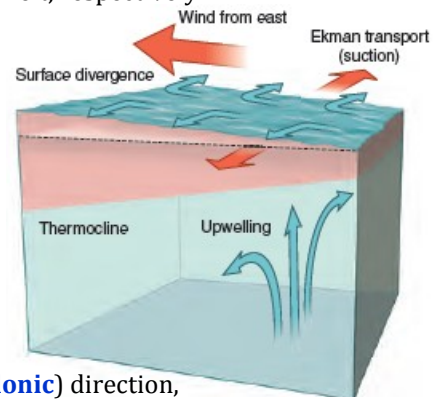
Ekman Transport & Coastal Sea Level

Overview

- **Ocean flow field** can be described as **additive combination** of the following **2 components:**
  1. **Ekman Transport –** part of the flow that responds to **wind-stress forces** exerted at sea surface
  2. **Geostrophic component** –the flow that responds to forces from **horizontal fluid-pressure gradients**

- **Winds**, **Friction**, & the **Coriolis effect** act in concert to generate patterns of flow of the upper ocean
- The **movement** of **water** in **response** to these **forces** is called "**Ekman Transport**"

- The first observations of **Ekman**-type processes were made in the Arctic Ocean by Fridtjof **Nansen**
- **Nansen** observed that sea ice floating on the ocean surface drifted n a direction 20-30˚ to the right of the wind.
- Upon his return, **Nansen** explained his puzzling observations to V. Walfred **Ekman**
- **Ekman's** explanation of **Nansen's** observations:
  1) As the wind blows across the surface of the ocean, it sets the water in motion, but because of the **Coriolis effect**, the water moves to the **right** of the wind
  2) As the top layer begins to move, it **drags the layer beneath it**, due to **friction**
  3) As each layer moves & drags the layer beneath it, the direction of flow is directed more towards the right, & because of friction, each layer moves a bit **more slowly**
  4) The result of these forces is a "**Spiral**," like a stack of cards, each of which moves in a different direction at a slower speed from top to bottom.
- This pattern of flow is now called the "**Ekman Spiral**"
- Almost a century later, in **1995**, high-resolution acoustic doppler current profilers were deployed allowing oceanographers to actually see the **Ekman Spiral**
- The **net result** of Ekman Transpot is to direct the surface layer of the ocean **45**˚ to the right in the Northern Hemispere, & 45˚ to the left in the Southern Hemisphere
- The **Mean Flow** (the average speed & direction) is directed **90**˚ to the right or left, respectively
- This has important implications for the surface circulation
- The **prevailing winds** (Easterlies & Westerlies) move water **90**˚ to the right or left, as a result, **water** tends to **pile up** in the **middle** of the **gyres**
- The "piling up" of water by the **Ekman Transport** generates a **horizontal pressure gradient** (from **high** to **low** pressure), it is acted upon by the **Coriolis Effect** and, in the Northern Hemisphere, deflects to the right.
- Ultimately, a steady-state balance is reached between the **Coriolis Effect** & the **horizontal pressure gradient** & the water flows **perpendicular** to the direction of the 2 opposing forces



- In the Northern Hemisphere, currents (**gyres**) move in a **clockwise** (**anticyclonic**) direction, while in the Southern Hemisphere, currents (gyres) move in a **counter-clockwise** (**cyclonic**) direction
- This steady-state flow, caused by the horizontal pressure gradient & the Coriolis Effect is called "**Geostrophic Flow**"
- "**Geostrophic**" means Earth turning; thus "**Geostrophic Flow**" refers to the flow under the influence of the turning Earth, i.e. the Coriolis Effect.
- The currents generated by the geostrophic flow are called "**Geostrophic Currents**"
- Most major ocean currents are Geostrophic Currents

Ekman Transport & Coastal Sea Level

	Ekman Flow (Ekman Transport)	**Geostrophic Flow** (Geostrophic Component)

