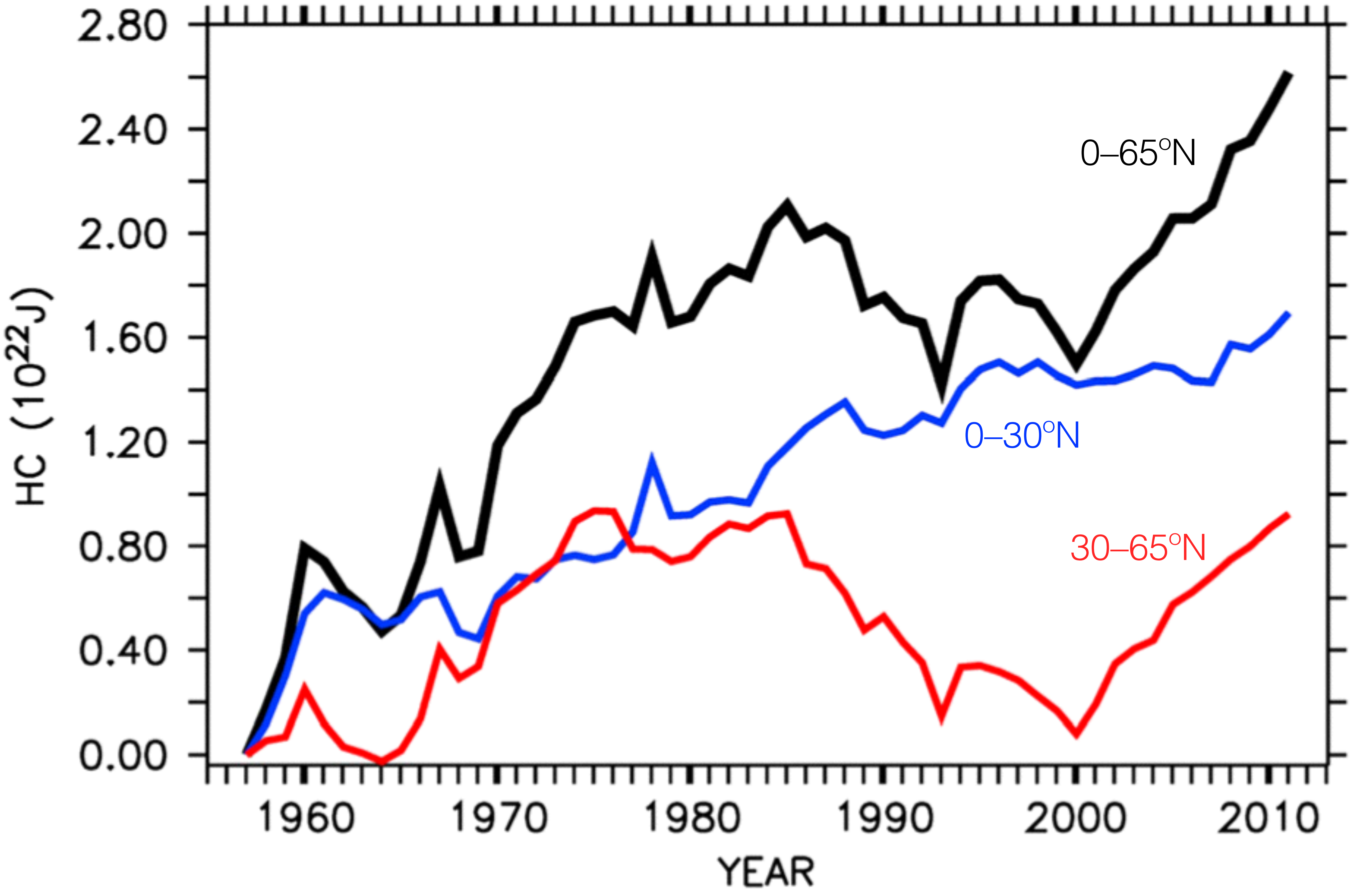
Observed changes are consistent with reanalysis estimates from ORAS4

Note: observations in Southern Ocean are very uncertain!

Chen and Tung, 2014

Natural Variability?

