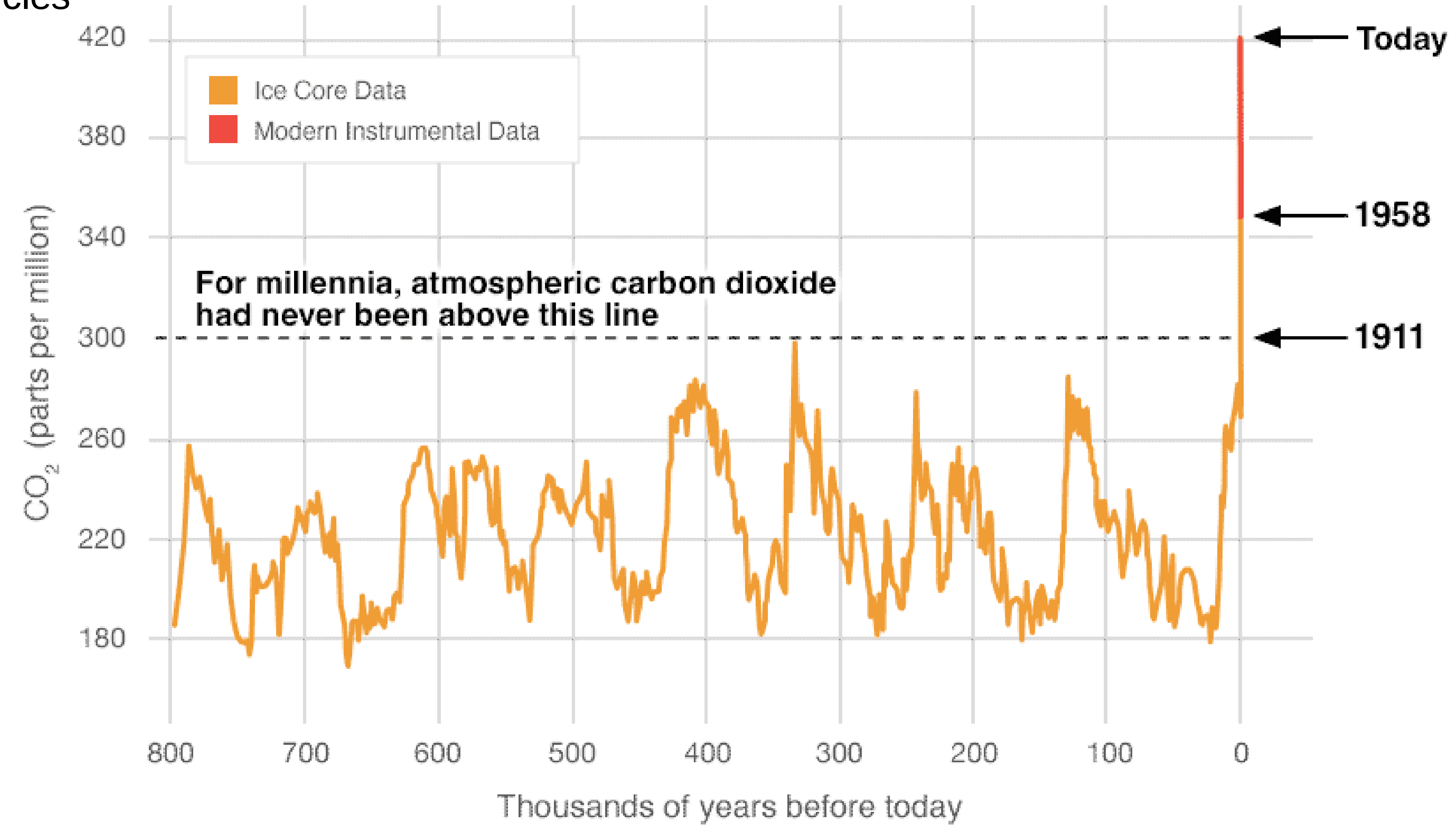
# The Carbon Cylce

A short introduction

- Cycles of glaciation-deglaciation
- Milankovic cycles



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Earth Syst. Sci. Data, 15, 5301–5369, 2023
https://doi.org/10.5194/essd-15-5301-2023


Open Access Earth System Science Data

### Global Carbon Budget 2023

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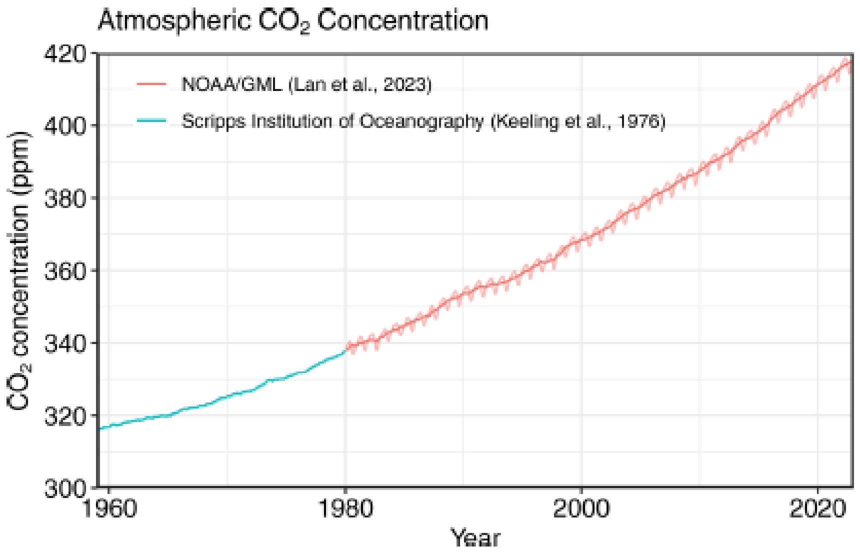


**Figure 1.** Surface average atmospheric $CO_2$ concentration (ppm). From 1980, monthly data are from NOAA/GML (Lan et al., 2023) and are based on an average of direct atmospheric $CO_2$ measurements from multiple stations in the marine boundary layer (Masarie and Tans, 1995). The 1958–1979 monthly data are from the Scripps Institution of Oceanography, based on an average of direct atmospheric $CO_2$ measurements from the Mauna Loa and South Pole stations (Keeling et al., 1976). To account for the difference in mean $CO_2$ and seasonality between the NOAA/GML and the Scripps station networks used here, the Scripps surface average (from two stations) was de-seasonalized and adjusted to match the NOAA/GML surface average (from multiple stations) by adding the mean difference of 0.667 ppm, calculated here from overlapping data during 1980–2012.

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Global Carbon Budget 2023

Natural carbon budget is balanced

Anthropogenic carbon cycle leads to

- Accumulation of $CO_2$ in the atmosphere
- 'CO$_2$ fertilisation' of the terrestrial vegetation
- Acidification of the oceans

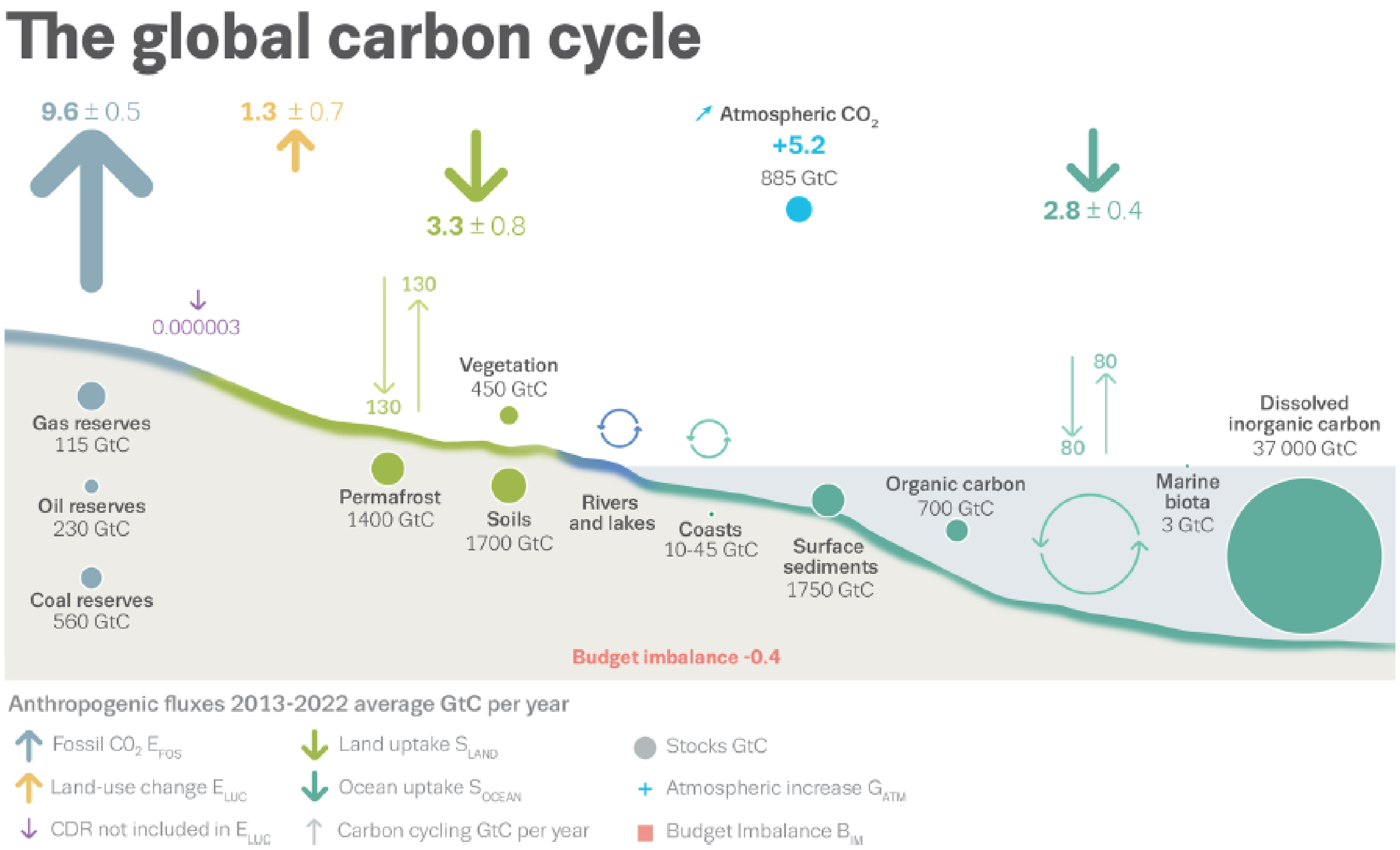
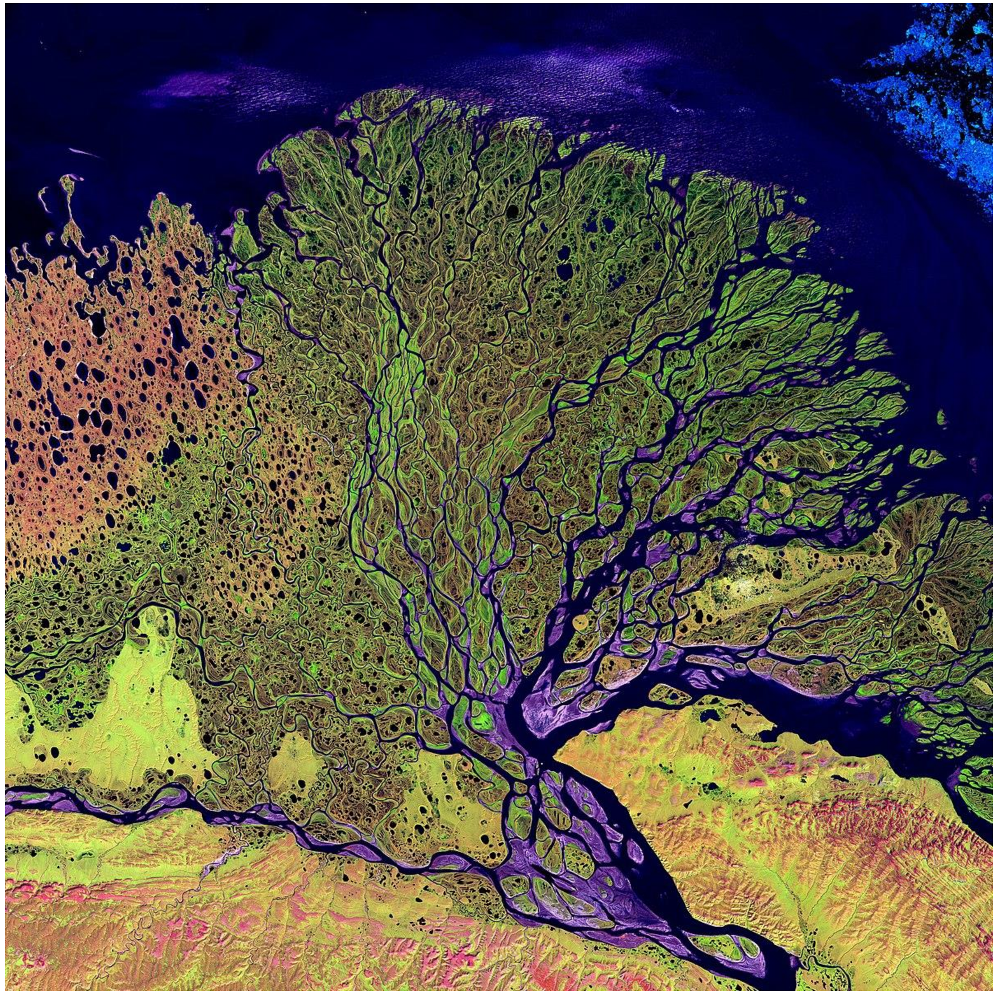



