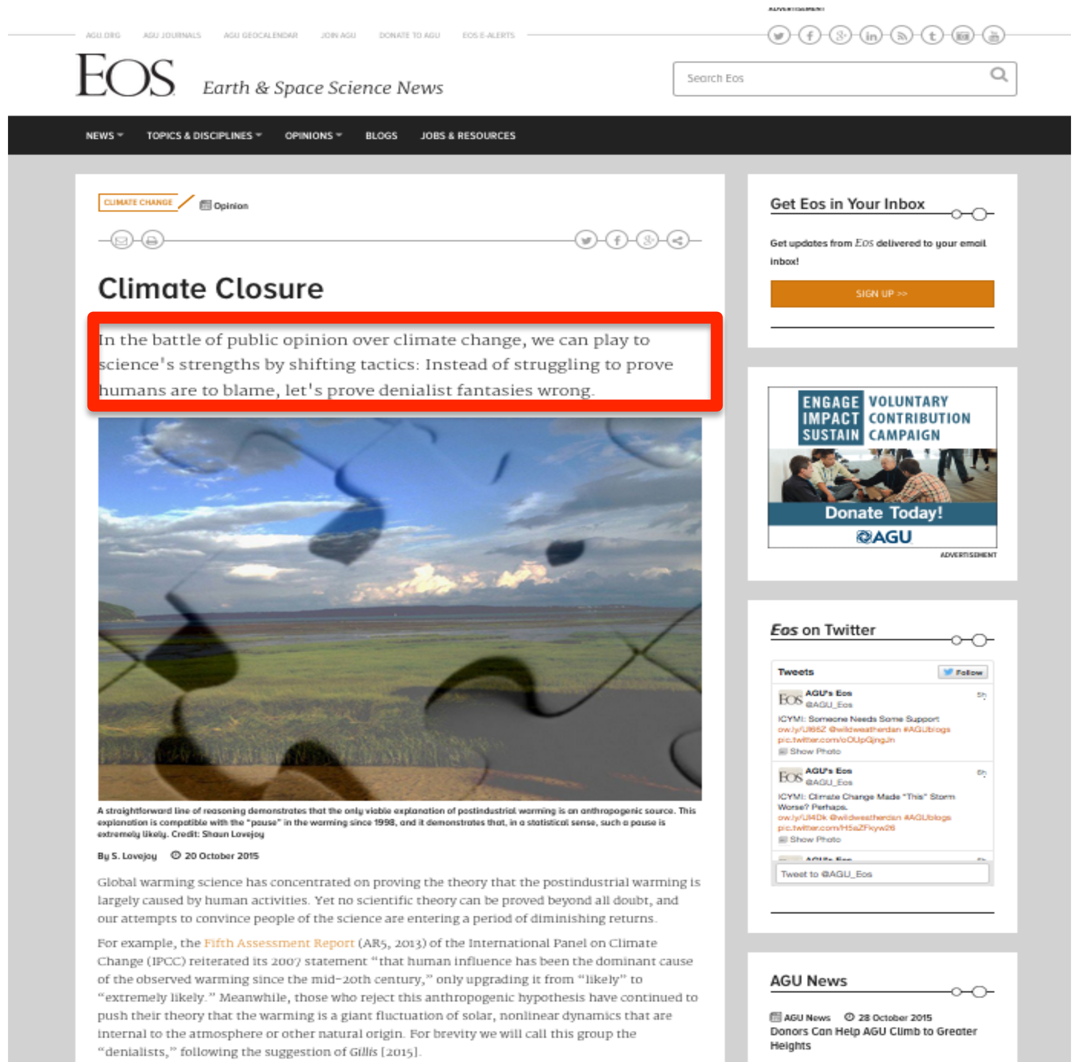
Why the warming can't be natural: the nonlinear geophysics of climate closure

Lorenz Lecture
16 December, 2015

S. Lovejoy, McGill, Montreal

Climate Closure



Published Oct. 20, 2015
>1000 comments

Continuum mechanics

Low level (fundamental)

deterministic

Large Re ↓

Laws of turbulence

Classical:

Richardson, Kolmogorov, Corrsin, Obukhov, Bolgiano

High level

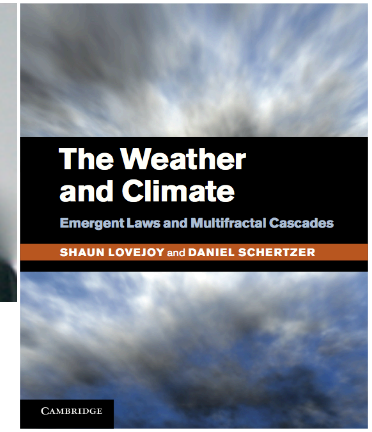
stochastic

Vortices in strongly turbulent fluid

(M. Wiczek, numerical simulation, 2010)

Pioneers of turbulence

Laws of Atmospheric Turbulence



Lovejoy and Schertzer 2013

Pioneers

Differences

homogeneous

Isotropic

Fluctuations ≈ (turbulent flux) x (scale)^H

Wavelets

Cascading,Multifractal
Turbulent flux

Anisotropic
Space-time
Scale function

Fourier domain:

$$\left(\frac{Variance_{observables}}{wavenumber}\right)=\left(\frac{Variance_{flux}}{wavenumber}\right)(wavenumber)^{-2H}$$

