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Abstract:	Atmospheric physicists Paul Williams is staring at a rainbow and contemplating the atmosphere. As an atmospheric physicist he is looking for dart-shaped waves he thinks hold the key to understanding a very different chaotic system, the weather. In the atmosphere too, waves are whipped up with no obvious cause, perhaps an air current collides with a rock on a mountain or the legendary butterfly flaps its wings. Williams thinks that some of these waves, those called inertia-gravity waves, bear much of the blame for the unpredictable nature of the weather. Meteorologists assume that inertia-gravity waves cannot affect the development of weather because they are much smaller in scale than forecasting models deal with, which typically have a minimum resolution of 1000 kilometres. But Williams thinks this assumption is wrong. His experiments with a spinning bucket have convinced him that forecasters should replace some of the painstakingly calculated values of temperature and pressure in their models with random numbers to stand in for the unknown effect of inertia-gravity waves.

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Making Waves

Predicting the weather is already a chancy business. So how come forecasters want to put more randomness into their work?

PAUL WILLIAMS is staring at a rainbow and contemplating the atmosphere. But he isn't looking at the sky. Instead he is watching colourful patterns form in a spinning bucket filled with a concoction of water and oil. As the bucket turns, tiny chaotic currents which form in this mixture show up as light and dark spirals against the rainbow background. The view is mesmerising.

Williams's work has a serious aim beyond the beauty of this experiment. As an atmospheric physicist he is looking for dart-shaped waves he thinks hold the key to understanding a very different chaotic system: the weather. "The problem with the atmosphere is you can't do experiments on it," says Williams, who is at the University of Reading in the UK. But he can do experiments on his fluid, which is dragged round inside the bucket as it spins, just as the turning of the Earth pulls the atmosphere round. In the atmosphere too, waves are whipped up with no obvious cause: perhaps an air current collides with a rock on a mountain or the legendary butterfly flaps its wings. Williams thinks that some of these waves, those called inertia-gravity waves, bear much of the blame for the unpredictable nature of the weather.

Inertia-gravity waves are between a few kilometres and hundreds of kilometres long. On clear days, it is sometimes possible to see the telltale diagonal lines of wispy clouds that are organised by the chevron-shaped waves. No one completely understands how inertia-gravity waves form, but they are known to be a kind of turbulence that arises when the atmosphere is out of equilibrium and air moves to compensate. One common cause of such turbulence is when a large air current comes up against a steep mountainside and is pushed upwards. Often some of the rising air will overshoot the mountain top, causing air to fall downwards again. At other times, inertia-gravity waves are detected much higher in the atmosphere, where the relatively still air of the stratosphere is disturbed by a narrow current of fast-moving air known as the jet stream.

Meteorologists assume that inertia-gravity waves cannot affect the development of weather because they are much smaller in scale than forecasting models deal with, which typically have a minimum resolution of 1000 kilometres. But Williams thinks this assumption is wrong. His experiments with a spinning bucket have convinced him that forecasters should replace some of the painstakingly calculated values of temperature and pressure in their models with random numbers to stand in for the unknown effect of inertia-gravity waves.

The idea that injecting random noise could actually improve forecasts might sound absurd, but early results suggest that it works. Indeed it may be the only way to achieve long-term forecasts stretching months or even years into the future. Williams faces an uphill struggle trying to convince forecasters to change. "Weather forecasters are desperate to believe the atmosphere is deterministic," he says. "To accept you have to put some noise in is quite abhorrent because it's an admission you're not getting everything right."

The trouble is that weather forecasts do not deal with the fleeting inertia-gravity waves, but with large, relatively slow-moving atmospheric waves called Rossby waves. Watch closely after stirring a cup of tea vigorously and you might see slow-moving bulges on the surface. Rotating in the same direction as you stirred, these Rossby waves move more slowly than the individual water molecules and tea particles. Williams sees the same thing on the surface of his spinning water and oil mixture.

