Observational approaches to the biologically driven carbon pumps (BCP)

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Workshop on: "Effects of climate change on the biologically-driven ocean carbon pumps"
March 21, 2015
Santos, Brazil

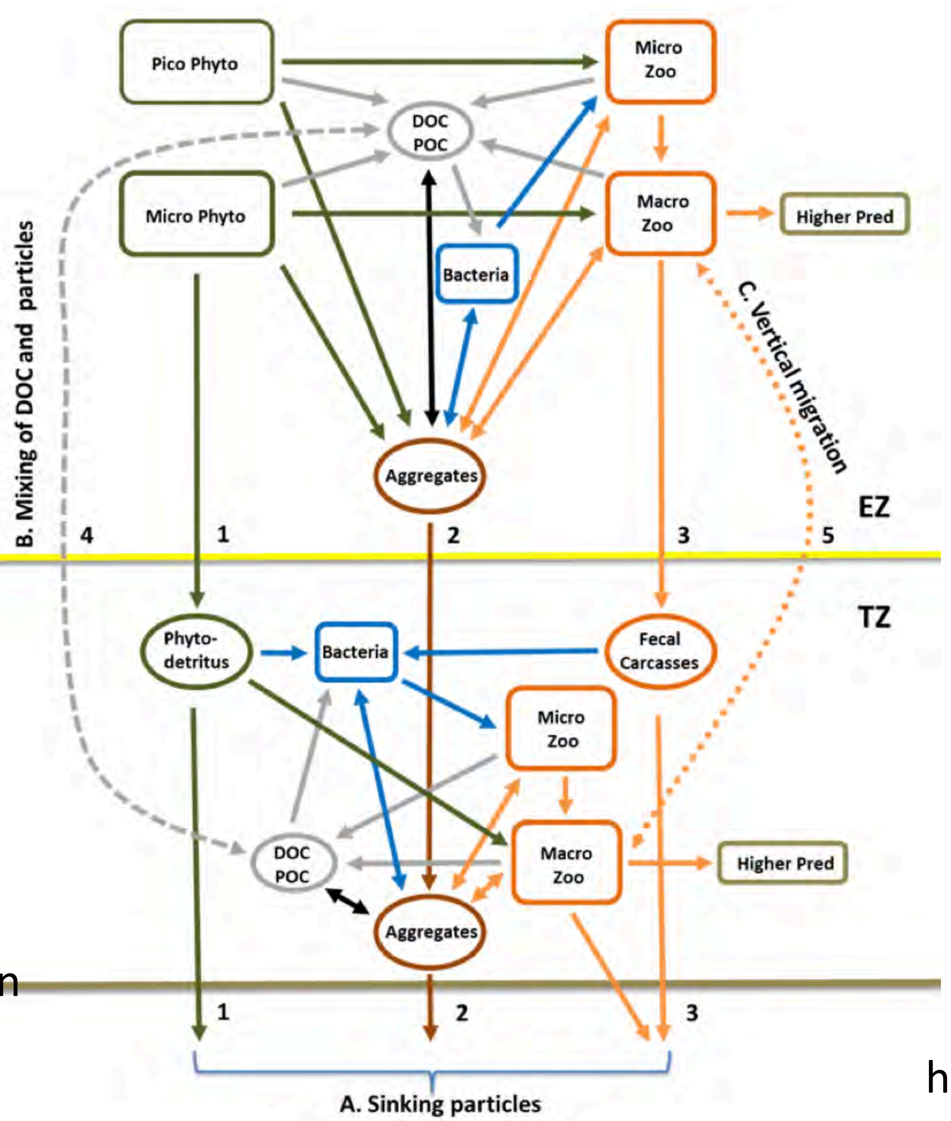
The EXPORTS "wiring diagram" of the BCP

Particle Export Efficiency = PE_{eff} = EF/ PP

Export Flux

Transfer Efficiency = TE_{eff} = SF/ EF

Sequestration Flux



- Squares represent living biota (phytoplankton, zooplankton and bacteria)
- Circles represent stocks of non-living matter (POC, aggregates, fecal pellets, etc.)
- Arrows indicate carbon flow and key processes

- Can approach this by measuring all stocks and all arrows

http://exports.oceancolor.ucsb.edu

A particle-centric view of the biological carbon pump (with apologies to the microbial C pumpers out there)

- Particle dynamics (aggregation, disaggregation, remineralization, sinking) determine the **strength** and **transfer efficiency** of the biological pump
- Recall that Stokes sinking is *linearly* proportional to particle excess density, and proportional to the *square* of particle diameter
- Greater aggregation and sinking should promote stronger and more efficient BCP
- Greater disaggregation and remineralization should promote weaker and less efficient BCP