$$=(wavenumber)^{-\beta}$$

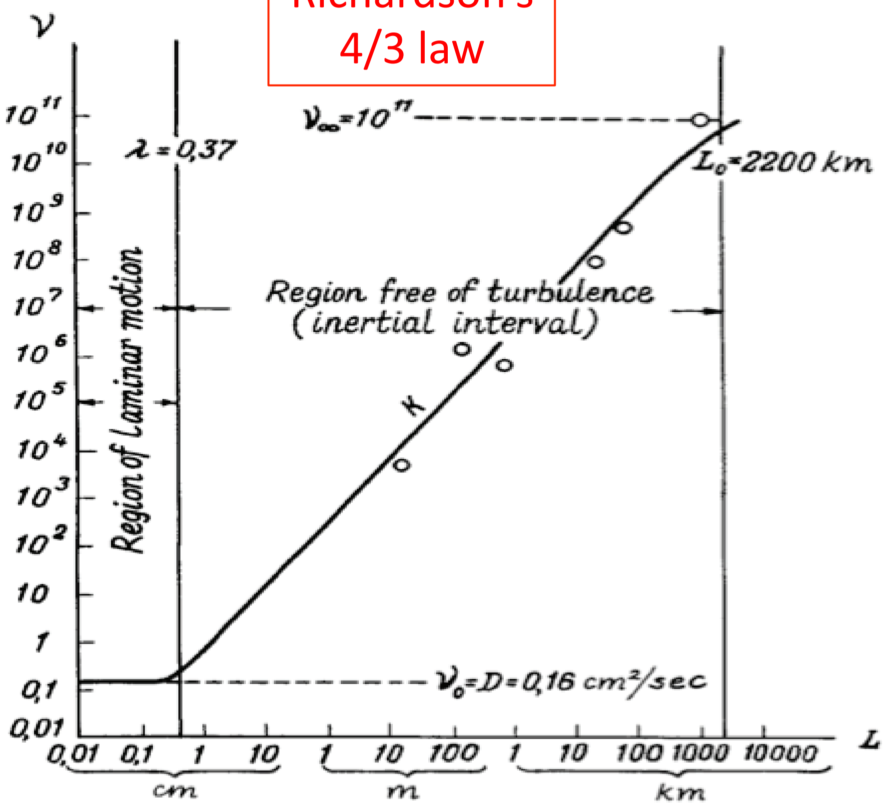
Space: $E(k) \approx k^{-\beta}$

Time: $E(\omega) \approx \omega^{-\beta}$

Space

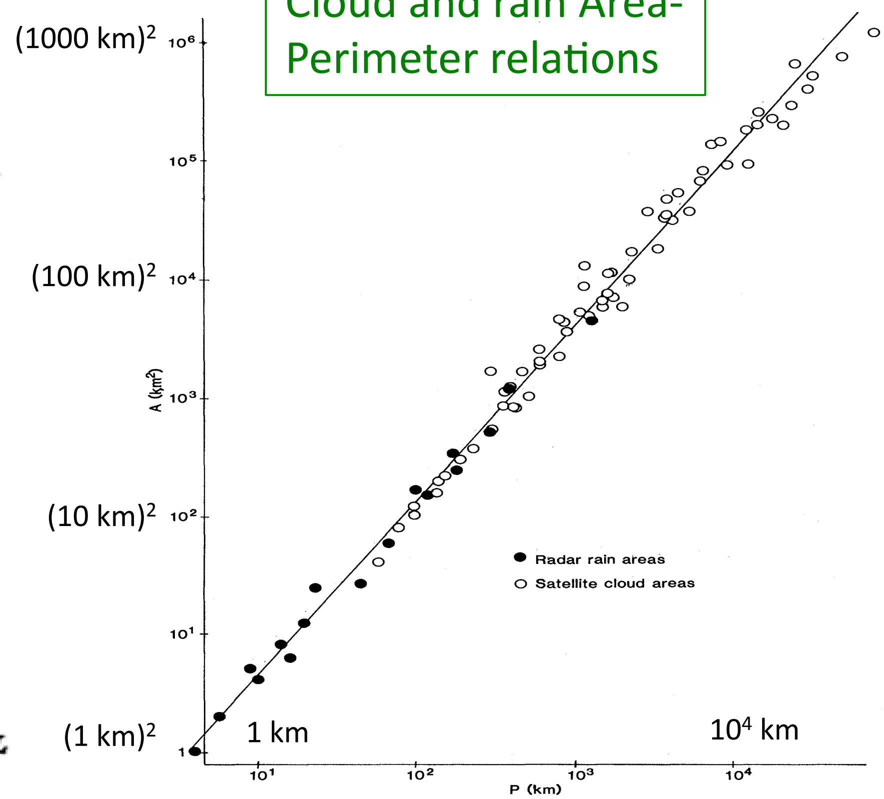
Early indications of wide range scaling

Richardson's 4/3 law



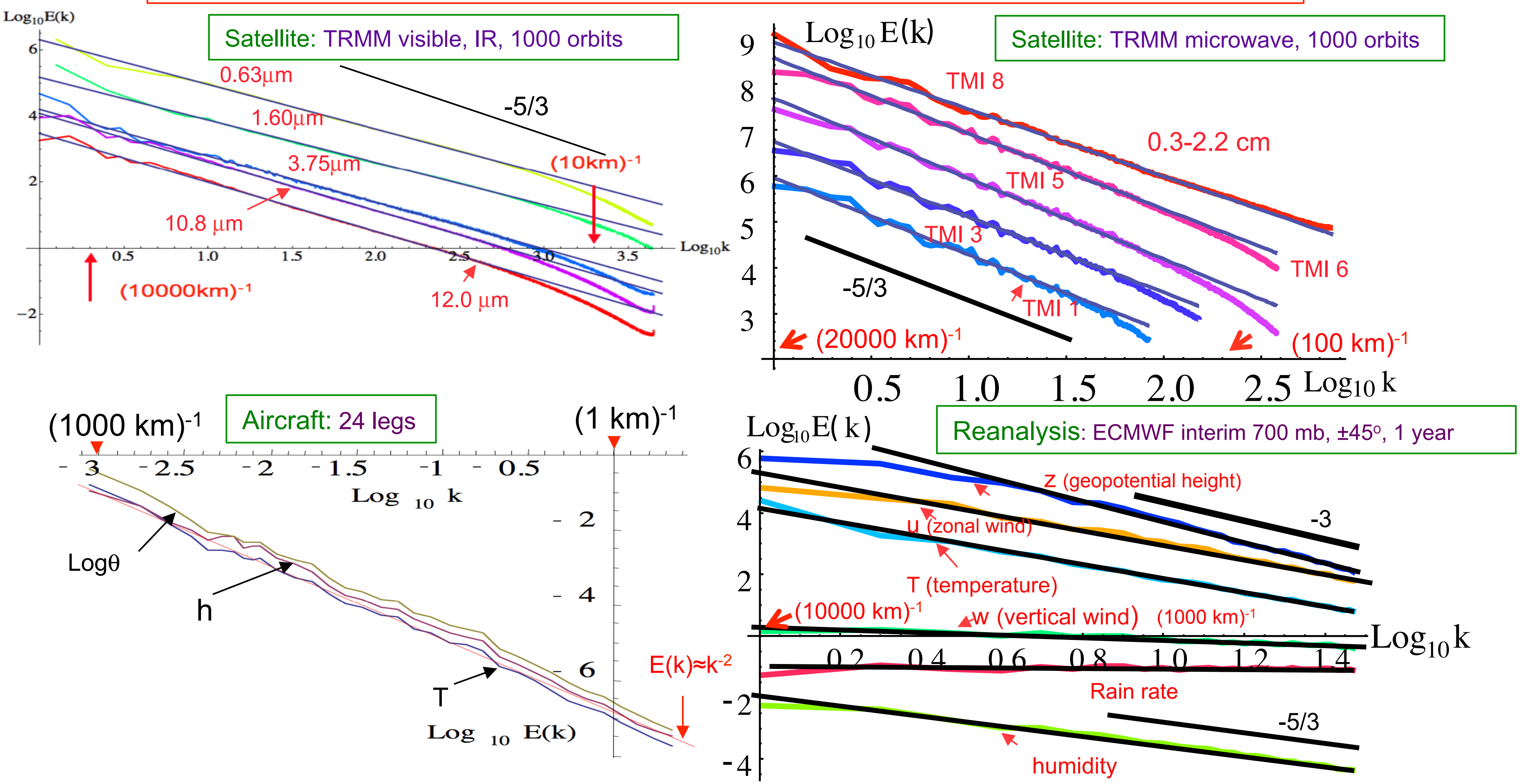
Richardon 1926, redrawn by Monin 1972

Cloud and rain Area-Perimeter relations



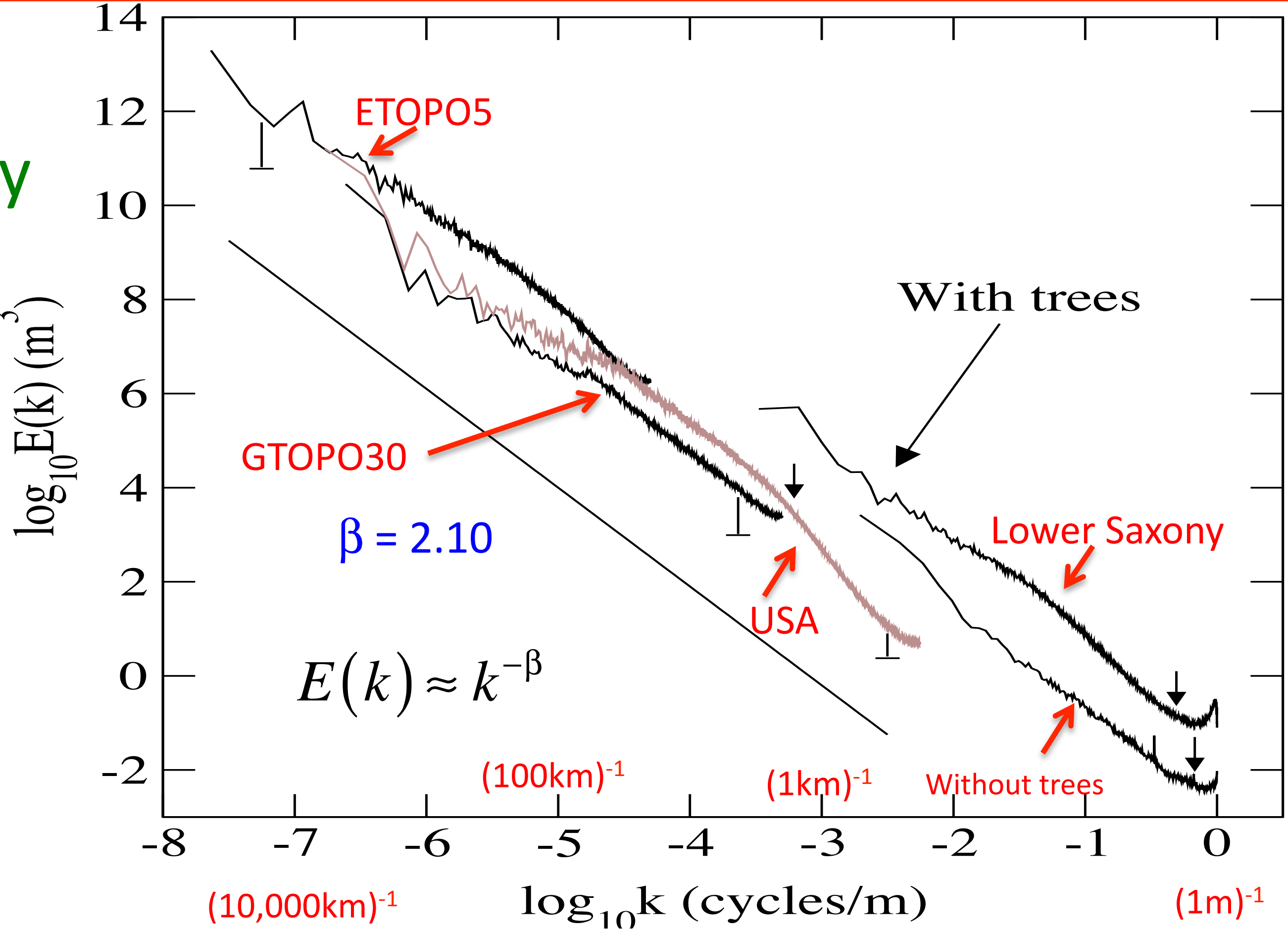
Lovejoy, 1982, Science

Planetary scale Horizontal Scaling $E(k) = k^{-\beta}$



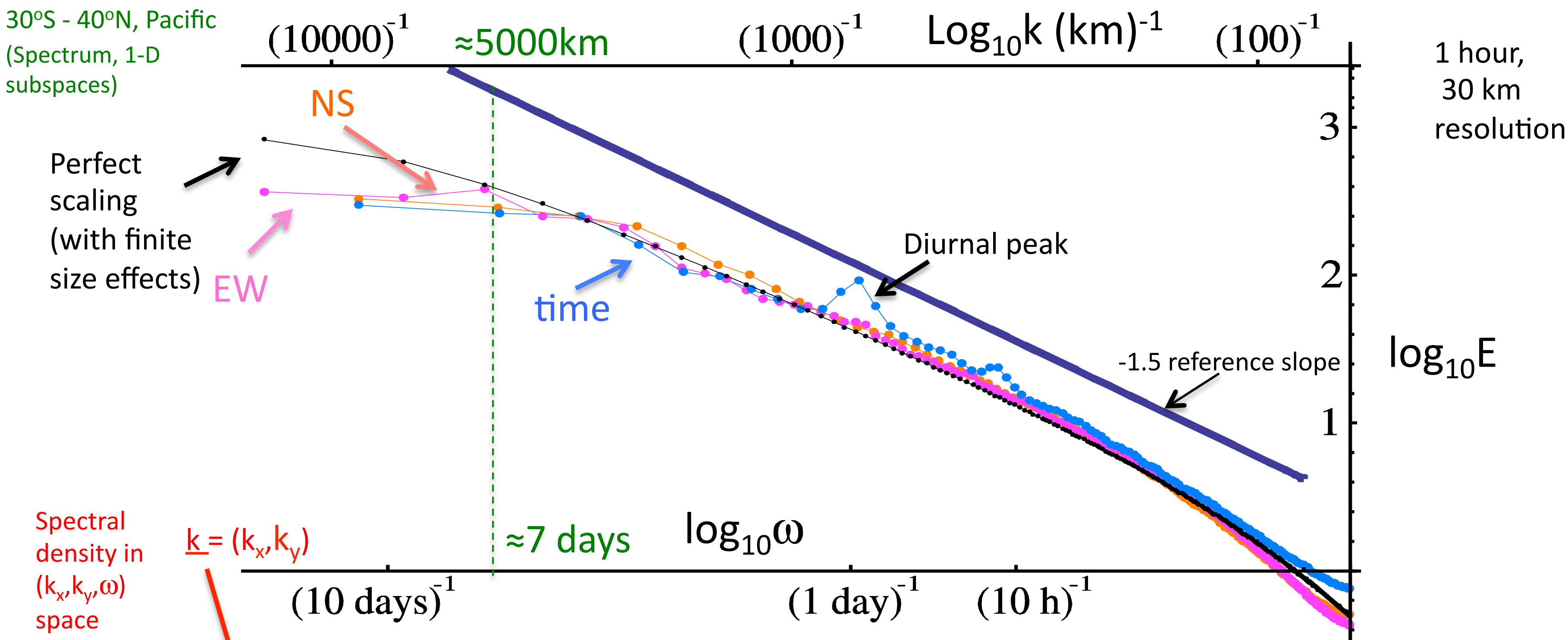
Atmospheric Boundary conditions

Topography



Gagnon, Lovejoy and Schertzer, 2006

Planetary scale space-time scaling: 1400 MTSAT IR images

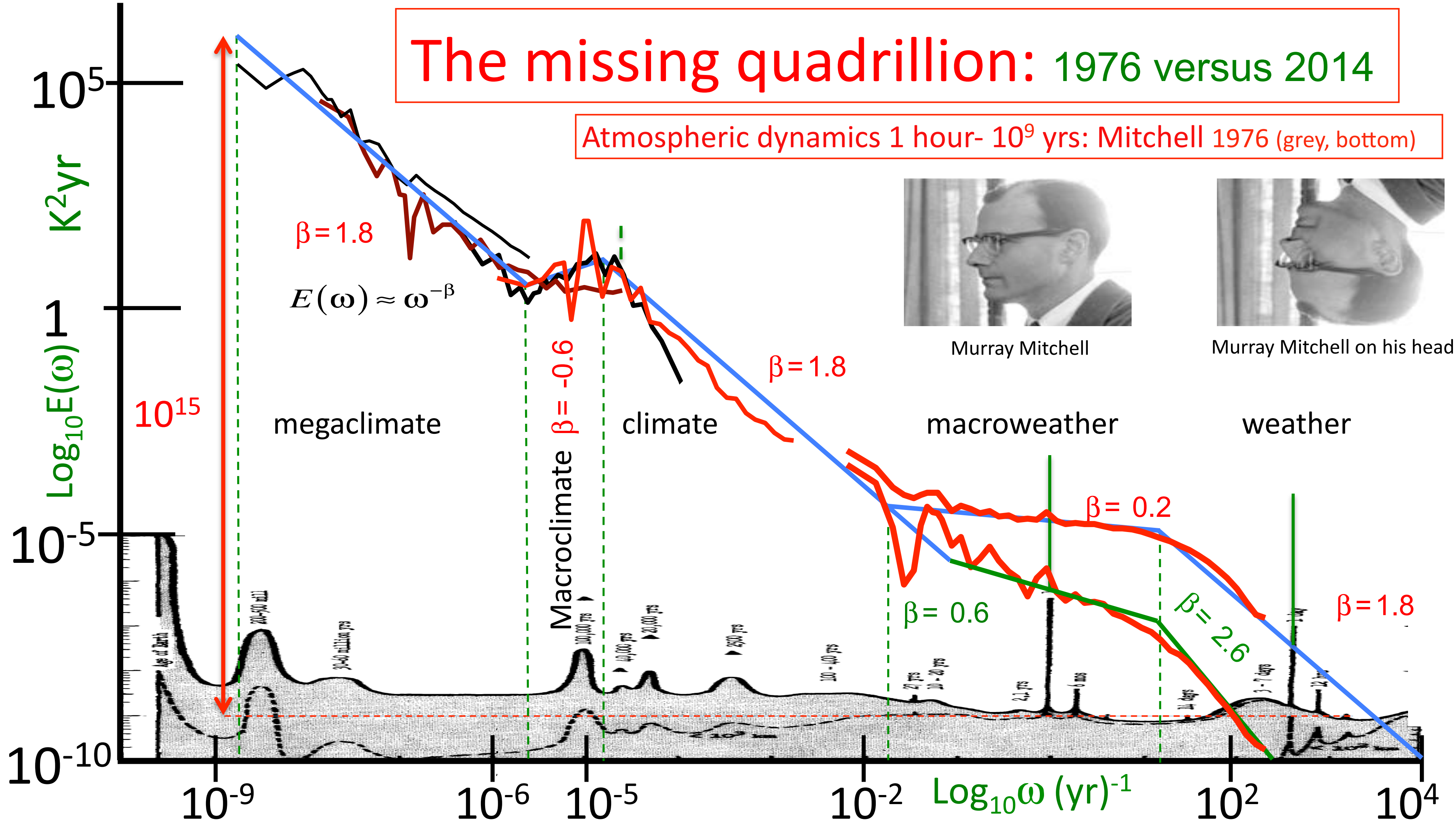


$$P\left(\lambda^{-1}\left(\underline{k},\omega\right)\right)=\lambda^{s}P\left(\left(\underline{k},\omega\right)\right)$$

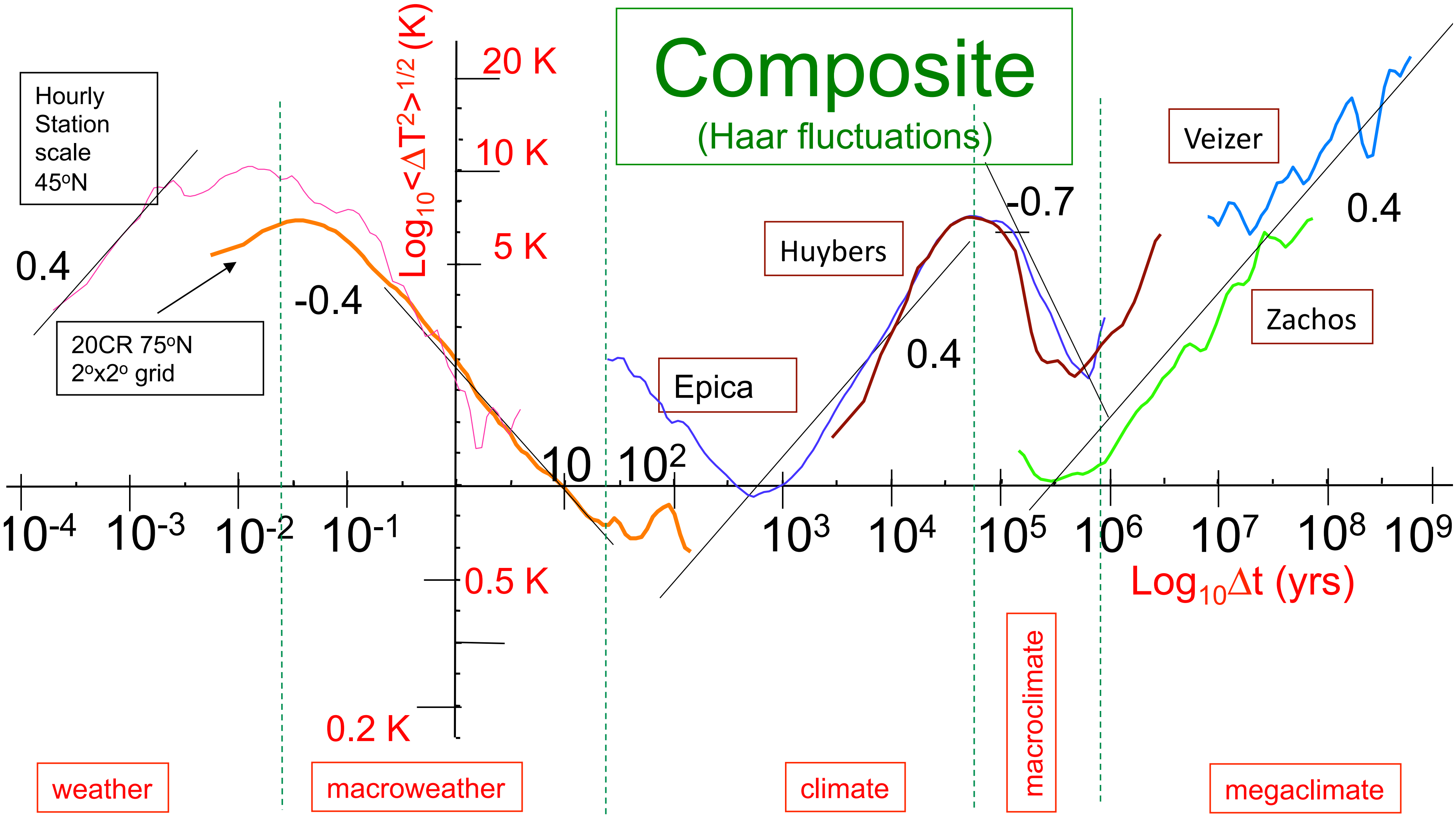
$\beta = s-2$

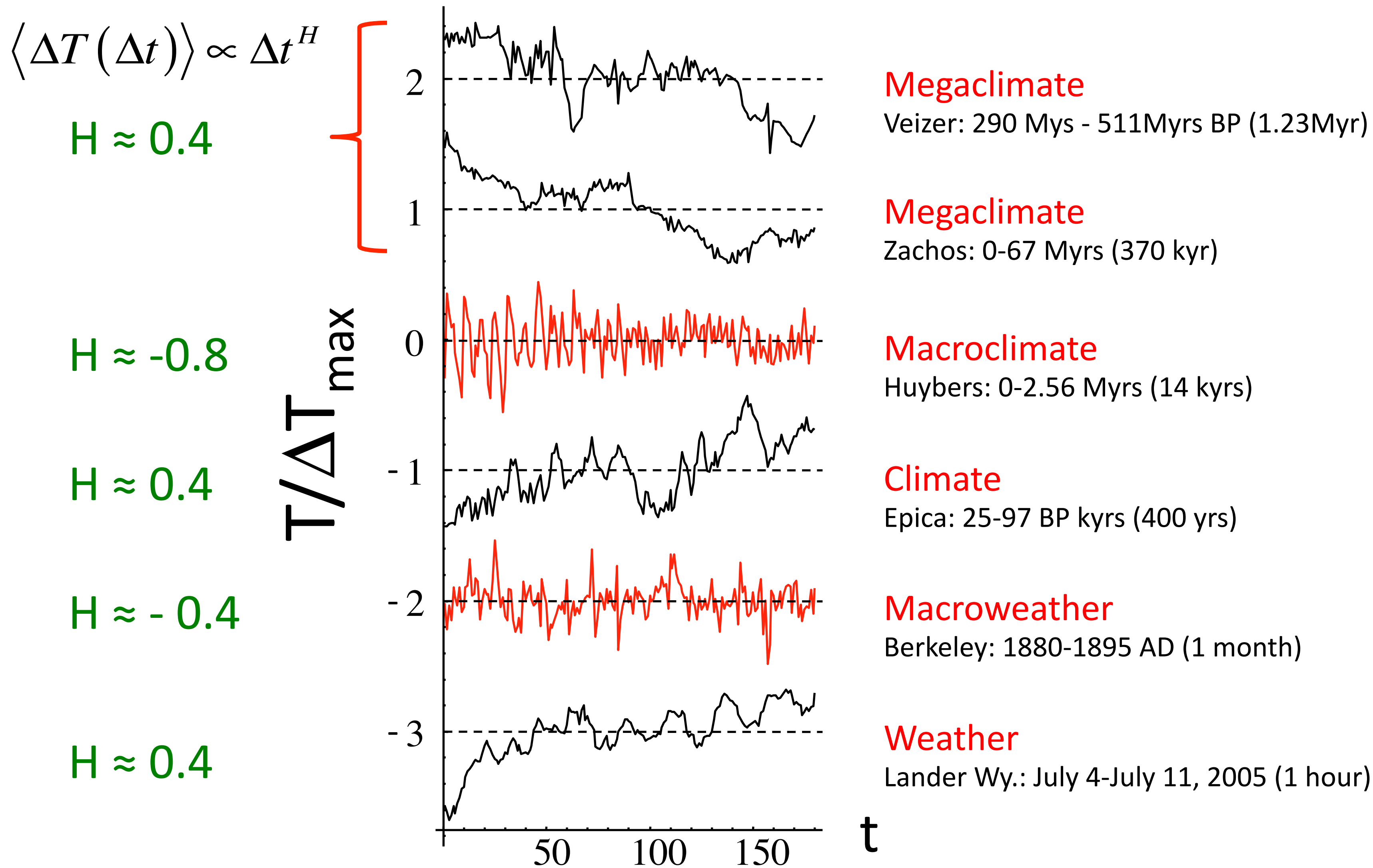
Accurate space-time scaling

Time



The missing quadrillion: 1976 versus 2014
Atmospheric dynamics 1 hour- 10^9 yrs: Mitchell 1976 (grey, bottom)
Murray Mitchell
Murray Mitchell on his head
K²yr
Log10E(ω)
10^5
1
10^-5
10^-10
10^15
β=1.8
E(ω) ≈ ω^-β
megaclimate
Macroclimate β= -0.6
climate
β=1.8
macroweather
weather
β= 0.2
β= 0.6
β= 2.6
β=1.8
10^-9
10^-6
10^-5
10^-2
Log10ω (yr)^-1
10^2
10^4