**Figure 2.** Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2013–2022. See legend for the corresponding arrows. Flux estimates and their 1 standard deviation uncertainty are as reported in Table 7. The uncertainty in the atmospheric $CO_2$ growth rate is very small ($\pm 0.02$ Gt C yr$^{-1}$) and is neglected for the figure. The anthropogenic perturbation occurs on top of an active carbon cycle, with fluxes and stocks represented in the background and taken from Canadell et al. (2021) for all numbers, except for the carbon stocks in coasts, which is from a literature review of coastal marine sediments (Price and Warren, 2016). Fluxes are in gigatonnes of carbon per year (Gt C yr$^{-1}$) and reservoirs in gigatonnes of carbon (Gt C).

# Estuaries

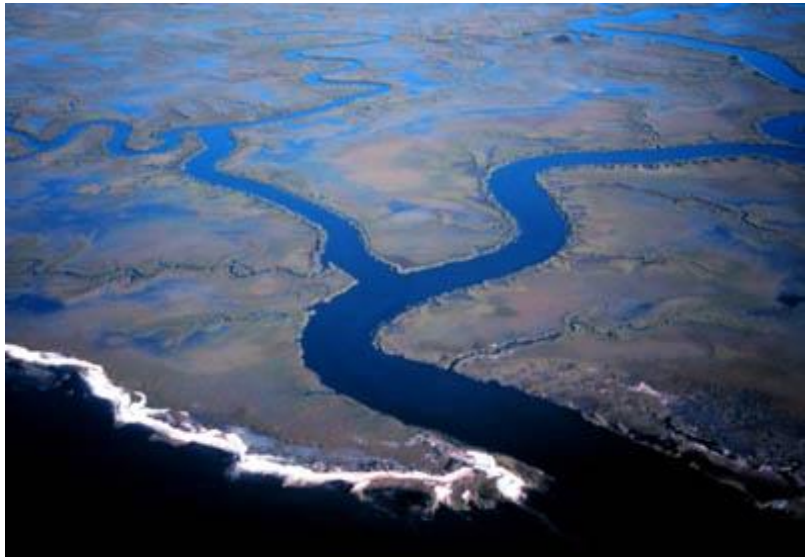
- Transition from freshwater to marine water
- Various geometries and geomorphologies

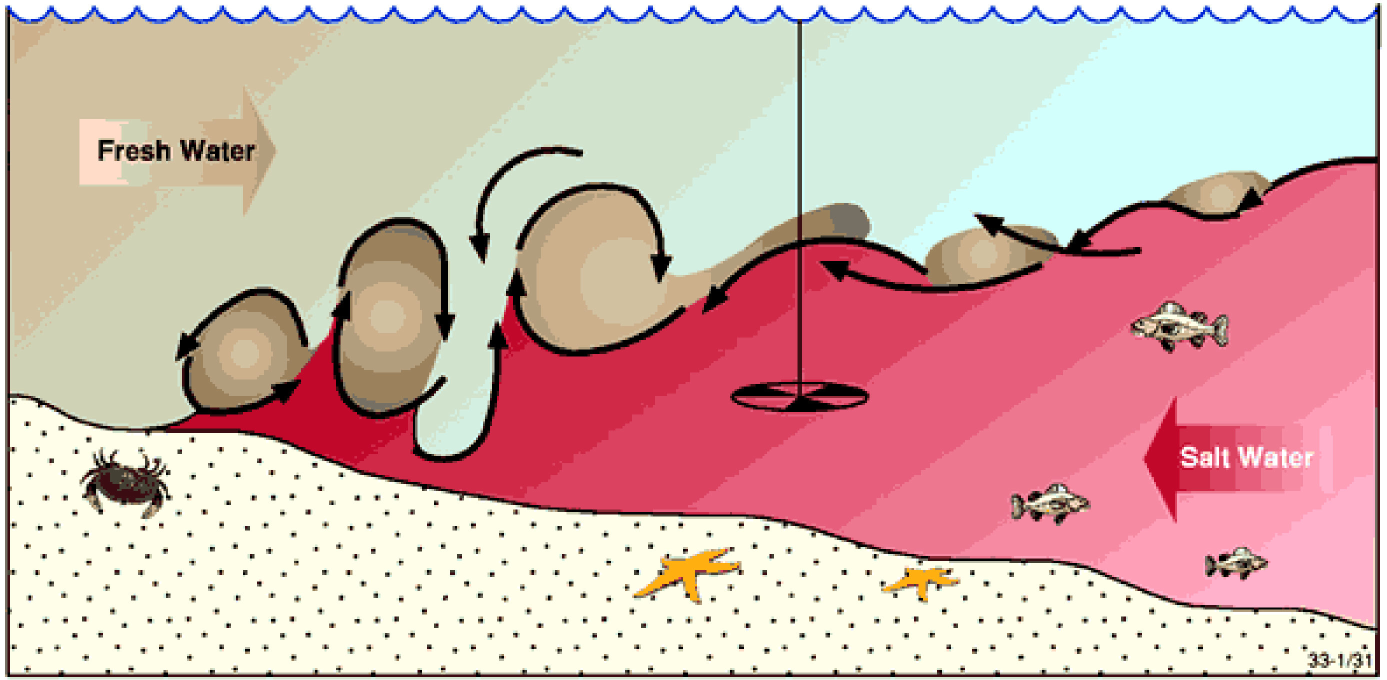


NASA Lena Delta

EPFL

# Estuaries






- Mixing zone between freshwater and saltwater
- Freshwater (lighter) flows seawards on top of the heavier saltwater, which flow land inwards
- Internal mixing wakes with extended residence times and flocculation of organic matter
- High productivity and biodiversity
- Large cities built next to eastuaries worldwide. Why?

# Wetlands

Okavango Delta

# Wetlands

Wetlands are areas where soils are saturated with water and/or covered by water all year or for varying periods of time during the year, including during the growing season.

Water saturation largely determines how the soil develops and the types of plant and animal communities living in and on the soil.

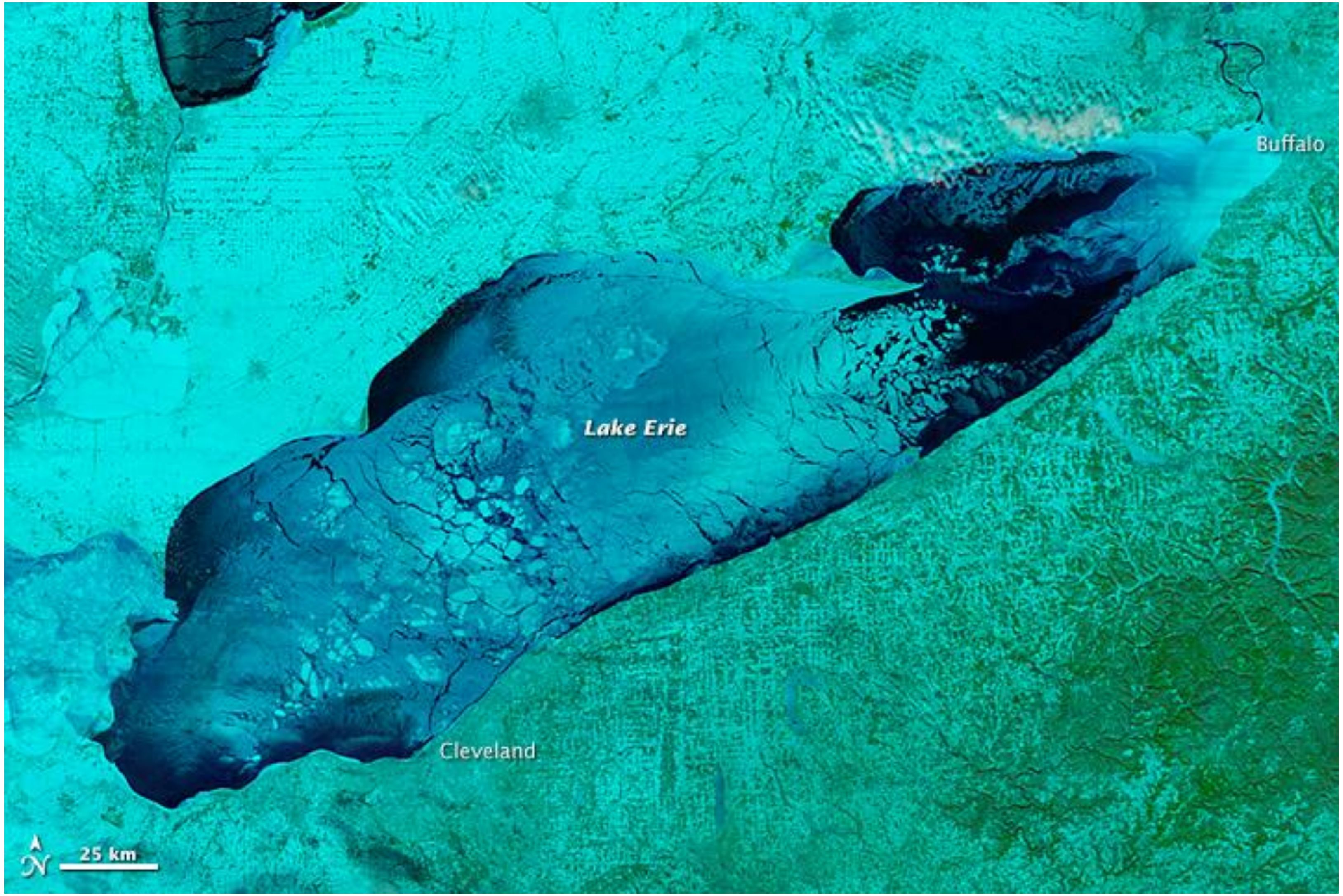
Wetlands are transition zones (in space and time) that support both aquatic and terrestrial species. Therefore, wetlands are particularly biodiverse.

The prolonged presence of water creates conditions that favour the growth of specially adapted plants (hydrophytes) and promote the development of characteristic wetland (hydric) soils.

