The climate is not what you expect

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Capsule Summary:

Contrary to popular ideas about the climate, what you really expect is macroweather. On scales of a human generation, the climate is what you get.

Abstract:

Prevailing definitions of climate are not much different from "the climate is what you expect, the weather is what you get". Using a variety of sources including reanalyses and paleo data, and aided by notions and analysis techniques from Nonlinear Geophysics, we argue that this dictum is fundamentally wrong. In addition to the weather and climate, there is a qualitatively distinct intermediate regime extending over a factor of ≈ 1000 in scale. For example, mean temperature fluctuations increase up to about 5 K at 10 days (the lifetime of planetary structures), then decrease to about 0.2 K at 30 years, and then increase again to about 5 K at glacial-interglacial scales.

Both deterministic GCM's with fixed forcings ("control runs") and stochastic turbulence-based models reproduce the first two regimes, but not the third. The middle regime is thus a kind of low frequency "macroweather" not "high frequency climate". Regimes whose fluctuations increase with scale appear unstable whereas regimes where they decrease appear stable. If we average macroweather states over periods ≈ 30 years, the results thus have low variability. In this sense, macroweather is what you expect.

We can use the critical duration of ≈ 30 years to define (fluctuating) "climate states". As we move to even lower frequencies, these states increasingly fluctuate –

appearing unstable so that the climate is *not* what you expect. The same methodology allows us to categorize climate forcings according to whether their fluctuations decrease or increase with scale and this has important implications for GCM's and for climate change and climate predictions.

1. Introduction

In his monumental "Climate: Past, Present, and Future" Horace Lamb argued that the early scientific view was the "climate as constant" [*Lamb*, 1972]. Reflecting this, in 1935 the International Meteorological Organization adopted 1901-1930 as the "climatic normal period". Following the post war cooling, this view evolved: for example the official American Meteorological Society glossary [*Huschke*, 1959] defined the climate as "the synthesis of the weather" and then "…the climate of a specified area is represented by the statistical collective of its weather conditions during a specified interval of time (usually several decades)". Although this new definition in principle allows for climate change, the period 1931-1960 soon became the new "normal", the ad hoc 30 year duration became entrenched and today 1961-1990 is commonly used. Mindful of the extremes, Lamb warned against reducing the climate to just "average weather", while viewing the climate as "…the sum total of the weather experienced at a place in the course of the year and over the years", [*Lamb*, 1972].

Lamb's essentially modern view allows for the possibility of climate change and is closely captured by the popular expression: "The climate is what you expect, the weather is what you get" (the character Lazurus Long in [*Heinlein*, 1973], but often attributed to Mark Twain). It is also close to the US National Academy of Science definition: "Climate is conventionally defined as the long-term statistics of the

weather…" [*Committee on Radiative Forcing Effects on Climate*, 2005] which improves on the "the climate is what you expect" idea only a little by proposing: "…to expand the definition of climate to encompass the oceanic and terrestrial spheres as well as chemical components of the atmosphere".

The Twain/Heinlein expression was strongly endorsed by the late E. Lorenz who stated: "Before embarking on a search for an ideal definition (of climate) assuming one exists, let me express my conviction that such a definition, when found must agree in spirit with the statement, "climate is what you expect"." [*Lorenz*, 1995]. He then proposed several definitions based on dynamical systems theory and strange attractors (see also [*Palmer*, 2005]).

A variant on this, motivated by GCM modeling, was proposed by [*Bryson*, 1997]: "Climate is the thermodynamic/ hydrodynamic status of the global boundary conditions that determine the concurrent array of weather patterns." He explains that whereas "weather forecasting is usually treated as an *initial value* problem … climatology deals primarily with a *boundary condition* problem and the patterns and climate devolving there from". Viewed this way, his definition could be paraphrased "for given boundary conditions, the climate is what you get".

There are two basic problems with the Twain/Heinlein dictum and its variants. The first is that they are based on an abstract weather - climate dichotomy, they are not informed by empirical evidence. The glaring question of how long is "long" is either decided subjectively or taken by fiat as the WMO's "normal" 30 year period. The second problem – that will be evident momentarily – is that it assumes that the climate is nothing more than the long term statistics of weather. While one might argue that this could

implicitly include the atmospheric response to significant slow external forcings, it still implausibly excludes the appearance of any new "slow", internal, uniquely climate processes.

The purpose of this paper is show that the weather-climate dichotomy is empirically untenable, that hiding between the two is a missing middle range spanning a factor of a thousand in scale (≈ 10 days to ≈ 30 years) characterized by qualitatively different dynamics. This new low frequency weather regime was dubbed "macroweather" since it is a kind of large scale weather (not small scale climate) regime [*Lovejoy and Schertzer*, 2012b], it fundamentally clarifies the distinction between weather and climate, the status and role of GCM models and the notion of climate predictabilty.

