AGGREGATION AND SINKING OF PLANKTON BLOOMS

George Jackson

Some of the many collaborators whose work on particles went into this talk:

David M. Checkley, Michael J. Dagg

Steve Lochmann, Adrian Burd, Lars Stemmann, Tammi Richardson, Colleen Petrik, Lionel Guidi, Marie-Paule Jouandet, Catarina Marcolin Morten Iversen, Hide Yamazaki

I. Intro: Sampling the Martin curve

- Most active region is just below the euphotic zone
- Very difficult to sample adequately
- Most samples traditionally from below most active region
- Need more intensive study in this region

More than 2/3 of flux decrease in first 100-150 m

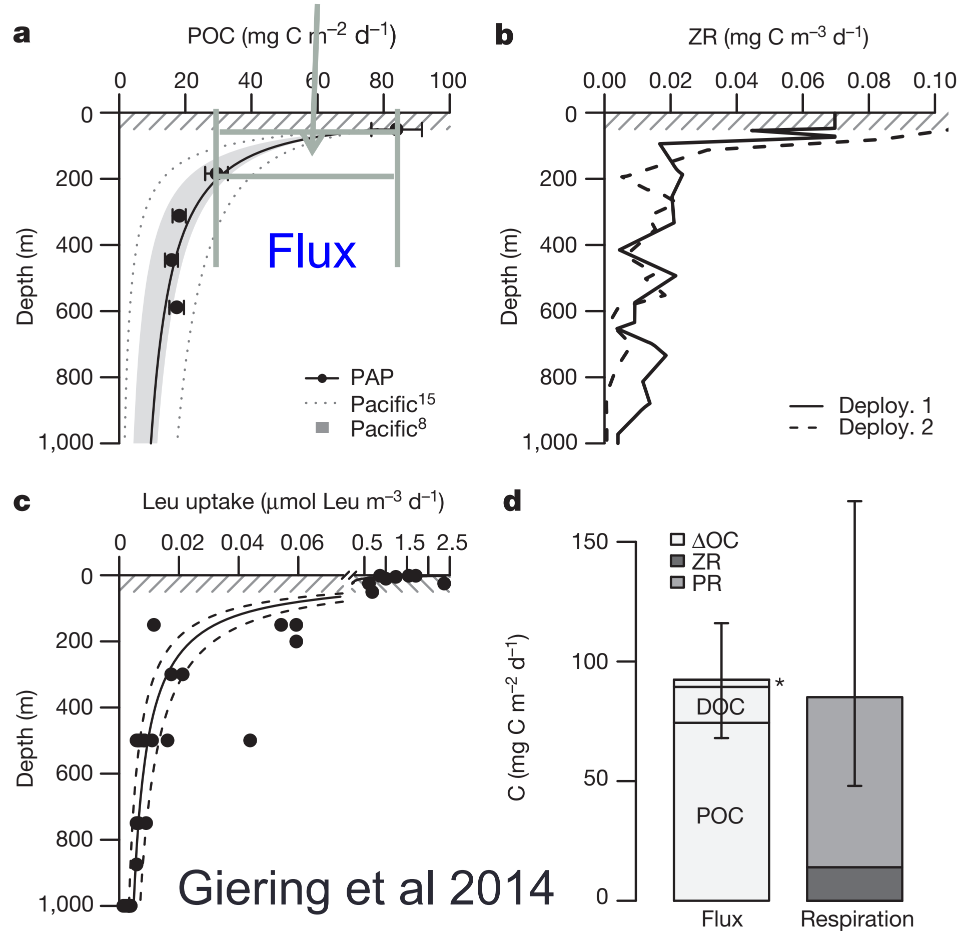


Figure 1 | Sinks and sources of organic carbon to the twilight zone. **a,** POC flux (black dots) below the mixed layer (shaded area) at the PAP site during 3–6

Goal of this talk

- What new things do we know about the formation and fate of aggregates
  - Using models/coagulation theory?
  - With new observation tools?

- What are the implications for ocean carbon cycle?

II: Overview of aggregation theory

- Small particles collide to form large particles. Rates depend on
  - Physical conditions (shear, particle density)
  - Stickiness
  - Particle size
  - …
- Rates vary nonlinearly with concentration
- Larger particles sink faster
- Key property is the size-dependence of concentration

Coagulation theory: predictions verified by observations

- 1. Coagulation determines the maximum particle algal concentration in the ocean. (Kiørboe et al. JMR 1994; Jackson and Kiørboe 2008 L&O; Jackson 2008 DSRI). (*not pursued further here)*

- 2. Aggregates fall ~50-100 m d^{-1}.(Petrik et al 2013 DSRI; Jackson et al 2015).

- 3. Coagulation can occur very rapidly (Kerguelen). Measurements at 400 m do not always reflect current export. (Jouandet et al. 2014 Biogeosci.)

Instantaneous aggregate flux can be large.

Rapid aggregation near the Kerguelen Islands: observations (Jouandet et al. 2014 Biogeosciences 11: 4393-4406)

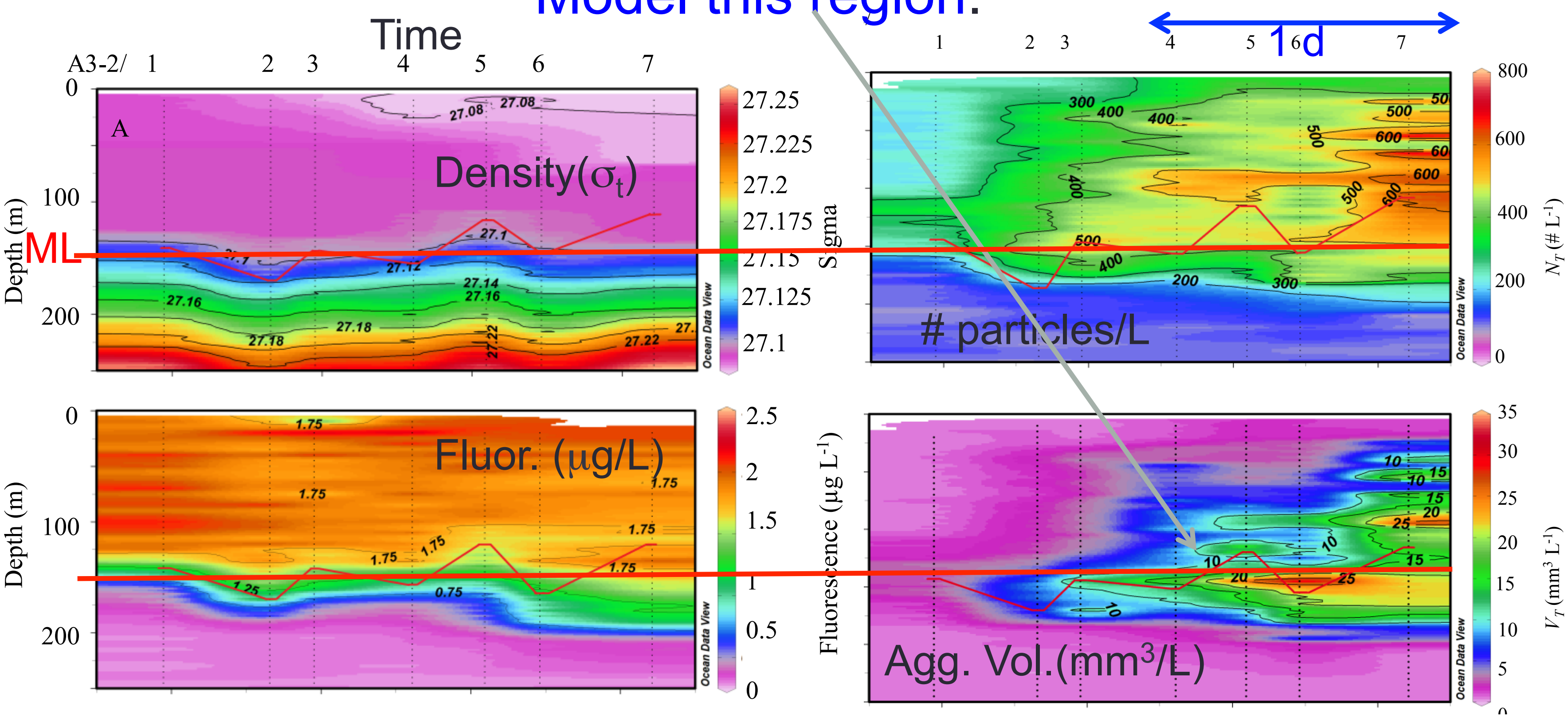
Sample water during a bloom off Kerguelen Islands.

Use CTD/Fluor, UVP particle counter.

7 profiles in less than 2 d.

Rapid aggregate formation at base of mixed layer (ML).

Model this region.

