Editorial

More on Coriolis

Starting in this issue *Weather* will further explore the consequences of the Coriolis force for atmospheric and oceanic processes over five instalments spread out into 2002. The articles follow on from the three 'Back to basics' articles by Anders Persson published in 2000. These sparked off a lot of debate, some of which you will have seen in the letters pages and more in the recent report on the *Weather* questionnaire. The aim of these further articles is to describe some commonly encountered dynamical features of the atmosphere and ocean in which the Coriolis force plays a significant role: inertial motion, geostrophic winds, the subtropical jet, the Ekman spiral in the oceanic and atmospheric boundary layers, and the night-time low-level jet. The limited mathematics in these are mostly contained in footnotes, and those without formal training can easily skip this without serious loss. I found the articles stimulating and thought-provoking. I hope you will do so too.

Grant Bigg

The obstructive Coriolis force
(Coriolis Part 4)

Anders Persson
Reading, Berkshire

> "It is a pleasure to find out how different observable phenomena of the physical world fit together . . . It is the discovering of the connection between physical phenomena and describing them by mathematical analysis, rather than the analysis itself, which is interesting."
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> (G. I. Taylor, quoted by Batchelor 1996, p. 261.)

Many textbooks give the impression that the Coriolis force is a highly esoteric force, some sort of mathematical correction term to manipulate coordinate transformations. Not only is it said to be 'fictitious', 'a pseudo-force', 'a mental construct' or a 'convenient artifice', but it is also said to be 'unable to do work'. The question arises: how can something so elusive be fundamental to the creation and motion of mid-latitude cyclones and jetstreams? The paradox begins to unravel when we realise that being 'fictitious' and 'unable to do work' do not have the same meaning in physics and mechanics as in colloquial English. Some of the confusion disappears when we distinguish between a purely optical or kinematic Coriolis effect, and a clearly physical or dynamic Coriolis effect in rotating systems (Persson 2000a). A striking demonstration of the power of the alleged illusory Coriolis force was conducted 80 years ago by a British scientist in Cambridge.

G. I. Taylor

Geoffrey Ingram Taylor (1886–1975)* (Fig. 1) was one of the great physicists of the twentieth century, among the last masters of both theory and experiment. He started his career as a meteorologist and in 1913 took part in a six-month expedition to the waters off Newfoundland. It was just after the *Titanic* disaster; Taylor and his colleagues were there to report on icebergs. In his spare time he conducted extensive measurements of the turbulent pro-

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* Not to be confused with Brook Taylor (1685–1731), the mathematician behind the famous theorem on power series which bears his name.

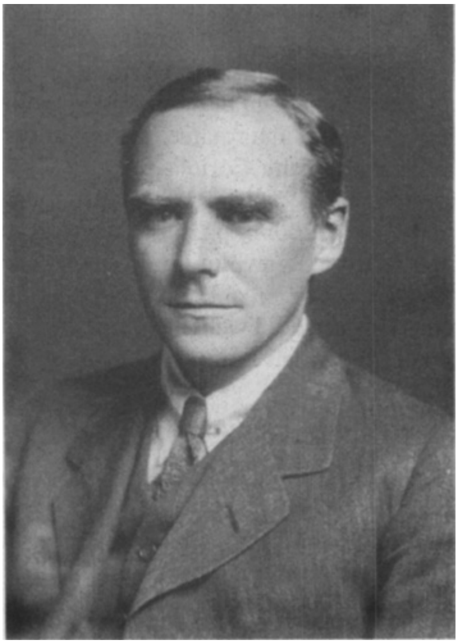

Fig. 1 G. I. Taylor, or 'GI' as he was known to his friends, graduated from Trinity College, Cambridge, in 1908 and started his career as a meteorologist in 1912 at the Cavendish Laboratory in Cambridge

cesses between water and air. During World War I he was engaged as an expert on turbulence, and it was then that his skill in this field emerged (Brenner and Stone 2000).

