Mount Everest in June 1924, Sir Francis Younghusband wrote the following: "One of the great mysteries of existence is that what is most awful and most terrible does not deter man but draws him to it".

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Back to basics:
Coriolis: Part 3 – The Coriolis force on the physical earth

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Many textbooks give the impression that the behaviour of a body on a merry-go-round tells us most of what we need to understand about the behaviour of other rotating systems, for example the earth. It is not so. The merry-go-round and the earth are dynamically two quite different systems. Whereas on a merry-go-round the dominating force is often the centrifugal force, *C*, which tries to throw out any body, this is obviously not the case on our

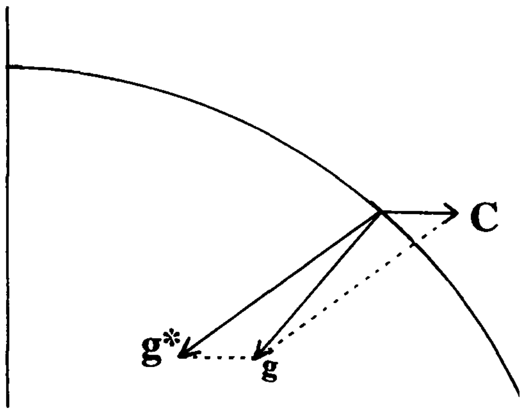

Fig. 1 The centrifugal force, C, *and gravitation,* g* *(per unit mass), on an ellipsoidal earth combine to form gravity,* g. *In the early stages of the earth's development an equilibrium was reached when the spheroidal earth changed into an ellipsoid with gravity pointing perpendicular to the surface. Gravitation,* g*, *however, points towards the centre of the earth.*

rotating earth. It is worth investigating why, since the earth is quite a fast-rotating planet, its radius, R, of about 6370 km and rotational speed, U, of 465 m s^{-1} at the equator yields a centrifugal acceleration of 3.4×10^{-2} m s^{-2} ($C = U^2/R$). At the equator the centrifugal acceleration is directed straight upwards, in the opposite direction to the 300 times stronger gravitation.

As we move away from the equator both R and U decrease. At 60°N or S they have halved and so has the centrifugal acceleration which is now 1.7×10^{-2} m s^{-2}. It is still directed perpendicular to the earth's axis, but for an observer at 60°N or S it is no longer straight upwards. One component is vertical and 8×10^{-3} m s^{-2}, another horizontal, pointing towards the equator, and around 1.4×10^{-2} m s^{-2}. This does not sound much, but after one hour the body would have acquired a speed of 53 m s^{-1} and travelled a distance of over 100 km. This horizontal centrifugal force has its maximum at 45°N or S where it is 1.7×10^{-2} m s^{-2}. At the poles there is no centrifugal force at all, since the distance to the axis of rotation is zero.

The ellipsoidal shape of the earth

So why are we not all drawn down to the equator within a day or so? Because the job is already done. During the course of the earth's early evolution, when it was a spinning deformable ball, the centrifugal force moved a substantial amount of mass from higher to lower latitudes to form a slightly flattened ball (or, to be more precise, an oblate ellipsoid) with a radius 21 km greater at the equator than at the poles. This has important consequences for gravitation, g^*, which will vary with latitude. The ellipsoidal shape of the earth puts a point on the equator farther away from the earth's centre than it otherwise would be. This on one hand weakens the gravitational pull, but it also adds an extra belt of gravitating material around the equatorial region which tends to strengthen it. The former effect dominates over the latter which means that the gravitational pull increases with latitude. If the earth stopped rotating, its shape would slowly return to a sphere.

The mechanism of the earth's Coriolis effect

So far we have discussed only the *gravitational* force and the centrifugal force separately. If we take into account their combined effect, we get the force of *gravity* or effective gravity* – the force which determines how much a body weighs. Gravity is pointing normal to the earth's surface which is the reason why the earth is no longer changing its form (Fig. 1).

Any stationary body on the earth's surface remains stationary due to a balance between these two strong and oppositely directed forces: the gravitational force, g^*, and the centrifugal force, C. However, this balance is valid only for stationary bodies: from Fig. 1 it is easy to see that a moving object will yield a slightly different centrifugal force and thus a slightly different direction and magnitude of gravity, g. The gravity of a body on the earth is therefore not, as is normally assumed, independent of the motion of the body relative to the earth. In

* Note that gravitation is the well known force between bodies, whereas gravity is a combination of gravitation and the centrifugal force. In some languages there is no clear semantic distinction between gravitation and gravity, which might cause further confusion.

particular, during motion the direction of gravity will no longer be perpendicular to the earth's surface but will have components in the vertical and horizontal directions: the modification of gravity of a body due to its motion relative to the earth's surface is the physical mechanism behind the Coriolis effect on a rotating planet.

