METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **17**: 236–242 (2010)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/met.205

Mathematics *versus* common sense: the problem of how to communicate dynamic meteorology

Anders Persson*
Meteorological Office, FitzRoy Road, Exeter, EX1 3PB, UK

ABSTRACT: The problems of communicating essential processes in dynamic meteorology are discussed, with examples. It is argued that the difficulty in conveying the concepts is not a result of the non-linearity of atmospheric and ocean motions, but their counter-intuitive nature. Although this might motivate the highly mathematical way dynamic meteorology is communicated, issues arise when the mathematics is poorly or wrongly interpreted. It is suggested that communication would be improved by laboratory experiments and observational evidence, while an historical background could help explain why a particular phenomenon is important. © Crown Copyright 2010. Reproduced with the permission of the Controller of HMSO. Published by John Wiley & Sons, Ltd

KEY WORDS dynamic meteorology; communication; general circulation; the Coriolis Effect; education; rotation; common sense.

Received 1 December 2009; Revised 11 February 2010; Accepted 22 April 2010

'Science can be beautiful, amazing, the best way of trying to understand the world. But it is difficult... if an idea fits with common sense, then it is almost certainly scientifically false... The world is just not built on a common-sense basis.' Lewis Wolpart, author of 'The Unnatural Nature of Science' (1994) in 'The Independent' 9 February 2005

1. Introduction

To meteorologists, whether they are modellers or forecasters, a good, intuitive, qualitative and physical grasp of dynamic meteorology, and in particular the general circulation of the atmosphere, is crucial, not only to detect possible shortcomings in their models but also to prevent unreflective discarding of unexpected results.

In the meteorological community, in particular in the United States, there is a growing concern that there is a general need for scientists and experts in communication to work together to improve public knowledge and understanding of geosciences, mainly in ocean-atmospheric circulation and interaction (Pandya *et al*., 2004; Roebber, 2005; Schultz, 2009). This is particularly important since students in introductory meteorology courses at universities are often the future leaders in the fields of business, journalism and education (Knox and Ackerman, 2005).

The dynamics of the general circulation of the atmosphere and the ocean is, however, considered to be a difficult subject because of its highly mathematical character. The late Professor Richard Reed at the University of Washington, Seattle, once wittily commented (Reed, 1990): 'The general success of the forecasts in data-rich areas bears witness to the fact that the cyclogenetical process is indeed now well understood – at least by the computer!'. In contrast, Edward Lorenz consistently argued that by applying equations already known to be precise, will not by itself increase our understanding of the atmosphere (Lorenz, 1960, 1984).

It will be argued here that the problem of understanding and communicating dynamic meteorology does not mainly lie in its complicated non-linear mathematics but in its highly counter-intuitive nature. The motions of the atmosphere and oceans are just not built on a common sense basis.

2. Some examples of the counter intuitive nature of dynamic meteorology

The discrepancy between intuitive 'common sense' and mathematics is not only a problem in dynamic meteorology. Studies of American university students taking introductory physics found, for example, that students tended to believe that a constant force is needed to produce a constant motion and the absence of forces will keep the object at rest or slow it down. These erroneous beliefs were based on a common sense experience of daily life, where frictional effects are important (see McDermott, 1998, for further references). In dynamic meteorology, non-intuitive processes not only involve frictionless motion but also the behaviour of stratified fluids and rotational effects.

2.1. Frictional and non-frictional motion

Meteorologists' 'common sense' is often based more on surface maps than upper-air maps. Since much of the

* Correspondence to: Anders Persson, Meteorological Office, FitzRoy Road, Exeter, EX1 3PB, UK.
E-mail: anders.persson@metoffice.gov.uk

motion in the upper atmosphere is essentially frictionless, it may come as a surprise to see how the upper winds, in contrast to the surface winds, almost as often move against the pressure gradient force, towards higher pressure (or geopotential) than with the pressure gradient force, towards lower pressure (or geopotential). When friction indeed is involved it is almost always taken for granted in the meteorological literature that it is counter-parallel to the flow. This again agrees with everyday experience, but it is only true for solid objects, not necessarily for gases and liquids where the deviation can be substantial (Arya, 1985, 1988).

