# The 2021 “Complex systems” Nobel prize:The climate, with and without geocomplexity

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**Abstract**

One half of this year’s Nobel Physics prize was awarded to statistical physicist Giorgio Parisi and the other - the first ever in geophysics - to climate scientists Syukoro Manabe and Klaus Hasselmann, the former for pioneering General Circulation Models (GCMs) and the latter (primarily) for proposing a statistical model explaining the climate as a slowly varying state driven by random weather noise. However, the Nobel committee recognized climate laureates’ work almost exclusively from the 1960’s and 70’s. We update their report with the contributions from nonlinear geophysics and discuss the implications for the unity of geoscience.

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# The 2021 “Complex systems” Nobel prize: The climate, with and without geocomplexity

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**Plain-Language summary**
The first Nobel geophysics prize was awarded to climate scientists Syukoro Manabe and Klaus Hasselmann, for their work primarily in the 1960’s and 70’s. Although the prize theme was “complex systems” this was a decade or two before complexity science and geocomplexity were founded. I a give a geocomplexity update and argue that it reveals a forty year old schism that can now be overcome.

## Abstract:

One half of this year’s Nobel Physics prize was awarded to statistical physicist Giorgio Parisi and the other - the first ever in geophysics - to climate scientists Syukoro Manabe and Klaus Hasselmann, the former for pioneering General Circulation Models (GCMs) and the latter (primarily) for proposing a statistical model explaining the climate as a slowly varying state driven by random weather noise. However, the Nobel committee recognized climate laureates’ work almost exclusively from the 1960’s and 70’s. We update their report with the contributions from nonlinear geophysics and discuss the implications for the unity of geoscience.

This year’s physics Nobel prize marks history as the first ever for geophysics. Half-shared by statistical physicist Georgio Parisi and half by climate scientists Syukoro Manabe and Klauss Hasselmann, the prize was nominally for “complex systems”, yet the two halves of the work were so disparate that at least one of the winners (Manabe) reportedly confessed to never having heard of another (Parisi). Ironically, Parisi’s important contribution to multifractals was not even mentioned in the committee’s 18 page report [*Physics*, 2021] in spite of its significant atmospheric and climate) applications. In addition, nonagenarians Manabe and Hasselmann were honoured primarily for work in the 1960’s and 70’s - before the Nonlinear revolution and before complexity science even existed. In this commentary, I focus on the climate half of the prize giving a succinct geocomplexity update.

Complexity science in general - and geocomplexity in particular - emerged in the wake of the 1980’s nonlinear revolution: notably deterministic chaos, fractals, nonlinear waves, self-organized criticality and somewhat later, network theory. Complexity physics took shape in the 1990’s (see the review [*Nicolis and Nicolis*, 2012]) whereas nonlinear geoscience can be roughly dated from the workshops on Nonlinear VAriability in Geophysics (NVAG 1-4, 1986 -1997), the establishment of the Nonlinear Processes division at the European Geophysical Society (1989), the Nonlinear Geophysics focus group at the American Geophysical Union (1997) and in 2009, an AGU session with accompanying geocomplexity workshop ([*Lovejoy et al.*, 2009]).

We can certainly celebrate the first geophysics Nobel and its recipients Manabe and Hasselmann, yet the committee’s presentation of the pioneers’ contributions as almost finished work, is problematic. Indeed, their report contains little hint that over the intervening decades geocomplexity has transformed our understanding of the atmosphere and climate system.

This transformation can be highlighted through a discussion of Hasselmann's climate model. Hasselmann's basic idea is that the weather drives the climate through random internal forcing. In a review and mathematical update, [*Arnold*, 2001] describes Hasselmann's idea as follows: "the slowly responding components of the system (such as the ocean, cryosphere and the biosphere), act as integrators of this random weather input in much the same way as a pollen grain in a liquid integrates the short time impact of the molecules to yields Brownian motion."