Taylor had a passion for finding agreement between theoretical results and observations, to see how to make the experimental conditions correspond with those assumed in theory. His intuition seemed to be based not so much on a great accumulation of empirical knowledge as on a deep understanding of the laws of physics (Batchelor 1996, pp. 250, 255, 258). He taught his students to be aware of the importance of the physical aspects of fluid dynamics: "Fluid dynamics is much less interesting if it is treated largely as an exercise in mathematics" (Batchelor 1967, pp. xiii–xvi). Much of the teaching in hydrodynamics at that time concerned problems which were mathematically solvable, but not necessarily related to reality. When engineers designed aeroplanes and submarines they needed to understand the forces that a body experiences when moving through air or water; but their constructions seemed not to behave as the mathematical models suggested (Taylor 1917, p. 107, 1974, pp. 1–15).

One of these hydrodynamical theorems stated that for a fluid in uniform rotation, the motion within the fluid does not vary vertically (parallel to the rotation axis).* Any added motion, for example caused by stirring the water, would be communicated vertically until the velocity was the same along the vertical. This seemed to defy common sense. In winter 1915/16 Taylor became aware through a colleague, John Proudman, that this indeed seemed to happen (Proudman 1916; Taylor 1917). To test this for himself Taylor designed a series of experiments with a rotating glass tank filled with water (Taylor 1921).

Taylor walls and columns

Taylor set the tank into rotation and waited until the whole tank–water system rotated with the same angular velocity. The surface of the water would then have a slightly concave shape indicating that a balance had been reached between the outward-pointing centrifugal force and the inward-pointing pressure gradient force. Then he stirred the water gently.

To trace the water motions he inserted small amounts of ink into the water. When, a short time later, he watched the tank from the side, the ink appeared to have dispersed normally and to have become almost invisible. When he observed it from above, he saw something different; the ink appeared as one long, sharply defined and highly convoluted line. Looking closer he found that in reality it was one thin sheet of ink seen edgewise that continued to spread till it was perhaps 20 or 30 times as long as the diameter of the basin. Its thickness had by then decreased until it was only a fraction of a millimetre thick. During all this time the sheet, later known as a 'Taylor wall', remained parallel to the axis of rotation (Fig. 2).

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* In a steady, rapidly rotating flow with angular velocity $\boldsymbol{\omega}$, the dominant forces are the pressure gradient and centrifugal forces, and the equations of motion reduce to $2\rho\boldsymbol{\omega} \times \mathbf{V} = -\nabla p$ where ρ is the fluid density, $\mathbf{V}$ the velocity and p the pressure. Taking the curl yields $\boldsymbol{\omega} \times \nabla\mathbf{V} = 0$ which means that there are no velocity variations along the direction of axis of rotation, which also means that it is difficult to stretch rapidly rotating bodies.

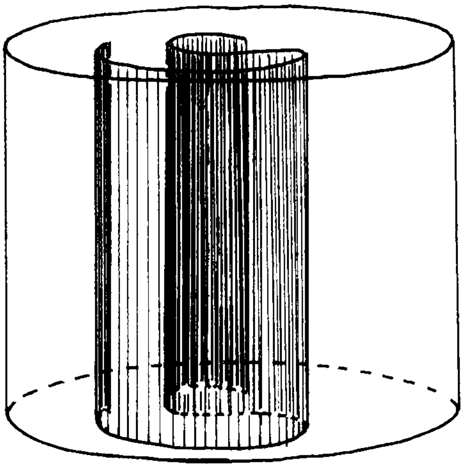

Fig. 2 The formation of a 'Taylor wall' by ink inserted into rotating water which had been stirred

In another experiment he inserted a drop of ink into the rotating water without stirring it. Since ink is slightly more dense than water it fell slowly to the bottom of the tank. But, instead of dispersing and colouring the water, it remained in a vertical column, later known as a 'Taylor column', moving around in the tank as a rigid body before it finally dispersed (Fig. 3). What happened was that when the ink started to spread out in horizontal directions, every ink particle was immediately affected by the Coriolis force acting at right angles to the motion. It forced the particles into curved motions, in circles of surprisingly small radii. A body moving with a velocity $\mathbf{V}_r$ in a rotating system under no other force than the Coriolis force, $2\omega\mathbf{V}_r$, will follow a so-called 'inertia circle' with a radius of $V_r/2\omega$ (Persson 2000b, p. 238). If Taylor's tank rotated with one revolution in two seconds ($\omega = \pi = 3.14$ rad s^{-1}), and the ink spread out at 0.5 cm s^{-1}, this would yield inertia circles with a diameter of less than 1 mm.