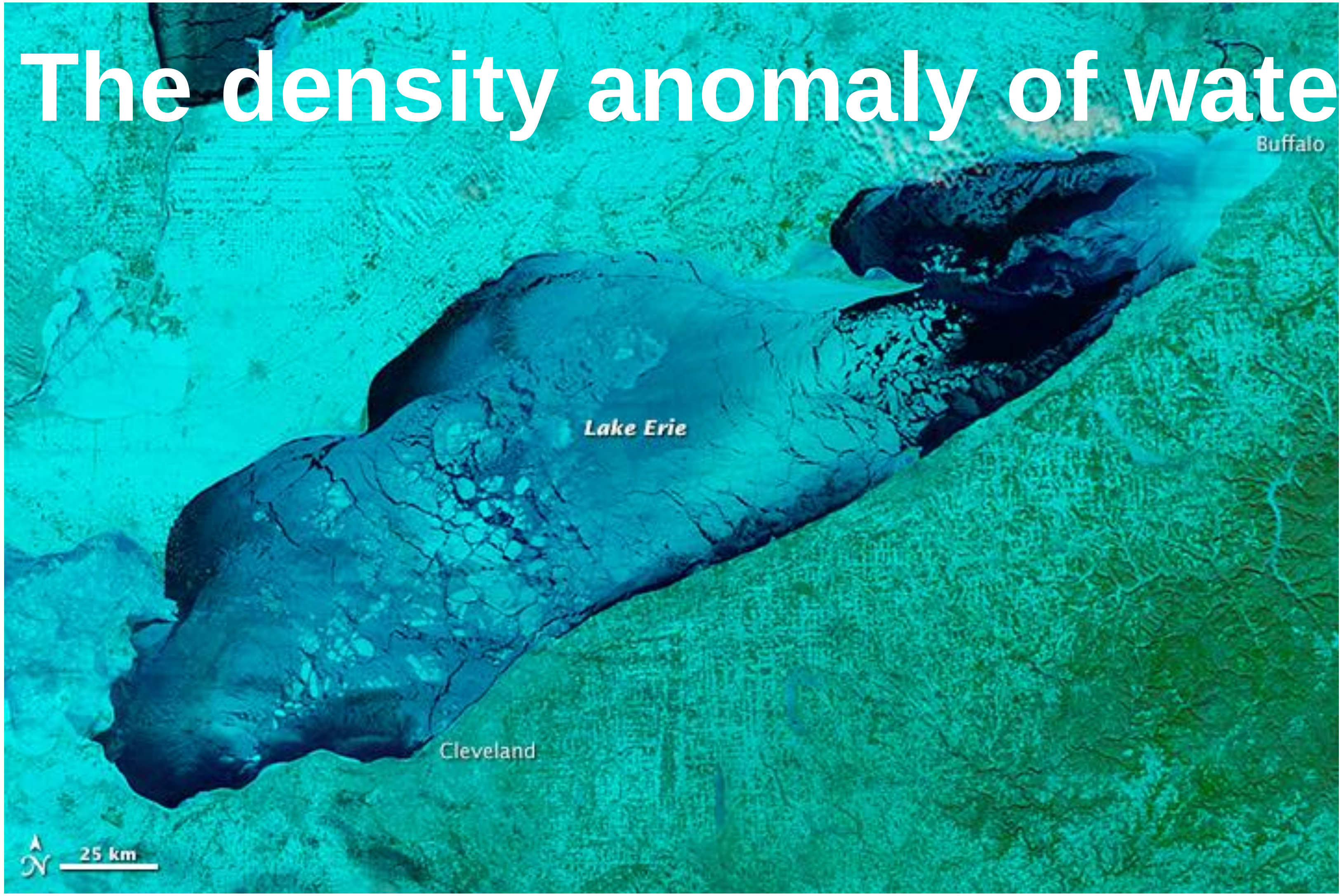
# Some properties of water and consequences for aquatic ecosystems

# Why does ice float?

# Why do lakes not freeze to ground?

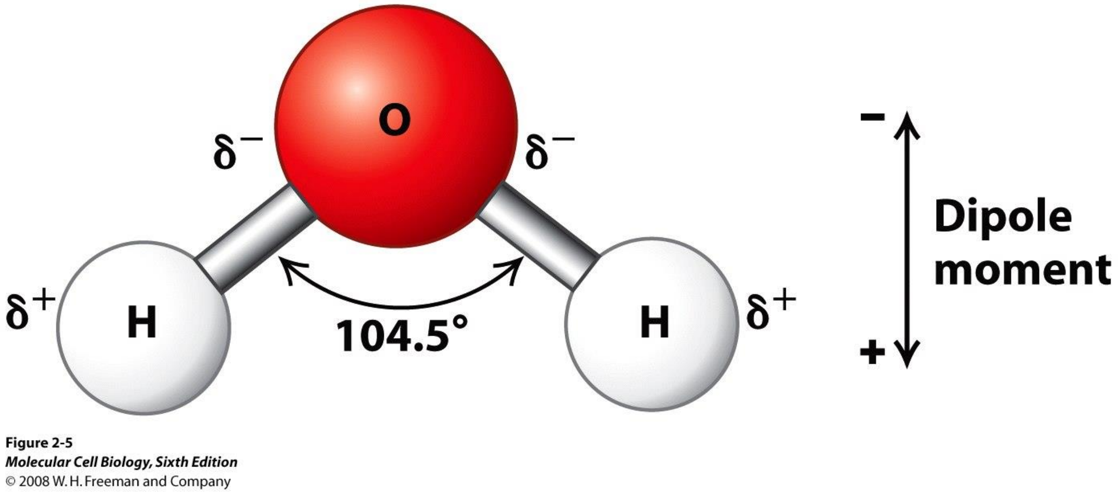


# Why do lakes not freeze to ground?

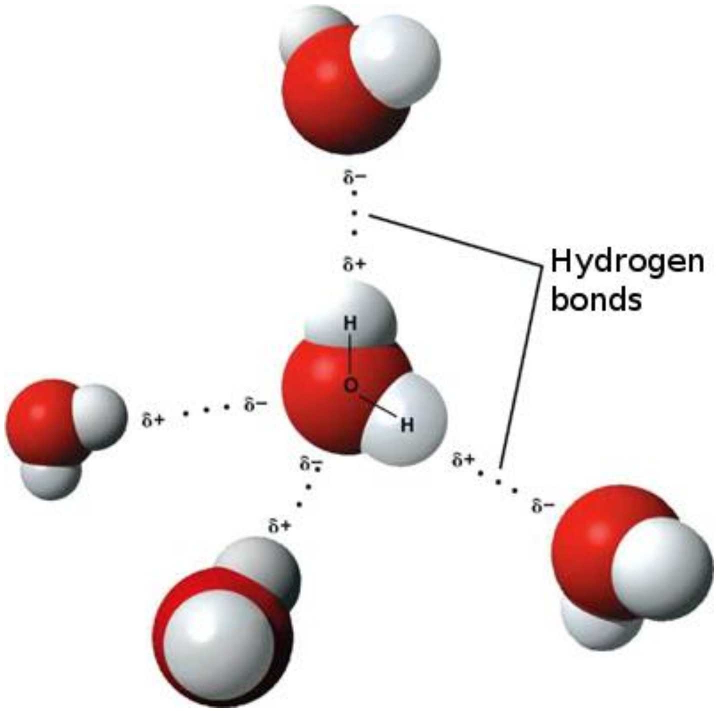



## The density anomaly of wate

# The density anomaly of water




Tetraheder
“flickering cluster”



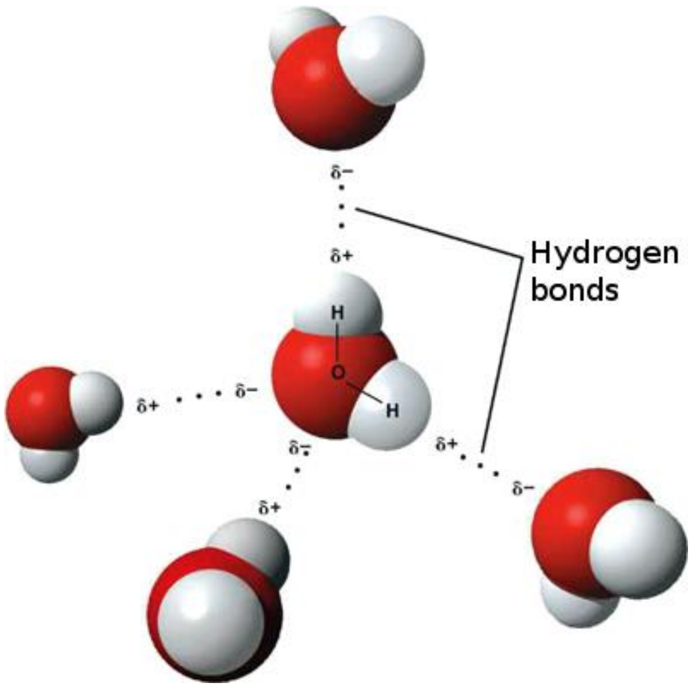

- H-O-H: 104.5°
- H-O: 0.0965 nm
- Oxygen: negative charge
- Hydrogen: positive charge
- strong dipole moment

 (μ = 1.84 Debye; charge x distance)

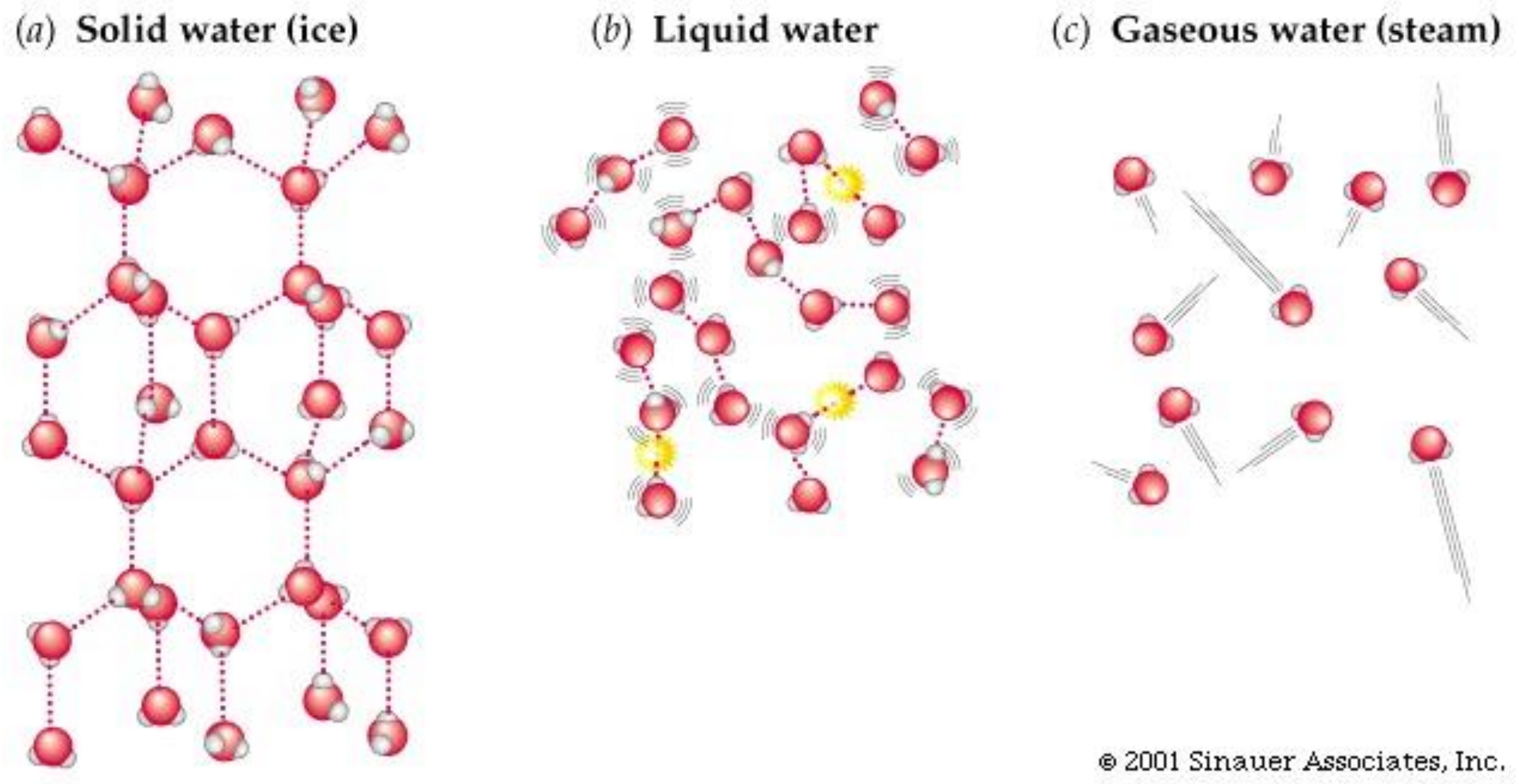
# The density anomaly of water

- Hydrogen-bonds: formation of supramolecular clusters (polyhydrols)
- Each molecule can link to four other molecules: tetraheder-like structure
- Highly labile structure: hydrogen bonds have a lifetime in the picosecond range - fluctuating network of hydrogen bonds
- Confers the very high fluidity to water
- Polarity makes $H_2O$ a highly attractive molecule for chemical reactions — major implications for life