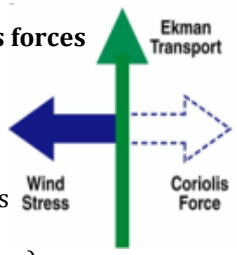
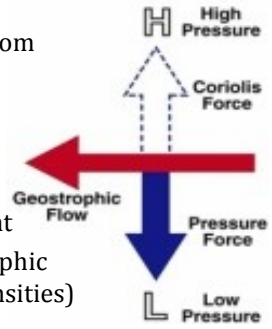
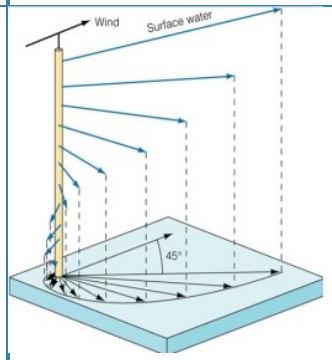
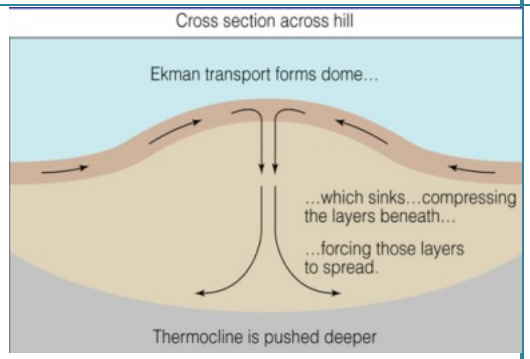
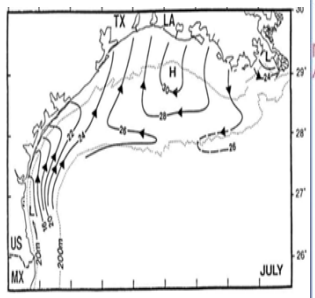
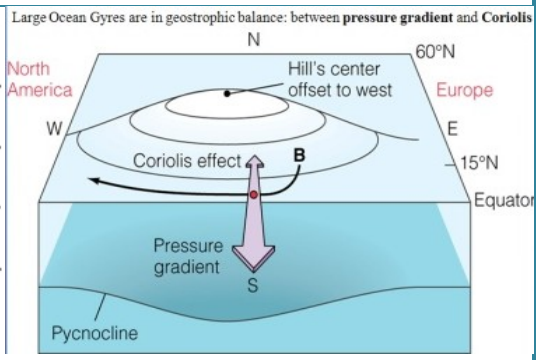
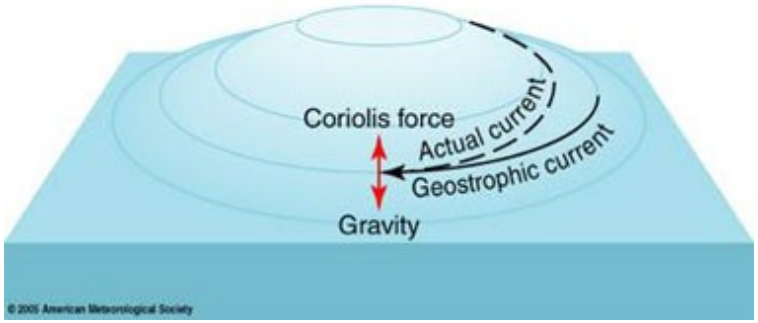
Description	- The part of the flow that responds to **wind-stress forces** exerted at sea surface
	- Accounts for:
	  - **pilling of water** in mid-ocean gyres
	  - **wind-related set-up/set-down** along coasts
	- **Ekman Spiral**: surface mixed layer (10-100m deep)
	 
		- The part of the flow that responds to **forces** from **horizontal fluid-pressure gradients**
		- it neglects time-dependant & nonlinear terms in equations of motion
		- It is what controls the big ocean gyres
		- High pressure will be to the right of the current
		- Geostrophic flow is eastimated from hydrographic measurements of temperature/salinity (Densities)
		- Wind is crucial!
		 

Diagram	  **Ekman Dynamics** **Open Ocean:** - Non-uniform wind speed and direction - Upwelling and Downwelling **Near Land :** - Parallel to the Coast - Upwelling and Downwelling **Shallow Water:** - Surface and Bottom Ekman Layers overlap - Transport tends more and more in the direction of the wind	 ➔ Wind driven flow  
Ex.	**Sargasso Sea** is an area of high water level because of the **pile-up** due to the **Ekman transport**	Circulation on the **Louisiana Shelf** is in some form of **geostrophic equilibrium** throughout the year