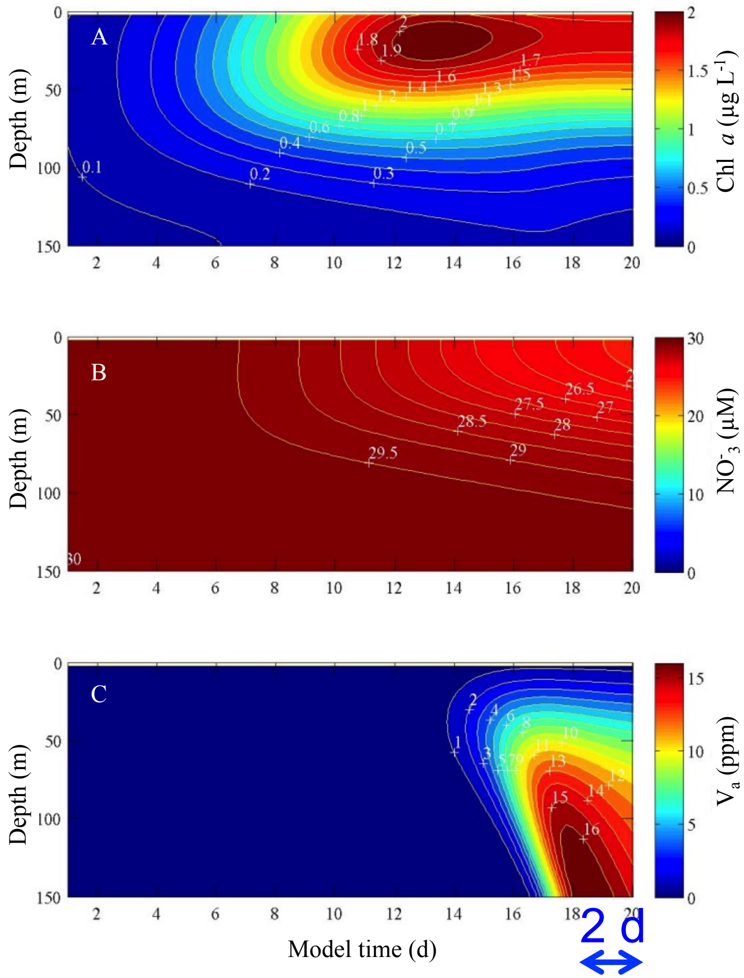


Kerguelen- 2
Model: evolution of aggregates over time and depth:

- Simulate algal bloom coagulation in vertical dimension (1-D)
- Depth to pycnocline at 150 m, not 250 m

Observe
- Rapid aggregate formation at similar time, algal conc., depth
- Particle max near bottom of mixed layer.

- (note the different temporal scale:
  obs. over ~2 d; model 20 d;
  obs. 0-250 m; model 0-150 m)

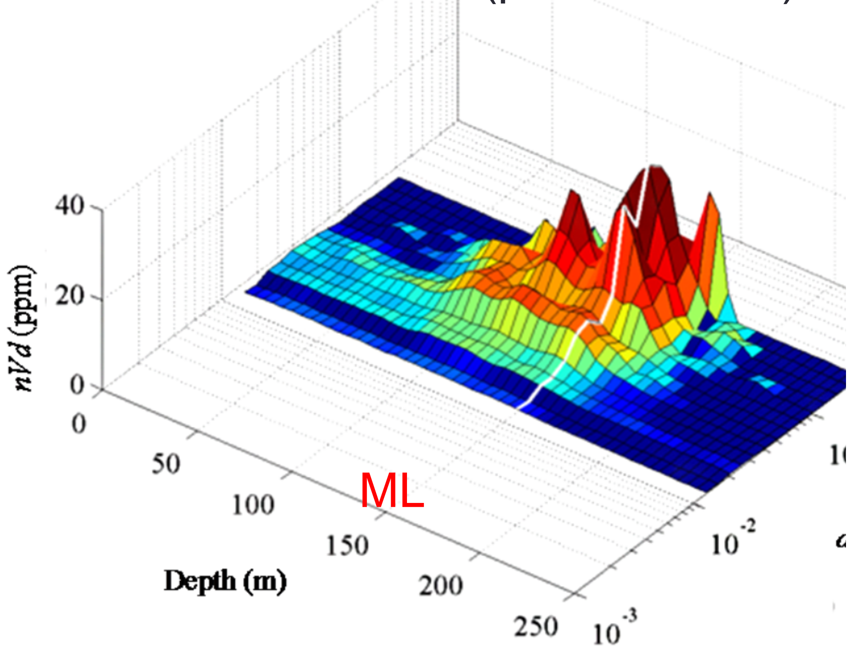


Kerguelen- 3:
Comparison of depth, size distributions

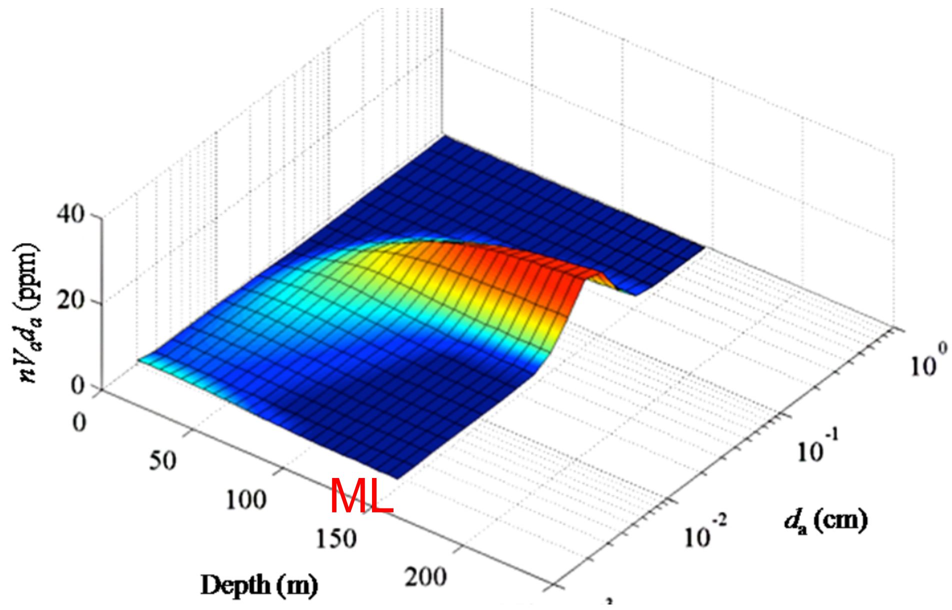
See similar depth, aggregate size distributions for observations, model

- Mass, size increases with depth
- Similar size, mass amounts

Observations (profile A3/2-5)



Model (d 20)



III. Use laser optical plankton (particle) counter to measure particle size distributions(plankton + aggregates)

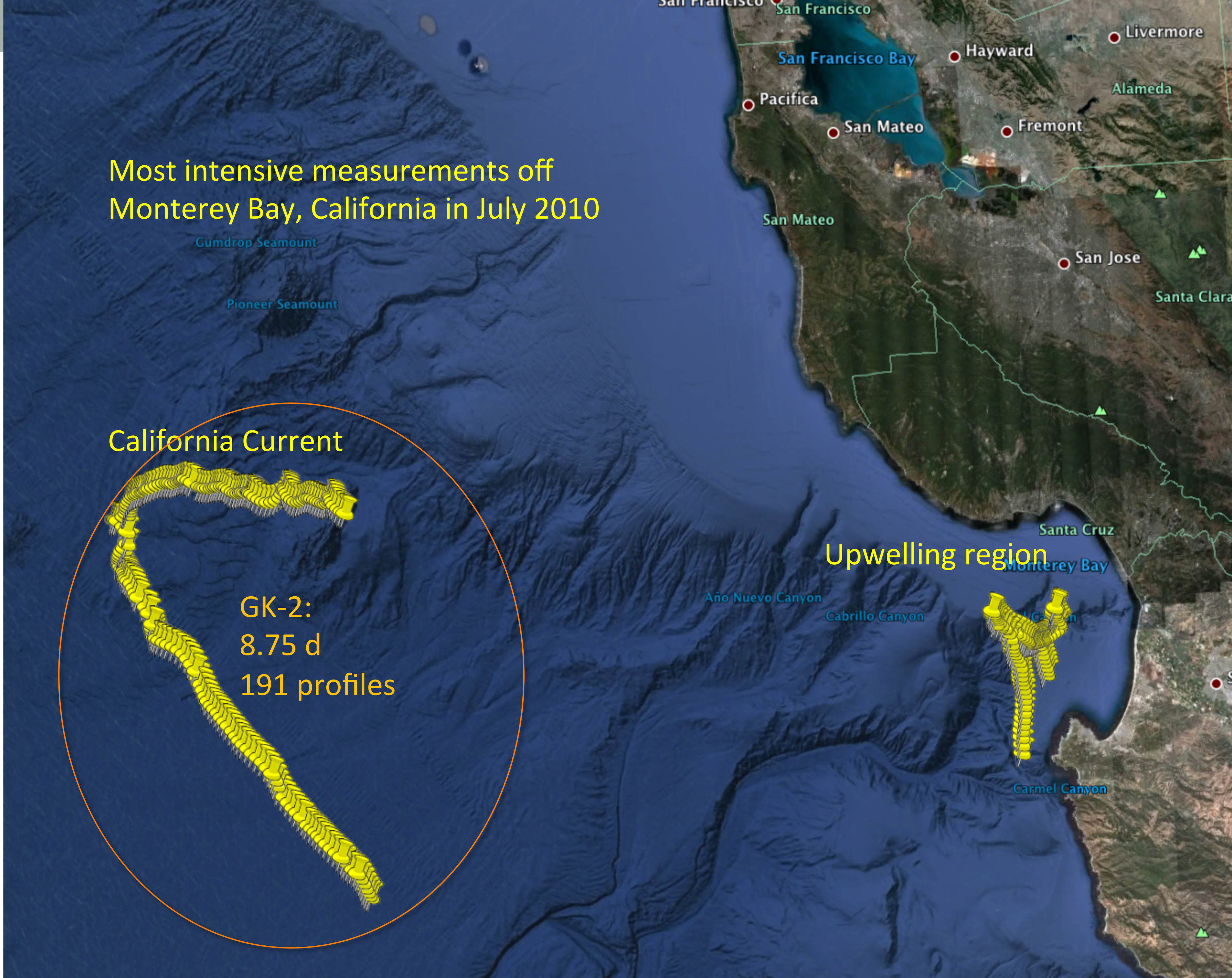
An autonomous profiling float: CTD, optical backscatter and/or chl fluor + particles (LOParticleCounter).

