Ocean MASTERCLASS

UNIT 5

Wind-Driven Currents and the Great Gyres

How the wind and the rotation of the Earth drive the great current loops of every ocean



Image: NASA Goddard Space Flight Center Scientific Visualization Studio

By the end of this unit, I should be able to answer these questions:

- Why does a steady wind in the Northern Hemisphere push the surface water to the right of its direction, and the wind-driven layer as a whole at right angles to it?
- Why is the sea surface in the middle of the North Atlantic about a metre higher than at its edges, and how does a satellite measure that to the centimetre?
- Why are the currents on the western side of every ocean basin, such as the Gulf Stream and the Kuroshio, narrow and fast, while those on the eastern side are broad and slow?
- How much water does the Gulf Stream carry past Cape Hatteras, and how does that compare with all the rivers on Earth?
- How did 28,800 plastic bath toys lost in the North Pacific in 1992 help oceanographers check their model of the surface currents?
- Why does floating plastic collect in the centres of the subtropical gyres and not along the coasts where it entered the sea?

A sailor who has crossed the North Atlantic knows that the water itself moves. Off Florida it runs north at the pace of a brisk walk, and a ship bound for Europe gains a day by riding it; off Portugal it drifts slowly south, and a ship bound for the Caribbean gains by following it. Between the two lies a loop of currents the size of a continent; every other ocean basin holds a loop like it, and this unit explains where the loops come from. The wind sets the surface in motion, the rotation of the Earth turns that motion sideways, water piles up in the middle of each basin, and the pile drives the currents around it. The same reasoning explains why the Gulf Stream is narrow and fast while its counterpart on the other side of the Atlantic is broad and slow, and why a plastic bottle dropped into the sea off Japan is more likely to end up in the middle of the Pacific than on a beach.

1 The wind on the water

When wind blows over the sea, it drags the surface along. The air rubs on the water, small waves roughen the surface and give the air more to push against, and the top layer of water begins to move. Oceanographers measure this push as the **wind stress**, the force that the wind exerts on each square metre of the sea surface, written as the vector $\vec{\tau}$ because it has a direction as well as a size. Its unit of measurement is the newton per square metre, which is the pascal, the same unit as pressure, but the stress acts along the surface rather than down into it. It cannot be measured directly over the open sea, so it is computed from the wind speed with a relation found by comparing careful measurements of both.

KEY EQUATION Wind stress

$$\tau = \rho_{\text{air}}\, C_D\, U_{10}^2$$

The wind stress τ on the sea surface grows with the square of the wind speed U_{10} measured 10 m above the water, where $\rho_{\text{air}} \approx 1.22\,\text{kg m}^{-3}$ is the density of the air and C_D is the **drag coefficient**, a pure number without a unit, about 1.3×10^{-3} for moderate winds. The relation is called the bulk formula for the wind stress; C_D is a value found by measurement rather than a constant of nature, and it rises to about 2×10^{-3} in gales, when the sea is rough.

Because the wind speed enters squared, a wind twice as strong pushes four times as hard. For example, a wind of $10\,\text{m s}^{-1}$, which sailors call a fresh breeze, gives a stress of $1.22 \times 1.3 \times 10^{-3} \times 100 = 0.16\,\text{N m}^{-2}$, which is the weight of 16 grams spread over a square metre. Spread over an area the size of a football pitch, about 7,000 square metres, the fresh breeze pushes with a force of 1,100 N, which is the weight of a heavy adult. The wind blows for days over thousands of kilometres, and the push adds up. The steady trade winds exert a stress of about 0.05 to $0.1\,\text{N m}^{-2}$ over the tropical oceans all year round, and the westerlies of the Southern Ocean reach 0.2 to $0.3\,\text{N m}^{-2}$.

Measurements with drifting buoys show that the water at the very surface moves at roughly 2 to 3 per cent of the wind speed, so a fresh breeze drives a surface drift of 20 to 30 centimetres per second. What surprised the first people who measured it carefully was the direction. During his Arctic drift of 1893 to 1896, which the excursion in Section 3 describes, Fridtjof Nansen (1861-1930) noticed that the sea ice around his ship moved 20 to 40 degrees to the right of the wind. Water under a steady wind does the same. The reason is the rotation of the Earth, and before the wind-driven currents can be understood, that reason has to be made precise.

2 The Coriolis effect

Unit 4 stated the rule as a principle: seen from the rotating Earth, anything that moves freely over large distances is deflected to the right of its direction of motion in the Northern Hemisphere and to the left in the Southern Hemisphere. Unit 4 also explained one case: air that moves toward the equator falls behind the ground, which moves faster toward the east there, and this turns the trade winds. The same rule applies to water, and this unit needs it as a number.

Figure 1 shows the cleanest way to see the deflection. A ball is rolled outward from the centre of a turntable that turns anticlockwise, which is how the Northern Hemisphere turns when seen from above the North Pole. Someone standing in the room sees the ball roll in a straight line, because no force acts on it sideways. Someone riding on the turntable sees the floor turn underneath the ball, and from their point of view the ball curves to the right. Nothing pushed it; the curve appears because the rider's floor, which is the frame in which the motion is described, is itself turning. On the Earth we are all riders, and we describe the motion of the sea relative to the turning ground, so the water appears deflected. The deflection has the same size whichever way the ball moves, and it applies to motion toward the east or west as well. A **parcel** of water, which is the small body of water that oceanographers follow as if it moved as one piece, circles the Earth's axis faster than the ground beneath it when it moves eastward, so it is flung slightly outward from the axis, like a passenger on a roundabout. At mid-latitudes, outward from the axis means partly upward and partly toward the equator, and toward the equator is to the right of an eastward motion.

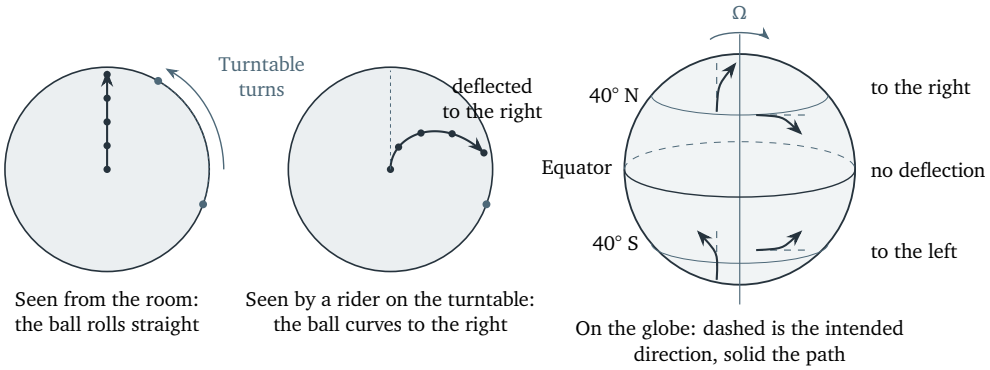


Figure 1. Left and middle: a ball rolled from the centre of a turntable that turns anticlockwise moves in a straight line for an observer in the room and curves to the right for an observer riding on the turntable; the grey dot on the rim marks the same spot on the turntable in both views. Right: on the rotating Earth, free motion is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, and not at all on the equator. Dashed arrows show where each parcel was heading, solid arrows the path it follows.

