Flux i transformació de petites partícules orgàniques a l'oceà mesopelàgic: un trencaclosques biogeoquímic i climàtic

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Ongoing biogeochemistry projects

CCiCC: Climate-Carbon Interactions in the Coming Century

DeCUSO: Decadal predictions of Carbon Uptake in the Southern Ocean

NeTNPPAO: Near-term predictability of net primary production in the Atlantic Ocean

ORCAS: Organic Carbon Sequestration in the Oceans

HORIZON 2020

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

SEVENTH FRAMEWORK PROGRAMME MARIE CURIE ACTIONS

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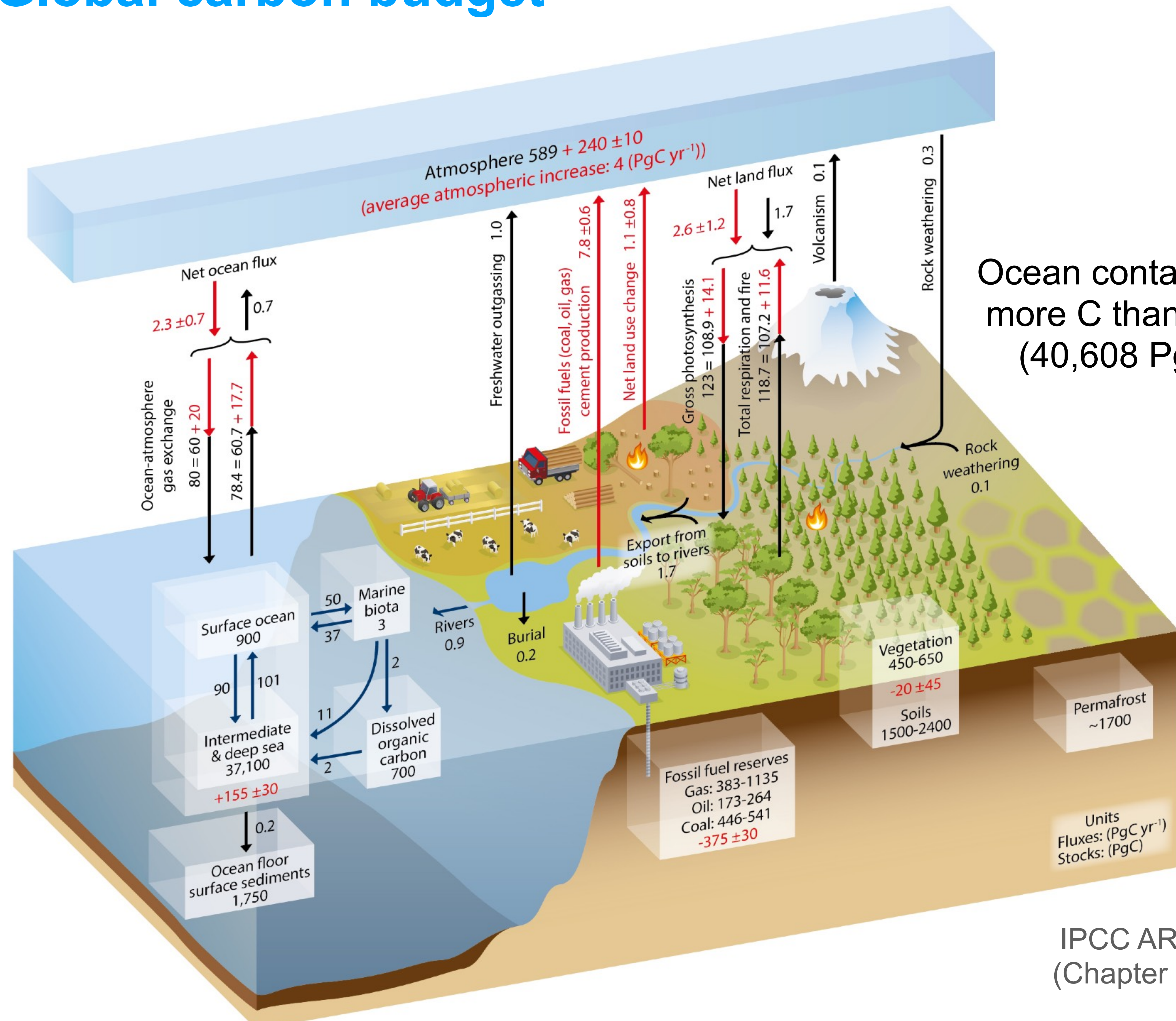
1/6. Climate and ocean carbon pumps

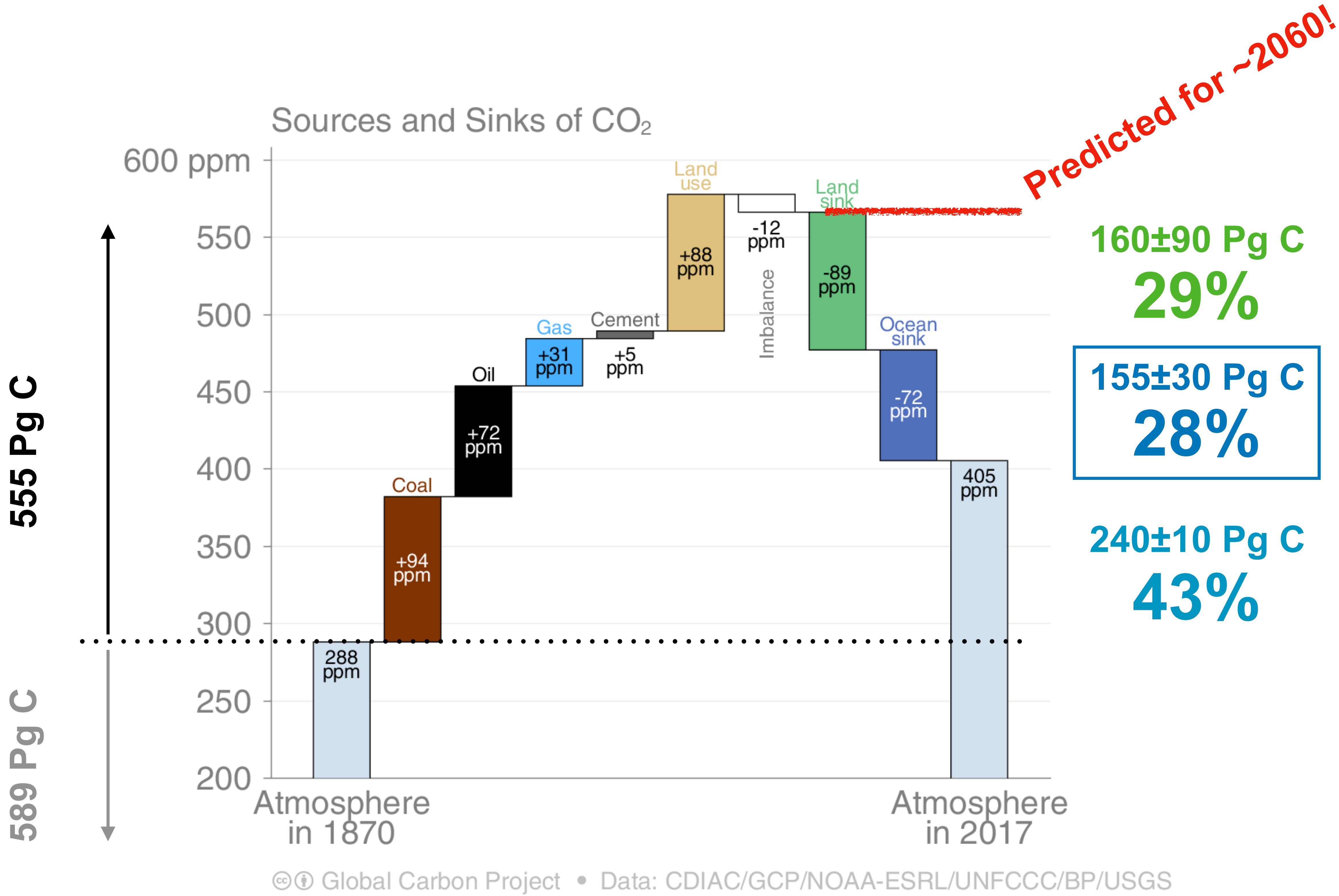
Global carbon budget



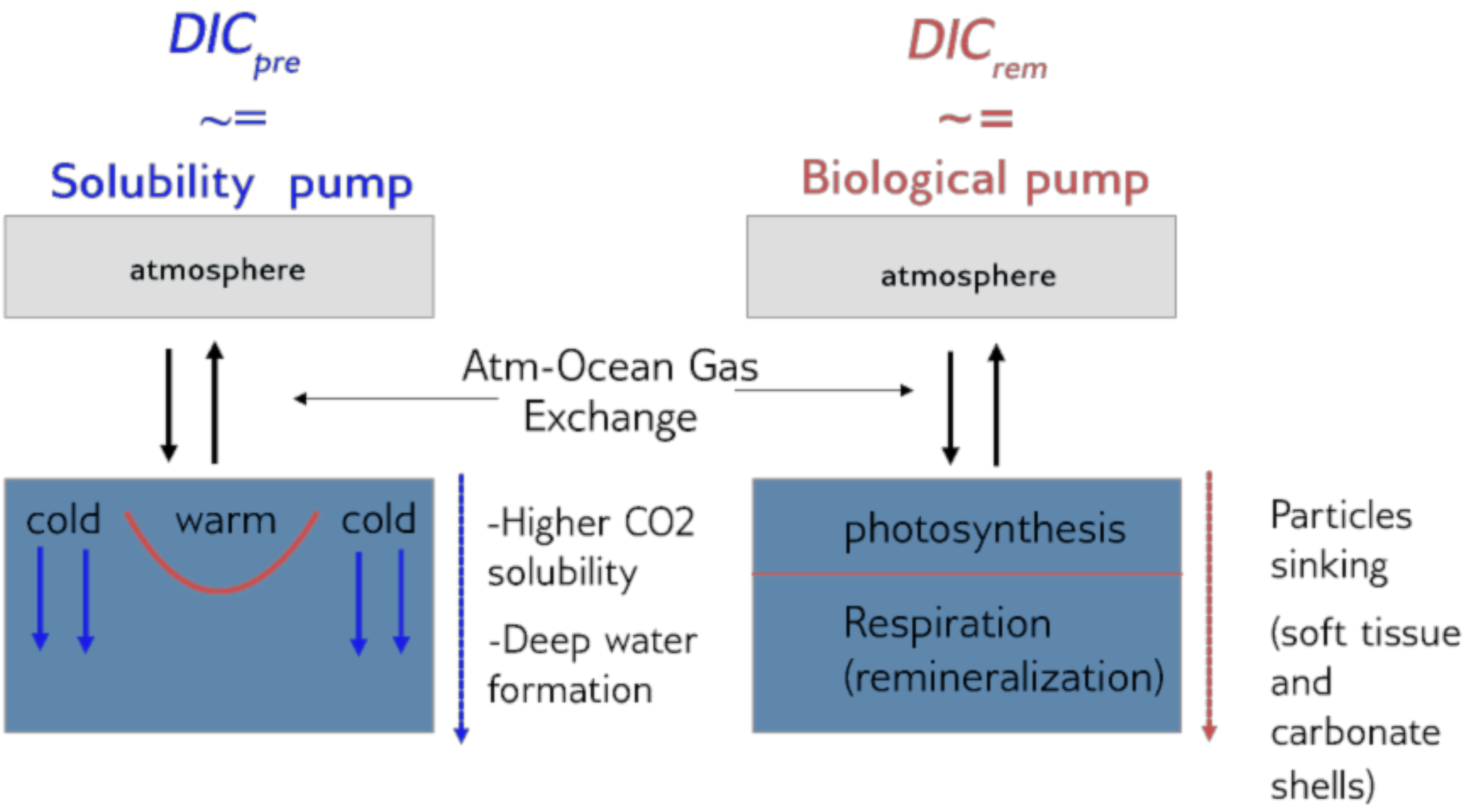
Ocean contains ~50 times more C than atmosphere (40,608 Pg / 829 Pg)

IPCC AR5 (Chapter 6)

Fate of anthropogenic CO_2 emissions

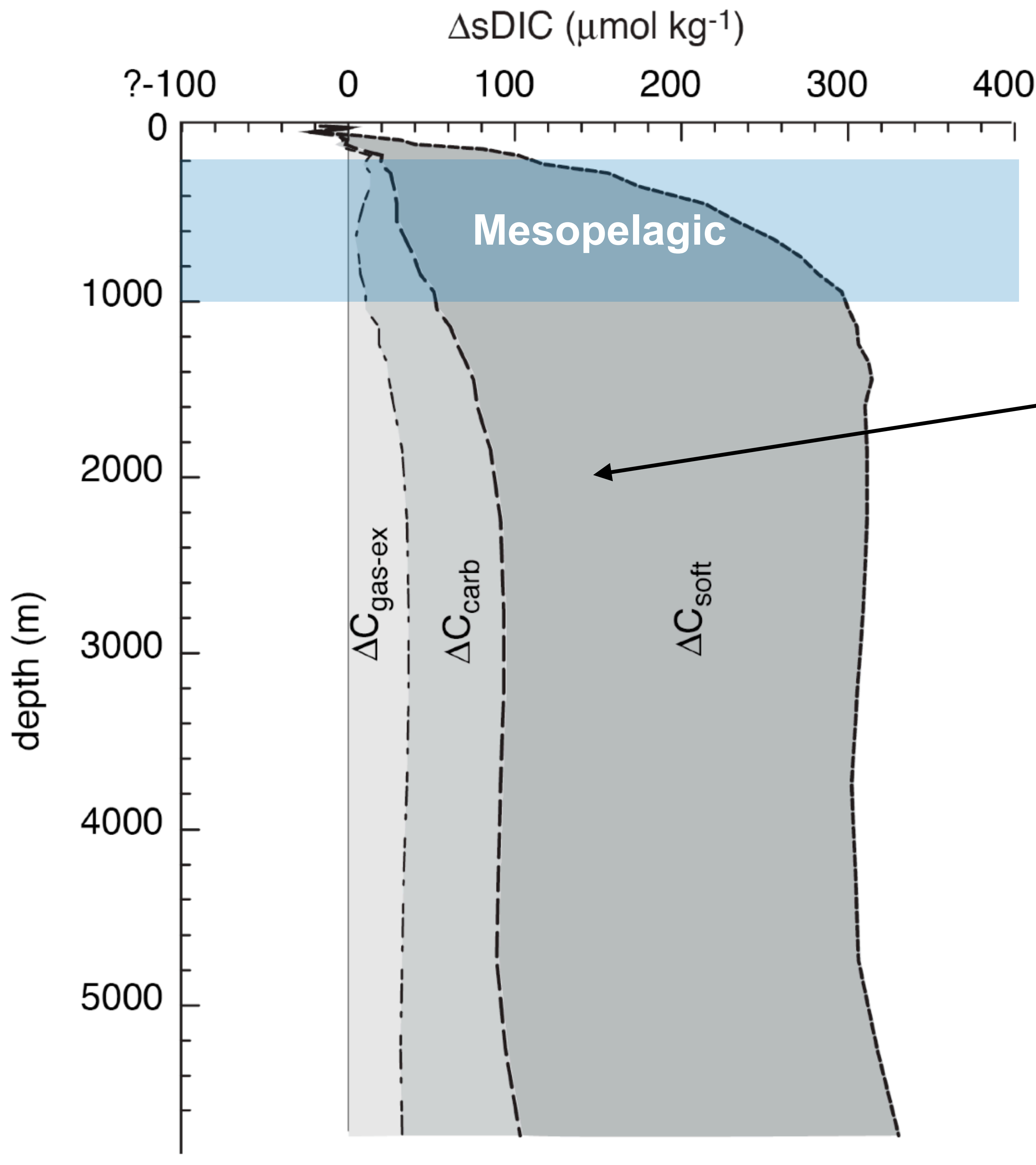


Ocean carbon pumps



Volk & Hoffert 1985

Working against thermodynamic equilibrium

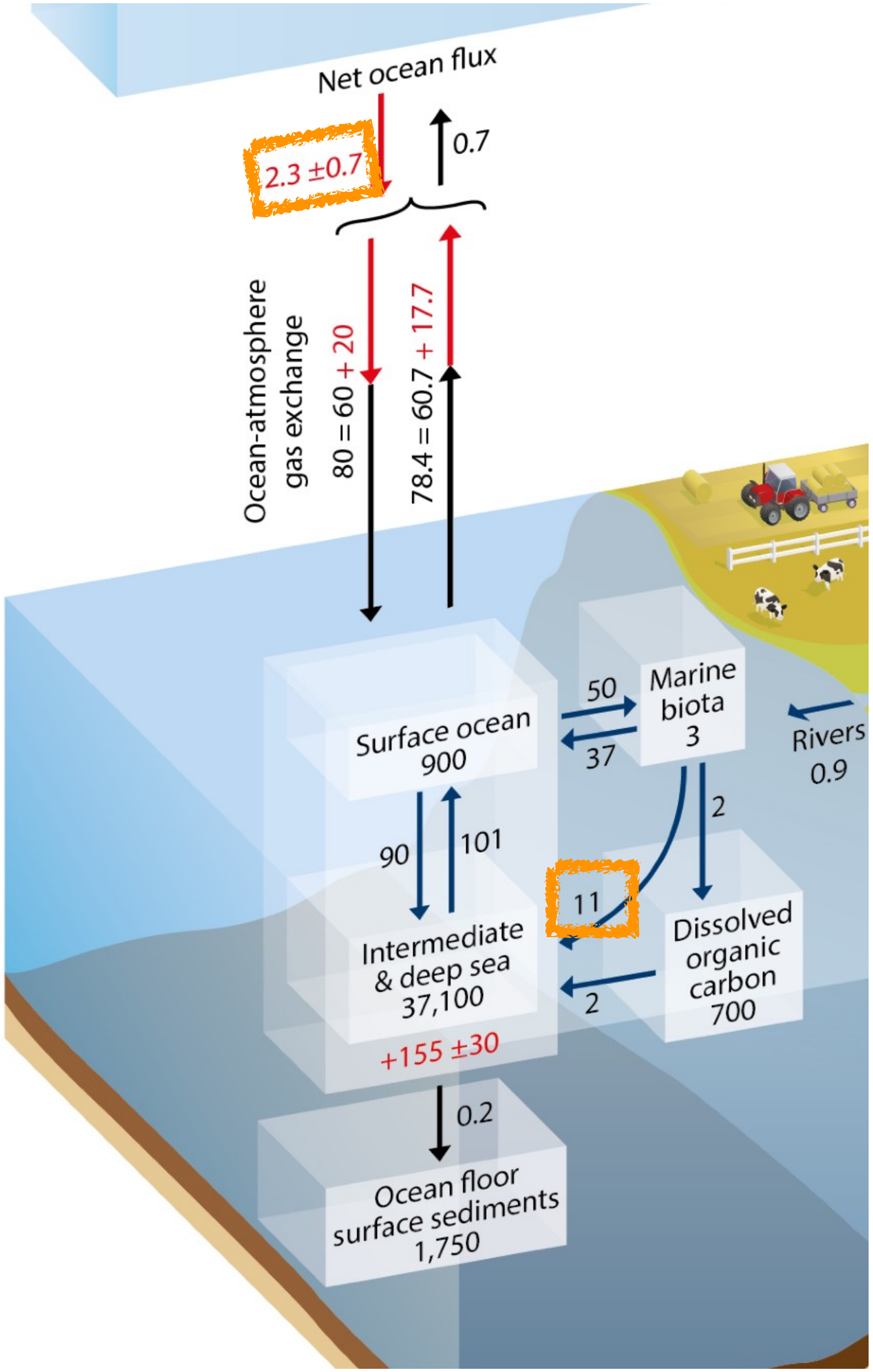


90% of DIC depth gradient is maintained by biological carbon pump

We need an ocean biogeochemical model to get it right.

Sarmiento & Gruber 2006

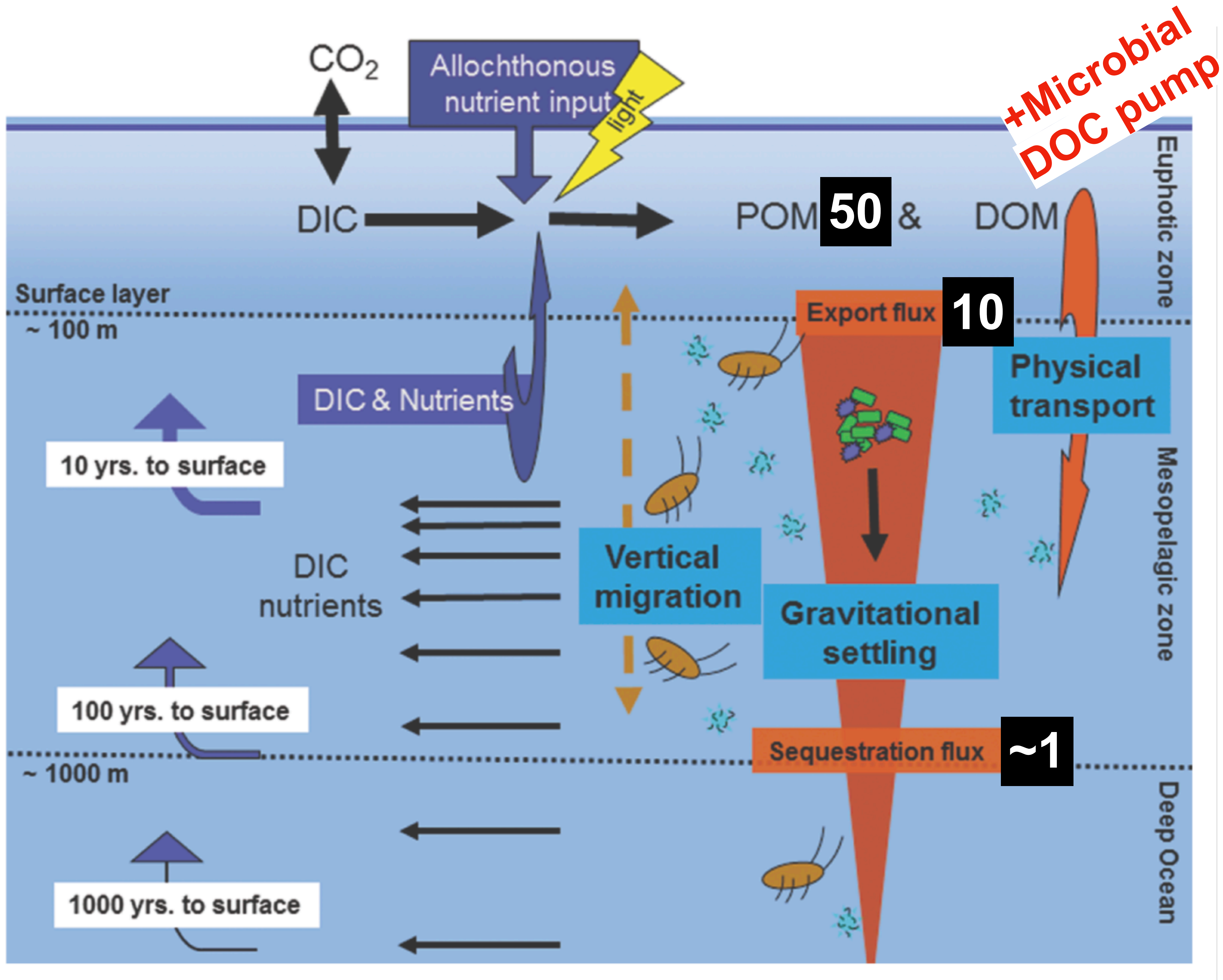
Global carbon budget



IPCC AR5
(Chapter 6)

- Oceanic CO_2 exchange is much larger than absorption of anthropogenic CO_2, and depends on joint operation of solubility and biological C pumps.
- Uncertainty in biological pump magnitude, interannual variability, and future response, is large enough to confound climate predictions and projections.