The analogy is quantitative: in both cases, the system obeys the Langevin equation:

$$\tau \frac{dT}{dt} + \lambda T = \gamma(t)$$

where $T$ is the temperature (or pollen grain velocity), $\tau$ is the relaxation time, $\lambda$ the climate feedback parameter and $\gamma(t)$ a white noise forcing. According to the equation, the temperature follows an Ornstein-Uhlenbeck process so that at high frequencies, the spectrum ($E$) is that of Brownian motion ($E(\omega) \approx \omega^{-\beta}$ with $\beta = 2$ and $\omega$ the frequency) and when $\omega$ is below $1/\tau$, $\beta = 0$ (white noise). While Hasselmann derived the Langevin equation on more general grounds (appealing to nonlinear dynamics), the Nobel committee helpfully recalled that the same equation (for the global temperature) is a consequence of the Budyko-Sellers [*Budyko*, 1969], [*Sellers*, 1969] energy balance model discussed below.

While Hasselmann's picture is seductive, we now know that it is flawed at both high and low frequencies: the behaviour of the temperature (and other atmospheric variables) is quantitatively and qualitatively different. To see this, consider fig. 1 that Hasselmann used to empirically justify his model (reproduced by the Nobel committee from [Frankignoul and Hasselmann, 1977]). It shows a Sea Surface Temperature (SST) spectrum from a single ten year long series. Also shown in fig. 1, is a modern update from 452 centennial length series. At the high frequencies we see that the absolute slope is closer to $\beta \approx 1.8$ than to the Brownian motion $\beta = 2$. While this difference may seem small, it has been amply confirmed by numerous analyses (reviewed in [*Lovejoy and Schertzer*, 2013]) and it corresponds to a different understanding of the ocean. Whereas Hasselmann's $\beta = 2$ corresponds to the integral of an (uncorrelated, unstructured) white noise, the value $\beta \approx 1.8$ is close to Kolmogorov's turbulent value (5/3) and is a consequence of ocean structures that are turbulent and spatially scaling (and strongly interacting) up to planetary scales.

Turning to the lower frequencies, rather than a flat ($\beta = 0$, white noise) spectrum, we find $\beta \approx 0.6$ (SST data). Also shown is the $\beta \approx 0.7$ spectrum inferred from analyses of 11 multicentennial GCM outputs with fixed external forcing ("control runs"). Once again, while the data and GCMs may appear to be close to Hasselmann's model, the qualitative differences are vast. While $\beta = 0$ Gaussian processes are completely unpredictable, processes with $0 < \beta \leq 1$ have long range memories that (increasing with $\beta$) may be so large that - with enough past data – they may be *infinitely* predictable (the $\beta = 1$ limit). Even in practice, monthly and seasonal forecasts become "past-value" – not initial value – problems [*Del Rio Amador and Lovejoy*, 2021b] and [*Del Rio Amador and Lovejoy*, 2019], [*Del Rio Amador and Lovejoy*, 2021a] show how to exploit this huge memory to make state-of-the-art monthly, seasonal and annual temperature forecasts.

The source of the temporal scaling in both low and high frequency regimes is not mysterious. Both ultimately have their origins in the wide range spatial scaling of the atmospheric and oceanic governing equations (and boundary conditions, see the review [*Lovejoy and Schertzer*, 2013]). The transition time scale in fig. 1 is simply the typical lifetime of planetary ocean structures and the analogous atmospheric transition (typically at about ten days) corresponding to the much shorter atmospheric lifetimes (and on Mars, the analogous transition is ≈2 days [*Chen et al.*, 2016]). For Manabe's heritage, this disagreement between the data and Hasselmann's model is fortunate: GCMs inherit the scaling from the governing equations so that their statistics (including multifractal intermittencies) agree fairly well with the data.

