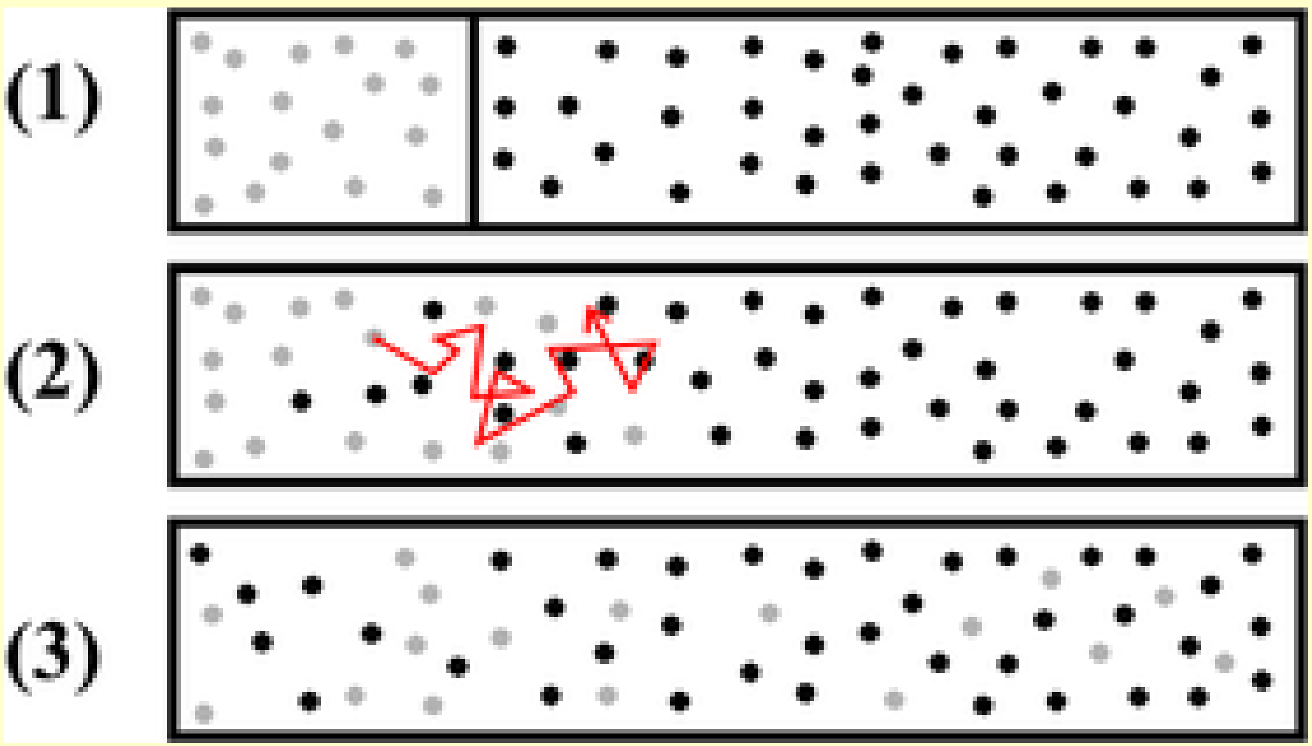
Lecture 7B:
Basic Forces and Coordinate System (Eddy and Molecular Viscosity)

Molecular Diffusion

Molecular diffusion is the thermal motion of all (liquid or gas) molecules at temperatures > absolute zero (-273 deg.C.).

The rate of this movement (N_A) is function of temperature, viscosity of the fluid, and the size (mass) of the molecules.



Very slow…

Poses limitation for diffusion of nutrients and waste in kelps

Molecular Diffusion

$$N_A = -D_{AB}\frac{dC_A}{dx}$$

Rate of Diffusion N_A, usually expressed as number of molecules diffusing across unit area in unit time (a flux).

Where:

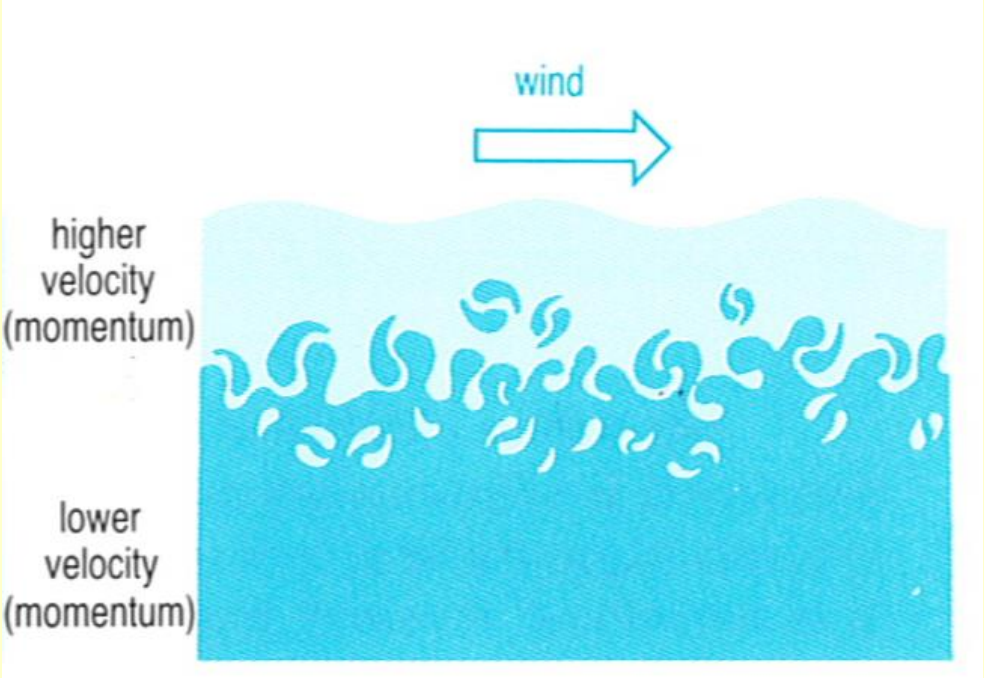
D is the Diffusivity of molecules of A through area B.

