Whistlestop Tour: Land-Surface Modeling & the Global Carbon Cycle

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Energy Budget Concept

- Energy In – Energy Out = Change in Energy
- For the land surface,
  - Energy in = Radiation
  - Energy Out = Radiation + Turbulent fluxes of “sensible” and “latent” heat
  - Change in energy = changes in temperature of soil, plants, water, & air

Land Surface Energy Budget

- Very little of the energy gained by net radiation is stored in the ground (G)
- Most is emitted as LW IR and turbulent fluxes of sensible (H) and latent heat (LE)
- Latent energy is then released into atmosphere when vapor condenses

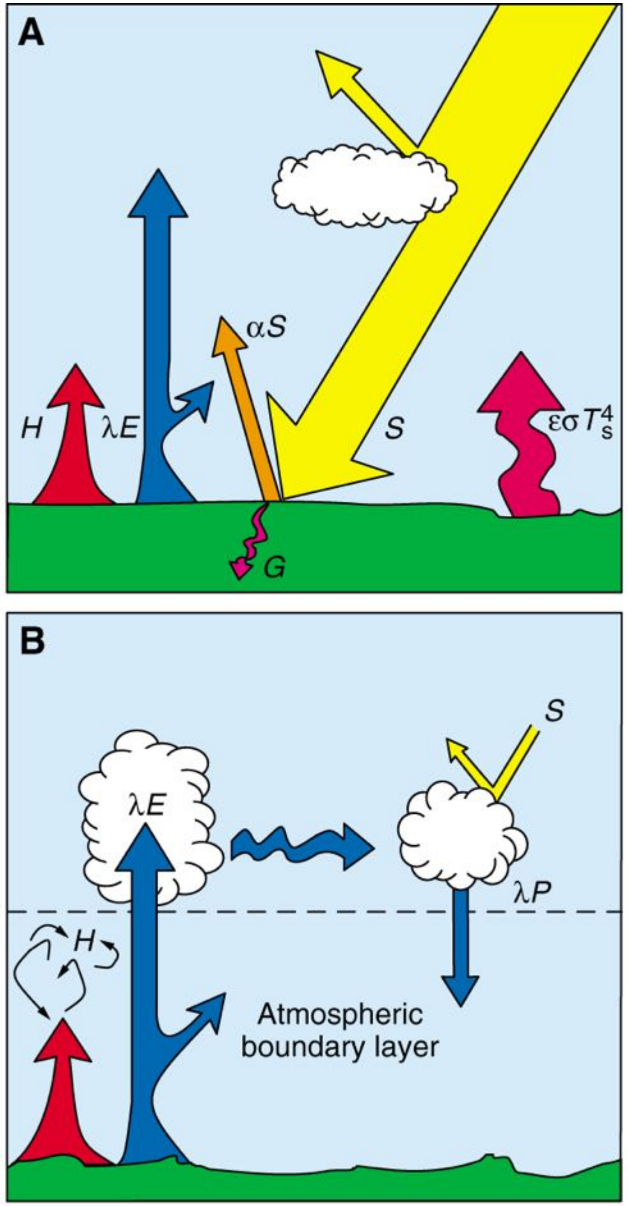


Fig. 1. Interactions between the land surface and the atmosphere that have direct impacts on the physical climate system. (**A**) Surface radiation budget. (**B**) Effect of heat fluxes on the atmosphere.

Surface Energy Budget

Storage change = Energy in – energy out

$$\rho c \frac{\Delta T}{\Delta t} \Delta z = (S\downarrow - S\uparrow + L\downarrow - L\uparrow) - H + \lambda E = G$$

$$R_{net} = (S\downarrow - S\uparrow) + (L\downarrow - L\uparrow) = H + \lambda E + G$$

net SW

net LW

sensible heat flux

Latent heat of vaporization

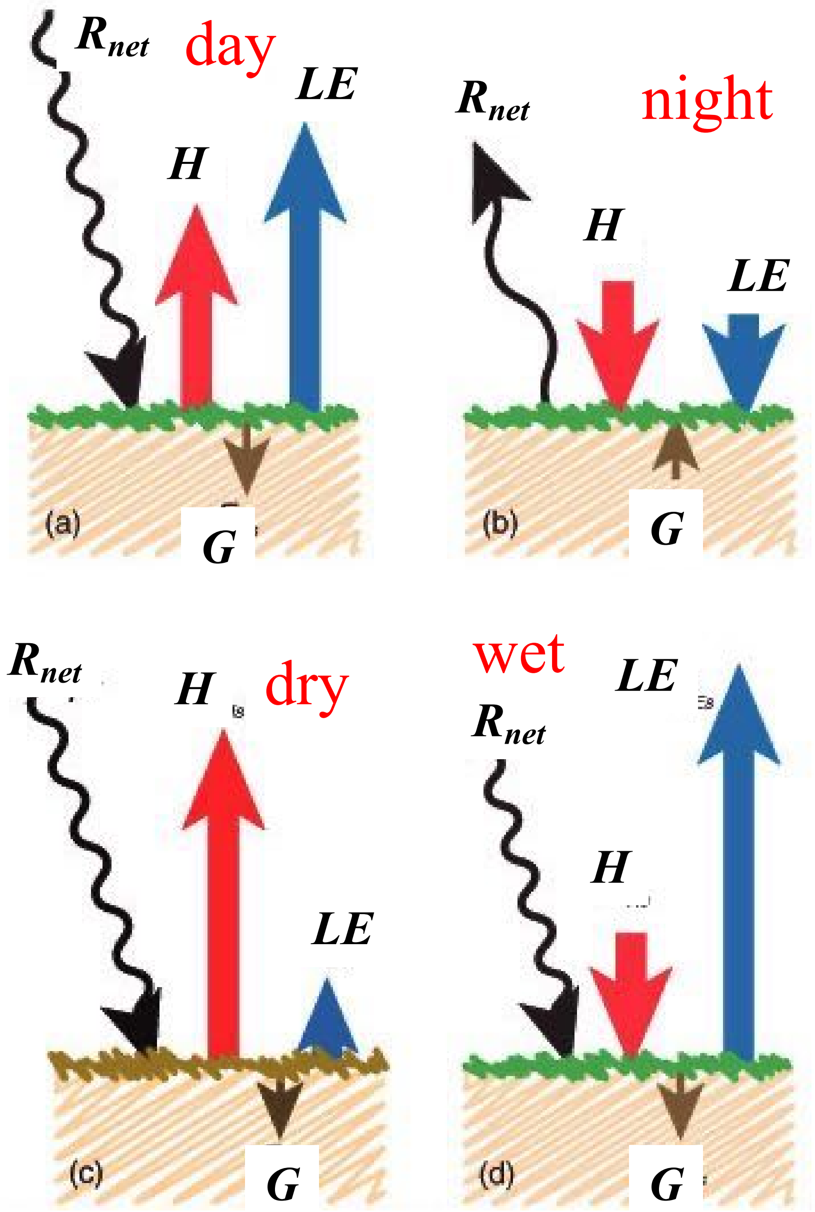
evap

ground heat flux

Role of the land surface:

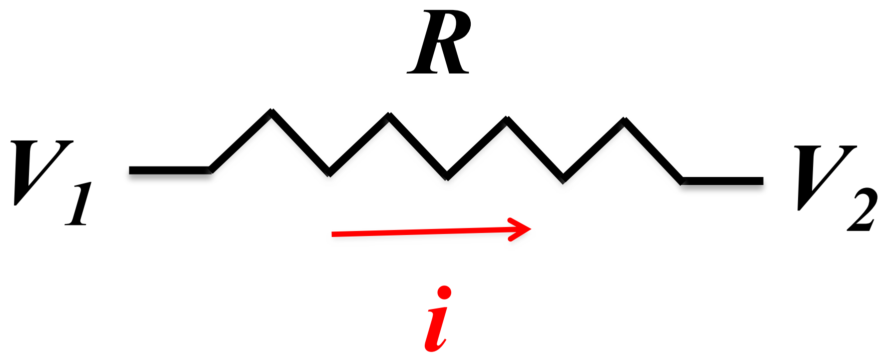
Partition of net radiation into turbulent fluxes & storage

Surface Energy Budgets



- R_{net} = H + LE + G
  ~ H + LE
- Daytime turbulent fluxes upward
- Night: turbulent fluxes downward (dew or frost!)
- Dry surfaces
  R_{net} ~ H
- Wet surfaces
  R_{net} ~ LE

Heat Fluxes ~ Currents



$$\Delta V = ir$$

voltage

$$i = \frac{\Delta V}{r}$$

current

resistance

- **Sensible heat flux**
  - Driving potential is a difference in temperature
  - H is proportional to ΔT
- **Latent heat flux**
  - Driving potential is a difference in vapor pressure
  - LE is proportional to Δe

Sensible Heat Flux

- Driving potential is a difference in temperature
- H is proportional to ΔT

$$H = \rho c_p \frac{\Delta T}{r} = \rho c_p \frac{T_S - T_a}{r}$$

H: Watts m^{-2}

ρ: density, kg m^{-3}

c_p: heat capacity, 1004 J K^{-1} kg^{-1}

r: aerodynamic resistance, s m^{-1}

$$\frac{(\text{kg m}^{-3})(\text{J K}^{-1}\ \text{kg}^{-1})(\text{K})}{(\text{s m}^{-1})} = \frac{(\cancel{\text{kg}}\ \text{m}^{-3})(\text{J}\ \cancel{\text{K}}^{-1}\ \cancel{\text{kg}}^{-1})(\cancel{\text{K}})}{(\text{s m}^{-1})} = \frac{\text{J s}^{-1}}{\text{m}^2} = \text{W m}^{-2}$$

Latent Heat Flux

- Driving potential is a difference in water vapor pressure
- LE is proportional to Δe

$$LE = \frac{\rho c_p}{\gamma}\frac{\Delta e}{r} = \frac{\rho c_p}{\gamma}\frac{e_S - e_a}{r}$$

Watts m^{-2}

"Psychrometric constant"

$\gamma = (C_p P)/(0.622\lambda)$

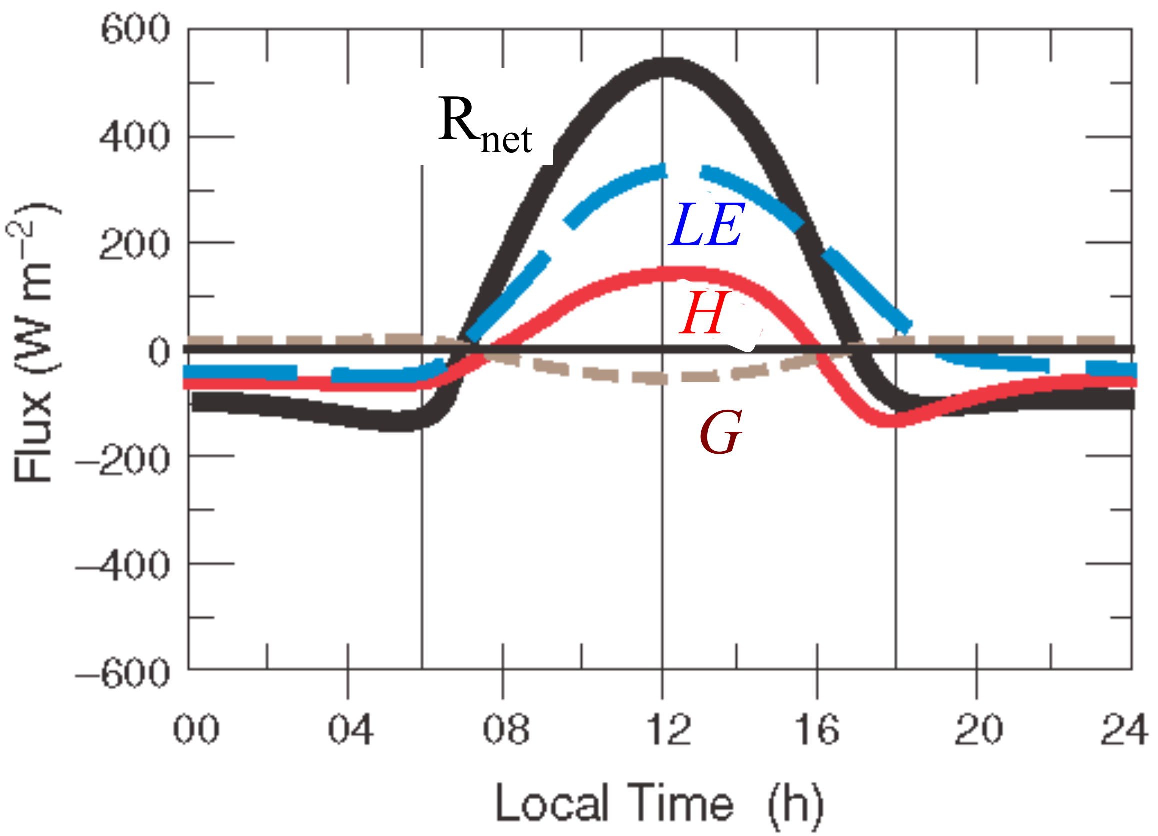
66.5 Pa °C^{-1}

aerodynamic resistance

s m^{-1}

Idealized Diurnal Cycle

- R_{net} follows cos(z) during day, negative at night (LW cooling)
- Downward turbulent fluxes at night
- Ground heat flux smaller: downward durng day and up at night



$$R_{net} = H + LE + G$$
$$\sim H + LE$$

Partition of Net Radiation

$$R_{net} = (S\downarrow - S\uparrow) + (L\downarrow - L\uparrow) = H + \lambda E + G$$

Ground heat flux

$$G = k(T_s - T_g)/\Delta z$$

$$H = -\rho C_p \frac{(T_a - T_s)}{r_H}$$

Sensible flux driven by ΔT

Latent flux driven by VPD

$$\lambda E = -\frac{\rho C_p}{\gamma}\frac{(e_a - e_*[T_s])}{r_W}$$

$\gamma = (C_p P)/(0.622\lambda)$ 66.5 Pa °C^{-1}

"Psychrometric constant"

Surface Energy Budget

Energy in = energy out + storage change

$$(1-r)S\downarrow + \varepsilon L\downarrow = \varepsilon\sigma(T_s + 273.15)^4 + H + \lambda E + G$$

$$(1-r)S\downarrow + \varepsilon L\downarrow = \varepsilon\sigma(T_s + 273.15)^4 - \rho C_p \frac{(T_a - T_s)}{r_H} - \frac{\rho C_p}{\gamma}\frac{(e_a - e_*[T_s])}{r_W} + k\frac{(T_s - T_g)}{\Delta z}$$

- **Can solve for surface temperature**
- **Physical properties: albedo, emissivity, heat capacity, soil conductivity & temperature**
- **“Resistances” are properties of the turbulence … depend sensitively on H!**