What is new and exciting, is that the precise origin of this long range memory can now be understood thanks to an updated derivation of Hasselmann's equation. As recalled in [*Physics*, 2021], the usual approach starts with the energy balance of the earth with outer space. In this case, the forcing term in eq. 1 (the right hand side) includes not only white noise (from "internal variability"), but also the instantaneous imbalance between short wave (visible) radiation from the sun and the outgoing black body (long wave, infra red) radiation. The imbalance is stored in the earth's subsurface and can emerge decades later, with this radiative forcing, eq. 1 is the Energy Balance Equation (EBE).

In the original EBE derivation, the (vertical) radiative imbalance at any point on the Earth was simply redirected towards the poles. This redirection approximation leads to the (order one) derivative term in the EBE ( $\tau dT / dt$ ), representing the rate that the (imbalance) energy is stored. With this integer ordered term, when the system is perturbed, it "relaxes" in a fast (exponential) manner to equilibrium. However, earlier this year, it was found that if the (correct) radiative - conductive surface boundary conditions are used, that the result is a (fractional) Half-order Energy Balance Equation (HEBE) where the derivative term in eq. 1 is replaced by $\tau^{1/2} d^{1/2} T / dt^{1/2}$ [*Lovejoy*, 2021a; b]. Fractional derivatives are convolutions with power laws - or equivalently, in the frequency domain - they are power law filters. Here they imply a spectrum β = 1, i.e. a (very!) long memory (power law) relaxation processes that physically corresponds to power law energy storage. Minor HEBE generalizations yield the Fractional EBE (the FEBE with derivative term $\tau^h d^h T / dt^h$ [*Lovejoy et al.*, 2021]) that is compatible with the observed β values (empirically, $h$ = 0.38±0.03, [*Procyk et al.*, 2021]).

We mentioned that the FEBE (i.e. the fractionally updated eq. 1) is driven by both external (including anthropogenic) deterministic forcing as well as (internal) Gaussian white noise. While the latter hypothesis seems natural – and it is indeed fairly realistic for this macroweather regime – it turns out that this Gaussian behaviour is actually quite exceptional, that geostatistics are on the contrary generally highly non-Gaussian, they are intermittent: this is where Parisi and multifractals come in.

Intermittency is often hidden from view but can be revealed by the simple expedient of a "spike plot" [*Lovejoy*, 2018], see fig. 2. By taking the (normalized) absolute first differences of series (time) or transects (space), they (almost) invariably reveal transitions that are so strong that – were the processes Gaussian - their probabilities of occurrence would often be lower than $10^{-12}$ (even on the short series in the figure, taken from three of the atmospheric regimes). The understanding of these huge multifractal spikes – their origin in scaling dynamics as well as their implications – was the work of decades, and it included an important early contribution by Nobel laureate Parisi who not only coined the term "multifractal" but also pointed out an important and elegant link between multifractal statistical moments and probability distributions [*Parisi and Frisch*, 1985].

This brief update underscores the historically poor connections between atmospheric and climate science with nonlinear geophysics: over the decades, the respective scientific communities have only weakly – and intermittently – interacted. The problem is hardly new. Since at least

[*Richardson*, 1922], atmospheric science has been under tension between its deterministic (e.g. numerical) and statistical (turbulence) strands. In a recent non-technical book [*Lovejoy*, 2019], I have argued that the conjunction of numerical and nonlinear revolutions in the 1970's provoked a schism with the two strands developing largely in parallel.

Today - four decades later - these strands can be re-united. This is possible on the one hand because by persistently modelling smaller and smaller structures - "chasing the details" - the numerical models have become big enough - and accurate enough - to display the statistical behaviour predicted by nonlinear geophysics – including their scaling and intermittency. On the other hand, the nonlinear (statistical) strand has spawned realistic stochastic models that statistically account for the collective dynamics of huge numbers of interacting structures and processes. The two approaches are thus rapidly converging as it becomes increasingly clear that just as with statistical mechanics and thermodynamics - both levels of understanding can co-exist without contradiction, and both can be profitably exploited.