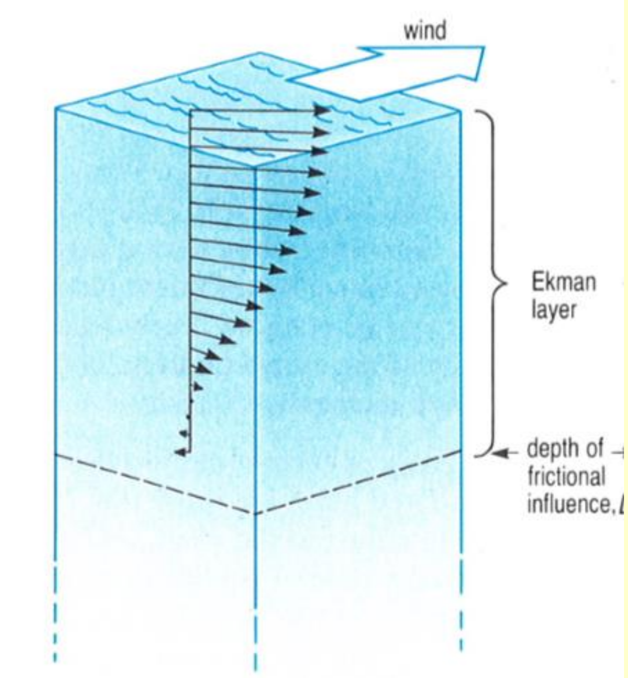
$-dC_A/dx$, is the gradient in concentration.

C_A is the concentration of A and X is distance.

NOTE: The negative sign arises because diffusion spreads molecules down an existing gradient. Concentration of A decreases as the distance x increases.

Turbulence and Mixing





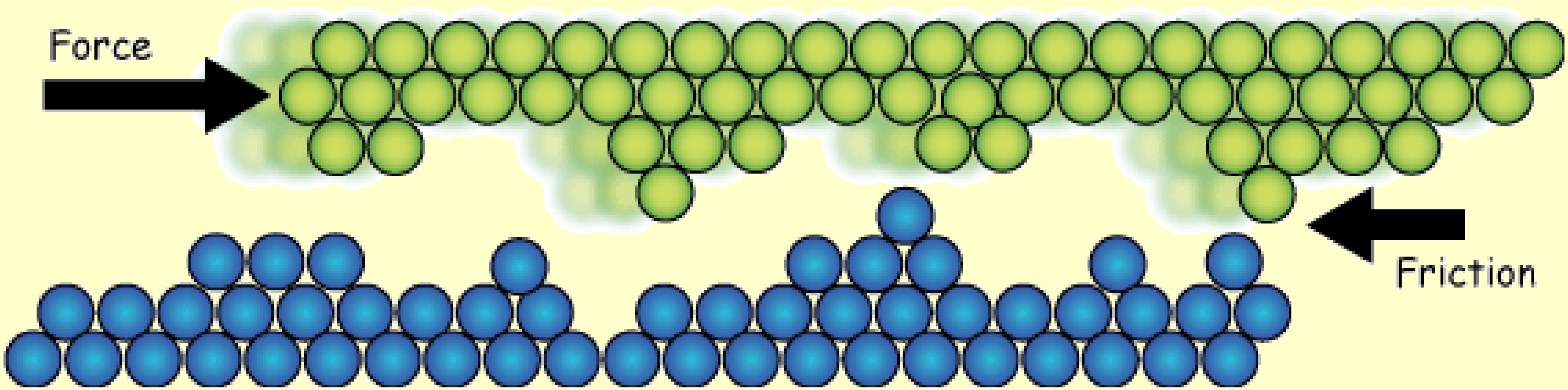
Momentum transfer accelerates water molecules, down to the "depth of frictional influence" (D) related to the speed and duration of the wind.

As soon as the water parcels are in motion, Coriolis starts affecting their movement by deflecting them.

Friction

- Resistance of a fluid to motion (or more properly, the resistance to the transfer of momentum) due to the interactions between water molecules (laminar flow) or between parcels of water (turbulent flow and mixing).

- This resistance to the transfer of momentum is parameterized (estimated) by the term "viscosity".



What is Viscosity?

