The Coriolis force and drifting icebergs (Coriolis Part 6)

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"Man wants to know, and when he ceases to do so, he is no longer man."
(Fridtjof Nansen, on the reasons for polar expeditions, Mackay 1991, p. 179)

When Norway was relieved of its unhappy union with Sweden in 1905, it could for the first time appoint its own ambassadors. The man chosen for the United Kingdom was a man of extraordinary intellectual power and moral stature. Fridtjof Nansen (1861–1930), nowadays mostly remembered as an explorer, statesman and humanitarian, was also an ardent scientist in biology, zoology and oceanography. In his youth he had already taken part in voyages into the Arctic regions and Greenland. It was during one of these expeditions that he made a discovery that would have a great impact on oceanography and meteorology.

Drifting icebergs

In August 1893, when he was only 32, Nansen made an epic journey around the Arctic Ocean on a specially strengthened ship which he allowed to freeze into the ice pack. It was carried by the currents to reach 86°13′N, 415 km from the pole – further north than anybody had been before (Walker 1991a, p. 106). When Nansen came back to Norway in 1896 he started to analyse the material he had gathered and the observations he had made. Nansen regularly took advice on the interpretation of the oceanographic observations from another Norwegian, Vilhelm Bjerknes (1862–1951), then a professor at Stockholm University. Nansen's first question dealt with the mysterious dead-water phenomenon; ships would suddenly become stuck in a fjord or bay and lose response to steering. Bjerknes suggested, following Nansen's insight, that internal waves, formed on the boundary surface separating strata of different densities, accounted for the effect. One of Bjerknes's students, Walfrid Ekman, laid out the mathematics which proved Bjerknes's theory (Gill 1982, p. 123; Friedman 1989, p. 42; Walker 1991b, p. 158).

In autumn 1901, while visiting Stockholm, Nansen posed another problem for Bjerknes. He had noted that both his ship and the free-floating ice drifted at an angle between 20 and 40° to the right of the prevailing wind. Nansen was not the first to observe this; it belonged to the experiences of seafarers in Arctic waters since time began. Like them, Nansen was puzzled, in particular since the leading oceanographic expert of the time, Karl Zöppritz, held that the drift should be in the direction of the wind. While the ship was slowly making its way through the ice pack there had been plenty of time for Nansen to reflect on these phenomena. The explanation that he eventually settled for was that the deflection was due to the earth's rotation. He also suggested that because sub-surface layers of water are set in motion from above (through the agency of internal friction), and are themselves affected by the Coriolis force, water must deviate progressively to the right as depth increases. In his opinion, "the angle of deviation will increase with depth until, at a certain depth, it is 90°, and at twice that depth 180°".

Ekman spirals

Bjerknes again called on Ekman who, in a matter of hours, had produced a preliminary solution which vindicated Nansen's hypothesis. He could also show that the downward turning of the currrent was along an inward, clockwise spiral (Ekman 1905). Nansen, Bjerknes and Ekman thus realised that the Coriolis force guides the flow not only of the atmosphere, but also of the oceans. Due to the earth's rotation, Nansen said, "the wind's power to produce currents is limited, and the effect cannot possibly reach the greatest depths, as stated by Zöppritz, except at the Equator" (Walker 1991b, p. 160). This is another consequence of the Coriolis force's tendency to resist all displacements.

East coast snow showers

Ekman went on to show that the same process is also at work in the atmosphere, but in an opposite way. Whereas in the sea it is the wind above the surface that provides the momentum, in the atmosphere it is the uneven surface of the earth that extracts momentum from the air. When the wind weakens, the Coriolis force also weakens, and the pressure gradient force drives the air towards lower pressure. Through internal friction (viscosity) the next air layer above will 'feel' this change in the wind and also be deflected. This layer will in turn 'rub' on the next layer above, and so on.

This 'Ekman effect' has many interesting consequences, for example for exposed east coasts such as the regions east of Norwich in England and Stockholm in Sweden. In wintertime at sea, northerly winds are often associated with showers when the cold air comes in over warmer water and becomes thermally unstable. Over the sea, where the friction is low, the wind is nearly geostrophic in direction and strength. Over the land, the Ekman effect makes the wind turn towards lower pressure, which for eastern coastal areas is towards the sea. The convergence along the coastline of the winds over the sea and the air coming from the land leads to an intensification of strong and persistent snow showers. At the same time, warmer surface water out in the sea might, due to the Ekman pumping, be driven closer to the land, contributing to the heating from below and thus further intensifying the convective conditions (Fig. 1).