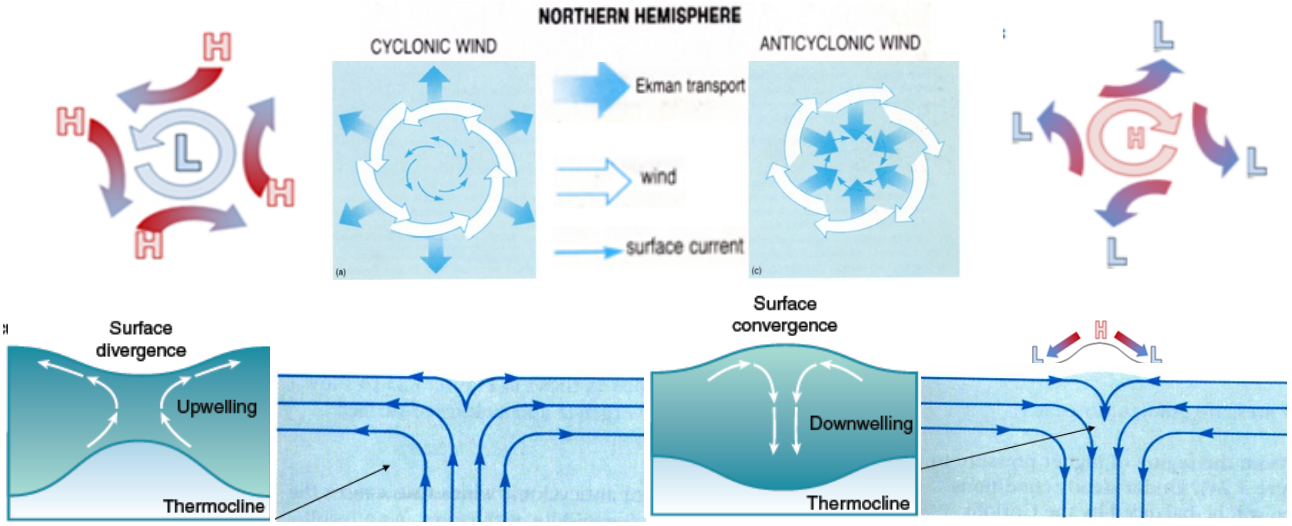
Ekman Transport & Coastal Sea Level

Cyclone

- **Counter-Clockwise**
- **Cold** (cold-core cyclonic eddy)
- **Divergence** at the sea surface leads to an **upwelling** of colder water
- ex. **Hurricanes**

Anticyclone

- **Clockwise**
- **Warm** (warm-core anticyclonic eddy)
- **Divergence** at the sea surface leads to an **upwelling** of colder water
- ex. **Loop Current**



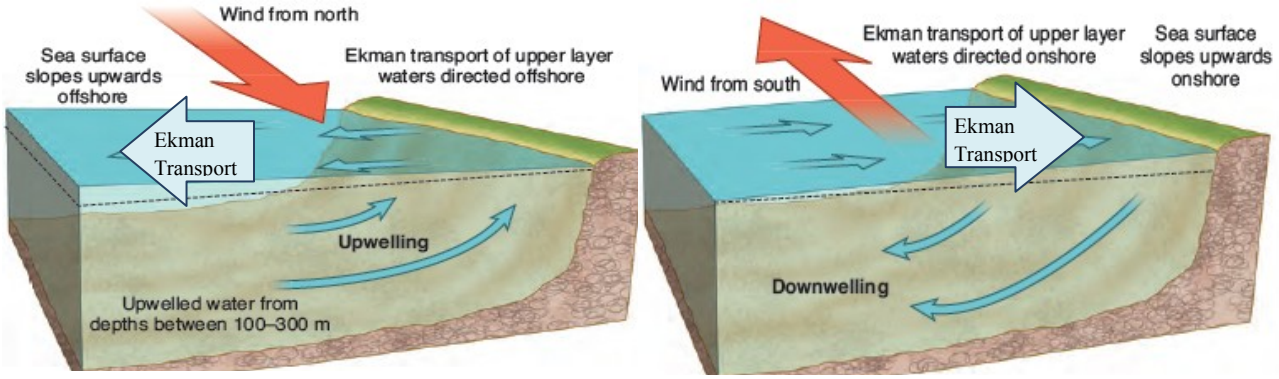
Upwellings & Downwellings are generated by Winds & Ekman Transport

Upwelling

- Coastal upwelling occurs as **northerly winds** move surface waters **offshore** in the Northern Hemisphere
- caused by **Low pressure** (storm centers) with **cyclonic** circulation
- can **boost** phytoplankton productivity by bringing deepwater nutrients up to the surface
- Most common along the equator & in coastal regions along eastern boundary currents
- Upwellings occur where **wind-generated Ekman transport** causes **surface waters to diverge**

Downwelling

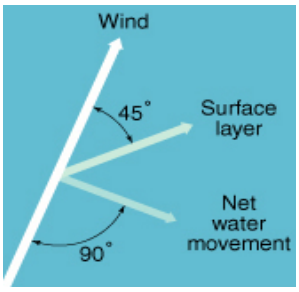
- Coastal downwellings occur as **southernly winds** move surface waters **onshore** in the Northern Hemisphere
- caused by **High pressure** systems with **anticyclonic** circulation
- can **limit** phytoplankton productivity by shutting off the deepwater supply of nutrients
- it has been suggested that regions in which high pressure systems persist (Bermuda, Hawaii, etc.) are **oligotrophic** because of the depression of the thermocline & limited nutrient supply