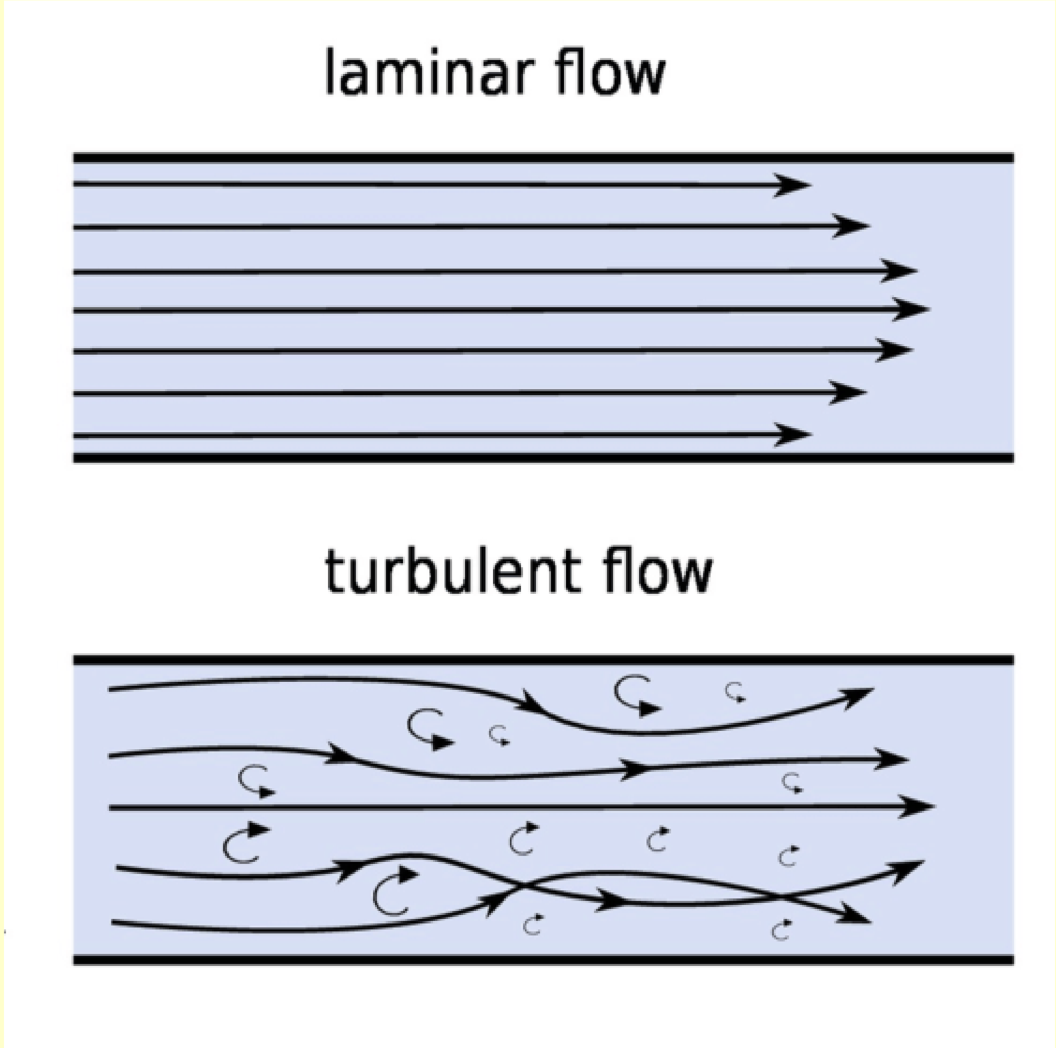
- Measure of resistance to momentum transfer
  (thought of as the transfer of velocity,
  but objects with the same velocity but
  different mass have different momentums)
- Useful parameter to understand the transfer of motion within the ocean and between the ocean and the atmosphere

- The magnitude of viscosity in the ocean is variable and generally poorly known
- It varies depending on the “type” of flow

Two Types of Flow: Laminar or Turbulent

Molecular viscosity (between water molecules)

Eddy viscosity (between water parcels)