2. The variability characterized by spectral composites

Notwithstanding the existence of several strong periodicities (notably diurnal and annual), the atmosphere is highly variable over huge ranges of space-time scales. In addition, it has long been recognized (e.g. [*Lovejoy and Schertzer*, 1986], [*Wunsch*, 2003]) that even at the longer climate scales, most of the variance in the spectrum is from the continuous background. Any objectively based definition of weather or climate must therefore start from a clear picture of the atmosphere's temporal variability over wide scale ranges.

The first - and still most ambitious - single composite spectrum of atmospheric variability [*Mitchell*, 1976], ranged from hours to the age of the earth (≈ 10^{-4} to 10^{10} *yrs*), fig. 1 shows a modern version. Given the rudimentary quality of the data at that time, Mitchell admitted that his composite was mostly an "educated guess". His framework reflected the prevailing idea that there were numerous roughly periodic processes, with a

continuous background spectrum $E(\omega)$ made up of a hierarchy of white noise processes and their integrals (i.e. Ornstein-Uhlenbeck processes with spectra $E(\omega) \approx \omega^{-\beta}$ with $\beta = 0$, 2 respectively). The spectral spikes were therefore superposed on a spectrum consisting of a series of "shelves" and represented distinct physical processes. He explained his idea as follows:

"As we scan the spectrum from the short-wave end toward the longer wave regions, at each point where we pass through a region of the spectrum corresponding to the time constant of a process that adds variance to the climate, the amplitude of the spectrum increases by a constant increment across all substantially longer wavelengths. In other words, each stochastic process adds a shelf to the spectrum at an appropriate wavelength" [*Mitchell*, 1976].

By the early 1980's, following the explosion of scaling (fractal) ideas it was realized that scale invariance was a very general symmetry principle often respected by nonlinear dynamics, including many geophysical processes and turbulence. The signature of a scaling process is a power law spectrum, linear on a log-log plot. Although in order to accommodate the wide range of scales, Mitchell had found it "necessary to resort to logarithmic coordinates", there was no implication that the underlying processes might have nontrivial scaling over any significant range. In contrast, scaling symmetries, were explicitly invoked to justify the alternative composite picture ([*Lovejoy and Schertzer*, 1984; *Lovejoy and Schertzer*, 1986] which profited from early ocean and ice core paleotemperatures. These analyses already clarified the following points: a) the

distinction between the variability of regional and global scale temperatures with the latter having particularly long scaling regimes, b) that there was a scaling range for global averages between scales of the order of 10 *yrs* (τ_c in the notation here) up to ≈ 40 - 50 *kyrs* with an exponent $\beta_c \approx 1.8$, c) that a scaling regime with this exponent could quantitatively explain the magnitudes of the temperature swings between interglacials: the "interglacial window".

In the last 15 years this picture has been supported by the quite similar scaling composites of [*Pelletier*, 1998] and [*Huybers and Curry*, 2006]. The latter in particular made a data intensive study of the scaling of many different types of paleotemperatures collectively spanning the range of about 1 month to nearly 10^6 years. In addition, even without producing composites, other authors shared the scaling framework, e.g. [*Koscielny-Bunde et al.*, 1998], [*Talkner and Weber*, 2000], [*Ashkenazy et al.*, 2003; *Rybski et al.*, 2008]. Their results are qualitatively very similar - including the positions of the scale breaks; the main innovations are a) the increased precision on the β estimates and b) the basic distinction made between continental and oceanic spectra including their exponents. We could also mention the composite of [*Fraedrich et al.*, 2009] which is a modest adaptation of Mitchell's innovating by introducing a single scaling regime from ≈ 3 to ≈ 100 *yrs*.

Using real temperature and paleotemperature data, examples showing the behaviours in the three different regimes are graphically illustrated in fig. 2. Notice that in the weather regime (bottom) the temperature seems to "wander" up or down, temperature differences typically increase over longer and longer periods; the same behavior is evident in the climate range (top). However the low frequency macroweather

regime has a totally different appearance with successive fluctuations on the contrary tending to cancel each other out, i.e. with decreases followed by partially cancelling increases (and visa versa). This is discussed in more detail below, including the key critical exponent H =0 that qualitatively distinguishes the “wandering” or “cancelling” behaviors; H =0 corresponds roughly to a critical spectral slope β =1.