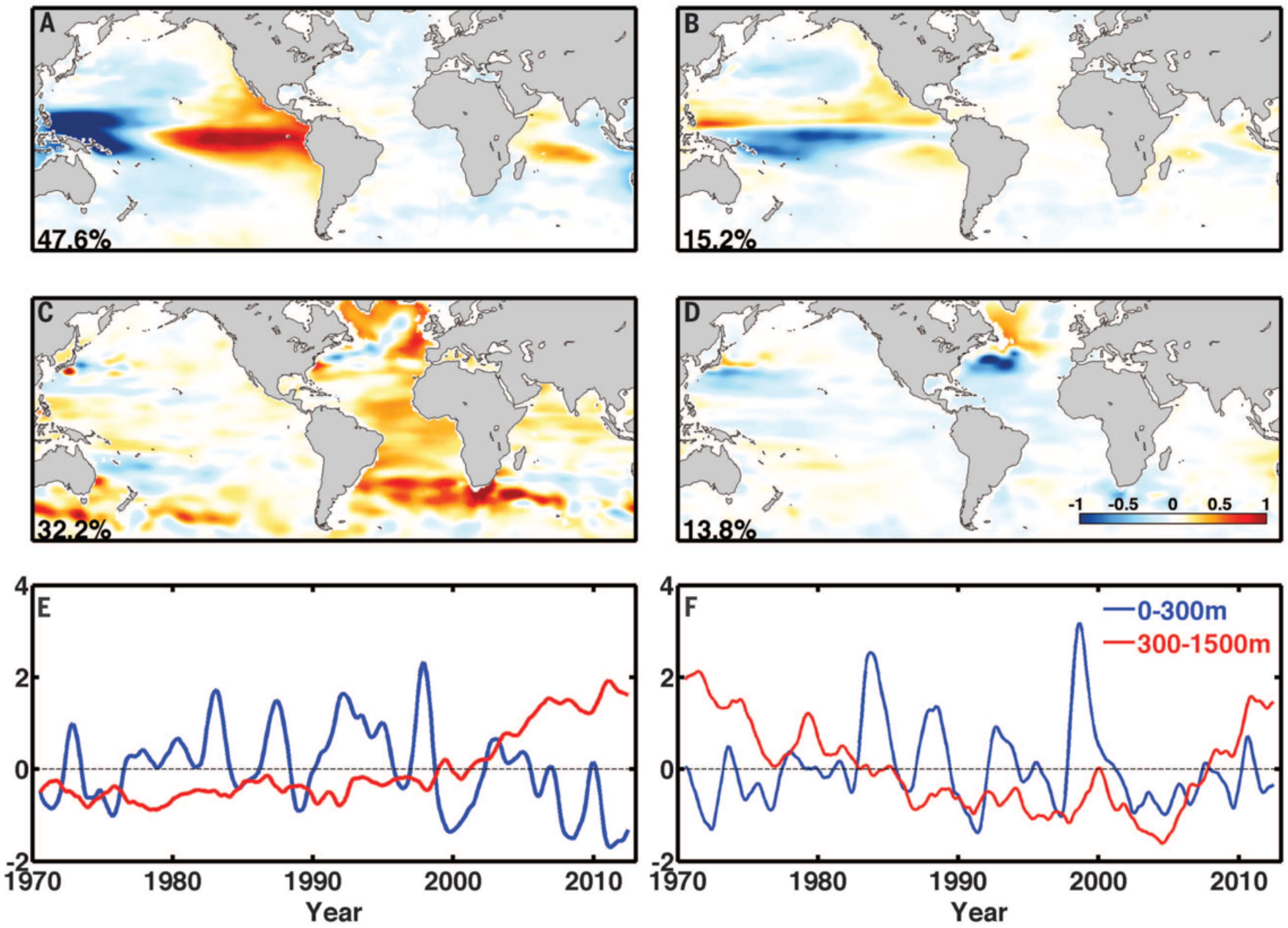
Changes in ocean heat content in the North Atlantic occur mainly at higher latitudes, and are anticorrelated with GMST



Häkkinen et al., 2015

Natural Variability?

The Pacific dominates SST variability, but the Atlantic and Southern Oceans dominate deep-ocean heat content changes



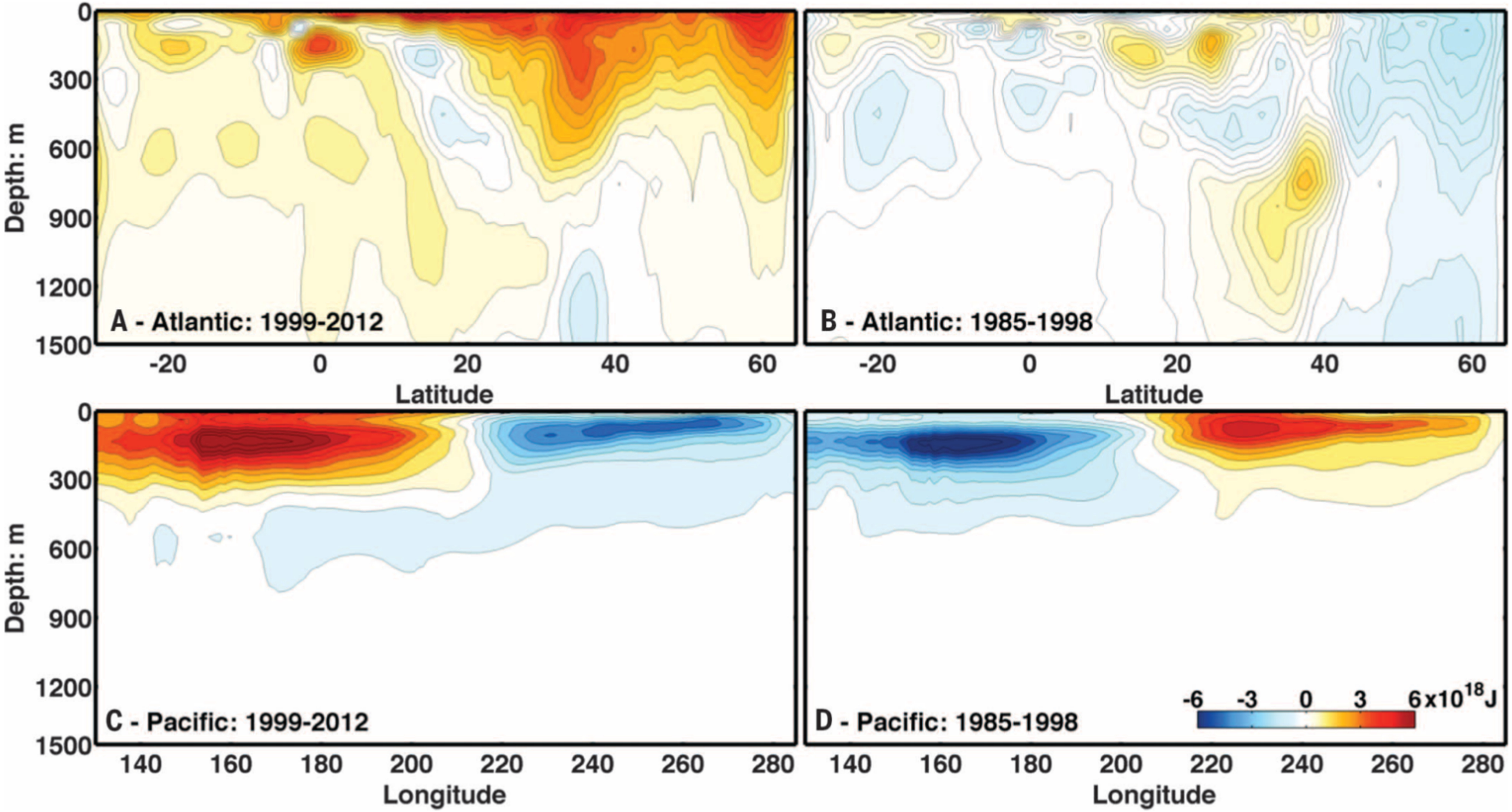
First two EOFs of OHC, 0~300 m: Dominated by changes in Pacific

