Temporal Power-Law Characteristics of the Atmospheric General Circulation

Paul Kushner, Dmitry Vyushin & Josh Mayer
Department of Physics, University of Toronto

Papers:
V & K, submitted to J. Climate. (Methods, obs analysis.)
V & K, in prep. (Model/obs comparison.)
V, K & M, in prep. (IPCC AR4 analysis.)

Outline

- Introduction

  Characterizing Dec-Cen Climate Variability

- Methods & Data

  Estimating the Hurst exponent

- Observational analysis

  Analyzing ERA40 temperature data.

- Model-observation intercomparison

  Insights and a surprise.

- Conclusion

Introduction: Dec-Cen Variability

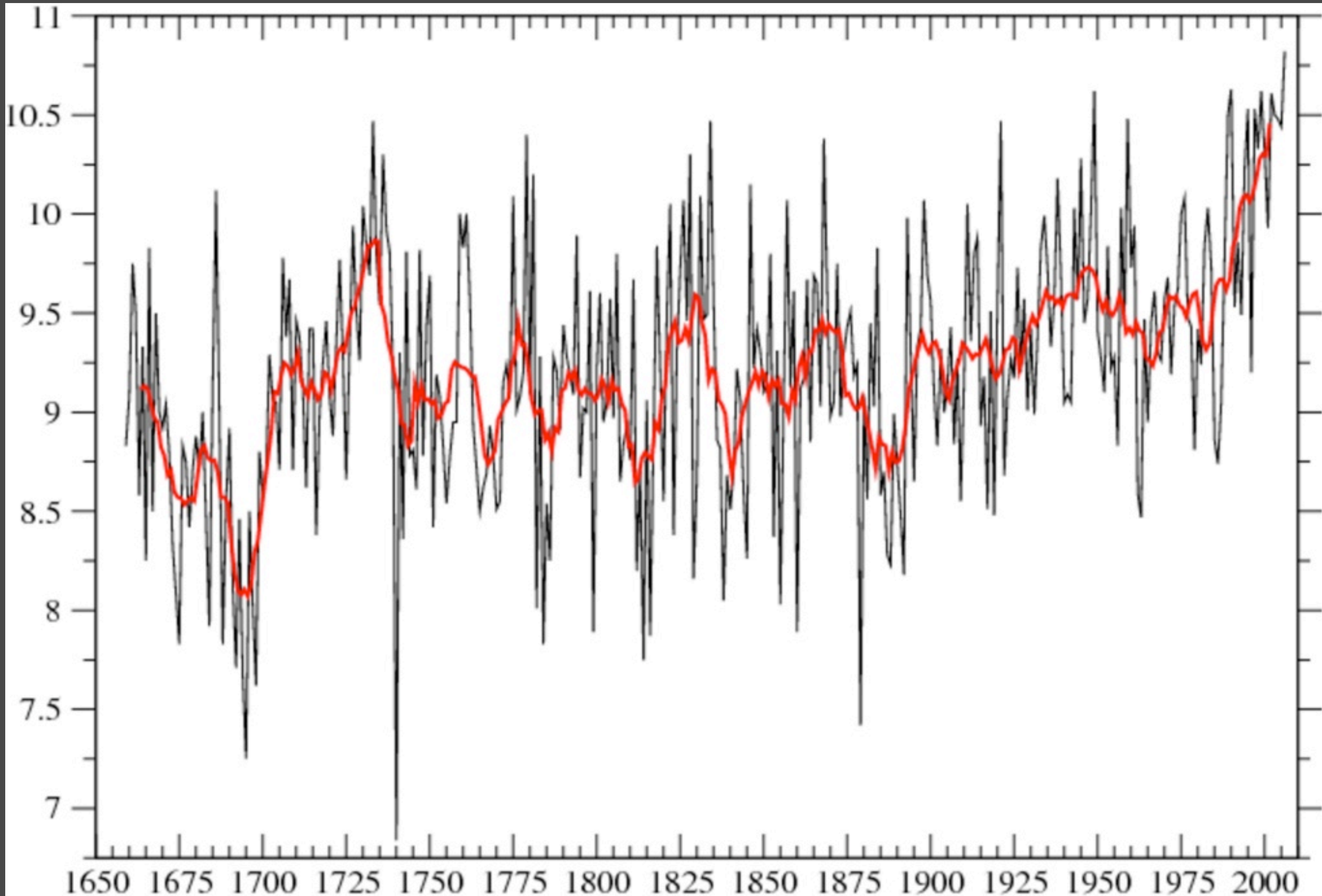
We explore "internal" 10-100 y climate variability.

- Distinct from externally forced variability such as greenhouse warming forced trends.
- Arises from ocean-atmosphere(-biosphere?) variability on timescales longer than ENSO.
- "Virtually nothing is known" about it (Wigley and Raper 1990).

Applications:

- Distinguishing forced from spontaneous trends.
- Identifying periodic modes.

Annual Mean Central England Temperature



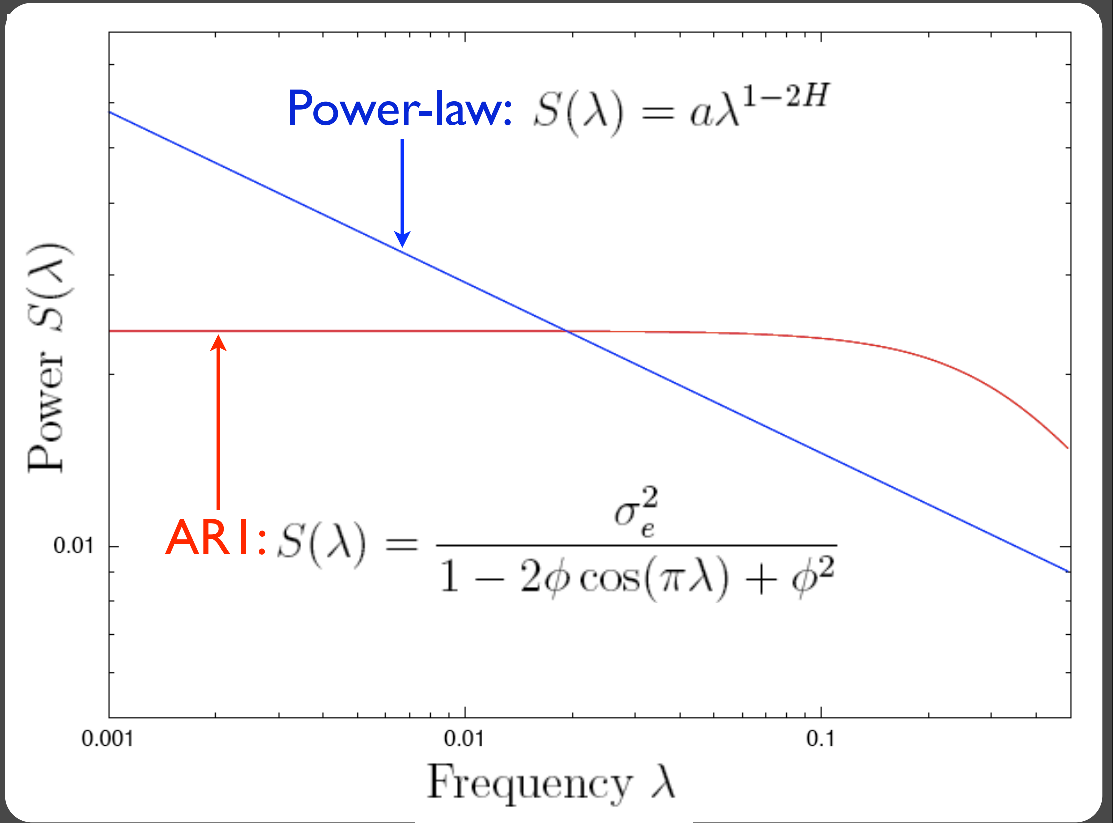
Two-parameter Climate Noise Models

AR 1/red noise:

- Parameters: variance & lag-1autocorrelation ϕ, $0 \leq \phi \leq 1$.
- Classical Hasselman model, fast noisy atmosphere + slow damped ocean.

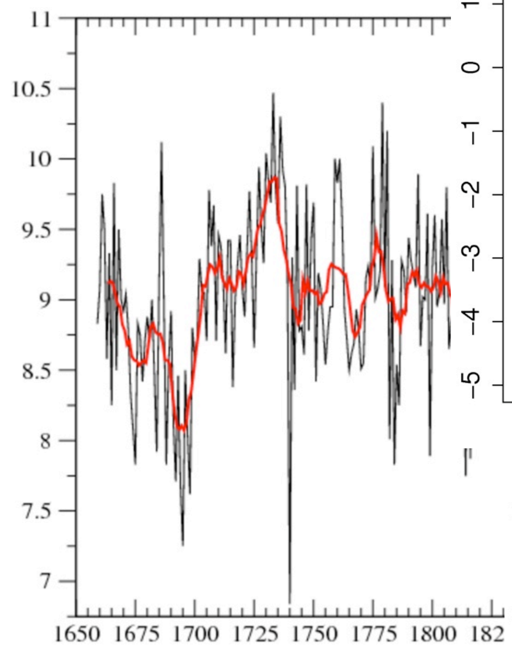
Power law/scaling:

- Parameters: variance and Hurst exponent *H*, $1/2 \leq H \leq 1$.
- No simple unambiguous physical model.

