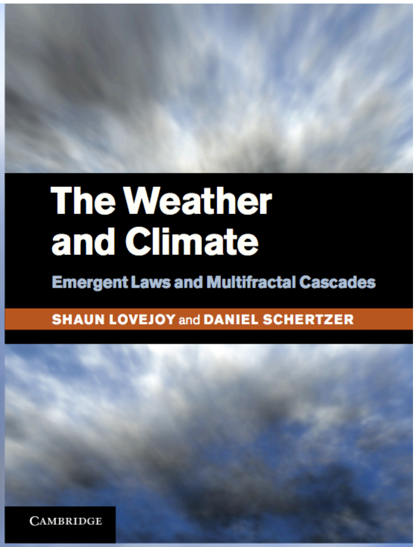


The Weather and Climate

Emergent Laws and Multifractal Cascades

SHAUN LOVEJOY and DANIEL SCHERTZER

CAMBRIDGE

Scaling fluctuation analysis and statistical hypothesis testing of anthropogenic warming

GEC3, Nov. 29, 3:30

S. Lovejoy McGill, Montreal

The need for GCM-free approaches to anthropogenic climate change

- Limitations of models: they converge (very slowly!) to *their* climates… not *ours*.
- GCM uncertainties: 1979-2013: 1.5-4.5K, no convergence
- The focus on model issues removes us from real world issues: e.g. the focus on "equilibrium" or "transient" climate sensitivities rather than "effective climate sensitivities".
- Global warming is only evaluated *indirectly* using models (e.g. "fingerprinting"): the data is not fully exploited.
- The exclusive reliance on GCM's for assessing anthropogenic warming gives ammunition to climate skeptics.
- The statistical hypothesis that the warming is due to natural variability must be statistically tested. The failure to reject this hypothesis gives ammunition to climate skeptics.

Introduction:

What is Climate?

The climate is not what you expect…

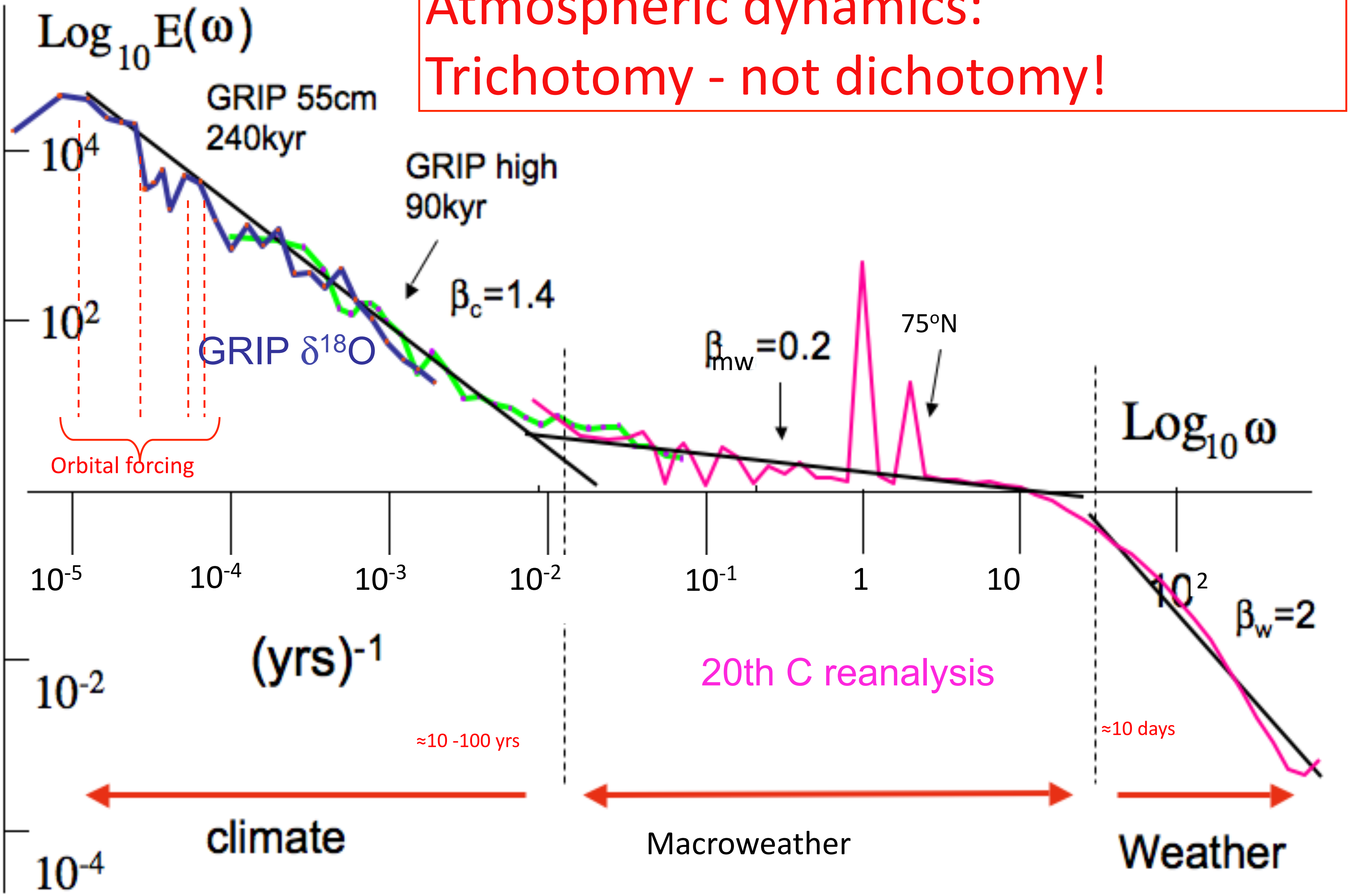
"Climate is what you expect, weather is what you get."

-Lazarus Long, **character in R. Heinlein 1973**

"**Climate in a narrow sense is usually defined as the "average weather"** ... The classical period is 30 years, as defined by the World Meteorological Organization (WMO)… Climate in a wider sense is the state, including a statistical description, of the climate system."

-Intergovernmental Panel on Climate Change, 2007

Atmospheric dynamics: Trichotomy - not dichotomy!



Two data sources only GRIP, 20CR

Lovejoy and Schertzer 2011

Scaling fluctuation analysis

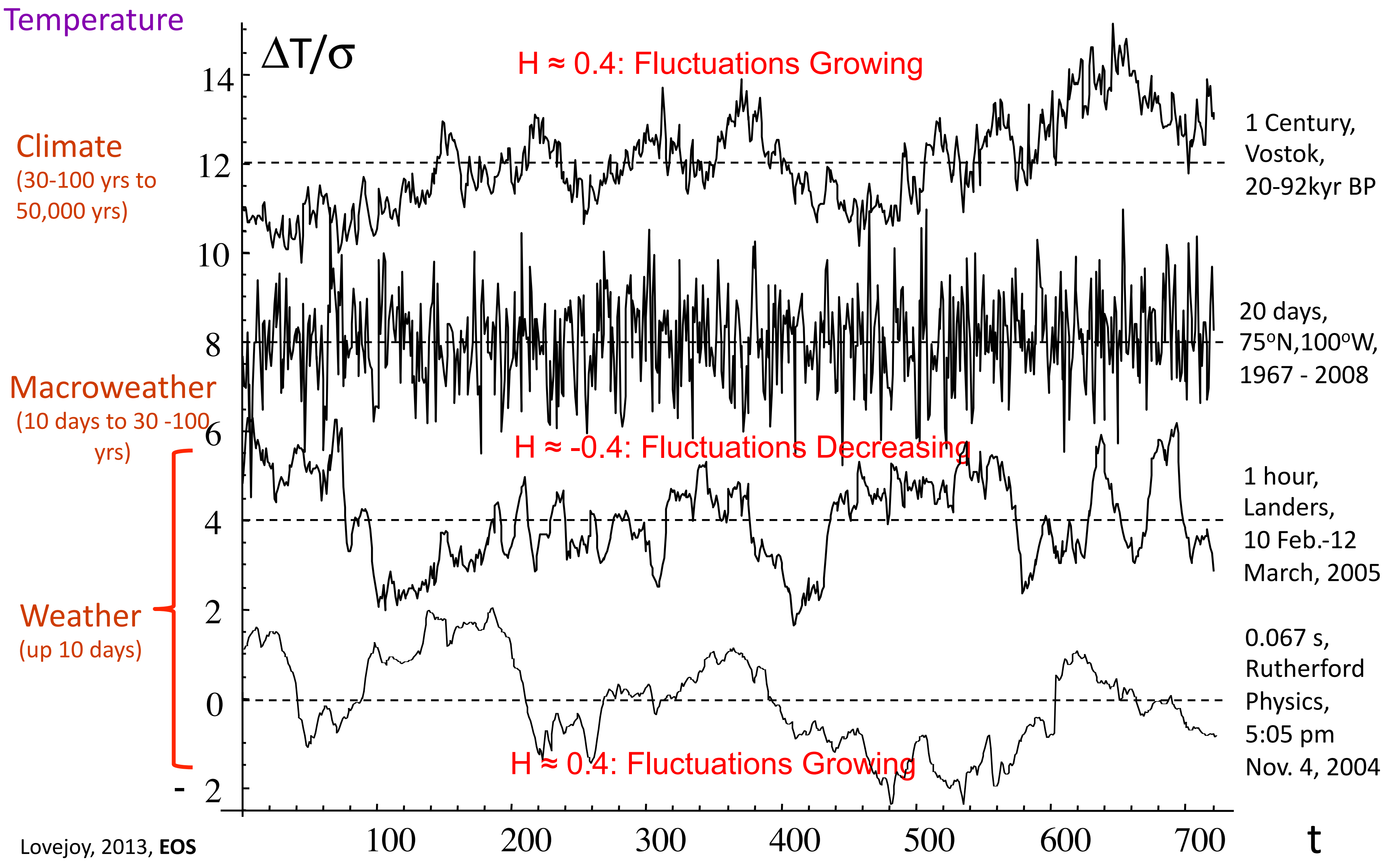
Trichotomy:

Weather – macroweather - climate

$$\langle \Delta I \rangle = \langle \varphi \rangle \Delta t^{H}$$

Fluctuation

= constant



Lovejoy, 2013, **EOS**

Basic characteristics of the three regimes

Fluctuation

$$\langle \Delta I \rangle = \langle \varphi \rangle \Delta t^{H}$$

= constant

> "Climate is what you expect, weather is what you get."
>
> *-Lazarus Long,* **character in R. Heinlein 1971**

Weather:

$\Delta t < \tau_w$ (≈ 10 days): H>0,

Fluctuations grow with scale "unstable"

"...Weather is what you get"

Macroweather:

(10 days ≈) $\tau_w < \Delta t < \tau_c$ (≈ 10- 100 yrs): H<0,

Fluctuations diminish with scale;

atmospheric states are "stable".

"Macroweather is what you expect..."

Climate:

(10- 100 yrs ≈) τ_c <≈ Δt <≈ 100 kyrs: H>0,

Fluctuations grow with scale; atmospheric states are "unstable", subject to "climate change".

"The climate is not what you expect..."

Difference, Tendency, Haar fluctuations

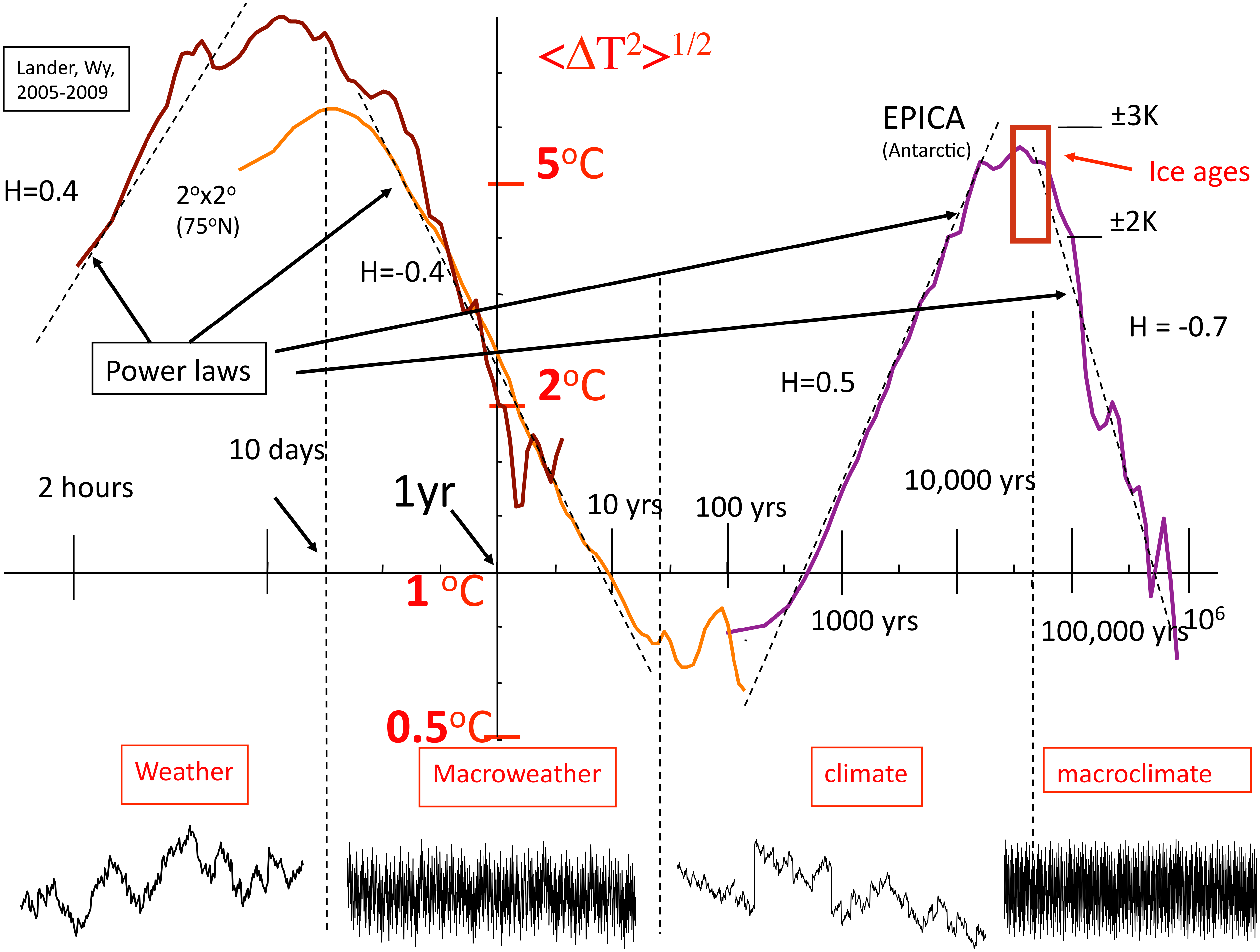
Differences: The difference in temperature between t and t+Δt

Tendency: The average of the temperature (with overall mean removed) between t and t+Δt

Haar: The difference between the average of the temperature from t and t+Δt/2 and from t+Δt/2 and t+Δt

Relations:

When $1 > H > 0$: Haar ≈ difference
When $0 > H > -1$: Haar ≈ tendency


Lander, Wy, 2005-2009
$<\Delta T^2>^{1/2}$
H=0.4
2°x2° (75°N)
H=-0.4
5°C
2°C
1 °C
0.5°C
EPICA (Antarctic)
±3K
Ice ages
±2K
H = -0.7
H=0.5
Power laws
2 hours
10 days
1yr
10 yrs
100 yrs
1000 yrs
10,000 yrs
100,000 yrs
10^6
Weather
Macroweather
climate
macroclimate

Range of exponents over which average fluctuations at scale Δt corresponds to frequency 1/Δt

Fluctuation

$$\langle \Delta I \rangle = \langle \varphi \rangle \Delta t^{H}$$

= constant

$$E(\omega) = \left\langle \left| \tilde{I}(\omega) \right|^{2} \right\rangle = \omega^{-\beta}$$

$$\beta = 1 + 2H - K(2)$$

Multifractal “correction”

Statistic	Range of H	Range of β	Comment
Spectrum	$-\infty < H < \infty$	$-\infty < \beta < \infty$	$E(\omega) \approx \omega^{-\beta}$
Difference	0<H<1	1<β+K(2)<3	“Poor man’s wavelet”
Tendency Fluctuation	-1<H<0	-1<β+K(2)<1	Average with overall mean removed (standard deviation= “Climactogram”, also called the “Aggregated Standard Deviation”)
Haar	-1<H<1	-1<β+K(2)<3	Difference of means of first and second halves of interval
Detrended Fluctuation Analysis (DFA, polynomial order n)	-1<H<(n+1)	-1<β+K(2)<3+2n	Also multifractal extension (MFDFA), usually linear: n=1, Not a wavelet
Mexican Hat Wavelet	-1<H<2	-1<β+K(2)<5	2nd Derivative of a Gaussian
Generalized Haar	-m<H<n	1-2m<β+K(2)<3+2n	Simple implementation, Interpretation not simple

