Climate Variability from Weeks to Centuries, and its Relevance for Climate Change

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Outline

- Variability from the intra-seasonal scale to the decadal scale - an introduction, by way of examples.

- Example of mechanisms for various timescales. Selective rather than comprehensive.

- Ocean heat uptake and relation, if any, to global warming.

Who cares?

- If we are going to argue that there might be surprises (Eli, Kerry etc.) then we have to *understand* the nature of climate variability. Otherwise, the skeptic could argue that the warming we have so far seen is also just a surprise.

I will be mildly opinionated throughout....

But First....

On the importance of having both GCMs and TMs (Toy Models, or Theoretical Models, or just plain 'Theory') in our bag of tools.

"When you follow two separate lines of thought, Watson, you will find some point of intersection that approximates the truth."

Said by a wise Professor of Climate Science to her Graduate Student.

(Actually said by a cocaine addict, Sherlock Holmes, to his physician, Dr. Watson).

What is, or what should be, climate science?

- A reductionist aspect, namely GCMs. We try to reduce the climate system to the 'laws' of physics — Newton's laws (via Navier Stokes), the laws of thermodynamics, electromagnetism (via radiative transfer).
  - This would be our most fundamental theory, if we were to succeed.

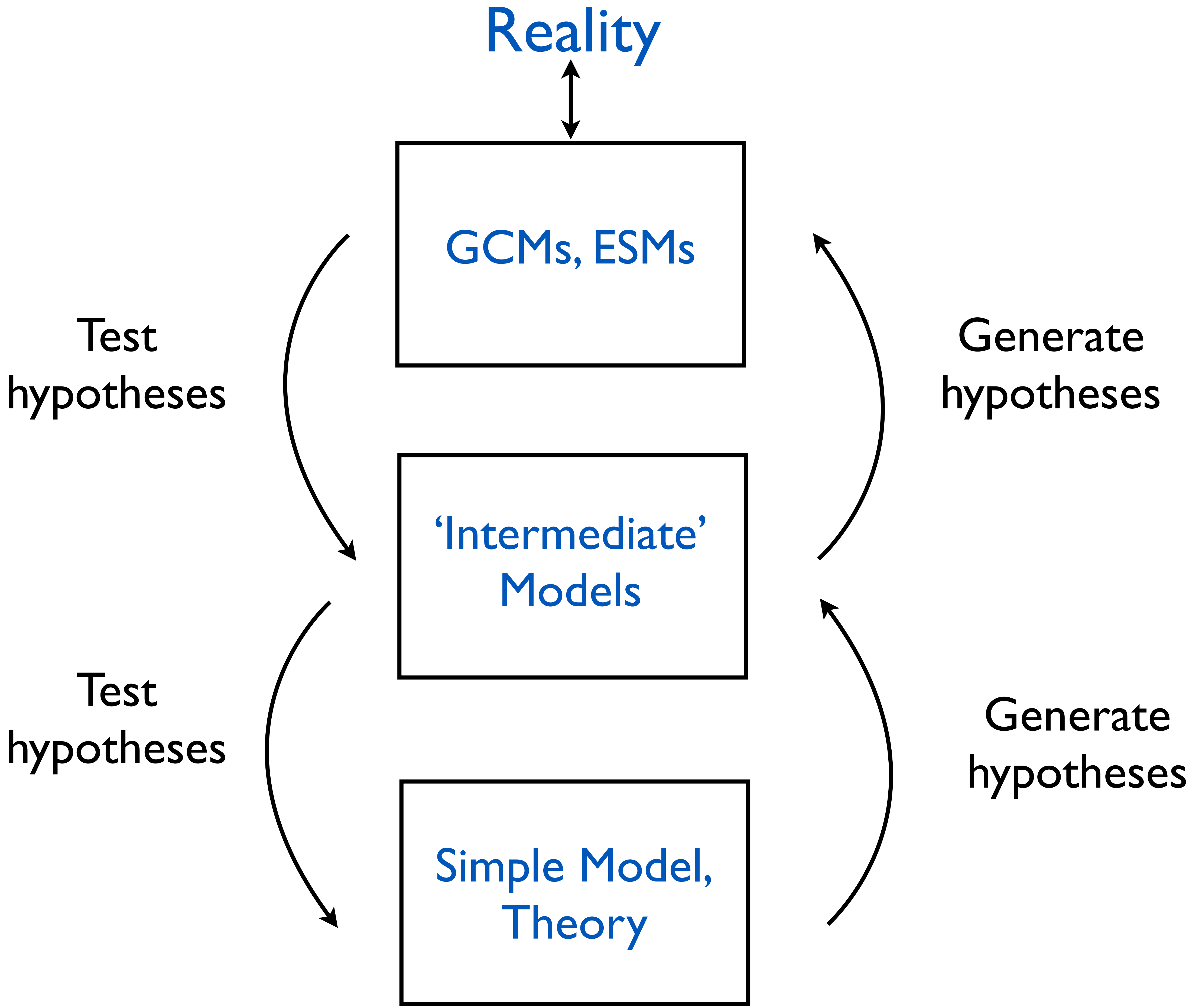
Q. Do you want to hear my theory of the Gulf Stream?

A. It's the Navier Stokes Equations.

(Chris Garrett)

What is, or what should be, climate science?

- A reductionist aspect, namely GCMs. We try to reduce the climate system to the 'laws' of physics — Newton's laws (via Navier Stokes), the laws of thermodynamics, electromagnetism (aka radiative transfer).
  - This would be our fundamental theory, if we were to succeed.
- But we are a long way from that ideal. Two problems:
  - GCMs are far from perfect. They also have ad hoc aspects.
  - Even if GCMs were perfect, they are not economical — don't directly predict emergent phenomena.
- We need models that deal directly with the phenomena we are interested in.
  - 'Theory' including GFD, Toy Models.
  - 'Intermediate models' in a connected hierarchy.


Reality
GCMs, ESMs
Test hypotheses
Generate hypotheses
'Intermediate' Models
Test hypotheses
Generate hypotheses
Simple Model, Theory

Why bother?

- To improve GCMs.
    - Suggest hypotheses, to suggest ways of proceeding and of parameterizing, to point out dangers,etc.
- To directly predict phenomena of interest more parsimoniously. To help understand.

If GCMs were perfect, the second point might be regarded be an indulgence. But GCMs never will be perfect (IMHO).

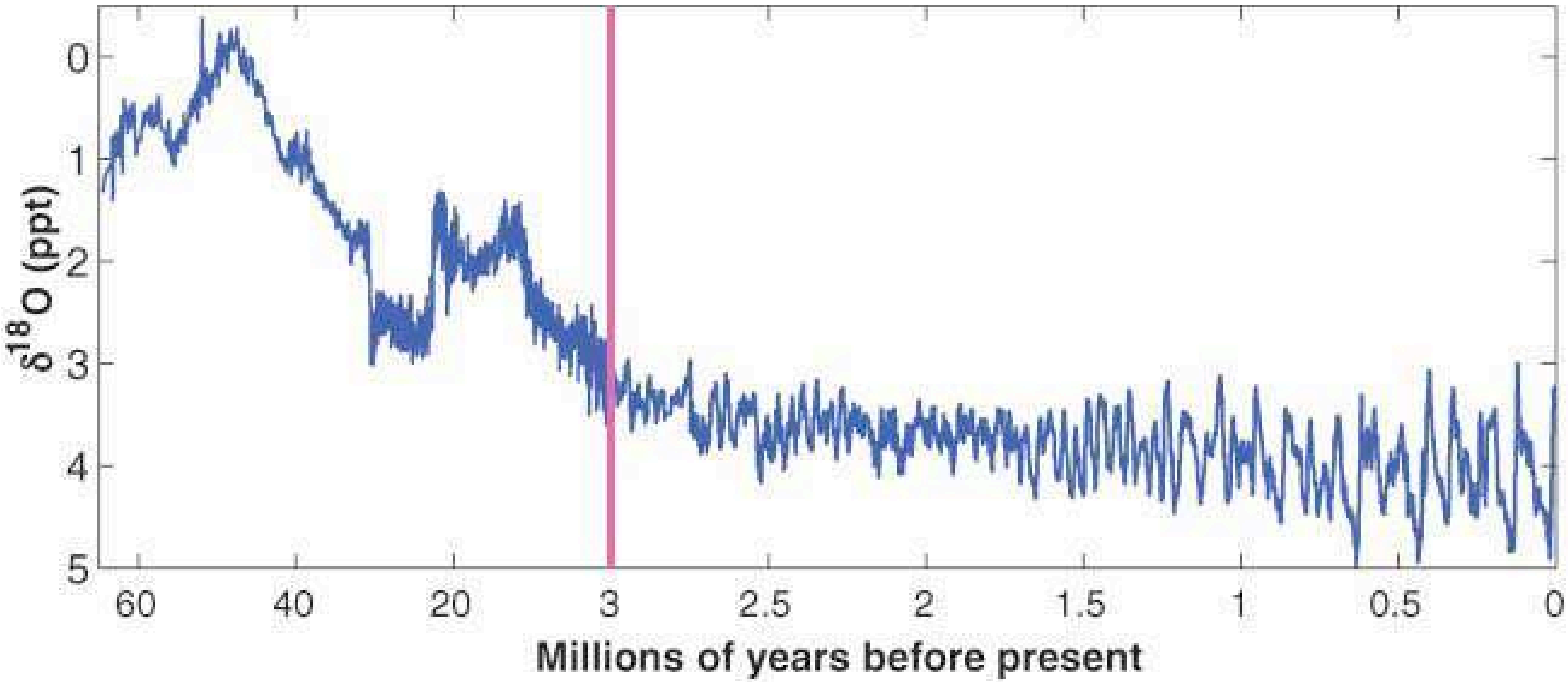
Enough Already

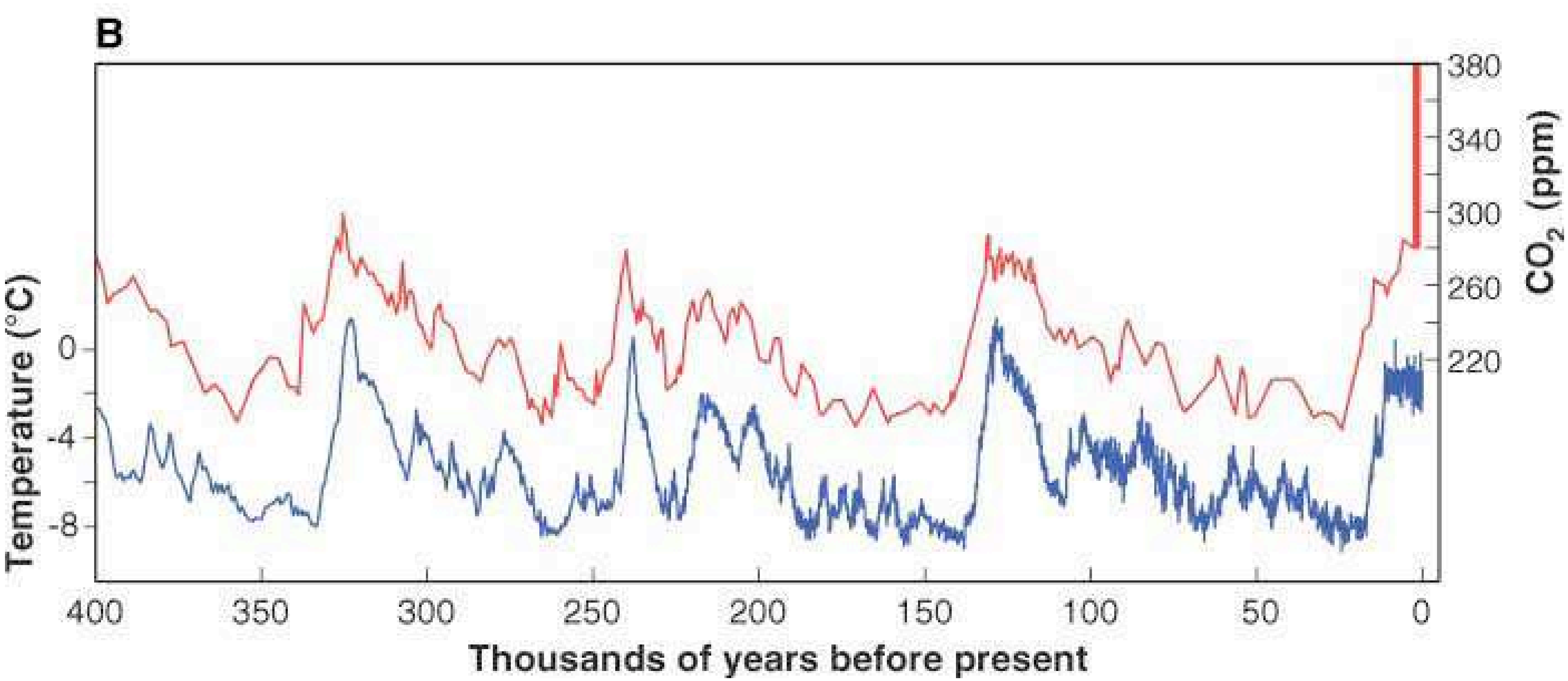
It is a safe rule to apply that, when an author writes with a misty profundity, he is talking nonsense.

Alfred North Whitehead.

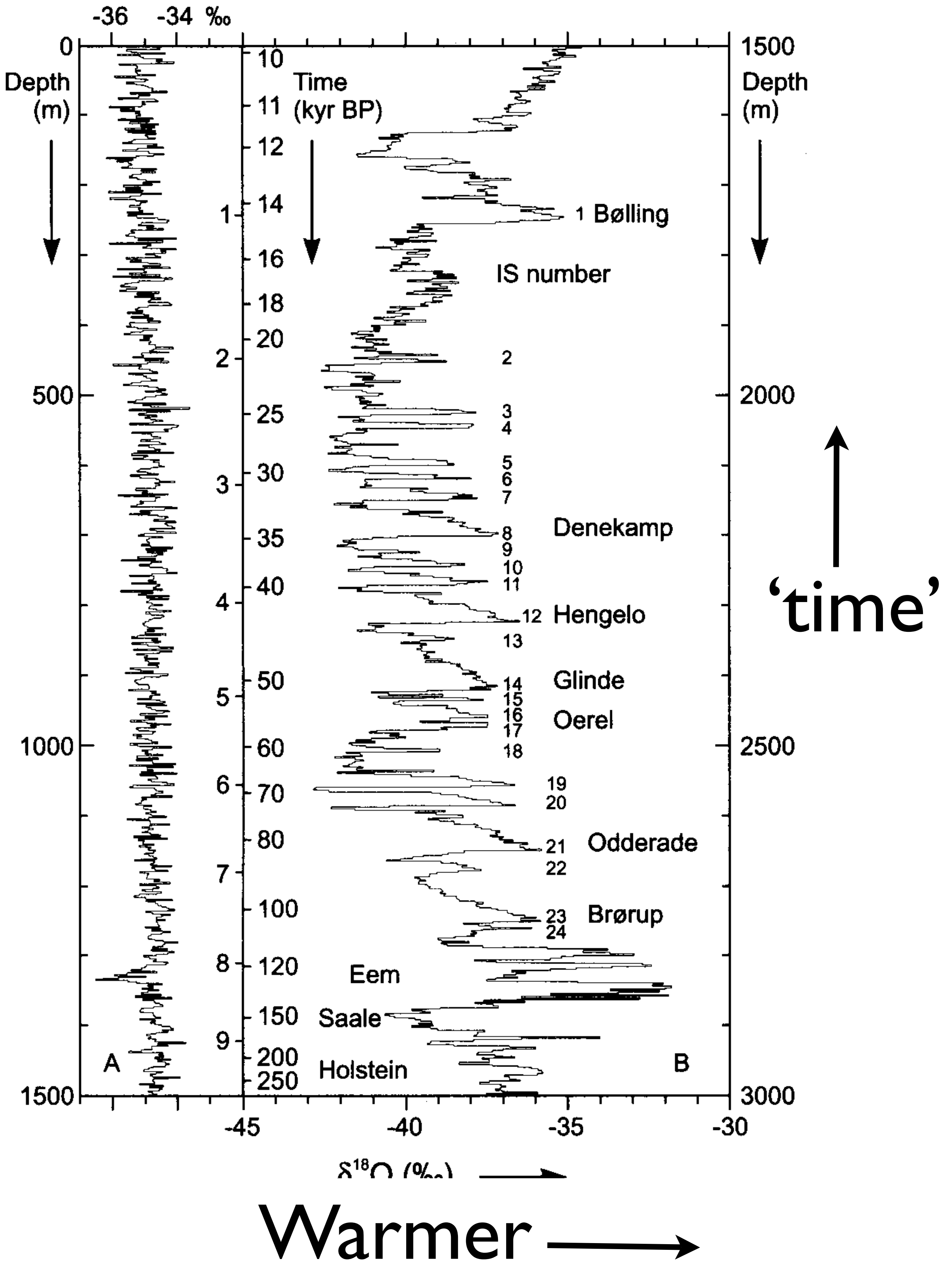
Paleo Record

(Zachos et al, Petit)





Observational Evidence - examples



The GRIP Record

(Dansgaard 1993)

$$\delta^{18}O = \frac{[^{18}O/^{16}O] - [^{18}O/^{16}O]_{std}}{[^{18}O/^{16}O]_{std}}$$

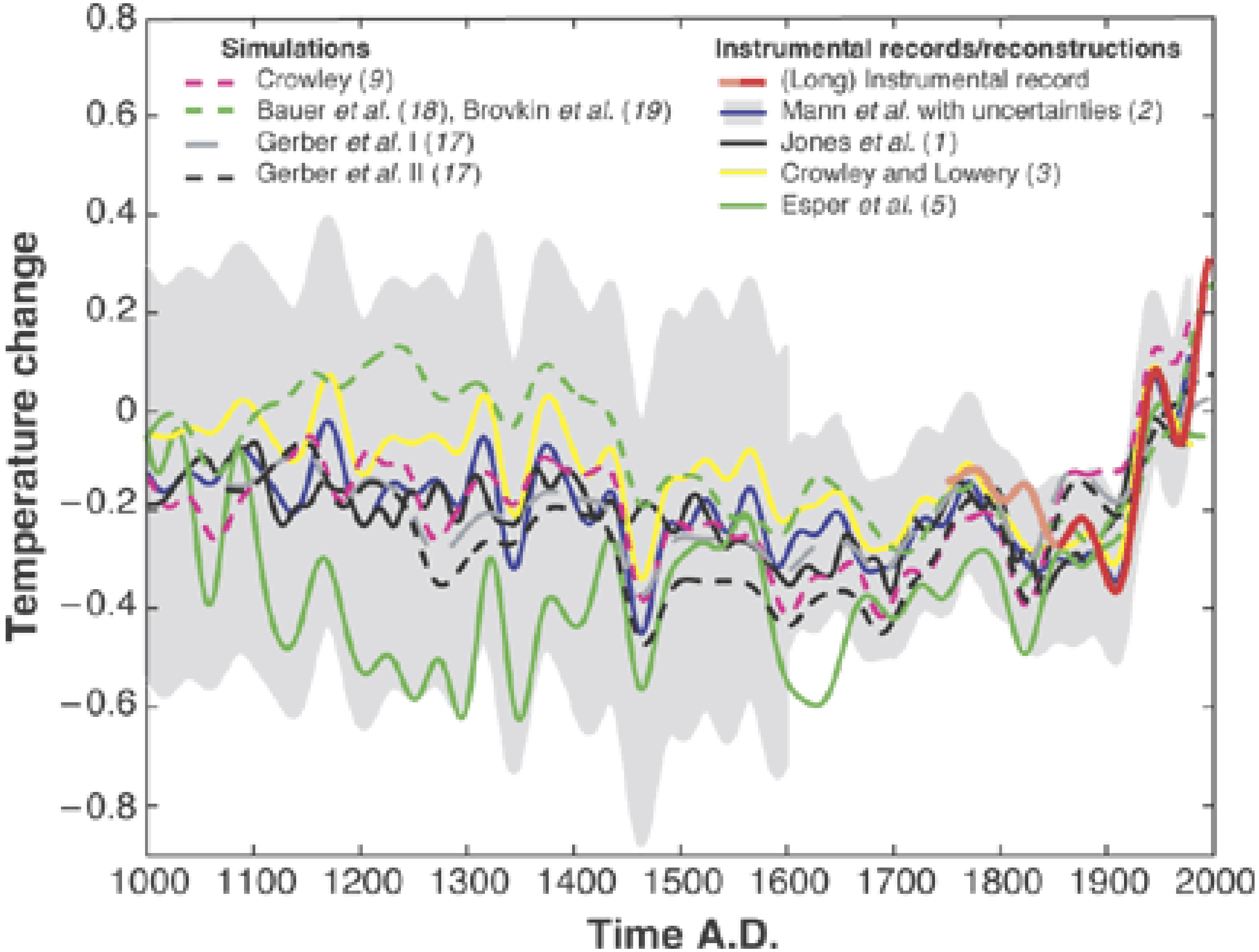
Isotopic concentration is a function of the temperature at which the condensation occurs. The lower vapor pressure of water vapour containing $\delta^{18}O$ affects its condensation as a function of temperature, and higher ratios of $\delta^{16}O$ in the ice core indicate higher temperatures. Calibration is fraught with difficulties....

Dated using depth, in combination with ice flow models and comparison with other proxy records. Issues about dating remain....