Horizontal component of gravitation

If a body is moving to the east, in the direction of the earth's rotation, the centrifugal force acting on it will increase and push the body towards the equator. If the motion is to the west, against the direction of the earth's rotation, the centrifugal force will weaken. This allows the horizontal component of gravitation to get the upper hand and deflect the body towards the pole*. In both cases the deflection is to the right of the movement (in the Northern Hemisphere). This deflection can be made clear by redrawing Fig. 1 with the horizontal and vertical components of gravitation and the centrifugal force (Fig. 2).

For north–south (meridional) movement the change in the centrifugal force will be affected by the change of the radius of curvature of the trajectory of the body. In contrast to a stationary body, which will have its radius of curvature defined by the latitude circles, a body moving meridionally will follow a trajectory with a radius of curvature shorter or longer than the latitude circle (depending on whether the motion is poleward or equatorward). The centrifugal force will change and will no longer point straight in a north–south direction. The horizontal component of the centrifugal force, C_H, can therefore be decomposed into one component pointing radially outwards, our 'normal' centrifugal force for a stationary object, and a remaining component, pointing to the right of the motion. In both cases the deflection is to the right of the movement (in the Northern Hemisphere). The mechanism of the Coriolis effect on a rotating ellipsoidal planet can also be expressed as: the disturbed balance between the horizontal components of the gravitation and the centrifugal forces (Fig. 3).

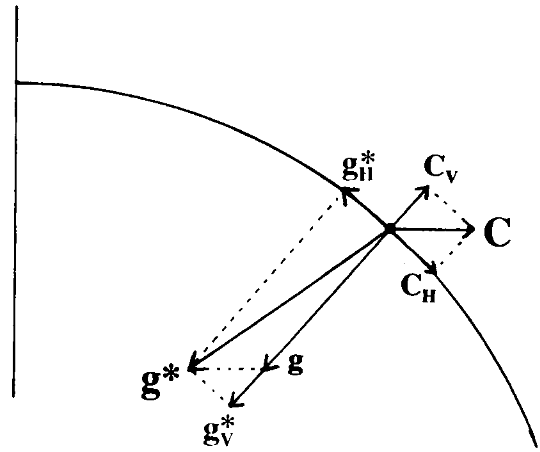

Fig. 2 A modification of Fig. 1 with the gravitational force, g, and the centrifugal force, C, decomposed into horizontal and vertical components. Note that now gravity, g, appears as the difference between the vertical component of gravitation, g_v^*, and the vertical component of the centrifugal force, C_v. The balance that makes a body remain stationary is between the horizontal component of gravitation, g_H^*, and the horizontal component of the centrifugal force, C_H. If the body moves eastward (perpendicular into the paper) the centrifugal force will increase and C_H will push it equatorward (to the right of the motion); if the motion is westward, against the rotation (out from the paper), the centrifugal force will weaken which will allow the horizontal component of gravitation, g_H^* to push the body poleward.*

The decisive difference between the merry-go-round or turntable and the rotating earth is the existence of a restoring force, g_H^*, pointing poleward trying to bring the body towards the centre of rotation. We can simulate a restoring force on a turntable by making it parabolic (Fig. 4). Such a turntable was in use in meteorological education at the Massachussetts Insti-

* The importance of the horizontal component of gravitation was explained in the nineteenth century in the very first book on dynamic meteorology (Sprung 1885; see also Sprung 1881). Durran (1993), Ripa (1997) and Phillips (2000) have recently paid new attention to it. More than 50 years ago L. F. Richardson was close to a rediscovery when he tried to find out which physical force was deflecting easterly winds poleward. Unfortunately he looked only at deviations from the centrifugal force and overlooked the role of the horizontal component of gravitation. Consequently he concluded that the Coriolis force was "a mystery to be explained otherwise" (Richardson 1946).