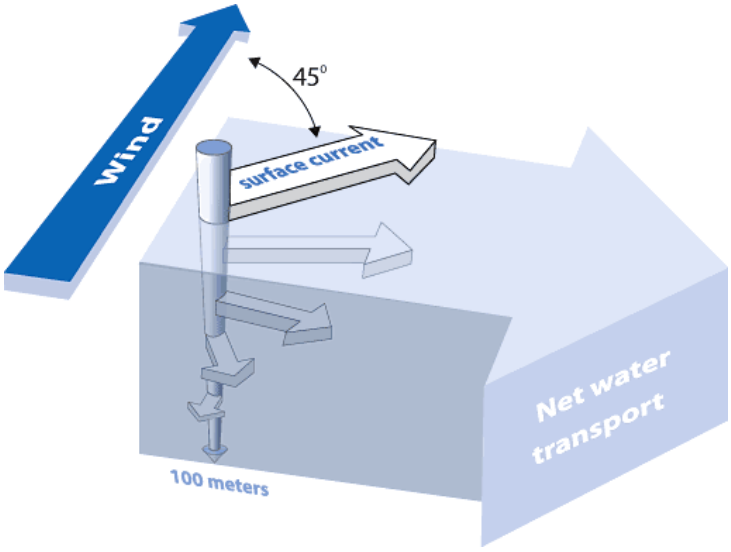


Ekman

➢ Ekman Transport

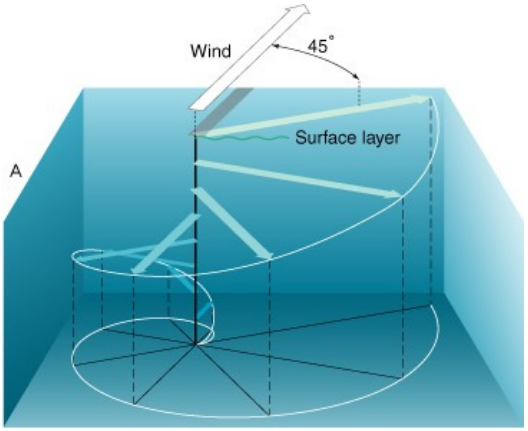
- Net water transport
- the sum of layer movement due to the **Ekman spiral**.
- **Theoretical Ekman** transport in the Northern Hemisphere is **90˚** to the right of the wind





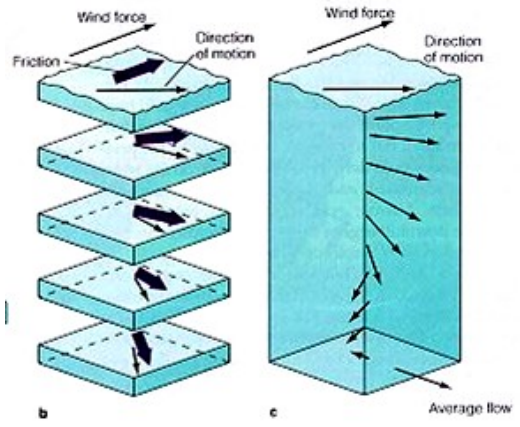
➢ Ekman Spiral

- A theoretical model of the effect on water of wind blowing over the ocean
- Because of the **Coriolis effect**, the surface layer is expected to drift at an angle of 45˚ to the right of the wind in the Northern Hemisphere and 45˚ to the left in the Southern Hemisphere.
- Water at successively lower layers drifts progressively to the right (N) or left (S), though not as swiftly as the surface flow.



➢ Ekman Depth

- the depth of frictional resistance (1,000m or 1km)
- where the net flow is 90˚ to the right of the wind
- the wind mixed layer



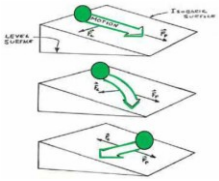
➢ Ekman Number (E_k) $\frac{\text{Friction}}{\text{Coriolis}}$

- In any rotating flow, the **Ekman number** is the ratio of **viscous forces** to **Coriolis forces**
- When the Ekman number is small, disturbances can propagate before decaying owing to frictional effects.
- The Ekman number **describes the order of magnitude** for the thickness of an **Ekman layer**, a boundary layer in which viscous diffusion is balanced by Coriolis effects, rather than the usual convective inertia.