The size of the effect was worked out by Gaspard-Gustave de Coriolis (1792-1843) in 1835 for machines with rotating parts, long before anyone applied it to the sea. For motion along the Earth's surface, the result is an acceleration at right angles to the velocity whose size is the speed of the motion multiplied by a number that depends only on the latitude.

KEY EQUATION The Coriolis parameter

$$f = 2\,\Omega\,\sin\varphi, \qquad a_C = f\,v, \qquad T_i = \frac{2\pi}{|f|}$$

The **Coriolis parameter** f at latitude φ is twice the rotation rate of the Earth, $\Omega = 7.29\times10^{-5}\ \mathrm{rad\,s^{-1}}$ (one turn in 23 hours and 56 minutes), multiplied by the sine of the latitude. A parcel moving at speed v is deflected sideways with the acceleration $a_C = fv$, to the right of its motion where f is positive (Northern Hemisphere) and to the left where it is negative (Southern Hemisphere). Left alone, the parcel goes round a full circle in the **inertial period** T_i, so called because nothing but the parcel's own inertia and the turning Earth is involved. At the equator $f = 0$, at 43° of latitude $f = 1.0\times10^{-4}\ \mathrm{s^{-1}}$, and at the poles $1.46\times10^{-4}\ \mathrm{s^{-1}}$.

Two things about this acceleration decide the rest of the unit. First, it is tiny: a current of $0.2\ \mathrm{m\,s^{-1}}$ at 45° N feels $a_C = 1.03\times10^{-4}\times0.2 = 2\times10^{-5}\ \mathrm{m\,s^{-2}}$, which is only two millionths of the acceleration of gravity, and that is why nobody notices it when draining a bath, whatever the popular story says. Second, it never stops, and a sideways push that lasts a day turns even a slow current right round, so any motion in the sea that lasts longer than a few hours has to be described with f in the equations. The deflection is often called the Coriolis force, and this unit uses that name when it sets forces against each other, but no agent pushes the water; the force appears only because we measure motion against a turning Earth.

WORKED EXAMPLE How long a parcel of water takes to turn a circle

Suppose a storm has set the surface water at 45° N moving at $0.2\ \mathrm{m\,s^{-1}}$ and then dies away, so that the water is left alone with the Coriolis acceleration. How long does it take to come round in a circle, and how big is the circle? At 45° N,

$$f = 2\times7.29\times10^{-5}\ \mathrm{s^{-1}}\times\sin45^\circ = 1.03\times10^{-4}\ \mathrm{s^{-1}},$$

and the inertial period is $T_i = 2\pi/f = 6.1\times10^4$ s, which is 17 hours. A parcel that goes round a circle of radius r at speed v has the acceleration v^2/r toward the centre (the centripetal acceleration of circular motion), and here that acceleration is supplied by fv, so $r = v/f = 0.2/(1.03\times10^{-4}) = 1{,}900$ m. At

10° N the Coriolis parameter is only $2.5 \times 10^{-5}\ \mathrm{s}^{-1}$, the period is 69 hours, almost three days, and the circle has a radius of 8 km. These inertial oscillations really exist: after a storm, current meters on a mooring, an instrument line anchored to the sea floor, record the water going round at exactly the inertial period of their latitude for several days, until friction wears the motion down.

CHECK YOUR UNDERSTANDING Question 1

At which latitude is the Coriolis parameter f exactly half of its value at the pole?

(A) 15°
(B) 30°
(C) 45°
(D) 60°

The solution is at the end of the unit.

3 Ekman's answer

Nansen's observation that ice drifts to the right of the wind went to a physicist, and the physicist's answer became the first equation of ocean dynamics.

EXCURSION ***The drift of the* Fram *and a doctoral student's answer***

Wreckage from the American ship *Jeannette*, crushed by the ice north of Siberia in 1881, had turned up on the coast of Greenland three years later, and Nansen concluded that the Arctic ice drifts across the polar basin toward the Atlantic and that a ship frozen into it would drift the same way. He had the *Fram* built with a rounded hull that the ice would lift rather than crush, sailed her to the New Siberian Islands, and let her freeze in at the end of September 1893. She drifted for almost three years, and the ice released her north of Spitsbergen on 13 August 1896.

One of Nansen's many measurements puzzled him, because the ice drifted 20 to 40 degrees to the right of the wind. He guessed the reason: the Earth's rotation deflects the ice, the ice drags the water below it, and each layer below moves a little more to the right and a little more slowly than the one above. Unable to work out the mathematics himself, he put the problem to the Norwegian physicist Vilhelm Bjerknes (1862-1951), who passed it to a student of his, Vagn Walfrid Ekman (1874-1954). Ekman made it the subject of his doctoral thesis, defended at Uppsala in 1902, and published the full theory in 1905 under the title "On the influence of the Earth's rotation on ocean-currents".

Ekman considered the simplest possible case: a steady wind blowing over a deep ocean of uniform density, far from any coast, in which each layer of water drags the layer below it with a friction that is the same at every depth. He asked what steady flow results when the wind stress at the top, the friction between the layers, and the Coriolis force on every layer are in balance. The answer is in Figure 2 and in the following principles.

PRINCIPLES Ekman's principles of the wind-driven layer

1. The surface current flows at an angle of 45° to the right of the wind in the Northern Hemisphere (to the left in the Southern Hemisphere).
2. With increasing depth the current turns further to the right and becomes weaker, so that the

tips of the current arrows trace a spiral, the **Ekman spiral**. At the **Ekman depth** D_E the current points opposite to the surface current and has fallen to about one twentieth of its surface value; the wind-driven layer is, in practice, this deep.

3. The water transported by the whole layer, added up from the surface to the Ekman depth, moves at exactly 90° to the right of the wind (to the left in the Southern Hemisphere). This is the **Ekman transport**.
4. The Ekman transport depends only on the wind stress, the density of the water, and the Coriolis parameter; the friction between the layers decides how deep the spiral reaches and how fast the surface moves, but not how much water is carried sideways.