3. Evidence for scaling in the three regimes

Taken individually, for the weather ($\Delta t \approx< \tau_w$; $\tau_w \approx 10$ days), macroweather ($\tau_w < \Delta t < \tau_c$; $\tau_c \approx$ 10-30 *yrs*), and climate ($\Delta t > \tau_c$), there are now numerous studies supporting the scaling picture and estimating various scaling exponents in each. Starting with the climate regime, numerous paleo temperature series (mostly from ice and ocean cores) have been analyzed with broad agreement on their scaling nature and with spectral exponents mostly in the range $\beta_c \approx$ 1.3 to 2.1 over range from hundreds to tens of thousands of years, [*Lovejoy and Schertzer*, 1986], [*Schmitt et al.*, 1995], [*Ditlevsen et al.*, 1996], [*Pelletier*, 1998], [*Ashkenazy et al.*, 2003], [*Wunsch*, 2003], [*Huybers and Curry*, 2006], [*Blender et al.*, 2006], [*Lovejoy and Schertzer*, 2012c]. Diverse analysis techniques including spectra, difference and Haar structure functions as well as Detrended Fluctuation Analysis were employed so that the results are fairly robust. In addition, as discussed below, further analyses from surface temperatures, multiproxy reconstructions and 138 year long Twentieth Century reanalysis, lend this further quantatitive support.

Similarly, in the low frequency macroweather regime, there are now many studies finding scaling with spectral exponents β_{lw} <1, e.g. for the temperature; with some

variation in β_{lw} between oceans and continents, northern latitudes and tropics: [*Lovejoy and Schertzer*, 1986], [*Pelletier*, 1998], [*Huybers and Curry*, 2006], [*Fraedrich and Blender*, 2003], Koscielny-Bunde et al., 1998, Bunde et al., 2004, [*Eichner et al.*, 2003], [*Lennartz and Bunde*, 2009], [*Blender et al.*, 2006], [*Fraedrich et al.*, 2009], [*Lanfredi et al.*, 2009]. Since β_{lw} is small, log-log spectra appear as fairly flat "spectral plateaus". A review of the ubiquitous empirical evidence for this include, analyses of the temperature, wind, humidity, geopotential height, rain, vertical wind, and the North Atlantic Oscillation and Pacific Decadal Oscillation indices [*Lovejoy and Schertzer*, 2010], [*Lovejoy and Schertzer*, 2012b].

Of the three regimes, the only one where the idea of a roughly scaling background spectrum is still somewhat controversial is the higher frequency weather regime (scales < $\tau_w \approx 10$ days). To understand the debate, recall that the classical turbulence theories describing the statistical variability in the weather regime are all based on isotropic scaling, the most famous being the Kolmogorov $k^{-5/3}$ spectrum for the wind (k is a wavenumber). However, the strong vertical atmospheric stratification prevents isotropic scaling from holding over any scale ranges spanning the scale thickness of the atmosphere (≈ 10 *km*). One must therefore, abandon either the scaling or the isotropy assumption. Following Kraichnan's development of 2-D turbulence and Charney's extension to quasi geostrophic turbulence, the usual choice was to retain isotropy and to divide the dynamics into 2D isotropic (large scale) and 3D isotropic (small) scale regimes ([*Kraichnan*, 1967], [*Charney*, 1971]). However, starting with [*Schertzer and Lovejoy*, 1985], a growing body of evidence and theory has supported the alterative anisotropic scaling hypothesis. Thanks both to modern empirical evidence

(e.g. the review [*Lovejoy and Schertzer*, 2010], [*Lovejoy and Schertzer*, 2012b] and a recent massive aircraft study [*Pinel et al.*, 2012]), but also to theoretical arguments showing that the governing equations are symmetric with respect to anisotropic scaling symmetries ([*Schertzer et al.*, 2012]), the question increasingly has been settled in favor of anisotropic scaling (see the recent debate [*Lovejoy et al.*, 2009], [*Lindborg et al.*, 2010a; *Lindborg et al.*, 2010b], [*Lovejoy et al.*, 2010], [*Schertzer et al.*, 2011], [*Yano*, 2009], ([*Schertzer et al.*, 2012]). The implications of this anisotropic spatial scaling for the temporal statistics are discussed in [*Radkevitch et al.*, 2008] and [*Lovejoy and Schertzer*, 2010].

A review of diverse evidence from reanalyses, in situ and remotely sensed data (see [*Lovejoy and Schertzer*, 2010], [*Lovejoy and Schertzer*, 2012b] for reviews) shows that for wind, temperature, humidity, pressure, short and long wave radiances, β_w is commonly in the range 1.5 -2 (certainly >1). The existence of a basic transition in the range ≈ 5 – 20 days has been recognized at least since [*Van der Hoven*, 1957] noted a low frequency spectral "bump" at around 5 days. Later, the corresponding features in the temperature and pressure spectra were termed "synoptic maxima" by [*Kolesnikov and Monin*, 1965] and [*Panofsky*, 1969]. More recently, in the same spirit as Mitchell, the transition has been modeled (e.g. [*AchutaRao and Sperber*, 2006]) as an Orenstein-Uhlenbeck process i.e. with $\beta_w = 2$, $\beta_{lw} = 0$, corresponding to $H_w = 1/2$, $H_{lw} = -1/2$, although as can be seen in fig. 3 (discussed below), this is not a very accurate approximation and can be misleading. Finally, [*Vallis*, 2010] proposed a (nonscaling) midlatitude explanation using baroclinic instabilities.

