break off. The Desert of Kalahari will float after it, no longer a desert but an oceanic island, flourishing like Zanzibar.

While the "bow" of a traveling continent is piled up into mountains, some magma clings to the "stern," tearing away pieces of land. Hence, islands are drifting in the wake of the floating continents and on most of them volcanoes are active. More than seventy-five per cent of the presently active volcanoes stand on these backwash islands in the sea of magma. Asia offers the most spectacular example.

Asia is turning to the northwest, its backwash being along the southern and eastern shores. The chains of islands that girdle the continent from the Aleutians in the north, over the Kuriles, Japan, the Philippines, to the scattered world of the Southern Pacific, all of them volcanic and all of them fragile, are the foam on the waves in the wake of the traveling ship.

All modern science has become dynamic. The time-honored concept of a monumental, enduring universe has exploded into the fireworks of drifting galaxies; the "forever unbreakable" atom has been split into the lightning of mesons and neutrinos; matter, the "eternal matter," has radiated away in waves. The theory of the floating continents is a timely attempt to attack geological problems with a dynamic, one could almost say a biological, approach. This is a merit the work of Wegener will never lose. The theory may be discarded; its animating influence can never be lost.

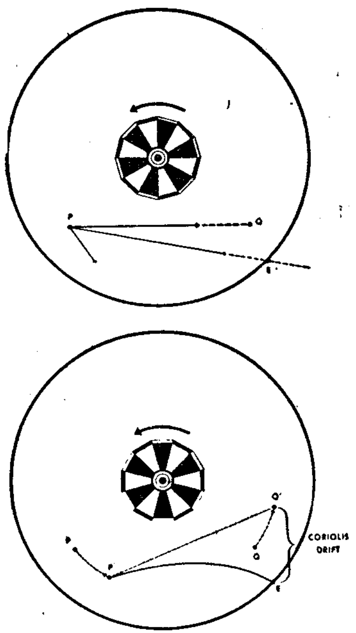
JAMES E. McDONALD

The Coriolis Effect

All of us are aware of at least one consequence of the daily rotation of the earth on its axis: the rising and setting of the sun, and the endless succession of day and night. There are other effects, however, of which few persons are aware. One of these is the curious "Coriolis effect," described in this article from the *Scientific American*, issue of May, 1952, Vol. 186, No. 5, (and reprinted by permission of the magazine). Dr. James E. McDonald, the author, is associate director of the Institute of Atmospheric Physics at the University of Arizona. The illustration is reprinted by permission of Irving Geis.

It is a curious fact that all things which move over the surface of the earth tend to sidle from their appointed paths—to the right in the Northern Hemisphere, to the left in the Southern Hemisphere. Since man has managed to make himself one of the most mobile of creatures, one might think that so ubiquitous an effect must long have been a matter of common knowledge. It has not been and still is not, even in this era of rapid speeds, which accentuate the sidling tendency. Probably few people realize that as they drive down a straight highway at sixty miles per hour this all-pervading drift would carry them off the road to the right at the rate of some fifteen feet per mile were it not for the frictional resistance of the tires to any lateral motion.

The sidewise drifting tendency is called the Coriolis effect, after the nineteenth-century French mathematician G. G. Coriolis, who made the first complete analysis of it. The effect is due simply to the rotation of the earth, and it appears in all motions as soon as we refer those motions to any co-ordinate system fixed with respect to the earth (e.g., the latitude-longitude grid).



Merry-go-round experiment demonstrates Coriolis drift. Seen from above, the merry-go-round rotates counterclockwise. In the top drawing a man at P attempts to throw a ball to a man at Q. The rotational motion of the man at P (short arrow), however, causes the ball to head in the direction PE. In the bottom drawing the man at P has moved to P', the man at Q to Q' and the ball crosses the edge of the merry-go-round at E. To the rotating observers on the merry-go-round the ball appears to have described a curve.

There is really only one satisfactory way to obtain a vivid impression of the nature of the Coriolis principle. That is to go to a carnival. Every carnival worth the name has a Coriolian co-ordinate system: viz., the merry-go-round. With only a few balls as laboratory equipment and two assistants, one on the merry-go-round with you and the other on the ground, you can carry out many interesting Coriolian experiments.