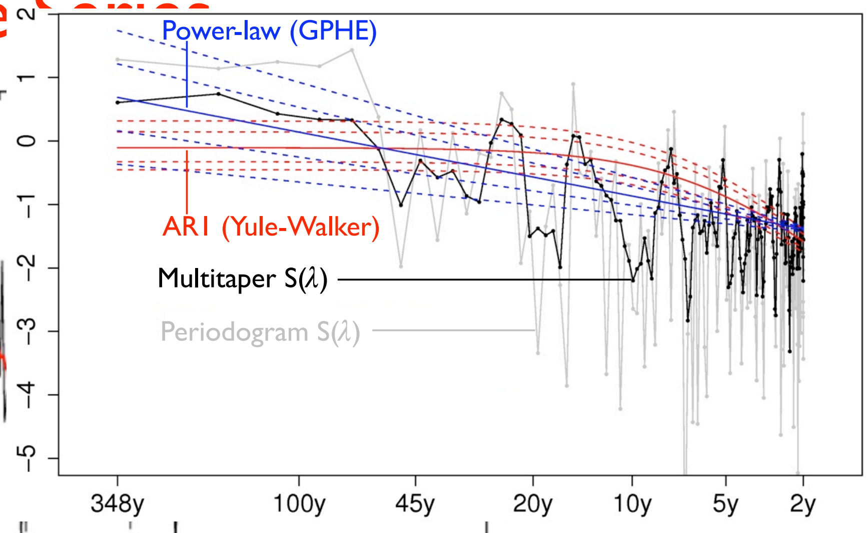


Central England Temperature: A Best Case

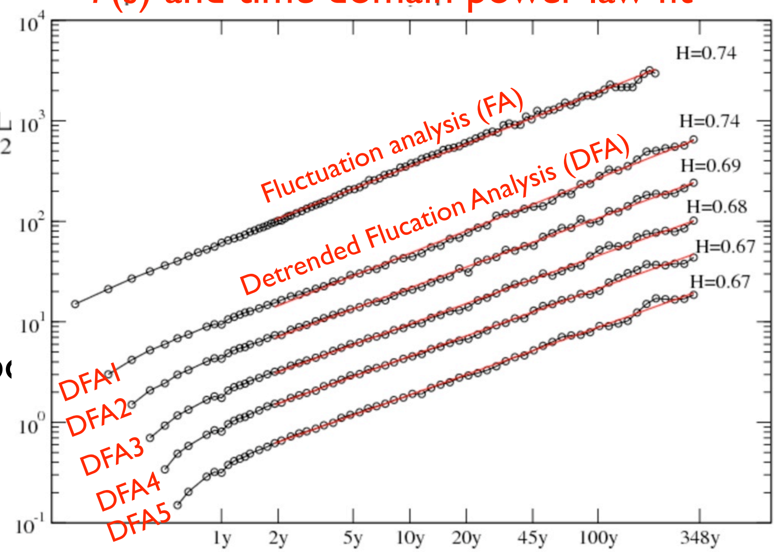
Time S



S(λ), AR1 fit, spectral domain power-law fits



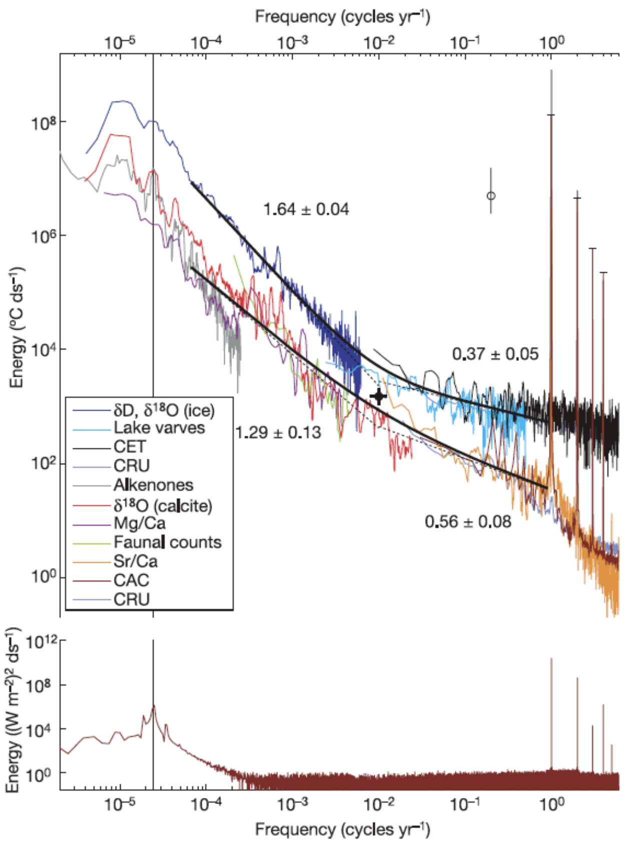
F(s) and time domain power-law fit



CET unambiguously fits p(
("Portmanteau test").

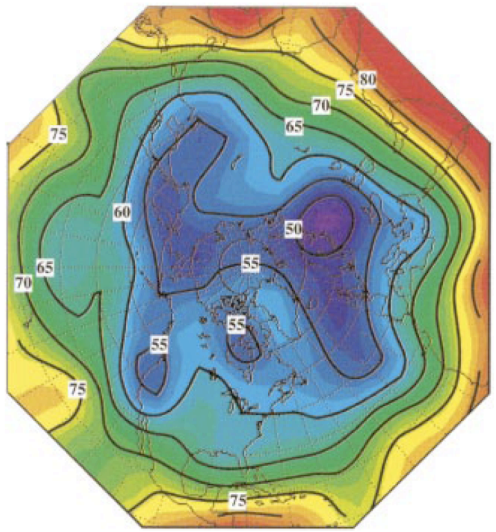
Previously Documented Powerlaw Behavior

S(λ) in paleo temperature proxies



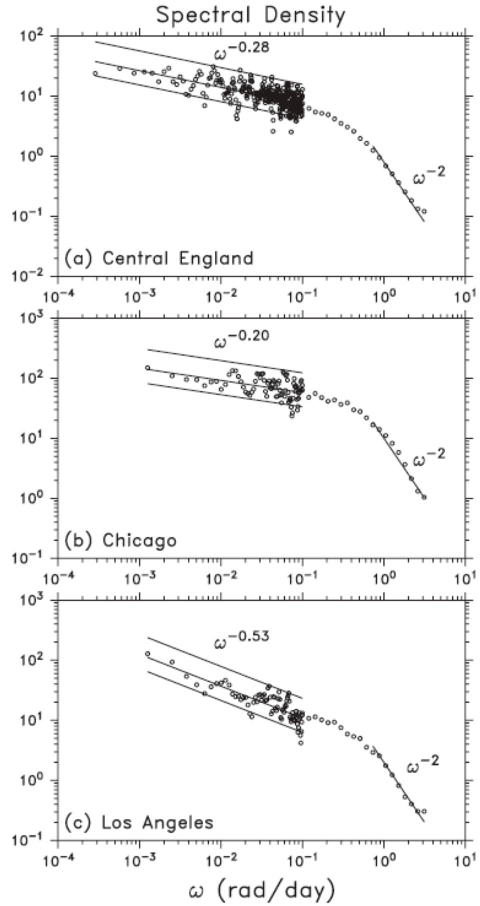
Huybers and Curry 2006

H x 100
in midtroposphere



Tsonis et al. 1999

S(λ) in surface temperature records



Caballero et al. 2002

Model-Observational Intercomparisons

Global Climate Models Violate Scaling of the Observed Atmospheric Variability

R. B. Govindan,[1,2] Dmitry Vyushin,[1,2] Armin Bunde,[2,*] Stephen Brenner,[3]
Shlomo Havlin,[1] and Hans-Joachim Schellnhuber[4]

PRL 2002

Volcanic forcing improves Atmosphere-Ocean Coupled General Circulation Model scaling performance

D. Vyushin,[1] I. Zhidkov,[1] S. Havlin,[1] A. Bunde,[2] and S. Brenner[2]

GRL 2004

Past results have proven controversial and sensitive in surprising ways.

Introduction

Power-law models

- Fit dec-cen $S(\lambda)$ at least as well as AR1.
- Capture buildup of power at low frequencies.
- Provide alternative "null hypothesis" for detecting trends and periodicities.

Working assumption: if you're careful and aware of the ambiguities, power law characterization can be useful.

Objective: to characterize and interpret power-law behavior for the atmospheric general circulation for the recent (50 y) record, from the surface to the stratosphere.

Methods

- We test and apply several methods for calculating Hurst exponent *H* from $S(\lambda) \sim \lambda^{1-2H}$.