17 deployments up to 12+d from surface to 100 -200 m ~hourly.

Extract total aggregate volume concentration w depth. Look for zooplankton

Results in Checkley ea 2008 L&O; Jackson ea 2011 DSR; Petrik ea 2013 DSR; Dagg ea DSR 2014)

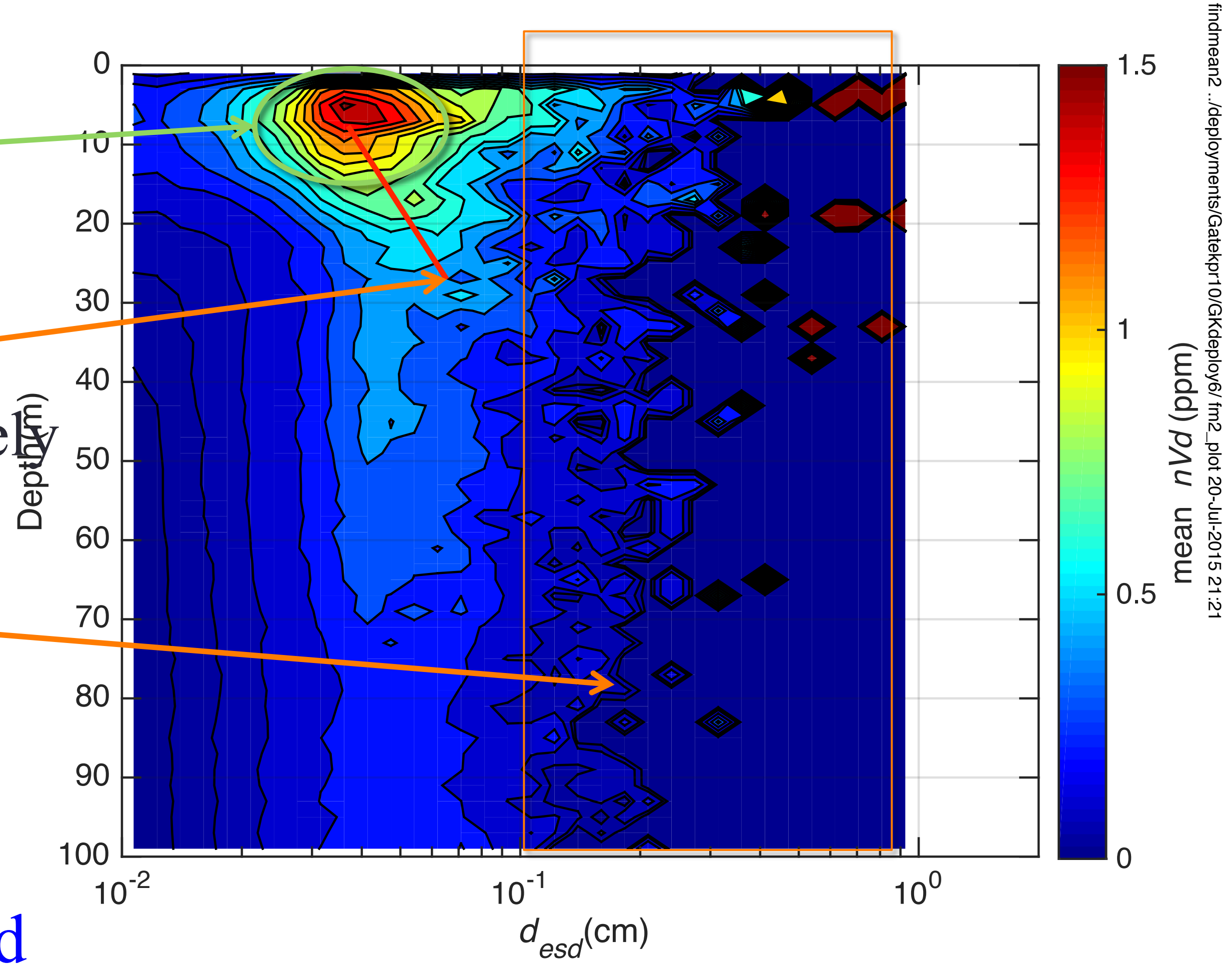
2.5 m long 36 kg in air



Most intensive measurements off
Monterey Bay, California in July 2010
California Current
GK-2:
8.75 d
191 profiles
Upwelling region
San Francisco
San Francisco Bay
Hayward
Livermore
Alameda
Pacifica
San Mateo
Fremont
San Mateo
San Jose
Santa Clara
Gumdrop Seamount
Pioneer Seamount
Santa Cruz
Año Nuevo Canyon
Cabrillo Canyon
Carmel Canyon

Typical *nVd* profile (particle "mass" distribution)

- Average over 2 m intervals
- Well defined max,
  here at ~8 m depth,
  300-700 um ESD
- Increase in mean ESD w depth
- Particles >0.1 cm extremely variable
  - Small number of counts problem

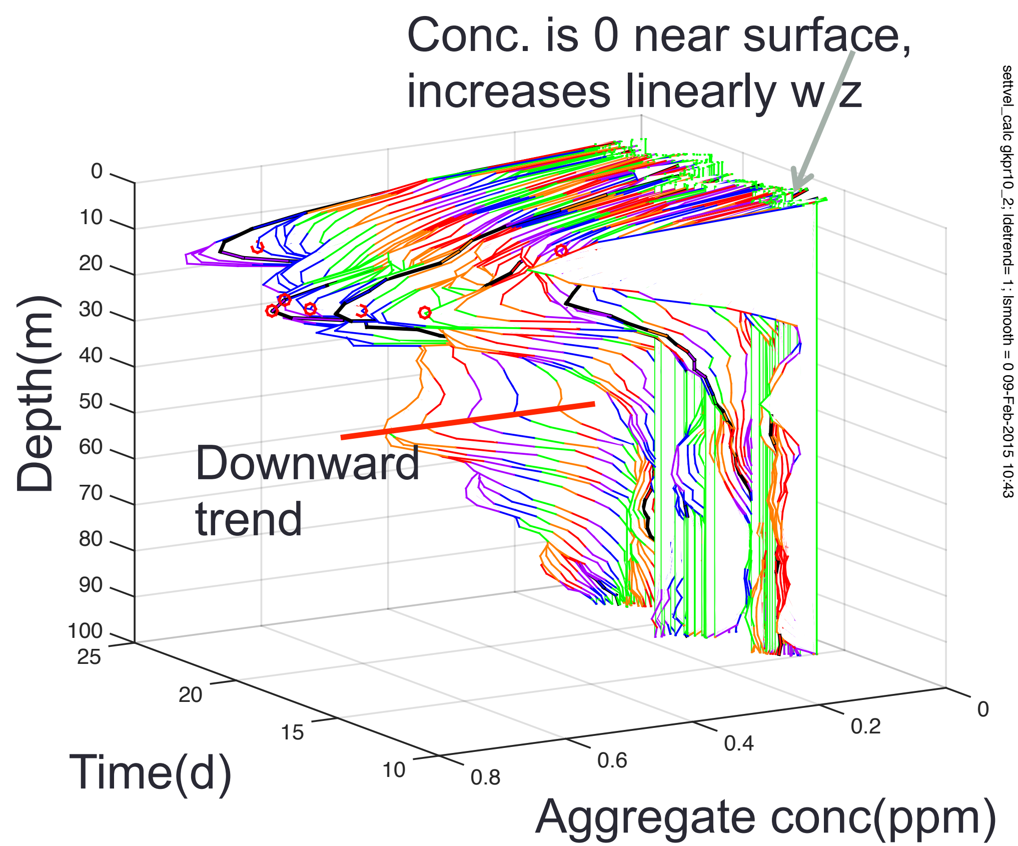


Extract an aggregate signal from the size distribution (published voodoo).

