Storm in a teacup

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Paul D. Williams
Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, Oxford University

At first sight, the good old cup of tea hardly seems a likely arena for performing ground-breaking science experiments. Indeed, in a highly rigorous survey, 100% of the respondents (my four lab mates) said they would rather just drink the stuff than study it. But the events that take place in the average cuppa are more exciting than most people realise. Specifically, the tea currents in the cup can closely mimic, in microcosm, many of the complex flow phenomena exhibited by the earth's atmosphere.

It turns out that there is a very intimate connection between the fluid dynamics of a freshly stirred cup of tea, and those of an atmosphere on a rotating planet. It does not matter that tea vortices are only a few centimetres across, whereas typical atmospheric vortices can measure thousands of kilometres. The underlying balance of the physical forces can be the same, and that is all it takes for the governing equations to be mathematically similar. So every time you stir a cup of tea (or coffee) you are running a miniature atmospheric simulation. This invariance in the equations of motion is called 'dynamical similarity', and has been known about since at least the nineteenth century. It is a concept of great importance to meteorologists, since it allows conclusions to be drawn about atmospheric phenomena by making observations of the analogous flows in the laboratory.

Vettin (1884) was probably the first person to exploit dynamical similarity, by carrying out rotating laboratory experiments as analogues of atmospheres on rotating planets. He studied the surface flow in a rotating pan of fluid with a lump of ice near the centre, representing a polar ice cap, and (to the scorn of many of his contemporaries) drew meteorological conclusions from his results.

The main benefits of studying atmospheric flows indirectly in the laboratory are that the system is under the complete control of the experimenter; that global high-resolution measurements can be taken systematically; and that experiments can be repeated as many times as required. None of these statements hold when the atmosphere is studied directly. Indeed, it seems clear that we should not want to perform experiments on the real atmosphere, for fear of what the consequences might be if the experiment goes wrong! Dynamical similarity allows us to conduct experiments on miniature 'atmospheres' in the laboratory without the many approximations of computer models; without the risks of tampering with our climate system; and with a guarantee that our conclusions will be applicable to the real atmosphere so long as the dynamical similarity principle holds.

Following in the footsteps of Vettin and many subsequent workers, I have spent the past four years exploiting dynamical similarity to draw meteorological conclusions, in pursuit of my DPhil. Admittedly, for practical reasons, my experimentation vessel was actually a bucket-sized steel cylinder rather than a teacup. I didn't really use tea as the working liquid either, but the principle is exactly the same. A photograph of the apparatus is shown in Fig. 1. The cylinder has a diameter of 25 cm and a depth of 25 cm. A second cylinder, of smaller diameter, has been inserted at the centre of the main cylinder, for practical reasons, and the liquid representing the atmosphere is the bright region which fills the annular gap between the two cylinders. The apparatus is mounted on a rotating turntable to mimic the rotation of the earth, and the tall metal frame supports a video camera which views the system from about 2 m above.

The aim of the laboratory experiments has been to investigate some of the properties of atmospheric waves. Existing high above

Fig. 1 The laboratory 'teacup', as seen from above. The tank has a transparent glass base and lid. Bright white light illuminates the apparatus from below, and is received by a video camera above. The lid, in contact with the liquid, is made to rotate under computer control relative to the turntable, which also rotates. This provides an instability from which Rossby-type waves can grow.

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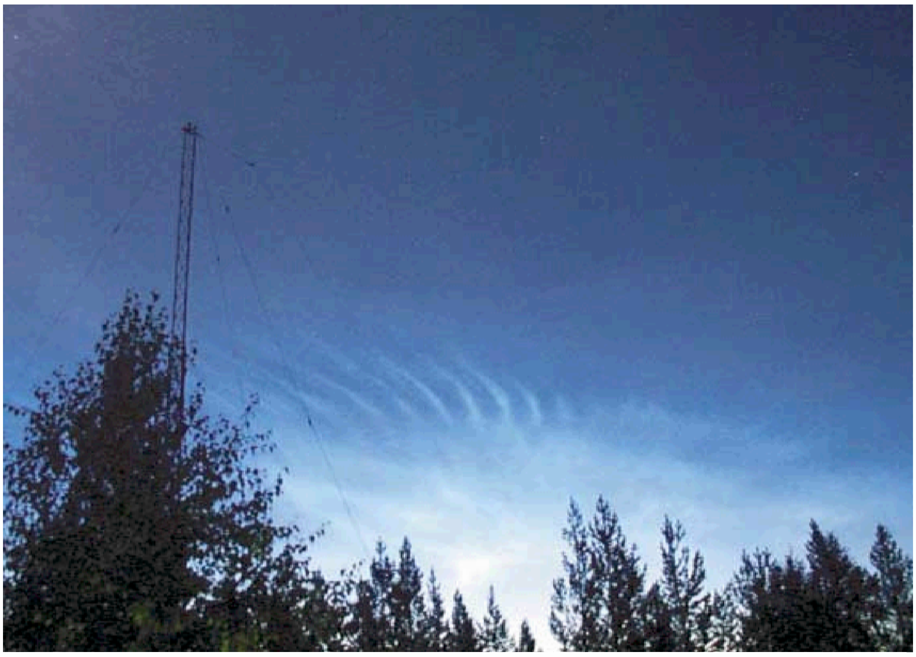

Fig. 2 Atmospheric inertia-gravity waves in the night sky. In this case, the waves are visible from the surface of the earth because they are travelling within a noctilucent cloud. Had the surrounding air not had such a large water vapour content, condensation might not have occurred, and then the wave would have remained invisible to the human eye and passed by unnoticed.

our heads, these waves are much like ocean waves, except that they are invisible to us because there is no well-defined surface at the top of the atmosphere. The movement of atmospheric waves across the globe causes our weather, and so a detailed understanding of how they operate is crucial in the field of meteorology.

