Ocean Circulation, Geochemical Mass Balance

Topics covered today:

- Relationships between large-scale circulation and biogeochemistry
  - Wind driven circulation
  - Typical seasonal mixed layer
- Balance of constituents in the ocean
  - Weathering
    - Reverse Weathering, hydrothermal vents
  - Geochemical Mass Balances
    - Residence times

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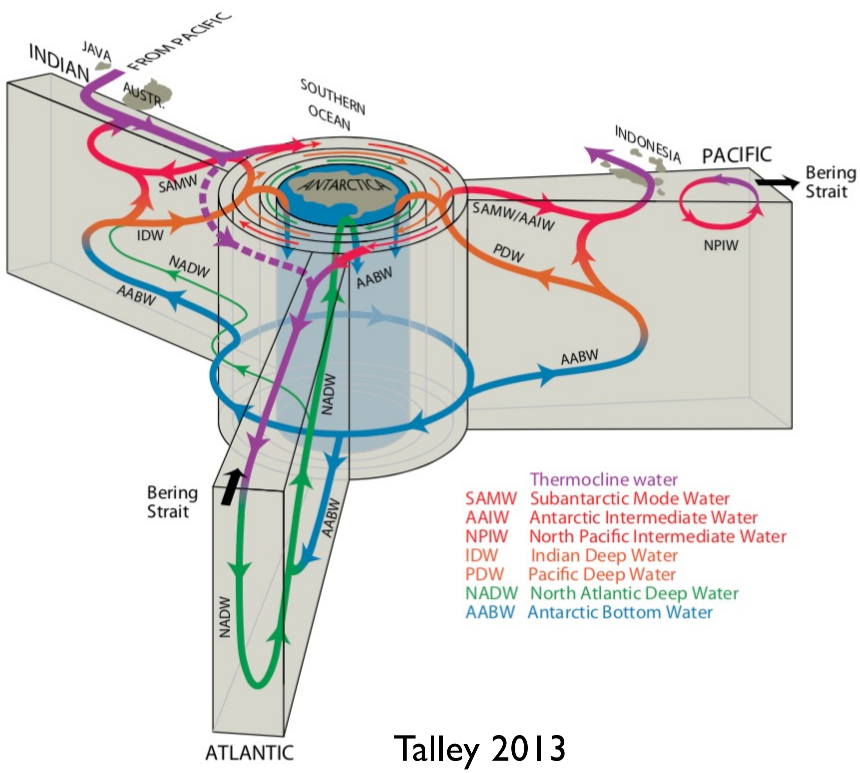
Circulation and biology

- Every measurement we make must be considered against the backdrop of physics and biology.

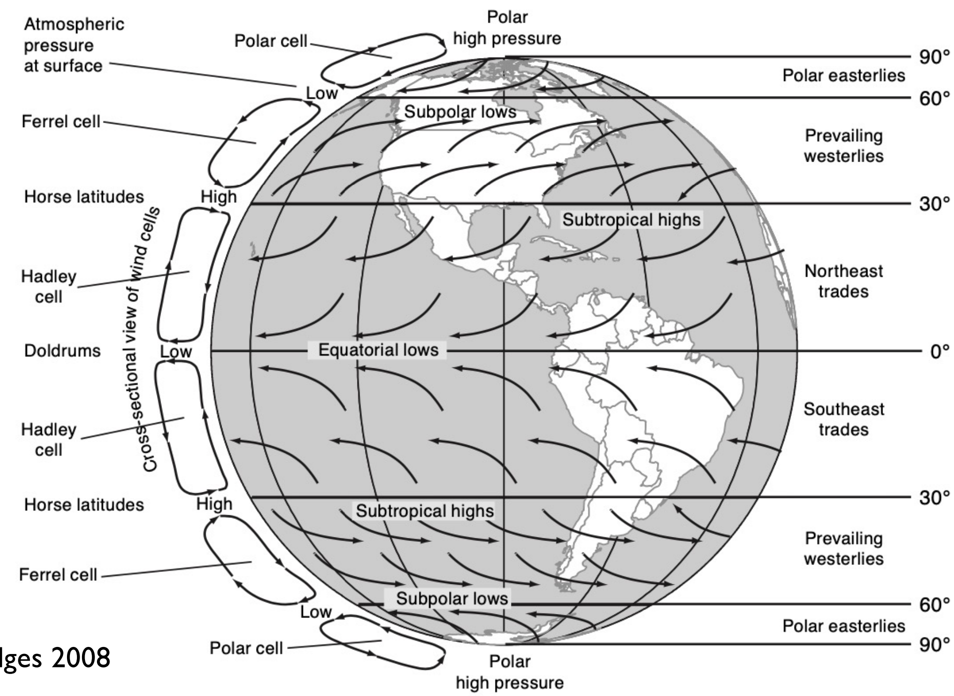


Talley 2013

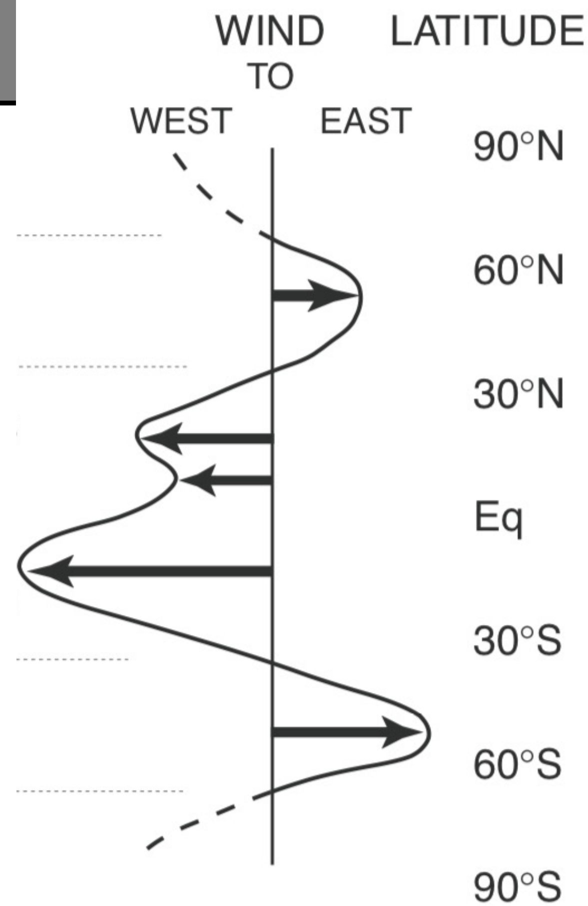
Circulation:

- Overturning
  - Large scale transport of water throughout the ocean
  - Time scales of hundreds to a thousand years
- Wind driven
  - Both short and long-term impacts
  - Local nutrient availability, mixing with depth
  - Formation of gyres, coastal upwelling regions

Wind driven circulation



Emerson and Hedges 2008

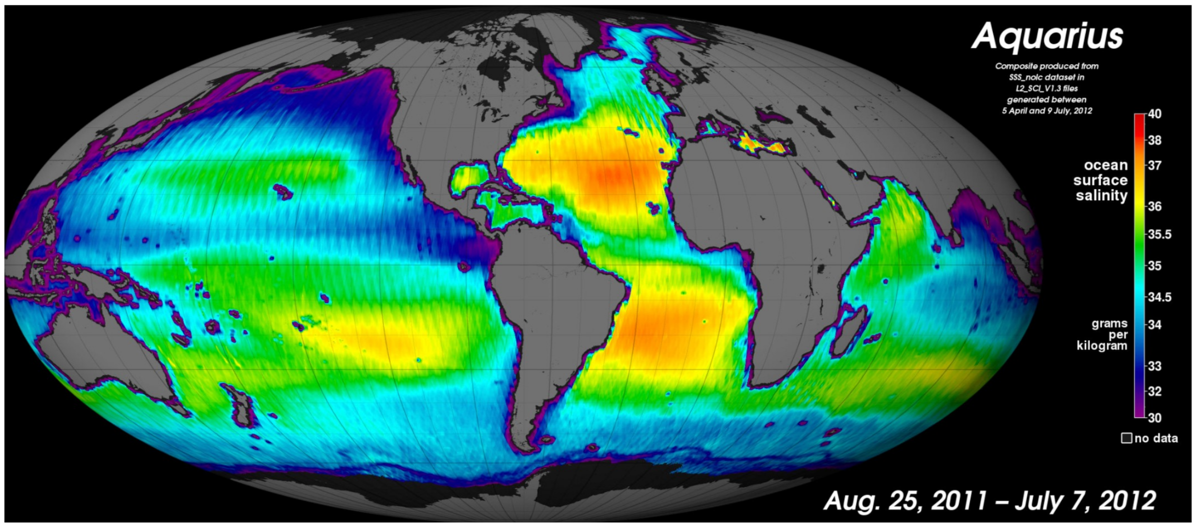


Sarmiento and Gruber 2006

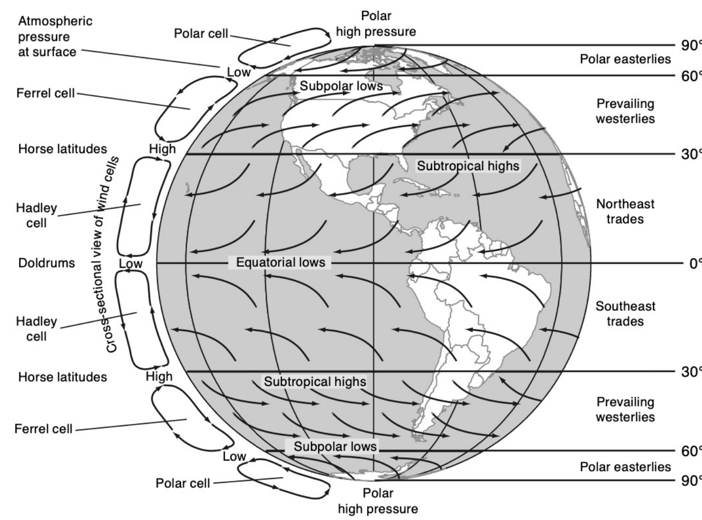
Coriolis "force" describes the apparent curvature of winds, currents to the right in the N Hemisphere and left in the S Hemisphere