First two EOFs of OHC, 300~1500 m: Dominated by changes in Atlantic/SO

Chen and Tung, 2014

Natural Variability?

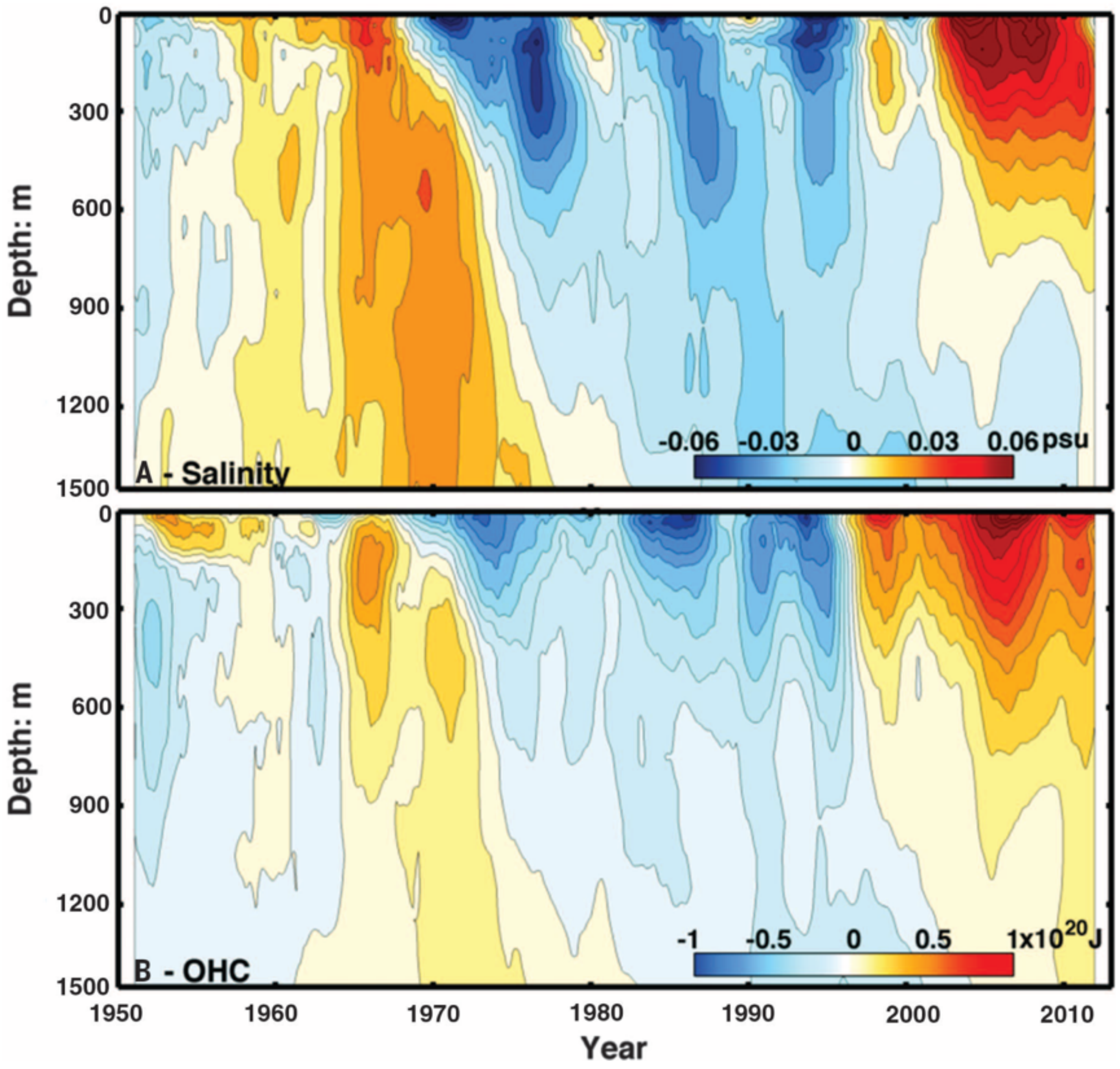
Atlantic OHC changes extend down beyond observed layers;
Pacific OHC changes limited to upper 300 m



Chen and Tung, 2014

Natural Variability?