A seductive feature of the (anisotropic) scaling framework is that it fairly

accurately predicts the weather to macroweather transition scale $\tau_w \approx 10$ days. The argument is as follows: the sun provides ≈ 1 kW/m^2 of heating with a 2% efficiency of conversion to kinetic energy ([*Monin*, 1972]). Since the energy is distributed reasonably uniformly over the troposphere, this leads to a turbulent energy flux density (ε) close to the observed global value $\varepsilon \approx 10^{-3}$ W/Kg ([*Lovejoy and Schertzer*, 2010]). The model predicts that this turbulent energy flux is the fundamental driver of the horizontal dynamics and thus to the prediction that planetary structures have eddy-turnover times of $\approx \varepsilon^{-1/3} L_e^{2/3} \approx 10$ days where L_e =20000 km is the largest great circle distance on the earth. The analogous calculation for the ocean using the empirical ocean turbulent flux $\varepsilon \approx 10^{-8}$ W/Kg, yields a lifetime of ≈ 1 yr which is indeed the scale separating a high frequency "ocean weather" regime (with β_{ow}>1) from a low frequency one with β_{lo} <1 [*Lovejoy and Schertzer*, 2012c], see fig. 3.

This picture allows us to understand the weather/macroweather transition since it validates the use of the stochastic turbulence based Fractionally Integrated Flux model (FIF, i.e. cascades [*Schertzer and Lovejoy*, 1987]). The FIF shows that whereas in the weather regime, fluctuations depend on interactions in both space and in time, at lower frequencies they become "quenched" so that only the temporal interactions are important and τ_w marks a "dimensional transition" [*Lovejoy and Schertzer*, 2010]. Physically, at scales $\Delta t<\tau_w$ the statistics depend on structures with lifetimes Δt; at scales $\Delta t<\tau_w$ they depend on the statistics of many planetary sized structures. In addition, the basic FIF model predicts [*Lovejoy and Schertzer*, 2012c] low frequency weather exponents typically in the range $0.2 < \beta_{lw} < 0.6$ (i.e. $-0.4 < H_{lw} < -0.2$).

4. Real space fluctuations and analyses

In spite of the now burgeoning evidence that the atmosphere's natural variability is scaling over various ranges, the idea has not received the attention it deserves and at least over decadal, centennial and millennial scales, the natural variability is still largely identified with quasi-periodic behaviours (for examples of periodicities ranging from multidecadal to millennial scales see [*Delworth et al.*, 1993], [*Schlesinger and Ramankutty*, 1994], [*Mann and Park*, 1994], [*Mann et al.*, 1995], [*Bond et al.*, 1997], [*Isono et al.*, 2009]). One of the reasons for this focus on quasi periodic behavior is that spectra are not ideal for understanding scaling processes. For these, the corresponding real space analyses are more straightforward to interpret; this is particularly true when comparing spectra from different data types with different resolutions. In this section we show how this works.

In order to understand the qualitatively different behaviors in fig. 2, consider fluctuations ΔT. In a scaling regime, these will change with scale as $\Delta T = \varphi\, \Delta t^H$ where H is the fluctuation (also called the "nonconservation" exponent; it is denoted "H" in honor of Edwin Hurst but in general it is not the same as the Hurst exponent). φ is a controlling dynamical variable (e.g. a turbulent flux) whose mean $<\varphi>$ is independent of the lag Δt (i.e. independent of the time scale). The behavior of the mean fluctuation is thus $<\Delta T> \approx \Delta t^H$ so that if $H>0$, on average fluctuations tend to grow with scale whereas if $H<0$, they tend to decrease.

Although it is traditional (and often sufficient) to define fluctuations by absolute differences $\Delta T(\Delta t) = |T(t+\Delta t) - T(t)|$, for our purposes this is *not* sufficient. Instead

we should use the absolute difference of the mean between t and $t+\Delta t/2$ and between $t+\Delta t/2$ and $t+\Delta t$. Technically, this corresponds to defining fluctuations using Haar wavelets rather than "poor man's" wavelets. While the latter is adequate for fluctuations increasing with scale (i.e. $H>0$), mean absolute differences cannot decrease and so when $H<0$, they do not correctly estimate fluctuations. The Haar fluctuation (which is useful for $-1<H<1$) is particularly easy to understand since (with proper "calibration") in regions where $H>0$, it can be made very close to the difference fluctuation and in regions where $H<0$, it can be made close to another simple to interpret "tendency fluctuation". While other techniques such as Detrended Fluctuation Analysis [*Peng et al.*, 1994], [*Kantelhardt et al.*, 2002; *Monetti et al.*, 2003] perform just as well for determining exponents, they have the disadvantage that their fluctuations are not at all easy to interpret (they are the standard deviations of the residues of polynomial regressions on the running sum of the original series; see [*Lovejoy and Schertzer*, 2012a]).