Impact of circulation / winds on salinity

Radiometer-derived sea-surface salinity
- Aquarius spacecraft



- Rising air cools, drops moisture
- Sinking air warms, takes up moisture



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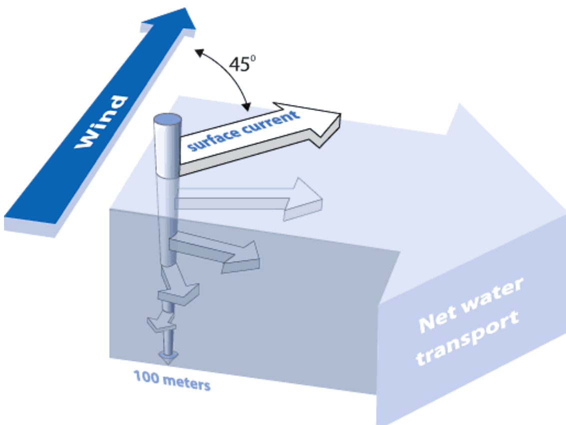
Upwelling / downwelling

- Ekman transport:



- Friction + Coriolis means that net water transport is 90 deg. to the left or right of winds

https://oceanservice.noaa.gov/education/

Upwelling / downwelling

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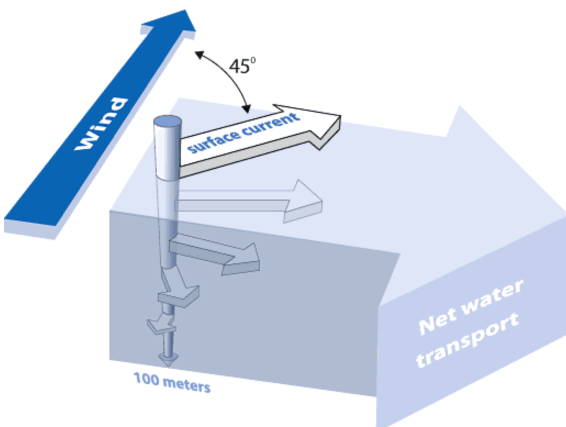

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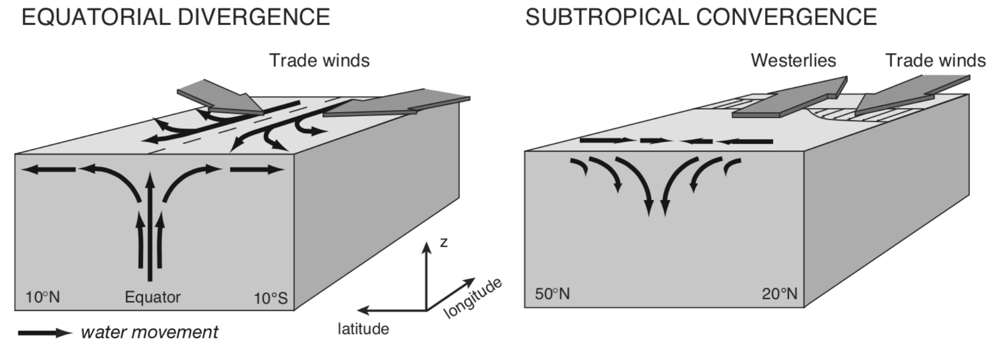

FIGURE 2.2.8: (a) Equatorial divergence and upwelling resulting from Ekman transport driven by trade winds [*Thurman*, 1990]. (b) Ekman downwelling resulting from convergent Ekman transport driven by the westerlies and trade winds.

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Sarmiento and Gruber, 2006

Upwelling / downwelling

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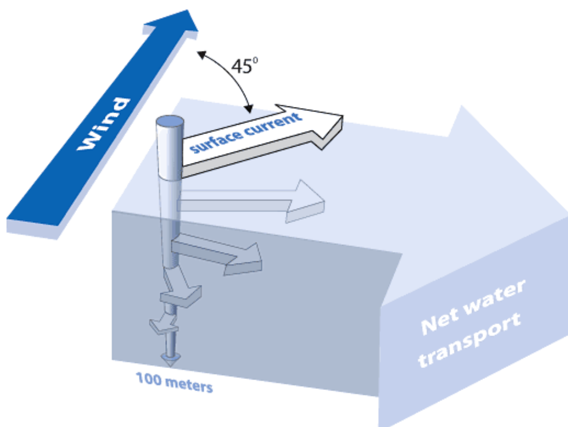

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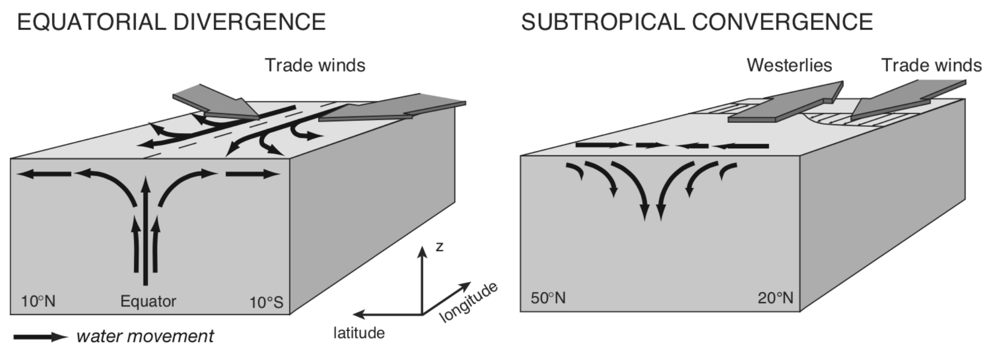

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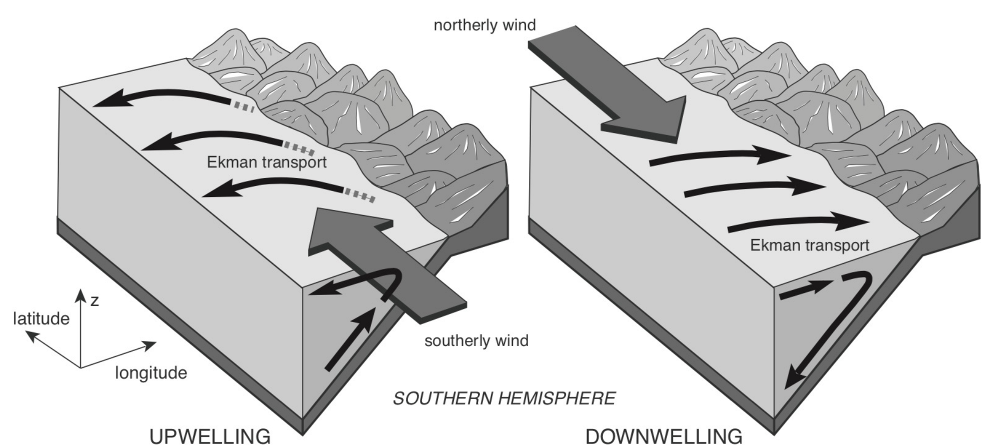

FIGURE 2.2.6: Ekman transport and associated upwelling and downwelling resulting from wind blowing parallel to shore [*Thurman*, 1990]