Changes in ocean heat content are largely consistent with changes in salinity, hinting at a possible mechanism



Salinity mechanism

- stronger AMOC brings saltier water north
- high salinity allows this water to sink, sequestering heat at deeper layers
- this water is also relatively warm, so that it melts nearby sea ice
- mixing with fresh water from sea ice melt reduces downward mixing of imported water, reducing the AMOC strength

Chen and Tung, 2014

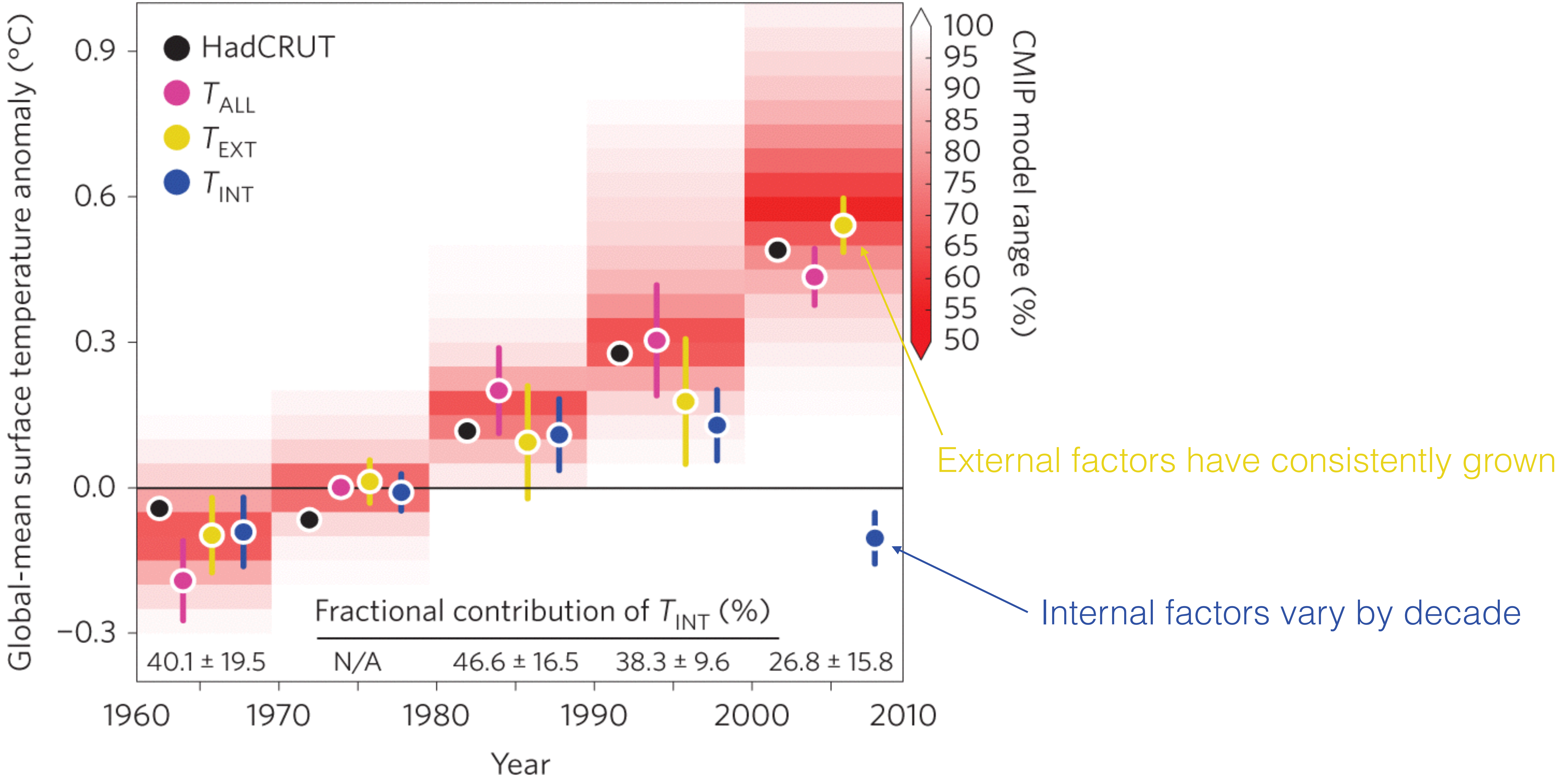
Natural Variability?

Models indicate that Pacific SST is critical, but observations show that the maximum ocean heat uptake is elsewhere

- Is there a link between the Atlantic and Pacific variability?
- Could the Pacific variability drive the Atlantic variability via Rossby wave dynamics (Trenberth et al., 2013)?
- Could Atlantic warming enhance water vapor transport to Pacific, leading to a negative phase of the IPO (McGregor et al., 2014)?
- How to reconcile climate model experiments that indicate less deep convection in the North Atlantic with observations that indicate more deep convection in the North Atlantic?

A Combination of Factors?