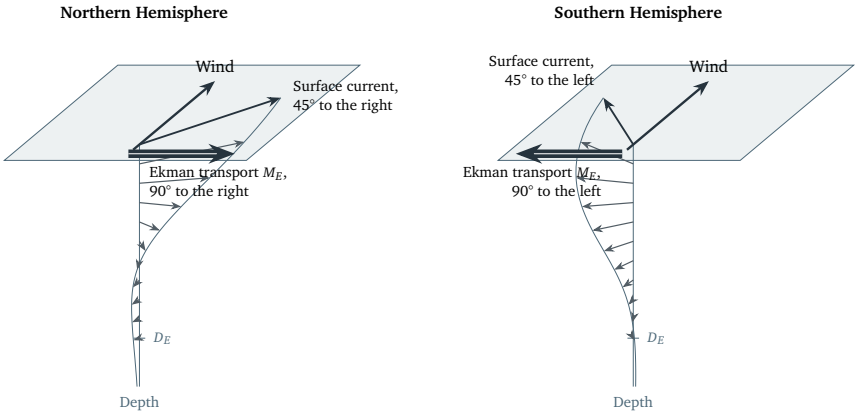


Figure 2. The Ekman spiral for a wind blowing toward the top of the page, drawn from Ekman's solution. Each arrow is the current at one depth, from the surface down to the Ekman depth D_E in steps of one tenth of D_E; the grey curve joins their tips. The surface current is turned 45° from the wind, the deeper currents are turned further and are weaker, and the transport of the whole layer (the thick arrow on the surface plane) is at right angles to the wind. The Southern Hemisphere is the mirror image.

The third principle is the one that matters most, and it can be understood without the spiral. Take the whole wind-driven layer as one slab of water. The wind pushes the slab along the wind direction. The slab moves, so the Coriolis force acts on it, at right angles to its motion. In a steady state the two must cancel, which fixes both the direction and the amount of the motion.

DERIVATION The Ekman transport from a balance of two forces

Consider a column of the wind-driven layer standing on one square metre of sea surface, of depth D_E and density ρ, so its mass is ρD_E. The wind stress τ pushes on its top with the force τ (a stress is a force per square metre, and the column has a top of one square metre). Below the Ekman depth the water is at rest and exerts no friction, and the layers inside the column only pass momentum among themselves, so the only other force on the column as a whole is the Coriolis force. If the column moves with the mean velocity $\bar{v}$, that force has the size $\rho D_E f \bar{v}$, which is its mass times the Coriolis acceleration, and it points at right angles to $\bar{v}$, to the right in the Northern Hemisphere.

For the two forces to cancel, the Coriolis force must point against the wind, so $\bar{v}$ must point in the one direction whose right-hand side is against the wind, which is 90° to the right of the wind. Equating the sizes gives $\rho D_E f \bar{v} = \tau$, and the volume of water that crosses a line one metre wide each second is $D_E \bar{v}$, so

$$M_E = D_E \, \bar{v} = \frac{\tau}{\rho f}.$$

The depth D_E and the mean speed $\bar{v}$ have cancelled out of the product, which is the content of the fourth principle. The spiral itself follows from working out the friction between the layers, which goes beyond this unit; its result is $D_E = \pi\sqrt{2A_z/|f|}$, where A_z is the friction coefficient between the layers (the eddy viscosity). For a typical value of $A_z = 0.01\,\mathrm{m^2\,s^{-1}}$ and $f = 10^{-4}\,\mathrm{s^{-1}}$ this gives $D_E = 44\,\mathrm{m}$.

KEY EQUATION The Ekman transport

$$M_E = \frac{\tau}{\rho f}$$

The volume of water carried by the wind-driven layer across each metre of a line at right angles to its motion, in $\mathrm{m^2\,s^{-1}}$, equals the wind stress τ divided by the density of seawater ρ and the Coriolis parameter f. The transport is directed 90° to the right of the wind in the Northern Hemisphere and 90° to the left in the Southern Hemisphere. It holds for a steady wind over deep water away from the equator, where f is too small for the balance to form; multiplied by the length of a line in metres it gives a transport in cubic metres per second.

WORKED EXAMPLE A fresh breeze at 30° N

A wind of $U_{10} = 10\,\mathrm{m\,s^{-1}}$ blows steadily toward the west over the subtropical Atlantic at 30° N, near the northern edge of the trade winds, which blow this way along the whole southern side of the gyre. How much water does it move, and where to? The stress, from the bulk formula with $\rho_{\mathrm{air}} = 1.22\,\mathrm{kg\,m^{-3}}$ and $C_D = 1.3 \times 10^{-3}$, is

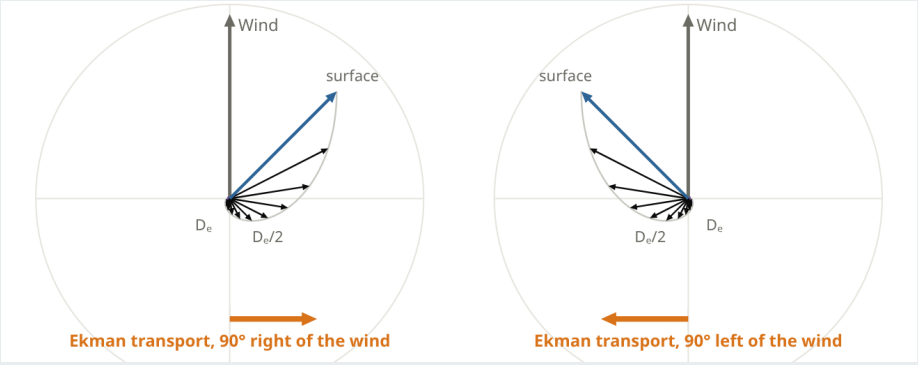
$$\tau = 1.22 \times 1.3 \times 10^{-3} \times 10^{2} = 0.159\,\mathrm{N\,m^{-2}}.$$

At 30° N the Coriolis parameter is $f = 2\Omega \sin 30° = \Omega = 7.29 \times 10^{-5}\,\mathrm{s^{-1}}$, and with $\rho = 1{,}025\,\mathrm{kg\,m^{-3}}$ the Ekman transport is

$$M_E = \frac{0.159}{1{,}025 \times 7.29 \times 10^{-5}} = 2.1\,\mathrm{m^2\,s^{-1}}.$$

Every metre of a north-south line therefore passes 2.1 cubic metres of water per second, directed 90° to the right of a westward wind, which is toward the north. Across the width of the Atlantic at this latitude, about 6,000 km, that is $2.1 \times 6 \times 10^{6} = 1.3 \times 10^{7}\,\mathrm{m^3\,s^{-1}}$, or 13 Sv in the sverdrup of Unit 1, one million cubic metres per second. The trade winds therefore push about 13 Sv of surface water northward, which is more than ten times the flow of all rivers on Earth, out of the tropics and toward the middle of the basin.

