

Ekman, Transport & the Florida Current

The same rotating-earth machinery, run in water instead of air

Everything in the Coriolis handout applies here unchanged — same $f = 2\Omega \sin \phi$, same deflection to the right in the northern hemisphere, same fall-off with latitude. What changes is the fluid. Air is stirred by turbulence through a kilometre of atmosphere and is essentially unstratified near the surface. Water is dense, viscous, sharply stratified, and passes momentum downward very reluctantly. The result is that the atmosphere's friction-layer spiral is spread over thousands of feet, while the ocean's is crushed into the top fifty or hundred metres — and in that shallow layer the flow manages to turn not just partway but **all the way around**.

Vagn Walfrid Ekman worked this out in 1905 as a doctoral student, and the problem was handed to him by Fridtjof Nansen, who had noticed while frozen into the Arctic ice aboard *Fram* that the drift of the ice ran consistently 20° to 45° to the right of the wind rather than downwind. Nansen guessed it was the Earth's rotation. Ekman did the mathematics and found something better than Nansen expected.

The wind does not drive the current downwind

Wind blowing over water does not push the water along; it drags on it. That surface stress sets the top few centimetres moving, and the instant they move, Coriolis begins deflecting them to the right. The thin surface layer settles into a balance between the wind stress pulling it downwind and Coriolis pulling it sideways, and it ends up moving at **45° to the right of the wind**. That top layer then drags the layer beneath it, which gets deflected further right and moves slower — and so on down, each layer driven by the one above and turned a bit further right, until the motion dies out.

The number to give the deck

Wind-driven surface drift runs at roughly **3% of the wind speed**. Twenty knots of wind over open water builds about **0.6 knots** of surface current in the direction 45° right of the wind — and it takes a good many hours of steady wind to get there. That is the drift term in your set-and-drift estimate before you have a fix to work from.