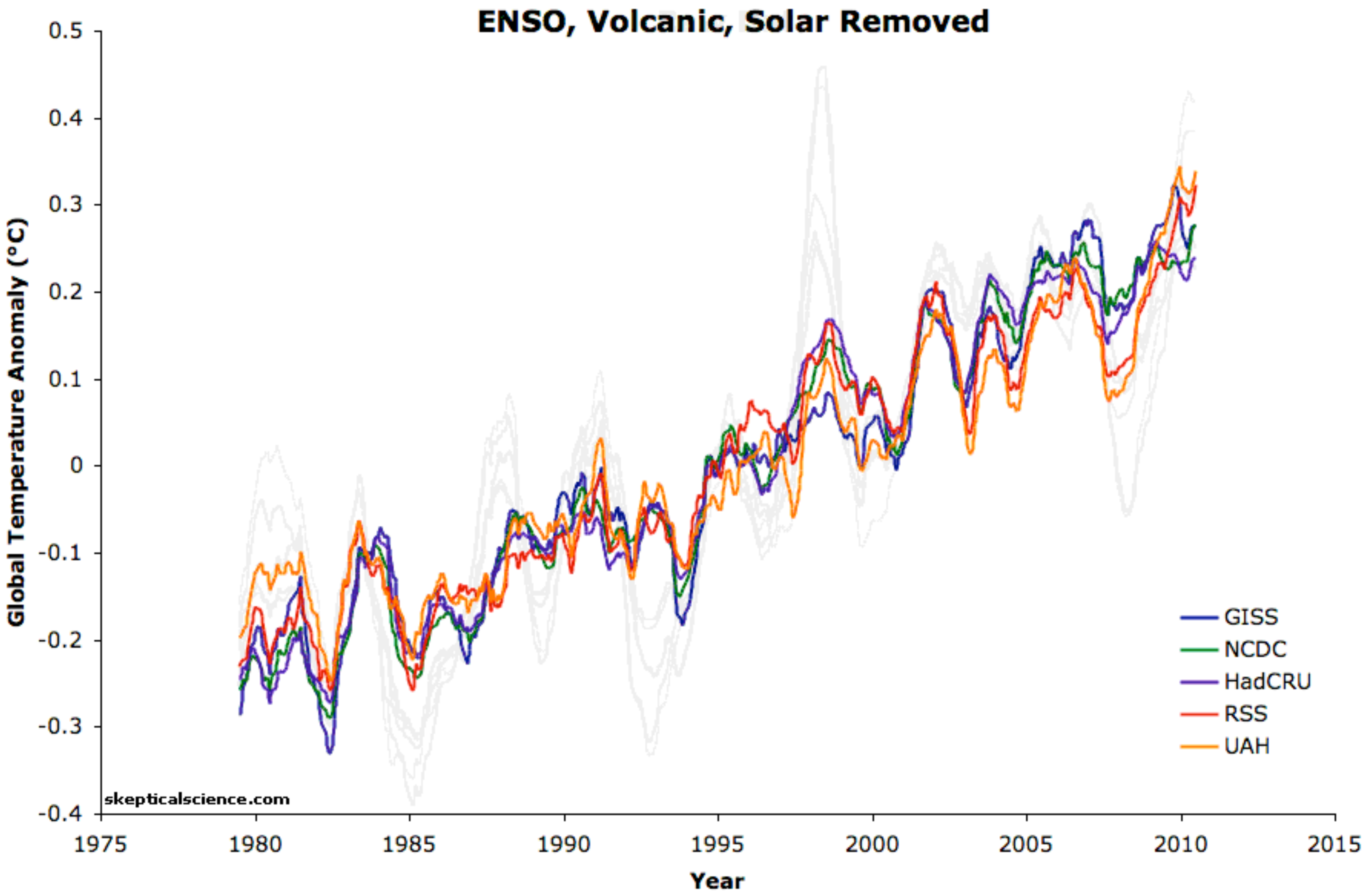
We can use models to decompose warming into external and internal factors



Watanabe et al., 2014

A Combination of Factors?

In addition to adjusting the forcings experienced by models, we can try to remove the effects of forcings from observations