Biological carbon pump(s)



EP/NPP = e-ratio ~ 0.20

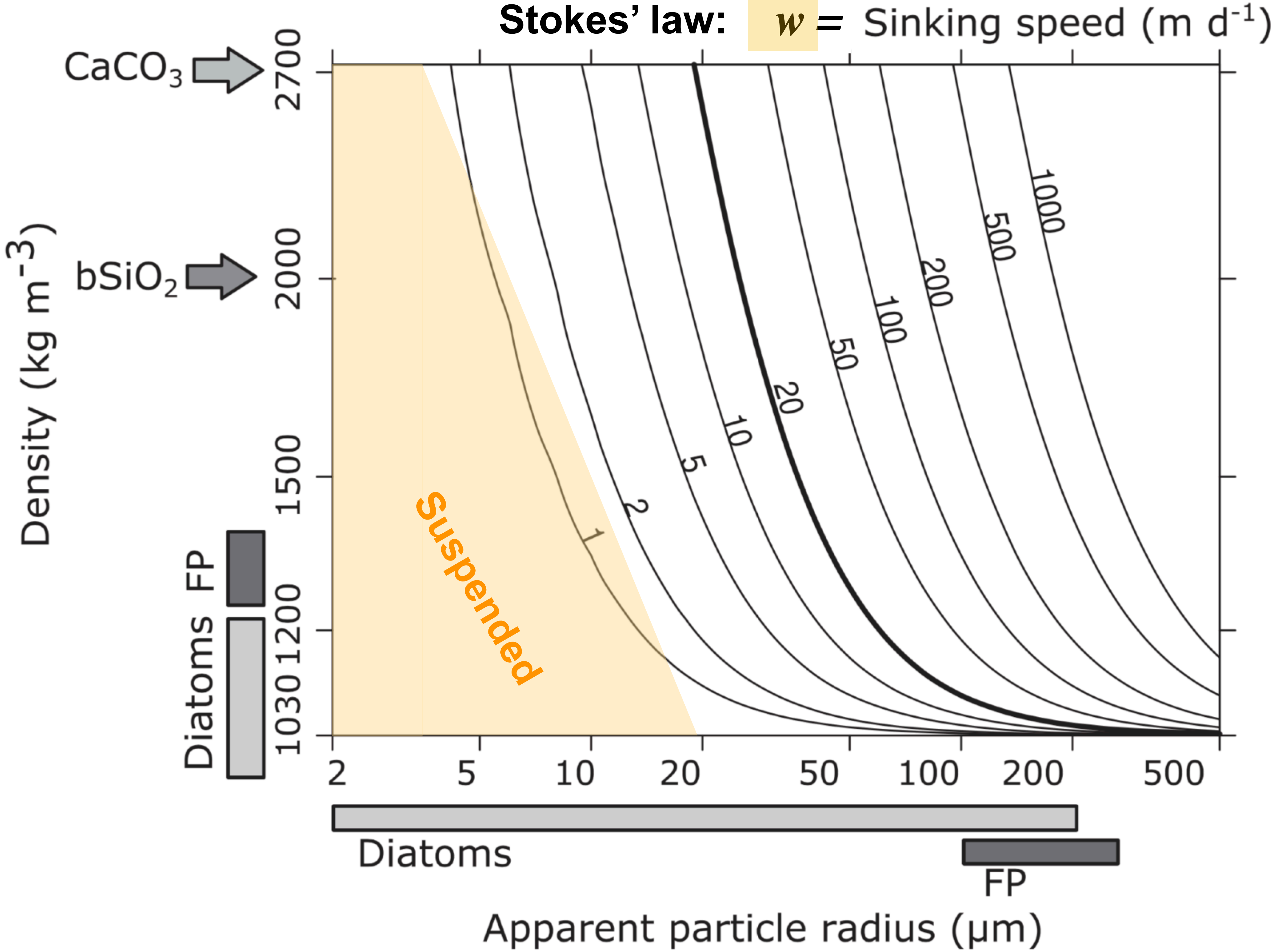
Transfer efficiency

Flux units: Pg C y^{-1}

Passow & Carlson 2012 MEPS. See also
Buesseler & Boyd 2009, Legendre et al. 2015 PiO

Particle size and density control sinking speed*…

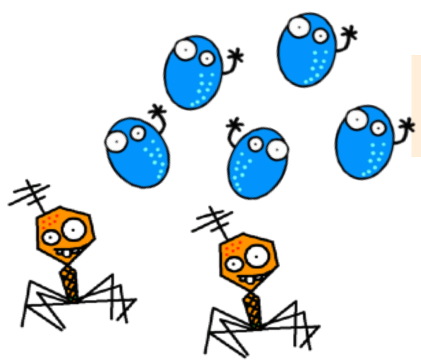
Stokes' law: w = Sinking speed (m d^{-1}) = $\frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2$



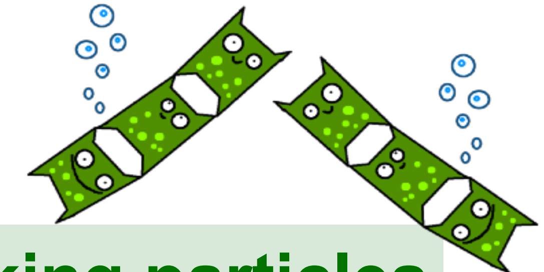
*shape and seawater viscosity too

Giering et al. 2016 JGR

…So large/dense particles *should* dominate the flux

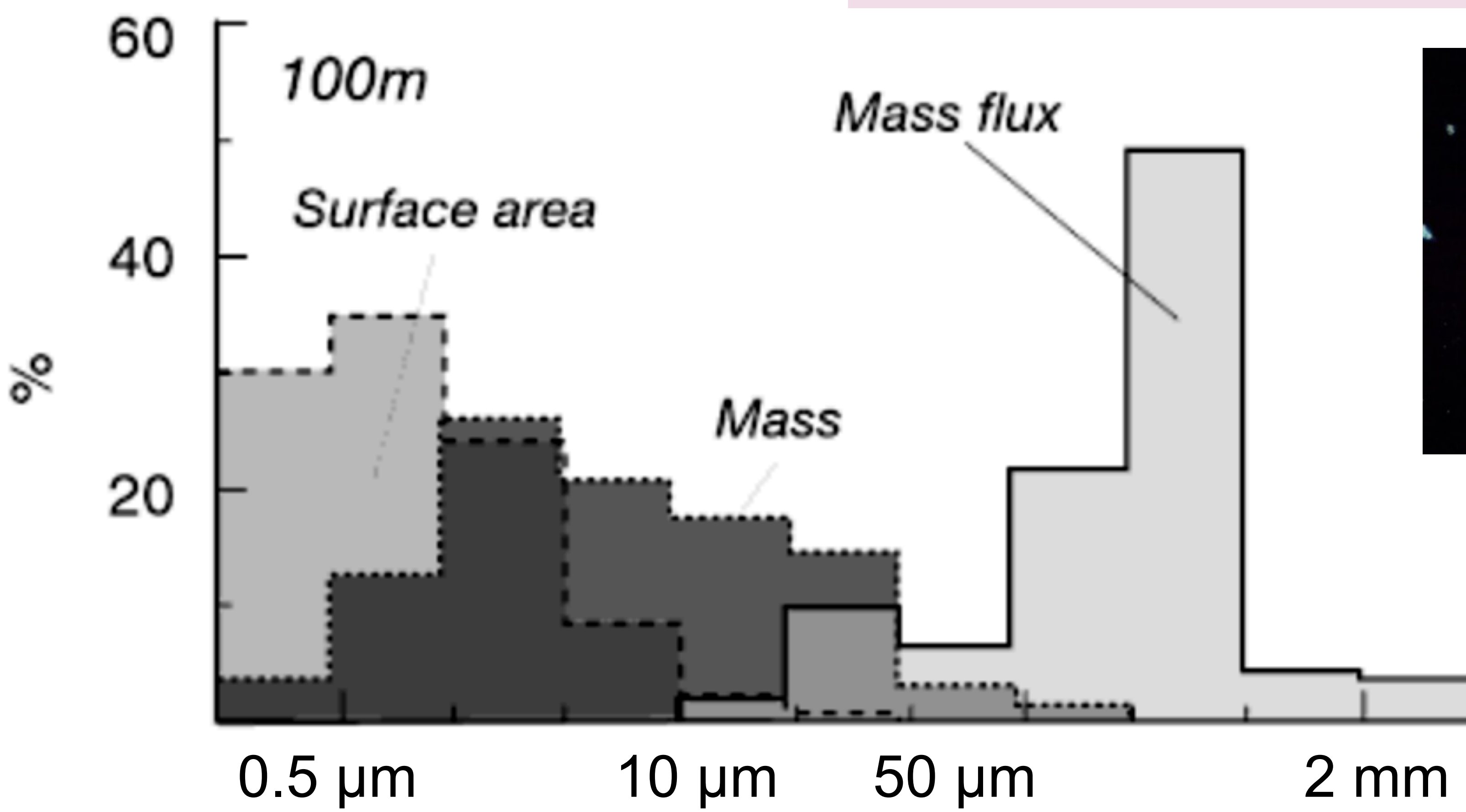


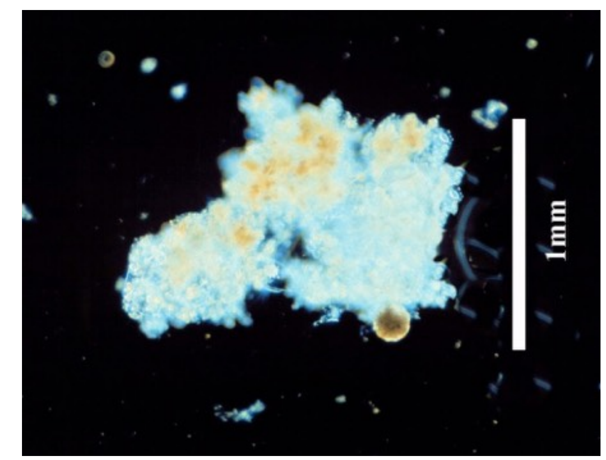
Suspended



Slow sinking particles

Fast sinking aggregates





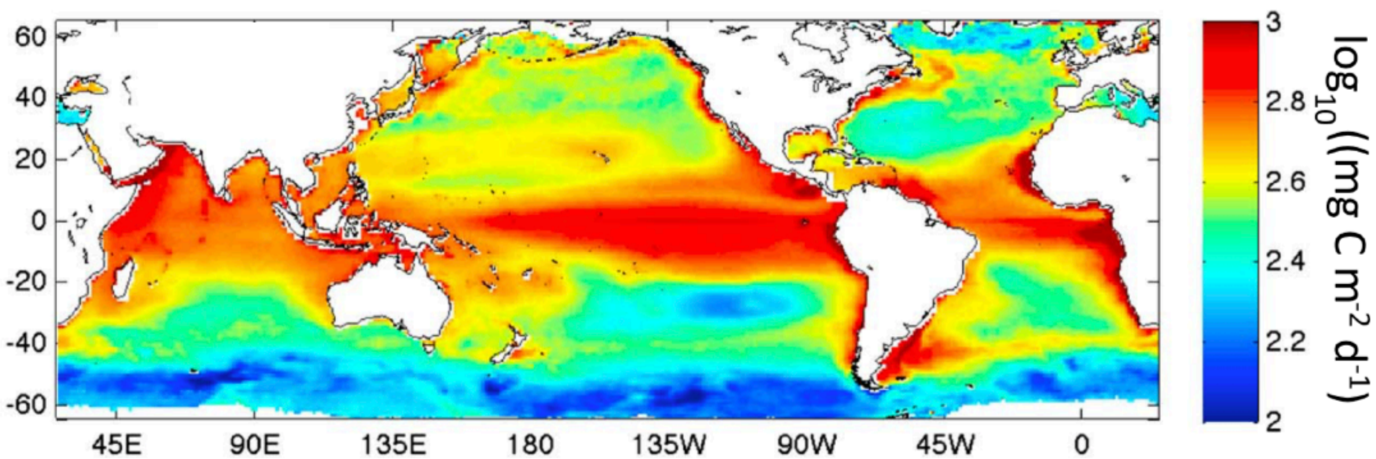
Drawings: Clara Ruiz-González

Clegg & Whitfield 1990 DSR (in Sarmiento & Gruber 2006). See also Stemmann & Boss 2012 ARMS

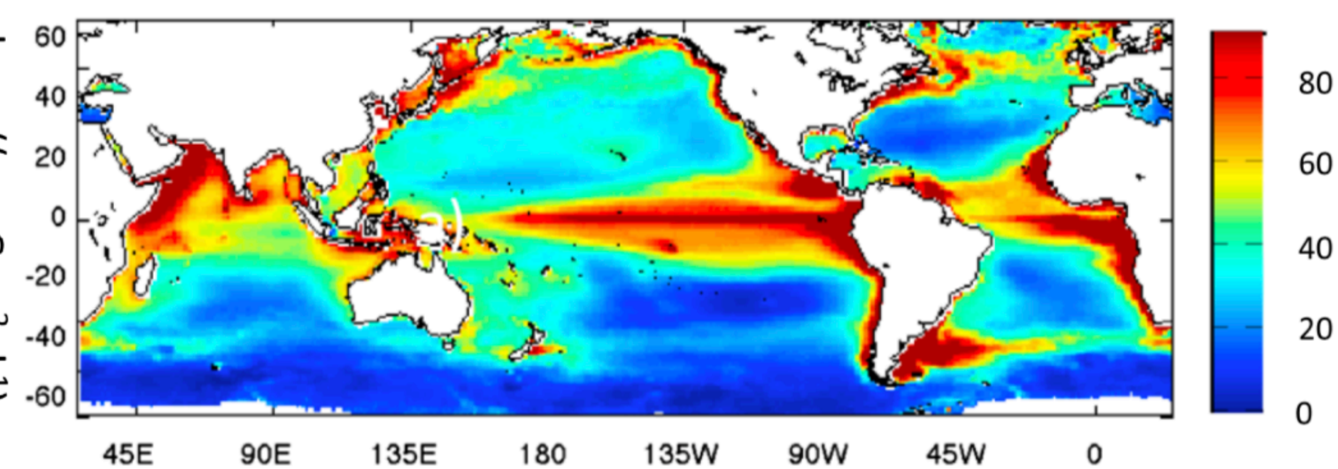
Export Production = NPP x e-ratio

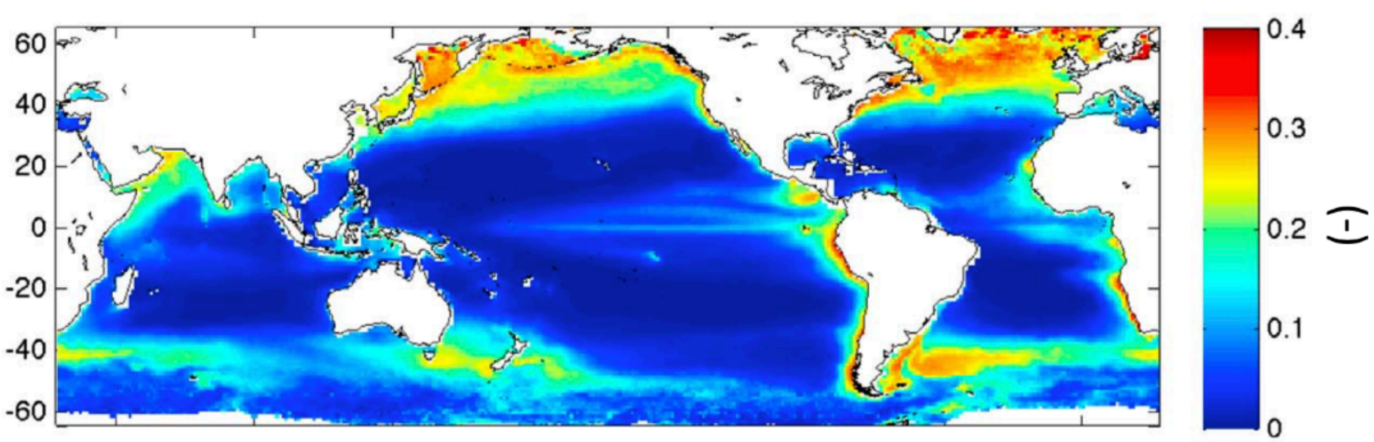
Productivity

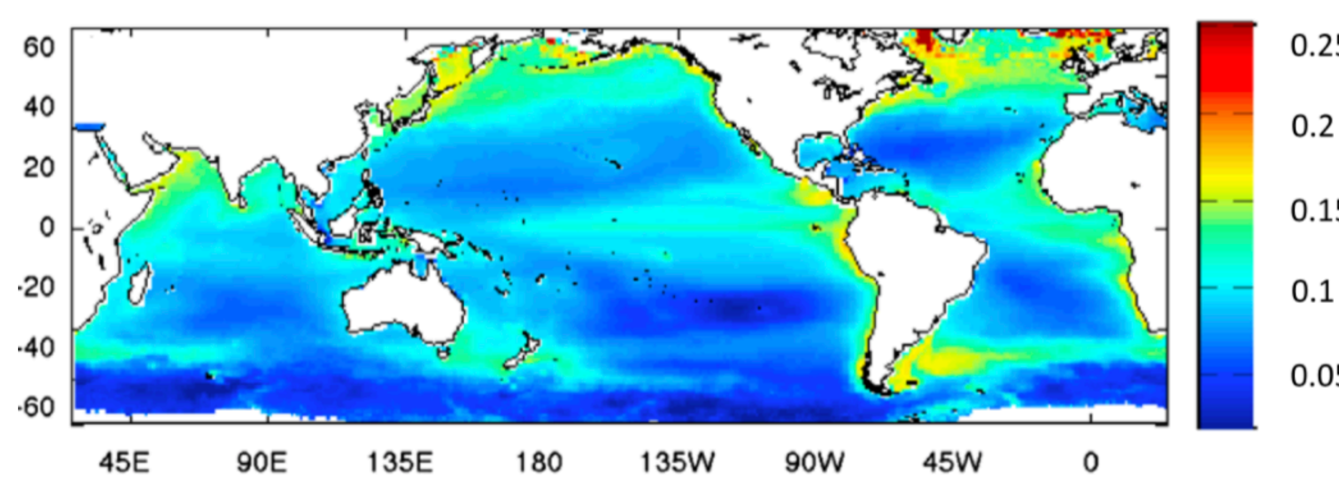
Net primary production (NPP)



Export production (EP)







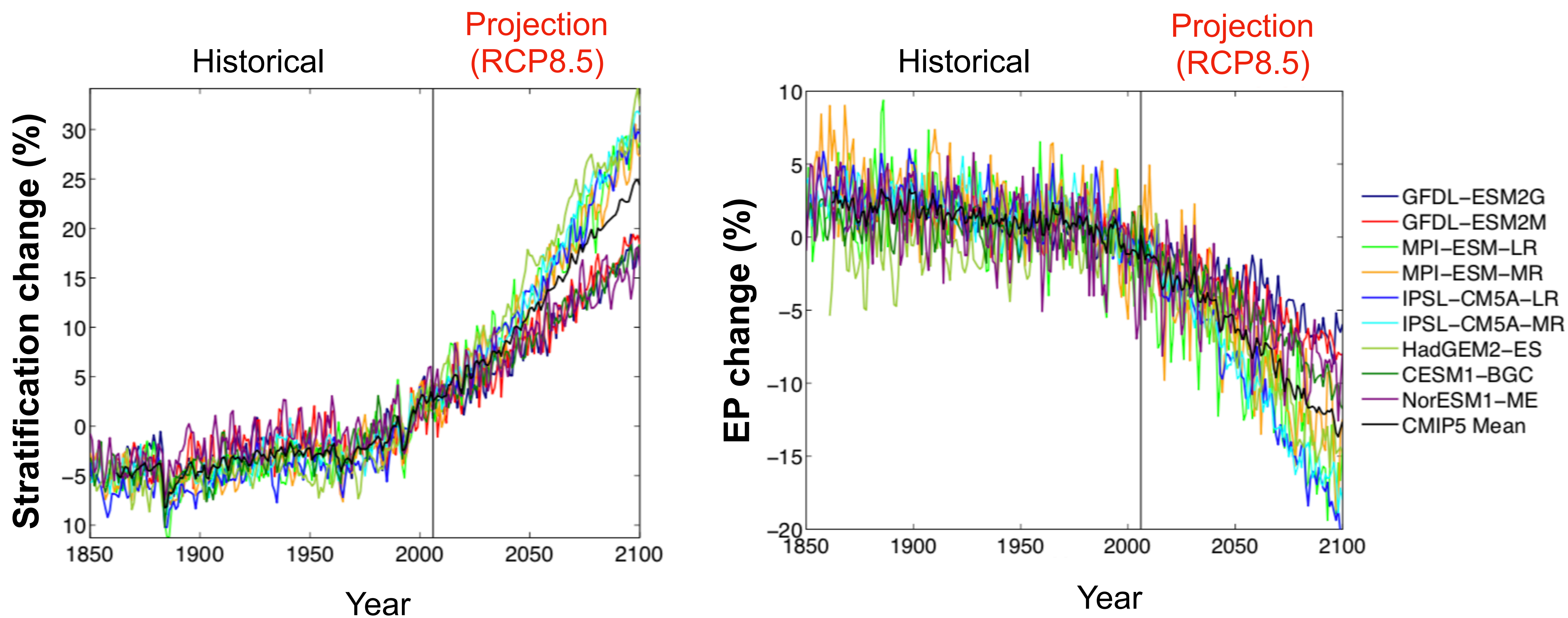
"Large" phytoplankton (~diatoms) fraction

e-ratio = EP/NPP

Ecosystem structure

Siegel et al. 2014 GBC

Global projections: more stratification, less export?



Fu et al. 2016 BG
See also Laufkötter et al. 2016 BG

2/6. Particle fluxes through the mesopelagic

Sediment traps

Fixed sediment traps: moored, surface tethered

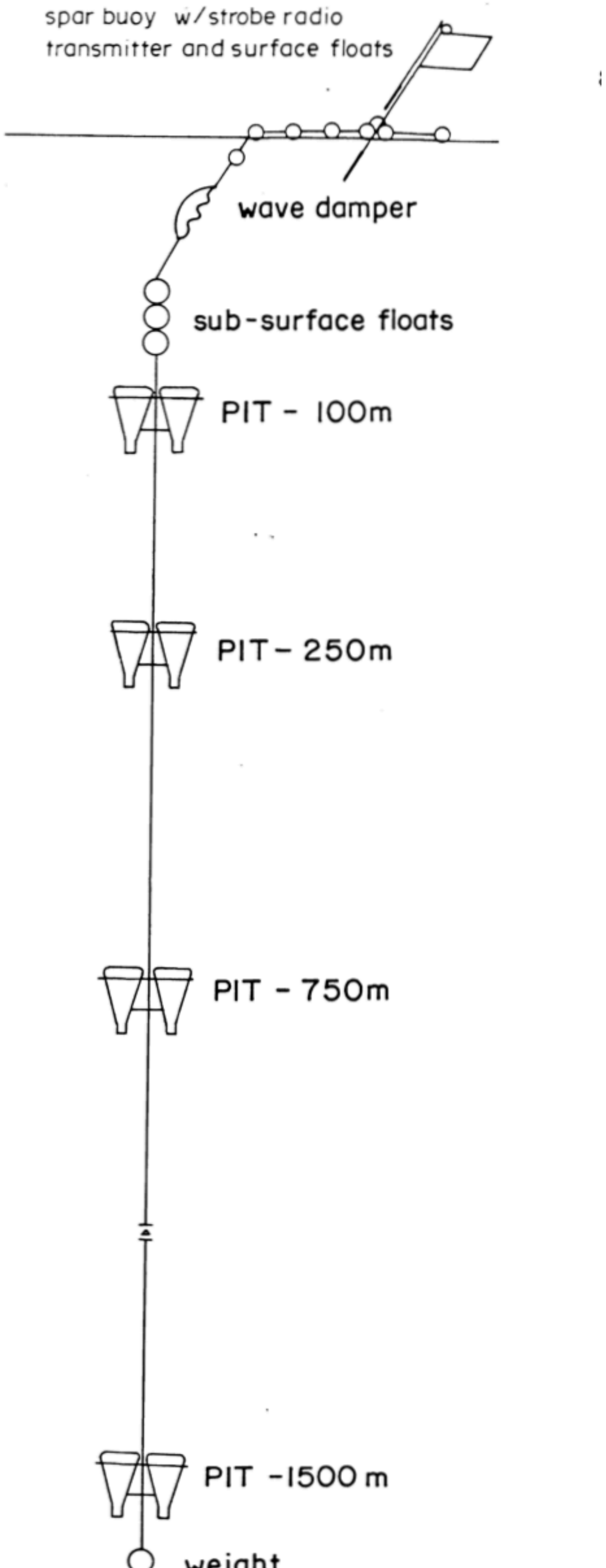
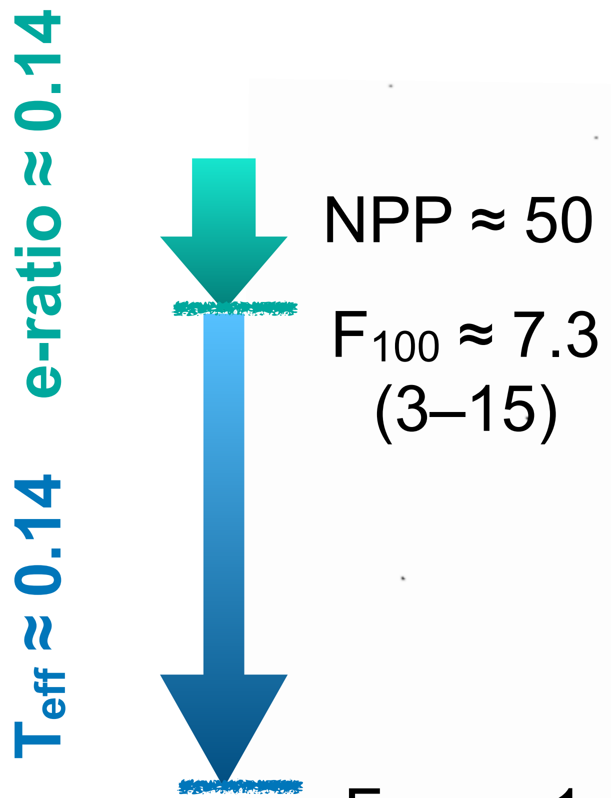


FIG. 3. Flotation system used for both UCSC and MLML traps during VERTEX I.