The spiral, level by level

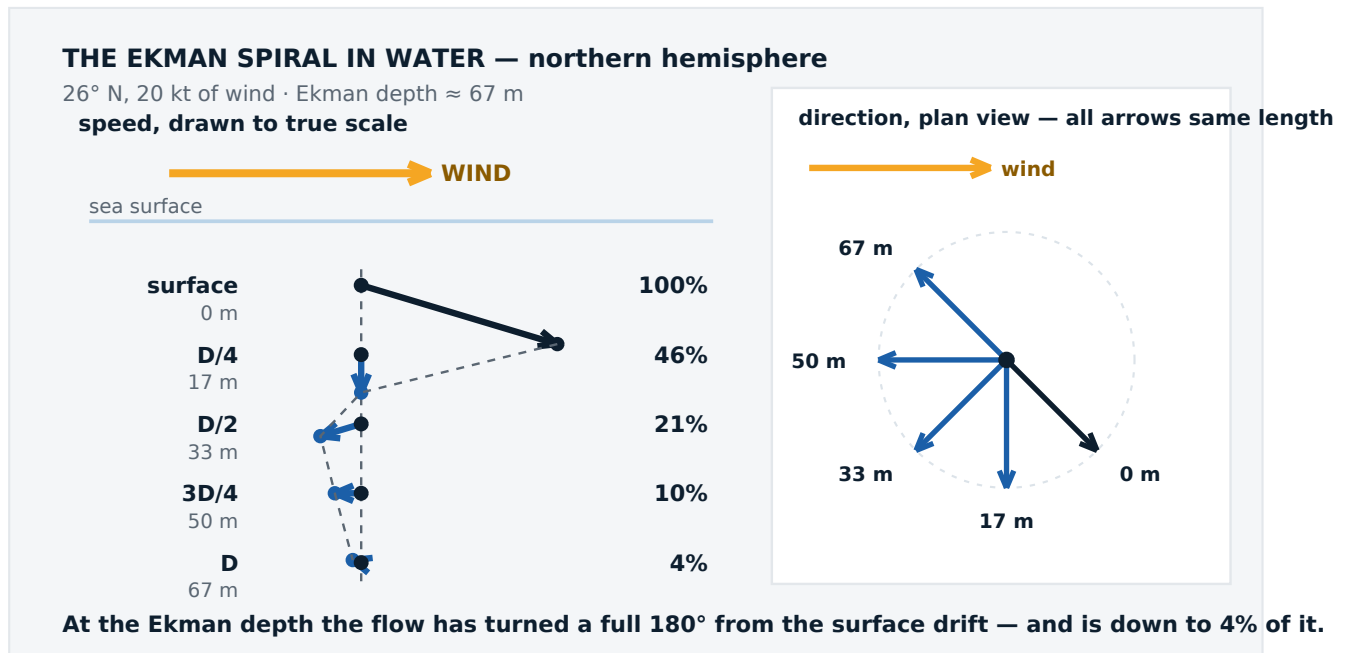


Figure 1 · The idealized Ekman spiral — true relative speeds on the left, direction on the right.

Two things there are worth pausing on. Speed falls off as $e^{-\pi z/D}$, so one Ekman depth down you are at about **4%** of the surface drift. And the direction at the bottom of the spiral is a full 180° from the surface — water at 65 metres creeps the *opposite* way to water at the top, driven by the same wind.

How deep does it reach?

The Ekman depth goes as wind speed over the square root of $\sin \phi$: $D = 4.3 W / \sqrt{\sin \phi}$, W in metres per second. Stronger wind drives momentum deeper; higher latitude turns the flow faster and shuts the spiral down shallower.

Wind speed	Surface drift $\approx$ 3% of wind	Ekman depth at 26° N $D = 4.3 W / \sqrt{\sin \phi}$	Ekman depth at 45° N
10 kt	0.3 kt	33 m	26 m
20 kt	0.6 kt	67 m	53 m
30 kt	0.9 kt	100 m	79 m
40 kt	1.2 kt	134 m	105 m

Where the textbook 45° is a lie, gently

The clean 45° assumes a constant eddy viscosity and an infinitely deep, unstratified ocean. Neither is true. Real measurements put the surface drift more like **20° to 40°** right of the wind, and a shallow mixed layer compresses the whole spiral. The transport result on the next page survives regardless — which is the point that matters.

Add the whole column up: Ekman transport

Here is the result Ekman is really famous for. If you stop worrying about any individual layer and instead integrate the entire spiral from the surface down to where it dies, all the sideways components cancel and what is left points exactly **90° to the right of the wind** in the northern hemisphere — 90° to the left in the southern. Not approximately. Exactly, and independently of the eddy viscosity, the depth, and all the messy assumptions that make the 45° only approximate.

