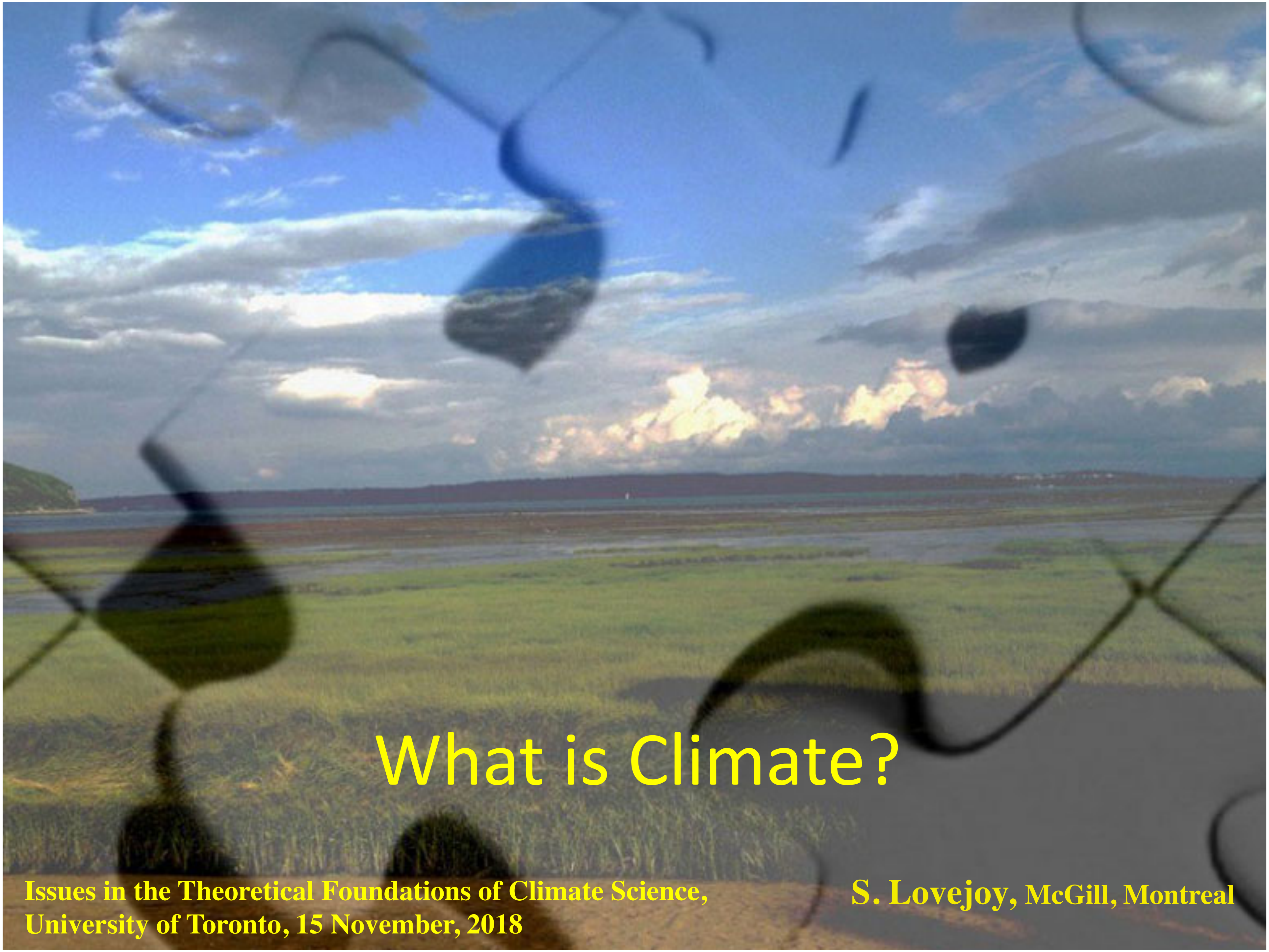


What is Climate?

Issues in the Theoretical Foundations of Climate Science, University of Toronto, 15 November, 2018

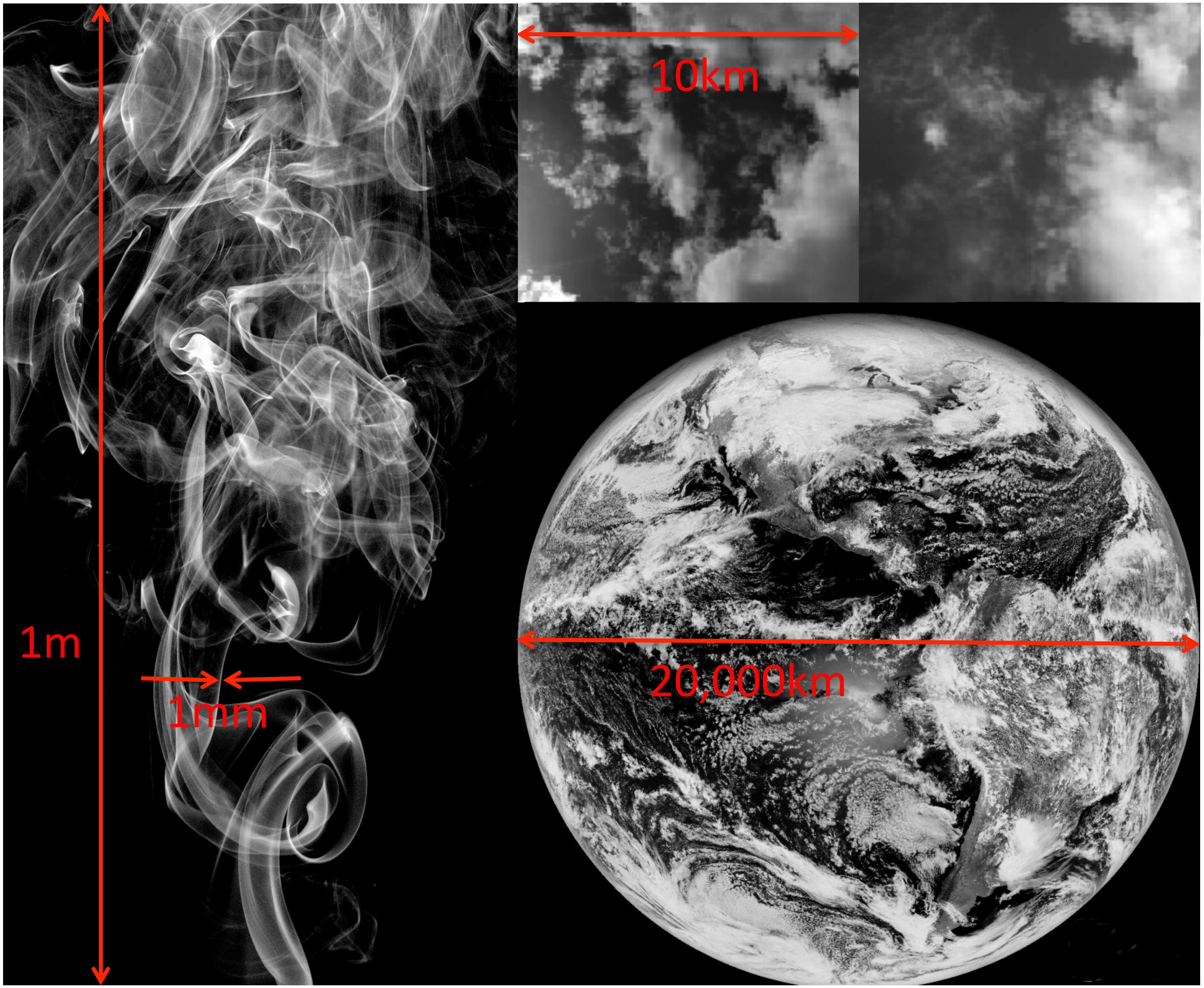
S. Lovejoy, McGill, Montreal

A voyage through scales

Zooming through scales by the billion

1mm - 10,000 km

A voyage through scales: Space, 0.1mm – 10,000km

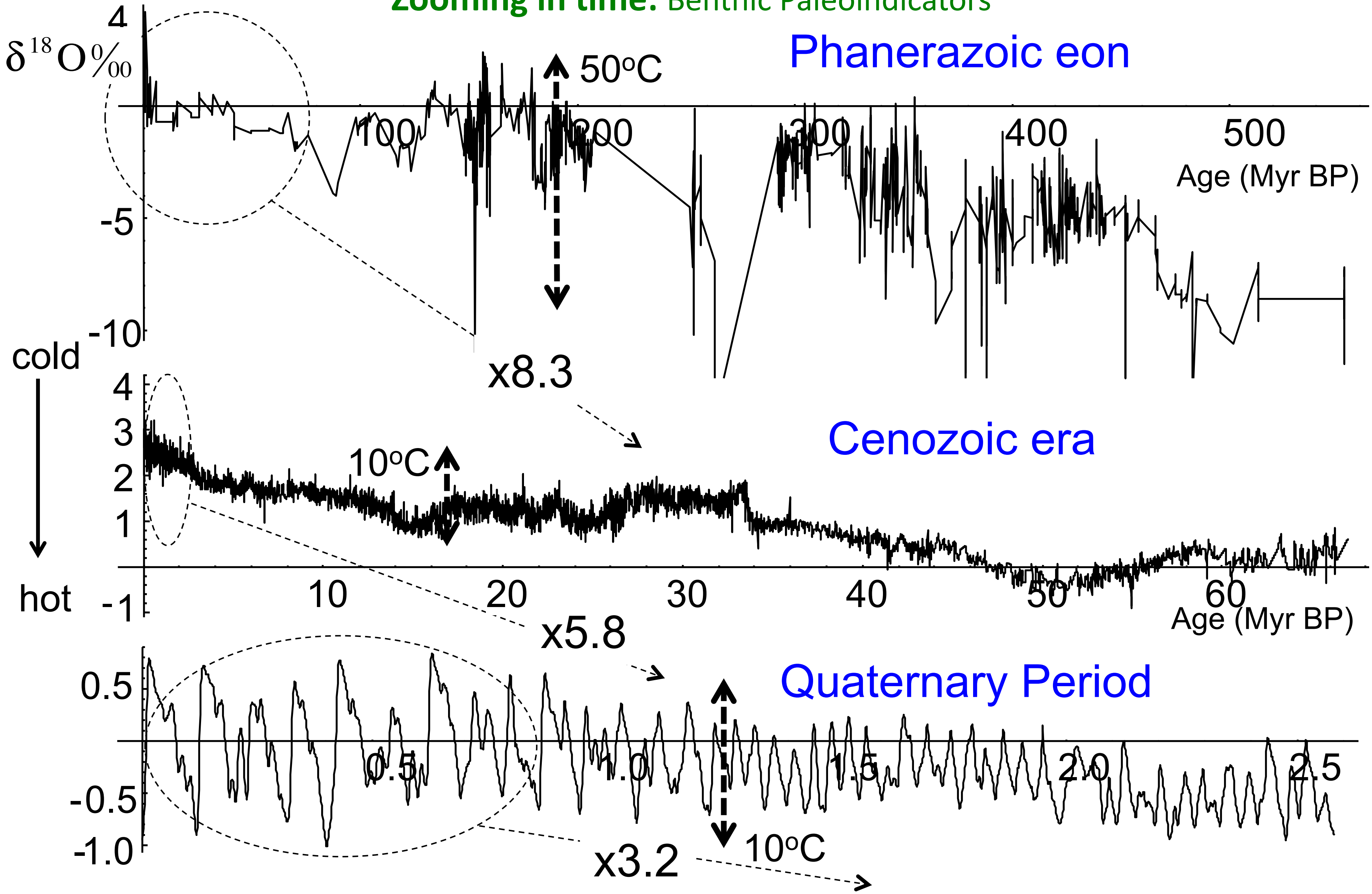


A voyage through scales

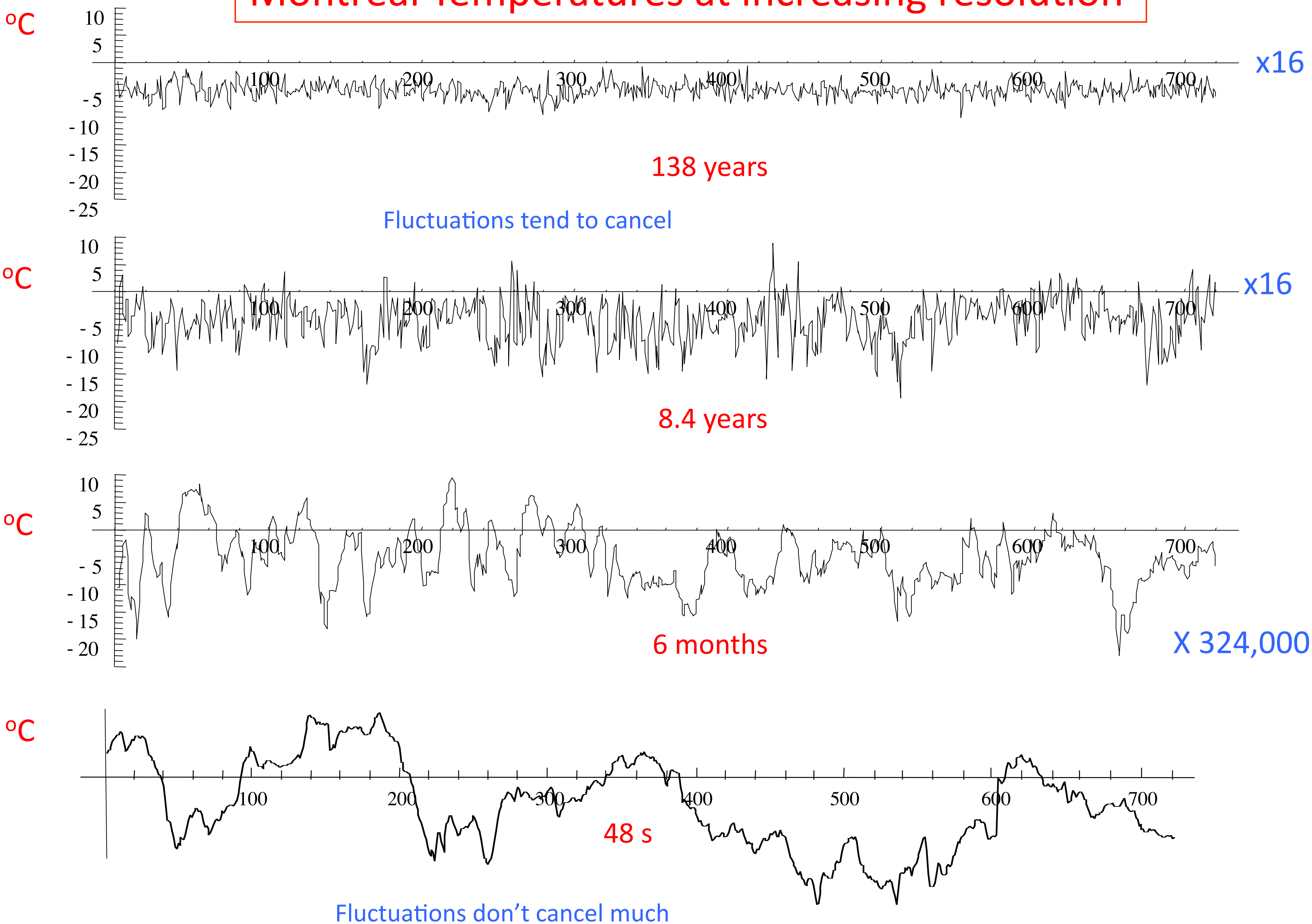
Zooming through scales by the
billion billion
milliseconds to half a billion years