2.2. Stratified fluids and gases

The following counter-intuitive and illuminating experiment example was enthusiastically promoted by the late oceanographer Adrian Gill (1937–1986) (Gill, 1982). A glass jar is one-third filled with vinegar. When the jar is moved back and forth horizontally, with a certain regular pace, the vinegar surface oscillates. If the glass jar is then filled by another one-third, with oil on top of the vinegar, and is moved in the same way, will the vinegar surface, now interfacing the oil above, oscillate with larger, smaller or the same amplitude? From a common sense notion one would expect that it will oscillate with less amplitude because of the burden of the oil above. In reality, the opposite happens: the vinegar surface oscillates with significantly larger amplitudes (Figure 1). When the burden of oil is lessened (its amount or density reduced) the vinegar will, paradoxically, oscillate less.

2.3. Rotation

Motion under rotation is famously counter-intuitive as demonstrations of gyroscopes and spinning bicycle wheels demonstrate. It is not difficult to be logically-mathematically convinced that, for example, a spinning top will not easily fall over. Still, according to debates in the teacher-oriented American Journal of Physics, university students still want to know 'what is really going on'.

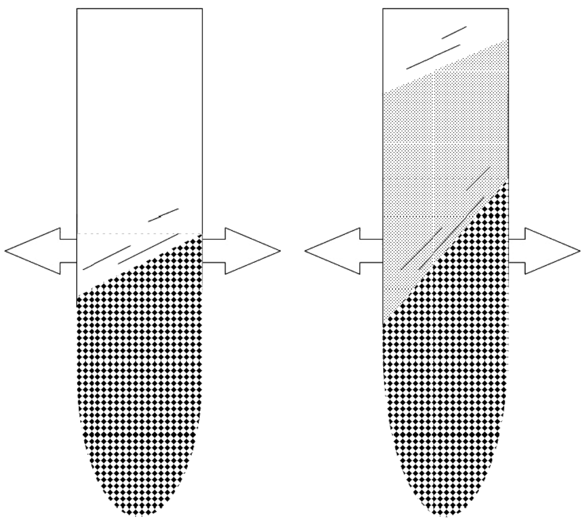

Figure 1. Two glass jars with vinegar only (left) and vinegar and oil (right) are moved horizontally backward and forward with the same pace. When the vinegar is interfacing air above it oscillates with less amplitude than when it is interfacing the oil above.

The same seems to be true for meteorological students. McNoldy *et al*. (2003) noted that, although textbooks in dynamic meteorology provided detailed mathematical arguments, most meteorological students did not truly grasp the concepts until they were also shown them as laboratory experiments. Roebber (2005) found that the lack of understanding was often related to the mathematics of the equations of motion, which confirms the observation by Stommel and Moore (1989) that students regard the Coriolis Effect as 'mysterious' and a result of 'formal mathematical manipulations'. A frustrated Scandinavian colleague once told me: 'the Coriolis Effect cannot be understood, only mathematically derived' (Peder Aakjœr, personal communication, 1999). This brings up the role of mathematics in communicating physics in general and dynamic meteorology in particular (see also Appendix A).

3. The role of mathematics in physics communication

Considering the counter intuitive nature of dynamic meteorology, it is evident that successful communication must be based on a correct mathematical basis. There are, however, several reasons why purely mathematical descriptions are insufficient.

3.1. Mathematics: the easy bit?

The French physicist and 1991 Nobel Prize laureate Gilles de Gennes (1932–2007) caused controversy in his homeland when he claimed that education in physics was too mathematical and that current programmes in physics were no more than mathematics in disguise. Many might agree with him, but perhaps not for the reason de Gennes brought forward. His argument was that 'mathematics is the easiest bit in physics' (de Gennes, 1994). The ability to derive a certain mathematical equation is a necessary condition, a first easy step to acquire a physical understanding, but it is not sufficient. The difficult part, according to de Gennes, is to understand what the mathematics means, how it relates to observations and how it connects with other theories.

Most controversial was de Gennes' opinion that the over-emphasis on mathematics in physics education was motivated by pure convenience: to make it easier for the teachers to fulfill their lecturing obligations. They could also mark exams more quickly if the problems were deductive rather than inductive, i.e. about deriving mathematical expressions rather than interpreting observed phenomena in mathematical terms.