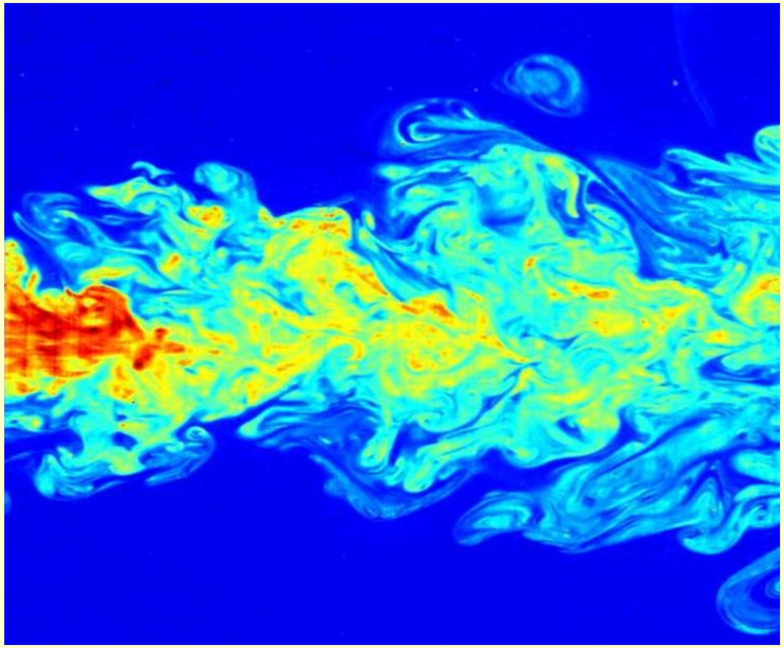


Laminar Flow

Molecular viscosity describes resistance to flow between molecules

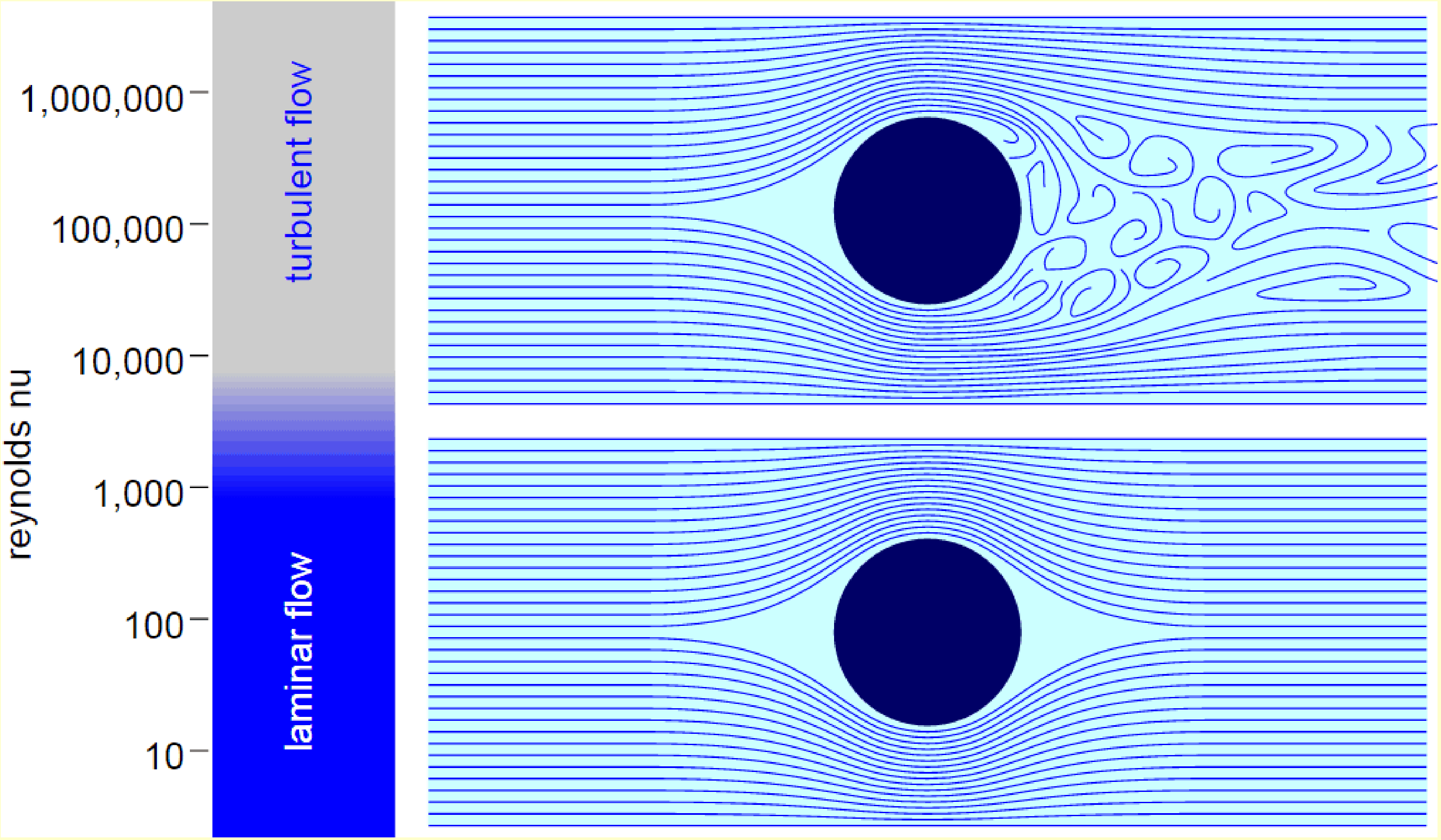
Turbulent Flow

Eddy viscosity describes momentum transfer in the sea, and between the sea and the air overhead



Reynolds Number (Re) Definition

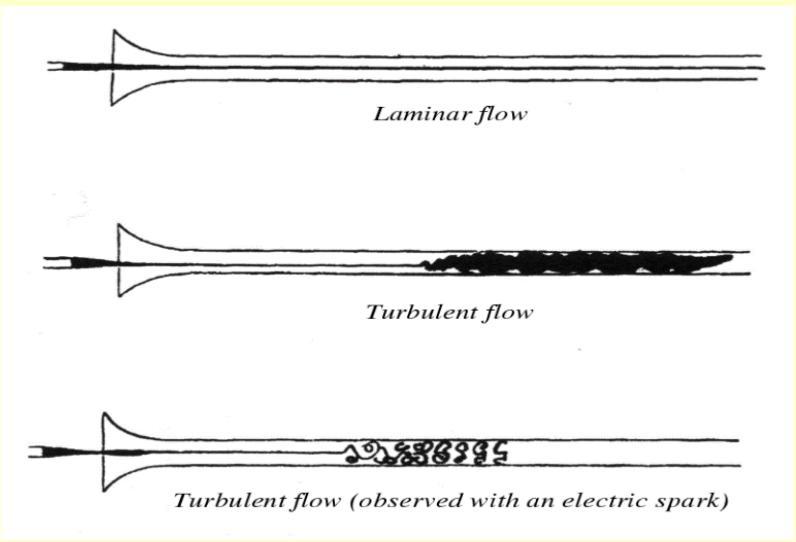
Dimensionless quantity used to help predict flow patterns in different fluid flow situations.