The magic ping-pong ball

Taylor then arranged an experiment which even more strikingly demonstrated the power of the Coriolis force by releasing a ping-pong ball from the bottom of the tank (Fig. 4). When the fluid in the tank was rotating, the ping-pong ball rose more slowly than when the tank was stationary. Again it is a consequence of the Coriolis force which tries to prevent replacement of the water. When the ball is rising, water above it must spread out horizontally to leave room for the ball; water below it must be sucked in, also horizontally. Both motions are perpendicular to the axis of rotation and therefore affected by the Coriolis force, which will force the water parcels into

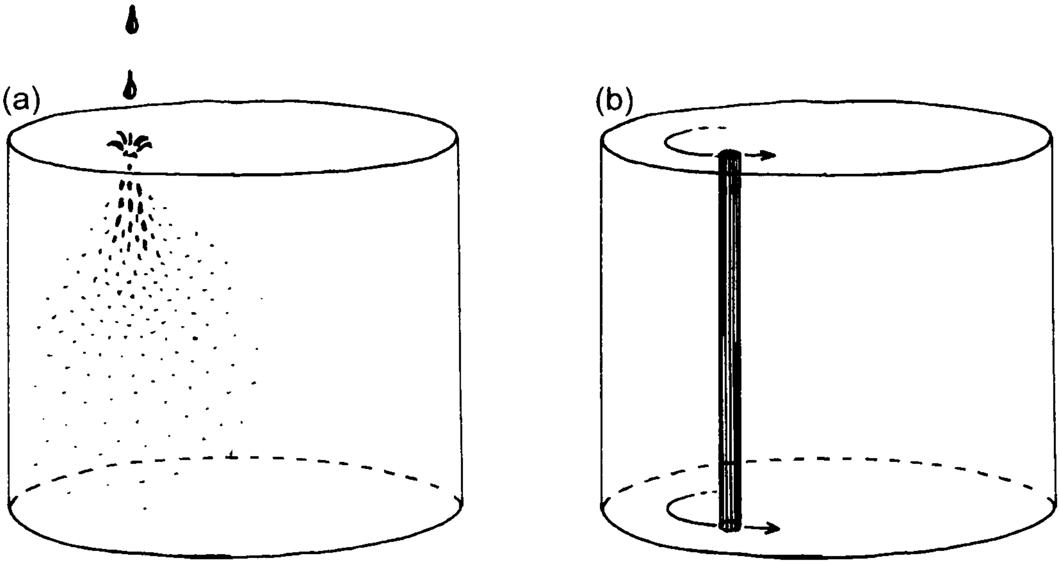

Fig. 3 Schematic of the creation of a Taylor column. When the water is not rotating, the ink dropped into the water disperses evenly (a); when it is rotating, the ink is prevented from moving horizontally very far and is confined into a 'Taylor column' (b).

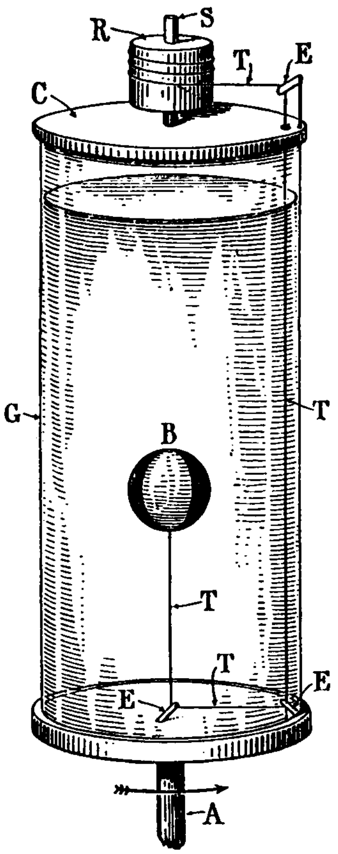

Fig. 4 The experiment with the ping-pong ball (from Taylor 1921). The letters are not relevant to this paper.

small circular inertial motions.* The water above the ball will be prevented from spreading out to give room to the ball; the water below the ball will be prevented from being sucked in behind the ball.

Taylor's experiments remind us of the fundamental fact that the Coriolis force is not just 'deflecting' moving bodies, but opposes their displacement by trying to restore them to their initial position (Batchelor 1967, p. 556).