With southerly winds the Ekman effect will be inverted. It will now contribute to a wind divergence along the coastline, with sinking motions and cloudless conditions. The water nearest the coast will be 'pumped' out to sea and replaced by colder water from below. This colder water surface will make it more difficult for convection to start and thus further stabilise the air.

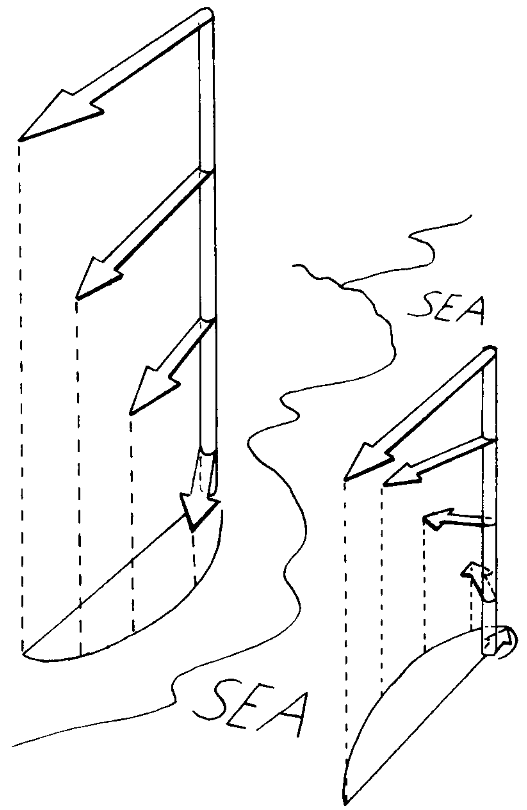

Fig. 1 Schematic illustration of Ekman spirals in the atmosphere and oceans, curving in different direction

Ekman pumping

The deflection of water sideways relative to the steering wind, the so-called 'Ekman pumping', has important consequences for the dynamics of the oceans. Over the equatorial Pacific the steady trade winds from the east drive the surface water towards the west. Although the Coriolis force is weak close to the equator, it has an accumulated deflective effect on the water due to the steadiness of the driving wind, and deflects the surface water away from both sides of the equator. This leads to an outflow of surface water which causes an upwelling of colder water from deeper layers to the sea surface.

This is seen in the sea surface temperature as a narrow strip along the equator (Fig. 2).

Drifting in the ocean

There is more to the story about drifting icebergs in the Arctic – something that will eventually lead us to a fresh way of looking at atmospheric motions. Let us look more closely at their day-to-day movement. It is controlled by their size and shape, the previous and present wind, surface wind current, and general ocean current. Winged icebergs, those with sail-like pinnacles around the central mass, are particularly influenced by the winds.

The momentum of icebergs is so great that once in motion they continue for long after the wind has subsided. This inertial motion will be picked up by the Coriolis force and the iceberg will be driven into an inertia circle which is then carried forward by the basic ocean current. Such an inertial oscillation can last for about a week if the wind remains weak. A typical period for inertial oscillations at polar latitudes is 14 hours. So it is not uncommon, but still highly surprising, to see an iceberg, around seven hours after the wind has abated, moving in a direction opposite to which the wind is blowing.

Cycloid curves

An inertia circle carried forward by a basic current – a motion which is a combination of rotation and translation – follows a geometric curve which is called a cycloid.* It can be constructed by the locus of a point, attached to a circle, that rolls along a straight line. If the point is on the circle, the curve is an ordinary cycloid (Fig. 3(a)); if it is fixed outside, it is an extended cycloid (Fig. 3(b)); and if it is inside the circle, it is a contracted cycloid (Fig. 3(c)).