Penman-Monteith Equation

"Thermodynamic" energy balance

$$\lambda E = (R_n - G) - H = (R_n - G) + \rho C_p (T_a - T_s)/r_H$$

"Turbulent" energy balance

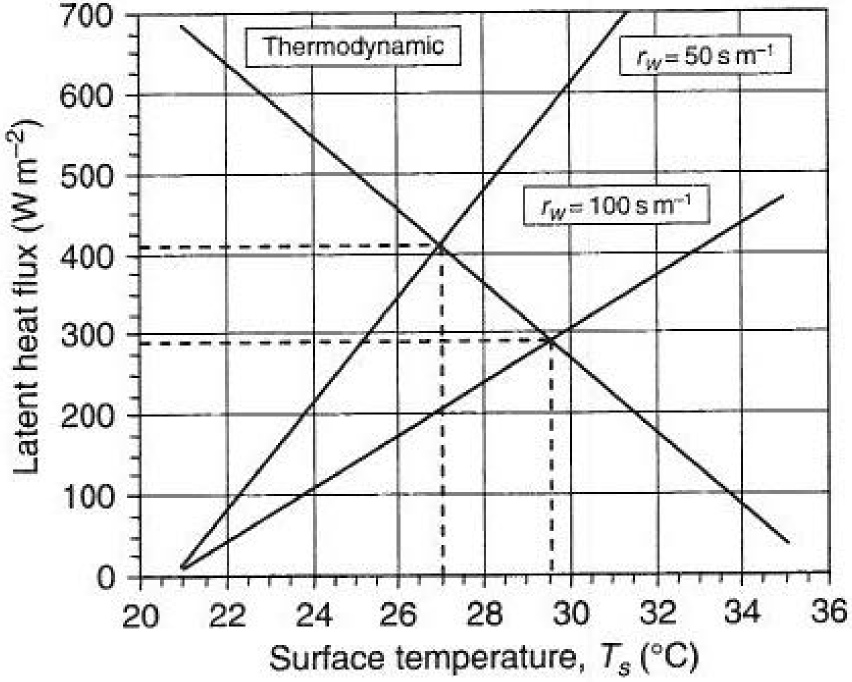
$$\lambda E = \frac{\rho C_p}{\gamma} \frac{(e_*[T_a] + s(T_s - T_a) - e_a)}{r_W}$$

Solve for surface temperature

$$T_s - T_a = (r_H/\rho C_p)(R_n - G - \lambda E)$$

$$e_*[T_s] = e_*[T_a] + s(T_s - T_a)$$

VPD approximated by linearization of Clausius-Clapeyron equation



Solutions to P-M Equation

Latent heat flux

$$\lambda E = \frac{s(R_n - G) + \rho C_p(e_*[T_a] - e_a)/r_H}{s + \gamma(r_W/r_H)}$$

Sensible heat flux

$$H = \frac{(R_n - G)\gamma^* - \rho C_p(e_*[T_a] - e_a)/r_H}{s + \gamma^*}$$

Surface temperature

$$T_s = T_a + \frac{(R_n - G)\gamma^* r_H/\rho C_p - (e_*[T_a] - e_a)}{s + \gamma^*}$$

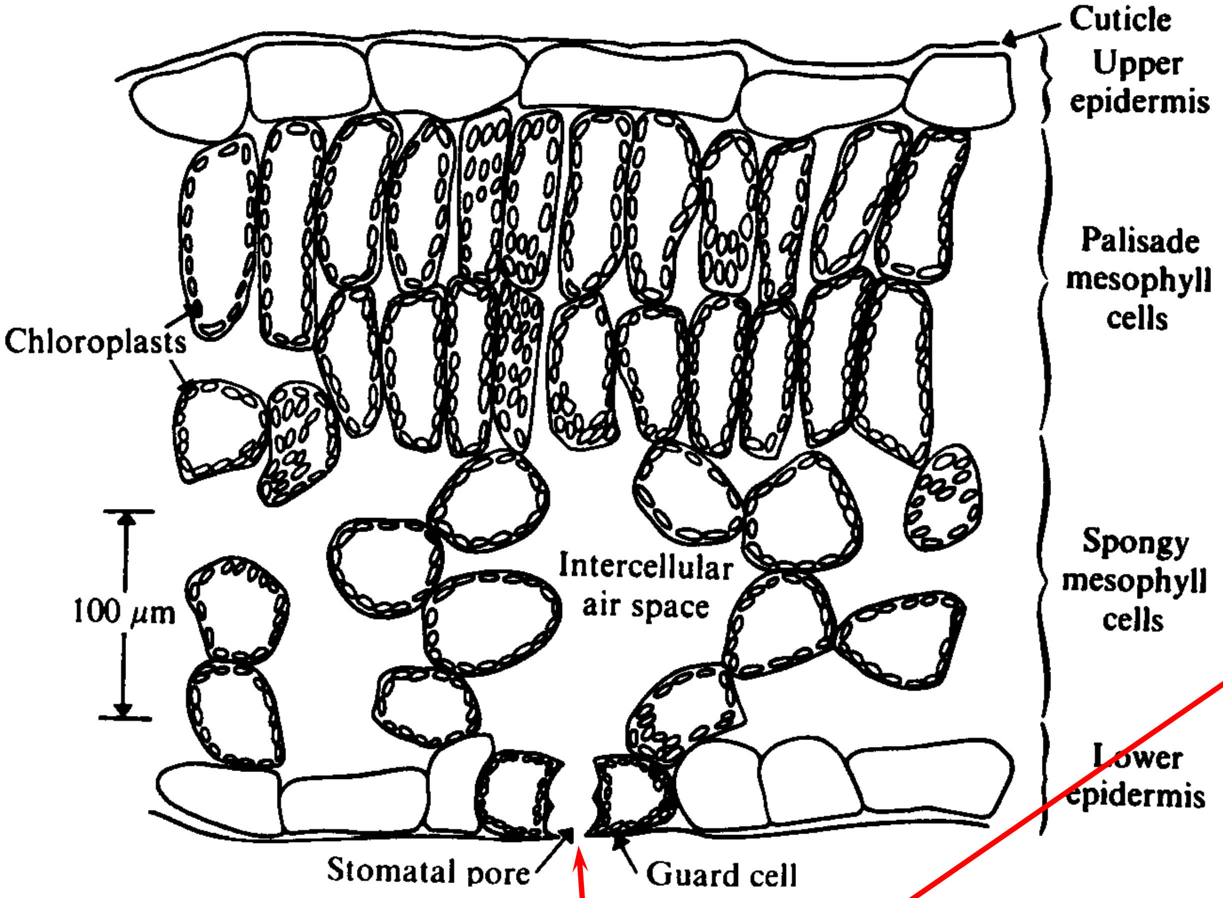
Turbulent Fluxes

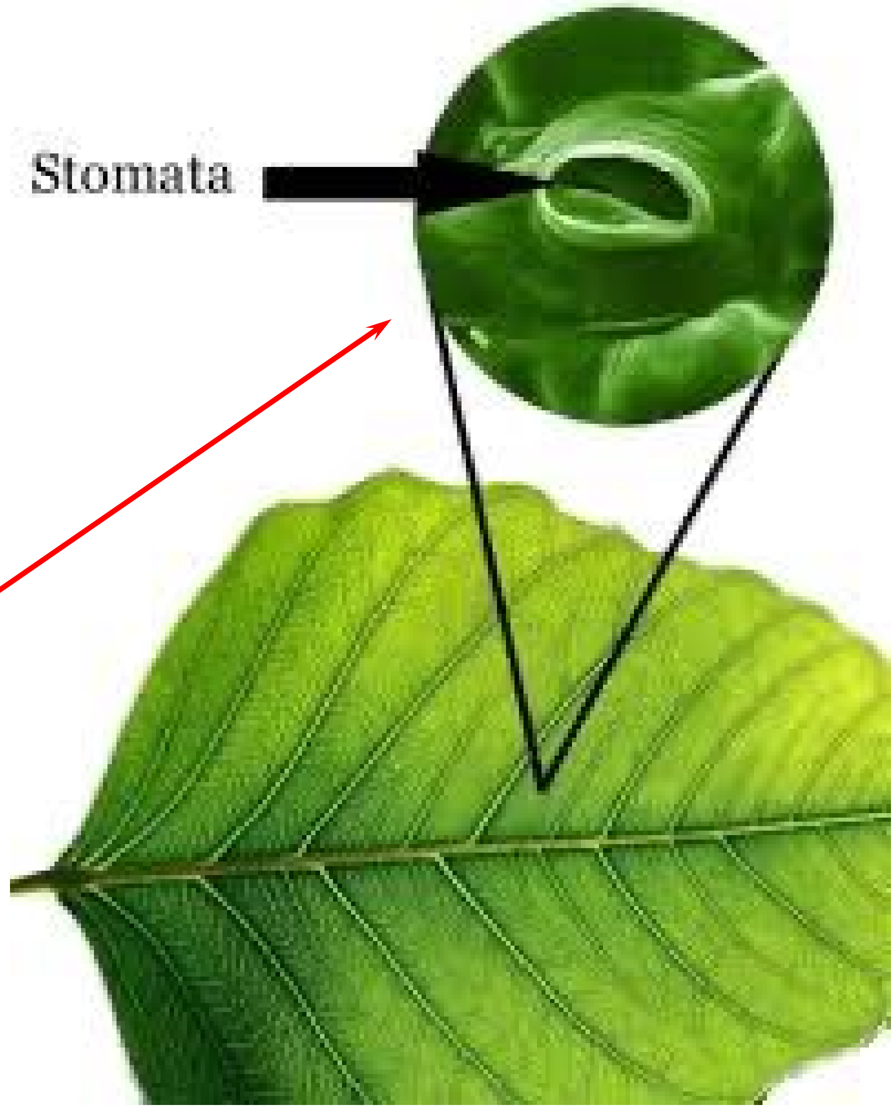
$$H = \rho c_p \frac{\Delta T}{r} = \rho c_p \frac{T_S - T_a}{r}$$

$$LE = \frac{\rho c_p}{\gamma} \frac{\Delta e}{r} = \frac{\rho c_p}{\gamma} \frac{e_S - e_a}{r}$$

aerodynamic resistance
$s\ m^{-1}$

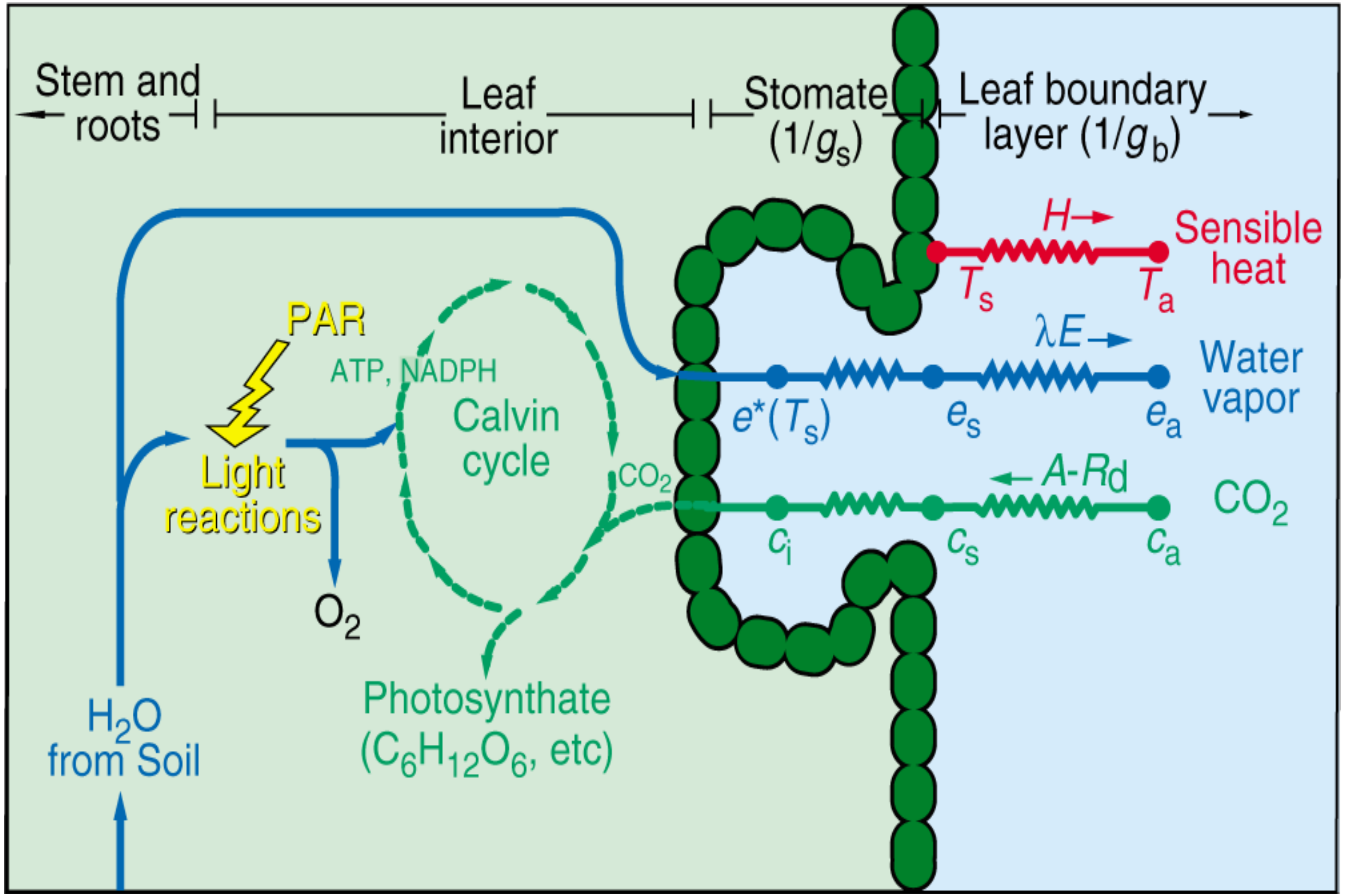
Leaf Anatomy





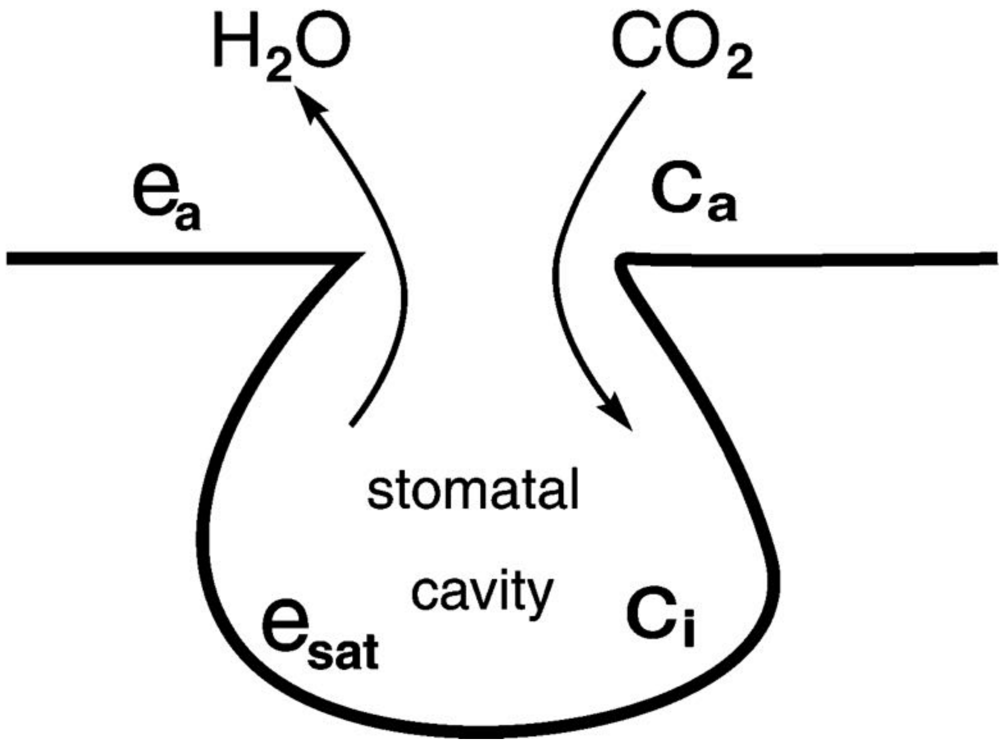
Stomate
(pl. stomata)

Stomatal Physiology



- Heat, water, and carbon **fluxes are coupled by physiology**
- **Scaling to canopy and landscape** fluxes based on **resource allocation**

