ARCHITECTURE OF CLOUDS - CLOUDS AS ARCHITECTURE
Scale-Invariance as a *Symmetry* in Natural Systems and Artificial Environments

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In one of his poems, Charles Baudelaire (1821–1867) evokes his contemplation of those 'moving architectures that God makes out of vapors, wonderful constructions of the intangible.' We immediately recognize clouds. In few words the essence of cloud geometry, turbulent yet delicate, is captured and related to architecture, regarded by some as one of the most purpose-driven of all applications of geometry. The poet —as well as any child— would be shocked to hear how clouds are modeled in state-of-the-art Global Circulation Models (GCMs) when estimating local radiation budgets, i.e., when dealing with the raw energetics that fuel atmospheric motions. This trivially symmetric model is a perfectly flat slab, uniformly filled with identical water droplets! How can this un-inspiring vision prevail in the face of compelling observational evidence of the rich fractal structure of cloudiness [4]? Simply because, at current computer capacities, the smallest details in the big atmospheric dynamical picture are several hundred kilometers in scale! Furthermore, processes at these "small" scales are to be treated as expediently as possible in order to get back to the more important business of integrating Newton's laws of motion. Under these constraints, the visual contrast between the smooth, regular flow patterns predicted by our best computer models and the rough, spotty quality of radar and satellite images is hardly a surprise. And this divorce is deeper than meets the eye: using (generally point-wise) observations to improve the numerical forecast has become an intricate art known as "data assimilation." In recent years, re-engineered GCMs known as Large Eddy Simulators (LESs) have been used to focus on cloud scale phenomena. Still the smallest details resolved by LESs are hundreds of meters in scale and we know that the real atmosphere is variable down to centimeters at least; so the race to "small-enough" scales is apparently lost. But where does Nature's attention to detail come from?

Exaggerating slightly, dynamical meteorology is working under Laplace's paradigm which epitomizes the arrogant rationalism of the early 19th century: *given the initial conditions of every* *particle (parcel of air) in the Universe (atmosphere), we can in principle compute all that has happened and will happen.* Corollary: neither God nor dice have any role in any of this! P. S. de Laplace (1749–1827) was an astronomer specializing in planetary motion and his world ticks like clockwork according to the laws of classical mechanics, symmetrically in time. Emmy Noether (1882-1935) brilliantly demonstrated that every symmetry obeyed by the equations of motion —their invariance with respect to space-time transformations— can be mapped to a conserved quantity: time-reversal and/or -translation to conservation of energy; space-translation to that of linear momentum; rotation to angular momentum. Her powerful formalism has become a cornerstone in the edifice of much of contemporary physics. Noether's theorem has indeed been extended from particles to fields (gauge-invariance of Maxwell's equations yields conservation of electrical charge) and to quantum mechanics and quantum field theory (leading to the powerful *CPT* theorem). When any of these symmetries are observed to be "broken" by exotic particles created at high energies, we gain penetrating insight into the deepest structure of matter.

At the end of the 19th century, Ludwig Boltzmann (1844–1906) enters. His statistical mechanics have a humanistic flavor, in sharp contrast with Laplace's vision: *we will never know all the details, nor do we really care; in very large systems, only the most probable sequences of configurations are ever observed anyway.* In other words, we perceive Nature macroscopically; at that level —and in spite of exactly time-reversible dynamics on the microscopic level— we never see all the molecules of a dye collect into a single drop that is then expelled from a glass of water. Entropy must increase. The *observed* Universe is fundamentally asymmetric.

Using only classical thermo-hydrodynamics, Ed Lorentz showed in 1963 that even an ultra-simplified model of atmospheric motion was so sensitive to initial conditions that its long-term behavior is unpredictable in practice. This phenomenon was latter called "chaos," an intentionally paradoxical term in view of the deterministic nature of his model. A specialized computer, the "digital orrery," was eventually built to show that planetary motion is chaotic. Even in his field of expertise Laplace was wrong after all: the solar system is inherently unstable!

The common cause of both chaotic behavior and small-scale atmospheric variability can be traced to the nonlinearity of the governing equations. In linear systems, small causes lead to small effects. This is generally not the case in natural systems; metaphorically, the flutter of a butterfly can spawn hurricanes. They are typically dissipative too, i.e., with energy and/or mass flowing in and out and/or changing phases; clouds are a prime example. Do nonlinear systems generically obey symmetries? Yes, and they are of a new type: invariance under changes of scale or "zooms." This means that small parts of the system look like bigger ones, as in a fractal but generally in a probabilistic sense. The statistical manifestation of scale-invariance is that average properties, compiled at a variety of scales, follow power laws in the scale parameter (although, in most cases, not exactly for every realization) and the physically relevant quantity is the exponent of the power law. Is there a Noether's theorem giving us the conservation laws for every scale-invariant system? No, not yet, and we certainly need to broaden the usual concept of "conservation," due to dissipation, phase changes and forcing.