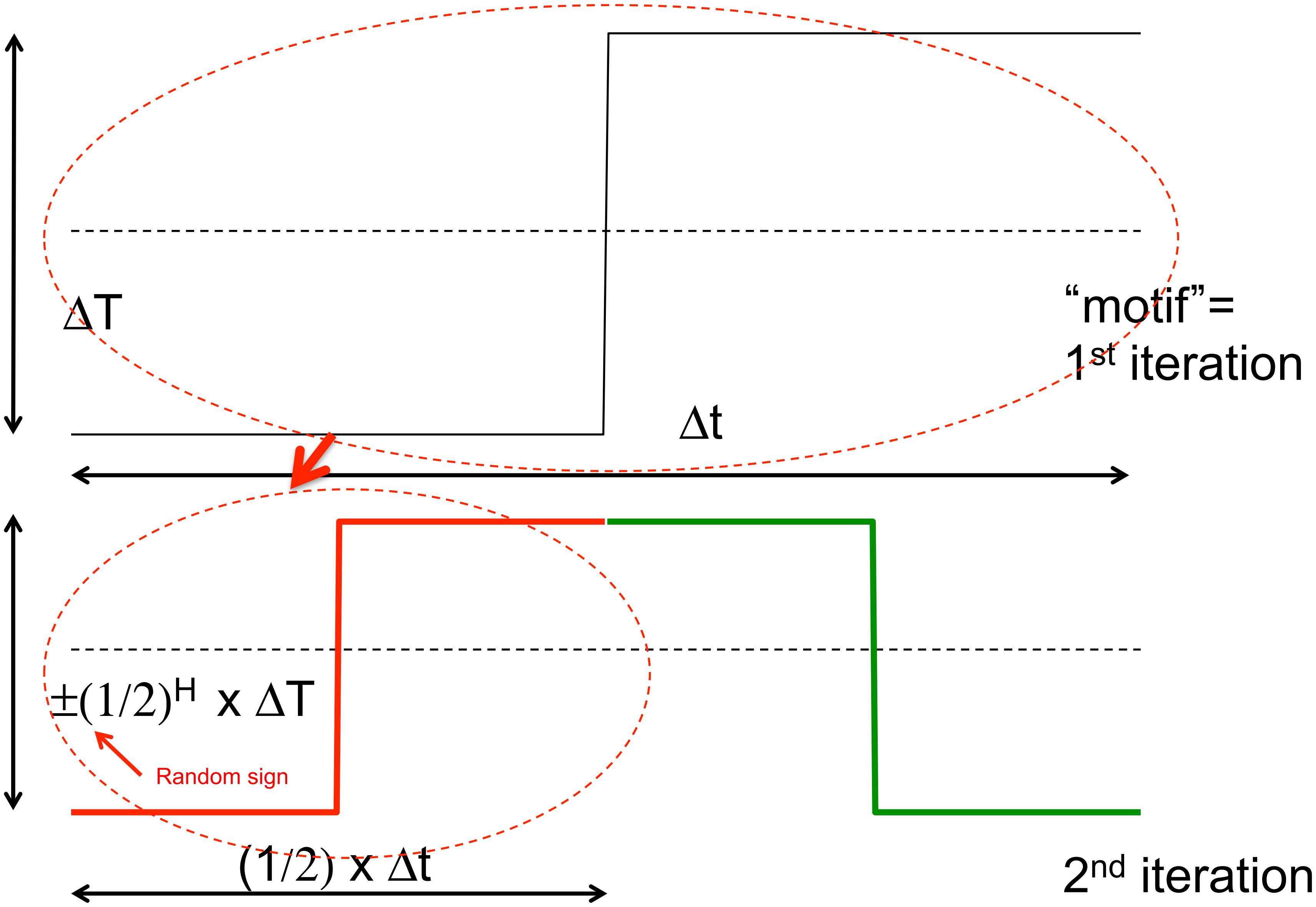
Simple interpretation

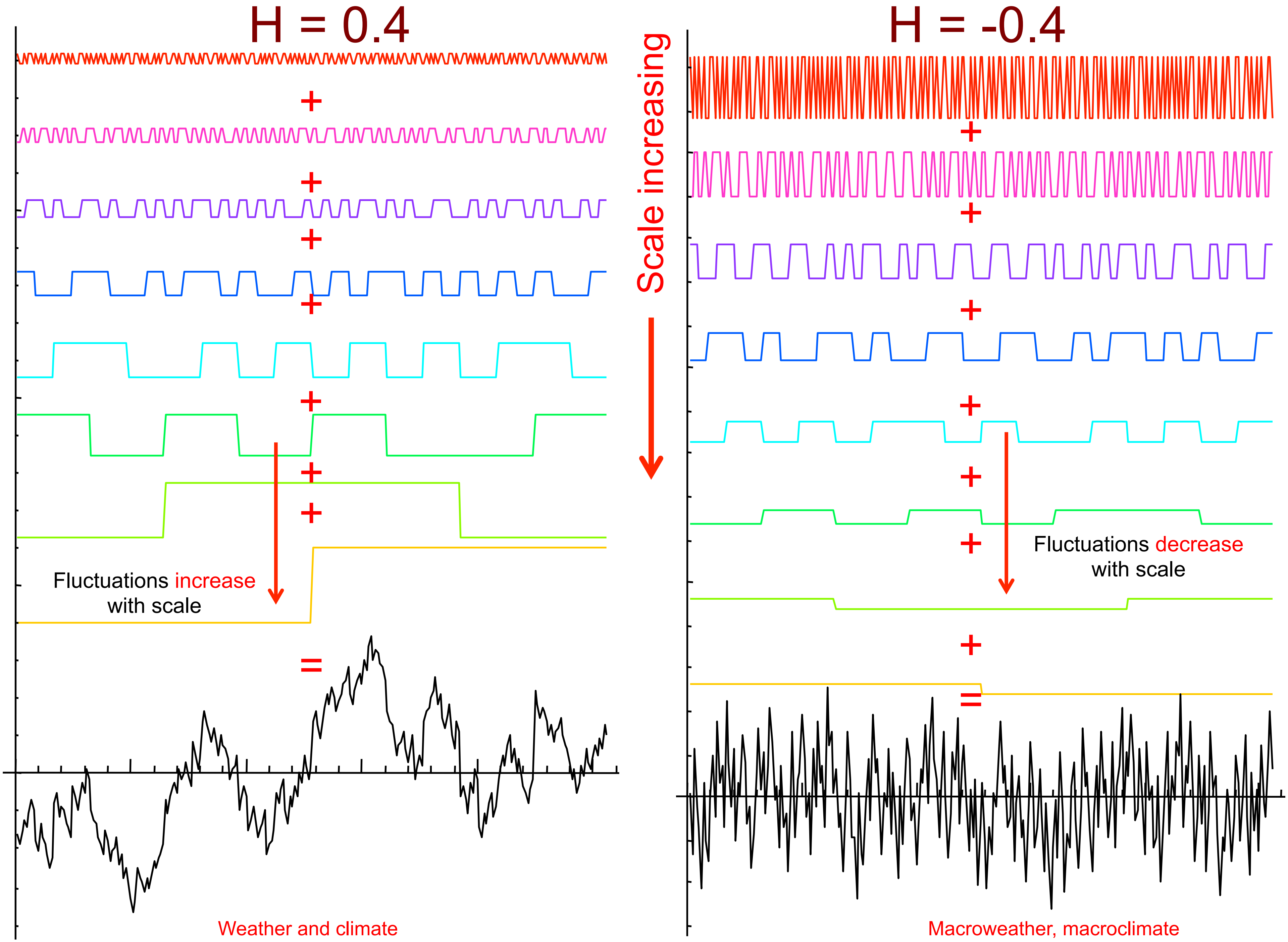
To understand the different regimes

The fractal H model

(Lovejoy 2013)

(fractal dimenension= 2-H)




H = 0.4
H = -0.4
Scale increasing
+
=
Fluctuations increase with scale
Fluctuations decrease with scale
Weather and climate
Macroweather, macroclimate

Anthropogenic warming due to Greenhouse gases: origins and limitations of GCM approaches

Father of climate sensitivity estimates

Svante Arrhenius

(1859 –1927)

In 1896 predicted CO_2 doubling would increase the earth's temperature by 5-6°C

Father of numerical models of the atmosphere

Lewis F. Richardson

(1881-1953)

In 1920, first numerical integration of equations (10^{-2} Flops (?)) →

3,120,000 cores: 3×10^{16} Flops →

MilkyWay-2: World's fastest supercomputer (June 2013)

National University of Defense Technology, Changsha, China

GCM's uncertainties:
no convergence

Evolution of estimates of sensitivity to CO_2 doubling

Date	1896	1979	1990	1995	2002	2007	2013	2013
Source	Arrhenius	US Acad. Sci.	IPCC AR1	IPCC AR2	IPCC AR3	IPCC AR4	IPCC AR5	This study
Sensitivity	5 -6	1.5 -4.5	1.5 -4.5	1.5 -4.5	1.5 -4.5	2 -4.5	1.5 -4.5	1.94 -4.24

Uncertainty due to
water vapour feedbacks

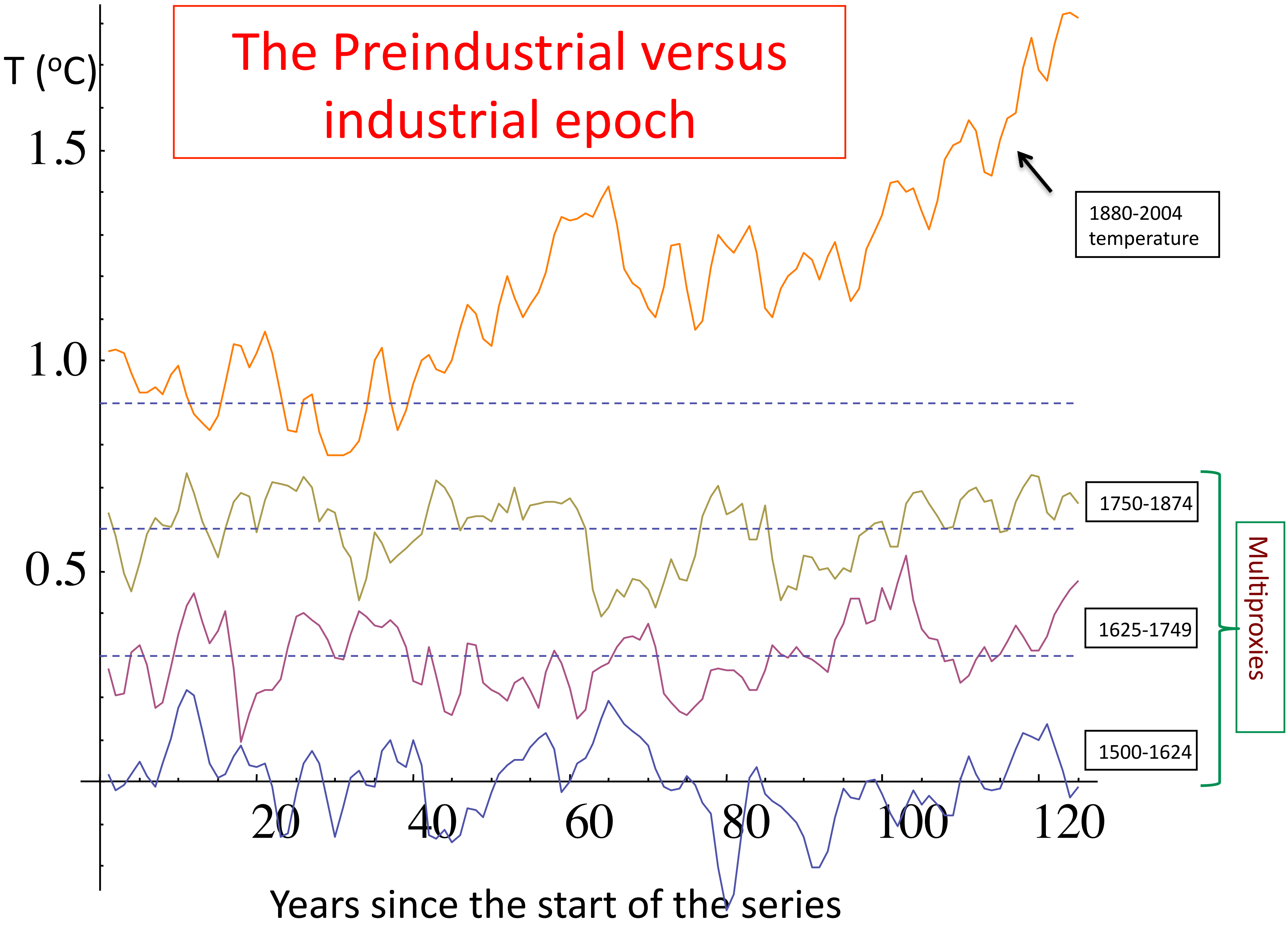
GCM's: Uncertainty due to water vapour, clouds and aerosols

Uncertainty due to
ocean- atmosphere lag

> "…due to profound uncertainties, primarily with the hydrological cycle, we are still unable to rule out the possibility that anthropogenic climate change will be catastrophic for humanity over the coming century, or something to which we can adapt relatively easily…"
>
> -Tim Palmer, president of the Royal Meteorological Society, 2012

Primary evidence for anthropogenic warming

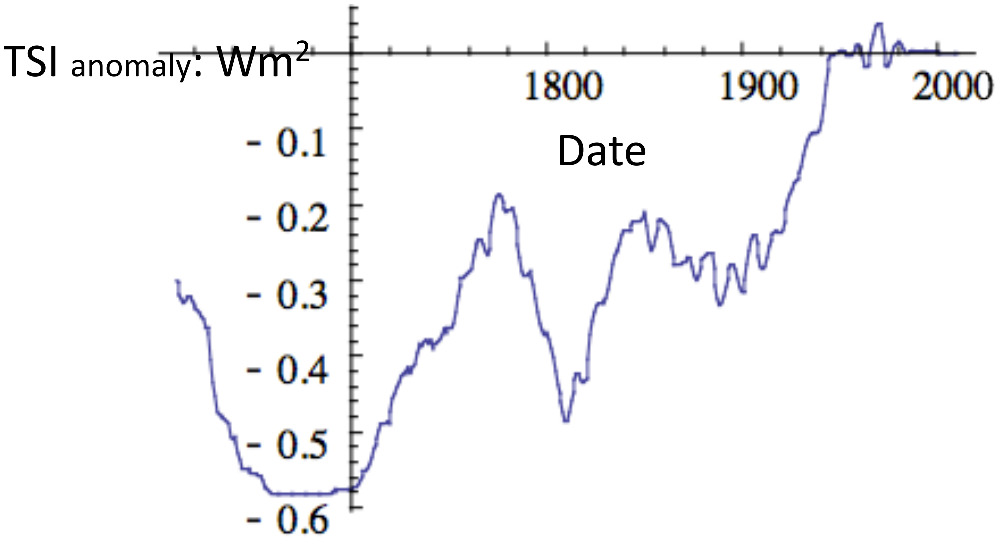
The Preindustrial versus industrial epoch



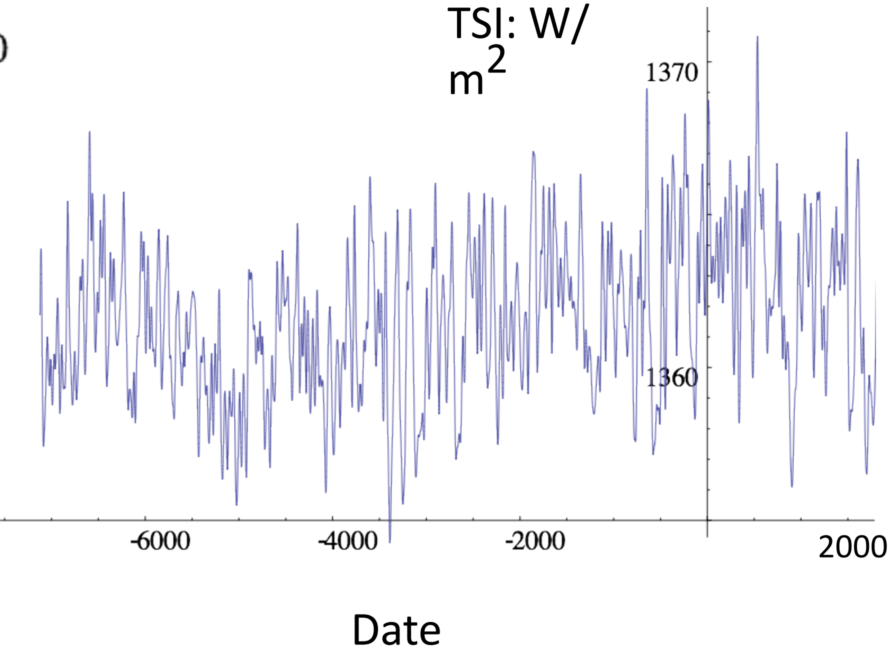
Warming: don’t blame the sun or volcanoes!

Solar forcing

Sunspot derived “background”
(Wang et al 2005)



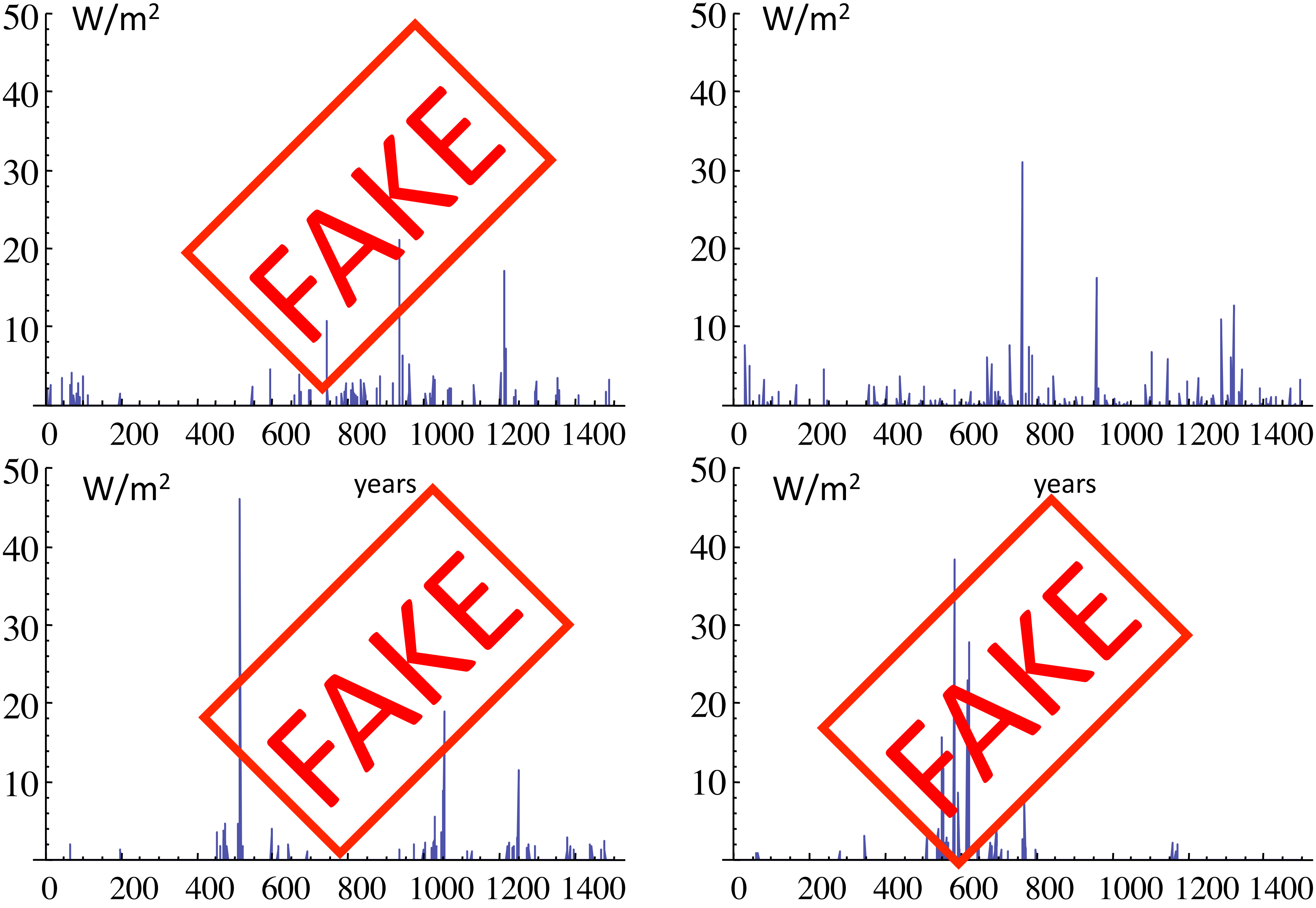
^{10}Be solar reconstruction
(Shapiro et al 2011)