Foster and Rahmstorf, 2011

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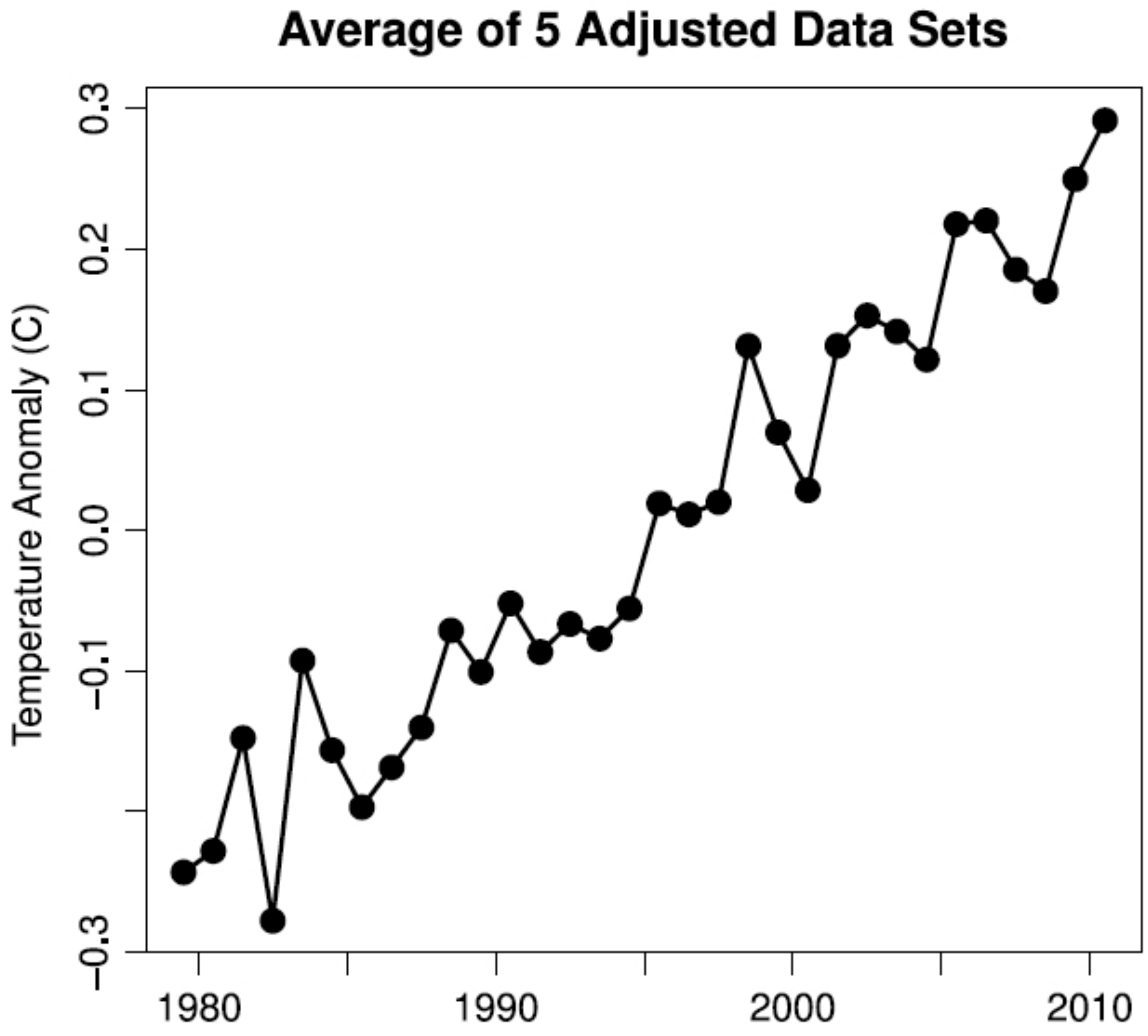
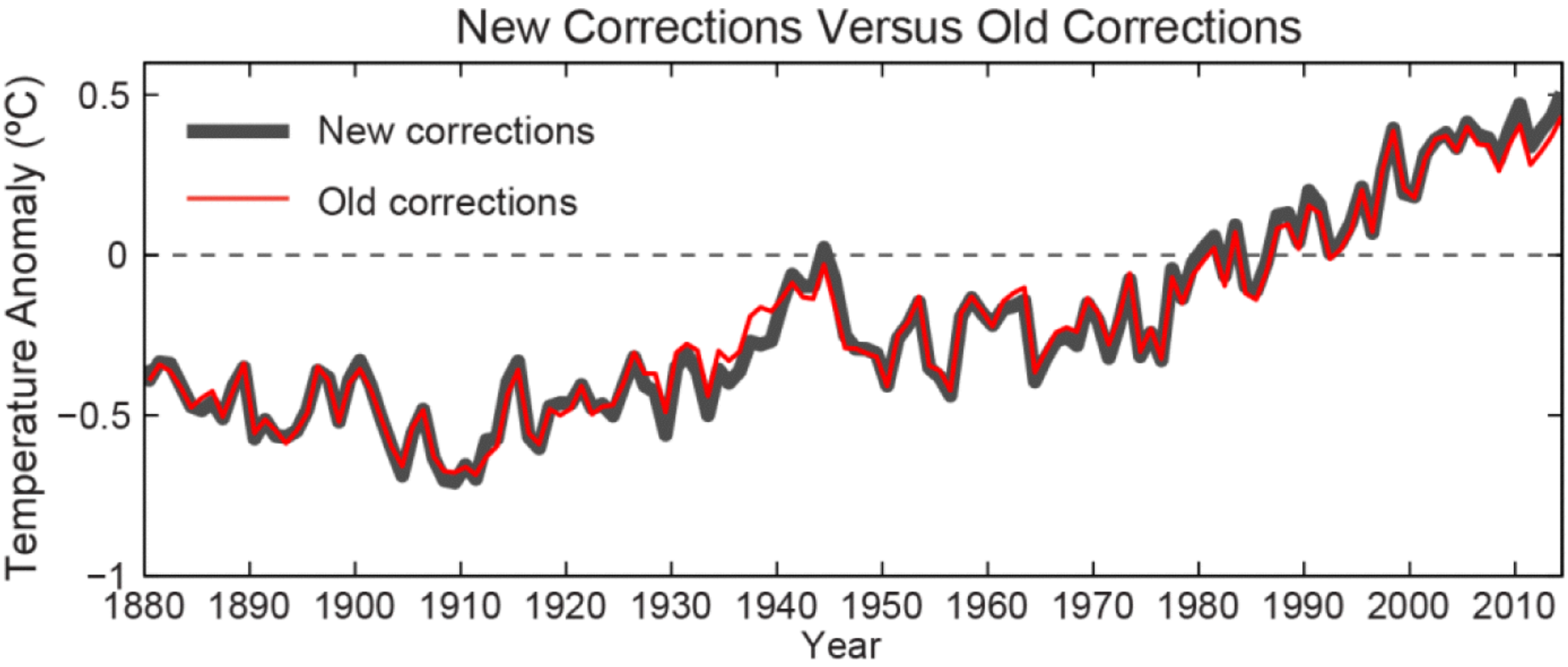


The warming signal is clear and consistent when the major modes of natural variability are removed from the global mean surface air temperature data

Foster and Rahmstorf, 2011

A Matter of Perspective?

The “hiatus” largely disappears in the newest version of the NOAA SST analysis



published June 4, 2015

Karl et al. 2015

A Matter of Perspective?

