What is the Climate?

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Trichotomy, not dichotomy

We all have an intuitive understanding of the weather as referring to the state of the atmosphere at a given time and place and to the climate as a kind of average weather. A popular expression of this dichotomy is "the climate is what you expect, the weather is what you get" ([*Heinlein*, 1973], often attributed to Mark Twain). Implicit is the notion of climate as a kind of constant natural state to which the weather would converge if we averaged it over a long enough period. A corollary is that climate change is a consequence of "climate forcings" which are external to the natural climate system and which tend to prevent averages from converging to their true values. In this framework, past climate change may be attributed to orbital changes, variations in solar output, volcanic eruptions etc. For the recent period, we may add anthropogenic forcings.

The empirical characterization of atmospheric variability has largely concentrated on possible periodicities (notably the 11 year solar cycle). This is unfortunate since almost all of the variability comes from a "background" continuum of time scales not from a finite number of periodic ondulations ([*Lovejoy and Schertzer*, 1986], [*Wunsch*, 2003]). The characterisation of this wide range variability – which turns out to be scaling (power law) - has been neglected and consequently current scientific climate notions are not much different from the popular ones. A typical example is: "Climate is conventionally defined as the long-term statistics of the weather…" (US National Academy of Science: [Committee on Radiative Forcing Effects on Climate, 2005]). Or - in the theoretical framework of GCM's (Global Climate Models) - "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" [*Bryson*, 1997]. This could be paraphrased: "for given boundary conditions, the climate is what you expect" (see [*Lorenz*, 1995]) and it justifies the use of GCM's to model the climate (see however [*Pielke*, 1998]).

How do these abstract notions compare with the real atmosphere? Fig. 1a shows examples from weather scales (space and time, the bottom curves at 280 m and 1 hour resolutions) and at two lower resolutions (top curves, 20 days and 1 century). Although this shows temperatures, other atmospheric fields (wind, humidity, precipitation, etc.) are qualitatively the same ([*Lovejoy and Schertzer*, 2012a]). Notice that the weather curves "wander" up or down resembling a drunkard's walk typically increasing over larger and larger distances and times periods. The 20 day resolution curve has a totally different character with upward fluctuations typically being followed by nearly cancelling downward ones. Averages over longer and longer times tend to converge, apparently vindicating "the climate is what you expect" idea: we anticipate that at decadal or at least centennial scales that averages will be virtually constant with only slow, small amplitude variations. However the century scale curve (top) displays again a weather - like variability (quantified in fig. 1b). There are thus three qualitatively different regimes –

not two. While the high frequency regime is clearly the weather and the low frequency regime the climate, the new "in between" regime was described as a "spectral plateau" and later dubbed "macroweather" since it is a kind of large scale weather (not small scale climate) regime, (see below and [*Lovejoy and Schertzer*, 1986], [*Lovejoy and Schertzer*, 2012a]).

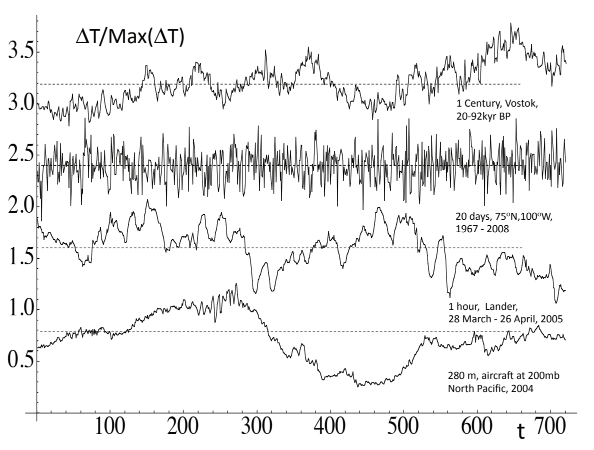

Fig. 1a: **Dynamics and types of scaling variability:** Representative temperature series from weather (space and time), macroweather and climate ($H \approx 0.4, 0.4, -0.4, 0.4$, bottom to top respectively). Each samples is 720 points long and was normalized by its overall range (bottom to top: 2.86 K, 27.8 K, 16.84 K, 7.27 K, dashed lines indicate means). The resolutions are 280 m, 1 hour, 20 days and 1 century, the data are from an aircraft at 200