Tetraheder
“flickering cluster”



# The density anomaly of water




- Highly structured, regular matrix
- Maximisation of realized hydrogen bonds

- Poorly structured
- Relatively few hydrogen bonds

- Unstructured and loose
- No or little hydrogen bonds

EPFL

# The density anomaly of water

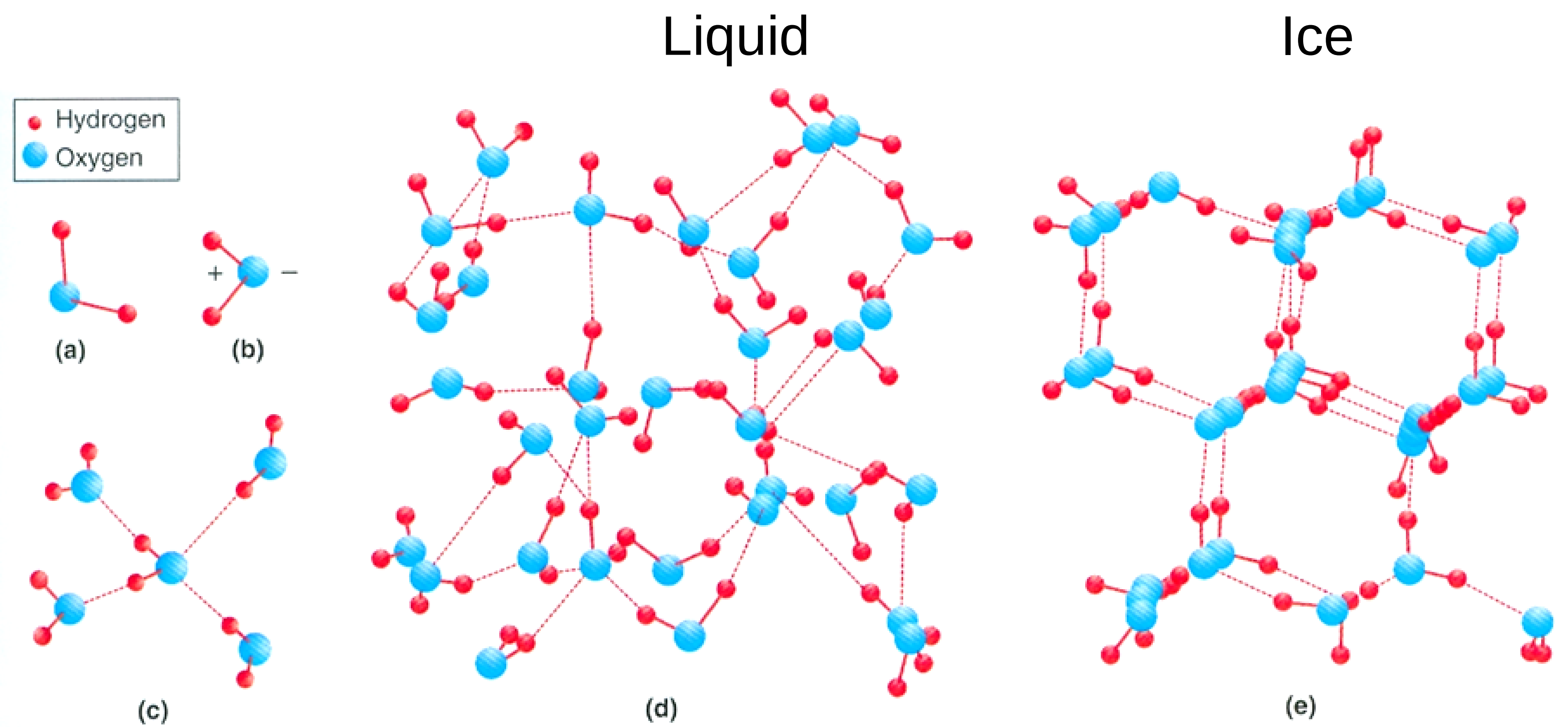



**Figure 3.3 |** The structure of water. (a) An isolated water molecule, showing the angular arrangement of the hydrogen atoms. (b) Polarity of water. (c) Hydrogen bonds to one neighboring molecule of water. (d) The structure of liquid water. (e) The open lattice structure of ice.

# The density anomaly of water

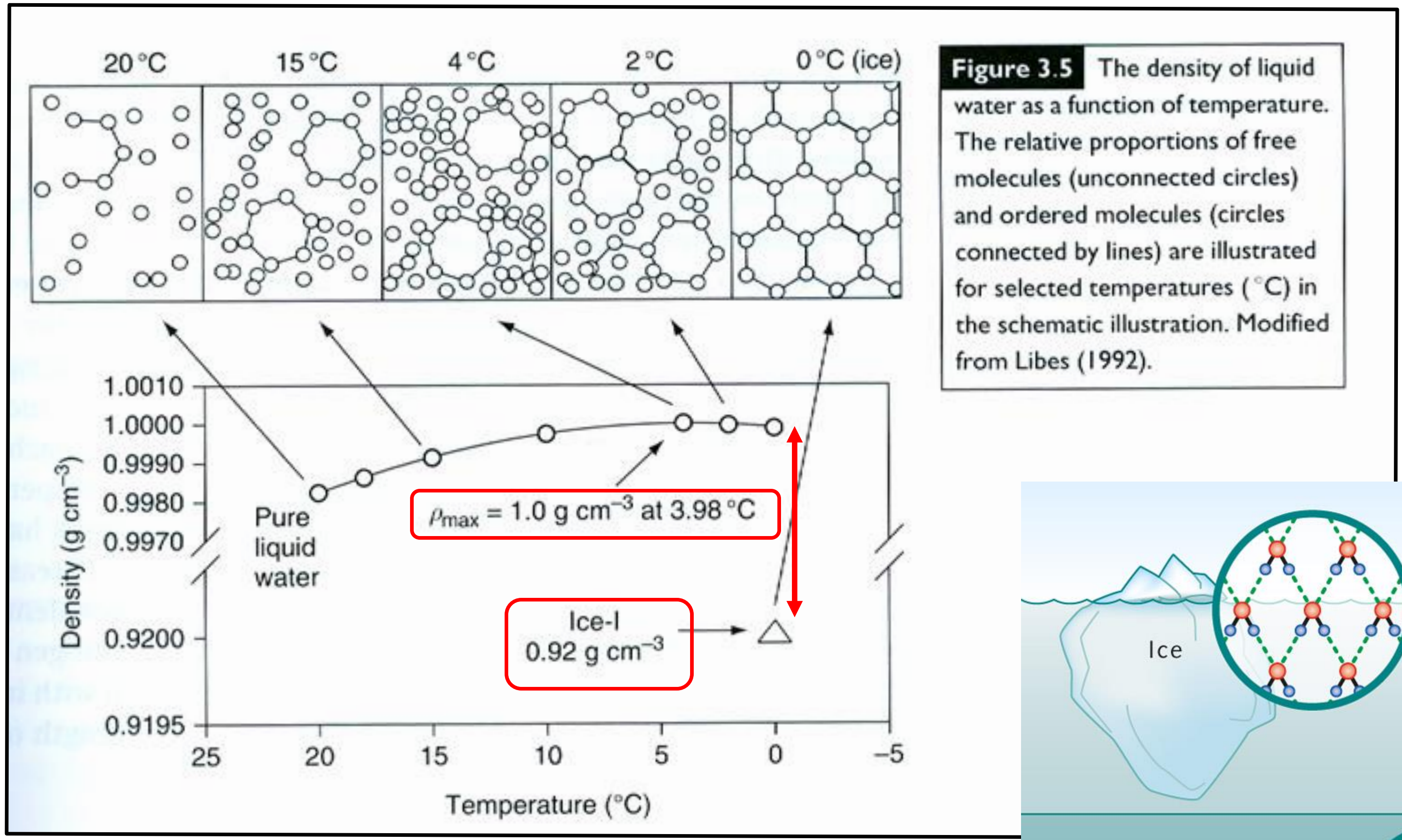
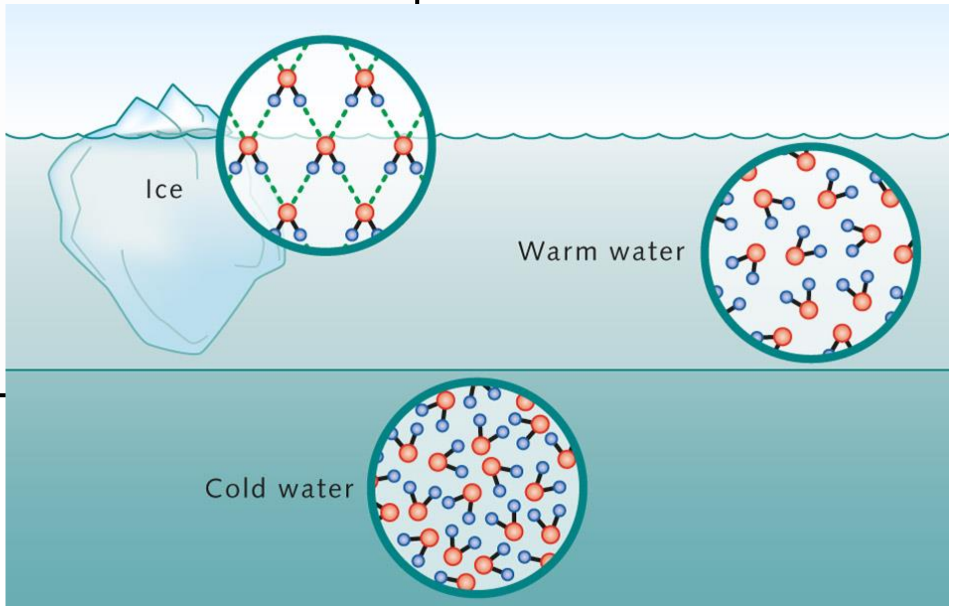



**Figure 3.5** The density of liquid water as a function of temperature. The relative proportions of free molecules (unconnected circles) and ordered molecules (circles connected by lines) are illustrated for selected temperatures (°C) in the schematic illustration. Modified from Libes (1992).