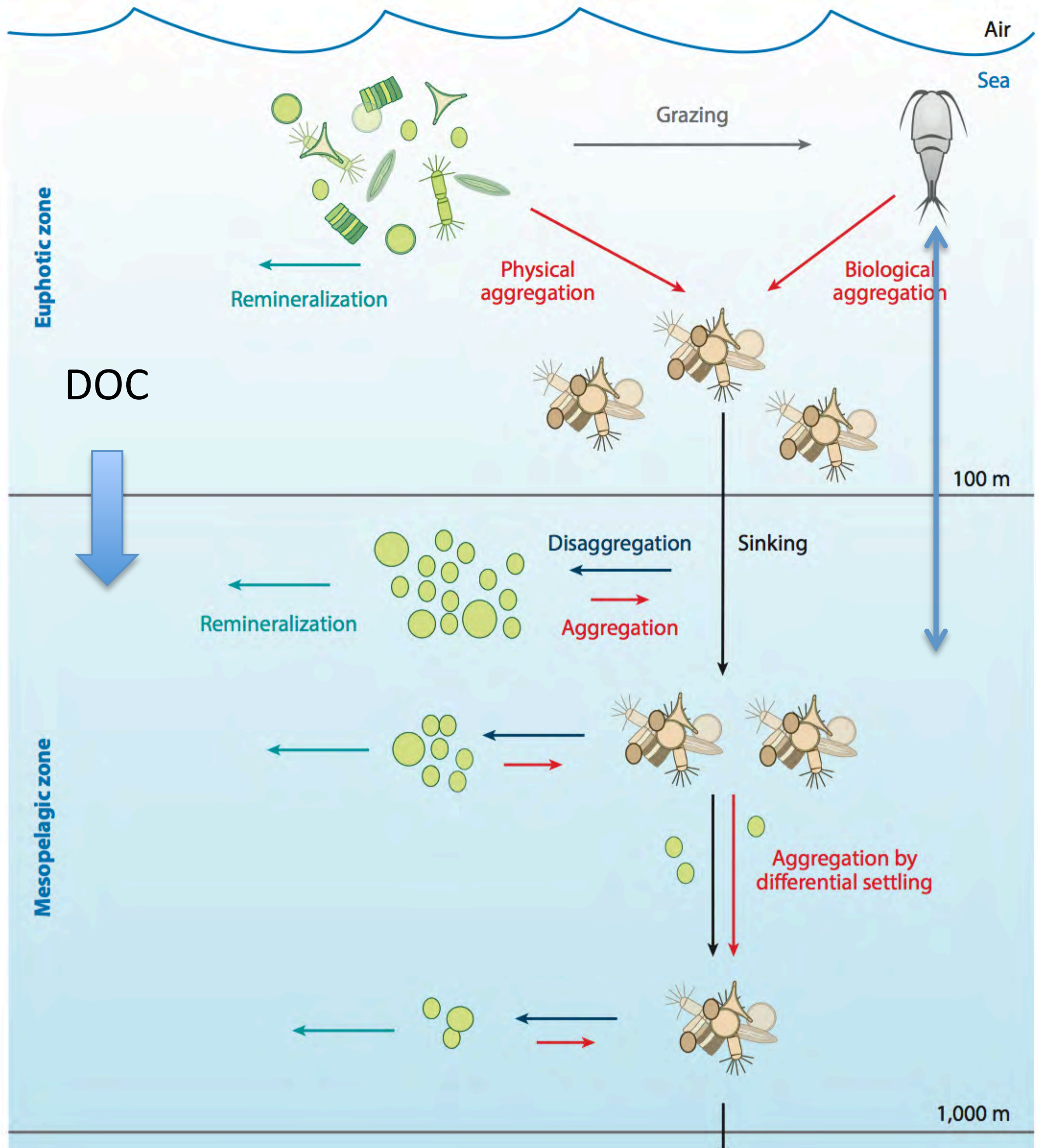


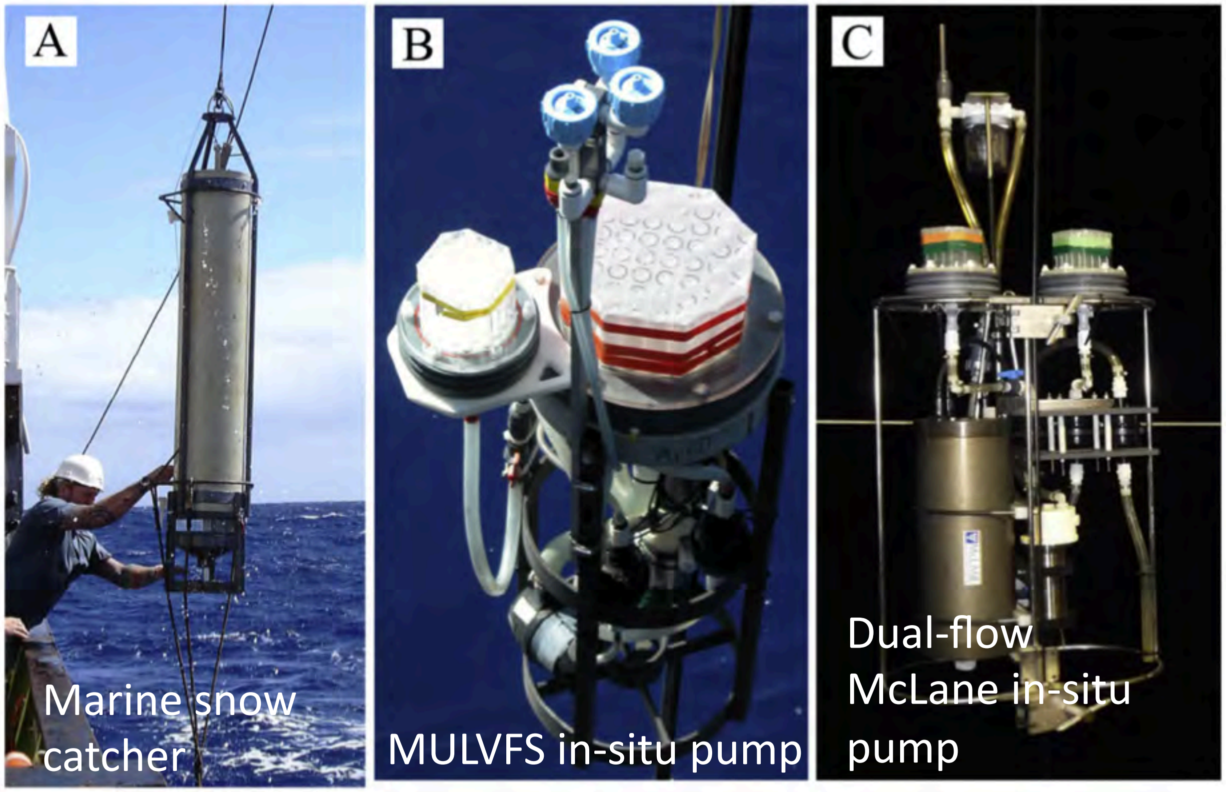
Figure from Lam and Marchal 2015 Ann Rev Mar Sci

To understand particle dynamics, we collect or image particles

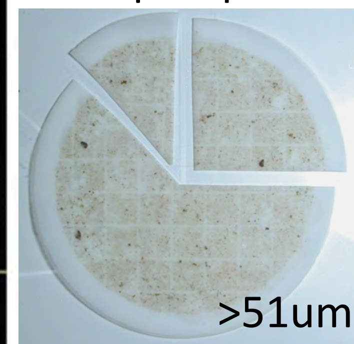
Method	Pro	Con
Collecting	-Chemical measurements can be made: composition (POC, mineral content), biomarkers as indicators of fecal vs fresh algal matter, radionuclides (Th)	-Size distribution and morphologies of particles possible but very difficult (eg. Bishop et al. 1986 Prog Ocean; Dagg et al. 2014 DSR) -limited spatial and temporal resolution possible
Imaging	-Particle size distribution can be determined -can potentially go onto autonomous platform and sample at high temporal and spatial resolution!	No physical sample to measure, so particle composition (POC and mineral content) must be inferred optically

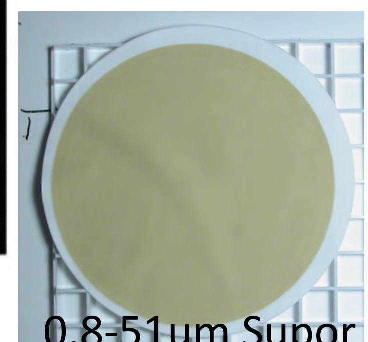
Collecting suspended particles

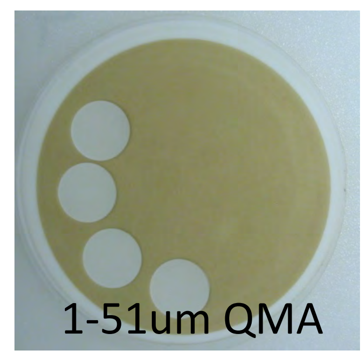
A.M.P. McDonnell et al./Progress in Oceanography xxx (2015) xxx–xxx

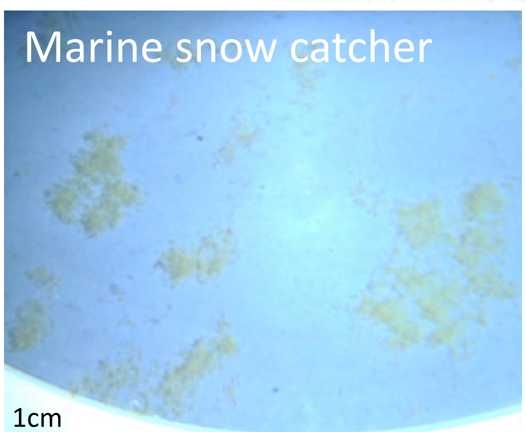


Dual-flow McLane in-situ pump

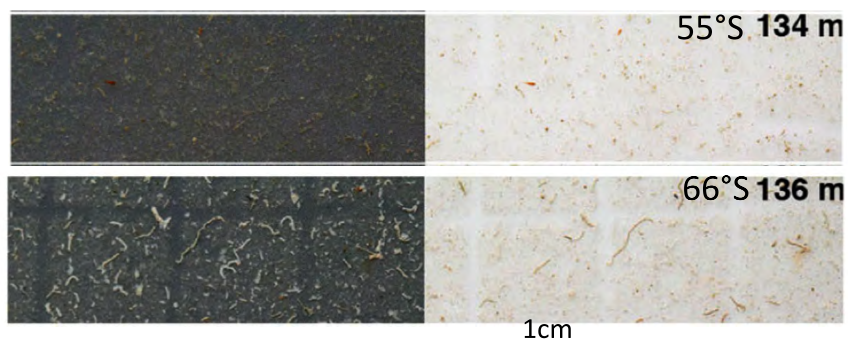






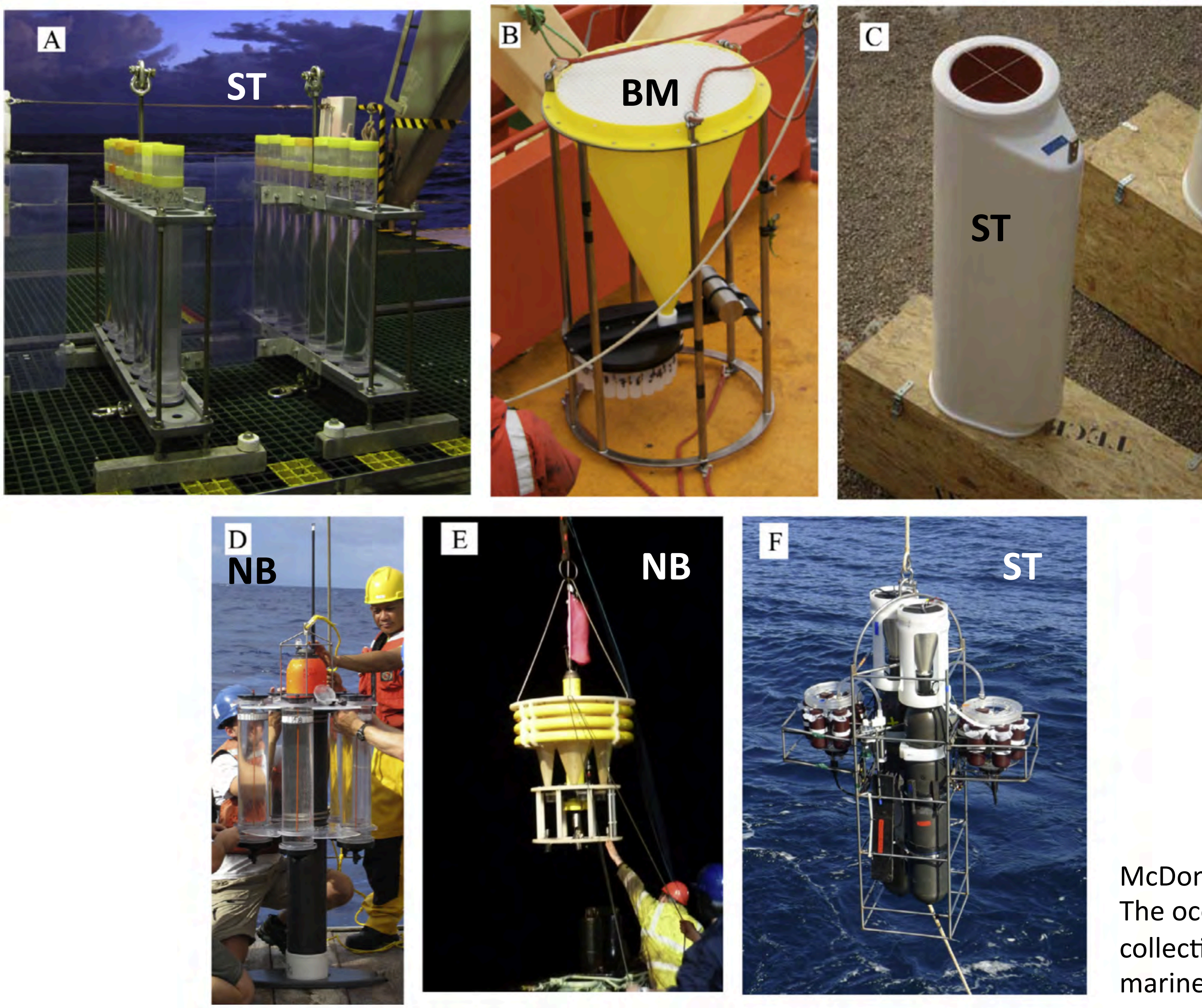


MULVFS in-situ pump >51um



Collecting sinking particles

A.M.P. McDonnell et al. / Progress in Oceanography xxx (2015) xxx–xxx



Bottom moored (BM)

B. McLane time-series trap

Surface Tethered (ST)

A. PITS trap
C. Technicap PPS time-series trap
F. Optical Sediment Recorder

Neutrally Buoyant (NB)

D. NBST
E. PELAGRA

McDonnell et al. 2015. Prog. Oceanogr. The oceanographic toolbox for the collection of sinking and suspended marine particles.