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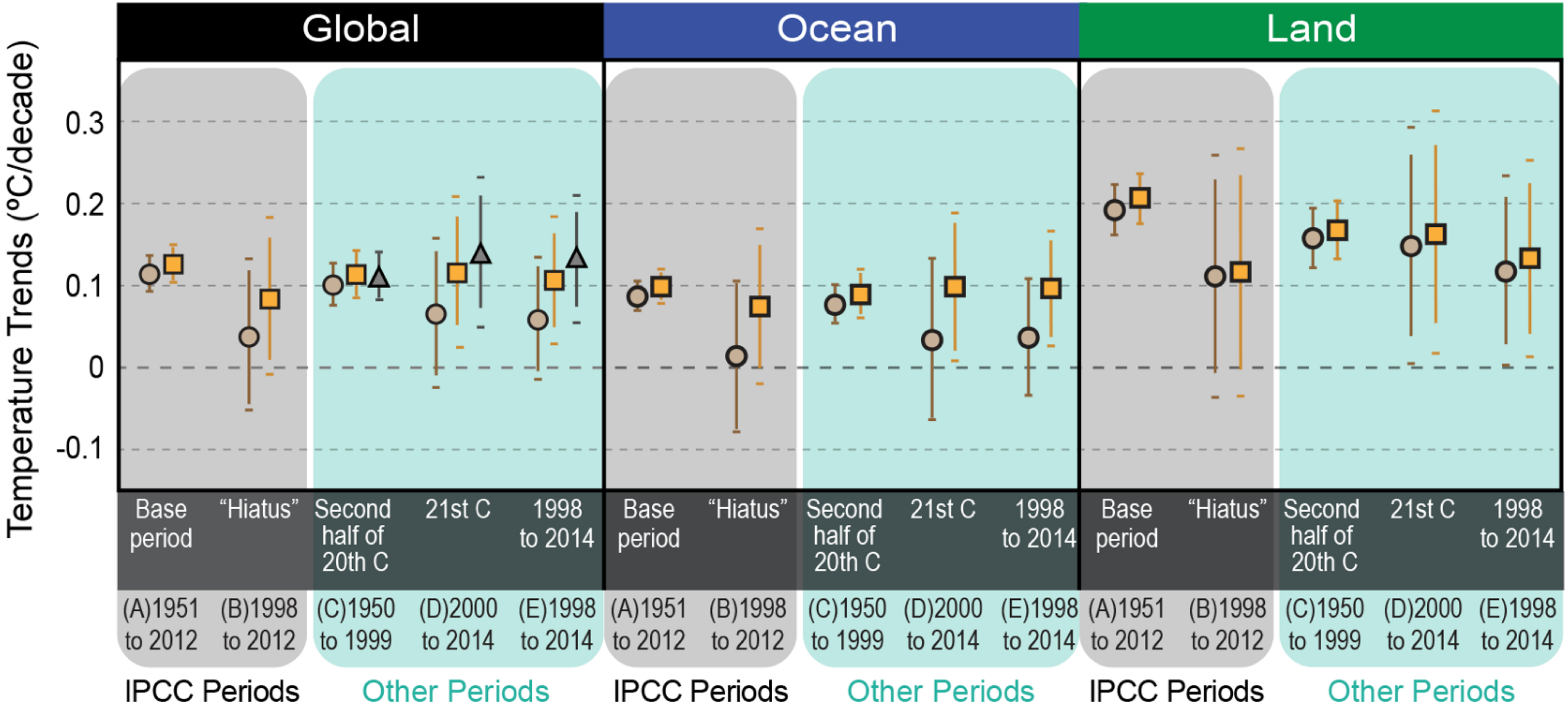


published June 4, 2015

Karl et al. 2015

A Matter of Perspective?

One of the most important metrics of climate change is the climate sensitivity

How much warmer does the Earth get for a given forcing?

- **Equilibrium climate sensitivity**: the change in temperature after all feedback mechanisms have responded to the forcing (exc. vegetation and ice sheets)
- **Transient climate sensitivity**: the change in temperature after a gradual change (e.g., a doubling of CO_2 in increments of 1% per year) at the time when the change is complete (i.e., at the time of the doubling)
- Equilibrium climate sensitivity occurs after a much longer time because some of the feedbacks are slow
- Feedbacks (and other forcings) may either increase or decrease the climate response, so that the equilibrium sensitivity may be larger or smaller than the transient sensitivity

A Matter of Perspective?

Estimates of equilibrium climate sensitivity range from 1 to 6°C, with a best guess of about 2–3°C

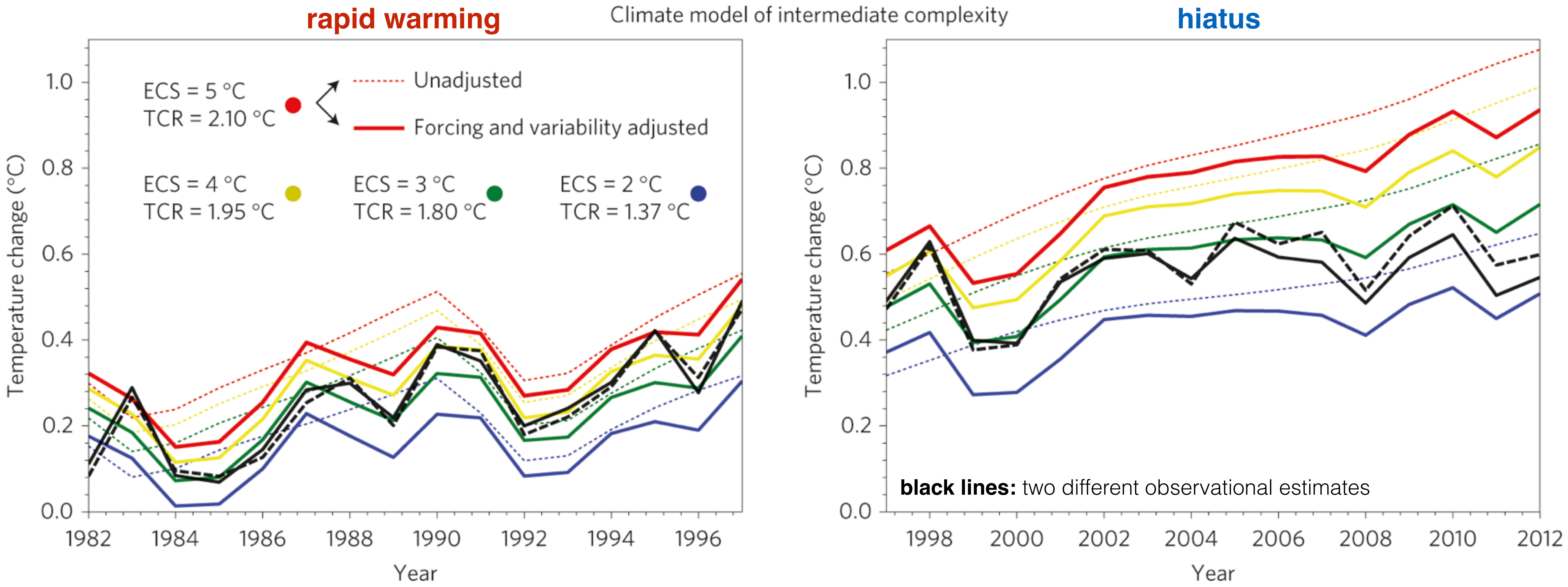
How much warmer does the Earth get for a doubling of CO_2?