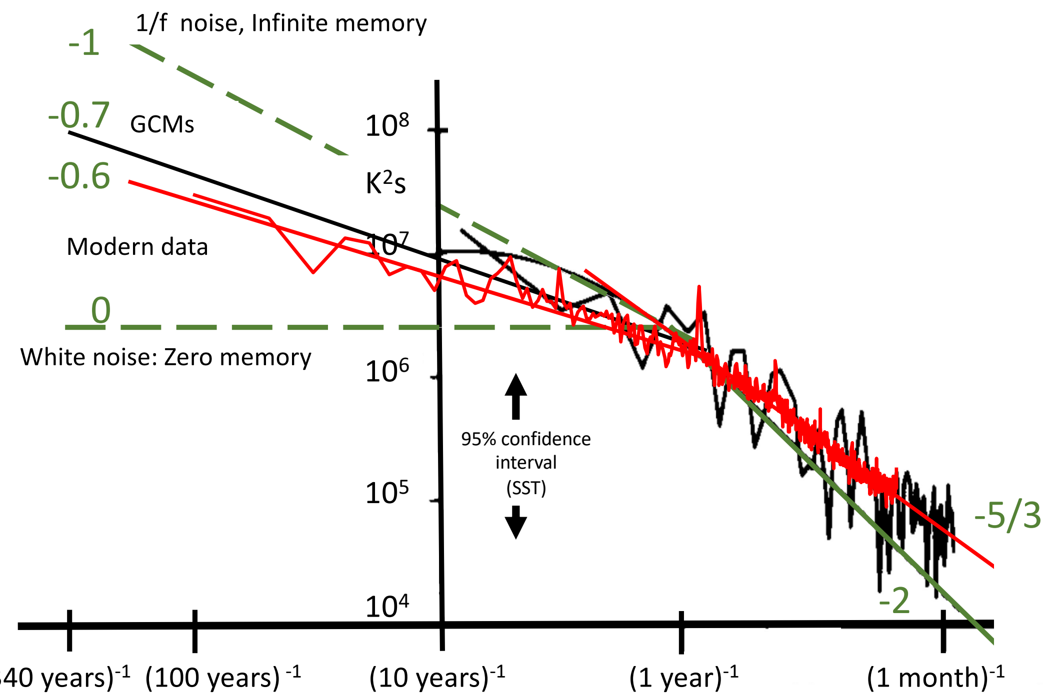


**Fig. 1:** The black spectrum is from a single North Atlantic SST series over the frequency range $(1\text{month})^{-1}$ to $(10\text{ years})^{-1}$ (from [*Frankignoul and Hasselmann*, 1977] reproduced by the Nobel committee [*Physics*, 2021] with the original 95% confidence interval indicated). The figure has been updated with superposed spectrum from 452 SST series from 1911-2010 (red, from [*Lovejoy and Schertzer*, 2012]). The red reference line indicates scaling behaviours $E(\omega)\approx \omega^{-\beta}$ with $\beta = 0.6$. Also shown (black line to $(340\text{ years})^{-1}$) is the scaling behaviour ($\beta = 0.7$) inferred from analyses of global temperatures from control runs from 11 different GCMs, [*Lovejoy*, 2019].

Finally, several theoretical scaling behaviours (straight lines on this log-log plot) are shown: at high frequencies Brownian motion $\beta = 2$ as well as the turbulent $\beta = 5/3$ spectrum. Then, at low frequencies, the dashed lines with $\beta = 0$ and $\beta = 1$ indicate white noise and 1/f noise respectively. Gaussian processes with $0<\beta \leq 1$ have long memories varying between the extremes of 0 and infinity.