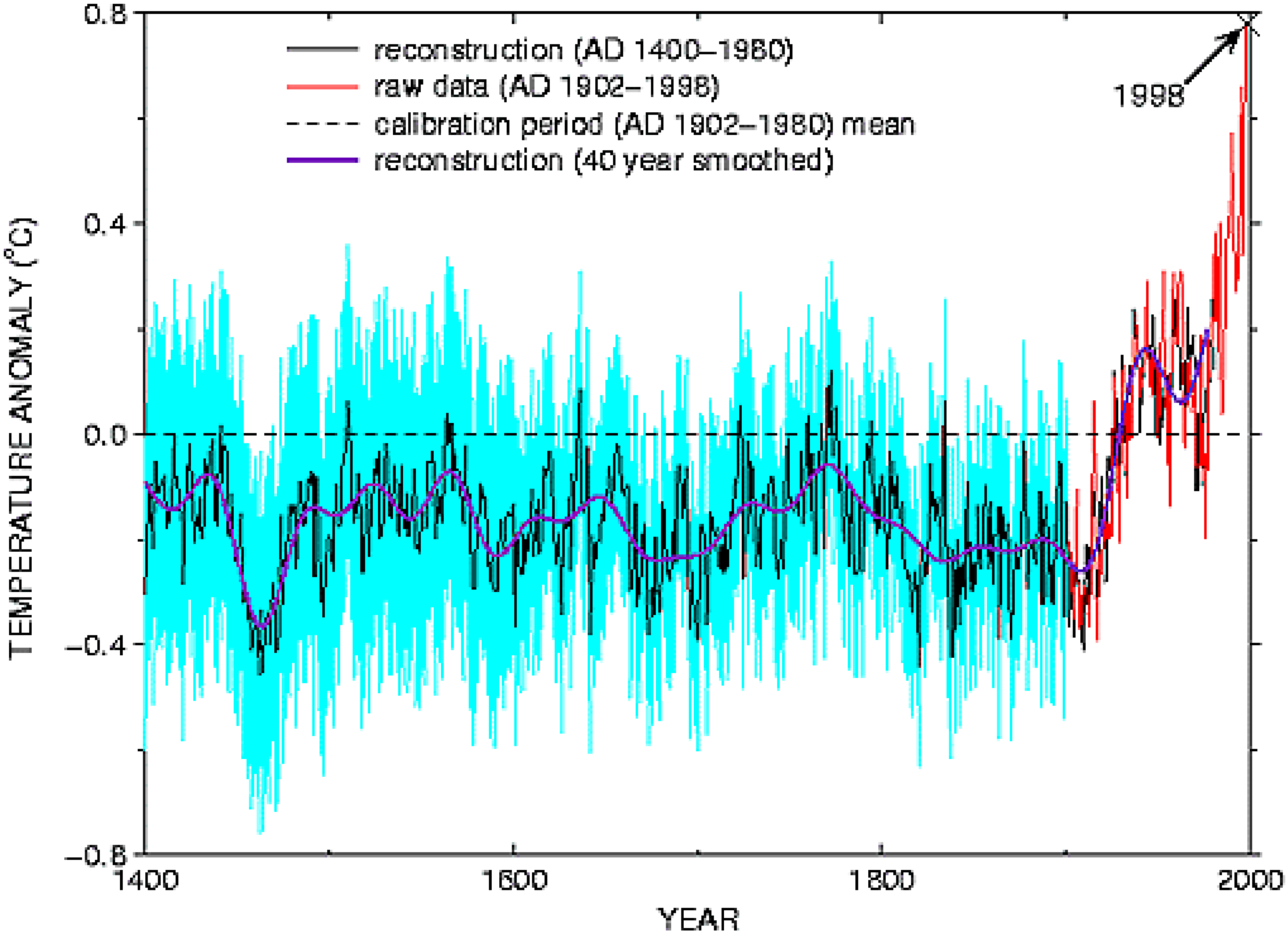
Observational Evidence - examples

Climate Variations

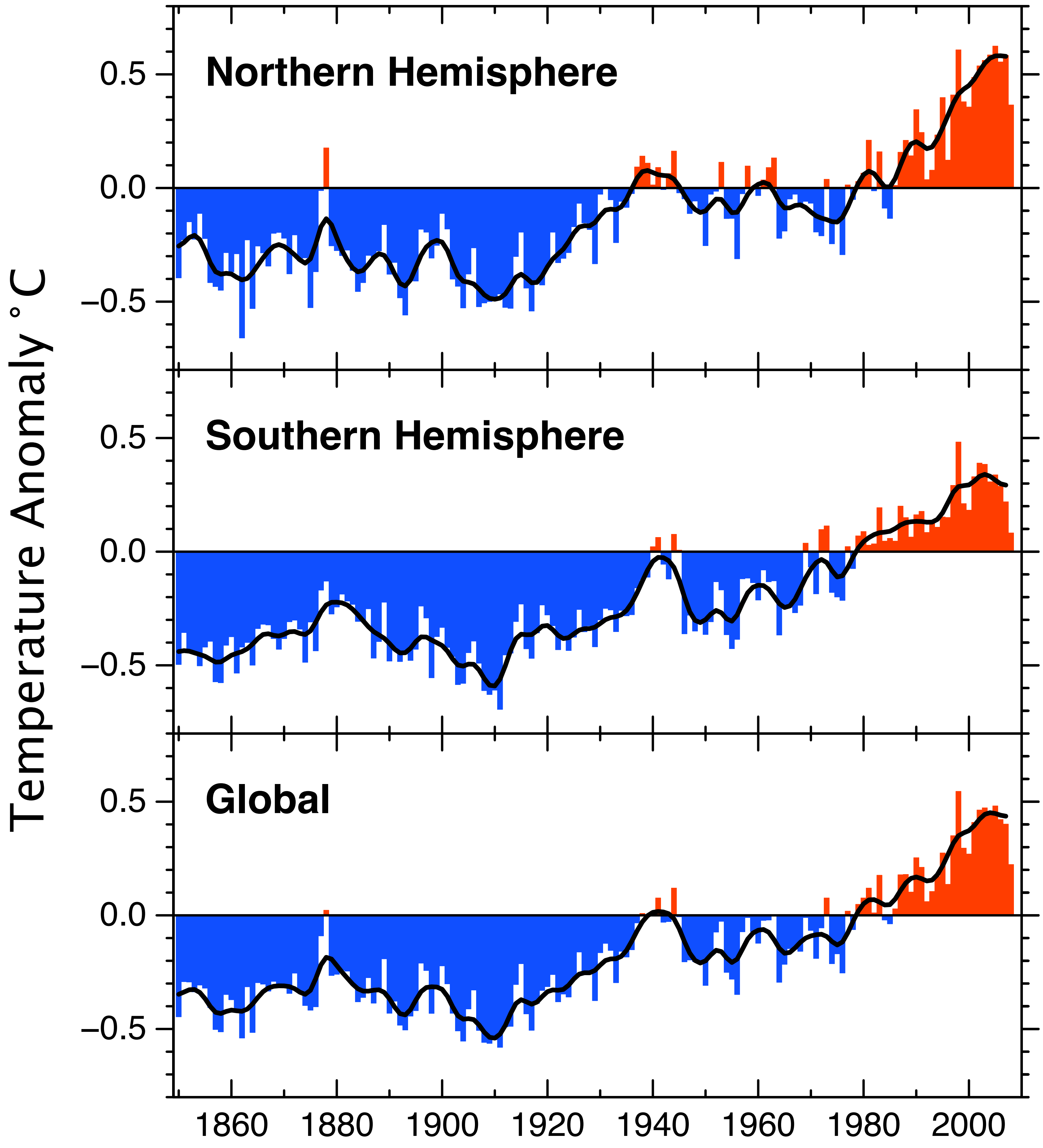
Temperature over the past millennium, reconstructed from multiple records and proxies (M. Mann).



Temperature over the past 600 years.

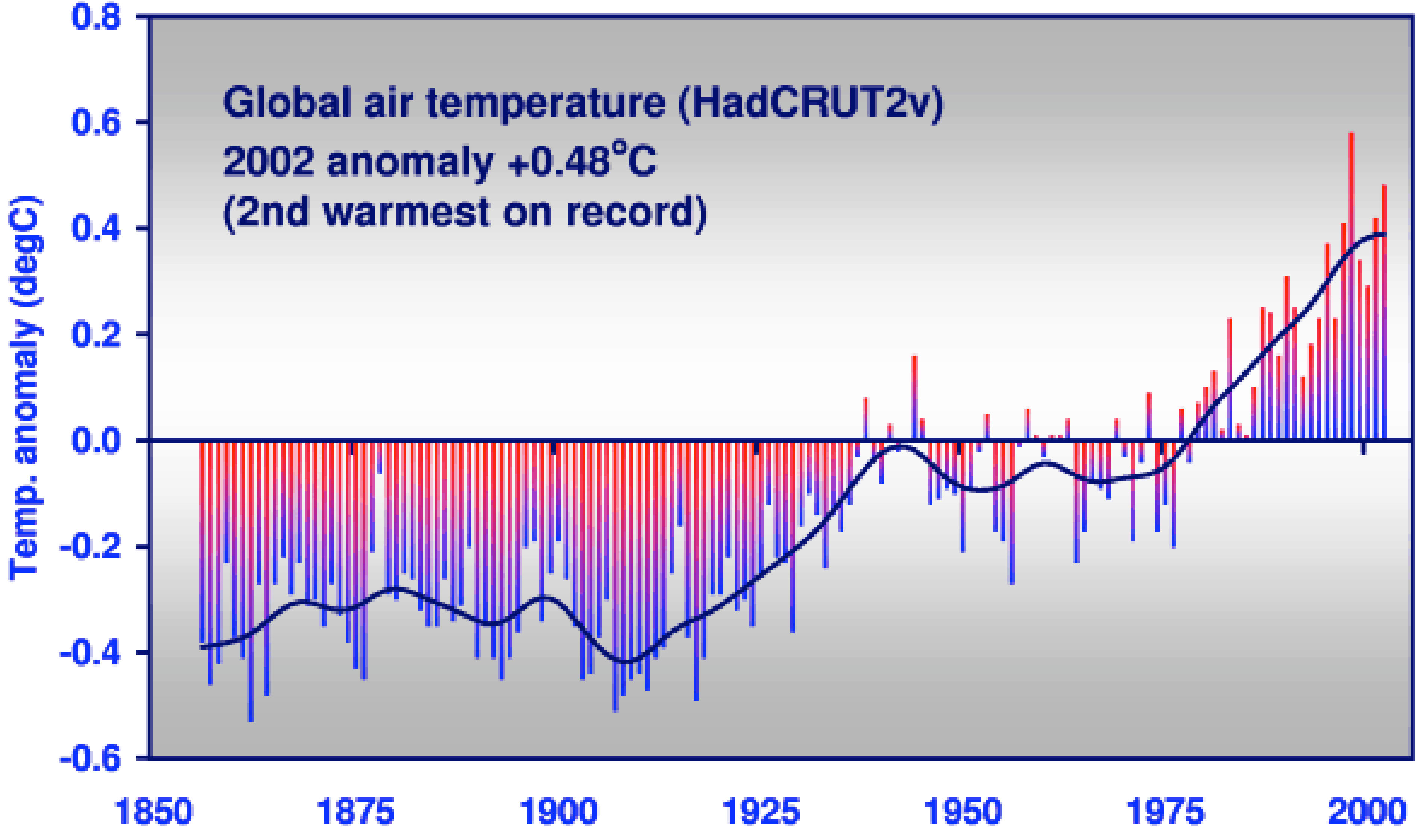


Global Temperature, HadCRUT3

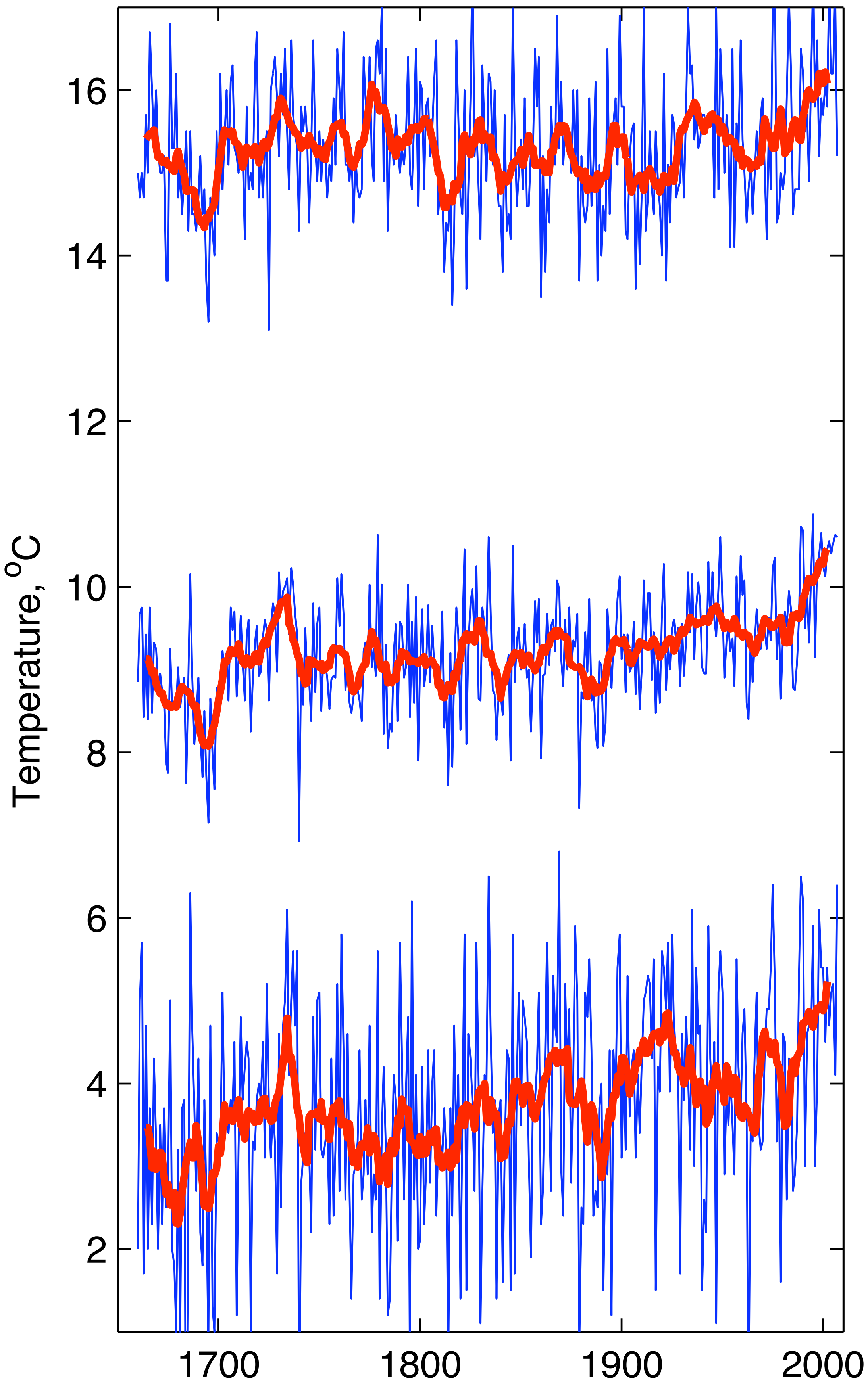


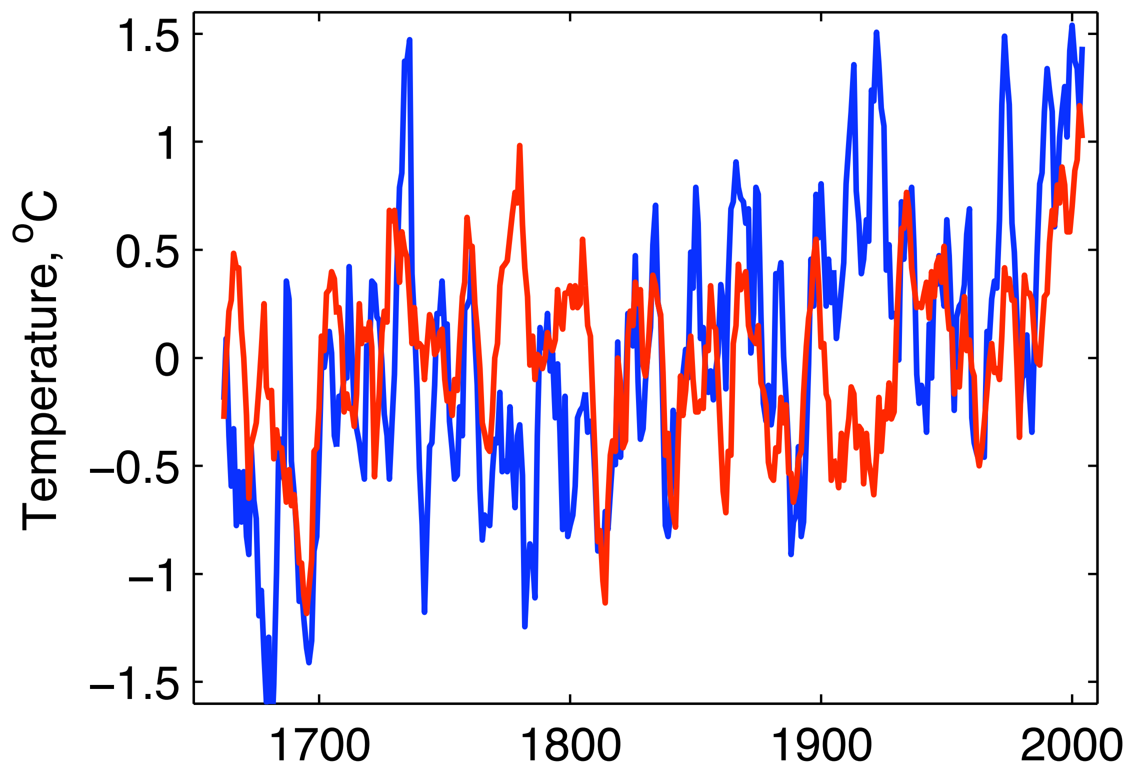
Climate Variations

Temperature over the past 150 years
(Univ. East Anglia and UK Met Office)



Central England Temperature (HADCET, Parker et al 1992)

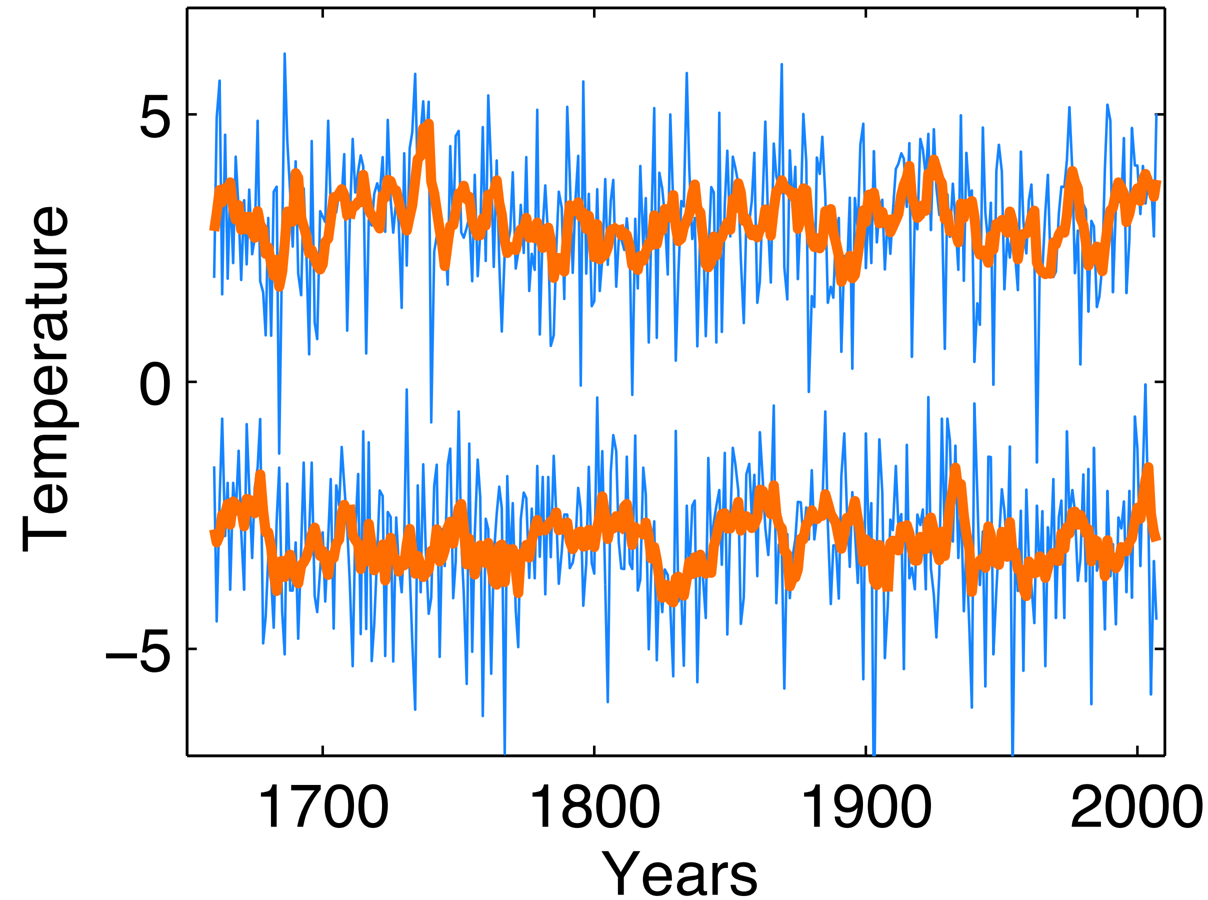




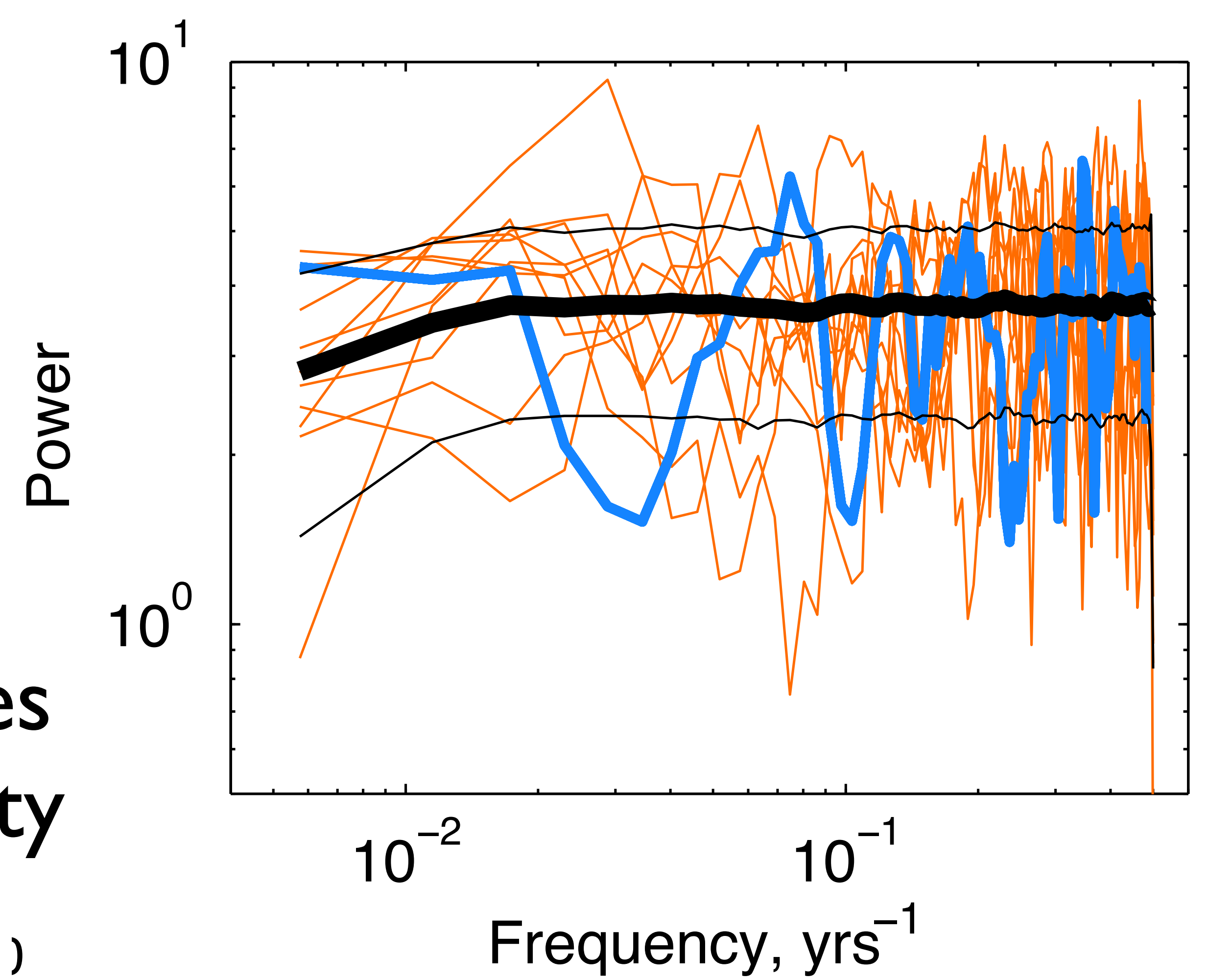
Above: Summer and Winter, means removed

Left: Summer, Annual Mean, Winter.