Martin et al. 1983,
Buesseler et al. 2007 JMR

Martin's *b* (a.k.a. the magic exponent)



(Units: Pg C y^{-1})

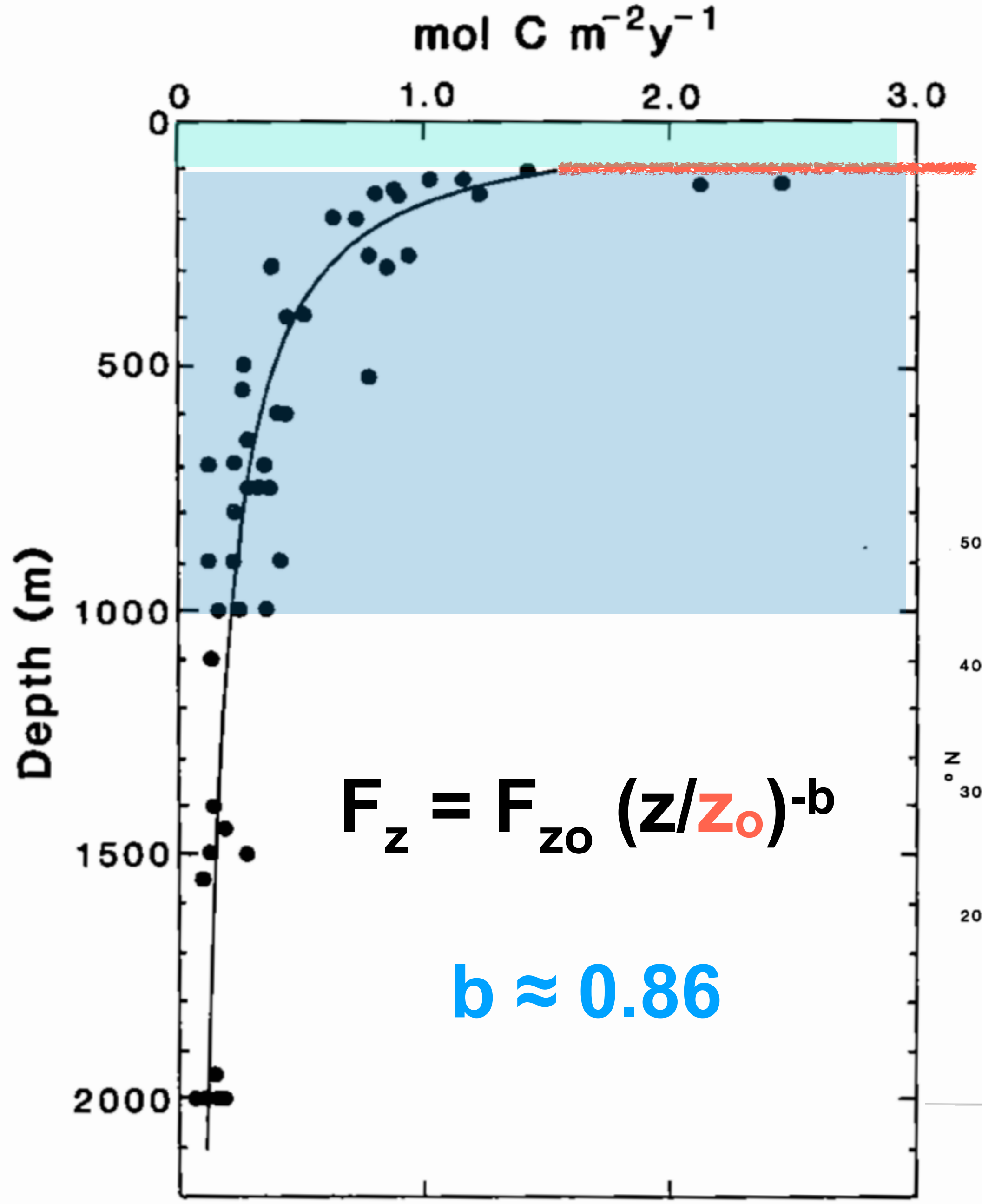


Fig. 5. Open ocean composite (OOC) fluxes for C using the means of replicates at various depths from Stas 2, 4, 5, II, III and NPEC: $F = 1.53(z/100)^{-0.858}$; $r^2 = 0.81$; $n = 48$.

Martin et al. 1987

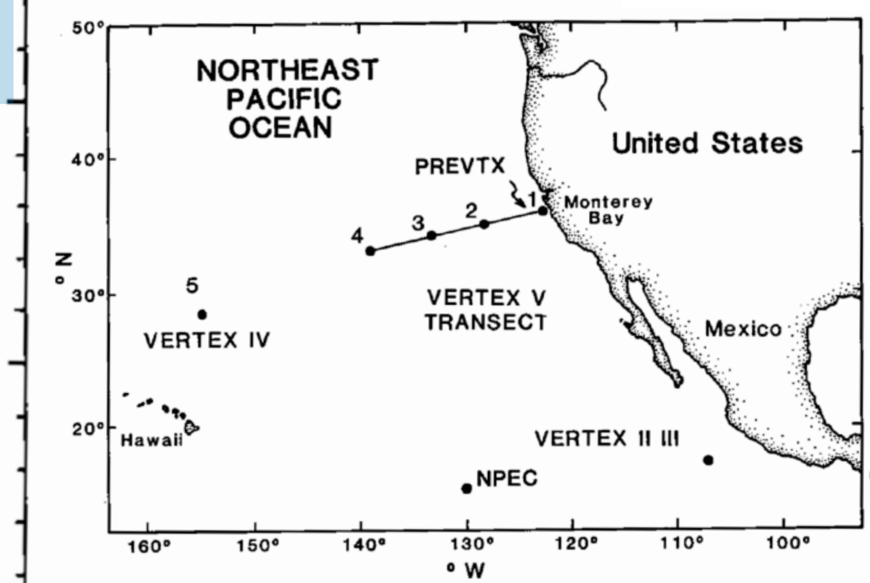
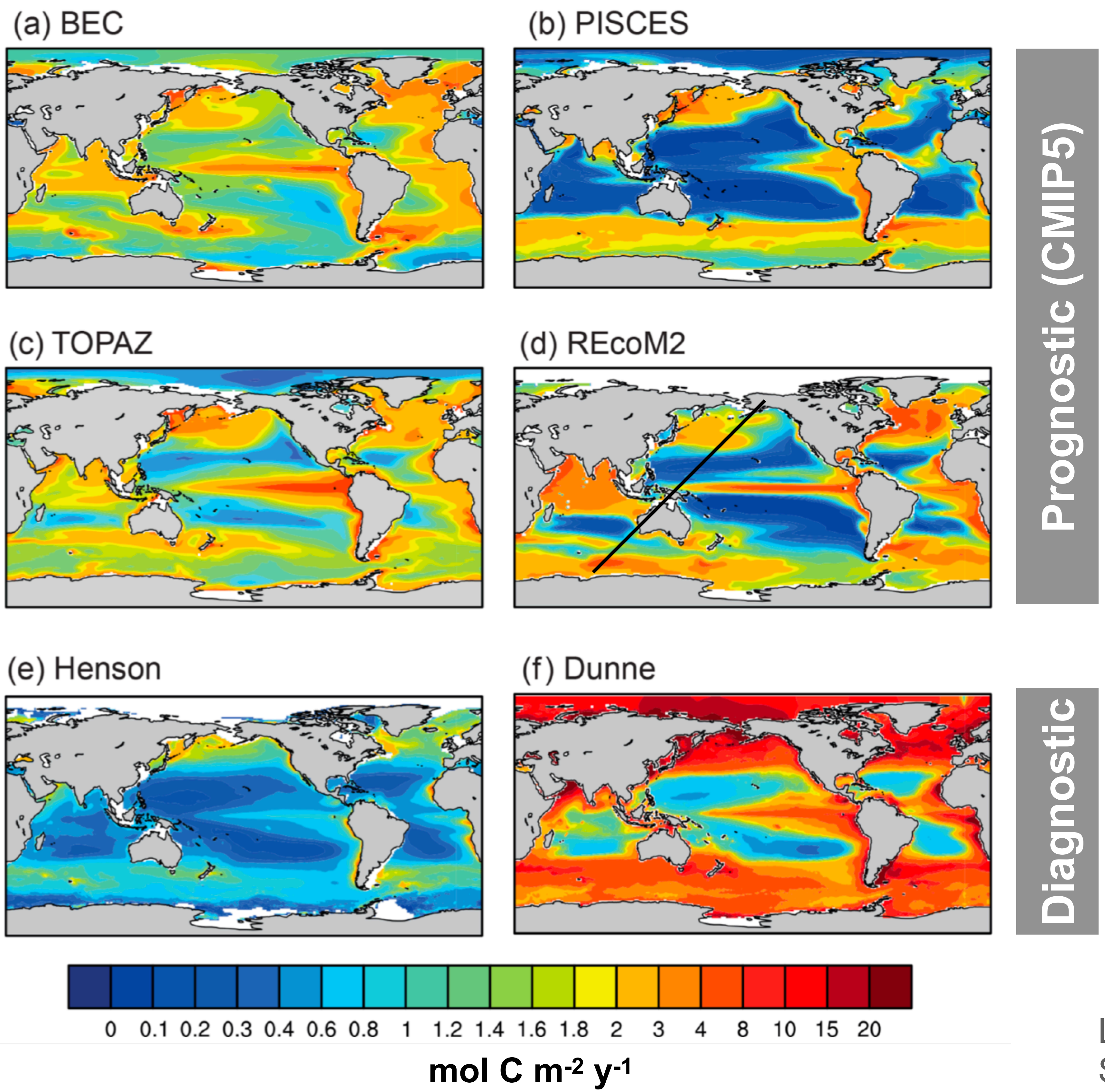


Fig. 1. VERTEX station locations.

Current EP estimates are no better



4.6–7.2 Pg C y^{-1}

4.0–12.9 Pg C y^{-1}

Laufkötter et al. 2016 BG
See also Palevsky & Doney 2018 GRL

Sediment traps

Fixed sediment traps: moored, surface tethered

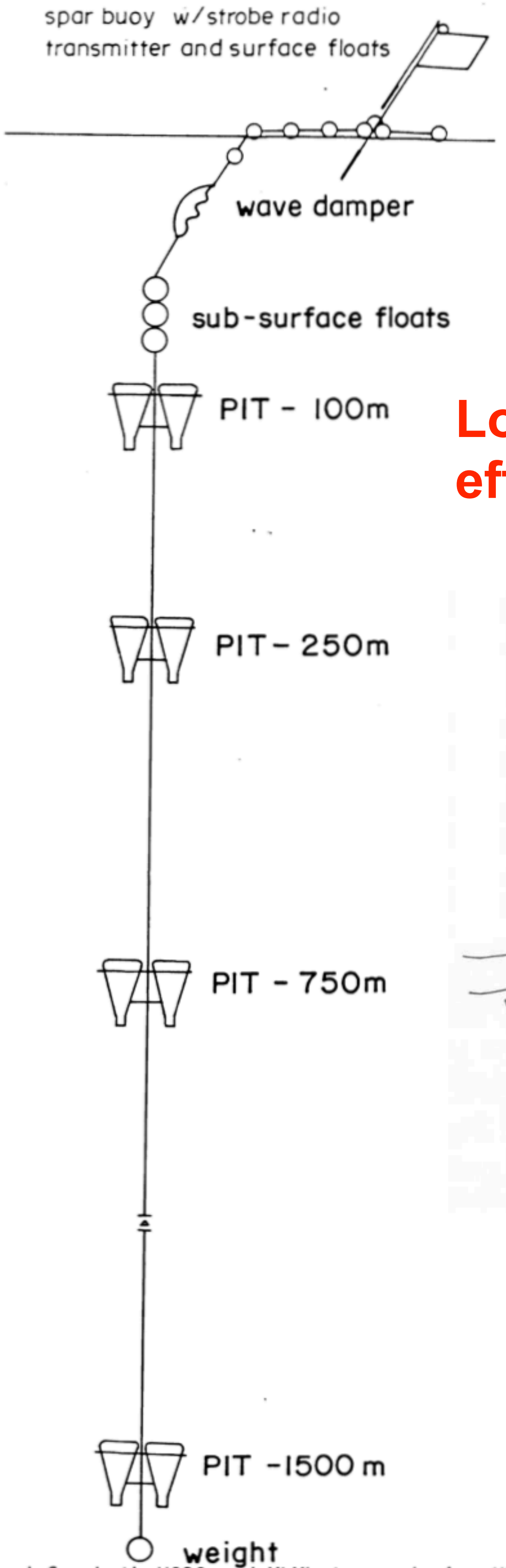
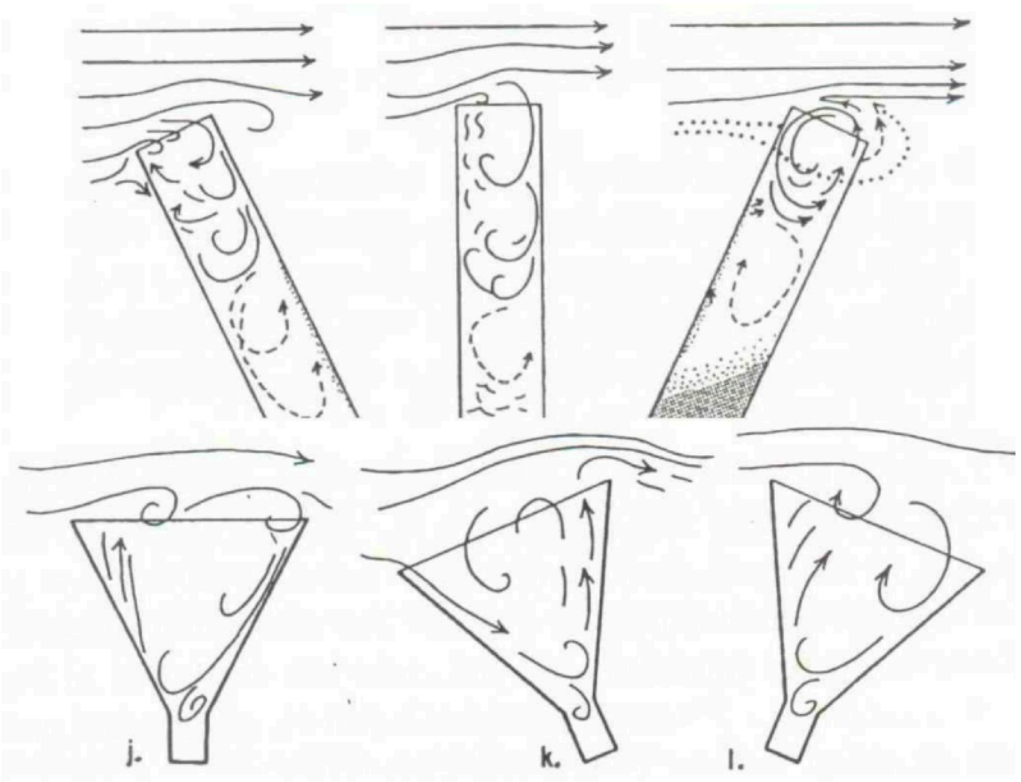


FIG. 3. Flotation system used for both UCSC and MLML traps during VERTEX I.

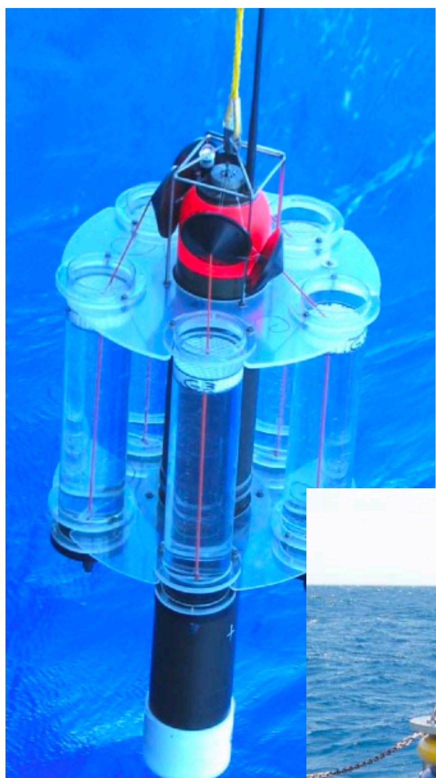
Low (>40%) and erratic trapping efficiency in the mesopelagic



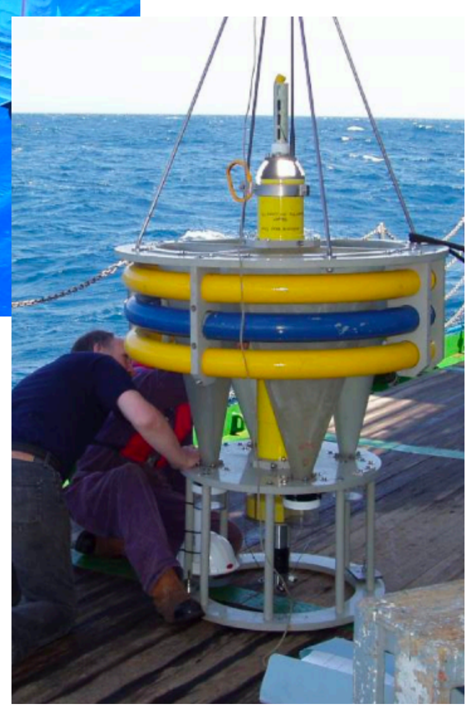
Martin et al. 1983,
Buesseler et al. 2007 JMR

Particle flux measurement: current methods

Neutrally buoyant sediment traps



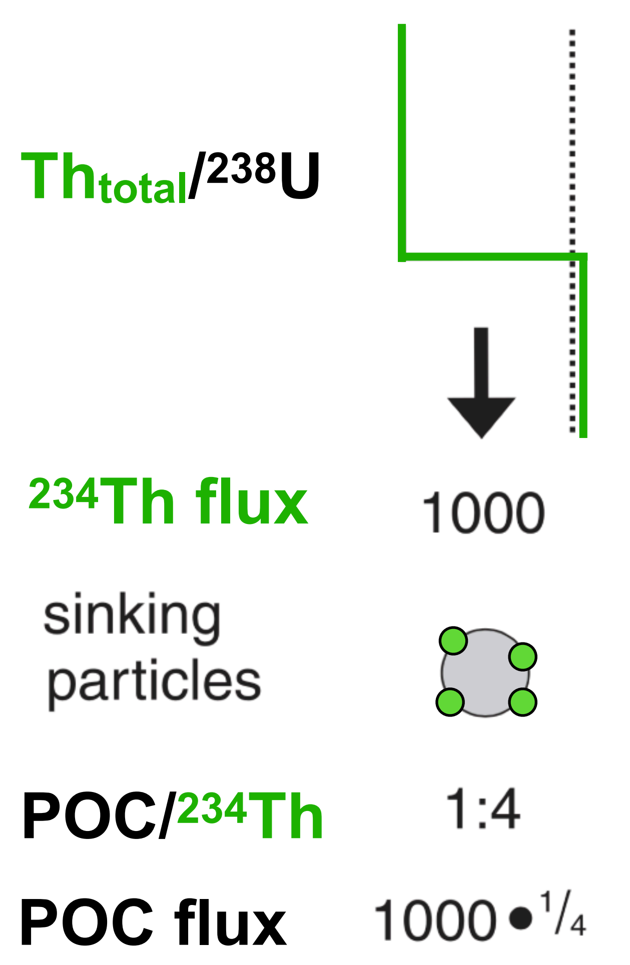
NBST



PELAGRA

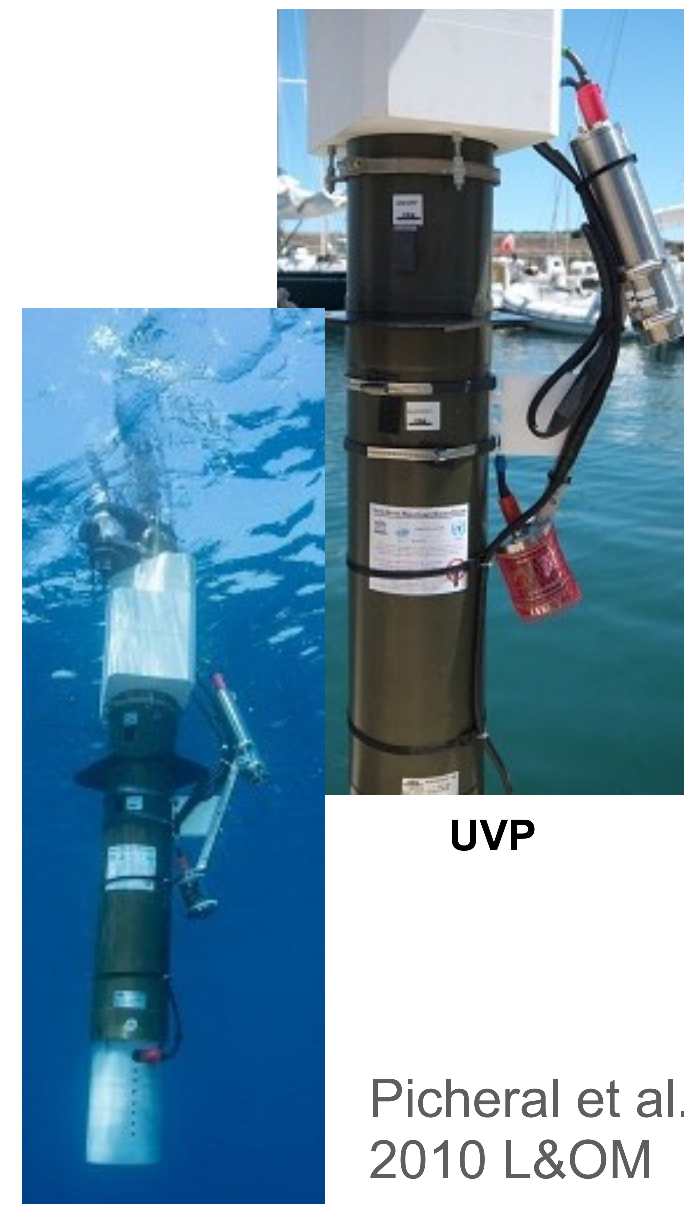
Valdes & Price 2000, Lampitt et al. 2004