Dependence on timescale/λ range (HF cutoff, LF cutoff) — Physics & stats literature (Remark)

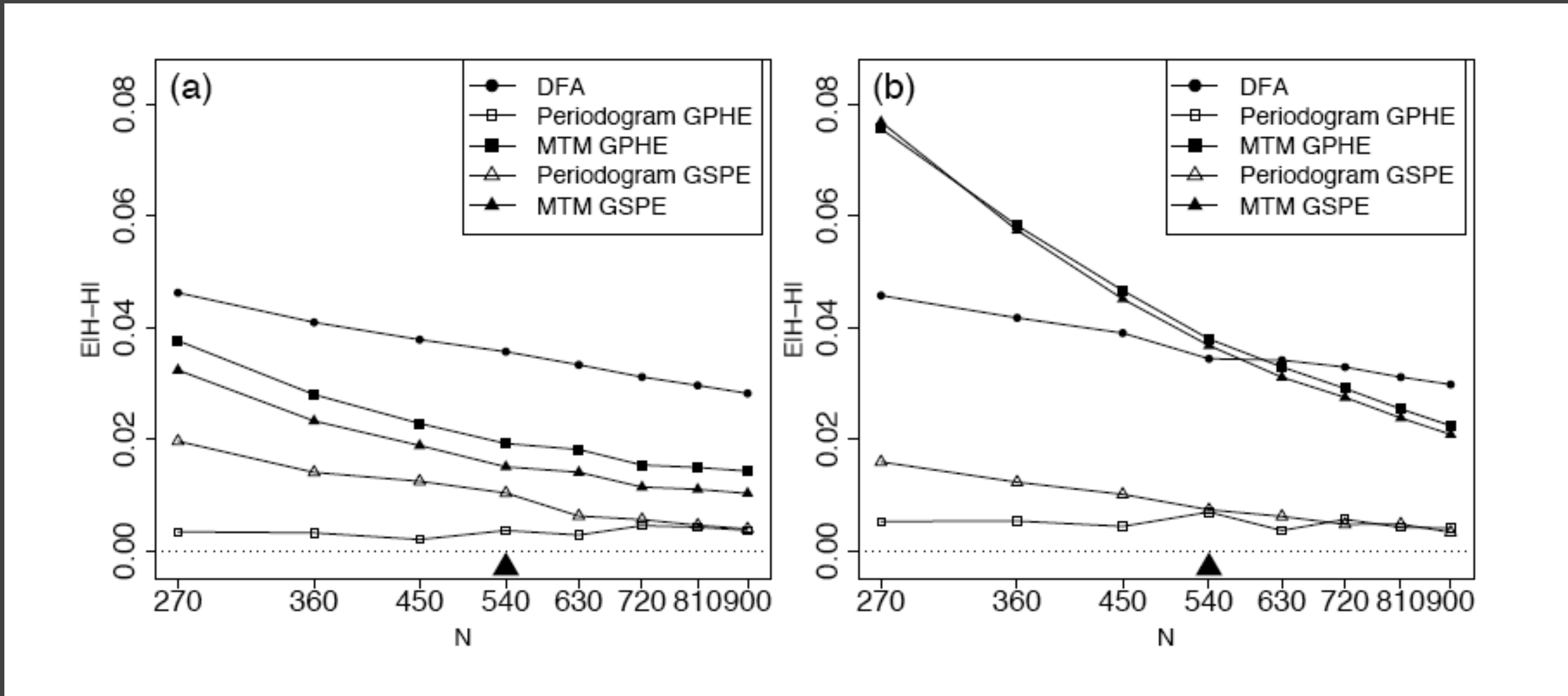
Time Domain (DFA)

Spectral domain:
- Least squares & max. likelihood
- Periodogram & multitaper spectra

Method	HF cutoff	LF cutoff	Remark
DFA(t)	s_{short}=18m	s_{long}=11y	Kantelhardt et al. (2001)
DFA(a)	s_{short}=18m	s_{long}=45y	this study
GPHE(t)	λ_{high}=1/18m	λ_{low}=1/15y ($l = 2$)	Robinson (1995b)
GPHE(a)	λ_{high}=1/18m	λ_{low}=1/45y ($l = 0$)	Hurvich et al. (1998)
MTM GPHE(t)	λ_{high}=1/18m	λ_{low}=1/15y ($l = 2$)	McCoy et al. (1998)
MTM GPHE(a)	λ_{high}=1/18m	λ_{low}=1/45y ($l = 0$)	this study
GSPE(t)	λ_{high}=1/18m	λ_{low}=1/15y ($l = 2$)	this study
GSPE(a)	λ_{high}=1/18m	λ_{low}=1/45y ($l = 0$)	Robinson (1995a)
MTM GSPE(t)	λ_{high}=1/18m	λ_{low}=1/15y ($l = 2$)	this study
MTM GSPE(a)	λ_{high}=1/18m	λ_{low}=1/45y ($l = 0$)	this study

- All methods work well for pure power law stochastic processes (ARFIMA).

E.g. convergence of *H* for ARFIMA



Methods

Data used

- Focus on temperature as primary meteorological field.
- “Reanalysis products” that merge data + models for last 50 years: NCEP and ECMWF
- Climate models from GFDL and from PCMDI/CMIP3/IPCC archive.

Seasonal cycle removed.

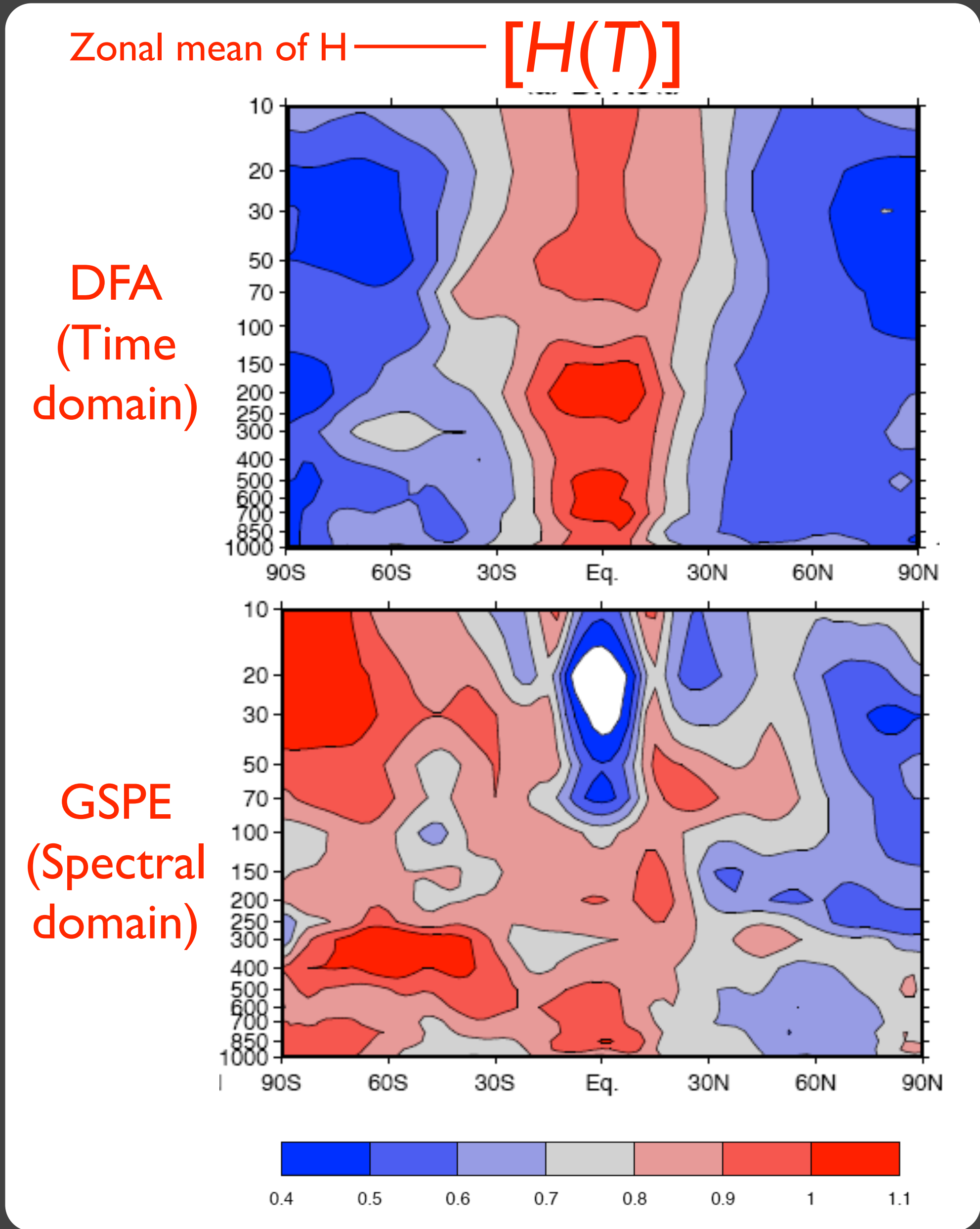
Test impact of filtering for well known climate signals using simple linear filtering.

Observational Analysis

Estimating *H* in the ERA40 Reanalysis

First Results

- We here compare *H*(*T*) for ERA40 data using DFA (time domain) and GSPE (spectral domain) methods.
- The methods produce very different pictures!
- We account for these differences by:
  1. Making time scale ranges consistent.
  2. Filtering well known climate signals.