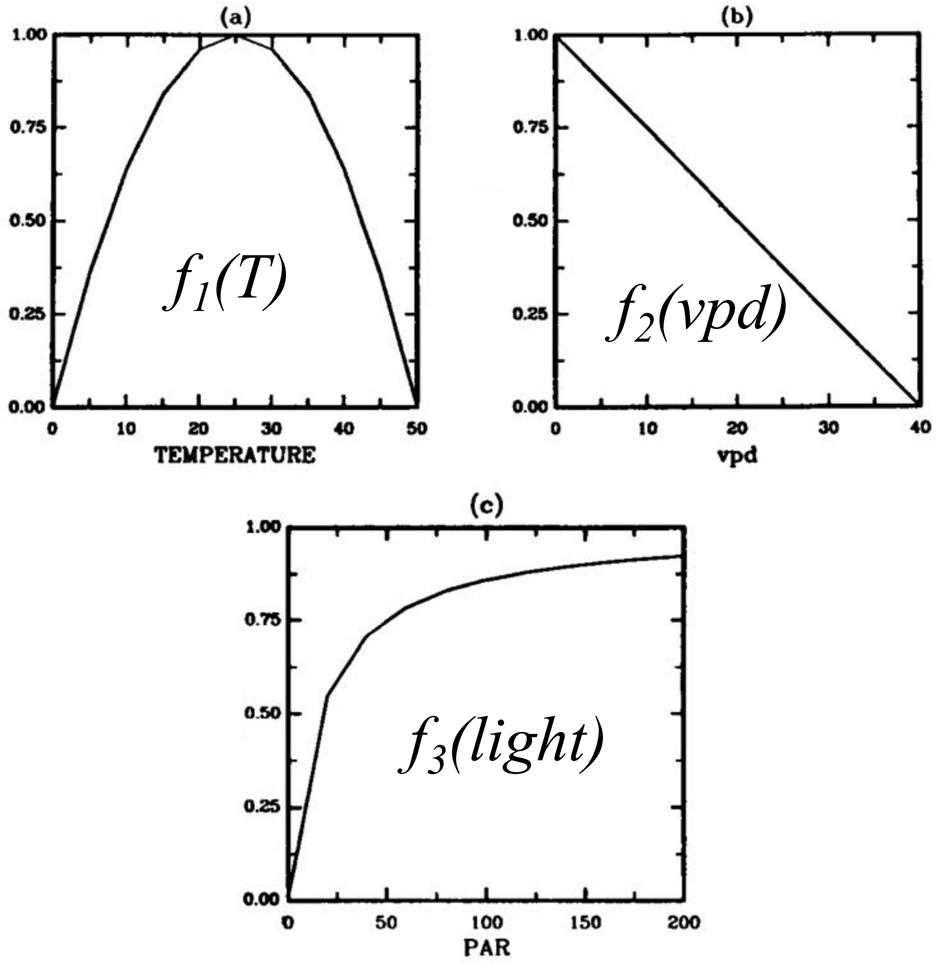
Carbon and Water



- Plants eat CO_2 for a living
- They open their stomata to let CO_2 in
- Water gets out as an (unfortunate?) consequence
- For every CO_2 molecule fixed about 400 H_2O molecules are lost

Canopy Conductance, c. 1990

$$g_s = g_{s,\max} f_1(T) f_2(vpd) f_3(PAR)$$



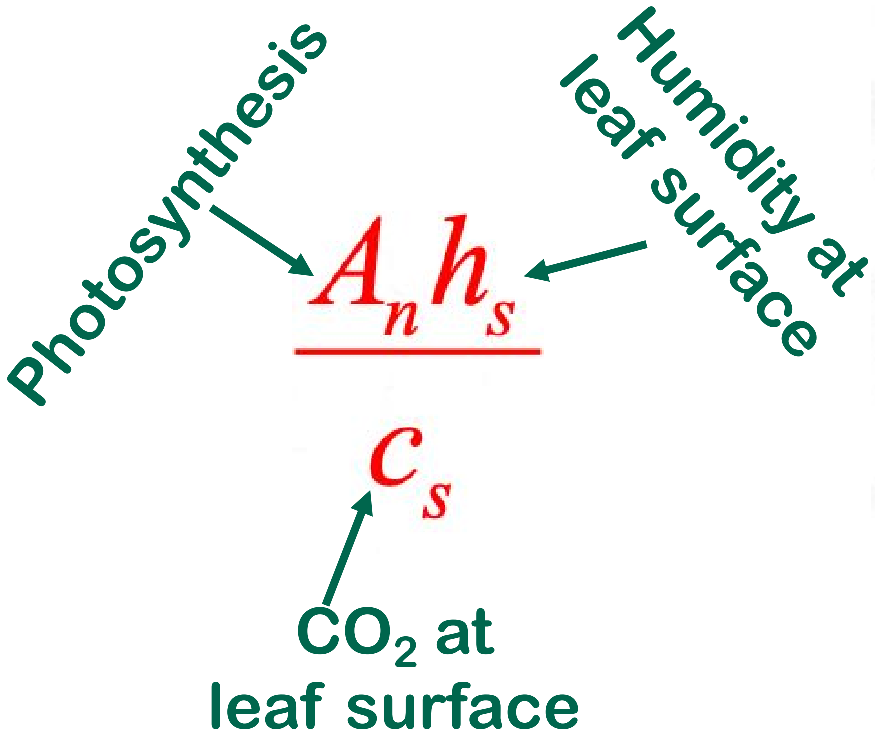
BATS, Dickinson et al, 1986

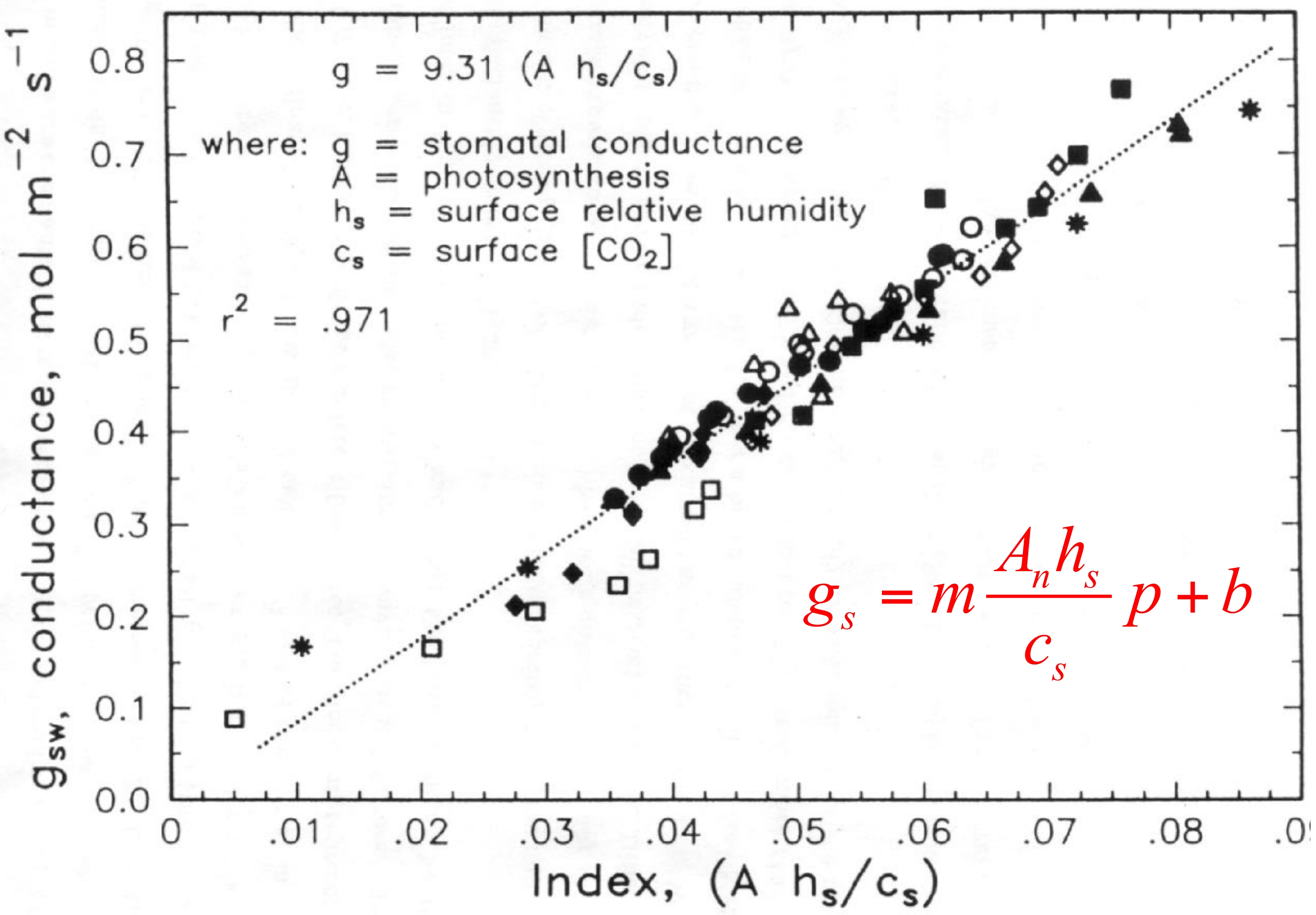
$$\lambda E = \beta \left[\frac{e^*(T_s) - e_r}{r_a + r_c} \right] \frac{\rho c_p}{\gamma}$$

- **Maximum conductance scaled down by empirically-derived factors**
- **Assumed independence of limitations**

Ball-Berry Relationship

- **Stomatal conductance is linear w/ an index that reflects plants physiological strategy**
- **Light, vpd, leaf temperature effects all collapse among multiple different species**





Photosynthesis and Conductance

Stomatal conductance is linearly related to photosynthesis:

(The "Ball-Berry-Collatz" parameterization)

$$g_s = m \frac{A_n h_s}{c_s} p + b$$

stomatal conductance → g_s; photosynthesis → A_n; RH at leaf sfc → h_s; CO2 at leaf sfc → c_s

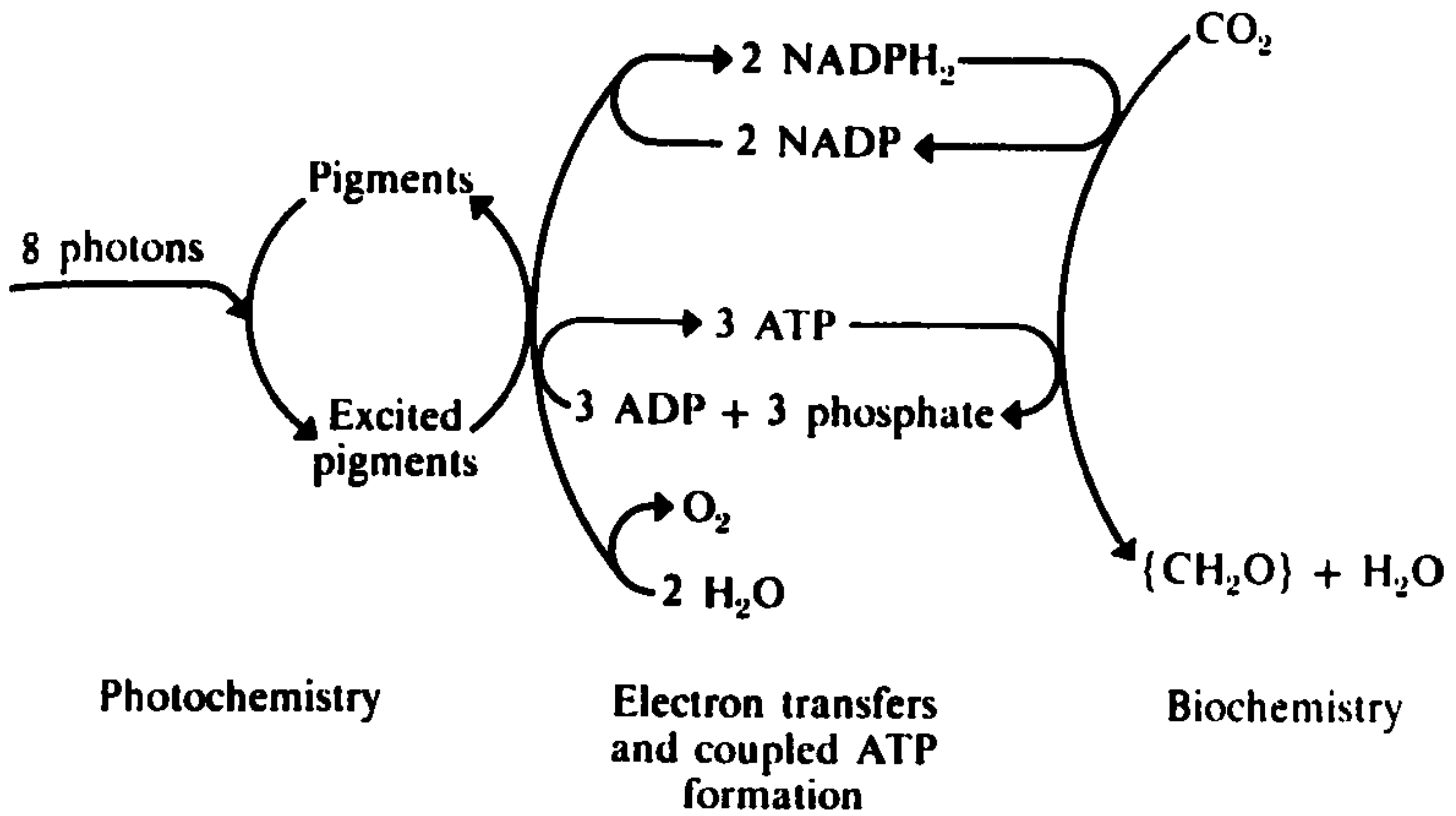
Photosynthesis is controlled by three limitations

(The Farquahar-Berry model):

$$A_n = \min(A_C, A_L, A_S) - R_d$$

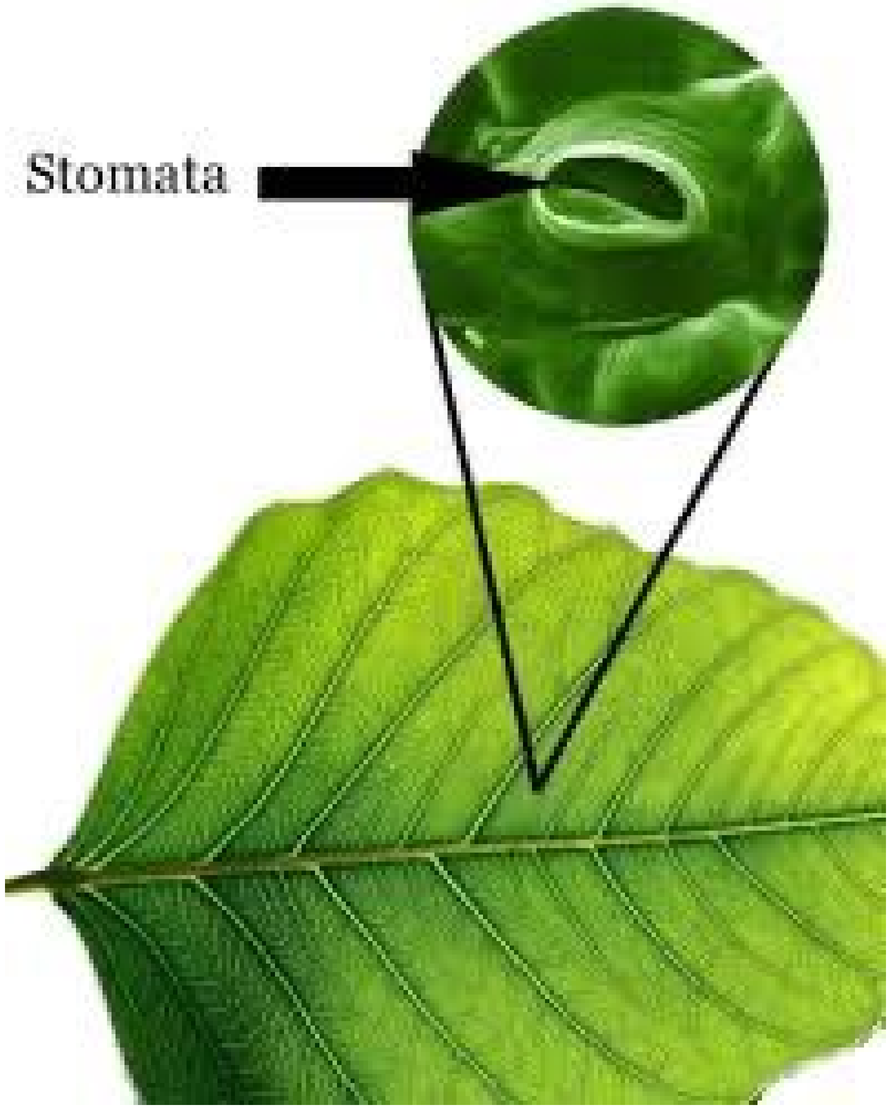
Enzyme kinetics ("rubisco") → A_C; Light → A_L; Starch → A_S