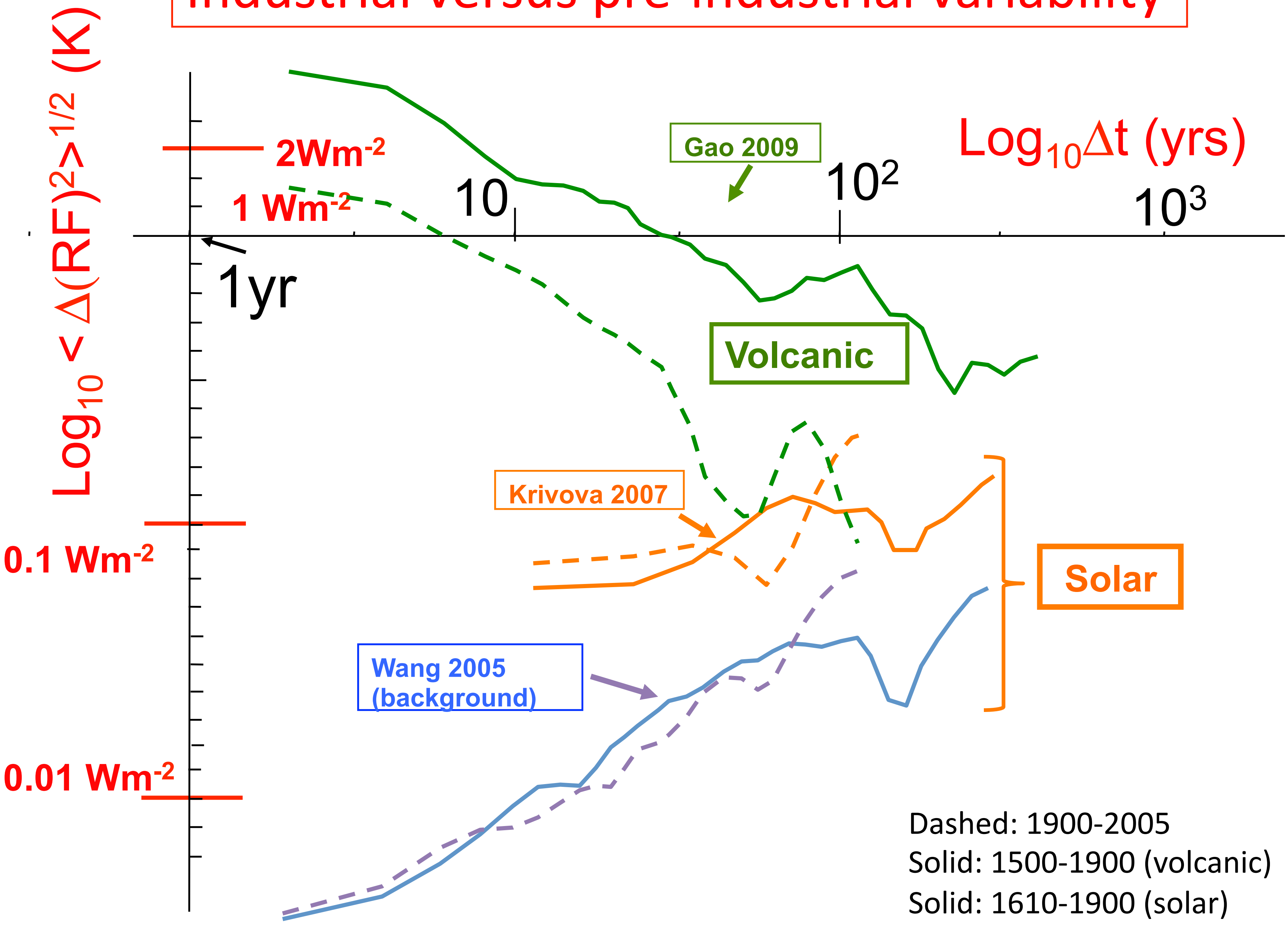
$H \approx +0.4$

$H \approx -0.4$

Volcanic forcings over last 1500 years are mujltifractal (intermittent), yet statistically stationary



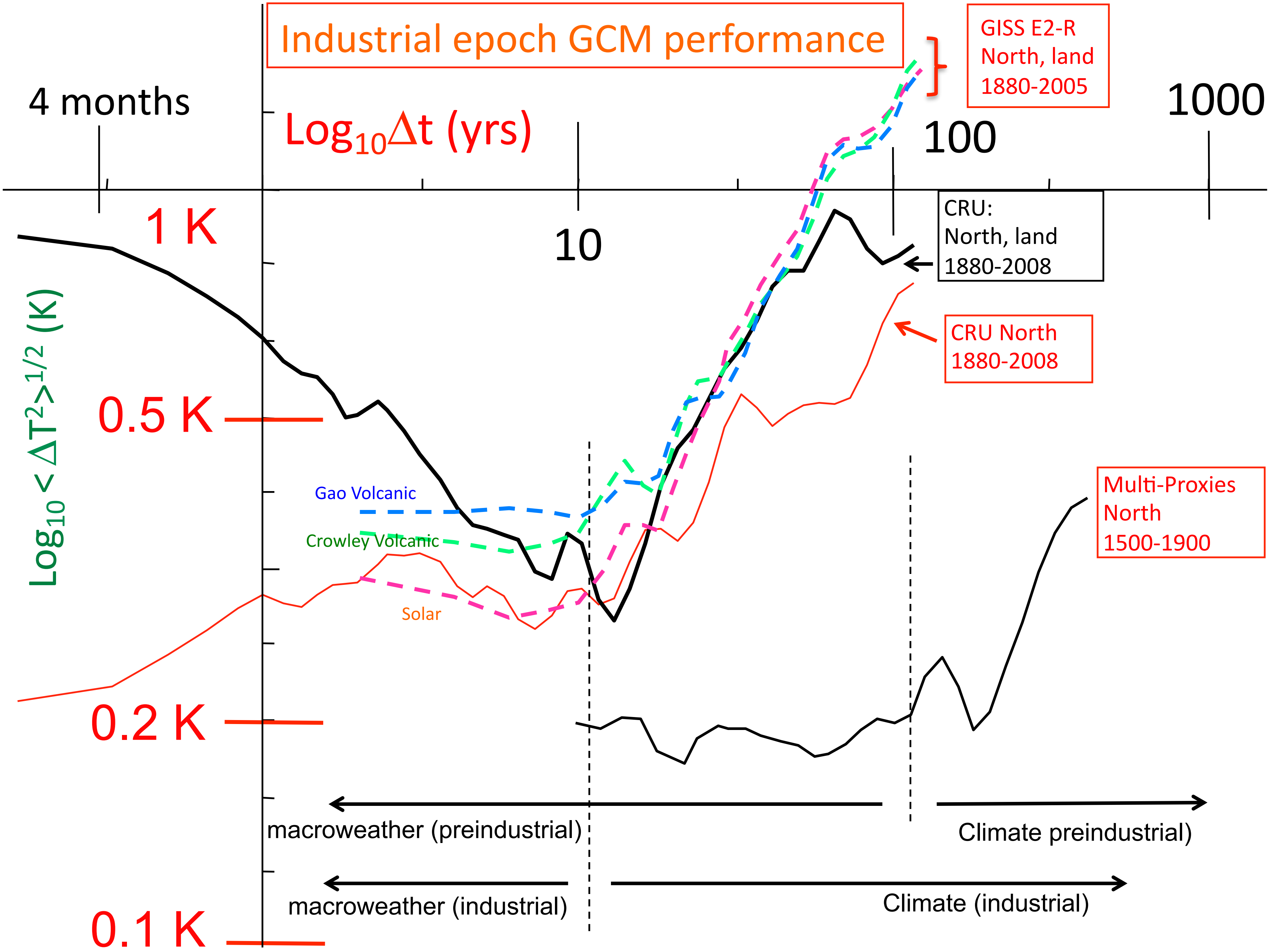
Industrial versus pre-industrial variability



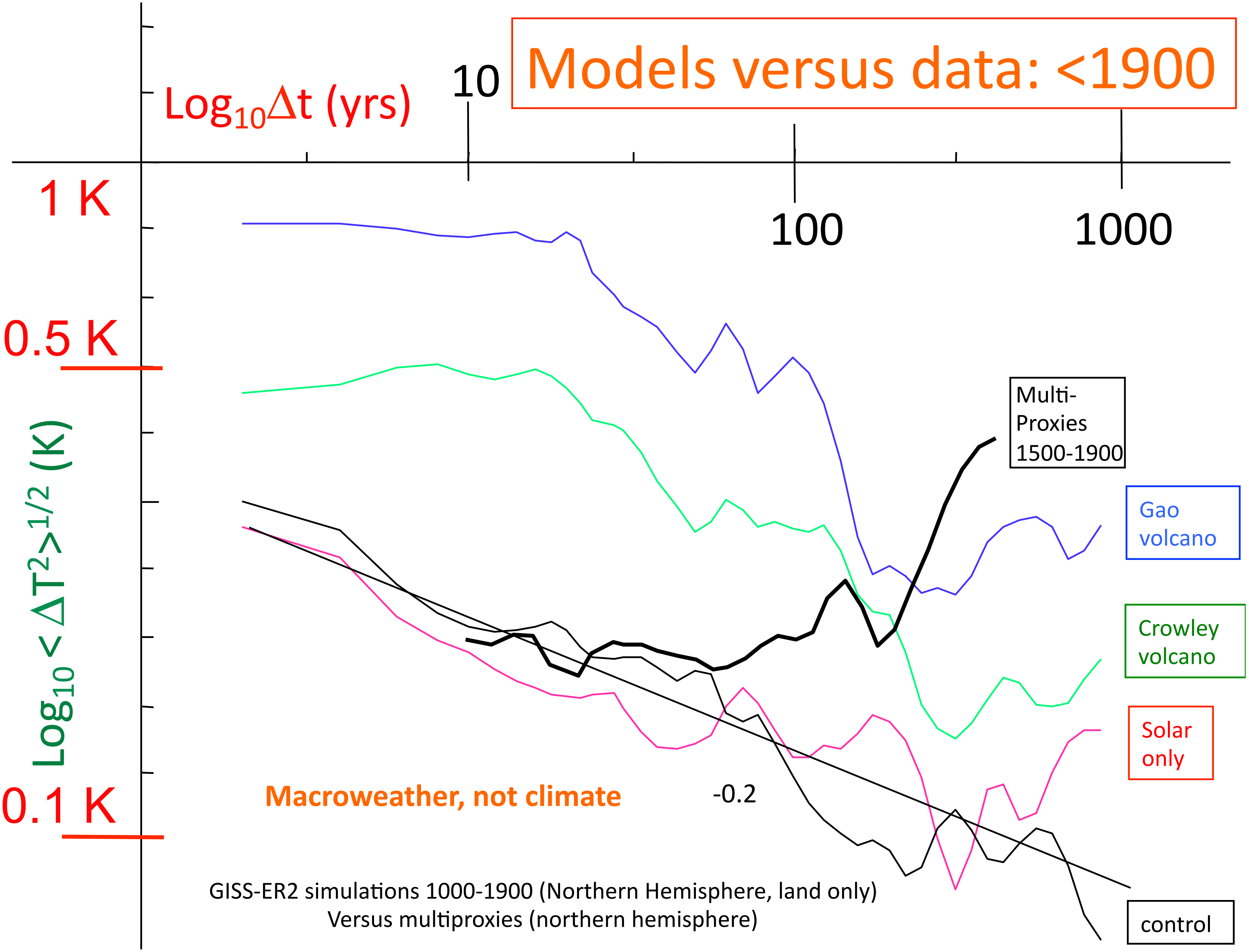
Dashed: 1900-2005
Solid: 1500-1900 (volcanic)
Solid: 1610-1900 (solar)

How well do the GCM’s do?

Performance quantified by scaling fluctuation analysis


Industrial epoch GCM performance
GISS E2-R
North, land
1880-2005
4 months
Log$_{10}$Δt (yrs)
1000
100
10
1 K
0.5 K
0.2 K
0.1 K
Log$_{10}$<ΔT^2>$^{1/2}$ (K)
CRU:
North, land
1880-2008
CRU North
1880-2008
Gao Volcanic
Crowley Volcanic
Solar
Multi-Proxies
North
1500-1900
macroweather (preindustrial)
Climate preindustrial)
macroweather (industrial)
Climate (industrial)

Models versus data: <1900

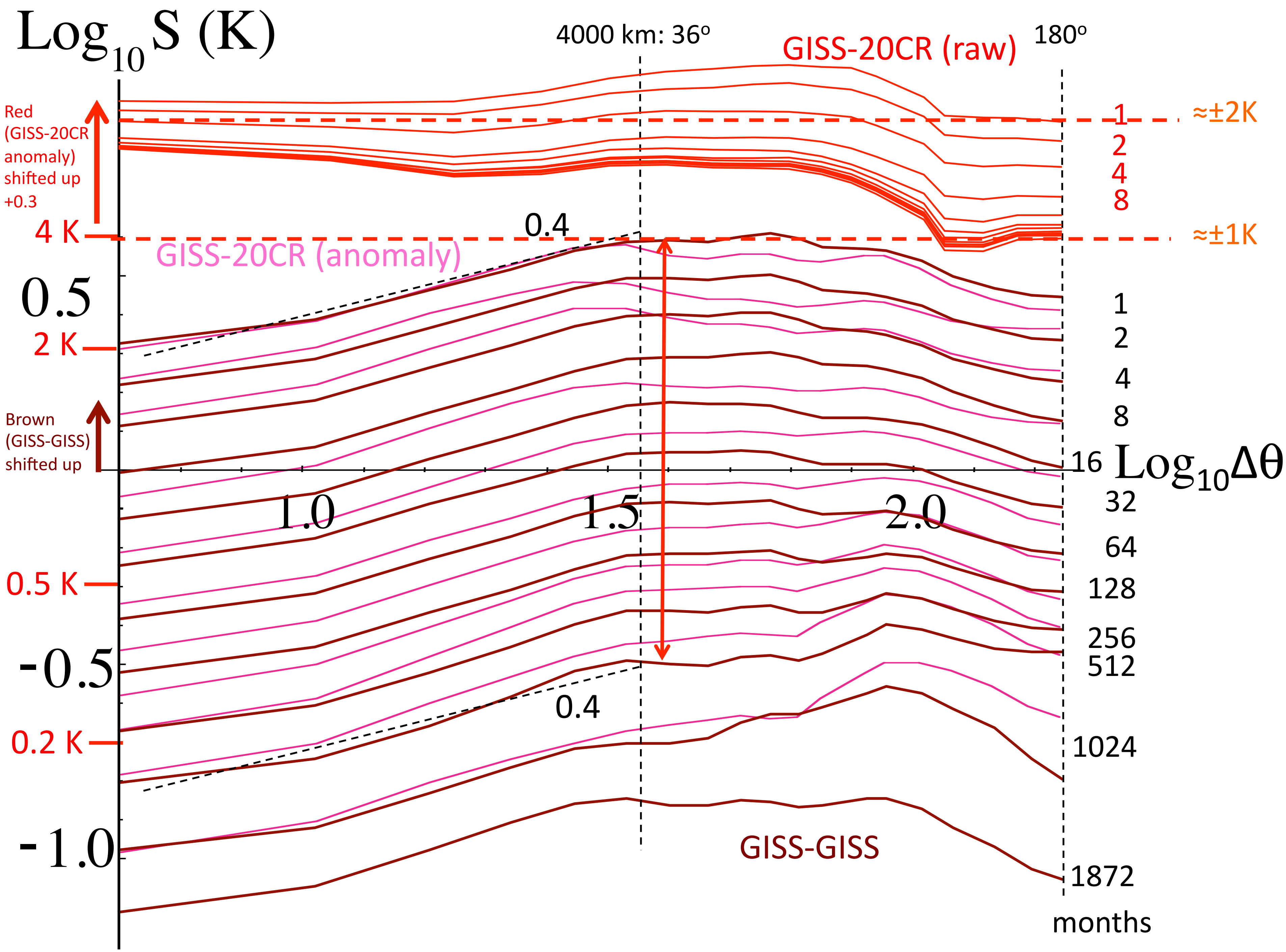


Macroweather, not climate

GISS-ER2 simulations 1000-1900 (Northern Hemisphere, land only)
Versus multiproxies (northern hemisphere)

Converge of GCM’s:

Their climate v.s. our climate


Log$_{10}$S (K)
4000 km: 36°
GISS-20CR (raw)
180°
Red (GISS-20CR anomaly) shifted up +0.3
4 K
≈±2K
≈±1K
1
2
4
8
0.4
GISS-20CR (anomaly)
0.5
2 K
1
2
4
8
Brown (GISS-GISS) shifted up
16
Log$_{10}$Δθ
1.0
1.5
2.0
32
64
0.5 K
128
256
-0.5
512
0.4
0.2 K
1024
-1.0
GISS-GISS
1872
months

GCM-free quantification of
Anthropogenic effects
(including extremes)*

Premise: if anthropogenic warming is as strong as claimed, then why do we need huge numerical models to demonstrate it?

*Thanks to the Quebec Skeptical Society!