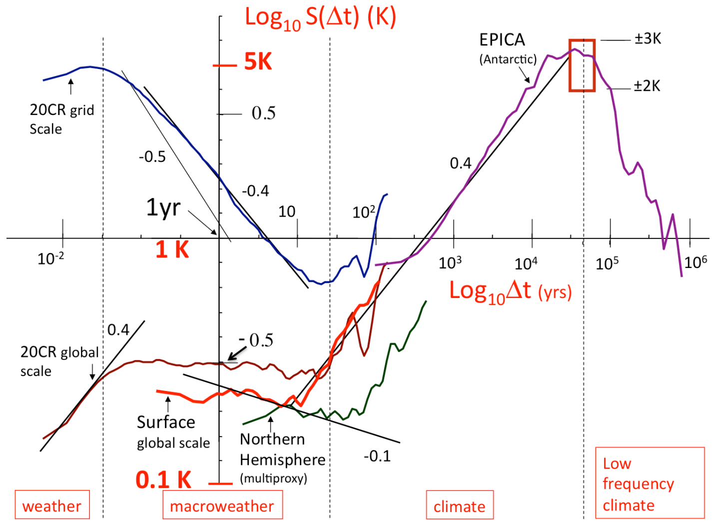

Fig. 1b: **Temperature standard deviations ($S(\Delta t)$):** Left, top: grid point scale (2°x2°) daily fluctuations globally averaged from the 20CR. Below left: the same but globally averaged (brown); Below (red) the average of the three in situ surface series as well as $S(\Delta t)$ from three multiproxy northern hemisphere reconstructions (green, see [*Lovejoy and Schertzer*, 2012b]). Right: the EPICA Antarctic series at 50 yr resolution. Also shown is the interglacial "window" (rectangle) and reference slopes $\approx H = -0.4, +0.4, -0.1$,

mb (north Pacific), Lander Wyoming, the 20th Century reanalysis (20CR) and Vostok (antarctic).	-0.5 (Gaussian white noise).

Atmospheric variability from days to 800,000 years

Consider temperature fluctuations ΔT at various times scales Δt. Although it is traditional to define fluctuations by the absolute differences of the temperature at time t and $t+\Delta t$, 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 $t+\Delta t$, i.e. use "Haar" rather than "poor man's" wavelets. Although this distinction may seem arcane, starting in the 1980's, analyses using differences and spectra were not sufficiently clear. The failure to define fluctuations in this way is at least partly responsible for lack of awareness of macroweather [*Lovejoy and Schertzer*, 2012c].

Once estimated, the variation of the fluctuations with scale can be conveniently quantified by their standard deviations $S(\Delta t)$. When $S(\Delta t)$ is estimated using temperatures (and surrogates), one obtains the log-log fig. 1b. Notice that the temporal curves in fig. 1a correspond to different linear regions with slopes H alternating in sign (≈ 0.4, -0.4, 0.4 respectively). In each region, $S(\Delta t) \approx \Delta t^H$ so that the weather, macroweather and the climate are roughly power laws (scaling) and are distinguished by their exponents. $H>0$ implies that fluctuations grow with scale, $H<0$ that they diminish so that these exponents quantify both "wandering" and "cancelling" behaviour. The transitions occur roughly at $\tau_w \approx 5$ - 10 days and $\tau_c \approx 10$-30 *yrs* (a fourth low frequency climate regime beyond ≈ 100 *kyrs* is beyond our scope). Also note the difference between the local and global fluctuations. Finally we have indicated the "glacial/interglacial window": in order to explain the transitions into and out of the ice ages (with half period ≈ 30 to 50 *ky* and amplitude ±3 to ±5 *K*), the curve must pass through this window. Starting at $\tau_c \approx 10$ - 30 *yrs*, one can plausibly extrapolate the global $S(\Delta t)$'s using $H = 0.4$ through it (see [*Lovejoy and Schertzer*, 1986] for similar estimates and see [*Pelletier*, 1998], [*Huybers and Curry*, 2006] for scaling spectral composites).

