## Novel Observations of Carbon Export from Autonomous Lagrangian Carbon Flux Explorers

Menu:

**Carbon Flux Explorer**
**High Wintertime Sedimentation in California Coastal Waters**

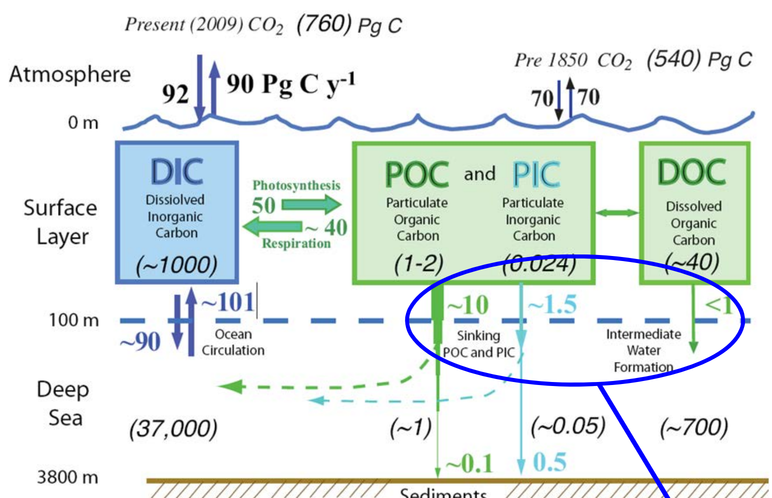
With… Michael Fong, Todd Wood
Tim Loew, Hannah Bourne, Mike Mclune, Mati Kahru
Christina Hamilton, Gabrille Weiss, Imari Walker, Xiao Fu
and many more

*0545 June 22 2007 Recovery of Carbon Flux Explorer*

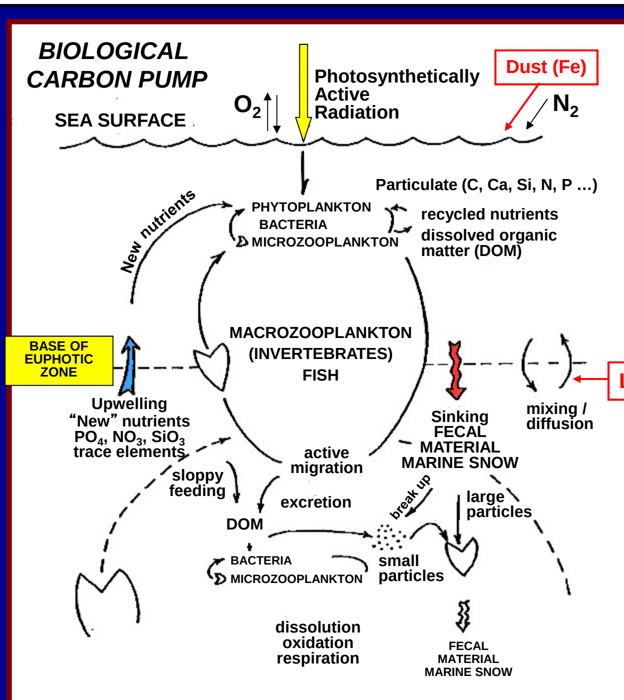
*OCE 1538686*
*OCE 0936143*

Ocean Carbon and Biogeochemistry (OCB) Summer Workshop, Woods Hole July 24-28 *2016*
*IOS/Tully • SIO Instrument Development Group • LBNL Engineering • UCB Undergraduates.*

**Net Thermodynamic $CO_2$ uptake, aka "Solubility Pump"**
**quite well understood & empirically measured**

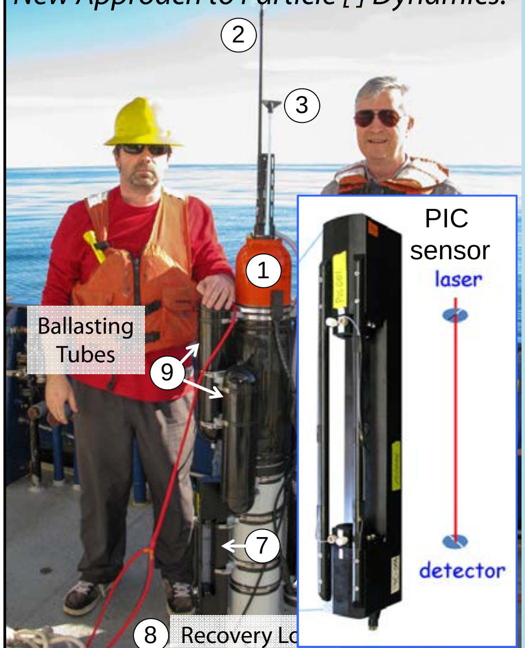



**The Ocean Bio-Carbon pump *is fast*, <u>must be understood</u>.**
**Is today's pump (EXPORT, UPWELLING) in balance?**
**How do we find out?**




# Particle Concentration and Flux Important Indicators of Processes

## *New Approach to Particle [ ] Dynamics:*




OCE 0964888

## *The Carbon Explorer 2.0*

*Deployed at PAPA Feb 2013*

(1) *Modified Scripps SOLO float*

*Fast Profiling*
*(diurnal profiles to 1000m)*
*Long Lived ~1 year*
*(battery limited)*

(2) *Argos Antenna*
(3) *Bi-directional Iridium Satellite Telemetry & GPS*

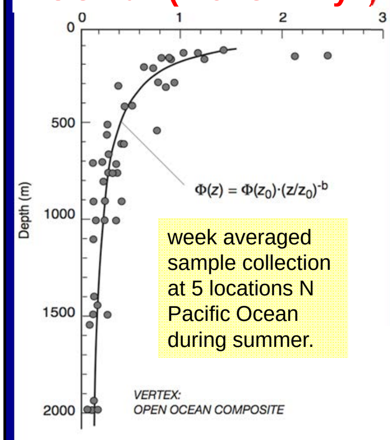
*Temperature, Salinity*
(4) *Particulate Organic Carbon (digital 10 Hz, 14 bits)*
(5) ***Particulate Carbon Flux Index***
(6) *Scattering (analog)*
(7) *Particulate Inorganic Carbon (digital, 10Hz, 14 bits)*

*Mission life expected*
*400,000 m of profiles*

## Challenges of Measuring Particle Fluxes

*1987 Martin et al. formula or varients: used in almost all carbon cycle models*

**POC flux (mol C $m^{-2}$ $y^{-1}$)**




Surface Tethered Sediment Traps

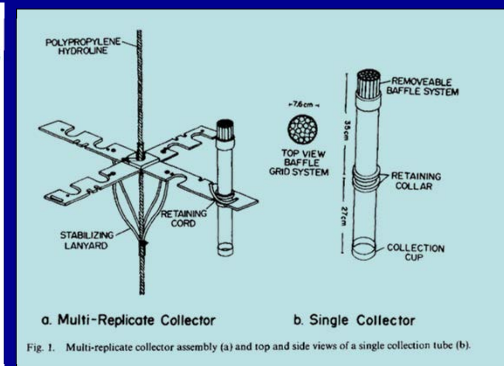
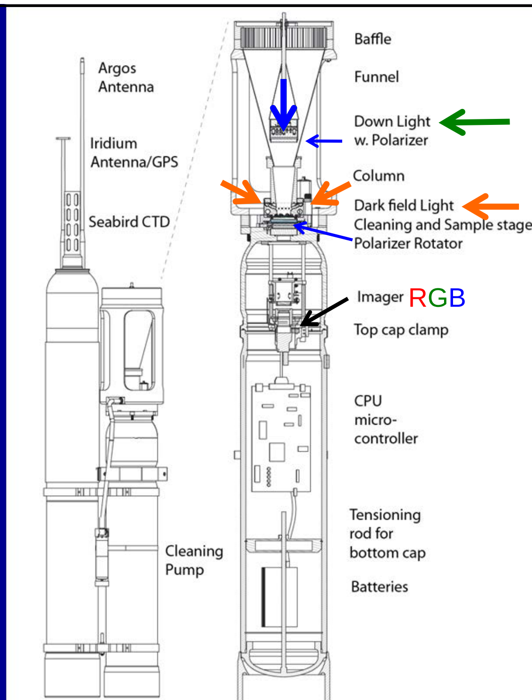



Fig. 1. Multi-replicate collector assembly (a) and top and side views of a single collection tube (b).