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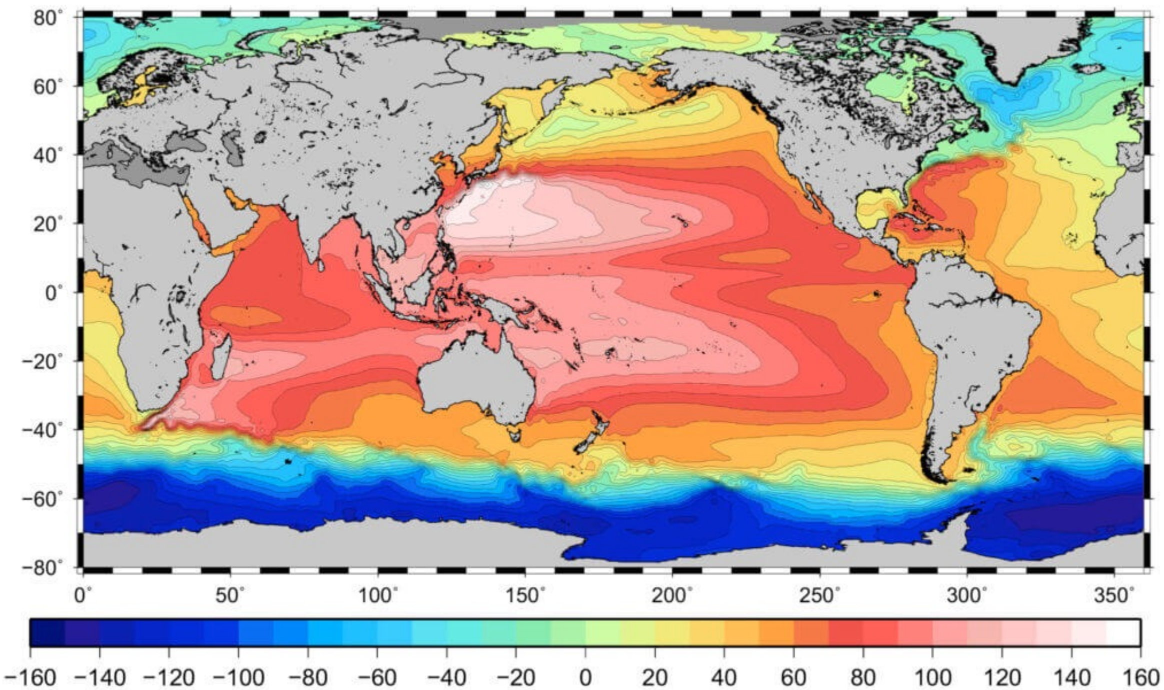
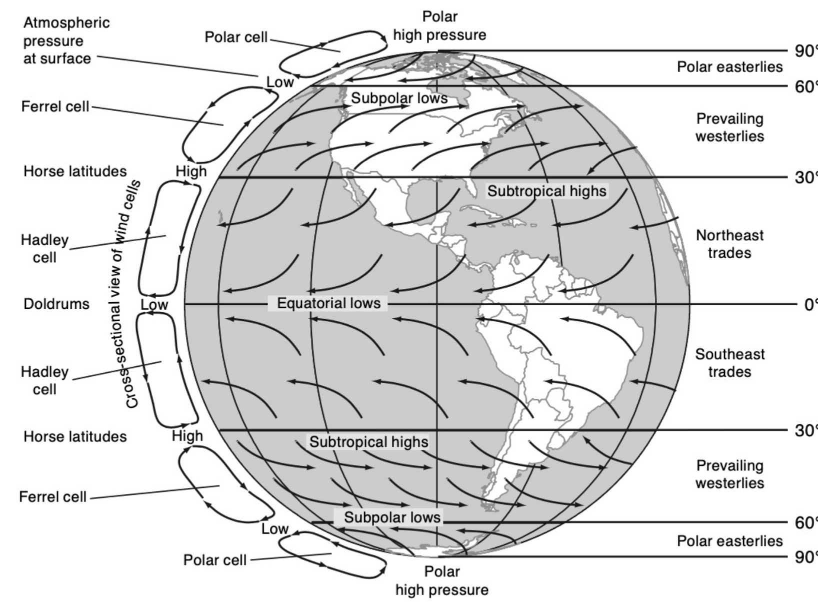
Sarmiento and Gruber, 2006

Formation of ocean gyres



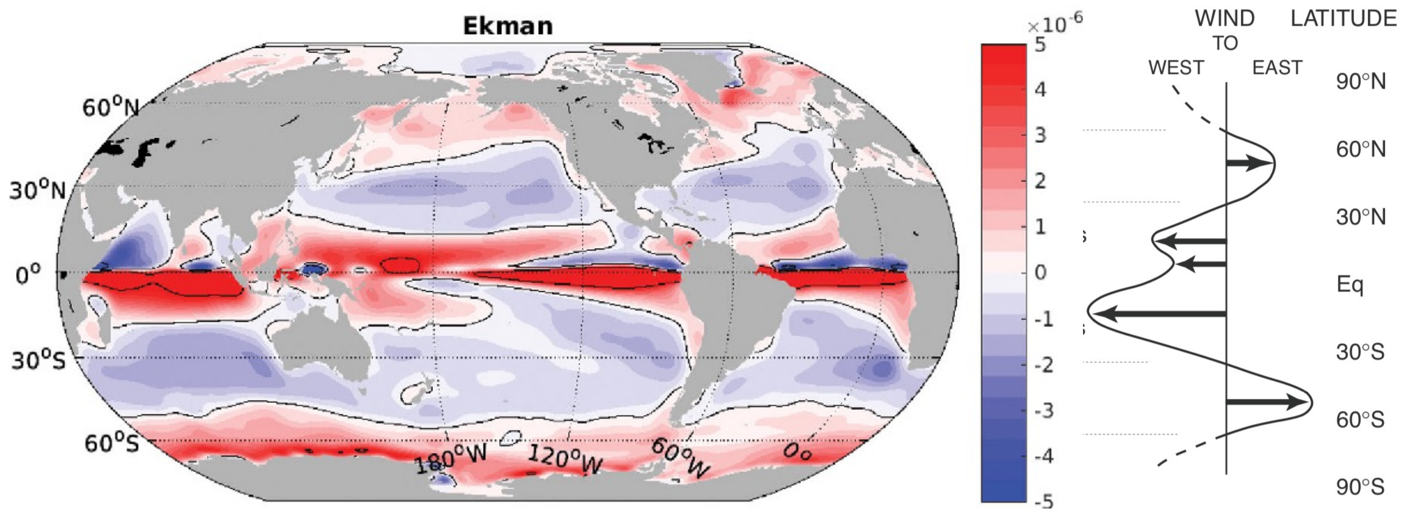


SSH in cm

Emerson and Hedges 200

ESA, mean SSH in cm, https://ggos.org/about/org/fa/unified-height-system/

Global Ekman pumping:

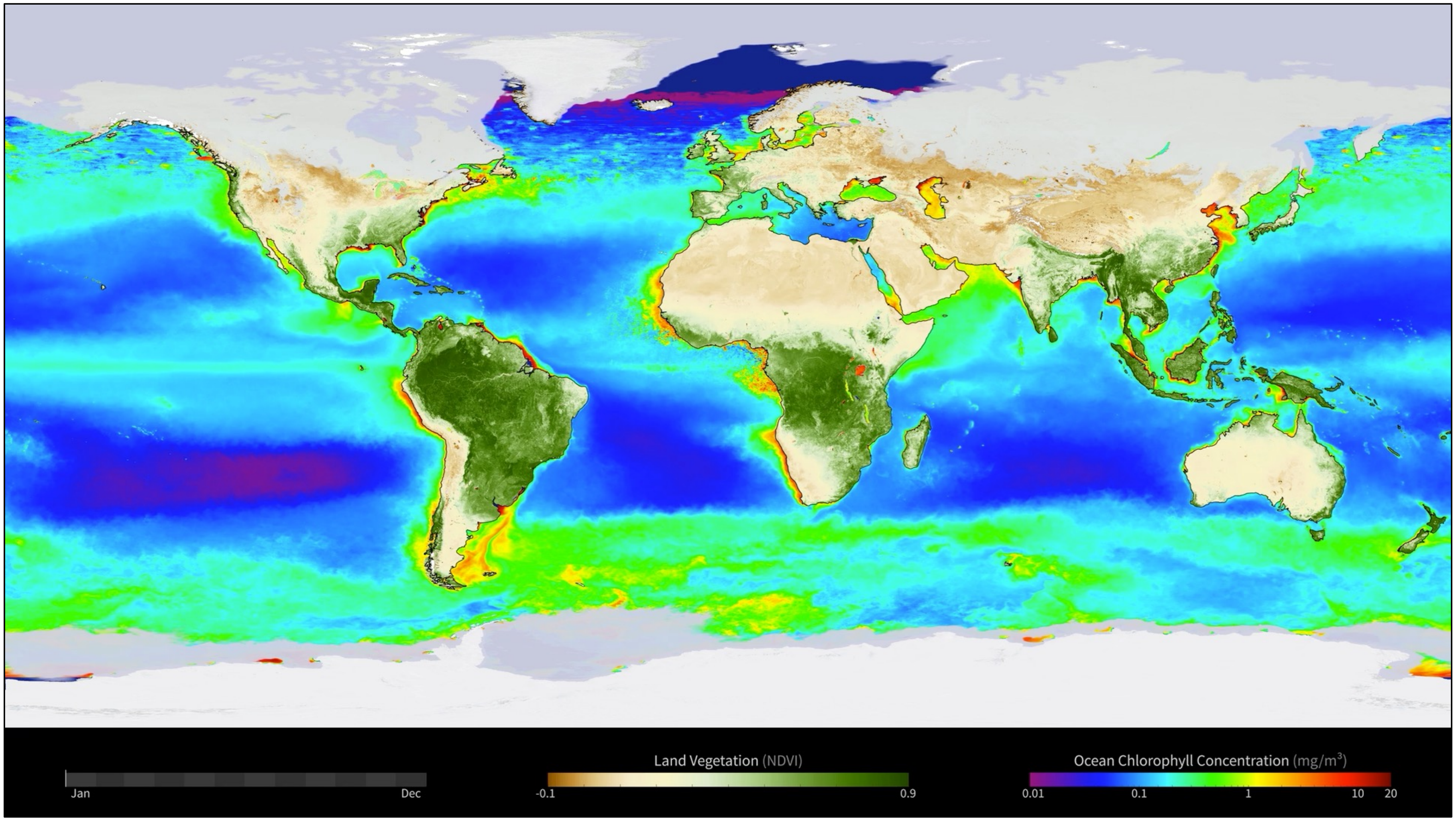


Upwelled water via Ekman pumping brings higher nutrients into the sunlit ocean surface.

What does that lead to?