Accidental Taylor columns

About 30 years after Taylor's, another interesting experiment took place. At the University of Chicago, Dave Fultz had erected an intricate apparatus to simulate atmospheric motion in a rotating saucepan where the water at the centre was cooled and that at the edges was warmed (Fultz *et al.* 1959). However, before he could get started he had to overcome many practical problems. One was to find a tracing technique for detecting the motions of the liquid, *i.e.* particles that are distinguishable optically and that follow the motion of elements of the fluid. The interpretation and evaluation of the particle-streak photographs were complicated if the water surface was accidentally stirred, either by irregularities in the motor or because the axis of rotation was not absolutely vertical. An error of a few seconds of arc was enough to cause vibrations (David Fultz, personal communication). These caused the formation of spontaneous Taylor columns, which made the streaks strongly curved, looped or cusped during the exposure time.

Fultz's photograph (Fig. 5) shows more or less what would happen in our atmosphere if there was no continuous driving force such as the differential heating from the sun. Ran-

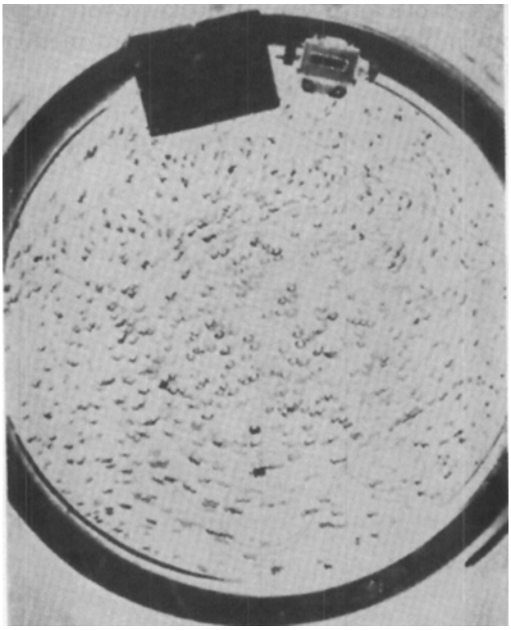

Fig. 5 The inertia circles in Fultz's experiment. In one example, the inertia circle horizontal trajectories entirely dominated near the centre due to the wave motion (Fultz et al. *1959).*

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* According to Batchelor (1996, p. 86, footnote 2) this is equivalent to the statement that, as a consequence of the Coriolis forces being strong, the divergence of the (vector) component of the fluid velocity in the plane normal to the axis of rotation is small everywhere.

domly induced gusts here and there would result in a myriad of inertia circle winds all over the globe.

Rotating saucepan

The Coriolis force affects only motions that are perpendicular to the axis of rotation, not parallel to it. This can be seen in an experiment where a saucepan full of boiling water is set in rotation. A fluid element starting at the centre spirals upwards in a clockwise direction (for an anticlockwise rotation of the saucepan). As the fluid element approaches the top it crosses over and starts spiralling downwards in an anticlockwise direction. This is strange enough; there is more to come. When the fluid element gets halfway down it reverses its sense of spiralling (to clockwise) and proceeds downwards. As it reaches the bottom it crosses back towards the centre and starts to ascend, only to reverse the spiralling halfway (Fig. 6). The sense of spiralling changes halfway because the water at the middle level alternates from being sucked into the spiral to being spread out from the spiral. An inward motion will be turned, by the Coriolis force (for anticlockwise rotations), into an anticlockwise spiral; outward motions will be turned into a clockwise spiral.

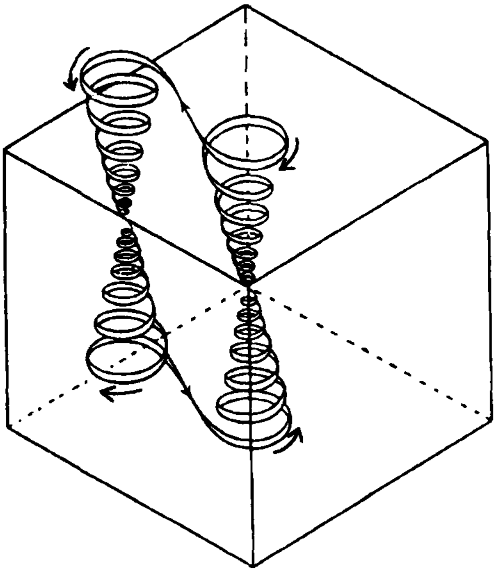

Fig. 6 A fluid element circulates in spiralling motions in a rotating tank of water which is heated from below (after Chandrasekhar 1961, p. 111)

Taylor's experiments showing the Coriolis force holding together a column of ink in a rotating water tank give us a new way to look at atmospheric motions. They remind us, although we perhaps should have realised this anyhow, that the Coriolis force not only deflects the air, but also tries to turn it back from whence it came.