Extract aggregate concentration fn depth, time

- Aggregates have small concentrations near surface, increase as fall
- There is a distinct subsurface maximum
- Evidence of falling events

Example of distribution of aggregate concentration w depth, time off California

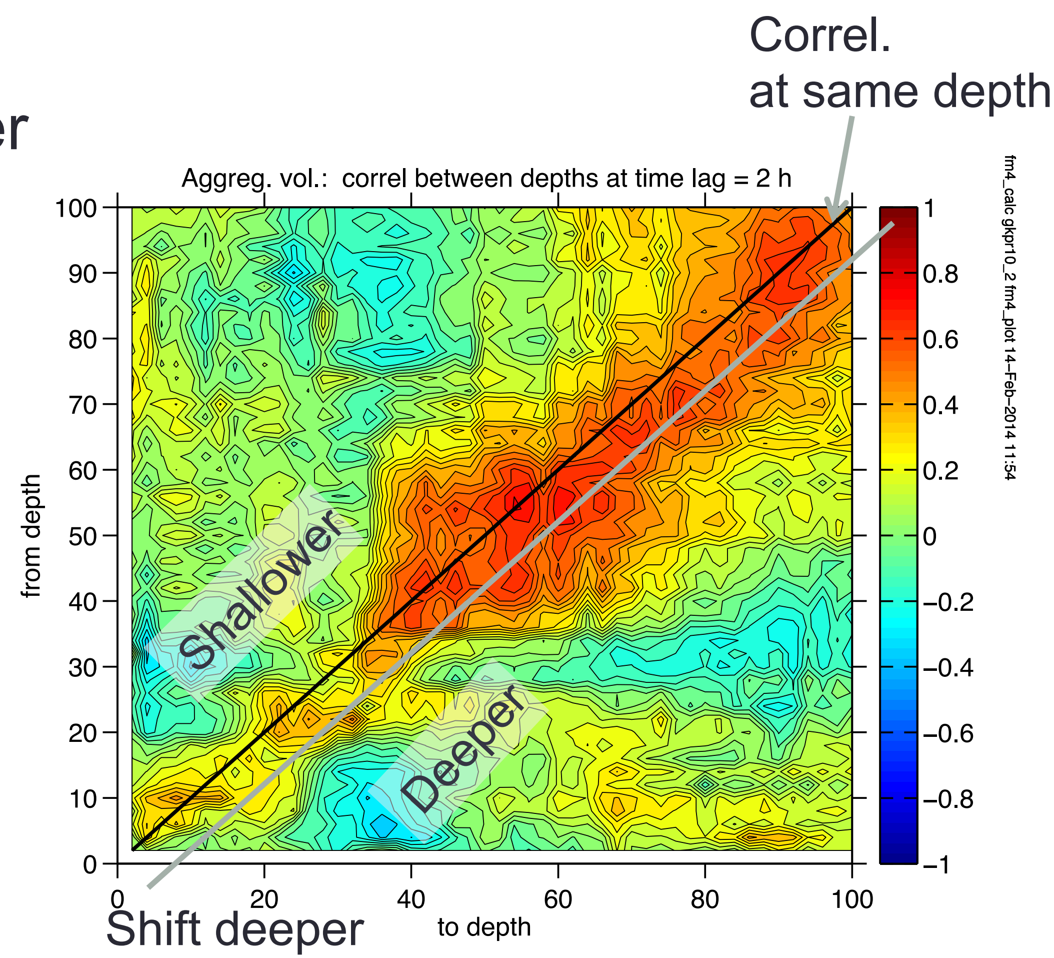


Correlate aggregate volumes between depths for different 2 h offset

Higher correlation with deeper locations than shallower.

Falling!

Look for general patterns by averaging all pairs for same offsets.

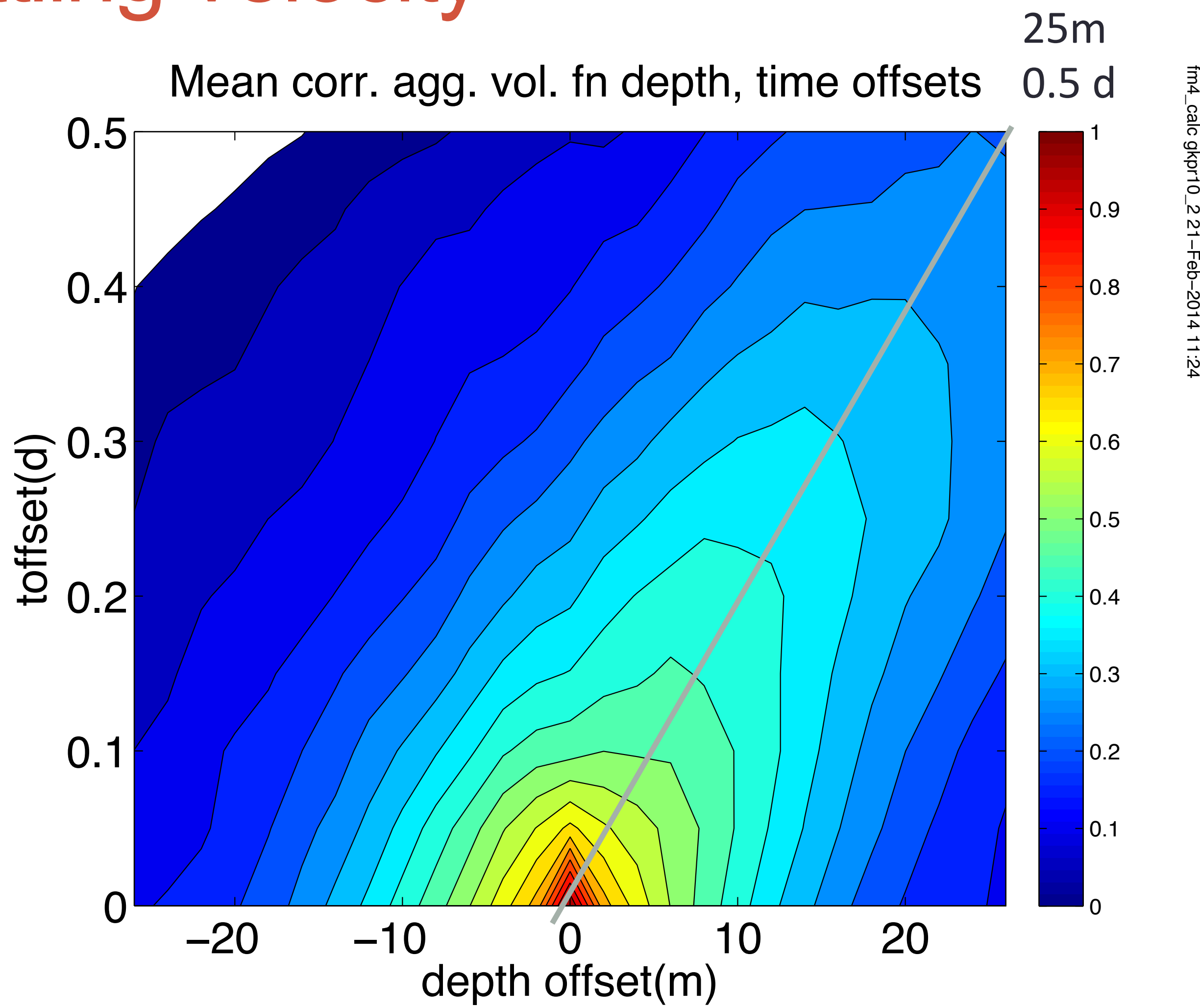


Method 1: Isolate sinking signal of aggregates: settling velocity

Average all correlation values for given depth, time offsets.

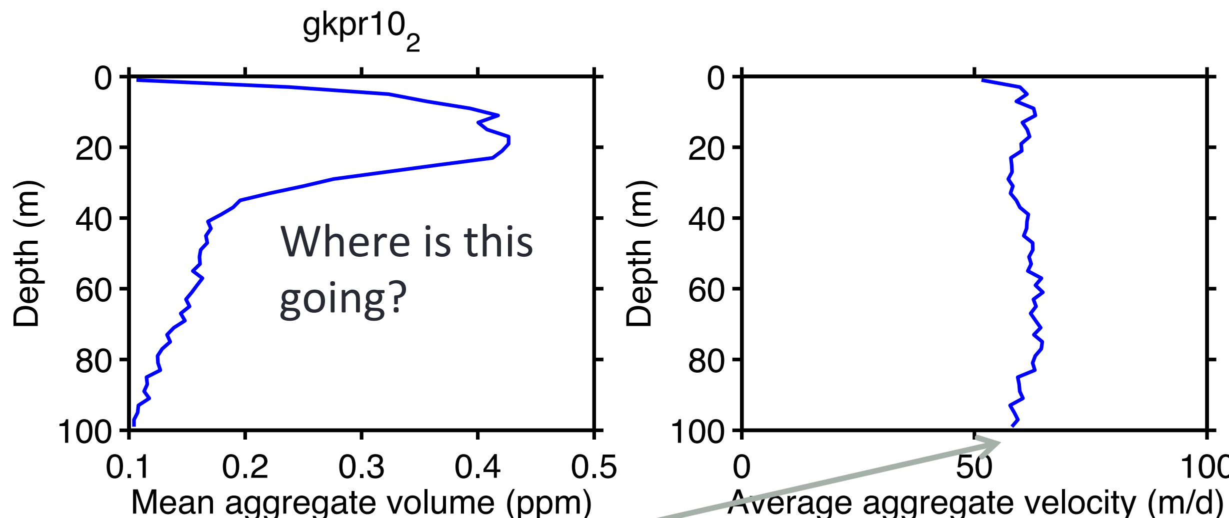
Clear evidence for settling!