Liang et al. 2017

Impact of circulation / winds on biology



NASA merged productivity: https://svs.gsfc.nasa.gov/30709

Seasonal mixing

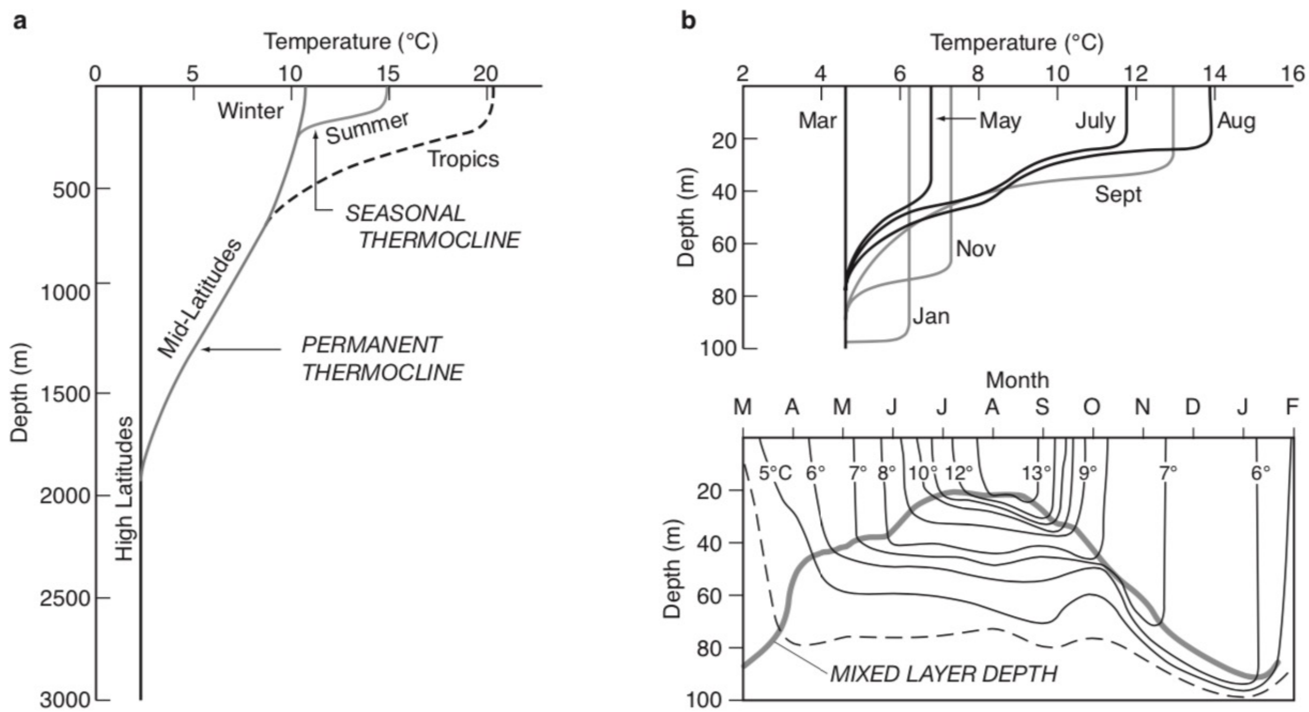
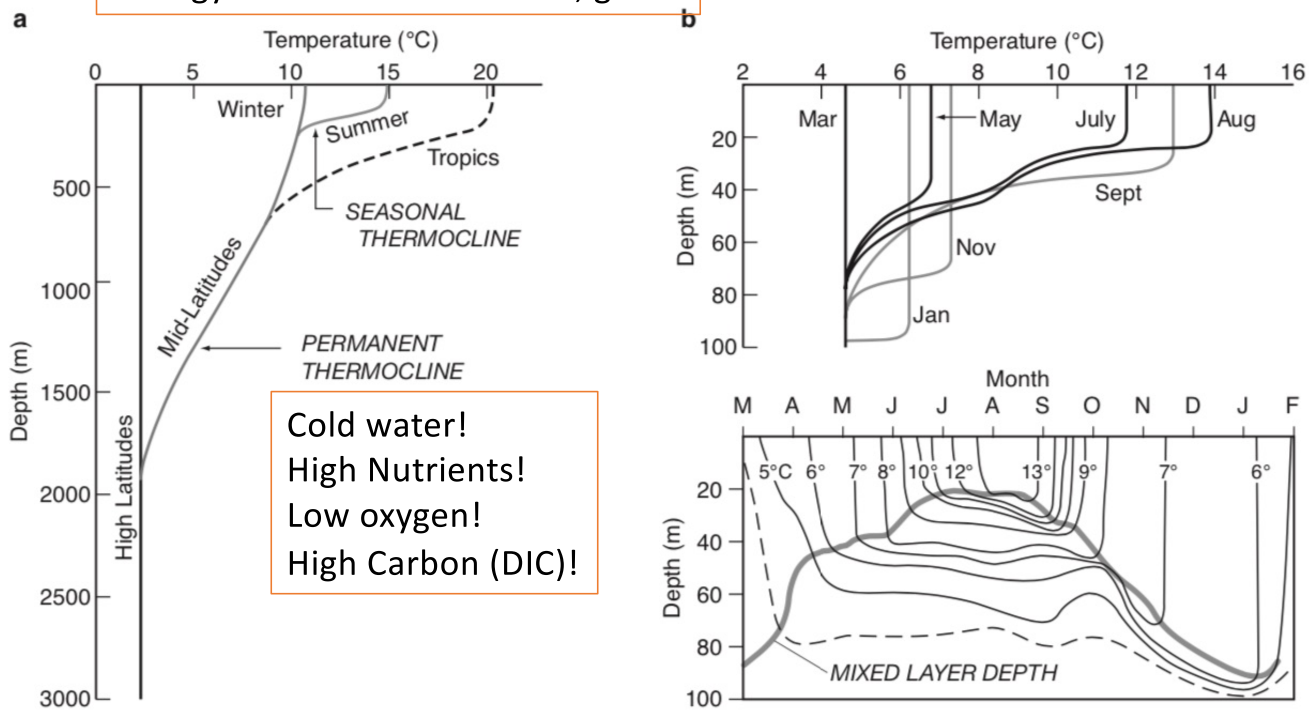


FIGURE 2.3.2: (a) Schematic illustration of terminology used to describe various features of the thermocline [*Knauss*, 1997]. (b) Seasonal behavior of the mixed layer at 50°N, 145°W in the eastern North Pacific [*Pickard and Emery*, 1990].

Sarmiento and Gruber 2006

Seasonal mixing

Biology! Air-sea fluxes of heat, gases



Cold water!
High Nutrients!
Low oxygen!
High Carbon (DIC)!

FIGURE 2.3.2: (a) Schematic illustration of terminology used to describe various features of the thermocline [*Knauss*, 1997]. (b) Seasonal behavior of the mixed layer at 50°N, 145°W in the eastern North Pacific [*Pickard and Emery*, 1990].

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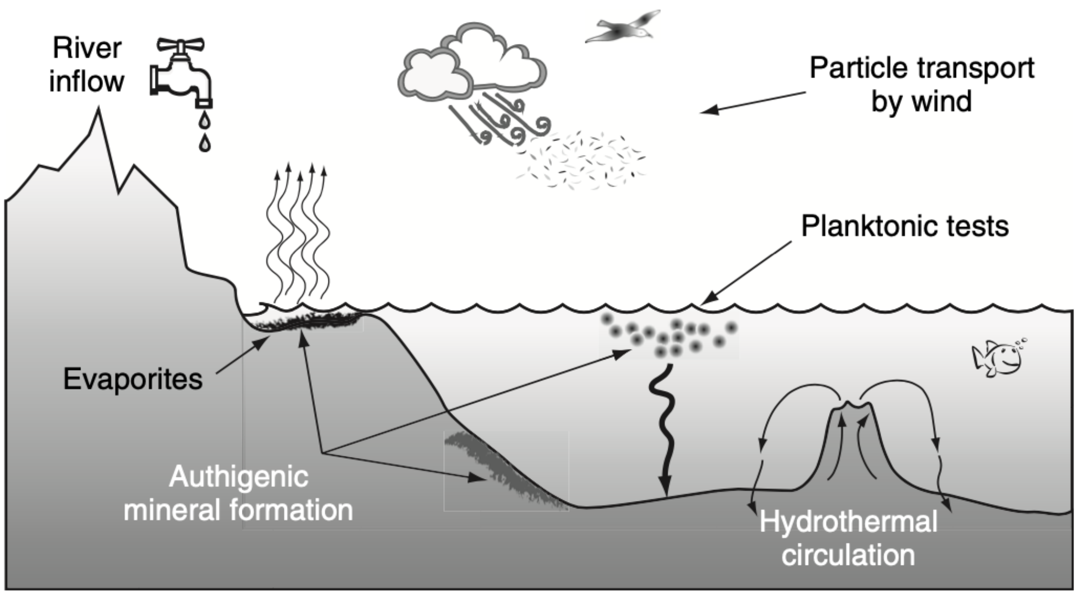
Balance of ocean constituents



Major ocean transports / fluxes / balances

- Geologic – balance between river inflow and sediment / hydrothermal loss
  - Steady state, long-term changes
- Surface / deep ocean – production and consumption of organic matter
  - Respiration in water / sediment column
- Air-sea exchange