When the merry-go-round starts up, you begin a game of catch. Things will probably go very poorly for several throws (which is the reason for your taking the precaution of equipping yourself with several balls). The ball will seem to veer from its thrown direction in the most amazing fashion. Let us say the merry-go-round turns counterclockwise, as does the earth when viewed from above the North Pole. If it makes one complete turn in ten seconds, and you throw the ball at a speed of twenty feet per second toward an assistant standing fifteen feet from you on the merry-go-round, the apparently curving ball will miss

the assistant by a little over six feet to the right. When you throw a ball to your other assistant, in the outer world off the merry-go-round, it will again seem to drift rightward. This time, however, by great concentration you may be able to fix your attention on the nonrotating framework of the outer world sufficiently to sense that the ball is really moving as it ought to move, and you may even make proper allowance for the merry-go-round's rotation so that the ball reaches your assistant's hands.

The apparent strangeness of the balls' behavior in these experiments arises from the fact that almost inescapably you take the merry-go-round as your reference system, and in this system the laws of dynamics in their usual form simply do not hold. No such difficulties confront the assistant who stands out on firm ground. He is not so compelled to view these motions with respect to your rotating co-ordinate system. He will feel certain that the balls have at all times been moving in well-behaved fashion. If he has a little understanding of the problem, he may be able to explain to you that the drifting to the right which you seem to see is really due to the fact that your system is turning out from under the moving balls.

The earth is a spherical merry-go-round, and all of the Coriolis drifts we observe when we use terrestrial co-ordinate systems are due ultimately to the fact that the earth, like the merry-go-round, is always spinning out from under our dynamical systems. To be sure, there are certain subtleties that enter into some Coriolis effects, but at bottom the whole thing is just the merry-go-round idea. To an observer conscious of Newton's second law of motion, the apparent "acceleration" (deflection from a straight path) of an object moving over the earth suggests that some force is acting on it, and he is strongly tempted to speak of the Coriolis "force." For convenience, meteorologists and others who are concerned with the Coriolis effect do treat it as a force, and their equations work out all right. What they set down as a force in the Newtonian equation is actually a correction for the apparent acceleration. The pure dynamicist looks at it in a different way: he likes to regard these motions as occurring in obedient Newtonian fashion in what he calls "inertial space."

Now let us look at some interesting examples of the Coriolis effect, as it applies to projectiles, flight, vehicles, ocean currents, and even our weather. The Coriolis effect is greatest near the North and South Poles (where the earth turns most rapidly under a moving object) and decreases to zero at the Equator. The magnitude of the effect also depends directly on the speed of the moving object.

In middle latitudes of the Northern Hemisphere a bullet fired with a velocity of 800 feet per second at a target 400 feet away will drift one-tenth of an inch to the right (without considering wind effects or any other interference). That is, in the half-second during which the bullet is in flight, the rotation of the earth has shifted the bull's-eye by about one-tenth of an inch. This is not serious to a pistol marksman, but the effect can make quite a difference to a long-range gunner. A battleship gunner who takes dead aim at the bridge of a destroyer 20 miles away and fires a shell at 2,500 feet per second will miss the destroyer completely, because the lateral Coriolis drift will be more than 200 feet. In World War I the shells of the giant German gun called Big Bertha, which bombarded Paris from a firing site some seventy miles away, took three minutes to reach their destination, and they underwent a Coriolis drift to the right amounting to almost a full mile—an error for which the German ballistics experts carefully allowed.

For a really dramatic effect we can take the case of a rocket fired from the North Pole and aimed at, say, New York City. Assuming, for the sake of simplicity, that the rocket travels at a constant speed of a mile per second, it will be in flight for about fifty-five minutes. During all of this time the target, New York City, will be traveling at eighteen miles per second through solar-system space (the speed of the earth's movement around the sun) and will also be turning with the rotation of the earth at the rate of fifteen degrees of longitude per hour. As the result of these motions the rocket, at the end of fifty-five minutes, will come to earth in some cornfield in northeastern Illinois, not far from Chicago!