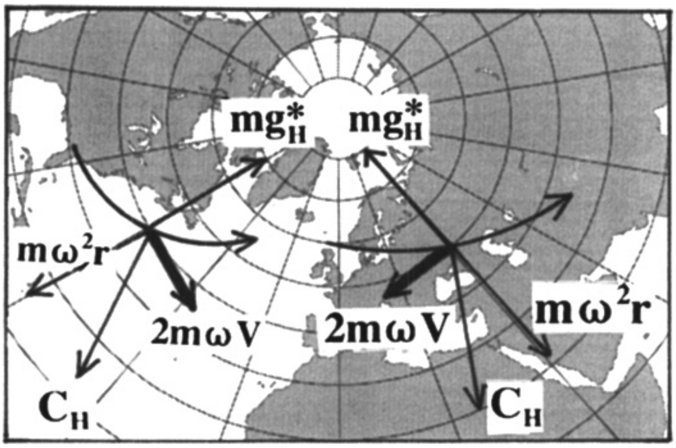

Fig. 3 If a body on the earth moves meridionally with a velocity, **V**, *its trajectory (seen from outside the earth) will follow a poleward or equatorward spiral, as depicted over the Atlantic or Europe respectively in the figure. For these trajectories the horizontal centrifugal force,* C_H, *will no longer point radially away from the poles, parallel to the longitudes. It can then be decomposed into one component,* $m\omega^2\mathbf{r}$, *the radial centrifugal force, and* $2m\omega\mathbf{V}$, *the Coriolis force. The horizontal component of gravitation,* mg^*_H, *will be unaffected.*

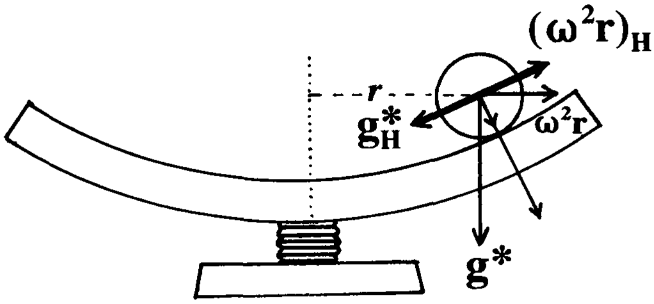

Fig. 4 By making the surface of a turntable parabolic, we can simulate the Coriolis effect corresponding to the dynamics of the earth. For a certain rotation, ω, *the ball will find a state of rest where the horizontal gravitation,* g^*_H, *pointing towards the centre is balanced by* $(\omega^2 r)_H$, *the outward-directed horizontal component of the centrifugal force (see Durran 1993, 1996). Note that on this turntable, in contrast to the earth, the vertical component of the centrifugal force adds to the gravitational push. (The subscript H stands for 'horizontal' on the turntable.)*

tute of Technology in the 1950s (Durran 1996; Norman Phillips, personal communication*).

Inertia circles

On an ellipsoidal earth any motion under inertia will be entirely determined by the Coriolis force acting at right angles to the motion. Such a force will create a near-circular motion†, clockwise in the Northern Hemisphere. This has some interesting consequences.

Remember the golfer in Part 1 (Persson 2000) who struck a ball with a speed of 2 m s^{-1}? If he missed the hole, the ball would not, as might be expected, gradually disappear out of sight (we assume there is no friction slowing it

* See also the website on http://satftp.soest.hawaii.edu/ocn620/coriolis/ created by the University of Hawaii, where visitors can play with their own virtual parabolic turntable!

† 'Near-circular' because the Coriolis force varies with latitude. It is a common misconception that a body moving over the surface of a planet follows a great circle. This is true if there is no friction, in which case the body does not take part in the earth's rotation and acts in the same way as a satellite.

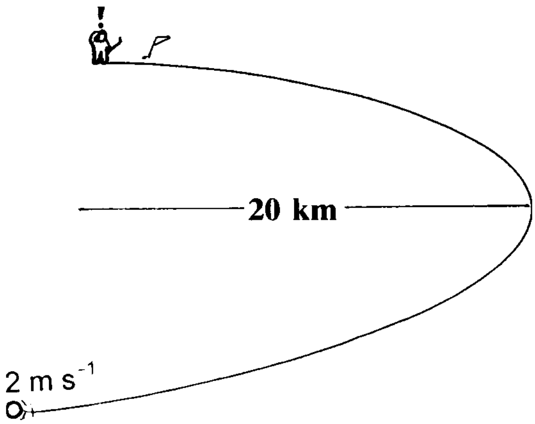

Fig. 5 A golfer putting a ball with a speed of 2 m s^{-1} and missing the hole would, if he had a sufficiently large (and frictionless) green, experience how the ball, would return near to him after 17 hours, having moved in a near-circular path with a radius of 20 km

down). The Coriolis force, constantly deflecting the ball at right angles to its motion, will make it follow a large, almost-circular path*. To the golfer's surprise, the ball, after 17–18 hours, would be coming back not far away from the point where he struck it (Fig. 5)!

