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Chaos and spontaneous stochasticity: two sides of (un)predictability

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In 1963 Lorenz discovered what is usually known as “chaos”, that is the sensitive dependence of deterministic chaotic systems upon initial conditions. Since then, this concept has been strictly related to the notion of unpredictability pioneered by Lorenz. However, one of the most interesting and unknown facets of Lorenz ideas is that multiscale fluid flows could spontaneously lose their deterministic nature and become intrinsically random. This effect is radically different from chaos.
Turbulent flows, like the ionosphere, are the natural systems when Lorenz ideas can be touched by the hand. They can, indeed, be described via the Navier-Stokes or MHD equations, thus conforming to the class of deterministic dissipative systems, as well as, present rich dynamics originating from non-trivial processes in scale space, non-stationary forcing, emerging behaviors, and geometrical constraints. This complexity appears via non-hyperbolic chaos, randomness, state-dependent persistence and predictability. All these features have prevented a full characterization of the underlying turbulent (stochastic) attractor, which will be the key object to unpin this complexity.

Here we discuss the theoretical framework behind these two concepts strictly related to the intrinsic randomness and predictability of multiscale (turbulent) fluid flows. We present a novel formalism to map unstable fixed points to singularities of turbulent flows and to trace the evolution of their structural characteristics when moving from small to large scales and vice versa, providing a full characterization of the attractor. We provide evidence that the large-scale properties of turbulent flows display universal statistical properties that are triggered by, but independent of specific physical properties at small scales showing a stochastic nature. This “spontaneous stochasticity” is interpreted as the counterpart to Richardson cascade, giving substance to the intrinsic nature of randomness in turbulence.