INTERACTIVE The Ekman spiral under your wind



Set the wind speed and the latitude and watch the spiral redraw in both hemispheres, seen from above with the wind blowing toward the top; the stress comes from the bulk formula, the transport from the Ekman relation, and the depth from Ekman's rule of thumb, about 50 m for a fresh breeze at mid-latitudes. Notice that the transport always stands at right angles to the wind, that doubling the wind quadruples it, and that toward the equator it grows without limit, the sign that the theory stops applying there.

Click the picture or this link to try it in the online version of this unit.

Real winds are not steady and the real ocean is not uniform, so the clean spiral is hard to find in measurements, and the surface current is usually turned less than 45° from the wind, because the mixed layer stirs the momentum downward faster than Ekman's uniform friction allows. The transport, which does not depend on the friction, holds up well: in 1987 James Price and colleagues at the Woods Hole Oceanographic Institution in Massachusetts measured the currents under a mooring in the Sargasso Sea closely enough to see the spiral turn with depth and to confirm that the transport matched the wind stress.

4 The hill in the middle of the ocean

Now put the Ekman transport under the real winds of Unit 4. Over the subtropical North Atlantic the trade winds blow toward the west between about 10 and 25° N, and the westerlies blow toward the east between about 35 and 55° N. The Ekman transport is to the right of each: northward under the trades, southward under the westerlies. Both push surface water toward the belt between them, around 30° N. The water converges there, and water that converges at the surface has nowhere to go but down. This slow downward motion, called **Ekman pumping**, is only tens of metres per year, but it pushes the warm surface layer downward and makes the thermocline of Unit 3 deepest in the middle of the subtropical gyres, several hundred metres below the surface.

Warm water takes up more room than the same mass of cold water, so a column of the sea with a thick warm layer stands a little taller than one without, and the sea surface is higher where the warm layer is thick; the converging water adds to the pile directly. The middle of the subtropical North Atlantic is, quite literally, about one metre higher than its edges. Figure 3 shows the height of the sea surface across the gyre as measured from space, and it has the shape of a broad hill with one side much steeper than the other: from the coast of Morocco the surface rises by half a metre over 5,000 km to a crest in the Sargasso Sea, just outside the Gulf Stream, and then falls by three quarters of a metre within 200 km at the western edge, where the Gulf Stream runs.

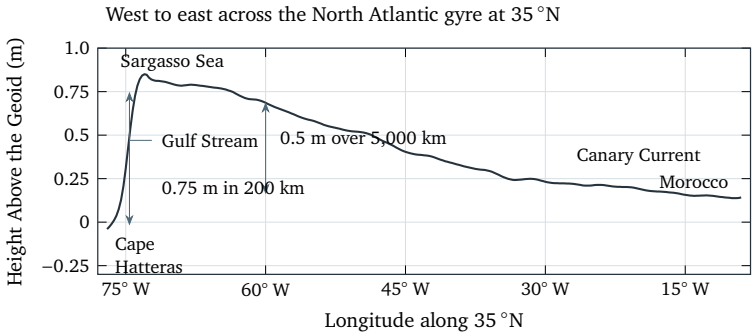


Figure 3. The mean height of the sea surface above the geoid from west to east across the North Atlantic subtropical gyre along 35° N, from the DTU22 mean dynamic topography of DTU Space, which combines two decades of satellite altimetry (1993 to 2012) with a satellite gravity model. The gentle eastern slope and the steep western slope across the Gulf Stream are the two sides of the hill; the heights are relative to the surface the sea would have if it were at rest.

How a satellite measures a hill a metre high on an ocean 5,000 km wide deserves a paragraph. A **radar altimeter** sends pulses straight down and times their return, which gives the distance to the sea to within about 2 cm, and the satellite's own position is known to a similar precision from laser ranging and satellite navigation. Subtracting one from the other gives the height of the sea surface above a reference ellipsoid, the smooth mathematical shape that stands in for the Earth, and that height is dominated by something that has nothing to do with currents: the uneven pull of gravity, which raises the resting sea surface by tens of metres over regions of dense rock and lowers it elsewhere. This resting surface is called the **geoid**; it has bumps a hundred times larger than the hill of a gyre, and it was measured separately by the gravity satellites GRACE (2002 to 2017) and GOCE (2009 to 2013). What remains after the geoid is subtracted is the **dynamic topography**, the part of the sea surface shaped by the motion of the water, which is what Figure 3 shows. The first altimeter accurate enough for this, TOPEX/Poseidon, was launched by NASA and the French space agency CNES on 10 August 1992, and its successors have measured the sea surface without a gap since.

A hill of water does what any hill of fluid does: it presses outward. The water under the crest is deeper than the water at the edge, so the pressure at any depth is higher under the crest, and the difference pushes the water from the high side toward the low side.

Where the sea surface height η changes by $\Delta\eta$ over a horizontal distance Δx, every parcel of water below feels an acceleration $g\,\Delta\eta/\Delta x$ down the slope, which is g times the slope. The reason is that the extra water on the high side weighs $\rho g\,\Delta\eta$ more per square metre, and that extra weight pushes on a column of water of length Δx whose mass is $\rho\,\Delta x$ per square metre of its cross-section; force divided by mass gives $g\,\Delta\eta/\Delta x$. What happens when the water starts to move downhill is the same thing that happened to the ball on the turntable. The downhill motion is deflected to the right, and keeps being deflected, until the water flows along the slope rather than down it, with the hill on its right hand in the Northern Hemisphere. Then the pressure force, pointing downhill, and the Coriolis force, pointing to the right of the flow, which is uphill, are opposite and equal, and the flow is steady. Such a current is called **geostrophic**, from the Greek for Earth and turning.

PRINCIPLE The geostrophic principle

In a steady current on a scale of tens of kilometres or more, away from the equator, the pressure force of the sloping sea surface is balanced by the Coriolis force,

$$f\,v = g\,\frac{\Delta\eta}{\Delta x},$$

which is the **geostrophic balance**; its derivation goes beyond this unit. The water flows along the lines of equal sea surface height at the speed $v = g\,(\Delta\eta/\Delta x)/f$, with the higher water on its right in

the Northern Hemisphere and on its left in the Southern Hemisphere: clockwise around a hill and anticlockwise around a hollow north of the equator, the other way round south of it. A map of the sea surface height is a map of the surface currents.