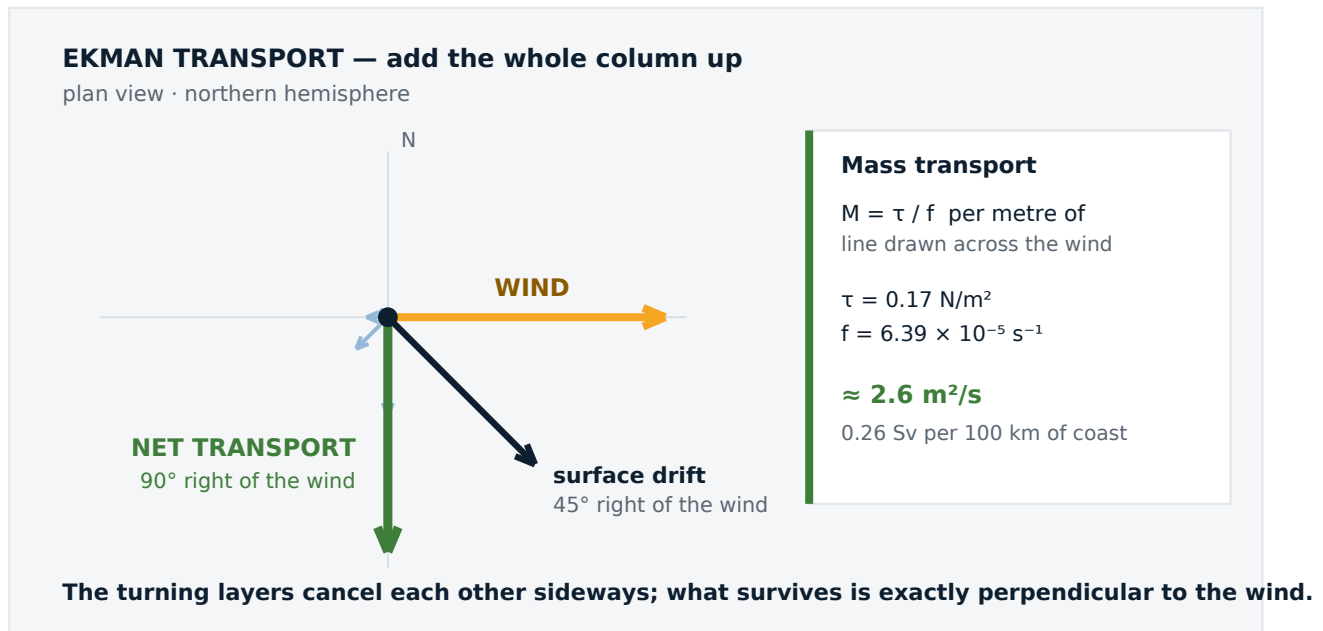


Figure 2 · Net Ekman transport is rigorously perpendicular to the wind, whatever the details of the spiral.

The magnitude is just as clean: the transport per metre of line drawn across the wind is the wind stress divided by the Coriolis parameter.

$$M = \tau / (\rho f)$$

Wind stress itself comes from $\tau = \rho(\text{air}) \cdot C(d) \cdot W^2$, with a drag coefficient around 1.3×10^{-3} for moderate winds. Notice the latitude dependence runs the wrong way from intuition: because f is in the denominator, **the same wind moves more water at low latitude than at high.**

Latitude	$f \text{ (s}^{-1}\text{)}$	Wind	Stress $\tau \text{ (N/m}^2\text{)}$	Transport $\text{(m}^2/\text{s)}$	Per 100 km (Sv)
26°	6.39×10^{-5}	20 kt	0.17	2.6	0.26
26°	6.39×10^{-5}	30 kt	0.38	5.8	0.58
45°	10.31×10^{-5}	20 kt	0.17	1.6	0.16
60°	12.63×10^{-5}	20 kt	0.17	1.3	0.13
10°	2.53×10^{-5}	20 kt	0.17	6.5	0.65

What transport does when it hits something

Transport perpendicular to the wind is a curiosity until the water has nowhere to go. Then it becomes the organizing principle of the world's fisheries.

Coastal upwelling

Put a coastline on the left of the wind in the northern hemisphere and Ekman transport carries surface water away from the shore. Something has to replace it, and the only available water is underneath — so cold, nutrient-rich water is drawn up from a hundred metres or more. That is why the great cold-water fisheries sit on **eastern** ocean margins with equatorward winds: California, Peru and Chile, northwest Africa, and Benguela off Namibia. It is also why the water off Monterey is 12 °C in August at the same latitude as comfortable swimming on the Atlantic side.