Coriolis

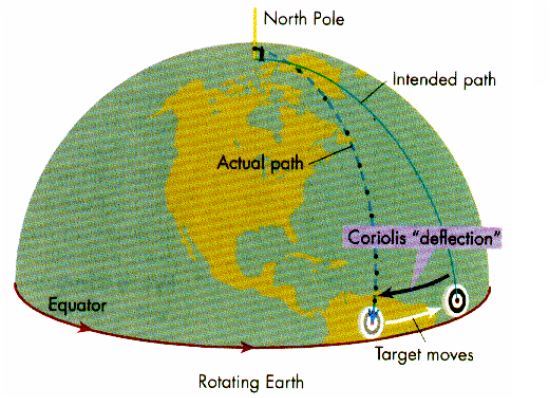
➢ Coriolis Effect

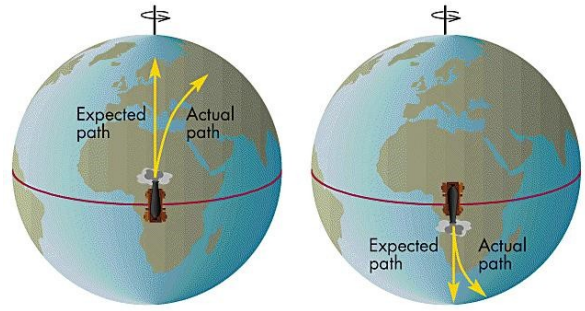
- The apparent **deflection** of **a moving object** from its initial course when its speed & **direction** are measured in reference to the surface of the **rotating Earth**.
- The object is deflected to the **right** of its anticipated course in the Northern Hemisphere & to the left in the Southern Hemisphere.
- The deflection occurs for **any horizontal movement of objects** with mass and has **no effect at the equator**
- This effect is **caused by** the **rotation** of the **Earth** & is **responsible** for the **rotation direction** of **cyclones**
- As a consequence, **winds** around the **center** of a **cyclone** rotate **counterclockwise** on the northern hemisphere & clockwise on the southern hemisphere.



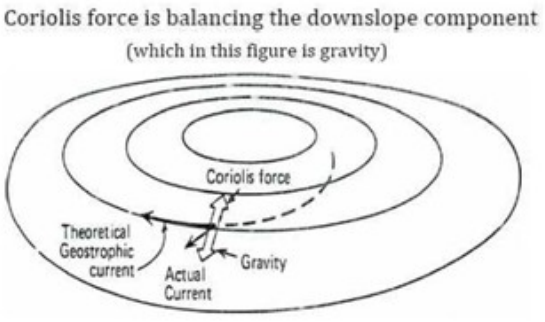
➢ Coriolis Force

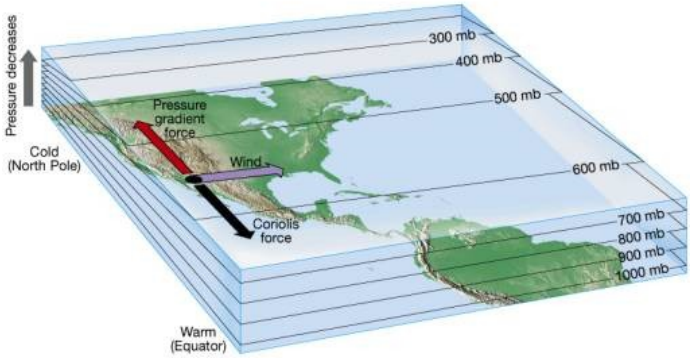
- an inertial force in the Earth reference frame, caused by the Earth's rotation.
- Essentially a parcel curves to the right until the parcel is moving at a right angle to the downslope where the forces balance
- Perpendicular to the velocity
- curves the trajectory, the speed of the object does not increase
- to the right of motion in the Northern hemisphere, to the left in the southern hemisphere
- The **Coriolis Force** appears in equation of motion (as the **Coriolis term**) in a rotating frame of reference and causes the **Coriolis effect**.





A Projectile fired northward **B** Projectile fired southward





➢ Western Intensification

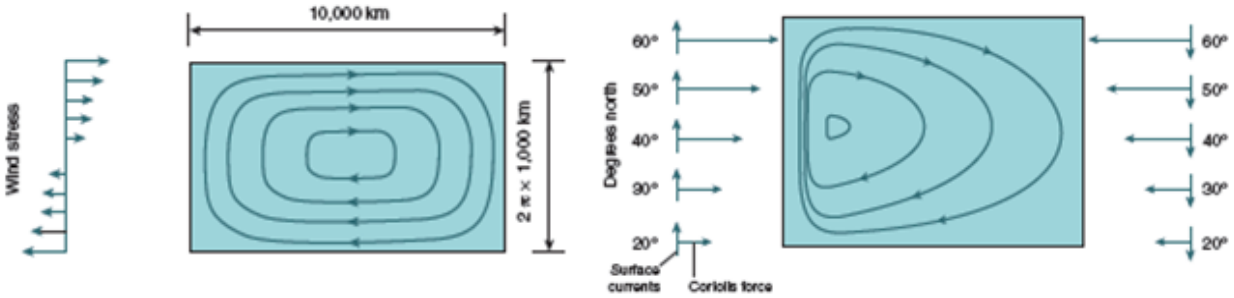
- "**Western Intensification**" explains why **Western Boundary Currents** are **faster** & **narrower** than Eastern Boundary Currents
- While oceanographers observed this phenomena early on, they weren't able to explain it until 1948, when Henry **Stommel** proposed that Western Boundary phenomena could be caused by **variations** in the **Coriolis Effect** with **Latitude**
- Because the Coriolis Effect becomes **stronger** at higher latitudes, he reasoned that it might account for the **narrowing of streamlines** on the western boundaries of gyres