Central England Temperature, Real and Shuffled.



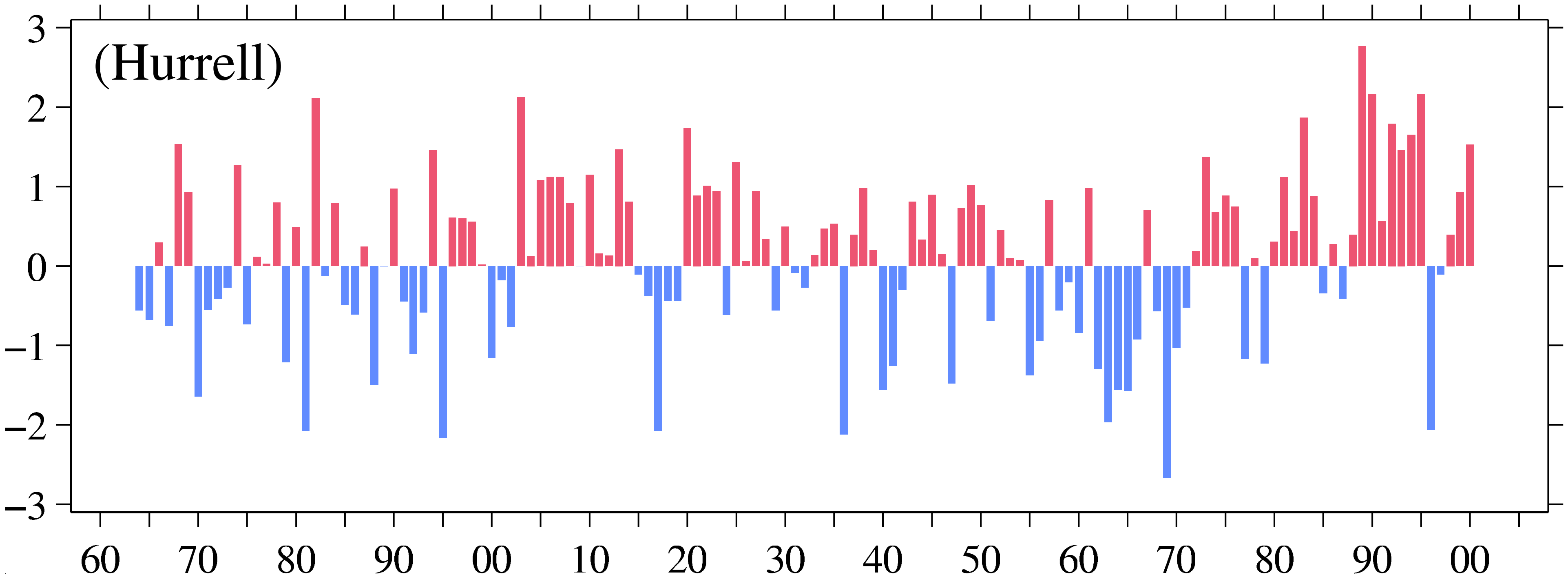
Power Spectra of above

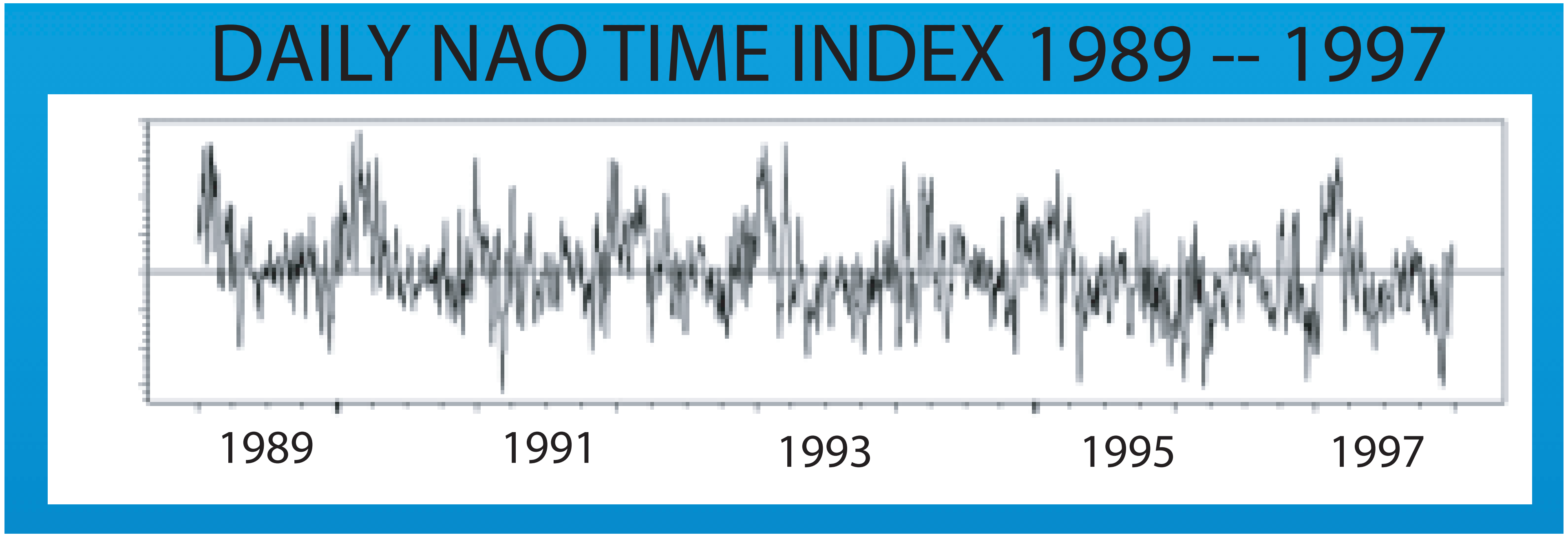


Conclude using other studies in addition: Decadal Variability is present but weak.

Interannual Variability

The NAO Index

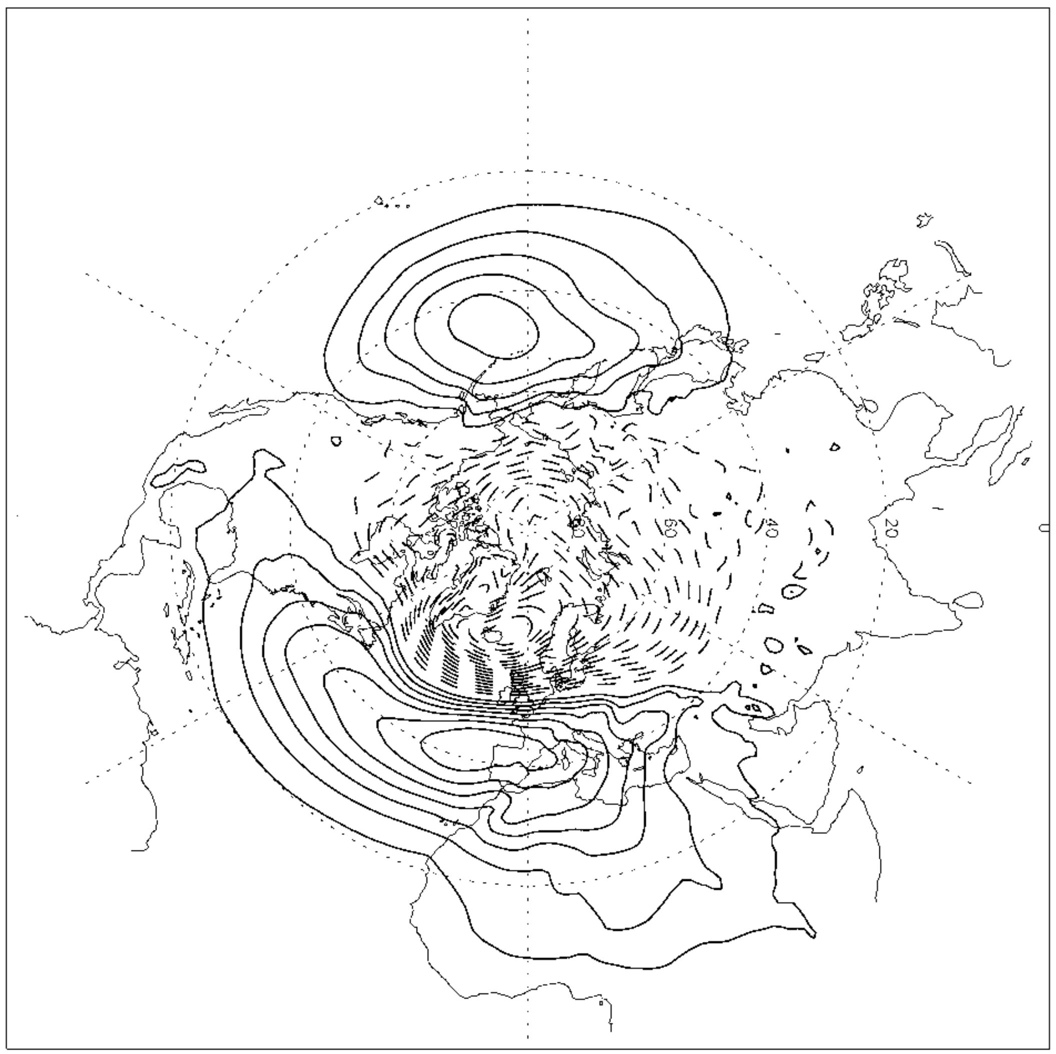




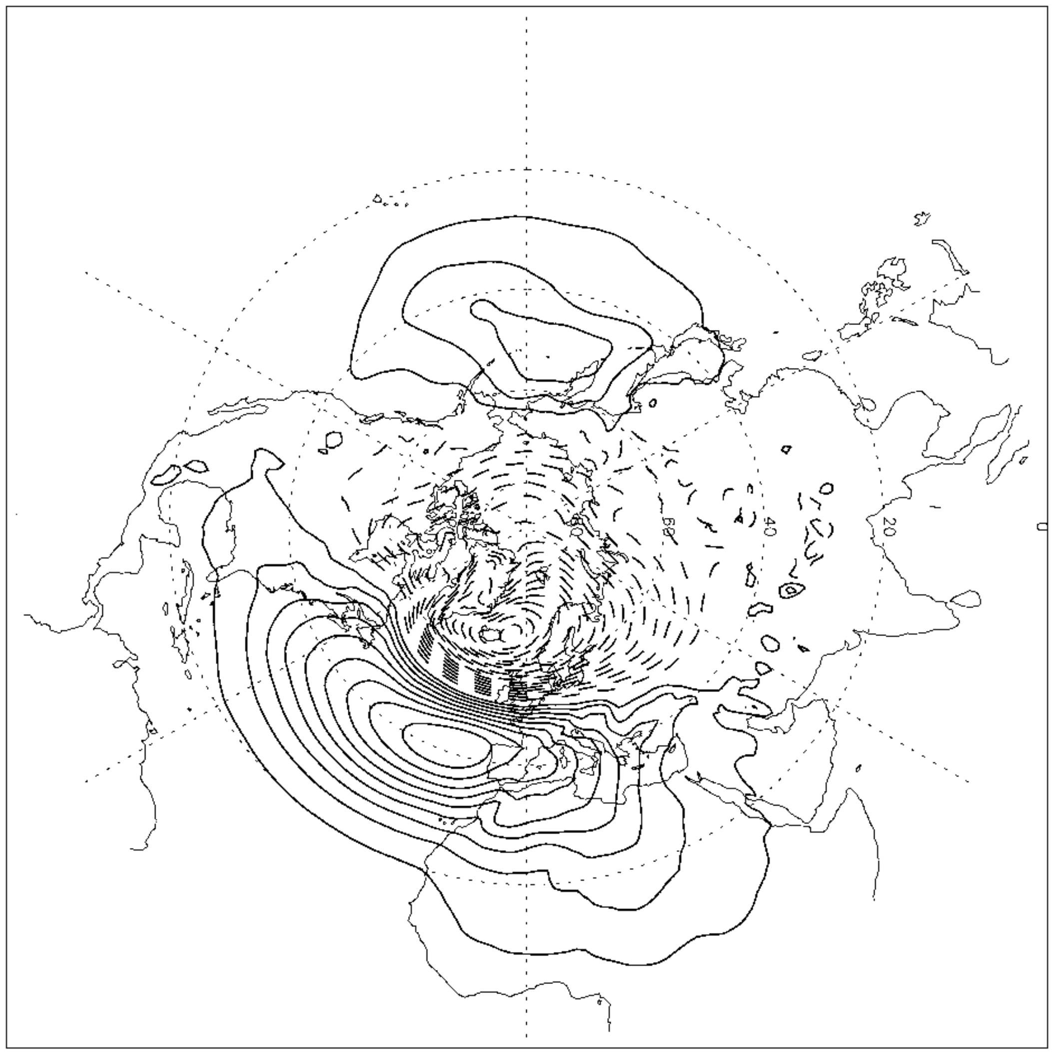
Time series of the NAO index. NAO is sometimes defined as the anomalous pressure difference between polar low and subtropical high. J. Hurrell's index is normalized Lisbon-Stykkisholmur sea-level pressure difference in Winter.

Spatial Patterns of Intra-Seasonal and Interrannal Variability

Sea-level pressure, winter (DJF)



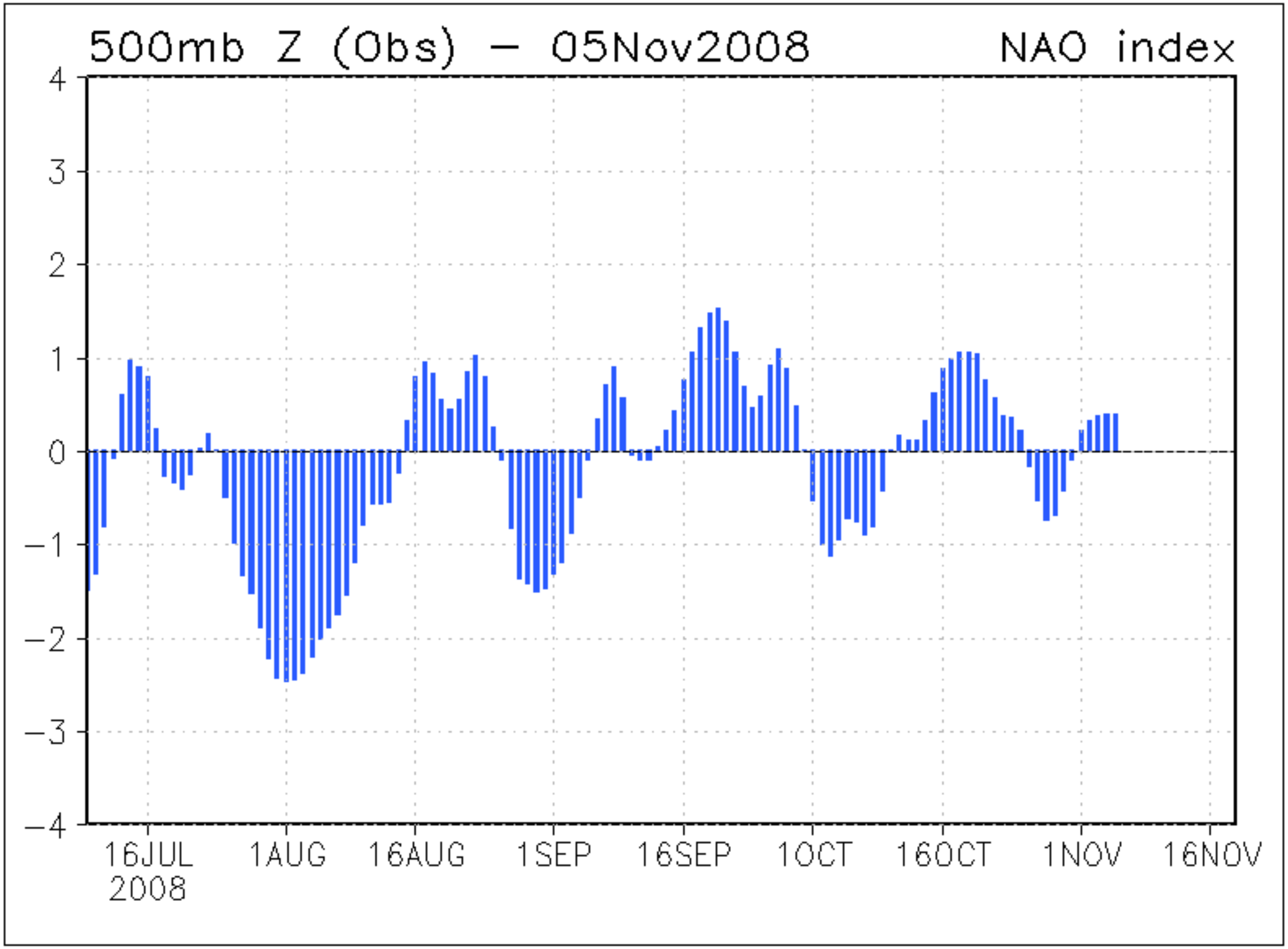
First EOF (hemispheric)



First EOF (Euro-Atlantic)

Ambaum et al, 2004

NAO Daily Index



Mechanisms of Climate Variability

Involving atmosphere-ocean system on timescales up to centennial

- Atmospheric origin. The atmosphere might independently vary on timescales longer than those normally associated with the baroclinic lifecycle ('regimes').

- Atmospheric variability might be reddened by presence of an ocean with a large heat capacity, leading to a red spectrum of climate variability. This has become the *Null Hypothesis*. (Hasselmann, Frankignoul).

- *Coupled modes* — non-trivial interactions between the ocean and atmosphere. The ENSO cycle is the only uncontroversial example.

- Primarily an oceanic origin, e.g. MOC variability. Ocean variability might affect the atmosphere, and so the climate, without the need for coupled modes. Decadal scale variability.

- Changes in forcings external to the ocean-atmosphere system. e.g., changes in atmospheric composition, CO2, volcanoes.

- Structural Instability. Small parameter changes might lead to large climate changes, and so to interannual and interdecadal (possibly longer) climate changes.

Atmospheric Variability.

- Baroclinic timescale - the Eady time: $\sigma \equiv \frac{0.3\Lambda H}{L_d} = \frac{0.3U}{L_d}$
  - Timescale is of order days. (1000 km/10m/s = 1 day)
- Geostrophic turbulence has a similar timescale.
- Do atmosphere-only numerical models give order-of-magnitude longer timescales?