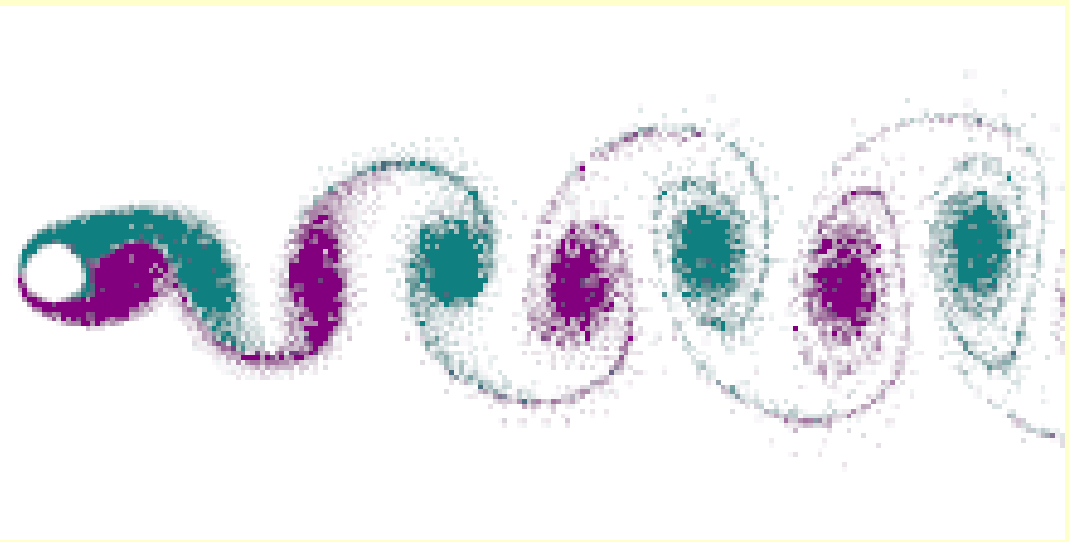


Reynolds Number Formula

Re = Inertial Forces / Viscous Forces
Re = (V * L) / ν

V = velocity of fluid
L = length of obstacle or diameter of fluid
ν = kinematic viscosity of fluid





Reynolds Number Units

Re = Inertial Forces / Viscous Forces

$$Re = \frac{\text{Length} * \text{Speed}}{\text{Kinematic Viscosity}} = \frac{m * m / s}{m * m / s}$$

Kinematic Viscosity = Dynamic Viscosity / Density

- ν is the kinematic viscosity of fluid (m^2/s)

- μ is the dynamic viscosity of fluid ($N \cdot s/m^2$; $kg/m \cdot s$)
- ρ is the density of the fluid (kg/m^3)

Two Viscosities

- There are two formulations of viscosity:
- Dynamic viscosity and Kinematic viscosity

- Dynamic viscosity has units of kg m^{-1} sec^{-1} (as above)
- Kinematic viscosity = Dynamic viscosity / Density

- Kinematic viscosity therefore has units of:
  - kg m^{-1} sec^{-1} * ρ^{-1} or kg m^{-1} sec^{-1} * m^3 kg^{-1} or m^2 sec^{-1}

- Kinematic viscosity also called an eddy diffusion coefficient is used to describe turbulent ocean flux

- Equations of motion use dynamic viscosity (kinematic viscosity * density) to compute momentum transfer

Reynolds Number Implications

Laminar flow occurs at low Re, where viscous forces dominate, and fluid motion is smooth and constant.

Turbulent flow occurs at high Re, where inertial forces dominate, and produce chaotic flow instabilities.

Laminar flow domain:

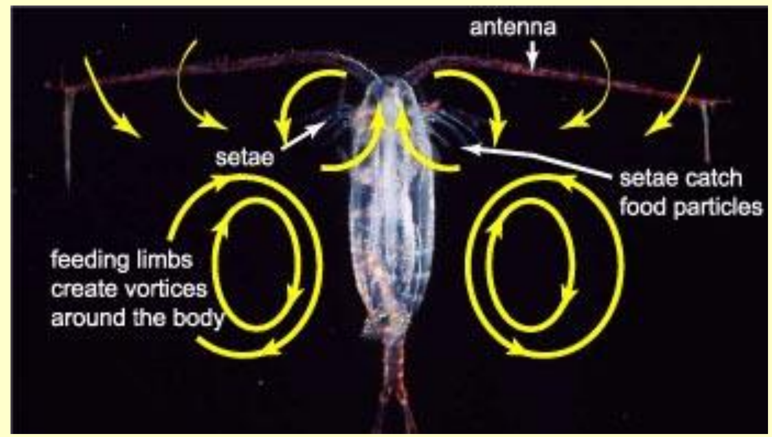
- Bacterium ~ 1×10^{-4}
- Ciliate ~ 1×10^{-1}
- Smallest fish ~ 1

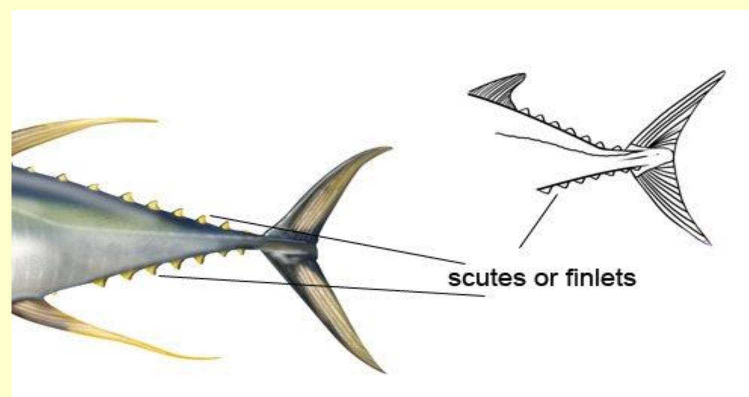
Onset of turbulent flow:

~ 2.5×10^{3} for pipe flow

~ 10^{6} for boundary layers

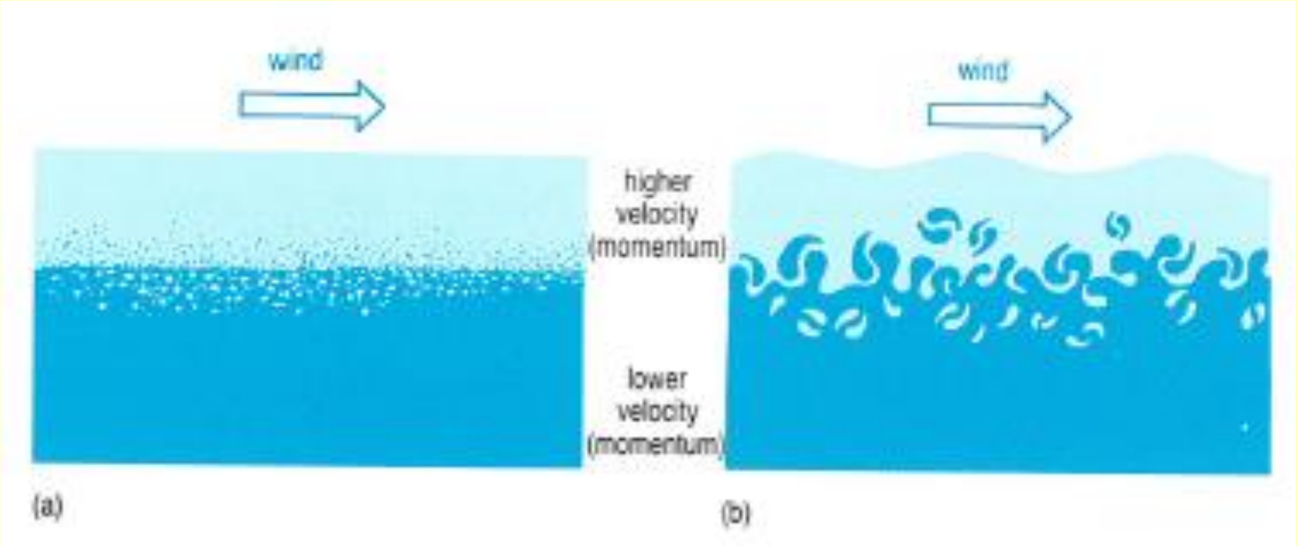
- A blue whale ~ 4×10^{8}
- A large ship ~ 5×10^{9}

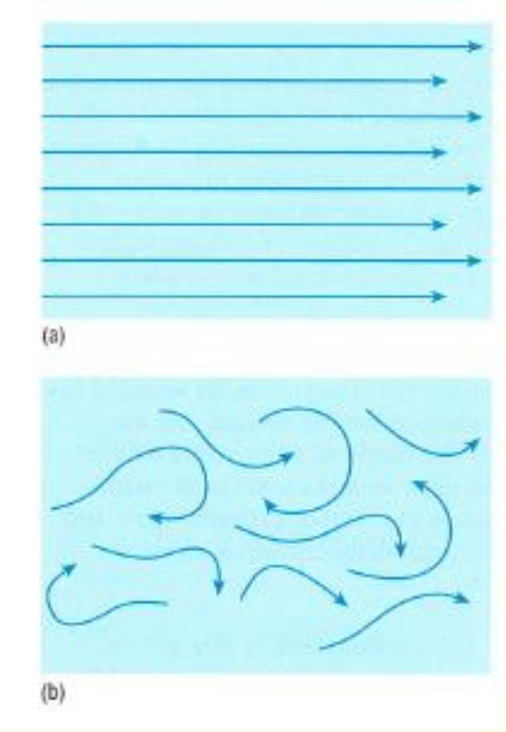




Molecular and Eddy Viscosity

TOS Ocean Circulation Chapter 3





(a) Molecular viscosity (laminar flow) water parcels move in same direction

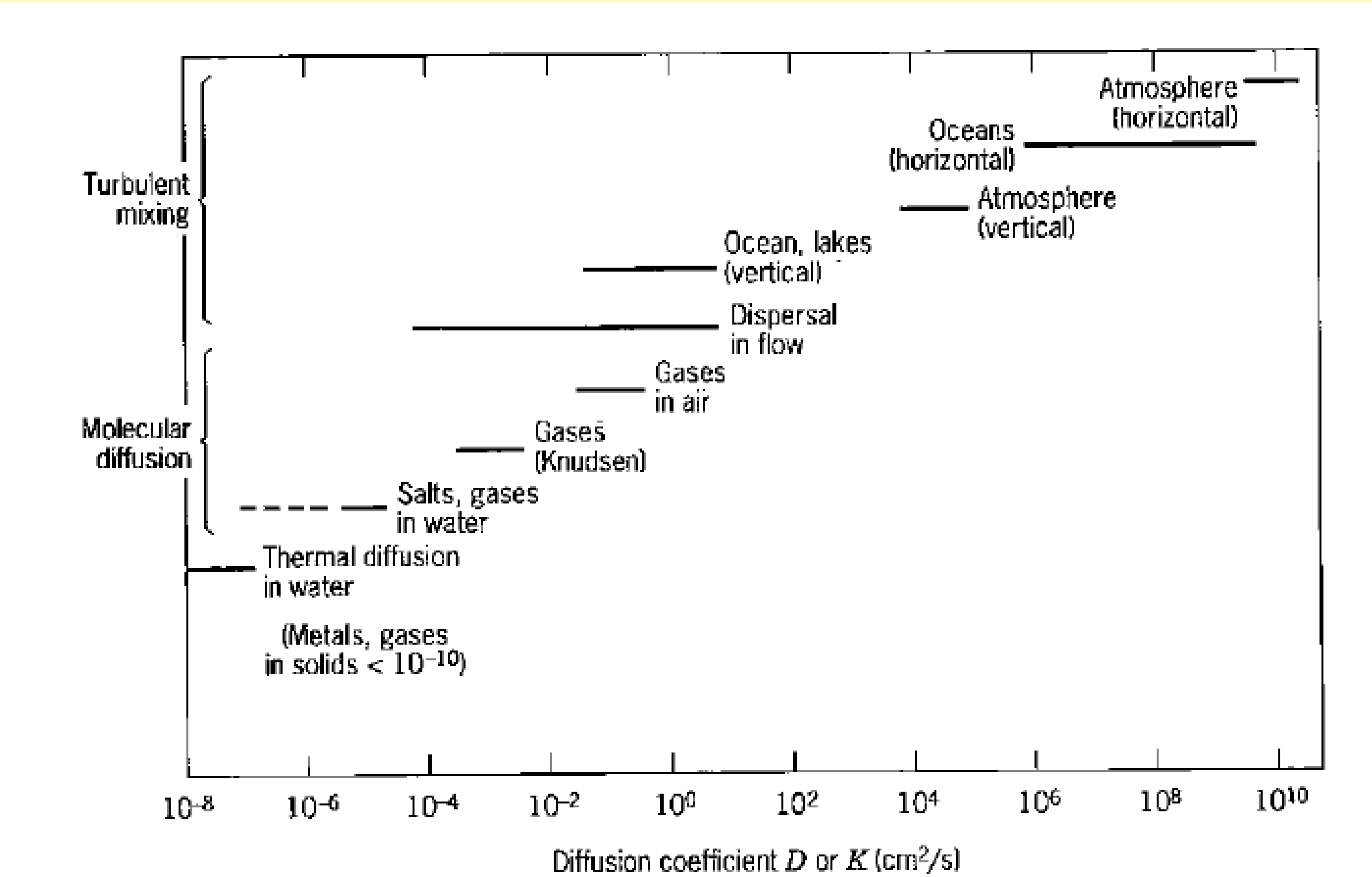
(b) Eddy viscosity (turbulent flow) hypothetical paths of water parcels