- On Earth, water is present in its liquid, solid and gaseous phase
- Water has its highest density at 3.98 °C
- Ice has a lower density (0.92 g/cm$^3$) than liquid water; therefore, it floats on the liquid, warmer and heavier water

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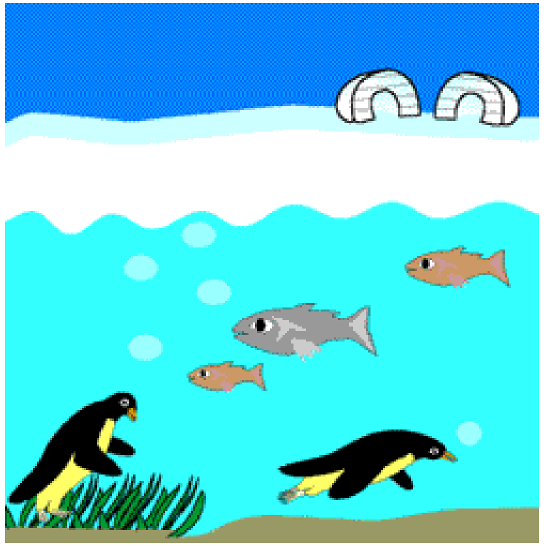
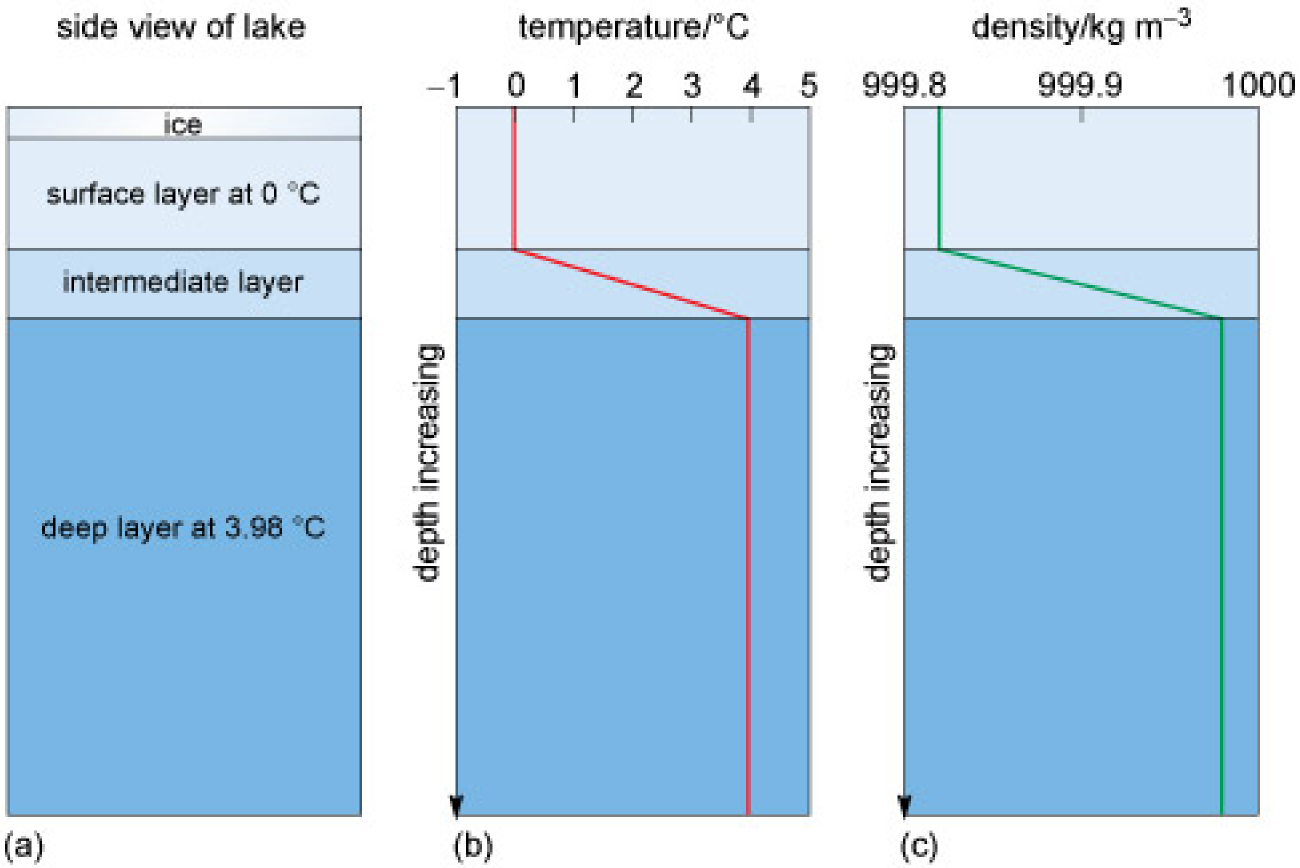
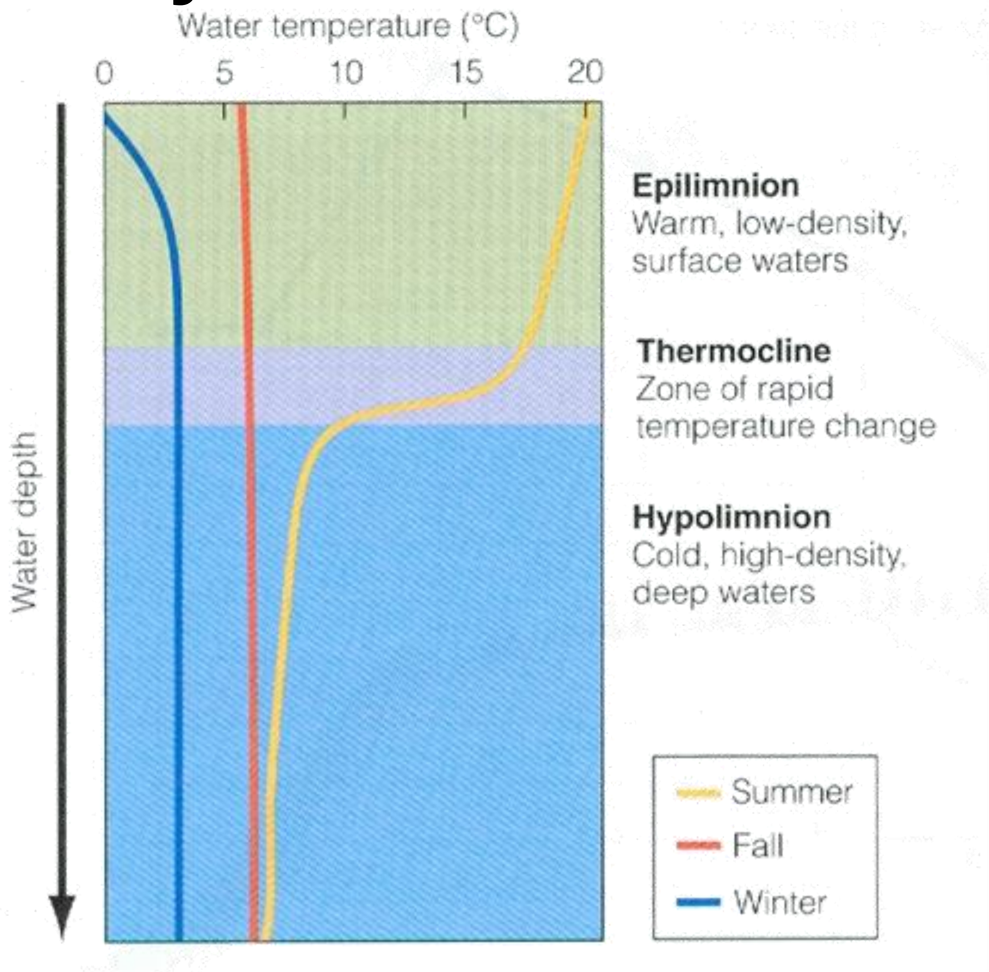
# What are ecosystem consequences of the water density anomaly?





# What are some ecosystem consequences of the water density anomaly?

- Thermal stratification of lakes
- We will see more when we talk about lakes



# Specific thermal capacity of water and implications

Thermal capacity of water is a measurable physical quantity equal to the ratio of the heat added to (or removed from) water to the resulting temperature change.

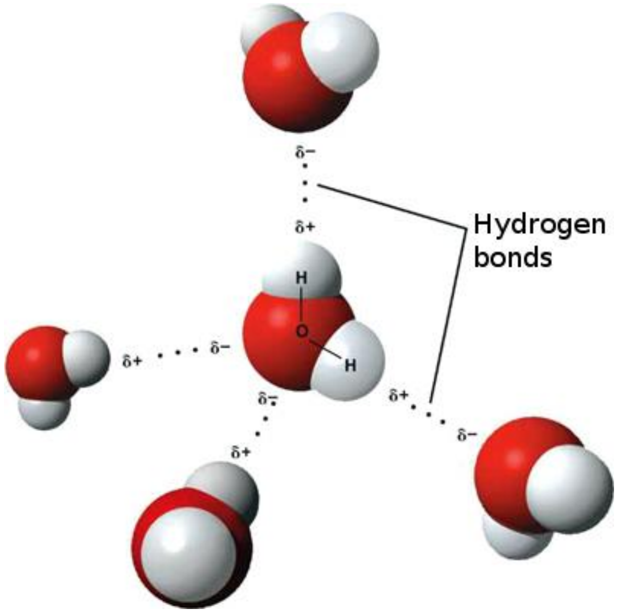
High specific thermal capacity of liquid water: 4.184 Joules of energy required to heat one gram of water by one degree

Compared to metal, for instance, water is relatively resistant to thermal shifts

→ Thermal stability, gas dynamics (oxygen dissolved in the water), microclimate etc

| Substance | Specific heat (J/g °C) |
|---|---|
| Water | 4.2 |
| Wood | 1.7 |
| Iron | 0.0005 |
| Mercury | 0.14 |
| Ethyl alcohol | 2.4 |

# Specific thermal capacity of water and implications




- Heat is the energy generated from the movement of molecules.
- Given that water molecules are linked to other water molecules via hydrogen bonding, there must be a certain amount of heat energy to first disrupt the hydrogen bonds and then to speed up movement of the molecules, thereby causing water temperature to rise.
- As such, the investment of one calorie of heat results in relatively little change in water temperature because much of the energy is utilized to break hydrogen bonds rather than to quicken the movement of water molecules.

# Specific thermal capacity of water and implications

Thermal variation of water in streams and river

- Downstream shifts of day-night variability
- Downstream shifts of mean water temperature