Roebber (2005) found a similar tension in meteorology between students and faculty teachers. One student told him in an interview: 'We did equations all the time, derivations constantly, so we would think about why we were doing this. Spent 5 days doing a derivation, all

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math all the time, and wondering why we were doing that'. In the same vein, Schultz (2009) points out that students tend to be goal-seeking learners, wanting to see connections between theory and real-world applications. In contrast, professors tend to be knowledge-seeking learners, preferring theory and learning for the sake of learning. Unfortunately, the curriculum in most atmospheric-science programs tends to be written from a knowledge-seeking perspective.

3.2. The relation between mathematics and physics

Richard Feynman (1918–1988) was another physicist and Nobel Laureate (and excellent science communicator) who thought much about the relation between mathematics and physics. In his book on the character of physical law, he devoted a chapter to this one issue (Feynman, 1992). Even though he argued strongly that if one wants to learn about nature it is necessary 'to understand the language that she speaks in', namely mathematics, he also stressed the importance of not confusing mathematics and physics.

Mathematics is a way of going from one set of statements to another along lines of abstract reasoning already prepared by the mathematicians. Mathematicians are, however, only dealing with the structure of reasoning and are not necessarily concerned about possible physical interpretations. 'But the physicist has meaning to all his phrases. That is a very important thing that a lot of people who come to physics by way of mathematics do not appreciate. Physics is not mathematics, and mathematics is not physics. One helps the other' (Feynman, 1992).

So, although Nature speaks in mathematical terms, humans also speak in their different tongues: 'In physics you have to have an understanding of the connection of words with the real world. It is necessary at the end to translate what you have figured out into English, into the words, into the blocks of copper and glass you are going to experiment with. Only in that way can you find out whether the consequences are true. This is a problem which is not a problem of mathematics at all' (Feynman, 1992).

3.3. Loose or unclear definitions

The discrepancy between colloquial language and a strict scientific nomenclature is a problem in communicating dynamic meteorology. So, for example, it is scientifically correct to say that the Coriolis force is 'fictitious', but it is therefore wrong, as suggested by Emmanuel (2005) and explicitly stated by Walker (2007), to suggest that it is an 'optical illusion'. In elementary mechanics 'work' has an exact meaning of conversion between potential and kinetic energy. It is, therefore, scientifically correct to say that the Coriolis force does not 'do work', but it is wrong to infer from this that it doesn't 'do anything'. 'The whole definition of work in physics may seem strange to beginners since it is a matter of everyday domestic experience that one expends the most effort, and accumulates the most frustration, when failing to move objects such as pianos and bottle tops! As so often happens, the root of the problems is that the word chosen to convey a technically precise meaning also has a much wider (and often more vivid) connotation outside physics' (Andy White, personal communication, 11 November 1998).

The word 'forcing' is used in many different contexts in dynamic meteorology, in contexts which do not always agree with its colloquial meaning. Modifying the vorticity in one grid point, 'forces' the winds to change in a wide area. Motions in the stratosphere are said to 'force' motions in the troposphere (as with the oil the vinegar) where perhaps 'interaction' would be more appropriate.

3.4. Different mathematical ways to explain the same phenomenon

Another one of Feynman's messages is that the same physical processes can often be understood and communicated in different mathematical ways (Feynman, 1992). Gravitation can, for example, be mathematically understood in (at least) three ways: as action-at-a-distance, as the consequence of a potential field, or from a variational principle. These are all mathematically equivalent, but conceptually and pedagogically very different (Feynman, 1992). An illuminating geophysical example, although for simplicity a non-meteorological one, is the interaction between the Earth and the Moon.

The sum of the Moon's orbital momentum and the Earth's spin can be considered constant (disregarding the Sun and the other planets). Since the rotation of the Earth is slowing down, mainly because of the friction between the Earth and the tides, the Earth's spin angular momentum is slowly decreasing. It can be said that 'in order to' conserve the system's total angular momentum, the Moon's orbital angular momentum 'has to' increase by a transport of angular momentum from the Earth to the Moon. The Moon will thereby slowly go out in a wider orbit.