E&H Fig. 2.2

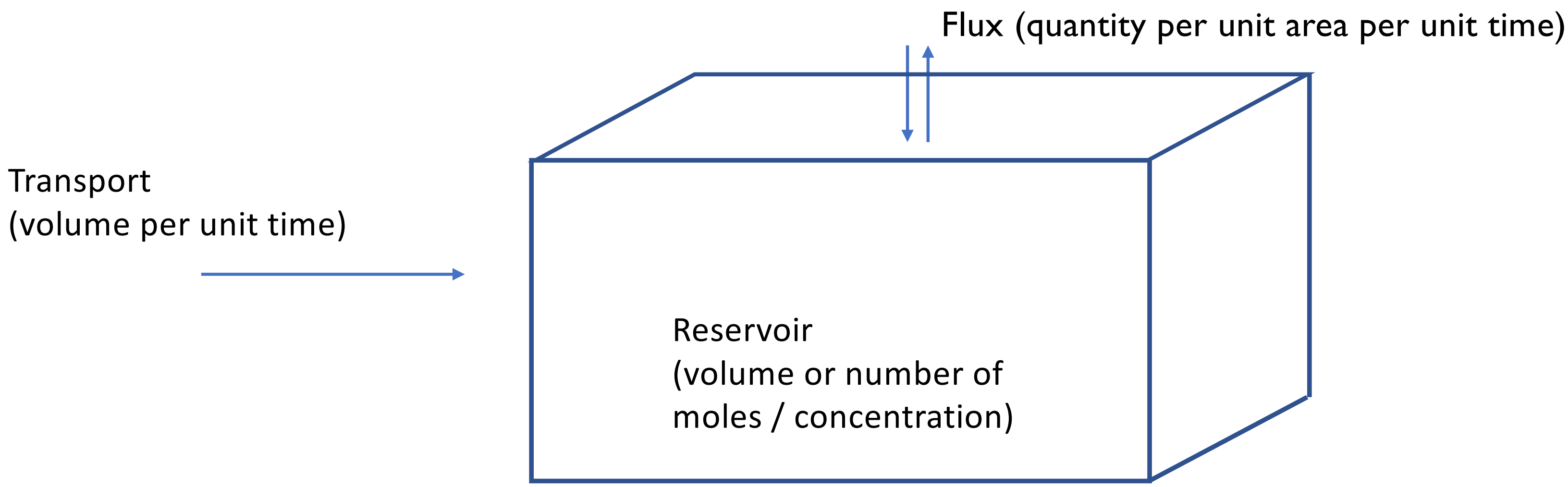
Geochemical Mass Balance

Two types:

1. Balance between reactants (igneous rocks and volcanic gases) and products (sediments, sedimentary rock, and seawater)

2. Geochemical cycles and the balancing of inputs with outputs from various reservoirs: ex. seawater

Terminology: Fluxes, transports, reservoirs/ volumes



Examples:

- Concentration: mol O_2 kg^{-1} or mol O_2 m^{-3}
- Flux: mol O_2 m^{-2} d^{-1}
- Transport: m d^{-1} or mol d^{-1}
- Reservoir: mol O_2

Geochemical Mass Balance

Inflow
(volume per unit time)

Reservoir
(volume or number of moles / concentration)

Outflow
(volume per unit time)

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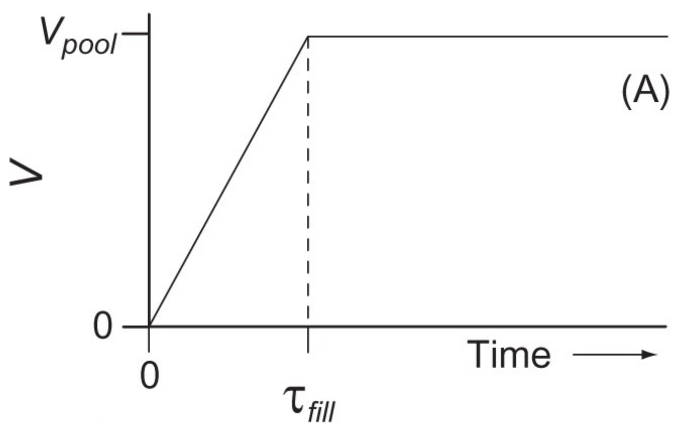

Residence / fill time of a volume:

$$\tau_{fill} = \frac{inventory\ (vol)}{inflow\ (\frac{vol}{time})} = \frac{V}{f}$$

Geochemical Mass Balance

Inflow
(volume per unit time)

Reservoir
(volume or number of moles / concentration)

Outflow
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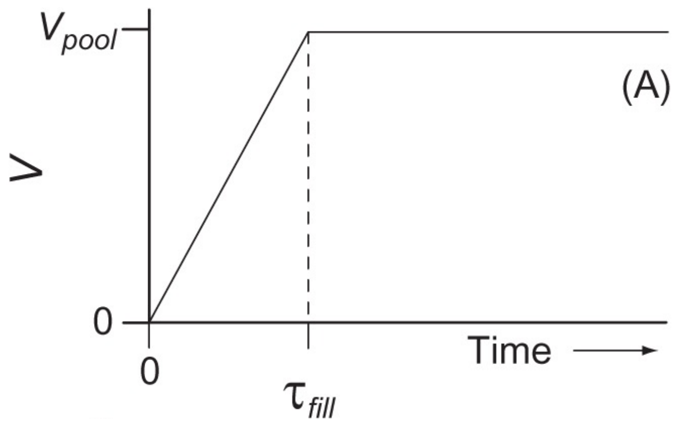
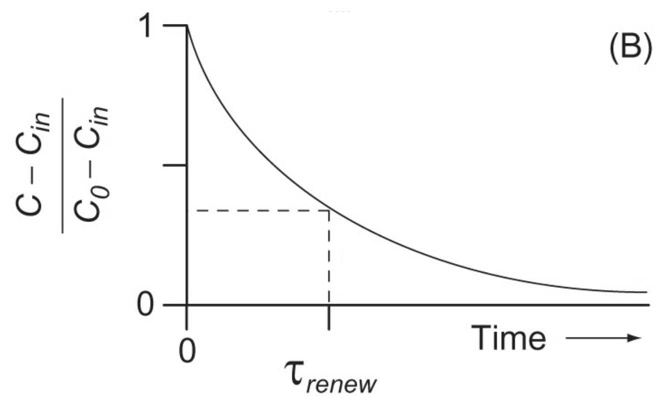




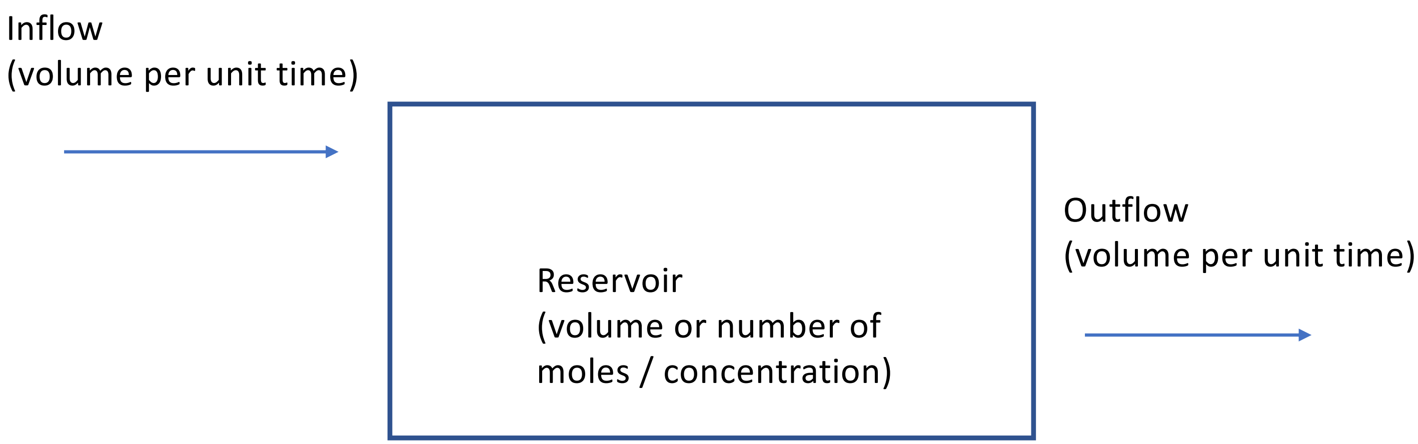
Residence / fill time of a volume, defined as:

$$\tau_{fill} = \frac{inventory\ (vol)}{inflow\ (\frac{vol}{time})} = \frac{V}{f}$$

Residence time of a tracer:

$$\tau = \frac{inventory\ (mol\ or\ vol)}{inflow\ (\frac{mol\ or\ vol}{time})} = \frac{[C]V}{f}$$

Geochemical Mass Balance



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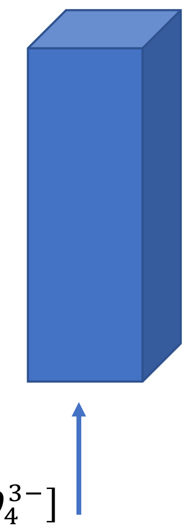
General equation for calculating concentration at time t:

$$C_t - C_{inflow} = (C_0 - C_{inflow})e^{-\left(\frac{f}{V}\times t\right)}$$

Geochemical Mass Balance

1 m x 1 m column



h = 50m

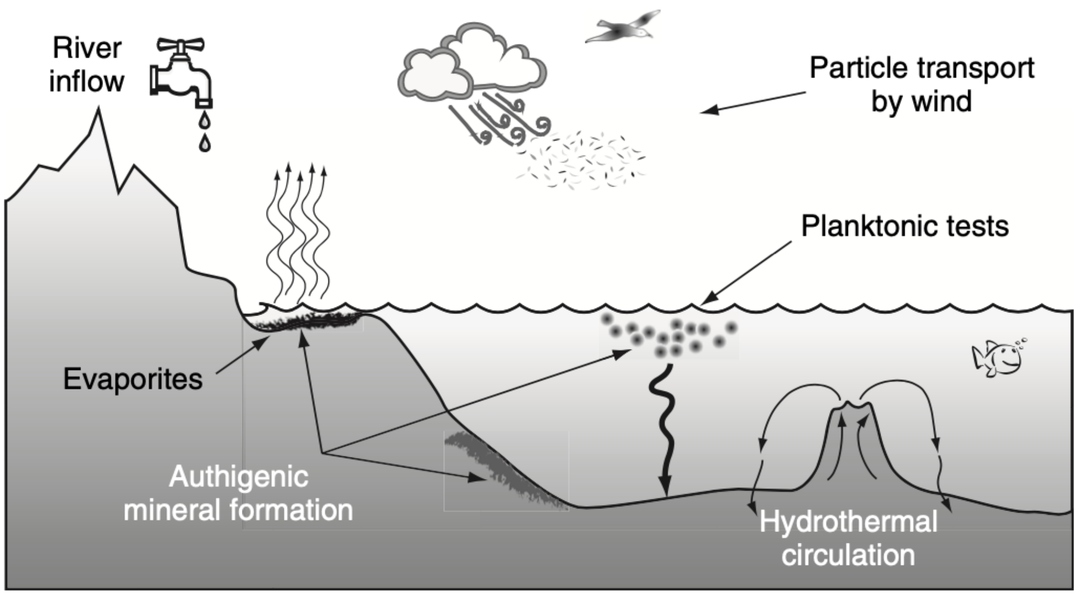
f_{in} = 5 m/d
C_{in} = 2 µmol kg^{-1} $[PO_4^{3-}]$