Particle dynamics from particle geochemistry

- Undertanding the geochemistry of the sinking and suspended particle pools can give us qualitative (eg. biomarkers) and quantitative (eg. thorium isotopes) information about the degree of exchange between the two pools (and thus about the workings of the BCP)
- Two examples:
  - Organic biomarkers
  - Thorium isotopes

Geochemically linking suspended and sinking particles: organic biomarkers

- Spring: Suspended and sinking particles more different—less exchange; more fecal pellets in sinking particles; suspended particles have biomarkers of fresh pigment material: arrived through disaggregation of rare, rapidly sinking phytoplankton aggregates
- Summer: suspended and sinking particles more similar, and show a shift from zooplankton-processed to microbially processed material.

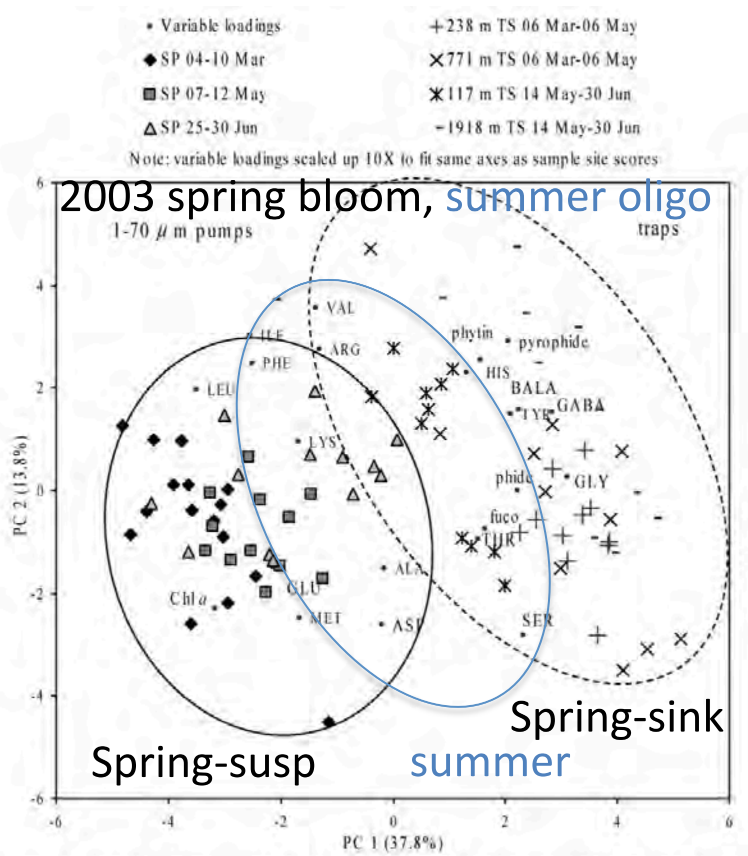


Fig. 7. Principal component analysis on all 2003 pump and TS trap amino acid and pigment data. Variable loadings are scaled up 10× and plotted on the same axes as sample site scores.

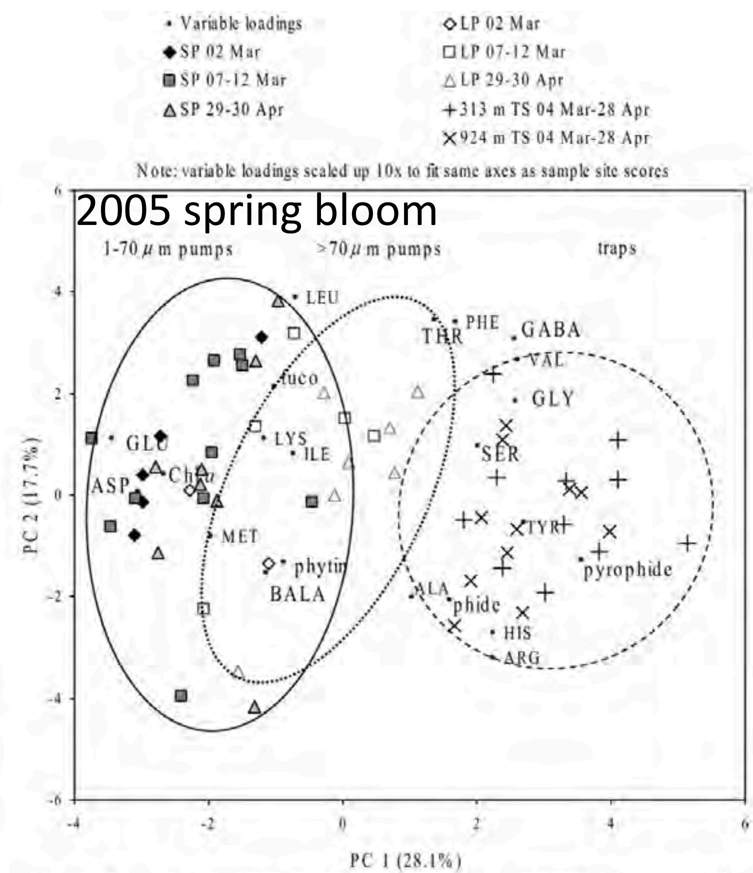
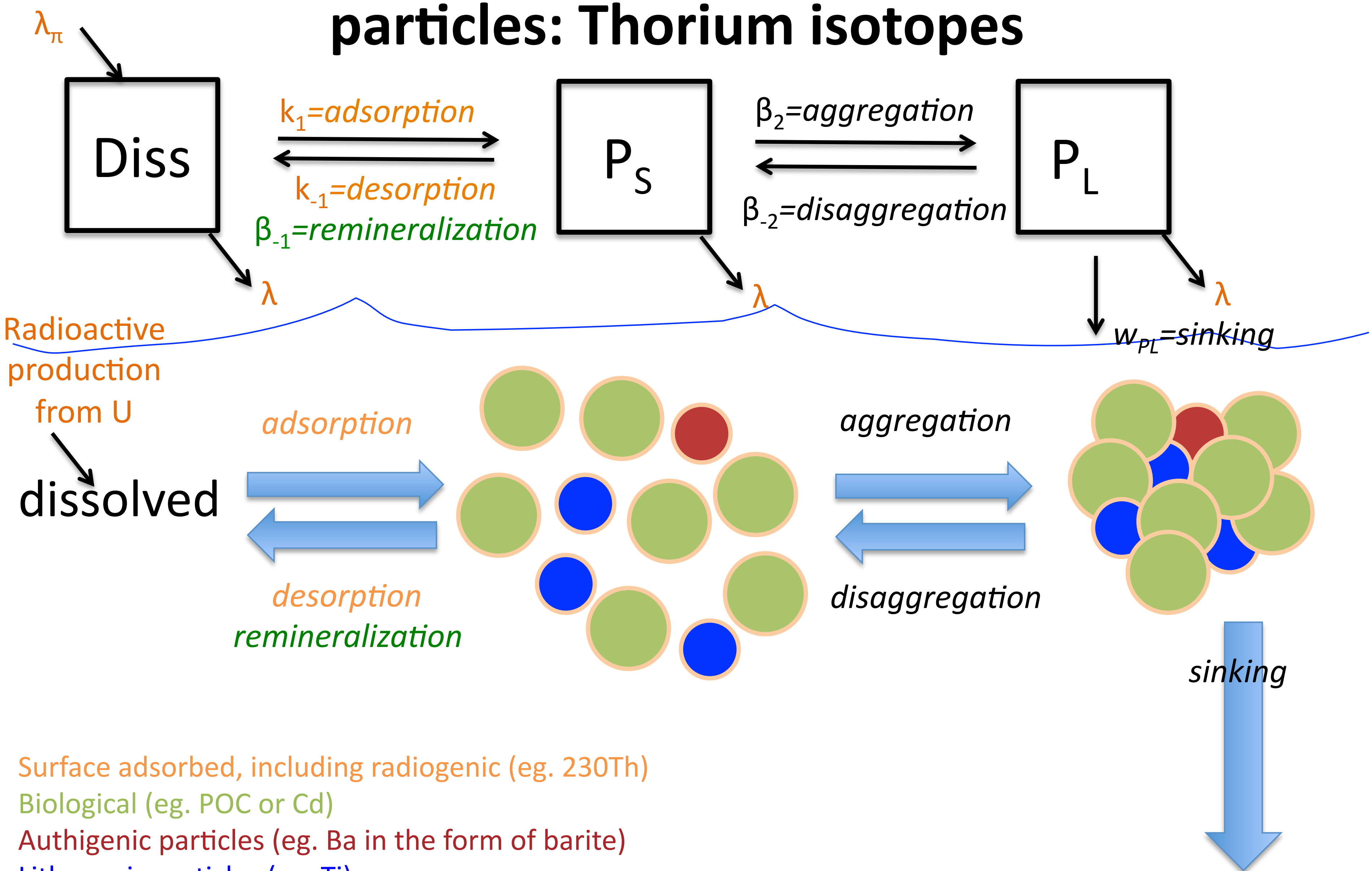


Fig. 8. Principal component analysis on most 2005 pump and all TS trap amino acid and pigment data. Variable loadings are scaled up 10× and plotted on the same axes as sample site scores.