The two systems

It has turned out, quite surprisingly, that by far the simplest way to qualitatively understand the Coriolis force on the earth is to consider our planet as it actually is, a rotating oblate ellipsoid where the dominating forces are gravitation and the centrifugal force. In our mathematical calculations we replace this physical system with a mathematical system where the earth is a sphere and there is no gravitation or centrifugal force. They are replaced by gravity and the Coriolis force (Fig. 6). The mathematical earth model allows us several practical and pedagogical advantages since all the calculations that we perform yield the same results as those in the realistic system.

* For a circular motion with the speed V=2 m s^{-1} in a circle with radius R, the outward-directed centrifugal acceleration, U^2/R, is balanced by the inward-directed Coriolis acceleration fV (where the Coriolis parameter f=10^{-4}s^{-1} at 43 N) which leads to R=20 km. The time it takes to travel around is $2\pi/f$, which in our case is 17.5 hours. Note that the Coriolis force acts as an inward centripetal force, not as an outward centrifugal force as stated by Brunt (1934, p. 162, 1941, p. 167) and Meteorological Office (1991, p. 54). This would imply an inertia circulation in the opposite, anticlockwise, direction.

The mystery deepens

So far our attention has focused on how the Coriolis force affects movements of bodies on merry-go-rounds and on the surface of spheroidal planets. But how does this help us to understand the dynamics of the atmosphere? Not very much, to be honest. To paraphrase Churchill: we have not even reached the end of the beginning. What has been shown is that standard pedagogical reasoning, which cannot explain what is going on in simple rotating systems, can hardly help us to understand the atmosphere either. These articles have suggested a way to understand the Coriolis force which may provide a starting point for further explorations of the geostrophic balance and the dynamics of the atmosphere, to unravel other mysteries and confusions. A natural question at this stage, for example, is: how can the Coriolis force be so fundamental in the creation and motion of mid-latitude cyclones and jet streams when it is fictitious and unable to do work? It is a good question, and I am sure that, somewhere out there, there is a good answer to it.

Acknowledgement

It was Norman Phillips who made me aware of the fact that the centrifugal force is the dominating force on a merry-go-round and that this system is not really suitable for an understanding of the Coriolis force. Discussions with him and Olivier Talagrande helped to clarify the relation between gravitation, gravity, and the earth's centrifugal force.

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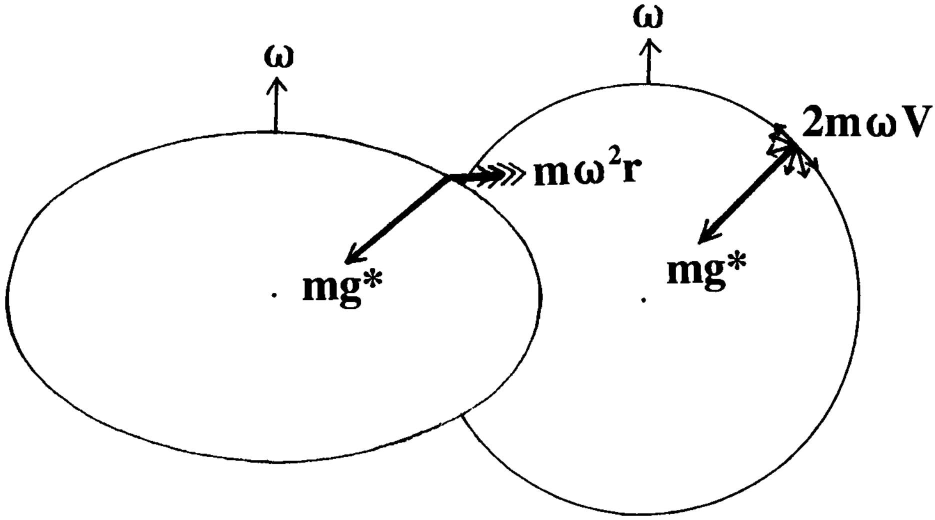

Fig. 6 The two earth systems: one is a real model of the rotating, ellipsoidal planet with gravity and the centrifugal force, the other a mathematical model with a rotating sphere without any centrifugal force and with gravity pointing straight to the centre. There is no horizontal component of any centrifugal force or gravitation. They are replaced by a Coriolis force which makes a body behave in the same way as in the real system.

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Will-o'-the-wisp revisited

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The existence of an ephemeral bluish luminous exhalation associated with marshy places appears to have been commonly accepted when Sir Isaac Newton was writing his *Opticks* (Newton 1704), and many sincere and convincing eyewitness accounts have been traced in the scientific literature up to and including the nineteenth century (Talman 1932; Mills 1980). Unfortunately, the phenomenon was never photographed (much less captured in a gas jar or examined spectroscopically) and appears to have become very rare by the beginning of the twentieth century. Amongst the last published discussions on the subject was a