Short deployments
Tied to ship availability




3 Lighting modes
Dark Field

Transmission

X polarized Transmission

5 Mpix Imaging (RGB)
*Set f.no, shutter, & focal distance*

Image resolution 13 µm

## OPTICAL QUANTIFICATION OF EXPORT

Attenuance (derived from transmission)

*Proxy for Particulate Organic Carbon*

**$POC_{ATN}$ FLUX --- units: mATN-cm$^2$ cm$^{-2}$ d$^{-1}$**

Birefringence (Cross Polarized Photon Yield)

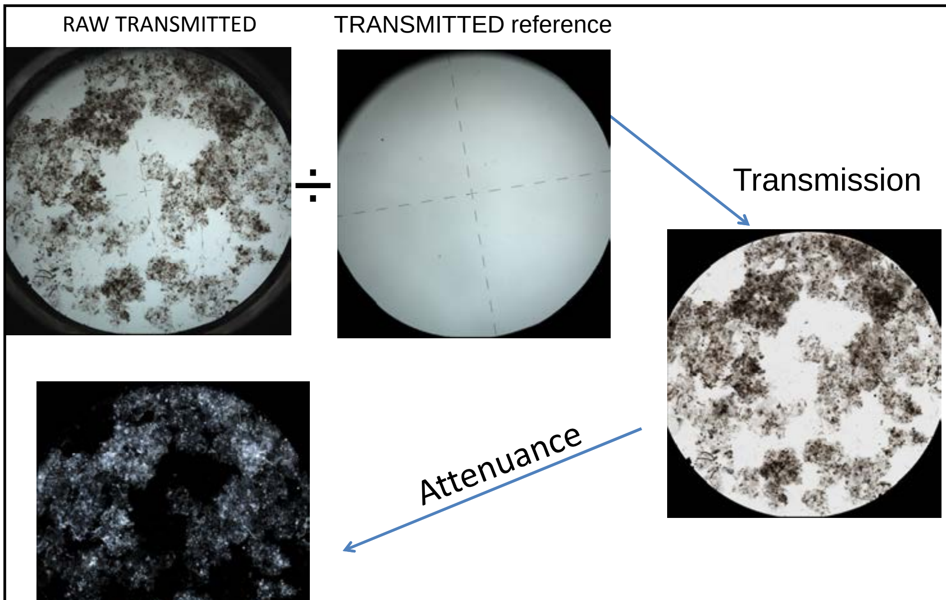
*Proxy for Particulate Inorganic Carbon. ($CaCO_3$) - shell materials that make aggregates sink*

**$PIC_{POL}$ FLUX --- units: ppm-cm$^2$ cm$^{-2}$ d$^{-1}$**

Darkfield: (side illuminated reflectance)

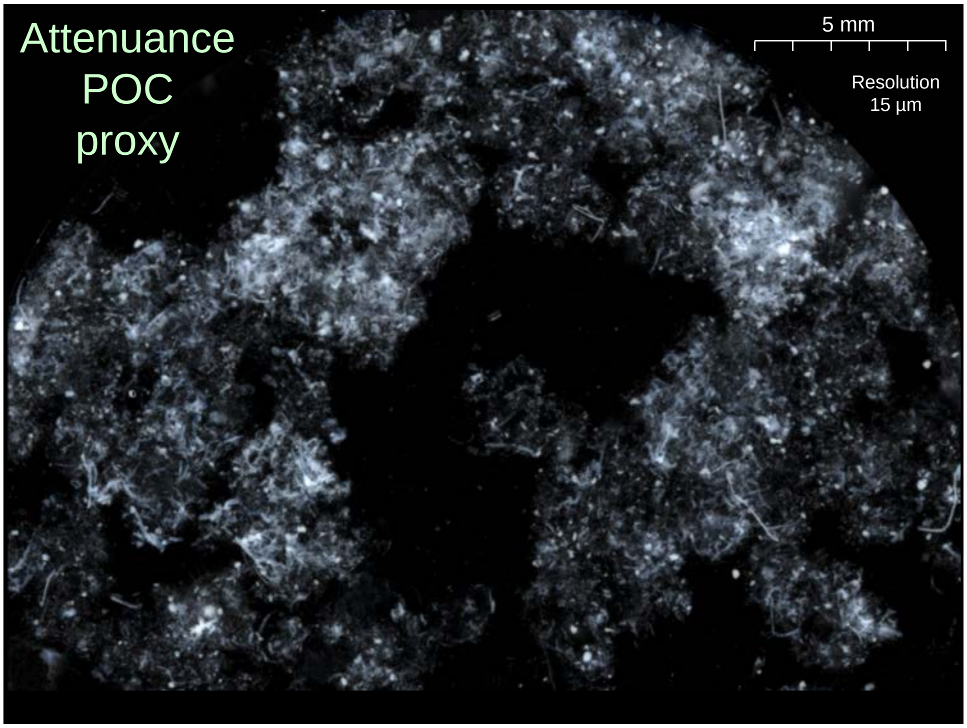
*Color of particles – Pigments – Fine structures – e.g. Other modes possible.*

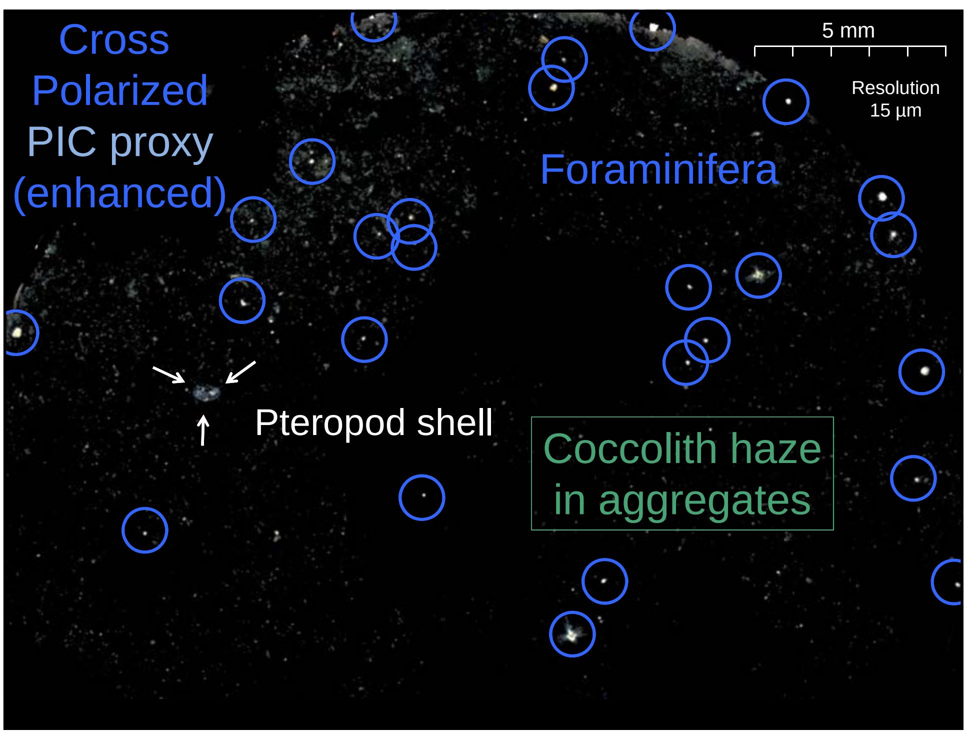
*Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016*