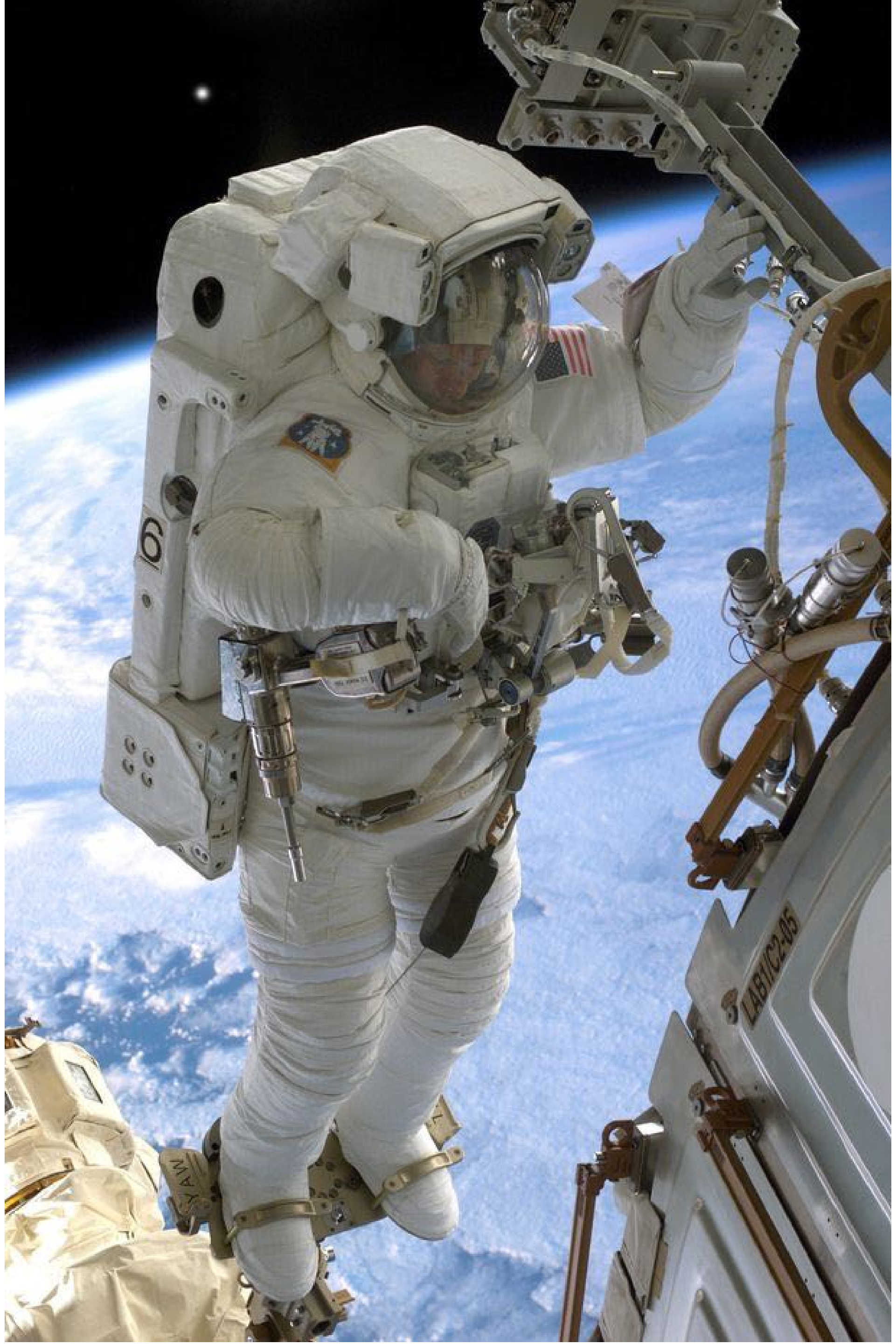
Light and Dark



Canopy Integration

- Photosynthesis and transpiration are linked via stomatal conductance
- Mechanistic understanding of biophysics for leaf-level fluxes
- How to integrate to entire canopy?
  - Could multiply fluxes (mol m^{-2} s^{-1}) at leaf level by total leaf-area index
  - That would assume all leaves have same properties and physical environment
  - What about shading inside canopy?
  - How does a plant respond to shading over time?





to
Boldy Go

Canopy Integration

$$\frac{I(L)}{I_0} = e^{-kL}$$

L = "cumulative LAI" (vertical coordinate)

$$k = \frac{G(\mu)}{\mu}$$

G(μ) = projected LAI normal to beam

$$A_{canopy} = A_{sun-leaf} \int_0^{L_T} e^{-kL} dL$$

$$= A_{sun-leaf} \left[\frac{-\left(e^{-kL_T} - 1\right)}{k} \right]$$

$$= A_{sun-leaf} \Pi$$

$$\Pi \equiv \frac{1 - e^{-kL_T}}{k} = \frac{FPAR}{k}$$

- How to efficiently integrate leaf-level equations across all **leaf angles and light levels**?
- Assume light levels drop off inside canopy according to **Beer's Law**
- Maximum photosynthesis rate (V_{max}) depends on **Rubisco**, an enzyme used to catalyze C fixation
- Rubisco is mostly **nitrogen** (most abundant protein on Earth)
- Assume **plant allocates scarce N where it will yield the most C gain (following time-mean light!)**

Canopy scaling factor Π ~ FPAR … get by remote sensing

C_3 and C_4 Photosynthesis

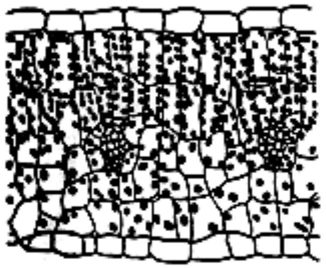
- Most plants produce sugars by the pathway outlined above, in which the first organic compounds have three carbon atoms (C_3)
- Some tropical and subtropical plants have evolved a separate mechanism in which the first products have four carbon atoms (C_4)
- C_4 photosynthesis is a mechanism to overcome photorespiration (high O_2/CO_2 ratio, high T)
- Involves active transport of dissolved CO_2 to specialized "bundle-sheath" cells to overwhelm O_2 at Rubisco active sites
- Uses energy to do this … only "pays off" when photorespiration is a big problem
- Evolved only ~ 10 My ago, when CO_2 levels dropped

C_3 vs C_4 Differences

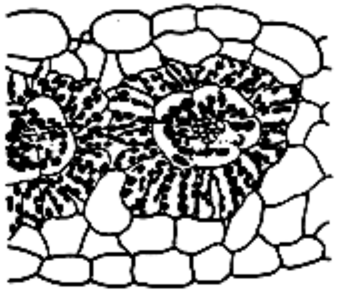
Physiology

distributed chloroplasts

C_3

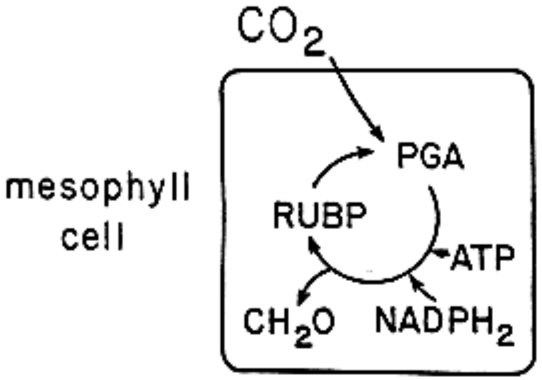


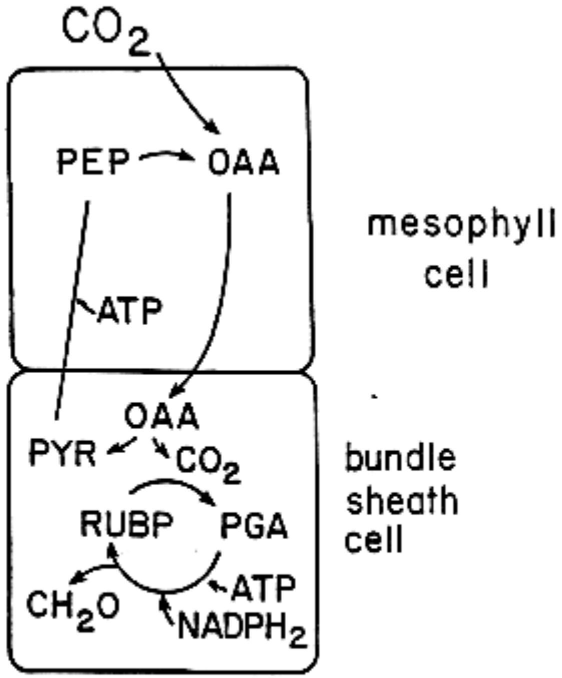
C_4



bundle sheath

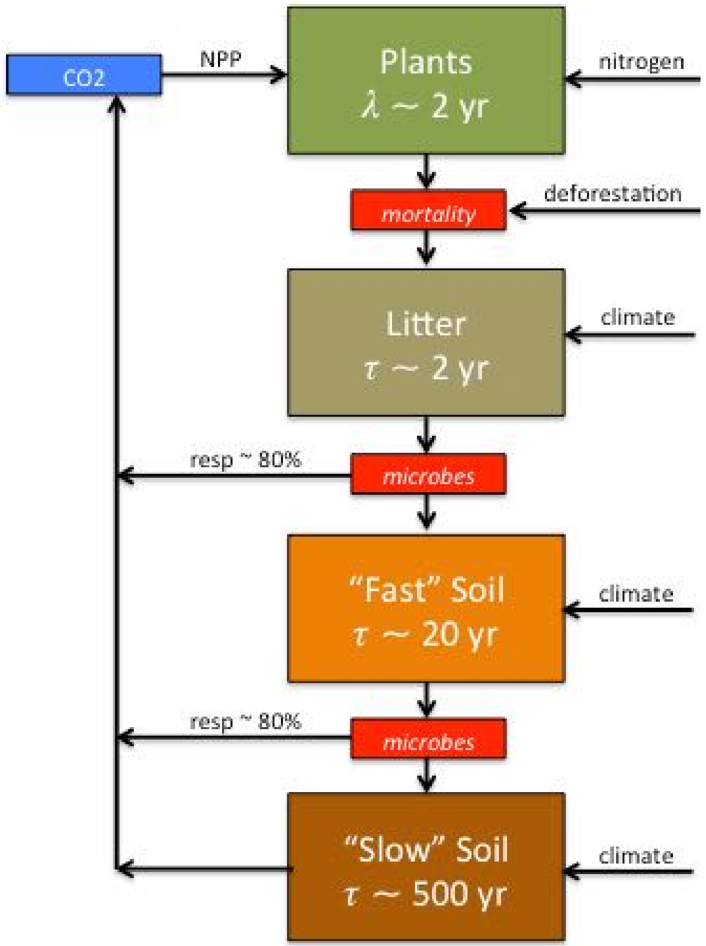
Biochemistry





Cascading Carbon Pools

Conceptual Model



Mathematical Model

$$\frac{dP}{dt} = NPP - MORT$$

$$\frac{dL}{dt} = MORT - \frac{L}{\tau_L} Q_{10}^{\frac{T-T_0}{10}}$$

$$\frac{dF}{dt} = \left[\frac{L}{\tau_L}(1-\epsilon) - \frac{F}{\tau_F}\right] Q_{10}^{\frac{T-T_0}{10}}$$

$$\frac{dS}{dt} = \left[\frac{F}{\tau_F}(1-\epsilon) - \frac{S}{\tau_S}\right] Q_{10}^{\frac{T-T_0}{10}}$$

Symbols used:

- NPP = Net primary production (photosynthesis minus plant respiration, in GtC/yr)
- MORT = plant mortality (transfers carbon from live plants to dead litter, GtC/yr)
- τ_L, τ_F, τ_S = turnover time for carbon in litter, fast, and slow soil pools (years)
- ϵ = efficiency of microbial respiration (fraction of what they "eat"" that turns into CO2)
- Q_{10} = fractional increase in decomposition rates per 10 degrees of warming
- T = temperature (Celsius), prescribed from a simple climate model using the IPCC SRES A2 emissions scenaro.