The basic physical interpretations are straightforward. In the weather regime, larger and larger fluctuations "live" for longer and longer times. At any given Δt, the fluctuations are dominated by structures with corresponding spatial scales, this relationship holds up to structures of planetary scales whose lifetimes are ≈ 10 days. This is well estimated by combining scaling with the observed mean solar energy flux forcing of $\approx 10^{-3}\text{m}^2\text{s}^{-3}$ (the turbulent energy per mass per time flowing from large to small scales [*Lovejoy and Schertzer*, 2012b]). In the macroweather regime, the fluctuations are dominated by averages of many planetary scale structures, and these tend to cancel each other out so that averages diminish as the time scale increases. At around 10 to 30 years these weaker and weaker fluctuations - whose origin is in weather dynamics - become dominated by fluctuations from increasingly strong lower frequency processes. These are due not only to changing external solar, volcanic orbital and anthropogenic "forcings" – but presumably also to new and increasingly strong slow (internal) climate processes such as deep ocean or land-ice dynamics - or by a combination of the two: forcings with internal feedbacks. The result is the climate regime with fluctuations growing with time scale in a weather-like manner.

Climate modelling, prediction and anthropogenic effects

GCM "control runs" (with fixed boundary conditions i.e. with fixed atmospheric composition, solar output, orbital parameters and without volcanism) are found to generate a macroweather regime with $H \approx -0.4$ out to the extreme low frequency limit of the models (several millennia: [*Blender et al.*, 2006], [*Rybski et al.*, 2008], [*Lovejoy and Schertzer*, 2012a]). Since GCM's are essentially weather models with extra couplings, the name "macroweather", is appropriate. Using the trichotomy weather, macroweather, climate, we can naturally define "climate states" as the averages over macroweather at the scales at which the variability is at its lowest (≈ 30 *yrs*) thus conveniently justifying the "climate normal" concept (and indeed nuancing it since 30 yrs is an average over different geographical locations and epochs). "Climate change" thus naturally refers to the change in climate normals at longer (climate) time scales.

Skeptics of this choice are invited to consider the alternative trichotomy: weather, climate, macro-climate. In this case, the notion of climate variability would include (deseasonalized) monthly scale atmospheric variability. The corresponding climate would be "forced" by the weather, with its statistics given by mere weather models. The challenge for GCM's would be to predict the effects of "macro-climate forcings" on the macro-climate. Since the impact of global warming on the mean fluctuations is only visible at scales > 10 - 30 *yrs*, mankind would not alter the climate, but rather the "macroclimate". Finally, surrogates of past atmospheric states would be termed "paleo - macro - climate data".

Irrespective of nomenclature, 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 observed "background" climate variability out to ≈ 100 *kyrs*. Analysis of several simulations of the last millennium shows that their low frequency variability is too small [*Lovejoy and Schertzer*, 2012a]. In addition, the H's of the reconstructed forcings are typically negative so that they typically become weaker - not stronger - with scale and are unlikely to account for the observed increase in climate variability with scale (H>0, [*Lovejoy and Schertzer*, 2012d]).

Whatever the ultimate source of the growing fluctuations, a careful and complete characterization of the scaling in space as well as in time will allow for new stochastic methods for predicting the climate that exploit the system's "memory" implicit in the power law behaviours. By quantifying the natural variability as a function of space-time scales, it opens up the possibility of distinguishing natural and anthropogenic variability using rigorous statistic hypothesis testing. 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 may be missing important slow processes.

Conclusions

The prevailing weather-climate dichotomy is empirically untenable, it should be replaced by a weather- macroweather - climate trichotomy. The state to which weather starts to converge when averaged is not the climate but macroweather. True climate processes only emerge from macroweather at even longer times, and this thanks to new slow internal climate processes coupled with external forcings. Whatever the cause, it is an empirical fact that the emergent synergy of these processes yields fluctuations that on average again grow with scale and become dominant typically on time scales of 10 - 30 *yrs* up to ≈ 100 *kyrs*.

If the climate really *was* what you expected, there would be no climate change, and – since one expects averages - predicting the climate would simply consist in the determination of the immutable "climate normal". 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.

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