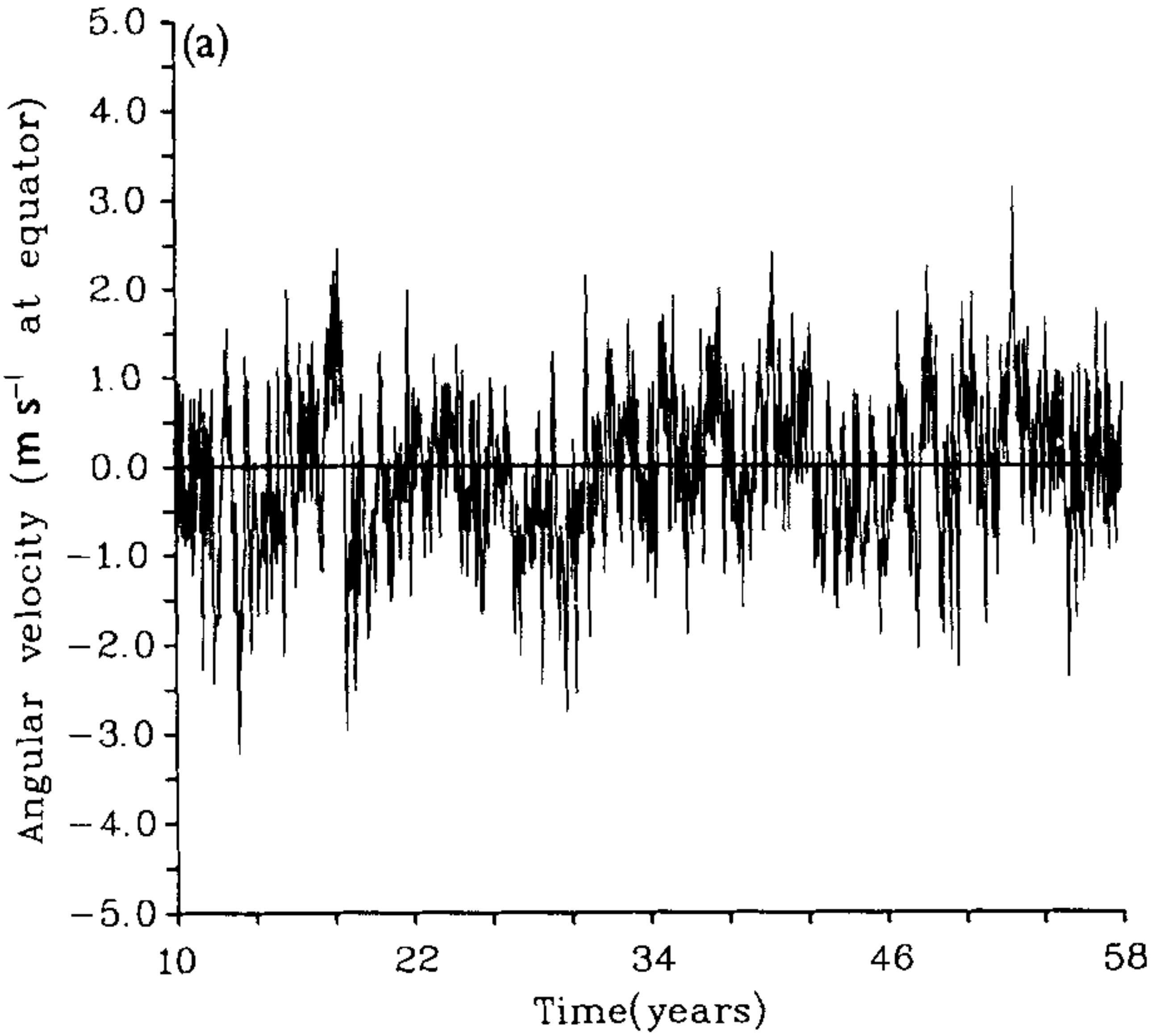
I believe the answer to this question is `not importantly'.

However, there are curious results to the contrary.

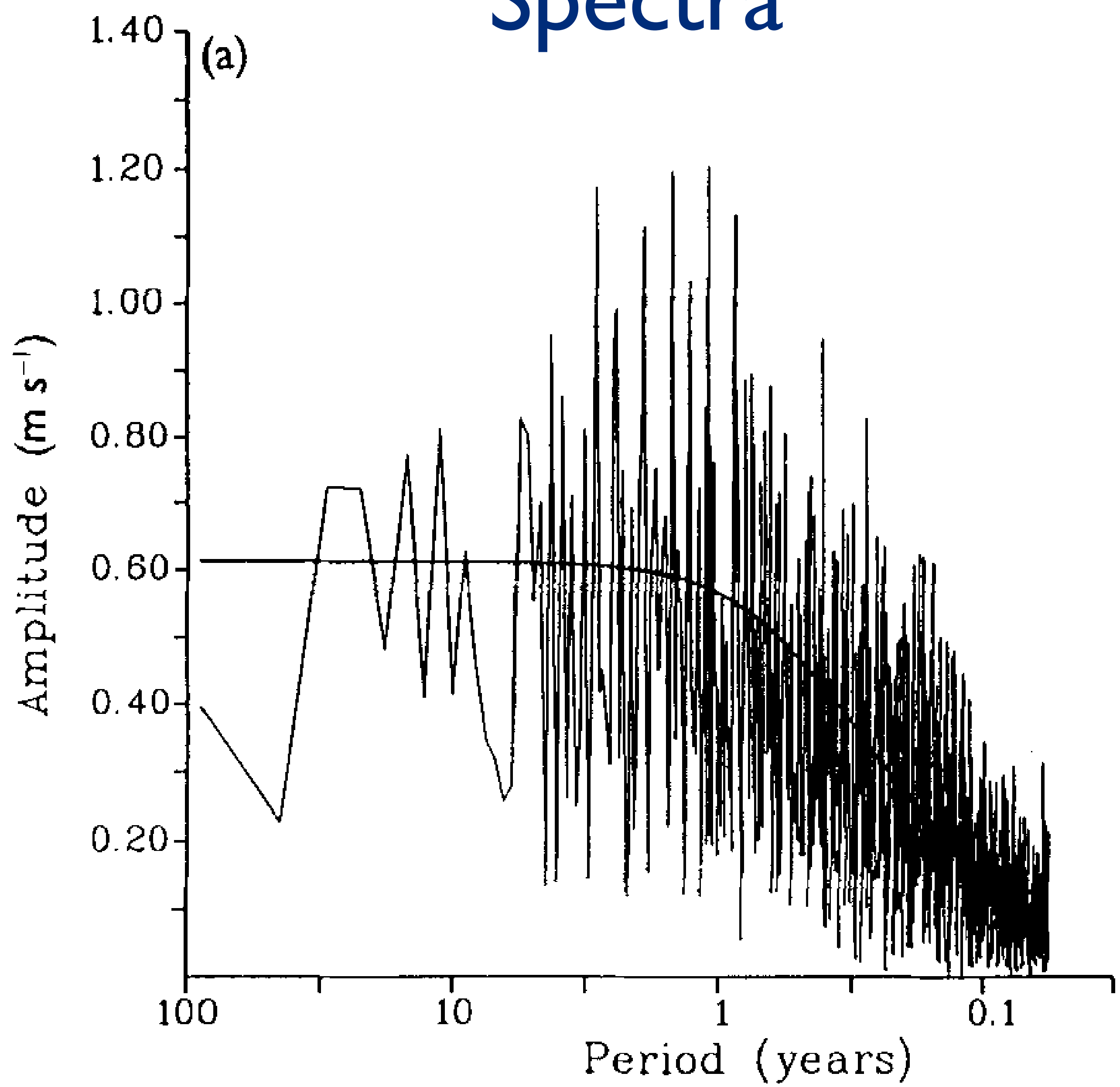
Result from James and James (1992)

Atmosphere-only GCM, simple forcing, low resolution

Time Series



Spectra



Looks like red noise – but not 'just' red noise.

Interpretation

J & J is an interesting result, for the shoulder of the noise comes at a timescale of about one year — far longer than any purely atmospheric timescale. Nevertheless, it seems unlikely (to me) that this effect is causing natural variability on decadal timescales, or even interannual timescales, because:

1. No mechanism is apparent that could produce such variability, except as a residual of intra-seasonal variability. (But this is a very weak argument — an `argument from personal incredulity', made (in)famous by Bishop Wilberforce.)

2. If atmosphere were able to produce regime-like behaviour when steadily forced, it is likely that a seasonal cycle would disrupt any regime behaviour that persisted beyond a few months.

Nevertheless, James and James did obtain their result.

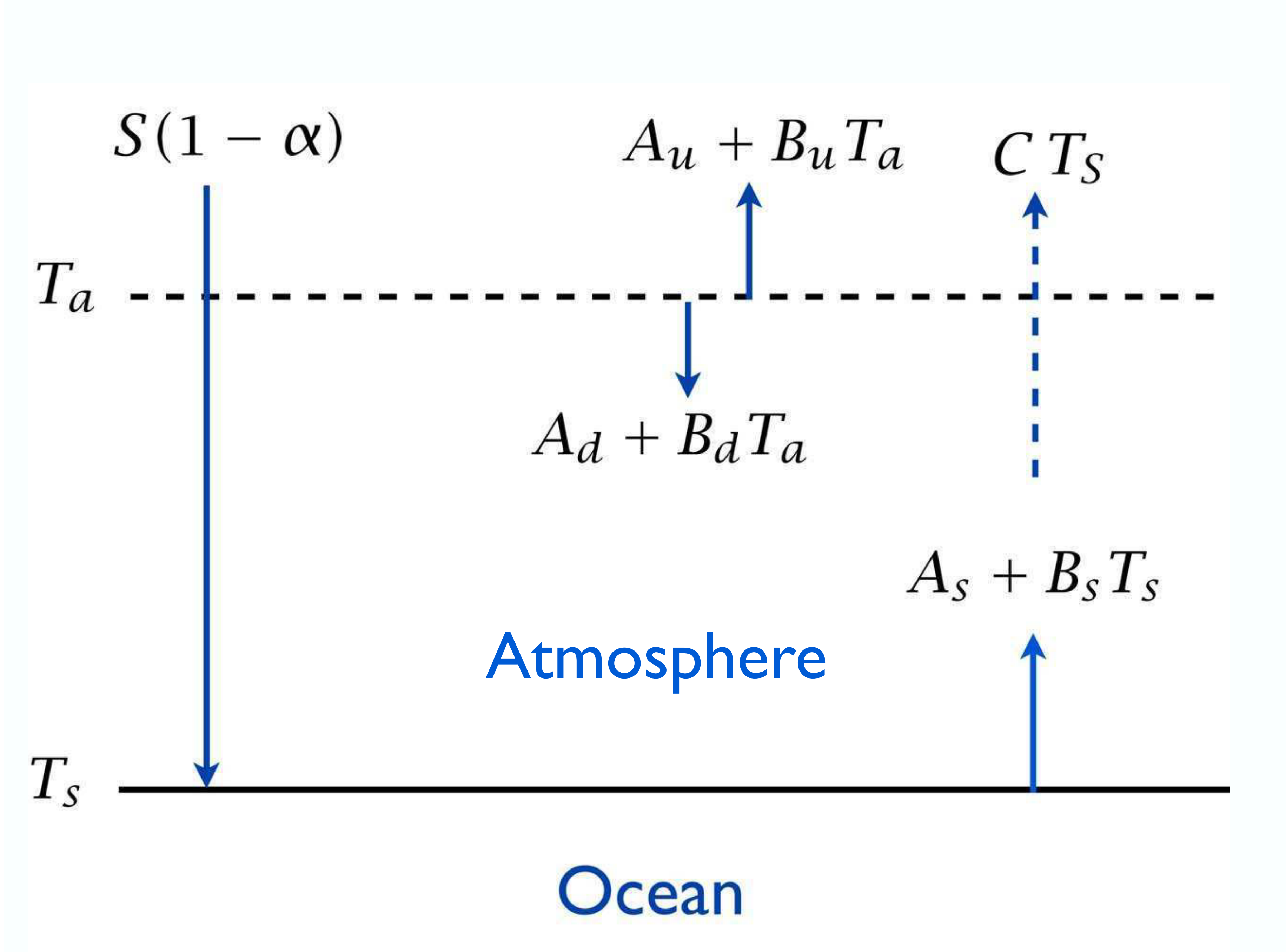
Remains mysterious, a dynamical curiosity.

The Null Hypothesis *(Hasselman)*

- That the atmospheric ‘noise’ (weather etc) is reddened by interaction with the oceanic mixed layer.
- It is a ‘null hypothesis’ because the mechanism almost certainly does exist. How significant it is is another matter,
- The interaction with the upper ocean is probably the primary mechanism slowing global warming on the decadal-to-century timescale.

Simple Model

Barsugli and Battisti

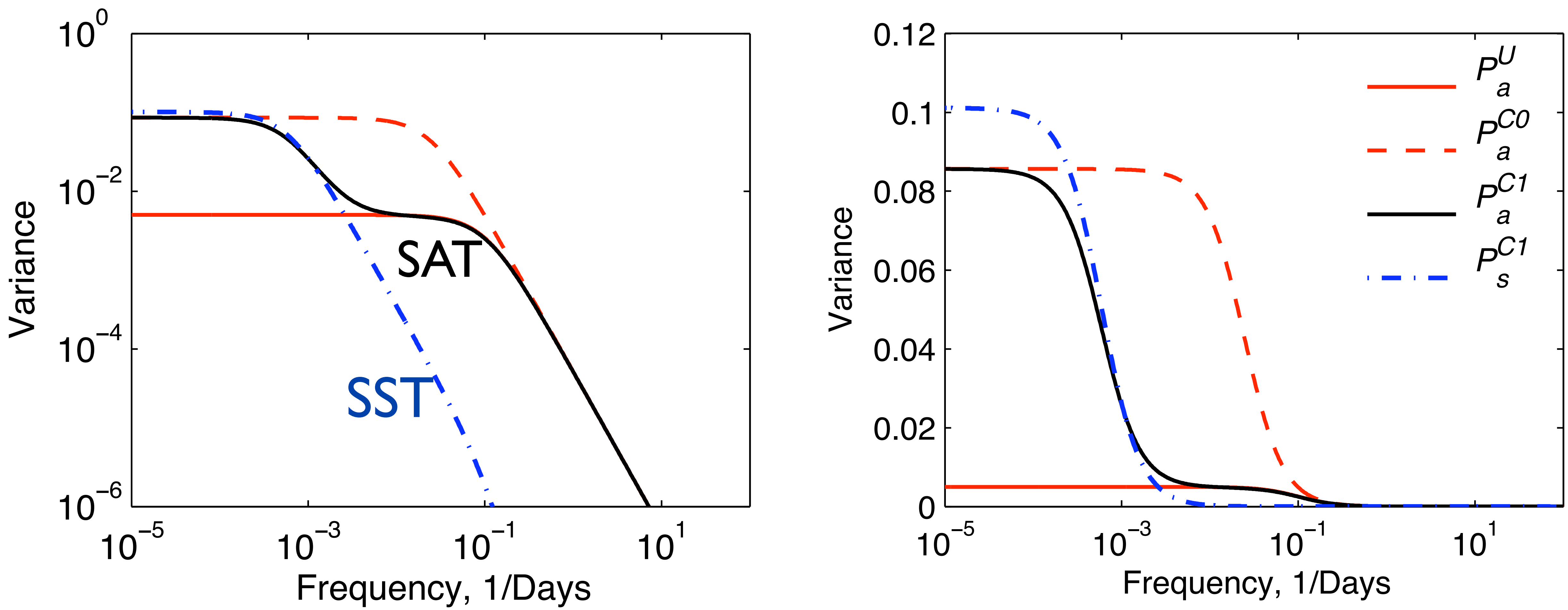


$$C_s \frac{\partial T_s'}{\partial t} = B_d T_a' - B_s T_s', \qquad C_a \frac{\partial T_a'}{\partial t} = B_2 T_s' - B_3 T_a' + \sigma \dot{W}.$$

Solution

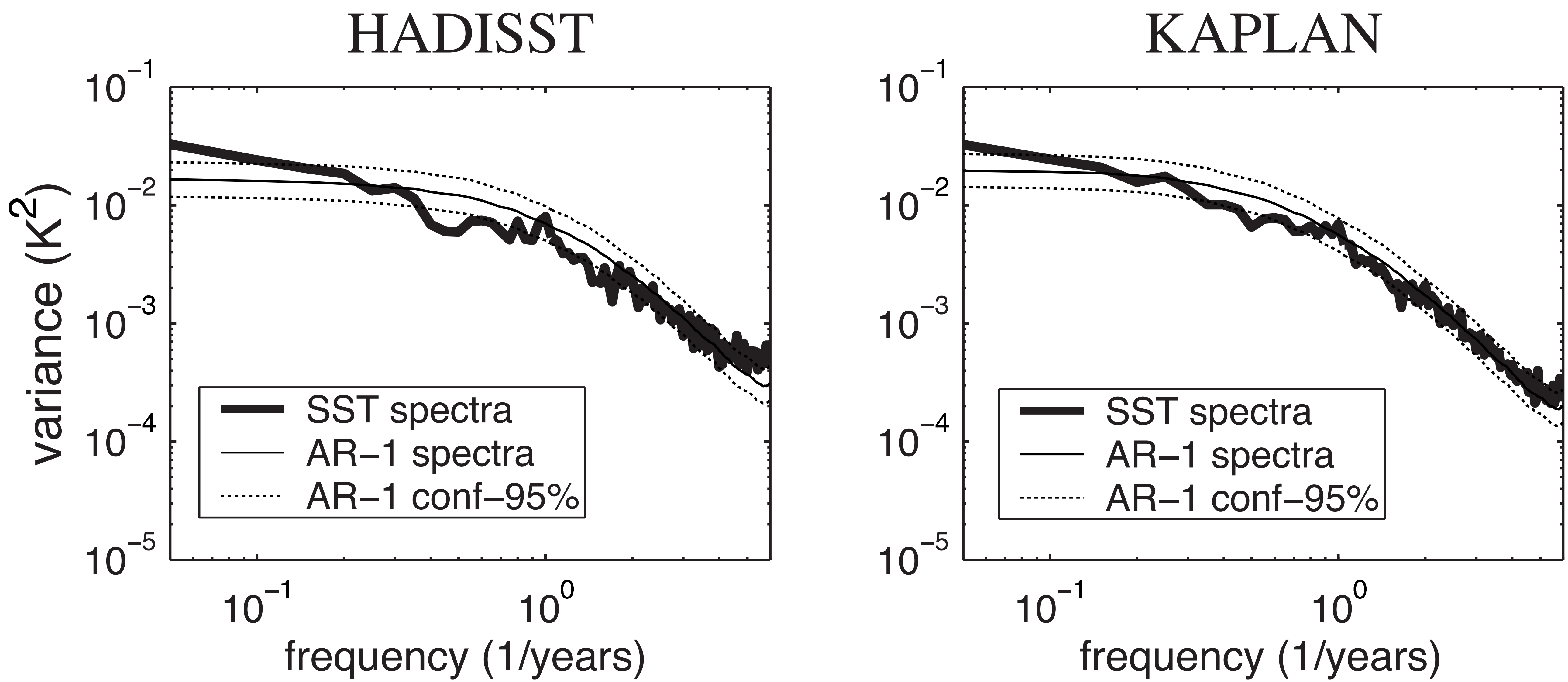
- Obtaining solutions is straightforward --- Fourier transform.
- Most realistic case is one with small atmospheric heat capacity and larger oceanic heat capacity.
- Solutions are 'red noise' for surface temperature, and almost white noise for the atmosphere.
- The 'shoulders' of the spectra are determined by the decay timescales of atmosphere and ocean, and so the heat capacities and radiative parameters.

Solution



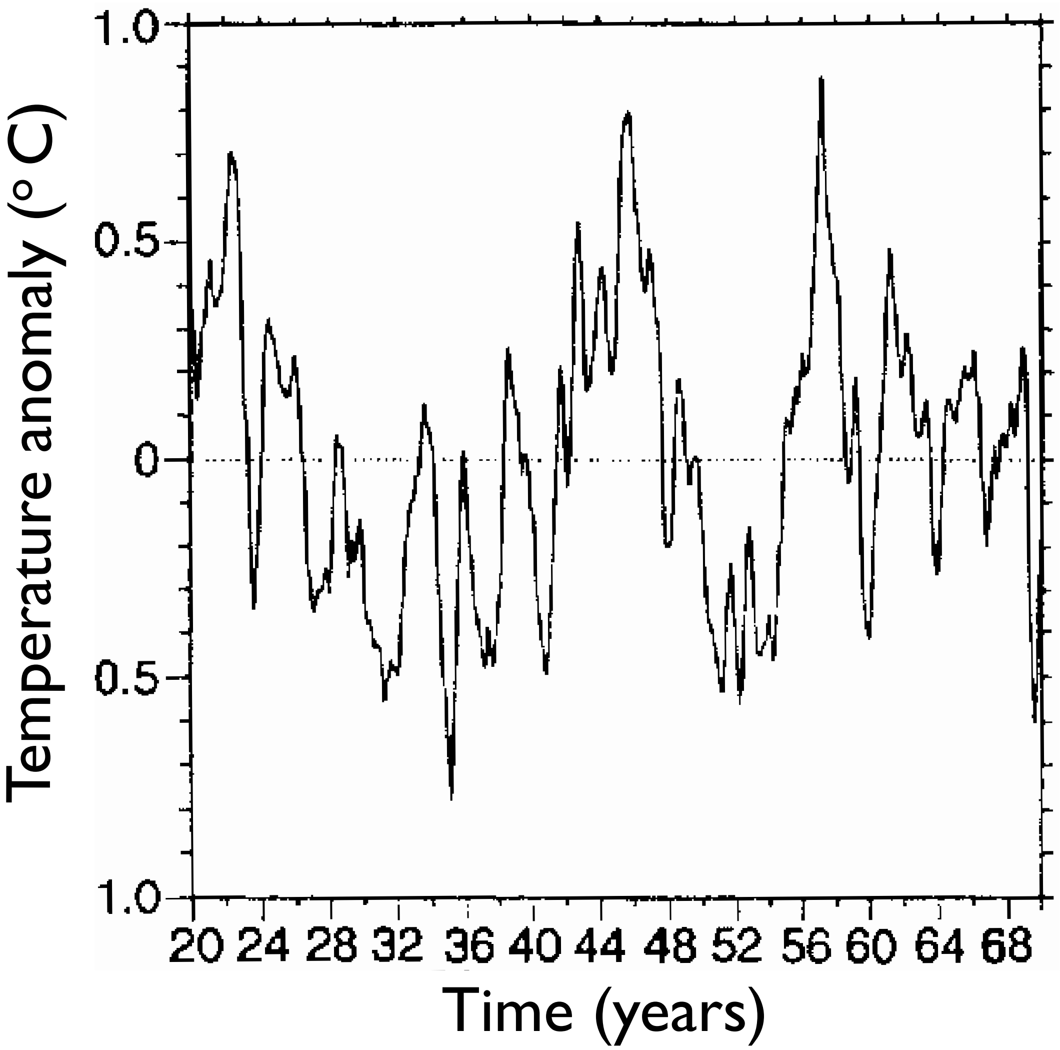
- Atmospheric white noise is reddened by the ocean.
- For reasonable parameters ocean is white at timescales longer than about 1000 days.