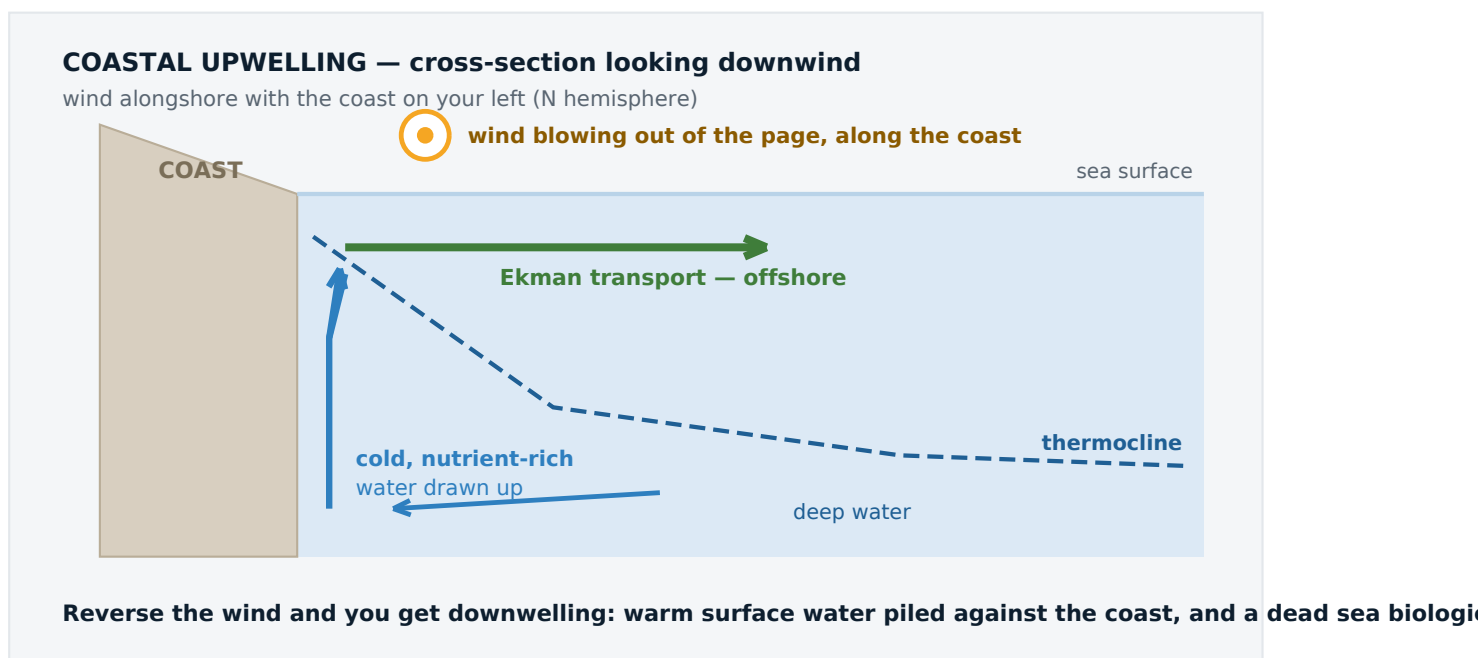


Figure 3 · Coastal upwelling. Offshore Ekman transport at the surface is replaced from below, lifting the thermocline against the coast.

Reverse the wind — coast on your right — and the transport piles warm surface water against the shore, pushes the thermocline down, and you get downwelling: warm, clear, and biologically empty.

Equatorial upwelling, and the pumping of the open ocean

The equator does the same trick without a coastline. The trade winds blow from the east along both sides of it. North of the line, transport is 90° to the right — northward. South of the line, 90° to the left — southward. The two pull apart, the surface diverges, and cold water rises along the equator. That is the **equatorial cold tongue**, visible on any Pacific sea-surface-temperature chart, and its collapse when the trades slacken is the opening move of an El Niño.

Out in the open ocean the same logic runs on the curl of the wind field rather than on a boundary. The trades blow west in the tropics and the westerlies blow east in mid-latitudes; between them, Ekman transport converges on the middle of the subtropics from both sides. Water piles up there. The centre of the North Atlantic gyre — the Sargasso Sea — sits roughly **one metre higher** than the water at its edges. This is called Ekman pumping, and it works in reverse under the subpolar gyre, where divergence sucks water upward.

From a hill of water to a current

That metre-high mound is a pressure gradient, and from there the story is exactly the one from the atmosphere handout. Water tries to run downhill, away from the centre of the mound. The moment it moves, Coriolis deflects it right. It turns until Coriolis balances the downhill pressure gradient, and then it stops going downhill and runs **around** the mound instead — clockwise in the northern hemisphere. That is a **geostrophic current**, and it is the same balance as the geostrophic wind with sea-surface slope standing in for isobars.