Particle-scavenged radioisotopes



Buesseler et al. 2006 MarChem

Optical devices, imaging



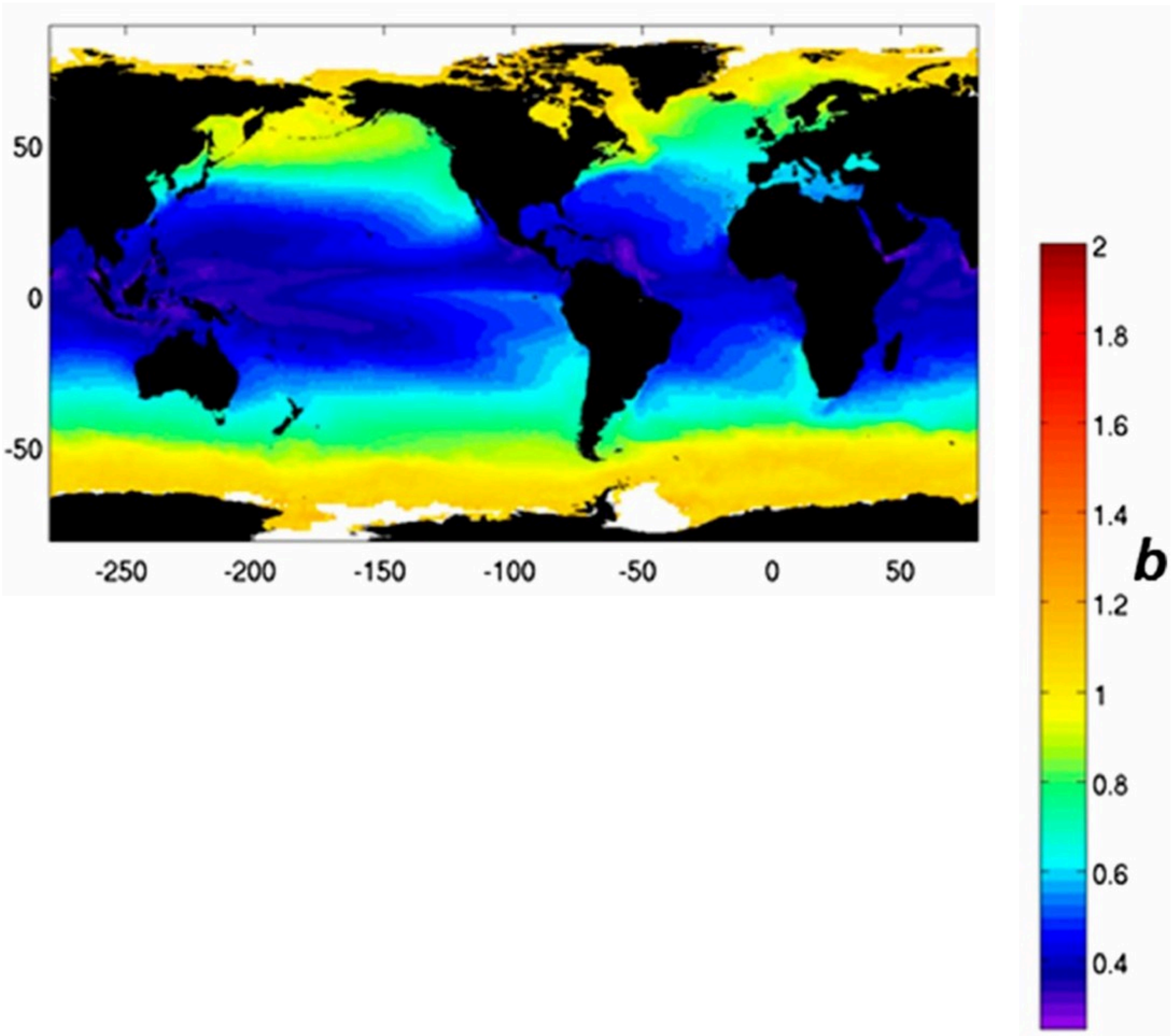
UVP

Picheral et al. 2010 L&OM

POC flux attenuation

- MLD to 2000 m (^{234}Th or particle size spectra combined with 2000 m trap data).

(Henson et al. 2012 GBC, Guidi et al. 2015 GBC)

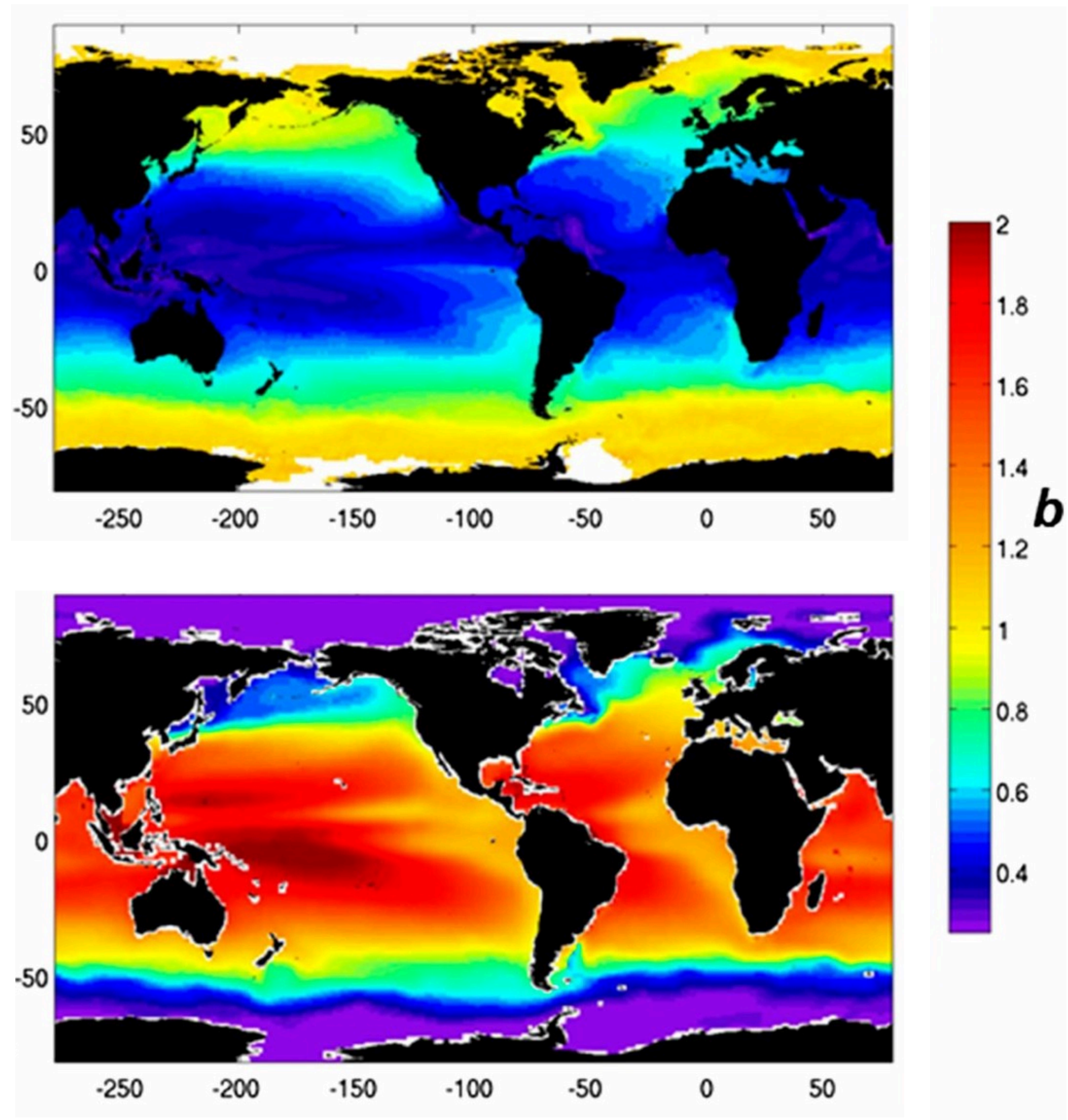


POC flux attenuation: mesopelagic ≠ bathypelagic

- MLD to 2000 m (^{234}Th or particle size spectra combined with 2000 m trap data).

(Henson et al. 2012 GBC, Guidi et al. 2015 GBC)

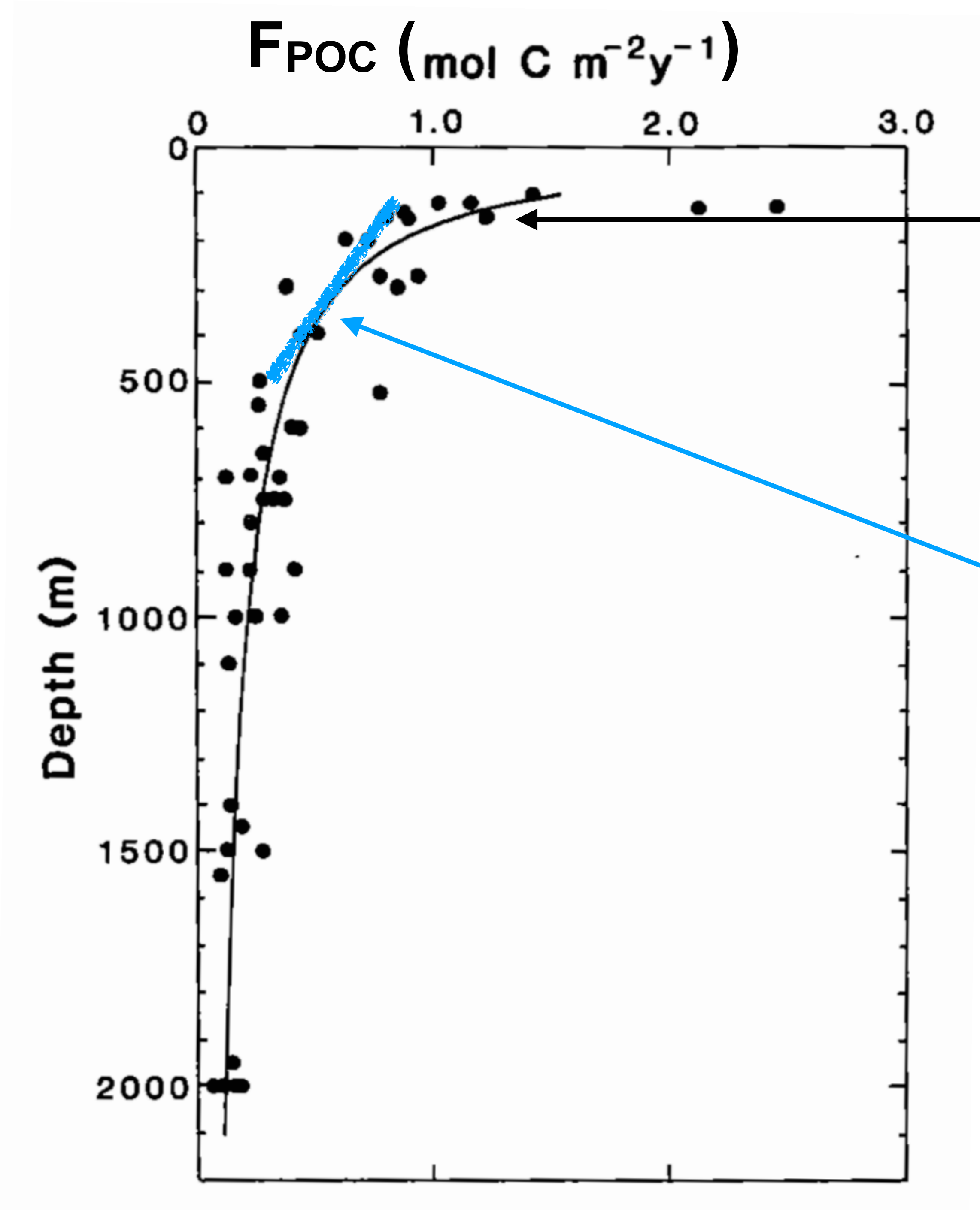
- MLD to 600 m (neutrally buoyant sediment traps –PELAGRA).



Marsay et al. 2015 PNAS

3/6. Budgets: making sense of observations

Change in vertical flux = net carbon demand



F_{POC} = w [POC]

At steady state, over large enough areas and long periods:

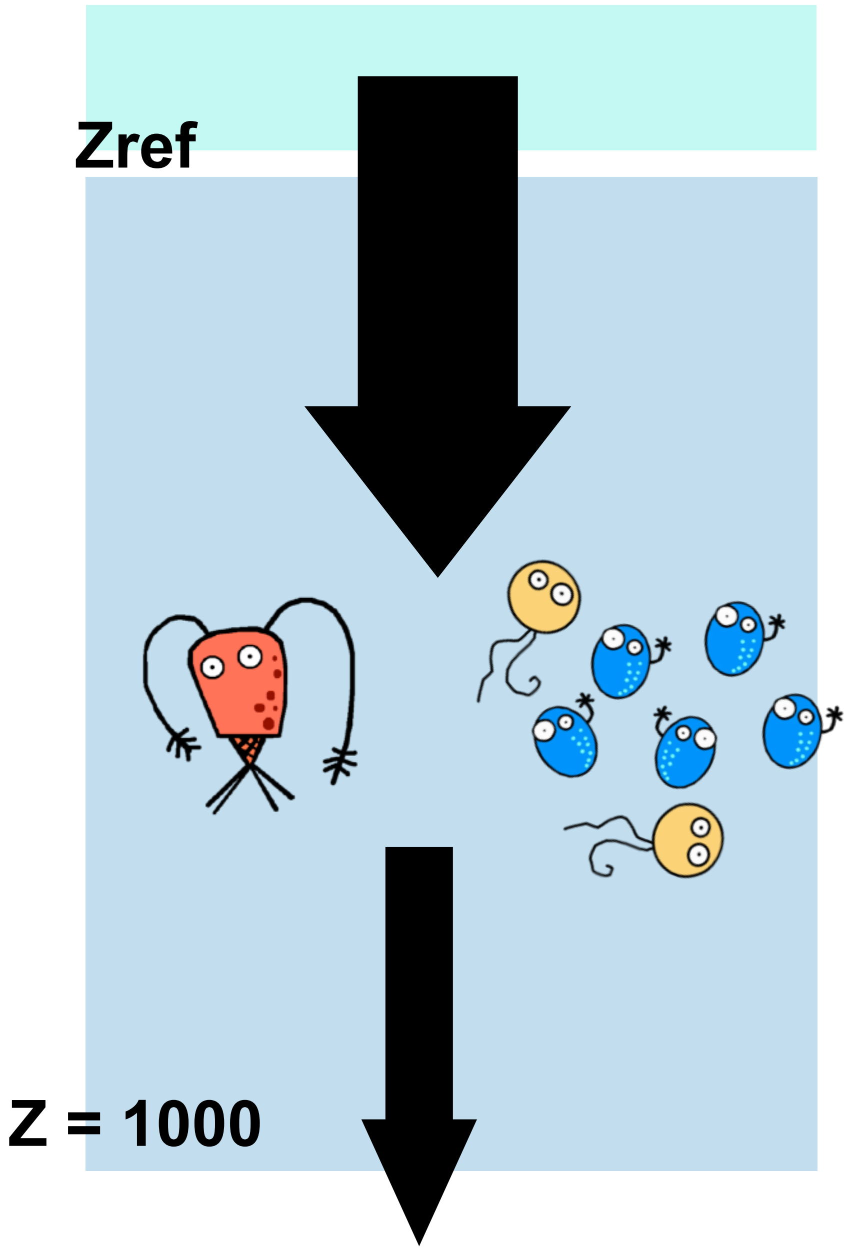
$d(F_{POC})/dz =$

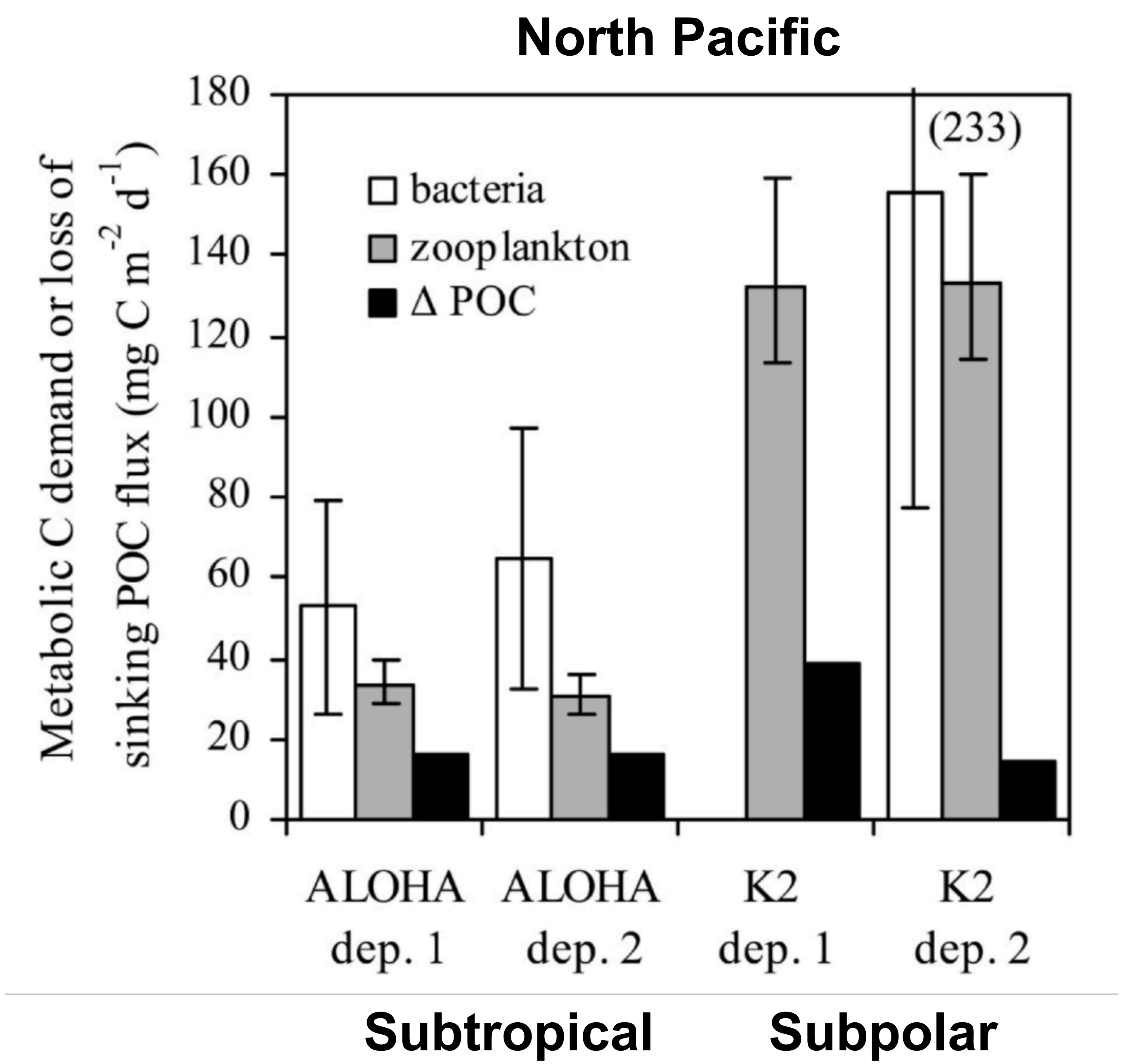
$d(w\,[POC])/dz \approx k_{NET}\,[POC]$

Martin et al. 1987 DSR,
Sarmiento & Gruber 2006

Mesopelagic budgets cannot be closed

Heterotrophic carbon demand is not met





Drawings: Clara Ruiz-González

Steinberg et al. 208, Burd et al. 2010 DSR

Mesopelagic budgets cannot be closed

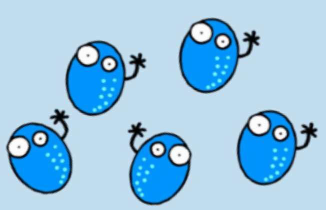
Global estimates of EP < prokaryotic carbon demand

NPP ≈ 50 (12.5)

Zref

EP ≈ 10 (2.5) **+ 2.5** (0.7)

(POC + DOC)



Respiration

Net input ≈ 9 (2.3) **<<** **PCD = 130** (32) $\approx \frac{\mathbf{13}\ (3.2)}{0.10} = \frac{\text{Prok. prod.}}{\text{Prok. growth eff.}}$

(**PCD = 15** using median Prok. Prod.)

Z = 1000 **Deep export ≈ 1** (0.25) **+ DOC**

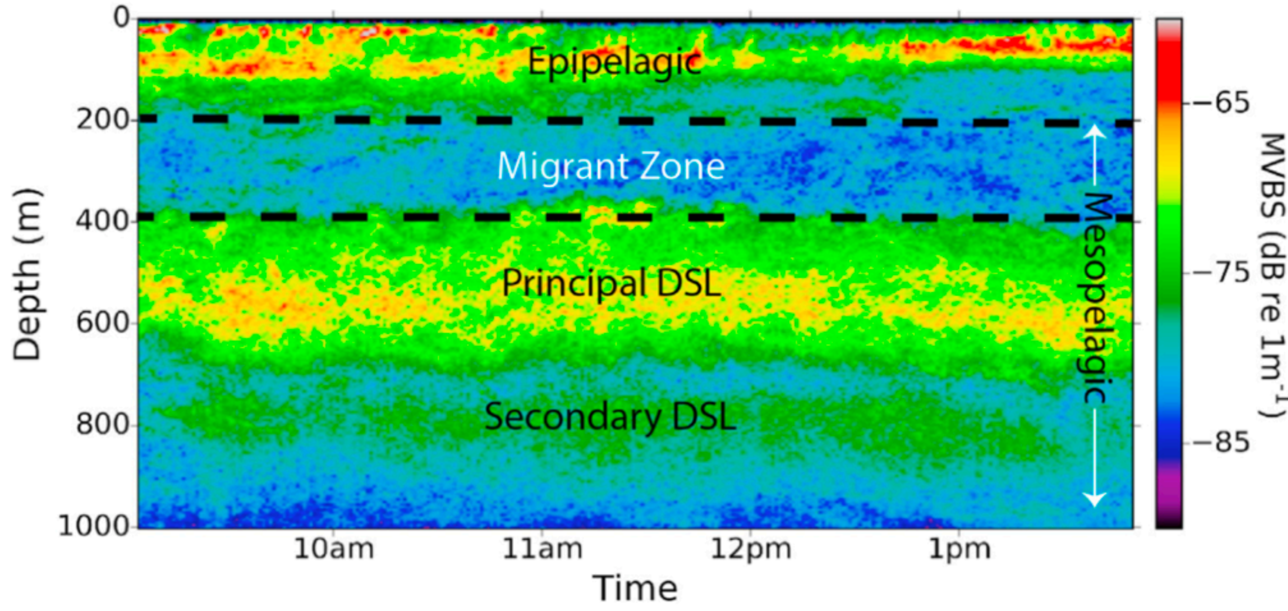
Global estimates
Units: Pg C y^{-1} (mol C m^{-2} y^{-1})

Arístegui et al. 2009 L&O, Burd et al. 2010 DSR, Sarmiento & Gruber 2006

Mesopelagic budgets cannot be closed

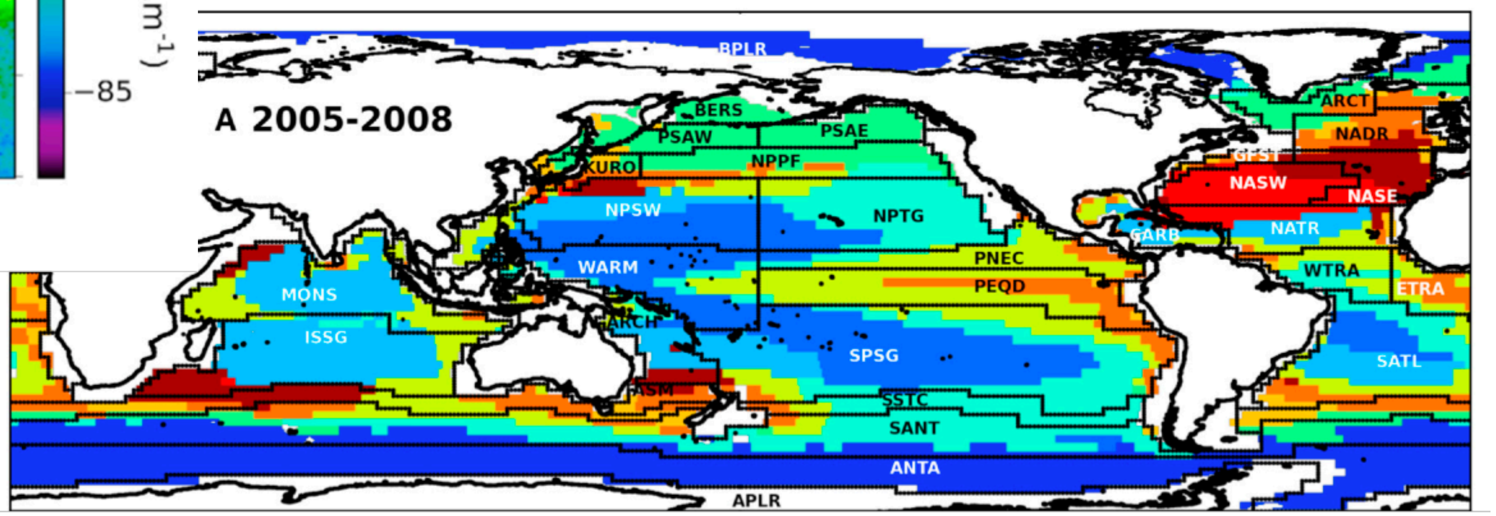
Mesopelagic fish biomass revised upwards

- ~13 Pg wet weight (**10x**) based on acoustics. Higher trophic efficiency invoked (Irigoien et al. 2014 NComms)
- 2.4 Pg wet weight, (**2x**) based on modelling (NEMO-MEDUSA) (Anderson et al. 2018 ICES JMS)



Deep scattering layers detected with echosounding

Statistical/biogeographical upscaling



Proud et al. 2017 Curr. Biol.