Abramson et al. 2010 L&O

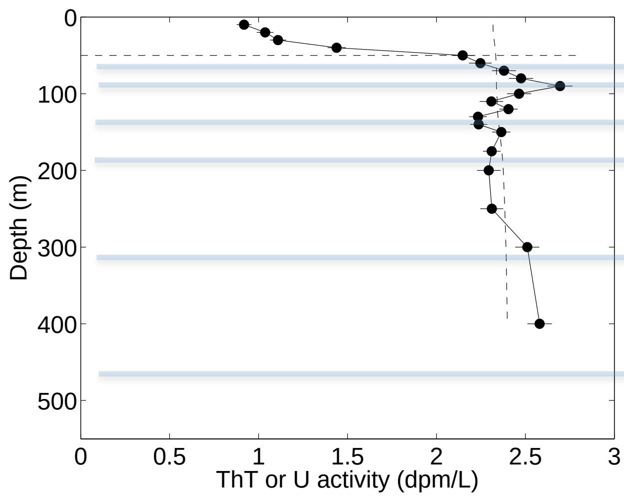
Geochemically linking suspended and sinking particles: Thorium isotopes



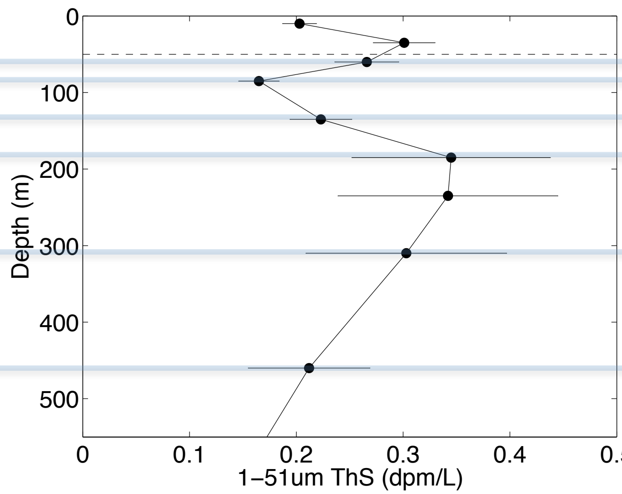
Surface adsorbed, including radiogenic (eg. 230Th)
Biological (eg. POC or Cd)
Authigenic particles (eg. Ba in the form of barite)
Lithogenic particles (eg. Ti)

Observations—NW Pacific VERTIGO stn K2d1

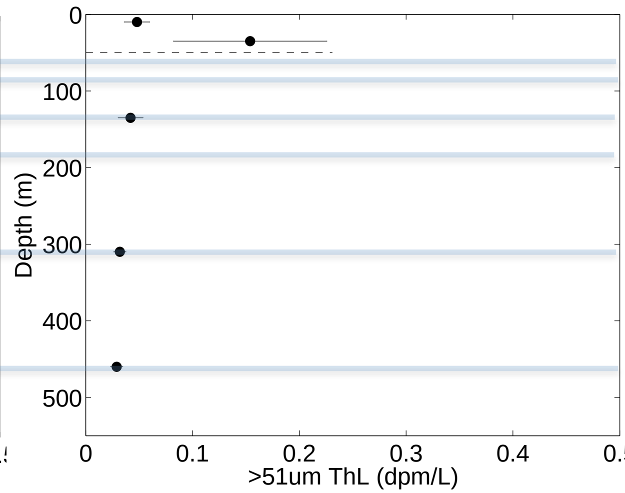
^{234}Th—Total

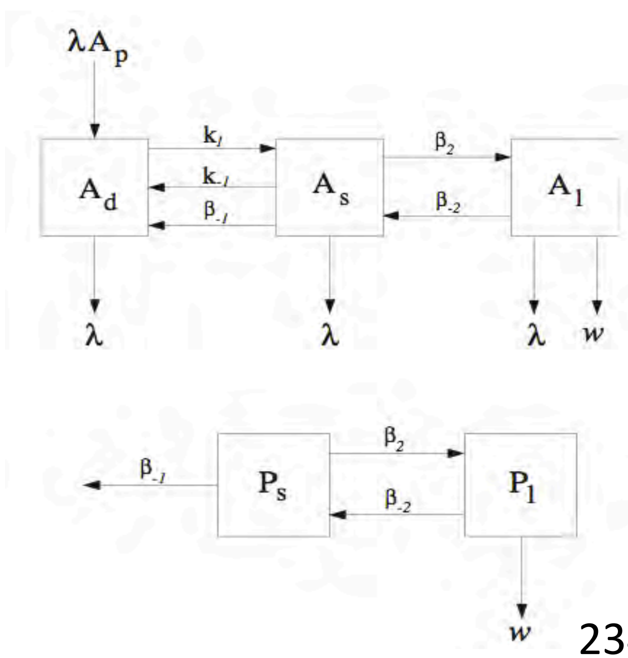


^{234}Th—small part.

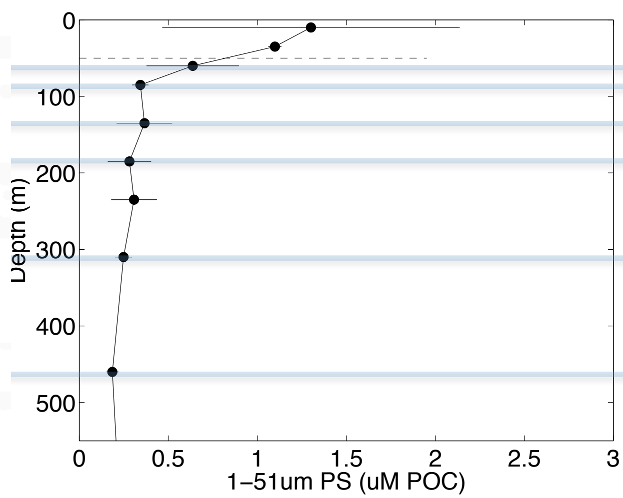


^{234}Th—large part.

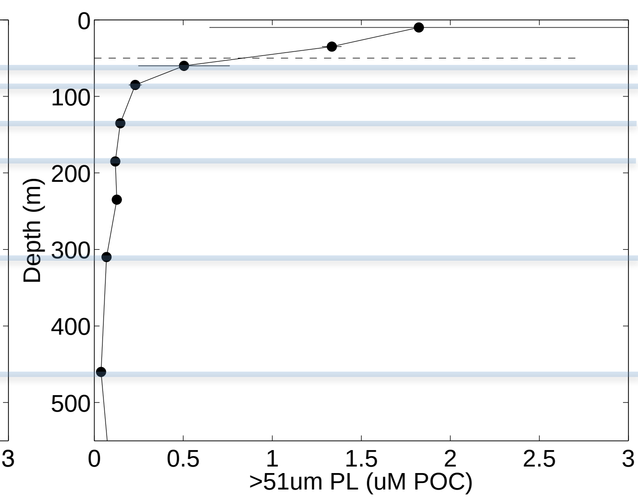




[POC]—small part.

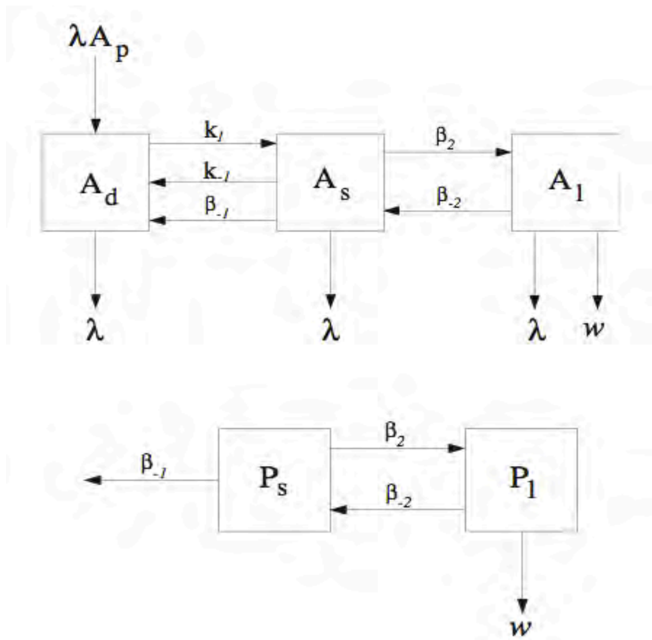


[POC]—large part.