A voyage through scales: Time, 0.001s – 4.5 billion years

Zooming in time: Benthic Paleoindicators



Montreal Temperatures at increasing resolution

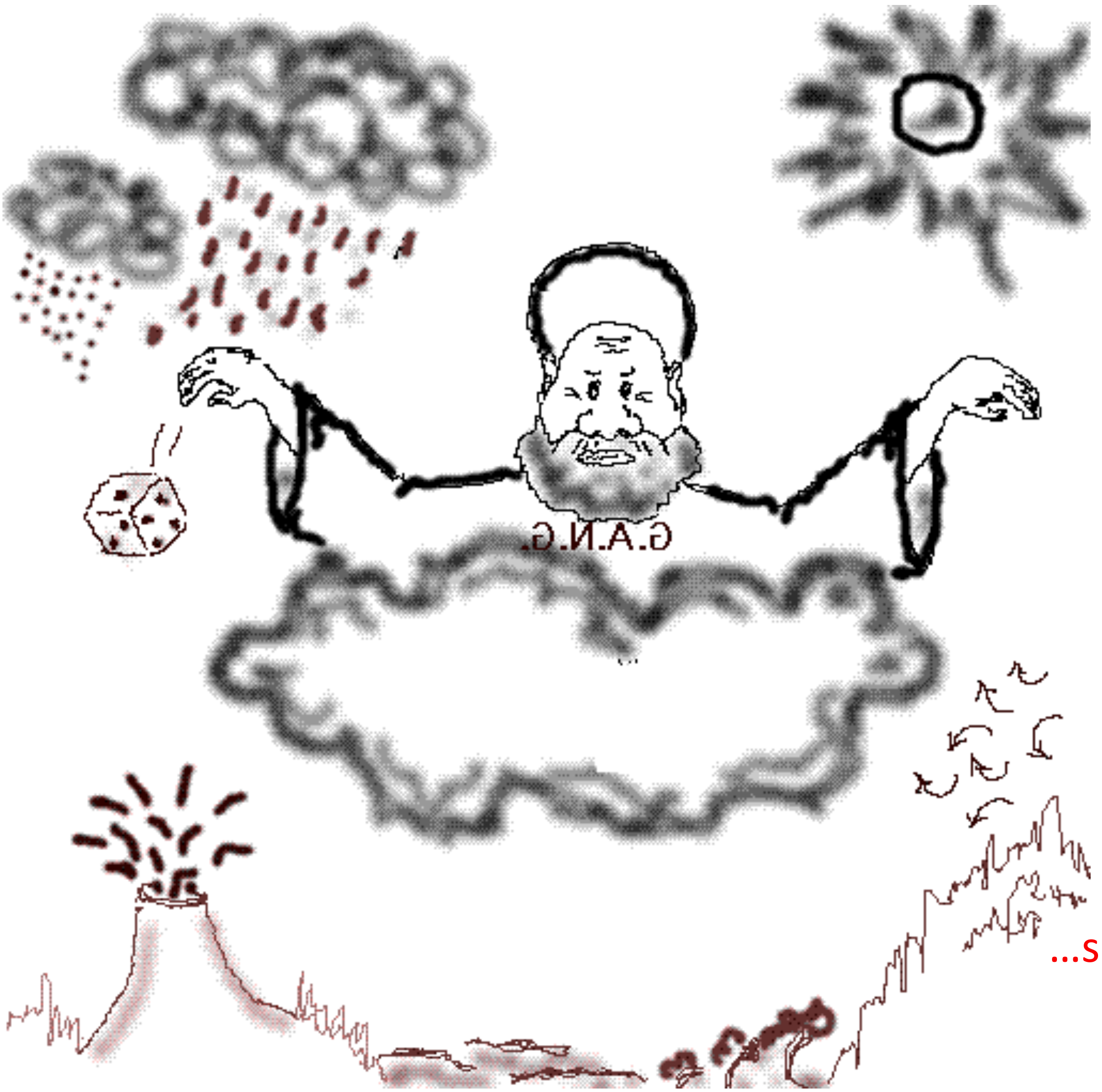


How to understand this mind-boggling variability? (1)

Deterministic or random?

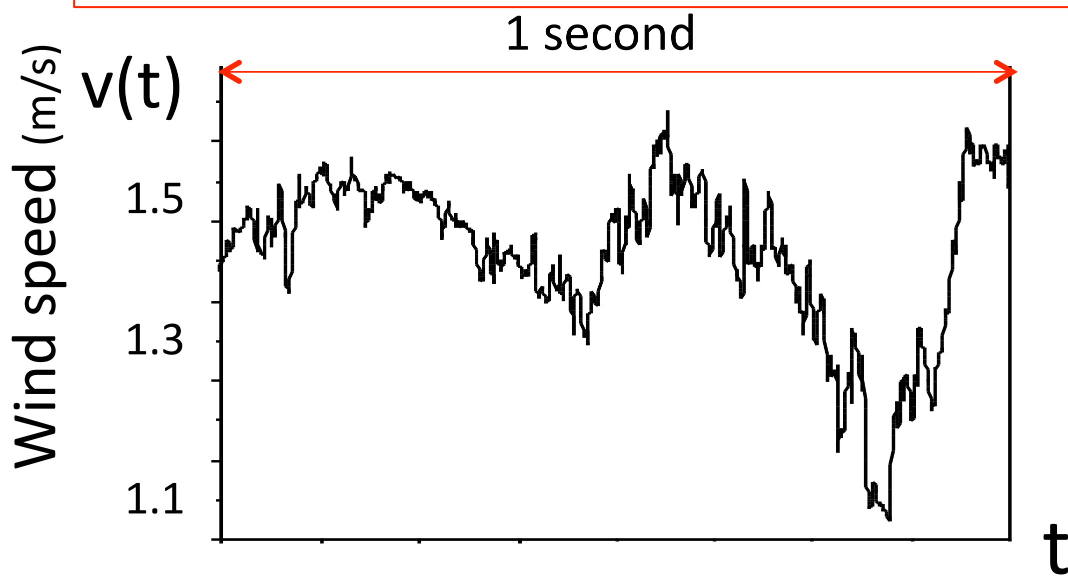
Which Chaos?

How does God play dice??

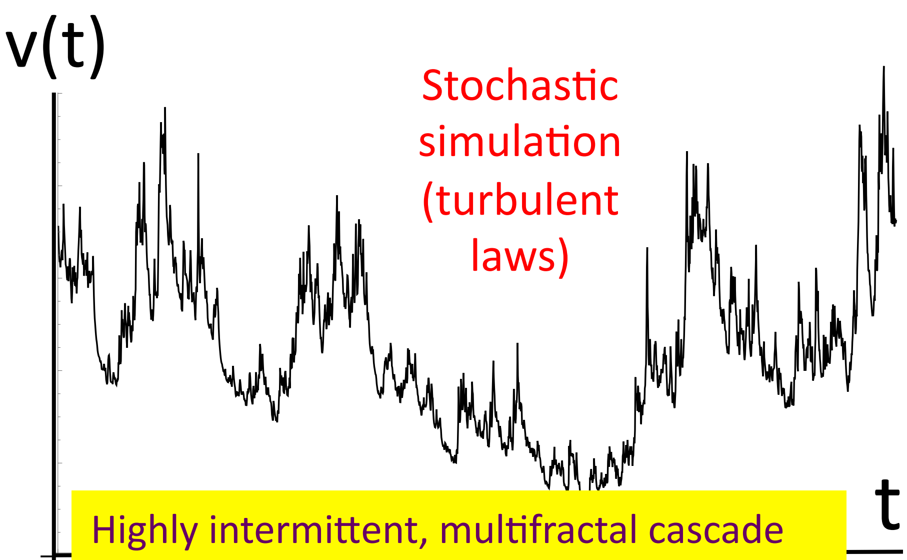


...sorry Einstein!

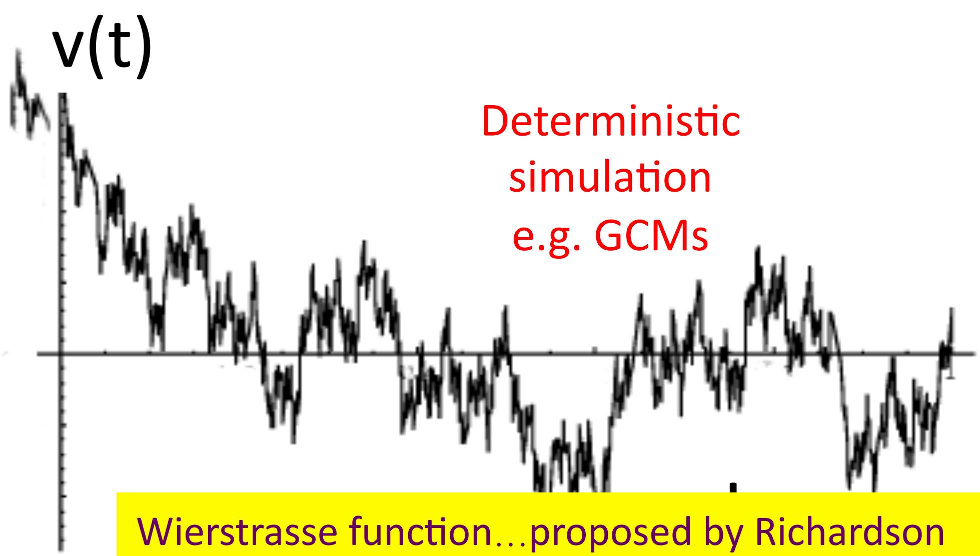
Which Chaos?
Stochastic or Deterministic?



Data, roof of physics building



Highly intermittent, multifractal cascade model proposed in 1987



Wierstrasse function…proposed by Richardson 1926: “Does the wind have a velocity?”

Cosmos versus Chaos through the ages

Chaos-Cosmos (ancient Greeks): first there was chaos… then cosmos…

Scientific ideas about determinism and randomness:

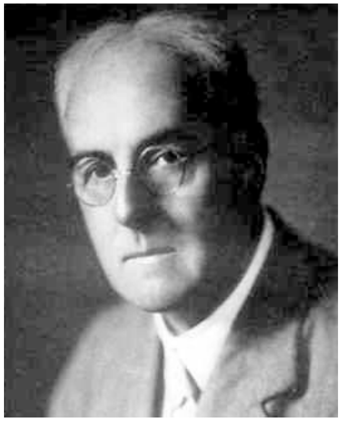
Determinism: God supplies the initial conditions (e.g. planets in orbits, Newton, 1670's)
"…if a sufficiently vast intelligence exists…" Laplace (1749-1827).

Chance: Ignorance, subjective
"Chance is nothing" Voltaire: (1694-1778).

Chance: Irrelevance of the details
Statistical Mechanics e.g. the bell curve distribution of molecular velocities in a gas (Maxwell, Gibbs, Boltzman, 1870-1900).

Chance: Objective chance, Stochastic Chaos in systems with many degrees of freedom
Quantum Mechanics: Born interpretation of the wave function (1926)
Mathematics: Kolmogorov axiomatized probability theory (1933).

Determinism: Random-like Deterministic Chaos in systems with few degrees of freedom (Lorenz 1963).

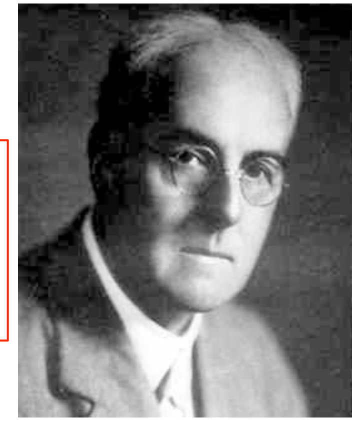


1922

Janus-faced

(two strands)

1926



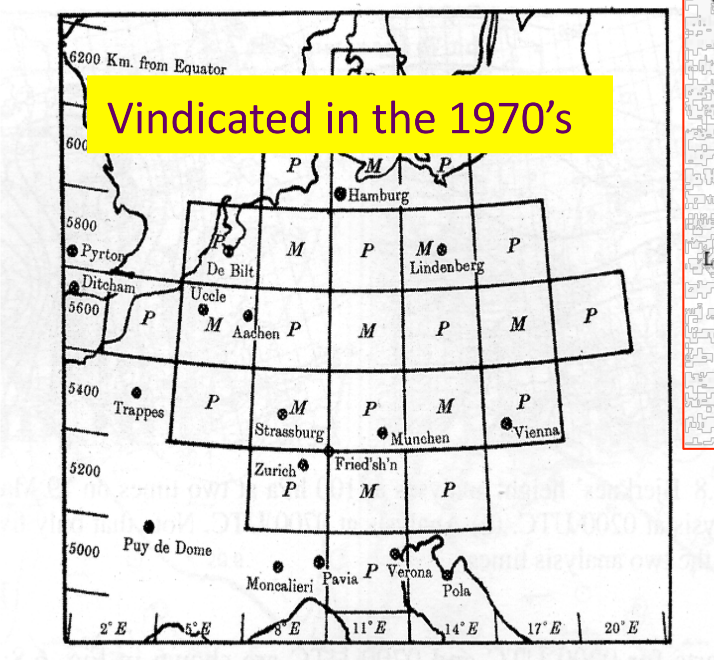
Richardson and NWP

Father of numerical weather prediction

Richardson, turbulence, scaling

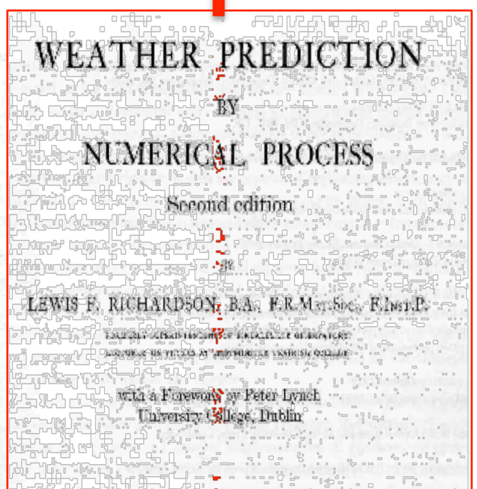
Grandfather of turbulent cascades

Determined the pressure tendency at grid point M



Vindicated in the 1970's

It took six weeks of calculation… and he was wrong by a factor of 100!



WEATHER PREDICTION

BY

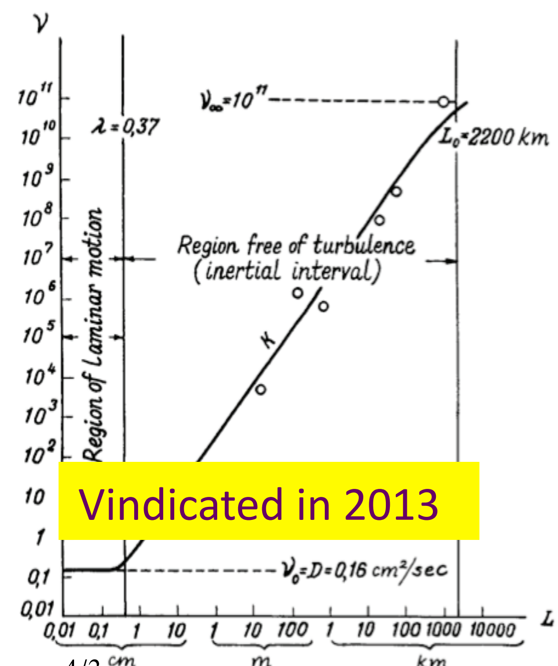
NUMERICAL PROCESS

Second edition

BY

LEWIS F. RICHARDSON, B.A., F.R.Met.Soc., F.Inst.P.

with a Foreword by Peter Lynch
University College, Dublin



Vindicated in 2013

(Redrawn by Monin 1972)

$$\nu(L) = KL^{4/3}$$

constant

Effective viscosity

since $\nu = L\Delta v$

Kolmogorov's contribution was $K = \varepsilon^{1/3}$

The Nonlinear Revolution
1970 - 1990 - present

The Deterministic Chaos Revolution: The Butterfly Effect

-Tiny perturbations could be amplified

-Random looking phenomena might not be random after all…

-Backlash: an attempt to resurrect Newtonian determinism

The Stochastic Chaos alternative: scale symmetries, fractals, multifractals

-Objective randomness…

Two revolutions: unity lost

Up until 1970's weather and climate science were a pragmatic combination of both deterministic and statistical approaches.

The Numerical revolution: NWPs, GCMs

Milestones:
Initialization
Ensemble forecasting
4D var (data assimilation)
Extension to climate
Earth System Models

Today: GCMs increasingly answer all questions
-Simulation replaces understanding
-Science reduced to engineering
-Theory/data connection broken

The Nonlinear revolution

Milestones:
Irrelevance of details, Stochastic chaos
Objective randomness
Scaling symmetries
Fractals, multifractals
Anisotropic scaling
Empirical vindication of Richardson
Understanding

Separate nonlinear processes divisions
EGU (1989), AGU (!997)

2010's: Unity refound?