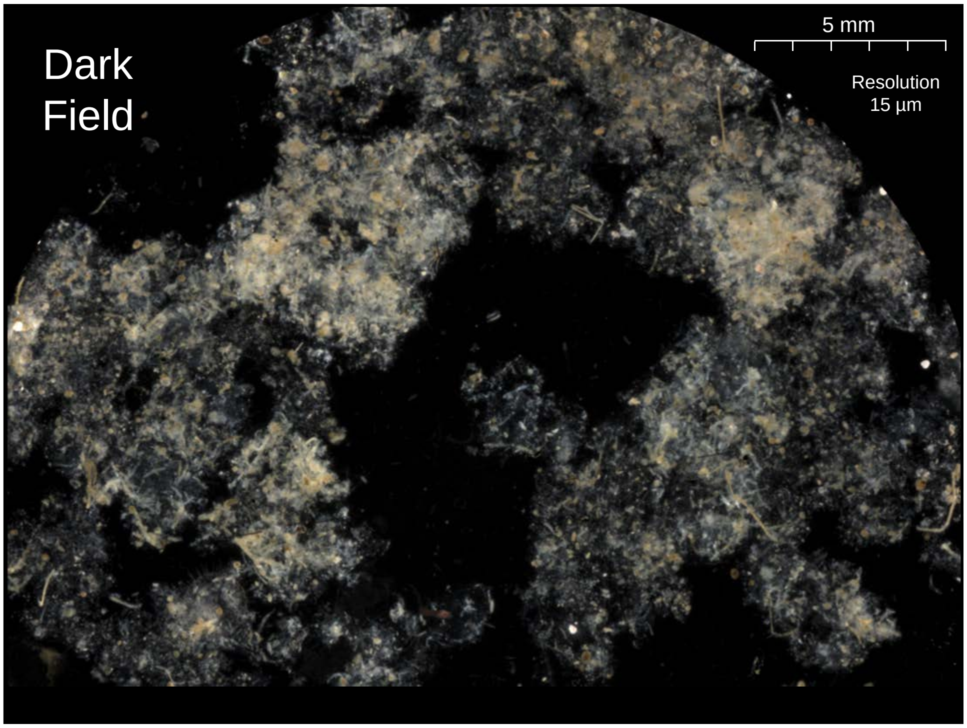



$$ATN = -\log_{10}(\text{Transmission})$$

*Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016*


Attenuance
POC
proxy
5 mm
Resolution
15 µm


Cross
Polarized
PIC proxy
(enhanced)
5 mm
Resolution
15 µm
Foraminifera
Pteropod shell
Coccolith haze
in aggregates



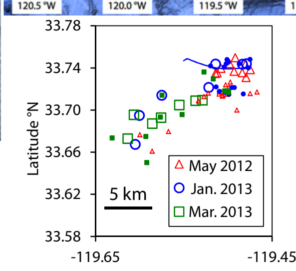

# *Does High Surface Chlorophyll mean high carbon export & sedimentation?*

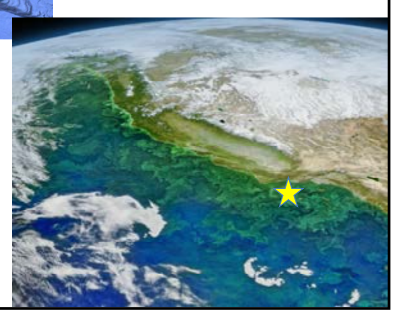


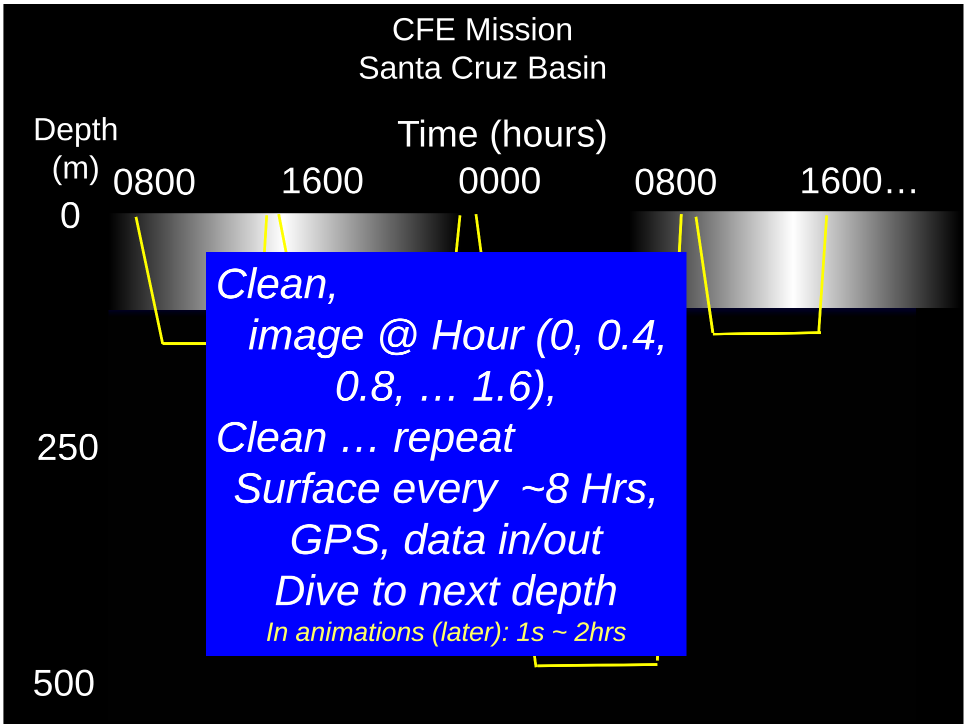
Santa Cruz Basin Study Site

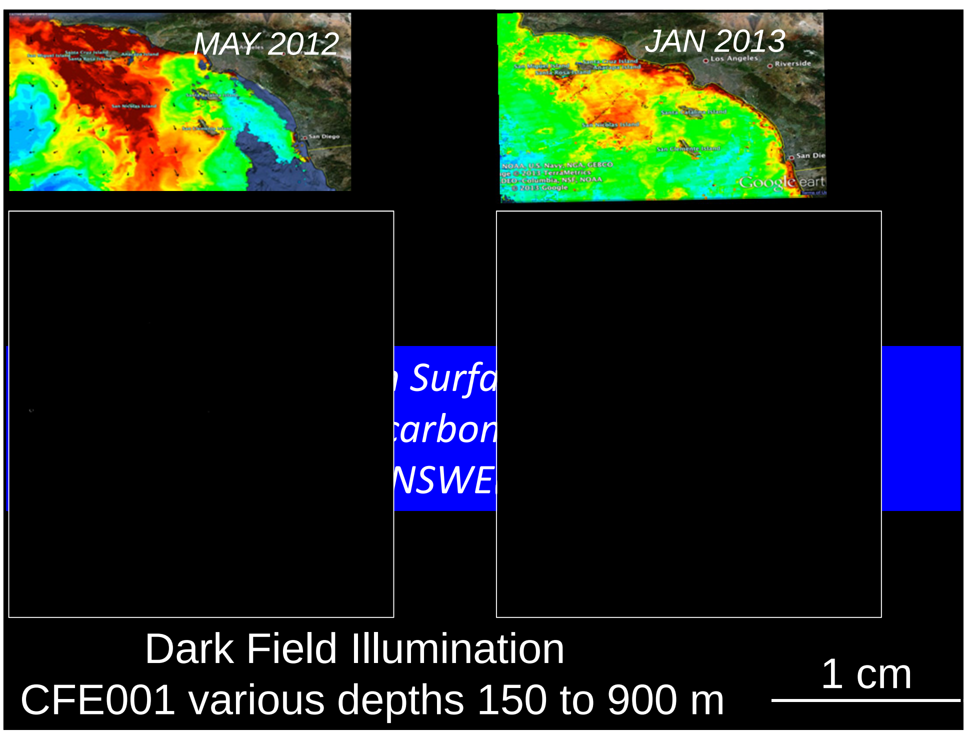
Moored trap deployments
Santa Barbara Basin (SBB)
(e.g. Thunnel 1998)