Two simple theoretical innovations

1. Deterministic Anthropogenic $T_{anth}(t)$

   Stochastic natural variability $T_{nat}(t)$ ←

   Statistically stationary

responses to both volcanic, solar and any other natural forcings ≠ pure "internal" variability

2. Use of CO_2 radiative forcing as a linear surrogate of all anthropogenic forcings (justified by economic activity).

Climate in the recent epoch:
Natural variability and anthropogenic change

$$\boxed{T_{globe}(t) = T_{anth}(t) + \Delta T_{natural}(t) + \varepsilon(t)}$$

Anthropogenic contribution **(deterministic)**

Small fluctuations due to natural variability **(stochastic)**
Includes responses to solar, volcanic and other natural forcings

Measurement error: ≈ ±0.03K

Anthropogenic concentration proportional to the CO_2 radiative forcing

$$T_{anth}(t) = \lambda_{CO2,eff} R_{F,CO2}$$

The climate sensitivity (K/(W/m²))

CO_2 radiative forcing (W/m²)

Standard relation for CO_2 radiative forcing

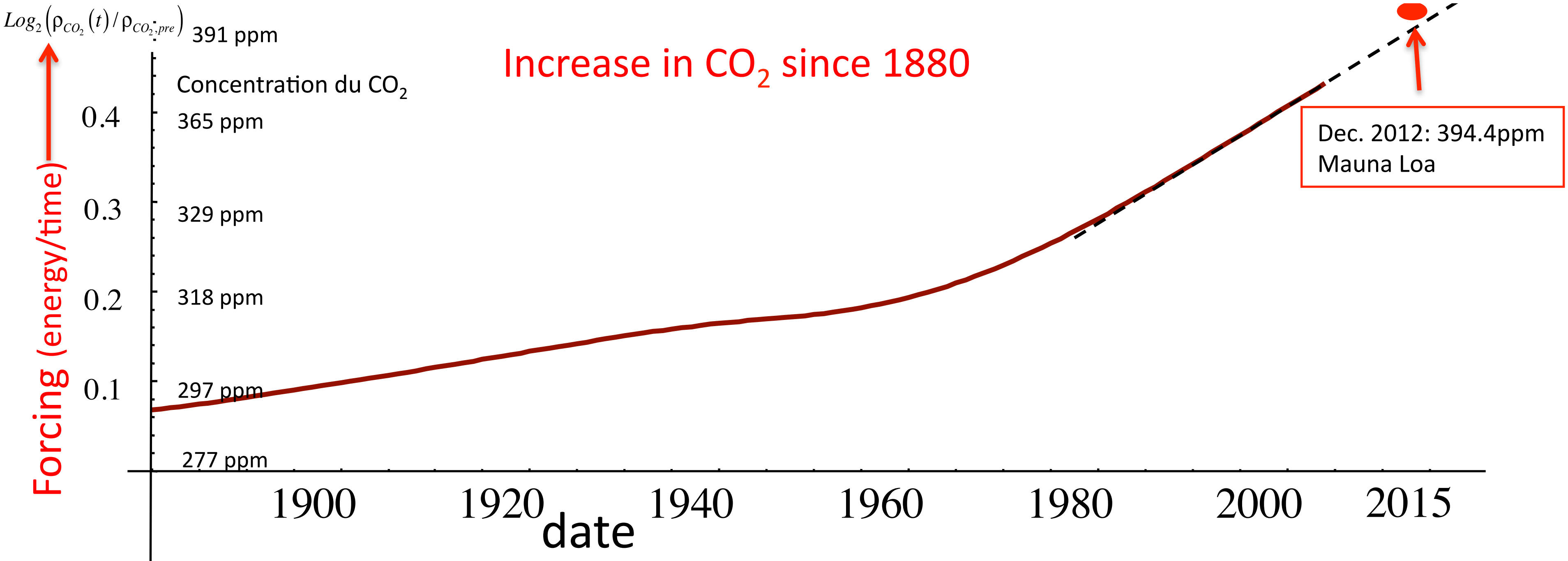
Radiative forcing of CO_2 doubling

$$R_{F,CO_2} = R_{F,2xCO_2} \log\left(\rho_{CO_2} / \rho_{CO_2,pre}\right); \quad R_{F,2xCO_2} = 3.7W/m^2; \quad \rho_{CO_2,pre} = 277\,ppm$$

CO_2 concentration

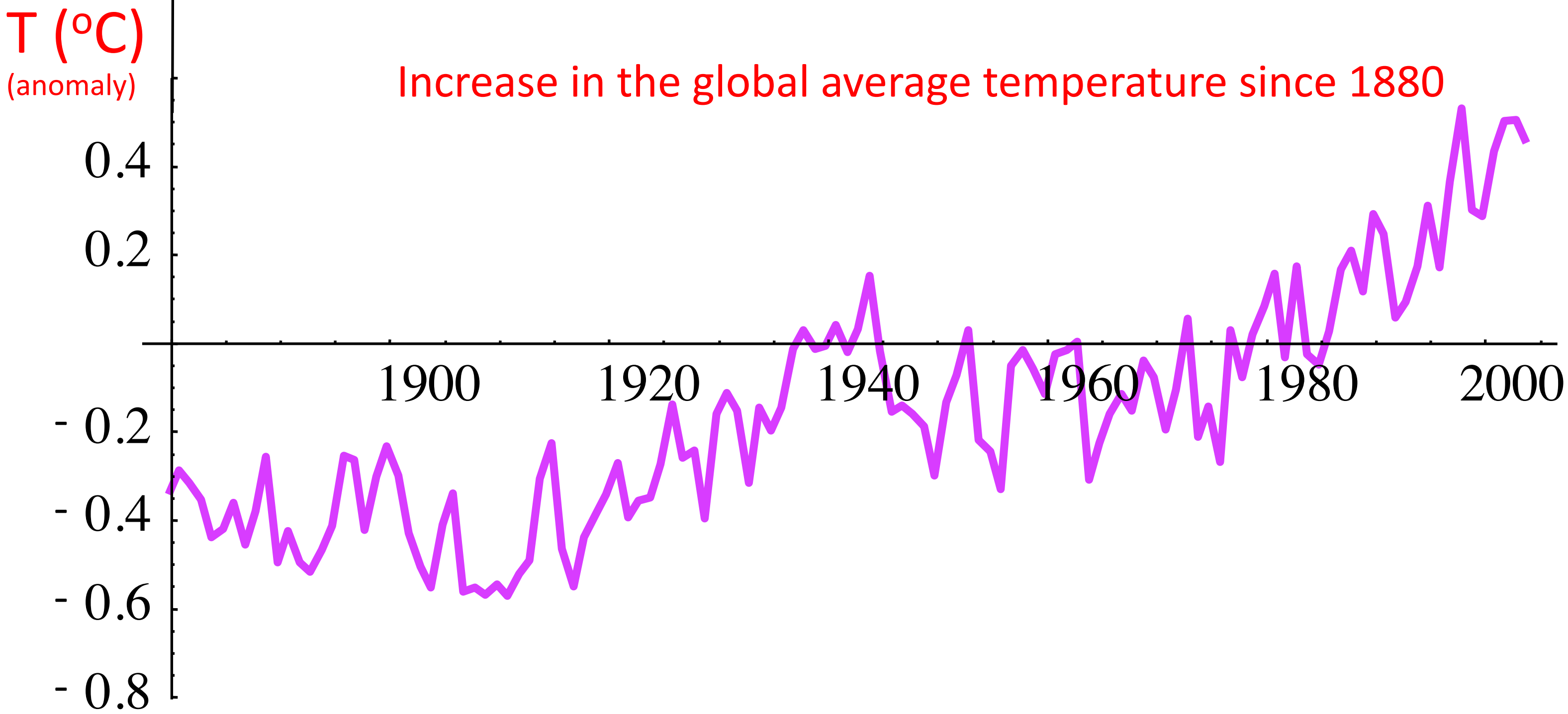
Pre-industrial concentration

Increase in CO_2 since 1880

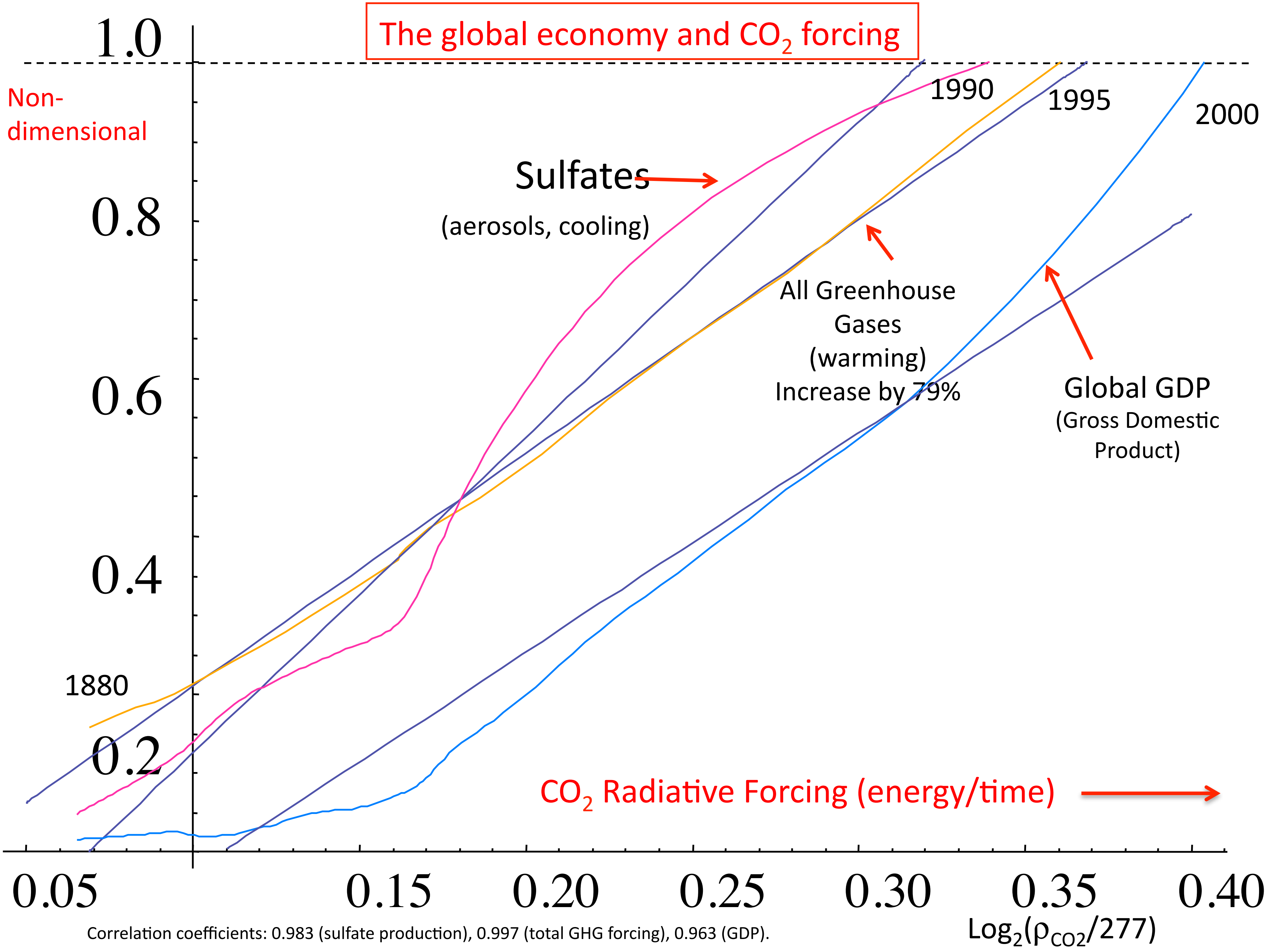


Dec. 2012: 394.4ppm
Mauna Loa

Increase in the global average temperature since 1880

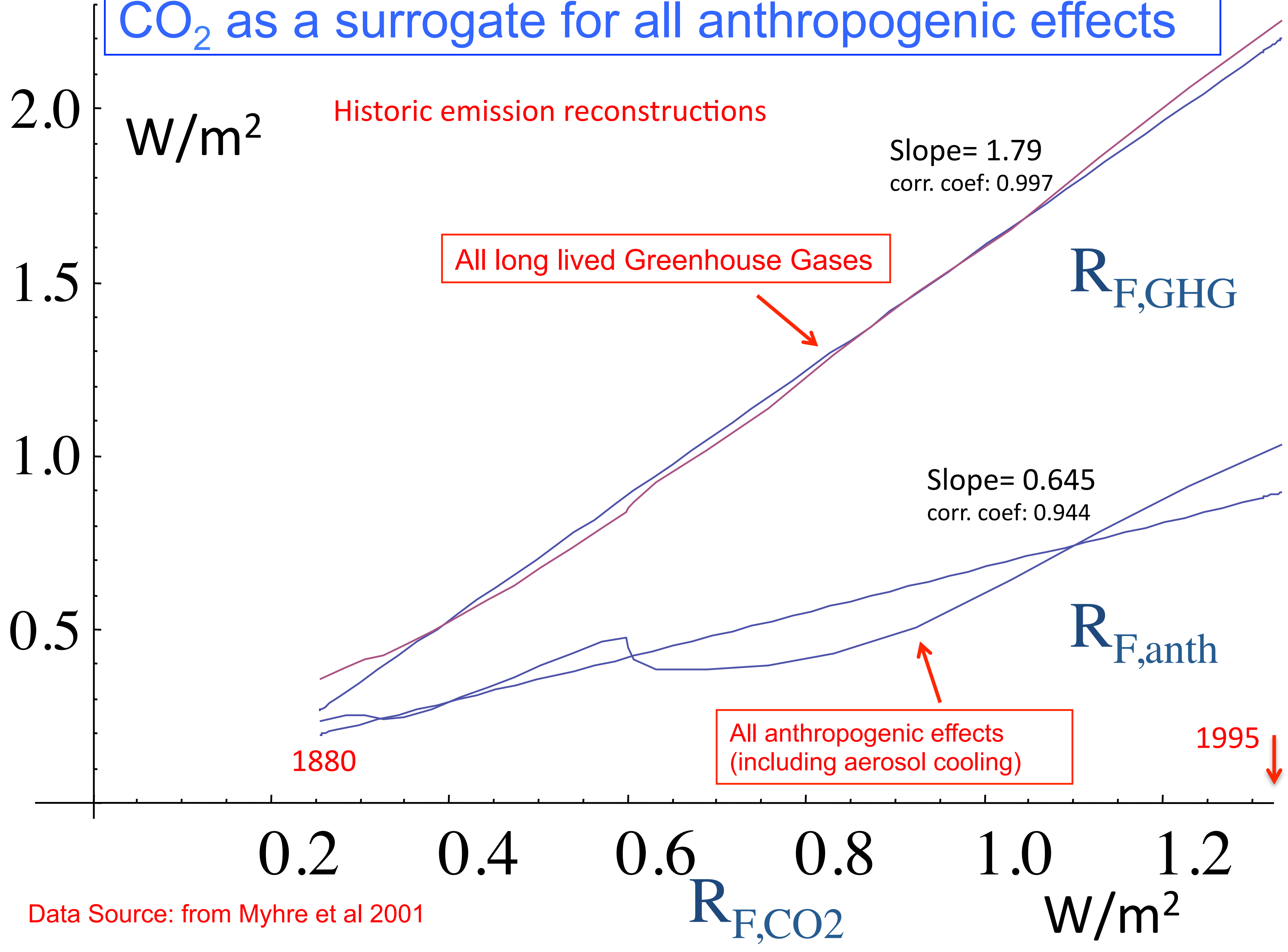


The global economy and CO_2 forcing



Correlation coefficients: 0.983 (sulfate production), 0.997 (total GHG forcing), 0.963 (GDP).

CO$_2$ as a surrogate for all anthropogenic effects



Data Source: from Myhre et al 2001

Natural variability as a perturbation to anthropogenic change

Effective climate sensitivity ($K/(W/m^2)$)

$$T_{globe}(t) = \lambda_{2xCO2,eff} \underbrace{\log_2\left(\rho_{CO_2}(t)/\rho_{CO_2,pre}\right)} + \Delta T_{natural}$$

Proportional to CO_2 radiative forcing (W/m^2)
Linear **Surrogate** for all anthropogenic forcings
(determinstic)

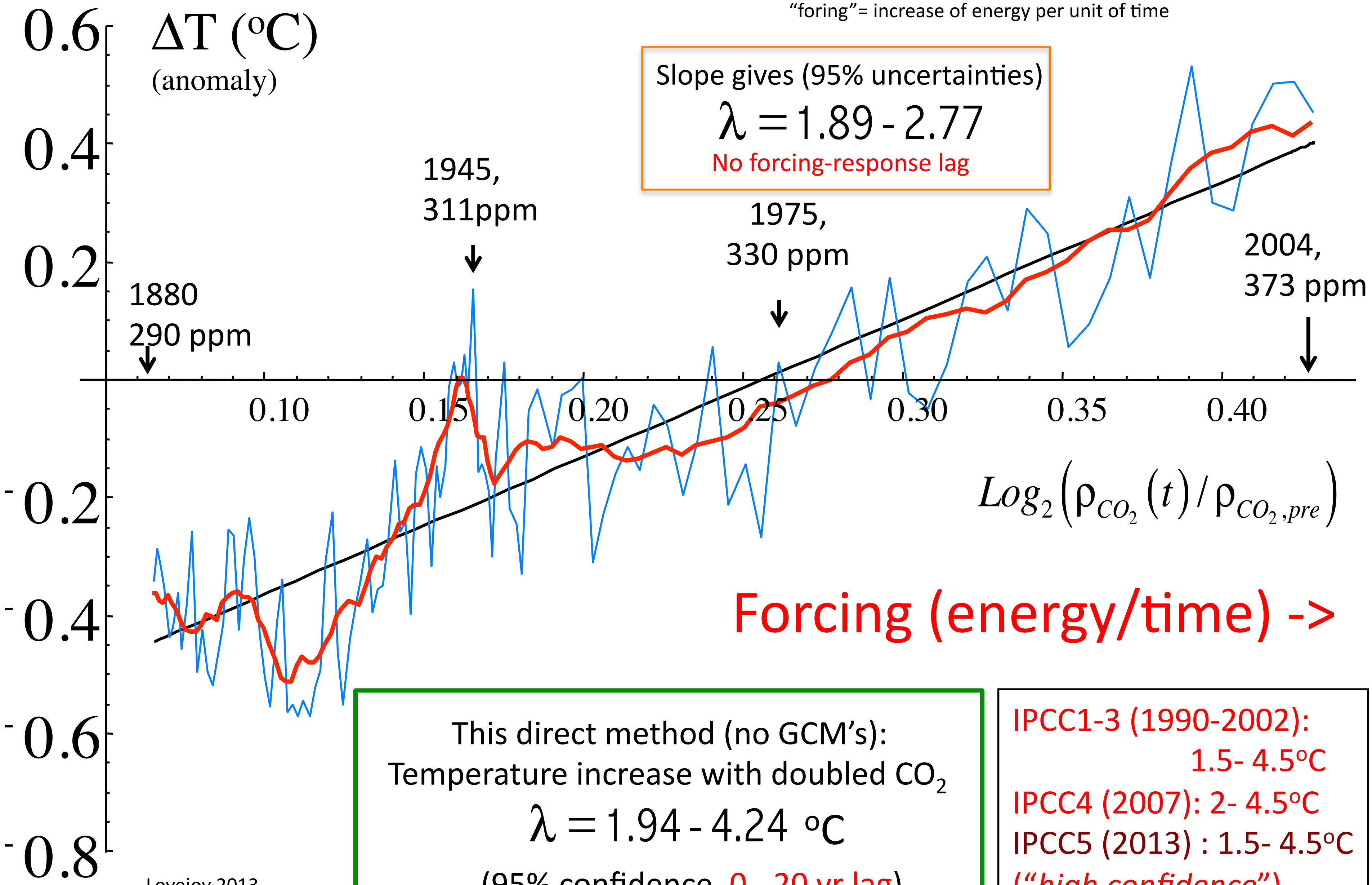
Small fluctuations due to natural variability (stochastic).
Includes responses to solar, volcanic and other natural forcings.