GCMs respect scaling laws… and control runs can be stochastically forecast, and scaling yields better climate projections

The neglected strand of atmospheric science:

Pioneers of turbulence

Laws of Atmospheric Turbulence

Pioneers

Differences

homogeneous

Isotropic

Fluctuations ≈ (turbulent flux) x $(\text{scale})^H$

Wavelets

Cascading, Multifractal
Turbulent flux

Anisotropic
Space-time
Scale function

1983-present

Fourier domain:

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

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

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

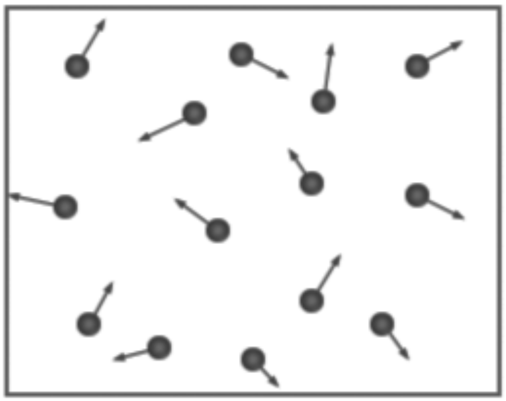
Time: $E(\omega) \approx \omega^{-\beta}$

How to understand this mind-boggling variability? (2)

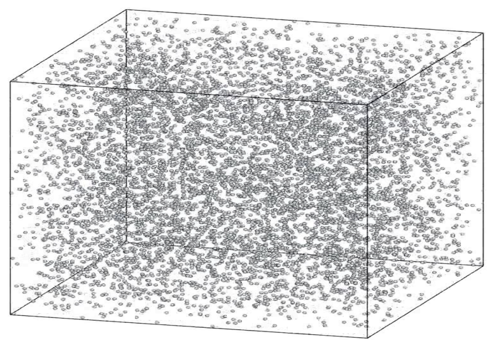
High level or low level laws?

Emergent laws: Which level?

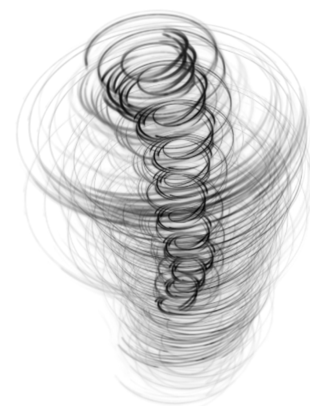
Mechanics of a few particles



Statistical Mechanics: many particles



Collective behaviour of Thermodynamics, continuum mechanics, GCMs

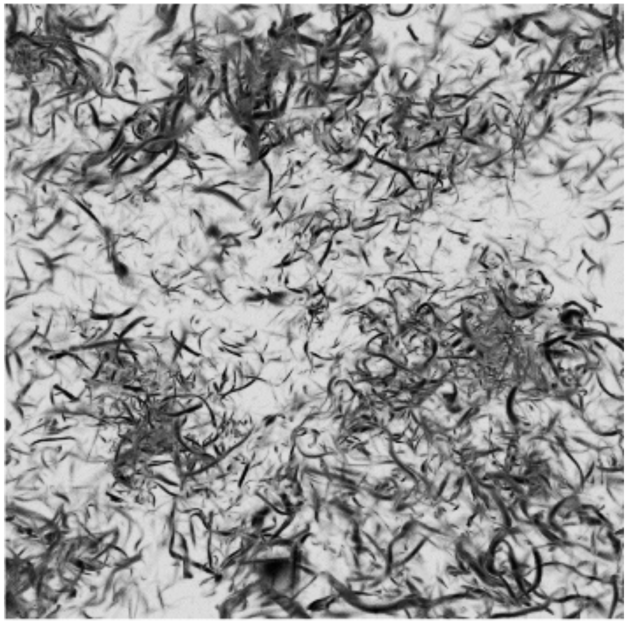


Irrelevance of most of the details, collective behaviour of many, many components

The hierarchy continues

Continuum mechanics of a single vortex

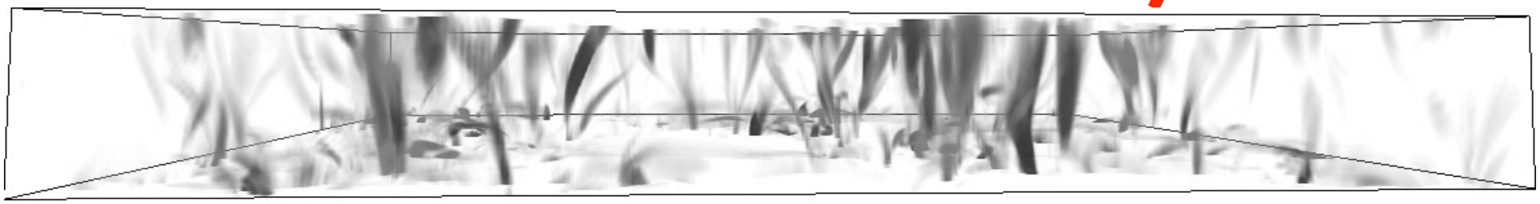
Collective behaviour of many vortices: Turbulent laws



"spaghetti" picture

Irrelevance of most of the details, collective behaviour of many, many components

Continuum mechanics Of several vortices



How to understand this mind-boggling variability? (3)

What about the "details"?

Do we (deterministically, mechanistically, *numerically*) account for as many details as possible?

Or

Are most details *irrelevant* and we just need their statistics ?

Scalebound or scaling?

Supercomputers… or laptops?

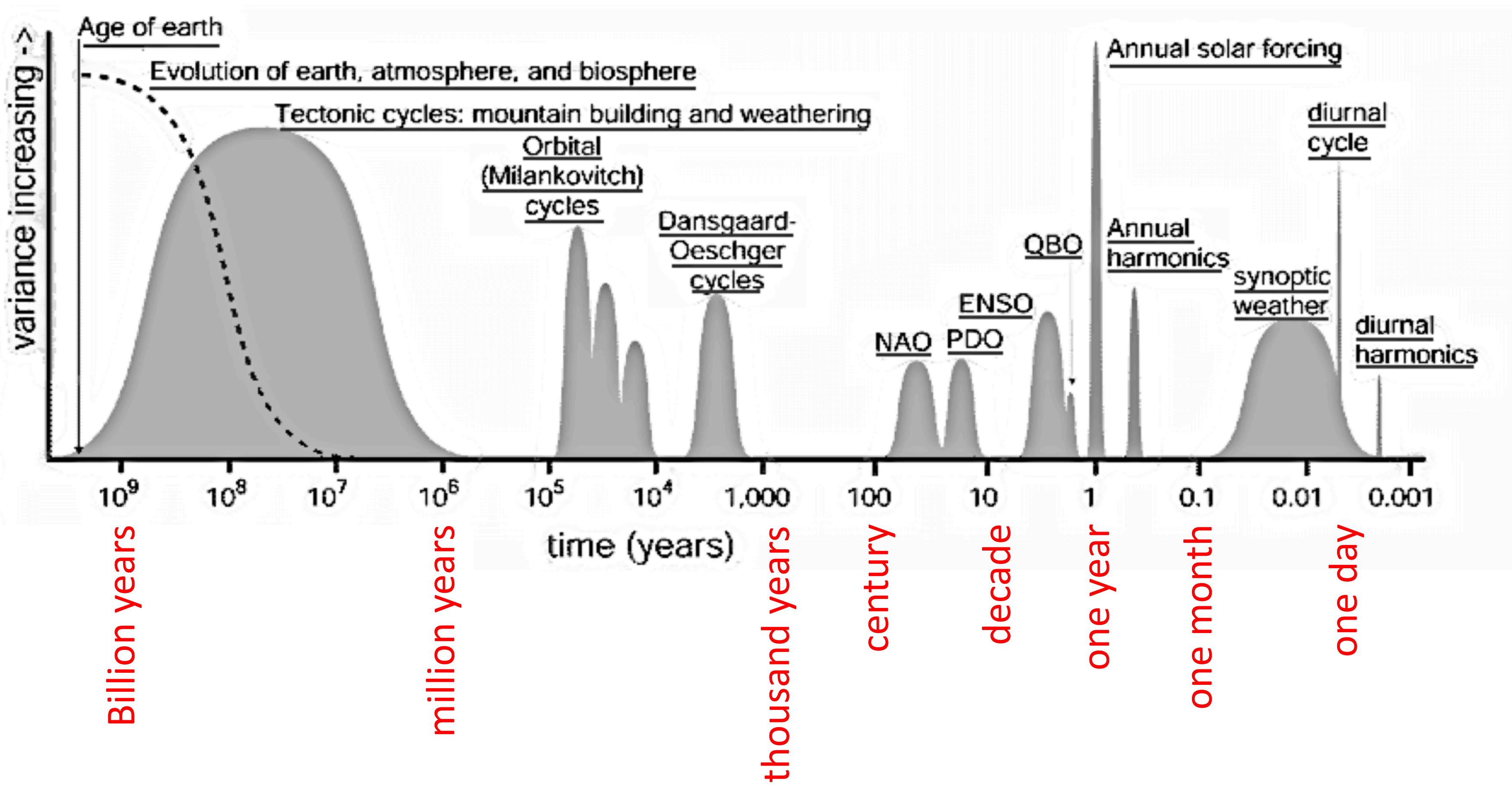
From Van Leeuwenhoek to Mandelbrot

Scalebound thinking and the missing quadrillion

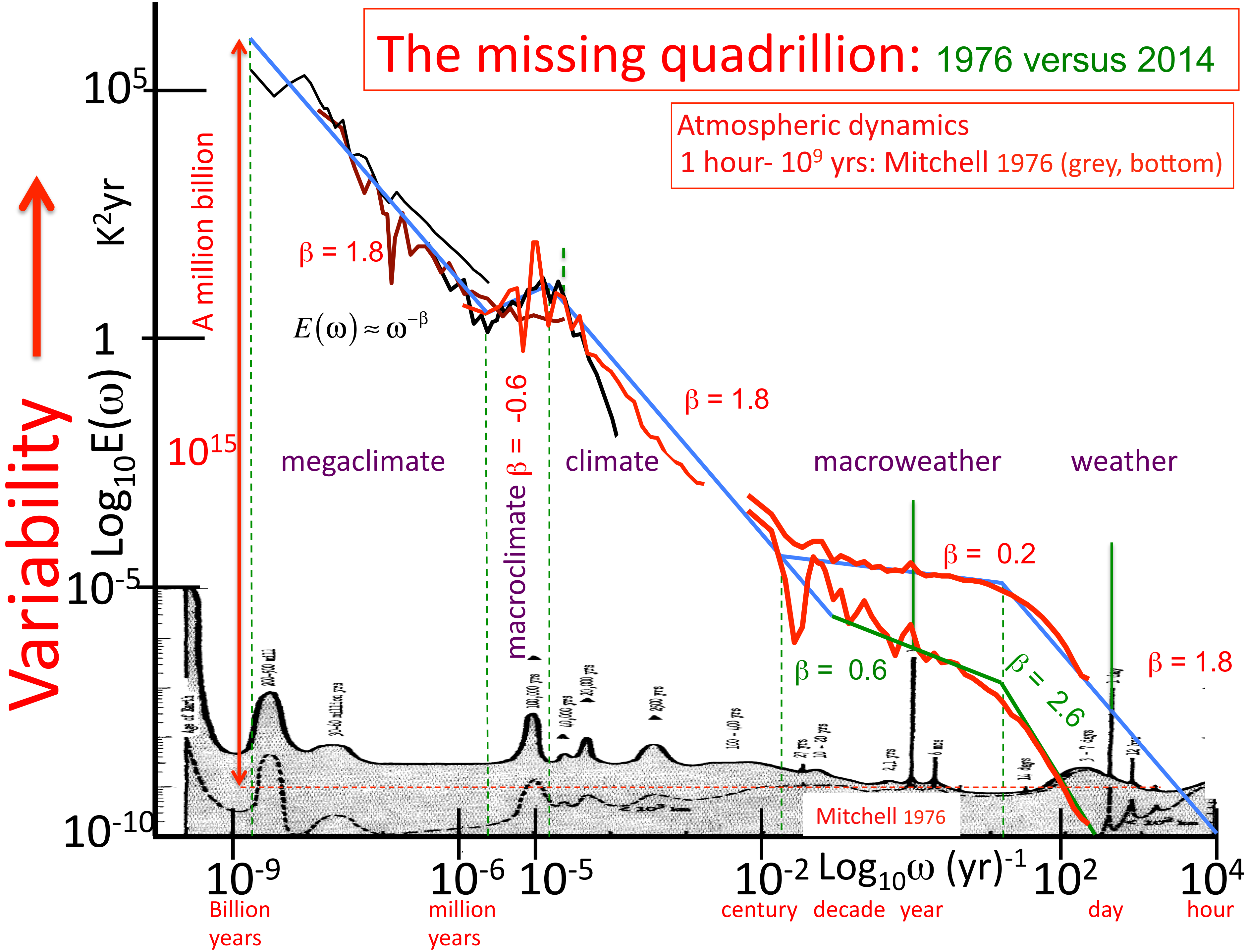
The Scalebound view

Van Leeuwenhoek discovering a “new world” in a drop of water (circa 1690)

Scalebound "Powers of ten" view

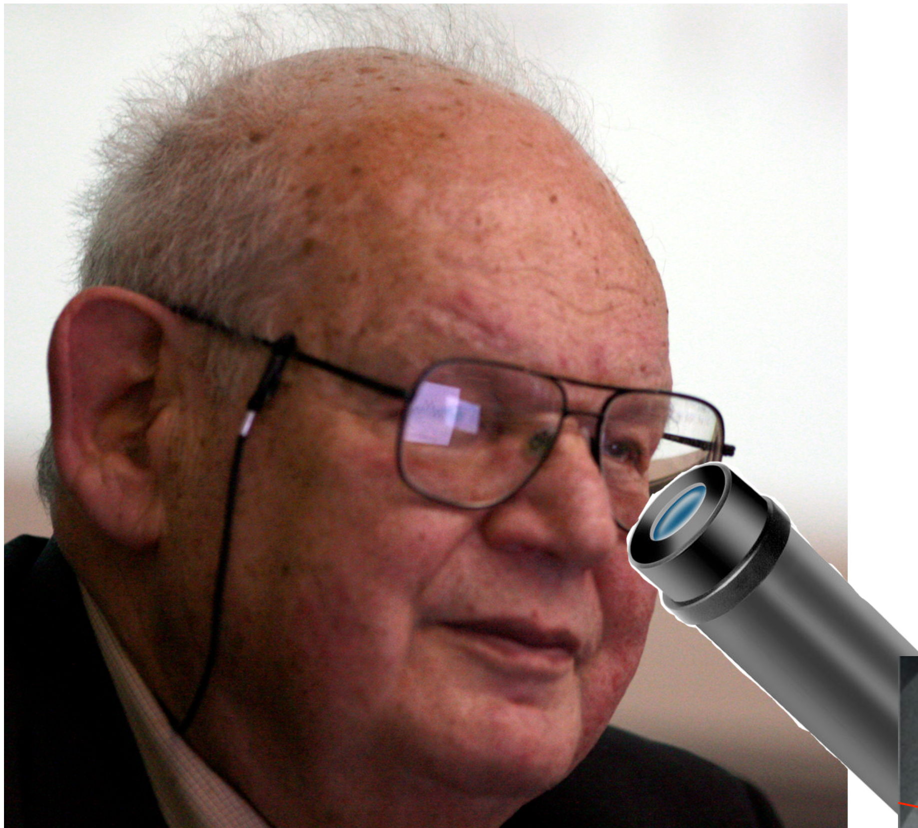


Official National Oceanographic and Atmospheric Administration (NOAA) website 2015

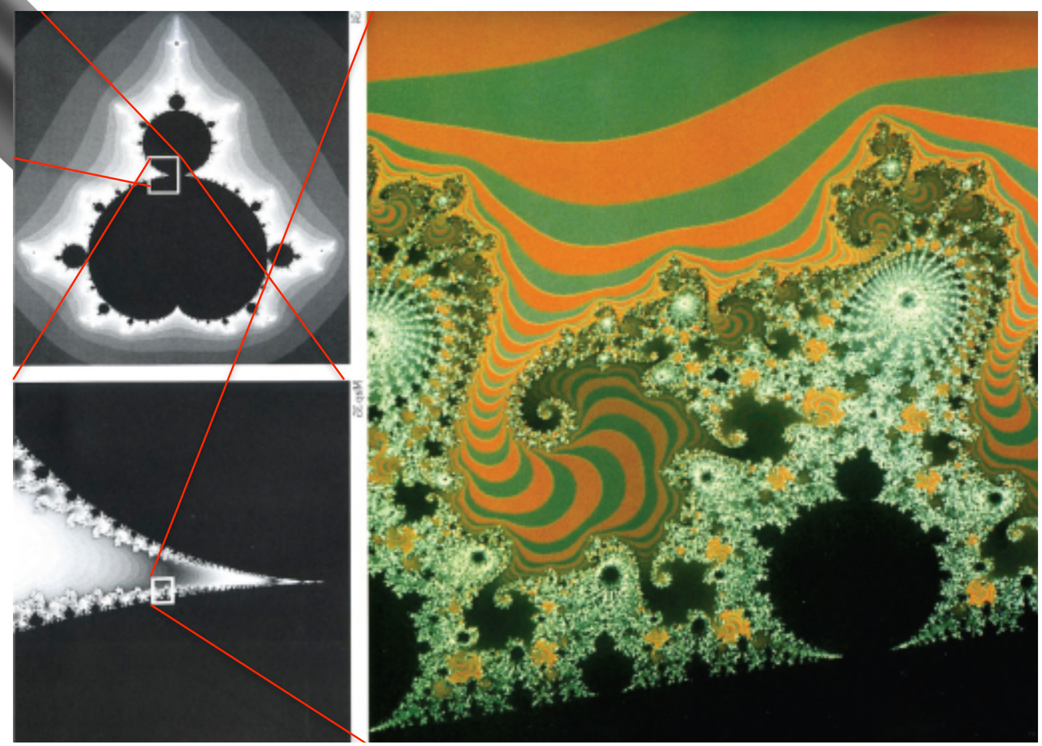


The missing quadrillion: 1976 versus 2014
Atmospheric dynamics
1 hour- 10^9 yrs: Mitchell 1976 (grey, bottom)
Variability
K²yr
Log10E(ω)
A million billion
10^15
10^5
1
10^-5
10^-10
β = 1.8
E(ω) ≈ ω^-β
β = -0.6
macroclimate
megaclimate
climate
β = 1.8
macroweather
weather
β = 0.2
β = 0.6
β = 2.6
β = 1.8
Mitchell 1976
10^-9
10^-6
10^-5
10^-2
Log10ω (yr)^-1
10^2
10^4
Billion years
million years
century
decade
year
day
hour