So which is larger ? molecular of eddy viscosity

- Viscosity is a measure of the resistance to momentum transfer. Viscosity opposes Re.
- Higher viscosity indicates more resistance to momentum transfer. Leads to a smaller Re.

- More rapid momentum transfer when dealing with parcels than molecules of liquid or gas.
- Therefore eddy viscosity is larger than molecular viscosity because the transfer of momentum is faster when larger parcels of water are interacting.

Eddy Diffusion Coefficients (turbulent versus molecular)



Faster diffusion

Note:

Diffusion coefficient is another term for kinematic viscosity

Sometimes expressed as $cm^2\ sec^{-1}$

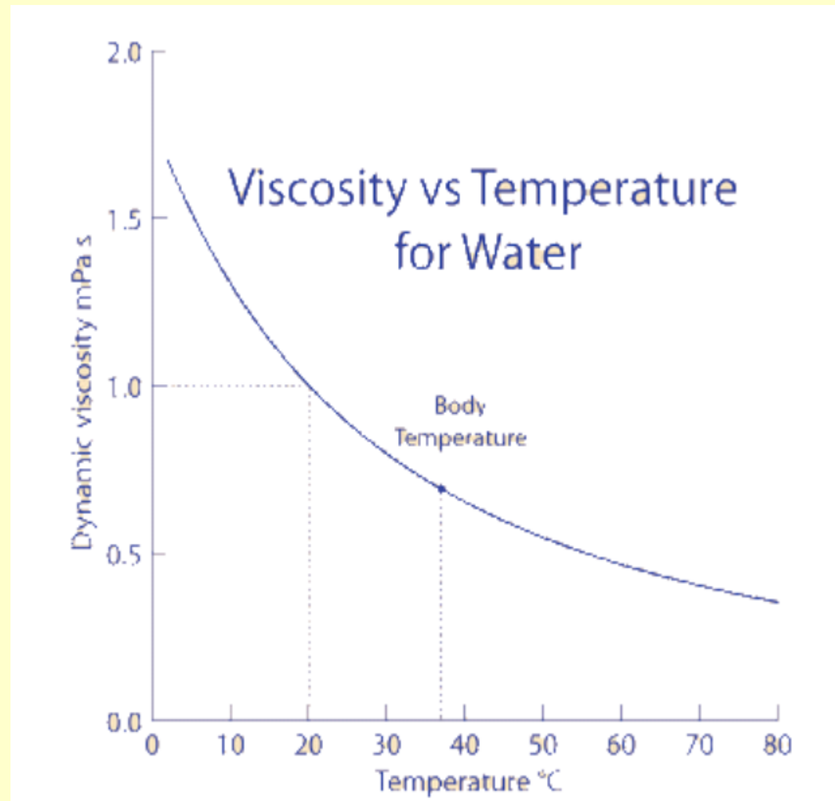
(Libes, 1992)

Viscosity

- One of most vexing parameters in ocean science
  - very important for momentum transfer
  - very difficult to quantify precisely

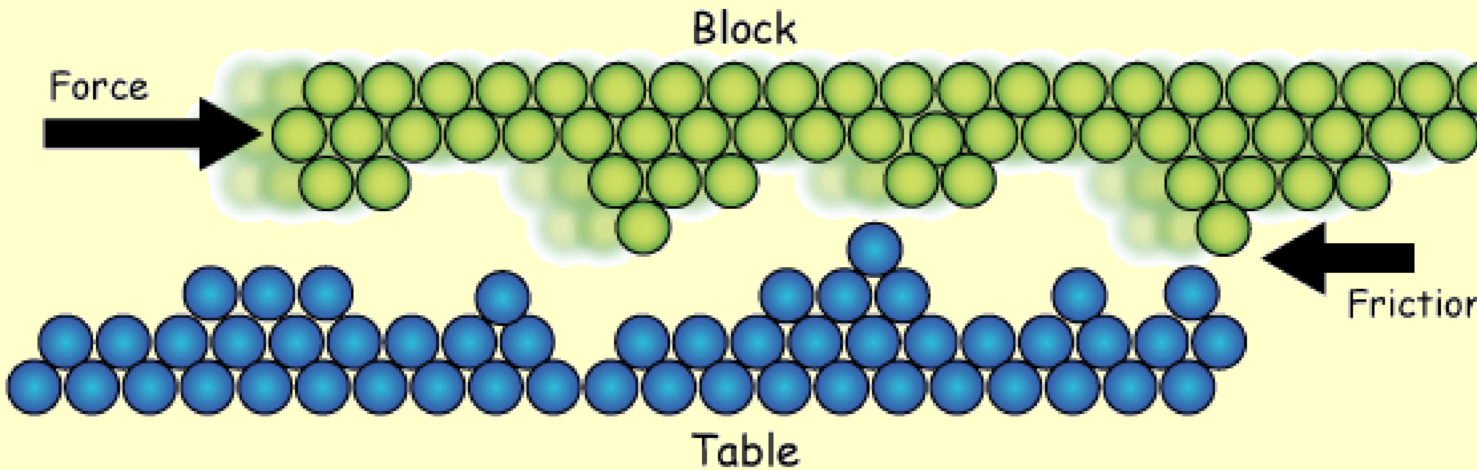
- Often treated as constant; but varies as a function of density (temp, pressure).