Aggregate settling velocity of 25 m/0.5 d=50 m d^{-1}



Method 2. Compare with velocity from agg. size distributions calculated from 1st principles

Have:
-Aggregate size distrib.
-Know particle settling as fn of diameter



Assume a $\Delta\rho$= 0.03 g cm^{-3}
(low end of Waite and Nodder, 2001)

Calculate an average aggregate velocity ~60 m d^{-1}.

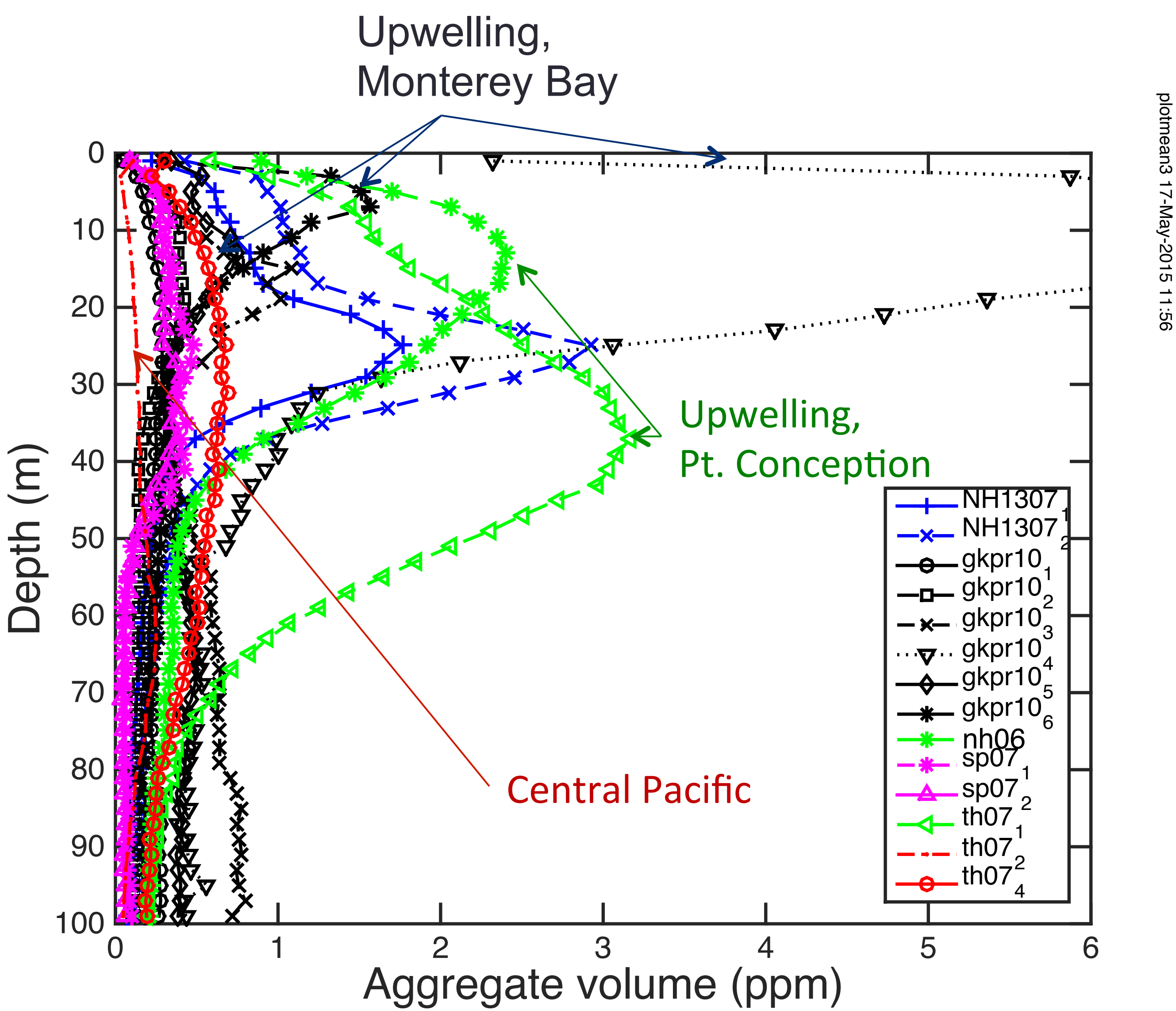
This is similar to our calculations from observations:
50 m d^{-1}!

Can use particle size distributions to calculate fluxes!

Average "aggregate" volume distribution

Total agg. Conc.

- Quite variable
- Very sharp decrease with depth around 50 m.



Calculate flux from sizes distrib, velocity (d<1mm)

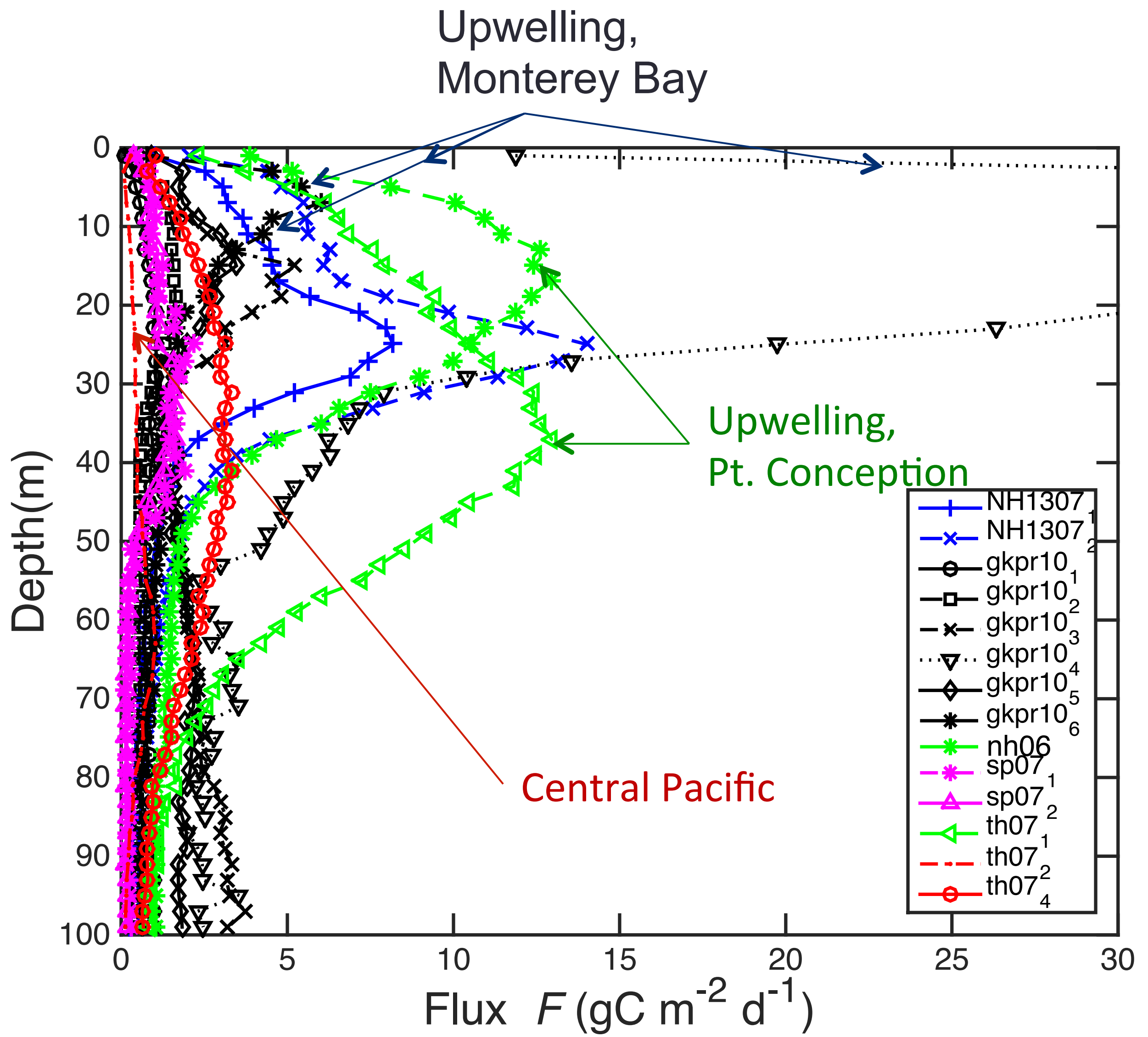
assume C:volume ratios

Flux in upper 100 m comparable to primary production.