The Scaling view



Mandelbrot (1924-2010)
zooming into the
Mandelbrot set



Classifying atmospheric variability using Scale Invariance

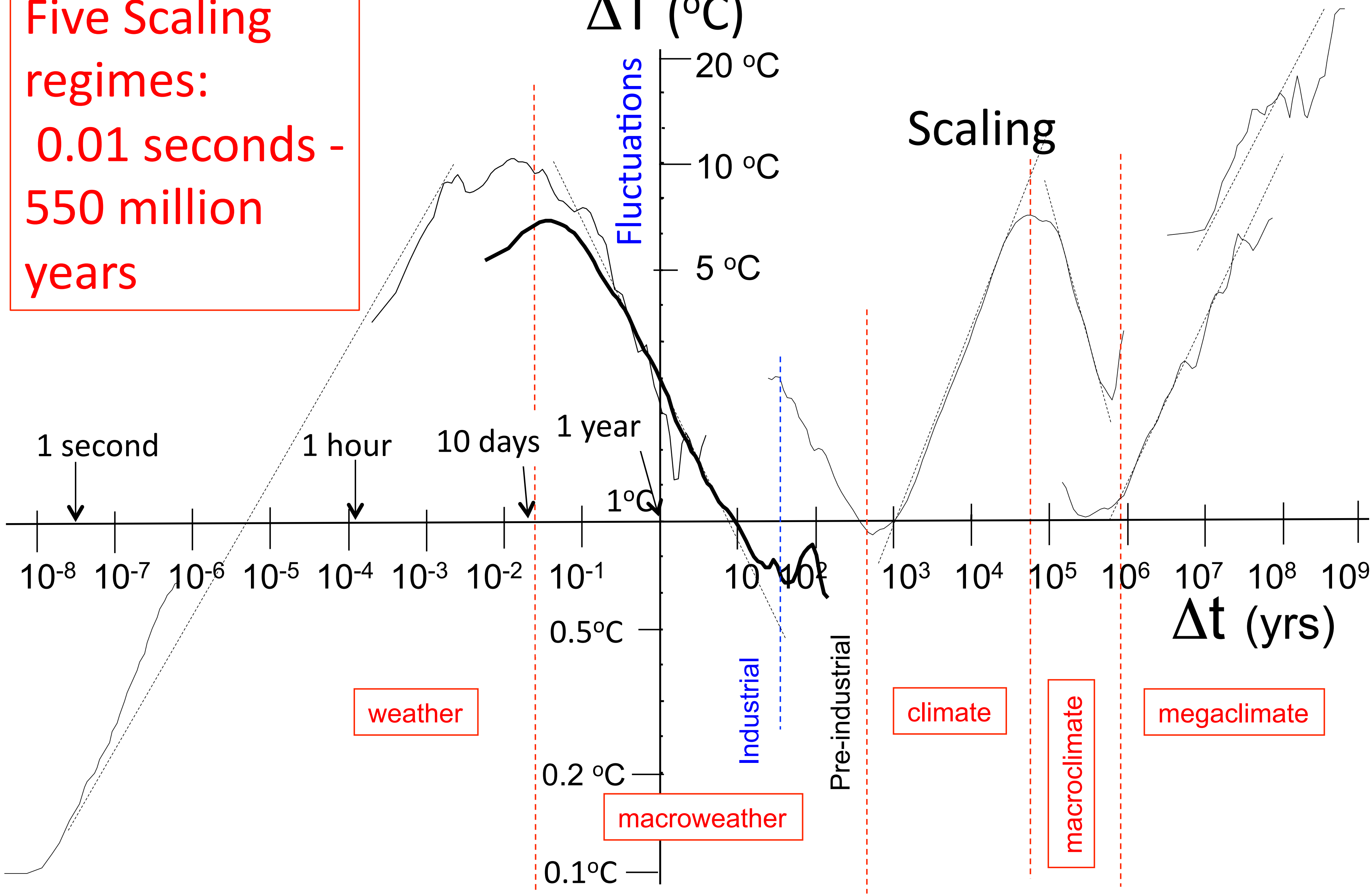
- What is the weather?

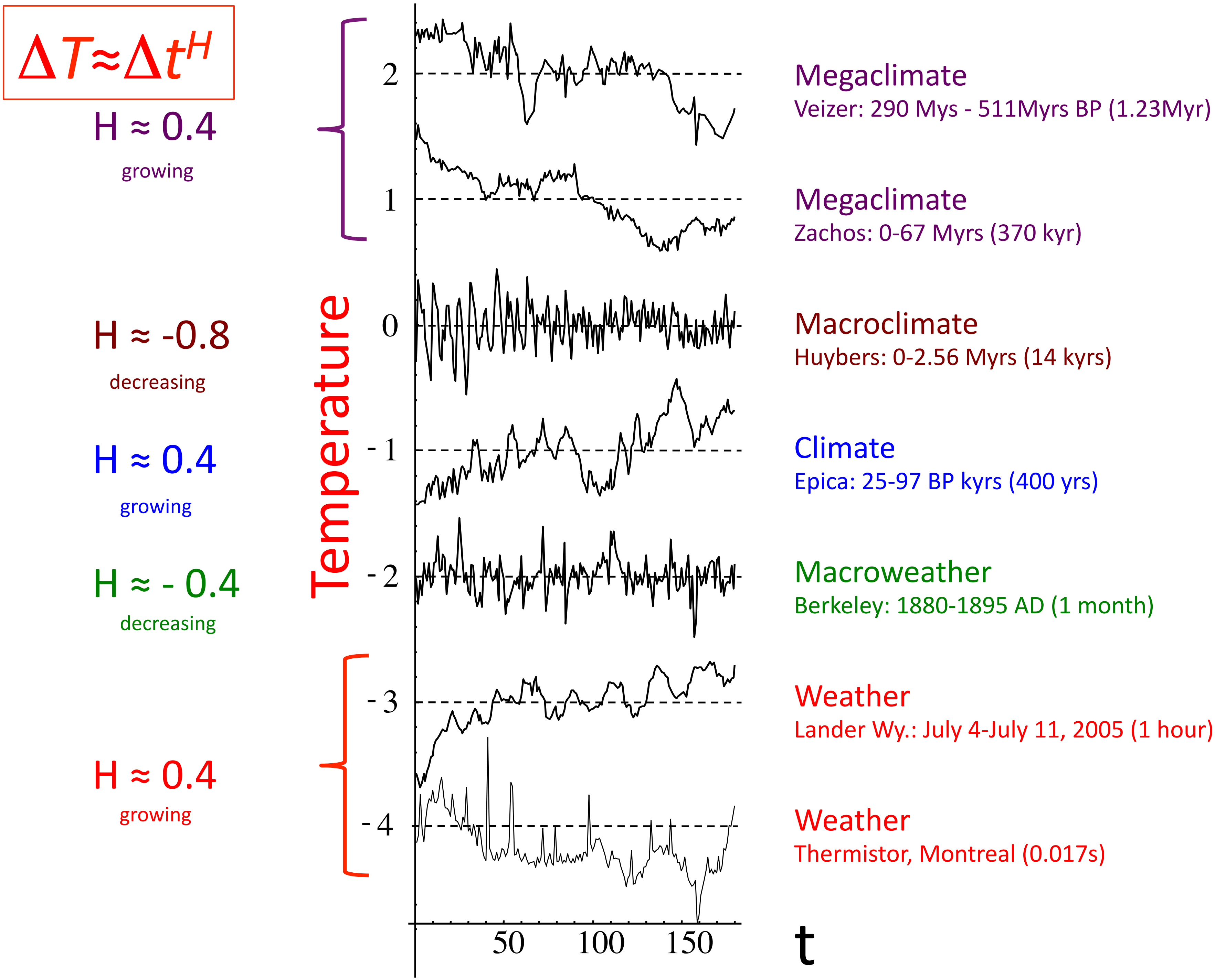
Macroweather?

- What is the Climate?

New simple technique (re)discovered in 2012: Fluctuation analysis

Five Scaling regimes: 0.01 seconds - 550 million years





ΔT≈Δt^H
H ≈ 0.4
growing
H ≈ -0.8
decreasing
H ≈ 0.4
growing
H ≈ - 0.4
decreasing
H ≈ 0.4
growing
Temperature
2
1
0
- 1
- 2
- 3
- 4
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)
Weather
Thermistor, Montreal (0.017s)

How does scaling help?

Scaling, scale invariance:

Typical Fluctuation ≈ $(\text{scale})^H$

H>0: Fluctuations grow with scale, unstable

H<0: Fluctuations decrease with scale, stable

~~"The climate is what you expect, the weather is what you get"~~

Expect Macroweather!

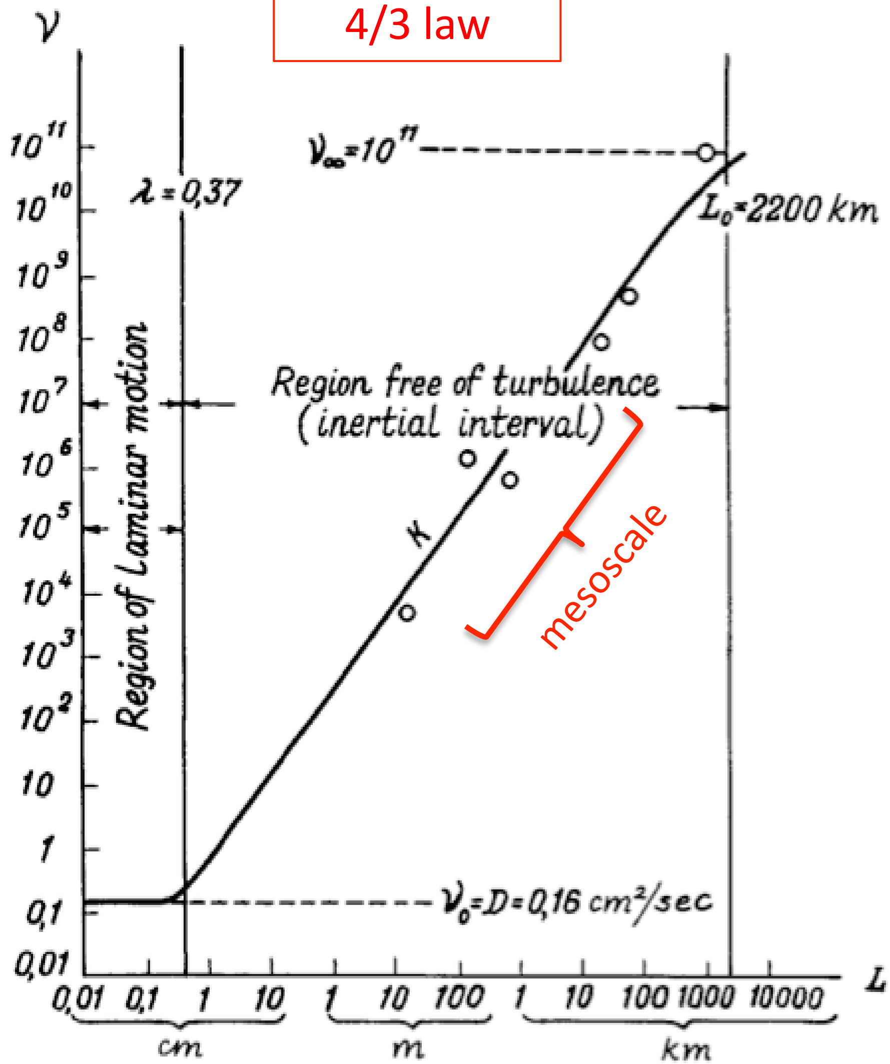
Weather: H>0, macroweather, H<0, climate, H>0

An overview of atmospheric turbulence

How is it that in 2018 there is no consensus on the large scale statistical properties of the atmosphere?

