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Weather, Macroweather, Climate: reuniting Richardson's strands

Shaun Lovejoy
McGill University, Department of Physics, Montreal, Canada (lovejoy@physics.mcgill.ca)

A hundred years ago, Lewis Fry Richardson made the first numerical weather forecast, founding the field of numerical weather prediction (NWP). Based on deterministic continuum mechanics, today it is not only ubiquitous in daily weather forecasts, but has been extended to seasonal predictions through to multidecadal climate projections.

But Richardson also pioneered the development of high level turbulent laws. In 1926 he proposed the "Richardson 4/3 law" of turbulent diffusion, a law that wasn't vindicated until 2013. Whereas NWP attempts to account for every whirl, cloud, eddy, structure, the 4/3 law exploits the idea of scaling to statistically account for the collective outcome of billions upon billions of structures jointly acting from millimetres up to the size of the planet.

The idea that high-level statistical laws could explain the actions of myriads of vortices, cells and structures was shared by successive generations of turbulence scientists. Unfortunately, they faced monumental mathematical difficulties largely connected to turbulent intermittency: the fact that most of the activity (e.g. energy flux) is inside tiny, violently active regions, themselves buried in a hierarchy of structures within structures. The application of turbulence theory to the atmosphere, encounters an additional obstacle: stratification that depends on scale.

The 1980's marked a turning point when Richardson's deterministic and statistical strands parted company, the unity of the atmospheric sciences was broken. While computers revolutionized NWP, the nonlinear revolution attempted to tame turbulent chaos with its fractal structures within structures.

In this talk, I summarize four decades of work attempting to understand atmospheric variability that occurs over an astonishing range of scales: from millimetres to the size of the planet, from milliseconds to billions of years. The variability is so large that standard ways of dealing with it are utterly inadequate: in 2015, it was found that classical approaches had underestimated the variability by the astronomical factor of a quadrillion. The new understanding I describe allows us to finally reunite Richardson's strands.

I show that the deterministic weather models respect the stochastic scaling laws very well. I explain "macroweather" and how it sits in between the weather and climate, finally settling the question: "What is Climate"? I answer the question "how big is a cloud?" and show that Mars is our statistical twin and why this shouldn't surprise us. I explain how the multifractal butterfly effect gives rise to events that are so extreme that they have been called "black swans".

By using data from the real world – not model – climate, and with the help of the Fractional Energy Balance Equation, I explain how the emergent scaling laws can make accurate monthly to decadal (macroweather) forecasts by exploiting an unsuspected but huge memory in the atmosphere-ocean system itself. I show how a good scenario of *economic* development might have led – one hundred years in advance - to accurate projections of our current 1^{o}C of global warming, and I'll show how the same scaling approach can help to significantly reduce the large uncertainties in our current climate projections to 2050 and 2100.