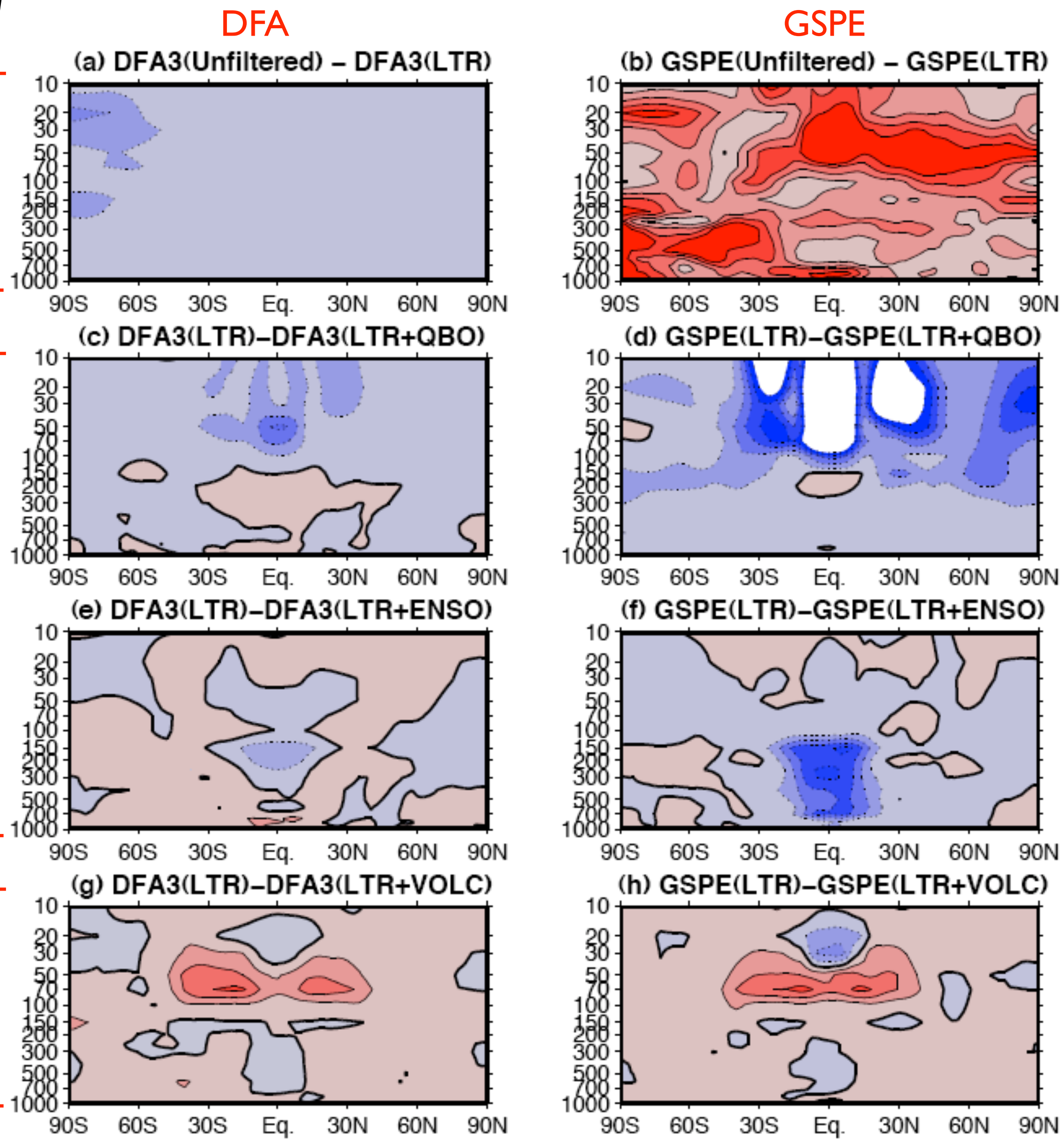


Impact of Filtering on *H*

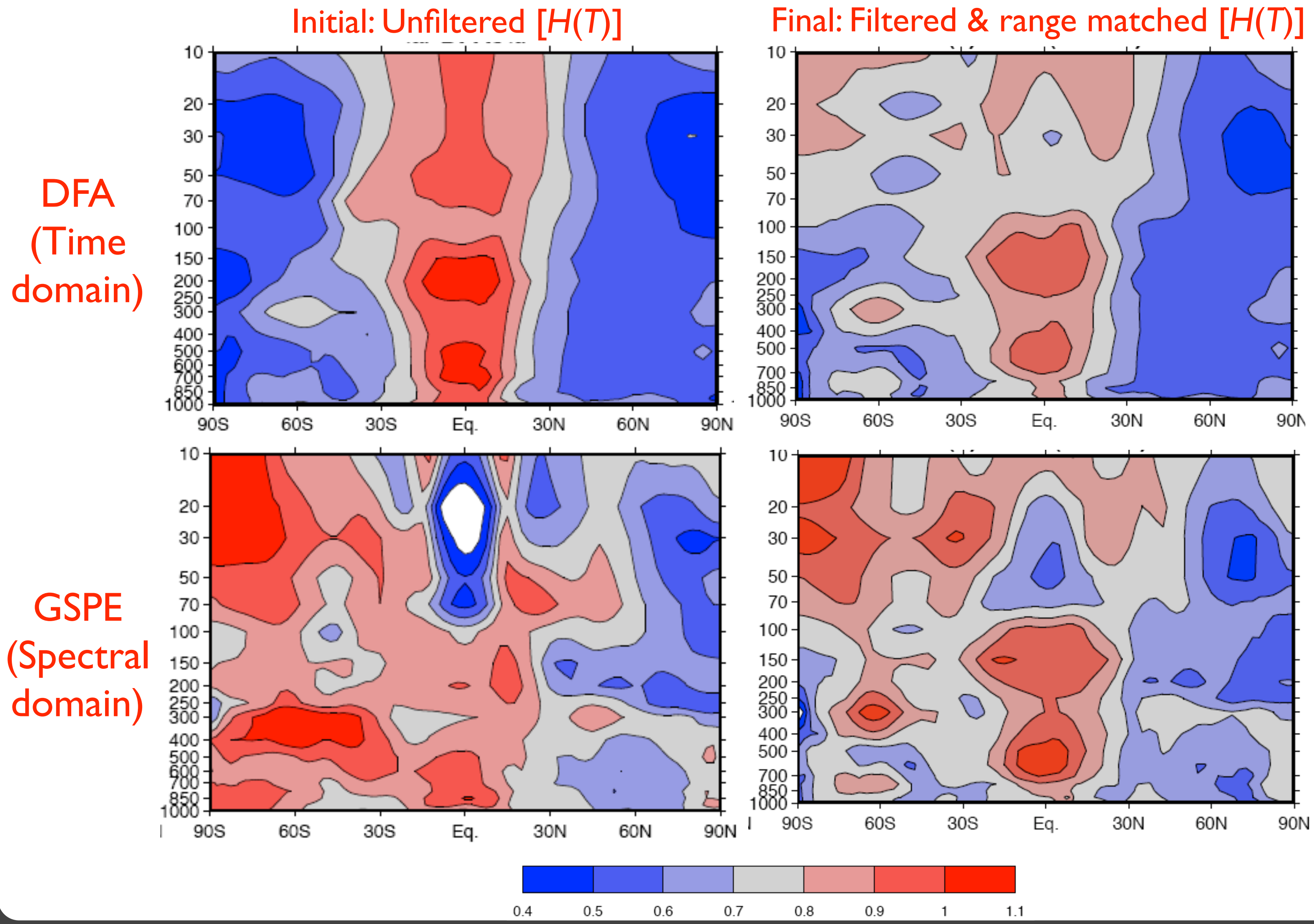
Linear trends increase *H* (steepen slope) for GSPE but not for DFA.

High-frequency periodicities like QBO and ENSO decrease *H* (shallow slope), more strongly for GSPE.

Volcanic forcing increases *H* similarly for DFA & GSPE.