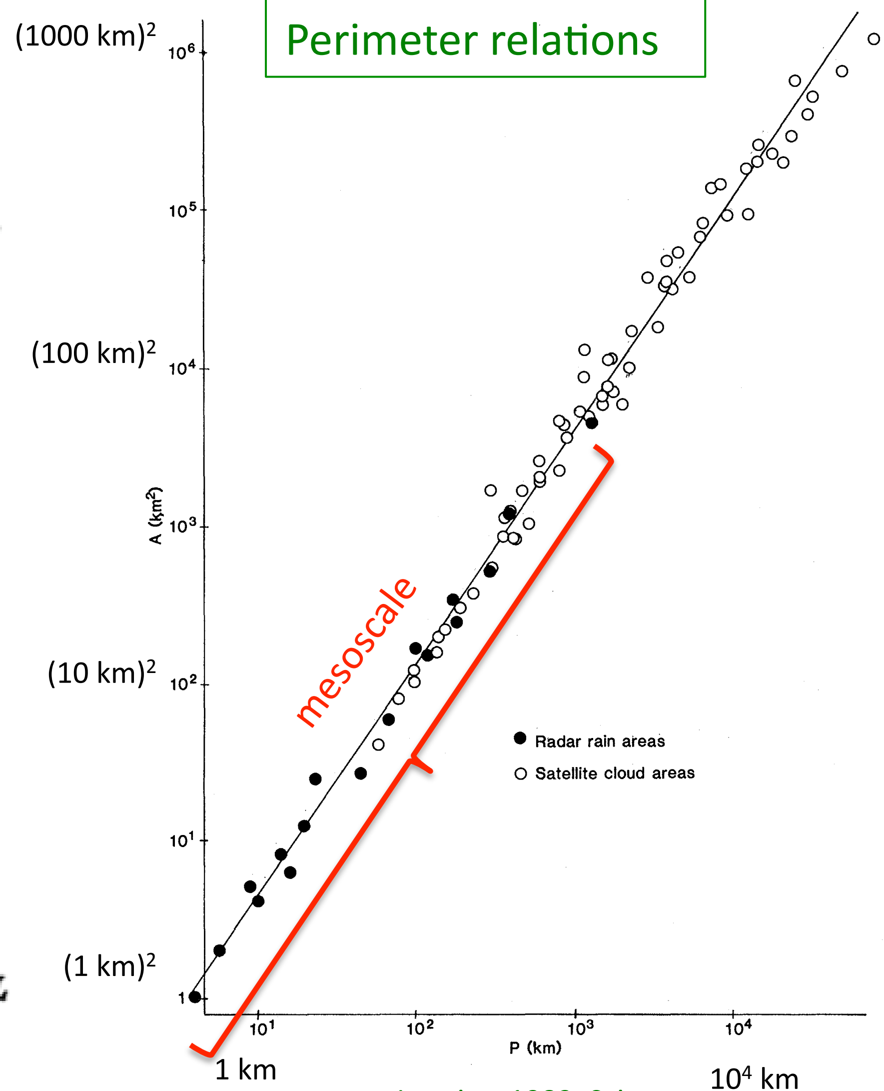
Early indications of wide range scaling

Richardson's 4/3 law



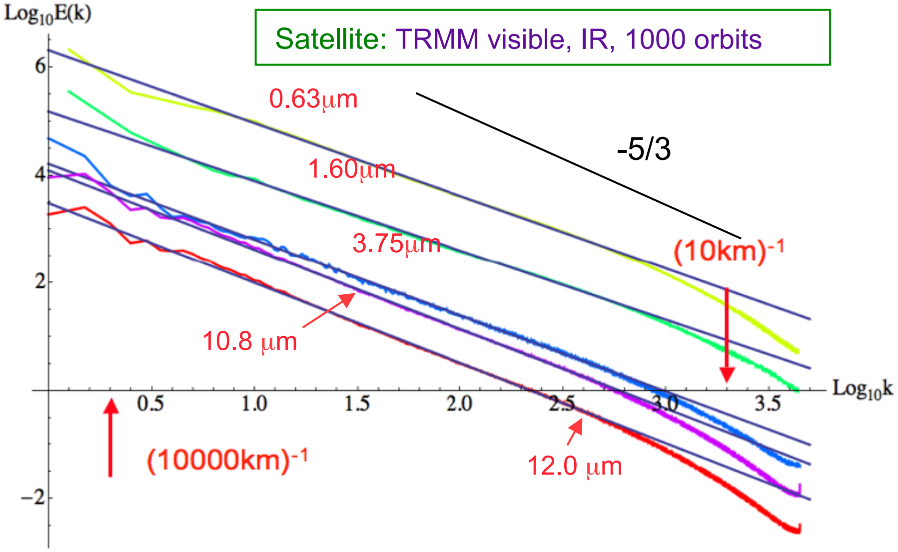
Richardon 1926, redrawn by Monin 1972

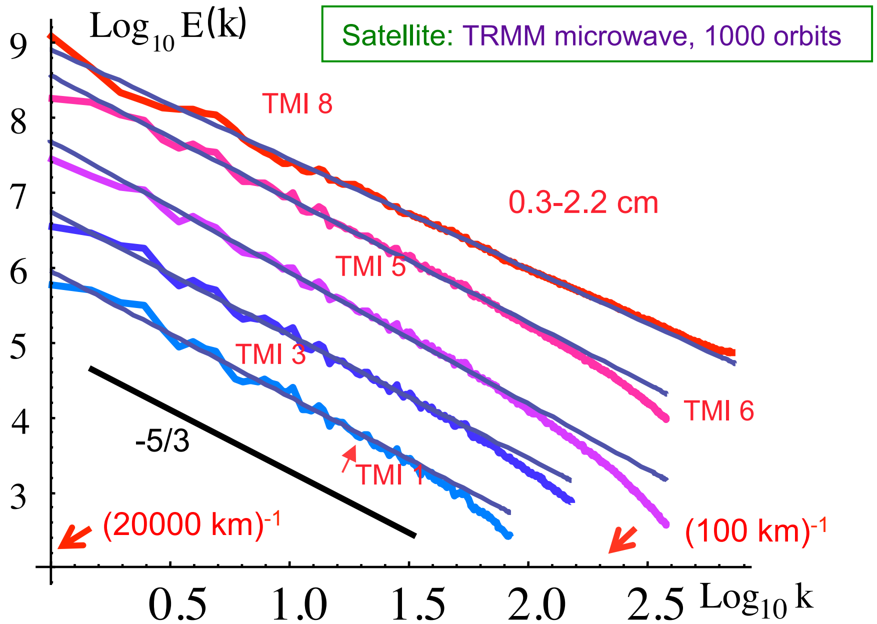
Cloud and rain Area-Perimeter relations

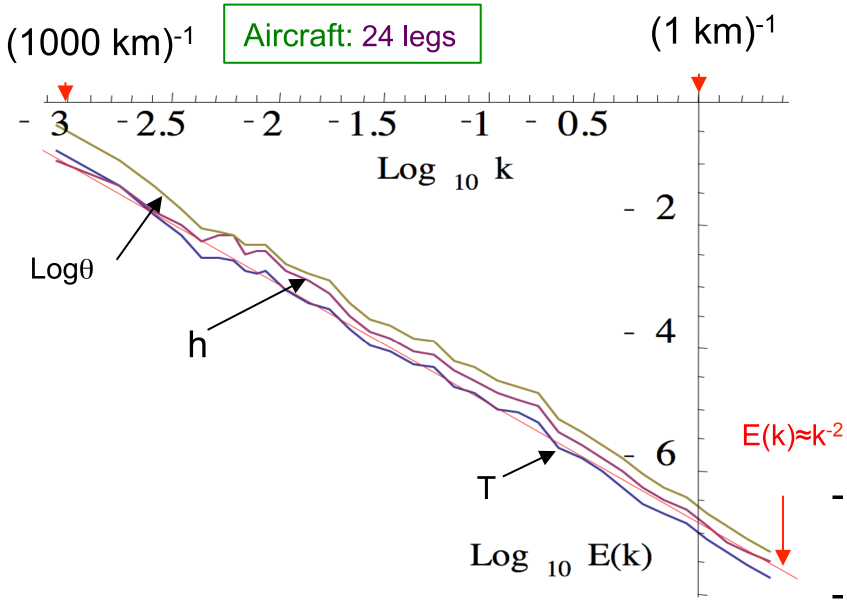


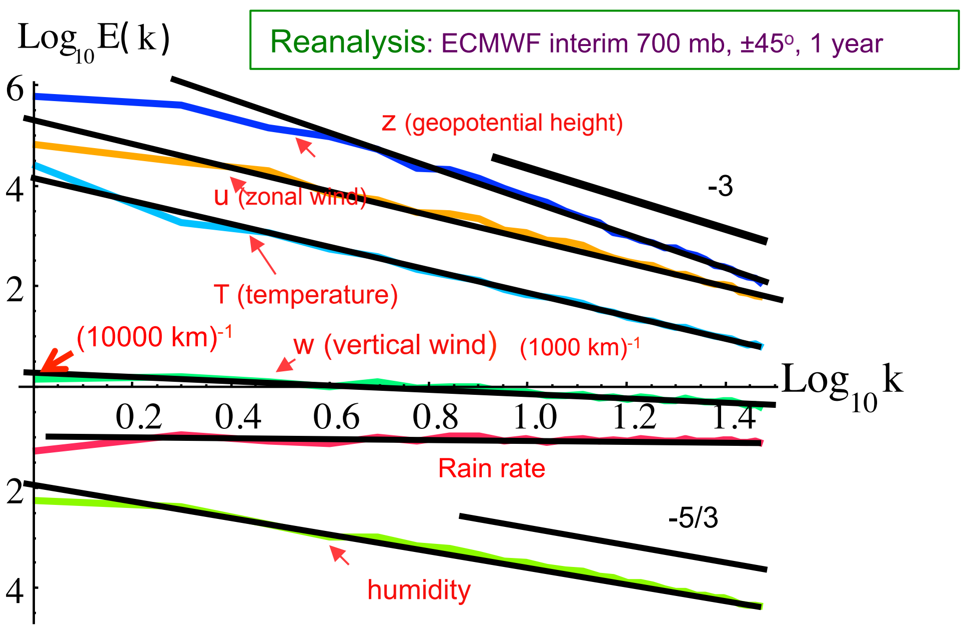
Lovejoy, 1982, Science

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









Origin of scaling…

Equations of motion

↓

Anisotropic (stratified) zoom scale ratio λ

↓

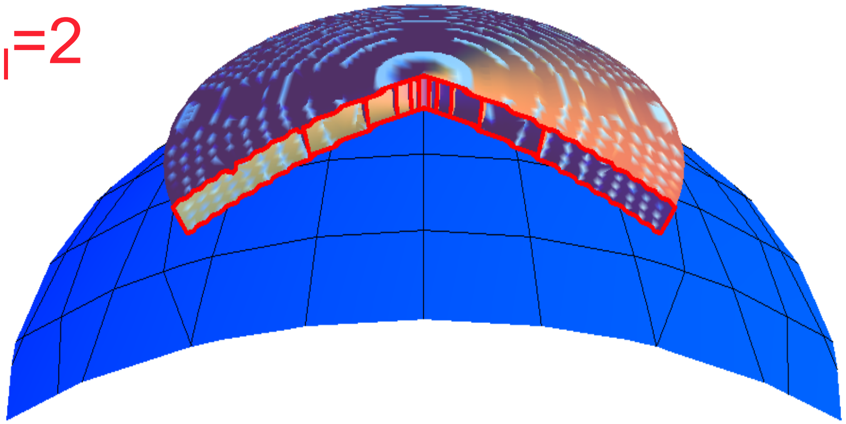
λ^{H} (Equations of motion)

Generalized Scale Invariance:

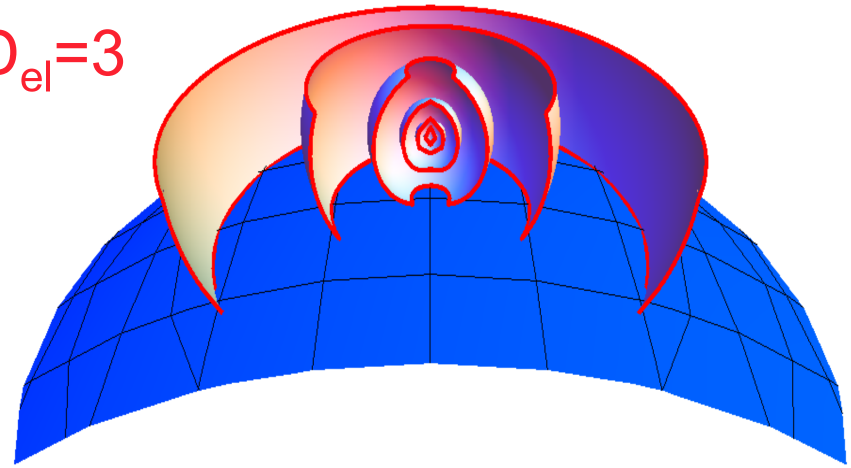
Scale is an emergent quantity determined by the turbulent dynamics….

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

$D_{el}=2$

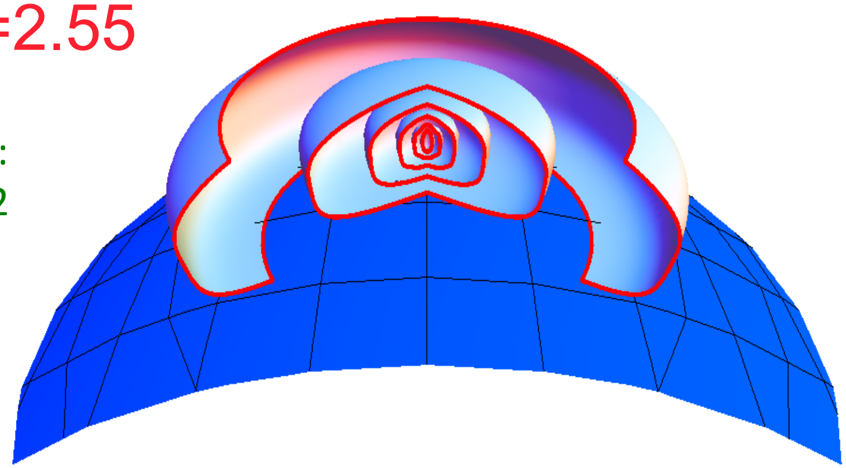


$D_{el}=3$



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

empirical:
2.57±0.02



The 23/9D model:

Bolgiano-Obukhov

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

Kolmogorov

Volume≈L·L·L^{Hz}≈L^{Del}

$D_{el}=2+H_z=23/9$

$H_z=(1/3)/(3/5)=5/9$

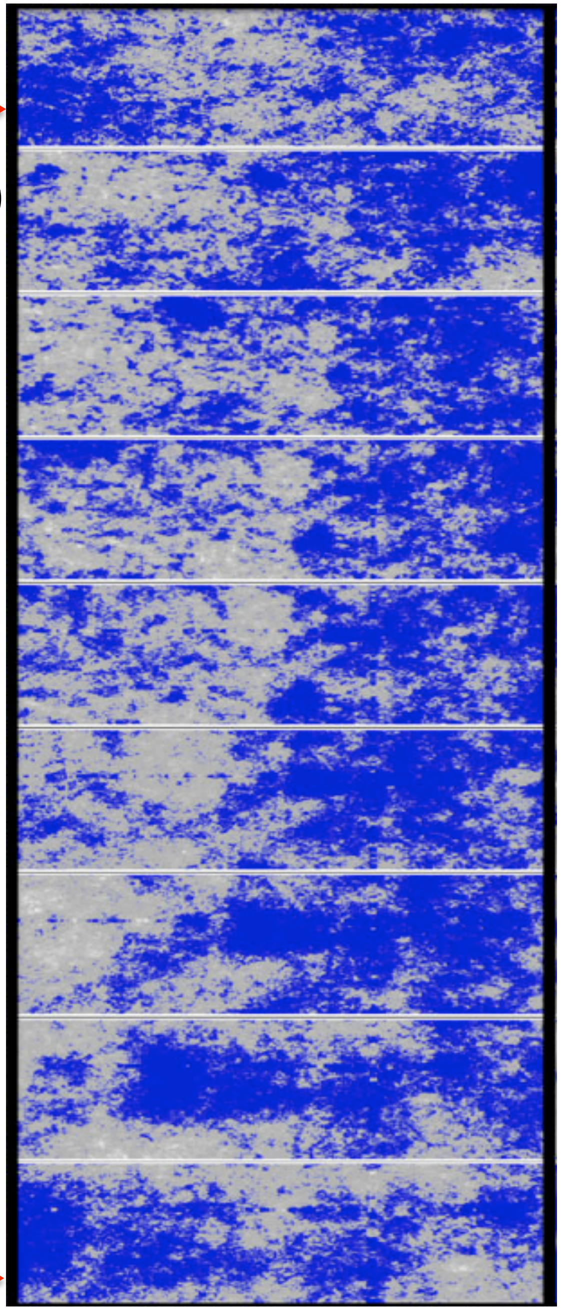
Anisotropic, Stratified Scaling

Stochastic

5km

Blow up X 2.9 (each)

Isotropic



Total: X5000

1 m

Stochastic Fractional Energy Balance Equation

FEBE

$$\tau^H \frac{d^H T}{dt^H} + T = \lambda \Im(t)$$

← Forcing (stochastic)

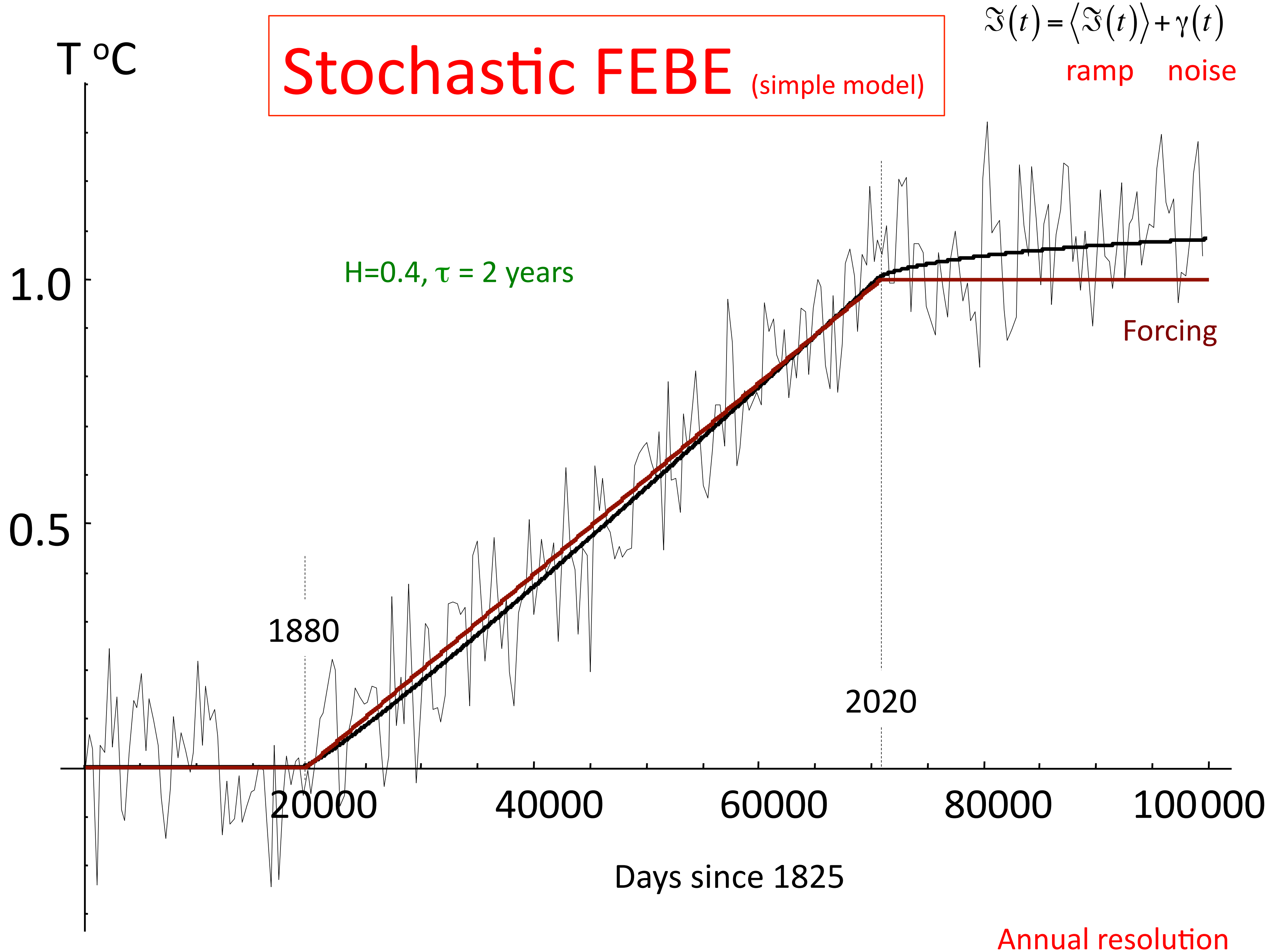
$$\Im(t) = \langle \Im(t) \rangle + \gamma(t)$$