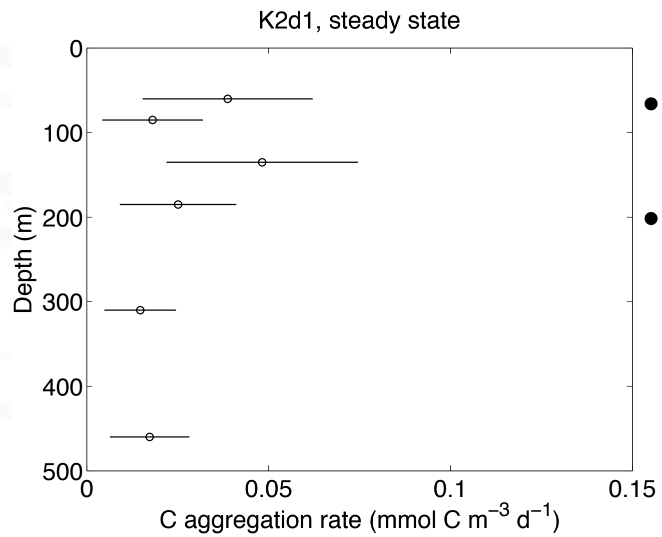


234Th from Buesseler et al. 2009; POC from Bishop and Wood 2008

Particle cycling rates in C units (C m^{-3} d^{-1})

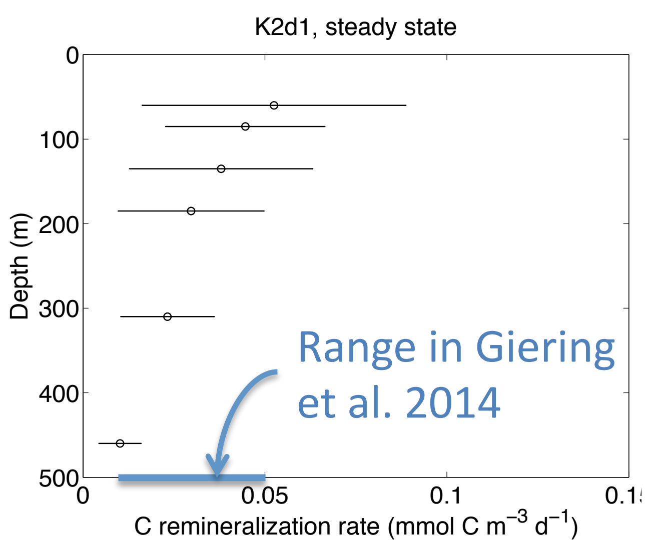


Aggregation

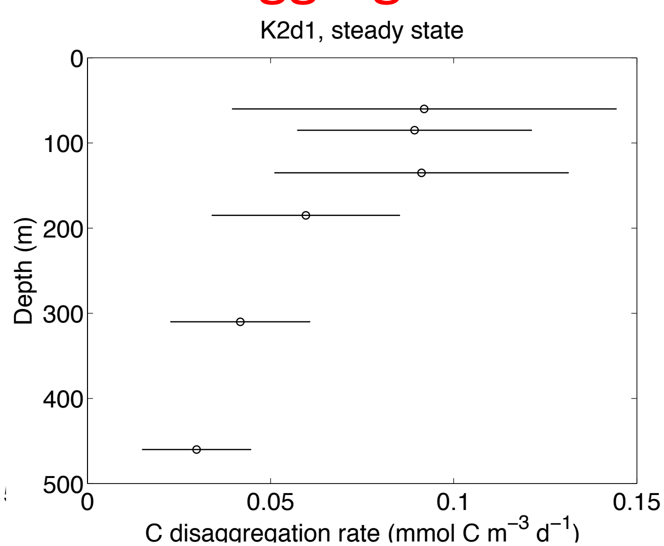


- Rates decrease with depth, as we would expect
- Disaggregation rates are larger than remineralization
- This is a reflection of the fact that large POC concentrations decreases more quickly with depth than small POC

Remineralization



Disaggregation



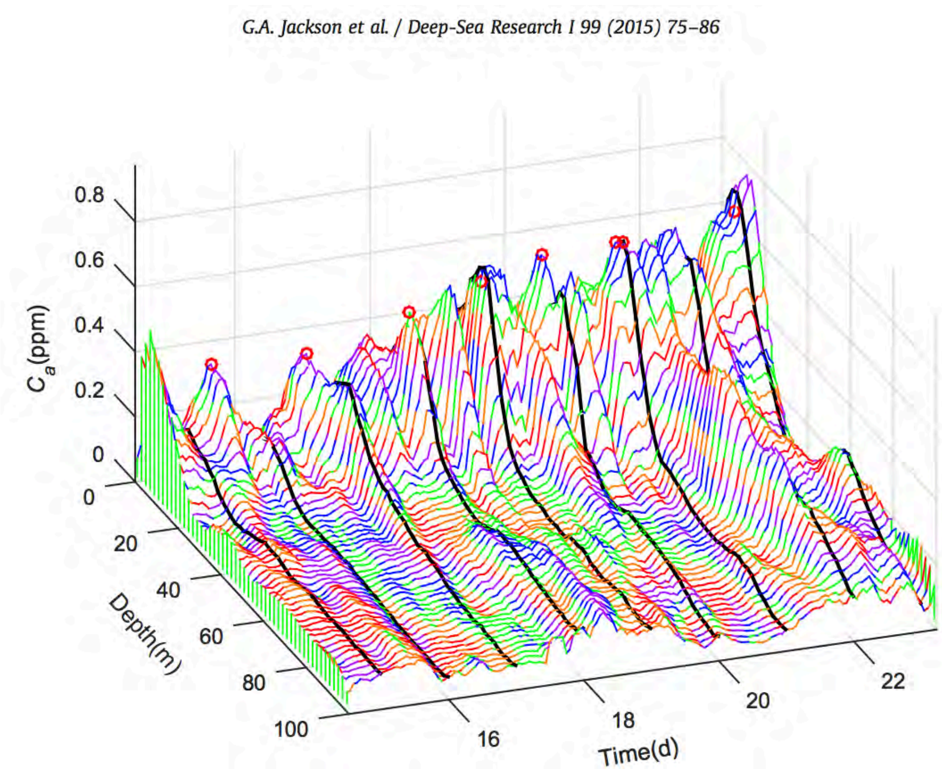
Giering et al. calculated respiration using leucine incorporation, CF and prokaryotic growth efficiency; zoop resp = f(body mass, T, resp quotient)

Linking suspended and sinking particles—summary

- Chemical analyses of sinking and suspended particles show variability in the degree of exchange (aggregation and disaggregation) between the suspended and sinking particle fractions as a function of season and location that correlate with changing dominance of fecal pellets
- Can invert observations of particle chemistry (eg. POC, thorium isotopes) for some particle cycling rates that are of same order with direct estimates (eg. respiration) and others that are impossible to measure directly (eg. aggregation and disaggregation rates)

Imaging of suspended particles—fast!

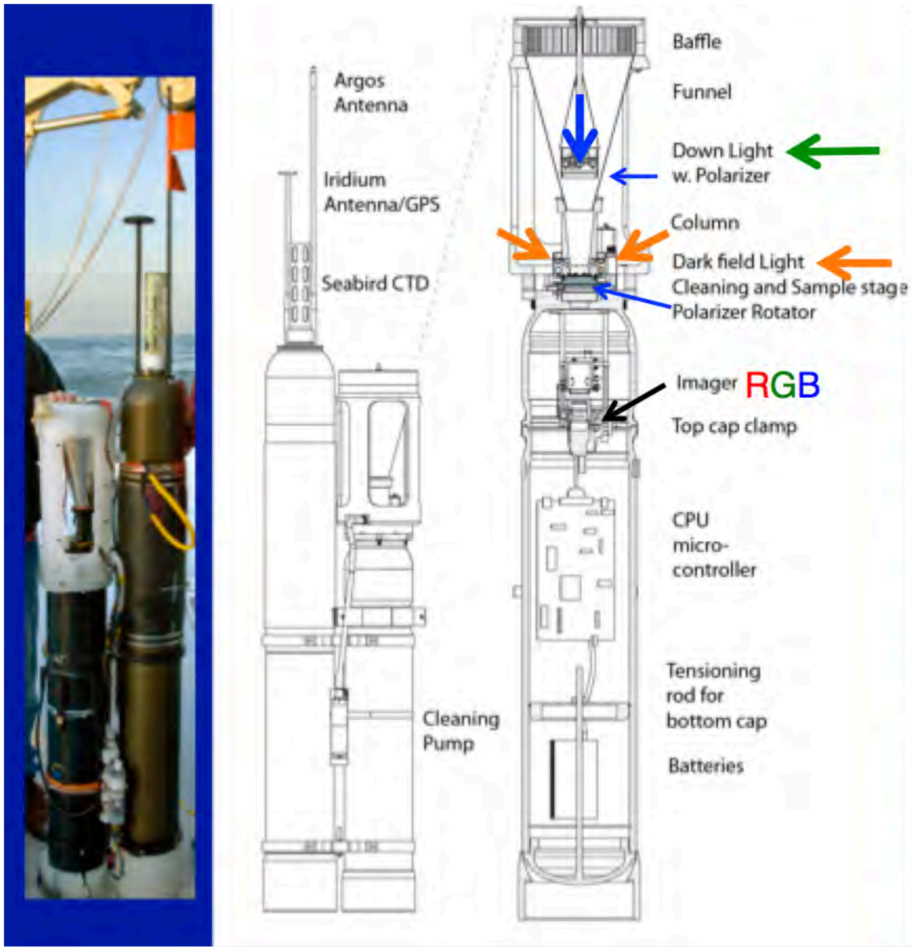
Size range	Name	Method
>100um	UVP-Underwater Vision Profiler VPR-Video Plankton Recorder LOPC-Laser Optical Particle Counter	Imaging Imaging Laser absorbance
Micro, nano-plankton	FlowCam Imaging Flow Cytobot CytoSense	Flow cytometry plus imaging