Convergence of *H* Estimation Methods

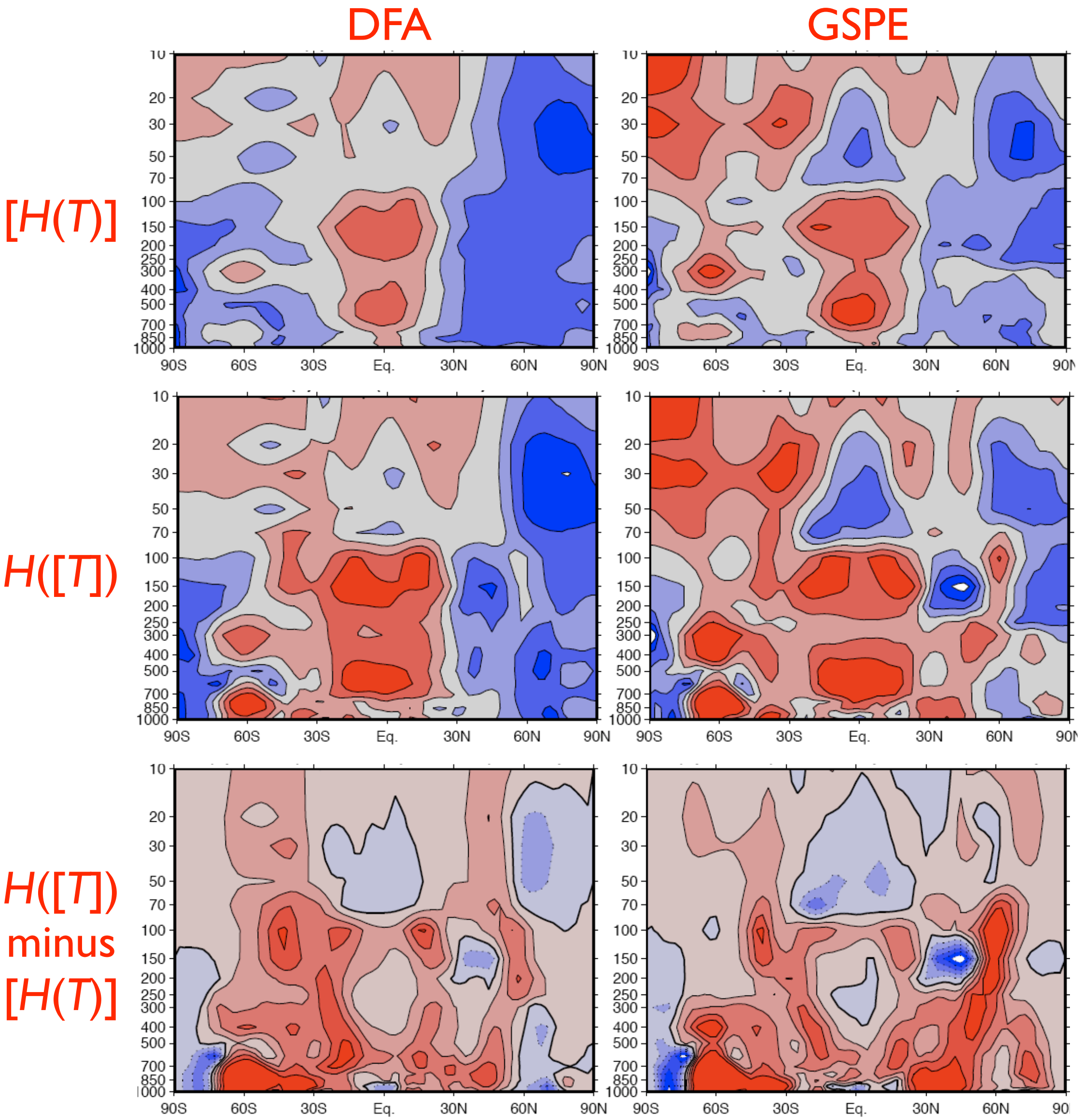


Power law behavior in the zonal-mean circulation

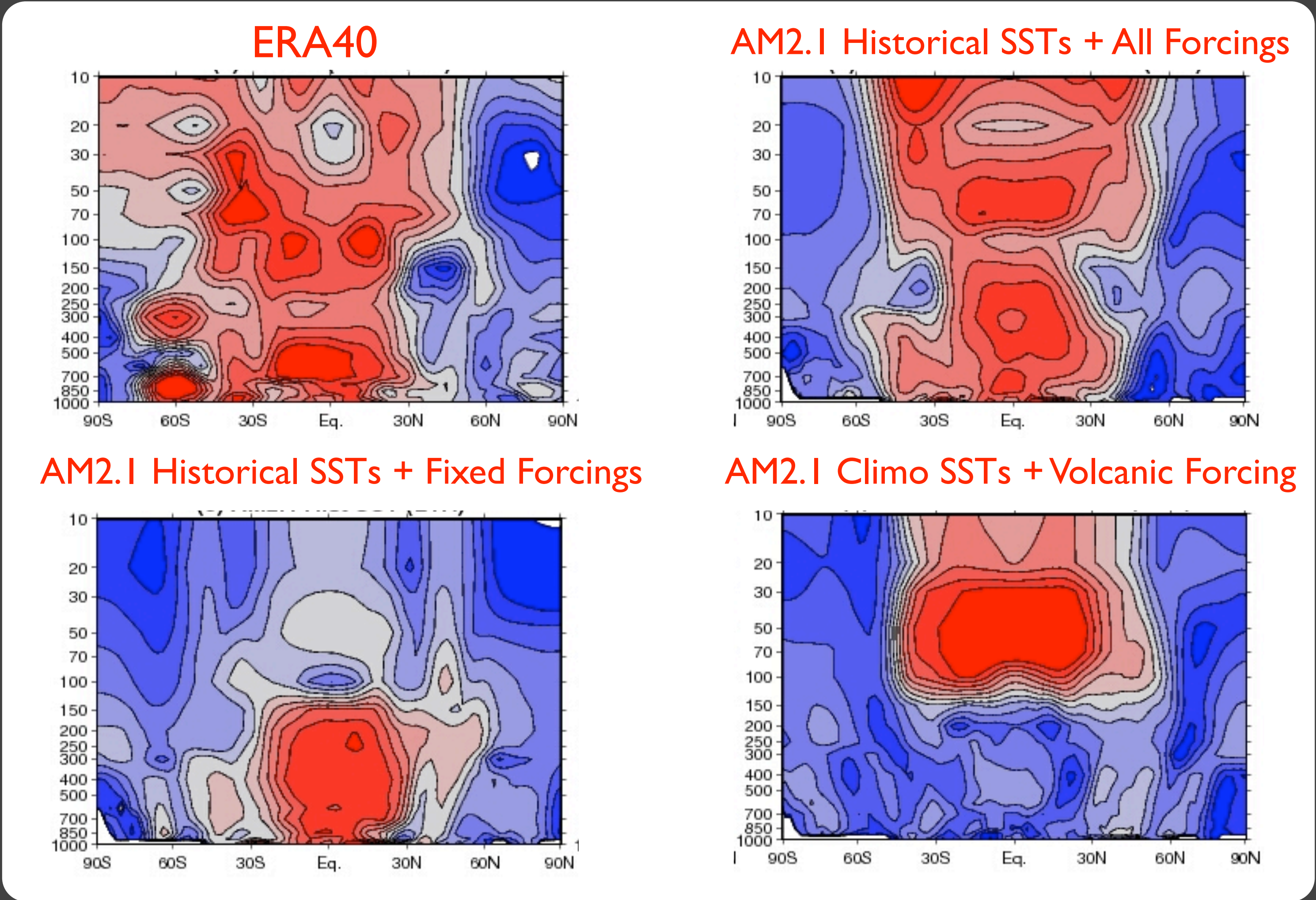
The previous analysis applied to *H* at each point.

The extratropical zonal mean circulation has a relatively large *H* compared to point values for *H*.

This reflects eddy zonal flow interactions and energy/angular momentum constraints.



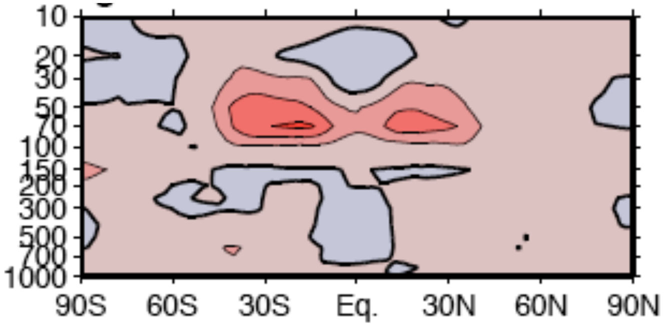
Modeling the Observed *H* Distribution



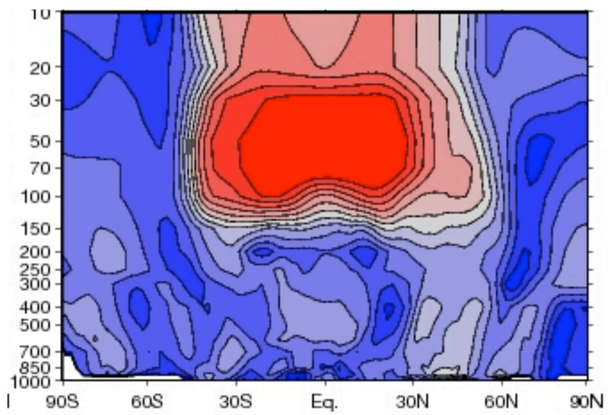
We use climate models to simulate and decompose *H*.

H signature in the stratosphere: Volcanoes

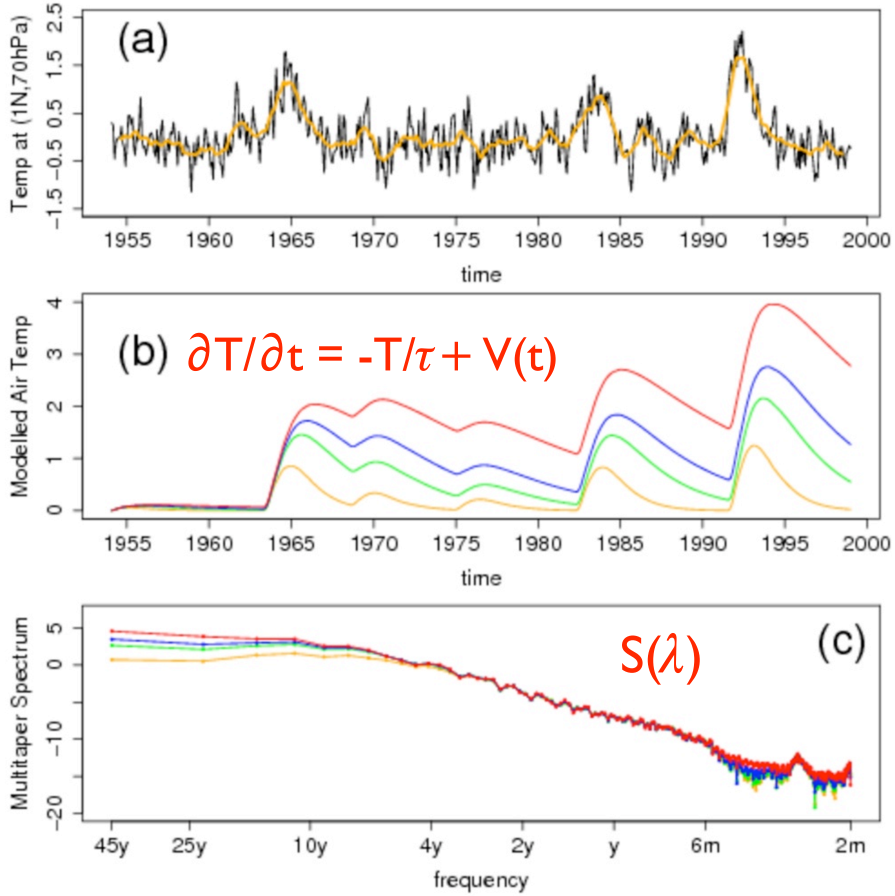
ERA40: Impact of filtering volcanic forcing