San Pedro Channel (SPB)
(e.g. Collins et al. 2011)



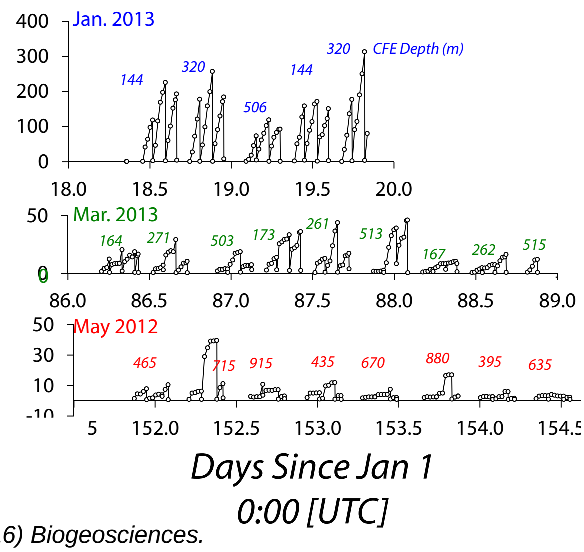




CFE Mission
Santa Cruz Basin
Depth
(m)
Time (hours)
0800
1600
0000
0800
1600…
0
250
500
Clean,
image @ Hour (0, 0.4, 0.8, … 1.6),
Clean … repeat
Surface every ~8 Hrs,
GPS, data in/out
Dive to next depth
In animations (later): 1s ~ 2hrs


MAY 2012
JAN 2013
Dark Field Illumination
CFE001 various depths 150 to 900 m
1 cm

## AVERAGE SAMPLE LOADING TIME SERIES $POC_{ATN}$ (mATN)

Sequential imaging of accumulated Particles over 1.6 hours followed by cleaning

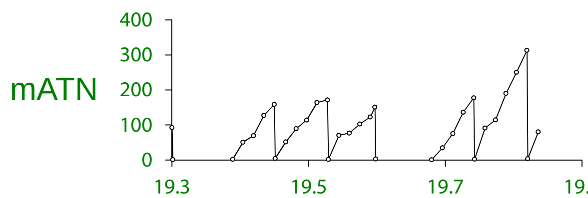



*Bishop et al. (2016) Biogeosciences.*

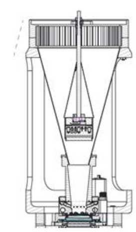
# Calculation of Attenuance Flux:

1) **Volume Attenuance** = Attenuance*Stage area

units: mATN-$cm^2$




Trap area
= 186.2 $cm^2$



Stage area
= 5.07 $cm^2$

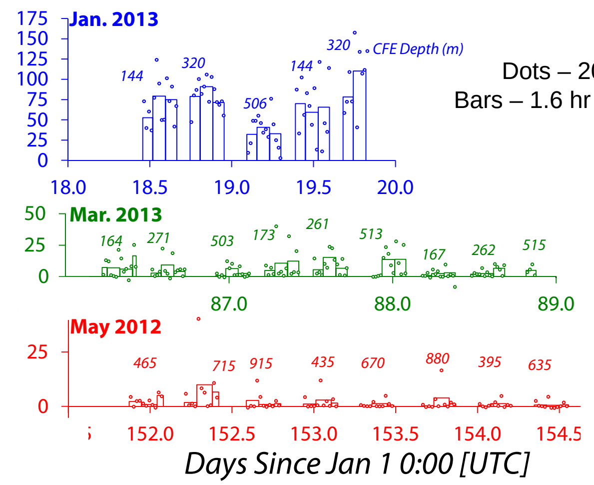
2) **Volume Attenuance Flux** =

$\Delta$Vol. Attenuance/ trap area /$\Delta$t

units: mATN-$cm^2$ $cm^{-2}$ $d^{-1}$

*Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016*

## $POC_{ATN}$ FLUX (mATN-cm$^2$ cm$^{-2}$ d$^{-1}$)

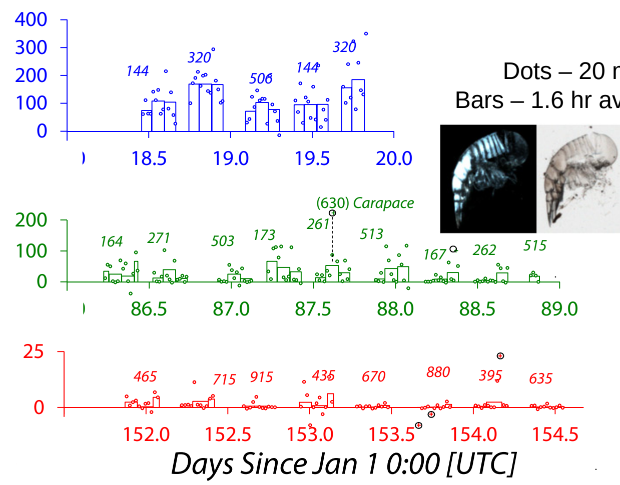



Dots – 20 min flux
Bars – 1.6 hr averaged flux

*Multiply by ~3 to get mmol C m$^{-2}$ d$^{-1}$*

*Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016*

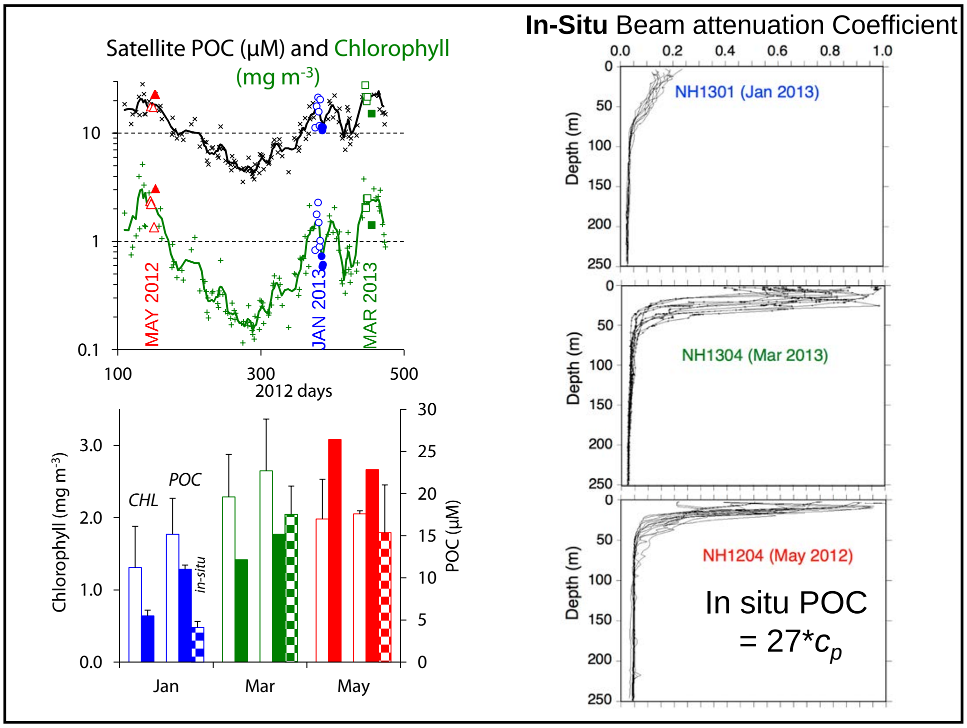
## $PIC_{POL}$ FLUX (ppm-cm$^2$ cm$^{-2}$ d$^{-1}$)