- **Plants grow logistically limited by nutrients**
- **Carbon from dead plants becomes litter**
- **Litter decomposes quickly into fast and then slow soil organic matter**

http://biocycle.atmos.colostate.edu/shiny/Land/


The
Oceans

Carbonation

- CO_2 dissolves in water to make carbonic acid
- That's why beer goes with pizza and Chardonnay goes with Brie
- Dissolves twice as well in cold water as warm water
- That's why beer & soda go flat when they warm up
- Cold polar ocean soaks up CO_2, warm tropical oceans release it

Carbonate Equilibria

Three equations (equilibria) in five unknowns

$$CO_2(\text{gas}) \longleftrightarrow CO_2(\text{dissolved}) \qquad [CO_2(aq)] = K_0 pCO_2 \qquad 6.1$$

$$[CO_2(aq)] + H_2O \longleftrightarrow [H^+] + [HCO_3^-] \qquad K_1 = [H^+][HCO_3^-]/[CO_2(aq)] \qquad 6.6$$

$$[HCO_3^-] \longleftrightarrow [H^+] + [CO_3^{2-}] \qquad K_2 = [H^+][CO_3^{2-}]/[HCO_3^-] \qquad 6.7$$

Add two more constraints

(“Titration Alkalinity”)

$$TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [NO_3^-] + [OH^-] - [H^+] \pm \text{minor species}$$

$$B(OH)_3 + H_2O \leftrightarrow H^+ + B(OH)_4^-, \qquad K_b = [H^+][B(OH)_4^-]/[B(OH)_3]$$

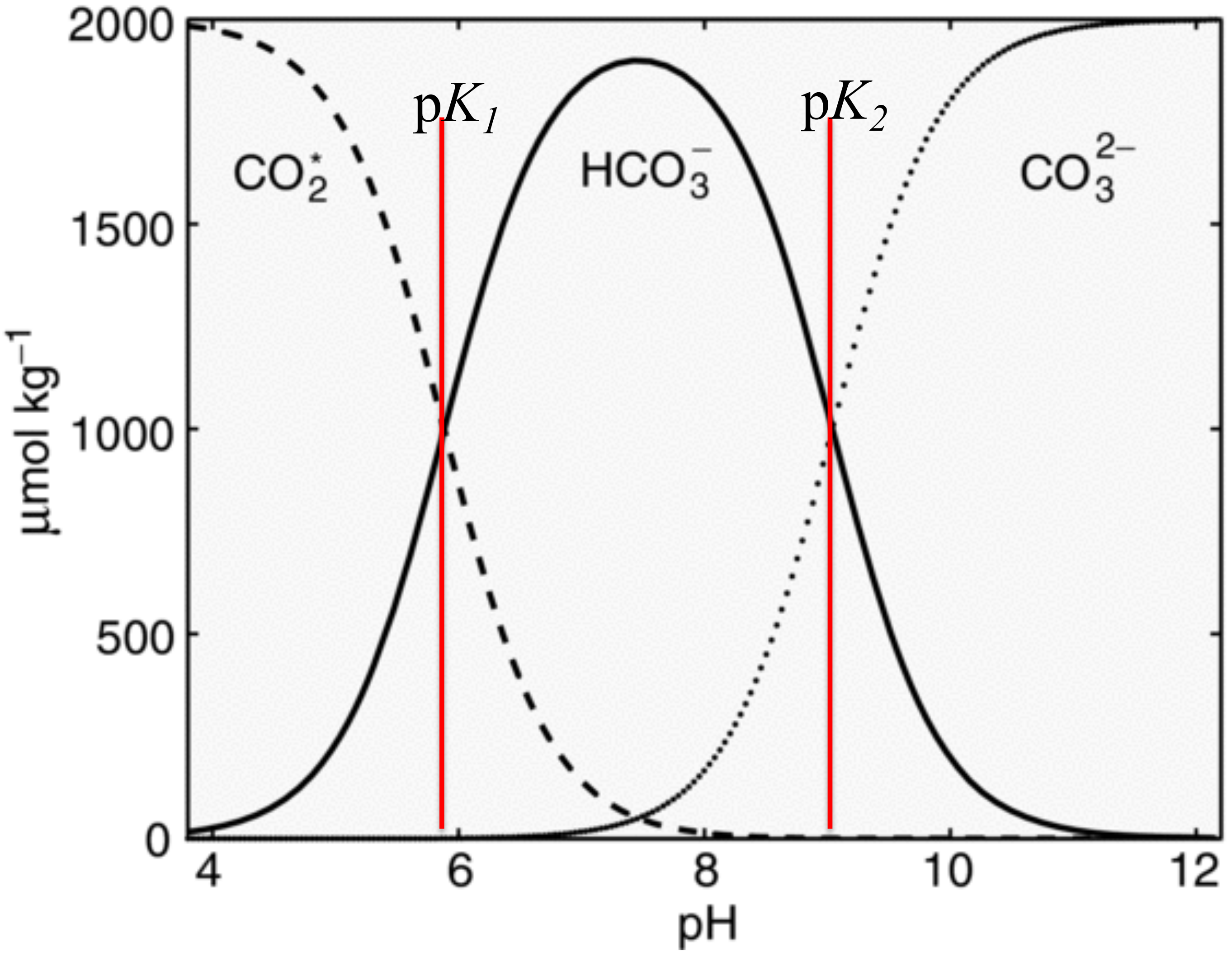
(Boric acid dissociation)

$$\Sigma B = 1.179 \times 10^{-5} S \text{ mol/kg}$$

(S = Salinity)

Speciation vs pH

"Bjerrum Plot"



Williams_Fig. 6.7

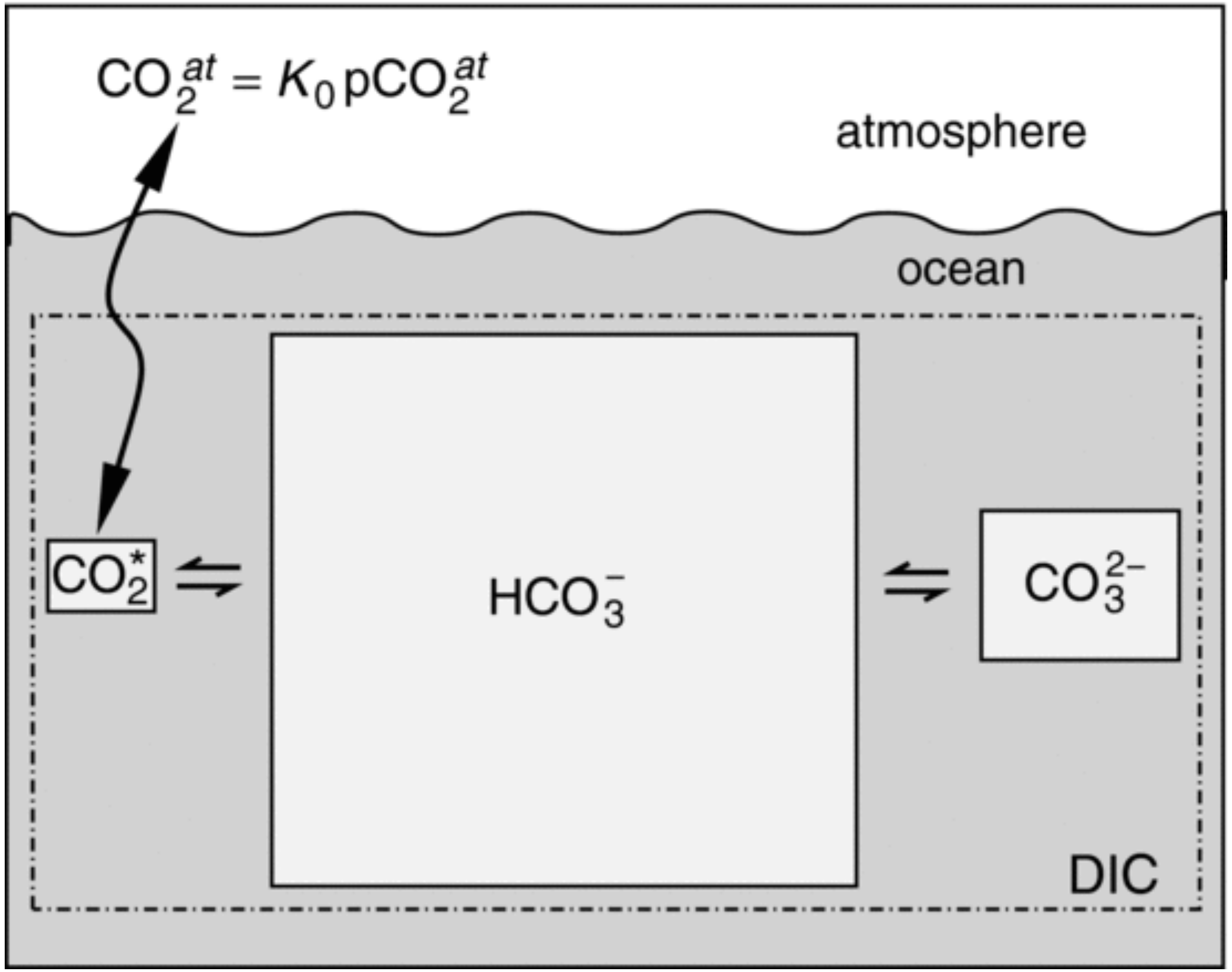
[CO_2*] = 10 μMol kg^{-1}

[HCO_3] = 1769 μMol kg^{-1}

[CO_3] = 223 μMol kg^{-1}

By far most dissolved CO_2 in the oceans is bicarbonate

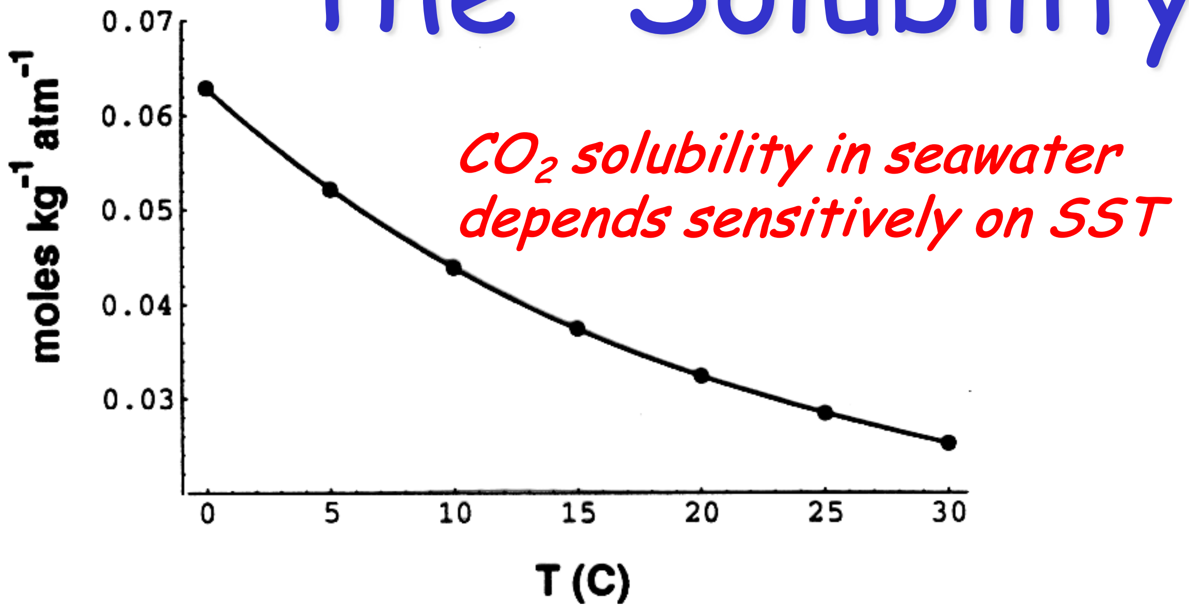
Buffering of Marine DIC

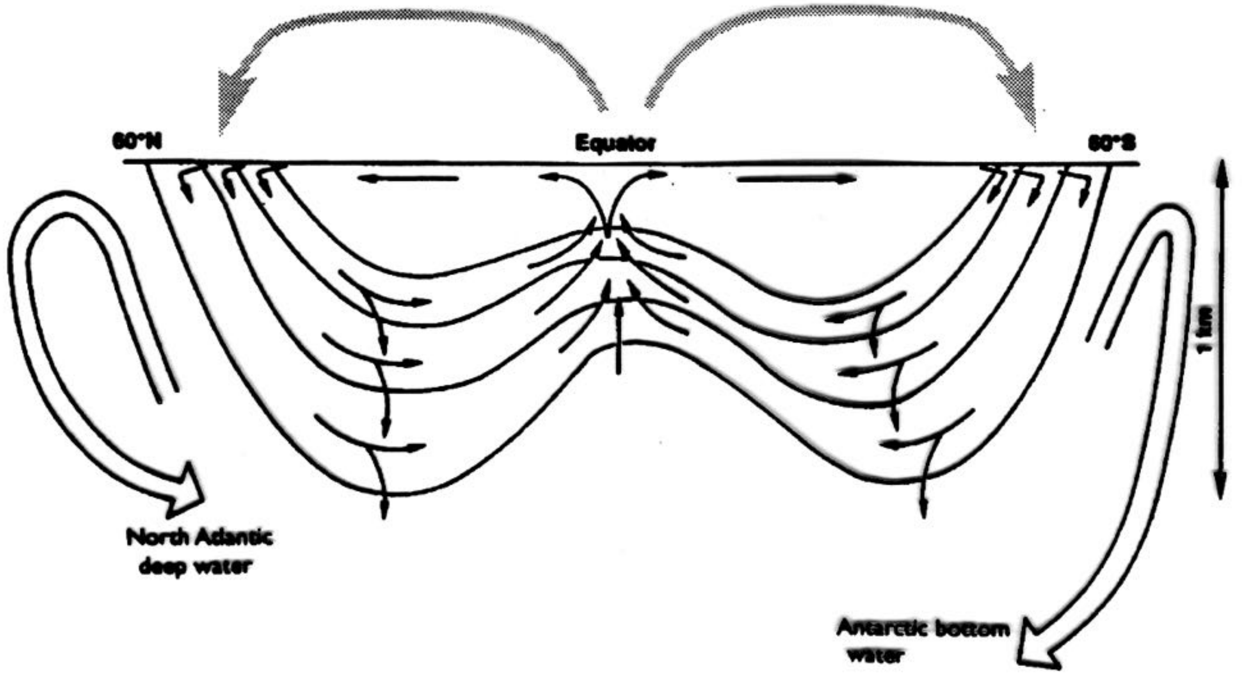


Williams_Fig. 2.20

Only a small fraction of DIC (CO_2^*) is in chemical equilibrium with atmospheric CO_2

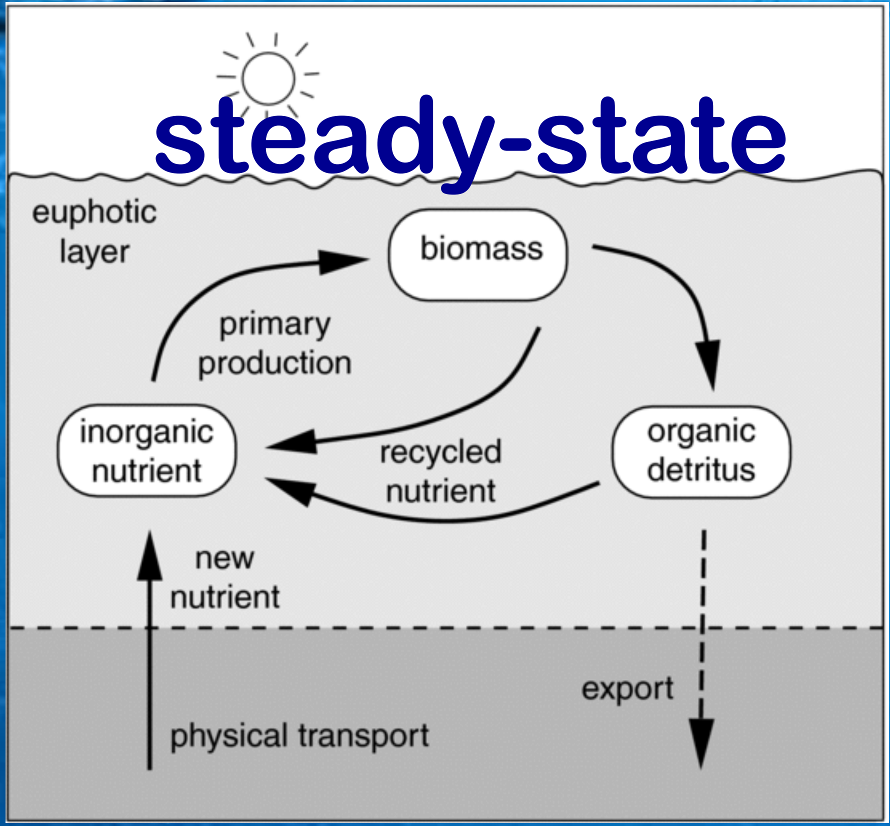
The "Solubility Pump"