Storage

Climate sensitivity

Assumptions:

a) linearity of response (forcing≈ 1% of long term mean)
b) Scaling of storage mechanisms


Stochastic FEBE (simple model)
$\Im(t) = \langle \Im(t) \rangle + \gamma(t)$
ramp noise
T °C
1.0
0.5
H=0.4, τ = 2 years
Forcing
1880
2020
20000
40000
60000
80000
100000
Days since 1825
Annual resolution

Stochastic Unification of externally forced and internal variability

The forcing:

Ensemble average (deterministic e.g. anthropogenic)

$$\Im(t) = \langle \Im(t) \rangle + \Im_i(t)$$

Random deviation due to "innovations"

$$\langle \Im(t) \rangle = F(t)$$ External forcing

$$\Im_i(t) = \sigma\gamma(t)$$ Internal forcing: "innovations" unbalanced internal heat sources

Amplitude of the innovations (σ)

Stochastic innovations (mean= 0) ($\gamma(t)$)

Temperature response: $$T(t) = \langle T(t) \rangle + T_i(t)$$

Forced response to external forcing ($\langle T(t) \rangle$)

Internal variability (Temperature anomalies) ($T_i(t)$)

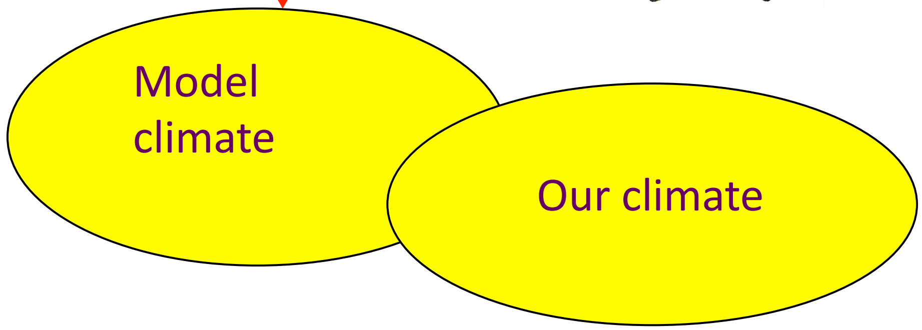
Clarification of internal versus externally forced variability

Externally forced variability: $\langle T(t) \rangle$

Internal: $T_i(t) = T(t) - \langle T(t) \rangle$

Forecasts and projections should be based on real world climates

Weather systems (<10 days) generated by GCMs
= random weather noise (statistics)…
but not fully realistic



Scaling models can use data to force convergence to the real climate.

Using scaling for long range (macroweather) forecasts

StocSIPS

Stochastic Seasonal to Interannual Prediction System

Based on high frequency FEBE response:

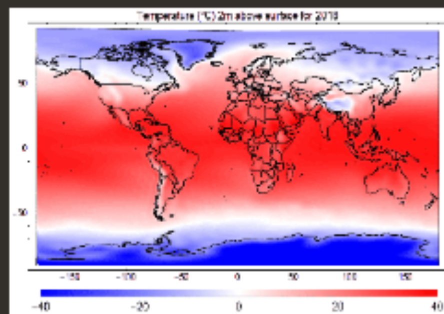
$$G_{high}(t) \propto t^{H-1}$$

StocSIPS

Stochastic Seasonal to Inter-annual Prediction System

Stochastic Seasonal to Interannual Prediction System

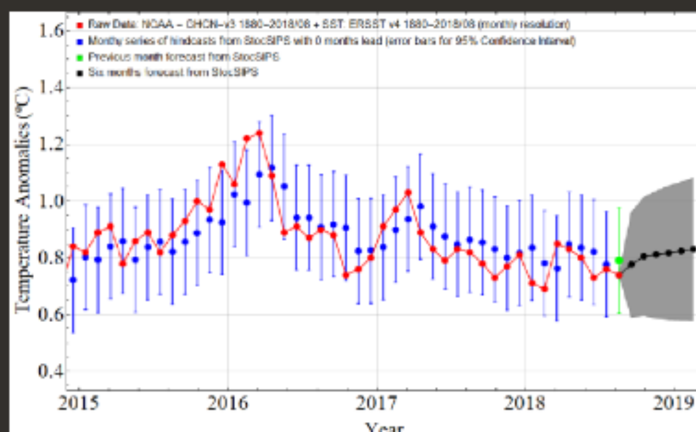
Home | Forecasts | CanStoc | Hindcasts | Verification | About StocSIPS | Contact Us



A different way of forecasting 1

The Stochastic Seasonal and Interannual Prediction System (StocSIPS) is a revolutionary new technique for forecasting the state of the atmosphere from several weeks to decades. The core StocSIPS technology is the ScaLINg Macroweather Model (SLIMM) forecast module. The science behind StocSIPS is the discovery that the atmosphere has a truly elephantine memory. This memory is exploited by SLIMM that extracts information from many years of past data.

Global temperature forecast and hindcasts for monthly, seasonal and annual resolutions



Monthly resolution (forecast)

Reference: Global temperature anomalies at monthly resolution (shown in red in the figure) updated until August, 2018 with respect to the 20th Century (1901-2000) average. Global Surface Temperature Anomalies taken from http://www.ncdc.noaa.gov/monitoring-references/faq/anomalies.php.

Hindcasts: The series of hindcasts with zero months lead time since 2015 produced with StocSIPS is shown in blue in the figure with the corresponding 95% confidence interval (green for the last month).

Forecast: The median forecast until June, 2018 is shown in black in the figure (grey for for the corresponding 95% confidence interval).

Monthly forecast | Monthly hindcast | Seasonal forecast | Seasonal hindcast | Annual forecast | Annual hindcast | RMSE

Regional temperature forecasts at different temporal resolutions and lead times

(main Forecast page here)

Stochastic Seasonal and Interannual Prediction System (StocSIPS)

Lovejoy, Del Rio Amador, Hebert, 2015

Fractional Gaussian noise = fGn (scaling, smoothed white noise)

$$T(t) = \sigma_\gamma \int_{-\infty}^{t} (t - t')^{-(1/2 - H)} \gamma(t') dt'$$

Gaussian noise

- Power law correlation. Vast memory that can be exploited.
- Predictor for -1/2 < H < 0 based on past data.

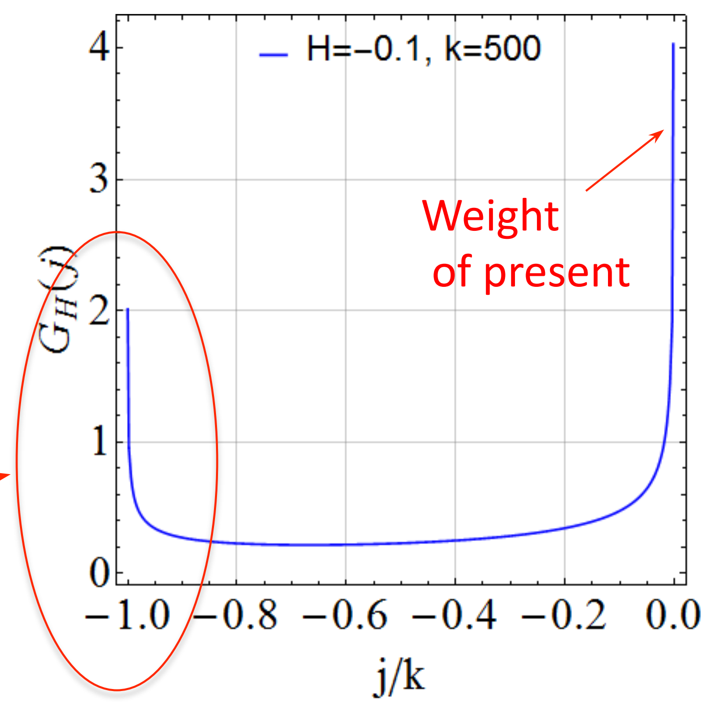
kernel

$$\hat{T}(n+k \mid n) = \sum_{j=0}^{p} G_H(j) T(n-j)$$

predictor

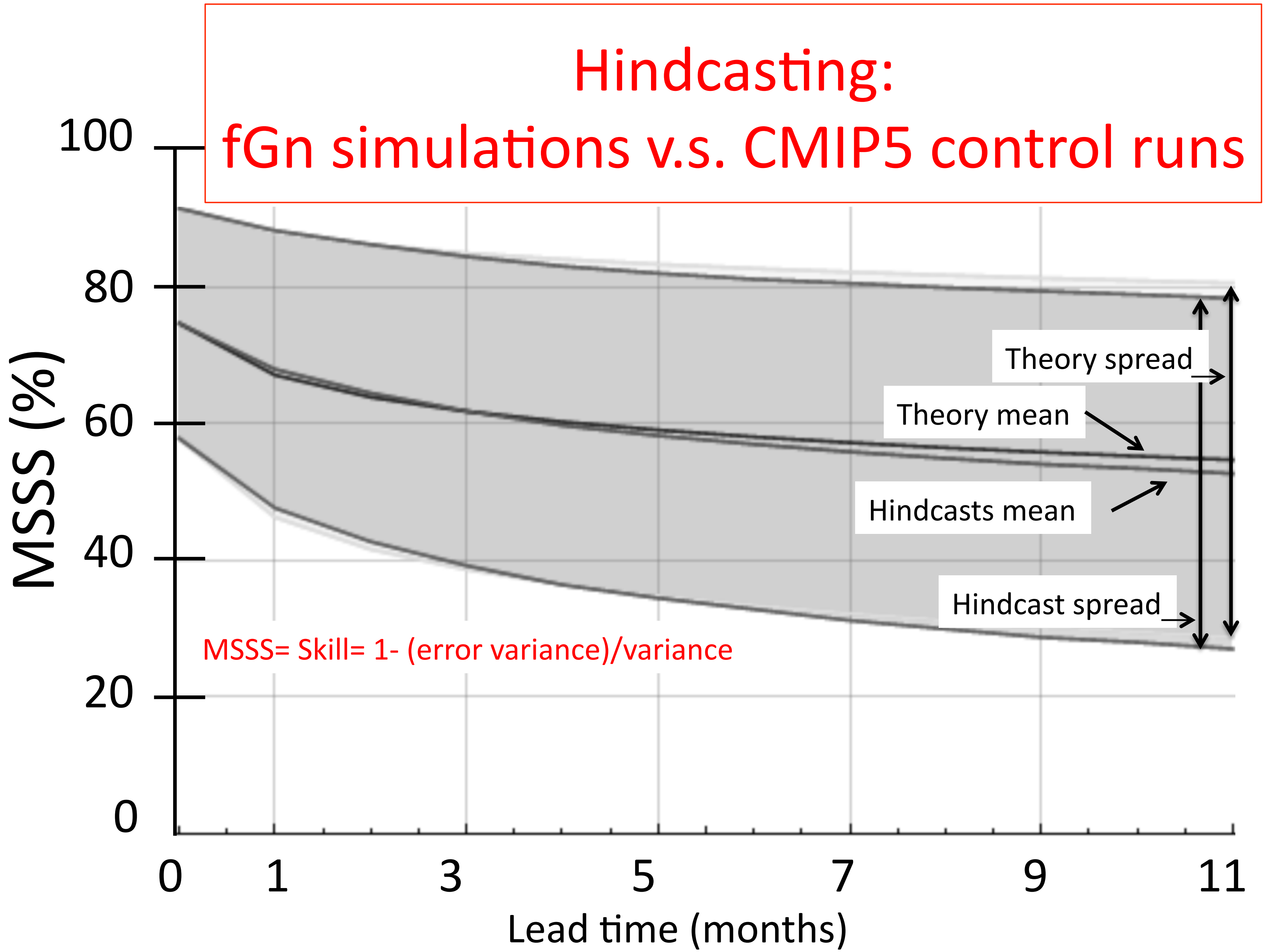
data

Kernel for $H = -0.1$



"The 'closest witnesses' to the unobserved past have special weight"

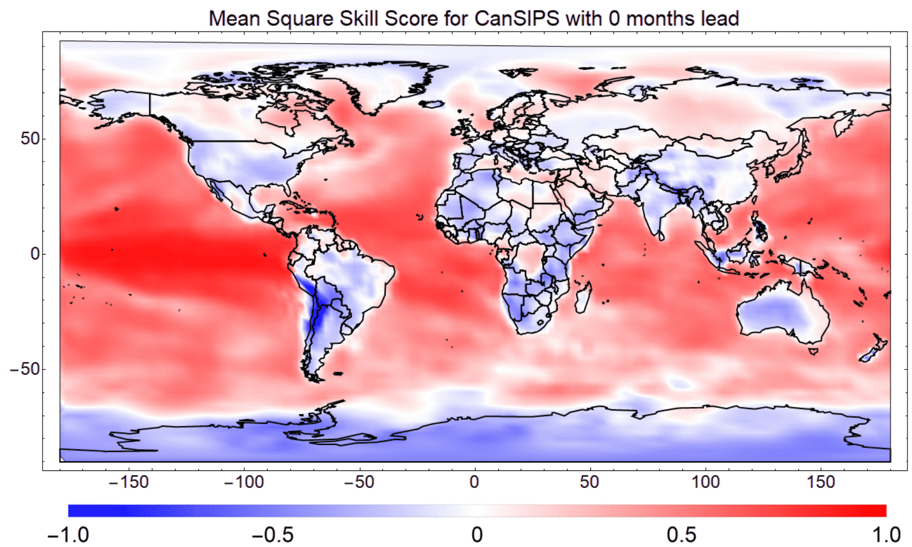
Grippenberg and Norris 1996



Hindcasting:
fGn simulations v.s. CMIP5 control runs
MSSS (%)
100
80
60
40
20
0
Theory spread
Theory mean
Hindcasts mean
Hindcast spread
MSSS= Skill= 1- (error variance)/variance
0
1
3
5
7
9
11
Lead time (months)

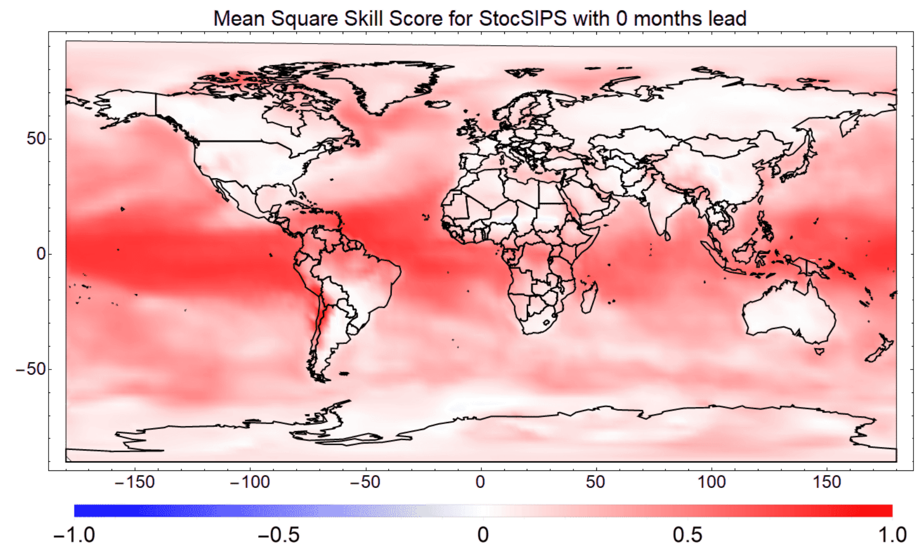
0-months lead Skill (hindcasts 1980-2010)