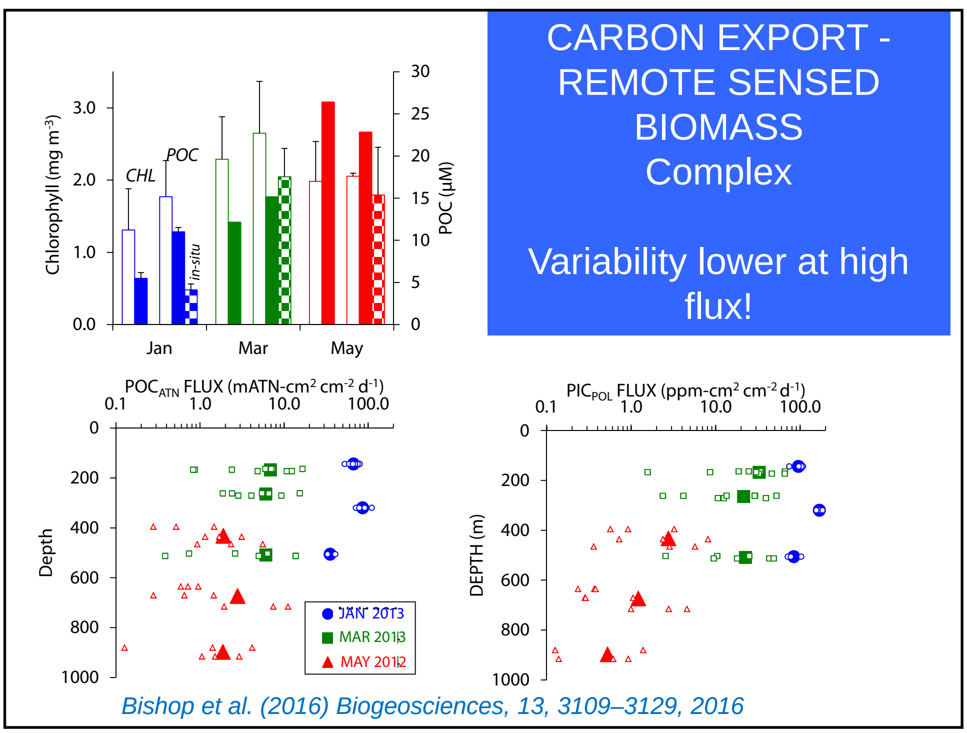



Dots – 20 min flux
Bars – 1.6 hr averaged flux

⊕ carapace and swimmer effect excluded from avg

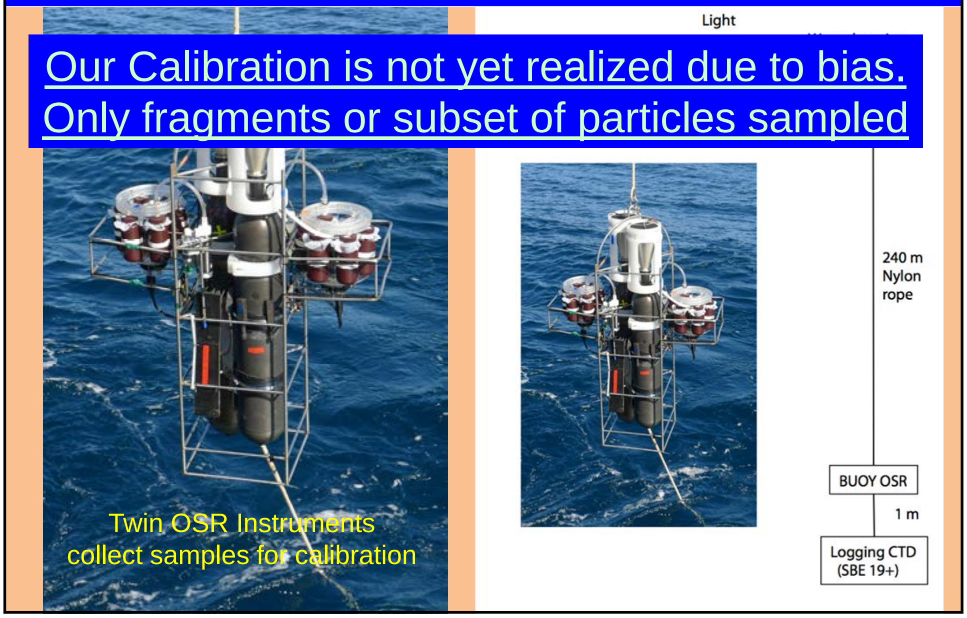
*Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016*

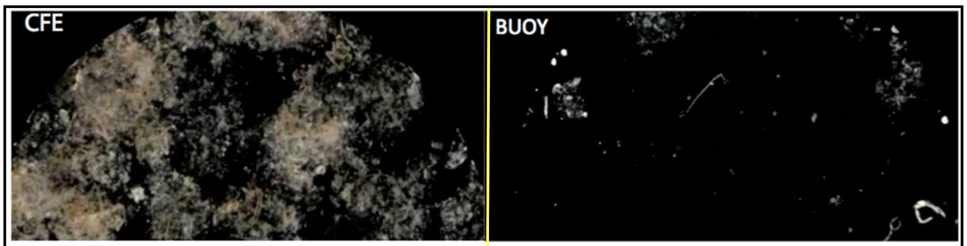

Satellite POC (µM) and Chlorophyll (mg m-3)
MAY 2012
JAN 2013
MAR 2013
2012 days
Chlorophyll (mg m-3)
POC (µM)
CHL
POC
in-situ
Jan
Mar
May
In-Situ Beam attenuation Coefficient
NH1301 (Jan 2013)
NH1304 (Mar 2013)
NH1204 (May 2012)
Depth (m)
In situ POC = 27*c_p


CARBON EXPORT - REMOTE SENSED BIOMASS
Complex
Variability lower at high flux!
Chlorophyll (mg m-3)
POC (µM)
CHL
POC
in-situ
Jan
Mar
May
POC_ATN FLUX (mATN-cm2 cm-2 d-1)
PIC_POL FLUX (ppm-cm2 cm-2 d-1)
Depth
DEPTH (m)
JAN 2013
MAR 2013
MAY 2012
Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016

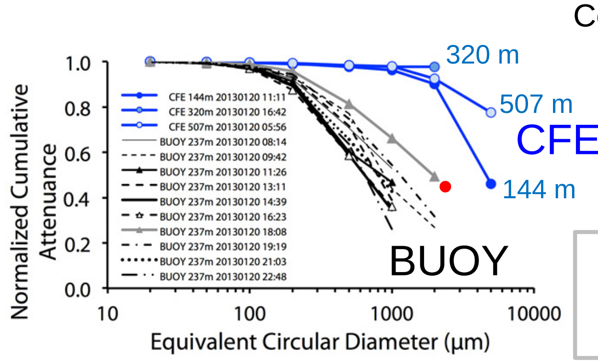
# (2) CALIBRATION OF CFE DATA
# BUOY SYSTEM: Optical Sediment Recorder

Our Calibration is not yet realized due to bias.
Only fragments or subset of particles sampled




← 2.5 cm →




Surface Tethered OSR Collected 1/20th of the particles
*Missed > 1.5 mm particles*

*Buoy saw little >2 mm material • except • when currents across trap <2 cm/sec*

## California Coastal Waters:

- High surface chlorophyll does not imply high sedimentation.
- Low surface chlorophyll (January): a lot hungry grazers – efficient export.
- High surface chlorophyll → left-over veggies
- Most carbonate is calcite (Forams, Coccoliths)
  vs. Preliminary CFE at PAPA – Aragonite &Pteropods
- Coastal Zone Carbon Cycle:
  - POC Flux (surface tethered baffled traps) likely underestimated by a minimum factor of 3 … at times as high as 20!
  - January 2013 Rates exceed highest trap POC flux measured in San Pedro Basin (and Santa Barbara Basin) by 8x.
  - Challenge for continuous observations. Cooperative autonomy or modified Glider?