Consider a water column with a 50 m wintertime mixed layer depth, initially at steady state:

What is the residence time of water in the system?

Given an initial concentration of 0.1 µmol kg-1, what would the concentration be after 10 days?

Balance of ocean constituents



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E&H Fig. 2.2

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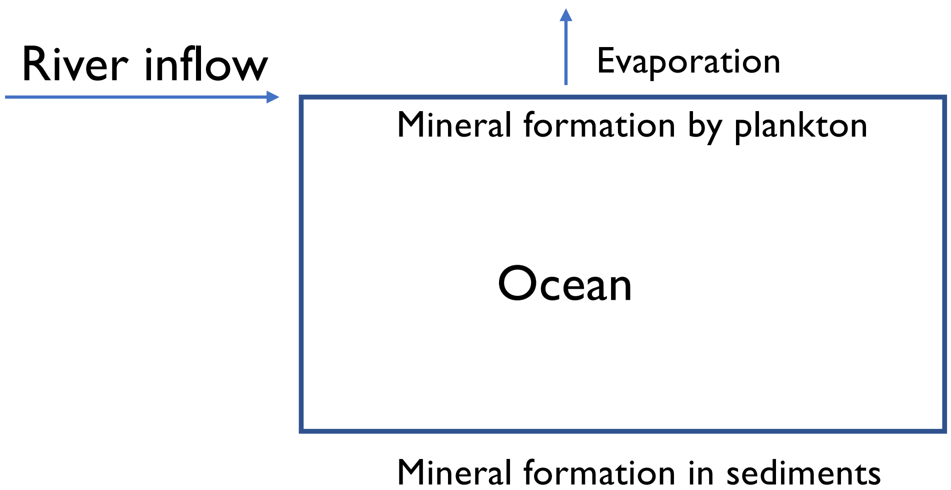

- Does $[C]_{river\ inflow}$ match $[C]_{ocean}$?

- Major ocean transports / fluxes / balances
  - Geologic – balance between river inflow and sediment / hydrothermal loss
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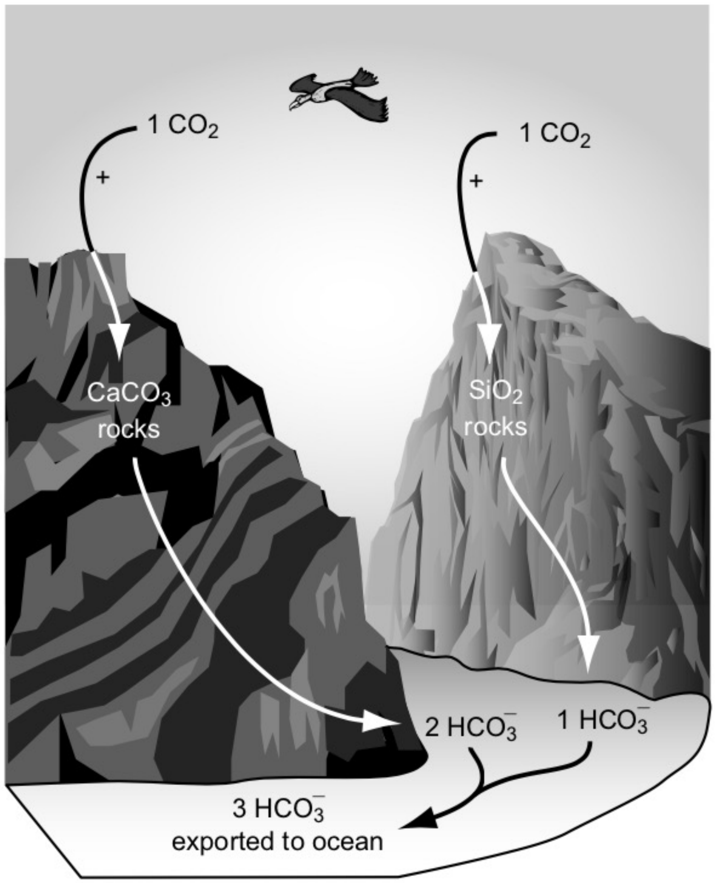
* Authigenesis – in situ formation of minerals (authigenic minerals)

E&H Fig. 2.2

Chemical weathering – supply of minerals to the ocean



- Carbon dioxide reacts with rocks to form the dissolved composition of rivers

Chemical weathering

- Basic idea: Carbon dioxide reacting with water to form H^+ that breaks down minerals to release ions

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Chemical weathering

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(a) CO_2 in soils reacts with water to form H^+ that dissolves $CaCO_3$ according to the net reaction (iii):

i	$CO_2 + H_2O \rightleftarrows HCO_3^- + H^+$
ii	$CaCO_3(s) + H^+ \rightleftarrows HCO_3^- + Ca^{2+}$
iii	$\underbrace{CaCO_3(s) + CO_2 + H_2O}_{\textit{carbonate rocks}} \rightleftarrows \underbrace{2HCO_3^- + Ca^{2+}}_{\textit{dissolved ions}}$

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carbonate rocks *dissolved ions*

(b) CO_2 in soils reacts with water to form H^+ that reacts with potassium feldspar to form the clay mineral (kaolinite) according to the net reaction (vi)

iv $\quad 2CO_2 + 2H_2O \rightleftarrows 2HCO_3^- + 2H^+$

v $\quad 2KAlSi_3O_8(s) + 2H^+ + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4(s) + 2K^+ + 4H_4SiO_4$

vi $\quad 2KAlSi_3O_8(s) + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4(s) + 2K^+ + 2HCO_3^- + 4H_4SiO_4$

K-feldspar *kaolinite* *dissolved ions*

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(c) CO_2 in soils reacts with water to form H^+ that reacts with phlogopite mica to form the clay mineral (kaolinite) according to the net reaction (ix)

vii $\quad 14CO_2 + 14H_2O \rightleftarrows 14HCO_3^- + 14H^+$

viii $\quad 2KMg_3AlSi_3O_{10}(OH)_2(s) + 14H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4(s) + 2K^+ + 6Mg^{2+} + 4H_4SiO_4$

ix $\quad \underset{\text{phlogopite}}{2KMg_3AlSi_3O_{10}(OH)_2(s)} + 14CO_2 + 15H_2O \rightarrow \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4(s)} + 2K^+ + \underset{\text{dissolved ions}}{6Mg^{2+} + 14HCO_3^-} + 4H_4SiO_4$

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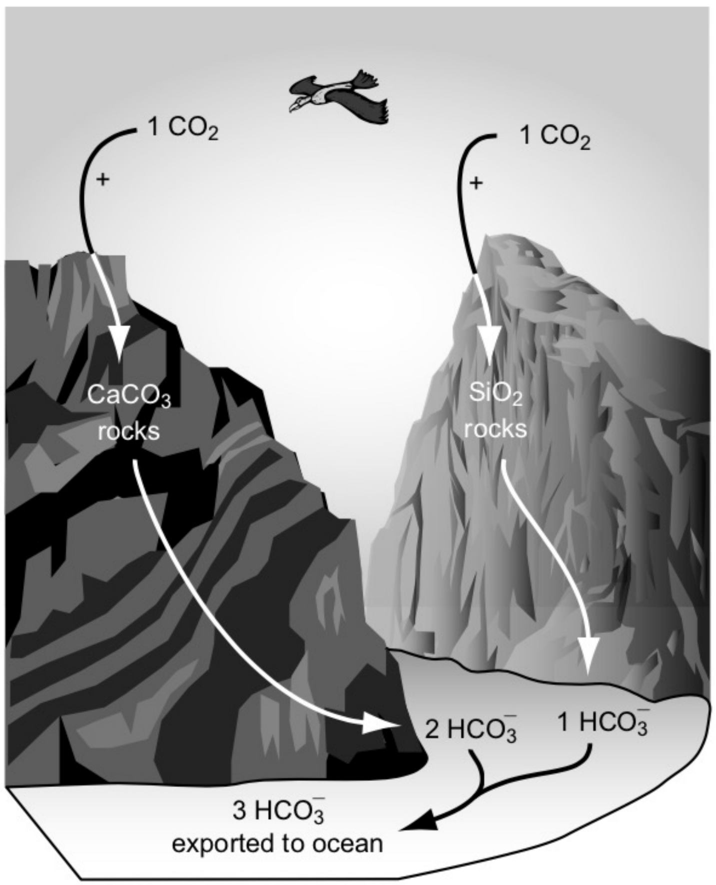
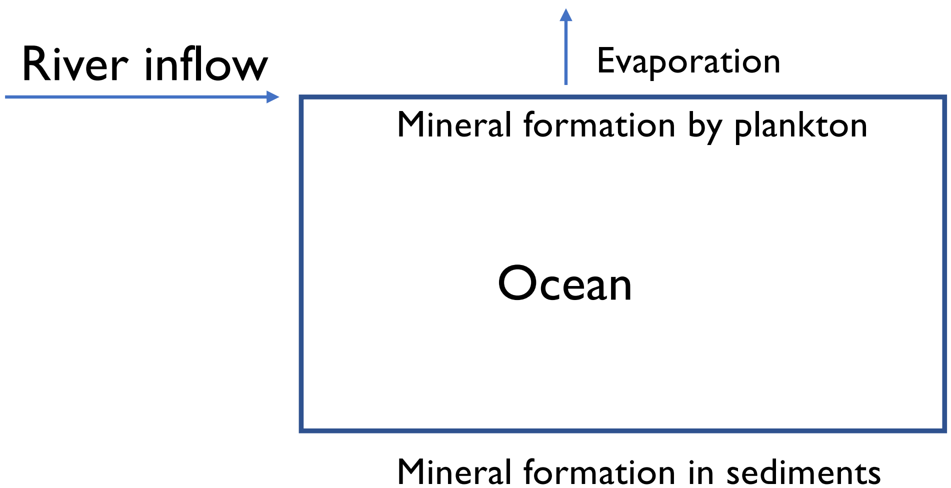
Chemical weathering