CanSIPS (GCM)

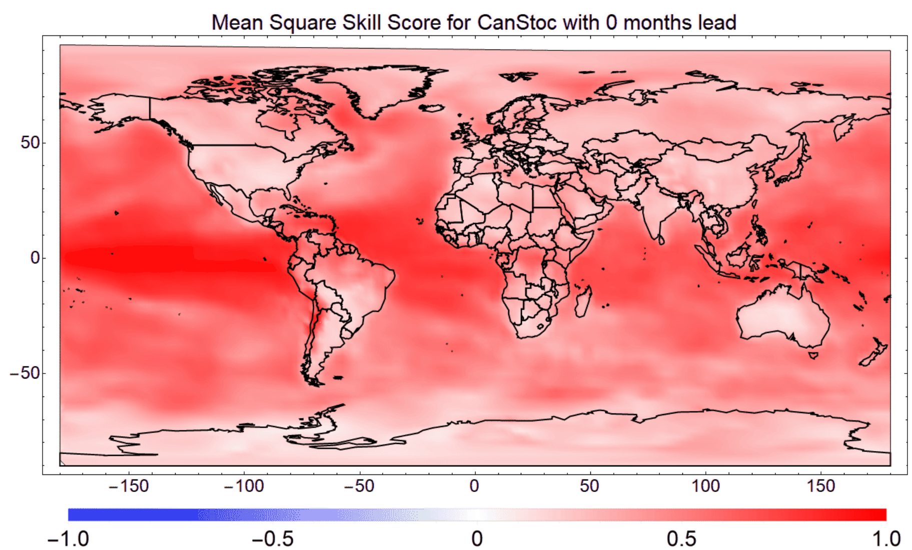


StocSIPS

Red: high skill, blue, low skill

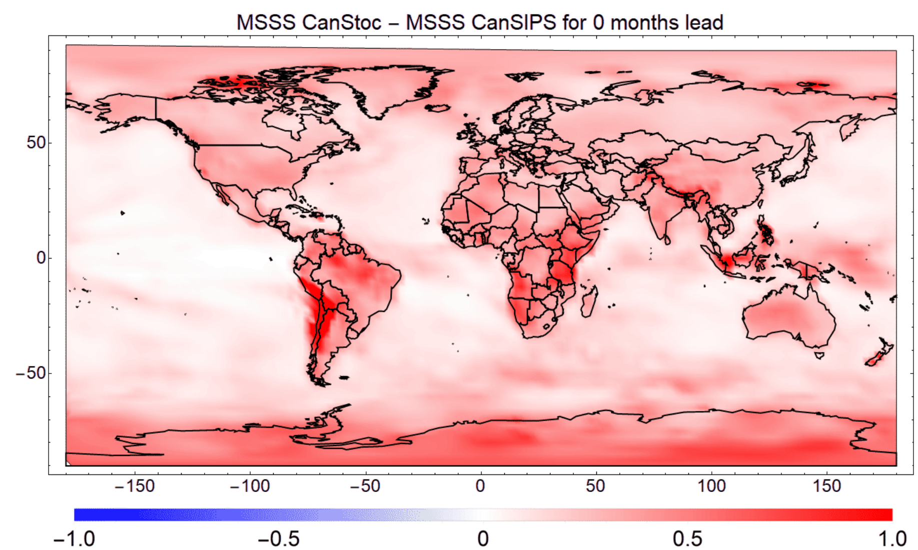


CanStoc (hybrid)



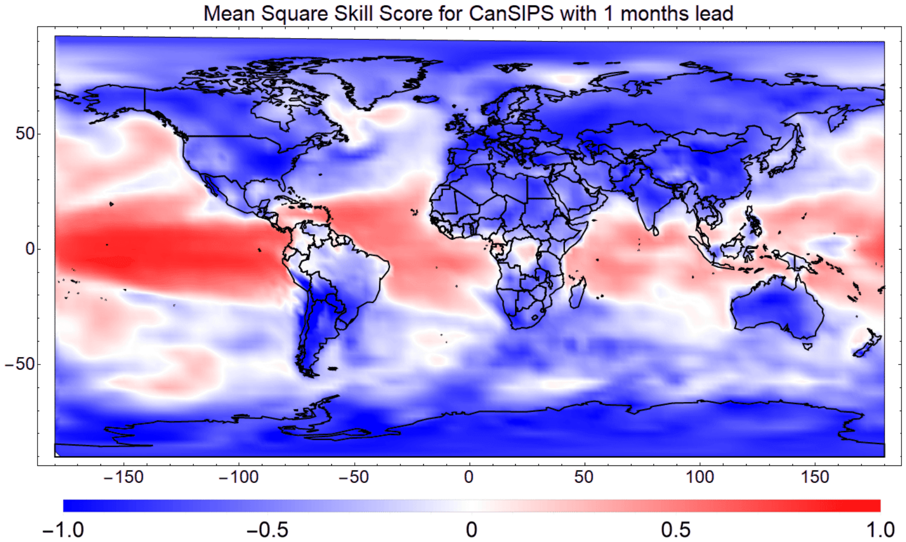
CanStoc - CanSIPS

Red: CanStoc higher skill than CanSIPS

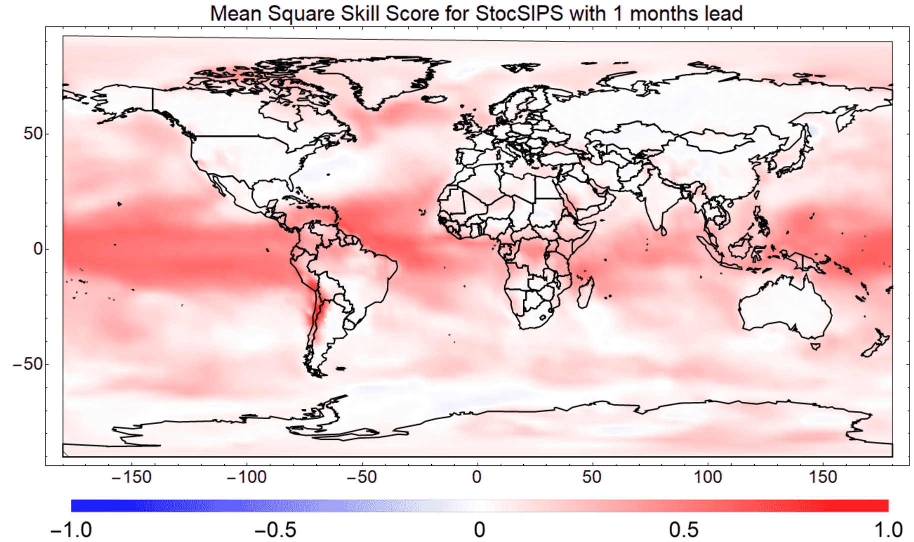


1-month lead (hindcasts 1980-2010)

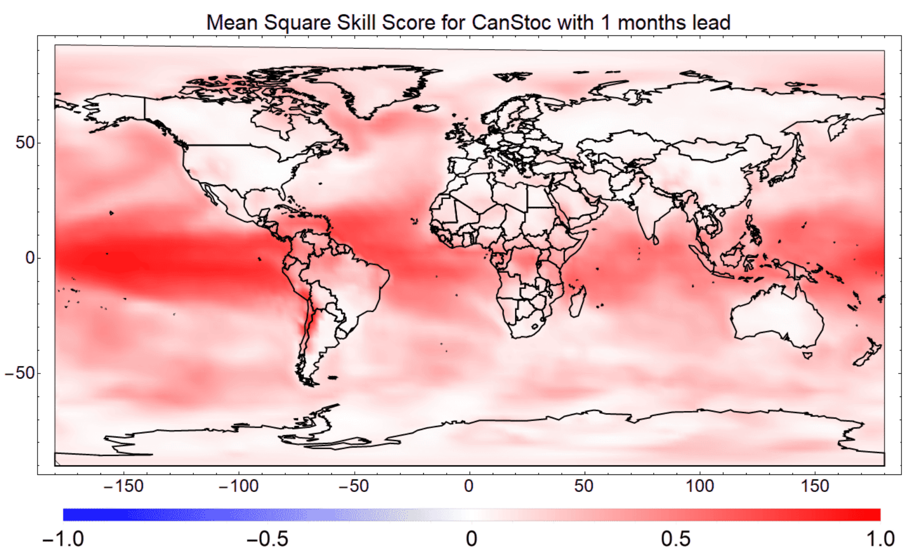
CanSIPS



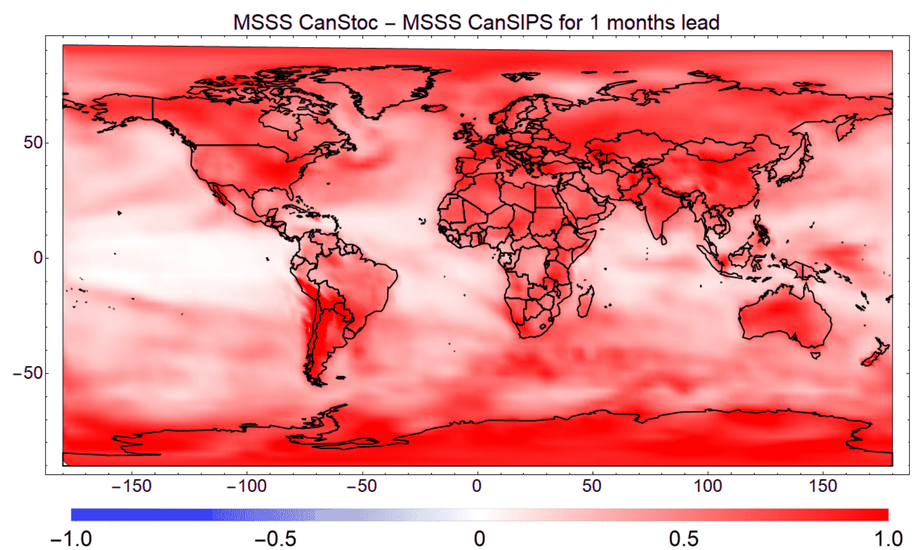
StocSIPS



CanStoc



CanStoc - CanSIPS



Using scaling for projections

- Key assumption: linearity of the response
- Based on step function response
- Scaling of storage
  - (consequence: power law relaxation to thermal equilibrium)

Based on low frequency FEBE response

$$G_{low}(t) \propto t^{-H-1}$$

2050-2100: An uncertainty crisis

GCM's: for CO_2 doubling:

US National Academy of Science (1979): 1.5- 4.5^{o}C

IPCC1	(1992):	1.5- 4.5^{o}C
IPCC2	(1996):	1.5- 4.5^{o}C
IPCC3	(2002):	1.5- 4.5^{o}C
IPCC4	(2007):	2- 4.5^{o}C
IPCC5	(2013):	1.5- 4.5^{o}C

Diminishing returns….

Two historical methods: simple and scaling

Forcing

Projections: Hebert, Lovejoy, Tremblay, 2018

$$T(t) = \lambda G_F * F$$

"*" = convolution:

$$T(t) = \lambda \int_{-\infty}^{t} G_F(t-t')F(t')dt'$$

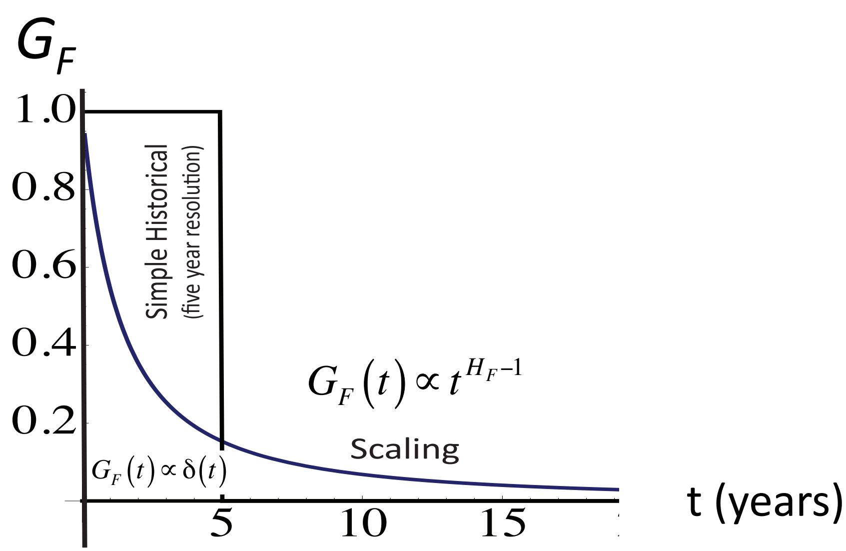
Simple $G_F(t) \propto \delta(t)$

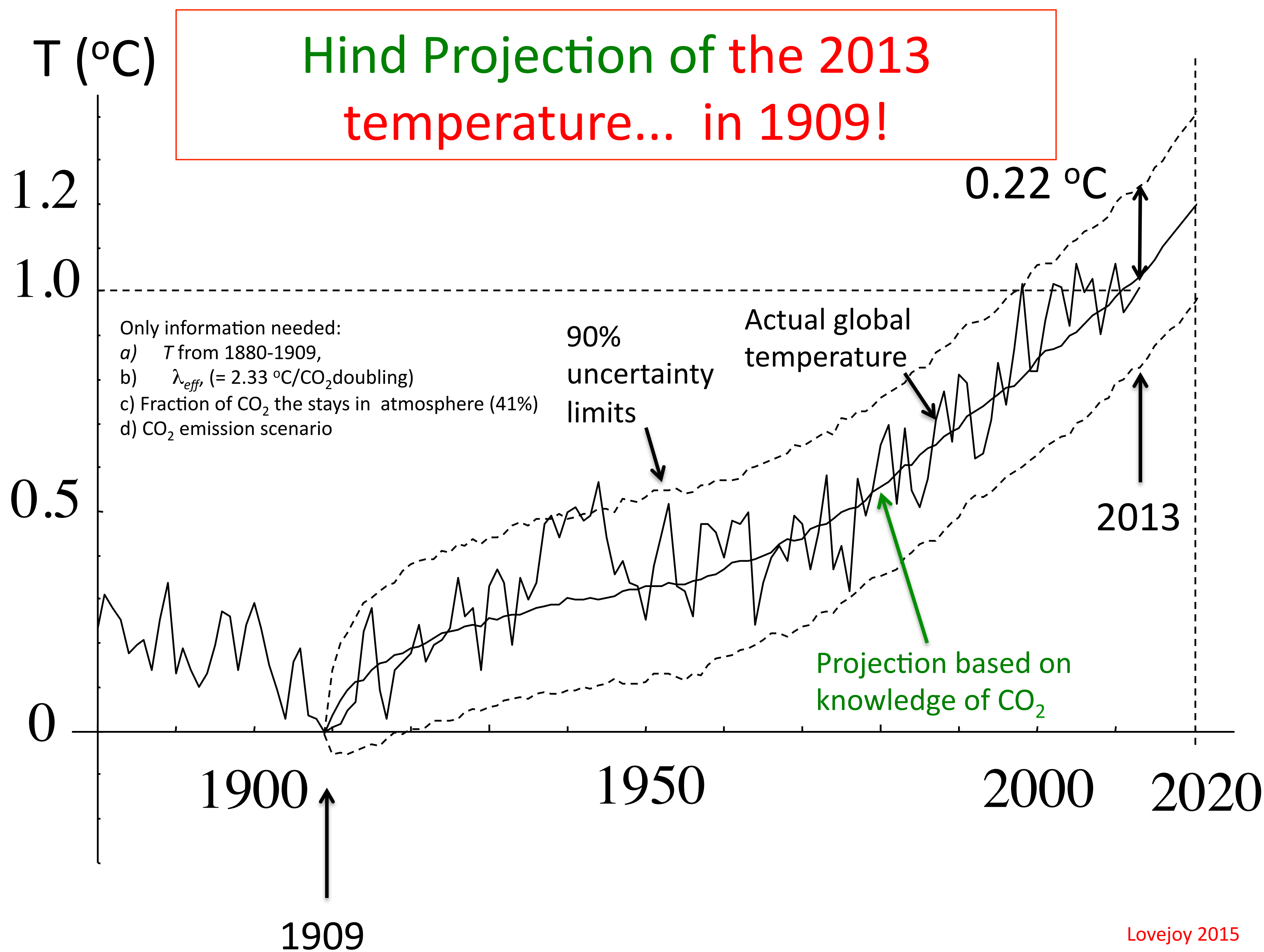
Scaling (long memory) $G_F(t) \propto t^{H_F - 1}; \quad t >> \tau$