The two-step worth writing on the board

The wind does not drive the Gulf Stream directly. The wind drives Ekman transport; Ekman transport builds the mound; the mound and Coriolis together drive the geostrophic current. It is an indirect chain, and it is why the ocean's great currents flow at right angles to the winds that ultimately cause them.

This also means a satellite altimeter measuring sea-surface height to a few centimetres is, in effect, a current meter for the whole ocean — the slope gives you the geostrophic flow directly. That is how the modern ocean-current products on your ECDIS and routing software are actually generated.

Why the fast one is always on the west

If the ocean were a simple basin the gyre would be a symmetric ring, with the same lazy current on both sides. It is not. Every subtropical gyre on Earth has a narrow, fast, deep current on its **western** boundary and a broad, slow drift on its eastern: Gulf Stream and Kuroshio on the west, Canary and California Currents on the east. The southern hemisphere does the same thing with the Agulhas and the Brazil Current.

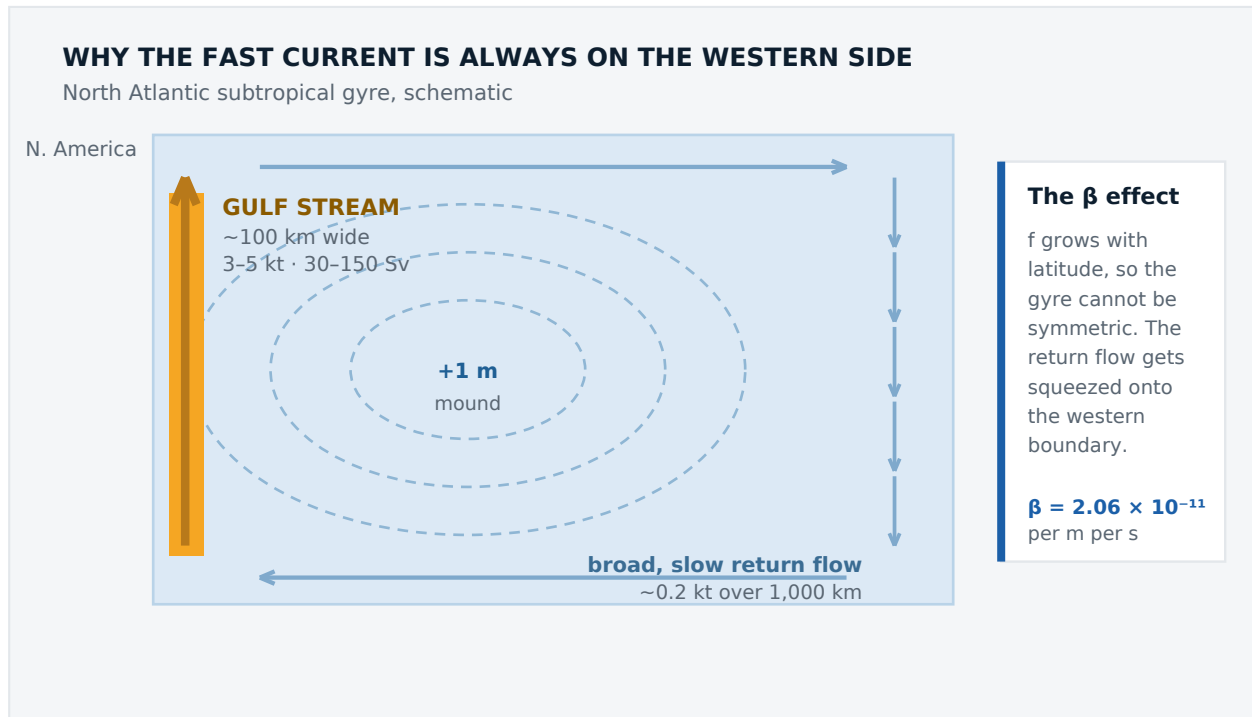


Figure 4 · Western intensification. The mound is displaced toward the western side, so the return flow is squeezed into a narrow, fast band.