## *NEXT STEPS for CFE*

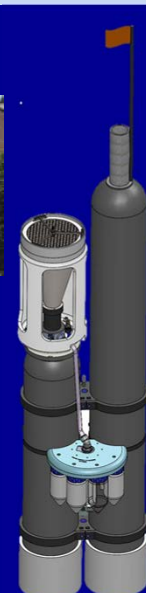
- August 2016. R/V Oceanus.
  First deployments of sample collecting CFE's.
  & PIT traps and McLane Pumps.
- Expect to have image analysis running aboard CFEs. Codes as described above.
- Mission capability 8 months @ hourly

PENDING – full autonomy

- Detection of living organisms.
- Onboard size analysis
  particle classification. E.g. coccoliths vs. Foraminifera vs. Pteropods.
  E.g. aggregate type. Size distribution…

*See Hannah Bourne's poster.*
*OBVIOUS : merge Carbon Explorer and CFE = > OCO float*

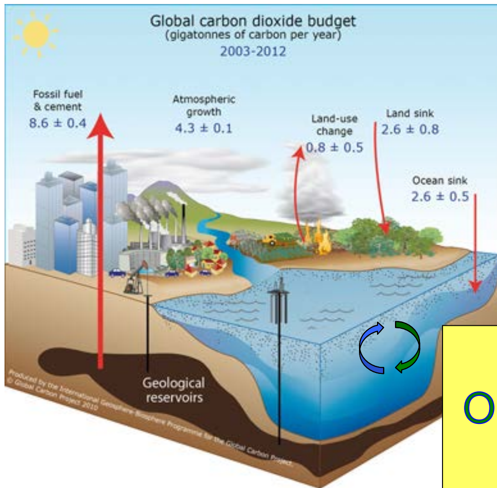
- Add transmissometer, PIC, and scattering …



GLOBAL CARBON PROJECT

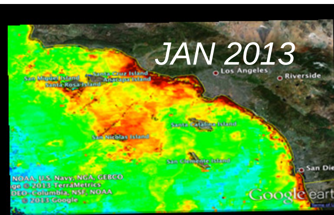
## Anthropogenic Perturbation of the Global Carbon Cycle

Perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2003–2012 (GtC/yr)




Stability of
Ocean Bio C pump
not known
but… can be known

Source: Le Quéré et al 2013; CDIAC Data; NOA




DRK ATN POL

CFE001 various depths 150 to 500 m

1 cm

20130120_123947_bckr

### Estimate of POC FLUX

Size analysis =>
equivalent circular diameter (d)
using ImageJ

+ empirical thickness, h (*fn* of d)
From Bishop et al. 1978.

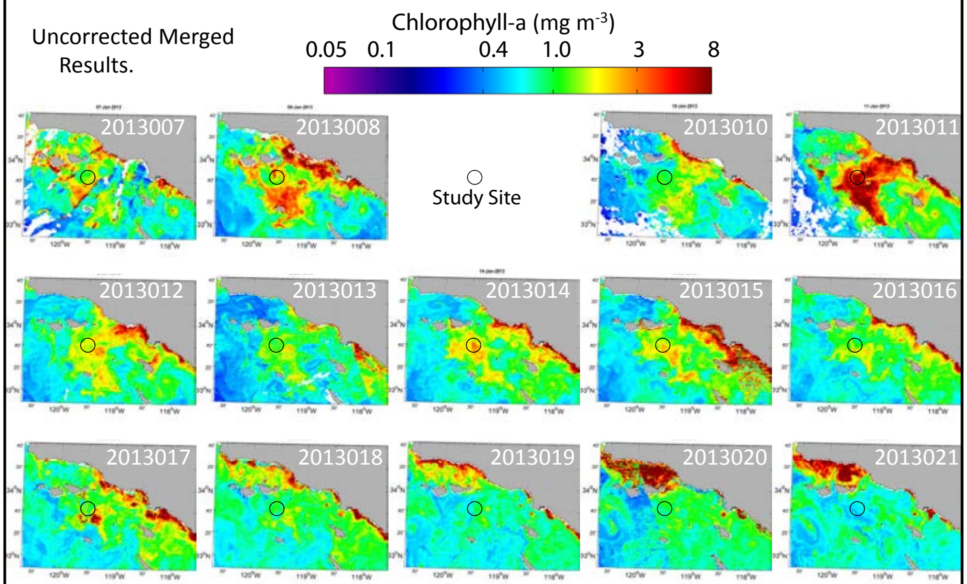
⇒ Aggregate volume = 0.113 $cm^3$

Dry weight Aggregate density 0.087 $g/cm^3$
From Bishop et al. 1978.

and ORG Matter fraction = 60%
=> ORG Mass = 0.0059 g
OM:C 1.88 (From Hedges)
⇒ C moles = 0.00026
Then use
Trap area = 0.0186 $m^2$
Time days = 0.0766

⇒ POC Flux = 183 mmol $C/m^2/d$
Vol Attn Flux = 66.2 => factor = 2.8

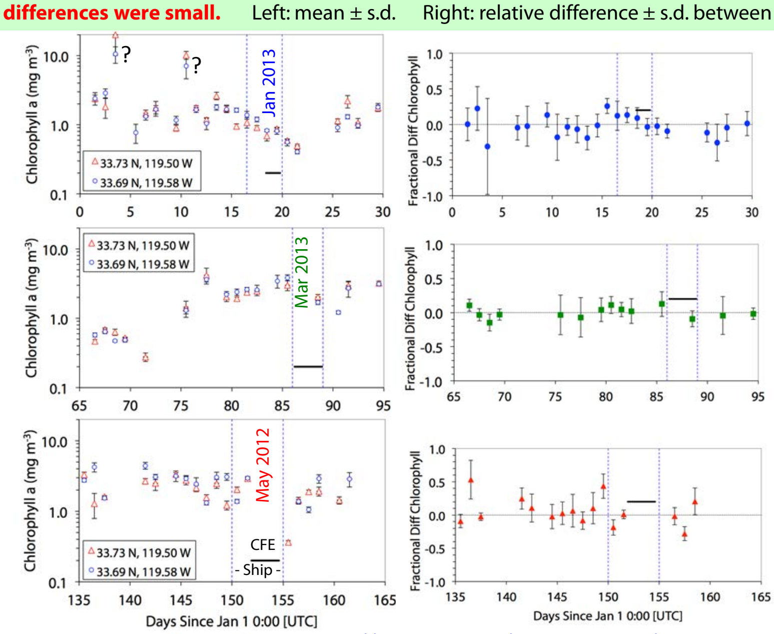
# Merged 1 Km Chlorophyll from Modis Aqua/Terra and VIIRS