The main type of atmospheric wave, called a Rossby wave, is the prototype of the disturbances that are responsible for the isobar patterns seen on weather forecast charts. It brings with it warm and cold fronts, which cause sunshine and rain. But there is a far smaller and weaker class of wave, known as an inertia-gravity wave, which propagates along with the Rossby wave. These weak inertia-gravity waves are not directly responsible for our weather, but they are still able to have an influence on it by impacting upon the motion of the weather-carrying Rossby wave. David and Goliath-style battles are acted out high in the sky every day, in which the inertia-gravity waves attempt to interfere with the stronger Rossby wave, exchanging energy and momentum, and potentially altering its speed and direction of travel. If they are successful, the rain that was originally headed for London might end up elsewhere.

From time to time, if the air is saturated with water vapour, the fluid motions associated with inertia-gravity waves can cause local condensation, and then the waves become visible to us as clouds. A stunning example is the photograph shown in Fig. 2, taken during the night in Kiruna, Sweden. The inertia-gravity waves tend to persist for around 15 minutes before dissipating. Typically, gravity waves of wavelengths in the range 5–50 km are visible from the ground in noctilucent clouds on around one night in three during the summer months, predominantly between latitudes 50 and 70°N and between 2200 and 0400 local time (Dalin, personal communication).

One problem with weather-forecasting computer models is that they do not explicitly take inertia-gravity waves into account, for reasons discussed by Lynch (2003). They are only represented implicitly, by using a parametrization of their expected effects on the flow. Though inertia-gravity wave parametrizations, such as that proposed by Hines (1997a, b), have undoubtedly improved the performance of forecasting models, they are still simply approximations which cannot possibly capture the full details of the nonlinear interaction between Rossby and inertia-gravity waves. The question that naturally arises is: is the missing part of the interaction significant enough to affect the reliability of numerical forecasting models? The answer has conventionally been thought to be 'no', although obtaining rigorous proof of this tacit assumption has always eluded researchers. Thanks to dynamical similarity, it has recently become possible to obtain a more definitive answer in the laboratory.

Amazingly, it is possible to observe the competing inertia-gravity and Rossby waves on a very small scale, in the laboratory experiment of Fig. 1. Experiments can be performed in which groups of inertia-gravity waves develop in the vicinity of a strong, Rossby-like wave, and one can watch in detail what happens as they attempt to impede its progress. The whole affair is captured on videotape for subsequent analysis. A typical still from the video footage is shown in Fig. 3, clearly showing two groups of inertia-gravity waves (one at '12 o'clock' and one at '6 o'clock') co-existing with a Rossby-like wave (responsible for the near-elliptical shape of the central blue-coloured region). The flow visualisation technique first described by Hart and Kittelman (1986) has been used to produce these coloured maps of the waves. It is interesting to compare the inertia-gravity waves in the atmosphere (Fig. 2) with those in the laboratory (Fig. 3). That waves on such dramatically different scales (around a centimetre in the laboratory and a few kilometres in the atmosphere) can appear so similar in form is testament to the power of dynamical similarity.

We have performed over 200 hours of experiments using the laboratory apparatus, and by carefully analysing the video tapes we have been able to come to conclusions about the circumstances under which the inertia-gravity waves appear, and the dynamical mechanisms by which they are generated. Such issues would have been much more difficult to investigate by looking at the real atmosphere. Importantly, we were also able to study the impacts of the inertia-gravity waves on the large-scale wave with which they coexist. We found that the inertia-gravity waves may be able to have a significantly stronger impact than has previously been thought. There are circumstances in which, via a phenomenon known as stochastic resonance, the inertia-gravity waves can dramatically alter the probability of a change from the state shown in Fig. 3 to that shown in Fig. 4. Transitions such as this seem to occur much more readily in the presence of inertia-gravity waves than in their absence. Our findings are backed up by computer simulations, and are described more fully in Williams *et al.* (2003).

Since time immemorial, fortune tellers have enchanted us with claims of ability to predict a person's future. This has often been done by studying the swirls in their cup of tea, as manifested by the shapes of tea-leaf deposits at the bottom of the cup. It is pleasing that the atmosphere's fortunes can now be told in a similar fashion, and that the scientific basis (for this augury at least) is sound. Cup of tea, anyone?