Another, and for our purpose more convenient, distinction between different cycloids is the relationship between the tangential speed of the rotating point and the translative speed of the circle. Extended cycloids result when the tangential speed of the rotation is larger than the translating speed, ordinary cycloids when the speeds are the same, and contracted cycloids when the tangential speed is less than the translative. The maximum speed is always at the top of the cycloid, where the tangential speed is in the same direction as the translative, and the minimum speed at the bottom, where the tangential speed is in the opposite direction to the translative. Where the circle touches the line, the speed is zero for an ordinary cycloid, and negative for an extended cycloid, *i.e.* the curve will make retrograde loops in which the point temporarily moves in the opposite direction.†

Cycloids in the oceans

Cycloids are commonly observed in the atmospheric and oceanic circulation. We have already encountered the extended cycloid in the previous article when we considered wind trajectories in a moving cyclonic circulation (Persson 2001, Fig. 5). It is the path which not only drifting icebergs will follow but also large parts of the world's oceans.‡ During a period of strong winds, the whole upper layer of the ocean will be set in motion. If the wind suddenly weakens, these water layers will continue to move in the direction in which they were moving when the wind ceased. This motion will become affected by the Coriolis force and forced into a circular motion, overlying the general ocean current.

Cycloid motions can therefore be seen in the daily monitoring of oceanographic buoys, reflecting the oscillations of the ocean surface after a storm. Depending on the strength of the ocean current and the wind-induced motion, the path can be an extended, ordinary, or a

* A more general name is trochoid. The literature (and the Internet) is full of interesting texts about these fascinating geometrical figures, which have strong links to natural phenomena – for example the shape of ocean waves (Kinsman 1965, p. 242).

† This helps us to answer the old catch question: "Which parts of a train in full speed, are, at one moment, moving backwards?" The answer is those portions of the bottom of every wheel which are just below the surface of the rail.

‡ See Sverdrup *et al.* (1942, p. 438), Gill (1982, p. 254) for a classic picture of a drifting buoy following extended cycloids in the Baltic Sea in summer 1933.

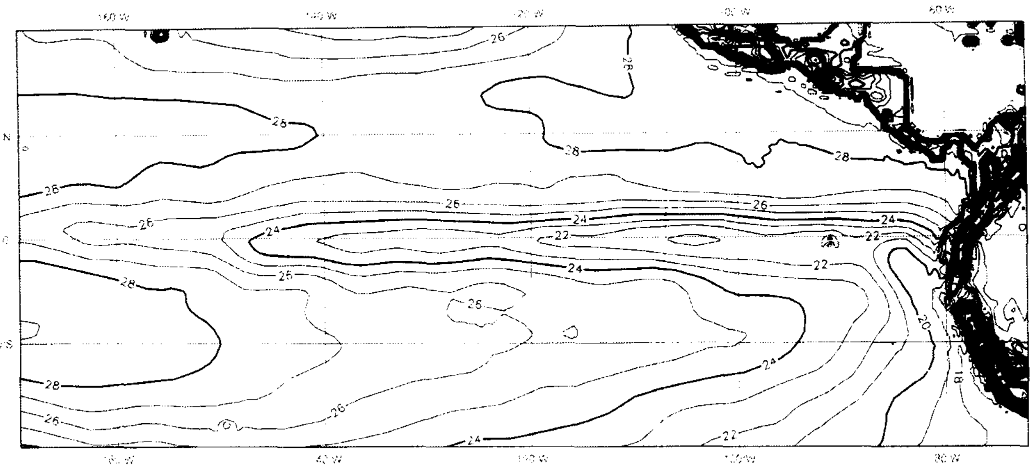

Fig. 2 Mean sea surface temperatures (°C) in the eastern part of the Pacific Ocean, 5 September–5 October 1998