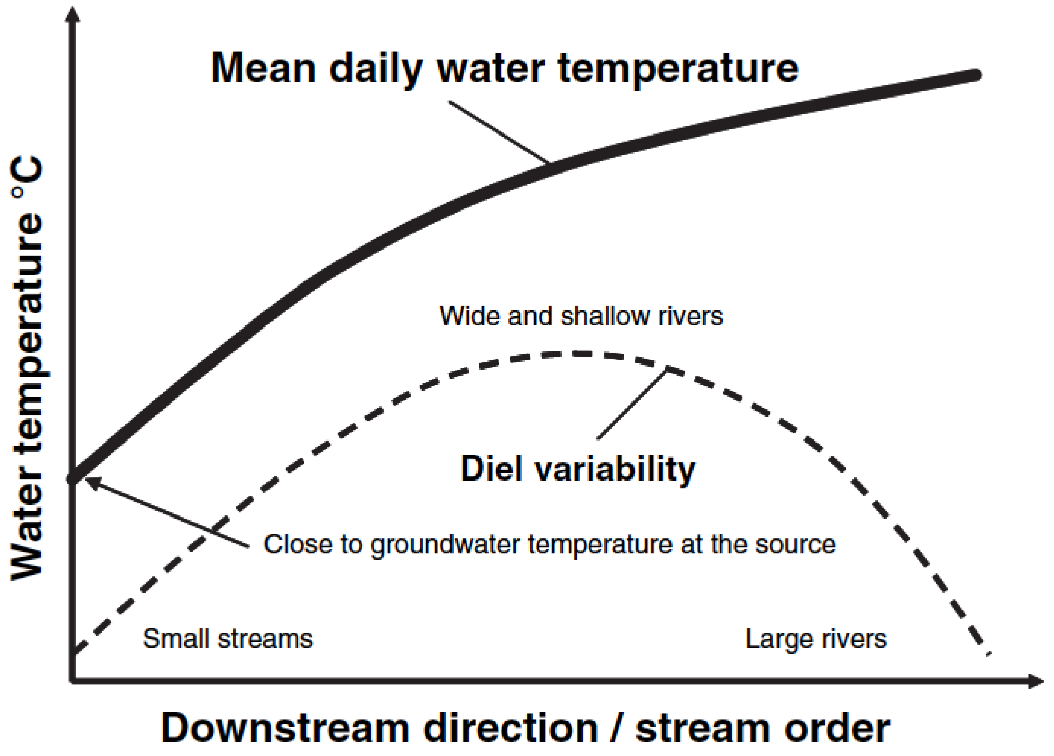



**Fig. 2** Mean daily and diel variability of water temperatures as a function of stream order/downstream direction.

*Cassie 2006 Freshwater Biology*

EPFL

## Why can bugs run over water or why do particles accumulate on the water surface?

Surface tension

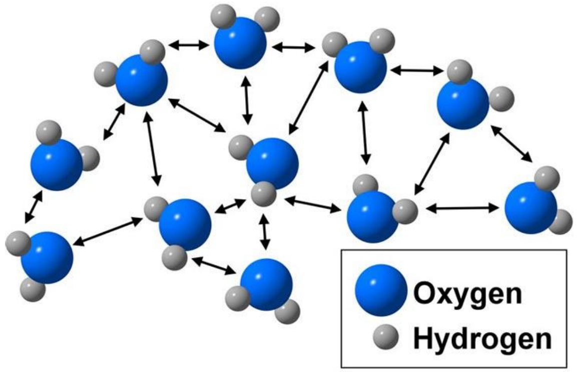
- Cohesion
- Adhesion

# Cohesion

Property of same molecules to stick together

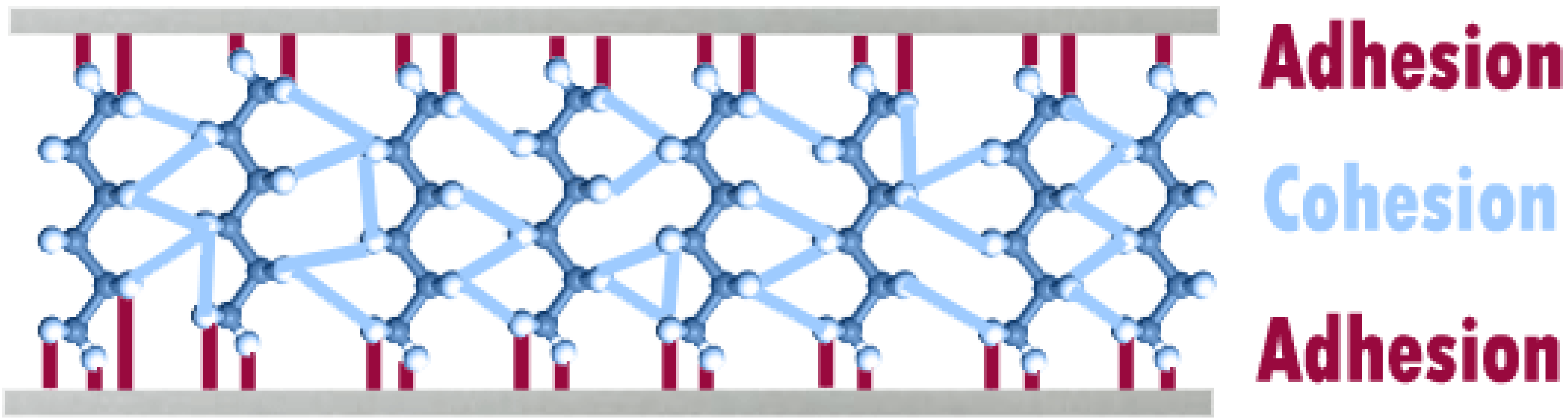
Water is strongly cohesive as each molecule can make four hydrogen bonds to other water molecules in a tetrahedral configuration.

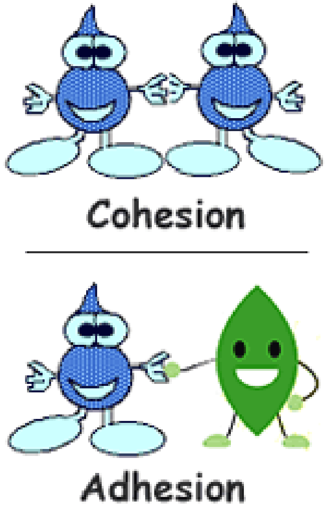
This results in a relatively strong Coulomb force between molecules.



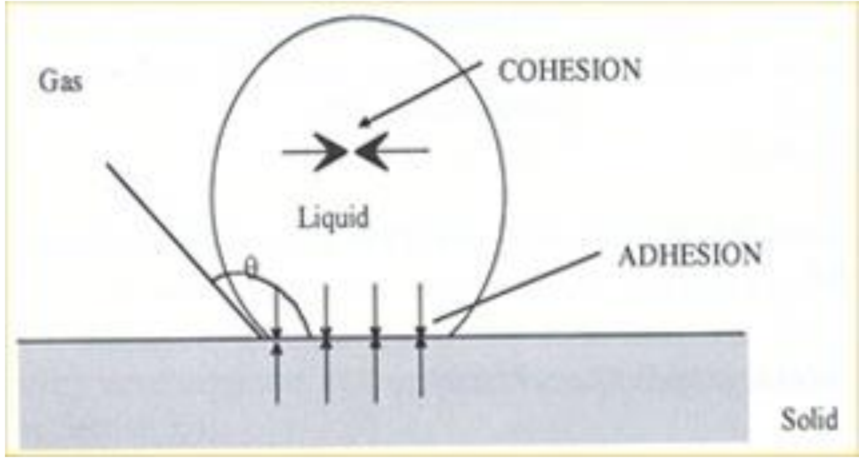
# Adhesion

Property of water molecules to adhese to other molecules



# Cohesion, adhesion, surface tension

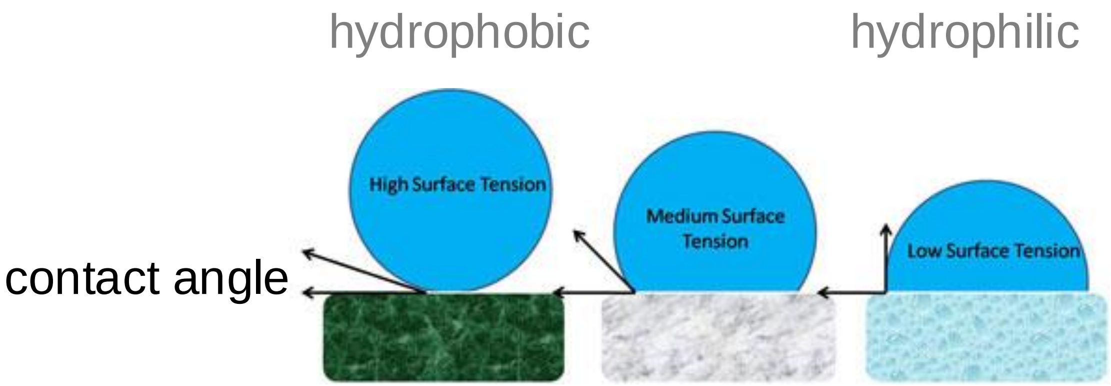



Lotus effect
'Self-cleaning' surfaces


Breathing oxygen from a airbouble

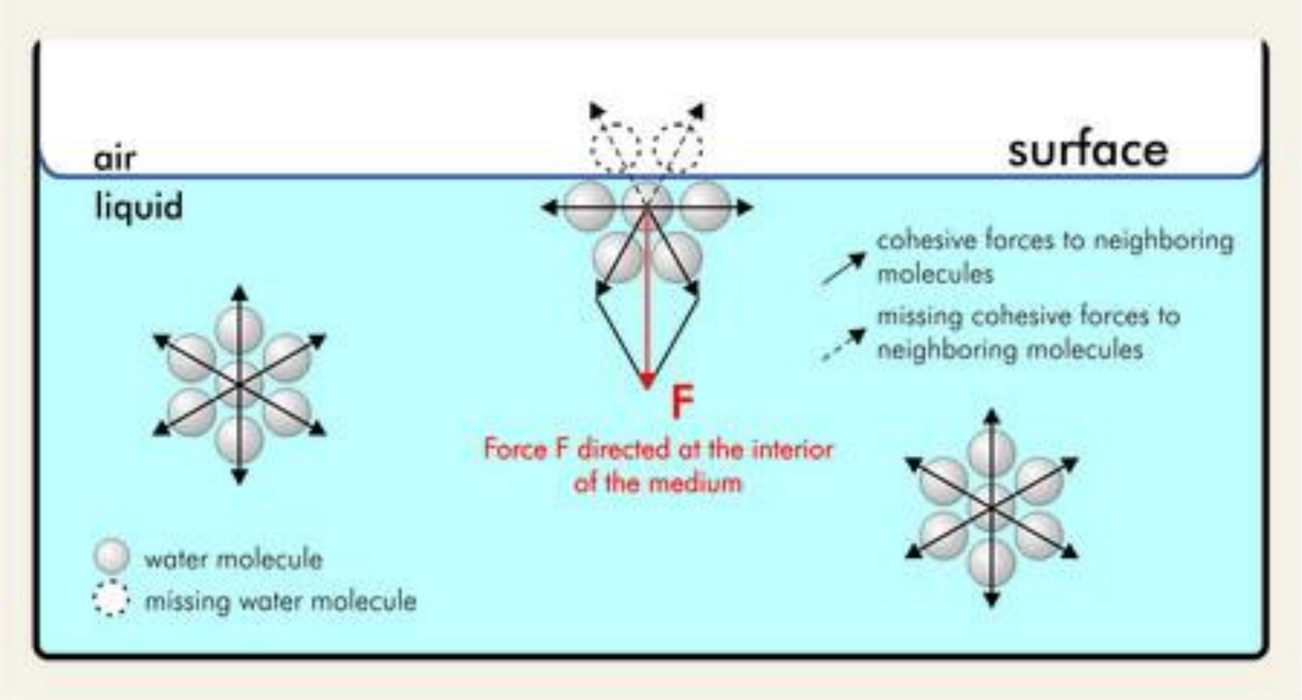
<u>Cohesion << Adhesion</u>:
Hydrophilic — wetted surfaces

<u>Cohesion >> Adhesion</u>:
Hydrophobic — unwetted (or poorly wetted) surfaces



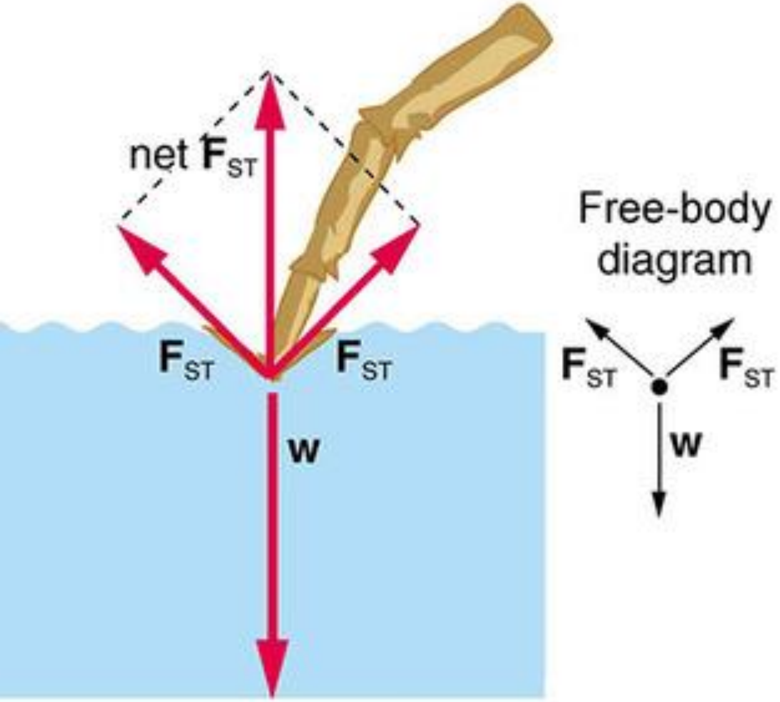
# Cohesion, adhesion, surface tension

Surface tension: results from cohesion between water molecules. Molecules at the water surface feel an attractive force pulling them toward the bulk of the water more than the solid or fluid at the interface.