WORKED EXAMPLE The two slopes of the Atlantic hill

Figure 3 gives the sea surface along 35° N, where $f = 2\Omega \sin 35° = 8.4 \times 10^{-5}\,\mathrm{s}^{-1}$. On the eastern flank the surface falls by 0.5 m over 5,000 km toward Morocco, a slope of

$$\frac{\Delta\eta}{\Delta x} = \frac{0.5\,\mathrm{m}}{5 \times 10^{6}\,\mathrm{m}} = 1.0 \times 10^{-7},$$

which is one metre of height in ten thousand kilometres. The pressure acceleration is g times this, $9.81 \times 10^{-7}\,\mathrm{m\,s}^{-2}$. That looks negligible, yet a parcel starting from rest and pushed by it alone would reach $1\,\mathrm{m\,s}^{-1}$ in twelve days, so something must hold it back, and that something is the Coriolis force once the parcel has turned. The geostrophic speed is

$$v = \frac{g\,\Delta\eta/\Delta x}{f} = \frac{9.81 \times 10^{-7}}{8.4 \times 10^{-5}} = 0.012\,\mathrm{m\,s}^{-1},$$

about one centimetre per second, directed along the slope with the hill on the right, which on the eastern flank means toward the south: this is the Canary Current, and the number is the right order of magnitude for it. On the western flank the surface drops by 0.75 m in 200 km, a slope of 3.8×10^{-6}, which is 38 times steeper, and the same calculation gives $0.44\,\mathrm{m\,s}^{-1}$ averaged across the 200 km, flowing north with the hill on its right. This is the Gulf Stream; its slope is concentrated in a core narrower than 200 km, where the speed reaches $2\,\mathrm{m\,s}^{-1}$.

The hill and the geostrophic principle together explain the shape of every subtropical gyre. Ekman convergence builds a hill between the trades and the westerlies, and the geostrophic flow around it runs clockwise in the Northern Hemisphere: westward on the equatorial side, poleward on the western side, eastward on the poleward side, and equatorward on the eastern side. In the Southern Hemisphere the Ekman transport is to the left of the wind, so the convergence still builds a hill between the trades and the westerlies, but the flow around it runs anticlockwise. Both are the same thing physically: a hill with the high water on the side to which the Coriolis effect deflects.

CHECK YOUR UNDERSTANDING Question 2

The subtropical gyres of the Southern Hemisphere turn anticlockwise. Which statement gives the reason correctly?

(A) The transport is to the left of the wind there, so the trades and westerlies still pile water up between them, and the flow around that hill with the Coriolis deflection to the left is anticlockwise

(B) The transport is to the left of the wind there, so the trades and westerlies pull the surface apart, leave a hollow between them, and the flow around a hollow is anticlockwise

(C) The trade winds of the Southern Hemisphere blow from the south-east rather than the north-east, and the surface water follows them round the basin in the opposite sense

(D) The water of the Southern Hemisphere is colder and denser, so it flows down the slope of the sea surface in the opposite sense to the warm water of the north

The solution is at the end of the unit.

5 The five great gyres

Figure 4 shows the result on a map. Each of the five subtropical basins holds a **subtropical gyre**, a closed loop of currents centred near 30° of latitude, turning clockwise in the Northern Hemisphere and anticlockwise in the Southern Hemisphere, and each loop is made of four named currents, listed in Table 1. On the western side a **western boundary current** carries warm tropical water poleward in a narrow, fast, deep stream. On the poleward side a broad drift carries it eastward across the basin. On the eastern side an **eastern boundary current** carries cooler water slowly back toward the equator in a band hundreds of kilometres wide, and on the equatorial side the trade winds drive the North or South Equatorial Current westward to close the loop. The two boundary currents are the warm and cold sides of each basin in the sea surface temperature map of Unit 4.

Gyre	Turns	Western Boundary Current	Eastern Boundary Current
North Atlantic	clockwise	Gulf Stream	Canary Current
South Atlantic	anticlockwise	Brazil Current	Benguela Current
North Pacific	clockwise	Kuroshio	California Current
South Pacific	anticlockwise	East Australian Current	Peru Current
Indian Ocean	anticlockwise	Agulhas Current	West Australian Current

Table 1. The five subtropical gyres with their boundary currents. The poleward sides are the North Atlantic, South Atlantic, North Pacific, South Pacific, and South Indian Currents, the equatorward sides the North and South Equatorial Currents of each basin; the Peru Current is also called the Humboldt Current.

Poleward of the westerlies the pattern reverses: between about 50 and 65° N the Ekman transports under the westerlies and the polar easterlies pull the surface water apart, the sea surface is a hollow rather than a hill, and the geostrophic flow around the hollow is anticlockwise. These are the **subpolar gyres**, one in the North Atlantic between Greenland, Labrador, and Scotland, with the cold Labrador and East Greenland Currents on its western side, and one in the North Pacific between Alaska and Kamchatka, with the cold Oyashio. In the Southern Hemisphere no continents stand in the way at these latitudes, and instead of a subpolar gyre the westerlies drive the Antarctic Circumpolar Current round the whole Earth, carrying about 130 to 170 Sv through Drake Passage, the strait between South America and Antarctica, which is more than any other current carries. The deep water that forms in the subpolar seas is the subject of Unit 8.

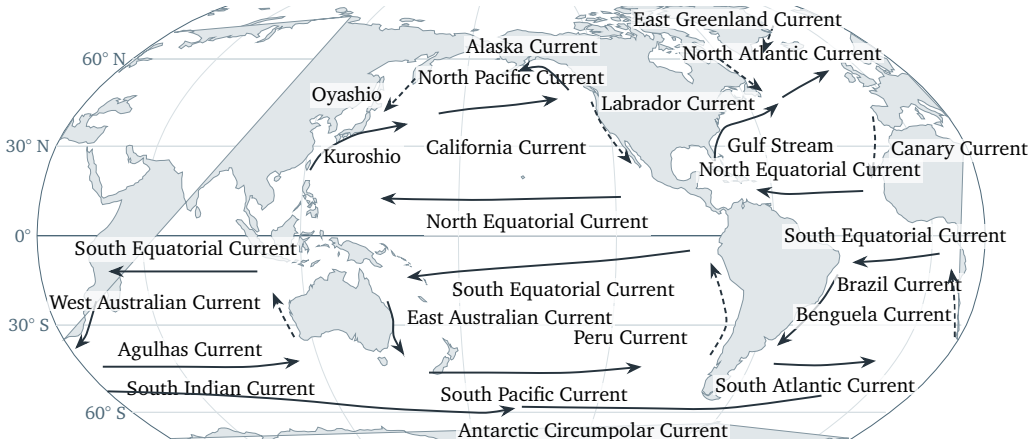


Figure 4. The surface currents of the world ocean on a Robinson projection with the Pacific in the centre, drawn after the standard descriptions of the circulation. Solid arrows are warm currents, dashed arrows cold currents. The five subtropical gyres fill the Pacific, Atlantic, and Indian Ocean basins between about 10 and 45° of latitude; the subpolar gyres of the North Atlantic and the North Pacific turn the other way, and the Antarctic Circumpolar Current runs unbroken around the globe. Coastlines from Natural Earth.