Large budget imbalance: Why?

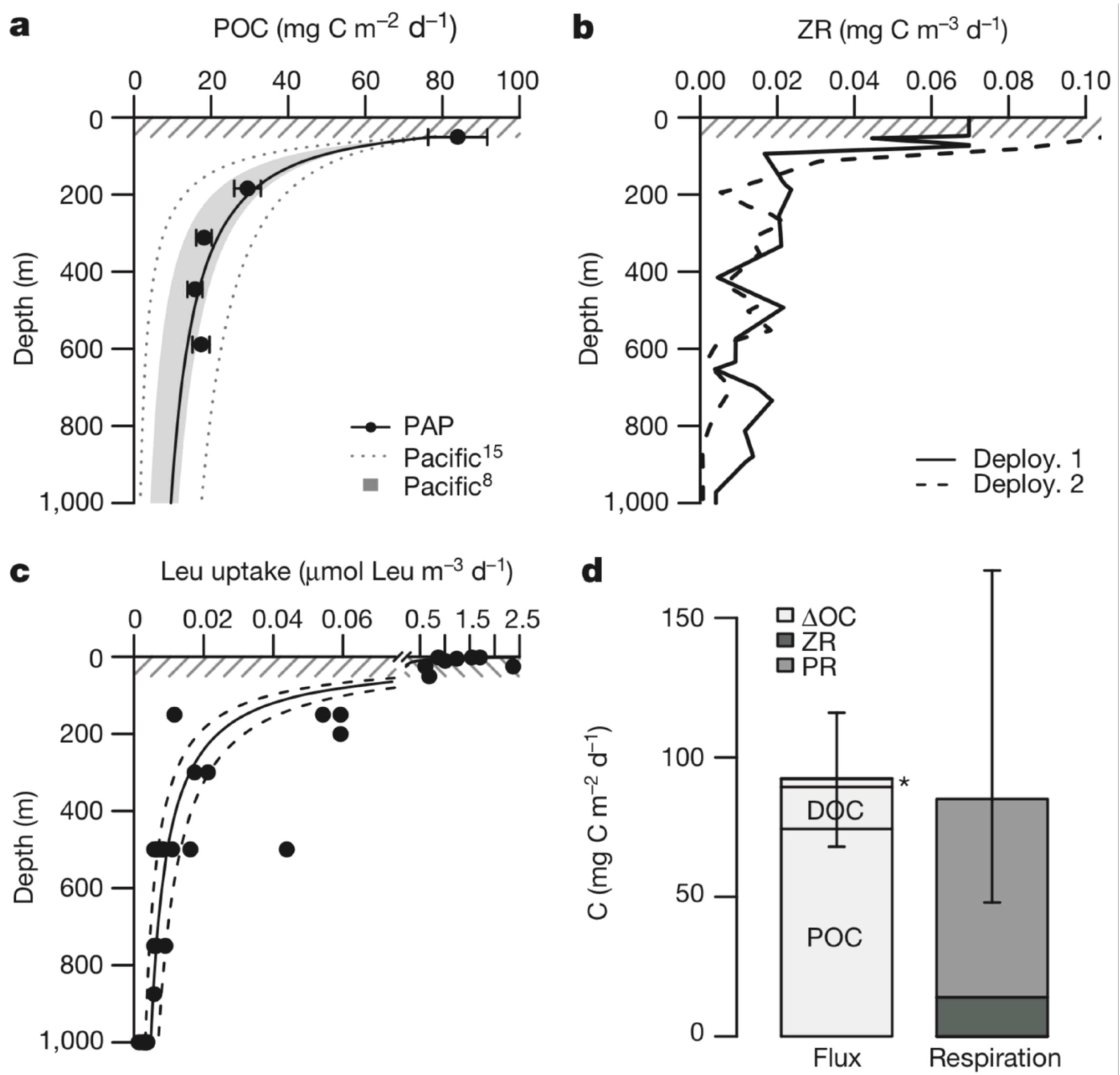
- **Inappropriate sampling**: low temporal-spatial resolution (sparseness, bias) and mismatch between epipelagic and mesopelagic process measurements (Henson et al. 2015 GBC)

- **Measurement uncertainties** in both particle flux and metabolic rates. (Buesseler et al. 2007 JMR, Arístegui et al. 2009 L&O, Buesseler & Boyd 2009 L&O, Burd et al. 2010 DSR…)

- **Mathematical assumptions**: steady state, constant sinking speed, constant decay rates (Villa-Alfageme et al. 2014 GBC, Giering et al. 2016 GBC…)

- **Unaccounted or poorly understood processes**:
  - **Flux of, and metabolism on, suspended and slow-sinking POC**
  - Diel and seasonal vertical migration (Aumont et al. 2018 GBC)
  - Poorly understood ecology, e.g. radiolarians (Guidi et al. 2016 Nature)
  - Chemoautotrophy (Arístegui et al. 2009 L&O)

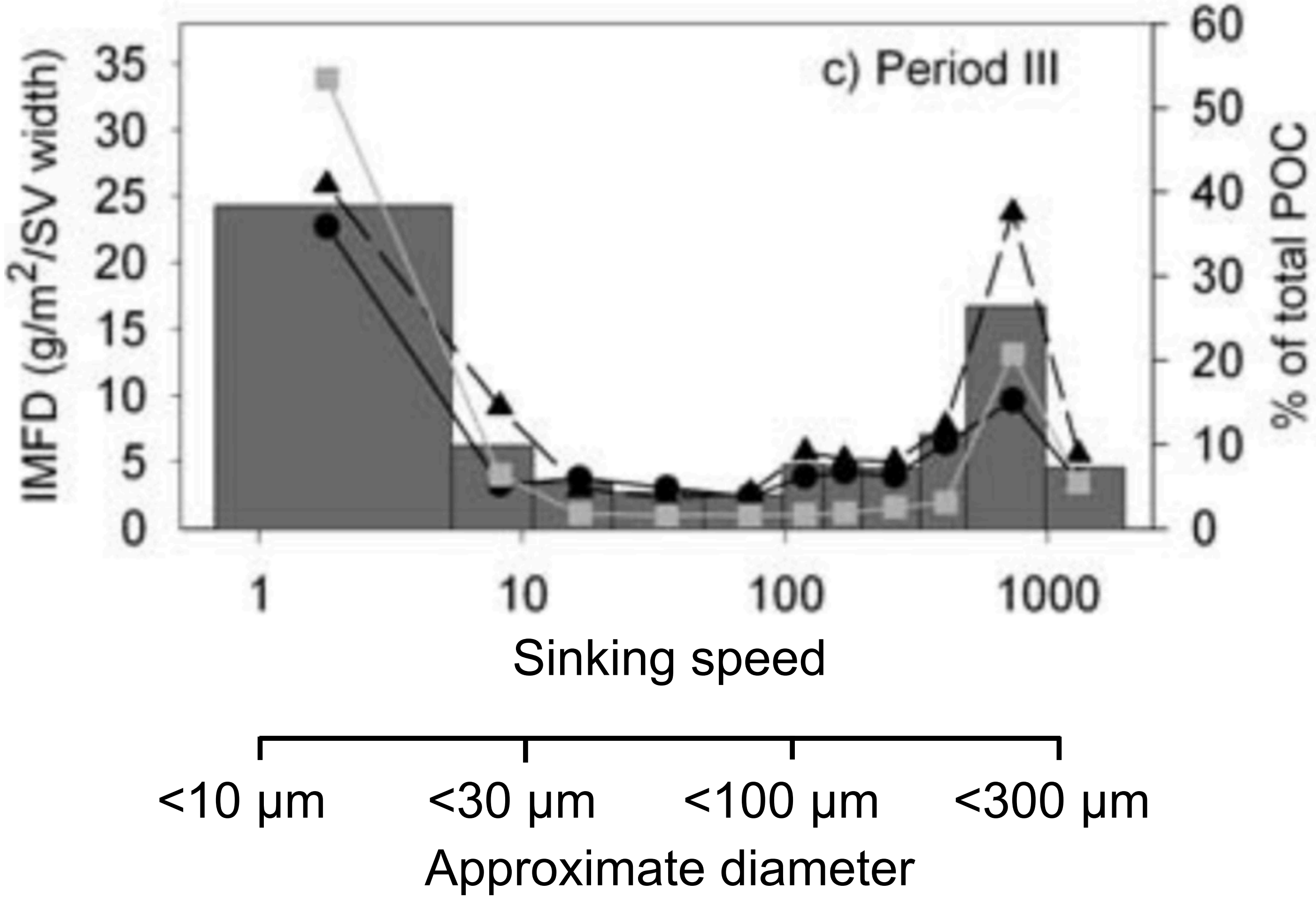
Budgets can (sometimes, nearly) be closed



Giering et al. 2014 Nature

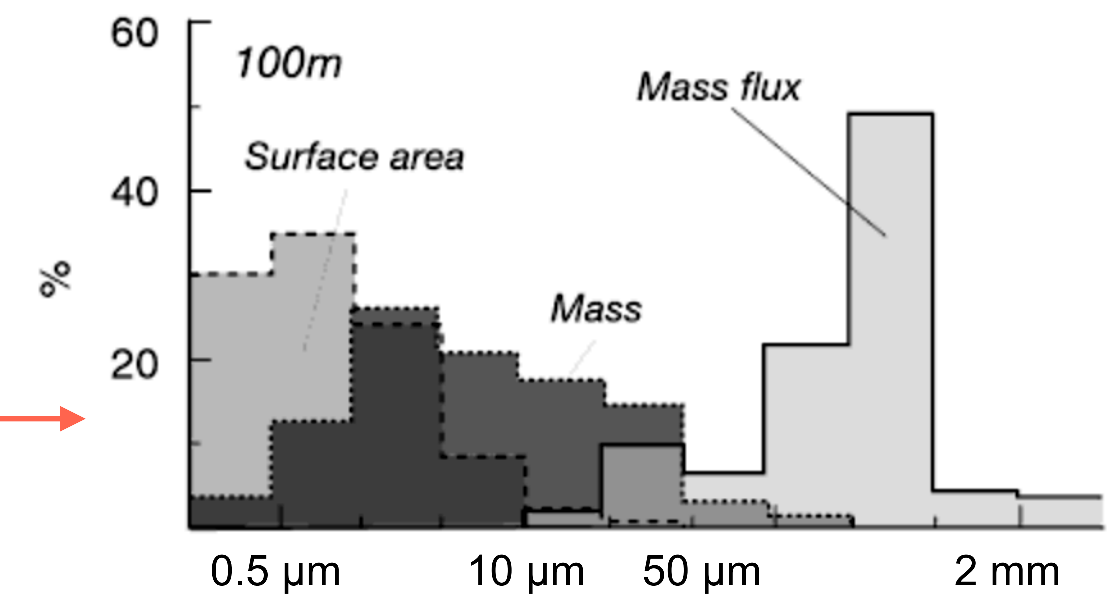
4/6. Suspended and slow-sinking particles: supply and cycling

Small particles (<20 µm) can dominate vertical flux



Bimodal POC flux dominated by small slow-sinking particles in Canary Current region (during at least half of the year)

At odds with classical theory



Alonso-González et al. 2010 GRL

High contribution by small POC: not an exception

- **Subtropical N Atlantic, Canary Current: >60%**, w < 10 m d^{-1} (d << 30 μm) during at least half of the year (Alonso-González et al. 2010 GRL).

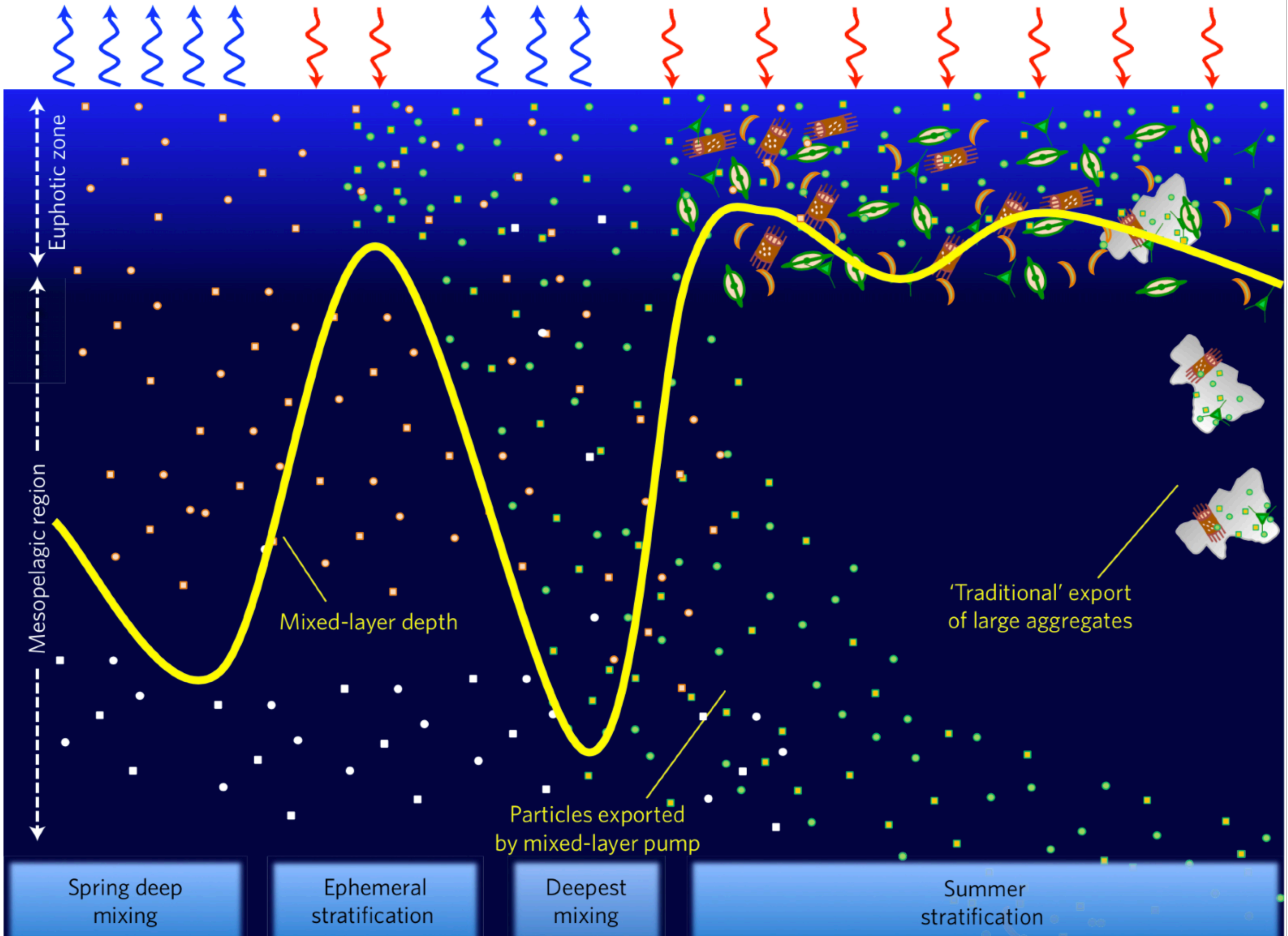
- **Temperate NW Atlantic (PAP): >60%**, w ≈10 m d^{-1} in August (Riley et al. 2012 GBC). Mean sinking speeds (radioisotope approach) increase with depth, incompatible with large aggregate-dominated flux (Villa-Alfageme et al. 2014).

- **Subpolar N Atlantic: >85%** in April, early bloom (Giering et al. 2016 JGR).

- **Subpolar N Pacific (K2): 15–50%** in August (Trull et al. 2008, Buesseler et al. 2007).

Physical supply: *mixed layer pump*

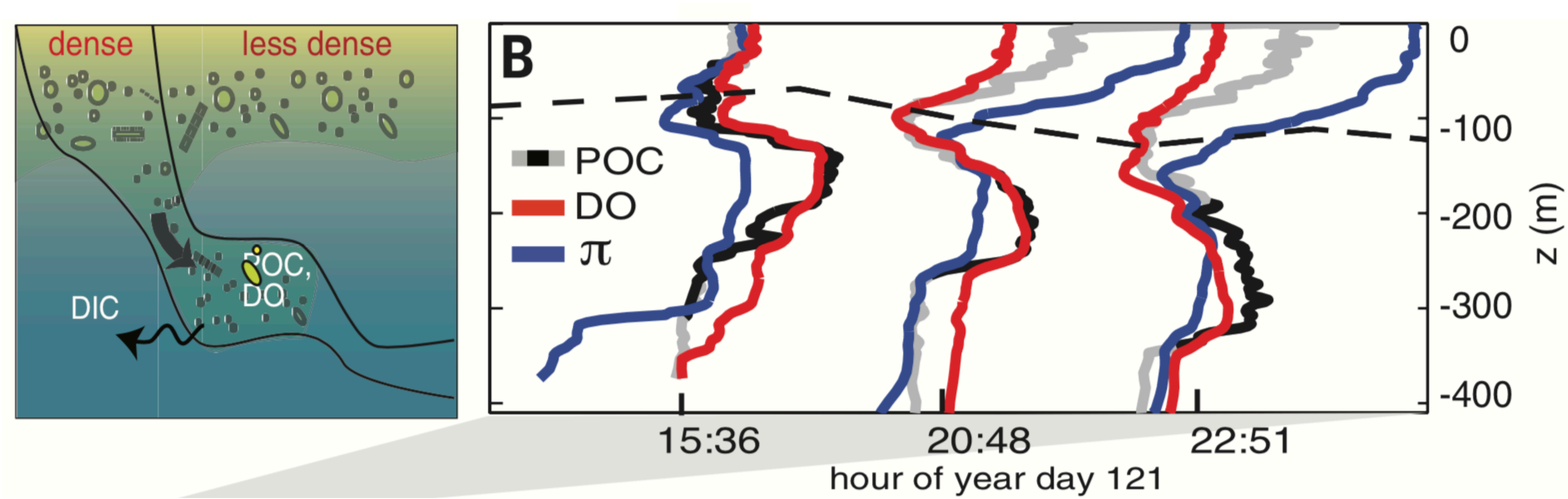
0.1–0.5 Pg C y^{-1} globally, **+5% of gravitational POC export (+23% at high latitudes)**. Intraseasonal MLD variability not accounted for.



Dall'Olmo et al. 2016 Nat. Geo. See also Gardner et al. 1995 DSR.