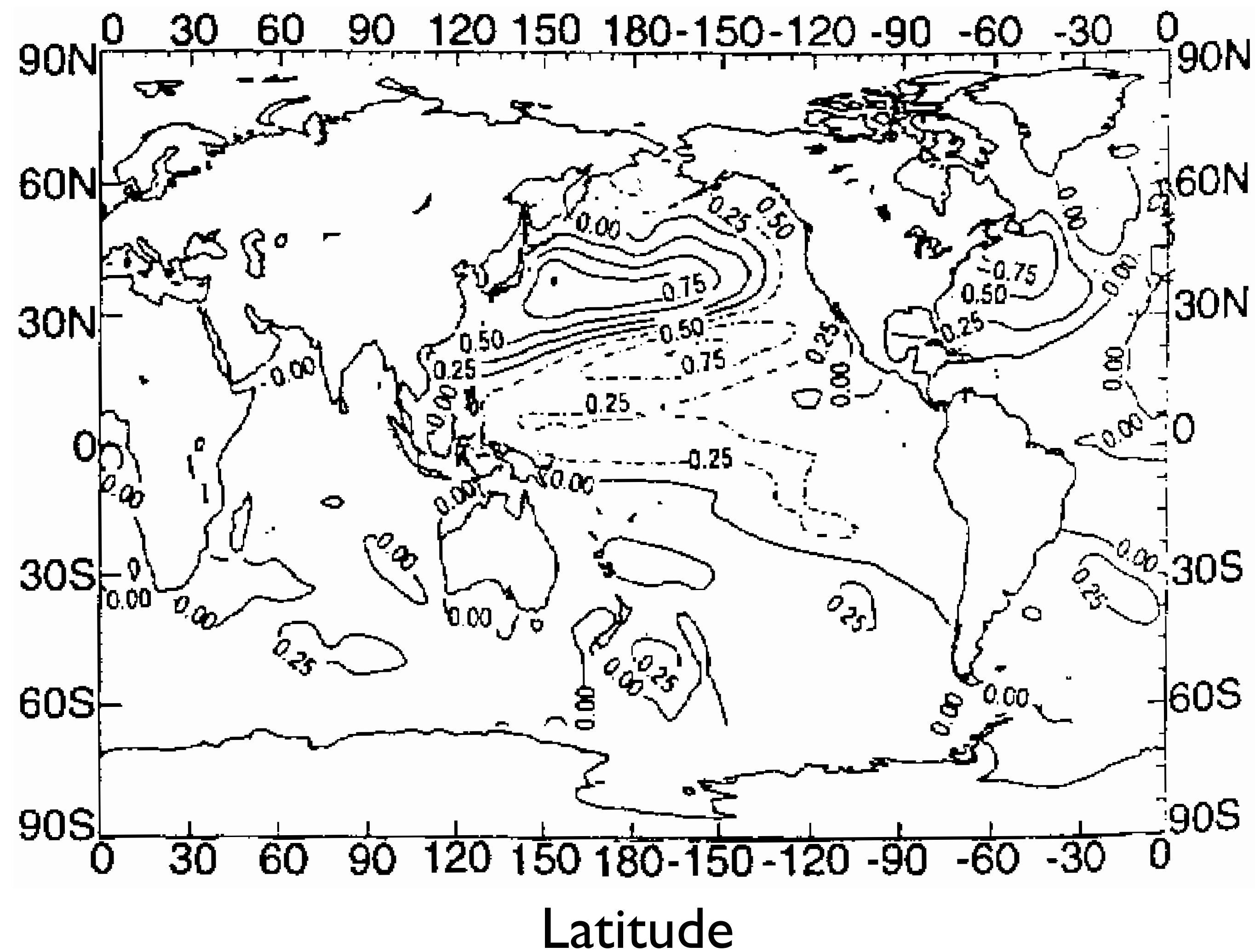
Observational tests (Dommenget)



Seem to suggest more power at long times than the model.

Dynamically Coupled Ocean-Atmosphere Interactions *(Latif and Barnett)*





- Latif and Barnett found coupled modes of variability, involving the wind-driven gyres interacting with the atmosphere.
    - SST anomaly produces winds and air-sea fluxes that reinforce the anomaly.
- Has not been robustly reproduced by other groups.
- El Nino remains the only robust example of dynamically coupled variability

Difficulties

Steps in a Sequence:

- The generation of some large-scale pattern of sea-surface temperature anomalies.
- The SST anomaly pattern must imprint itself on the atmosphere.
- The atmospheric dynamics must then act in such a way as to reinforce or maintain the SST anomaly pattern.

Although all of these steps seem possible, there are difficulties with each, and so the likelihood of entire chain of events occurring becomes somewhat delicate.

Rule of thumb:

On timescales of a season–year, SST anomalies are created by the atmosphere. On longer timescales, SSTs drive the atmosphere.

Climate Variability with an Essentially Oceanic Origin

- Ocean models are often found to produce natural variability on timescales of decades to centuries.
- Usually associated with variability in the meridional overturning circulation (MOC), leading to variability in oceanic meridional heat transport.
- Often associated with a compensation in the atmospheric heat transport.

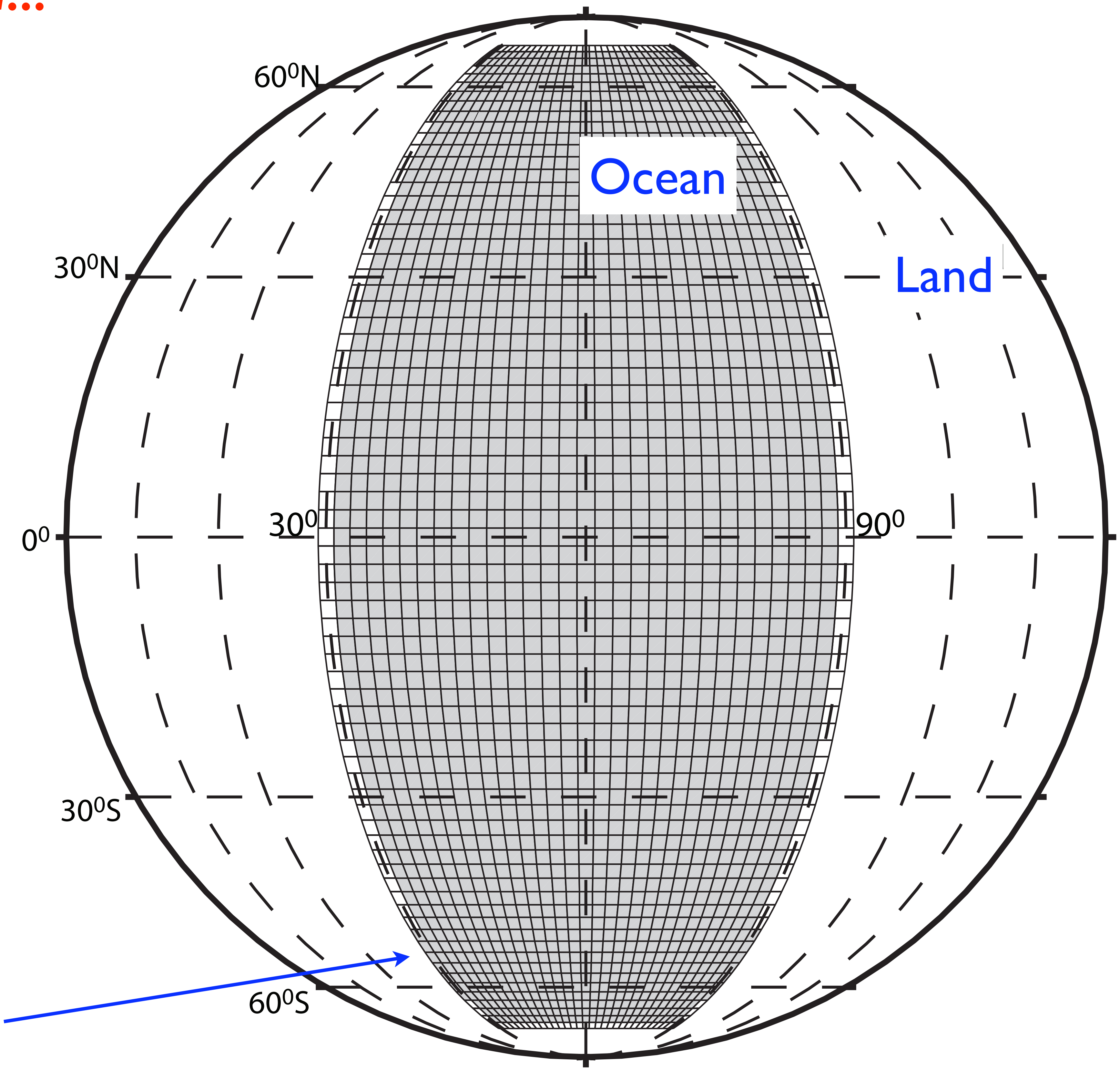
A difficulty in studying them is that very long integrations of coupled models are required, and in addition the analysis of the mechanism gets bogged down in details.

Our simple domain...