The cause, worked out by Henry Stommel in 1948, is that **f is not constant across the gyre**. It grows with latitude, and the rate of that growth — β , about 2.1×10^{-11} per metre per second at our latitude — breaks the symmetry. Water circulating around the gyre gains and loses rotation as it moves north and south, and the only way to balance the books over a closed circuit is to concentrate the return flow into a narrow western jet where friction can remove the excess. Everything that is remarkable about the Gulf Stream — its speed, its narrowness, its sharpness of edge — follows from the fact that the Coriolis parameter varies with latitude rather than being fixed.

Trivia worth a minute of class time

Benjamin Franklin, as deputy postmaster general, had the first useful chart of the Gulf Stream printed in 1769 after working out from a Nantucket whaling captain why the mail packets took two weeks longer westbound than the merchantmen. The British captains ignored the chart. The stream is roughly 30 sverdrups in the Florida Straits — about five times the combined flow of every river on the planet — and it is entirely invisible from a ship's deck except as set.

The Florida Current — our piece of it

Between Florida and the Bahamas the whole system is squeezed into a channel about 80 km wide, which is why we get the most reliable, most concentrated western boundary current anywhere on Earth right off the beach. The axis of the Florida Current sits roughly **10 to 15 nautical miles off Port Everglades**, with core surface speeds of **3.5 to 4 knots** and better on the strong days, setting almost due north. Inshore of the axis it falls away quickly, and close under the beach there is often a weak southerly countercurrent — which is exactly why the local delivery skippers run the beach southbound and the axis northbound.

Worked example — crossing to Bimini

Forty-eight miles, track 100° T, 20 knots through the water, and an average set of 2.5 knots toward 010° T — square to the track, which makes the arithmetic honest and easy. The crab angle is $\arcsin(2.5 \div 20) = 7.2^\circ$, so steer **107° T** and your speed made good is $20 \times \cos 7.2^\circ =$ **19.8 knots**. Ignore the correction and hold 100° for the 2.4-hour crossing and you arrive **6 miles north** of where you meant to be.