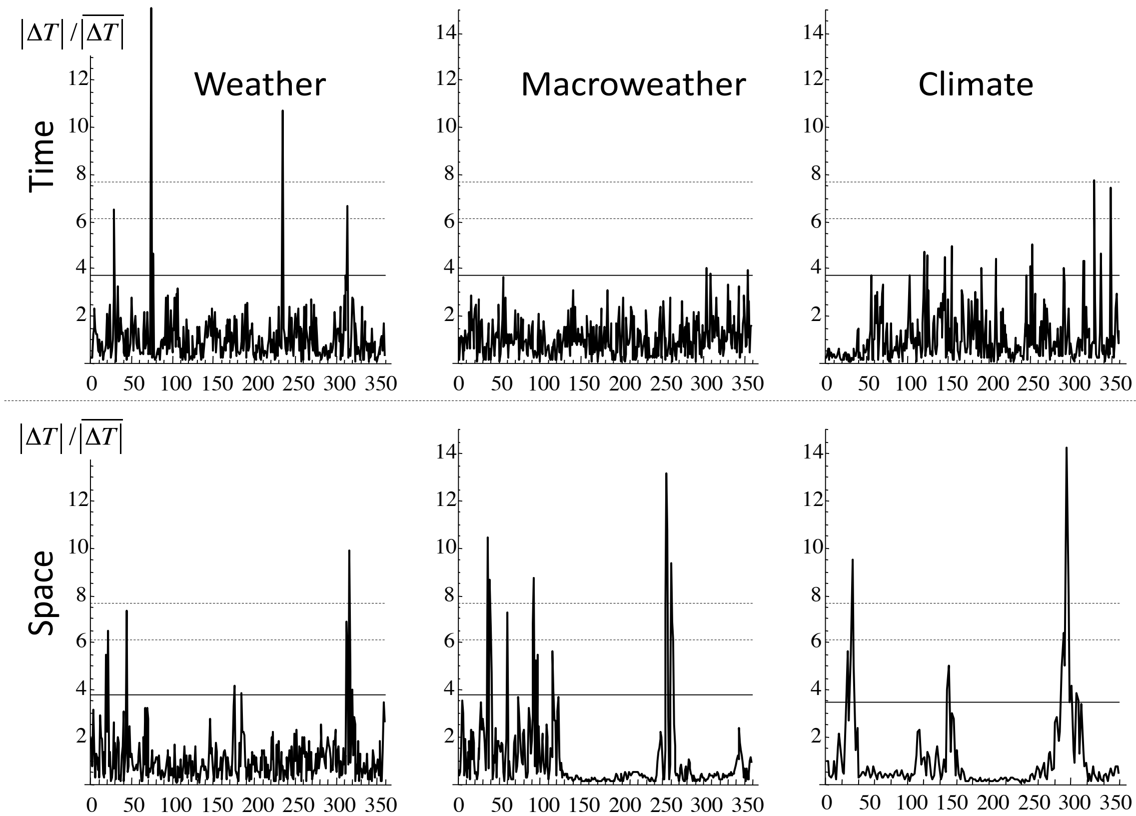


Fig. 2: Temperature spike plots for weather, macroweather, climate (left to right columns) and time and space (top and bottom rows). The solid horizontal black line indicates the expected maximum for a Gaussian process with the same number of points (360 for each with the exception of the lower right which had only 180 points), the dashed lines are the corresponding probability levels $p = 10^{-6}$, $p = 10^{-9}$ for Gaussian processes, two of the spikes exceed a ratio of 14; $p < 10^{-77}$. Although the spikes may seem extreme they, are easily understood and modelled with the help of multifractals.

The upper left is Montreal at 1 hour resolution; the upper middle is Montreal at 4 month resolution; the upper right, paleotemperatures from Greenland ice cores (GRIP) at 240 year resolution; the lower left is aircraft data at 280 m resolution; the lower middle, monthly resolution temperatures at $1^{o}$ spatial resolution; lower right, 140 year resolution in time, $2^{o}$ in space (at $45^{o}$N). Reproduced from [*Lovejoy*, 2019].

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