Justified if:

a) the anthropogenic effects do not effect the *type* of internal dynamic (variability),
b) nor their responses to (natural) external forcing

The Temperature is nearly linear with the CO_2 forcing

“foring”= increase of energy per unit of time



Slope gives (95% uncertainties)

$$\lambda = 1.89 - 2.77$$

No forcing-response lag

This direct method (no GCM’s):
Temperature increase with doubled CO_2

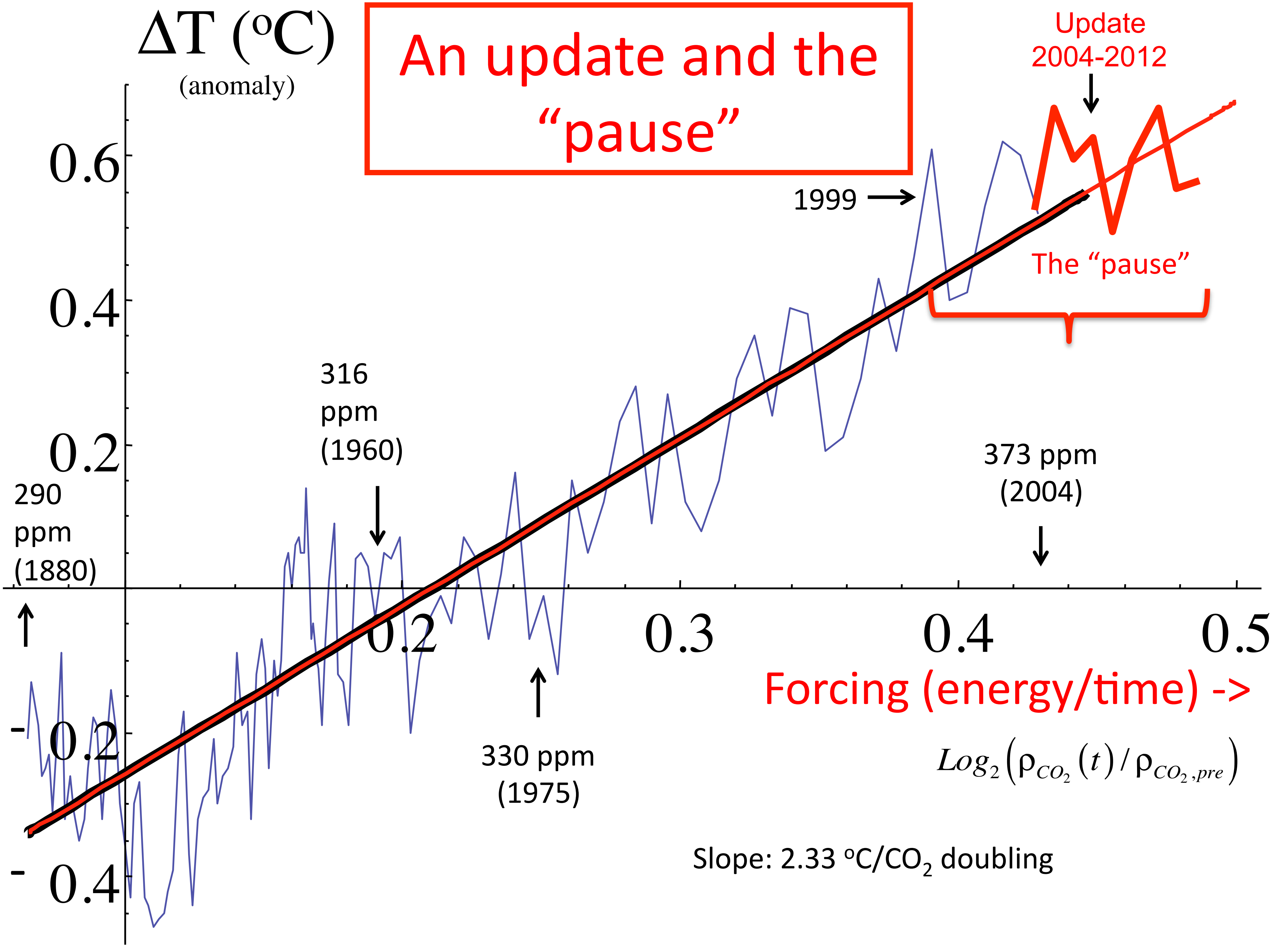
$$\lambda = 1.94 - 4.24 \ ^{o}C$$

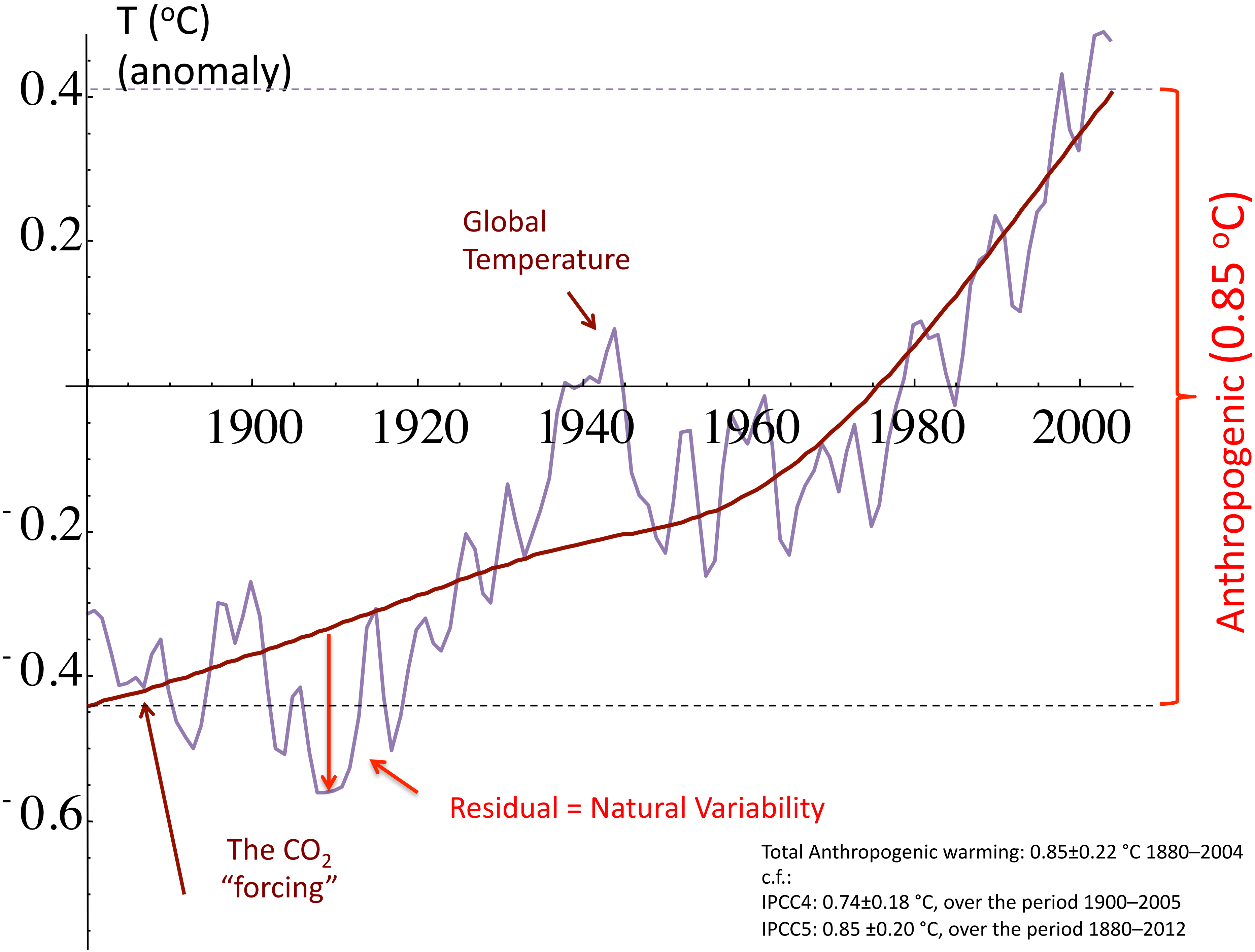
(95% confidence, 0 - 20 yr lag)

IPCC1-3 (1990-2002):
1.5- 4.5°C
IPCC4 (2007): 2- 4.5°C
IPCC5 (2013) : 1.5- 4.5°C
(“*high confidence*”)

Lovejoy 2013

An update and the "pause"





Global Temperature

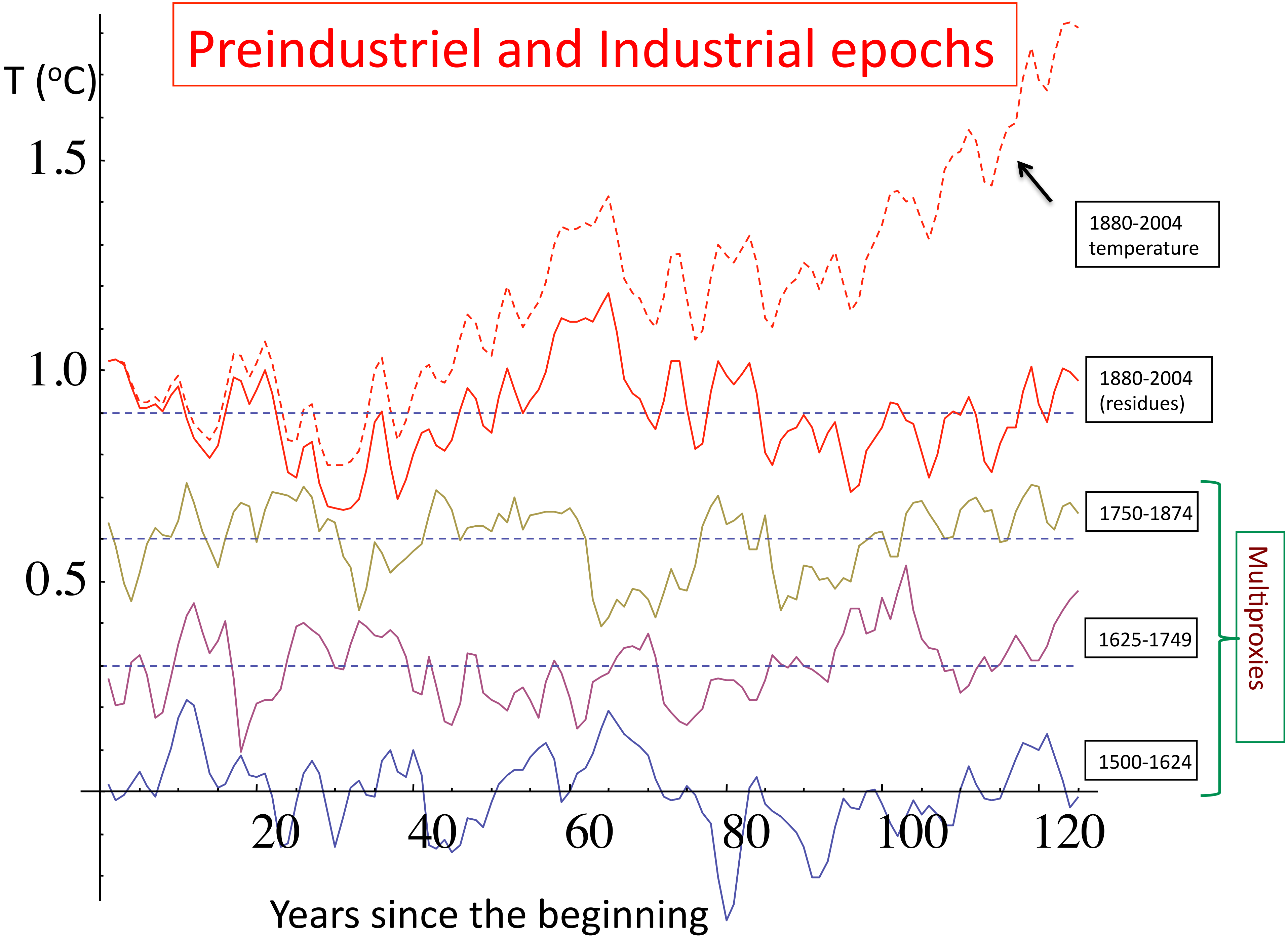
Anthropogenic (0.85 °C)

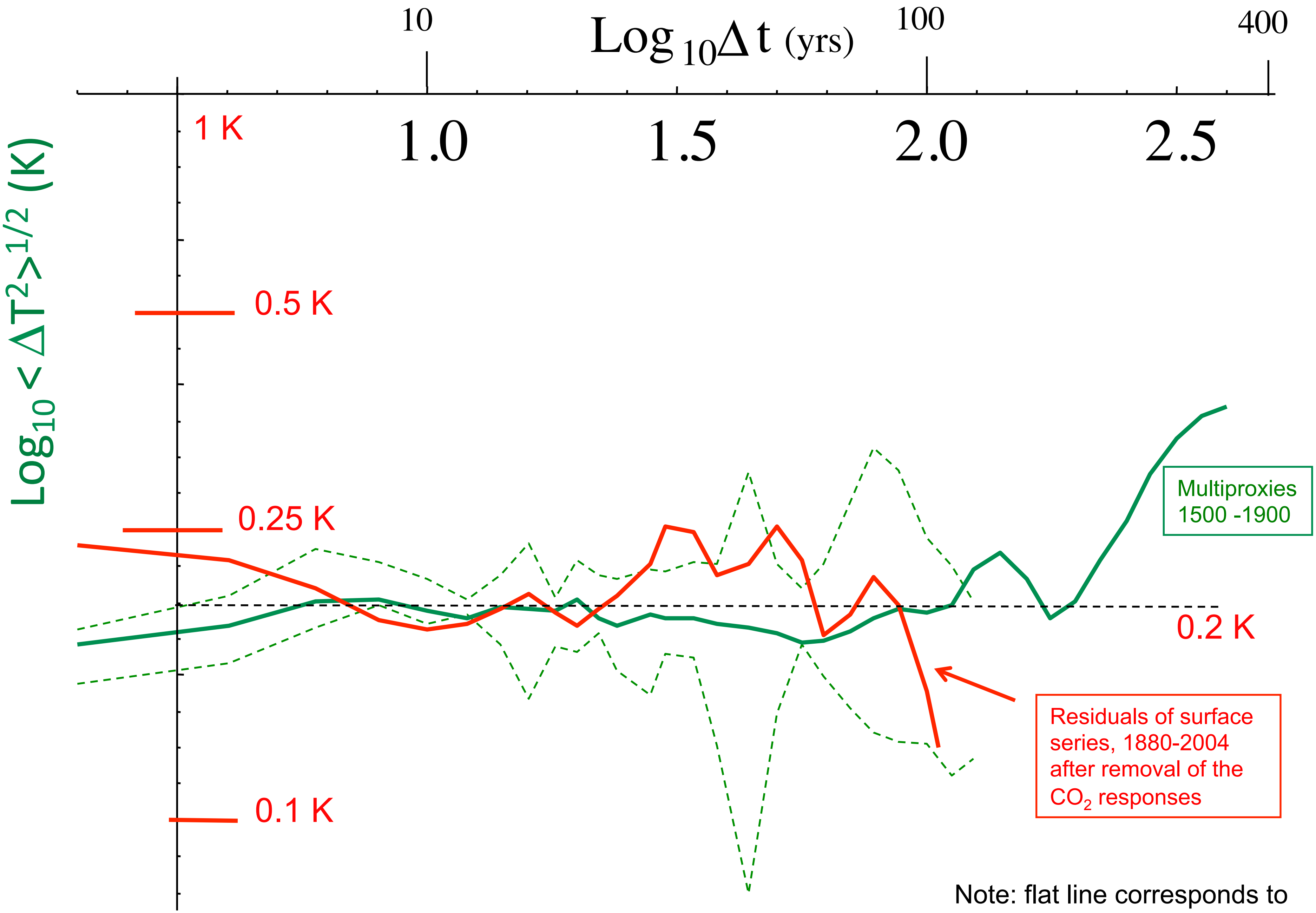
Residual = Natural Variability

The CO_2 "forcing"

Total Anthropogenic warming: 0.85±0.22 °C 1880–2004
c.f.:
IPCC4: 0.74±0.18 °C, over the period 1900–2005
IPCC5: 0.85 ±0.20 °C, over the period 1880–2012

Preindustriel and Industrial epochs





Multiproxies 1500 -1900

Residuals of surface series, 1880-2004 after removal of the CO_2 responses

Note: flat line corresponds to long range dependencies: $E(\omega) \approx \omega^{-1}$