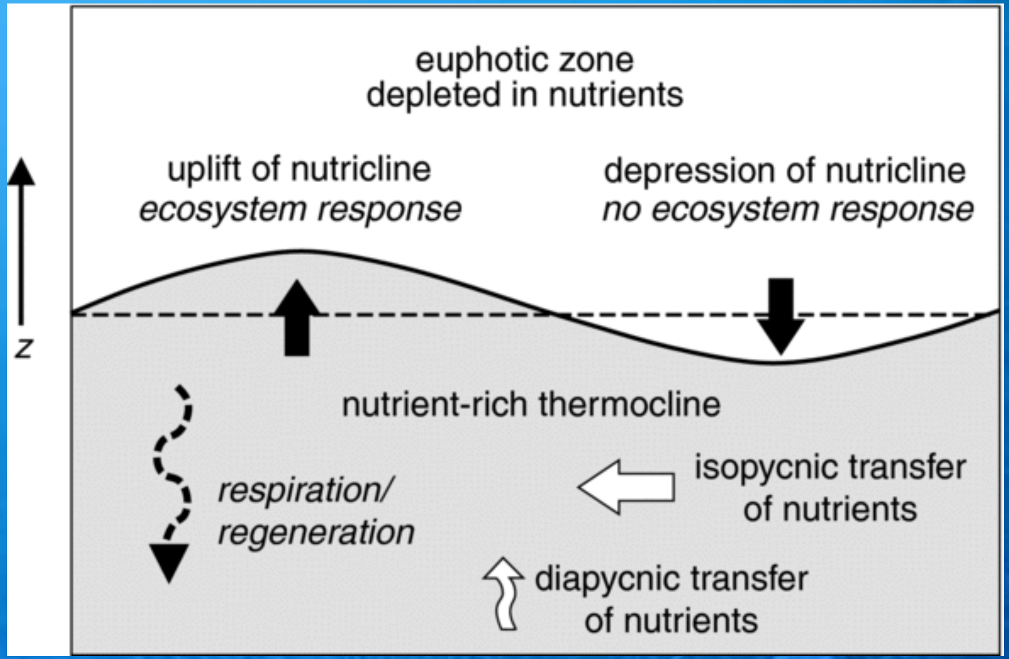


- CO_2 is highly soluble in cold high-lat waters
- Transported to deep ocean by convection and isopycnal mixing
- Dynamically-driven equatorial upwelling brings high-CO_2 water to surface
- Atmospheric transport closes the loop

Nutrient Cycling and the Marine Biological Pump

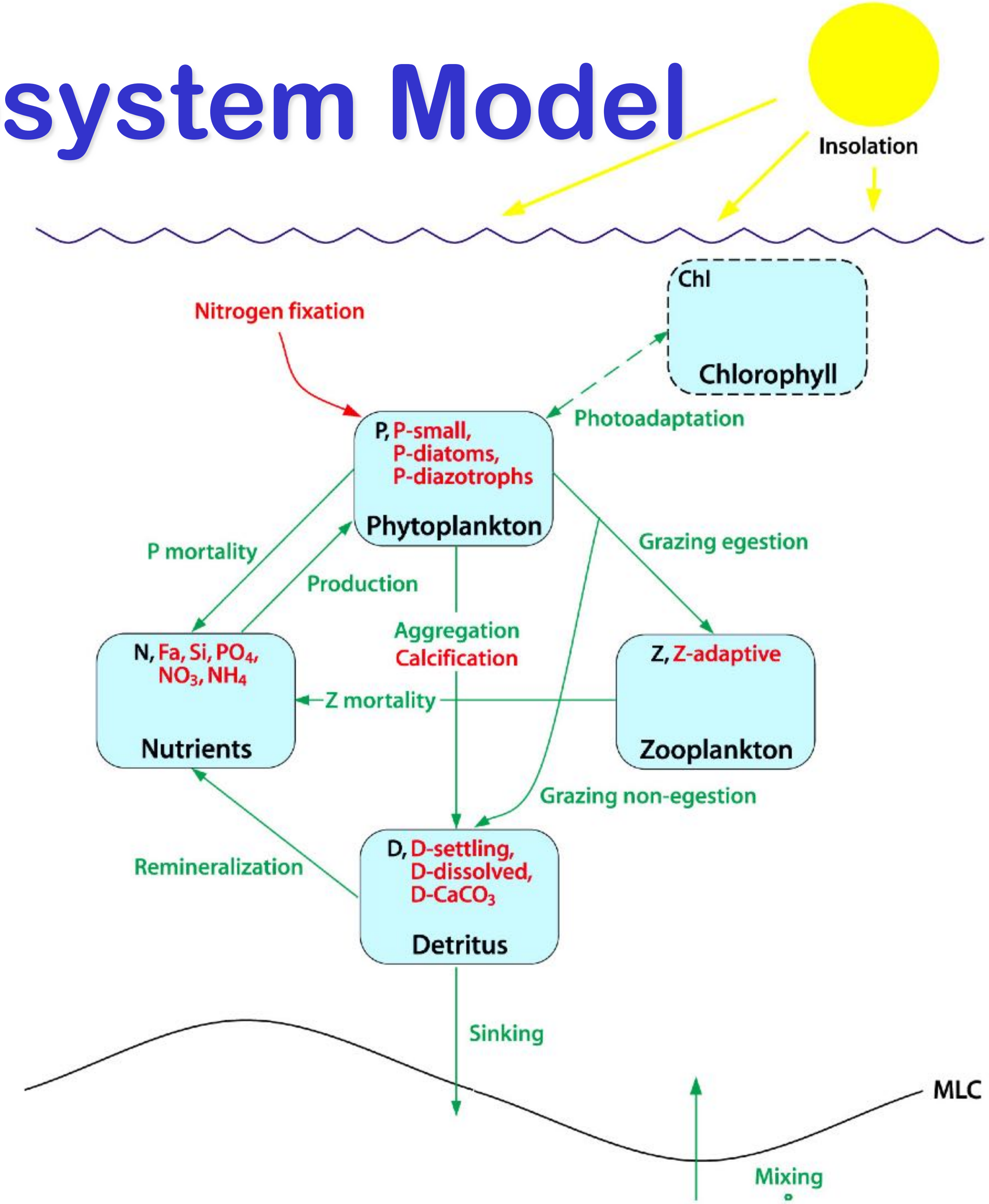


perturbed by wind



Marine Ecosystem Model

- Predict **PZND**, plus Chlorophyll
- Assume a single limiting "currency" (e.g., N) in each pool
- No interactions among individuals, just "pools"
- More recent models (red) include limitation by multiple nutrients, N-fixation, and size classes of organisms



Dark and Deep

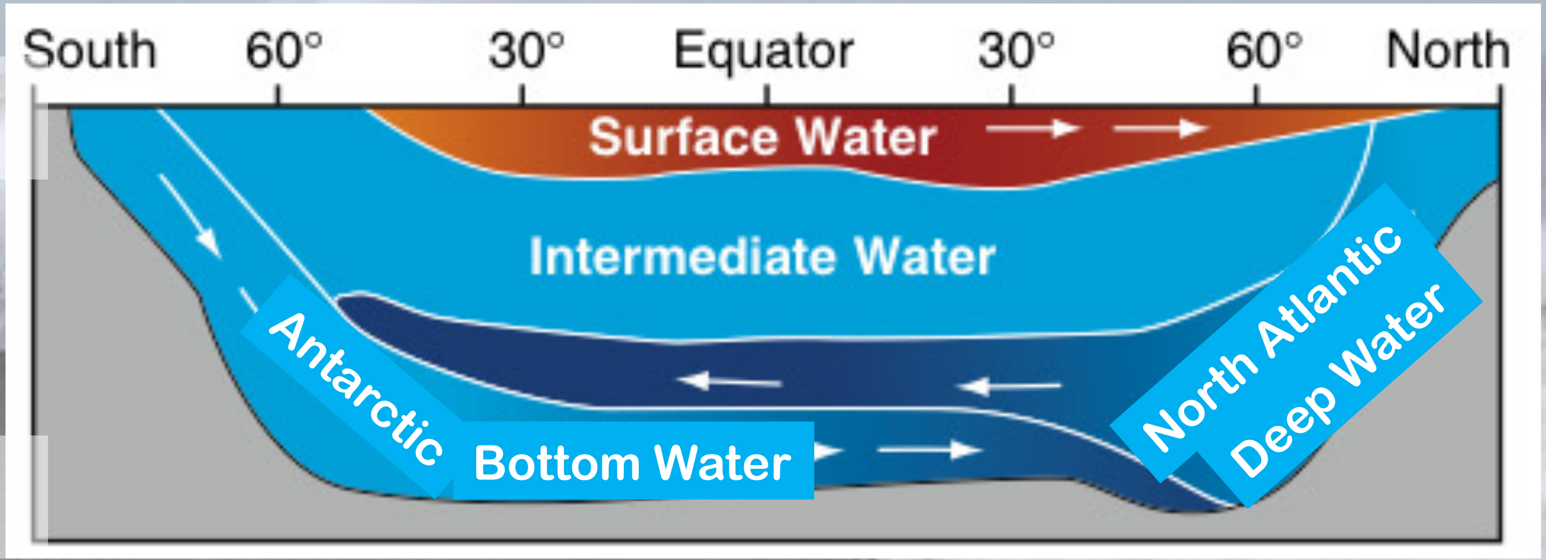
- Brightly colored equipment, fish, and corals at snorkel depths (10 – 20 feet)
- Red and orange go first, then yellow and green
- Below 50 feet, everything is progressively dimmer shades of blue

But the oceans are 13,000 feet deep!

really cold too!

Oceans Have Layers

surface

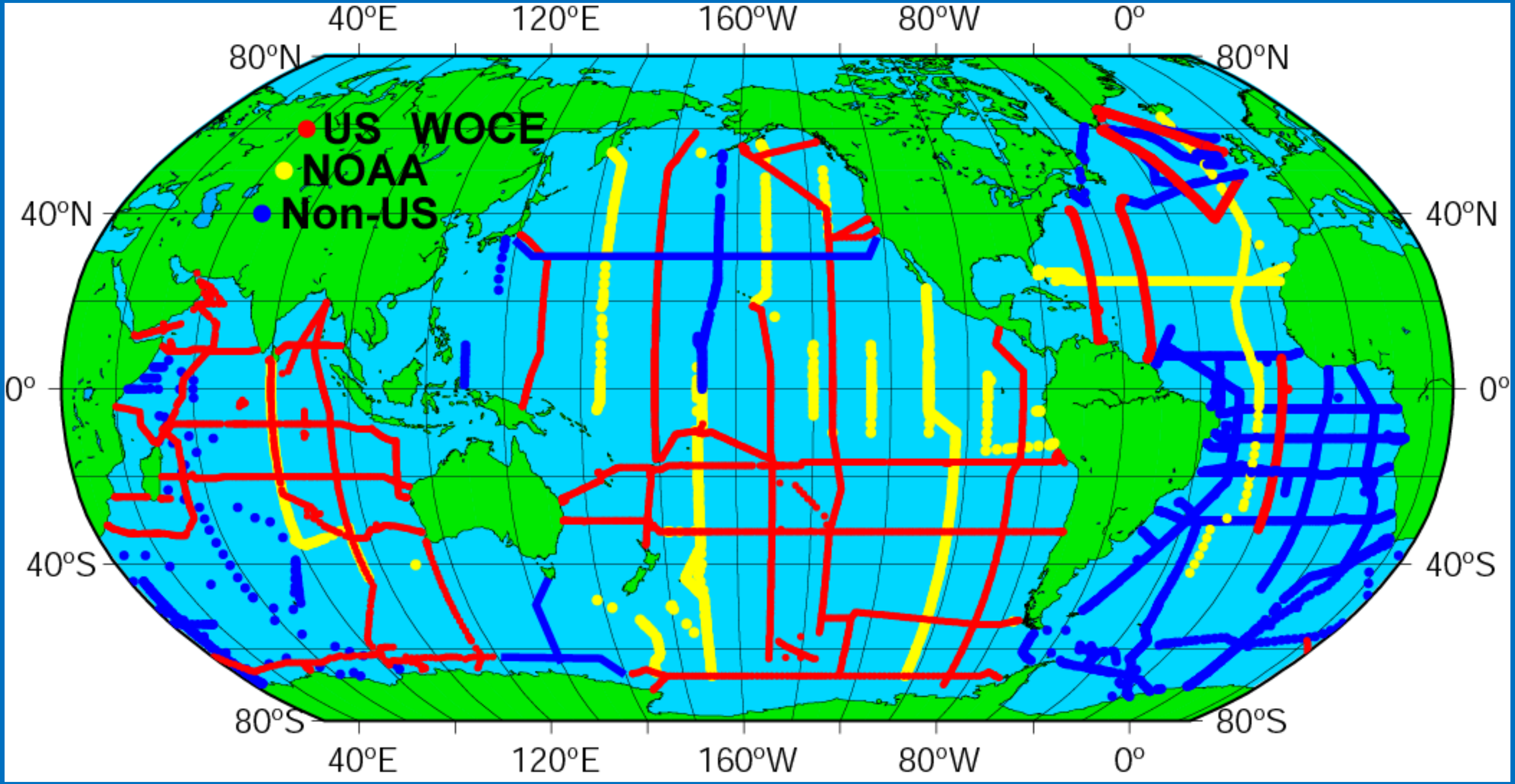


4000 m

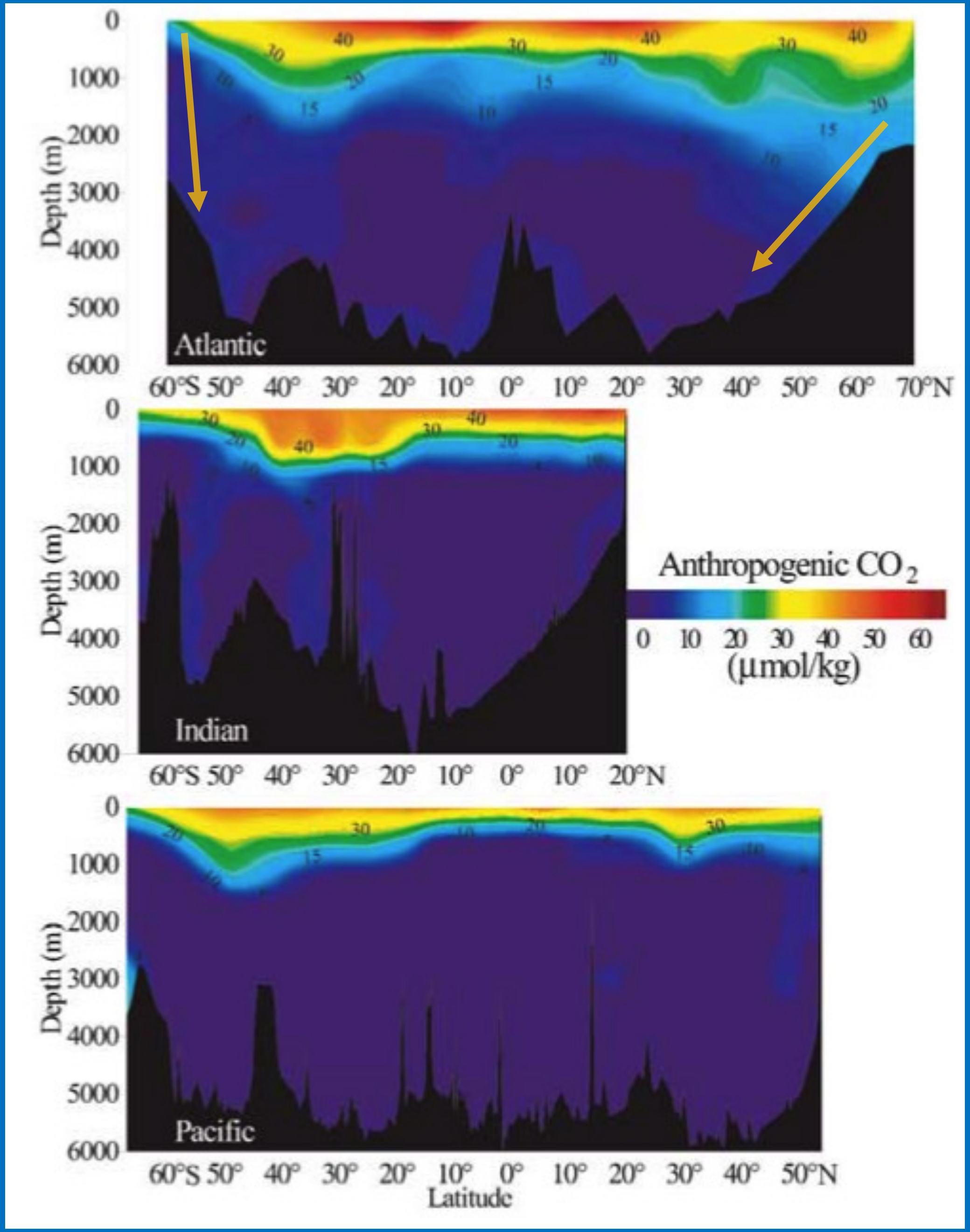
- Warm buoyant "raft" floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn't know we're here yet!