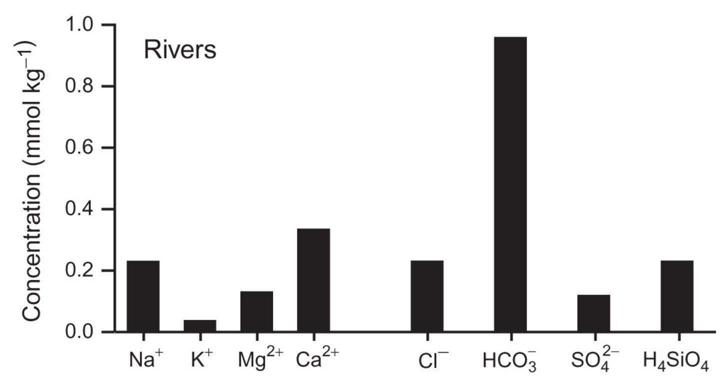


- Carbon dioxide reacts with rocks to form the dissolved composition of rivers
- Approximate equal weathering of $CaCO_3$ and SiO_2 rocks gives correct ratio of atmospheric to rock sources of HCO_3^-
- Do known river inputs match best estimates for formation of sediments on the ocean floor?

Balance of ocean constituents

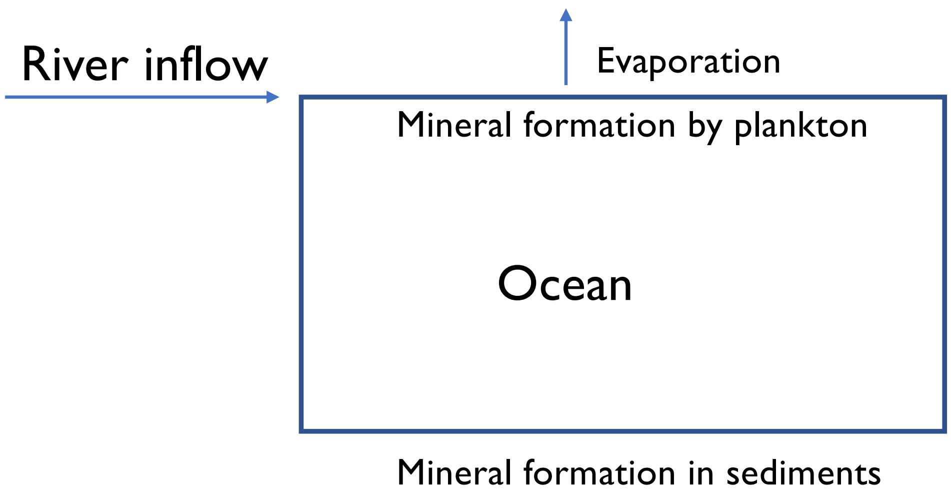


- Does $[C]_{\text{river inflow}}$ match $[C]_{\text{ocean}}$?



E & Hamme Fig. 2.3

Balance of ocean constituents



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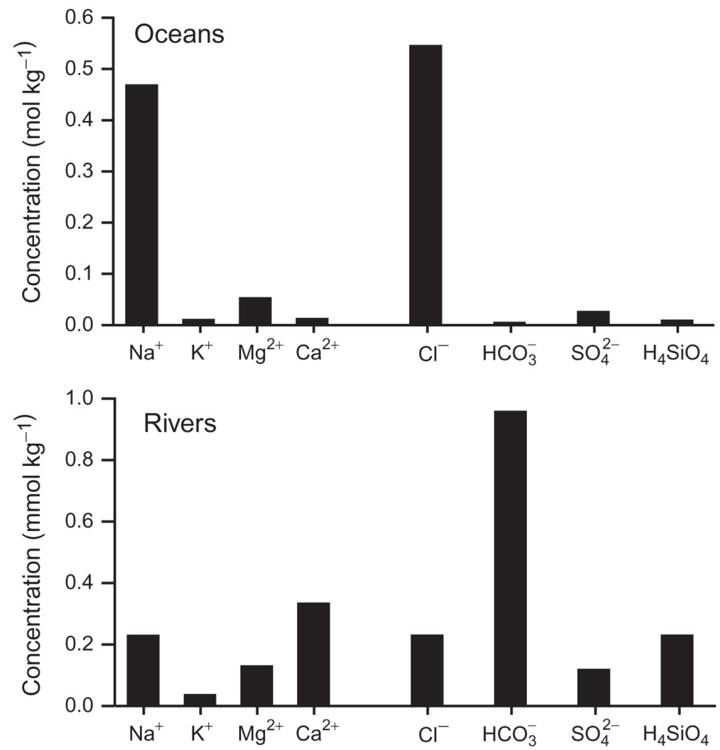


Concentration ratios

	Na^+/K^+	Mg^{2+}/Ca^{2+}	Na^+/Ca^{2+}	$(Mg^{2+}+Ca^{2+})/HCO_3^-$
Oceans	46	5.1	46	27
Rivers	6.0	0.39	0.70	0.48

E & Hamme Fig. 2.3

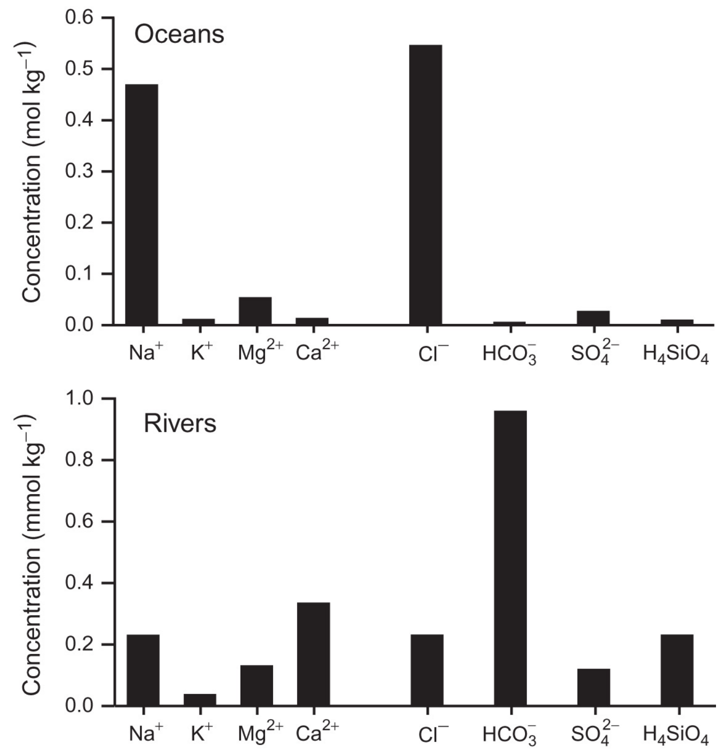
Balance of ocean constituents

Constituent	Seawater concentration (mmol kg^{-1})	Inventory[a] (10^{18} mol)	River water concentration (μmol kg^{-1})	River inflow[b] (10^{12} mol y^{-1})	τ (10^6 y)
H_2O					0.04
Na^+	469.1	647	231	8.6	75
Mg^{2+}	52.8	72.9	128	4.8	15
Ca^{2+}	10.3	14.2	332	12.4	1.1
K^+	10.2	14.1	38.4	1.4	10
Cl^-	545.9	753	220	8.2	92
SO_4^{2-}	28.2	38.9	115	4.3	9.0
DIC[c]	2.3	3.2	958	35.7	0.1
H_4SiO_4	0–0.2	0.1[d]	158[d]	5.9	0.01

$$\tau = \frac{inventory\ (mol)}{river\ inflow\ flux\ (mol\ yr^{-1})}$$

- Residence time of ocean water: 40,000 yrs (circulation time is ~1000 yrs)
- Most reactive ion: HCO_3^-
- Least reactive ion: Cl^-