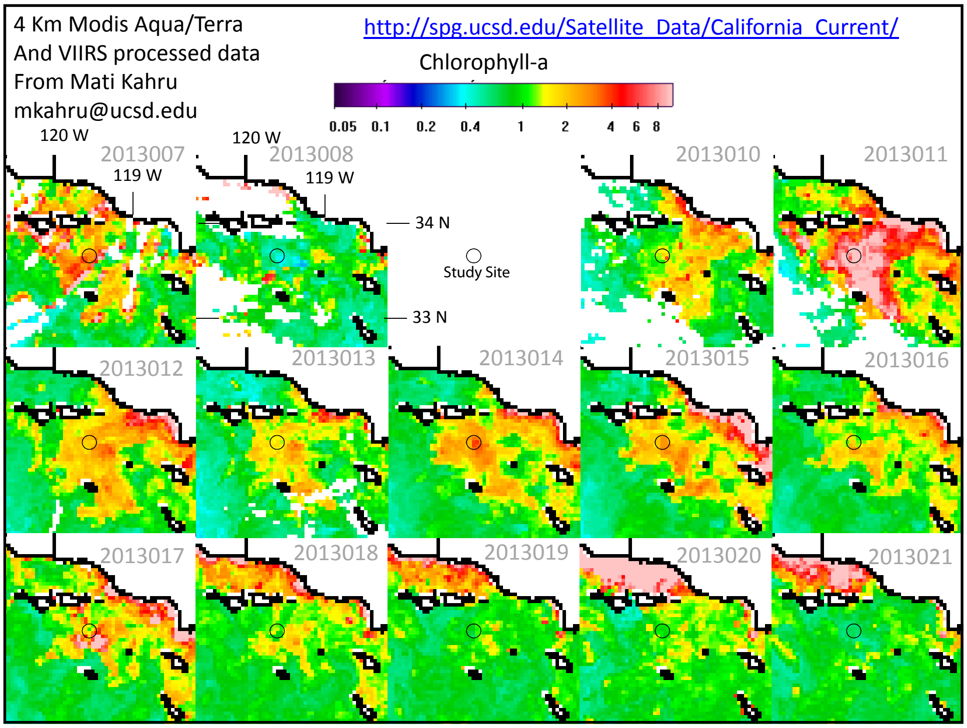

Mati Kahru mkahru@ucsd.edu
Replotted by Michael Fong

http://spg.ucsd.edu/Satellite_Data/California_Current/

**Were there significant spatial gradients near our study site at 1 km resolution?**
We searched 1 km satellite data within 2 km radius of 33.73N, 119.50W and 33.69N 119.58W.
**The differences were small.** Left: mean ± s.d. Right: relative difference ± s.d. between sites.



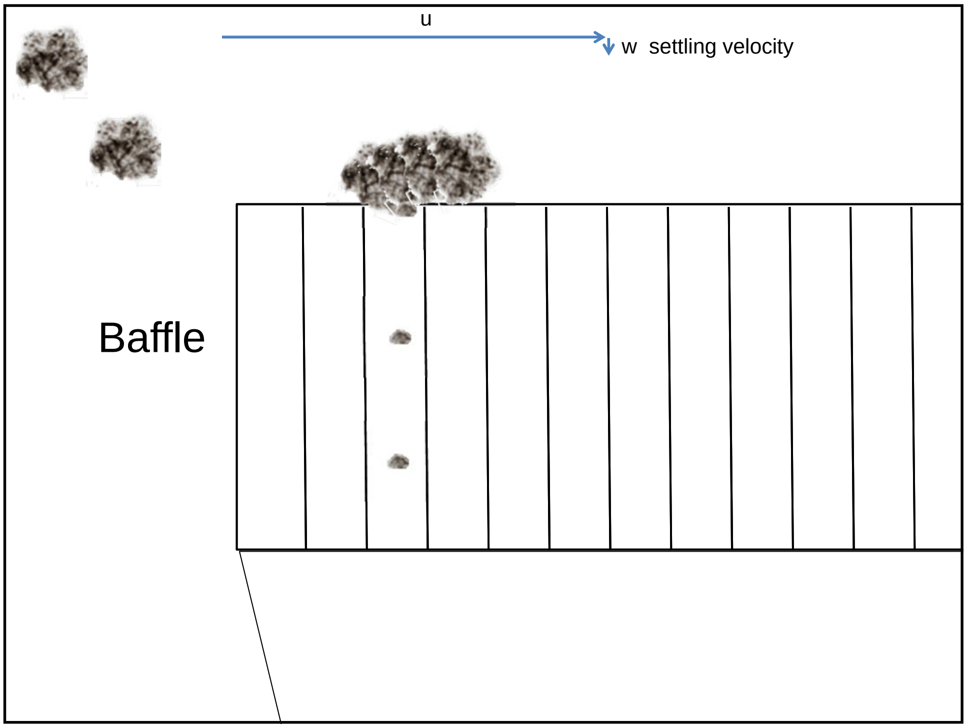

http://spg.ucsd.edu/Satellite_Data/California_Current/




Are Baffles a problem?

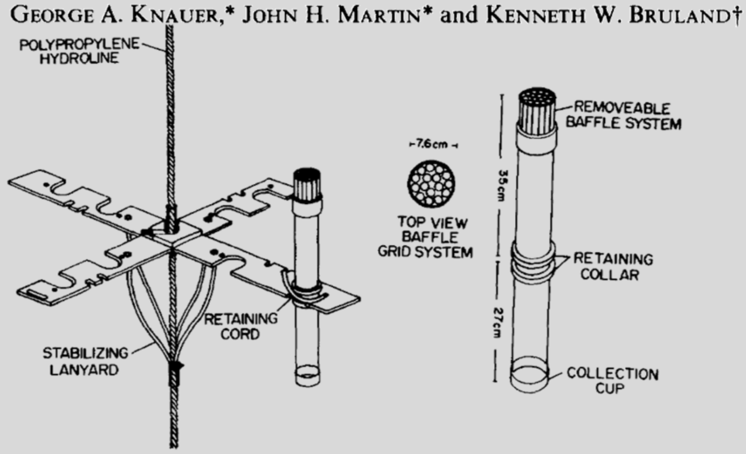
Aggregates that were lost were ~50% the size of the baffle openings

Horizontal Currents
10-20 cm/sec




**Fluxes of particulate carbon, nitrogen, and phosphorus in the upper water column of the northeast Pacific**

GEORGE A. KNAUER,* JOHN H. MARTIN* and KENNETH W. BRULAND†




a. Multi-Replicate Collector b. Single Collector

*K&M 1979. Defined the standard for particle flux sampling in upper ocean*
*Impossible to validate in coastal waters*

"Each tube had an inside diameter of 7.39 cm and was equipped with a baffle system (SOUTAR et al., 1977) that consisted of 16 smaller tubes (length 7.6cm). The top ends of the baffle tubes had been milled to a wall thickness of 0.06 mm to minimize surface area (about 5% of the cylinder mouth area which is 43 cm 2). We assume that materials hitting these edges fall into the collectors and contribute to the total flux. GARDNER (1977) has shown that open cylinders with a length-to-width ratio of approximately 2 or greater will yield representative fluxes. With our use of a baffle system, an adequate length-to-width ratio (8.4) and density gradients (see below), **we assume** that our traps sample the vertical flux" of particulate matter with reasonable accuracy. We also have 210pb data (see below) supporting our assumptions. However, like other investigators attempting to measure vertical fluxes, we presently have no way of definitely knowing whether our supposition is correct.