Composite
(Haar fluctuations)
Hourly Station scale 45°N
20CR 75°N 2°x2° grid
Epica
Huybers
Veizer
Zachos
0.4
-0.4
0.4
-0.7
0.4
20 K
10 K
5 K
0.5 K
0.2 K
Log10<ΔT2>1/2 (K)
10-4 10-3 10-2 10-1 10 102 103 104 105 106 107 108 109
Log10Δt (yrs)
weather
macroweather
climate
macroclimate
megaclimate



$\langle \Delta T(\Delta t) \rangle \propto \Delta t^H$
H ≈ 0.4
H ≈ -0.8
H ≈ 0.4
H ≈ - 0.4
H ≈ 0.4
$T/\Delta T_{max}$
2
1
0
- 1
- 2
- 3
50
100
150
t
Megaclimate
Veizer: 290 Mys - 511Myrs BP (1.23Myr)
Megaclimate
Zachos: 0-67 Myrs (370 kyr)
Macroclimate
Huybers: 0-2.56 Myrs (14 kyrs)
Climate
Epica: 25-97 BP kyrs (400 yrs)
Macroweather
Berkeley: 1880-1895 AD (1 month)
Weather
Lander Wy.: July 4-July 11, 2005 (1 hour)

The climate is not what you expect…

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

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

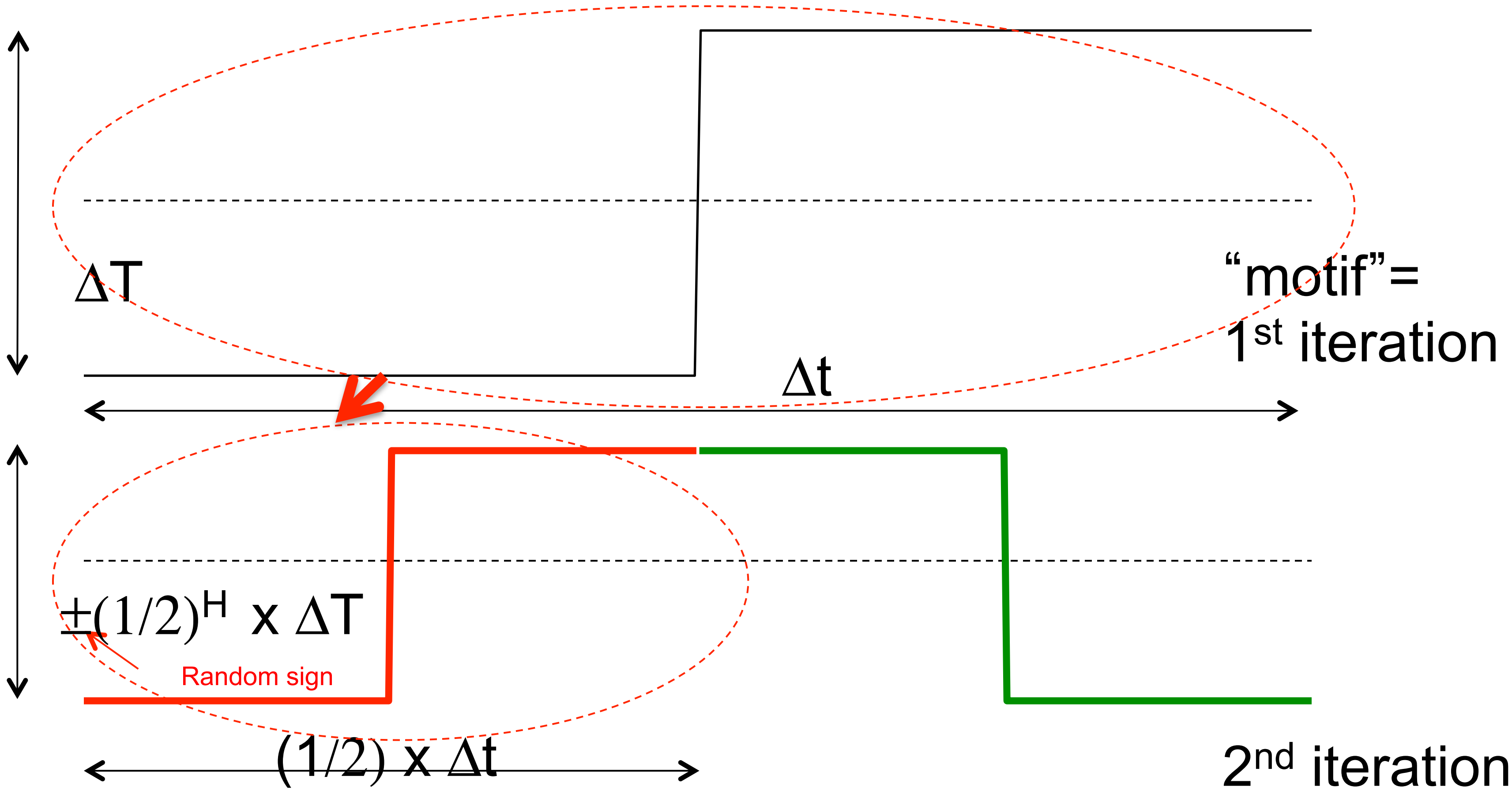
"Climate in a narrow sense is usually defined as the "average weather" …."
-Intergovernmental Panel on Climate Change, 2007

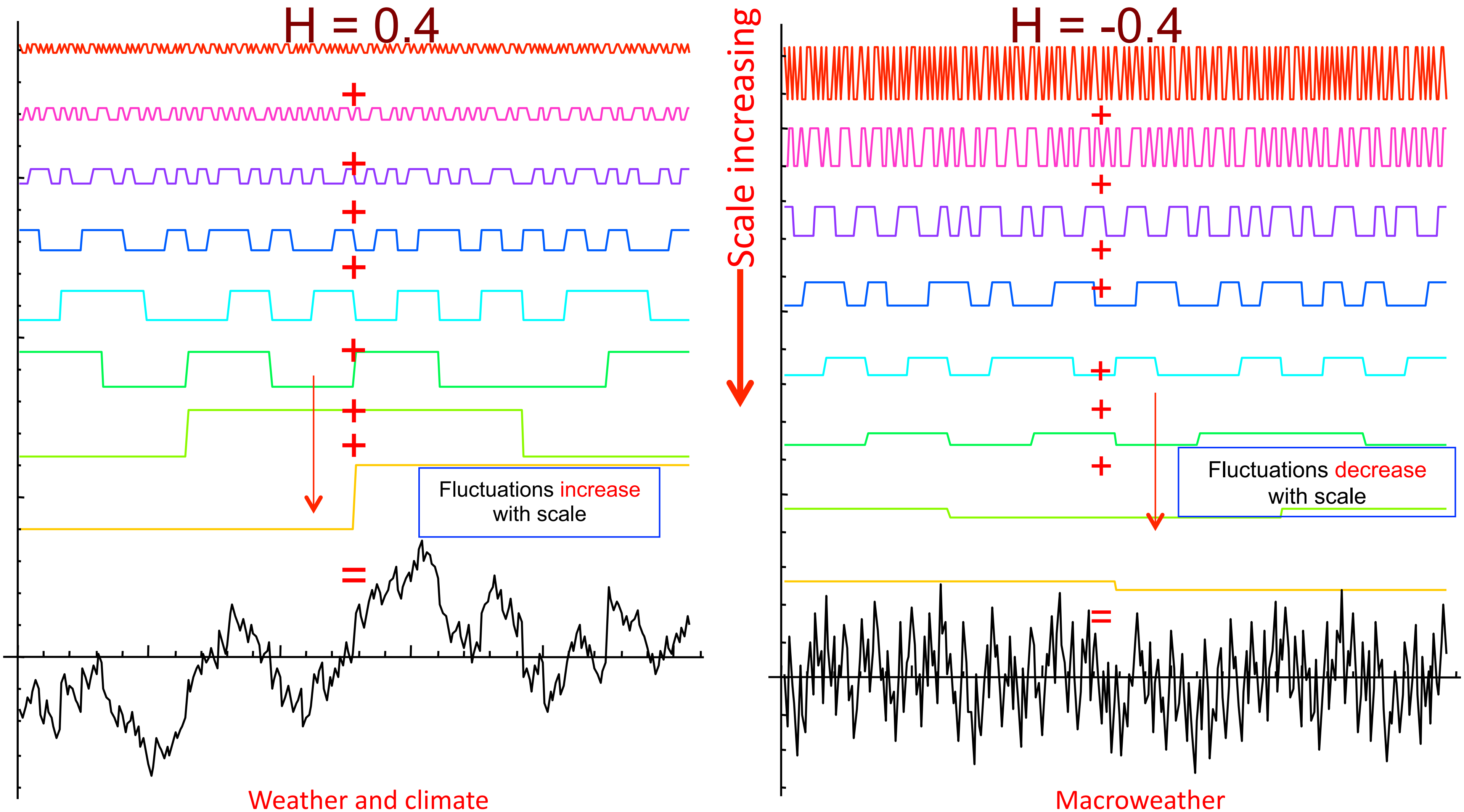
Expect macroweather!

Understanding the fluctuation exponent $\langle \Delta T(\Delta t) \rangle = \langle \varphi \rangle \Delta t^{H}$

The "H model"

(Lovejoy 2013, Lovejoy and Mandelbrot 1985)

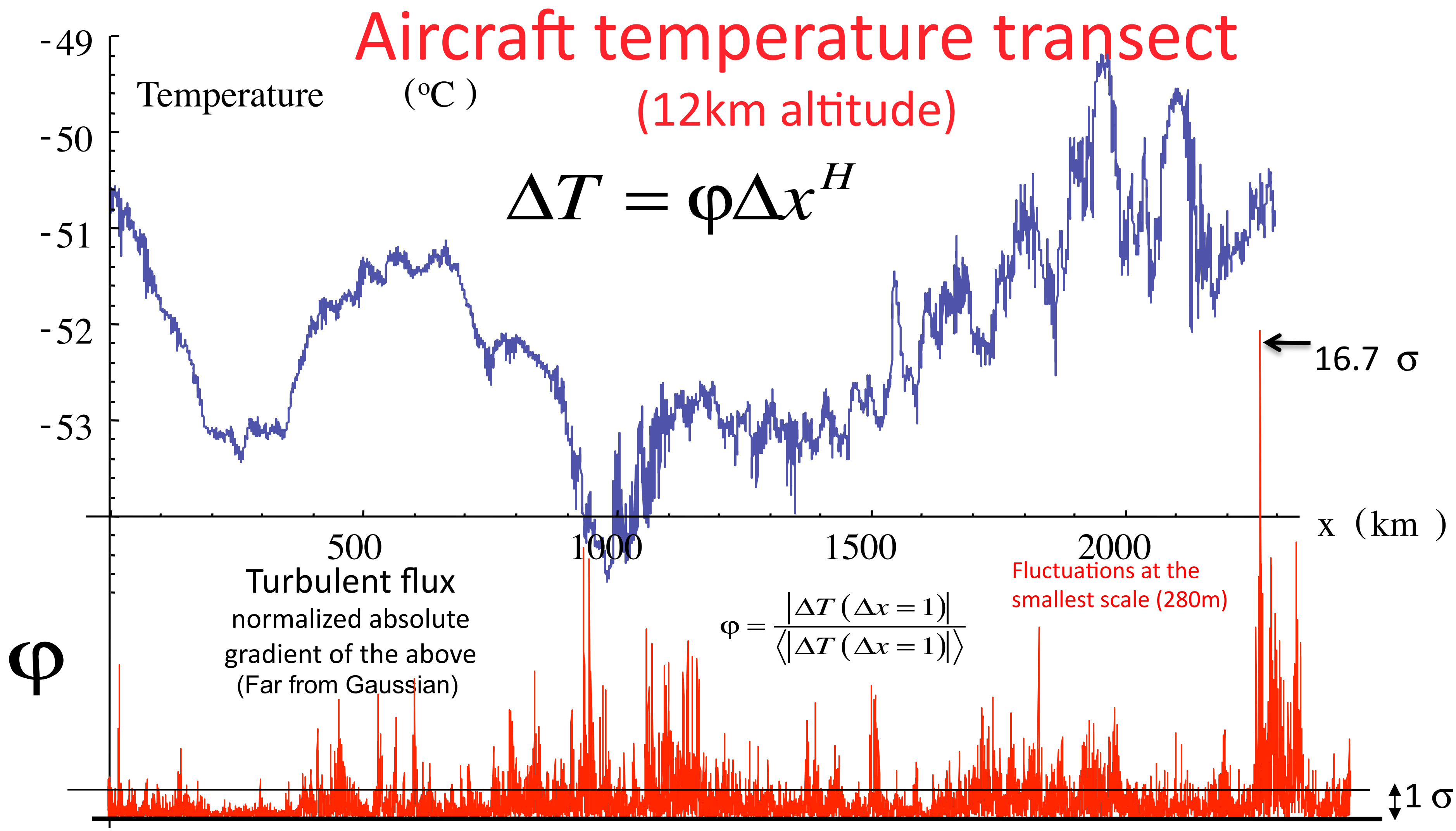




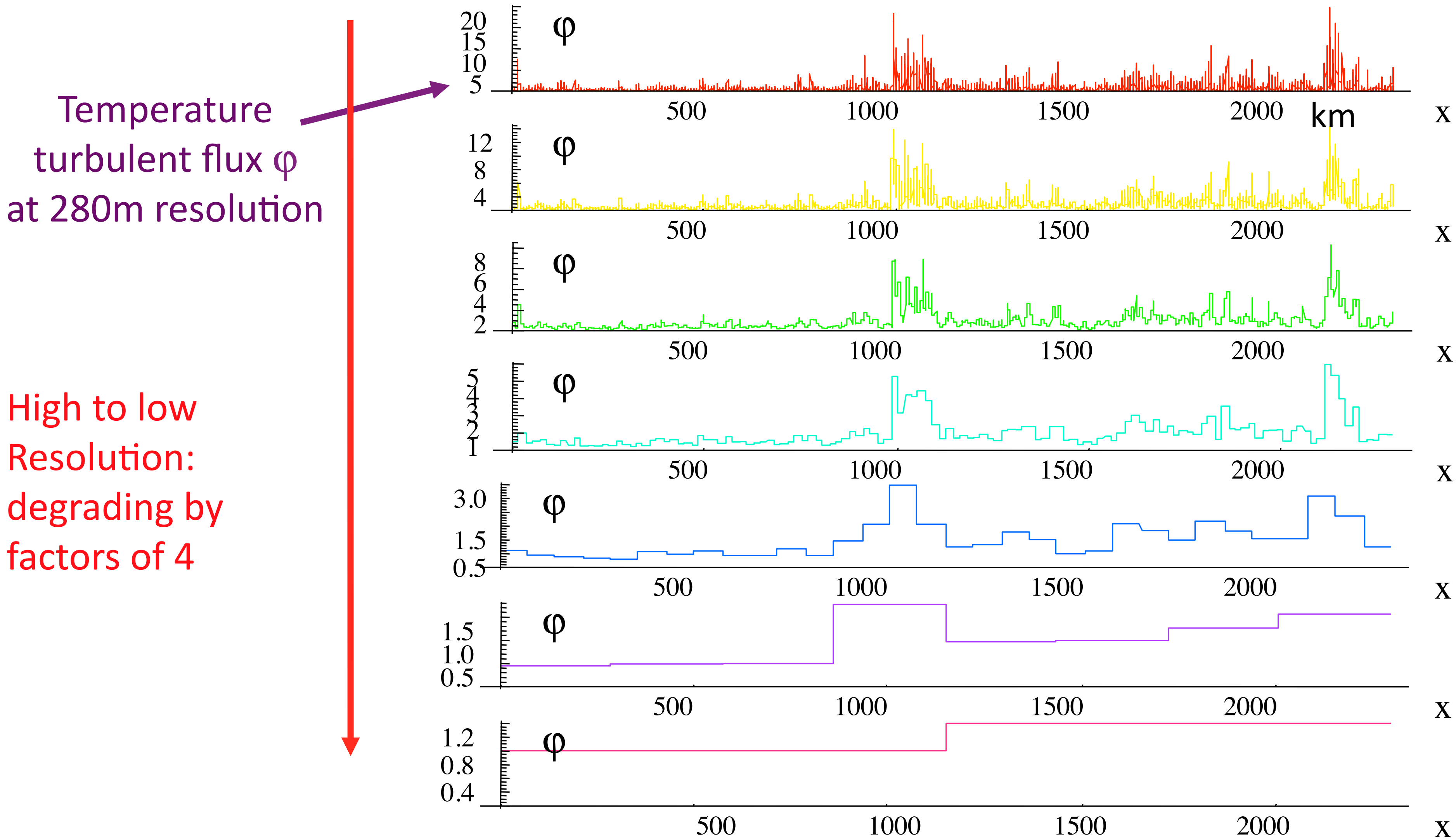
H = 0.4
H = -0.4
Scale increasing
Fluctuations increase with scale
Fluctuations decrease with scale
Weather and climate
Macroweather