The earthbound observers who have been plotting the apparent path of this rocket with their radar network will say that it traced out a graceful curve which started out straight

south in the longitude of New York City, but veered steadily westward, arriving in Illinois from a direction about eleven degrees east of north. A less provincial observer out in interplanetary space will see that the effect is entirely a result of the earth itself having turned out from under the moving rocket.

This is an idealized case; in actual situations the Coriolis effect is much less evident, because other forces such as air resistance, neglected in this example, also act on moving objects. Furthermore, the motion of a projectile fired from any place on the earth other than the Poles would be influenced not only by the Coriolis effect but also by the initial impetus from the circumpolar rotation of the launching site.

An airplane experiences Coriolis drifts which would lead to astonishing errors in long flights if no compensation were made for them. A jet fighter that set out on a great circle heading from Chicago to New York and flew at 600 miles per hour without changing its heading would miss New York by several hundred miles to the south (assuming no allowance for any wind). And if the same pilot tried to fly in a similar way from Seattle to New York, he would find himself down in South America by the time he crossed the meridian through New York! In actual flights a pilot continually banks his plane slightly leftward, in our hemisphere, to compensate for Coriolis drift. It should be noted that, large as these deviations due to the rotation of the earth are, they are still small compared to the effects of cross-winds normally encountered in actual flights. The pilot's Coriolis corrections are thus obscured by the jockeying necessary to compensate for wind drift. To compensate for the Coriolis drift and keep a 20,000-pound jet fighter on a straight terrestrial course at 600 miles per hour requires a leftward force of about fifty-five pounds in middle latitudes of the Northern Hemisphere. This the pilot manages by manipulation of the plane's wings.

Railroad cars are much more massive, so the Coriolis reaction in their case is greater. A 500-ton locomotive moving at 60 miles per hour develops a lateral pressure on the rails amounting to about 300 pounds in middle latitudes. This has given rise to the story that the wheels on trains wear unevenly. Such a result could hardly be detected on coaches or freight cars, which for railroading reasons have no definite right or left sides, and the Engineering Department of the Union Pacific Railroad has informed the author that even in the case of locomotive wheels the difference of wear on the flanges of the right and left wheels is too small to be measured.

Why is so universal (one should say, "so terrestrial") an effect not readily apparent in our everyday activities? The answer is that for many moving objects the tendency toward a lateral drift is quite easily counteracted as the motions proceed. Thus in the case of the car speeding down the highway at sixty miles per hour, the potential fifteen feet of shift per mile is prevented by the frictional resistance of the tires to lateral motion.

A walking man makes corrections for the Coriolis effect easily and quite unconsciously. On frictionless ice that prevented his making any small lateral corrections (but somehow still permitted him to walk!) a man walking at four miles per hour would drift from his intended straight path by about 250 feet at the end of one mile. Lost polar explorers are reported to have a strong tendency to circle steadily toward the right near the North Pole and to the left near the South Pole; this may very well be due to the Coriolis effect, which is about fifty per cent stronger at the Poles than in middle latitudes. It is said that even the penguins in the Antarctic waddle in arcs to the left, but this the author will have to see to believe.

Among all the physical phenomena in which the Coriolis effect plays a role, the most striking is the weather. Were it not for the Coriolis effect, winds on the earth would rush directly from higher-pressure areas to lower-pressure ones, and no strong "high" or "lows" could develop. Hence there would be no opportunity for the build-up of the intense cyclones and the large anticyclones that control and give variability to our weather, and our weather would be much less changeable than it is. This is precisely the situation in the tropics, where the Coriolis effect is zero or very small. In that almost Coriolis-free belt any atmospheric pressure differences produced by heating of the air at the ground are quickly smoothed out, and the region has well earned the name of "the doldrums." Hurricanes and typhoons never form closer to the Equator than about five

degrees of latitude.

Away from the Equator, however, the case is very different. There the Coriolis acceleration causes winds to veer around and blow at right angles to the pressure gradient, instead of parallel with it. The result is the pattern of strong lows and highs and circular movement that is responsible for changes in our weather.