Once estimated, the variation of the fluctuations with scale can be quantified by using their statistics; the q^{th} order structure function $S_q(\Delta t)$ is particularly convenient:

$$S_q(\Delta t) = \left\langle \Delta T(\Delta t)^q \right\rangle \tag{1}$$

where "<.>" indicates ensemble averaging. In a scaling regime, $S_q(\Delta t)$ is a power law; $S_q(\Delta t) \approx \Delta t^{\xi(q)}$, where the exponent $\xi(q) = qH - K(q)$ and $K(q)$ characterizes the scaling intermittency (with $K(1) = 0$). In the macroweather regime $K(2)$ is typically small ($\approx$0.01-0.03), so that the RMS variation $S_2(\Delta t)^{1/2}$ (denoted simply $S(\Delta t)$ below) has the exponent $\xi(2)/2 \approx \xi(1) = H$. In the climate regime this intermittency correction is a bit larger [*Schmitt et al.*, 1995] but the error in using this approximation ($\approx$0.06) will be

neglected. Note that since the spectrum is a second order statistic, we have the useful relationship $\beta = 1+\xi(2) = 1+2H-K(2)$. When $K(2)$ is small, $\beta \approx 1+2H$ so that as mentioned earlier, $H>0$, $H<0$ corresponds to $\beta > 1$, $\beta<1$ respectively.

When $S(\Delta t)$ is estimated for various in situ, reanalysis, multiproxy and paleo temperatures, one obtains fig. 3. The key points to note are a) the three qualitatively different regimes corresponding to the spectra in fig. 1: weather, (low frequency) macroweather and climate with $S(\Delta t)$ respectively increasing, decreasing and increasing again with scale ($H_w>0$, $H_{lw}<0$, $H_c>0$) and with transitions at $\tau_w \approx 5$ - 10 days and $\tau_c \approx 10$-30 *yrs* (we can also glimpse a fourth low frequency climate regime for scales larger than $\tau_{lc} \approx 100$ *kyrs*, but this is outside our scope), b) the difference between the local and global fluctuations, c) the "glacial/interglacial window" corresponding to overall ±3 to ±5 *K* variations (i.e. $S(\Delta t) \approx 6, 10$ *K*) over scales with half periods of 30 – 50 *kyrs*; the curve must pass through the window in order to explain the glacial/interglacial transitions. Starting at $\tau_c \approx 10$ - 30 *yrs*, one can plausibly extrapolate the global surface and 20CR 700 *mb* $S(\Delta t)$'s using $H = 0.4$ ($\beta \approx 1.8$), all the way to the interglacial window (with nearly an identical S as in [*Lovejoy and Schertzer*, 1986]). Similarly, the local temperatures and multiproxies also seem to follow the same exponent with slightly different τ_c's and seem to extrapolate respectively a little above and below the window.

These statistics may seem arcane but their physical interpretation is pretty straightforward. In the weather regime, larger and larger fluctuations "live" for longer and longer times: the "eddy turnover time". At any given time scale, the fluctuations are dominated by structures with corresponding spatial scales and this relationship holds up to structures of planetary scales with lifetimes ≈ 10 days. For periods longer than this,

the statistics are dominated by averages of many planetary scale structures, and these fluctuations tend to cancel out: for example large temperature increases are typically followed (and partially cancelled) by corresponding decreases. The consequence is that in this macroweather regime, the average fluctuations diminish as the time scale increases. At some point – at around 10 – 30 years depending on geographic location and time, these weaker and weaker fluctuations - whose origin is in weather dynamics - become dominated by increasingly strong lower frequency processes. These not only include changing external solar, volcanic orbital or anthropogenic "forcings" – but quite likely also new and increasingly strong slow (internal) climate processes - or by a combination of the two: forcings with feedbacks. Examples of such slow dynamical processes that are not currently incorporated into GCM's include deep ocean currents and land-ice dynamics. The overall effect is that in the resulting climate regime, fluctuations tend to grow again with scale in an "unstable" manner, very similar to the way they grow in the weather regime.

5. Implications for climate modelling, prediction

Numerical weather models and reanalyses are qualitatively in good agreement with the weather / macroweather picture described above, although there are still some quantitative discrepancies in the values of the exponents, possibly due the hydrostatic approximation or other numerical issues ([*Stolle et al.*, 2009], [*Lovejoy and Schertzer*, 2011]). However, climate models (GCM's) are essentially weather models with various additional couplings (with ocean, carbon cycle, land-use, sea ice and other models). It is therefore not surprising that control runs (i.e. with no "climate forcings") generate low frequency weather (with $\beta_{lw} \approx 0.2$, $H_{lw} \approx -0.4$), and this apparently out to the extreme low

frequency limit of the models (see the review and analyses in [*Lovejoy et al.*, 2012b] as well as [*Blender et al.*, 2006], [*Rybski et al.*, 2008]).