We can regard the circulation of the atmosphere and oceans as an ongoing struggle between two opposing forces: the differential heating between low and high latitudes creates pressure differences which the earth's gravitational pull tries to equalise by redistributing mass, causing winds. This equalisation is being constantly, and almost everywhere, obstructed by the Coriolis force which tries to bring back the air from whence it came, thereby restoring the pressure differences.

In the next paper: a bird taking off northwards from Heathrow Terminal 1 affected only by the Coriolis force is more likely to end up over the Bristol Channel than over The Wash.

Acknowledgements

I thank the friendly staff of the National Meteorological Library who helped me to find Taylor's papers. Discussions with Professor Emeritus David Fultz provided further insights into the counter-intuitive world of rotating fluids, of which only a fraction could be presented here.

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Readers' Forum

Readers are invited to contribute short questions on any meteorological topic. We will endeavour to obtain answers to all submitted questions.

The recovery of groundwater resources following the droughts of the 1990s

During the dry years of the 1990s we heard and read a great deal about record depletion of aquifers, and despair that they would ever recover. The last three years have brought several notable rainfall events. Have these led to substantial replenishment of aquifers, or has most of the rainfall been lost as runoff?

Greenford, Middlesex **J. P. Turnbull**

Terry Marsh replies:

During the summer, evaporation rates in the UK generally exceed rainfall amounts and therefore groundwater replenishment occurs largely during the winter. Following a cluster of relatively dry winters in the early and mid 1990s, groundwater levels in many wells and boreholes were at unprecedented minima in the early autumn of 1992. On the basis of data from a sparse network of observation wells and boreholes with long records, it is likely that the overall groundwater resources for England and Wales were at their lowest for at least 85 years (Marsh *et al.* 1994). Similarly depressed levels were recorded towards the end of the 1995–97 drought. The exceptionally low groundwater levels were of particular concern across much of the English lowlands where groundwater is the main source of water supply and is essential to sustain summer and autumn flows in spring-fed rivers.

The behaviour of winterbournes provides a tangible example of how, as aquifer storage is depleted, outflows (via springs and seepages) decrease. In prolonged droughts, groundwater levels can approach a natural base level below which no further decline will occur. Thus, even after lengthy periods of rainfall deficiency, a couple of wet winters will normally see groundwater levels recover substantially. Although the 1990s saw several protracted drought episodes, the decade as a whole was marginally wetter than average across the major aquifer outcrop areas (which are mostly in eastern and southern England). Several winters, including the last four, have been notably wet and the aquifer recharge season in the east extended beyond five months (five weeks being more typical of the driest winters). From a very low base in the summers of 1996 and 1997 groundwater level recoveries gained momentum through the following winters. Although on occasions, rainfall intensities locally exceeded the infiltration capacity of the soils, overall aquifer replenishment was heavy. Entering the new millennium, groundwater resources were around the long-term average throughout most of the country. A few exceptions could be found in areas where long-term groundwater abstraction has led to a significant lowering of water levels. During and following the remarkably wet autumn and early winter of 2000/01, groundwater levels exceeded long-term maxima over wide areas, resulting in record flows in some spring-fed rivers and triggering groundwater-induced flooding in many localities in southern England.

There are few, if any, close modern parallels to the variability of groundwater levels over the recent past (see Fig. 1) and some consistency can be recognised with favoured climate change scenarios. However, it is too early to say whether the recent large and sustained departures from average seasonal levels represent a pattern for the future. Increased winter rainfall in a warmer world may counter-balance increasing evaporative demands. In areas largely unaffected by abstraction, average groundwater levels as yet show no long-term trend. Natural groundwater systems are, however, finely balanced and it