

Weather, Macroweather, and the Climate



Weather, Macroweather, and the Climate

OUR RANDOM YET PREDICTABLE ATMOSPHERE

Shaun Lovejoy

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{ PREFACE }

In the closing months of the first world war, Lewis Fry Richardson made the first numerical weather forecast, founding the field of numerical weather prediction (NWP). Today, with the help of computers, this brute-force approach has been wildly successful. It is not only ubiquitous in daily weather forecasts, but also has been extended to seasonal predictions through to multidecadal climate projections. It is (almost) the unique tool used to inform policymakers about the climatological consequences of fossil fuel burning and other human impacts.

Yet Richardson was not only the founder of NWP, he 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 fully vindicated until 2013. Rather than attempting to account for every whirl, cloud, eddy, and structure, the $4/3$ law exploits the idea of scaling—a statistical relation between big and small, between fast and slow—to account for and understand the statistical outcome of billions upon billions of structures acting collectively from millimeters up to the size of the planet. Just as the diffusion of milk stirred in a cup of coffee doesn’t require tracking every molecule, so too can the atmosphere be *understood* without knowledge of every bump and wiggle on every cloud.

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 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. Although small puffs of smoke seem to be roughly roundish—or even vertically aligned—on a good day, even the naked eye can make out wide horizontal cloud decks that allow us to glimpse chunks of giant strata thousands of kilometers across.

The 1980s marked a turning point when Richardson’s deterministic and statistical strands parted company, and when the precarious unity of the atmospheric sciences was broken. On the one hand, computers revolutionized NWP, making the brute-force approach increasingly practical and hence prevalent. On the other hand, the nonlinear revolution—itself a tributary of computers—promised to tame chaos itself, including turbulent chaos with its fractal structures within structures. Throughout the next decades, scientific societies promoted nonlinear science by establishing nonlinear processes divisions and journals. While the nonlinear approaches were advancing understanding, NWPs mushroomed and extended their number crunching to include oceans and the climate.

This book is an insider’s attempt to reunite the two strands. It contains some history and a few human touches, but mostly it explains, as simply as possible, how we can *understand* atmospheric variability that occurs over an astonishing range of scales: from millimeters 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 classic approaches had underestimated the variability by the astronomical factor of a quadrillion (a million billion).

Although familiar treatments focus on a series of “scalebound” mechanisms, each operating over a narrow range of scales ranging from meteorological fronts to convective cells to storm systems—or from El Niño to global warming—in this book I take you by the hand and show you the atmosphere in a new light. Helped by high-level scaling laws operating over enormous ranges of scales from small to large, from fast to slow, I explain this new thing called “macroweather” and describe how it sits in between the weather and climate, finally settling the question: What is climate? I discuss how agriculture—and hence civilization itself—might be a result of freak macroweather.

I answer Richardson’s old question: Does the wind have a velocity? And the newer one: How big is a cloud? The answer turns out to explain why the dimension of atmospheric motions is $D = 23/9 = 2.555\dots$, which is more voluminous than theoreticians’ flat value $D = 2$, yet less space filling than the human-scale value $D = 3$. I 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 they have been called *black swans*. I show how—even accounting for the black swans—we can close the climate debate by statistically testing and rejecting the skeptics’ giant natural fluctuation hypothesis. 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 playfully imagine a 1909 International Committee for Projecting the Consequences of Coal Consumption to show how a good scenario of *economic* development might have led—one hundred years in advance—to accurate projections of our current 1°C of global warming, and I’ll show how the same scaling approach can help to reduce significantly the large uncertainties in our current climate projections to 2050 and 2100.

This book is aimed at anyone interested in the weather and climate; it assumes only some basic mathematics: power laws and their inverse, logarithms. However, for those who wish to delve beyond the basic narrative, there are extensive footnotes and endnotes. The footnotes are reserved for supplementary—but nontechnical—information, comments, and occasional anecdotes. The endnotes are more technical in nature, aimed at readers who want to dig deeper.^a In addition, there are also more than a dozen “boxes” that give even more technical information and

^a Many of the references may be freely downloaded from the site: <http://www.physics.mcgill.ca/~gang/reference.list.htm>.

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explanations. Although they are placed in the text at advantageous locations, they are designed to be “stand-alone” and can be either skipped or read in any desired order. Overall, there was an attempt to make the book interesting and accessible to readers with a wide range of backgrounds.

The book will have achieved its goal if you achieve a new, unified understanding of the atmosphere and if it convinces you that the atmosphere is not what you thought.