Drops greatly between 50 and 100 m

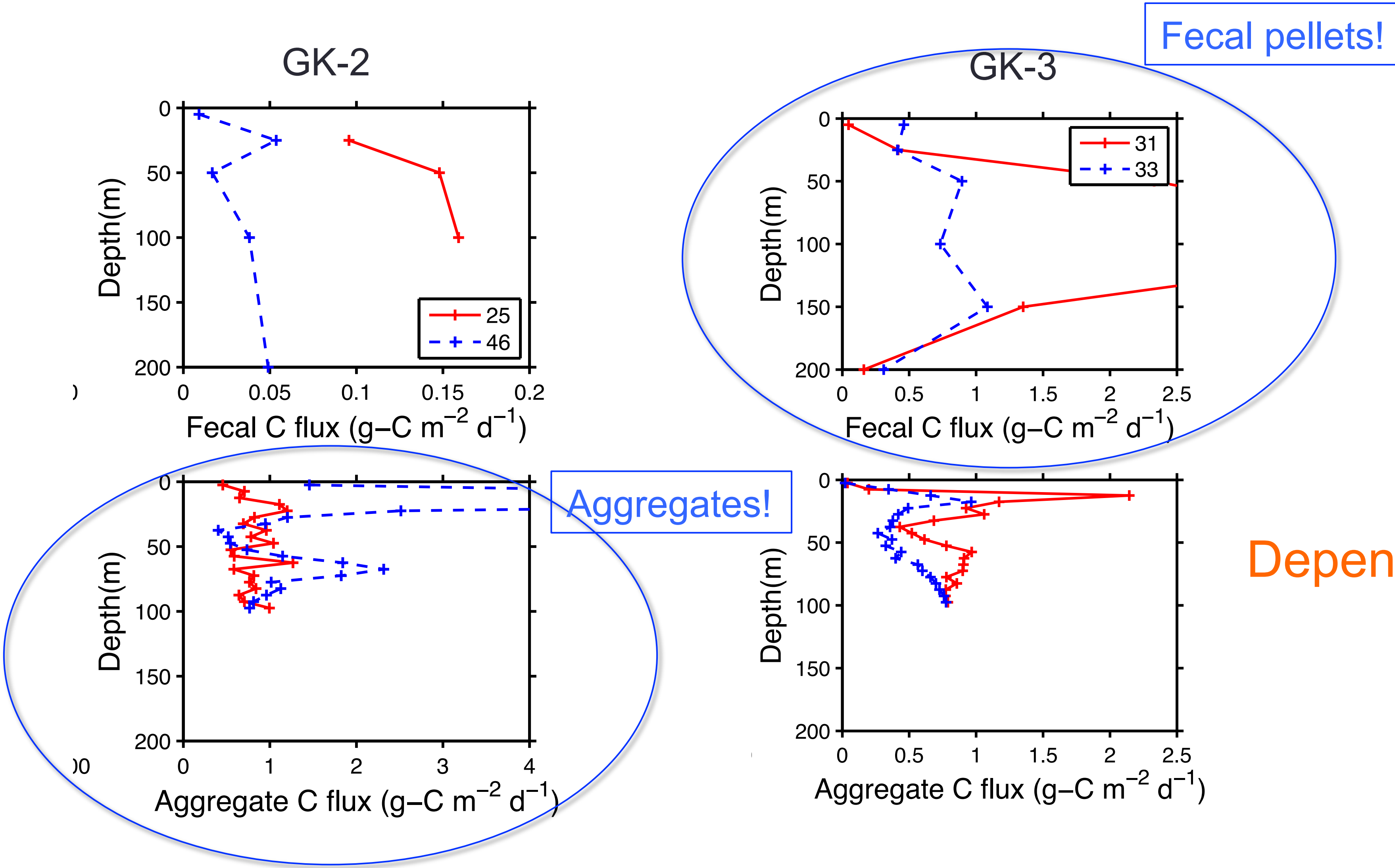
Implications:
Vertical movement significant process in cycling

Deeper zooplankton grazing/ microbial degradation important.



What about fecal pellets? (Dagg et al 2015)

Have 2 deployments to compare with fecal pellet collections.



Depends

IV. What happens to these aggregates?

- Concentrations, fluxes decrease rapidly with depth at base of euphotic zone.

- Why is the flux not getting downward?
  - Numbers are large
- If breaking up, should see an accumulation of POC/chl/ backscatter at particle-o-cline. Do not.

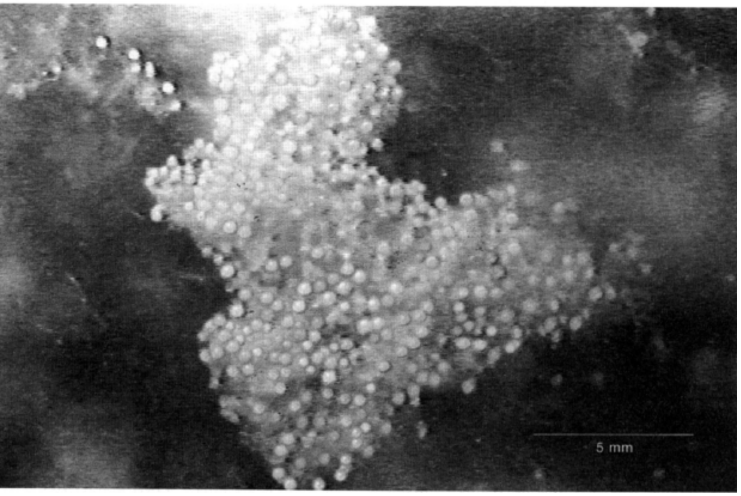
- Have two (incomplete) sets of information:
  - Data from net tows
  - Data from LOPC size distributions

Gatekeeper hypothesis

- Much grazing on organic matter is tied to settling particles.
- Flux/aggregate feeding could be an important process
- Animals important as gatekeepers for what enters the mesopelagic.

- Should see this reflected in animal grazing, distributions

Example of grazing removing aggregate flux



Diatom aggregate covered by *Noctiluca*
T&K 1998

Tiselius and Kiørboe (1998) found massive algal aggregation in Benguela Current, settling

…. but no flux out

Why?

Massive feeding by *Noctiluca* at bottom of euphotic zone

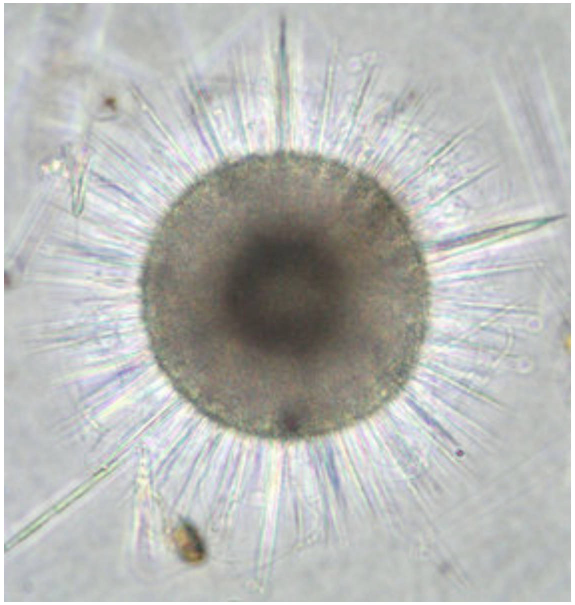
Perhaps it is relatively common.

e.g. *Neocalanus cristatus* (Dagg 1993)

Animal types expected to be flux feeders

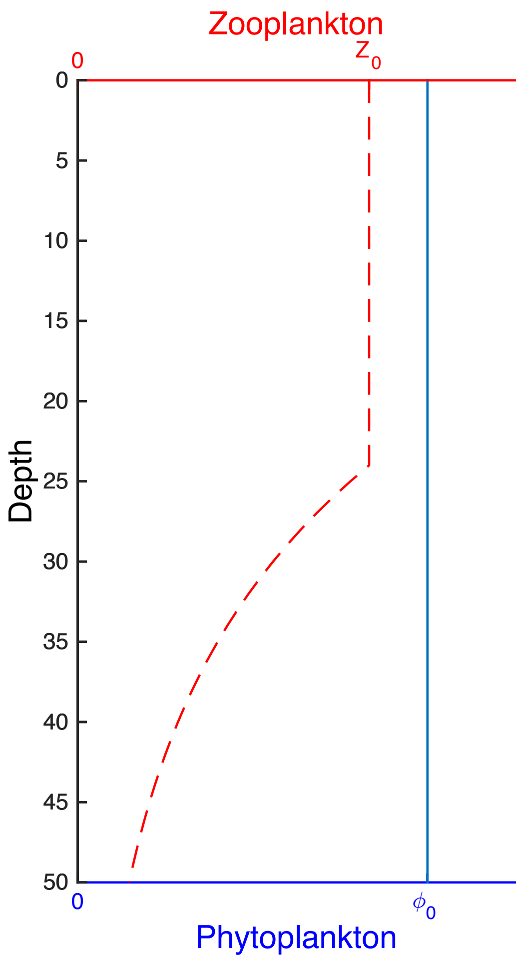
- Sarcodines; radiolarians
- Pteropods
- Dinoflagellates
- …?