EXCURSION *Franklin's chart and the captains who ignored it*

The Gulf Stream was the first current to be charted, and it was charted because the post was late. In 1768 Benjamin Franklin (1706-1790), then deputy postmaster general for the American colonies and living in London, was asked by the Board of Customs why the mail packets (the ships that carried the post) from Falmouth to New York took about two weeks longer than the merchant ships from London to Rhode Island, although the merchant ships sailed a longer route. Franklin put the question to his cousin Timothy Folger (1732-1814), a Nantucket whaling captain, who told him that the whalers knew a strong current running north-east off the American coast, had often met English packets in the middle of it, sailing against the current, and had told their captains so, but the captains "were too wise to be counselled by simple American fishermen". Folger drew the current on a chart, Franklin had it engraved and printed in London in 1768, and copies were sent to Falmouth for the packet captains, who paid them no attention.

That first printing was lost for two centuries, until the oceanographer Philip Richardson found two copies in the Bibliothèque Nationale in Paris and described them in the journal Science in 1980. The version in Figure 5 is the third, engraved by James Poupard and published in 1786 with Franklin's "Maritime Observations" in the Transactions of the American Philosophical Society. By then Franklin had crossed the Atlantic with a thermometer and found the water of the stream warmer than the sea on either side, so that a captain could tell from a bucket of seawater whether he was in it, which is how satellites find the Gulf Stream today.



Figure 5. The Franklin and Folger chart of the Gulf Stream in the version engraved by James Poupard for the Transactions of the American Philosophical Society in 1786. The stream is the dark band from the Straits of Florida along the American coast and out past Newfoundland; Franklin's remarks on how to avoid it are printed on the left. Credit: Library of Congress, Geography and Map Division, public domain.

5.1 The currents of the equator

Near the equator the simple picture needs two additions. The trade winds of both hemispheres drive the **North Equatorial Current** and the **South Equatorial Current** westward across each ocean, and between them, under the belt of light winds a few degrees north of the equator, the **Equatorial Countercurrent** flows east, against the trade winds on either side. Harald Sverdrup (1888-1957) explained it in 1947 as a consequence of the way the wind stress changes with latitude across the doldrums, as Unit 4 called that belt of light winds, in the theory that Section 6 takes up. In outline, the trade winds are weak in the doldrums and strong on either side, so the Ekman transports pile the sea surface into a low ridge on the equatorward side of the belt and pull a shallow trough on its poleward side, and the geostrophic flow between a ridge to the south and a trough to the north runs eastward.

The second addition was a surprise. In 1952 Townsend Cromwell (1922-1958), surveying tuna grounds in the central Pacific for the United States Fish and Wildlife Service, noticed that fishing gear lowered below the westward surface current was carried eastward. He had found the **Equatorial Undercurrent**, a ribbon of water about 300 km wide and 200 m thick, centred on the equator at a depth of around 100 m and flowing east at up to $1.5\,\mathrm{m\,s^{-1}}$. It exists because the trade winds pile warm water up in the west, so the sea surface slopes down toward the east and presses the water eastward at depth; away from the equator this pressure force would be turned into a geostrophic current along the slope, but on the equator $f = 0$ and

nothing turns it, so the water runs downhill toward the east beneath the layer that the wind drags west.

6 Why the western side is different

Table 1 hides the most striking fact about the gyres: the western boundary currents are nothing like their eastern counterparts. The Gulf Stream off Cape Hatteras is about 100 km wide, flows at up to 2 m s^{-1} at the surface, reaches more than 1,000 m down, and carries about 90 Sv. The Canary Current on the other side of the same gyre is nearly 1,000 km wide, flows at a few centimetres per second, and carries a few sverdrups in its upper layers. The Kuroshio south of Japan carries about 42 Sv according to repeated measurements along a section south of Shikoku combined with satellite altimetry, while the California Current on the far side of the Pacific carries roughly 10 Sv in a band almost 1,000 km wide; the Agulhas Current off South Africa, at about 70 Sv, is the strongest of the Southern Hemisphere. In every basin the return flow toward the pole is squeezed into a narrow, fast jet against the western coast, while the flow toward the equator spreads across the rest of the basin. Oceanographers call this **western intensification**.

The explanation came in 1948 from Henry Stommel (1920-1992), then a young researcher at Woods Hole, in a paper of five pages. He built the simplest model ocean that could have a gyre at all, a rectangular basin of uniform depth driven by westerlies along its northern edge and trade winds along its southern edge and slowed by friction at the sea floor, and solved it three times. With no rotation and with a rotation whose Coriolis parameter was the same everywhere, the gyre came out symmetric, as in Figure 6(a). With a Coriolis parameter that grew with latitude, as it does on the real Earth, the whole return flow crowded against the western wall, as in Figure 6(b). The cause was the change of f with latitude, which oceanographers write as $\beta = \Delta f / \Delta y$, the increase of the Coriolis parameter per metre northward, about 2×10^{-11} m^{-1} s^{-1} at mid-latitudes. The reason it matters can be told in words, with the idea of spin.

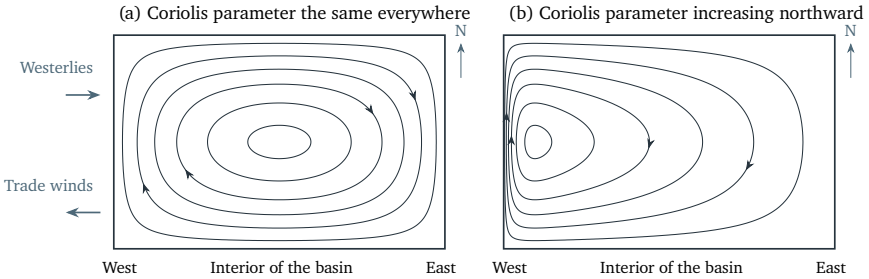


Figure 6. Streamlines of the wind-driven circulation in Stommel's rectangular model ocean, computed from his 1948 solution and drawn at equal intervals of transport, so that closely spaced lines mean a fast current. (a) With a Coriolis parameter that is the same everywhere the gyre is symmetric. (b) With a Coriolis parameter that increases northward, as on the real Earth, the poleward return flow is pressed against the western wall into a narrow, fast current, while the rest of the basin drifts slowly toward the equator. The arrows give the sense of the flow for a Northern Hemisphere gyre.