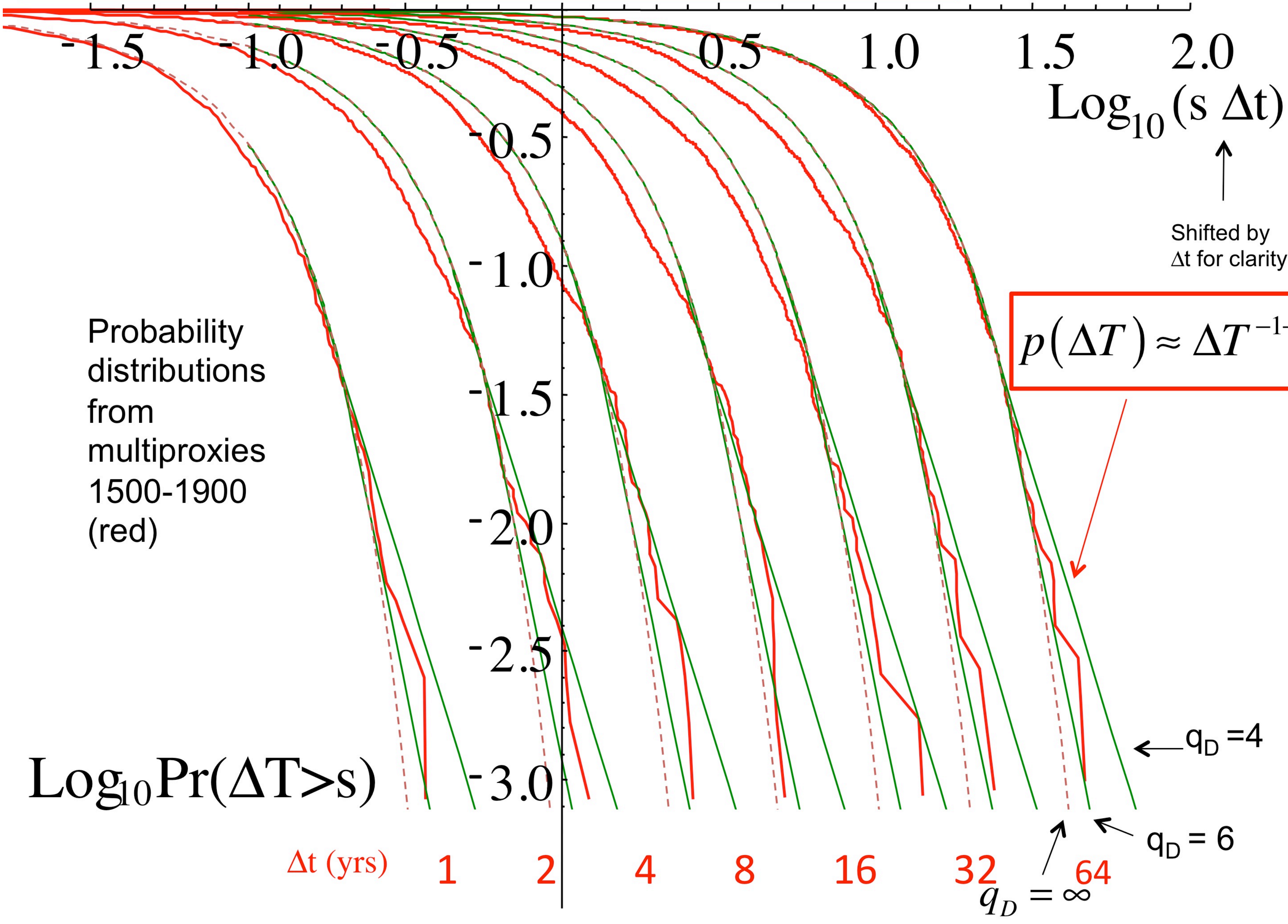
Statistical hypothesis testing

To be as rigorous and convincing as possible, we must demonstrate that the probability that the current warming is a natural fluctuation is low enough so that the natural variability hypothesis may be rejected with high levels of confidence.

GCM's can't provide reliable centennial scale probabilities, *we need multiproxies*.

Bracketing the temperature extremes with power laws

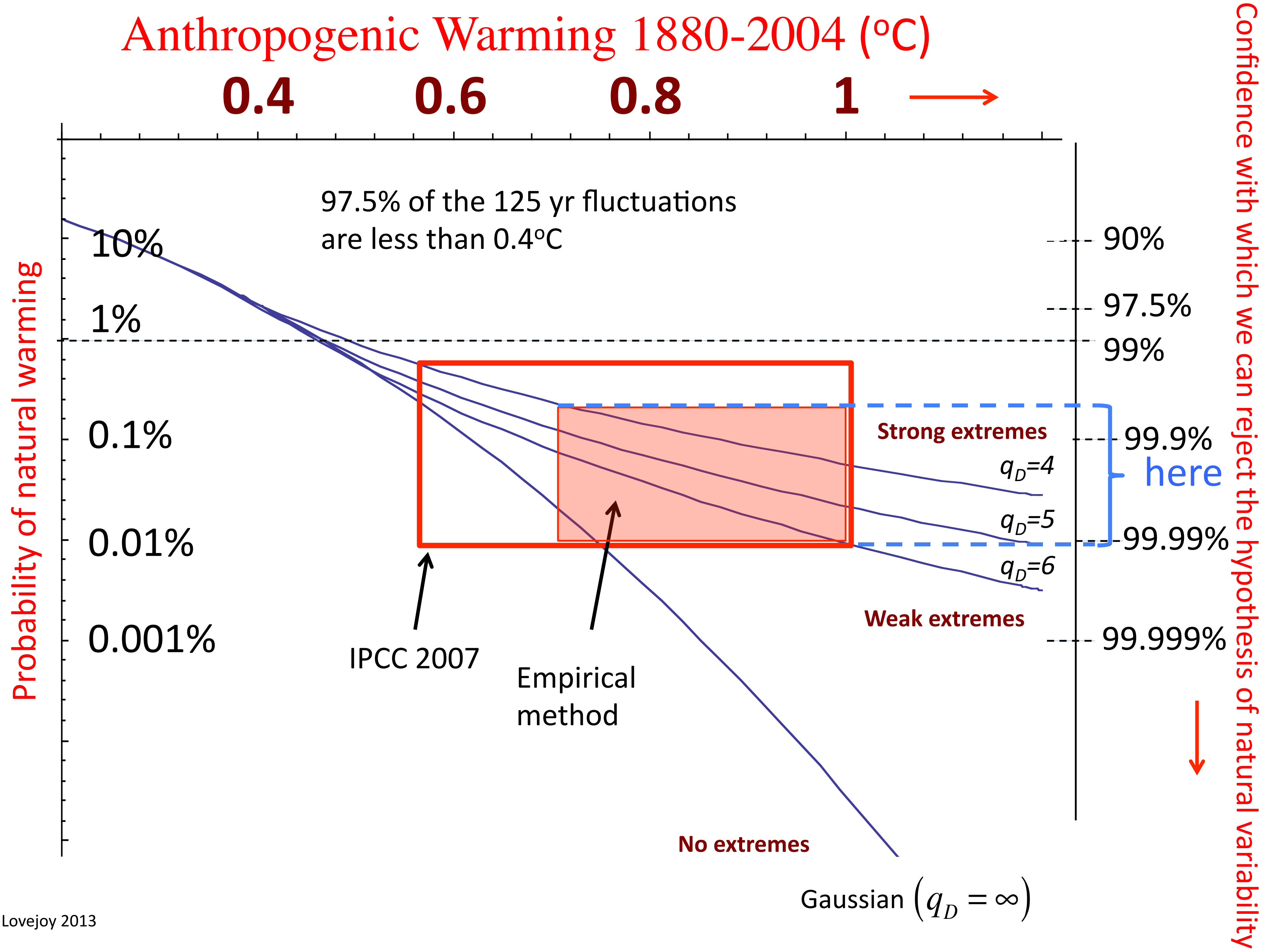
$$s^{-4} > \Pr\left(\Delta T > s\right) > s^{-6}$$



Shifted by Δt for clarity

$$p\left(\Delta T\right) \approx \Delta T^{-1-q_D}$$

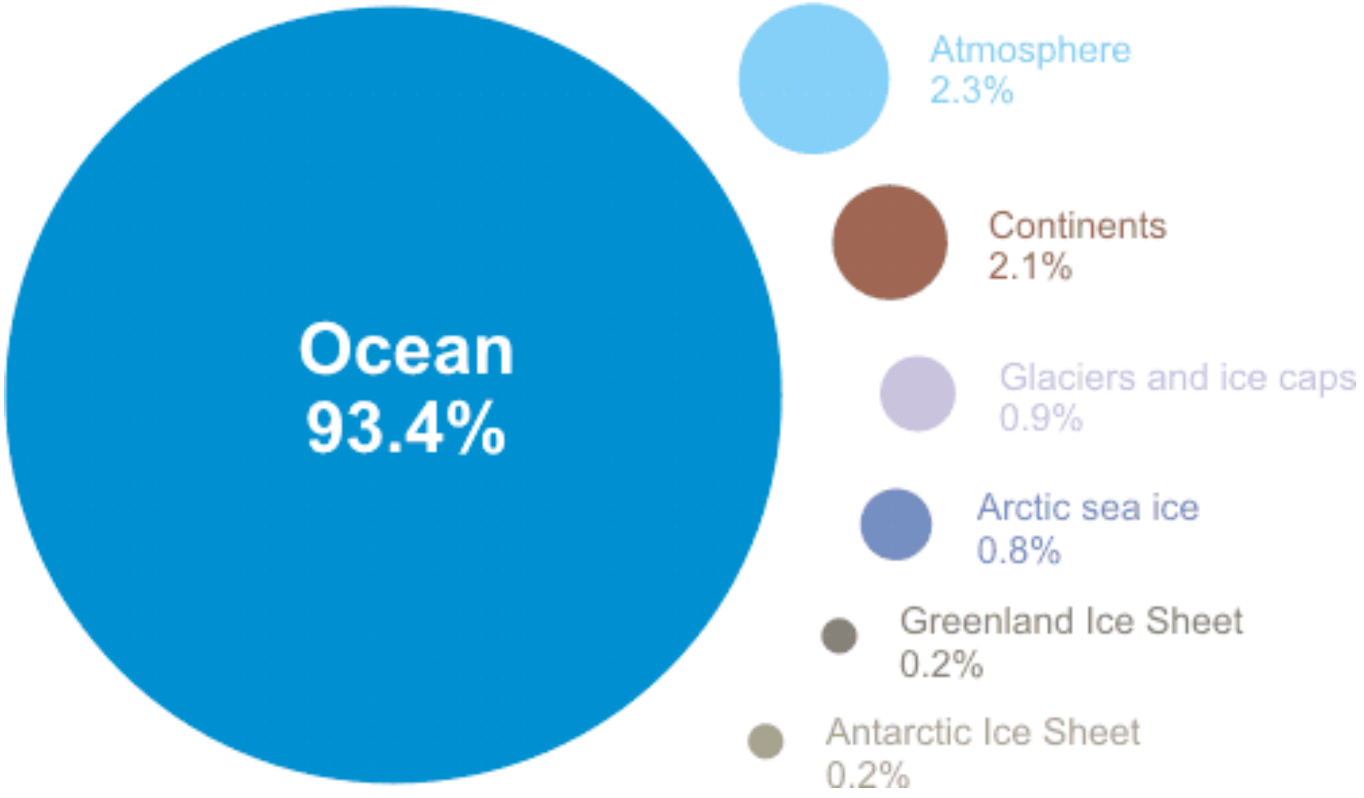
Probability distributions from multiproxies 1500-1900 (red)



Lovejoy 2013

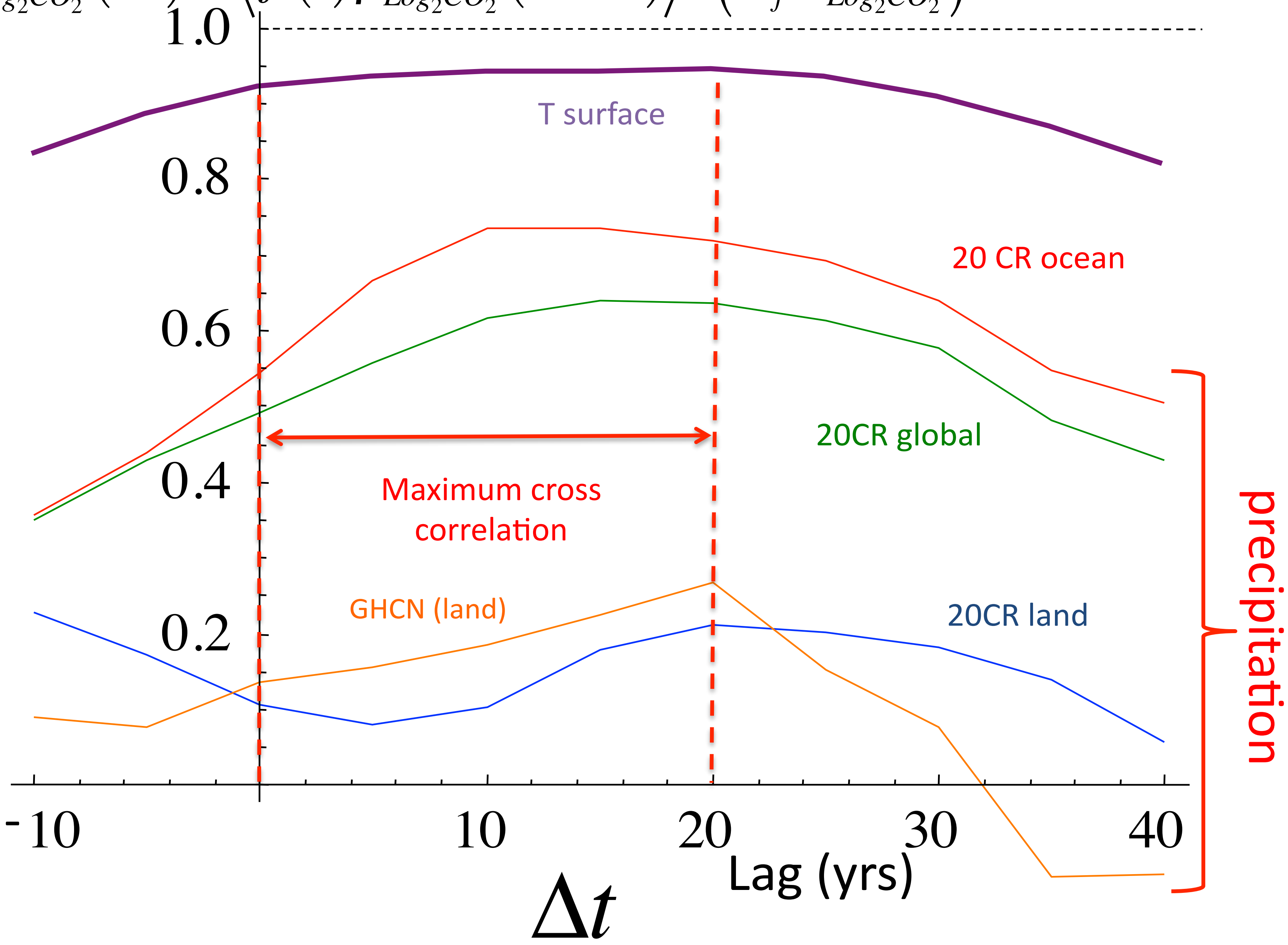
Ocean-Atmosphere Lag

Most of the direct heating goes to the ocean:

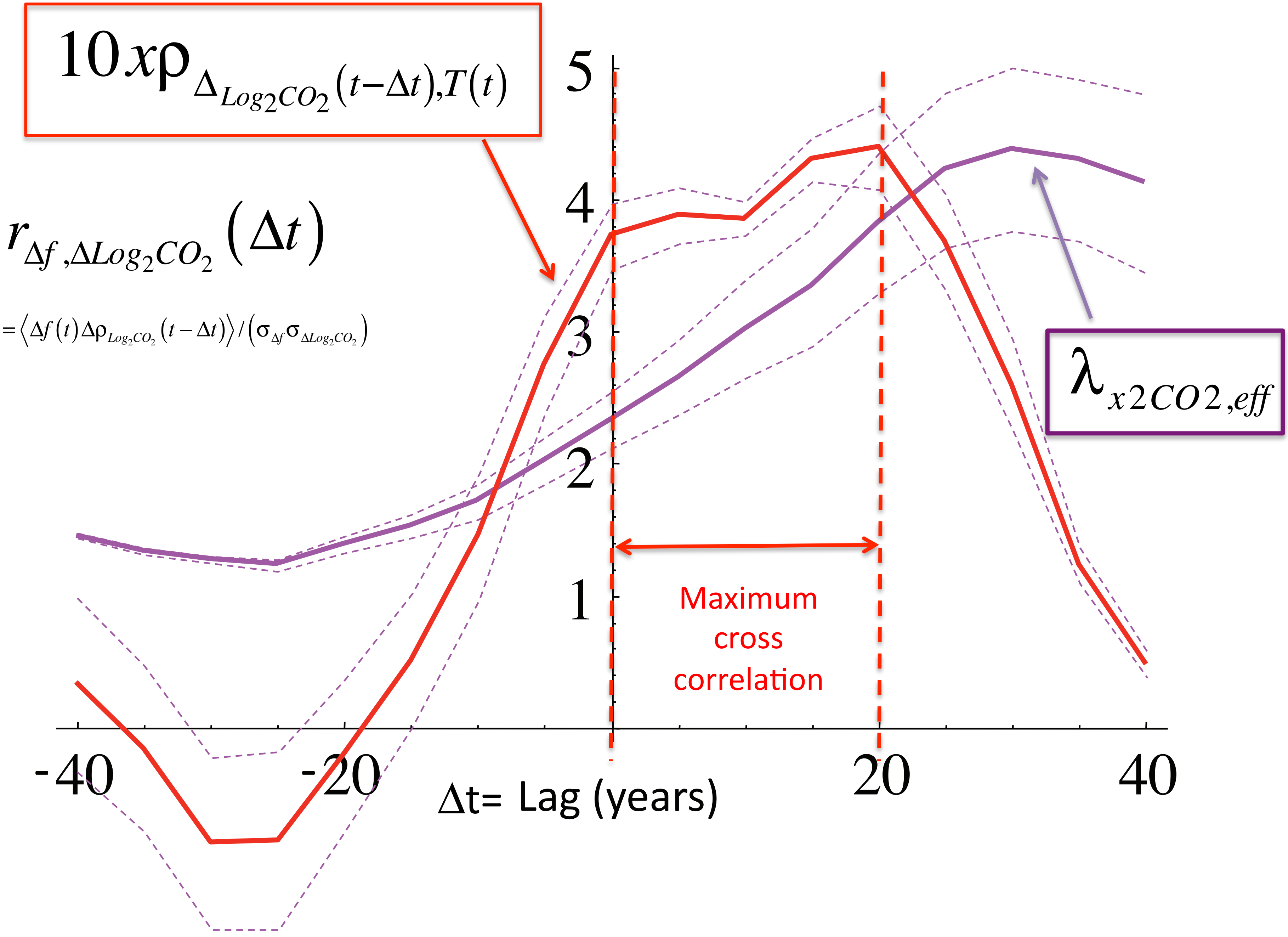


$$r_{f,Log_2CO_2}(\Delta t) = \left\langle f(t)\rho_{Log_2CO_2}(t-\Delta t)\right\rangle / \left(\sigma_f \sigma_{Log_2CO_2}\right)$$