On other planets, where the angular velocity of rotation is different from that of the earth, the Coriolis effect is correspondingly different. Jupiter and Saturn must have very marked Coriolis effects, because each rotates about two and a half times more rapidly than does the earth. Their atmospheres of hydrogen, methane, and ammonia must have very steep pressure gradients, if their winds compare in strength with ours. In contrast, the atmosphere of Venus is probably very calm, because Venus rotates much more slowly than the earth —perhaps once in about thirty terrestrial days.

Just as the motions of the atmosphere exhibit the Coriolis effect, so also do the more ponderous movements of the great ocean currents. To simplify the picture a bit, let us assume that the density of the sea is uniform. The oceans are not perfectly level, for the winds shift the waters and give them a gentle relief. Since water flows downhill, the natural tendency of the oceans' water is to flow from regions where the mean sea-level is relatively high to those where it is lower. But as soon as the water tries to move in so forthright a fashion, the Coriolis drift causes the moving water to veer off to the right (in the Northern Hemisphere). Eventually the currents flow steadily along the contour lines, with the water surface sloping upward to the right as one looks in the direction of flow. In practice, of course, internal eddy-stresses within the ocean and the winds blowing across the sea surface modify this trend. But the general rule still holds.

Lest the reader mistakenly conclude that he should have spotted these oceanic hills and valleys on his last sea voyage, it should be mentioned that the total difference of mean height across even the fastest-moving parts of the Gulf Stream system is only about a foot and a half in some eighty or ninety miles. Even this modest slope is only partly due to Coriolis effects, the remainder resulting from the sort of horizontal density gradients we have agreed to overlook. Yet, slight as such surface slopes may be, they constitute a major factor in the dynamics of the ocean currents.

People on the Pacific Coast are well acquainted with certain other consequences of the Coriolis acceleration, though not many realize this is the cause. Coriolis drift is mainly responsible for the notorious California fogs and coldness of the water on California's beaches. Off the California coast, where the prevailing winds are from the northwest, the wind stress and Coriolis drift generally combine to make the coastal waters sidle off in a southwesterly direction. As water is transported away from the shore toward the southwest, the deficit must be made up somehow. The water moving offshore is replaced by water rising from below. This upwelling brings up water from cold strata lying at depths as great as several hundred feet. As a result there is a cool strip of water along the California coast, superimposed, in fact, on the already cool California Current flowing down from the north. In summer the warm moist Pacific air streaming in from the northwest is cooled by the coastal water and this is what forms the fogs for which California regrets to be famous. A similar situation prevails off the coast of Peru and parts of the western coast of Africa.

Some geologists believe the Coriolis effect causes a river to erode one of its banks faster than the other. The Russian scientists P. A. Slavsov and Karl von Baer reported that river valleys in Siberia tend to have steep walls on their left side. Similar asymmetries have been observed in some Alaskan rivers, in the Missouri River and in a number of streams on Long Island. This supposed effect of the Coriolis drift is sometimes called Baer's law. But students of the effect have not all been willing to attribute it to the Coriolis influence. Even in a river a mile wide flowing at the fast rate of five miles per hour in middle latitudes of the Northern Hemisphere, the Coriolis drift to the right would pile up the water only a little more than one inch higher at the right bank than at the left bank. Possibly such a slight difference in height might cause significant differences in erosion over geological periods of time, but the question is still unsettled.

This is as good a place as any to correct the persistent misconception that the Coriolis acceleration causes the water to run out of a washbowl in a clockwise direction in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The Coriolis influence is so small at the velocity of water in a washbowl, the time involved is so short and other factors are so numerous (hands, noncircular bowl-shapes, and so on) that one may feel sure the Coriolis effect is never in control here. This is regrettable, because if it were, a washbowl would constitute a useful analogue of a cyclone in the atmosphere.

We shall consider one more possible case of a Coriolis effect. There is a theory that some birds may be guided in their migrations by sensitivity to the Coriolis acceleration and to geomagnetic latitude. H. L. Yeagley of Pennsylvania State College has recently studied this amazing theory in an effort to determine the navigating techniques of the homing pigeon.