DERIVATION **Stommel's argument, told with spin**

Think of the water in a column as able to spin about a vertical axis, like tea stirred in a cup. The column has two kinds of spin: its own, relative to the ground, which comes from the currents around it being faster on one side of the column than on the other (oceanographers call this difference the shear), and the spin of the ground itself, which turns about the vertical together with the planet, anticlockwise in the Northern Hemisphere like the turntable of Figure 1, fastest at the poles and not at all on the equator; this second spin is what the Coriolis parameter measures. Without any push, the sum of the two stays the same as the column moves, so a column that drifts toward the equator, where the ground spins less, must take on anticlockwise spin of its own to make up the difference, and a column that moves toward the pole must take on clockwise spin. The wind changes the sum: over a subtropical gyre, where the westerlies blow eastward on the poleward side and the trades blow westward on the equatorward side, the wind twists the surface clockwise, all the time, everywhere in the gyre.

In the broad interior of the gyre the balance is simple. The water drifts slowly toward the equator, and the anticlockwise spin it gains by doing so cancels the clockwise spin the wind feeds in; the Sverdrup relation below makes this exact. The water must return toward the pole somewhere, and on the way it gains clockwise spin from the change of latitude while the wind adds more, so the return current would spin up without limit unless something removed clockwise spin from it. Only friction can do that, and friction against a wall removes clockwise spin only from a current that already turns in the clockwise sense. A poleward current that is fastest next to a wall on its left, which is the western wall, does turn that way: its fast left edge and slow right edge rotate it like a wheel, clockwise seen from above, and the drag of the wall on the fast edge slows exactly that rotation. Against the eastern wall the shear would have the other sense and friction would add clockwise spin instead of removing it. The return flow can therefore run only along the western side, and it must be narrow, because friction has to work hard enough in that strip to remove all the spin that the wind put into the whole basin.

Two years later Walter Munk (1917-2019) replaced Stommel's bottom friction with friction between neighbouring currents, drove the model with the real winds of the Pacific, and recovered the Kuroshio, the North Pacific Current, the California Current, and the equatorial currents in roughly their observed positions. The western intensification survives in both models, and in every model since, because it does not depend on the kind of friction; it depends on β. The interior drift that Stommel's argument needs had been worked out the year before by Sverdrup, in the paper that explained the Equatorial Countercurrent: away from the boundary currents, the north-south transport of the whole water column is set by the way the wind stress changes from place to place, and by nothing else.

KEY EQUATION The Sverdrup transport

$$M_y = \frac{1}{\rho\,\beta}\,\operatorname{curl}\vec{\tau}, \qquad \operatorname{curl}\vec{\tau} \approx -\frac{\Delta\tau_x}{\Delta y}$$

The north-south volume transport M_y of the whole water column per metre of east-west width, in $\mathrm{m^2\,s^{-1}}$, is the curl of the wind stress divided by the density of seawater ρ and by β, the rate at which the Coriolis parameter increases northward. The **curl of the wind stress** measures how much the wind twists the sea surface; for a wind that blows east or west and changes only with latitude it is the northward change of the eastward stress τ_x with the sign reversed, which is the second form. Between the trades and the westerlies the curl is negative in the Northern Hemisphere, so the interior transport is toward the equator. This relation is called the **Sverdrup balance**; it holds for the steady interior of a basin, away from the boundary currents that carry the water back.

WORKED EXAMPLE Sverdrup's prediction and the Gulf Stream's transport

Over the North Atlantic the trade winds at 15° N exert a stress of about $0.1\,\mathrm{N\,m^{-2}}$ toward the west, so $\tau_x = -0.1\,\mathrm{N\,m^{-2}}$, and the westerlies at 45° N exert about $0.1\,\mathrm{N\,m^{-2}}$ toward the east, $\tau_x = +0.1\,\mathrm{N\,m^{-2}}$. The two latitudes are 30° apart, which is 3.3×10^{6} m, so the curl of the wind stress between them is about

$$\operatorname{curl}\vec{\tau} \approx -\frac{0.1-(-0.1)}{3.3\times10^{6}} = -6\times10^{-8}\,\mathrm{N\,m^{-3}}.$$

Because $f = 2\Omega\sin\varphi$ changes by $2\Omega\cos\varphi\,\Delta\varphi$ when the latitude changes by a small angle $\Delta\varphi$ in radians (the slope of the sine curve is the cosine), and a change of latitude $\Delta\varphi$ is a northward distance $R_\mathrm{E}\,\Delta\varphi$, the Coriolis parameter at 30° N grows northward at $\beta = 2\Omega\cos30°/R_\mathrm{E} = 2\times7.29\times10^{-5}\times0.866/(6.37\times10^{6}) = 2.0\times10^{-11}\,\mathrm{m^{-1}\,s^{-1}}$, where R_E is the radius of the Earth. The Sverdrup transport is

$$M_y = \frac{-6\times10^{-8}}{1{,}025\times2.0\times10^{-11}} = -2.9\,\mathrm{m^2\,s^{-1}},$$

southward, and across the 6,000 km width of the basin it adds up to $1.8\times10^{7}\,\mathrm{m^3\,s^{-1}}$, or about 18 Sv; a careful calculation with the measured wind field gives about 30 Sv for the North Atlantic. All of it must return northward in the Gulf Stream. Through the Straits of Florida the stream carries 32 Sv,

measured since 1982 by the voltage that the moving salt water induces in a disused telephone cable on the sea floor (seawater conducts electricity, and a conductor moving through the Earth's magnetic field generates a voltage, as the coil of a dynamo does), in good agreement with Sverdrup's number, although the agreement is partly luck, because the Florida Current also carries the warm upper branch of the overturning circulation of Unit 8, which is not driven by the wind.

Off Cape Hatteras the stream carries far more. Its width there is about 100 km, its flow reaches down about 1,000 m, and its speed averaged over that cross-section is about $0.9\,\mathrm{m\,s^{-1}}$, so the transport is

$$Q = 10^5\,\mathrm{m} \times 10^3\,\mathrm{m} \times 0.9\,\mathrm{m\,s^{-1}} = 9 \times 10^7\,\mathrm{m^3\,s^{-1}} = 90\,\mathrm{Sv},$$

about three times what the wind-driven balance supplies, and 75 times the flow of all the rivers on Earth. The extra 60 Sv is water that leaves the stream east of Hatteras, turns back south and west in tight loops on either side of it, and joins it again upstream. These recirculations are driven by the stream's own meanders and eddies, and they are why a western boundary current can carry much more than the Sverdrup balance predicts without contradicting it.

CHECK YOUR UNDERSTANDING Question 3

Suppose the Coriolis parameter had the same value at every latitude, so that $\beta = 0$. What would Stommel's model gyre look like?

(A) A narrow current on the eastern side of the basin and a slow drift across the rest of it

(B) No gyre at all, because the wind would push the water straight downwind in both belts

(C) A narrow current on the western side, as now, because the friction at the wall is the same

(D) A symmetric gyre with the same broad, slow currents on its eastern and western sides

The solution is at the end of the unit.