Stommel's model of Gyre Circulation in an Idealized North American Basin

In 1948, Henry Stommel showed that it is the variation of the Coriolis Parameter with latitude that is responsible for the Western Intensification of the major ocean gyres.

Stommel's Assumptions:
- Rectangular, bounded ocean of constant depth
- One side of the equator
- Tangent plane (flat ocean)
- East-west wind varying with y (wind stress in the figure below)
- Friction – to prevent acceleration

Without the Coriolis Effect | **With the Coriolis Effect**



This shows the importance of the Coriolis Term for explaining **Western Intensification**

Stommel's solutions – The left figure is for constant f
The right figure is for f varying linearly with y (**β-plane approximation**)
#'s = lines of constant elevation

-- VORTICITY --
Tendency to rotate
Horizontal changes in velocity
Velocity Shear

Top of object (N) pushed by a slower wind than the bottom of the object (S)

Another way to look at what happens is:

The Wind Stress puts Spin into the water and friction is required to take it out.

If there was nothing to take out the spin, then the gyre's spin would increase infinitely
→Friction counters the spin to balance it out

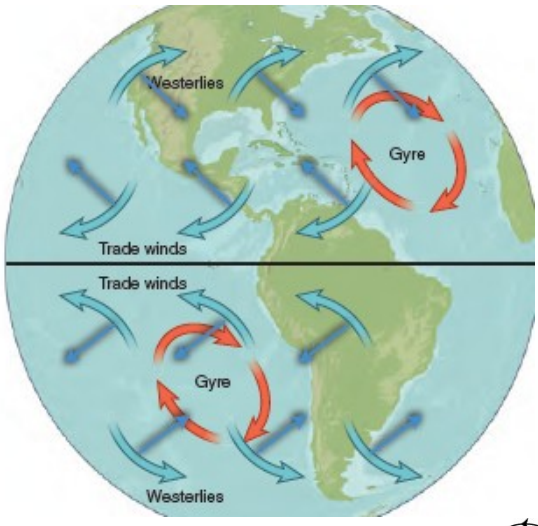
The Spin that is put into the ocean is called Vorticity

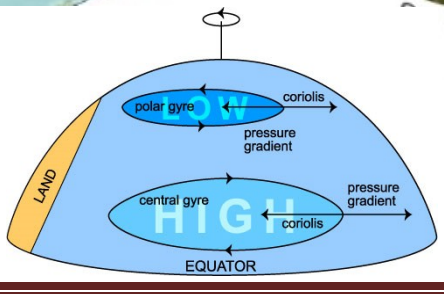
Terminology

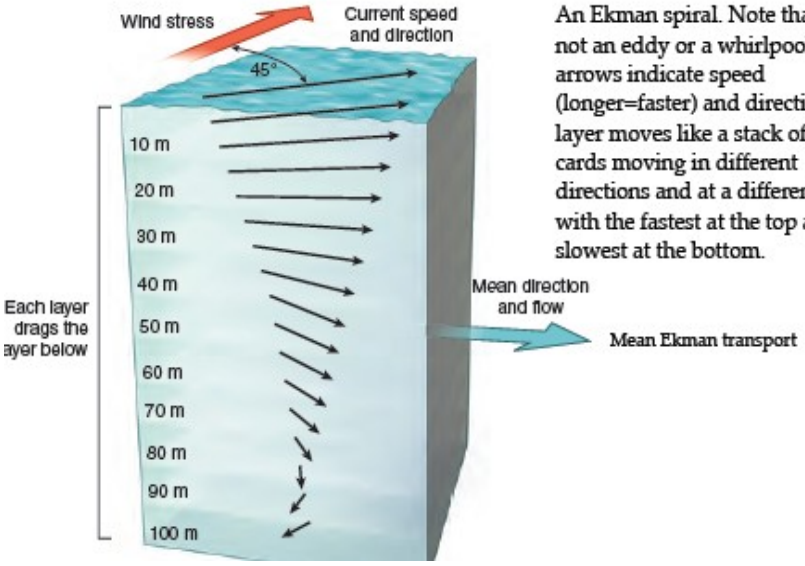
- **Geostrophic**
  - Describing a gyre or current in balance between the Coriolis effect & gravity
  - Literally "turned by Earth"
- **Air mass**
  - A large mass of air with nearly uniform temperature, humidity, & density throughout.
- **Atmospheric Circulation Cell**
  - Large circuit of air driven by uneven solar heating and the **Coriolis effect**.
  - Three circulation cells form in each hemisphere (the **Ferrel**, **Hadley**, & **polar** cells).
- **Countercurrent**
  - A surface current flowing in the opposite direction from an adjacent surface current
  -
- **Current** : Mass flow of water (usually horizontally)
- **Eddy**
  - A circular movement of water usually formed where currents pass obstructions, or between two adjacent currents flowing in opposite directions, or along the edge of a permanent current.
- **Eustatic Change** : A worldwide change in sea level, as distinct from local changes
- **Gyre**
  - Circuit of mid-latitude currents around the periphery of an ocean basin.
  - Most oceanographers recognize five gyres plus the Antarctic Circumpolar Current.