Intermittency Multifractality, Cascades

Is H enough?



Aircraft temperature transect
(12km altitude)
-49
-50
-51
-52
-53
Temperature (°C)
$\Delta T = \varphi \Delta x^H$
16.7 σ
x (km)
500
1000
1500
2000
Turbulent flux
normalized absolute
gradient of the above
(Far from Gaussian)
φ
$\varphi = \frac{|\Delta T(\Delta x = 1)|}{\langle|\Delta T(\Delta x = 1)|\rangle}$
Fluctuations at the
smallest scale (280m)
1 σ

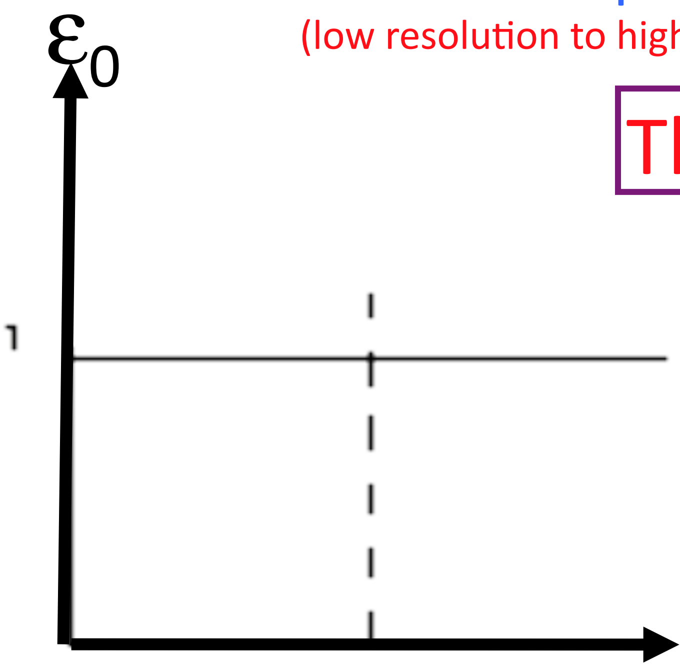


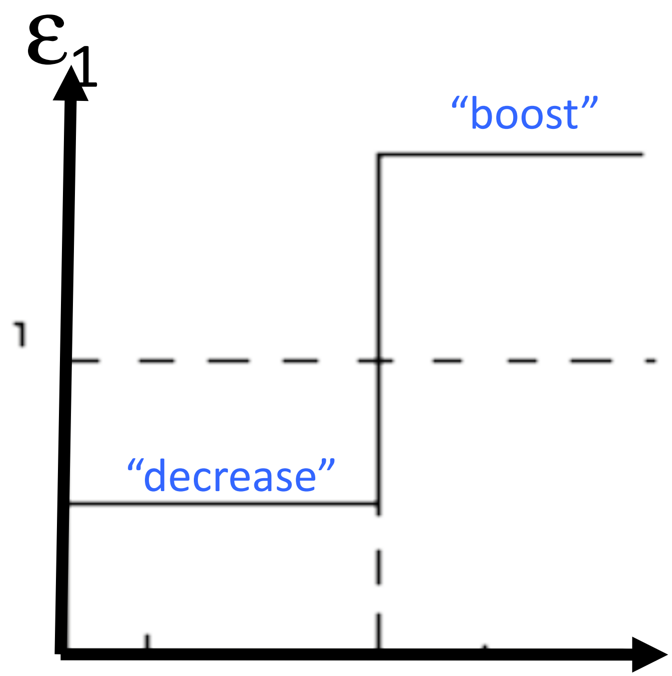
Temperature turbulent flux φ at 280m resolution
High to low Resolution: degrading by factors of 4
φ
km
x
500
1000
1500
2000

Cascades and Multifractals

Simulations: **multiplicative** introduction of small scale details
(low resolution to high)

The α model





Schertzer and Lovejoy 1983

Multiplicative Cascades

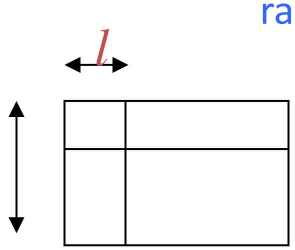
Generic statistical behaviour:

scaling — Turbulent flux — Scale invariant

$$\left\langle \varepsilon_{\lambda}^{q} \right\rangle \approx \lambda^{K(q)}$$

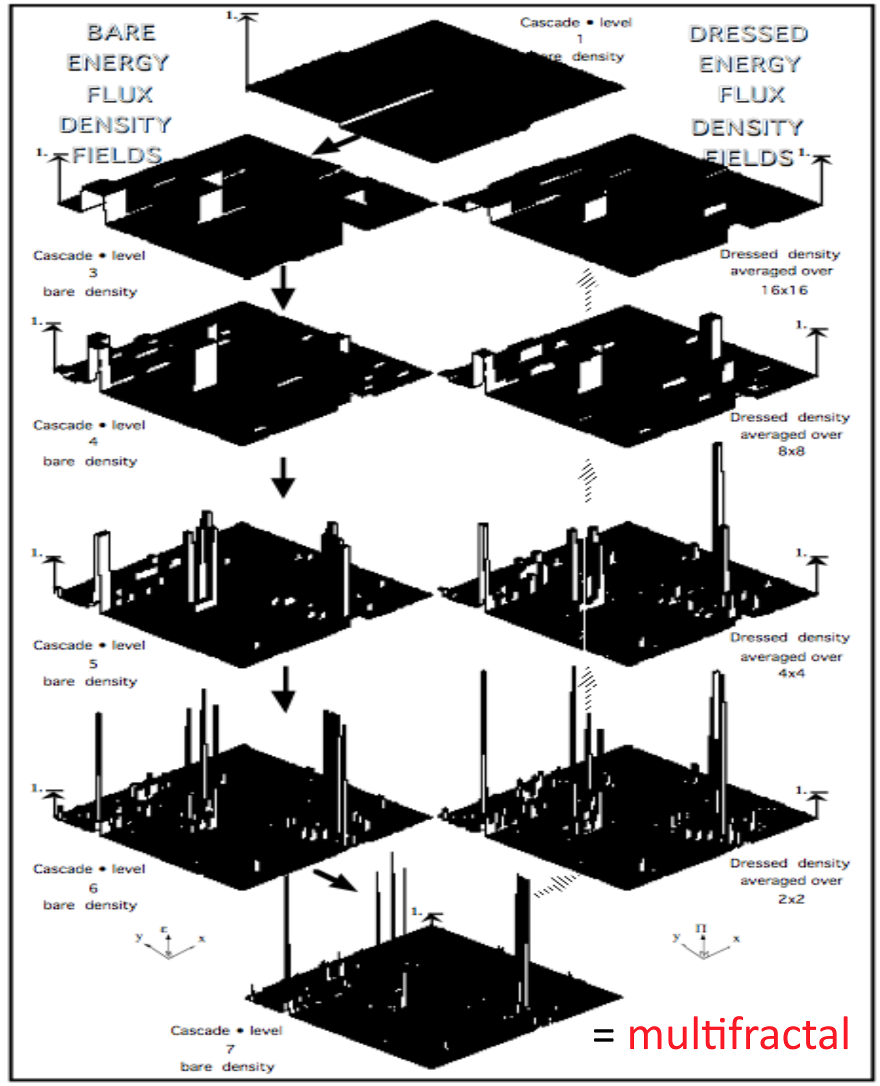
Statistical averaging

Resolution: ratio $\lambda = L/l$



Probabilities:

$$\Pr\left(\varepsilon_{\lambda} > \lambda^{\gamma}\right) \approx \lambda^{-c(\gamma)}$$



Early evidence of cascades:

Precipitation

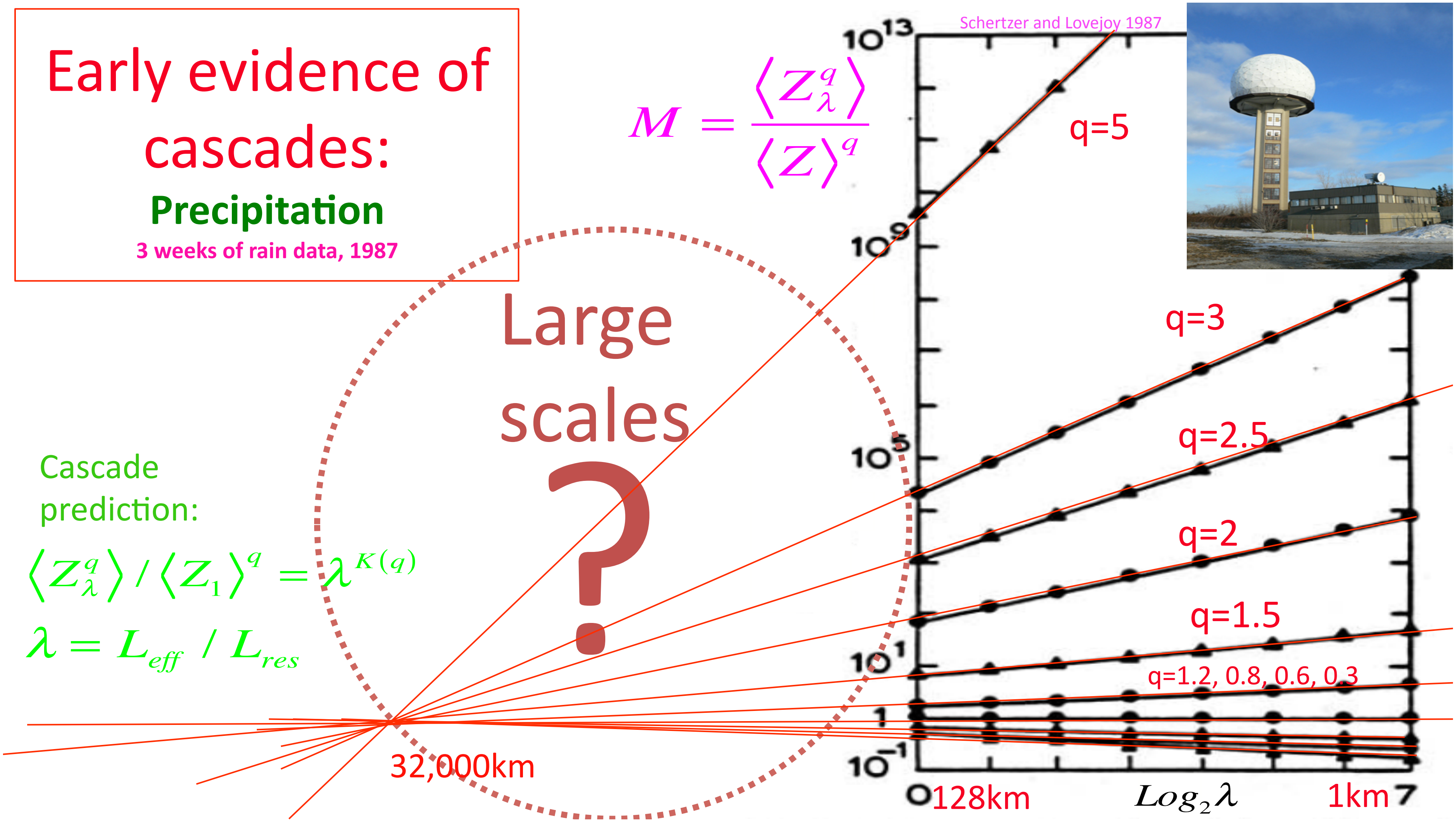
3 weeks of rain data, 1987

$$M = \frac{\langle Z_\lambda^q \rangle}{\langle Z \rangle^q}$$

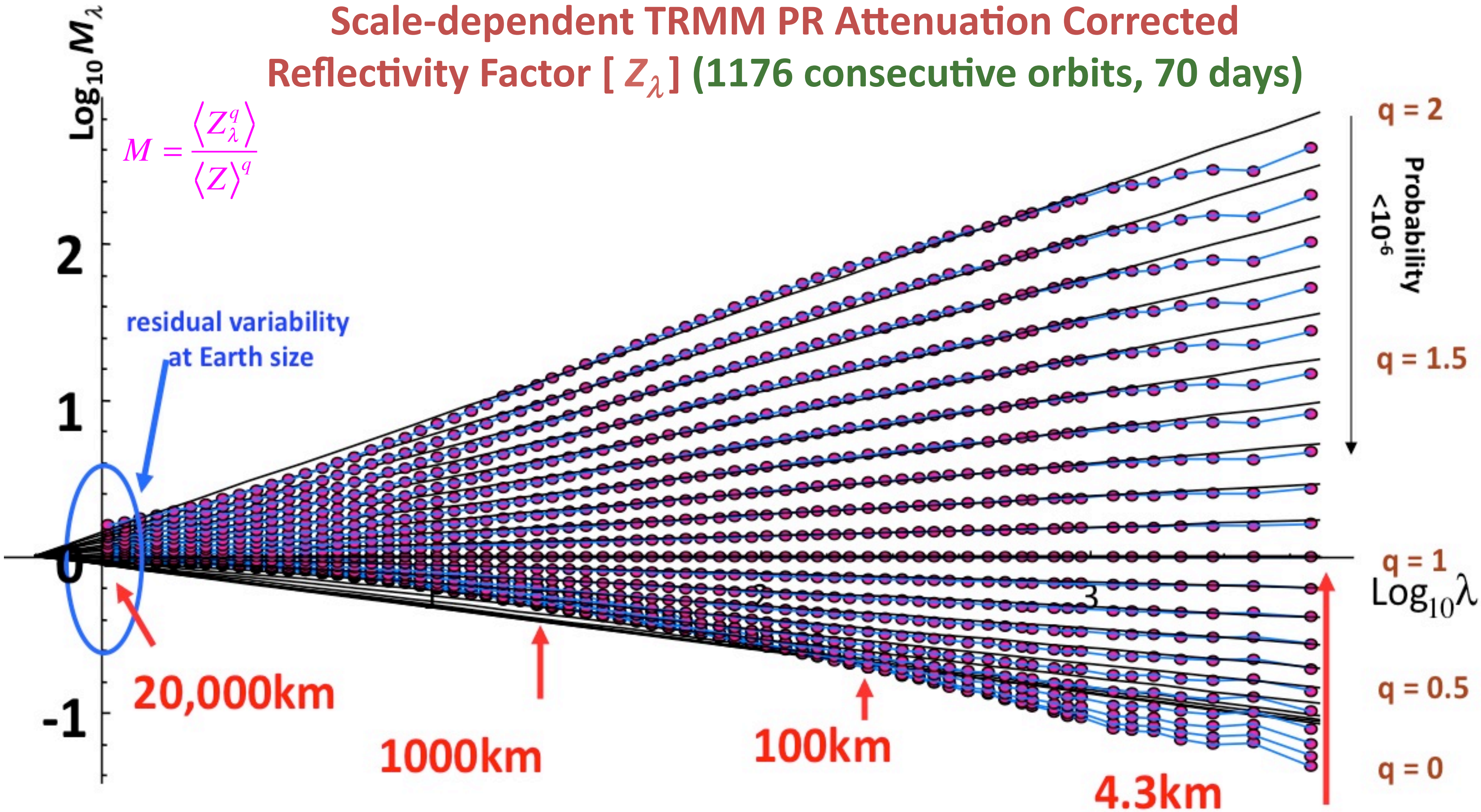
Cascade prediction:

$$\langle Z_\lambda^q \rangle / \langle Z_1 \rangle^q = \lambda^{K(q)}$$

$$\lambda = L_{eff} / L_{res}$$

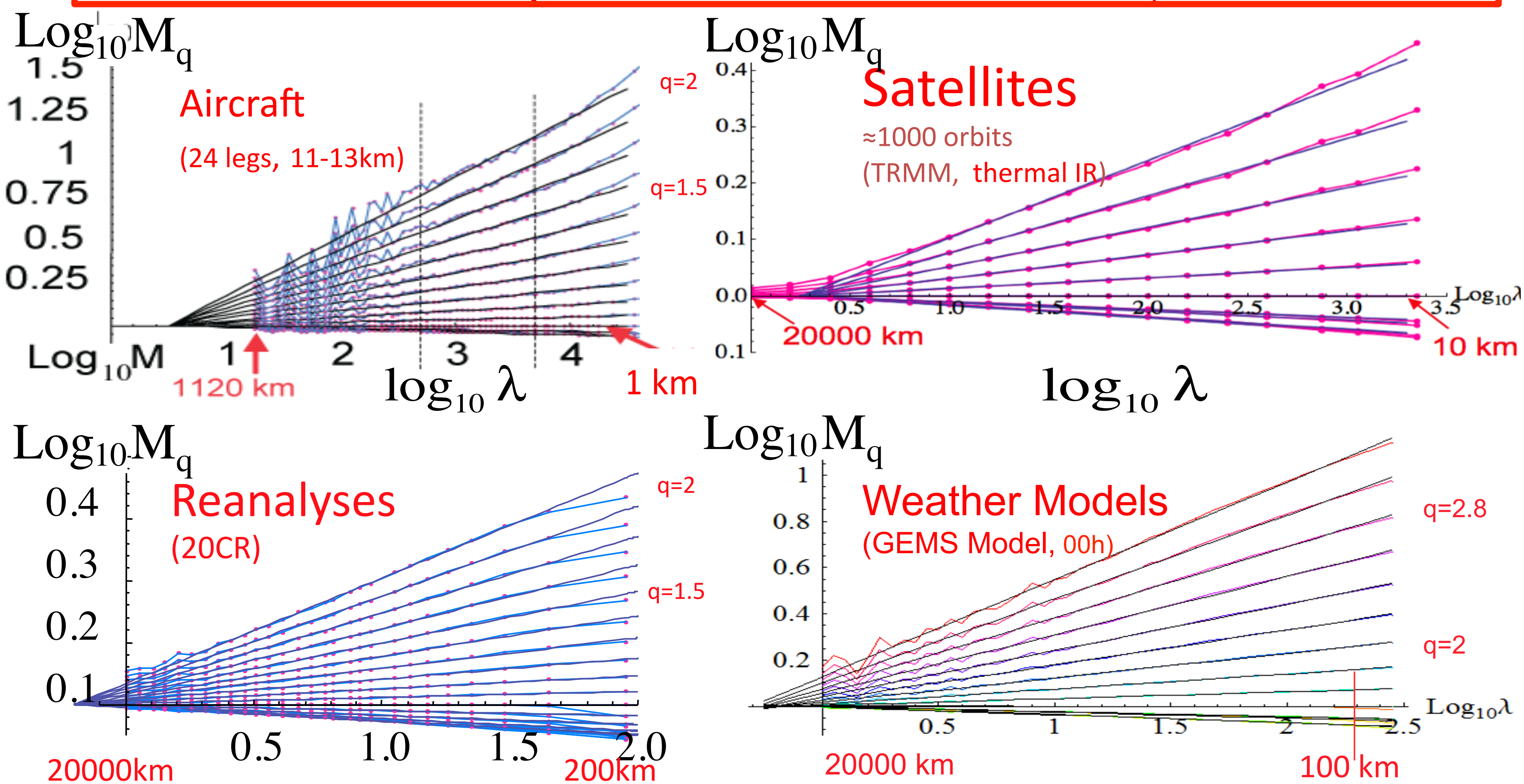


Scale-dependent TRMM PR Attenuation Corrected Reflectivity Factor [Z_λ] (1176 consecutive orbits, 70 days)



Lovejoy et al 2008

Horizontal Temperature Cascades $M_q \approx \lambda^{K(q)}$

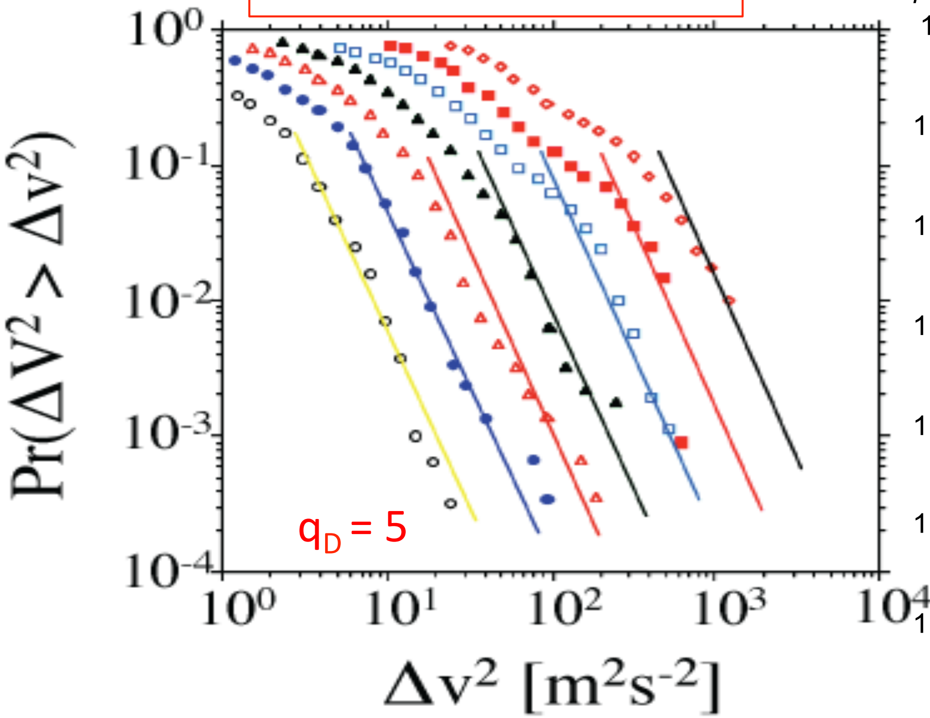


Multifractal Butterfly effect… (leads to black swans events)

$$\Pr(\Delta v > s) \approx s^{-q_D}$$

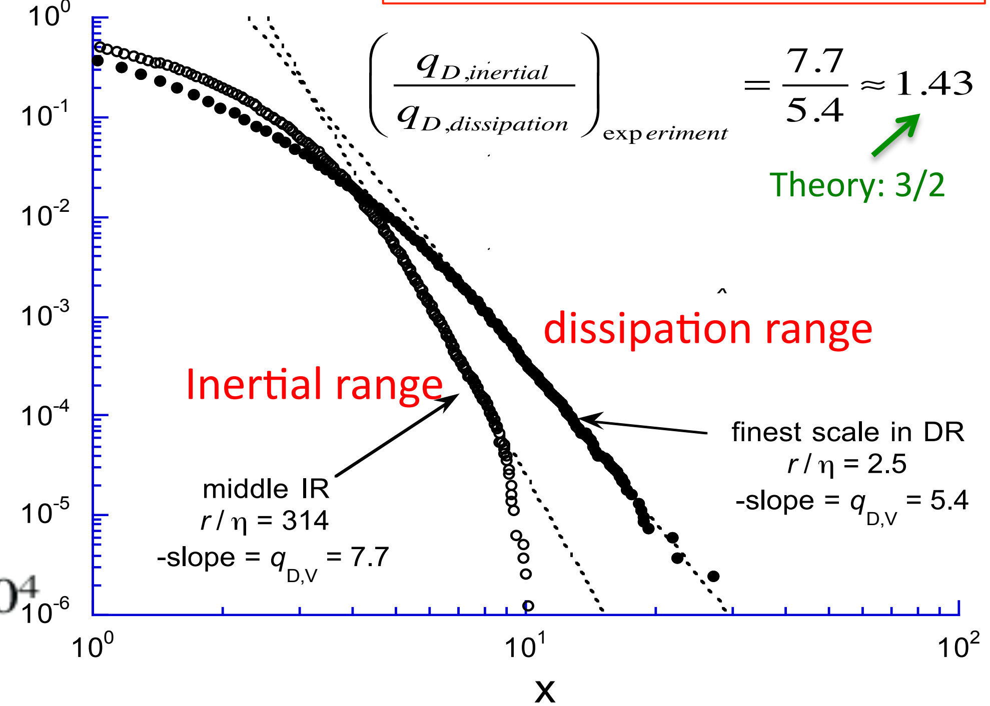
Moments order $>q_D$ determined by small scales

Horizontal Wind… then



Schertzer and Lovejoy 1985

Laboratory Turbulence…now

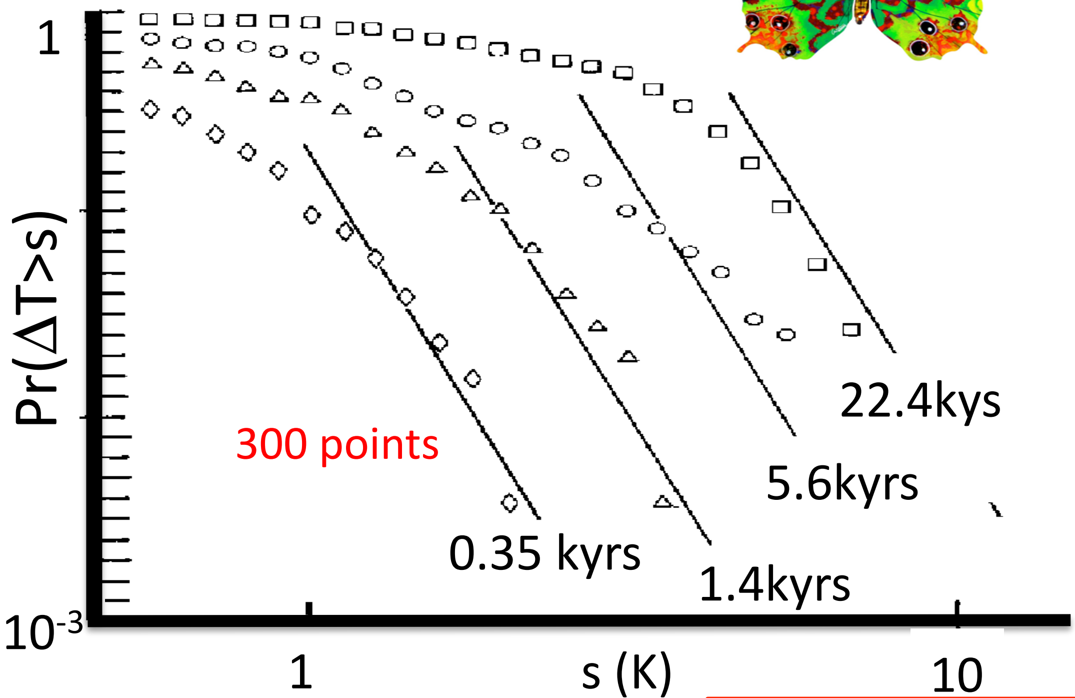


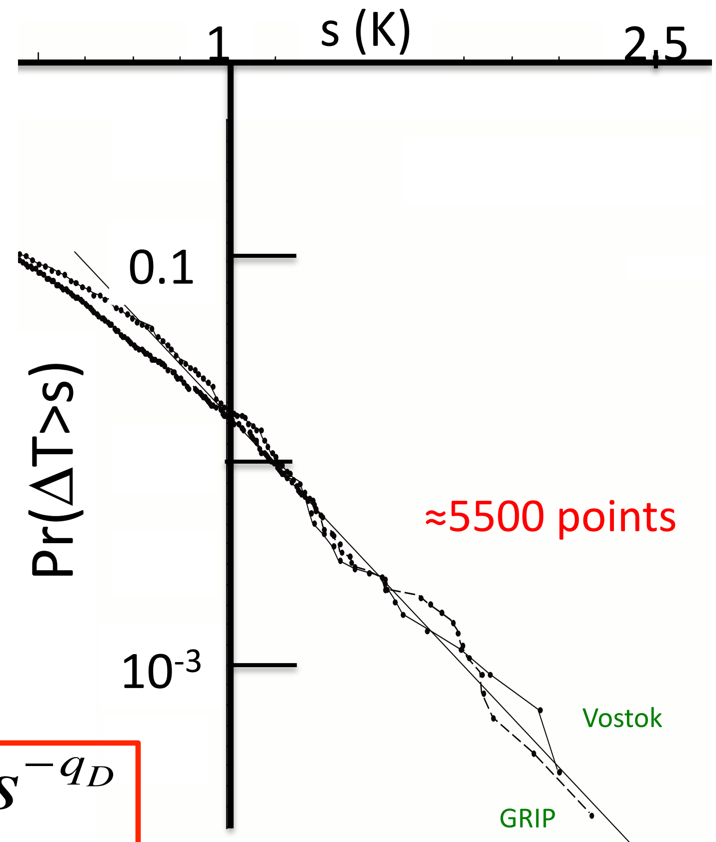
Radelescu, L+S+M 2002

Divergence of moments in Paleotemperatures…

Vostok (then)