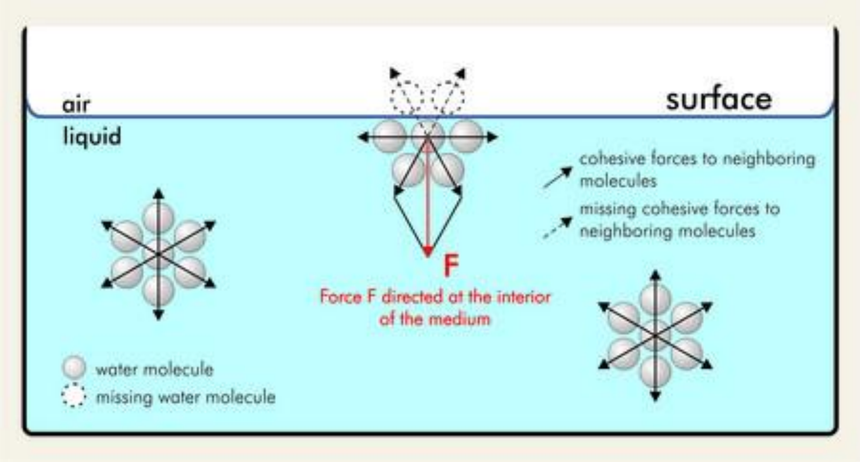
# Cohesion, adhesion, surface tension

## Implications

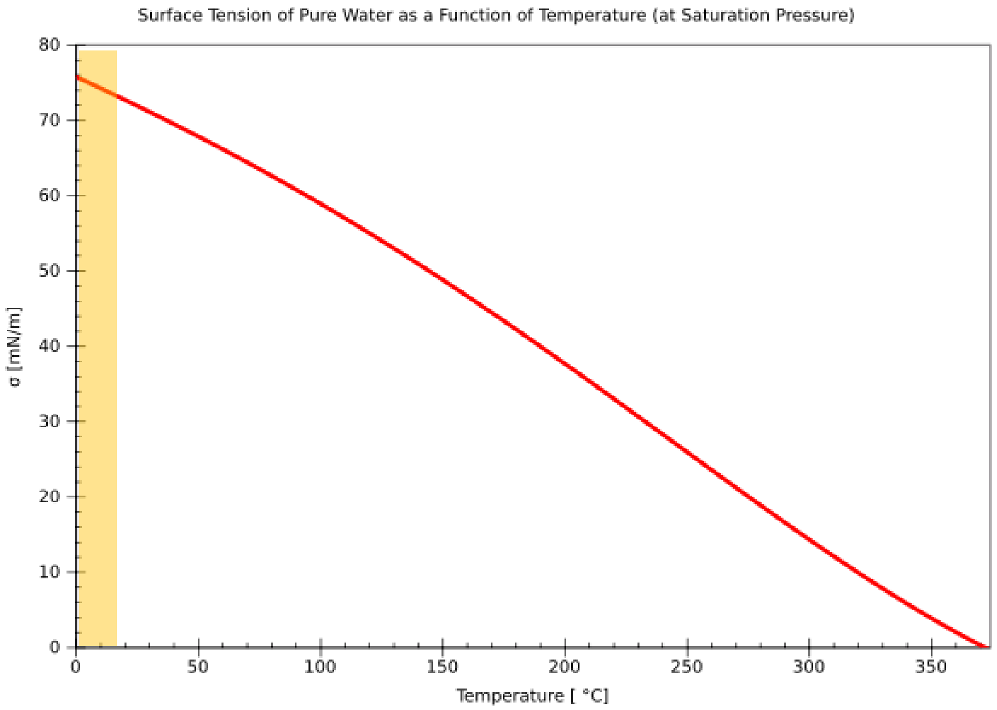




w: weight
$F_{ST}$: surface tension

# Cohesion, adhesion, surface tension




- Surface tension of water at 20 °C is 72.75 mN/m.
- Surface tension decreases with water temperature – but rather negligible for aquatic ecosystems



# Cohesion, adhesion, surface tension
## Implications

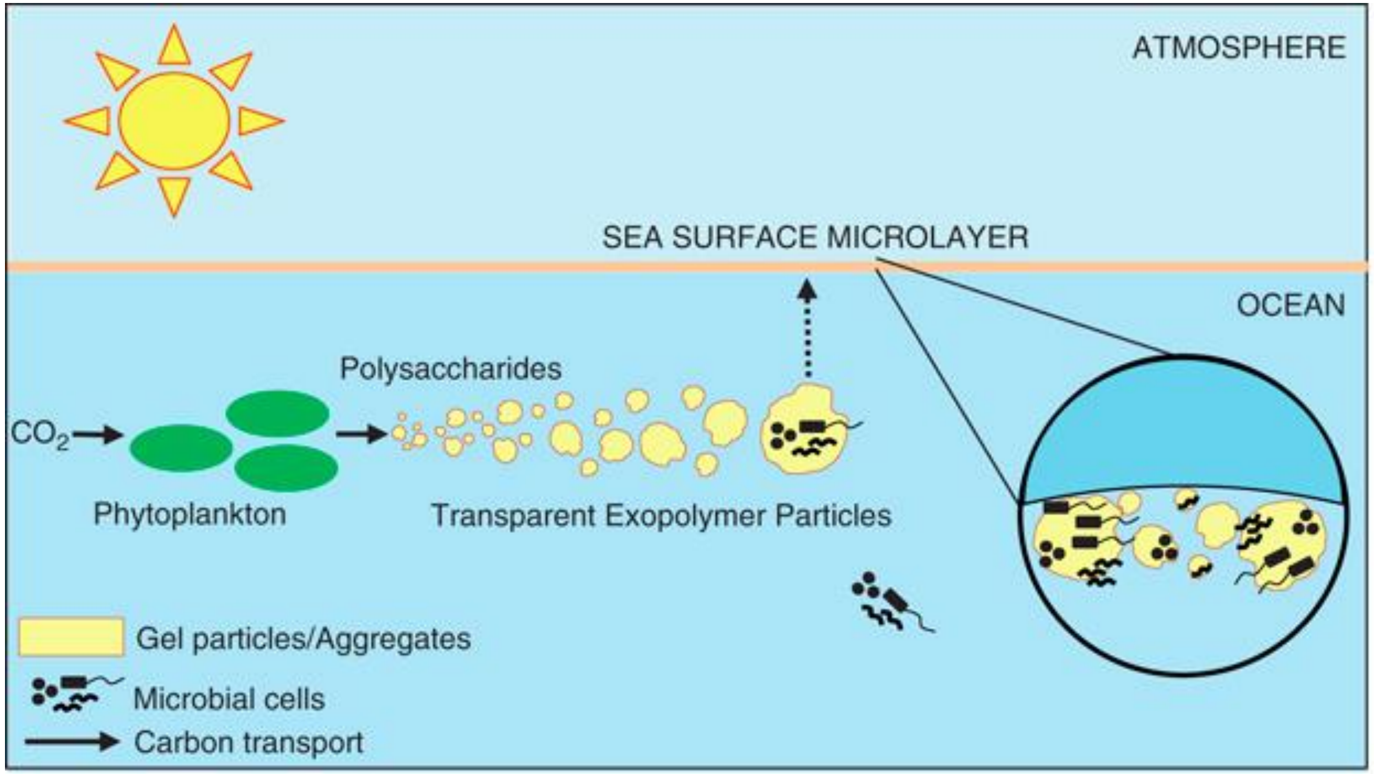
### Neuston

The community of organisms that lives on the water

…and feeds on the surface microlayer

# Cohesion, adhesion, surface tension

## Implications

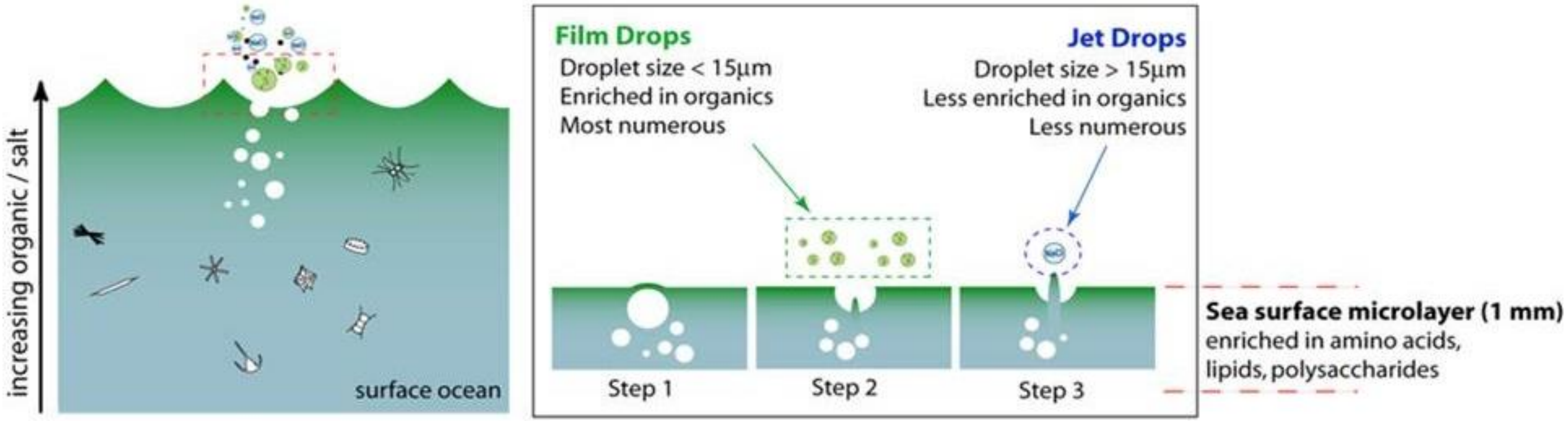



Surface microlayer

- Various molecules from atmospheric and aquatic origins
- Hydrophilic part directed toward the buld liquid; hydrophobic pard directed toward the air
- Rich microbial life
- Sustains higher trophic leves (neuston)

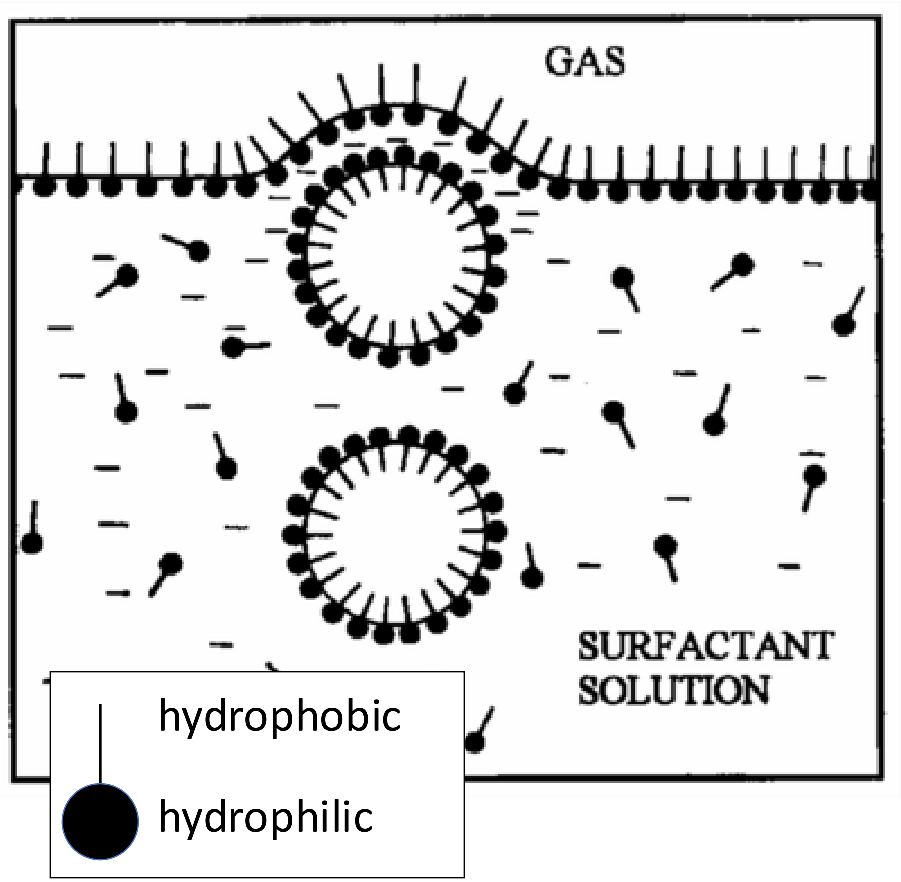
# Cohesion, adhesion, surface tension

## Implications




- Chemical aerosols
- Sea spray – viruses and bacteria transported around the globe
- Cloud condensation

