Tomorrow's weather: Cloudy, with a chance of fractals

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WE'VE all watched those vast heaps of cotton wool float across the sky. Lofted and shaped by updrafts of warm air, cumulus clouds mesmerise with their constantly changing shape. Some grow ever taller, while others wither and die before our eyes. All bear witness to the ceaseless roiling of the ocean of air we call the atmosphere.

Beautiful prediction (Image: Kerry Mitchell)

About 80 years ago, the British mathematician Lewis Fry Richardson was pondering the shapes of such clouds when a startling thought occurred to him: the laws that govern the atmosphere might actually be very simple.

Even at the time, with scientific meteorology still in its infancy, the idea seemed absurd: key equations governing the behaviour of the 5 million billion tonnes of air above us had already been identified - and they were anything but simple.

No one was more aware of this than Richardson, who is recognised as one of the founders of modern weather forecasting. Even now, the world's most powerful computers are pushed to their limits extracting predictions of future weather and climate from the equations he wrestled with using pencil and paper.

Yet Richardson suspected that behind the mathematical complexity of the atmosphere lay a far simpler reality - if only we looked at it the right way.

Now an international team of researchers analysing signals from satellites, aircraft and ground-based stations have found clear evidence that Richardson's intuition was right and that the complexity of the atmosphere could really be an illusion.

The results point to a new view of the atmosphere as a vast collection of cascade-like processes, with large structures the size of continents breaking down to feed ever-smaller ones, right down to zephyrs of air no bigger than a fly.

The implications promise to transform the way we predict everything from tomorrow's local weather to the changing climate of the entire planet. "We may never be able to view the atmosphere and climate in the same way again," says team member Shaun Lovejoy of McGill University in Montreal, Canada. "Rather than seeing them as so complex that only equally complex numerical models can make sense of them, we're seeing a kind of scale-by-scale simplicity."

Richardson had a reputation for having ideas decades ahead of his time. He pioneered the study of fractal geometry - the study of patterns that look the same no matter how much you magnify them - though the word "fractal" had yet to be coined. Look at the honeycomb pattern in a beehive, say, and the hexagonal structure is only visible if you're not too close or too far away. But look at some kinds of plants and you'll see their fronds are made up of ever-smaller versions of the overall leaf. This is known as scale invariance, and is a feature of fractals. Richardson noticed that coastlines have a similar property, their jagged outlines appearing just as jagged as one zooms in to ever-smaller scales.

Attempting to capture this mathematically, Richardson found the same behaviour in simple formulas called power laws, by which one quantity changes according to another raised to some power. Even something as simple as tiling your bathroom wall follows a power law: reduce the length of each square tile by $1/l$ and you'll need l^2 as many tiles. Such laws also reproduce the scale invariance of objects like ferns and coastlines, which retain the same basic form no matter how big the change in scale.

It was while looking for other examples of self-similarity that Richardson came to ponder the skies above: he noticed how the shape of clouds is constantly modified by the invisible whirls and eddies of turbulent air that surround them.

To get some insight into the laws governing turbulent fluids, Richardson performed simple experiments in which he threw bits of parsnip into a lake and watched how they moved apart under the action of the whirls and eddies on the surface. As with coastlines, Richardson found that a scale-invariant power law seemed to apply - an observation that inspired him to poetry: "Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls, and so on to viscosity" - a parody of Jonathan Swift's famous 18th-century doggerel about fleas and the little fleas that bite 'em.

But behind the humour lay Richardson's growing conviction that the atmosphere is just a collection of cascade-like processes, with large structures breaking down to feed ever-smaller ones, creating a fractal-like structure which acted according to power laws.

As with his work on weather forecasting, Richardson could only dream of a time when his ideas could be properly investigated. That time seemed to come in the 1980s, when fractals and scale invariance hit the scientific big time. Simple scaling laws were suddenly claimed to underpin everything from the size and frequency of earthquakes and avalanches to the rise and fall of stock markets. So why didn't anyone put Richardson's idea to the test and search for simple power laws describing the entire atmosphere?