This explanation, although mathematically impeccable, may leave the audience unsatisfied and trigger follow-up questions such as: how does the Moon 'know' that the Earth is spinning down; how does it 'know' it has to orbit faster, and, how fast is the angular momentum transported?

The answer to these questions is to be sought along quite different lines: it is the Earth's tidal water bulge that accelerates the Moon. Due to the friction between the surface of the Earth and the ocean water, the Earth's ocean tidal bulge does not point exactly towards the Moon, but slightly ahead. Therefore, the gravitational attraction felt by the Moon is not symmetrical but has a small forward-directed component. This will accelerate the Moon into a wider orbit by about 4 cm *per* year. During this process the system's total angular momentum is conserved (Figure 2).

While the first explanation enables tractable calculations of where the moon might be in, say, 100 000 years,

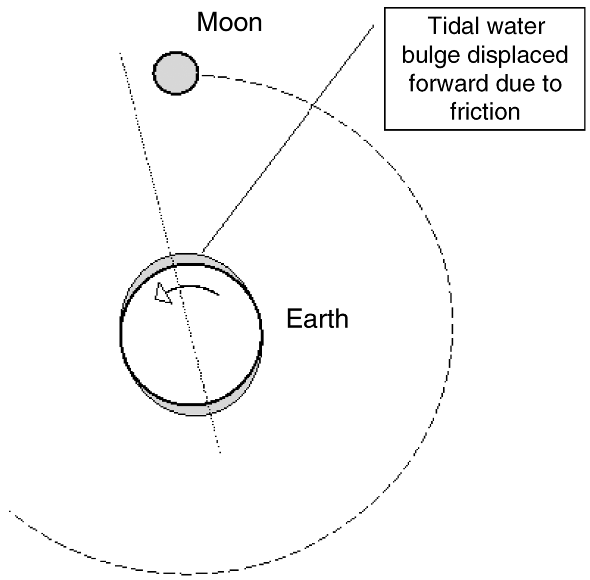

Figure 2. The Moon–Earth system with the ocean tidal bulge pointing slightly ahead of the moon's position.

the same calculation using the second explanation would demand enormous and, perhaps unattainable, computer resources. Although both explanations are scientifically equivalent, one provides means for calculations, the other an understanding of what is 'going on'.

3.5. The correct interpretation of mathematics

Mathematics is a powerful tool of communication because it saves enormous amounts of reflection and stores immense amounts of knowledge, but all this can break down if the mathematics is accompanied with erroneous or misleading qualitative interpretations (graphical or verbal).

Take, for example, the illustration of air moving under a constant pressure gradient, found in many textbooks and Internet sites. The equation of motion accelerated by a constant meridional pressure gradient force P_y is, in a Cartesian coordinate system:

$$\frac{du}{dt} - fv = 0\frac{dv}{dt} + fu = P_y \qquad (1)$$

Further manipulations yield the positions x and y along mathematically defined cycloid trajectories. However, these trajectories are not, as often depicted, like a well-behaved motorist entering the motorway adhering to the agreed geostrophic speed restrictions. They are rather like an aggressive motorist, who violates the speed restrictions and also swerves from one side of the road to the other (Figure 3).

The correct picture is a more or less realistic image of the process of small scale nocturnal jets (Persson, 2002a) and, applied on the large-scale unperturbed jet streams, explains their cycloid or 'banana' shape (Persson, 2002b, 2003b, 2004). What might at first to an audience appear as an artificial or abstract mathematical exercise turns out in the end to be more realistic and useful than the opportune 'common sense' image.

Other sources of confusion between mathematics and common sense involve ignoring the distinction between streamlines and trajectories, between Eulerian and Lagrangian averaging or treating averages or budgets as if they necessarily also represented instantaneous processes (Persson, 1998, 2002d).

4. Suggestions for efficient communication

Chapter 6.2 on super-imposed fluids in Adrian Gill's book sets out the recipe for a successful communication of complicated and non-intuitive processes: (1) a solid mathematical-theoretical basis, (2) laboratory experiments, (3) observational studies, and, (4) historical background, to, provide an intuitive 'feel' for the underlying dynamics. Another example covering the same subject is found in Walker (1991). Their approach is in line with the conclusions in the American studies, namely that 'the study of a new topic should begin by helping students develop a qualitative understanding of the material from direct experience or observations when possible' (McDermott, 1998).