Scaling Climate Response Function = SCRF

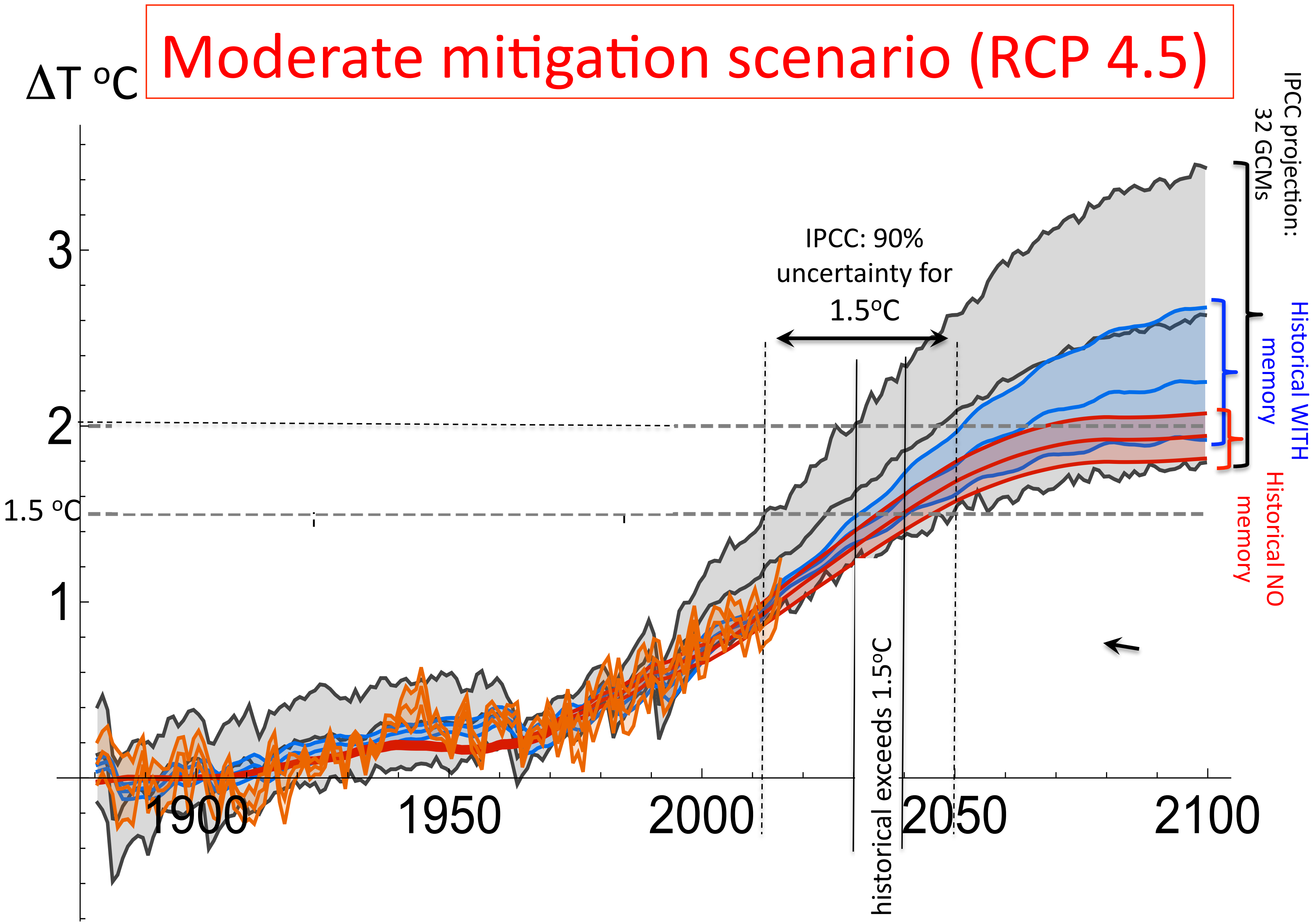
Response exponent: $H_F \approx -0.5 \pm 0.2$

High frequency truncation τ: Land-ocean coupling time (≈ 2 years)



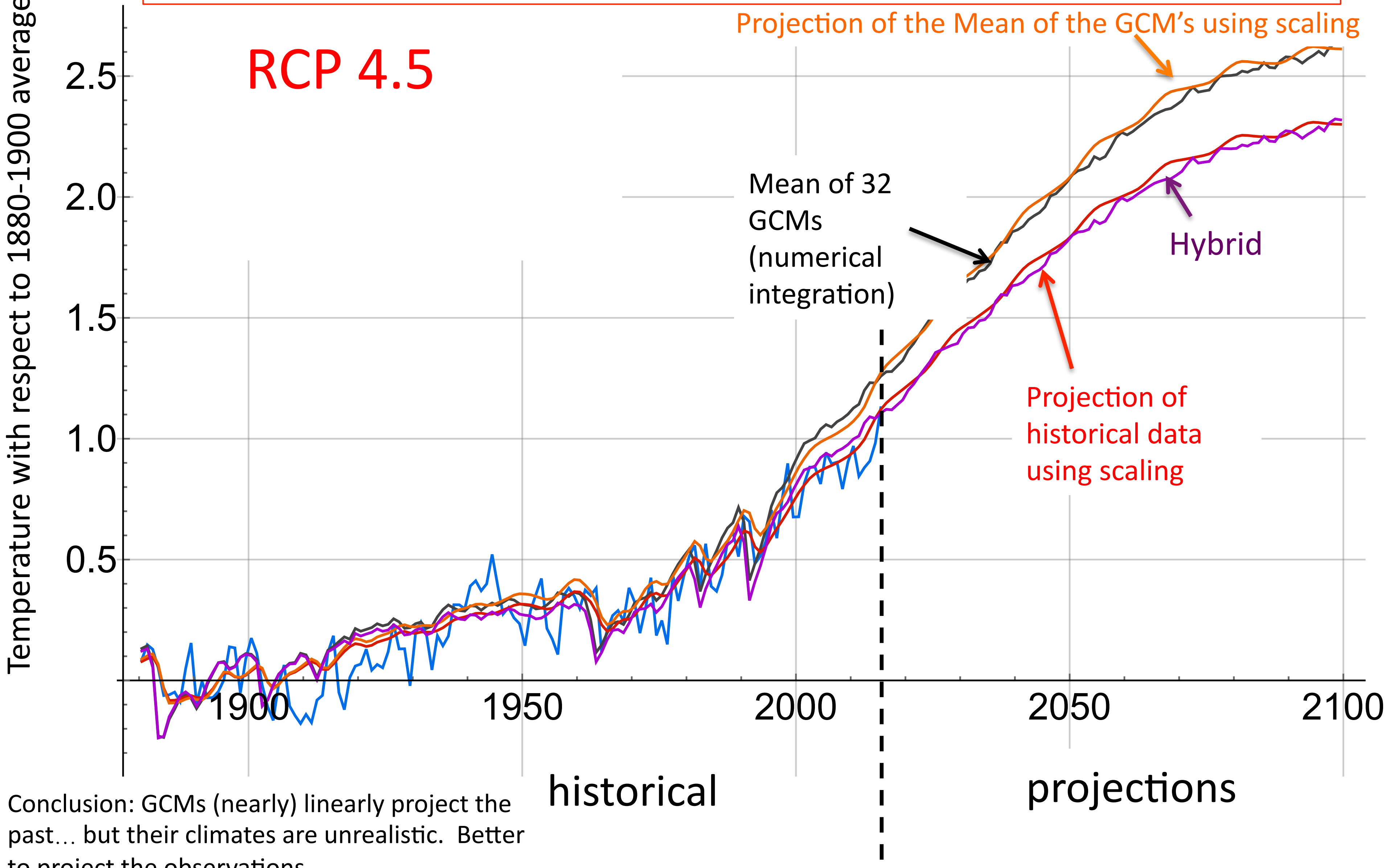


Hind Projection of the 2013
temperature... in 1909!
T (°C)
1.2
1.0
0.5
0
0.22 °C
Only information needed:
a) T from 1880-1909,
b) λeff, (= 2.33 °C/CO2doubling)
c) Fraction of CO2 the stays in atmosphere (41%)
d) CO2 emission scenario
90%
uncertainty
limits
Actual global
temperature
2013
Projection based on
knowledge of CO2
1900
1950
2000
2020
1909
Lovejoy 2015



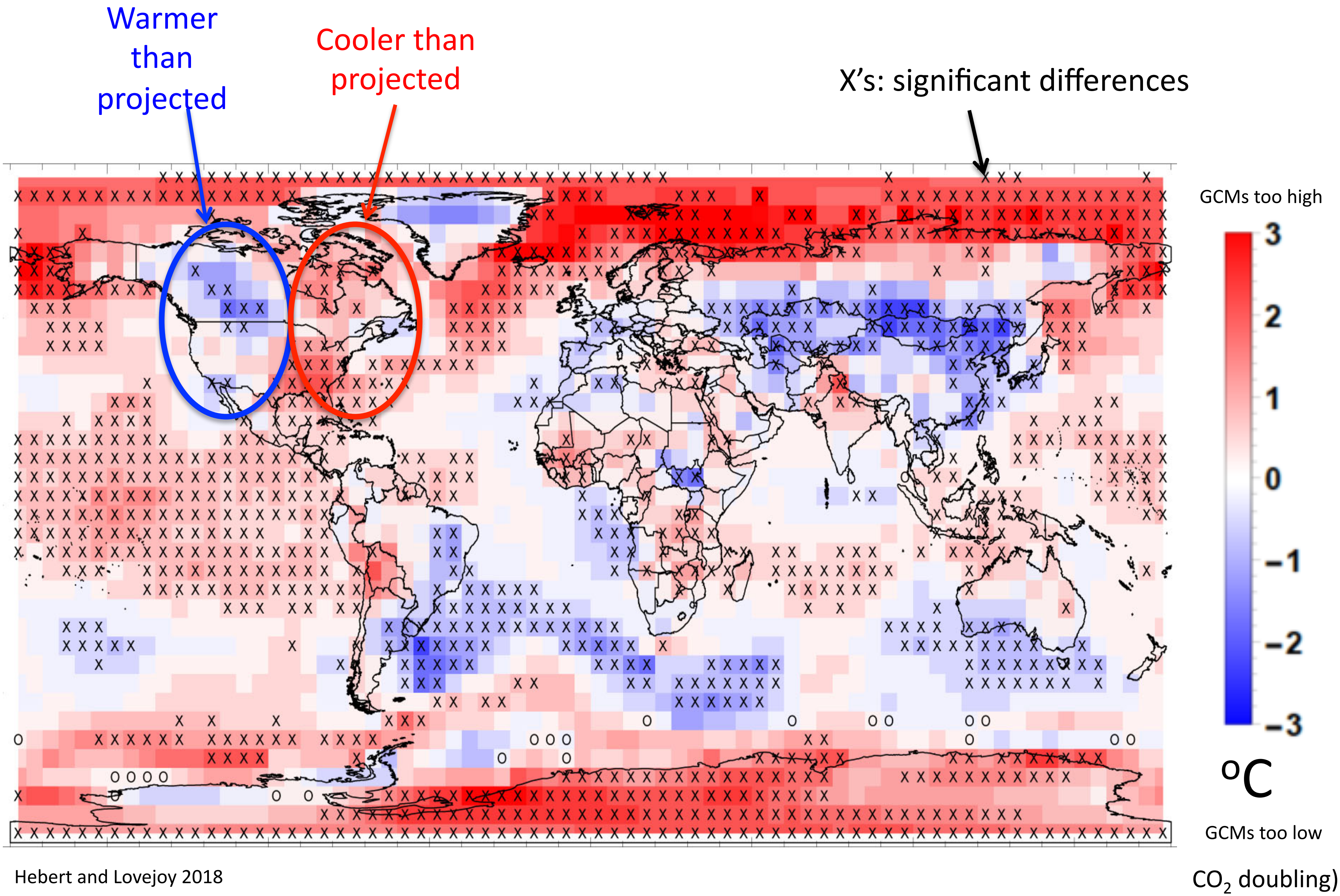
Moderate mitigation scenario (RCP 4.5)
ΔT °C
3
2
1.5 °C
1
1900
1950
2000
2050
2100
IPCC: 90% uncertainty for 1.5°C
historical exceeds 1.5°C
IPCC projection: 32 GCMs
Historical WITH memory
Historical NO memory

Validation: the historical method reproduces the past and predicts the GCMs



Conclusion: GCMs (nearly) linearly project the past… but their climates are unrealistic. Better to project the observations

Differences: (GCM's)- (Historical Method)



Hebert and Lovejoy 2018

2010's: Unity refound?

Developments ≈ 1980's-2010:

Empirical: sapce −time statistical scaling analyses extended from small to global scales, (aircraft, satellites). Also to numerical model outputs…
Theory: Multifractals (intermittency), Generalized Scale Invariance, anisotropic scaling of governing equations (scaling stratification).
Numerical: Many numerical problems solved, NWP extended to climate: GCMs. Verification of scaling of GCM outputs.

Post 2010:
GCM diminishing returns: climate sensitivity 1979 - present: 1.5-4.5^{o}C /CO_2 doubling.
Scaling for macroweather forecasting, including of GCM control runs.
Scaling improves climate projections, reduces uncertainty.

Climate Concepts: high versus low level laws (1)

	GCMs	Statistical Laws
What is Climate?	Control runs, strange attractors	Regime with fluctuations increasing with scale, beyond macroweather
Climate change?	Pullback-attractors	Change of climate states
Time scales	1 month (convenience), 30 years (fiat)	Objective transition scales τ_w, τ_c
Climate states	Average over 30 years	Average over τ_c
Macroweather states	Monthly anomalies	Average of anomalies over weather scales (τ_w) w.r.t. the current climate state (scale τ_c).
Equilibrium Climate Sensitivity	Asymptotic response to a step-function increase in forcing	Linear relation between forcing and response (memory can be estimated from internal variability).

Climate Concepts: high versus low level laws (2)

	GCMs	Statistical Laws
Externally Forced variability	The response to processes outside the climate system that increase or decrease energy fluxes into it.	The response to deterministic forcing: the ensemble average of the response.
Internal variability	Variability due to dynamics internal to the climate system.	The response to stochastic innovations: the difference between the actual state and the ensemble averaged state.
Uncertainty	-"Structural uncertainty"(each model has different climate), -Initial condition uncertainty	Stochastic forcings, part of theory/model.
Uncertainty (climate projections)	The dispersions of GCMs about Multi-Model Ensemble.	The dispersion in the reconstructions of historic forcings and historic responses.
Predictability limits	Deterministic limits	Stochastic limits

A consequence of relying of GCMs: theory is not empirically informed.
Ex.: The missing quadrillion.

The future of climate science

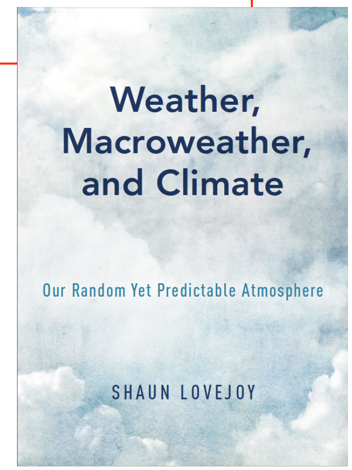
- GCMs are research tools, each with its own climate. Not always the best tools for forecasting or projecting.
- Relying on a unique tool (e.g. for projecting to 2050) is weak: grounds for skepticism

- Beyond deterministic predictability limit, GCM's are stochastic.
All they require are realistic grid scale statistics. This could be done at much lower resolutions, and with today's computers.
Deterministic, mechanistic small scale details are not needed: *irrelevant*!
Modelling structures at 1km that live for 15 minutes and then averaging everything over a factor of a million to make a decadal projection is an unnecessary waste of resources.

-Stochastic scaling models are already the most realistic for macroweather and climate temperature forecasts and projections … they could be possibly merged with GCM approaches for even greater accuracy.

- Better empirical grounding of theory.
- Better understanding of reality… and models!

Conclusions



1) Atmospheric variability is colossal — Underestimated by quadrillion
2) Which Chaos? — Stochastic or deterministic?
3) Which level? — High or low?
4) What about the details? — Scalebound or scaling?

   Supercomputers or laptops?

5) 1970's revolutions: numerical and nonlinear

   Divergence of Richardson's deterministic, stochastic strands

5) 2010's: Vindication of Richardson: new unity with the help of scaling

   co-existence of high and low level laws

6) Climate concepts reinterpreted in terms of high level statistical laws

   Climate sensitivity, uncertainty

7) Numerical models are just tools

   They are not a substitute for theory

   …..Diminishing returns of GCMs

8) New questions

   What are space time relations: in weather? In macroweather? In climate?