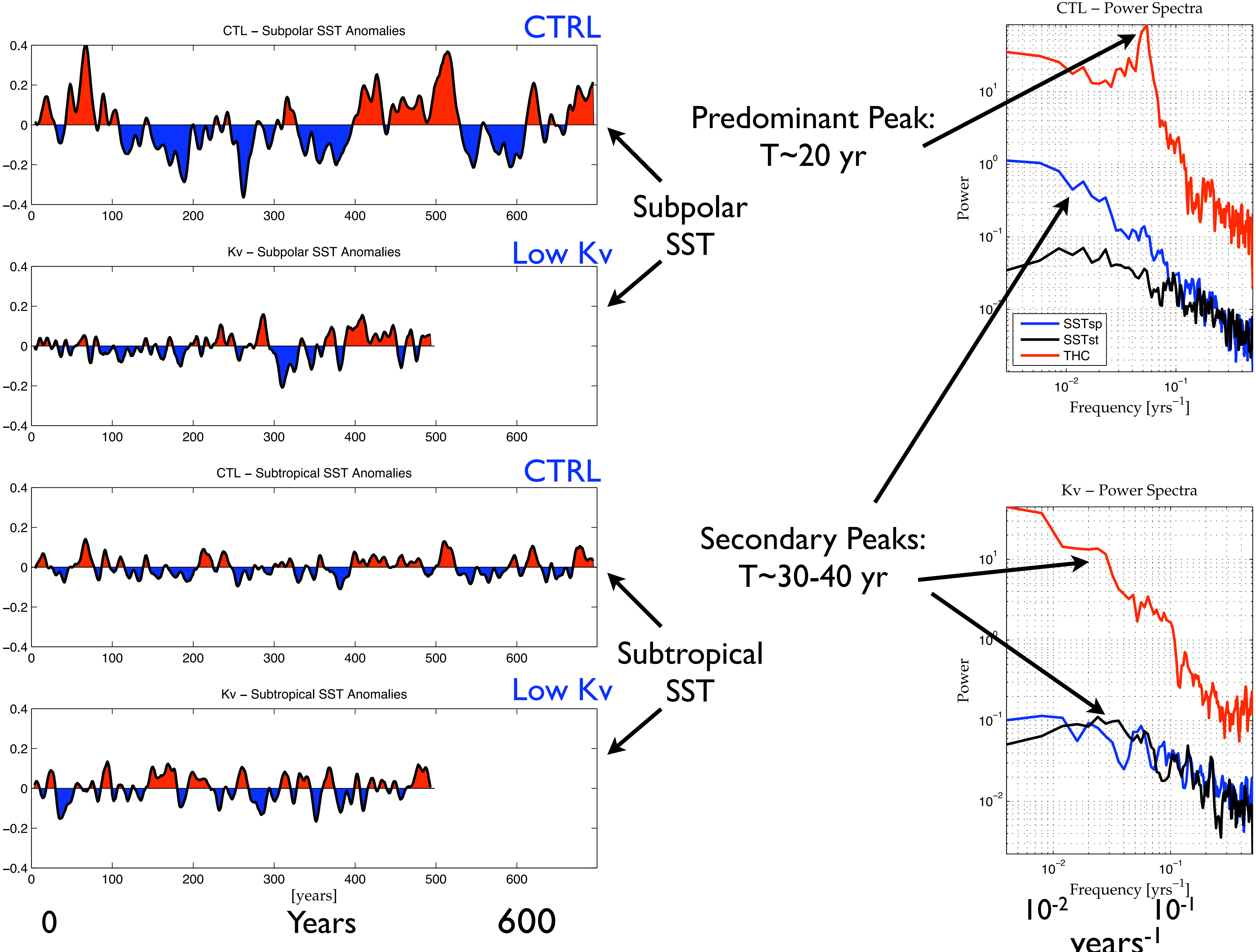
Resolution

Atmospheric Sector
$3^{\circ} \times 3.75^{\circ}$
7 levels

Oceanic Basin
$2^{\circ} \times 2^{\circ}$
24 levels



SST time series

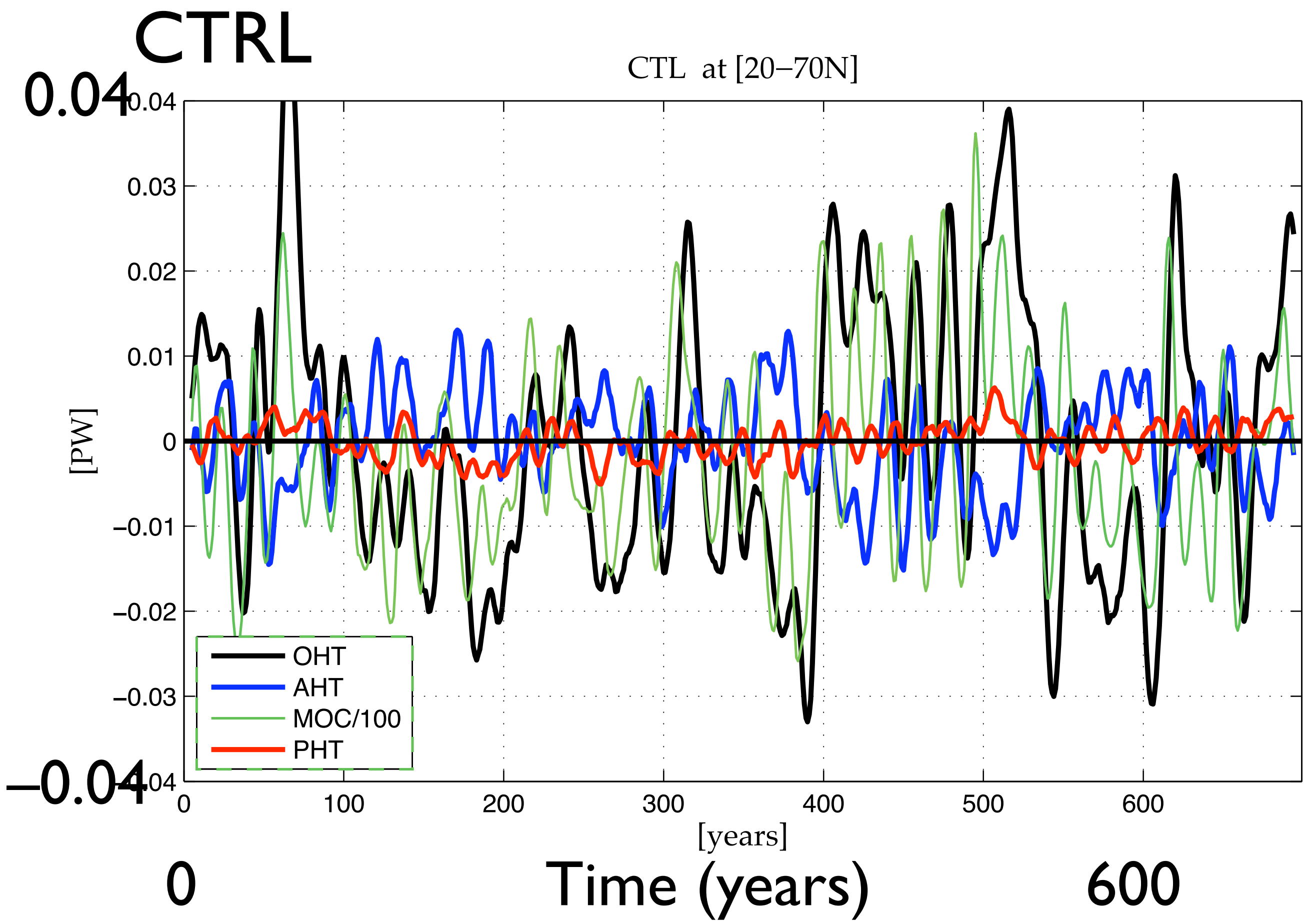


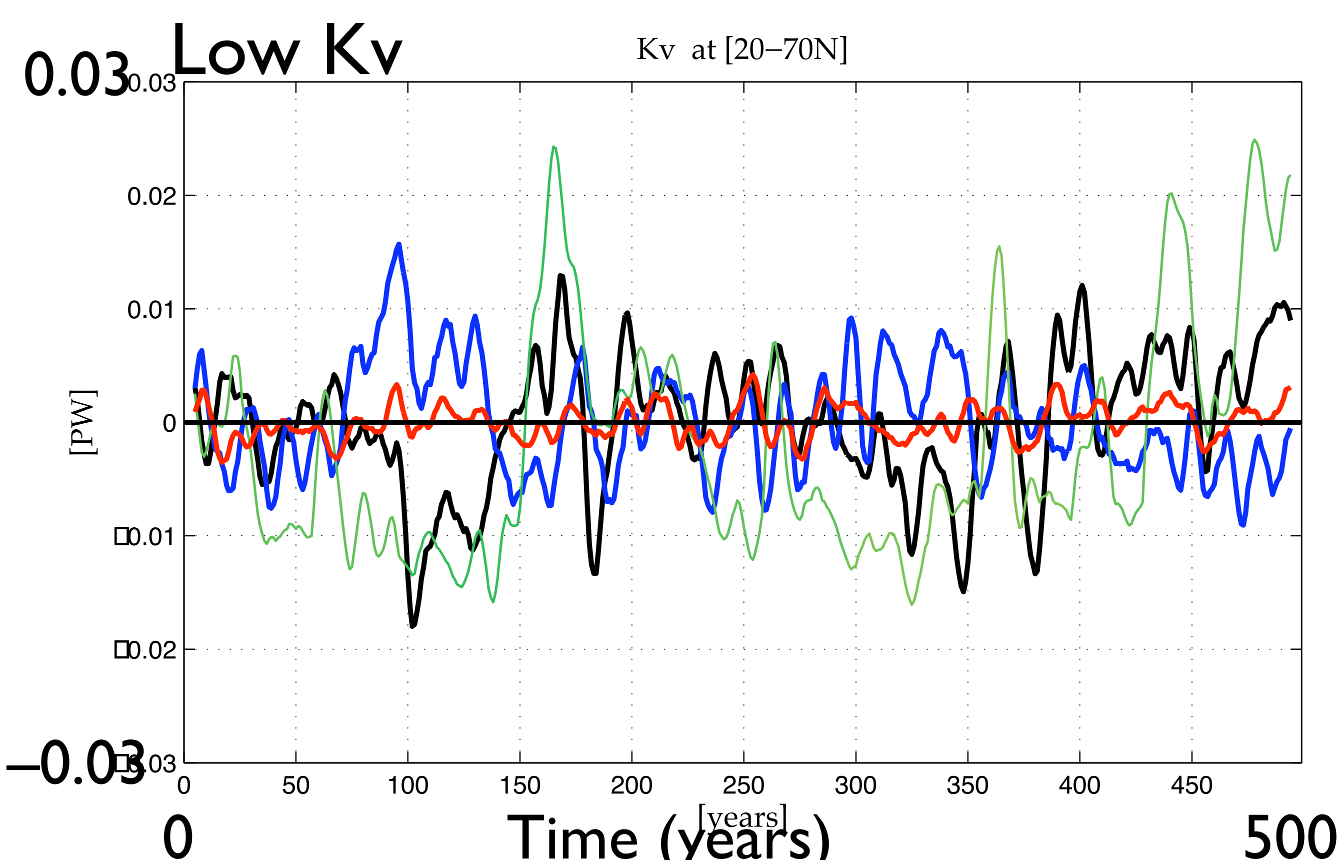
Variability of heat transport

1- High level of compensation in Extratropics

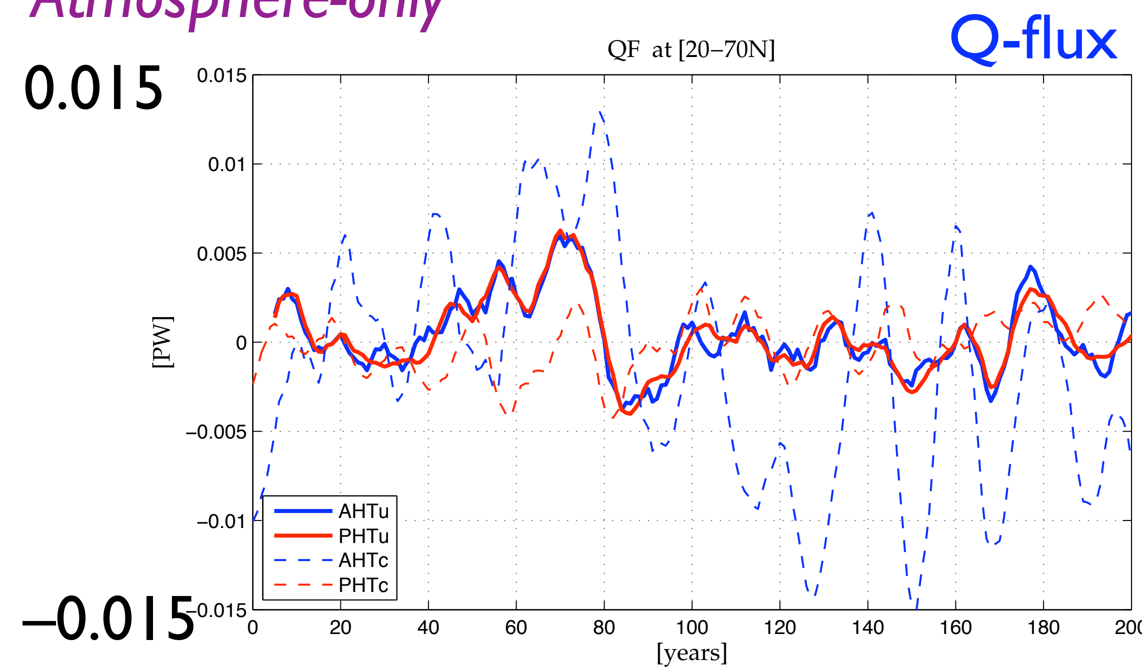
2- MOC anomalies leads OHT anomalies

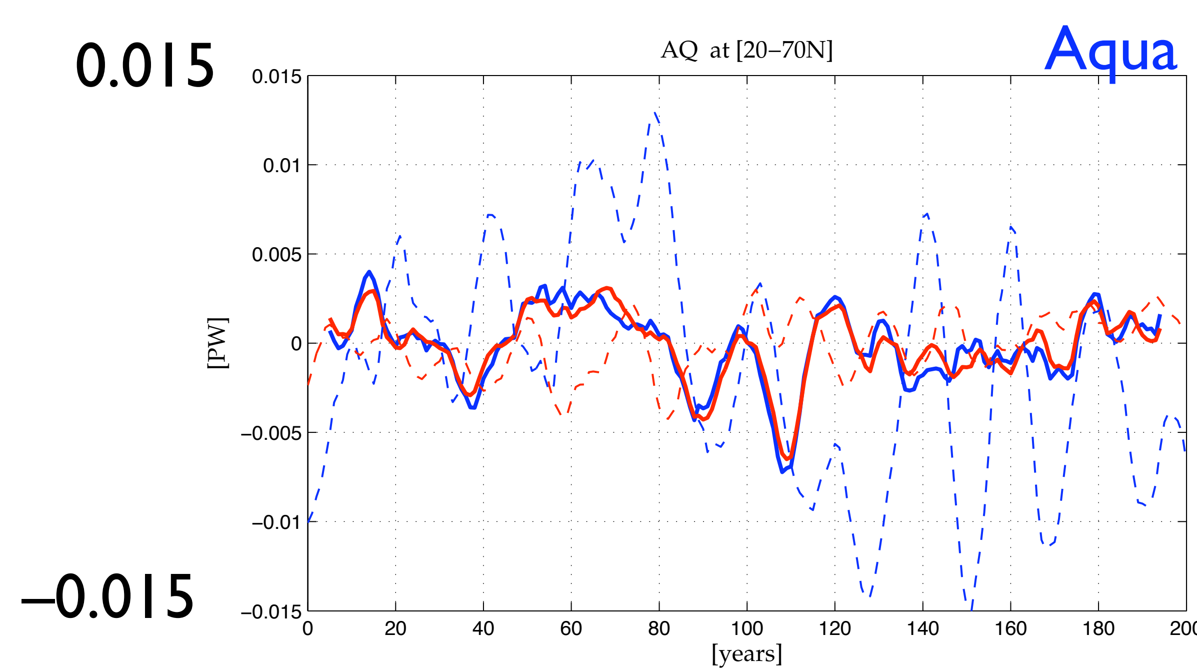
3- Planetary Heat transport goes like ocean heat transport



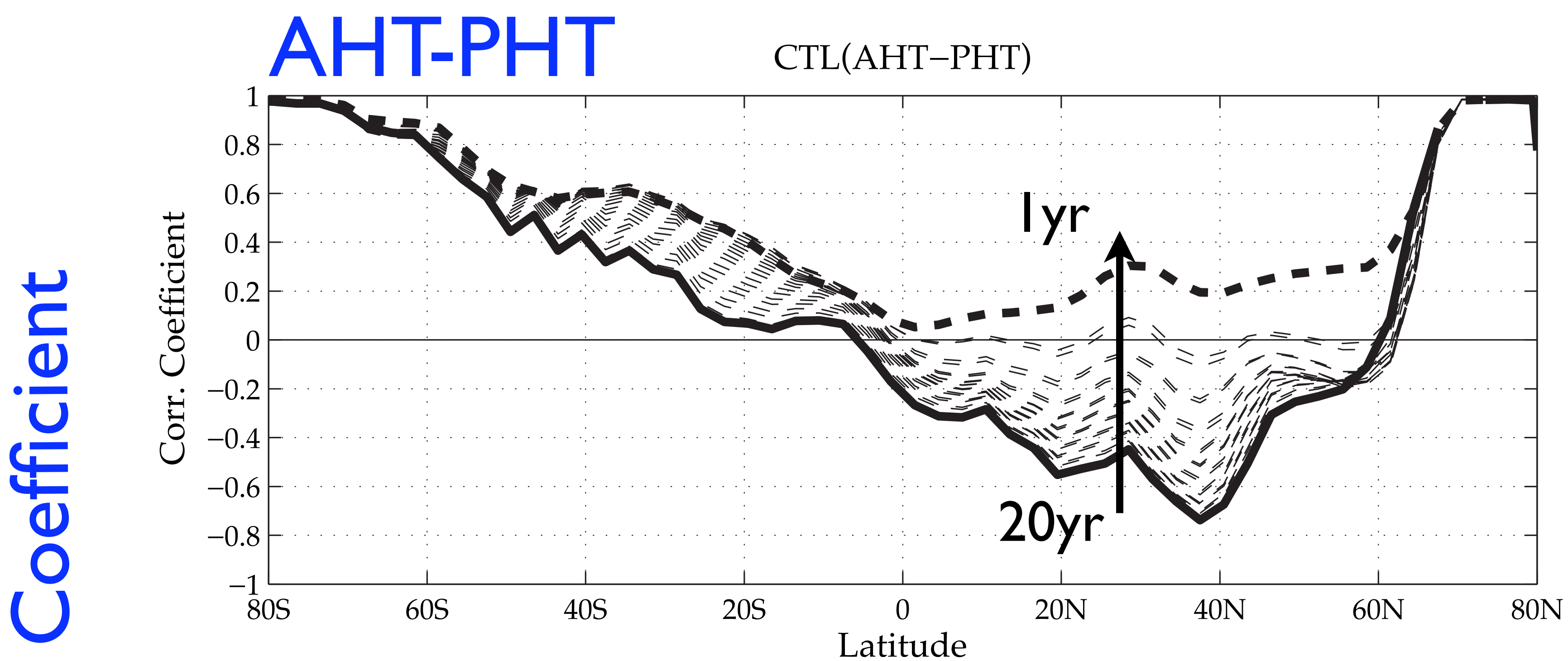


Atmosphere-only

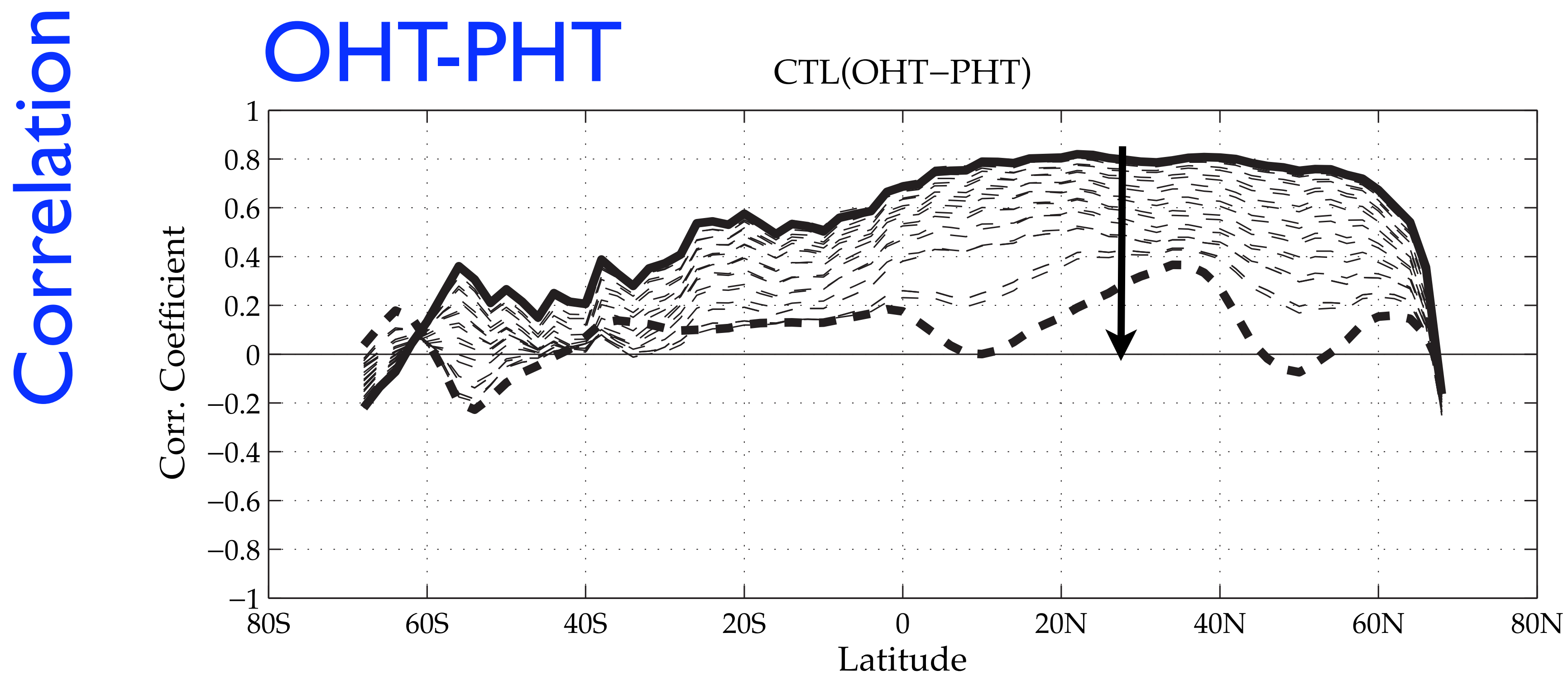




Timescales of dominance of oceanic vs atmospheric transport



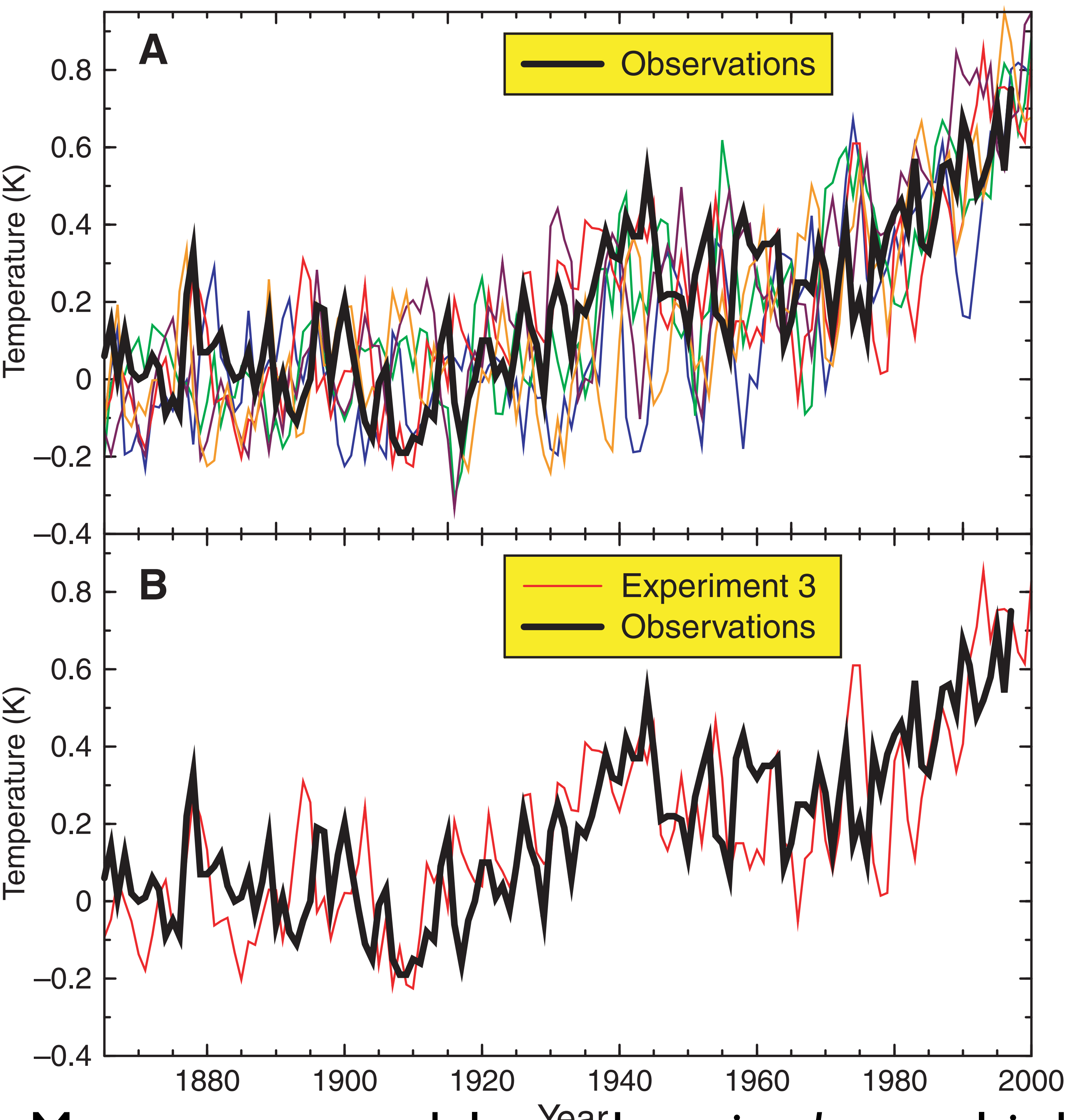
At Interannual periods, atmos is positively correlated with PHT

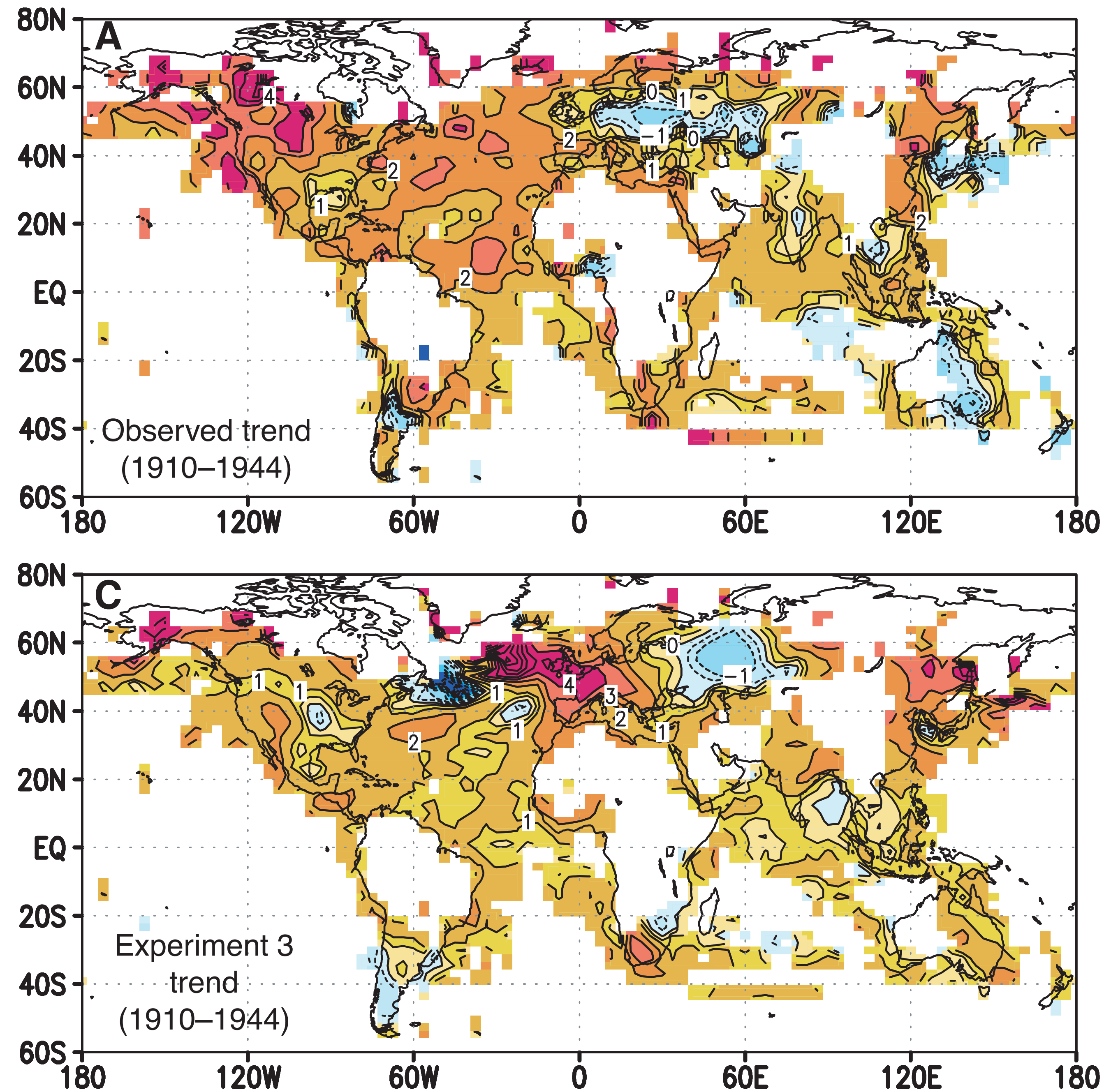


At Interdecadal periods, ocean is positively correlated with PHT

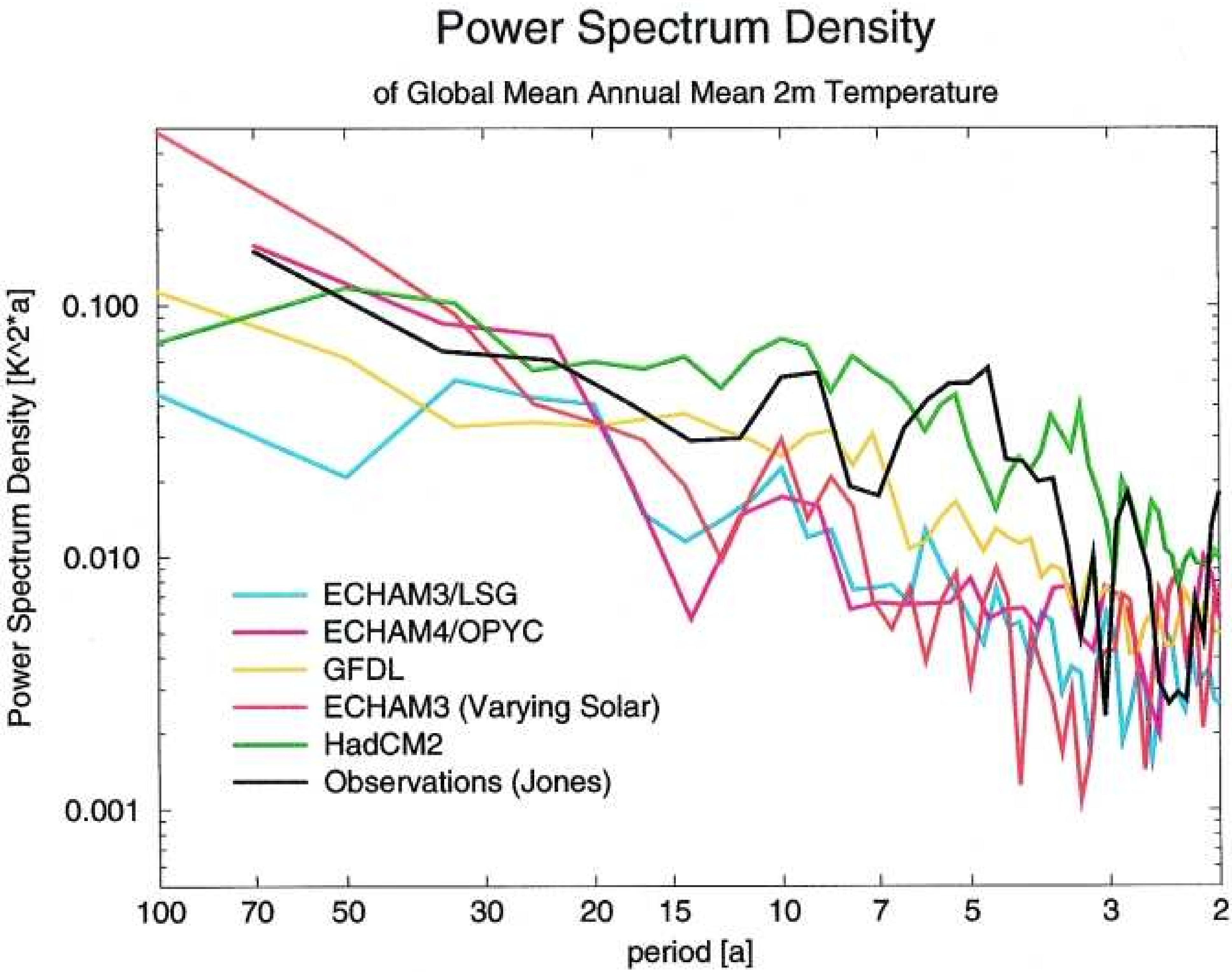
Results from IPPC class models

GFDL model (Delworth & Knutson, 2000)





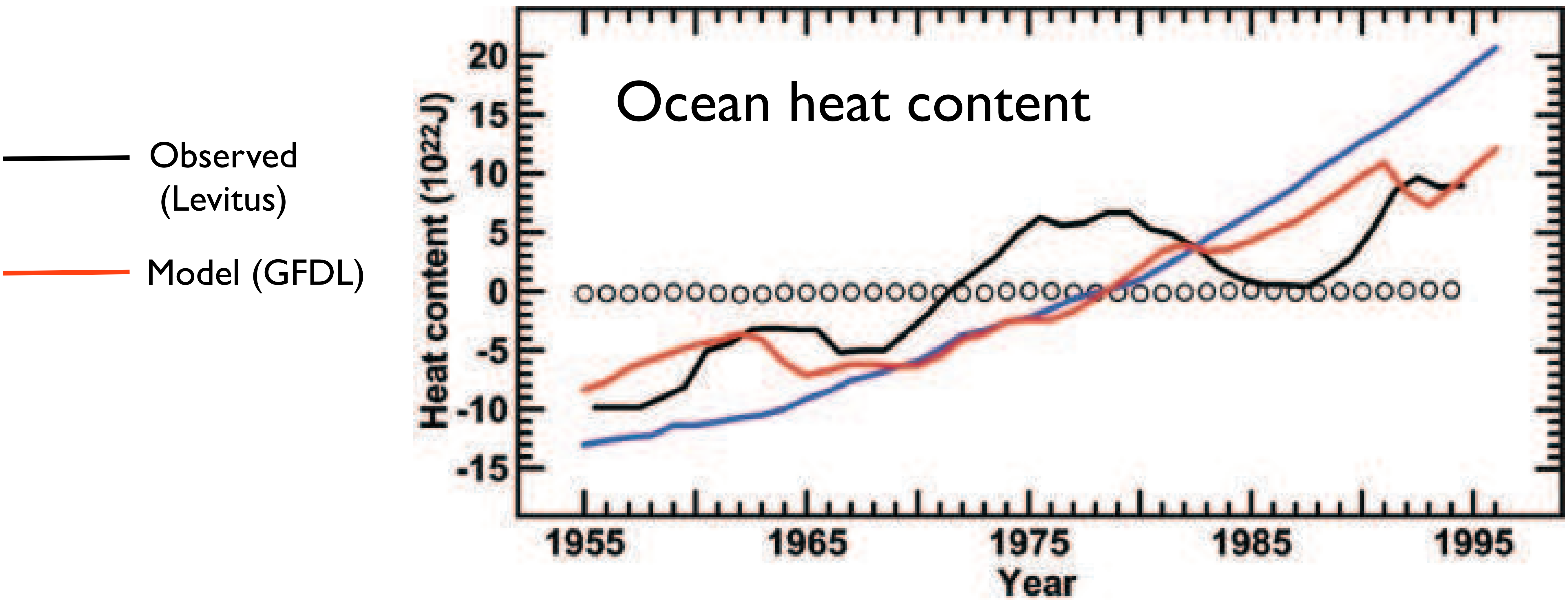
More recent models tend to give *less* multi-decadal variability and more decadal variability.