The mathematical basis: Good communication demands that the receivers are given proper motivation. The insights gained by deriving mathematical expressions, therefore, depend on how they are conducted. Equally important is a careful interpretation of what the equations actually tell us, or do not tell us. If there is more than one mathematical way to understand a process this will improve communication and deepen understanding.

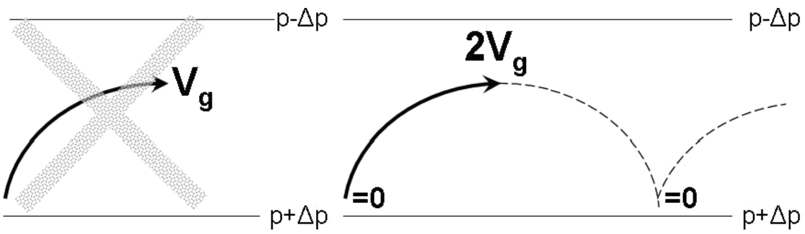

Figure 3. Two images of an air parcel accelerated by a constant pressure gradient. Left: The common, but erroneous and misleading, one where the wind smoothly attains the geostrophic speed and direction. Right: In reality, and in accordance with the mathematics, the air parcel will, counter-intuitively, be torn between the 'straight' pressure gradient force and the 'curved' Coriolis force, to follow a cycloid path. It will reach double geostrophic speed and, being highly super-geostrophic, be moved by the Coriolis force to the right, towards higher pressure and decelerate.

Laboratory experiments: Observations and/or laboratory experiments help to widen and enrich our common sense (Illari *et al*., 2009). Experiments with fluids are more easily conducted and visualized than experiments involving gases. The distinguished British fluid dynamicist H. P. Greenspan began his mathematically rigorous textbook with the opinion that '[laboratory] demonstrations really give the subject life and their role in *developing intuition* cannot be overestimated' (Greenspan, 1968; McNoldy *et al*., 2003, author's italics).

Observational evidence: Dynamic meteorology and physical oceanography are highly related and observations from the oceans can illuminate atmospheric processes and *vice versa* (Persson, 2001c). It is also interesting to note that oceanographic textbooks and articles make more use of observational evidence than similar texts in dynamic meteorology, despite the difficult problem in oceanography of acquiring observations.

Historical background: Historical storytelling, as suggested by Knox and Croft (1997), is not only entertaining, it can give additional information and above all makes sense of abstract theory. It provides an answer to why a particular phenomenon is important or interesting as new ideas and how to look at them. Gill (1982) and Walker (1991) underpin their narratives by providing an historic background, from Benjamin Franklin crossing the Atlantic in 1762 to how Nansen, Bjerknes and Ekman solved the 'dead water' mystery in 1904.

5. Summary

Meteorologists, as other scientists, must often discuss their results and share their knowledge with a wide audience of non-experts. This is particularly important in the current situation when the focus is on climate change. Both dynamic meteorology and physical oceanography are branches of fluid mechanics and belong to what is often called 'classical' mechanics, but few people have any first hand experience of the behaviour of stratified fluids or gases moving frictionless under rotation, which is often as difficult to intuitively comprehend and communicate as 'modern' physics. Communication can, however, be improved by upgrading our common sense, by making use of observations, laboratory experiments and historical background material, based on a correct interpretation of the underlying mathematics. The latter is important, since any skillful communication can be ruined if there are logical inconsistencies between mathematical expressions and physical experiments or observations.

Finally, good communication is not only of interest and value to non-experts but also to the experts themselves. Modern physicists have put much effort into explaining quantum mechanics and relativity to the interested non-expert. There have even been attempts to communicate how it would feel to be sucked into a black hole, what the universe looked like one second after the Big Bang and how to orientate oneself in an 11-dimensional string theory world. The scientific experts have done this not only from a sense of democratic and pedagogic responsibility, but also with an intent to understand their subject better. Albert Einstein, who spent a lot of time communicating his revolutionizing ideas to non-experts, allegedly said that 'You do not really understand something unless you can explain it to your grandmother'.