- With no feedbacks, a doubling of CO_2 results in a warming of ~1°C
- Coupled climate models suggest that the equilibrium climate sensitivity to a doubling of CO_2 is about 2°C~4.5°C, with a best guess of about 3°C
- Energy balance models suggest a different, slightly lower climate sensitivity of about 1.5°C~2°C
- Coupled models include representations of natural variability and indirect feedbacks; energy balance models are flexible and can easily incorporate new information from observations
- A change of 3°C in global mean surface temperature could be catastrophic
- Many of the estimates of climate sensitivity are based on the period of rapid warming — does the hiatus period mean we need to re-evaluate these?

A Matter of Perspective?

After adjusting forcings and natural variability during the early 2000s, both periods are still consistent with ECS ~3°C

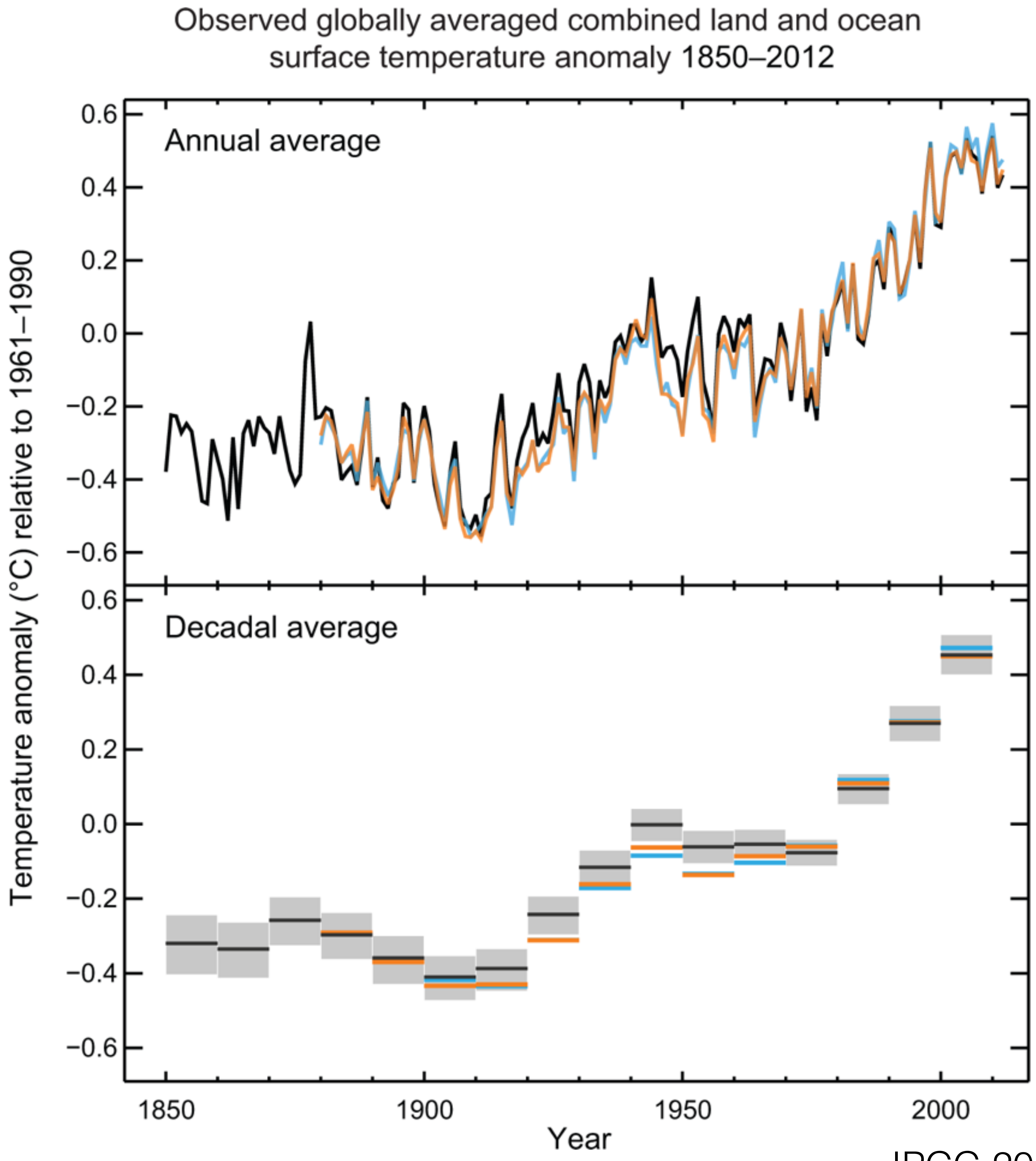
How much warmer does the Earth get for a doubling of CO_2?



Huber & Knutti, 2014

A Matter of Perspective?

- Regardless of the year-to-year changes, the early 2000s were still the warmest decade on record
- Average surface temperatures are only one indicator of climate change
- Extreme events (such as droughts, floods, and heat waves) have occurred more often
- Sea ice continues to disappear at a record pace
- Global mean sea level continues to rise
- Glaciers and ice sheets continue to melt
- 2014 was the warmest year on record, and 2015 threatens to be hotter still



IPCC 2013