Jackson et al. 2015 DSR1: LOPC on a solo float:

- High resolution sampling allows calculation of aggregate settling velocities
- Sedimentation was very episodic, with export occurring in ¼ of days

Imaging sinking particles: the C-Flux Explorer with Optical Sedimentation Recorder



3 Lighting modes

Dark Field
Color, pigments, fine structure

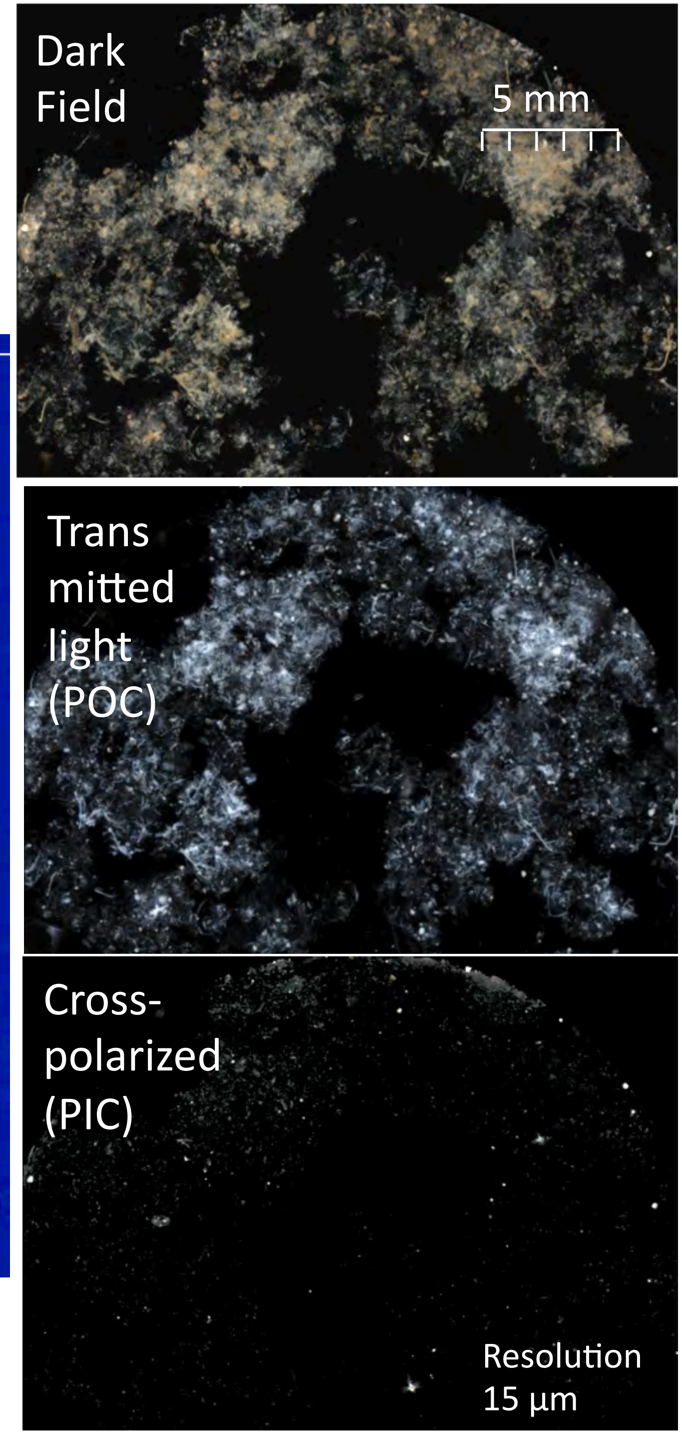
Transmission
POC

X polarized Transmission
PIC

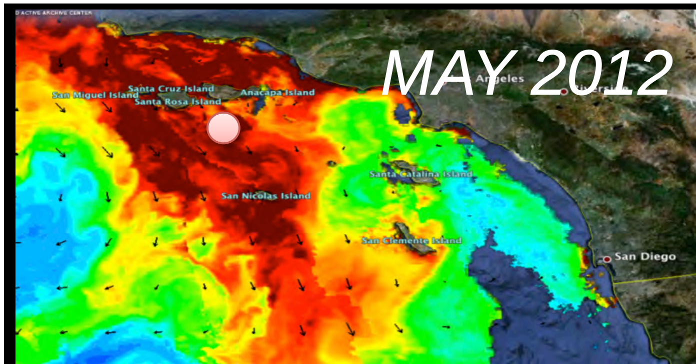
5 Mpix Imaging (RGB)

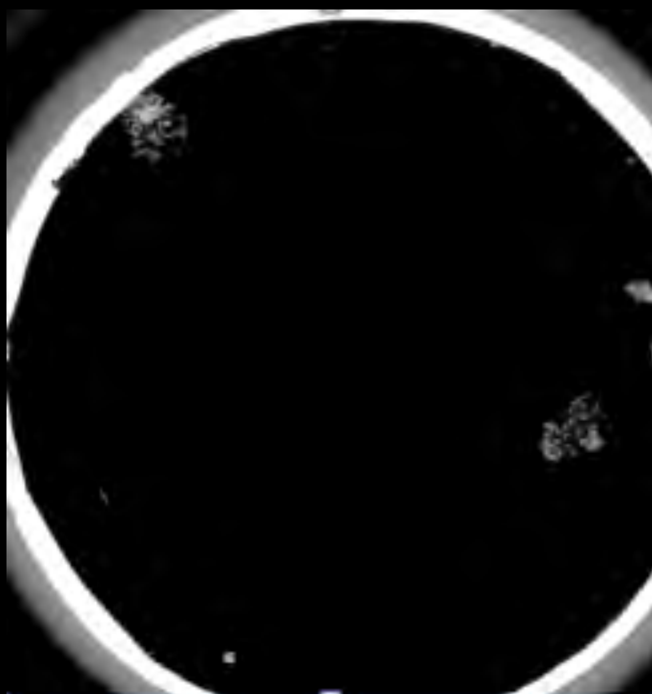
Set f.no, shutter, & focal distance

Image resolution 15 μm



Figures from Jim Bishop





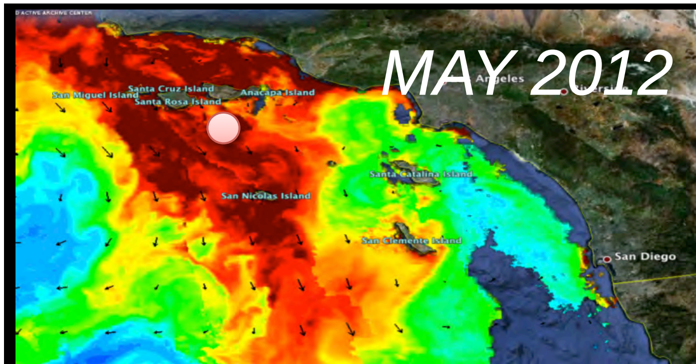
Clean,
image @ Hour (0, 0.5, 1.0, … 3.0),
Clean … repeat
Surface every 17 Hrs,
GPS, data in/out
Dive to next depth