Models have power comparable power to the observations on decadal timescales.

Could the observed warming come from Natural Variability?

Probably not: for that to happen, the ocean would have to *give up* heat to the atmosphere. But in fact, heat is going *into the ocean,* slowing the warming.



Relation to Global Warming (if any)

Natural variability on decadal scales appears to come primarily from the ocean. But it is unlikely that natural variability is responsible for temperature changes thus far.

- Timescale of observed warming (i.e., a century) is too long (or too short!) for any known mechanism of natural variability. But many caveats to this statement. Also, it is another 'argument from personal incredulity'.

- Observed global warming has similar patterns to those that models give for anthropogenic warming, not variability.

- Natural variability is too small. GCMs suggest half a degree or so.

- Natural variability of an oceanic origin that produced global warming would require a heat flux *from* the ocean. In fact, there has been a heat flux *into the ocean.*

The last two are the most powerful arguments. Evidently we need to know more about ocean heat uptake to reduce uncertainty, and differentiate between transient and equilibrium sensitivity.

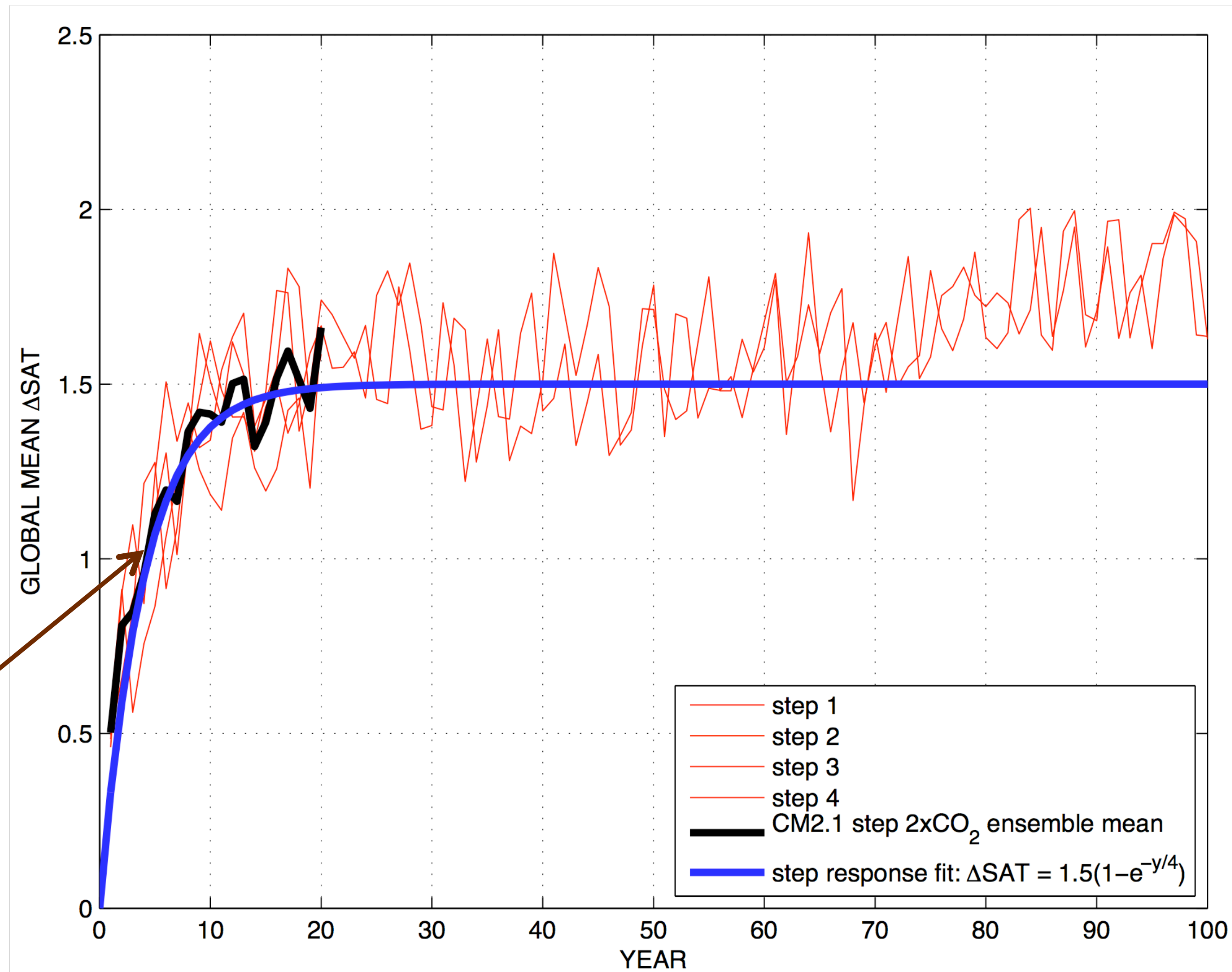
Ocean Heat Uptake

- A major source of uncertainty on the century and longer timescales lies in knowing what and how the energy uptake by the ocean is and will be.
- What is the effective heat capacity of the ocean and how does it vary with timescale?

Response of global mean temperature in CM2.1 to instantaneous doubling of CO2

Equilibrium sensitivity >3K

Transient response ~1.6K



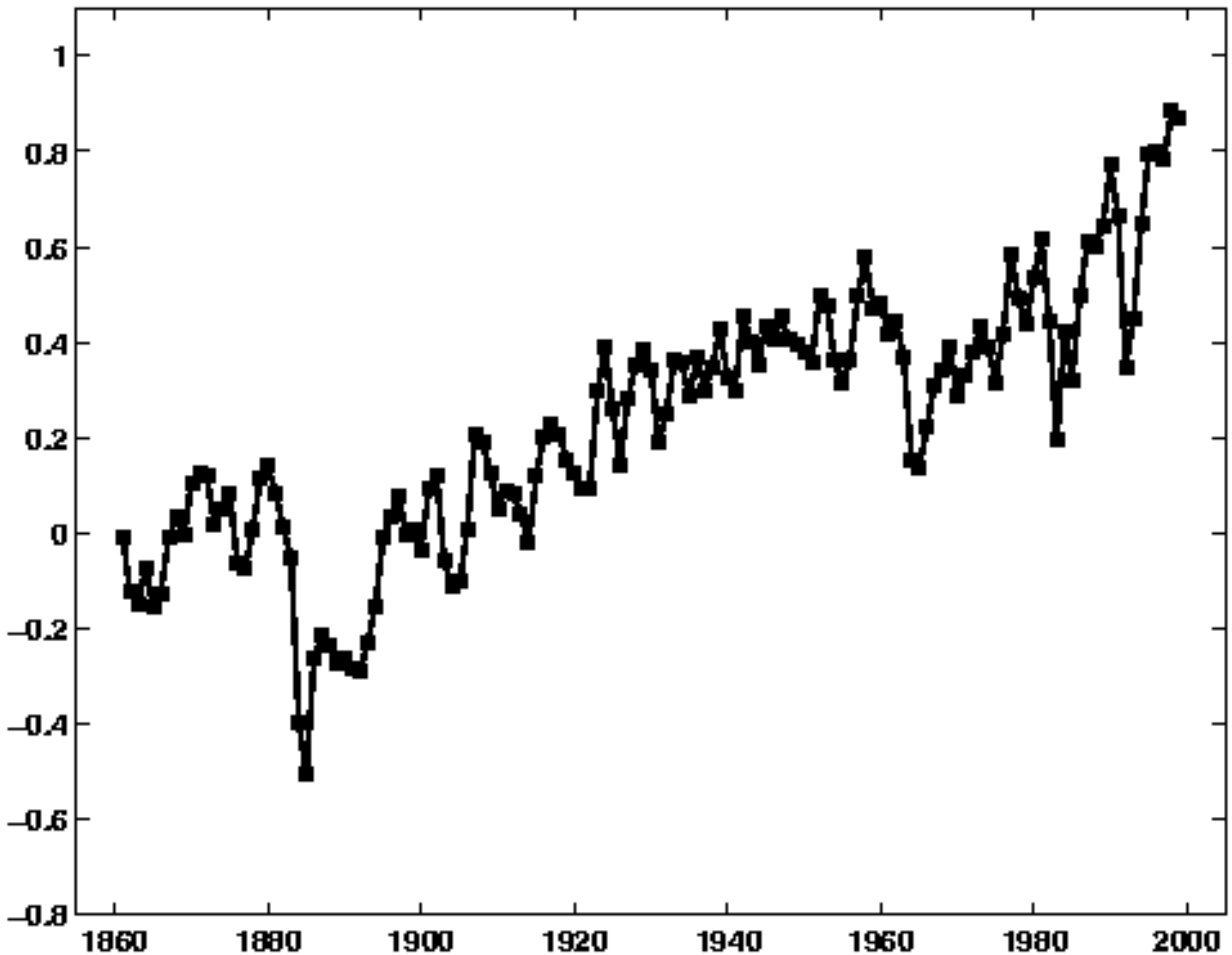
Slow response evident only after ~100 yrs and seems irrelevant for transient sensitivity

Fast response

$$T = (1.6K)e^{-t/(4\,yrs)}$$

Climate sensitivity = 3.7/1.6 = 2.2 W/(m^2 K^1)

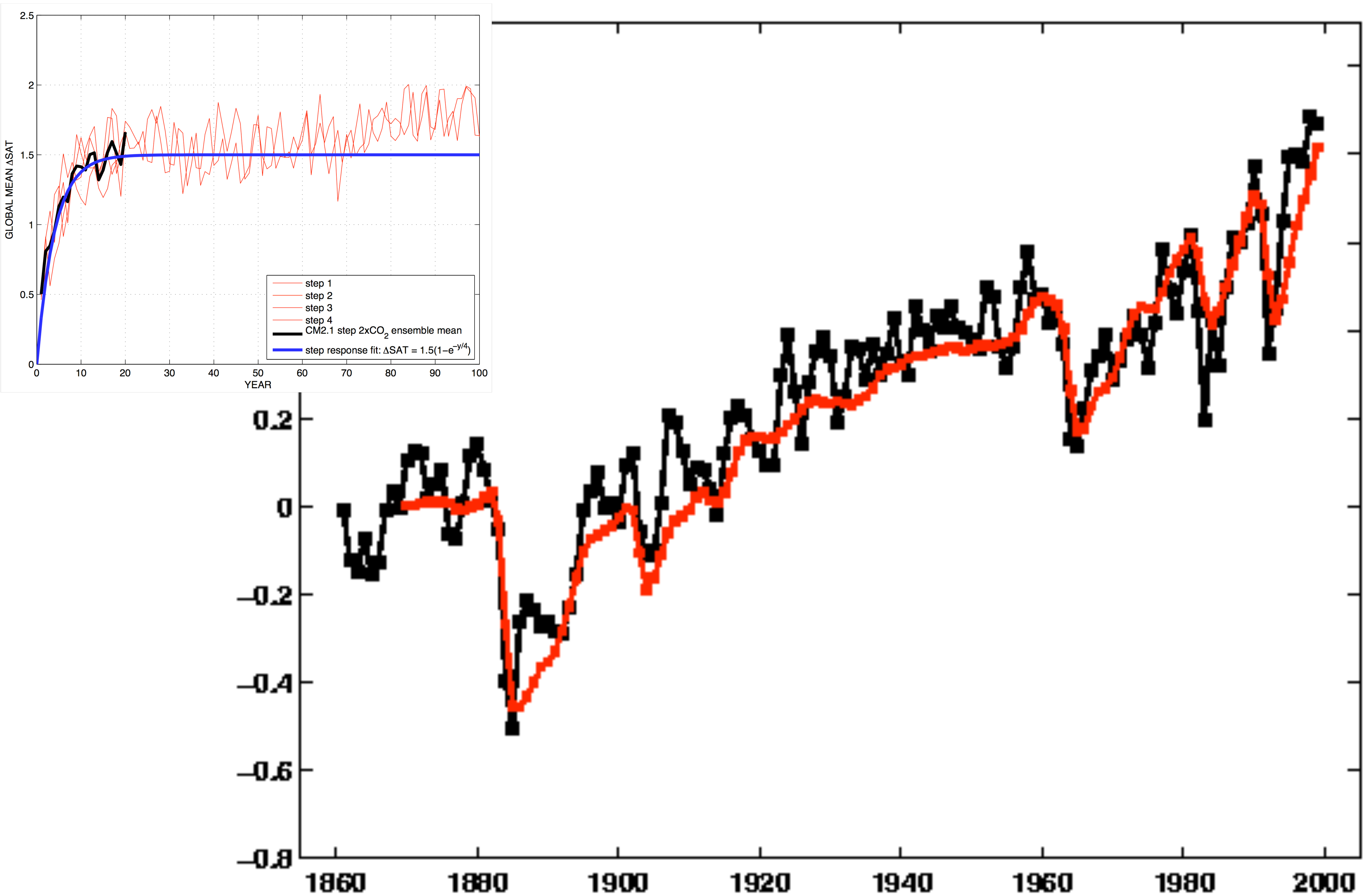
Temperature change averaged over 5 realizations of coupled model

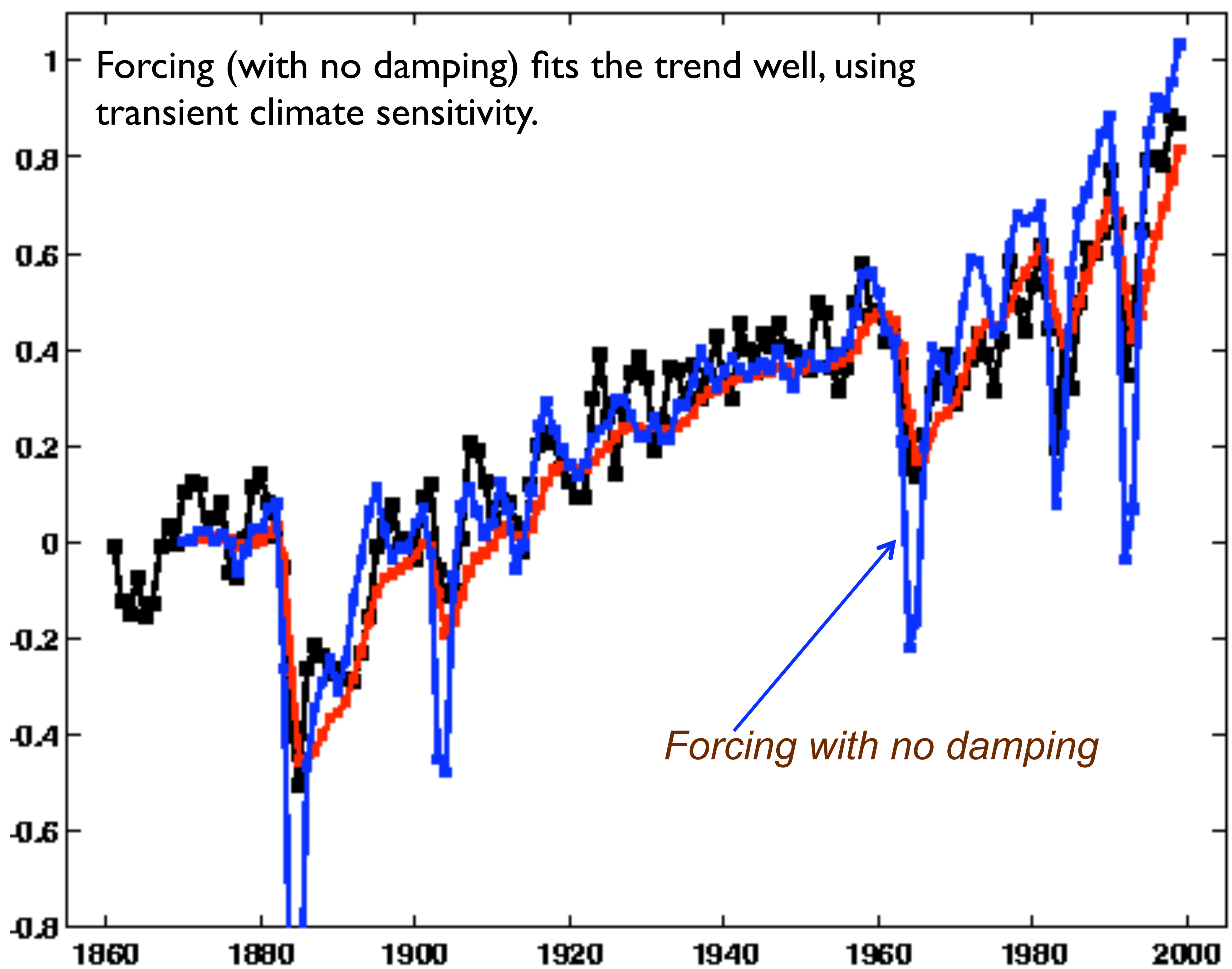


We can calculate the radiative forcing that produces this, and then fit an effective heat capacity to the system.