Clio pyramidata,
Gilmer and Harbison, 1986. Mar Biol.



Hexacontium sp.
© Jane K. Dolven
http://tolweb.org/Polycystine_radiolarians/121189

Zooplankton distribution for different feeding sources: models of zoo distrib.

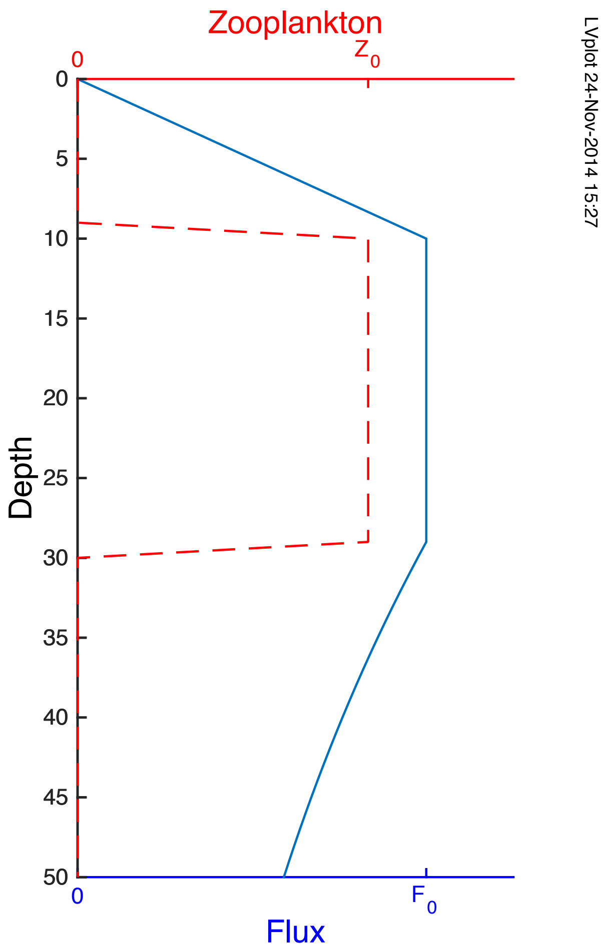


<-Phyto/zoo (NPZ model)

- Zoo uniform near surface

Aggregate/zoo ->

Zoo localized below prod max.



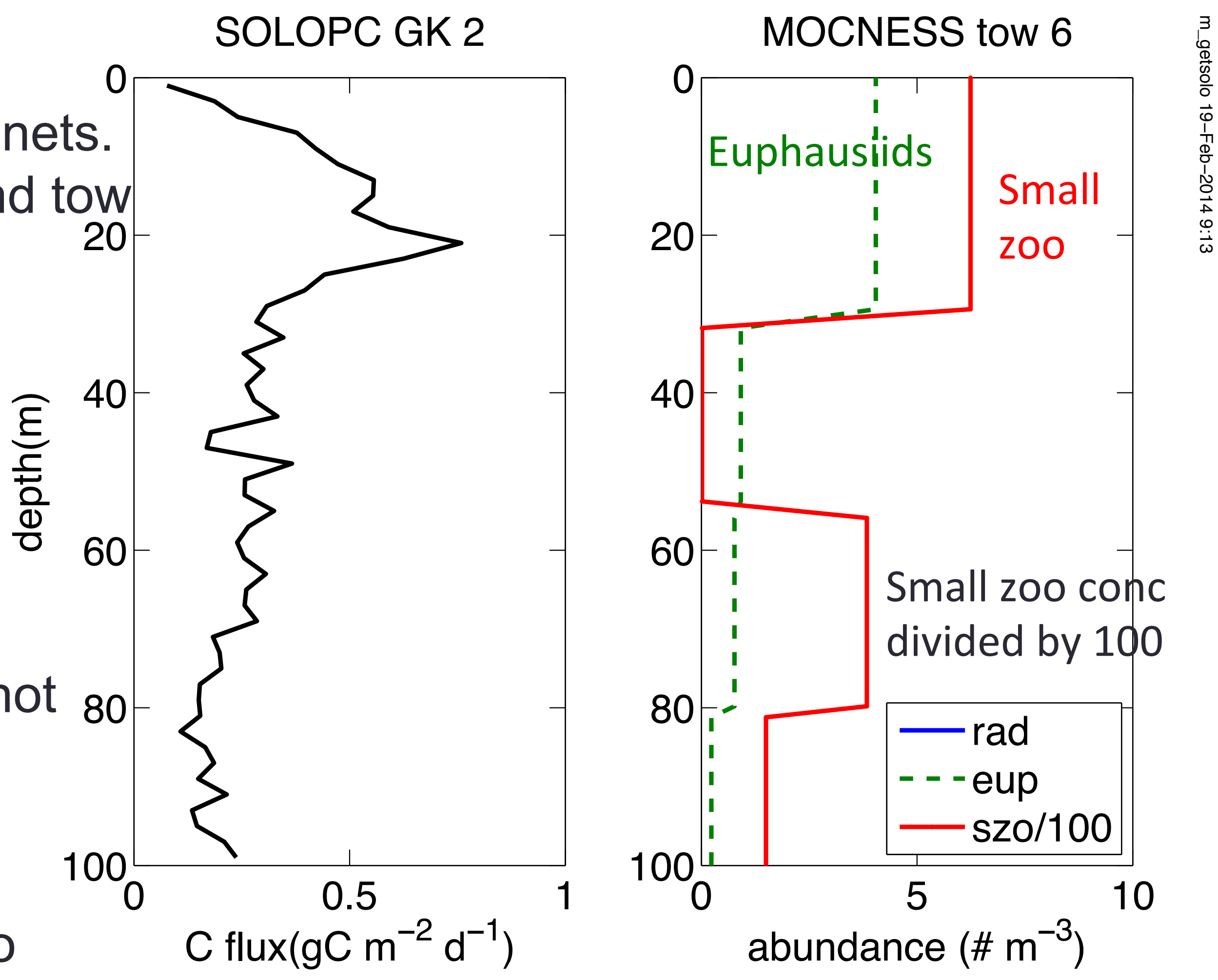
Observ: Zoo distributions vs SOLOPC flux

Animals collected using 202 um mesh MOCNESS nets. Flux estimated in 3h around tow

In this case,
- euphausiids and small zooplankton (e.g *Oncaea*, *Oithona*) are there
- radiolarians are deeper

Caveat: 202 um mesh is not optimal for catching small zoo, radiolaria

Does not capture microzoo

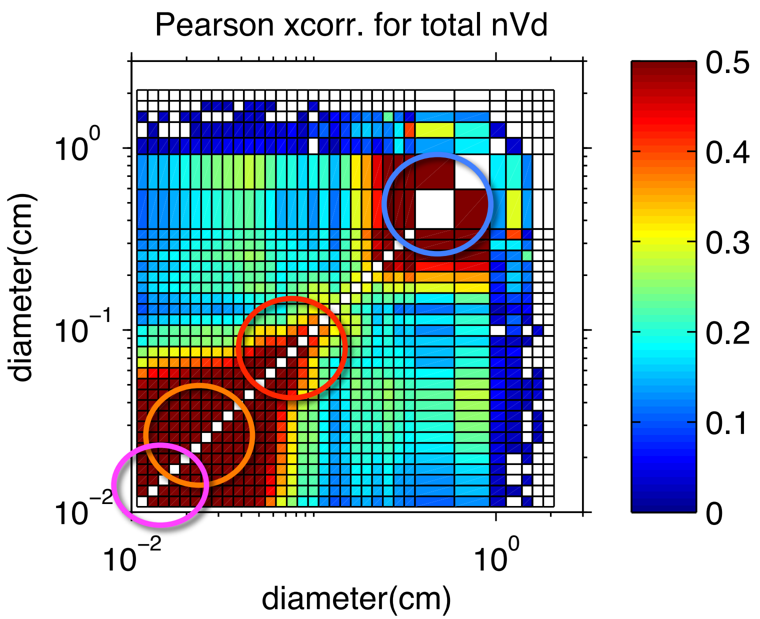


Use SOLOPC data for zoops.