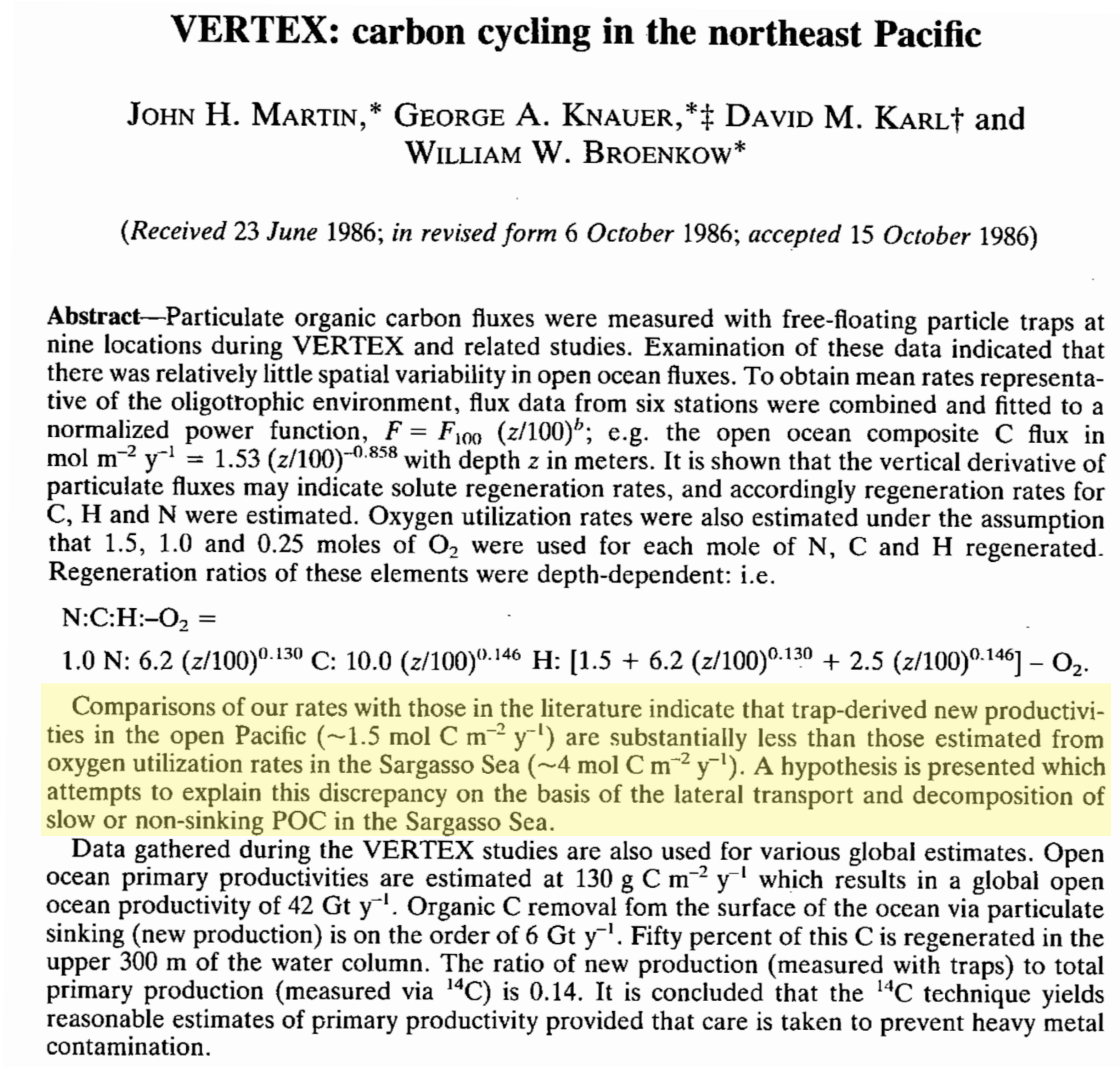
Physical supply: (sub)mesoscale *subduction pump*

- Subducting filaments along the perimeter of eddies. **Up to +100% of gravitational POC export** during restratification, especially in Southern Ocean (Omand et al. 2015 Science)



- Subduction pump observed in 1% of 4000 profiles (biogeochemical ARGO floats) in the Southern Ocean. **Up to +1% (spring) to +20% (summer) of gravitational POC export** (Llort et al. 2018 JGR)

Advection


VERTEX: carbon cycling in the northeast Pacific

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(*Received* 23 *June* 1986; *in revised form* 6 *October* 1986; *accepted* 15 *October* 1986)

Abstract—Particulate organic carbon fluxes were measured with free-floating particle traps at nine locations during VERTEX and related studies. Examination of these data indicated that there was relatively little spatial variability in open ocean fluxes. To obtain mean rates representative of the oligotrophic environment, flux data from six stations were combined and fitted to a normalized power function, $F = F_{100}\ (z/100)^b$; e.g. the open ocean composite C flux in mol $m^{-2}\ y^{-1} = 1.53\ (z/100)^{-0.858}$ with depth z in meters. It is shown that the vertical derivative of particulate fluxes may indicate solute regeneration rates, and accordingly regeneration rates for C, H and N were estimated. Oxygen utilization rates were also estimated under the assumption that 1.5, 1.0 and 0.25 moles of O_2 were used for each mole of N, C and H regenerated. Regeneration ratios of these elements were depth-dependent: i.e.

$$N{:}C{:}H{:}{-}O_2 =$$

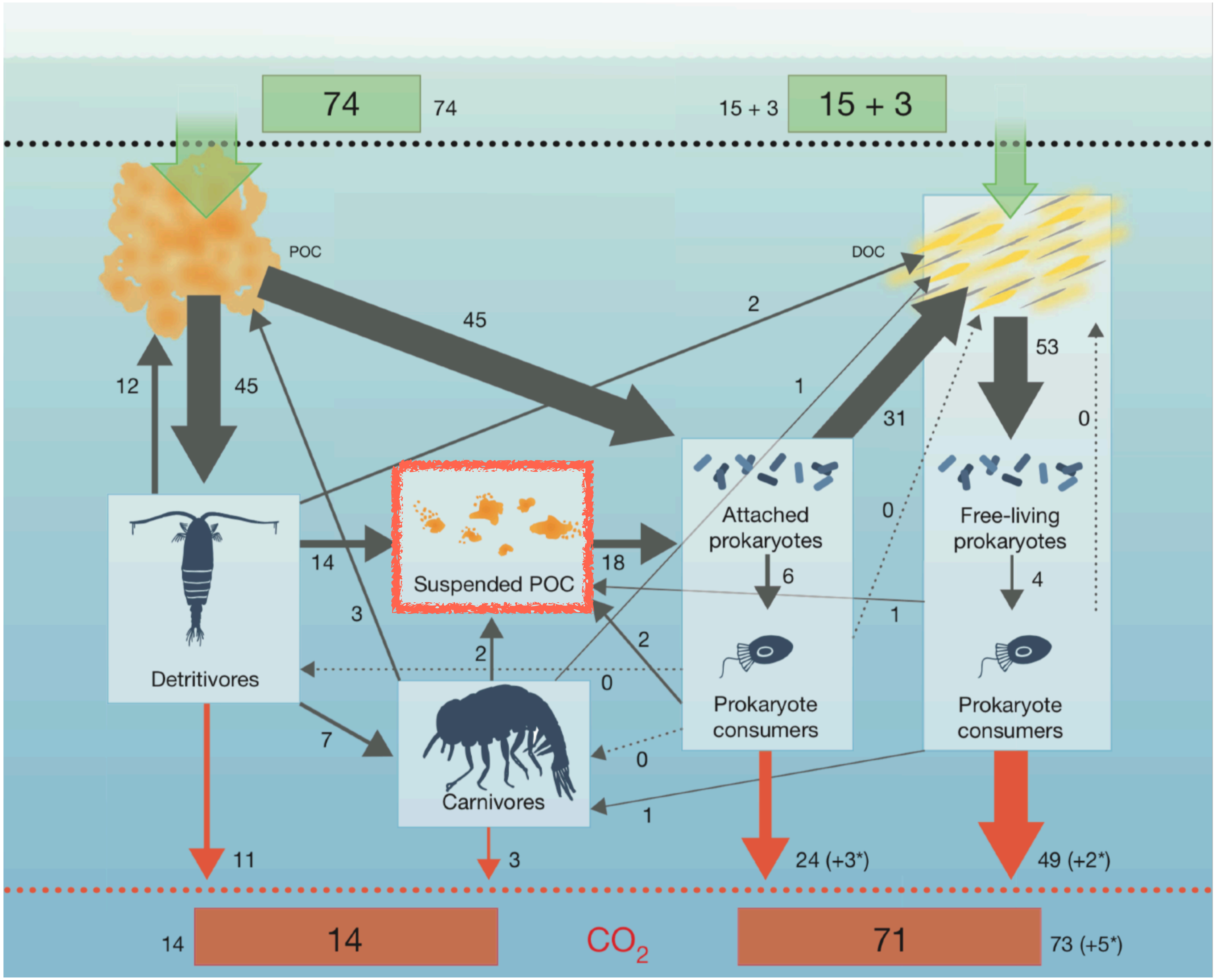
$$1.0\ N{:}\ 6.2\ (z/100)^{0.130}\ C{:}\ 10.0\ (z/100)^{0.146}\ H{:}\ [1.5 + 6.2\ (z/100)^{0.130} + 2.5\ (z/100)^{0.146}] - O_2.$$

Comparisons of our rates with those in the literature indicate that trap-derived new productivities in the open Pacific ($\sim$1.5 mol C $m^{-2}\ y^{-1}$) are substantially less than those estimated from oxygen utilization rates in the Sargasso Sea ($\sim$4 mol C $m^{-2}\ y^{-1}$). A hypothesis is presented which attempts to explain this discrepancy on the basis of the lateral transport and decomposition of slow or non-sinking POC in the Sargasso Sea.

Data gathered during the VERTEX studies are also used for various global estimates. Open ocean primary productivities are estimated at 130 g C $m^{-2}\ y^{-1}$ which results in a global open ocean productivity of 42 Gt y^{-1}. Organic C removal fom the surface of the ocean via particulate sinking (new production) is on the order of 6 Gt y^{-1}. Fifty percent of this C is regenerated in the upper 300 m of the water column. The ratio of new production (measured with traps) to total primary production (measured via ^{14}C) is 0.14. It is concluded that the ^{14}C technique yields reasonable estimates of primary productivity provided that care is taken to prevent heavy metal contamination.

Martin et al. 1987

Bio-transformation: fragmentation, sloppy feeding…

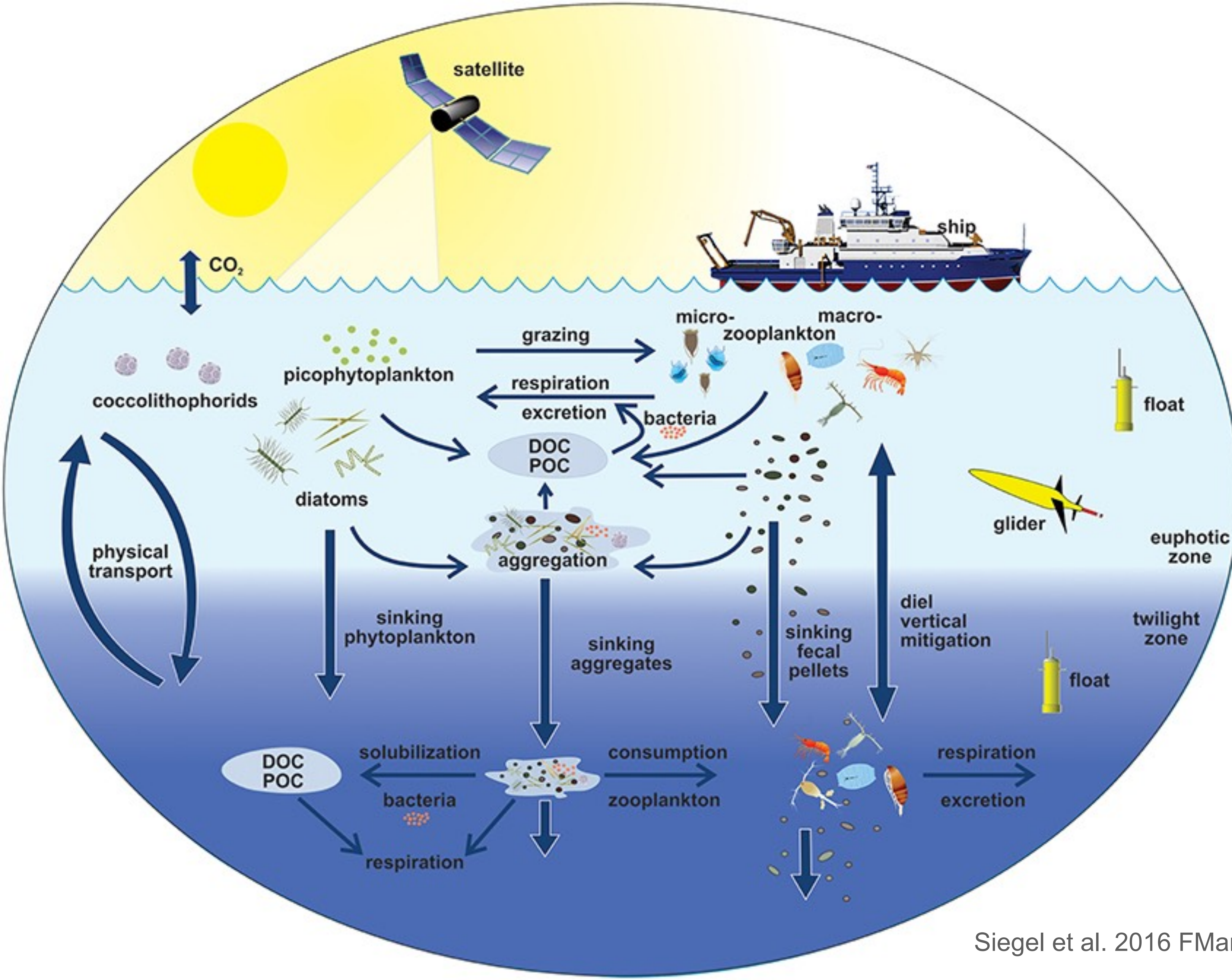


Giering et al. 2014 Nature

5/6. Tackling undersampling

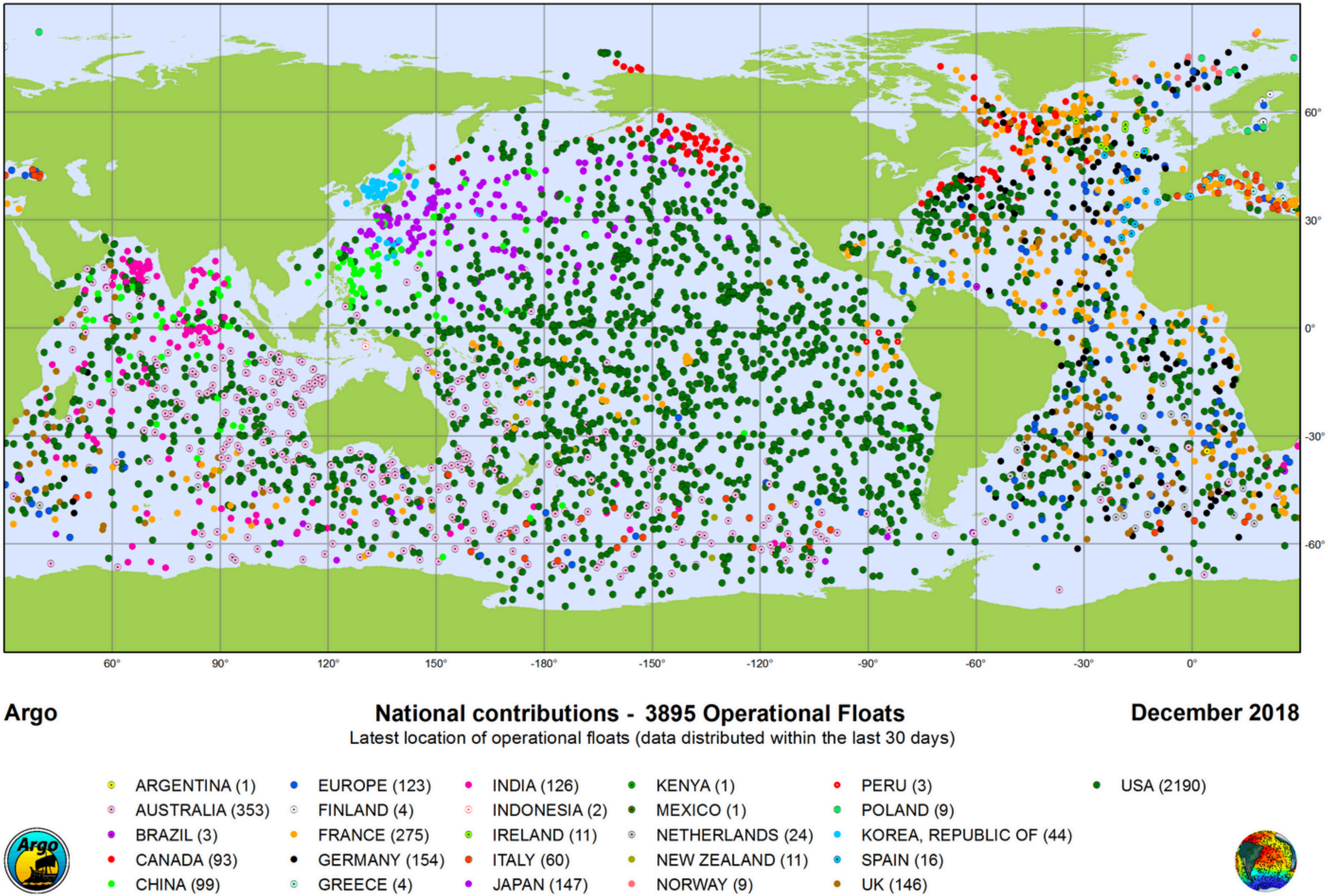
Walter Munk (2002):

“ My chief message is associated with the word SAMPLING. […] This is not an argument for more and more data, but for adequate sampling (a well-defined finite strategy). […] Most of the previous century could be called **a century of undersampling**. ”



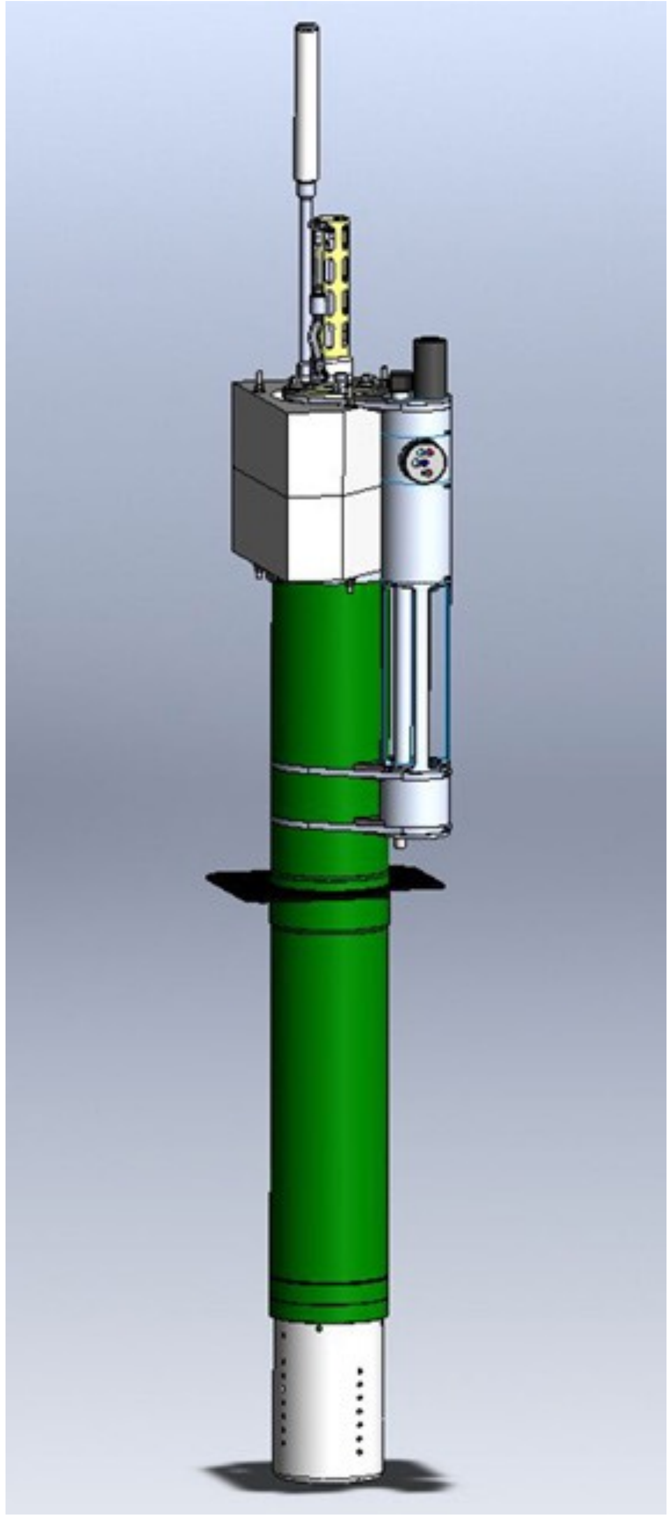
Siegel et al. 2016 FMarS

Core Argo floats: CTD



http://www.argo.net/

Biogeochemical Argo floats

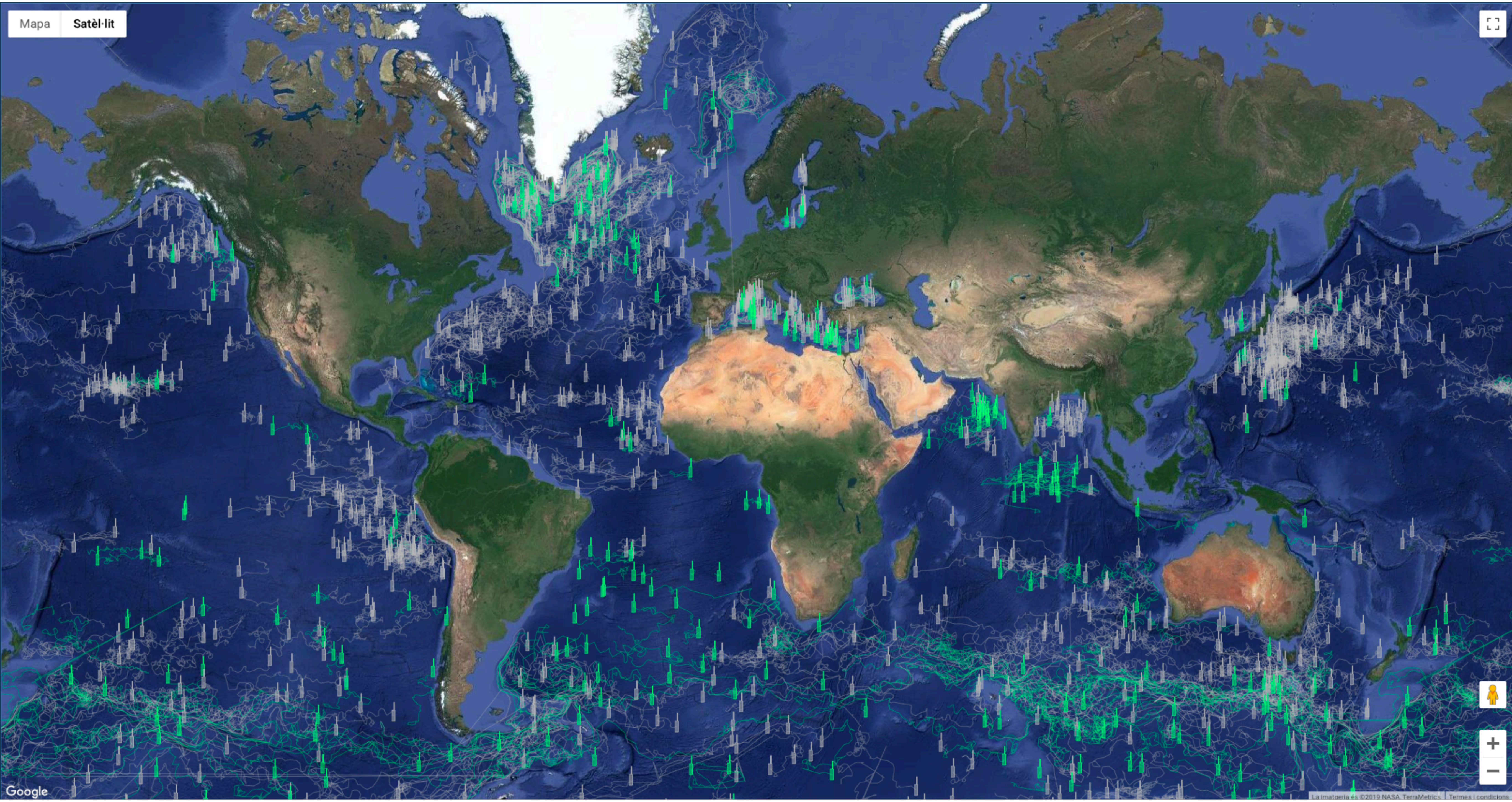


remOCEAN float

Common sensor packages:

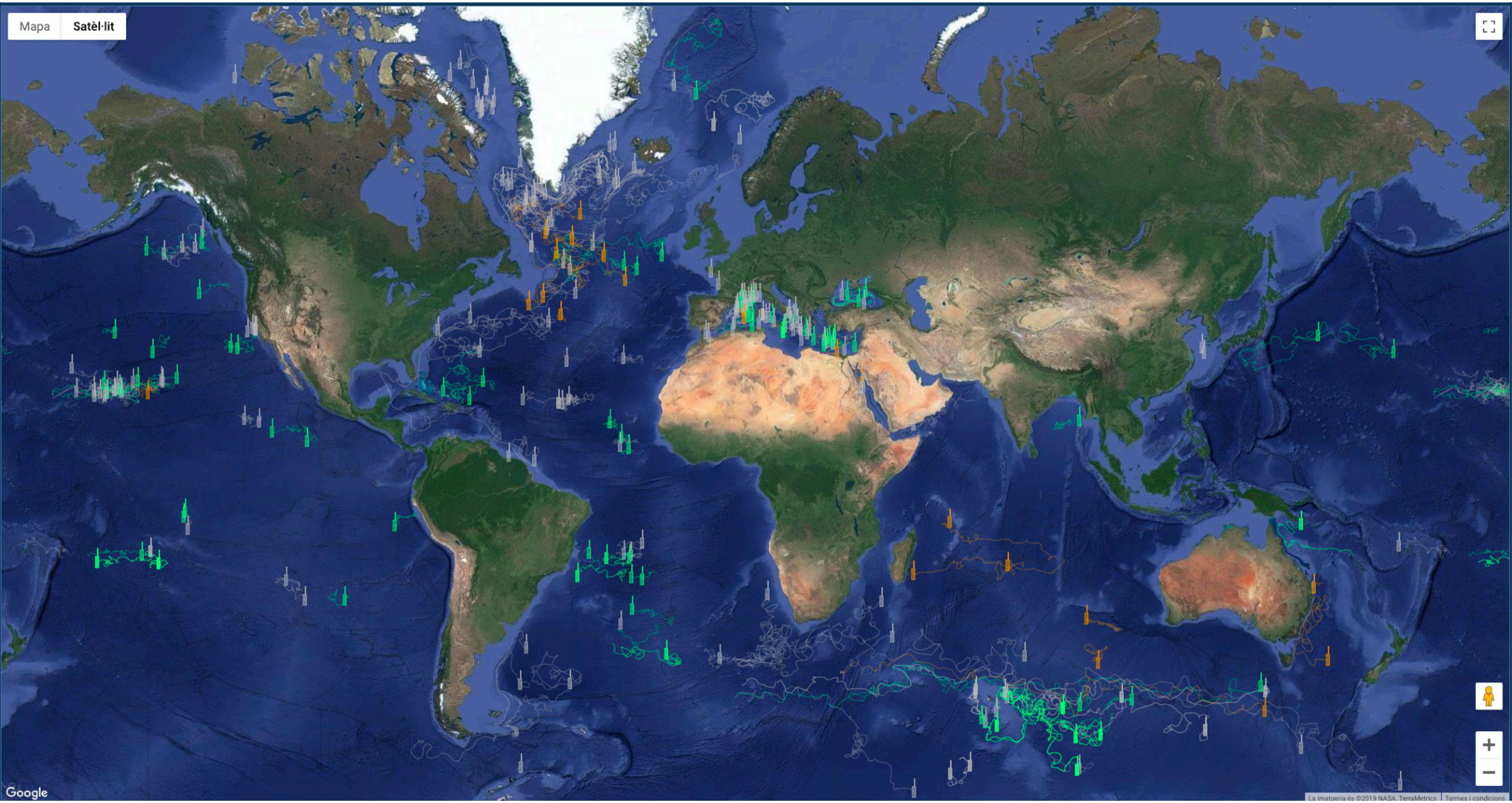
- **CTD**: salinity, temperature, depth
- **Dissolved oxygen** (optodes)
- **Bio-optics** (optodes)
  - Chlorophyll fluorescence
  - Particle backscatter ≈ POC
  - Beam atenuation ≈ POC
  - CDOM fluorescence
  - PAR
  - Spectral irradiance
- **Nitrate** (SUVA, etc…)
- More coming soon! Including particle imaging

Biogeochemical Argo floats: CTD + oxygen



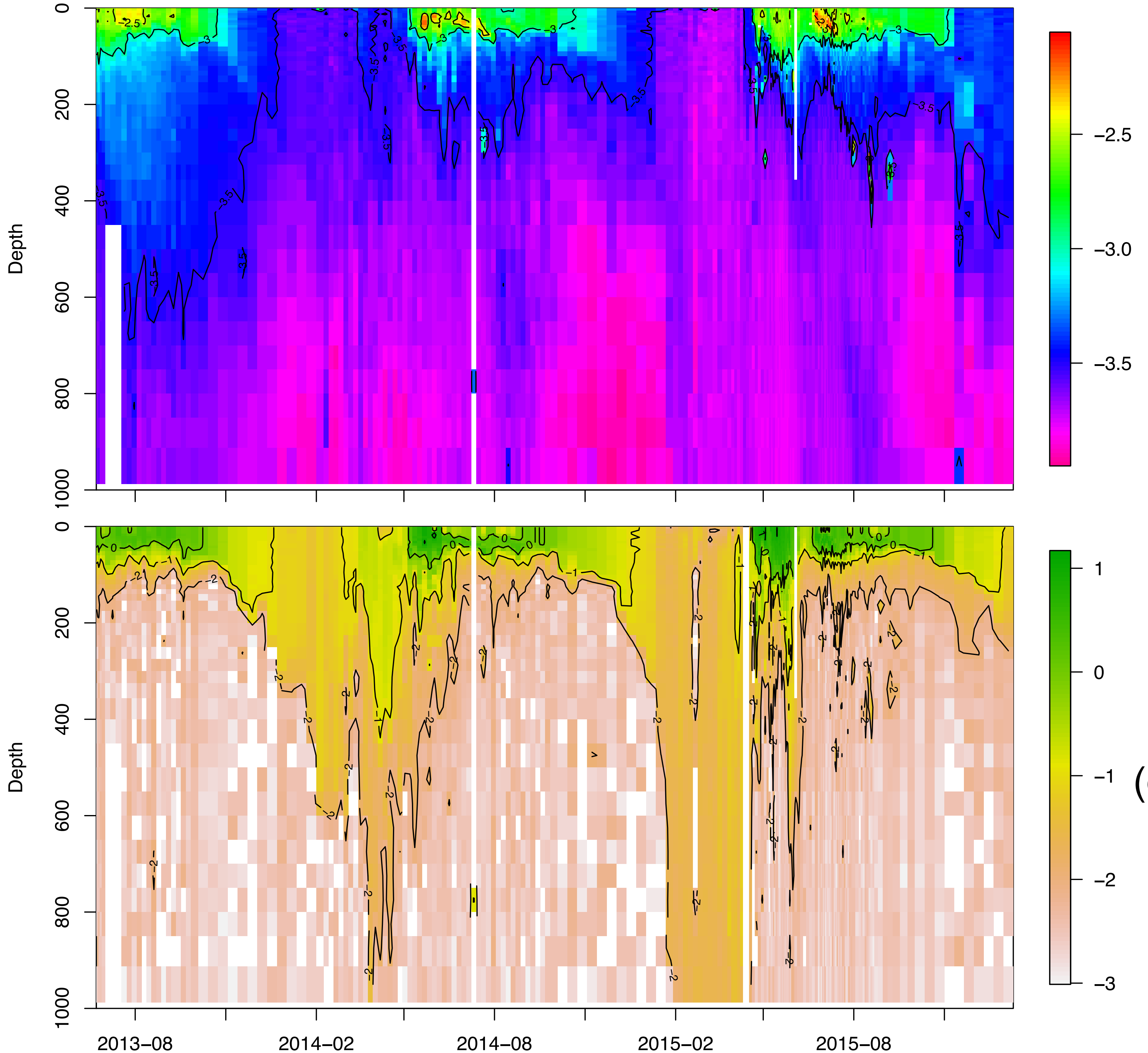
http://www.oao.obs-vlfr.fr/mapsg/en/

Biogeochemical Argo floats: CTD + bio-optics +



http://www.oao.obs-vlfr.fr/maps/en/

Small POC dynamics: a bgc-Argo time series



b_{bp700} ~ POC

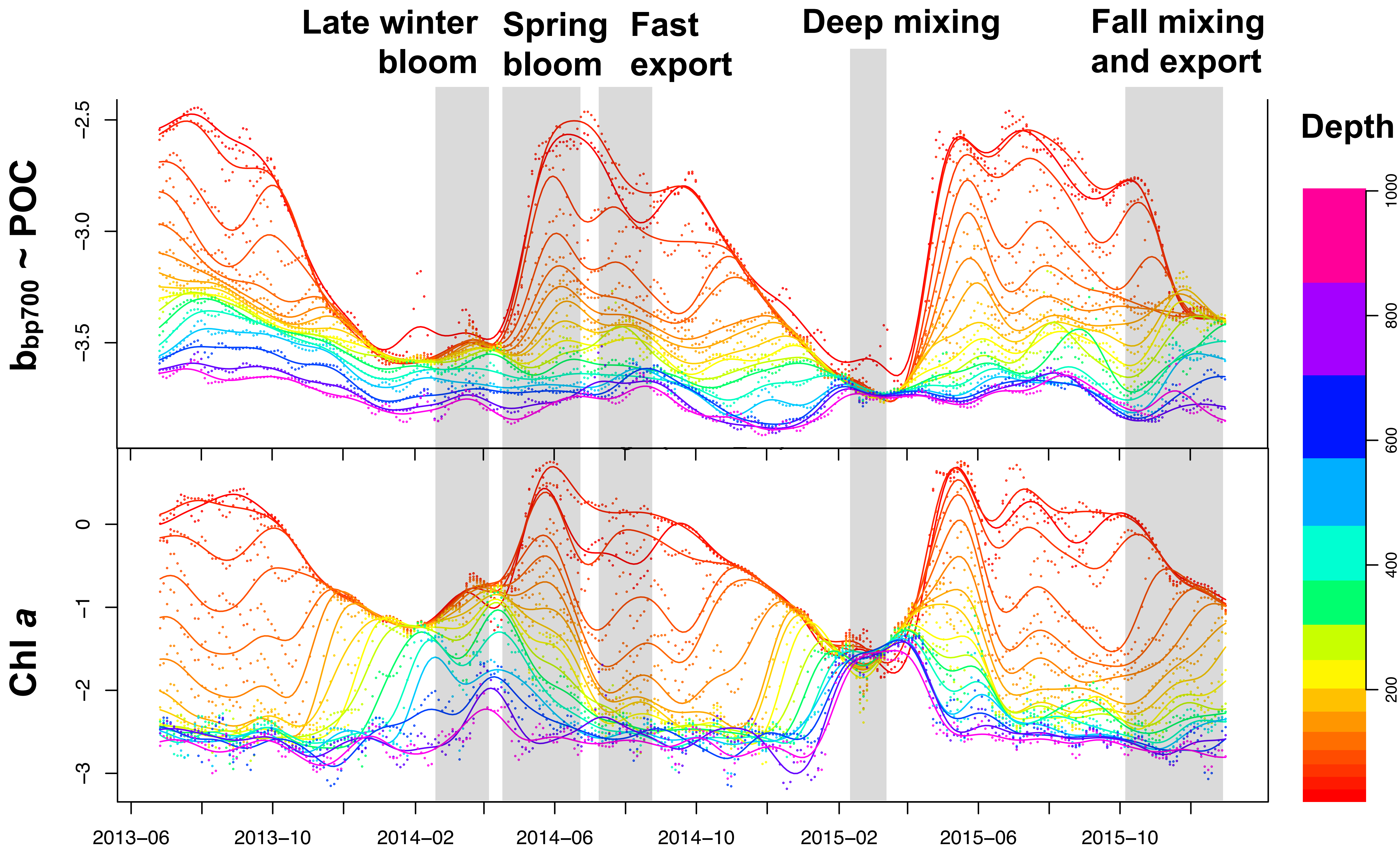
(log10 scale)

Chl a

(calibrated fluorescence, log10 scale)

Galí et al. in prep.

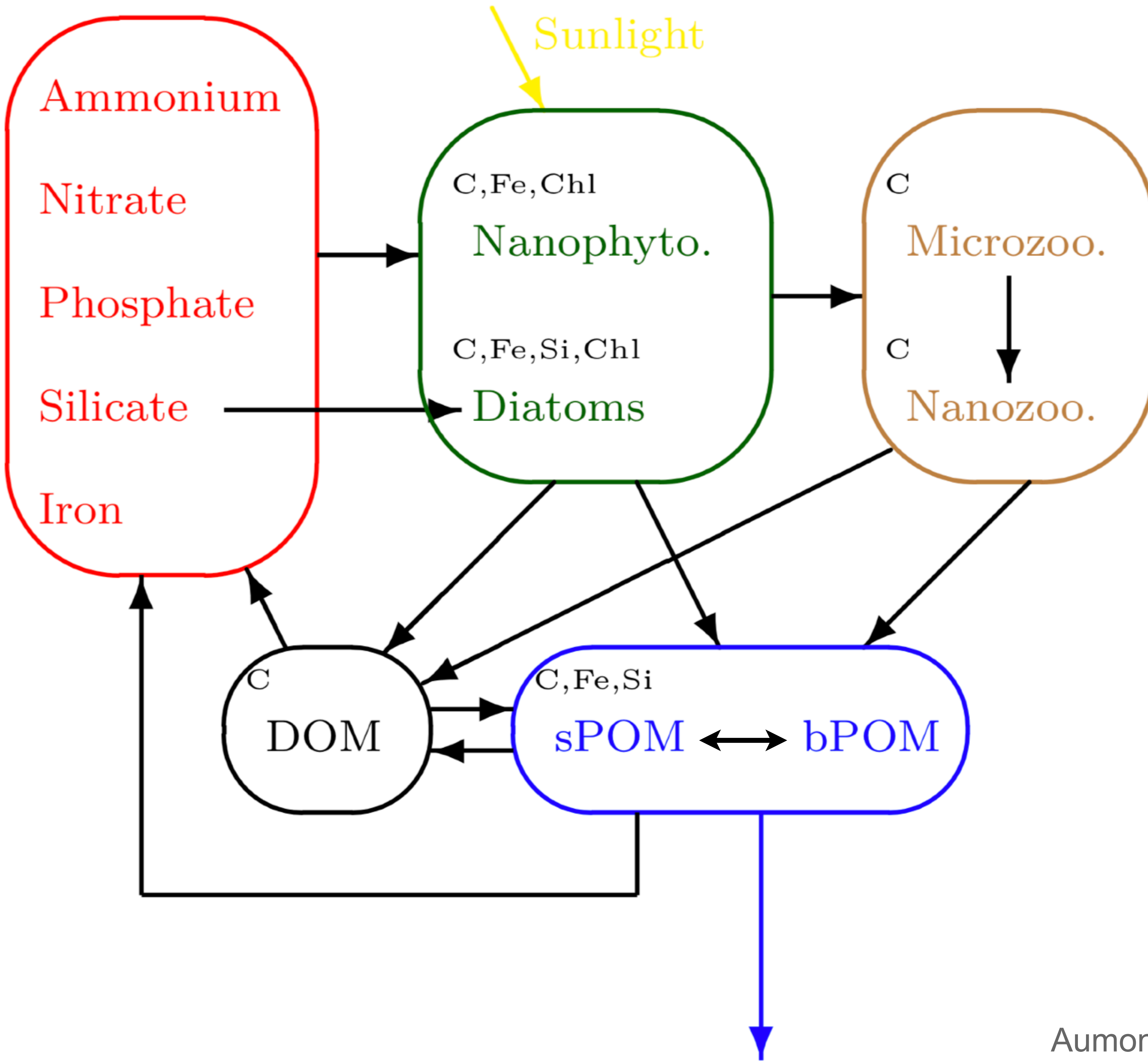
Small POC dynamics: a bgc-Argo time series



Galí et al. in prep.

6/6. Can bgc-ARGO data help constrain POC cycling in biogeochemical models?

Introducing PISCES



Aumont et al. 2017 BG

PISCES: reasonably complex?

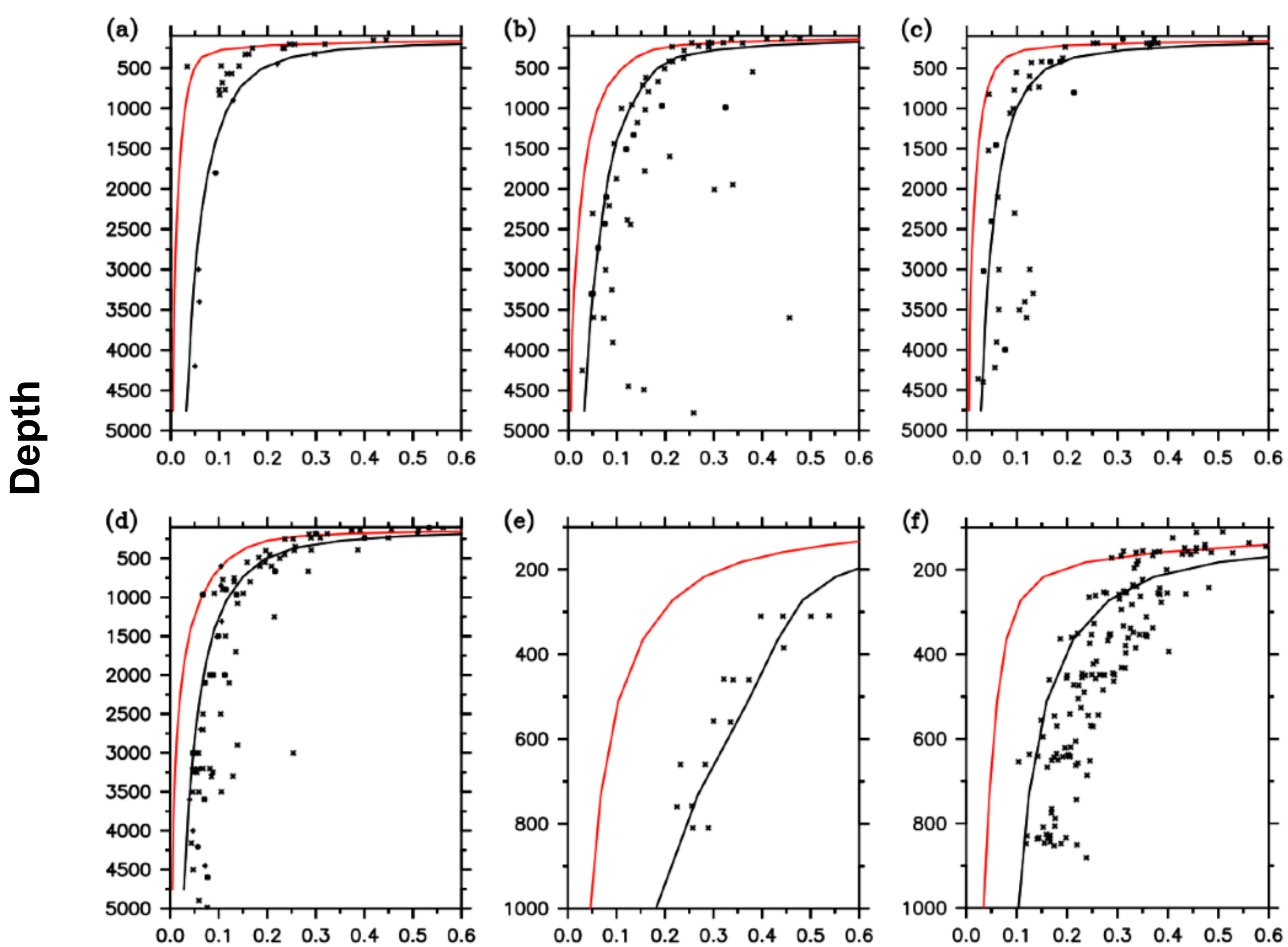
Representation of mesolepagic POC dynamics different biogeochemical models

Process	REcoM2	BEC	TOPAZ	PISCES
Phyto. agg	Yes	Yes	No	Yes
Agg. of DOC to POC	No	No	No	Yes
Grazing of particles	No	No	No	Yes
Ballasting	None	SiO_3, $CaCO_3$, dust	SiO_3, calcite, aragonite, dust	None
Different particle sizes	No	No	No	large and small
Remin. rate (d^{-1})	0.06–0.32 (at 0–30 °C)	implicit	0.53	0.025–0.24 (at 0–30 °C)
Sinking Speed ($m\,d^{-1}$)	20–120	implicit	100	2 (small POC), 30–200 (large POC)
Remin. length scale (m)	175–590 (at 0–30 °C)	200	188	8.3–80 (small POC at 30–0 °C) 205–2600 (large POC at 30–0 °C)

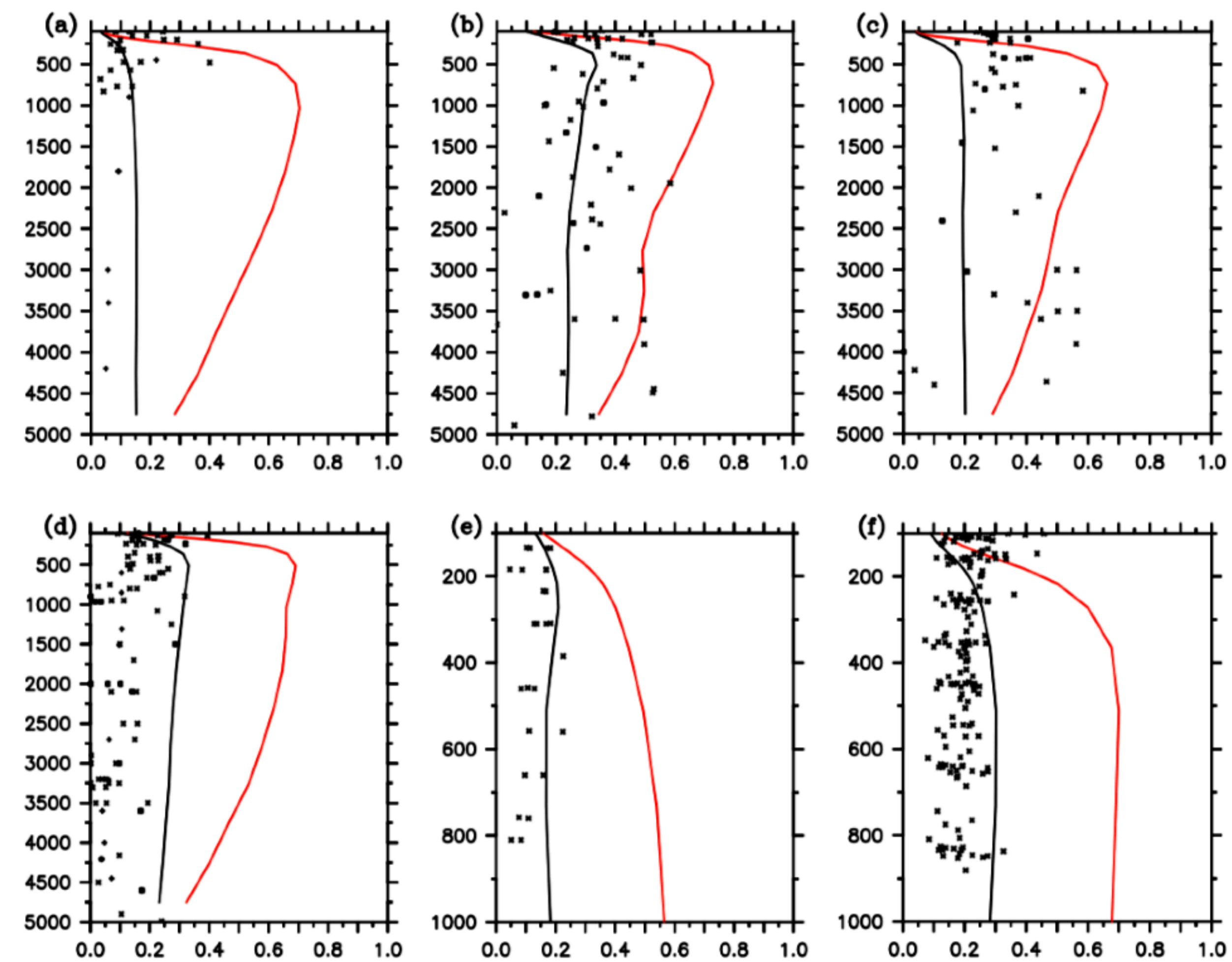
Laufkötter et al. 2016 BG

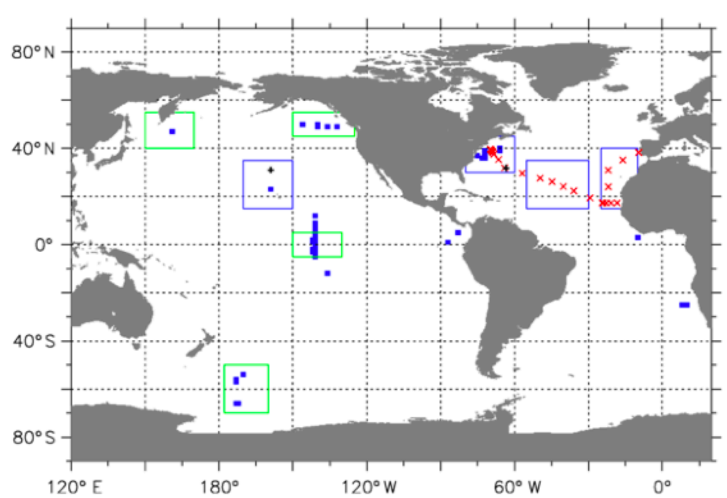
Impact of variable POC reactivity in PISCES