When a bird flies at constant ground speed in the Northern Hemisphere, its Coriolis acceleration toward the right grows greater the farther north it flies. Yeagley suggests that if, through some delicate sensory organ, the bird can detect slight differences in this acceleration, and can combine this information with an accurate estimate of its ground speed; it may be able to sense its geographical latitude. If, at the same time, another sensory organ with the necessary electrical properties senses differences in the minute electromotive forces generated by virtue of the bird's motion through the earth's magnetic field, then this plus the bird's estimate of its speed would provide a basis for sensing geomagnetic latitude. Now, since the magnetic poles of the earth are displaced some twenty degrees from the geographical poles, the parallels of geomagnetic latitude form a grid with the parallels of geographical latitude, and with this grid it is theoretically possible to navigate.

Most physicists would regard the theory as of very low *a priori* plausibility. Even assuming that a bird's senses are so delicate that it can detect the tiny differences in Coriolis acceleration and magnetic field, these cannot be translated into latitude until the bird has compared each effect with a very precise estimate of its ground speed. Furthermore, the bird must somehow allow for the effect of cross-winds, which is normally much greater than the Coriolis drift. As if this were not enough, the bird would have to defy relativity theory, which says that it could not distinguish the effects of the normal atmospheric electric field from those induced by the bird's motion through the earth's magnetic field. Yet despite these difficulties, certain features of Yeagley's theory seem to have been borne out by his extensive studies with homing pigeons.

If further research should confirm the magnetic-Coriolis theory of bird navigation, the solution of this deep mystery of the animal world will be rather more astonishing than the original mystery. It would certainly be startling to learn that this effect has been used by generations of golden plovers and Arctic terns to hold true to their courses as they fly over thousands of miles of trackless oceans.

Whether the birds are really that clever or not, we may be quite sure that they inexorably tend to drift as they fly. All things that move over the surface of our spinning earth, whether birds, winds, rivers, ocean currents, explorers, cars, trains, bullets, or rockets, are inevitably subjected to this effect as we view them in our terrestrial co-ordinate systems. Even when man gets away from his planetary home and stakes out better-behaved co-ordinate systems in interplanetary space, he will not be able to omit consideration of the Coriolis effect from his dynamics. For the solar system itself, along with all its near neighbors, is slowly but surely rotating around the hub of our galaxy, some 30,000 light-years away. Undoubtedly a precise analysis of the waddling of Antarctic penguins would show not only Coriolis effects due to the earth's circumpolar rotation, and similar but smaller effects due to our planet's annual circuit around the sun, but also a tiny Coriolis drift due to the stately whirl of our solar system about the center of the galaxy.

Here we find ourselves in somewhat the same situation as Archimedes with his earth-moving lever—all *we* need to demonstrate our point is a suitable co-ordinate system.

JOSEPH BERNSTEIN

Tsunamis

There are few natural catastrophes more terrifying than "tsunamis" or, as they are better though incorrectly known, "tidal waves." (Tidal waves are caused by subsea earthquakes and have nothing to do with tides.) Since shortly after World War II, tidal waves have been subjected to close study by oceanographers. In this article, Joseph Bernstein of the U. S. Navy Hydrographic Office tells what has been learned and how a start has been made toward devising a warning system to prevent disasters such as befell the Hawaiian Islands one day in May, 1946. The article is reprinted by permission of the publisher from the *Scientific American*, August, 1954 (Vol. 191, No. 2).

On the morning of April 1, 1946, residents of the Hawaiian Islands awoke to an astonishing scene. In the town of Hilo almost every house on the side of the main street facing Hilo Bay was smashed against the buildings on the other side. At the Wailuku River a steel span of the railroad bridge had been torn from its foundations and tossed 300 yards upstream. Heavy masses of coral, up to four feet wide, were strewn on the beaches. Enormous sections of rock, weighing several tons, had been wrenched from the bottom of the sea and thrown onto reefs. Houses were overturned, railroad tracks ripped from their roadbeds, coastal highways buried, beaches washed away. The waters off the islands were dotted with floating houses, debris and people. The catastrophe, stealing upon Hawaii suddenly and totally unexpectedly, cost the islands 159 lives and $25,000,000 in property damage.

Its cause was the pheonomenon commonly known as a