E & Hamme Fig. 2.3



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Mackenzie and Garrels 1966

Major ion		SO_4^{2-}	Ca^{2+}	Cl^-	Na^+	Mg^{2+}	K^+	H_4SiO_4	HCO_3^-
Mass removed in 10^8 *y* (10^{18} *mol*)		429	1238	821	861	477	143	589	3573
Mineral formed	Moles Removed	*Amount of ion remaining after reaction*							

River input that needs to be balanced by mineral formation

Mackenzie and Garrels 1966

Major ion		SO_4^{2-}	Ca^{2+}	Cl^-	Na^+	Mg^{2+}	K^+	H_4SiO_4	HCO_3^-
Mass removed in 10^8 *y* (10^{18} *mol*)		429	1238	821	861	477	143	589	3573
Mineral formed	Moles Removed	*Amount of ion remaining after reaction*							
Pyrite, FeS_2	215[a]	214	1238	821	861	477	143	589	3573

[a] Assume half of the SO_4 is removed by pyrite formation and half by $CaSO_4$ formation
[b] The biogenic opal (SiO_2) burial is taken from Tregeur and DeLaRocha, 2013

(b) Formation reactions:
Pyrite: $SO_4^{2-} + 2CH_2O(s) \rightleftarrows S^{2-} + 2CO_2 + H_2O$ followed by $Fe^{2+} + S^{2-} + S^0 \rightleftarrows FeS_2$

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Sodium Chloride, NaCl	821			0	40	477	143	589	1525
Opal, SiO_2	630[b]				40	477	143	0	1525

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Sodium Chloride: $Na^+ + Cl^- \rightleftarrows NaCl(s)$

Opal: $H_4SiO_4 \rightleftarrows SiO_2(s) + 2H_2O$

Possible additional sinks: Reverse weathering

Dissolution reactions in reverse – proposed as a way to remove excess ions from the ocean

- Deposited clay minerals on the ocean seafloor react with seawater, using up Mg^{+}, K^{+}, HCO_3^-

vi $$2KAlSi_3O_8 + 2\,CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4(s) + 2K^+ + 2HCO_3^- + 4H_4SiO_4$$

K-feldspar *kaolinite* *dissolved ions*

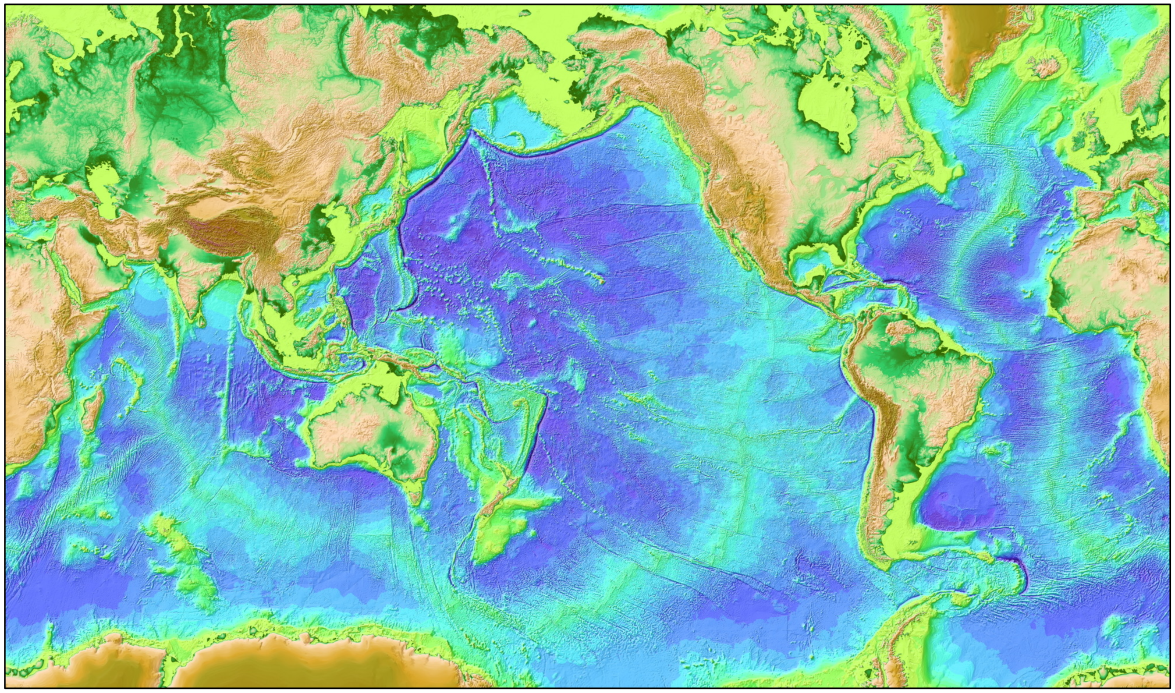
ix $$2KMg_3AlSi_3O_{10}(OH)_2(s) + 14CO_2 + 15H_2O \rightarrow Al_2Si_2O_5(OH)_4(s) + 2K^+ + 6Mg^{2+} + 14HCO_3^- + 4H_4SiO_4$$

phlogopite *kaolinite* *dissolved ions*

However, there's a problem! It is unclear how much these reactions actually occur.

What else are we missing from our picture of the ocean and inflows / outflows?

Possible additional sinks: Hydrothermal circulation



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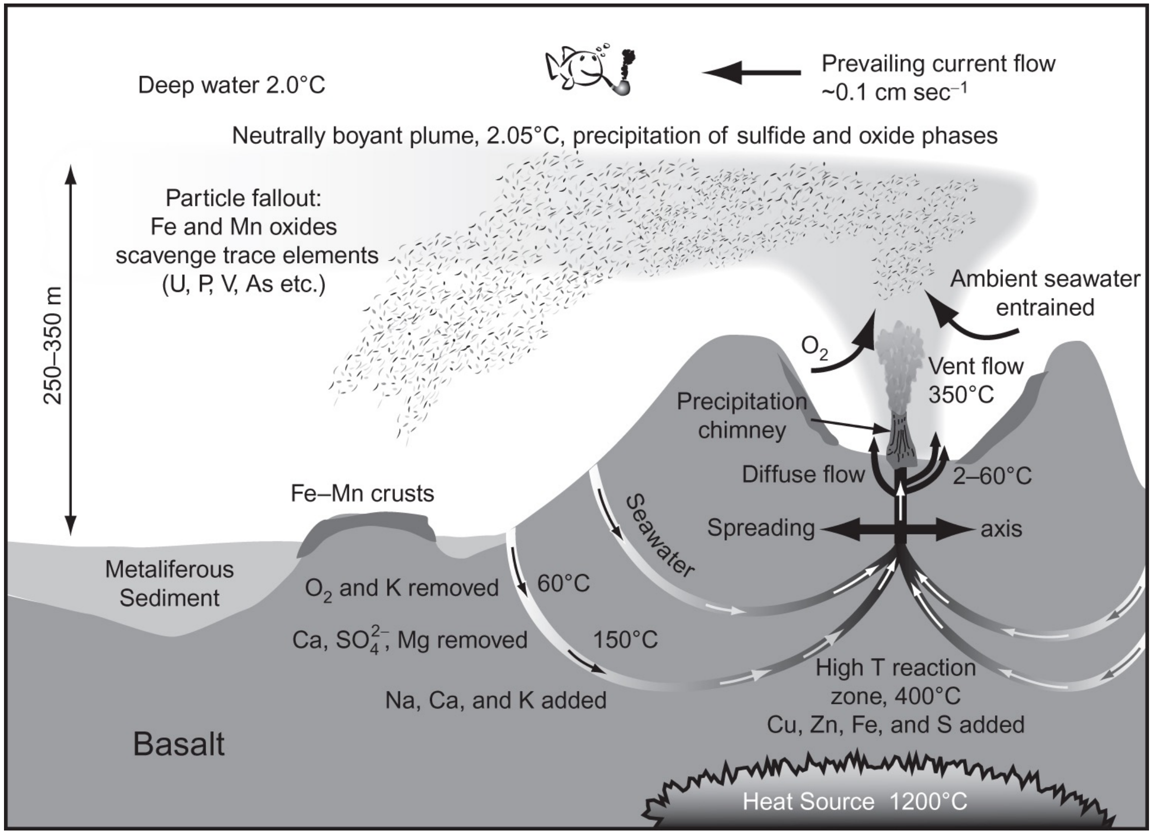
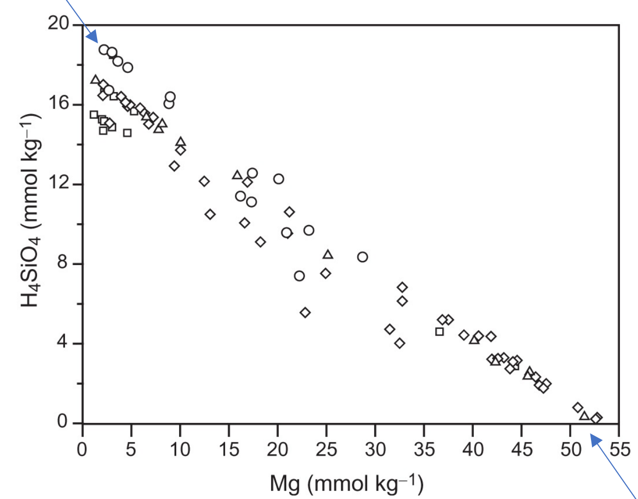


Emerson and Hamme, 2021

Hydrothermal end member



Seawater end member

In actuality, both reverse weathering and hydrothermal vents are responsible for removing excess ions, though magnitudes are unclear

Nick Hawco will cover hydrothermal vents later in the semester