Avoiding anthropogenic effects by considering the pre-1900 epoch, for GCM climate models, the key question is whether solar, volcanic, orbital or other climate forcings are sufficient to arrest the H <0 decline in macroweather fluctuations and to create an H >0 regime with sufficiently strong centennial, millennial variability to account for the "background" variability out to glacial- interglacial scales. Analysis of several last millennium simulations has found that at the moment, their low frequency variabilities are too weak [*Lovejoy et al.*, 2012b].

To understand this weak variability, one can examine the scale dependence of fluctuations in the radiative forcings (ΔR_F) of several solar and volcanic reconstructions; they are generally scaling with $\Delta R_F \approx A\Delta t^{H_R}$ [*Lovejoy et al.*, 2012a]. If $H_R \approx H_T \approx 0.4$, then scale *independent* amplification / feedback mechanisms would suffice. However it was often found that $H_R \approx -0.3$ implying that the forcings become weaker with scale - even though the response grows with scale. This suggests the need to introduce new slow – and hence hard to incorporate into GCM's - mechanisms of internal variability. Such mechanisms must have broad spectra; this suggests their dynamics involve nonlinearly interacting spatial degrees of freedom such as the deep ocean and land-ice dynamics mentioned above.

Whatever the ultimate source of the growing fluctuations in the H > 0 climate regime, a careful and complete characterization of the scaling in space as well as in time (including possible space-time anisotropies) allows for new stochastic methods for predicting the climate. The idea is to exploit the particularly low variability of the

averages at scale τ_c. The means of any relevant atmospheric or climate variables at this scale could be used to define "climate states", and the changes at scales $\Delta t > \tau_c$ define climate change. Even without resolving the question of the dominant climate forcing and slow internal feedbacks, one could use the statistical properties of the climate states - the system's "memory" implicit in the long range statistical correlations – combined with the growing data on past climate states in order to make stochastic climate forecasts.

Another attractive application of this scaling picture is that by quantifying the natural variability as a function of space-time scales, it opens up the possibility of convincingly distinguish natural and anthropogenic variability. This is possible because the stochastic scaling framework allows one to statistically test specific hypotheses about the probability that the atmosphere would naturally behave in the way that is observed, i.e. to formulate rigorous statistical tests of any trends or events against the null hypothesis. Only if the probabilities are low enough should the hypothesis that the observed changes are natural in origin be rejected. This is important because at the moment, we lack quantitative (and hence convincing) answers to questions such as: how can the earth have prolonged periods of cooling in the midst of anthropogenic warming; or was this winter's record mild temperature really evidence for anthropogenic influence? Finally, the systematic comparison of model and natural variability in the preindustrial era is the best way to fully address the issue of "model uncertainty", to assess the extent by which the models are missing important slow processes.

6. Conclusions

Contrary to [*Bryson*, 1997], we have argued that the climate is not accurately viewed as the statistics of fundamentally fast weather dynamics that are constrained by

quasi fixed boundary conditions. The empirically substantiated picture is rather one of unstable (high frequency) weather processes tending - at scales beyond 10 days or so and primarily due to the quenching of spatial degrees of freedom - to quasi stable (intermediate frequency, low variability) macroweather processes. Climate processes only emerge from macroweather at even lower frequencies, and this thanks to new slow internal climate processes coupled with external forcings. Their synergy yields fluctuations that on average again grow with scale and become dominant typically on time scales of 10 - 30 years up to ≈ 100 kyrs.

Looked at another way, if the climate really *was* what you expected, then – since one expects averages - predicting the climate would be a relatively simple matter. On the contrary, we have argued that from the stochastic point of view - and notwithstanding the vastly different time scales - that predicting natural climate change is very much like predicting the weather. This is because the climate at any time or place is the consequence of climate changes that are (qualitatively and quantitatively) unexpected in very much the same way that the weather is unexpected.

At a subjective level, from experience over the years, we all grow to expect certain stable patterns of macroweather (complicated by seasonal effects, but nevertheless recognizable from year to year) so that in daily discourse we may say “macroweather is what you expect, the weather is what you get”. However over generational scales - periods of 10 – 30 years - the macroweather we are accustomed to evolves due to climate change. Speaking to our children and grandchildren, the appropriate dictum would therefore be “macroweather is what you expect, the climate is what you get”.