GRIP and Vostok (now)





$$\Pr(\varepsilon > s) \approx s^{-q_D}$$

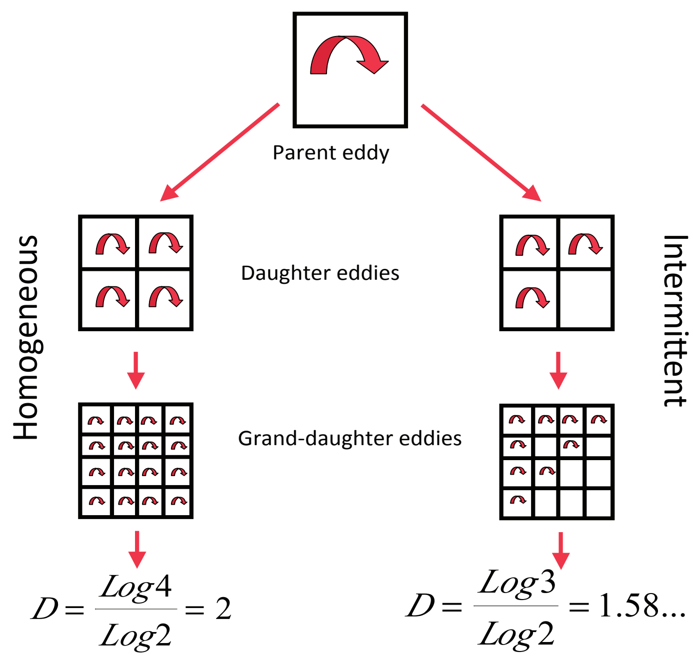
Lovejoy and Schertzer 1986

All the reference lines have $q_D \approx 5$

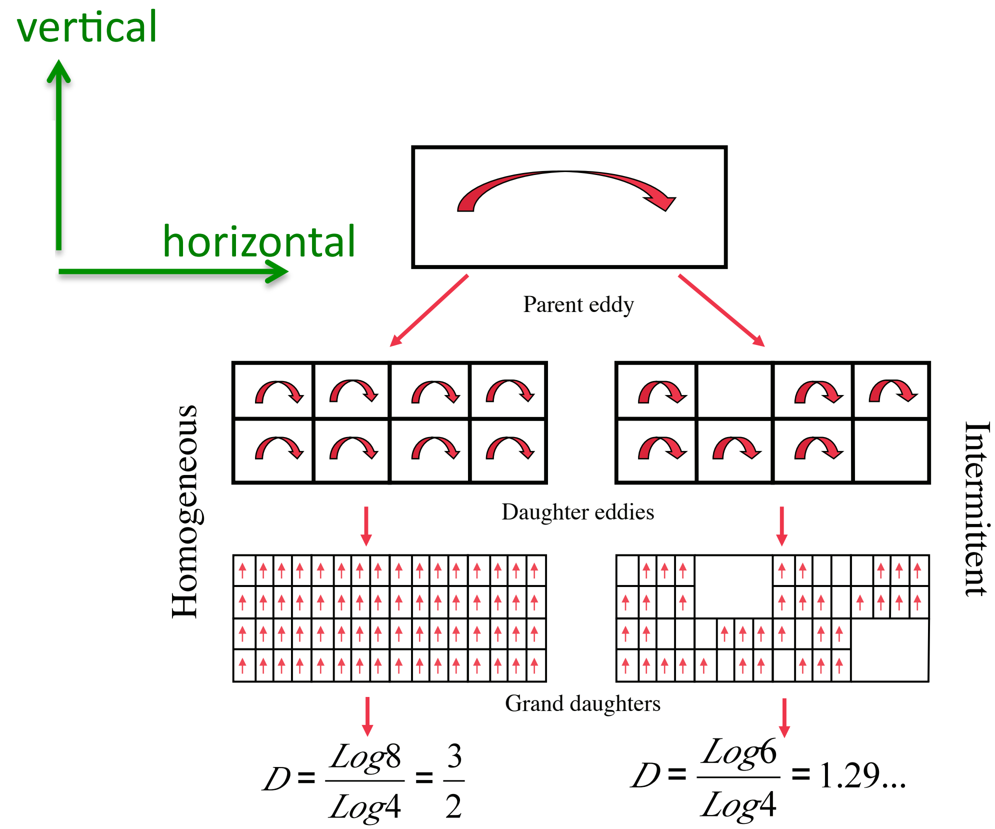
Lovejoy and Schertzer 2013

Stratification,
Scaling Anisotropy
and
Generalized Scale
Invariance

Isotropic CASCADES

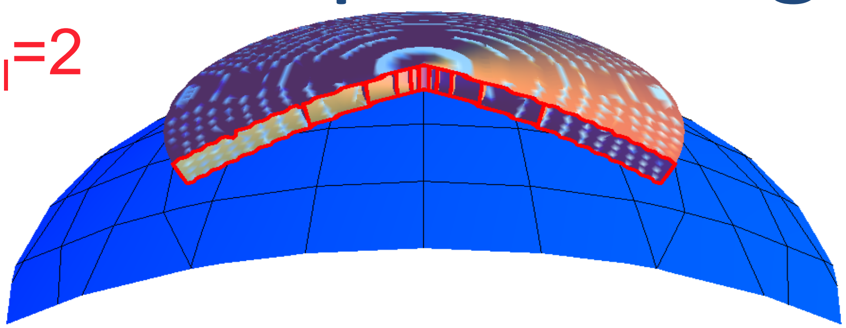


Stratified CASCADES

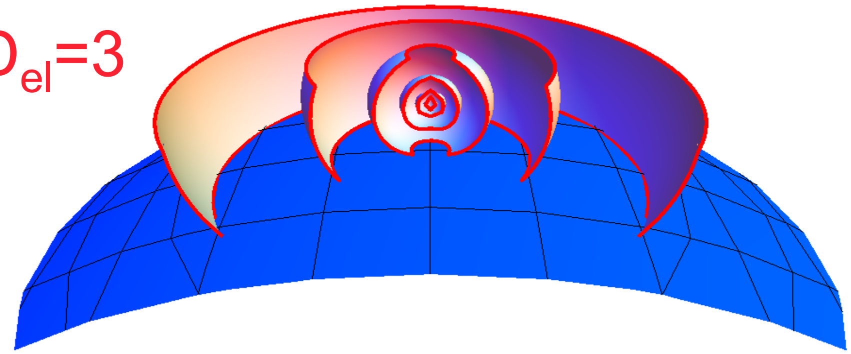


Anisotropic Scaling (Generalized Scale Invariance) (Schertzer and Lovejoy 1985)

$D_{el}=2$

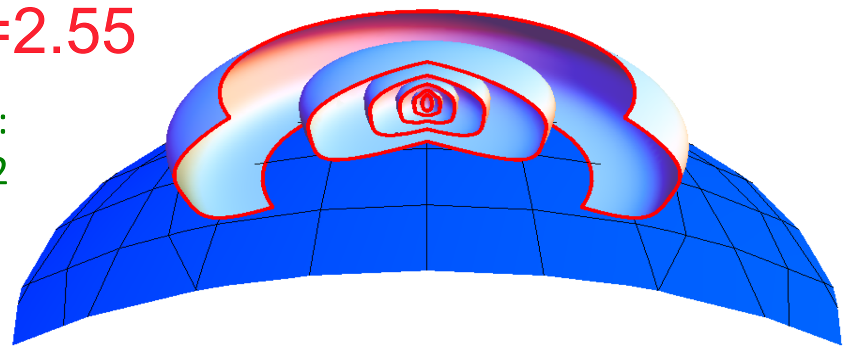


$D_{el}=3$



$D_{el}=23/9=2.55$

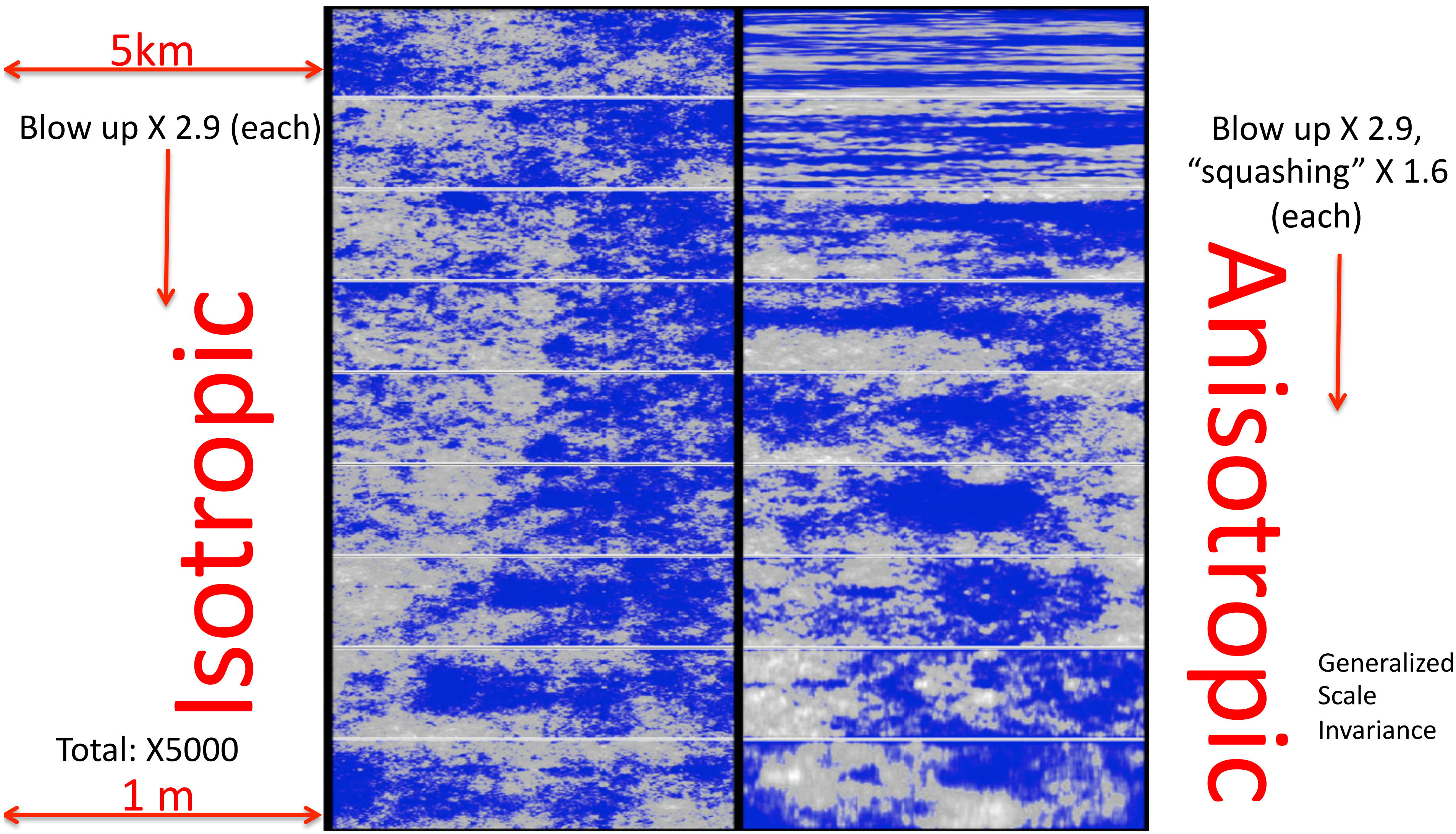
empirical:
2.57±0.02



The 23/9D model:

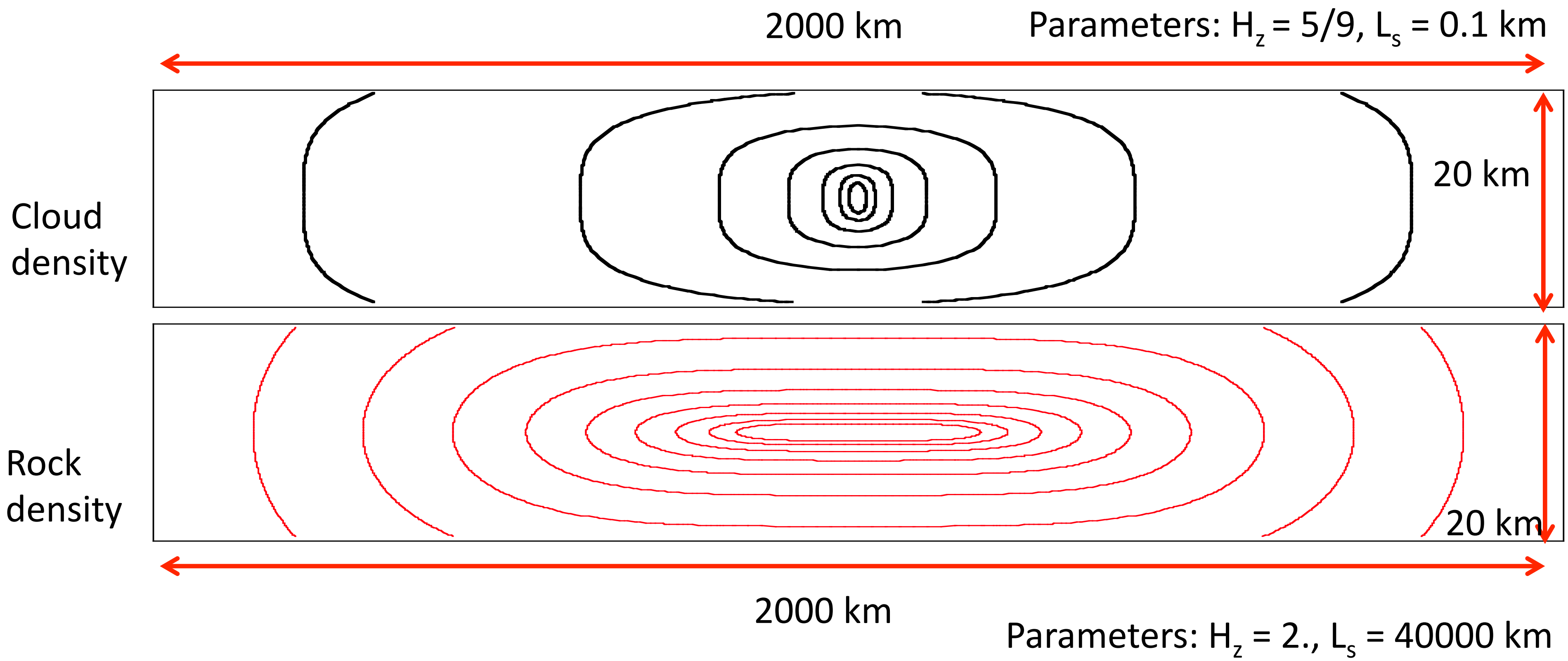
$$\underbrace{\Delta v(\Delta x)=\varepsilon^{1/3}\Delta x}_{\text{Kolmogorov}}{}^{1/3};\quad \overbrace{\Delta v(\Delta z)=\phi^{1/5}\Delta z}^{\text{Bolgiano-Obukhov}}{}^{3/5}$$

Volume≈L·L·L^{Hz}≈L^{Del} $D_{el}=2+H_z=23/9$ $H_z=(1/3)/(3/5)=5/9$



5km
Blow up X 2.9 (each)
Isotropic
Total: X5000
1 m
Blow up X 2.9,
"squashing" X 1.6
(each)
Anisotropic
Generalized
Scale
Invariance