Fit with

$$C\frac{dT}{dt} = F - \alpha T; \quad \alpha = 1.6 \;\; Wm^{-2}/K; \qquad \frac{C}{\alpha} = 4\,years$$

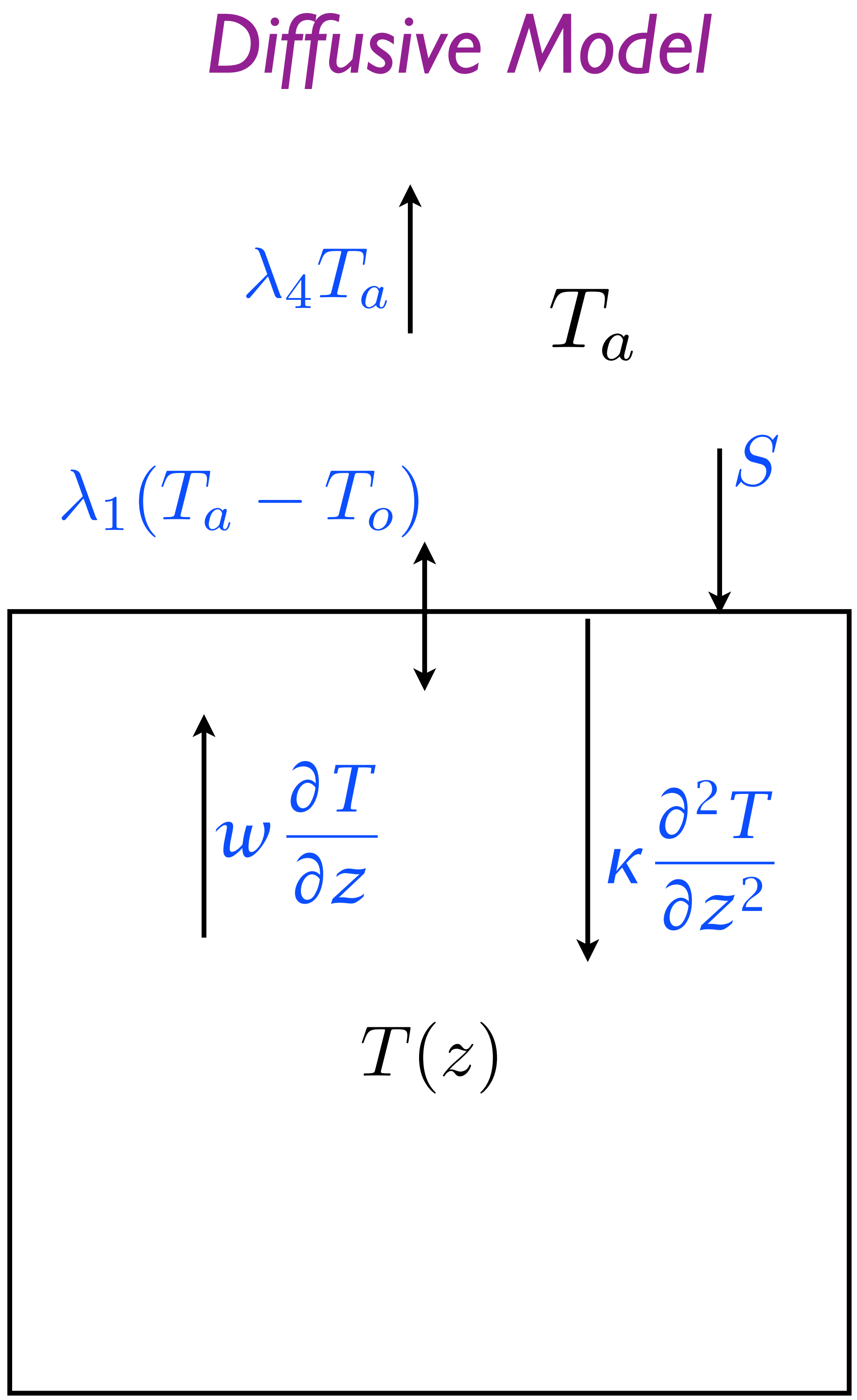


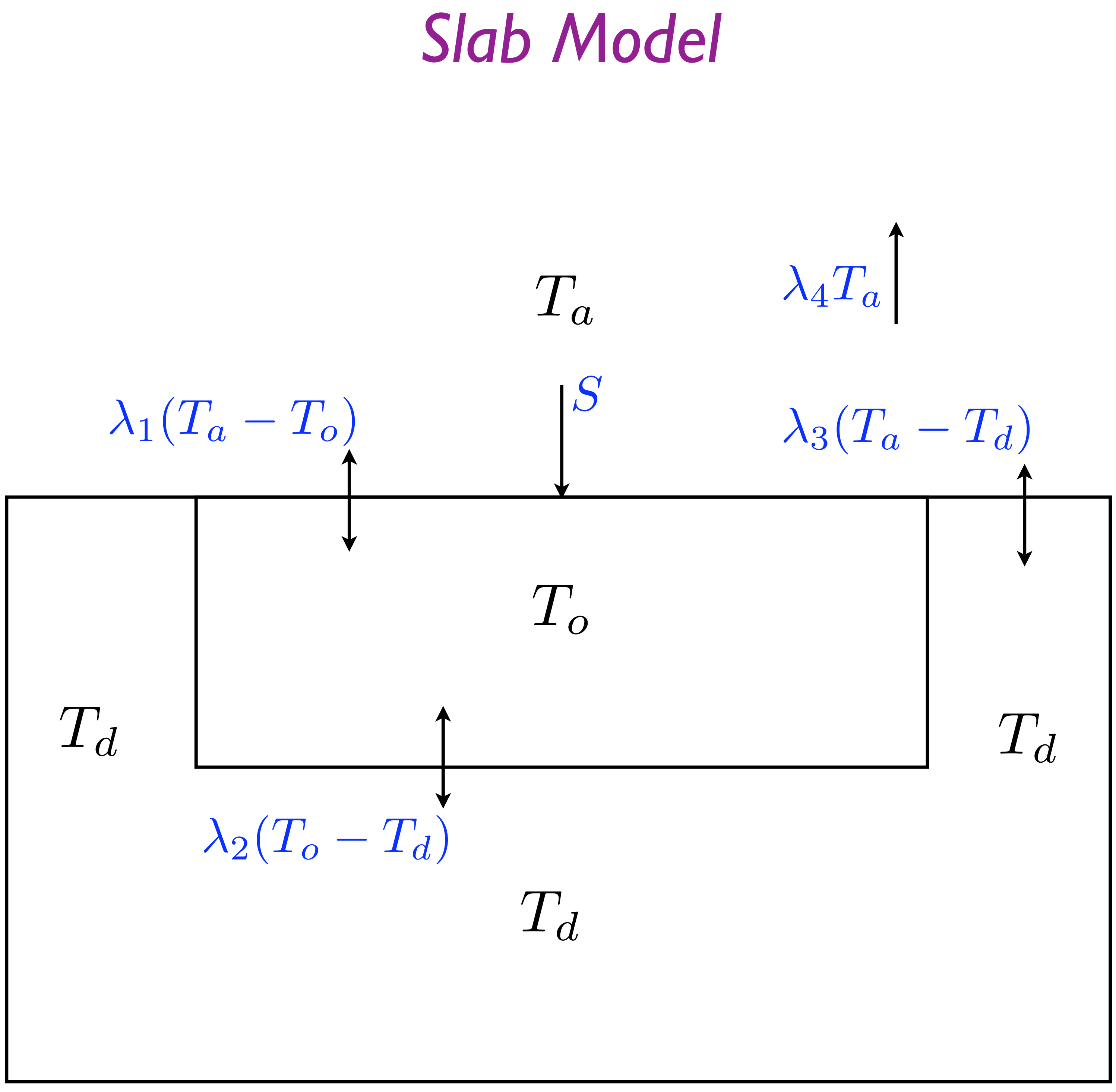

Forcing (with no damping) fits the trend well, using transient climate sensitivity.
Forcing with no damping
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
1860
1880
1900
1920
1940
1960
1980
2000

Further Investigation of Ocean Heat Uptake.

One goal: to produce an ocean model of comparable complexity to an atmospheric EBM for climate sensitivity studies, and in particular to determine the 'effective heat capacity' of the ocean (potentially a function of time).
Two simple candidates

- Upwelling diffusion model.
- A slab model (or maybe two slabs).





How do we figure out the appropriate parameters for these models? Or even if they are appropriate?

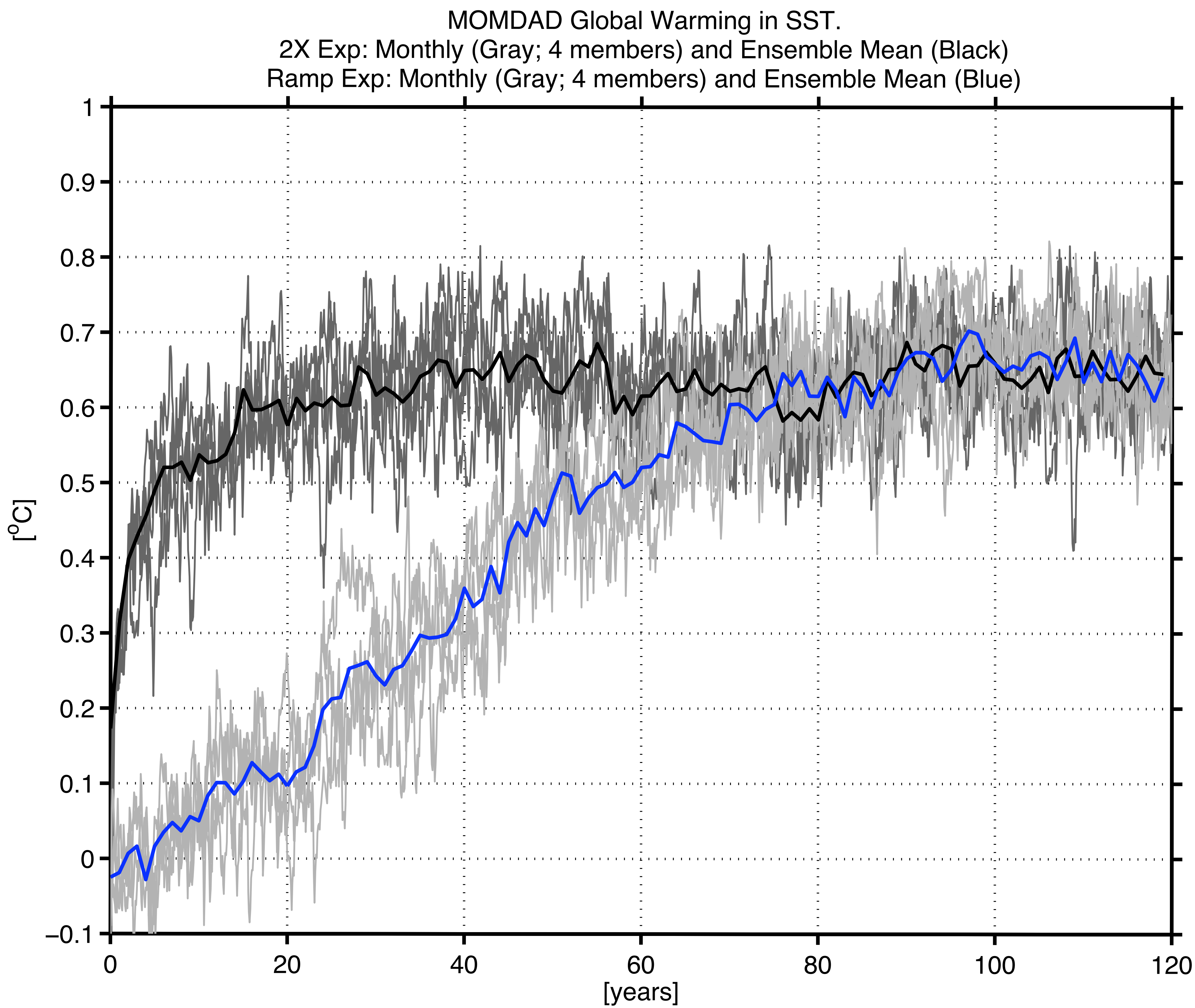
The Frequency Response of the Ocean

With M. Winton, I. Held, K. Takahashi, R. Farneti, P. Xie

- *Simple models have analytic solutions... to periodic forcing, to sudden changes and to ramp ups.*
- *Force 3D dynamical with such forcings.*
- *Fit parameters from analytic solutions to the numerical model solutions, and so determine 'frequency response of the ocean'*

Our conclusions thus far..... are inconclusive.

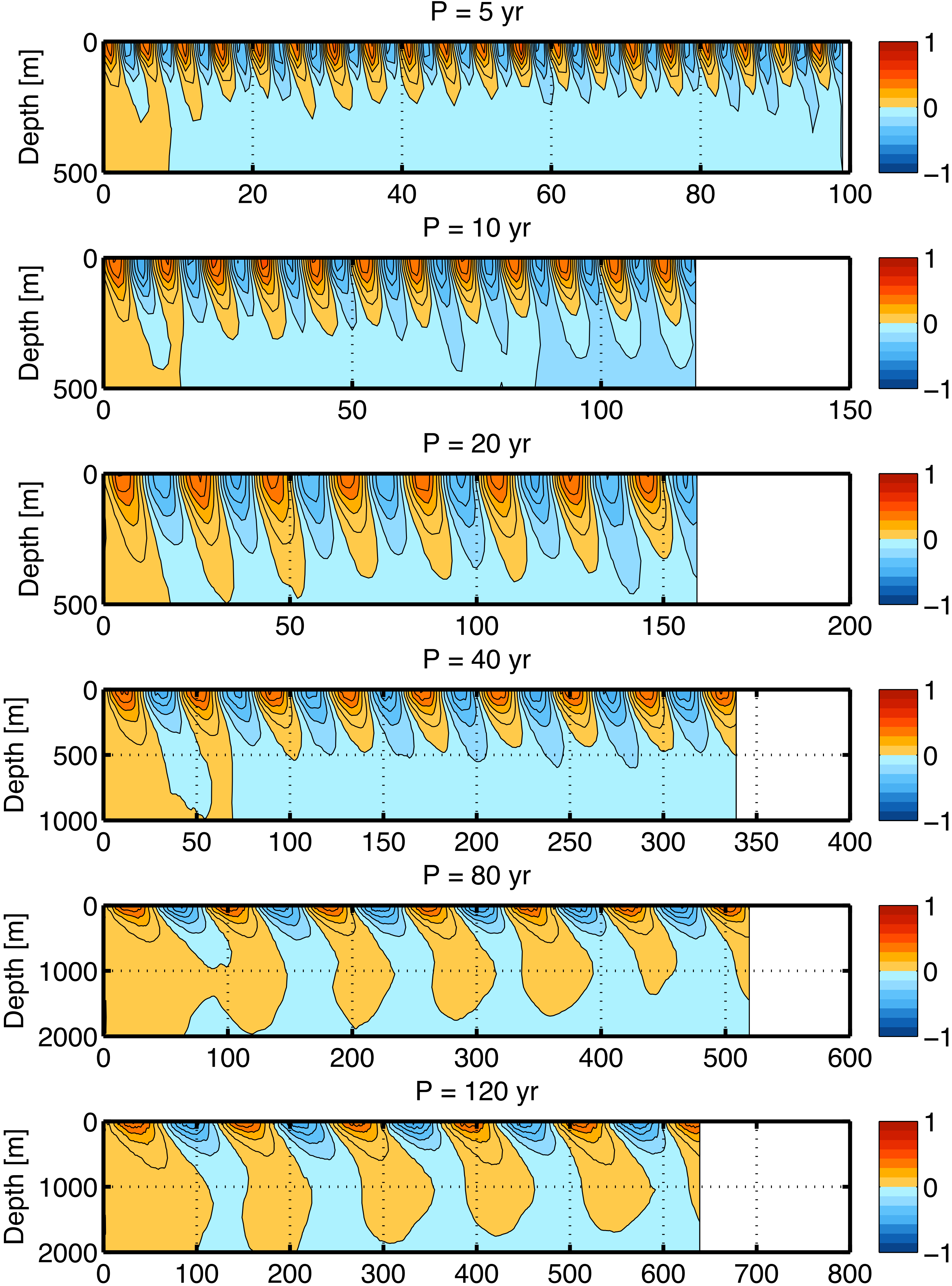
Switch-on forcing and ramp forcing in a coupled model



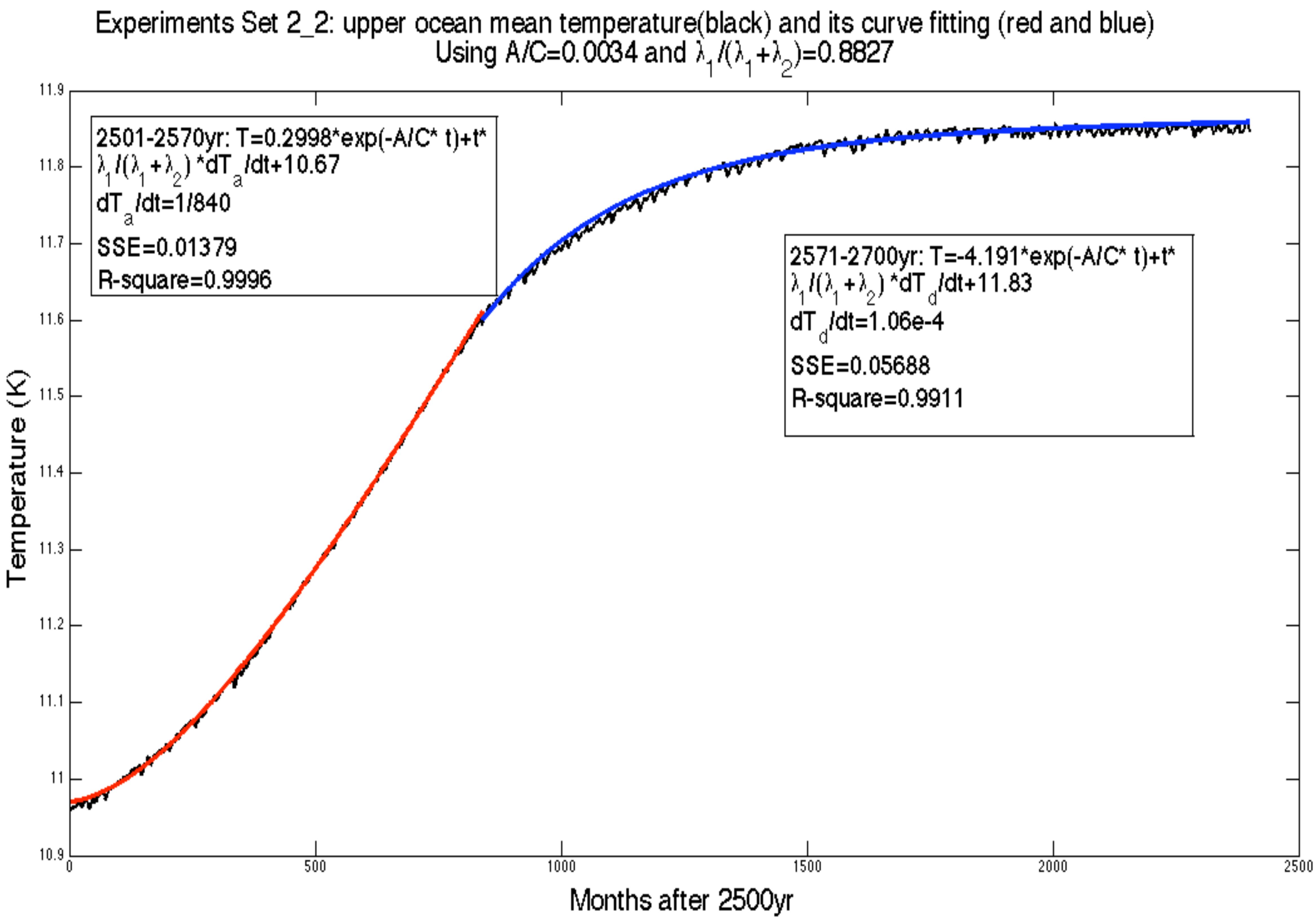
Periodic Forcing

With a diffusive ocean, the penetration depth should increase as the half power of the frequency.

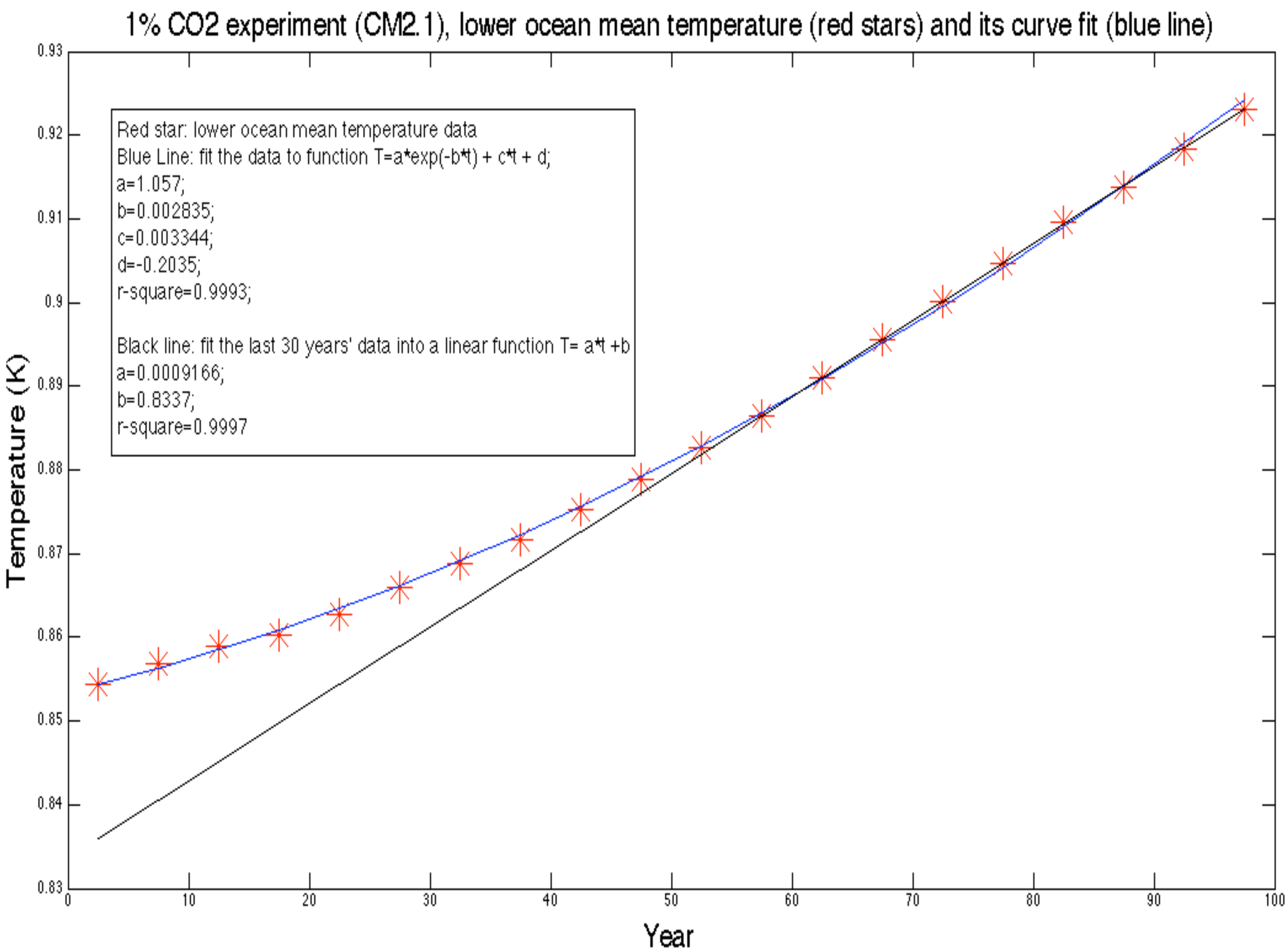
Roughly true, provided the perturbation is less than the depth of the main thermocline.



A Switch-on Experiment with an Ocean-only model (Peng Xie)



A Ramp Experiment with CM2.1, fit to a Slab Model *(Peng Xie)*



Ocean Heat Uptake

- Some experiments with a fully coupled model seem to indicate that, on the timescale of global warming, the ocean behaves as a simple slab with a depth of 100 m.
- But other experiments seem to give a longer timescale.
- Diffusive model seems qualitatively reasonable in some respects.
- Encourages us to think that a simple-ish ocean model could be constructed for climate sensitivity studies.

Thank you.

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