Observing the Deep Ocean

Observing the Deep Ocean



Global Ocean Survey Samples



Dissolved Fossil CO_2

- **Millions of direct measurements of dissolved CO_2 in the oceans**
- **Fossil CO_2 remains trapped near the surface where warm water floats**
- ***Deep water doesn't know we're here yet!***

Planetary Titration

Where Has All the Carbon Gone?

- Into the **oceans**
  - **Solubility pump** (CO_2 very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow “rain” of organic debris)

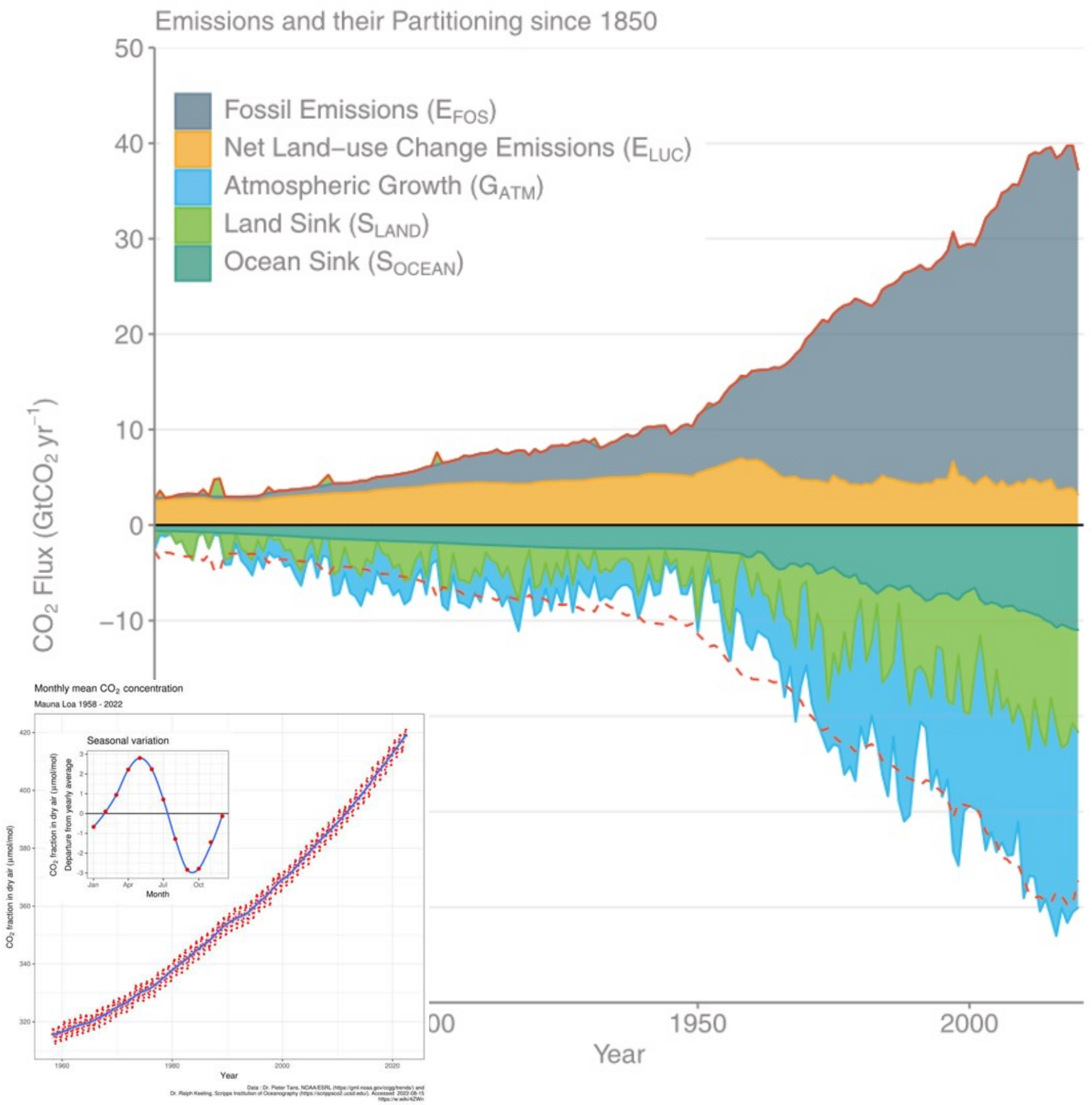
- Into the **land**
  - **CO_2 Fertilization** (plants eat CO2 … is more better?)
  - **Nutrient fertilization** (N-deposition and fertilizers)
  - **Land-use change** (forest regrowth, fire suppression, woody encroachment … but what about Wal-Marts?)
  - Response to **changing climate** (e.g., Boreal warming)

Sink Saturation

- Land – very vulnerable, very uncertain!
  - Only CO_2 fertilization has "legs"
  - N-deposition and Regrowth are transient
  - Boreal warming may switch to a huge source!
- Ocean – slow & safe for near-term, scary for the long term
  - Limited by rate of physical mixing into deep ocean against buoyancy
  - As surface water warms, mixing will slow
  - Thousands of years to reach equilibrium!
  - Acidification chemistry limits total uptake

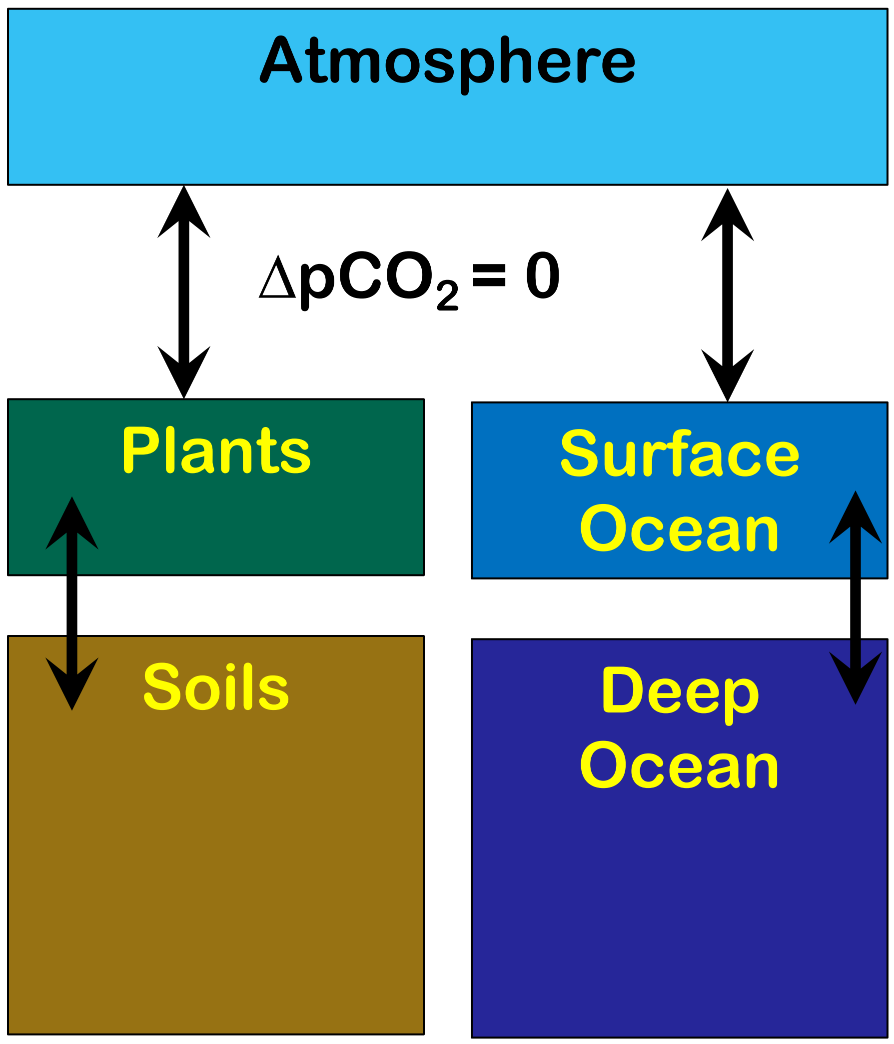
For Our Whole Lives

- CO2 has been increasing
- Growth has exceeded decomposition
- What will happen as emissions fall and CO2 stabilizes or decreases?



Simple Conceptual Model

- **Preindustrial equilibrium: Historically, there were no carbon sinks**



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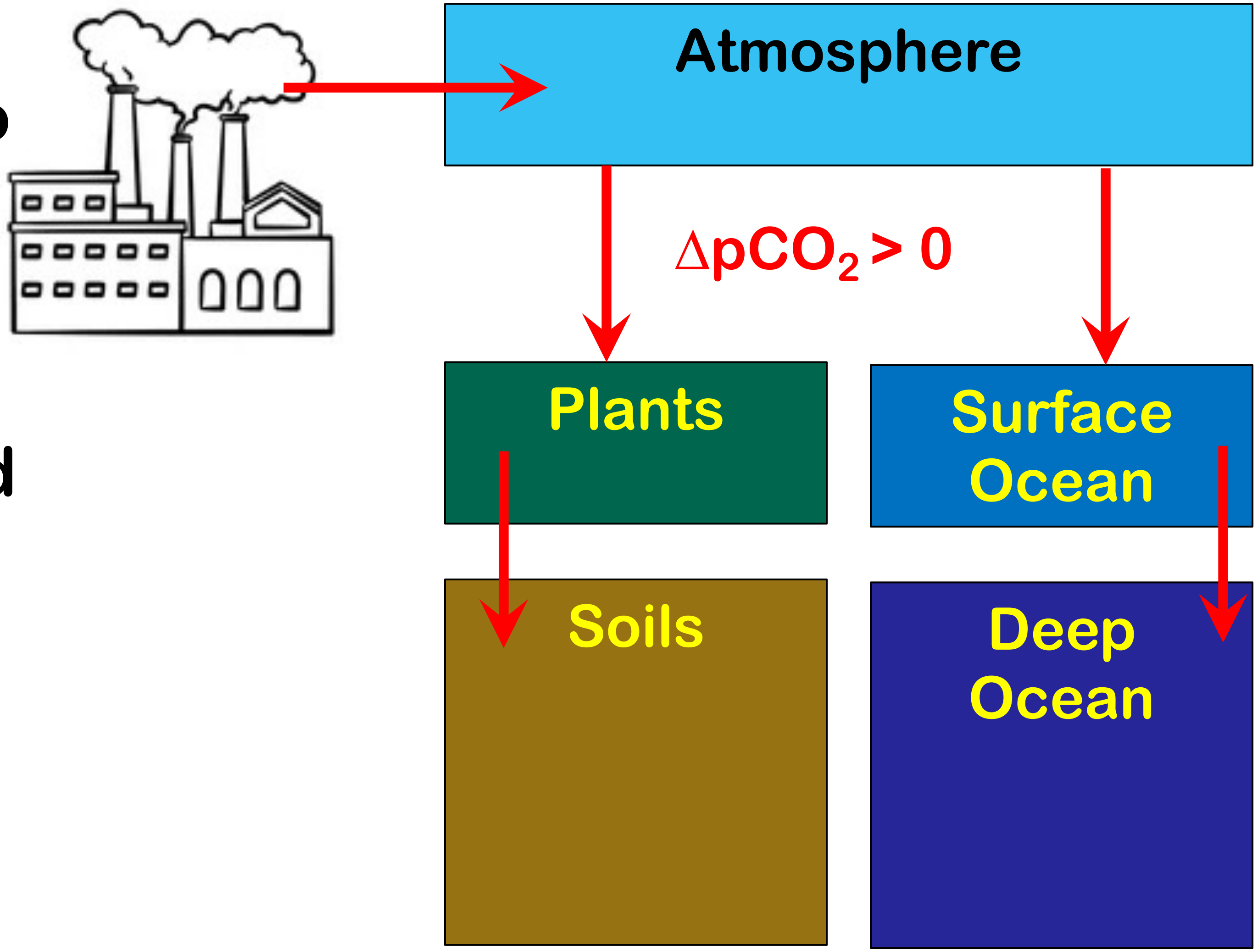

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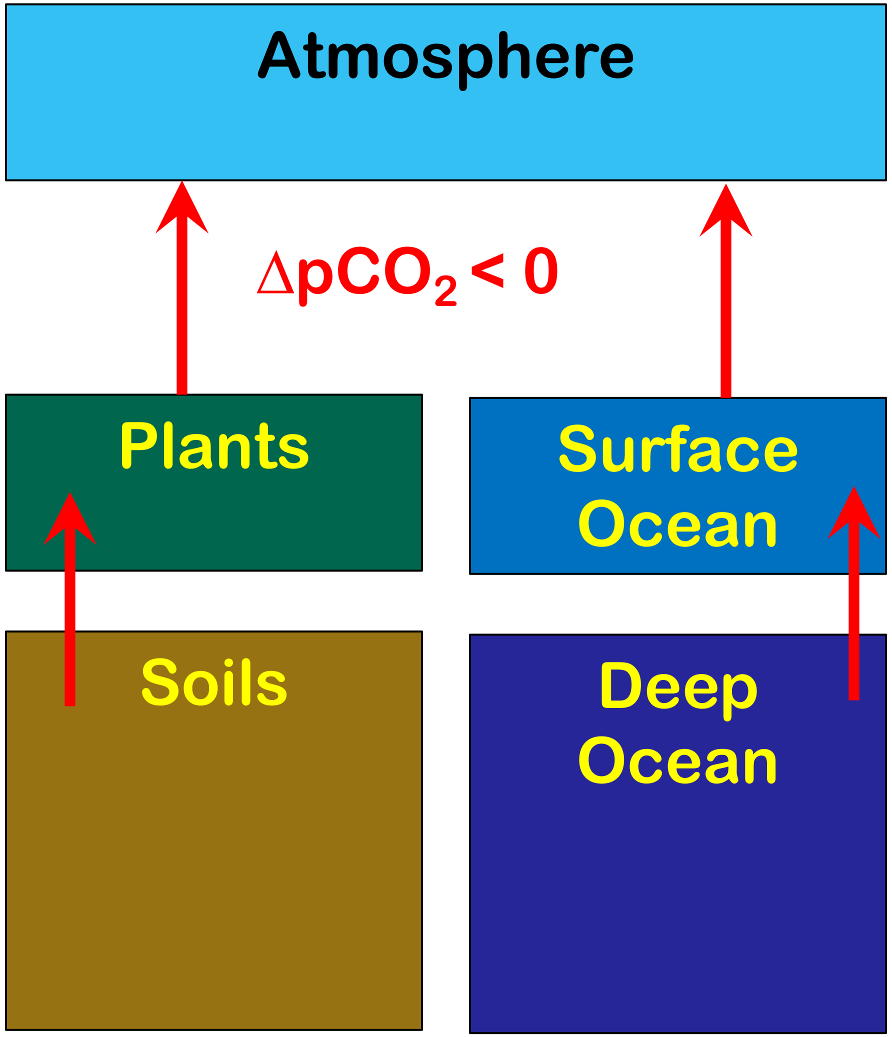
- Preindustrial equilibrium: Historically, there were no carbon sinks
- As atmospheric CO2 increased, carbon flowed into the surface ocean and land ecosystems
- As emissions slow and cease, ΔpCO_2 will fall
- If/when emissions reverse, so will the sinks