Total POC profiles



Large/Total POC





— Fixed reactivity (=lability)

— Reactivity continuum

* Observations

Aumont et al. 2017 BG

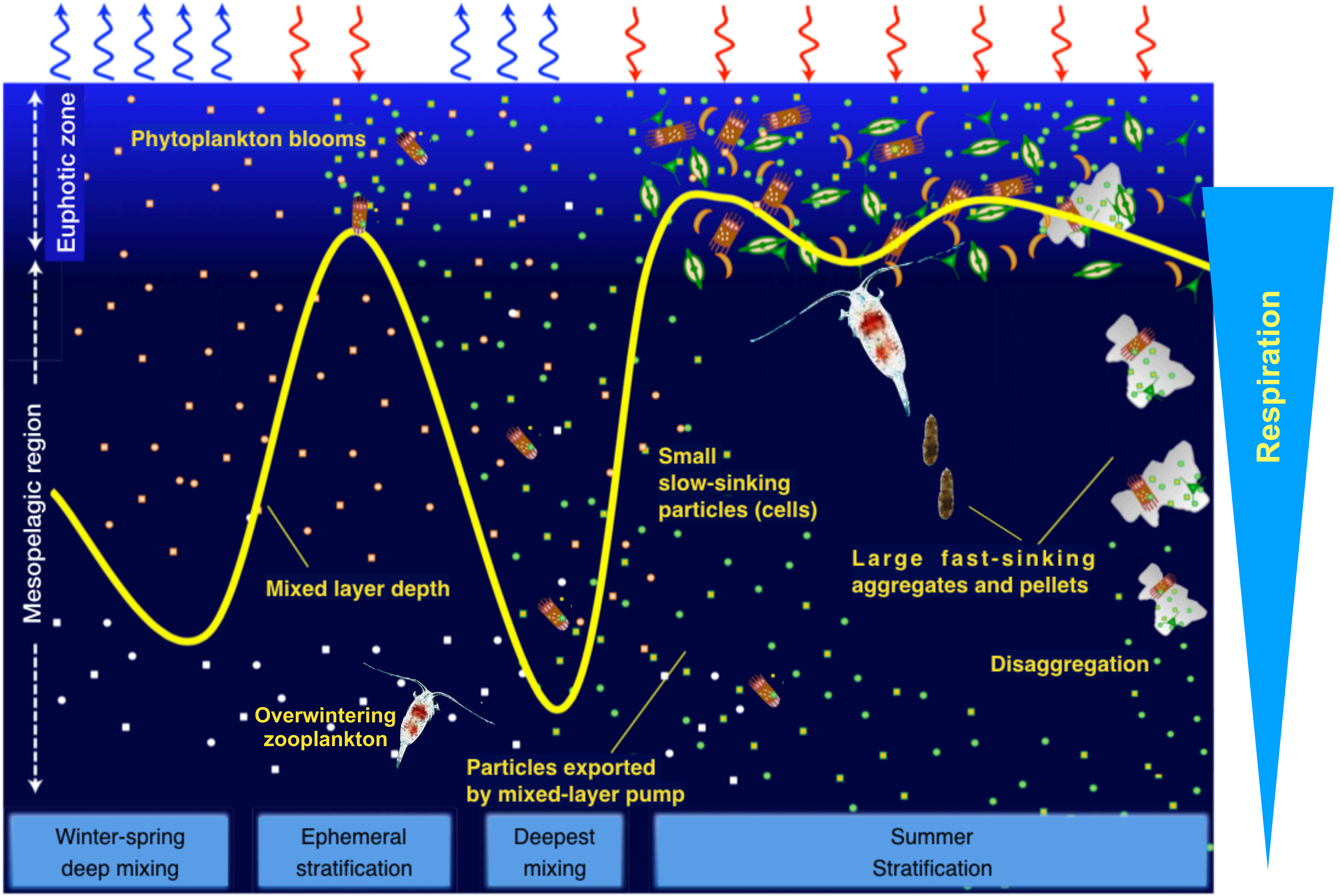
Conclusions

- Uncertainty in mesopelagic POC transformations has broad climatic impacts.
- Mesopelagic carbon budgets cannot be closed due to measurement sparseness, uncertainties and oversimplifying assumptions.
- Supply of small and slow-sinking particles, and related ecosystem metabolism, have been historically overlooked.
- High-resolution observations of epi- and mesopelagic ecosystems, combined with models, can help understand small POC transformations.

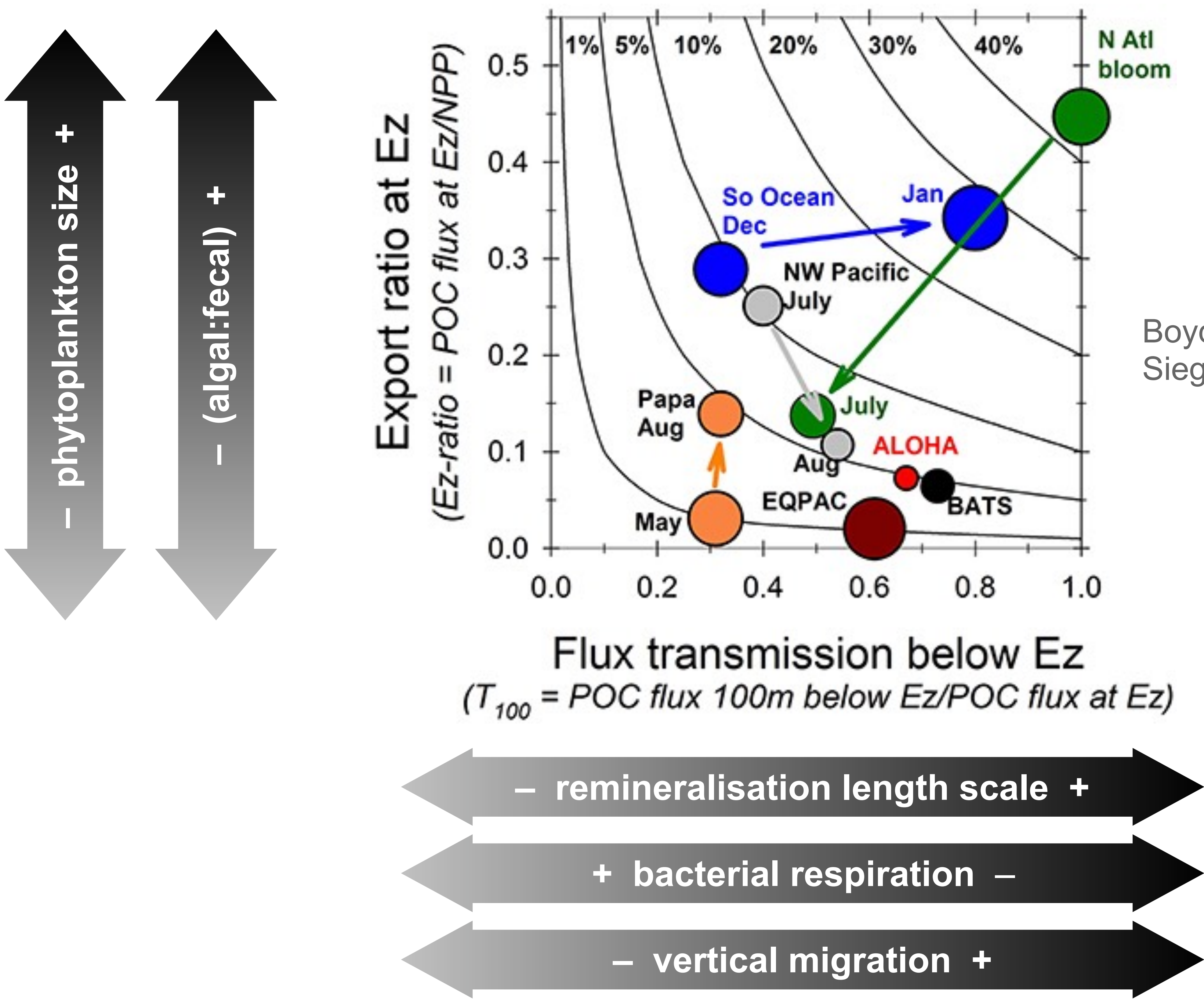
Moltes gràcies!

Backup slides

Rethinking small POC cycling

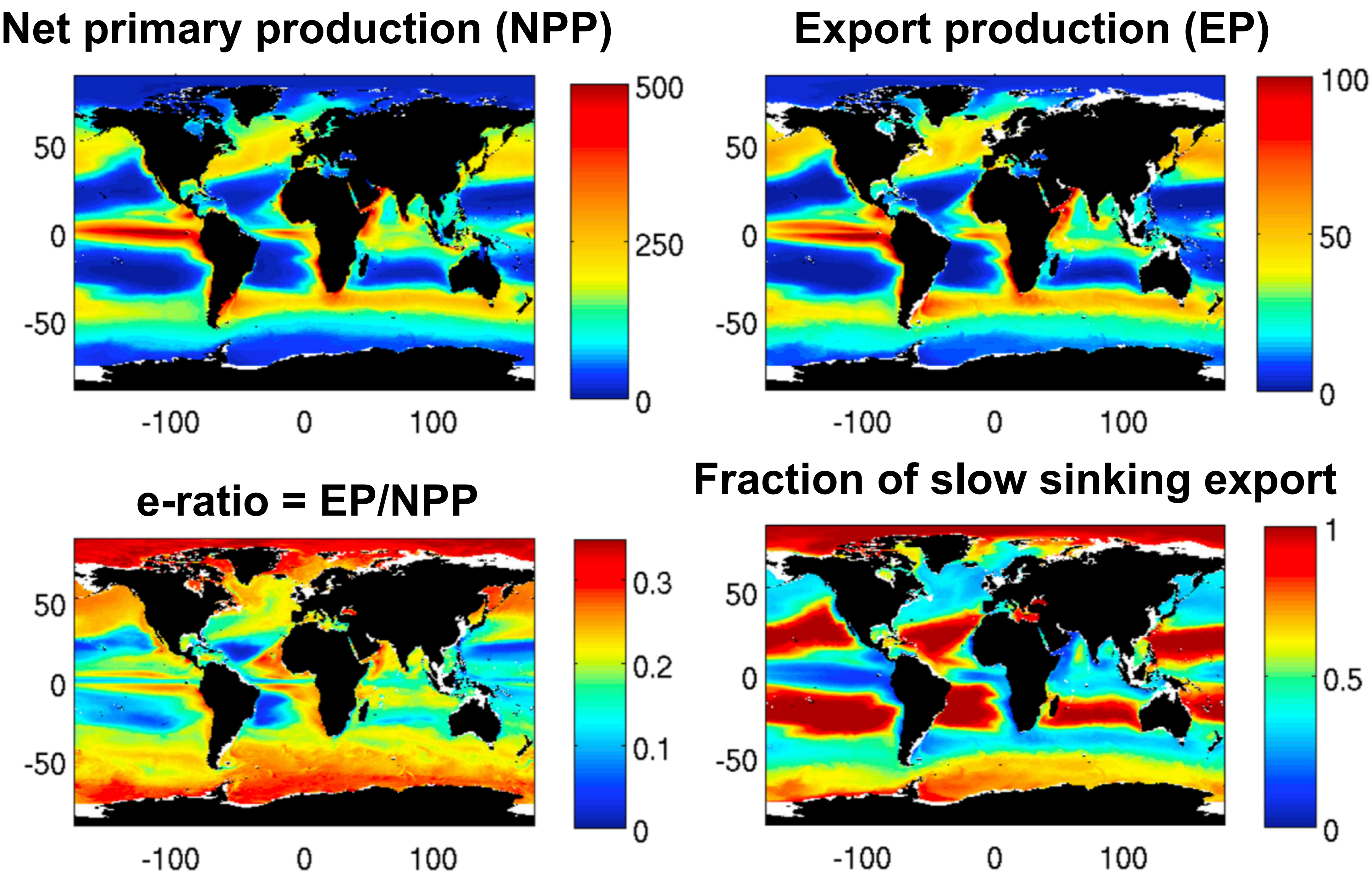


The upper mesopelagic as a key "POC filter"



Boyd & Buesseler 2009 L&O
Siegel et al. 2016 FMS

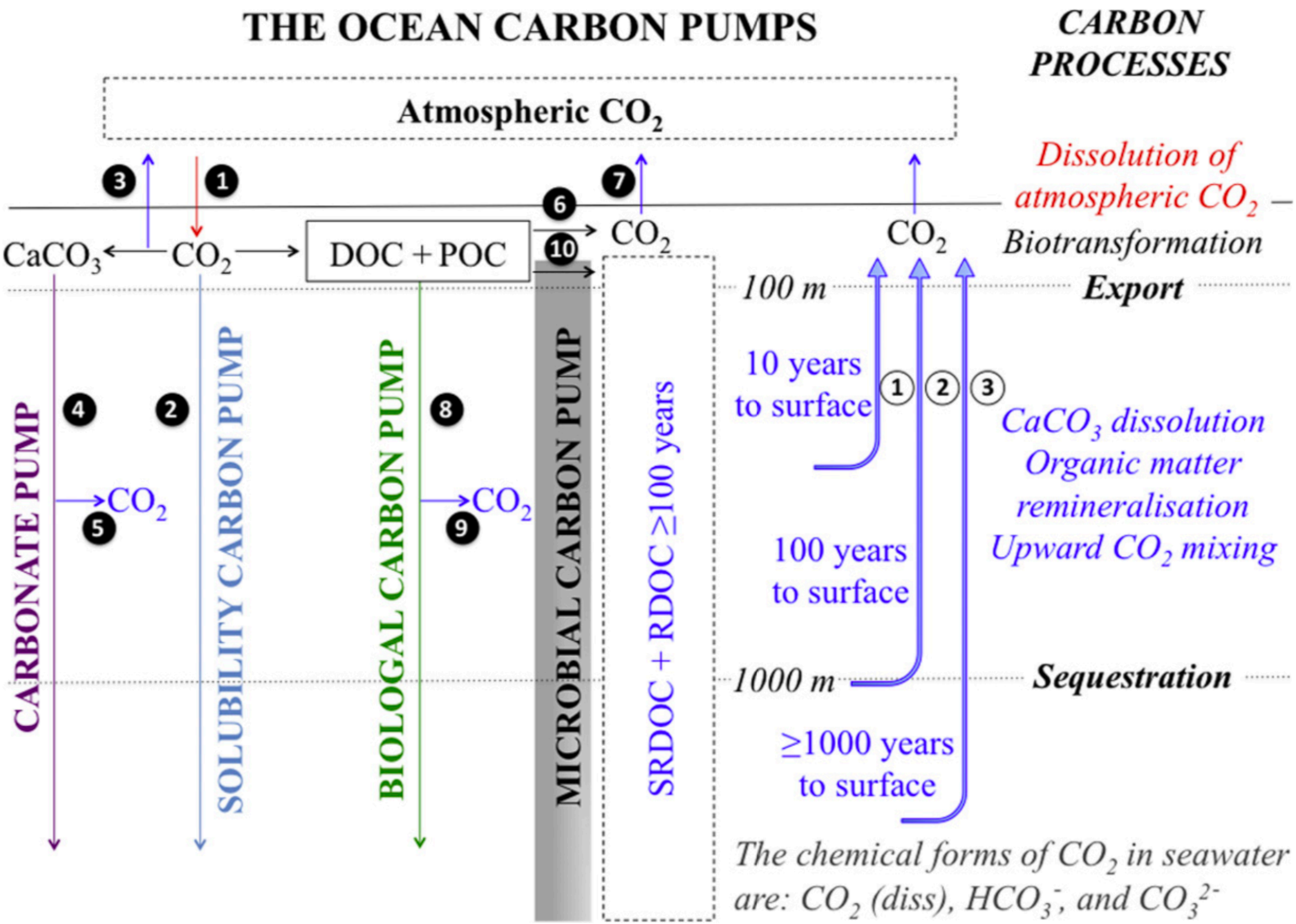
Global patterns of primary and export production



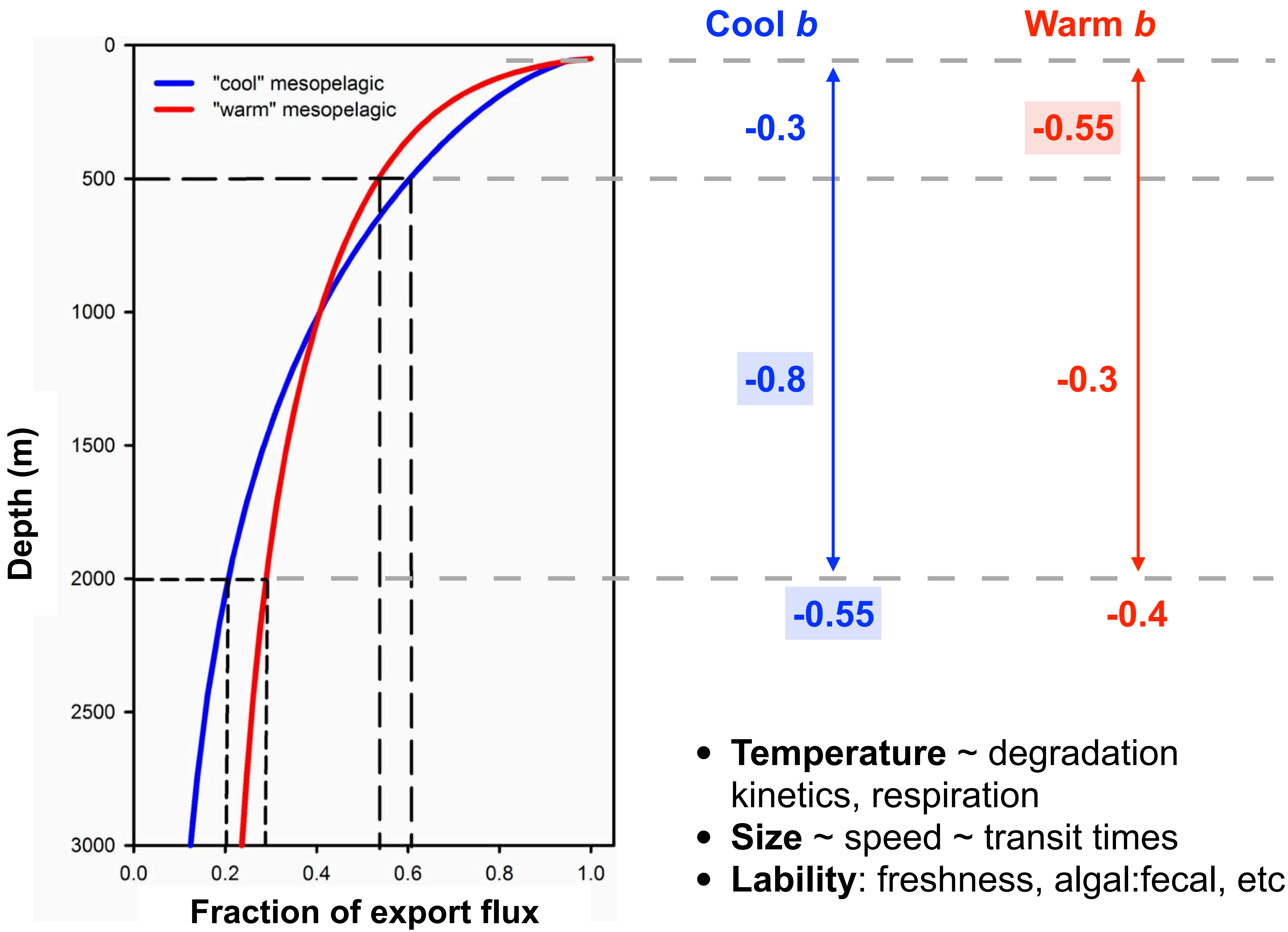
NEMO-MEDUSA model estimates

Henson et al. 2015 GBC

Carbon pumps



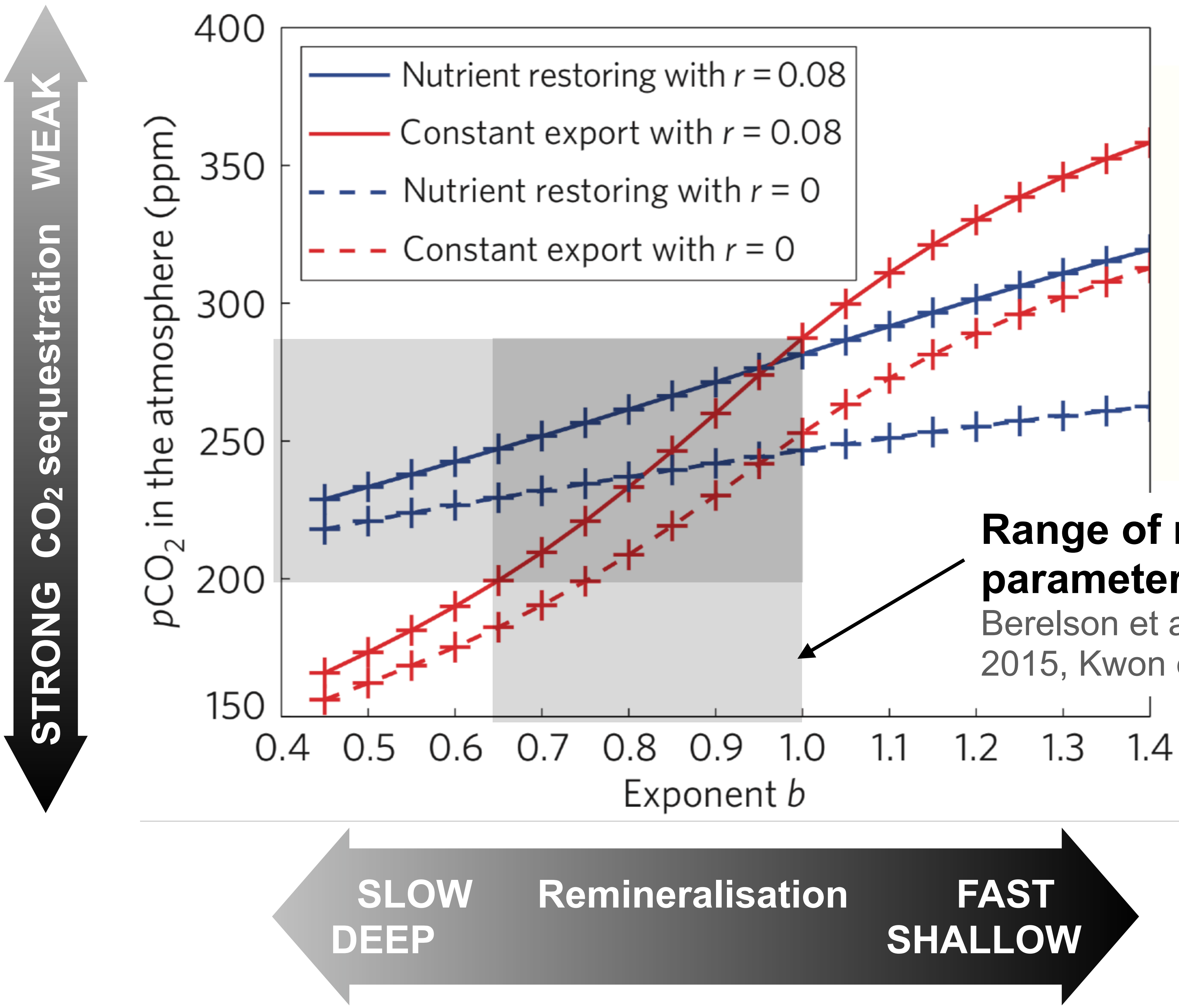
What controls mesopelagic POC processing?



- **Temperature** ~ degradation kinetics, respiration
- **Size** ~ speed ~ transit times
- **Lability**: freshness, algal:fecal, etc.

Marsay et al. 2015 PNAS

Climate sensitivity to mesopelagic POC processing



Range of remineralisation parameter *b* (Martin et al. 1987, Berelson et al. 2002, Guidi et al. 2015, Kwon et al. 2008)

Kwon et al. 2009 Nat. Geo.