Acknowledgements

This article is based on discussions over the years with colleagues; in particular at the European Centre for Medium-Range Weather Forecasts (ECMWF) and colleagues at the Met Office in Bracknell and Exeter. The author has also benefited from discussions with students on training courses and workshops organized by ECMWF, World Meteorological Organisation, University of Trento, the Nordic meteorological services and others. The author is also deeply indebted to Professor Norman A. Phillips and Professor George W. Platzman, who, as few others, have been able to reveal and communicate to me the counter-intuitive secrets of the atmosphere. Carla Karlström-Eggertsson, Haldo Vedin and the late Hans Alexandersson, at SMHI encouraged my research in this topic during many years.

Appendix A: the Coriolis Force Communicated.

This appendix exemplifies, from the author's experience, how mathematics, observations, experiments and history can be interlinked to provide a clear and consistent presentation of the Coriolis Effect. The main ambitions have been not only to counter the common notion that it is a 'mysterious' force resulting from a series of 'formal manipulations', but also, as much as possible to show how correct interpretations may unveil the complexities of the motions of the atmosphere and oceans by tending to confine or constrain moving air and water within relatively small areas, while at the same time pushing it westwards, against the Earth's rotation.

A.1. History

In the 1830s, in the midst of the industrial revolution, the French mathematician and engineer Gaspard Gustave Coriolis (1792–1843) wanted to calculate the centrifugal action on machines with internal parts moving relative to the rotation. He found that one had to take account of an addition to the centrifugal force, an extra force, which came to carry his name (Persson, 1998, 2000a).

A.1.1. Sideways deflection of vertical motion

The interest in what we today call the Coriolis Effect began more than 100 years before Coriolis was born. In the seventeenth century scientists discussed the possible sideways deflection of falling objects as proof that the

Earth was rotating. Newton was heavily engaged and there are reasons to believe that the incident with the falling apple relates to these discussions (Persson, 2003a). Early in the nineteenth century both Laplace and Gauss were involved in a contest to predict this deflection in an experiment of dropping stones in deep mine shafts.

A.1.2. Vertical deflection of horizontal motion

Coriolis made no reference to any geophysical application but the Hungarian nobleman and geophysicist Lorand Eötvös (1848–1919) applied Coriolis theory to the problem of measuring the gravitational attraction by the Earth. This cannot be measured directly, only through the Earth's gravity, the combined affect of gravitation and the centrifugal effect due to the Earth's rotation. The latter, in turn, depends on whether the observer is stationary or not. The vertical component of the Coriolis Effect has then been known as 'The Eötvös Effect' (Persson, 2000b).

A.1.3. Sideways deflection of horizontal motion

The realization of the sideways deflection of horizontal motion only came with Léon Foucault's 1851 pendulum demonstration in Paris. The French mathematician Poisson, who had calculated the deflective effect of the Earth's rotation on artillery grenades, was affirmative that pendulums would not be affected. Foucault's experiment proved him wrong and this initiated studies of the possible effect of the Earth's rotation on moving objects such as rivers, trains, winds and ocean currents.

A.2. The mathematics of the Coriolis Effect

The mathematical derivation of the Coriolis force is perhaps most convincingly and elegantly performed using vector algebra (French, 1971; Pedlosky, 1979; Gill, 1982). It highlights its three-dimensional nature and links effectively to each of the stories above.

The cross product in $-2\ \Omega \times V_r$ provides a simple rule of thumb: there is deflection only when a component of the relative motion (V_r) is perpendicular to the rotation (Ω). Consequently, objects moving parallel to the rotation axis are not affected (Persson, 1998, 2002d). The cross product also indicates that the Coriolis force, perpendicular to the motion, will tend to drive any moving object into a so called inertia circle of surprisingly small sizes, in the mid-latitudes around 100 km for motions of $10\ \text{m s}^{-1}$.

Since the Coriolis Effect is proportional to the sine of latitude, the radius of curvature of the inertia oscillations is larger towards the equator than toward the poles. This makes the circular oscillation open up westward, introducing the 'β-effect', a slow drift on the motion against the Earth's rotation (Persson, 2002d).