AM2.1 with volcanic forcing



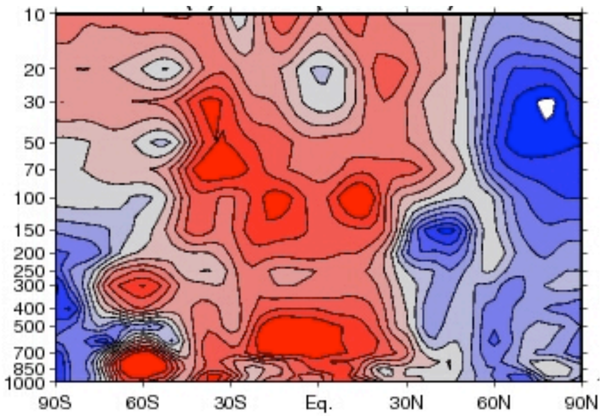
Simple Model for the Volcanic Response



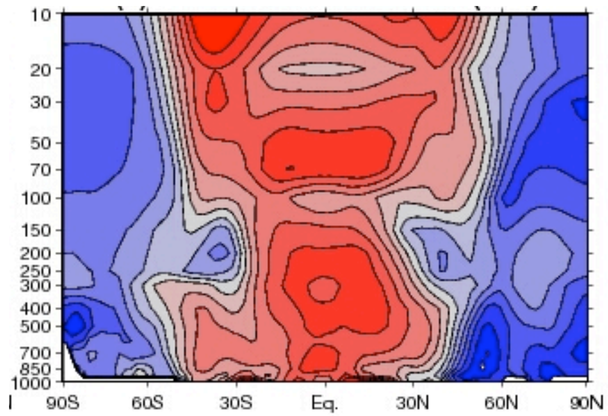
- *H* signature in stratosphere: direct response to volcanic forcing, not internally generated.

H signature in the tropics: SSTs

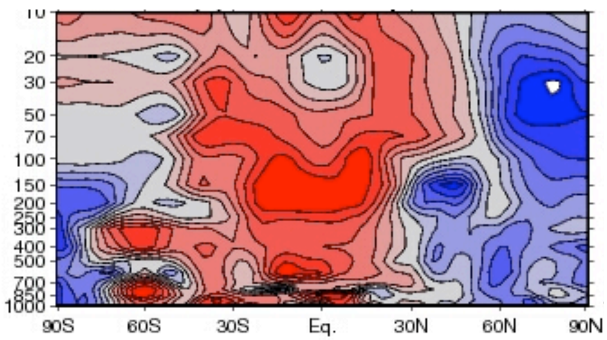
ERA40



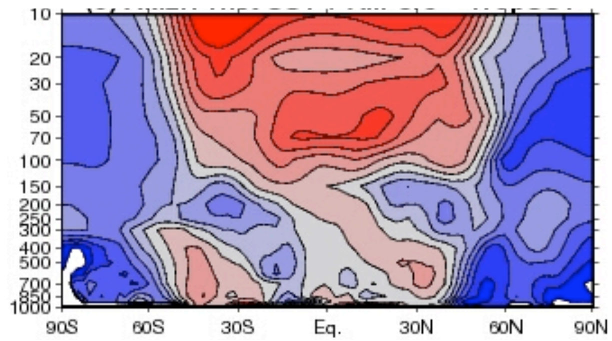
AM2.1



ERA 40 with Tropical SST filtering



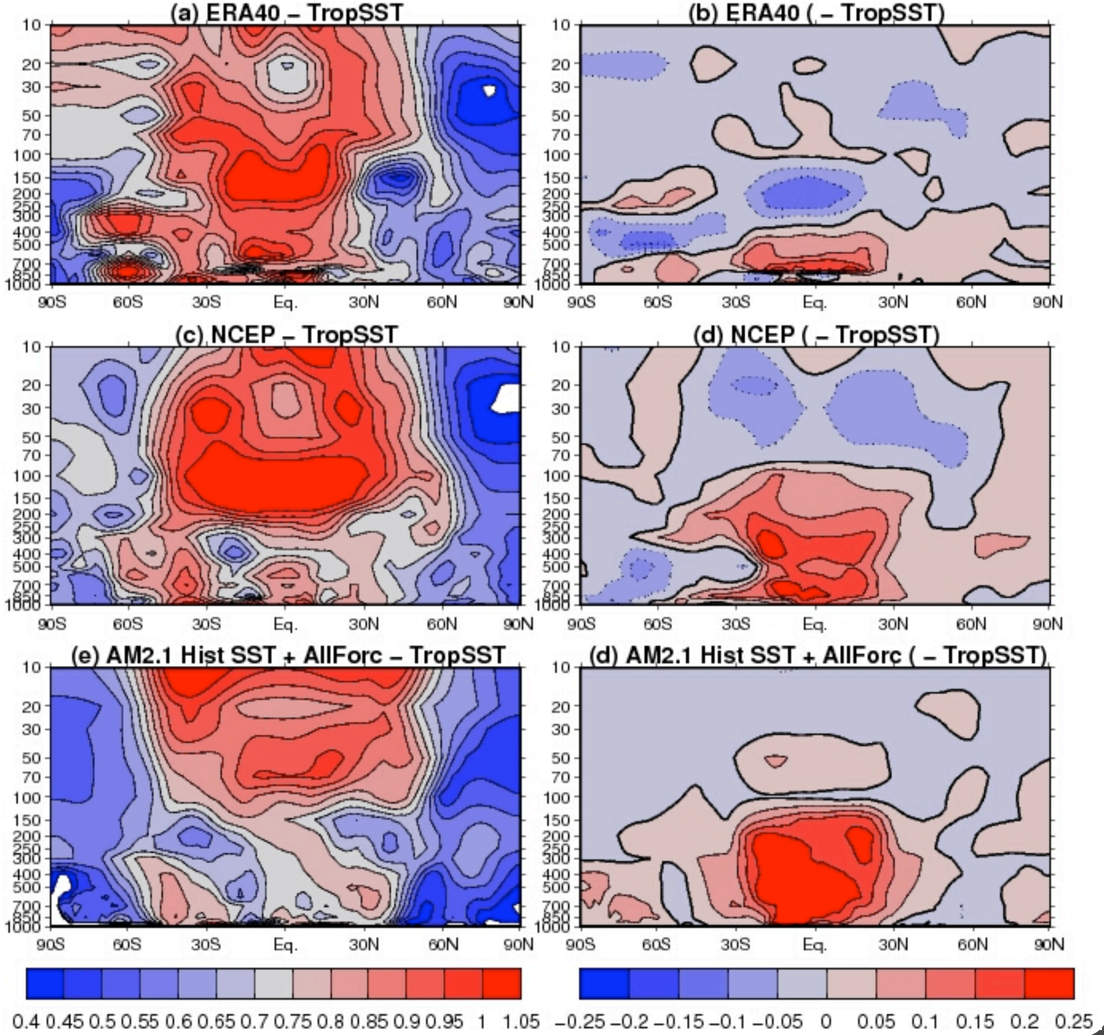
AM2.1 with Tropical SST filtering



- Tropical SSTs account for *H* signature in the model, but not in ERA40!