The net transport of water is 90 degrees to the right of the wind in the Northern Hemisphere and 90 degrees to the left of the wind in the Southern Hemisphere.

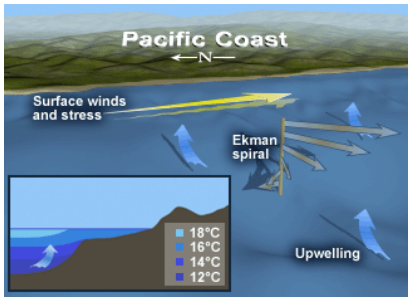
Net flow of upper ocean from surface to Ekman layer depth.

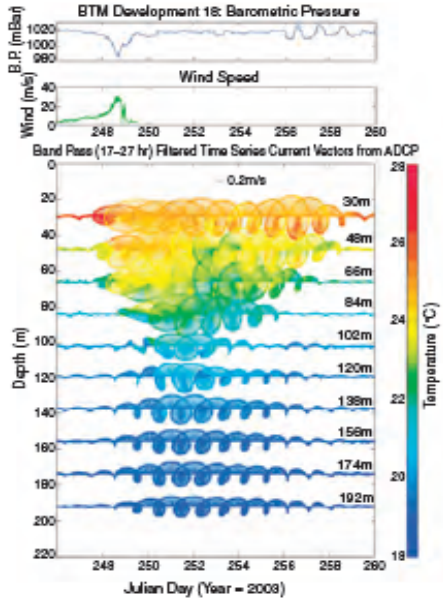




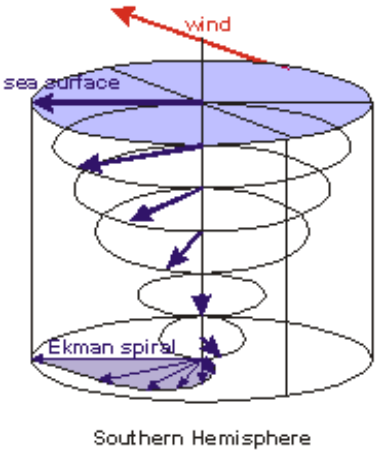


An Ekman spiral. Note that this is not an eddy or a whirlpool. The arrows indicate speed (longer=faster) and direction. Each layer moves like a stack of 3 x 5 cards moving in different directions and at a different speed, with the fastest at the top and the slowest at the bottom.