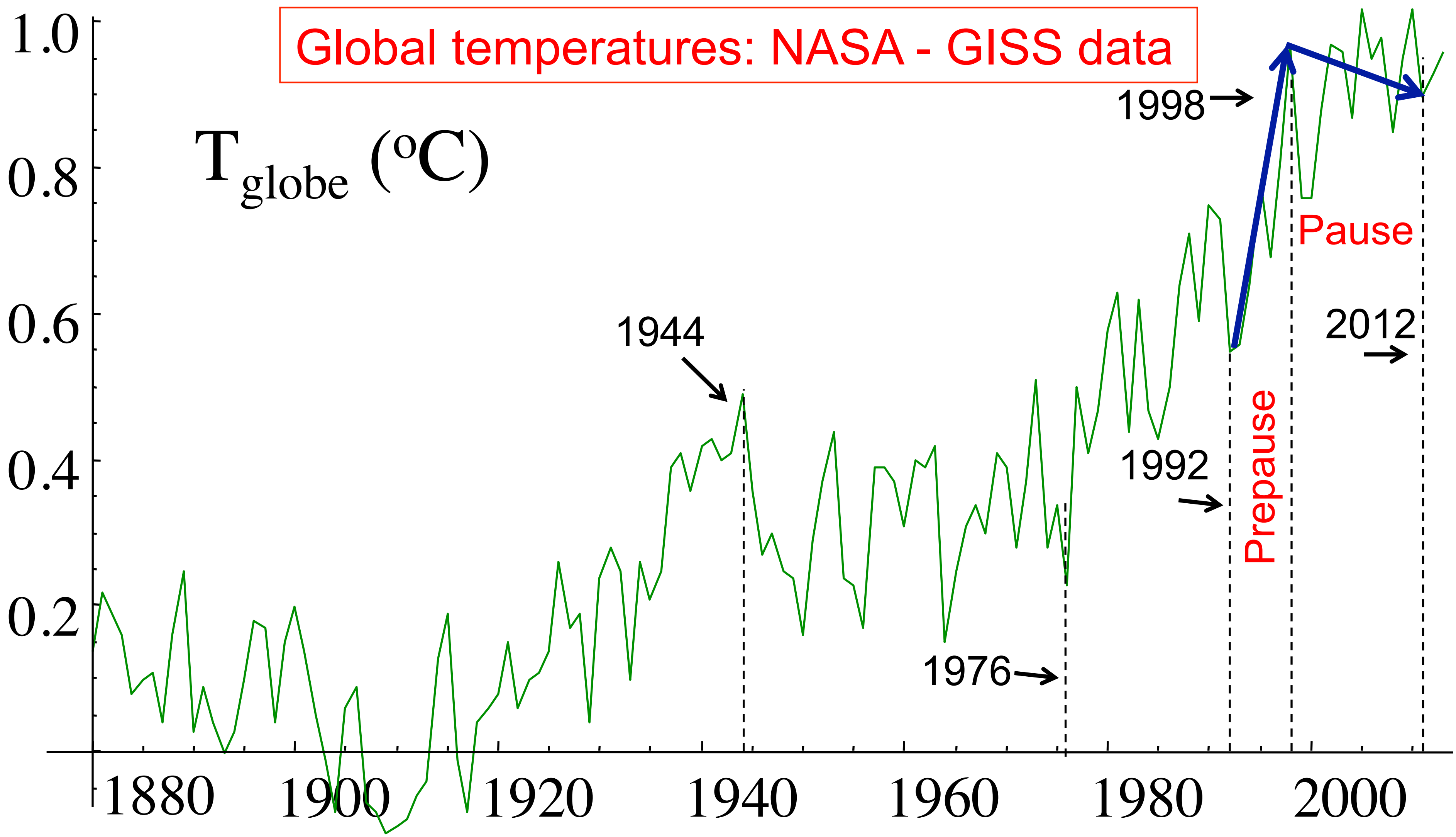
The unity of geosciences: clouds and rocks



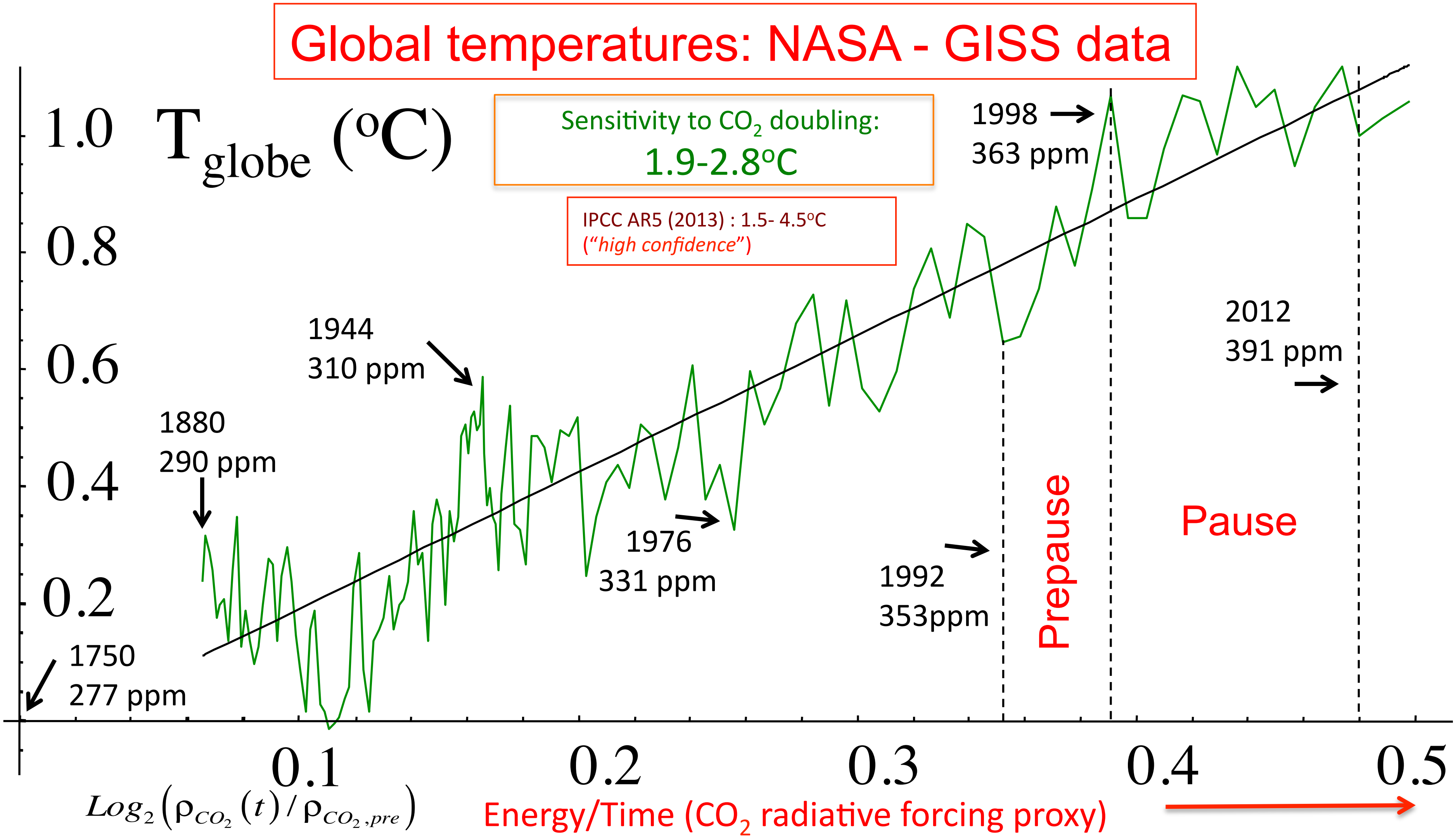
aspect ratios = 1/5

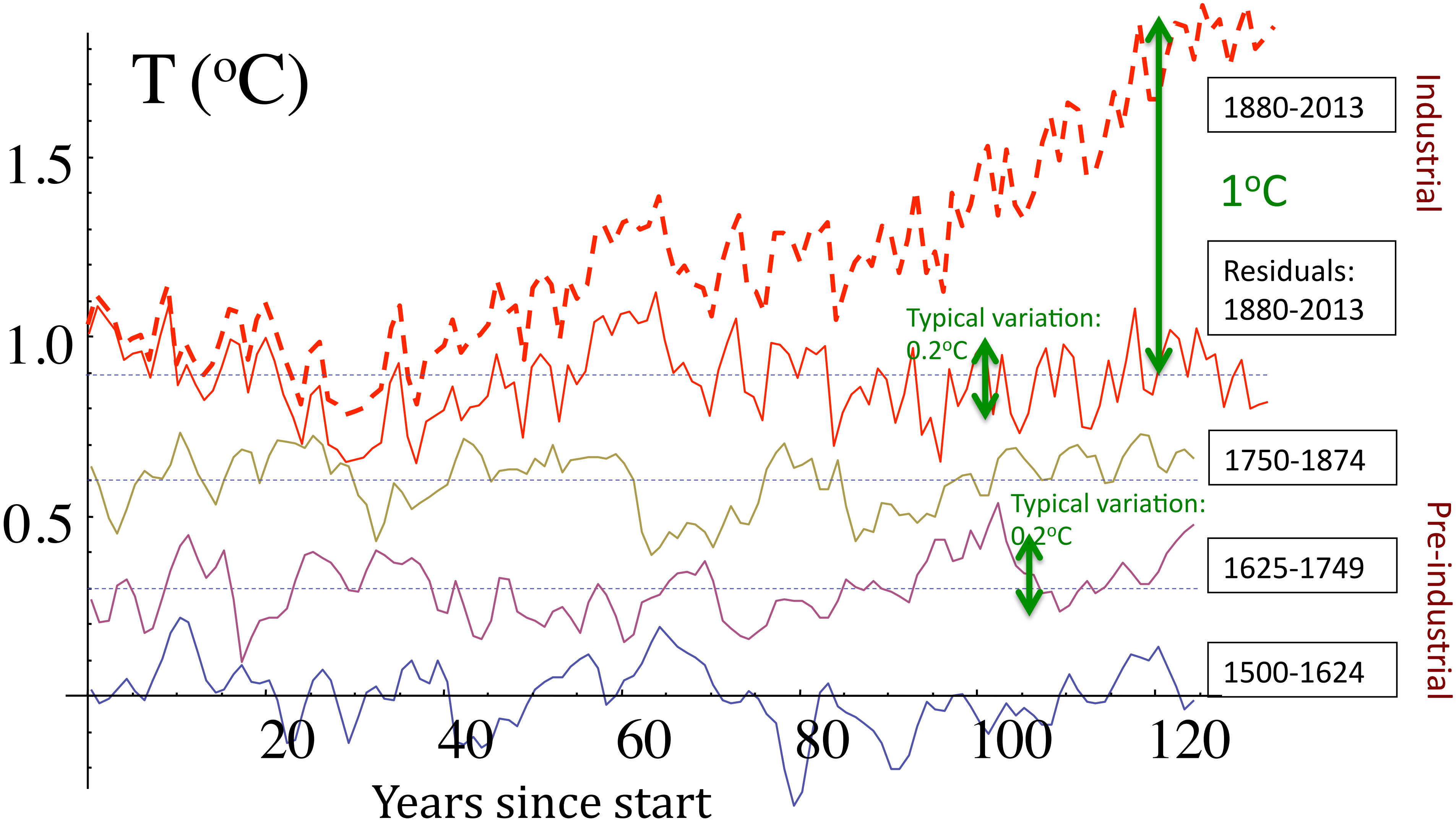
Lovejoy and Schertzer 2008

Statistical testing of Anthropogenic Warming



Global temperatures: NASA - GISS data
T globe (oC)
1.0
0.8
0.6
0.4
0.2
1880
1900
1920
1940
1960
1980
2000
1944
1976
1992
1998
2012
Prepause
Pause


Global temperatures: NASA - GISS data
T globe (°C)
Sensitivity to CO2 doubling:
1.9-2.8°C
IPCC AR5 (2013) : 1.5- 4.5°C
("high confidence")
1.0
0.8
0.6
0.4
0.2
1998
363 ppm
1944
310 ppm
1880
290 ppm
2012
391 ppm
1976
331 ppm
1992
353ppm
Prepause
Pause
1750
277 ppm
0.1
0.2
0.3
0.4
0.5
$Log_2(\rho_{CO_2}(t)/\rho_{CO_2,pre})$
Energy/Time (CO2 radiative forcing proxy)

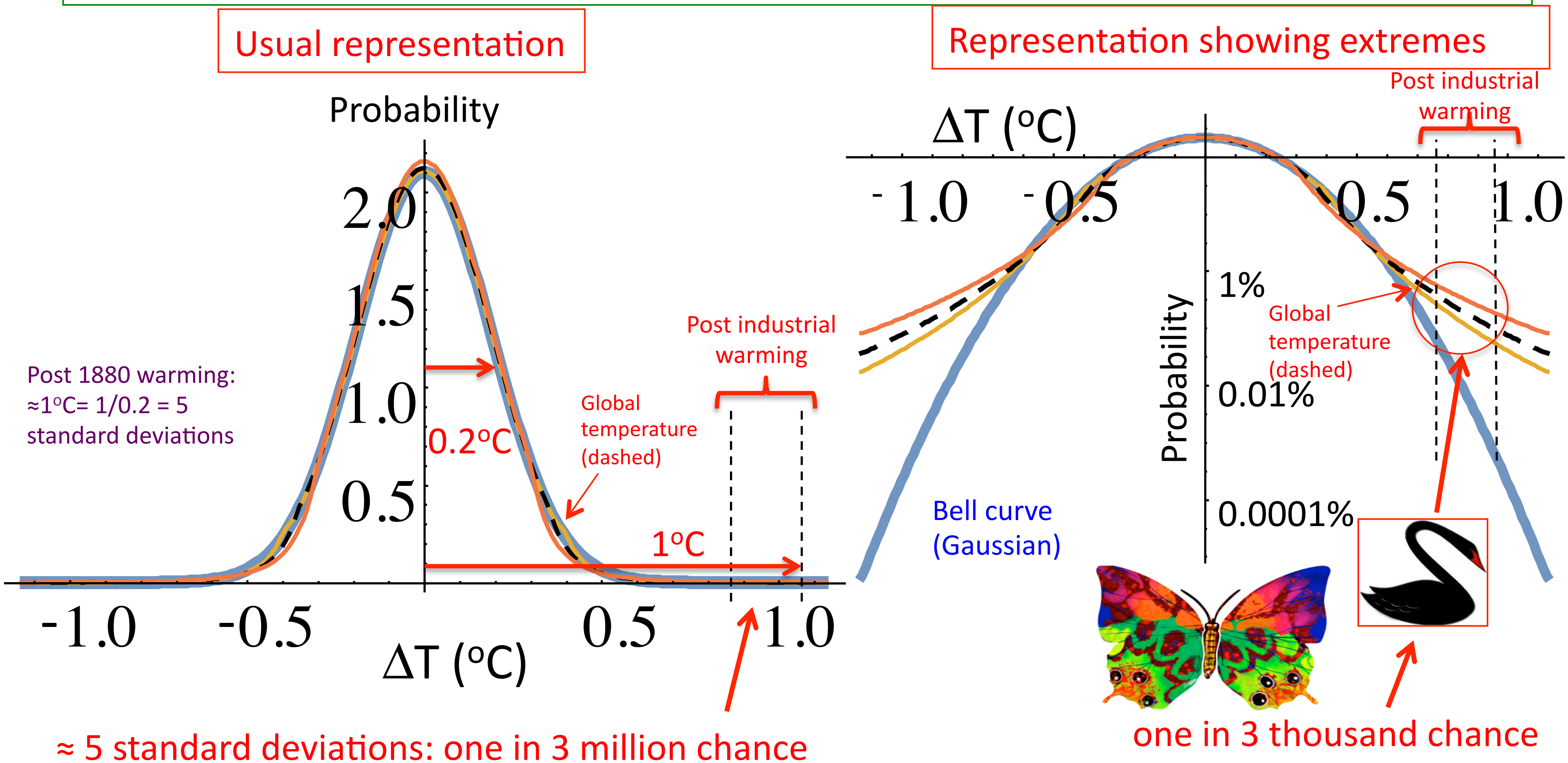


T (°C)
1.5
1.0
0.5
20
40
60
80
100
120
Years since start
1880-2013
Industrial
1°C
Residuals: 1880-2013
Typical variation: 0.2°C
1750-1874
Typical variation: 0.2°C
1625-1749
1500-1624
Pre-industrial

The Natural Warming Hypothesis

What is the probability of a ≈1°C global temperature increase over ≈ 125 years?