On the much larger scale of the Earth's atmosphere, Rossby waves move a few hundred kilometres an hour faster than the planet spins. As they move in the direction of the Earth's rotation, their net movement is from west to east. At any one time there are between six and 10 Rossby waves spaced out in a girdle around the planet, each one tens of thousands of kilometres long.

Forecasters model the movement of Rossby waves because they bring the weather. Their bulk motion from west to east explains why weather from the east coast of North America tends to show up in Europe a few days later. The peaks and troughs of Rossby waves correspond roughly to the weather fronts shown as wavy lines on weather forecasts.

A key assumption behind the forecasts is that these waves behave themselves. Given a picture of the current weather system in one place, constructed from satellite and ground-based measurements, calculations based on the fluid mechanics of Rossby waves will predict the movement of that weather system to the east. Look a few thousand miles east some days later and, bingo, you will find the predicted weather system. It might look a little the worse for wear by then, with weakening winds or moisture condensing out, but you will see essentially the same system of circulating air currents which has been carried east on the Rossby wave.

Yet forecasters know that Rossby waves behave unpredictably. Perhaps as often as every seven to 10 days, they change their speed or direction suddenly. Satellites soon spot the change, helping forecasters to tweak their models and get the short-term forecast back on track. But this unpredictability makes medium and long-term forecasting impossible. "There's something going on that's not being captured by the weather forecast," Williams says.

While he was doing his doctorate at the University of Oxford, his supervisor Peter Read wondered if the changes could be due to the influence of inertia-gravity waves. And without an atmosphere to experiment on, Williams set up the spinning bucket in his lab at Oxford with the help of Tom Haine, who is an expert on ocean currents at Johns Hopkins University in Baltimore, Maryland. The dogma in weather forecasting is that inertia-gravity waves are far too small to affect the evolution of Rossby waves. Yet the behaviour of Williams's spinning fluid seemed to support Read's hunch.

Using a video camera, Williams recorded the movement of Rossby waves in a water-oil mixture, then added surfactant and looked again. The soap-like molecules of surfactant have a love-hate relationship with water: one end of a molecule is attracted to it, while the other repels it. Williams saw that the surfactant lowered the surface tension at the interface between the water and oil layers enough for small-scale perturbations, similar to inertia-gravity waves, to develop. In contrast, the high surface tension at the interface between water and oil in the mixture without surfactant does not allow this, just as a stretched elastic band doesn't wrinkle.

He found that Rossby waves were extremely stable in the mixture without inertia-gravity waves. Two propagated smoothly through the spinning fluid for as long as he let the bucket spin. But the mixture with surfactant behaved differently. There Williams saw an extraordinary change in the Rossby waves. Within 10 seconds of the bucket starting to spin, an initial three Rossby waves had changed to two, and both remained as the bucket continued to spin.

To weather researchers the sudden change in the number of Rossby waves was a shocking result. "We didn't think we'd see something as impressive as this," Williams says. And if this happens in the atmosphere, it would explain the trouble that forecasters have in tracking Rossby waves, and therefore in predicting the weather. For example, a change from a train of six Rossby waves to five or four would mean that an individual Rossby wave could travel round the planet faster, moving weather more quickly. So a storm that forecasters thought would die out before it hit land could arrive early, while it is still raging.

Williams, Haine and Read think that the changes in the Rossby waves in a spinning water-oil mixture are caused by inertia-gravity waves. And this could be true in the atmosphere too. If the atmosphere is poised at a transition between different numbers of Rossby waves, a small perturbation could tip the balance.

To test the idea, Williams, Read and Haine modified the equations that weather forecasters use to model the atmosphere by incorporating the viscosity, buoyancy and volume of fluid in their spinning bucket. In effect, they created a weather forecasting model for their bucket.

Modelling the emergence of inertia-gravity waves precisely requires too much computer power to run a model with high enough resolution to capture their temporary and small-scale effect on the fluid. So to stand in for these waves, the researchers randomly varied the speed and pressure of the moving fluid in their model, on a scale that they knew was typical of inertia-gravity waves. Just as in the spinning-bucket experiment, putting inertia-gravity waves in the frame gave a very different forecast. They found that their modified models predicted the same spontaneous transitions in Rossby waves that were seen in the experiment.