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Figures and Captions:

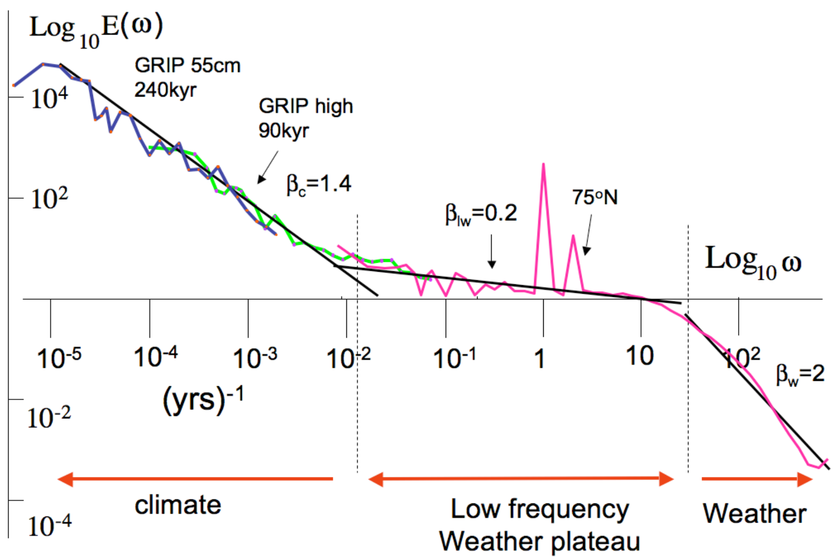

Fig. 1: **A composite temperature spectrum:** the GRIP (Summit) ice core $\delta^{18}O$ (a temperature proxy, low resolution along with the first 91 *kyrs* at high resolution (left), with the spectrum of the (mean) 75°N 20th Century reanalysis temperature spectrum, at 6 hour resolution, from 1871-2008, at 700 *mb* (right). The overlap (from 10 – 138 *yr* scales) is used for calibrating the former (moving them vertically on the log-log plot). All spectra are averaged over logarithmically spaced bins, ten per order of magnitude in frequency. Three regimes are shown corresponding to the weather regime with β_w= 2 (the diurnal variation and subharmonic at 12 hours are visible at the extreme right). The central low frequency macroweather "plateau" is shown along with the theoretically predicted β_{lw} = 0.2 - 0.4 regime. Finally, at longer time scales (the left), a new scaling climate regime with exponent β_c ≈1.4 continues to about 100 *kyrs*. Reproduced from [*Lovejoy and Schertzer*, 2012c].

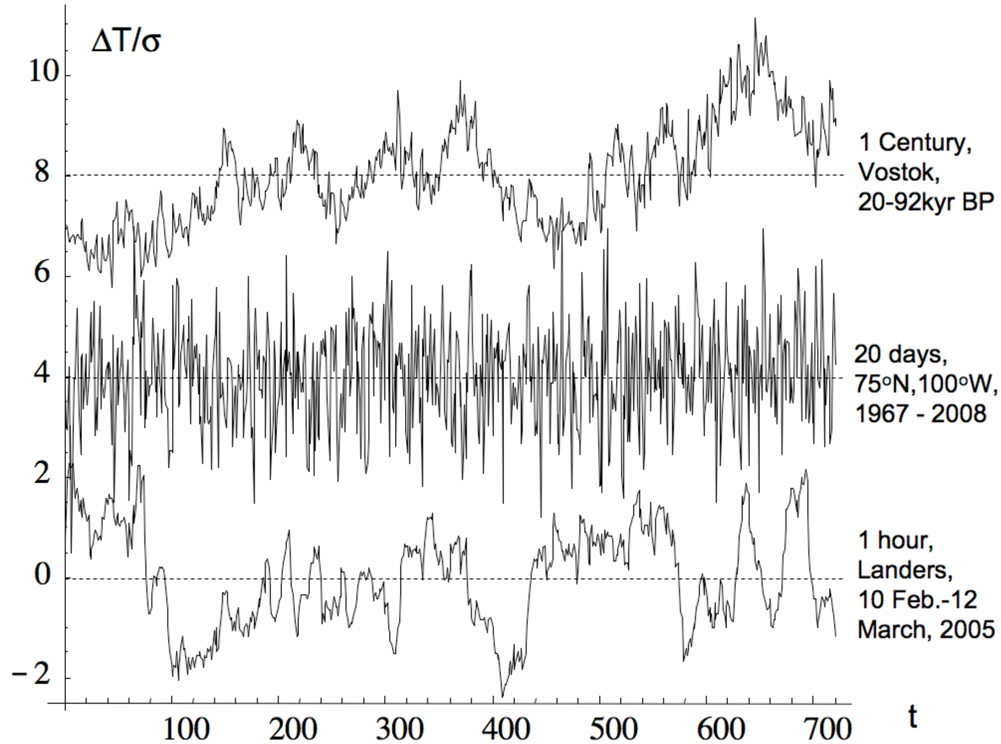

Fig. 2: **Dynamics and types of scaling variability:** A visual comparison displaying representative temperature series from weather, low frequency macroweather and climate ($H \approx 0.4$, -0.4, 0.4, bottom to top respectively). To make the comparison as fair as possible, in each case, the sample is 720 points long and each series has its mean removed and is normalized by its standard deviation (4.49 K, 2.59 K, 1.39 K, respectively), the two upper series have been displaced in the vertical by four units for clarity. The resolutions are 1 hour, 20 days and 1 century, the data are from a weather station in Lander Wyoming, the 20th Century reanalysis and the Vostok Antarctic station. Note the similarity between the type of variability in the weather and climate regimes (reflected in their scaling exponents although the H exponent is only a partial characterization).