A.3. Refutation of incorrect derivations and explanations

Effective communication demands that popular misconceptions be addressed. George Hadley might have been the first to point to the importance of the Earth's rotation for the general circulation of the atmosphere, but he was wrong to assume that the governing principle was conservation of absolute velocity. Since this is an easily understandable and therefore very popular explanation some effort must be spent to show that it has nothing to do with the Coriolis Effect (Persson, 2009). A mathematically interesting curiosity is a widespread and popular derivation of the Coriolis Effect which combines mathematically two intuitively appealing, but erroneous, assumptions and gets the right answer because the errors cancel out (Persson, 2002c).

A.4. Laboratory experiments

The deflection of a ball rolling over a turntable will only be partly due to the Coriolis Effect because the centrifugal effect is also present. The trajectory is an ever-widening spiral, instead of being confined to a small inertia circle. To study the pure Coriolis Effect it is therefore necessary to deform the flat turntable into a parabolic dish rotating around a vertical axis (Figure 4). The inward gravitational acceleration along the surface of the dish then exactly balances the outward centrifugal acceleration (Persson, 2000b). Durran and Domonkos (1996) provide a detailed account of how such an experiment can be conducted.

Another illuminating laboratory experiment involves a coloured liquid dropped into a water tank. When the tank is stationary the water is totally coloured, when it is rotating the coloured liquid is constrained by the Coriolis Effect in so called 'Taylor Columns' (Persson, 2001a; McNoldy *et al.*, 2003; Illari *et al.*, 2009).

A.5. Observational evidence

Drifting buoys in the oceans follow circular or cycloid trajectories (dependent on the presence and strength of ocean currents) and provide observational evidence of the Coriolis Effect (Persson, 2001b, 2001c). The diurnal veering of the sea breeze or nocturnal jets are perhaps the best examples of almost pure Coriolis effects.

More complex atmospheric phenomena involve the pressure gradient force and the resulting (quasi-)

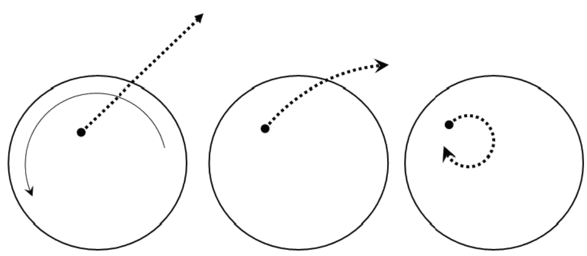

Figure 4. A ball is observed from outside, i.e. in the non-rotating frame, rolling over a *flat* merry-go-round (left), the same viewed from inside, i.e. in the rotating frame, (centre). In this case the ball will eventually disappear out of sight in an ever widening spiral. In the third image (right) the motion is viewed from inside a *concave, parabolically* shaped merry-go-round. In this case only the Coriolis Effect would be at work and the relative motion is confined to a small (inertia) circle.

geostrophic balance will disguise the pure Coriolis Effect. However, the cycloid shapes of large-scale jet streams reveal their connection to inertia circles and thus the Coriolis Effect (Persson, 2001c). The latitude dependence of the Coriolis Effect, the 'β-effect', contributing to a westward drift of all motions (Persson, 2001b, 2002e) is most clearly manifested in the asymmetric oceanic gyres (the Gulf Stream and the Kuroshio Current).

A.6. Non-observational evidence

Also, absence of observations can sometimes be illuminating. In the 1960s American and Russian space engineers thought they had found a way to create artificial gravity for their crews through the centrifugal action of rotating space platforms as depicted in the introductory sceneries in Stanley Kubrik's film '2001 a Space Odyssey'. However, at about the same time as the film was completed (1969) the space engineers realized it would not work, or rather would only work as the long as the passengers stood still. As soon as they moved the centrifugal force would change in the way described by Coriolis in 1835. Since the rotation of the space station would be on the order of 10^3 faster than the Earth's rotation and the Coriolis force correspondingly 10^3 stronger, centrifuges and other fast moving machinery might malfunction. The passengers on board would have problems walking and also get motion sick. What a better example that the Coriolis Effect is not an optical illusion!

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