7 What drifts on the surface

The cleanest way to see the surface currents is to drop something into the sea and follow it, and the Global Drifter Program of the United States National Oceanic and Atmospheric Administration has done this on purpose since 1979: about 1,300 **surface drifters** are at sea at any time, each a small float with a cloth drogue, a kind of underwater parachute, hanging 15 m below it, so that it follows the water at that depth rather than the wind, reporting its position by satellite several times a day. Their tracks give the map of the mean surface circulation that the arrows of Figure 4 summarize, and they show that a drifter rarely goes round a gyre in a tidy loop; it wanders, loops in eddies for weeks, and crosses a basin along a path that no other drifter shares.

The ocean has also run the experiment by accident. On 10 January 1992 a container ship on the way from Hong Kong to Tacoma lost twelve containers in a storm near 45° N, 178° E, in the middle of the North Pacific. One of them broke open and released 28,800 plastic bath toys (yellow ducks, blue turtles, green frogs, and red beavers), all of which float. In November 1992, ten months later, the first of them came ashore near Sitka in Alaska, 3,500 km to the east along the North Pacific Current and the Alaska Current, and the oceanographer Curtis Ebbesmeyer and his colleague James Ingraham used the landings, reported by people who search the beaches, to check a computer model of the surface currents built from wind data and drifter tracks; when the model was started at the spill site on the day of the storm, it put the toys at Sitka in the right month.

WORKED EXAMPLE **A drifter across the North Pacific**

How long should a floating object take from the spill site to Sitka? The shortest distance over the Earth's surface between 44.7° N, 178.1° E and Sitka at 57.1° N, 135.3° W is 3,460 km. Drifters in the North Pacific Current move eastward at a mean speed of about $0.15\,\mathrm{m\,s^{-1}}$, which is 13 km a day. Along the shortest path the crossing would take

$$t = \frac{3.46 \times 10^{6}\,\mathrm{m}}{0.15\,\mathrm{m\,s^{-1}}} = 2.3 \times 10^{7}\,\mathrm{s} = 267\,\mathrm{d},$$

about nine months. The toys needed ten, which is what one expects, since no floating object takes the shortest path and the current is not uniform along it. A speed of $0.15\,\mathrm{m\,s^{-1}}$ is worth remembering as the scale of a basin-crossing drift: less than a tenth of the Gulf Stream's core and ten times the geostrophic drift of the eastern flank in Section 4.

Floating things also collect in the middle of the gyres, and the reason is the Ekman convergence of Section 4. The surface water of the subtropics is pushed toward the centre of each gyre from both sides, and when it arrives there it sinks slowly, at tens of metres per year, as Ekman pumping. Anything that floats cannot follow the water down. It stays at the surface, and the next parcel of converging water carries it a little further in, so over years floating debris from all around a basin drifts toward the convergence and accumulates there. Five such accumulation zones exist, one in each subtropical gyre, and the largest, in the North Pacific between Hawaii and California, is usually called the Great Pacific Garbage Patch. A survey published in 2018 by Laurent Lebreton and colleagues, who towed nets and flew aircraft across it, estimated that it covers about 1.6 million square kilometres, which is about three times the area of France, and holds at least 79,000 tonnes of plastic. Even so, the name misleads: there is no island of rubbish and nothing to see from a ship's deck, because the plastic is mostly in fragments of a few millimetres. The survey's net tows caught on average less than one piece per square metre, and across the gyres as a whole the review of the research spotlight below gives about one piece per four square metres as typical, rising to one to ten per square metre in the most polluted water; it is the size of the area that makes the tonnage.

RESEARCH SPOTLIGHT

Erik van Sebille *Utrecht University*

What moves floating plastic across the ocean

Between 5 and 12 million tonnes of plastic are estimated to enter the sea from land every year, yet all the surveys of floating plastic together find less than 0.3 million tonnes at the surface, and to find out where the rest goes one has to know how the sea moves what floats. Erik van Sebille of Utrecht University and 37 co-authors reviewed, in a paper published in 2020 in Environmental Research Letters, everything that was known about the physical processes that carry floating plastic, from the scale of a whole gyre down to a single breaking wave. On the largest scale they confirm the picture of this unit: the Ekman transport under the trade winds and the westerlies converges in the five subtropical gyres, the converging water sinks and leaves the plastic behind, and this alone predicts the five accumulation zones that nets and drifters find. Below the gyre scale they collect what the Ekman picture leaves out: eddies that trap and release debris, the drift that waves give floating objects, the push of the wind on objects that stick out of the water, mixing of small pieces into the water column, and stranding on beaches. Together with fragmentation and sinking, these processes may account for some of the gap between what enters the sea and what is found floating; the review leaves the budget open and sets out the measurements that would close it.

Read the paper: van Sebille et al. (2020), The physical oceanography of the transport of floating marine debris, Environmental Research Letters 15, 023003

KEY POINTS

- The wind pushes on the sea surface with the stress $\tau = \rho_{\text{air}} C_D U_{10}^2$, about $0.16\,\text{N}\,\text{m}^{-2}$ for a fresh breeze of 10 m/s, and the surface water drifts at 2 to 3 per cent of the wind speed.
- The rotation of the Earth deflects every long-lasting motion sideways with the acceleration fv, where $f = 2\Omega \sin\varphi$ is the Coriolis parameter, about $10^{-4}\,\text{s}^{-1}$ at mid-latitudes and zero at the equator; water left alone circles once per inertial period $2\pi/f$, 17 hours at 45°.
- A steady wind drives the Ekman spiral in the top tens of metres, and the layer as a whole transports $M_E = \tau/(\rho f)$ per metre of width at right angles to the wind, to the right in the Northern Hemisphere and to the left in the Southern.
- Ekman transports converge between the trade winds and the westerlies and pile the sea surface into a hill about one metre high in the middle of each subtropical basin; the geostrophic flow around the hill is the subtropical gyre, clockwise north of the equator and anticlockwise south of it.
- Because the Coriolis parameter increases with latitude, the poleward return flow of every gyre is squeezed against the western side of its basin into a western boundary current such as the Gulf Stream, which carries about 90 Sv past Cape Hatteras; the Sverdrup balance $M_y = \text{curl}\,\vec{\tau}/(\rho\beta)$ fixes the slow equatorward drift of the interior.
- Drifters, lost bath toys, and floating plastic trace the surface currents, and floating debris collects in the centres of the gyres because the converging surface water sinks there and leaves whatever floats behind.

Solutions to the questions in the text: 1-B, 2-A, 3-D. The online version of this unit explains each answer.