Transient Climate Response to Emissions

"Definition"

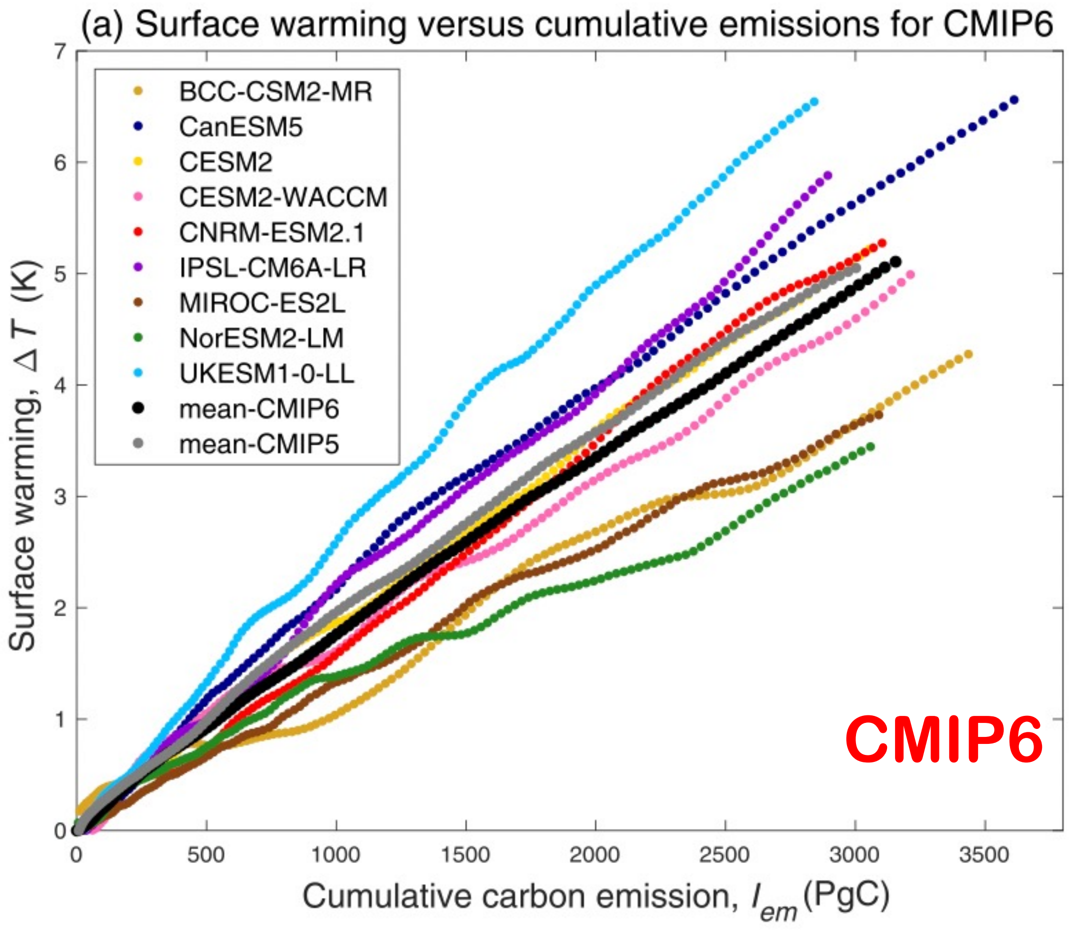
$$\Lambda = \frac{\Delta T}{E} = \frac{\Delta T}{\Delta C_a} \times \frac{\Delta C_a}{E}$$

TCRE

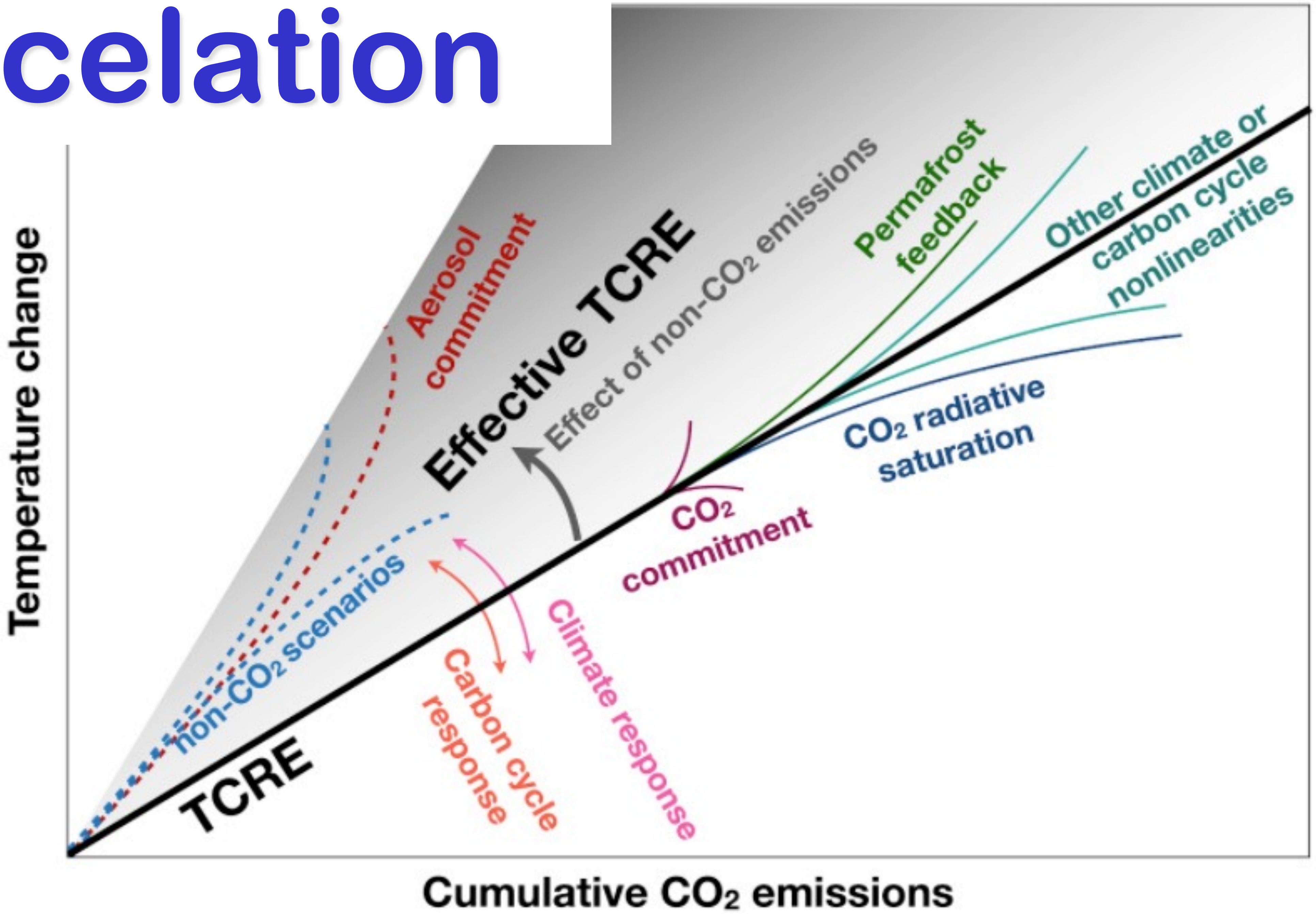
warming

CO_2 increment

cumulative emissions



Cancelation

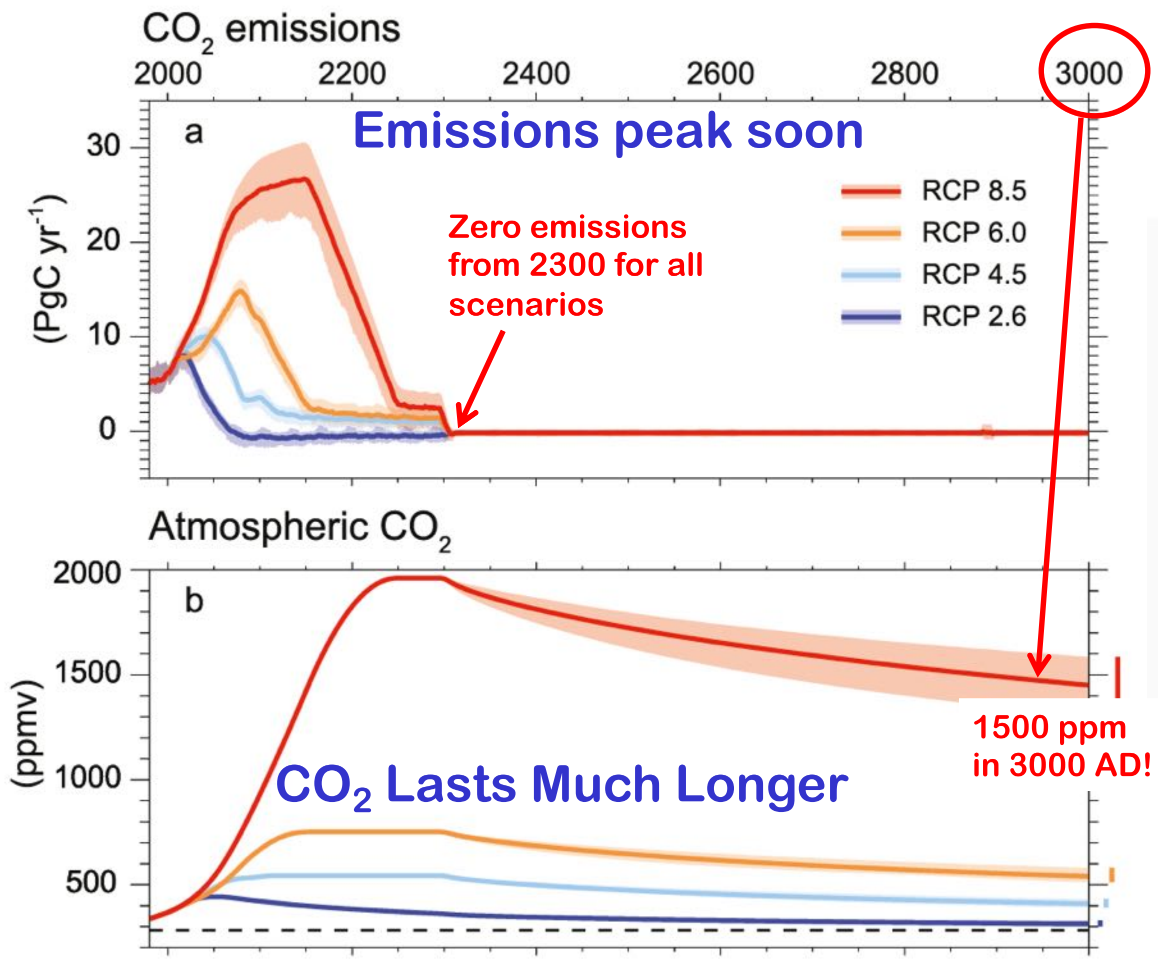


Implications of TCRE

- Every kg of carbon ever burned in all of history warms climate by the same amount
- When emissions stop, warming will stop almost immediately
- Warming is essentially permanent (without negative emissions)
- Negative emissions will only be about 50% effective

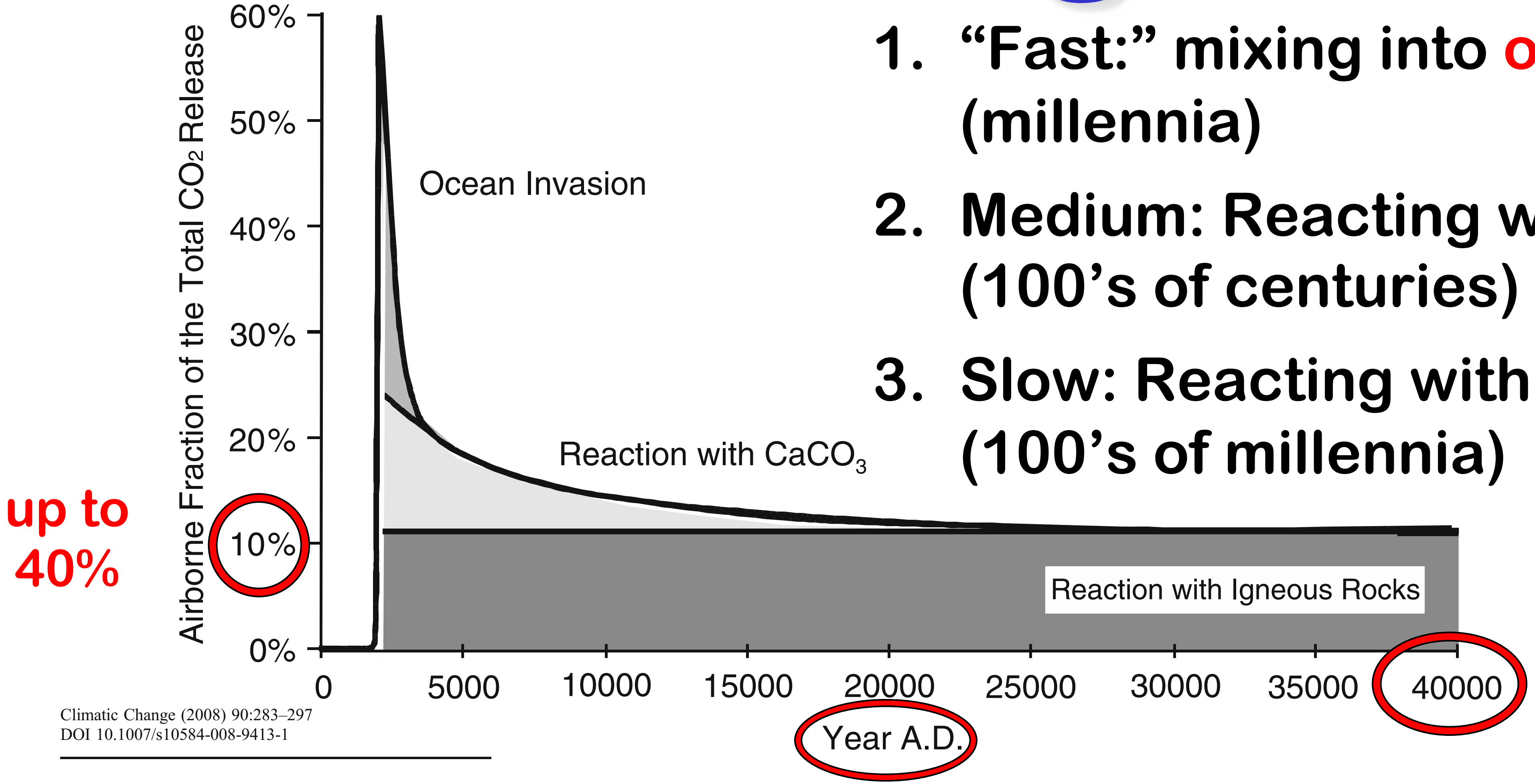
One-Way Warming

- Heating continues until we stop burning carbon
- After we stop burning coal, oil, & gas the CO_2 will stay in the air
- Climate will remain hot for thousands of years



Thermostat only turns one way!

The Long Tail



1. "Fast:" mixing into oceans (millennia)
2. Medium: Reacting w/seashells (100's of centuries)
3. Slow: Reacting with rocks (100's of millennia)

Climatic Change (2008) 90:283–297
DOI 10.1007/s10584-008-9413-1

The millennial atmospheric lifetime of anthropogenic CO_2

David Archer · Victor Brovkin

Some of the CO_2 we emit today will still be warming the climate 100,000 years from now!