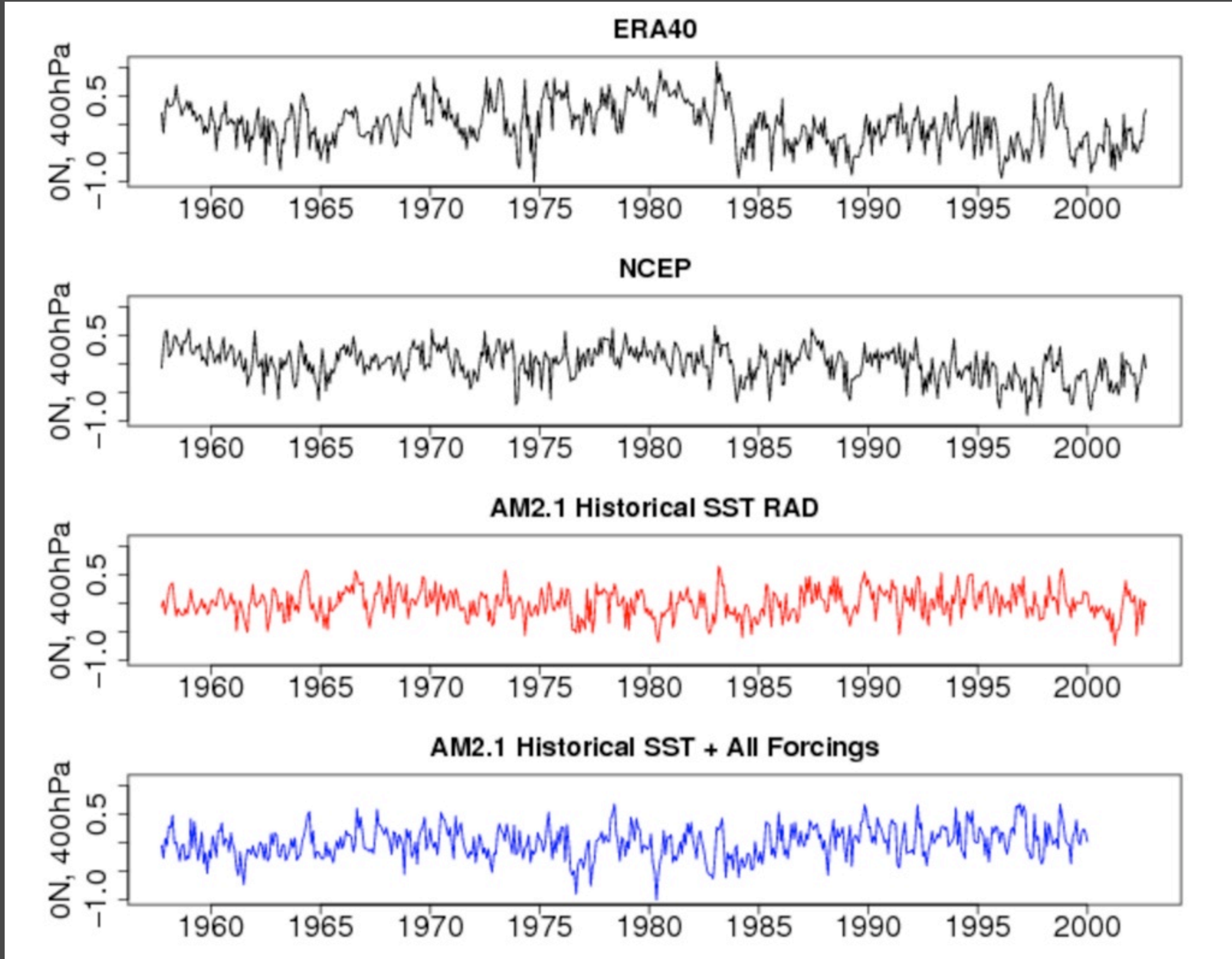
H([*T*]) with tropical SST filtering

Impact of tropical SST filtering



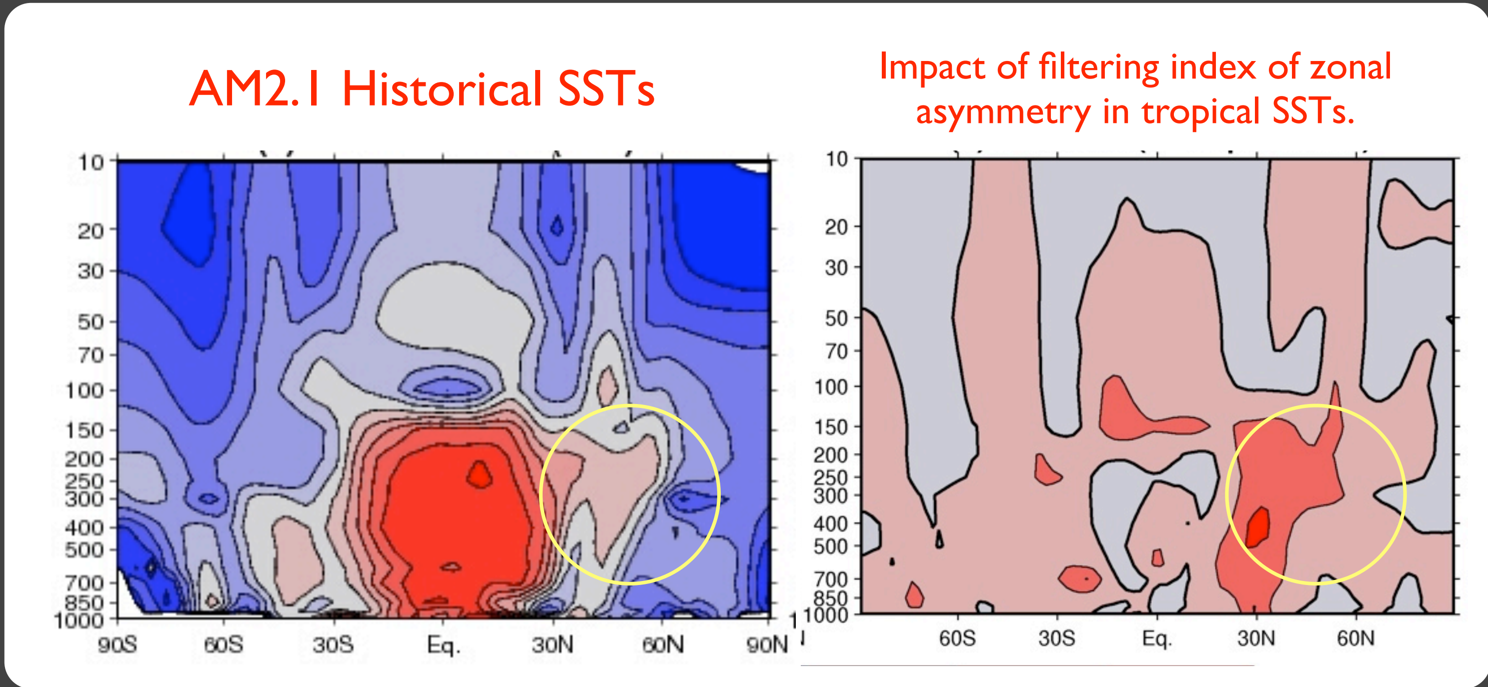
Notice the contrast between the NCEP and ERA40 products!

- NCEP Reanalysis & Model agree, and both disagree with ERA40. Data inhomegeneity issues?



ERA40
NCEP
AM2.1 Historical SST RAD
AM2.1 Historical SST + All Forcings
0N, 400hPa
−1.0
0.5
1960
1965
1970
1975
1980
1985
1990
1995
2000

Effect of Eddy Mean-Flow Interactions



Part of the extratropical H arises from wave forcing of zonal mean flows (ENSO like).

Conclusions

As an integral measure of low-frequency variability, *H* is a useful quantity to calculate.

But *H* signatures require careful interpretation:

- Climate trends,
- Volcanoes,
- Ocean-atmosphere coupling,
- Data problems.

Conclusions

Initial *H* estimates seemed non-robust, but we could account for the differences.

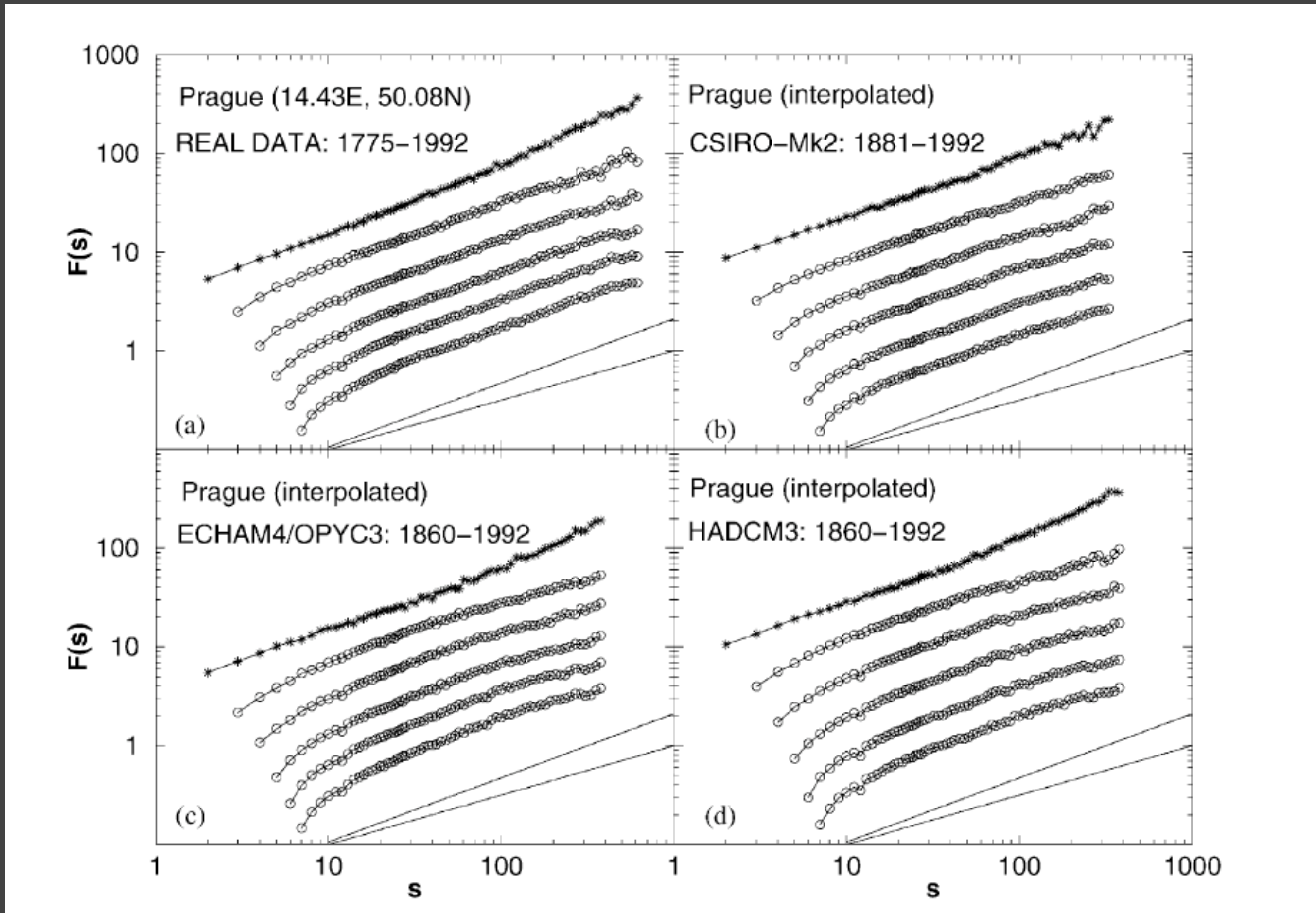
Three principal regions of large *H*:

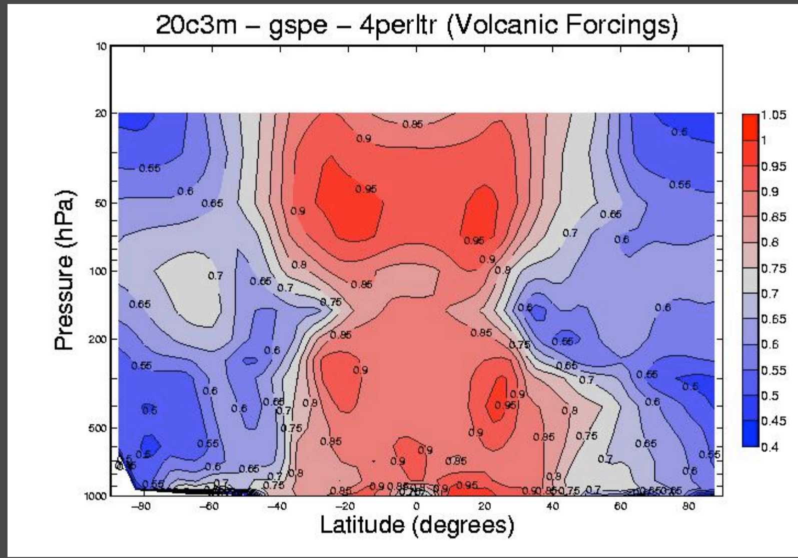
- Tropical-subtropical lower stratosphere,
- Tropical troposphere,
- Low extratropical troposphere (for [*T*])

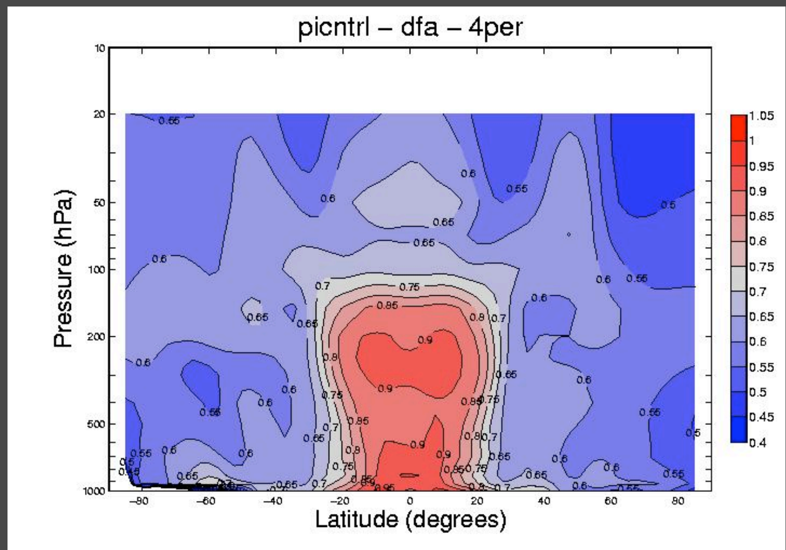
Demonstrated that volcanic forcing gives rise to power-law behavior in the lower stratosphere.

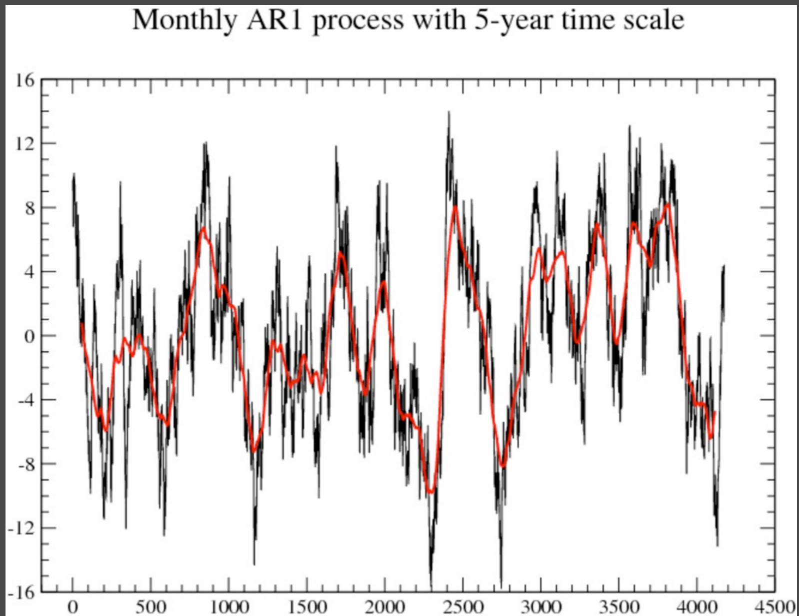
Propose that tropical air-sea interaction responsible for tropospheric *H* signature.

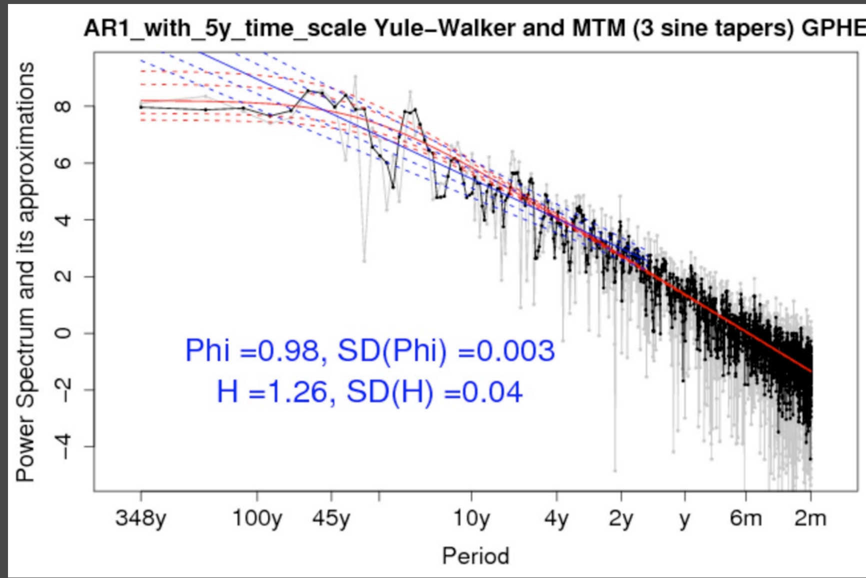
Supplemenatry Figures

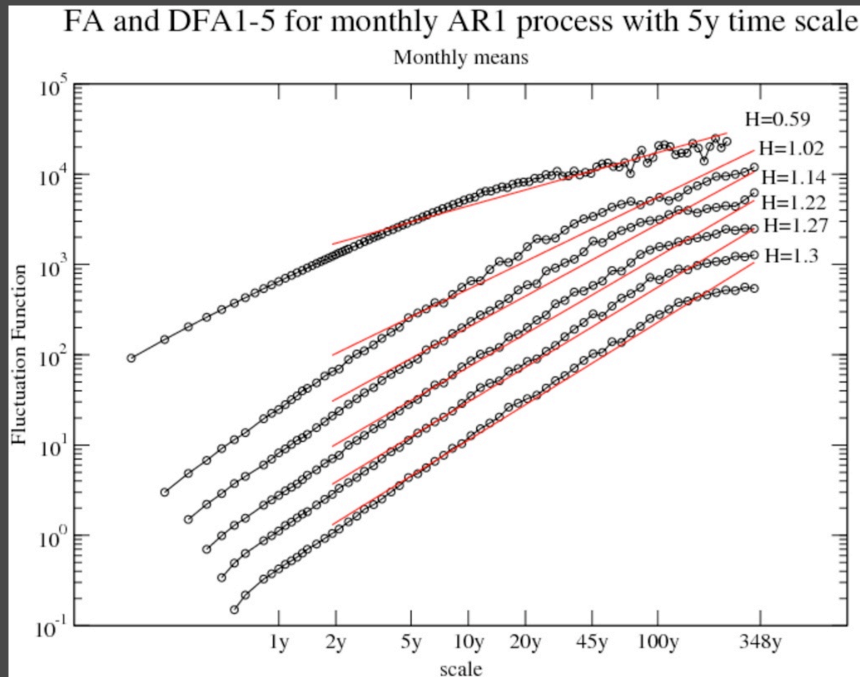



20c3m – gspe – 4perltr (Volcanic Forcings)
Pressure (hPa)
Latitude (degrees)


picntrl – dfa – 4per
Pressure (hPa)
Latitude (degrees)


Monthly AR1 process with 5-year time scale
16
12
8
4
0
-4
-8
-12
-16
0
500
1000
1500
2000
2500
3000
3500
4000
4500


AR1_with_5y_time_scale Yule−Walker and MTM (3 sine tapers) GPHE
Power Spectrum and its approximations
Phi =0.98, SD(Phi) =0.003
H =1.26, SD(H) =0.04
348y
100y
45y
10y
4y
2y
y
6m
2m
Period


FA and DFA1-5 for monthly AR1 process with 5y time scale
Monthly means
Fluctuation Function
H=0.59
H=1.02
H=1.14
H=1.22
H=1.27
H=1.3
1y
2y
5y
10y
20y
45y
100y
348y
scale