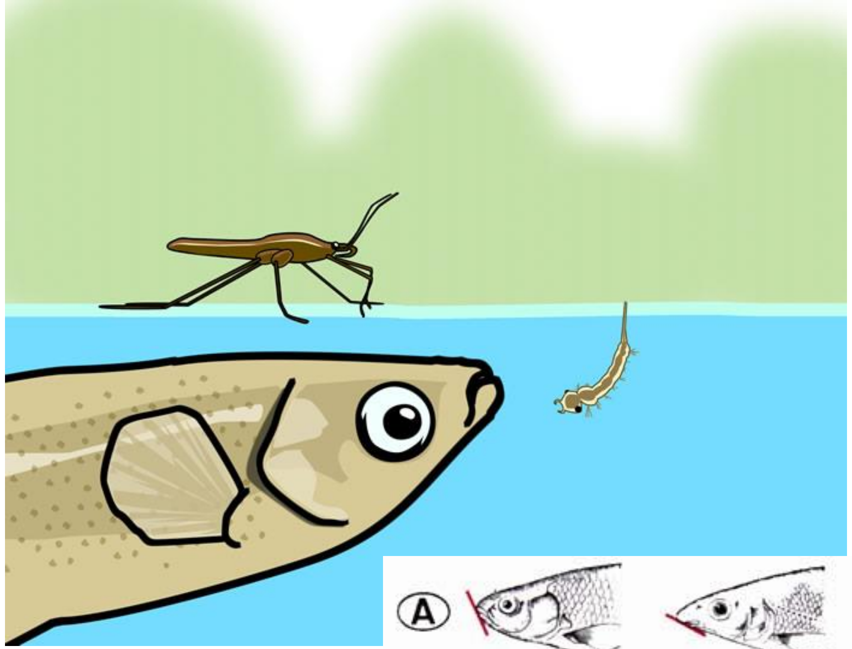
# Cohesion, adhesion, surface tension
## Implications

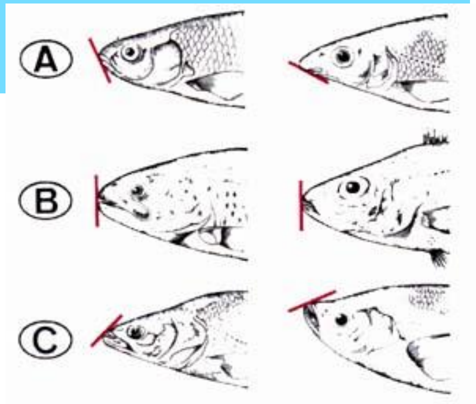



Foam formation

# Cohesion, adhesion, surface tension

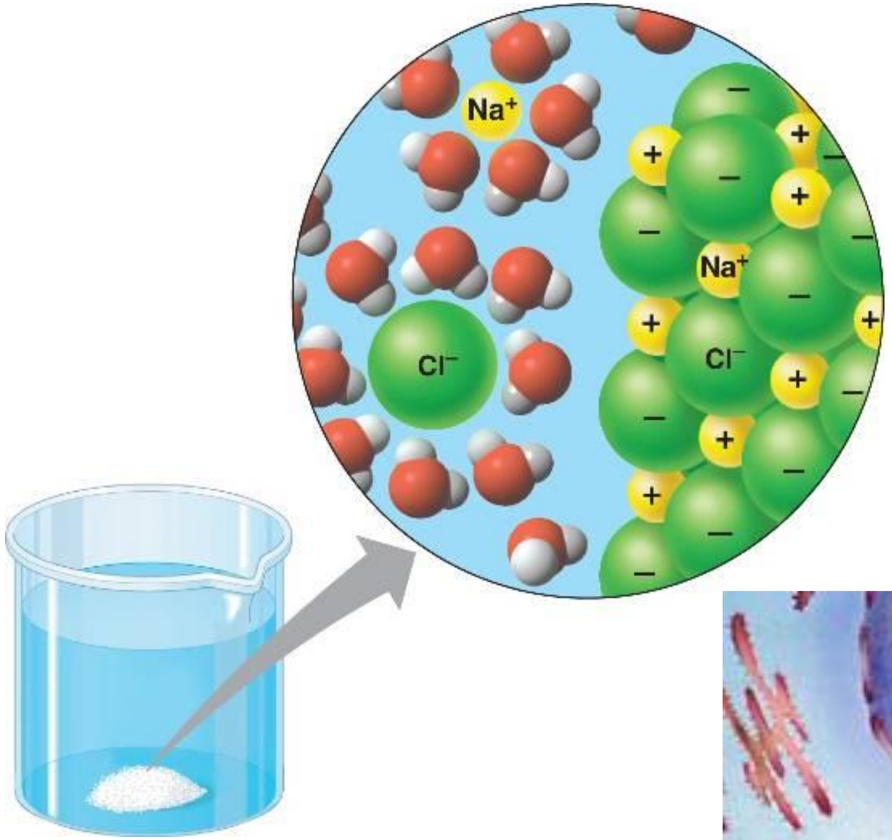
## Implications

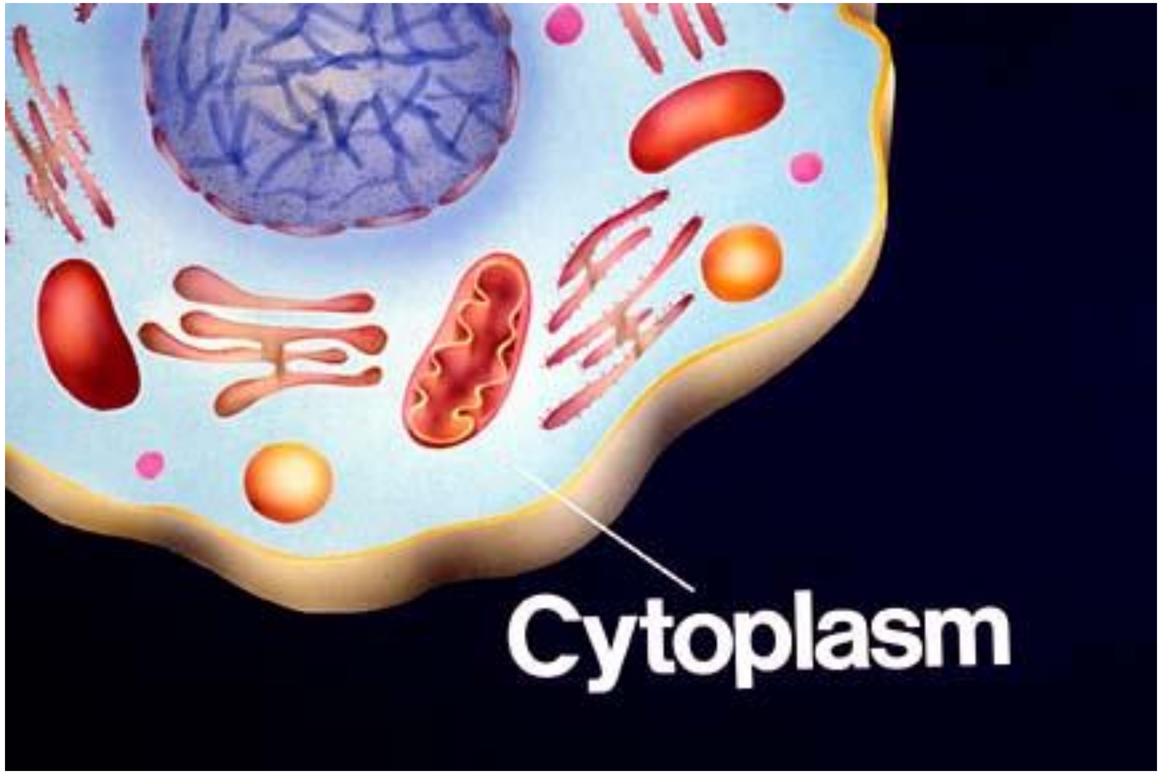





- Food web
- Filter for UV radiation
- Filter for gas exchange between the water and atmosphere

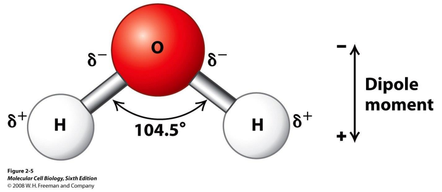
# Water as a solvent



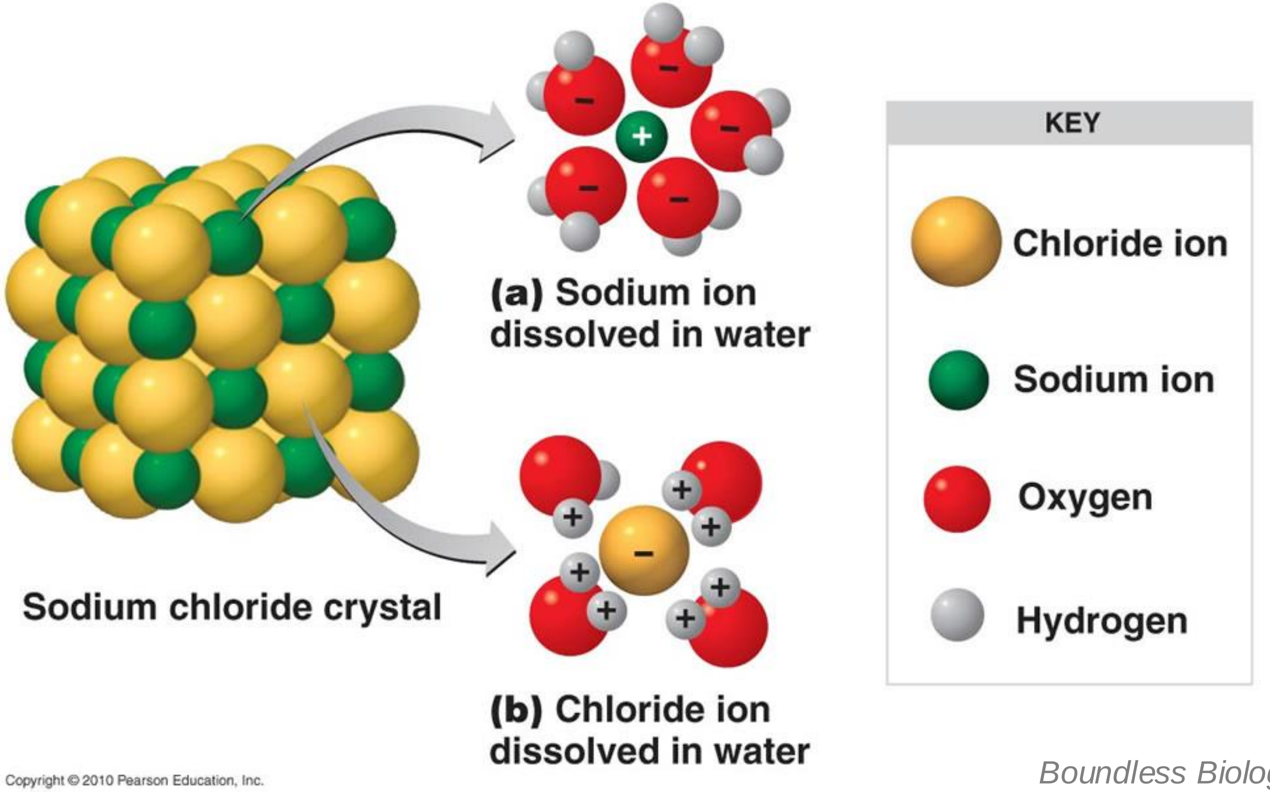



# Why is water such a good solvent?

Water dissociates salts by separating the cations and anions and forming new interactions between the water and ions




Strong dipolar character




*Boundless Biology*

Solvation shell

- Structure composed of water molecules
- Acts as a solvent and surround a solute species (e.g. ion); also referred to as a hydration sphere.

# Implications of water as a solvent?

”The matrix of life”
Nobel Laureate A. Szent-Gyorgy

Transportation of ions, oxygen and other solutes into cells and evacuation of metabolites from cells