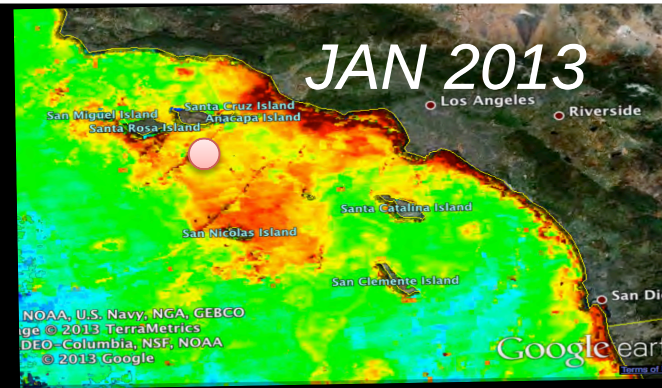
In animations: 1s ~ 3hrs; loops are ~1d

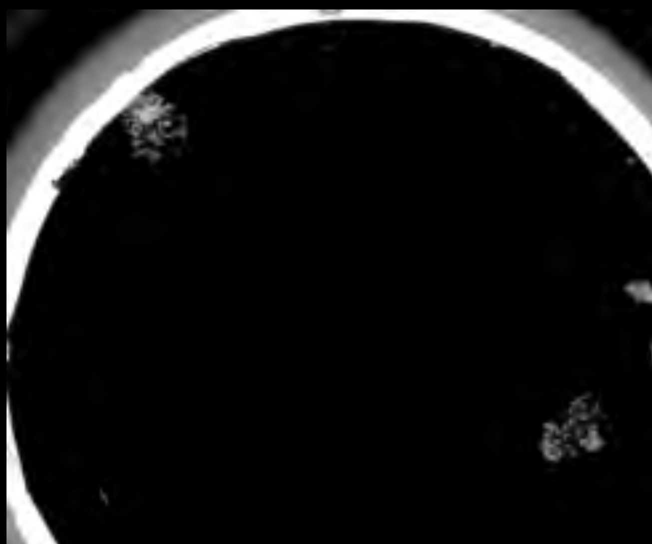
Slide from Jim Bishop

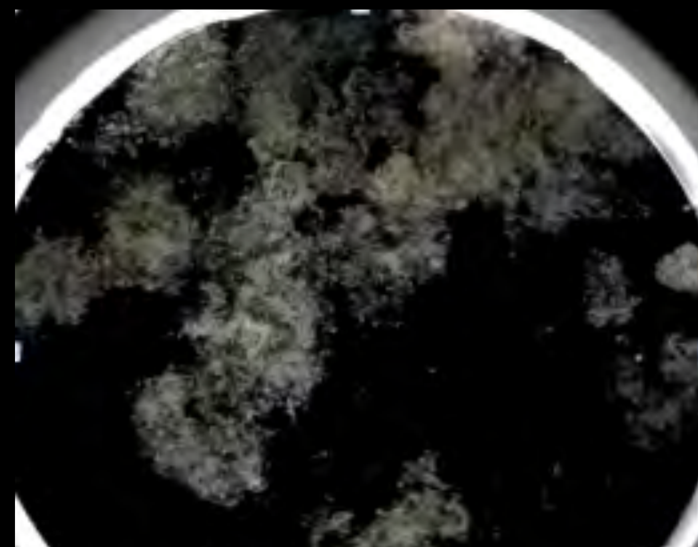
Open questions

1. What leads to high production, low export conditions?
2. What is the geographical distribution of flux? mismatch between geochemical methods and particle-based methods
3. Fecal pellets vs marine snow: important control on transfer efficiency?









Does High Surface Chlorophyll mean high carbon sedimentation?

NO: flux was 20x higher under low chl conditions

CFE001 various depths 250 to 750 m

Slide from Jim Bishop

Q1: what leads to high production, low export conditions?

- Has been observed elsewhere (eg. Maiti et al. 2013 GRL—Southern Ocean High productivity, low export)
- Some observations suggest this is a steady state condition
- Other regions may exhibit this condition transiently, and possibly not at all
- Need more time-series observations (hourly resolution? for months) of different kinds of ecosystems to monitor the initiation, peak, and decline (if present) of high productivity ecosystems that seem to have low export, and those that have high export (eg. NABE)
- Autonomous platforms are the way to answer this

Open questions

1. High production, low export: where is it a transient and where is it a steady state condition?
2. What is the geographical distribution of flux? mismatch between geochemical methods and particle-based methods
3. Fecal pellets vs marine snow: important control on transfer efficiency?

Comparing with other methods of estimating Export Flux

Method	Type of Method	Timescale of integration	Conceptual basis
Imaging/ filtration	Particle concentration	Seconds to hours	Must multiply by sinking rate to convert to flux; for imaging, must also convert # to POC; does not include DOC flux
Sediment traps	Particle flux	Days	Direct measurement of exported POC; Does not include DOC flux
^{238}U-^{234}Th disequilibrium	Particle/ geochemical flux	Weeks	234Th deficit due to particle scavenging; no DOC
O_2 mass balance (O_2/x, x=Ar, Ne, N_2)	Geochemical flux	Seasonal	Net O2 production is net community production = export production. Use inert Ar, Ne, or N2 to correct for physics. Measure over seasonal cycle in mixed layer

- When particle-only flux methods add in estimate of DOC flux, they are similar (within factor of 2) to O2 mass balance estimates (eg. Emerson et al. 1997, Emerson and Hedges 2008)

Q2: Mismatch between geochemical methods and satellite/model understanding of BCP distribution

Method	Type of Method	Export flux (mol C/m2/y)	
		Subtropical Pac (HOT)	Subarctic Pac (Stn P)
O_2 mass balance (O_2/x, x=Ar, Ne, N_2)	**Geochemical**	**2.7±1.7, 1.3±0.9**	**2.0±1.0**

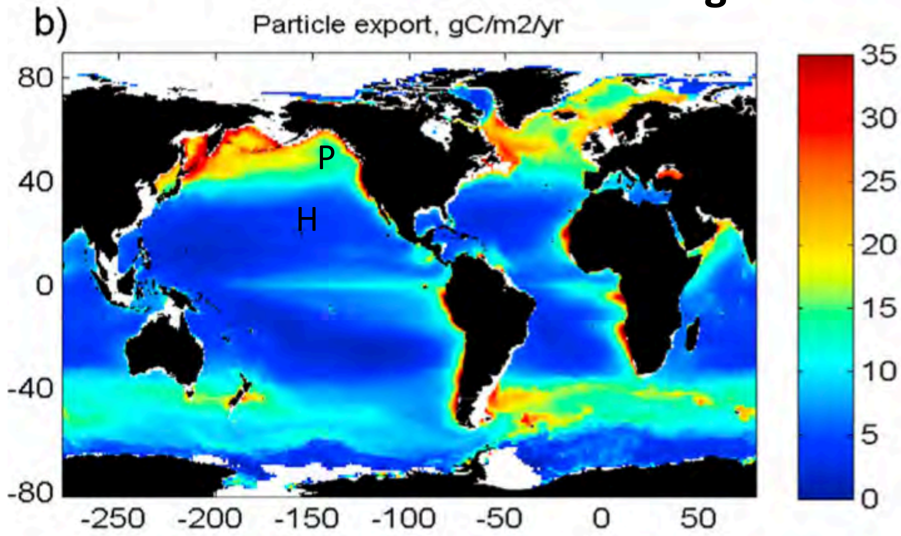
O_2 mass balance over an annual cycle at HOT vs Stn P suggest similar export flux!

Compare to our satellite/model view of export flux…

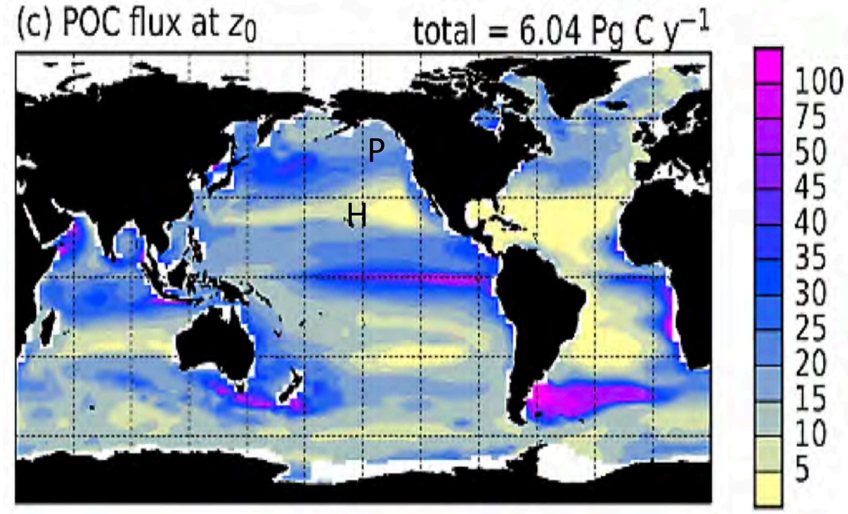
Q2: Mismatch between geochemical methods and satellite/model understanding of BCP distribution

Satellite and model estimates of export and sequestration flux suggest low/high flux in subtropical (H)/subpolar (P) regions

Henson et al. 2012 GBC: **satellite algorithms**



Lima et al. 2014 BG: **CCSM-BEC model**



EF

Methods for measuring Sequestration and Burial flux

- Sequestration flux is usually measured by bottom-moored time-series sediment traps
- Flux to seafloor has been estimated using benthic oxygen flux (oxygen consumption due to POC flux to seafloor)

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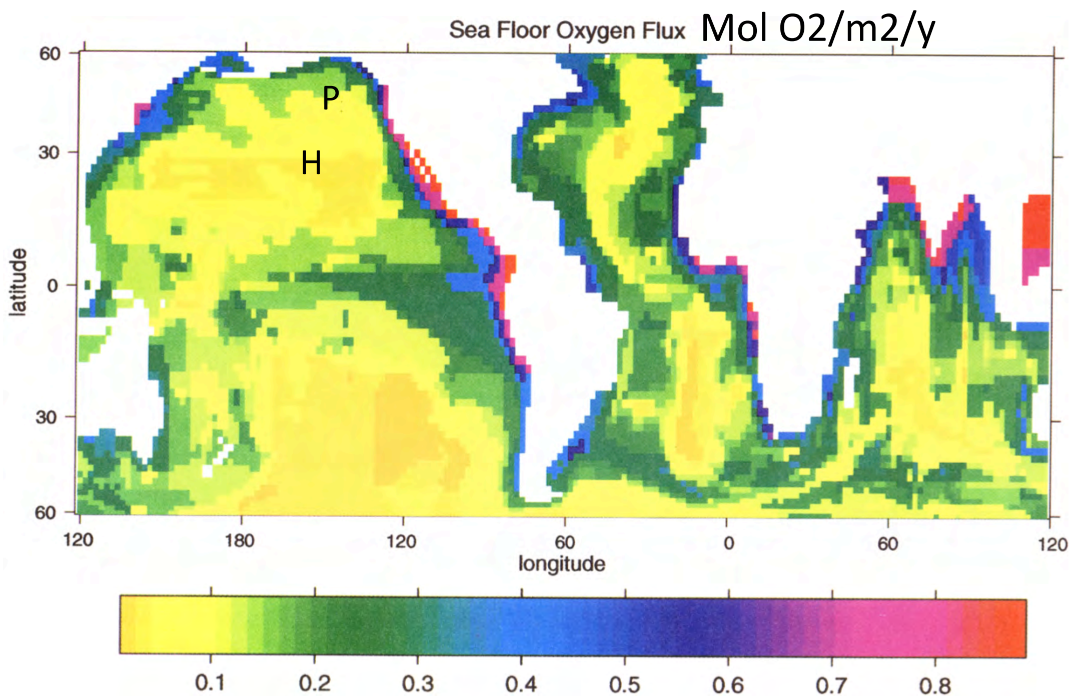

Benthic O2 consumption map (~POC flux to seafloor) from Jahnke 1996 also suggests that HOT and Stn P *could* be fairly similar...if so, then this means that subtropical regions could be burying as much POC as parts of subpolar regions.