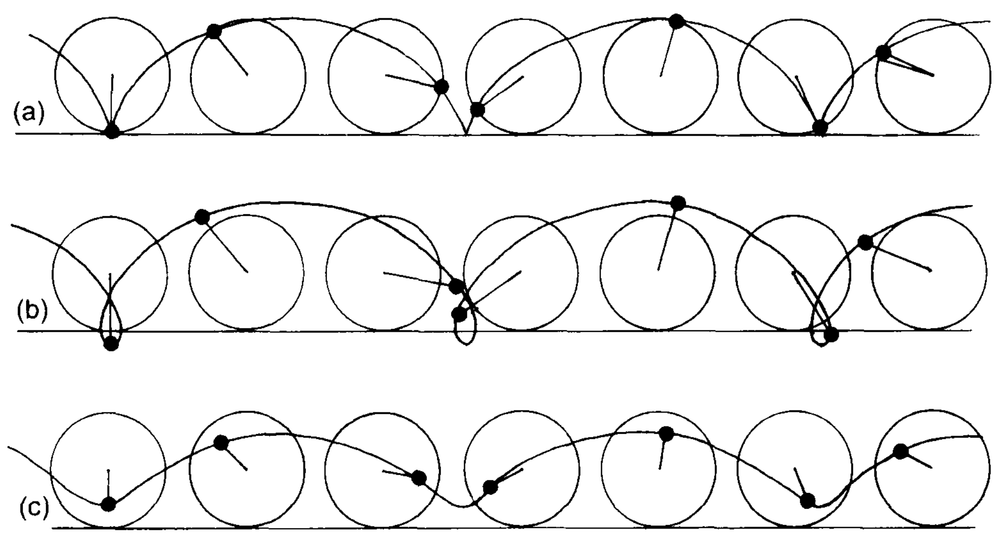

Fig. 3 (a) An ordinary cycloid, (b) an extended cycloid and (c) a contracted cycloid

contracted cycloid. The reports of the positions of these buoys are given to an accuracy of 0.1°. This cannot resolve the small radii of inertia oscillations at high latitudes. Since there are no oscillations at the equator, the best 'hunting ground' seems to be between 5 and 20° latitude.

My colleague, Antonio Garcia-Mendez at the European Centre for Medium-Range Weather Forecasts, who, among other things, monitors the global network of drifting buoys, helped me to find several interesting cases. One of these was 23 589, an automatic buoy drifting westwards in the south Indian Ocean towards Madagascar during April 2000 with an overall speed of about 0.4 m s^{-1} (Fig. 4(a)). On 19 April the buoy came under the influence of tropical storm *Innocente*. The wind rose to 10 m s^{-1} from the south-east, but during 20 April weakened to 3–4 m s^{-1}. This sudden wind change threw the upper layers of the ocean into inertia oscillations. These are reflected in the trajectory of the buoy (Fig. 4(b)). Over the 8-day period 20–27 April the buoy performed five inertial oscillations, with an average period of 1.6 days. This agrees well with what could