The problem, says Lovejoy, lies with the word "simple". When fractals began making headlines, researchers raced to find the power laws behind a host of natural phenomena. In particular, they sought the value of the "exponent" in these power laws, the one number that governed the extent to which the phenomenon in question changed with scale. (In the bathroom tile example, the exponent is 2.) But they soon ran into trouble. "They found that this single-exponent approach didn't always work," says Lovejoy. "Many phenomena failed to obey power laws with one exponent, and people started to give up on them, saying the idea was overly simplistic and had been oversold."

Among the ideas abandoned was Richardson's claim that the atmosphere is ruled by power laws. But in their race to move on, many researchers had overlooked the possibility that describing the atmosphere might be a tad more complex than describing a coastline - and so might have needed a slightly more sophisticated approach.

Take air pressure, for example. The familiar isobars on weather charts define regions of equal pressure, similar to the elevation contours on a map. Indeed, an isobar can be thought of as a kind of "coastline", described by its own fractal law. But there's a key difference: a coastline's shape is defined only at one specific value of height - sea level. In contrast, the isobars of air pressure form a whole array of shapes at different heights, like Russian dolls nested within each other. Air pressure is what mathematicians call a multifractal field, described by a whole set of power laws, rather than just one.

The failure of researchers to find simple power laws for the entire atmosphere says more about their naivety than about Richardson's idea, but it cast a long shadow over attempts to apply fractals to meteorology, as Lovejoy himself discovered early in his research career. Inspired by the work of the French mathematician Benoît Mandelbrot, who coined the term "fractal" in the 1970s, Lovejoy devoted half of his doctoral thesis to evidence for power laws governing rainfall. "I was getting ready to move on to my postdoctoral research when I learned that my thesis had been rejected," he recalls. "The examiner couldn't see any connection between fractals and rainfall and I was advised to remove all references to it."

Not wanting to risk a final rejection, Lovejoy did as he was told and resolved to publish the excised findings. They appeared in *Science* in 1982 (vol 216, p 185), along with Lovejoy's tentative claim that they might just be linked to Richardson's outlandish idea.

In the following years, Lovejoy teamed up with Daniel Schertzer, now at the University of Paris East, France, and set about searching for evidence for multifractal power laws lurking in weather data.

They focused on rainfall: a meteorological phenomenon whose familiarity masks the complexity of its origins. Triggered by a delicate balance of atmospheric factors, rainfall is tough to model even using the most powerful supercomputers. Yet by analysing data from the rain-detecting radar network around Montreal, Schertzer and Lovejoy found evidence for an underlying simplicity to the process.

The radar data allowed them to plot the amount of rainfall in an area, as they zoomed in and out at different scales. The researchers found their plots could be described by power laws with different exponents - a strong hint that rainfall is a multifractal process, with the underlying physics cascading down to ever-smaller scales.

While intriguing, the discovery was far from compelling. For a start, the data only allowed Schertzer and Lovejoy to extract power laws spanning scales between about 100 kilometres and 1 kilometre. To properly support their theory that the atmosphere is multifractal, they would have to show the scaling laws still held out to scales of tens of thousands of kilometres - the size of the entire planet.

The team realised that one source of meteorological data was up to the job: orbiting satellites. Scanning the planet evenly and in great detail, they build up a consistent picture at scales ranging from a few kilometres to the whole planet. And Schertzer and Lovejoy realised that a satellite launched in 1997 by NASA and the Japanese space agency JAXA could allow them to put the multifractal theory to a truly global test.

Orbiting the planet every 90 minutes, the Tropical Rainfall Measuring Mission (TRMM) peers down on a broad swathe of the Earth with sensors that detect the telltale signs of rainfall on scales down to a few kilometres. Together with their colleagues at McGill University and the University of Paris East, Schertzer and Lovejoy analysed 1200 consecutive orbits of TRMM, looking for signs of multifractal behaviour in the atmosphere.