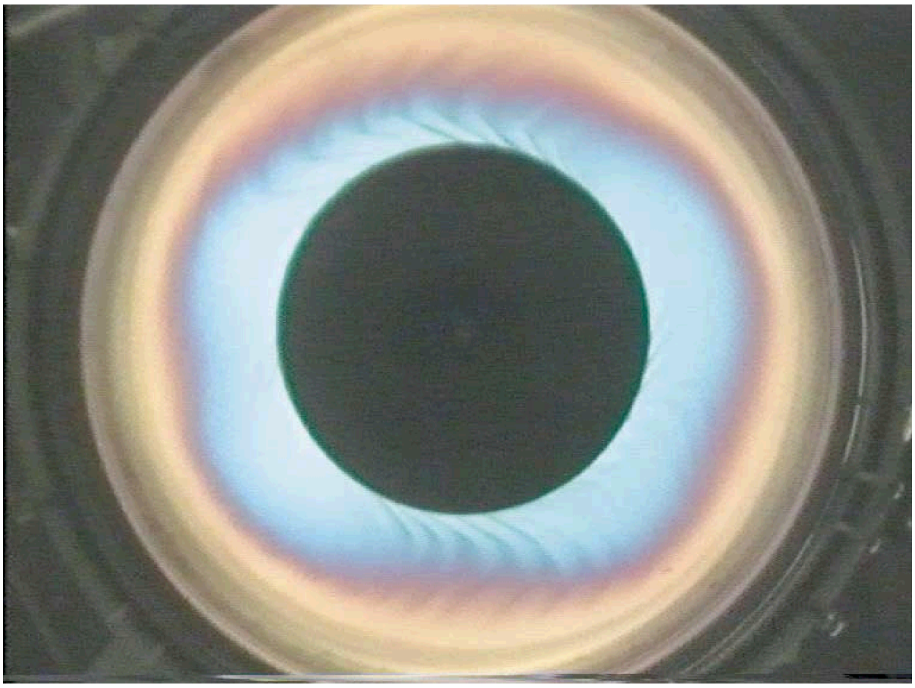

Fig. 3 Experimental image taken by the video camera which views the apparatus in Fig. 1. The tank rotates in the anticlockwise direction. The image can be interpreted by imagining that the North Pole is at the centre, and that the large outer circle represents the equator. A water–oil liquid fills the tank, and different colours in this image correspond to different heights of the interface between the water and oil – blue corresponds to a high interface, and yellow to a low interface.

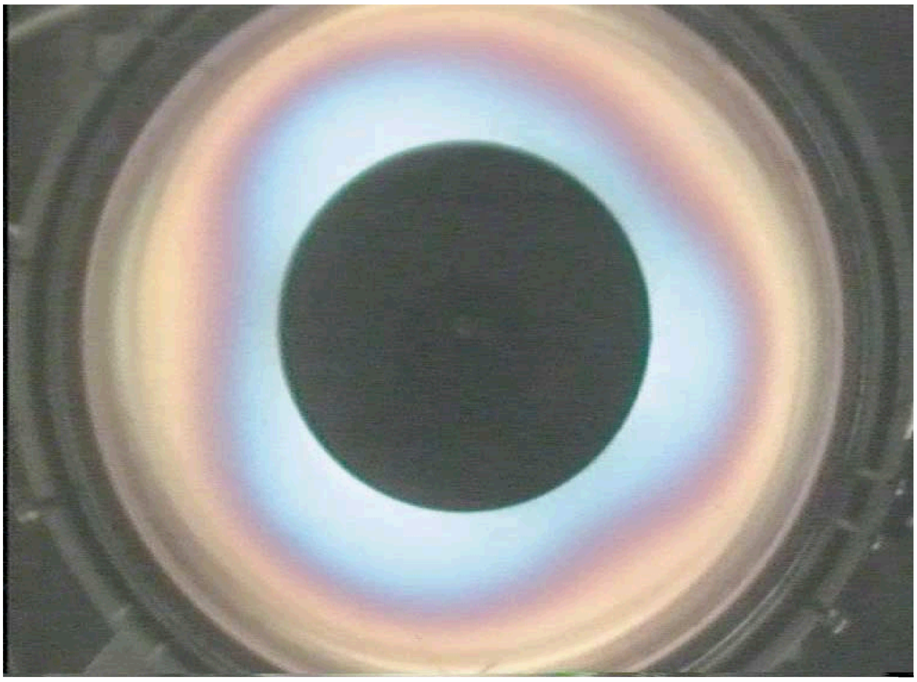

Fig. 4 A second experimental image taken by the video camera. This time, there are three wavelengths of the Rossby-like wave around the globe, as opposed to two in Fig. 3. Inertia-gravity waves seem to play an important role in inducing transitions between states such as those shown in Figs. 3 and 4. Although the atmosphere explores a significantly more chaotic regime than is seen in the laboratory experiments, it seems likely that atmospheric inertia-gravity waves might play a similar role in forcing local transitions.

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Correspondence to: Dr P. D. Williams, NCAS Centre for Global Atmospheric Modelling, Department of Meteorology, University of Reading, PO Box 243, Earley Gate, Reading RG6 6BB.
e-mail: p.d.williams@reading.ac.uk

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