At NASA's Goddard Space Flight Center and elsewhere, Boltzmannian approaches to building clouds-in-a-computer have been explored: lots of random detail is generated but only the statistics compiled at large-scales are important. "Bounded cascade" models [1] are scale-invariant by virtue of their recursive construction (fig. 1). Adapted from turbulent cascade phenomenology where the locally variable/globally "conserved" quantity is the rate of dissipation of kinetic energy by molecular viscosity, we redistribute the total amount of water here. The end-product is self-affine (fig. 2). Being a stochastic scale-invariant model, its statistical properties follow power laws in scale [5] that reproduce those of liquid water density fluctuations inside stratocumulus-type clouds (fig. 3*a*). Are the simulated optical properties of these models realistic too? Yes, even up to the occurrence of a break in the anticipated scaling symmetry of the reflectance field [2] (fig. 3*b*). Following the scheme of things in particle physics, can this spontaneous scale break be used to better probe cloud structure? Again, the answer is a very promising yes [3].

In summary, thanks to scale-invariant statistics and fractal geometry, scientists are now in a position to see what they are always looking for —namely, a certain simplicity— in the beautiful complexity of natural systems like clouds. Of course, writers and artists were doing just that all along but aesthetics are no longer the sole motivation: Baudelaire is vindicated and scientific benefit is reaped in the process.

References:

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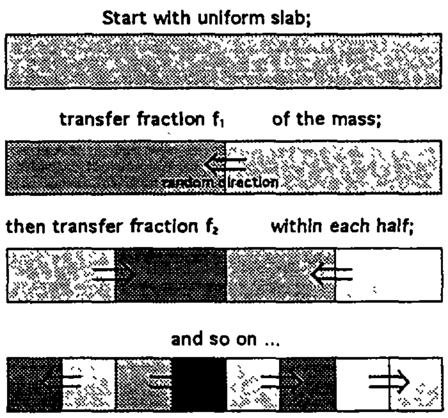

Figure 1: A recursive "cascade" algorithm for obtaining a realistic cloud model from the standard homogeneous one [1]. Mass fractions are transferred in randomly chosen directions at smaller-and-smaller scales as the cascade proceeds; steps n = 0,1,2,3 are illustrated.

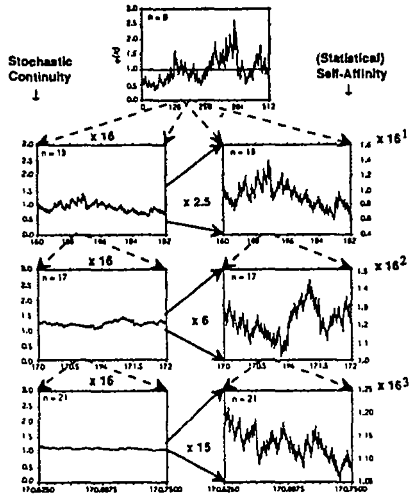

Figure 2: A series of zooms onto finer-and-finer parts of a bounded cascade; the l.h.s. demonstrates the "stochastic continuity" of the model (jumps are smaller at smaller scales), the r.h.s. its "self-affinity" (the graphs are all similar) [5].

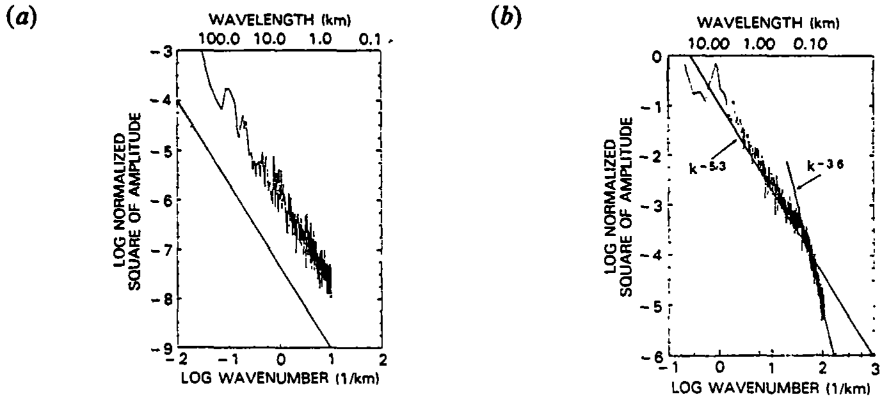

Figure 3: Spectral analyses of the fluctuations (a) of column-integrated liquid water in the atmosphere and (b) of the reflectance field measured at satellite level by LANDSAT (30 m resolution). The "spectrum" of a signal is defined as the sequence of squared amplitudes from a standard harmonic analysis. On the l.h.s. the straightness of the response as a function of frequency (or scale) in log-log axes means that a power law prevails throughout the range of scales; the slope of this line yields the exponent of the power law, in this case, -5/3. On the r.h.s. there is a "break" in the scaling at around 200 m; this is roughly the distance traveled laterally by solar photons before being reflected [2,3].