Earlier this year, they published their findings in *Geophysical Research Letters* (vol 36, p L01801) - and they were simply stunning. The satellite data generated a beautiful collection of fractals and followed power laws on scales from tens of thousands of kilometres down to about 10 kilometres.

"It's rare that fundamental theories that have been marginalised for 80 years are suddenly and decisively proven," says Lovejoy. "Yet this is what we believe we have done for Richardson's idea that atmospheric dynamics are cascade processes."

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Danny McKenna of the US National Center for Atmospheric Research in Boulder, Colorado, says the evidence for power laws is convincing. He believes they could prove vital in tackling one of the most notorious problems in modelling the atmosphere.

Going off grid

Today's computer models represent the atmosphere as a vast grid-like pattern of cells, whose meteorological properties are calculated using the complex equations formulated by Richardson and his successors. The finer the grid, the better the simulation, but even the world's fastest supercomputers can't cope when the grid is made up of cells smaller than about 100 square kilometres.

To get around the problem, modellers have come up with estimates of what happens inside the cells, called parameterisations. The problem with such parameterisations is that they can fall victim to the notorious butterfly effect, by which even small inaccuracies in the initial conditions can be magnified to huge size by the non-linear nature of the processes underlying the weather. This can lead to unreliable forecasts.

McKenna believes that the discovery of scaling laws could transform the situation by providing insights into phenomena that take place on scales smaller than 100 kilometres. Robin Hogan of the University of Reading, UK, agrees that they could be a big improvement on existing techniques. "Although we won't know what individual eddies are doing at this sub-grid scale, their net ability to, say, transport heat vertically could be estimated," he says.

Now Lovejoy's team is keen to see cascades extend the reach and reliability of current models. While the existing models cannot handle structures much smaller than 100 kilometres across, the cascades may continue down to scales smaller than a millimetre. "Cascades could help fill in that missing factor of 100 million or so," says Lovejoy.

To find out, he and his colleagues are now working with researchers at the US National Oceanic and Atmospheric Administration in Boulder, Colorado, on incorporating multifractal techniques into live computer models of the atmosphere. Their aim is to make both weather and climate models reliable at the finest scales possible. It's a challenging goal, but one that Lovejoy believes is achievable. "Obviously there are many issues to be resolved," he cautions, "and it may be some years before the techniques are implemented."

Nevertheless, it seems we are closing in on a new era in our understanding of the atmosphere, one in which computer models finally get to grips with its full complexity in all its beautiful simplicity. And with the need for reliable predictions of the future climate more pressing than ever, Richardson's genius may have cut through the clouds of complexity in the nick of time.

"The history of science shows that complex phenomena usually give way to underlying simplicity," says Lovejoy. "And simplicity points the way to the future".

A reality check for climate models

It's not just more reliable weather forecasts we can expect by swapping complex numerical models for the simpler ones advocated by British mathematician Lewis Fry Richardson. Robin Hogan at the University of Reading, UK, believes that such power laws could also act as a vital reality check on climate models. Put simply, if a given model doesn't reproduce the real atmosphere's multifractal behaviour and its power laws, something must be missing.

Which raises an obvious question: how well do current models of the atmosphere perform? After all, if there's any truth in Richardson's idea, their computational complexity should give rise to cascading simplicity. Jonathan Stolle at McGill University in Montreal, Canada, has teamed up with his colleague Shaun Lovejoy, and David Schertzer at the University of Paris East, France, to examine this issue - and so far the results are encouraging.

"We've recently demonstrated that the top traditional numerical models have virtually perfect cascade structures from around 10,000 kilometres down to 100 kilometres," says Lovejoy. Power laws may be able to extend the models' reach - and accuracy - even further.

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