Williams says that this raises the prospect of using random noise to stand in for tiny events in the atmosphere whose effects, like inertia-gravity waves, cannot be precisely modelled, either because the effect is not understood or, like the butterfly flapping its wings, is unknown to the forecaster.

There are preliminary indications that putting random noise into weather forecasts does improve them. Tim Palmer of the European Centre for Medium-Range Weather Forecasts in Reading, UK, injected noise into the forecasting model that the centre uses to issue official medium-term forecasts, which stretch forward months in advance.

The model was already an "ensemble forecast": it runs with a spread of possible input values around those actually measured by satellites. This produces a range of possible weather, which allows forecasters to anticipate extreme weather events that could be missed if the satellite data is slightly inaccurate.

The ensemble forecasts often get it wrong, however. "About once a week, the true weather lay outside the range that deterministic ensemble models were capable of predicting," Palmer says. So he tried changing the forecast to allow the flow of air under pressure to vary randomly while the model is running. Palmer saw the benefits straight away. "The introduction of the noise improved the skill of the forecast," he says.

Others have also had success using random noise in long-term forecasting, which stretches years into the future. David Neelin and Johnny Wei-Bing Lin at the University of California in Los Angeles model large-scale moist convection in the tropics — the movements of large masses of air which, on a local scale, produce clouds.

Last year they replaced the real measurements of moisture put into their model with values randomly generated at random locations. In this case, they intended the random noise to stand in for the unknown effects of clouds, which are smaller than their model can deal with. The resulting forecasts were more variable and gave a greatly increased chance of a storm brewing up, which were a better match with the statistics on real storms.

Getting the models to match real events more often is not the same thing as issuing accurate forecasts of a particular storm. No one has proved that noise can help there. Researchers need a better idea of how much noise to put in, and where to let it loose in the model. "There's a major challenge to get it accurate, because you're letting loose a can of worms into the process," Neelin admits. But he is convinced that putting the approach into practice in actual forecasts will eventually lead to improvements.

Convincing official forecasters to take on models full of noise will not be easy. "People say putting in random numbers is an odd thing to do to improve a forecast," Palmer says. Kerry Emanuel at the Massachusetts Institute of Technology in Cambridge, is one of these sceptics. He works on deterministic models of the tropics that take into account myriad physical and chemical processes in the atmosphere. He says it is crucial to be sure that the addition of noise, representing inertia-gravity waves, clouds or other randomly varying physical events, has the same effect as modelling these processes deterministically would. "At the moment people just guess what the numbers are and tune the results so the result looks nice," he says. He doesn't think that will lead to more accurate forecasting.

But as Neelin and Palmer accumulate evidence that noise can work, forecasters may soon have to face their worst fear. They have weathered more than a decade of popular fascination with chaos theory, the idea that tiny unknowable fluctuations make their job impossible. So far, their reaction has been to ignore it. But that may not be an option for much longer. As more and more evidence pours in supporting the idea that tiny changes make a huge impact, it may be time to put the messy real world squarely on their agendas. Bring on the butterflies.

"Random noise can stand in for tiny events in the atmosphere whose effects cannot be precisely modelled"

"The resulting forecasts gave a greatly increased chance of a storm brewing up, which were a better match with the statistics on real storms"

PHOTO (COLOR): Whether the problem is too much water or too little, improved forecasting would help. But can introducing randomness really be the answer?

PHOTO (COLOR): Extreme weather can create disasters that long-term forecasting might be able to avert

PHOTO (COLOR): The Dresden floods of August 2002 submerged the central railway station

PHOTO (COLOR): Storms and flooding in Tenerife, Spain, last year (above) and this year's Parisian heatwave both claimed numerous lives

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Reportd by Eugenie Samuel Reich

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