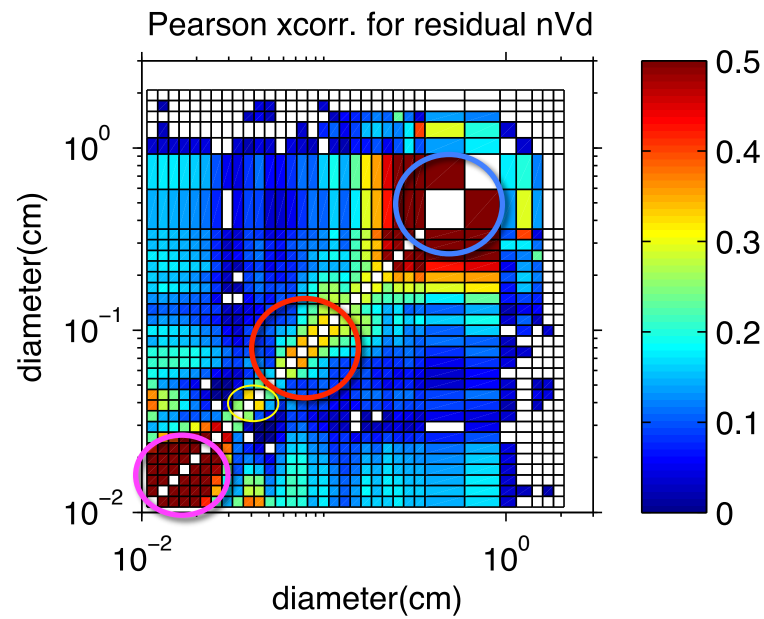
Correlate concentrations in different size bands of LOPC data.
Investigate with and without aggregate contribution.
Plot results as correlation matrix.
Find at least 4 characteristic groups in aggregate-free LOPC data.

1. Aggregates
2. Large 0.5-1 cm (Euphausiids?)
    1. + correlation with aggregate band
3. Medium 0.7-1mm (*Calanus*?)
4. Small 100-250 um (*Oncaea, Oithona*?)

With aggregates



Without aggregates



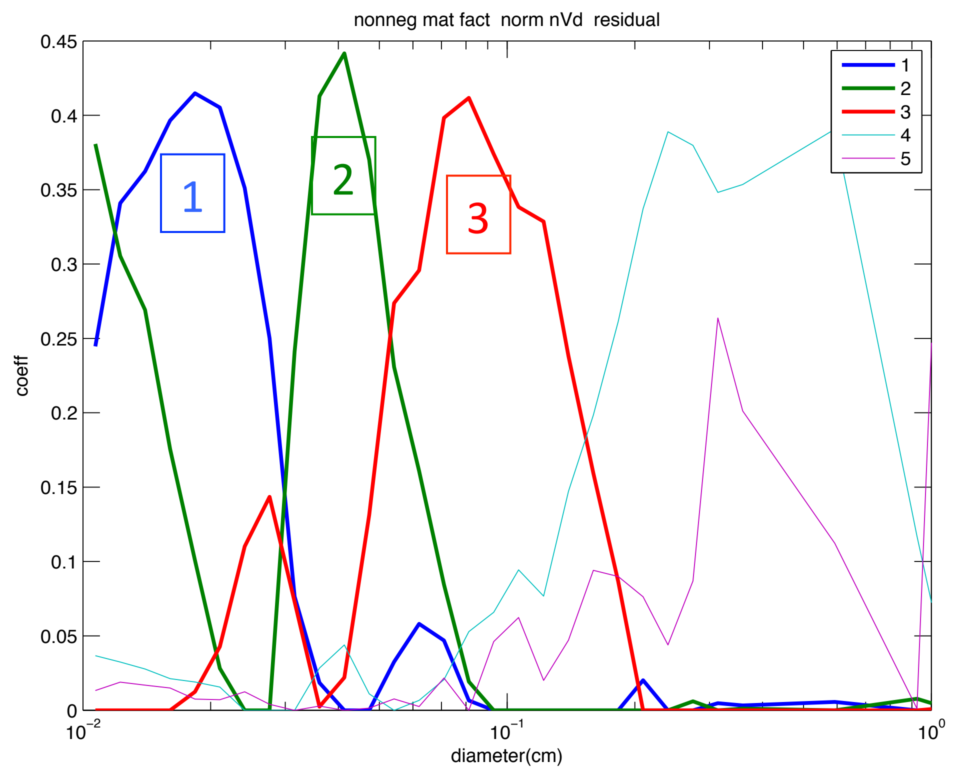
nVdcorr_lump gkpr10_2 gkpr10_2 19−Feb−2014 8:39

Isolate characteristic size-signature from SOLOPC size distributions for animal groups

Use Matlab mumbo-jumbo (nnmf.m) to isolate characteristic size distributions from *nVd* spectra (after removing aggregates)

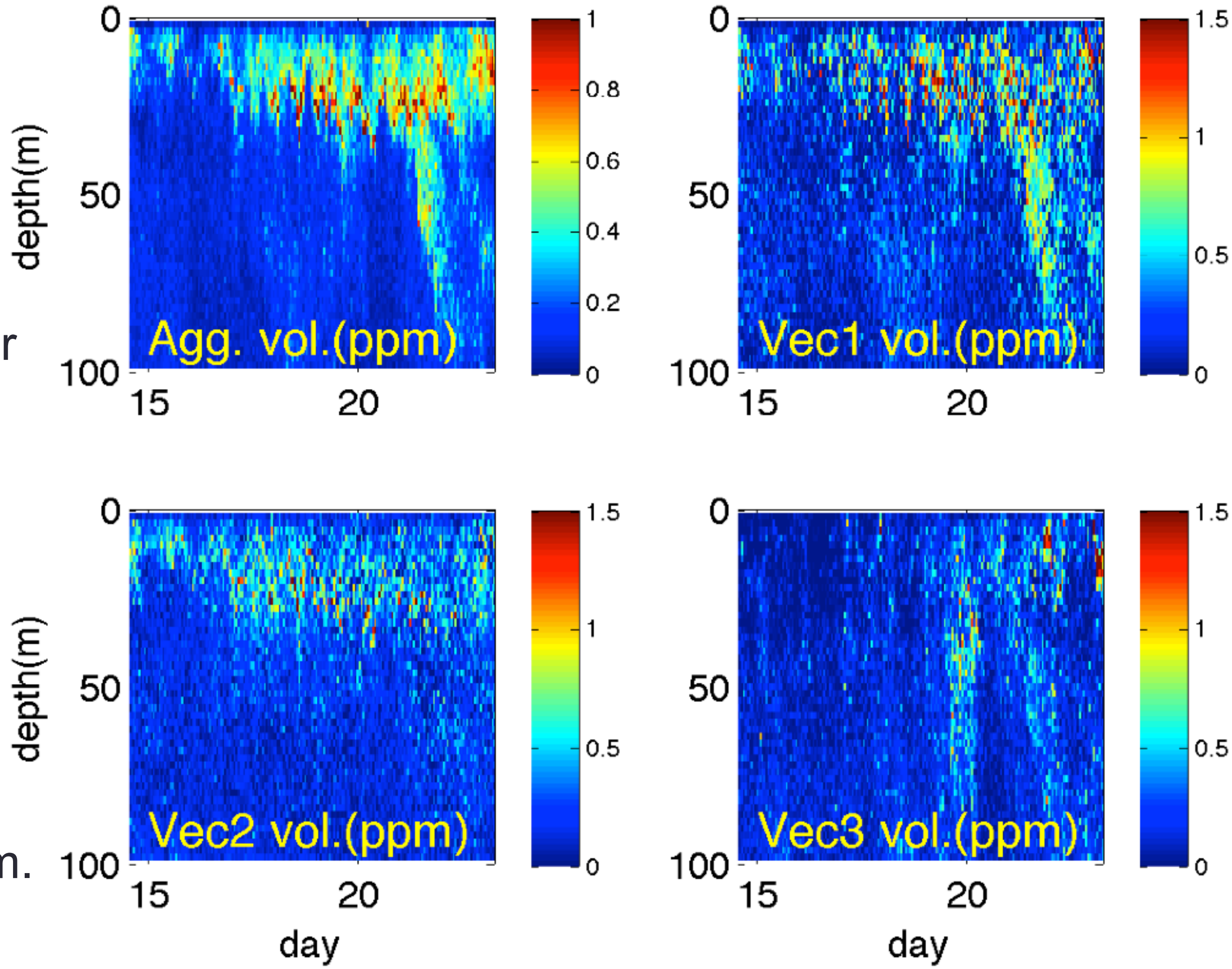
Determine their contributions in the observations.

- 1 - small (100-200 um), similar to *Oithona*, *Oncaea*
- 2 - mid (300-500 um)
- 3 - larger (0.5-1 mm), similar to *Calanus*



How are these zoo groups distributed?

- V1(small): tracks aggs
- V.2 (medium) at part. max, high agg. conc.
- V3(~1mm) occurs later, deeper



Correlation *r* w agg. decrease (-dV/dz)

- V1: 0.29
- V2: 0.46
- V3: 0.18

All action above 50 m.

Is V2 responsible?

V. Summary and Implications

- Feeding is sharply localized at base of particle max.
- Consistent with work by Fiedler, Napp showing feeding by zooplankton deeper than production max.
- Consistent with observations of flux feeding mode for some zooplankton (e.g., *Neocalanus cristatus* Dagg, T&K). Animal choices could be different for flux feeding rather than filter feeding.
- Affects the remineralization of nutrients, vertical flux out of euphotic zone.

Implications-2

- Vertical flux starts in the euphotic zone
- Zooplankton feeding may produce faster sinking fecal pellets, but:
- - it is siphoning off some of the vertical flux into respiration, growth. That is, decreasing flux
- - it is speeding up the individual settling speed, but not increasing the total flux.

- Different processes dominate in different parts of the water column, different locations. There is no one process dominant everywhere, all depths and times.