Q2: Mismatch between geochemical methods and satellite/model understanding of BCP distribution

Satellite and model estimates of export and sequestration flux suggest low/high flux in subtropical (H)/subpolar (P) regions

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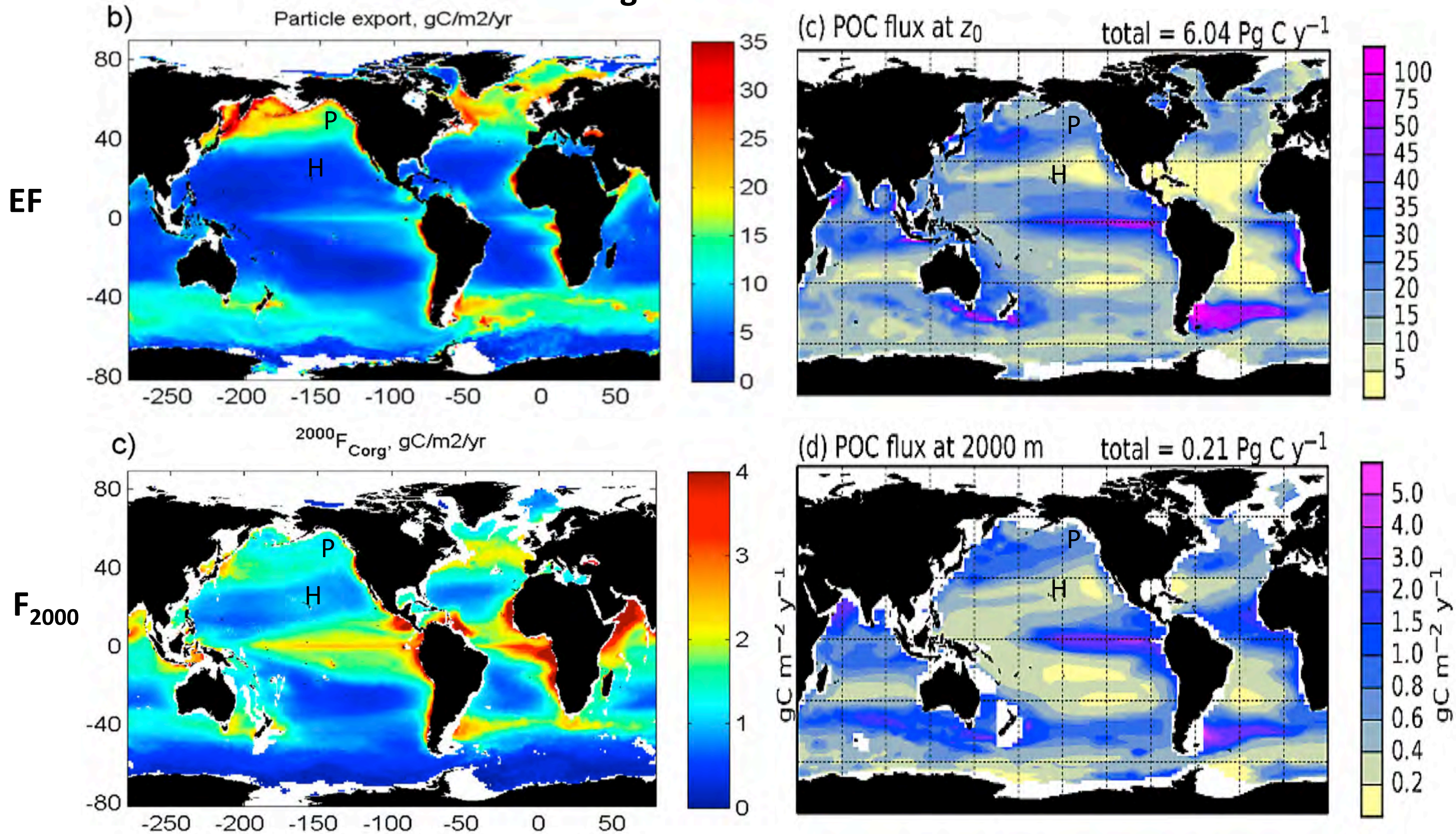

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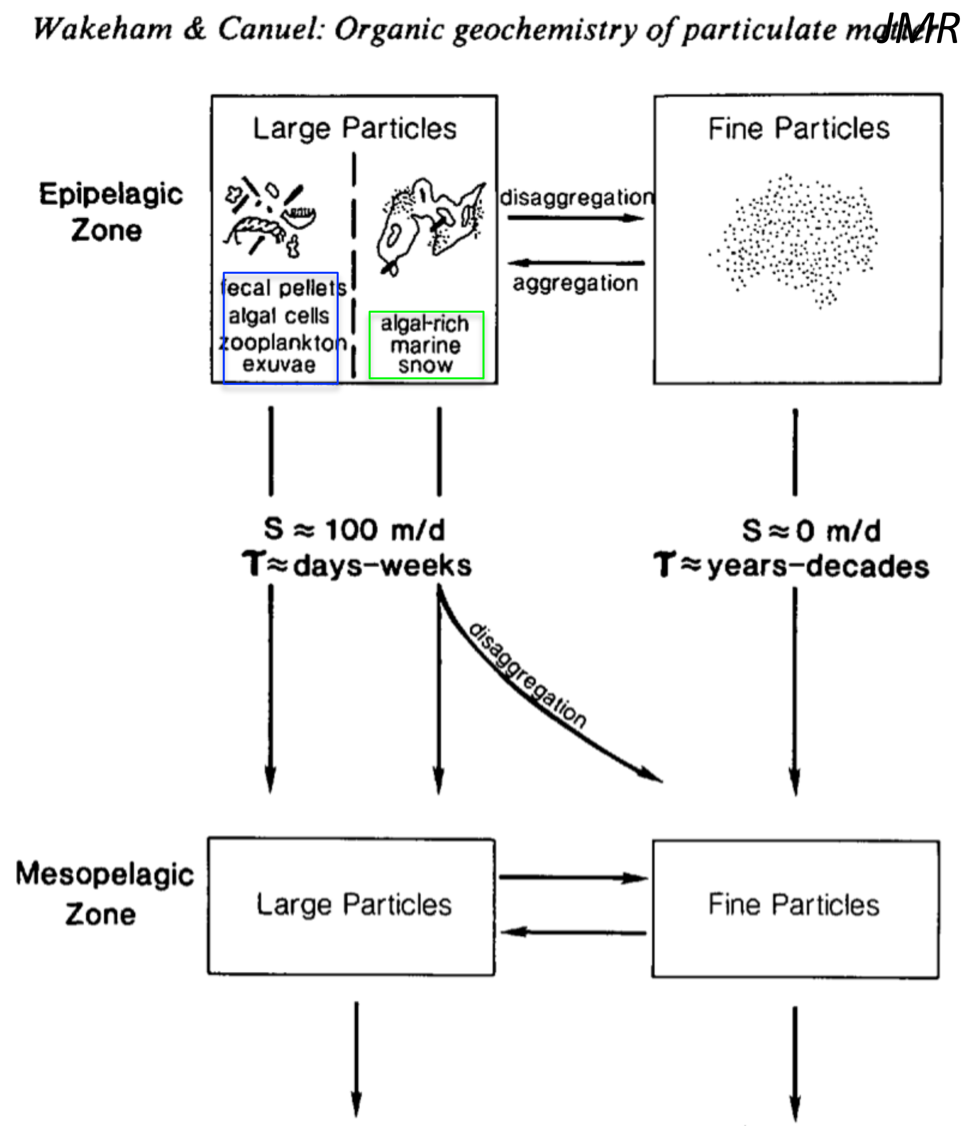
Q3: Fecal pellets vs marine snow: important control on transfer efficiency?

- From organic biomarkers, Wakeham and Canuel 1988 postulate that marine snow has higher rates of disaggregation, and so would have lower transfer efficiency than fecal pellets
- In contrast, huge sedimentation of marine snow aggregates also observed
- Sinking particles may shift seasonally from being dominated by one to the other—does this affect transfer efficiency?
- Autonomous platforms with imaging capability could address this
- Geochemical estimates of disaggregation rates in ecosystems dominated by one or the other could address this



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