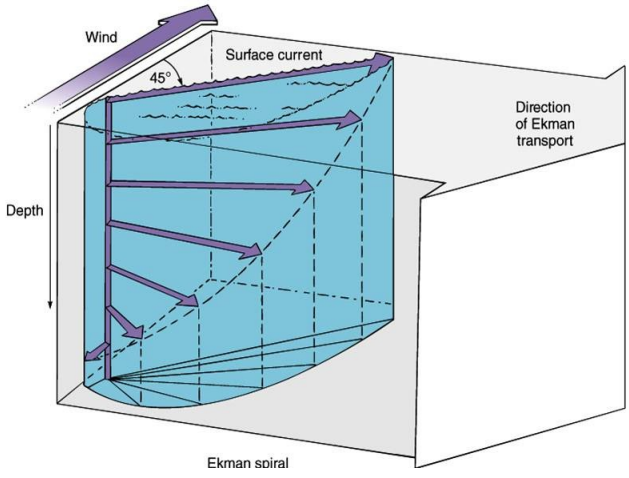


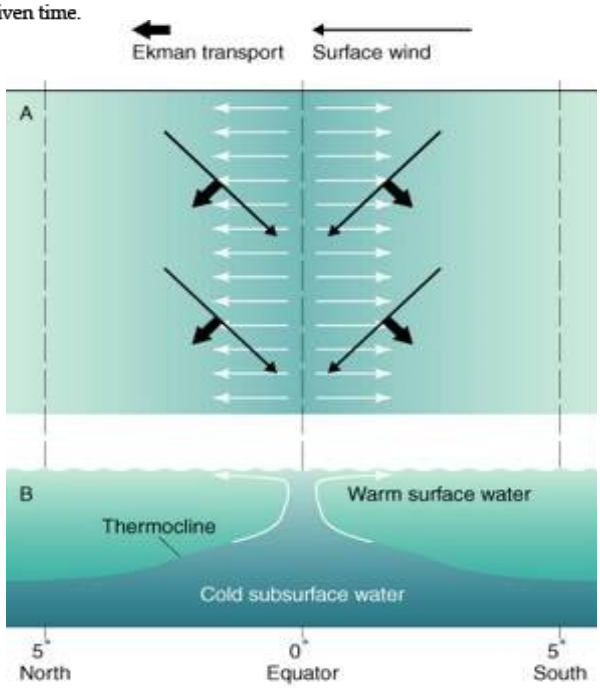


Professor Dickey captured this Ekman spiral when a hurricane passed over the Bermuda Testbed Mooring. The x-axis indicates time while the z-axis indicates depth. The lines illustrate direction and speed; a larger "loop" corresponds to a faster current. Colors on the lines indicate seawater temperature. If you study this graph carefully, you will see that current speeds decrease with depth and that current direction is offset for each depth at a given time.



Southern Hemisphere





Sea-Level

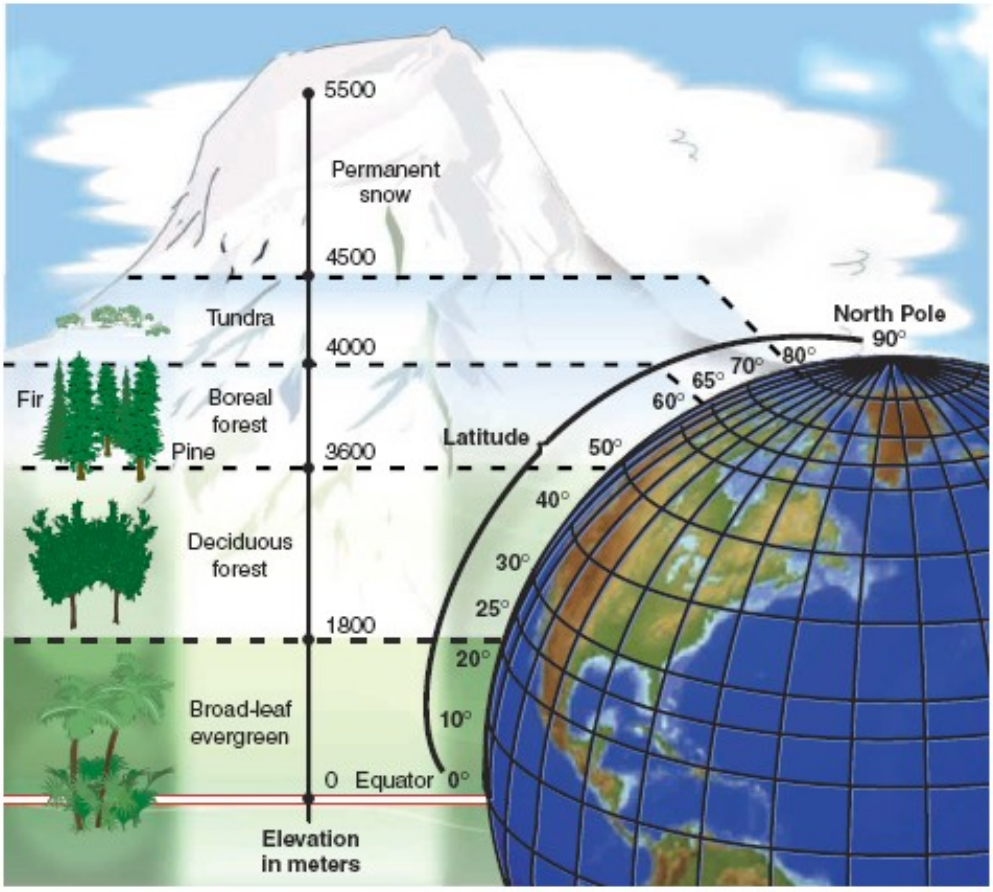


figure 6.9 **Relationship Between Height above Sea Level, Latitude, and Vegetation**
As one travels up a mountain, the climate changes. The higher the elevation, the cooler the climate. Even in the tropics, tall mountains can have snow on the top. Thus, it is possible to experience the same change in vegetation by traveling up a mountain as one would experience traveling from the equator to the North Pole.