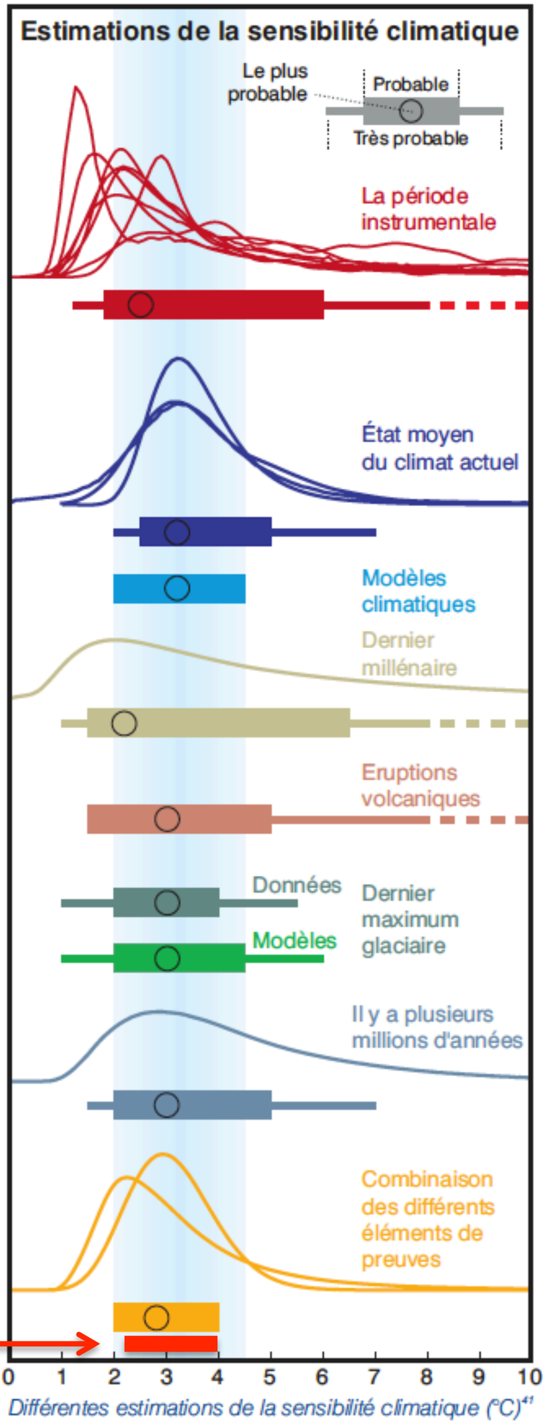
Crosscorrelations



Fluctuation crosscorrelations, effective climate sensitivities: 1880- 2004



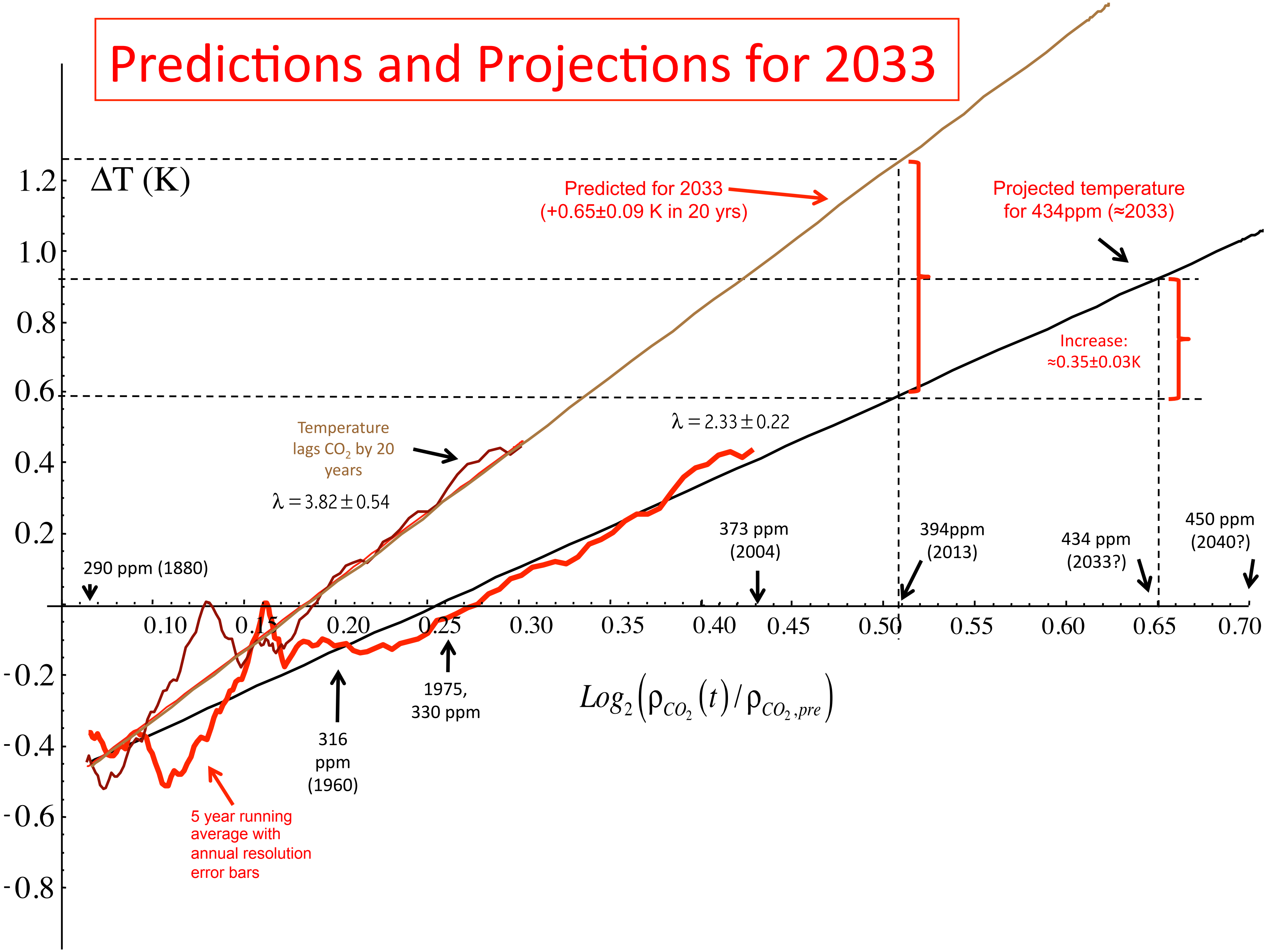
Various estimates of temperature increase with a doubling of CO_2



(Knutti et al 2008)

Our simple demonstration
3.08±0.58°C

Predictions and Projections for 2033



Predicted for 2033 (+0.65±0.09 K in 20 yrs)

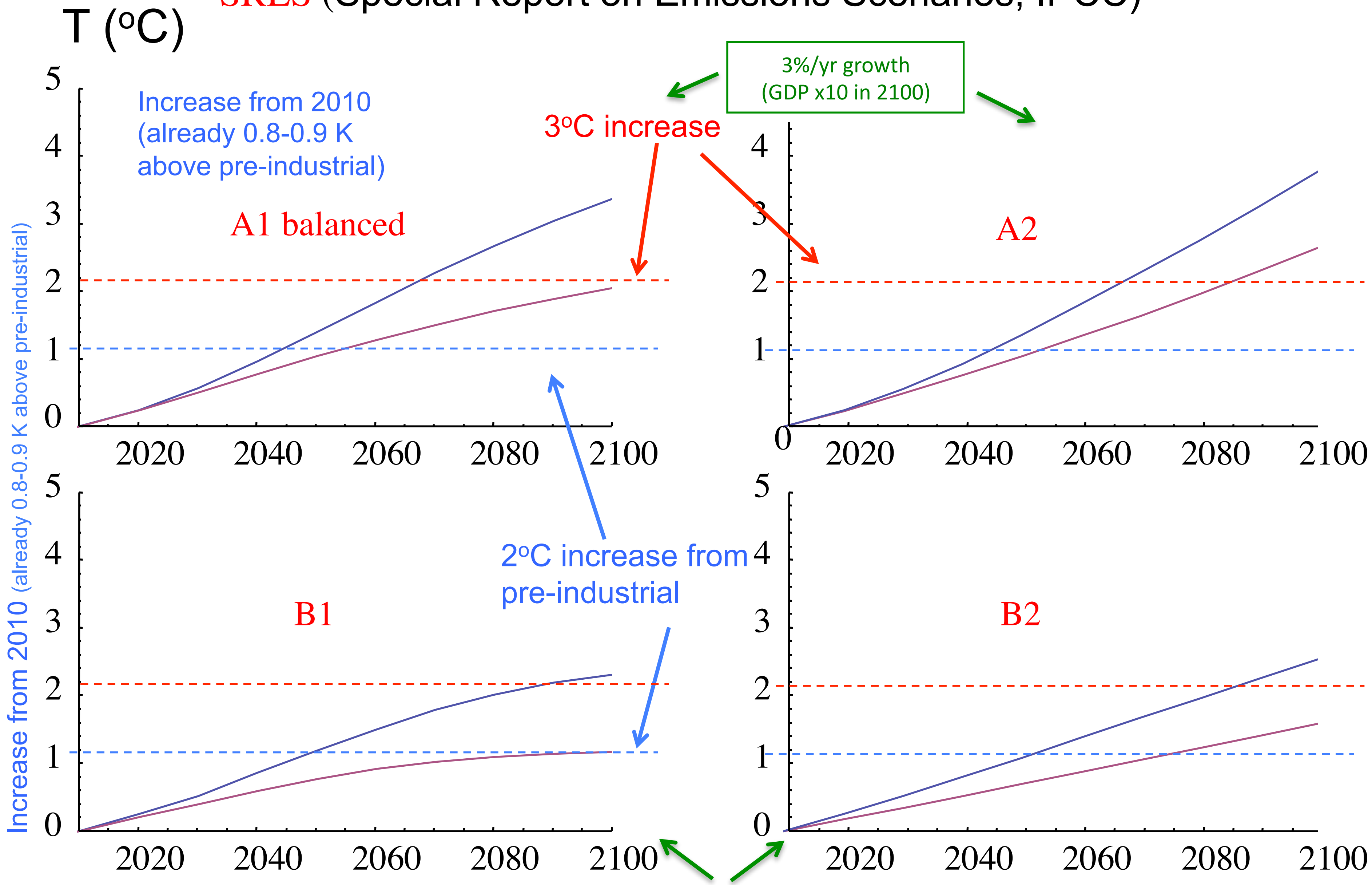
Projected temperature for 434ppm (≈2033)

Increase: ≈0.35±0.03K

Temperature lags CO_2 by 20 years

5 year running average with annual resolution error bars

SRES (Special Report on Emissions Scenarios, IPCC)



Increase from 2010 (already 0.8-0.9 K above pre-industrial)

3%/yr growth (GDP x10 in 2100)

3°C increase

2°C increase from pre-industrial

2%/yr growth (GDP x5 in 2100)

Blue is with, λ=3.82°C/ CO_2 doubling (extreme high)

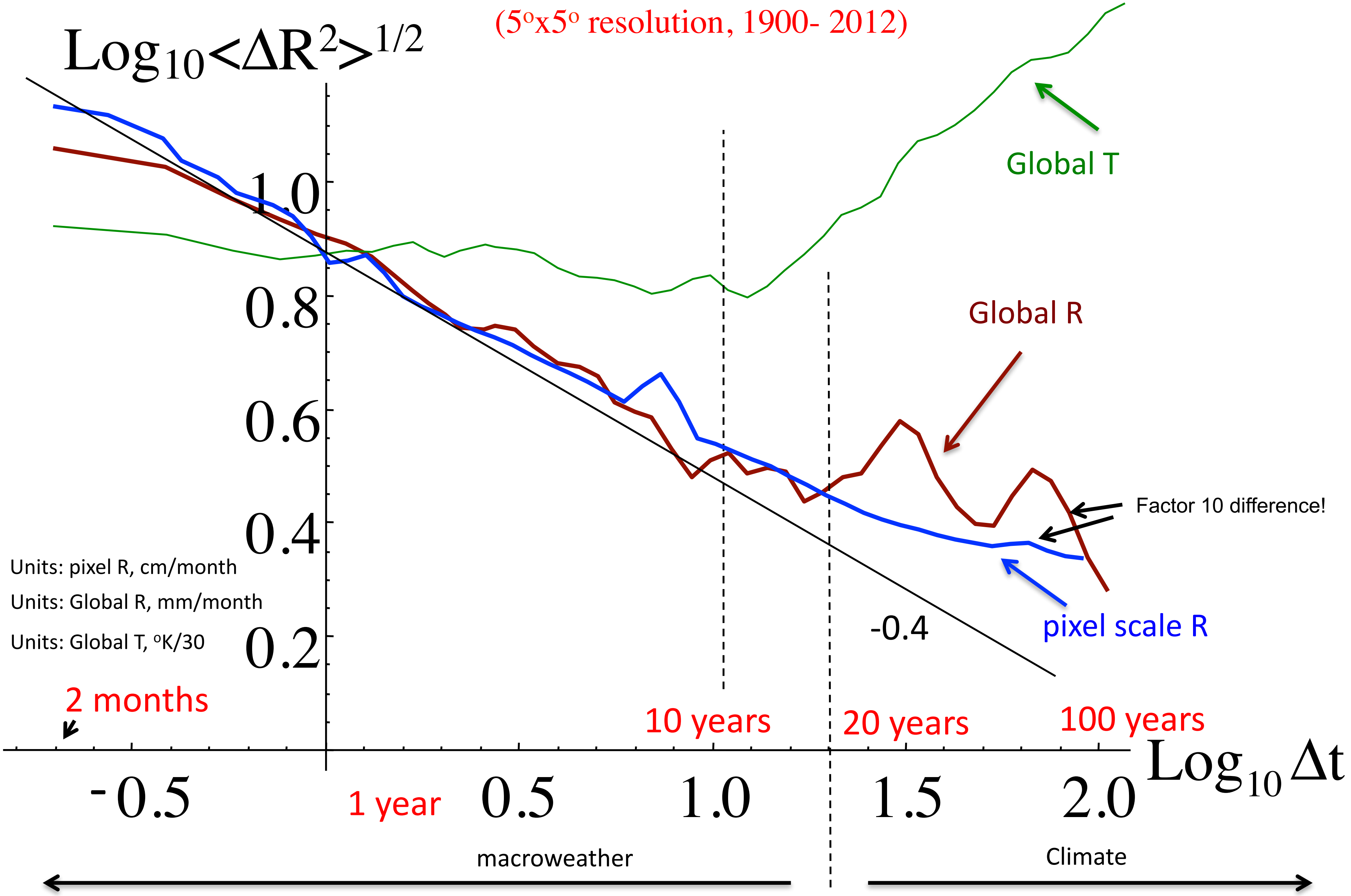
Red withλ=2.33°C/ CO_2 doubling (extreme low)

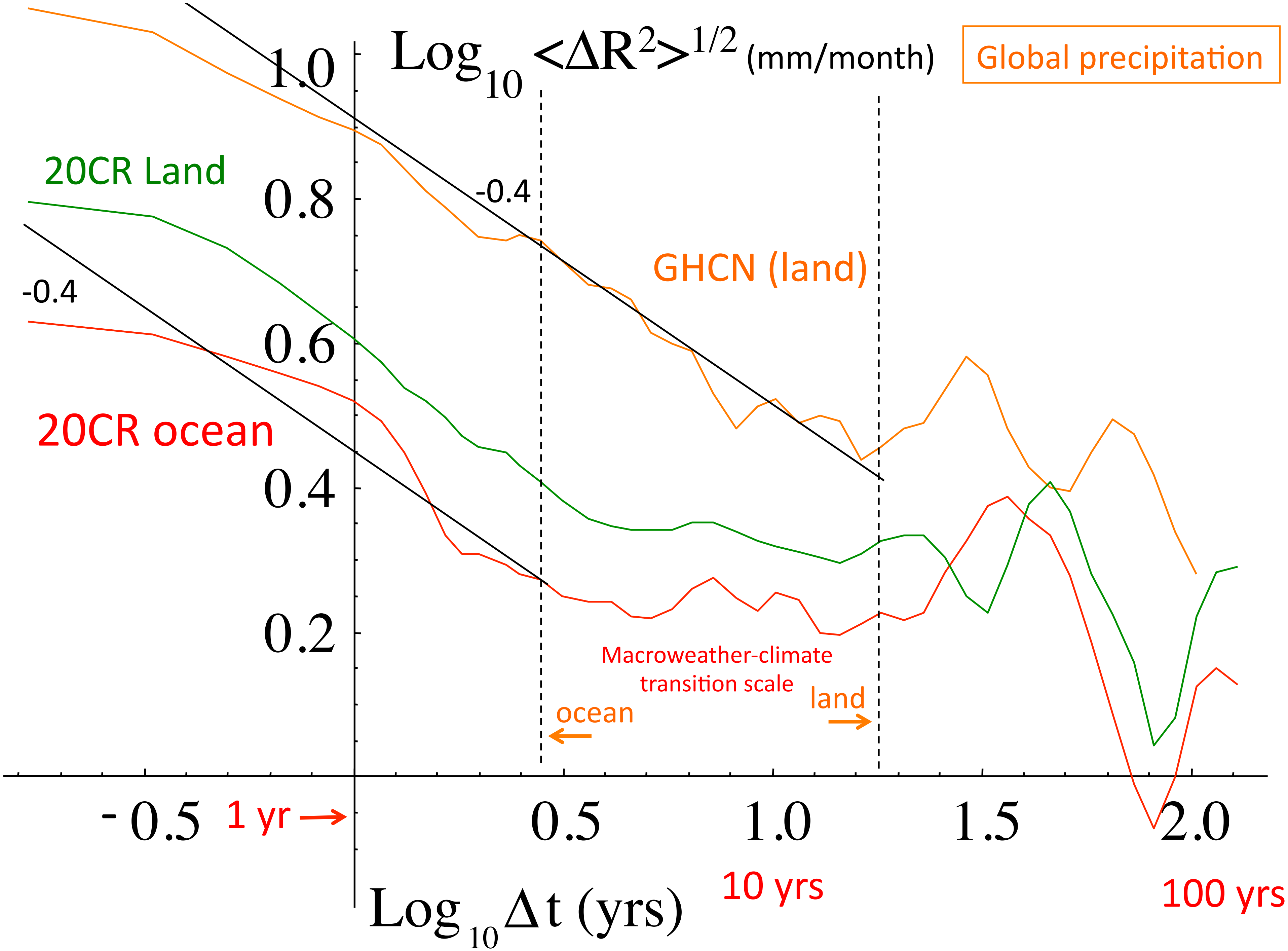
GCM-free analysis of Anthropogenic impacts on Precipitation