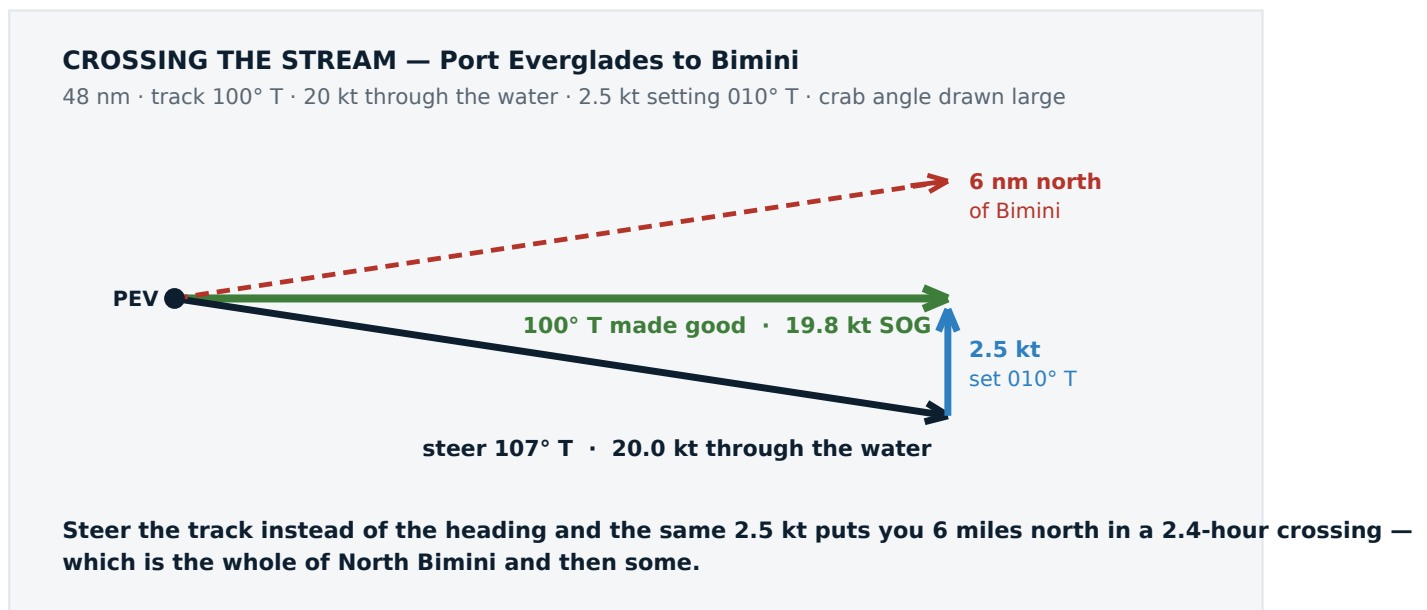


Figure 5 · The current triangle for the Bimini crossing. The set is square to the track, so the whole of it goes into the crab angle.

The part that actually kills people

A north-setting 3-knot current under a 25-knot northerly builds a sea that is short, steep, and completely out of proportion to the wind speed — wave height up, wavelength down, faces near-vertical. The Straits of Florida in a winter norther is genuinely dangerous water in a small boat, and the forecast wind speed alone will not tell your students that. Wind against current is the single most useful sea-state rule they can carry off the course.

Quick reference card

Item	Value / rule
Surface drift, wind-driven	$\approx 3\%$ of wind speed · 20 kt of wind ≈ 0.6 kt of drift
Surface drift direction	45° right of the wind in theory · $20\text{--}40^\circ$ observed (N hem.)
Rotation with depth	$45^\circ + 180^\circ \times (z/D)$ to the right; speed $\times e^{(-\pi z/D)}$
Ekman depth	$D = 4.3 W / \sqrt{\sin \phi}$ (W in m/s, D in metres)
At the Ekman depth	flow is 180° opposed to the surface drift, $\sim 4\%$ of its speed
Ekman transport	90° right of the wind (N hem.), 90° left (S hem.)
Transport magnitude	$M = \tau / (\rho f)$ per metre of line drawn across the wind
Coastal upwelling	wind alongshore with the coast on your LEFT (N hem.)
Equatorial upwelling	easterly trades diverge across the equator — the cold tongue
Subtropical gyre	Ekman convergence $\rightarrow \sim 1$ m mound $\rightarrow$ geostrophic flow around it
Gyre sense	clockwise in N hemisphere, anticlockwise in S
Western intensification	β effect; narrow fast current on the western boundary
Florida Current	~ 30 Sv · core $3.5\text{--}4+$ kt · axis roughly $10\text{--}15$ nm off Lauderdale
Crab angle for a set	$\arcsin(\text{current} \div \text{boat speed})$ when the set is square to track
Wind against the Stream	N or NE wind over a N-setting current = short, steep, dangerous
1 sverdrup (Sv)	$10^6 \text{ m}^3/\text{s}$ — about $5\times$ every river on Earth combined

Five questions to close the block

1. A steady 25-knot wind has been blowing from 090° for two days at 26° N. Roughly what surface drift would you allow, and in what direction? (About 0.75 kt, setting toward roughly 315° — downwind is 270° , then 45° to the right of that.)
2. Same wind. Which way is the net Ekman transport? (Toward 180° — 90° right of the direction the wind is blowing toward.)
3. You are on a coast that runs north-south with the ocean to the west, in the northern hemisphere. Which wind direction gives upwelling? (Northerly — coast on your left as you look downwind.)
4. Why is there no Gulf Stream on the eastern side of the Atlantic? (β — f varies with latitude, which forces the return flow into a narrow western boundary current.)
5. Crossing the Stream at 12 knots with a 3-knot set square to your intended track — what is your crab angle, and what does it cost you in speed made good? ($\arcsin(3/12) = 14.5^\circ$; $\text{SMG} = 12 \cos 14.5^\circ = 11.6$ kt.)