WIND INDUCED CIRCULATION

- The wind stress is the frictional force, per unit of area, acting on the sea surface as a result of the wind blowing over it. It is given by the expression:
  \[ \tau = cw^2, \text{ com } c = \rho_a c_D, \]
  where \( w \) is the wind speed, \( \rho_a \) is the air density and \( c_D \) is the drag coefficient.

- The wind stress depends on the following factors:
  - wind speed;
  - roughness of the sea surface;
  - prevailing atmospheric conditions.

- The wind stress blowing over the ocean causes transfer of momentum from the atmosphere to the ocean, given rise to two different phenomena:
  - gravity surface waves;
  - surface currents or drift currents.

- An empirical observation, valid for low wind speeds, is that the drift current is typically about 3% of the wind speed.
The effect of the wind stress at the surface is transmitted downwards as a result of **internal friction** caused by the **turbulent flow** of the water, and not simply by the viscosity of a laminar flow. The **eddy viscosity** (turbulent viscosity) is much higher than the molecular viscosity.

Differences between (a) laminar flow and (b) turbulent flow; the arrows show the different pathways of the individual water parcels.

Difference between (a) molecular viscosity, where the transfer of momentum between layers is associated with individual molecules, and (b) **eddy viscosity**, where the momentum transfer is associated with parcels of water.
WIND INDUCED CIRCULATION

- The **eddy viscosity coefficient** is the most important coefficient of friction to study the Ocean. It depends on the degree of turbulence and presents a wide range of variation:

  - $A_Z$ - **eddy viscosity coefficient** for the vertical mixing.
    Range of values: $10^{-2} - 10^2$ kg m$^{-1}$s$^{-1}$.

  - $A_H$ - **eddy viscosity coefficient** for the horizontal mixing.
    Range of values: $10^4 - 10^8$ kg m$^{-1}$s$^{-1}$.

- The fact that $A_H$ shows much higher values than $A_Z$ reflects the different extent of the vertical and horizontal mixing. The horizontal mixing is much higher than the vertical mixing, because the stability of the Ocean is much higher in the vertical coordinate than in the horizontal one.
The water parcel starts to accelerate in the wind direction; as soon as it starts to move, it rotates to the right due to the action of the Coriolis force; the steady state is reached when the three forces, $F_t$, $F_C$, e $F_b$, are in balance; at that time the surface velocity $V_0$ is constant (steady state) and makes an angle of 45º to the right of the wind direction.
Hypothesis of the Ekman Model to explain the wind induced circulation:

- Uniform wind field over all the Ocean;
- Infinite vertical and horizontal dimensions of the Ocean;
- Homogeneous Ocean, that means, $\rho=\text{constant} \rightarrow \text{Barotropic conditions}$;
- Horizontal sea surface, no slopes of the free surface;
- Stationary and negligible advective terms $\rightarrow$ linear model;
- Hypothetical Ocean, formed by an infinite number of horizontal layers; upper layer under the influence of the wind friction (wind stress) on top, and friction (eddy viscosity) with the layer immediately below; the horizontal friction is negligible ($A_H \approx 0$) and $A_Z = \text{constant}$;
- Layers moving under the influence of the Coriolis Force.
WIND INDUCED CIRCULATION – Ekman theory

Ekman model for the wind induced circulation (northern hemisphere):
(a) forces and velocity at the surface – the total friction force balances the Coriolis force and the current is perpendicular to both;
(b) plan view of the surface current velocity, $V_0$, and correspondent components, as well as the wind direction, aligned with the $y$ axis;
(c) perspective view of the exponential decrease of the current velocity with depth and it associated clockwise rotation;
(d) Plan view of the current velocity at equal depth intervals, representing the Ekman Spiral.

For increasing depths, the velocity vector diminishes of intensity and rotates to the right in the northern hemisphere (left in the southern hemisphere). The edge of the vectors shapes a logarithm spiral, the Ekman Spiral; the length of the arrows is proportional to the intensity of the current and their direction is the direction of the current.
WIND INDUCED CIRCULATION – Ekman theory

- Depth of influence of the wind friction or Depth of the Ekman layer, D:
depth at which the current induced by the wind is directly opposed to the
current induced at the surface; at that depth the intensity of the current is 1/23
of its value at the surface and the wind effect is considered negligible.

- The depth of the Ekman layer depends on the eddy viscosity coefficient, $A_z$,
and on the latitude $\phi$,

$$D = \pi \left( \frac{2A_z}{\rho f} \right)^{1/2} = \pi \left( \frac{A_z}{\rho \Omega \sin \phi} \right)^{1/2}$$

- The intensity of the mean in the Ekman layer – intensity of the mean current
integrated over all the Ekman layer,

$$\overline{V} = \frac{\tau_{zy}}{D \rho f}$$

- Ekman transport: - total volume of water transported per unit of time in a right
angle *cum sole* with the direction of the wind; the Ekman transport is
computed through the product of the mean velocity with the area of the
section perpendicular to the movement $\Rightarrow$ it is a transport of volume or a flow.
Left: Ekman spiral representing the pattern of currents induced by the wind in the northern hemisphere; Top layer balance of wind friction and Coriolis force; layer 2 dragged forward by layer 1 and behind by layer 3….etc.

Right: In the Ekman layer the wind stress is balanced by the Coriolis force. The mean motion of the Ekman layer is perpendicular to both - 90° to the right of the wind stress in the northern hemisphere.
WIND INDUCED CIRCULATION – Results of the Ekman theory

- Considering the balance between the friction forces and the Coriolis force in an infinite number of layers that constitutes the water column, Ekman concludes that:
  - the speed of the current induced by the wind decreases exponentially with the depth;
  - the direction of the surface current makes an angle of 45° with the wind direction, to the right (left) in the northern hemisphere (southern hemisphere); this deviation angle increases with depth ⇒ the simultaneous decrease of the speed and increase of the deviation angle with depth forms to the Ekman spiral.
  - the mean motion and the transport in the Ekman layer take place at a right angle with the wind direction, to the right (left) in the northern hemisphere (southern hemisphere).
As the sea floor approaches, the geostrophic current diminishes the speed due to the bottom friction. The Coriolis force diminishes too, since it is proportional to the speed. Thus, the pressure gradient force is not balanced anymore and the flow rotates to the left looking for a new balance. The new balance, between the Coriolis force, pressure gradient force and the bottom friction, is reached when the current velocity rotates 45° to the left. Anyway, at that point the velocity is zero!!! So, the current does not rotate the entire angle of 45°!!
CONVERGENCE AND DIVERGENCE IN THE OCEAN

Effect of a cyclonic and an anticyclonic wind on the surface and mixed layer – Ekman Pumping

Generation of a geostrophic current in an eddy induced by an anticyclonic wind in the northern hemisphere.
Several types of surface flows that induce vertical motion in the ocean: (a) divergence induces upwelling of the sub-surface waters; (b) convergence induces downwelling of the surface waters.
Schematic representation of the upwelling development on an eastern boundary on the ocean in the northern hemisphere.
Schematic representation of upwelling events induced by winds of variable cross shore intensity.

Main upwelling regions of the World Ocean.
COASTAL UPWELLING OBSERVED FROM THE SPACE

SST satellite image showing the upwelling region off North Africa.

SST satellite image showing the upwelling region off western Iberia.