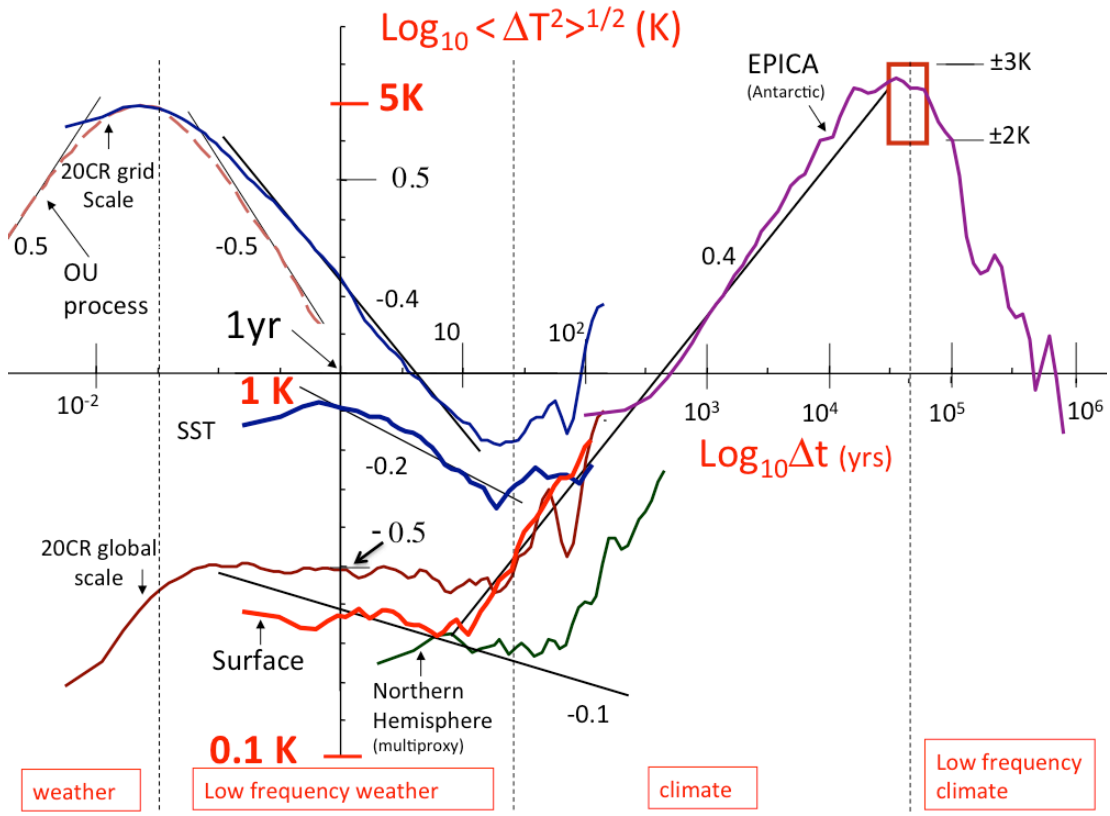

Fig. 3: **Empirical RMS temperature fluctuations ($S(\Delta t)$), local scale analyses:** On the left top we show grid point scale (2^ox2^o) daily scale fluctuations globally averaged along with reference slope $\xi(2)/2 = -0.4 \approx H$ (20CR, 700 *mb*). For comparison, the results for 50 simulations of Orenstein-Uhlenbeck (OU) processes are also given using simulations with a characteristic time of 3 days. The theoretical asymptotic slopes (0.5, -0.5) are added to show their convergence to theory. Just below this, we show the monthly NOAA CDC Sea Surface Temperature curve (5^o resolution, from 1900-2000); the transition from $\xi(2)/2 \approx 0.4$ to ≈ -0.2 occurs at $\tau_{ow} \approx 1$ *yr*. On the lower left, we see at daily resolution, the corresponding globally averaged structure function.

Globally averaged series: The same 20CR data but globally averaged (brown), The average of the three in situ surface series (NOAA NCDC, NASA GISS, CRU, red) as

well as the average of three post 2003 multiproxy structure functions; [*Huang*, 2004], [*Ljundqvist*, 2010; *Moberg et al.*, 2005], (see [*Lovejoy and Schertzer*, 2012c]).

Paleotemperatures: At the right we show analysis of the EPICA Antarctic series interpolated to 50 year resolution over ≈ 800 *kyrs*. Also shown is the interglacial "window".

The reference slopes are $\xi(2)/2$ = -0.4, -0.2 or +0.4; these correspond to spectral exponents $\beta = 1+\xi(2)$ = 0.2, 0.6, 1.8 respectively; a flat curve in the above corresponds to $\beta = 1$.

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