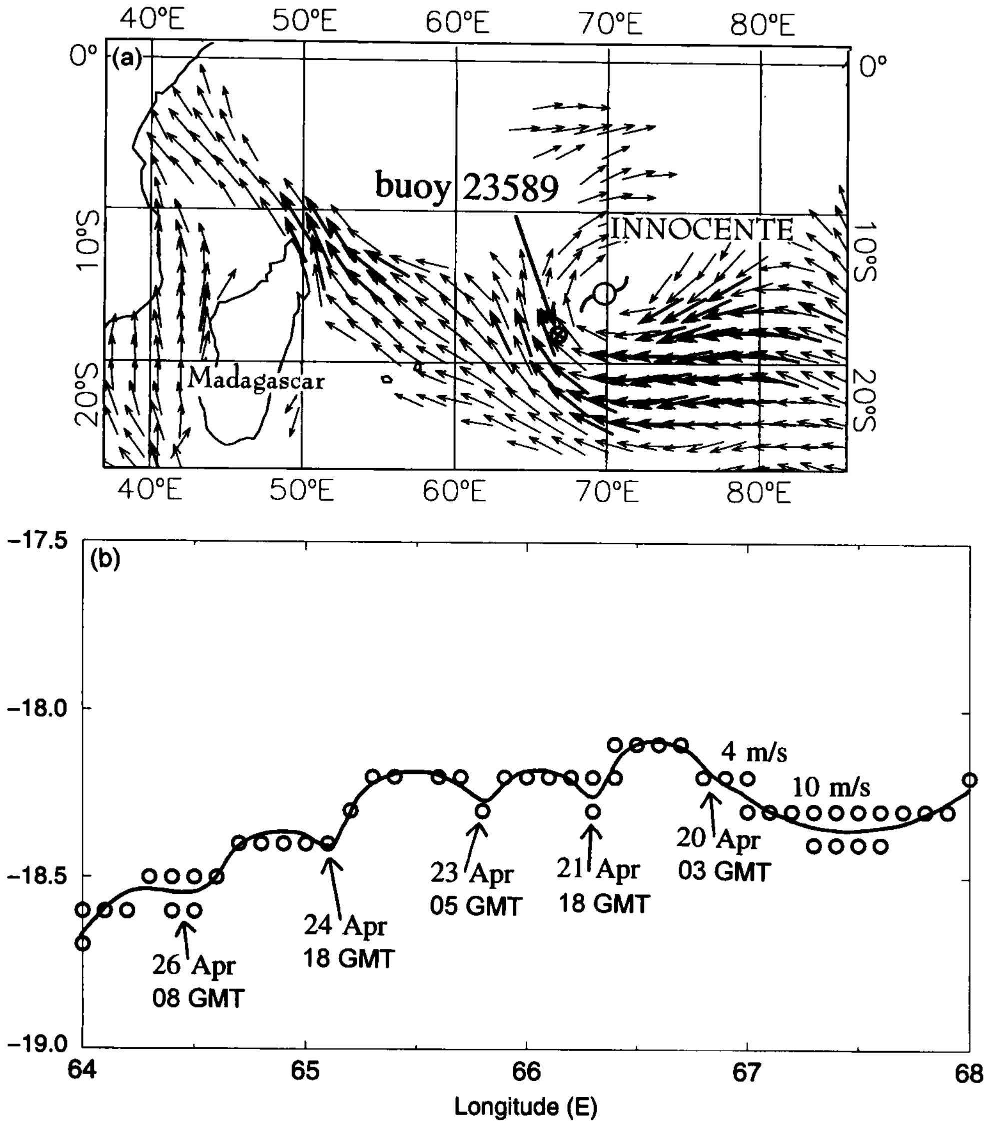

Fig. 4 (a) Position of automatic buoy 23 589 on 19 April 2000 and corresponding 10 m winds: thin arrows 5–7 m s^{-1}, thick arrows >8 m s^{-1}. On this day the buoy was caught up by a weakening tropical storm, Innocente, *approaching from the east. The strengthening southerly winds threw the upper layers of the ocean and the buoy into a north-westward motion. (b) Positions of automatic buoy 23 589 over the period 20–27 April 2000, after the upper layers of the ocean had been set into inertial motion on 19 April. The trajectory of the buoy shows clear contracted cycloidal inertial oscillations with a period of about 1½ days.*

have been expected. At 18–19°S the Coriolis parameter, f, is around $-0.46 \times 10^{-4}\,s^{-1}$ which yields a period of the inertia oscillation (half a pendulum day) of almost 1.6 days.

This section has been mostly about the Coriolis force in the oceans. In order not to support the opinion, occasionally expressed by my meteorological colleagues, that the Coriolis force is more important for oceanographers than meteorologists, in the next paper we will return to the atmosphere and meet cycloids in rather unexpected circumstances. When night falls, large increases in wind can occur some 100 m above the ground, affecting late-night thunderstorms, bird migration and the spread of pollution.

Acknowledgement

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Winter shamals in Qatar, Arabian Gulf

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The state of Qatar is an independent Arab state located on the western coast of the Arabian Gulf. It is a peninsula, covering an area of 11 437 km^2, that extends northwards into the Gulf for about 160 km and has a maximum width of 88 km. At the western neck of the peninsula, Qatar abuts Saudi Arabia, and to the east the United Arab Emirates (Fig. 1). The landscape of the country is generally flat and low-lying, with desert climatic conditions. The mean annual rainfall for Doha is only 75.6 mm. A brief summary of a few climatic elements is presented in Table 1. The data presented in this table are based on observations taken at Doha International Airport (25°15′N, 51°34′E; 11 m above sea-level) for the period 1962–90.

'Shamal', an Arabic word meaning 'north', is the name given to seasonal north-westerly/northerly winds with higher than normal strength. These winds occur during both winter and summer, due to synoptically driven systems, but with different characteristics. The summer shamal generally occurs with little interruption from early June to mid-July. Its occurrence is associated with the relative strengths of the Indian and Arabian thermal lows, and it is less significant than the winter shamal in terms of wind strength and accompanying weather conditions. The winter shamal, which occurs mainly from November to March, is associated with mid-latitude disturbances that progress from west to east. It occurs following cold frontal passages and is characterised by a shorter duration than summer shamals, but is frequently associated with adverse weather conditions such as thunderstorms, turbulence, temperature drop, high seas, etc. Summer shamals, being free from frontal wave disturbances, are not associated with any weather except dust haze causing poor visibility. Summer shamals have been relatively well studied in recent years (Membery 1983; Ali 1992, 1994; Hatwar *et al.* 1999).

Perrone (1979) made a detailed study of the