Precipitation and temperature:

GHCN=Global Historical Climate Network

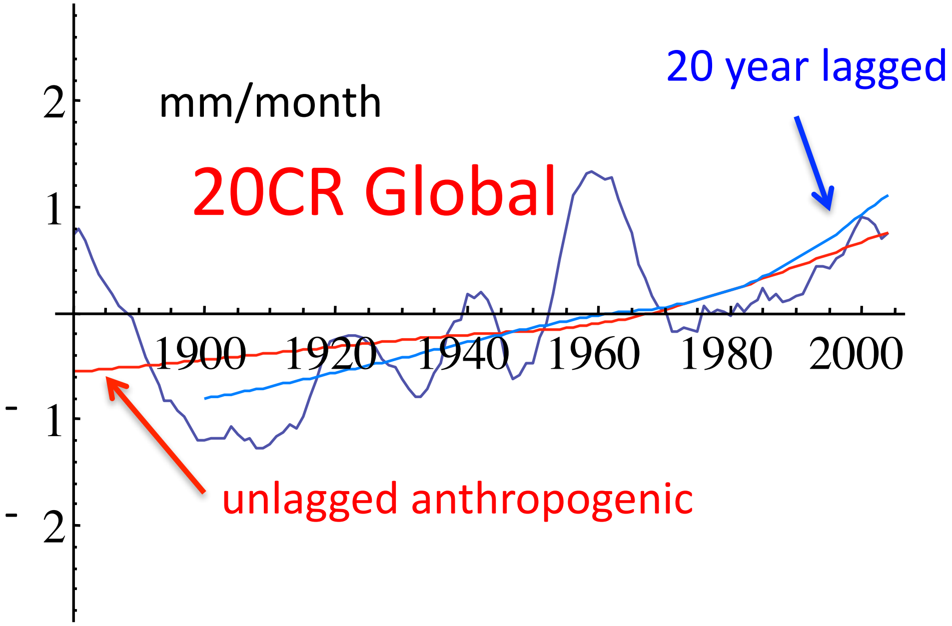
(5°x5° resolution, 1900- 2012)



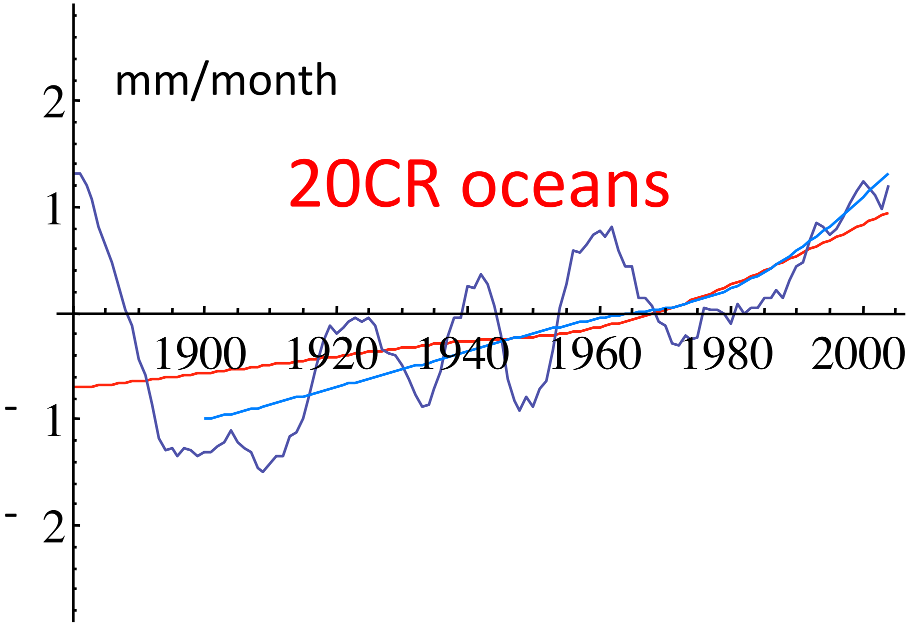


Global precipitation
Log$_{10}$ $<\Delta R^2>^{1/2}$ (mm/month)
1.0
0.8
0.6
0.4
0.2
20CR Land
20CR ocean
GHCN (land)
-0.4
-0.4
Macroweather-climate transition scale
ocean
land
- 0.5
1 yr
0.5
1.0
1.5
2.0
10 yrs
100 yrs
Log$_{10}$Δt (yrs)

Quantifying Anthropogenic changes in precipitation

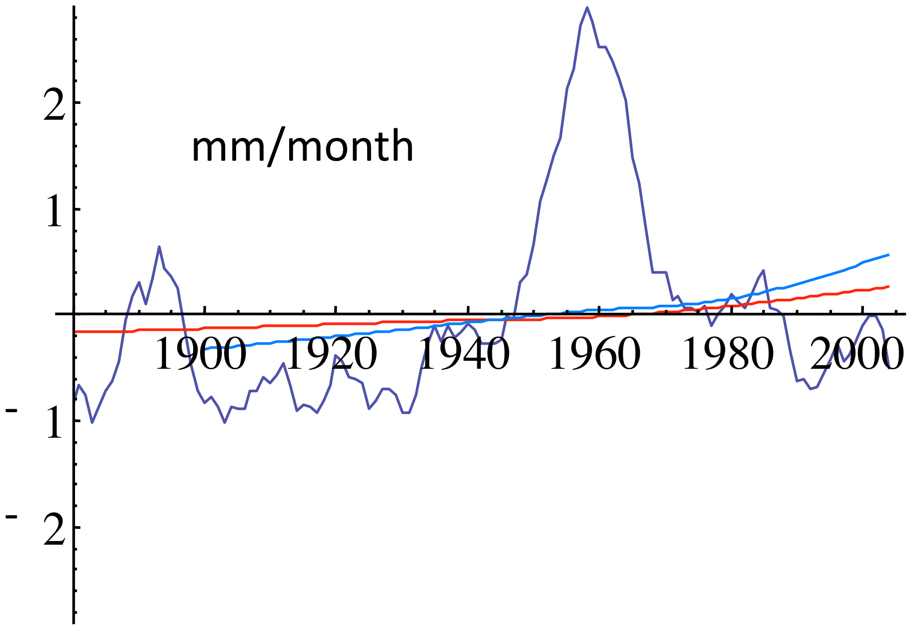


20CR Global

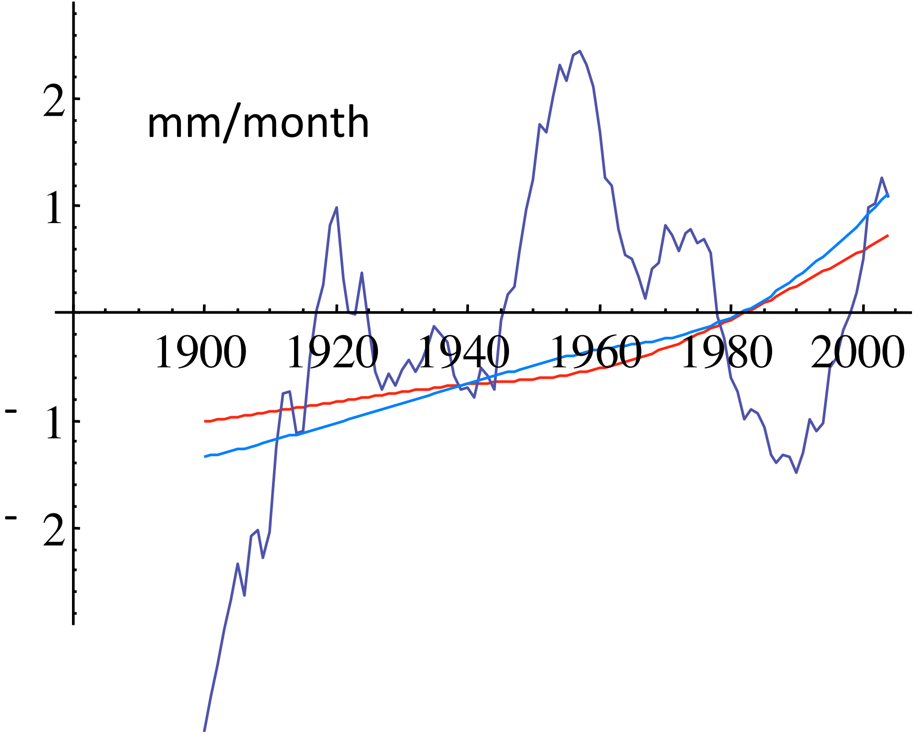


20CR oceans

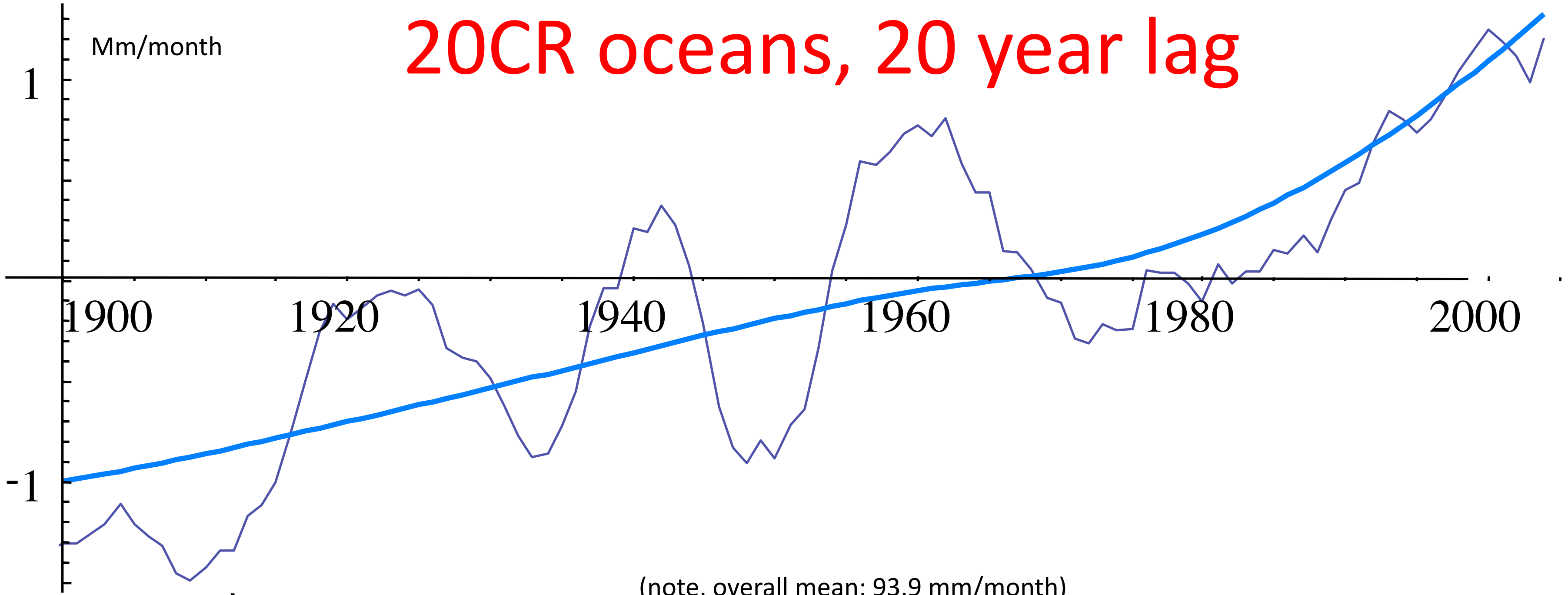
20CR land



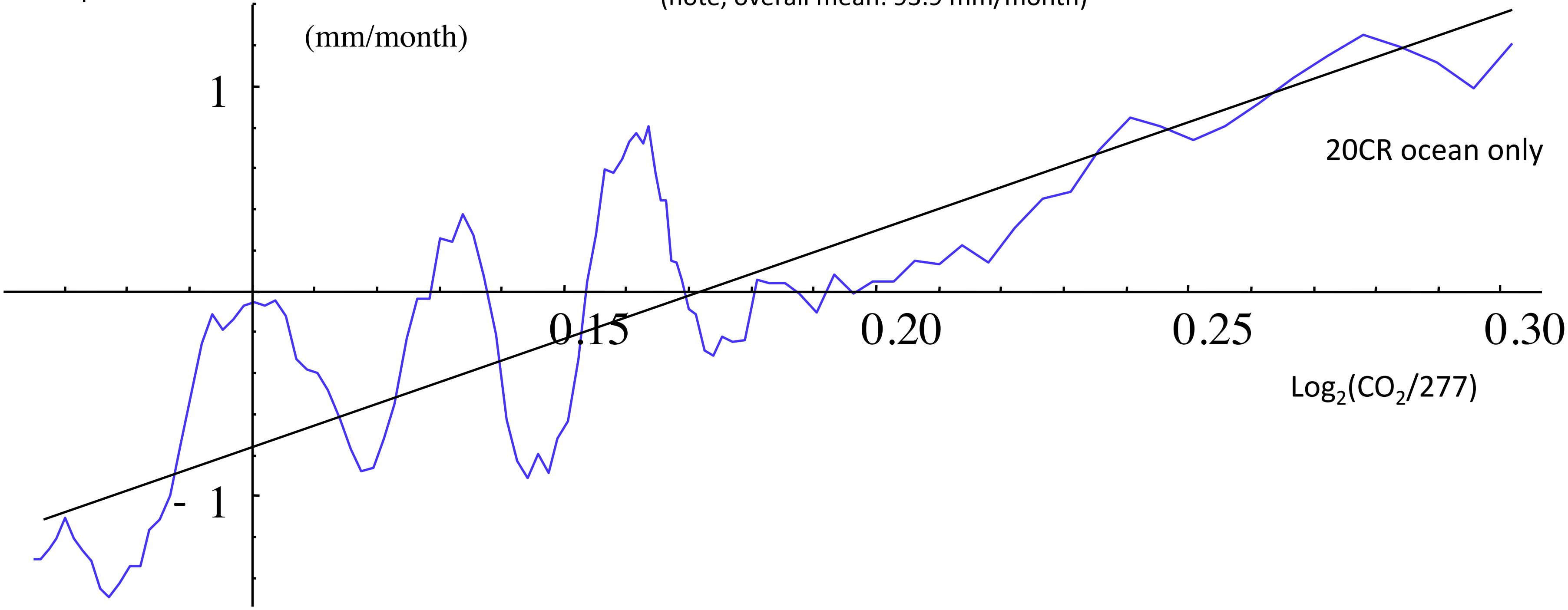
historical land



20CR oceans, 20 year lag



(note, overall mean: 93.9 mm/month)



Anthropogenic precipitation: increase rates for CO_2 doubling

	land	ocean	global
20CR, 0 lag	1.17±2.64	4.54±1.90	3.61±1.53
20CR, 20 yr lag	3.78±4.75	9.79±3.05	8.12±2.57
GHCN, 0 yr lag	5.18±3.64		
GHCN, 20 yr lag	10.37±5.43		

Red: increasing trend statistically significant at 95% level

All in mm/month, values for CO_2 doubling.

error bars are one standard deviation estimates.

20CR= Twentieth Century reanalysis, GHCN=Global Historical Climate Network.

Ocean mean: 93.9221 mm/month
Land mean: 84.5933 mm/month,
Global: 91.33 mm/month

Decadal increases in precipitation rate comparison IPCC4

	land	ocean	global
20CR, 0 lag	0.45±1.00	1.73±0.72	1.37±0.58
20CR, 20 yr lag	1.44±1.81	3.73±1.16	3.09±0.98
GHCN, 0 yr lag	1.97±1.39		
GHCN, 20 yr lag	3.94±2.07		
CRU (from, IPCC4)	1.10±1.50		
GHCN (from, IPCC4)	1.08±1.87		

IPCC4 (2007) {

Red: statistically significant at 95% level

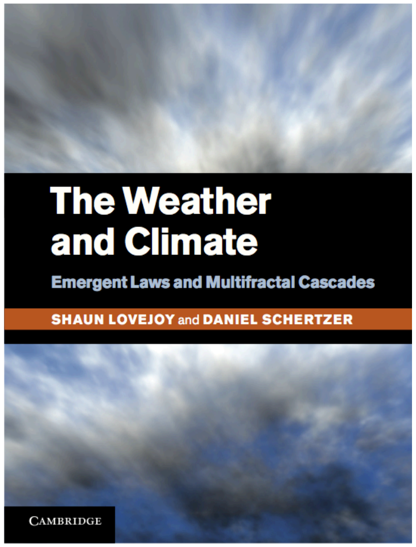
Blue: significant at 68% level

Green: not significant

Above are inferred anthropogenic increases in precip over the period 1900-2005 in mm/year/decade ($\log_2 CO_2/277$ increased by 0.333 over this period).

IPCC estimates are from decadal scale linear regressions (not w.r.t. CO_2 forcing). Since macroweather continues to about 30 years for precipitation, these are not statistically significant.

Conclusions


The Weather and Climate
Emergent Laws and Multifractal Cascades
SHAUN LOVEJOY and DANIEL SCHERTZER
CAMBRIDGE

1. Using scaling fluctuation analysis to characterizing the climate by its type of variability: expect macroweather not climate

2. The need for GCM-free approaches:
a) their climate not ours,
b) disarming climate skeptics
c) Using statistical hypothesis testing to rule out natural variability

3. Anthropogenic warming dominates macroweather at about 10 years rather than about 100 years (preindustrial).

4. The total anthropogenic warming is about 0.85°C, for CO_2 doubling, 3.08±0.58°C, GCM's: 1.5-4.5°C (1979-2013).

5. The probability that the warming since 1880 is natural is <1% (most likely <0.1%).

6. Precipitation is much "noisier" than temperature; anthropogenic effects detected mostly over ocean, not land, ≈ 30 year scale needed The total anthropogenic increase (oceans) is 9.79±3.05 mm/month for CO_2 doubling (>10% increase: highly statistically significant).