Probabilities of extremes: Bell Curve, Black Swans



Macroweather

(monthly, seasonal, annual, decadal)

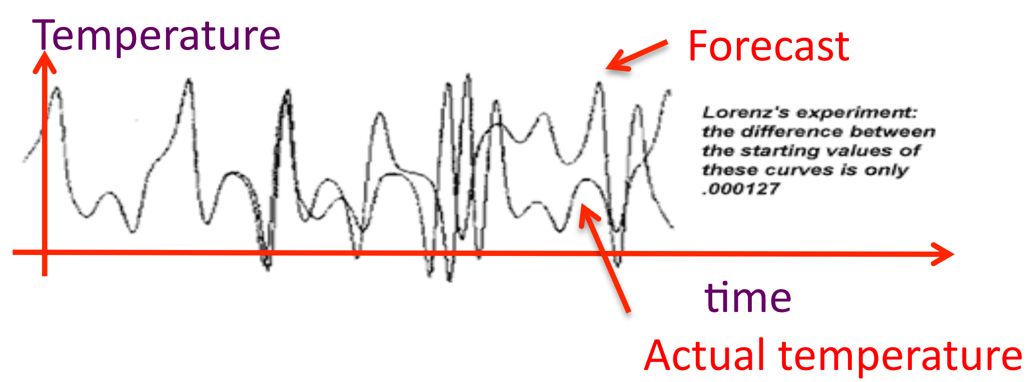
forecasting

Limitations of General Circulation Models and stochastic alternatives

Loss of *deterministic* predictability after 10 days

= "butterfly effect"

"Does the flap of a butterfly's wings in Brazil set off a tornado in Texas" Lorenz 1972



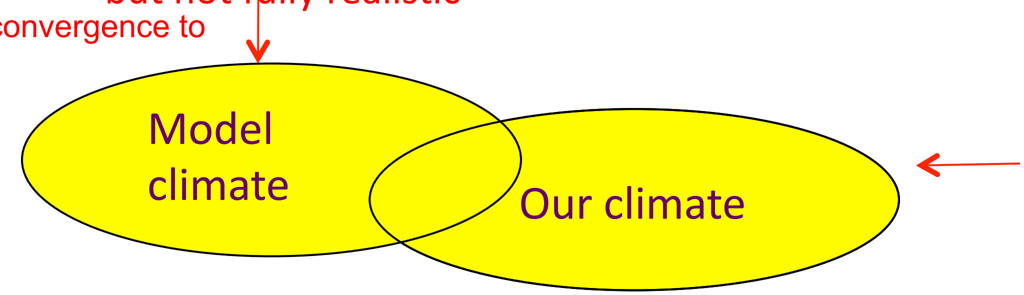
But by harnessing the butterfly effect we obtain some *stochastic* predictability....

GCMs for forecasts longer than ≈ 10 days

"Brute force"

Weather systems generated by GCMs
= random weather noise…
but not fully realistic

Averages: slow convergence to



Scaling laws generate
realistic noise

Potential advantages of stochastic forecasting:

a) More realistic weather "noise"

b) Ability to use empirical data to force convergence to the real climate

ScaLIng Macroweather Model (SLIMM)

1. Macoweather ≈ 30 years industrial, 100 years pre-industrial

$$\langle \Delta T \rangle \approx \Delta t^{H}$$ -1/2<H<0

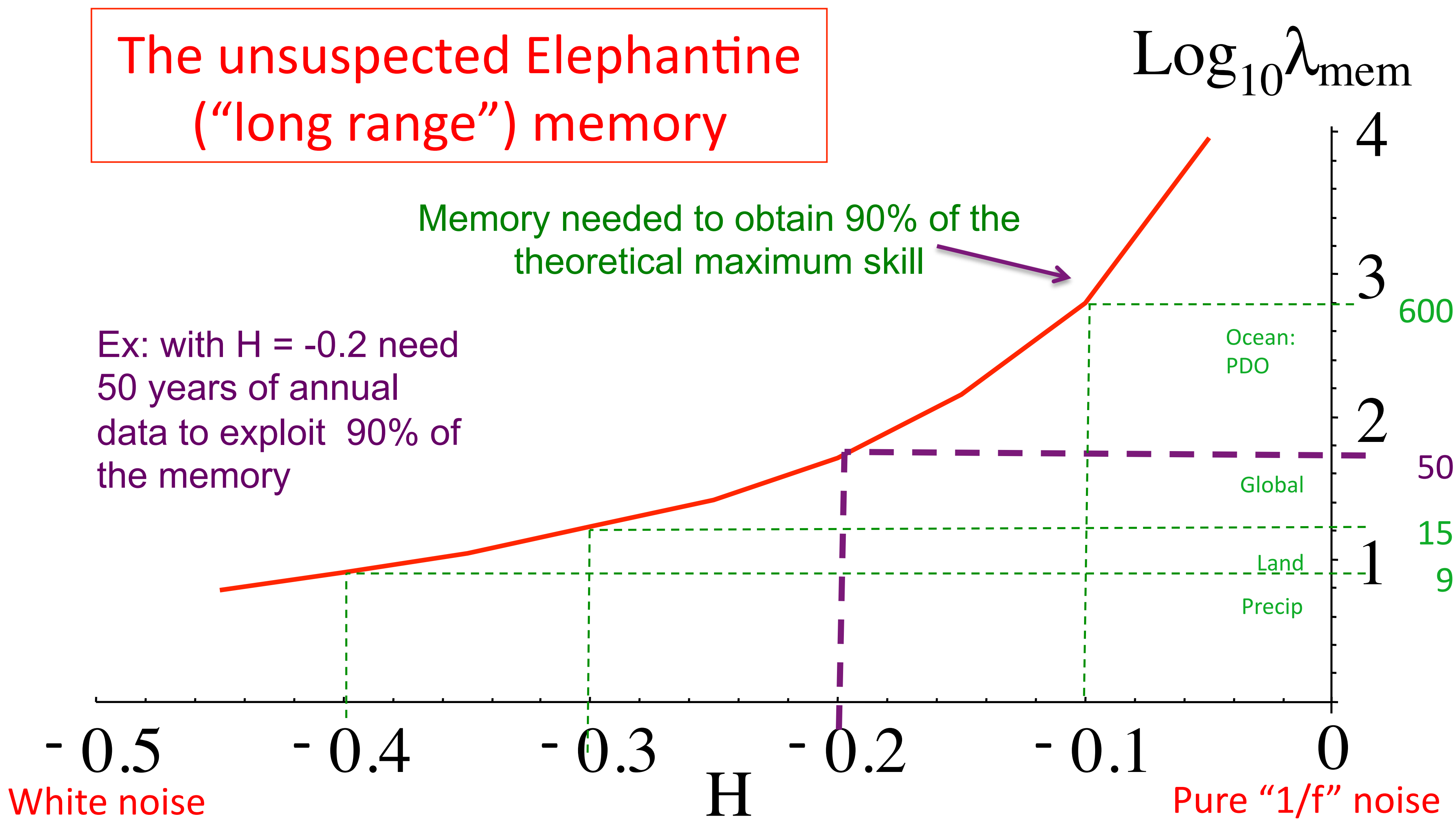
2. Simple model: fractional Gaussian noise:

$$T(t) = \int_{-\infty}^{t} (t - t')^{-(1/2-H)} \gamma(t') dt' \quad \Longleftrightarrow \quad \frac{d^{H+1/2}}{dt^{H+1/2}} T(t) = \gamma(t)$$

Gaussian white noise

Corresponds to fractional integral of order H+1/2 of white noise

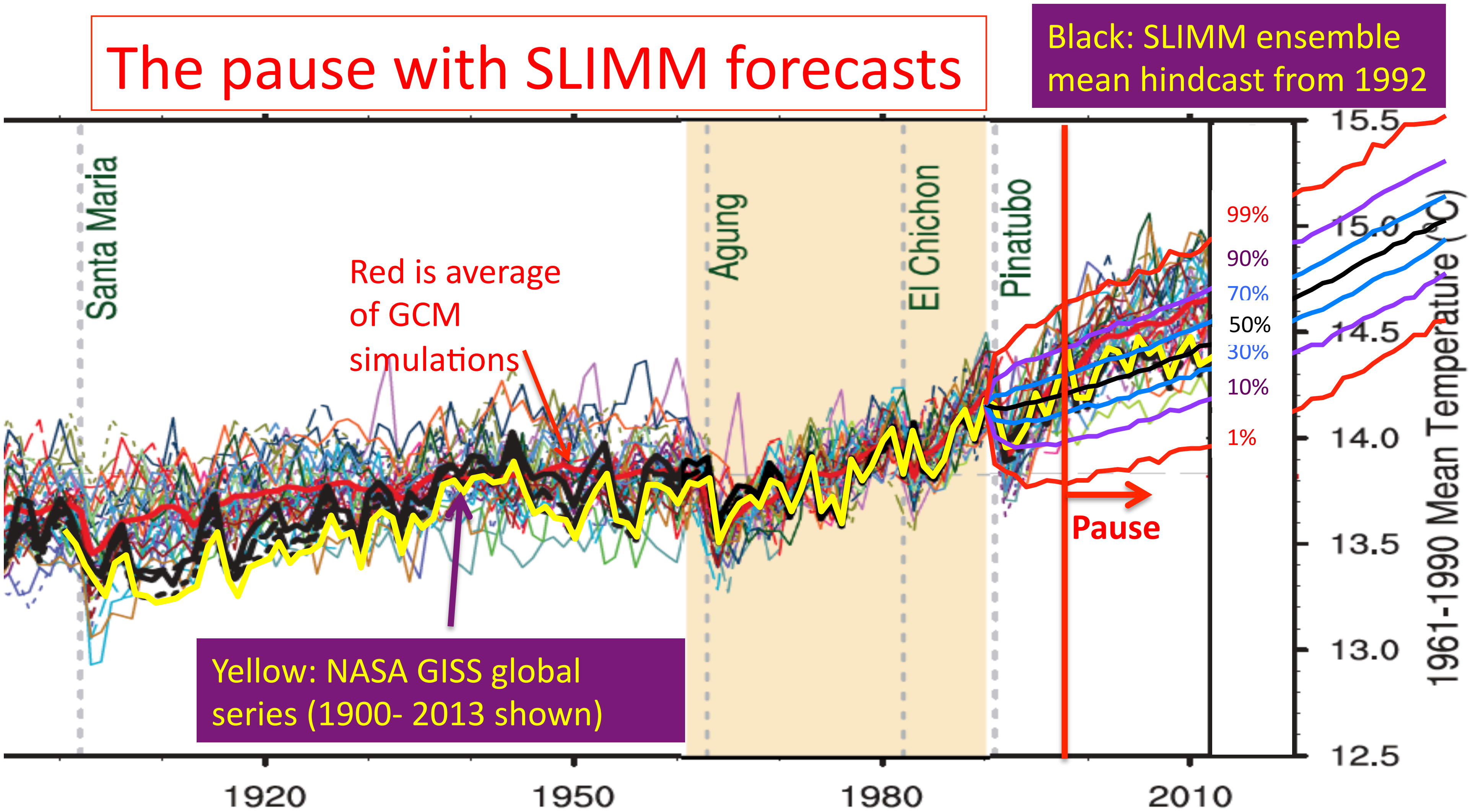
3. Vast memory due to power laws
4. Memory can be used for forecasting, the latter is a solved problem mathematically


The unsuspected Elephantine
("long range") memory
Log10λmem
4
3
2
1
600
50
15
9
Memory needed to obtain 90% of the
theoretical maximum skill
Ex: with H = -0.2 need
50 years of annual
data to exploit 90% of
the memory
Ocean:
PDO
Global
Land
Precip
- 0.5
- 0.4
- 0.3
- 0.2
- 0.1
0
H
White noise
Pure "1/f" noise

Using SLIMM to Hindcast the “Pause”, “slowdown”, “hiatus” since 1998

(The conditional probability of the pause)

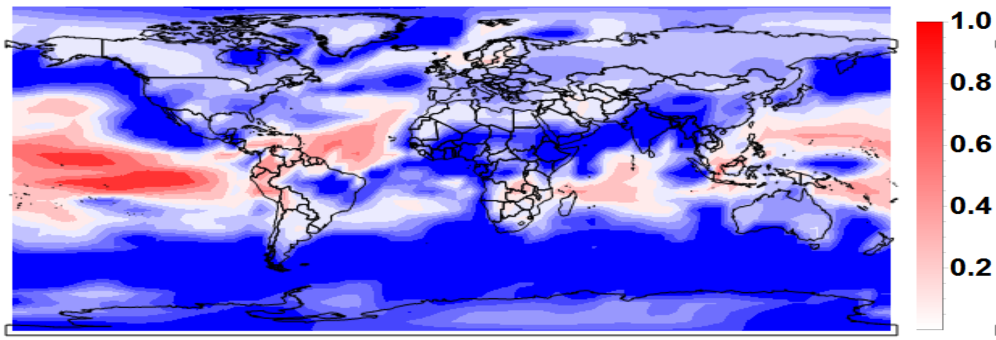
The pause with SLIMM forecasts



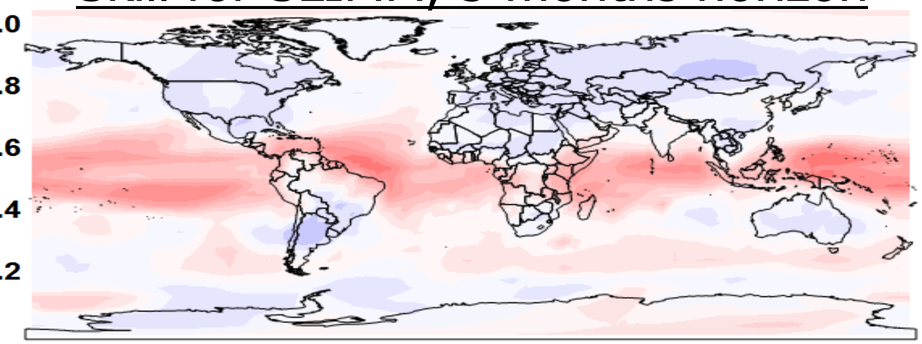
Regional monthly, seasonal, annual forecasting using SLIMM

Comparing seasonal (3 month) SLIMM and CanSIPS (GCM)

Skill for CanSIPS, 3 months horizon



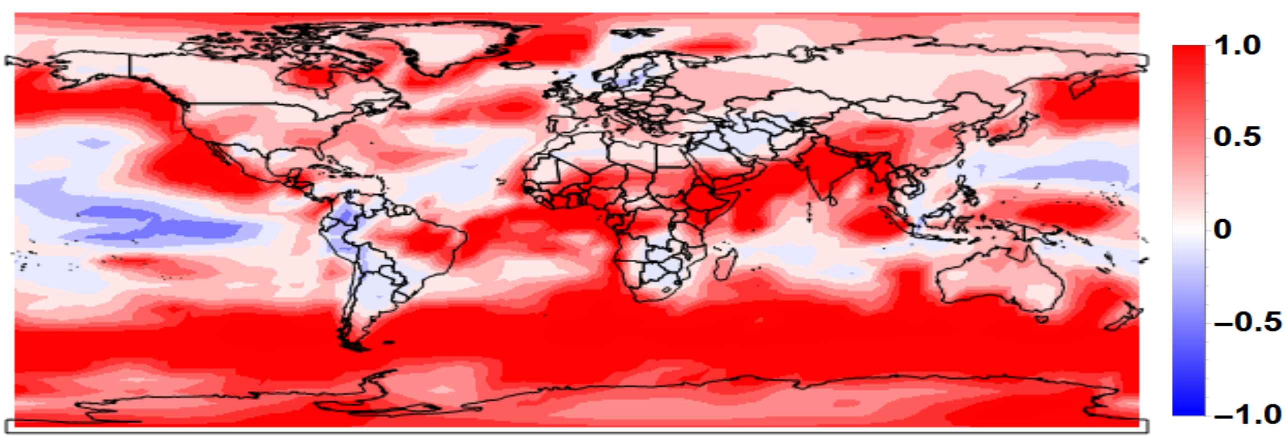
Skill for SLIMM, 3 months horizon



Blue= negative skill

Jan. 1982 – Dec. 2008

Difference of Skill SLIMM - CanSIPS



SLIMM>CanSIPS
90% of earth

Conclusions:
The (unfinished) geo-revolutions of our time

-Geodata and informatics:
Data sets spanning three or more orders of magnitude in space and in time are now increasingly available (remote sensing, in situ networks, reanalyses)

-Computing and in numerical modelling:
Ex.: General Circulation Models now span three or more orders of magnitude in scale, in time from minutes to Millenia.

-Nonlinear understanding:
Systems with dynamics spanning wide ranges of space-time scales:
fractals, multifractals, generalized scale invariance, extremes
(+deterministic chaos + self-organized criticality + networks+ nonlinear waves+…)