- The viscosity decreases with increasing temperature.
- Alternatively, the fluidity of any liquid increases with increasing temperature.



Parameterizing Viscosity

- Measured as the ratio of pressure (Newton / m^2 *i.e.,* pascals) to the internal acceleration in a fluid

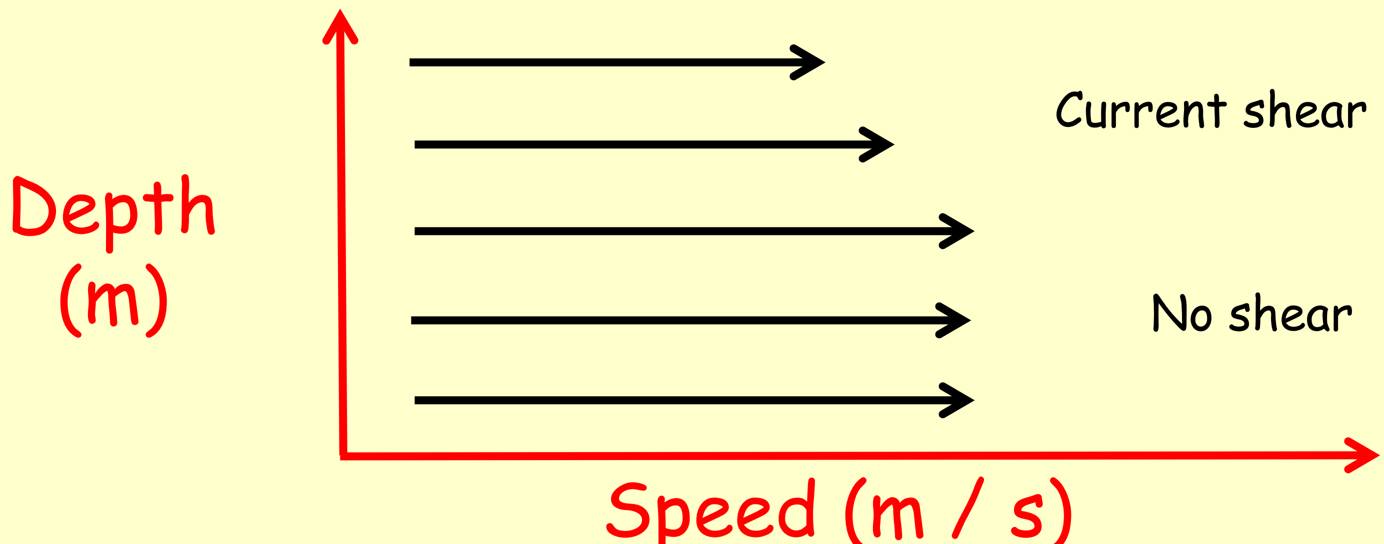


- Internal acceleration of the molecules is measured as a velocity gradient (or shear)
- Viscosity is therefore the ratio of force / m^2 (between two layers) relative to velocity shear

Viscosity is a ratio of pressure between two layers (Newtons / m^2) to velocity shear

So, what is velocity shear?

- A change in current velocity with depth



- Units of velocity shear:
  (m/sec) / (m) = sec^{-1}

Let's check the units

- Viscosity measured as ratio of force (in units of pressure) to internal acceleration in a fluid perpendicular to the pressure force
  - Note: pressure is force per m^2 and a function of both speed or velocity and mass (*i.e.*, momentum)
- Therefore:
  - Viscosity = pressure / velocity shear (perp. to pressure)
- Viscosity units are pascals divided by rate of change in velocity with depth
    - Pascal = N m^{-2} or kg m^{-1} sec^{-2}
    - Velocity shear = sec^{-1}
  - So viscosity units are kg m^{-1} sec^{-1}
- This viscosity is properly called "dynamic viscosity" (this is viscosity not divided by density)

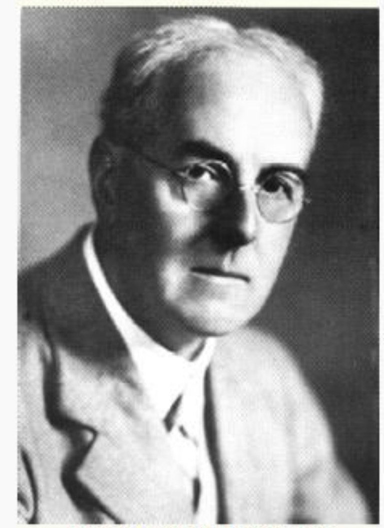
Horizontal and Vertical Eddy Viscosity

- Viscosity generally designated by letter A
  - A_z vertical eddy viscosity
  - A_h horizontal eddy viscosity

- Vertical viscosity (internal friction or resistance to momentum transfer) much greater than horizontal viscosity
- Due to the rapid density change in the vertical relative to the horizontal

Aside Poetry

Lewis Fry Richardson



Lewis Fry Richardson D.Sc., FRS

Physicist and meterologist
1881 - 1953

In his book "Weather Prediction by Numerical Process"