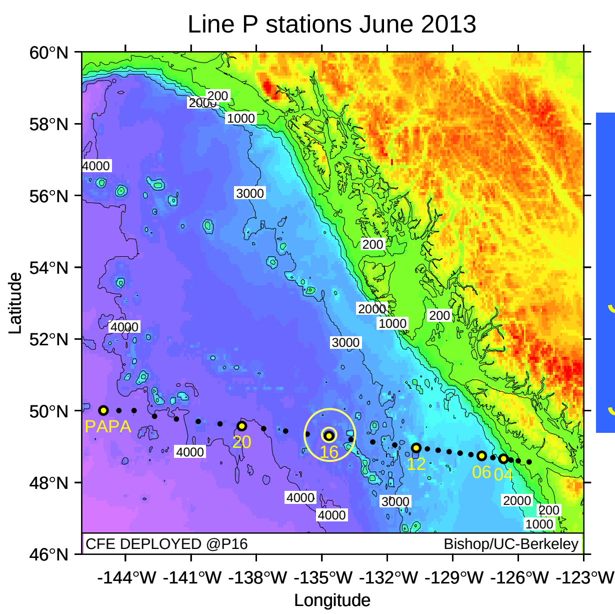
*K&M 1979. Defined the standard for particle flux sampling in upper ocean*

Tried Adding
2:1 Cylinders

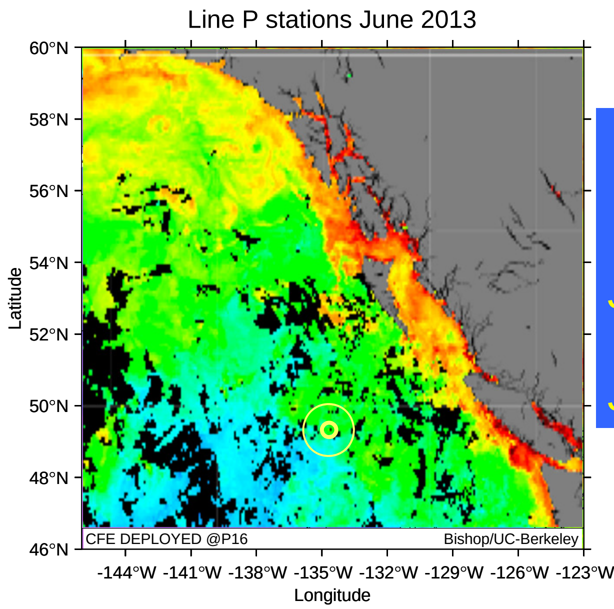
No significant
improvement

# Line P

- Corg flux ~ 4.5 to 3 mmol C $m^{-2} d^{-1}$
- Significant contamination by Cyprid Barnacle Larve (origin?). Seen in upper 300 m.
- Both CFE002 and CFE003 Saw reproduction event
  Clio Pteropods at 150 m.
- Most PIC was Aragonite!



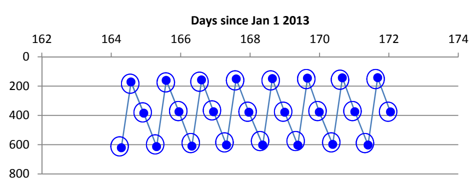

CFE 002
CFE003
Deployed
June 13 2013
Recovered
June 22 2013

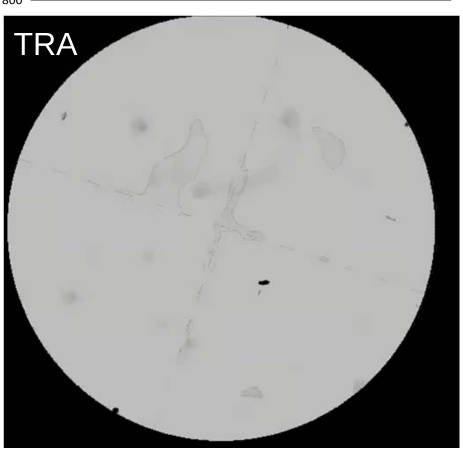



CFE 002
CFE 003
Deployed
June 13 2013
Recovered
June 22 2013

Monthly composite

CFE 003 at P16

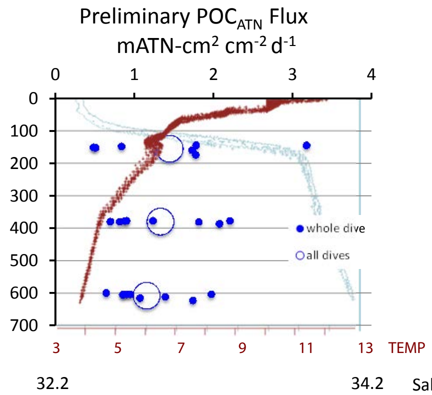


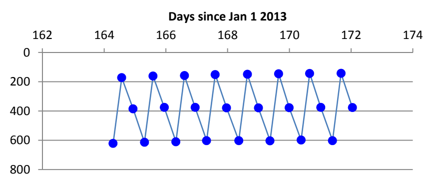


*MOST PIC FLUX IS ARAGONITE*

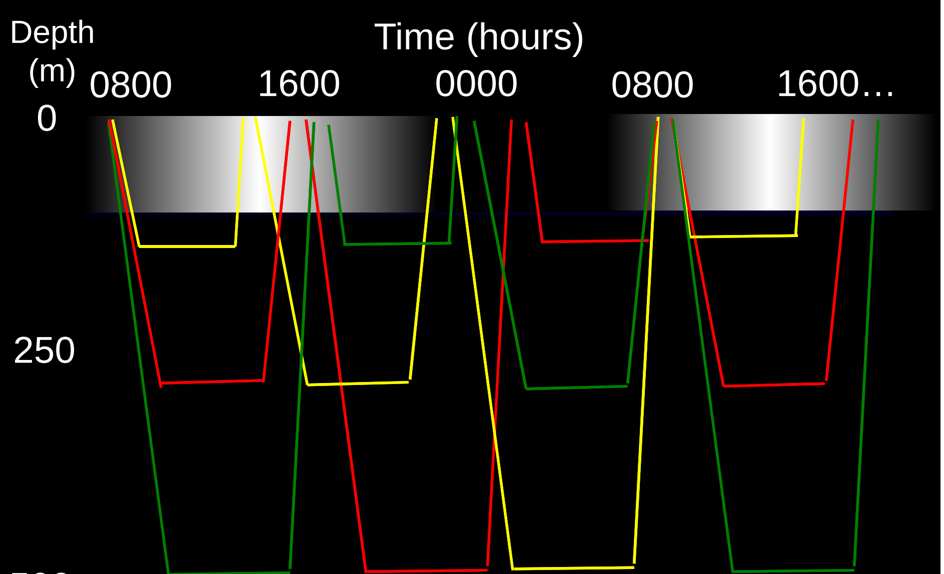
## CFE 003



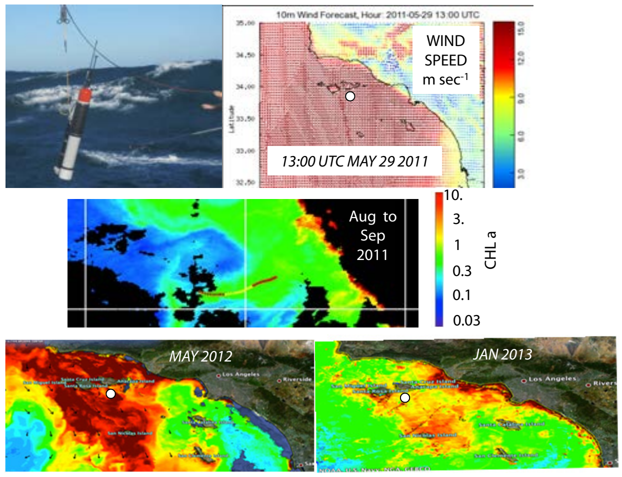

*Multiply by 3 to get mmol C $m^{-2}$ $d^{-1}$*




## CFE Mission
Sedimentation variability at 3 depths



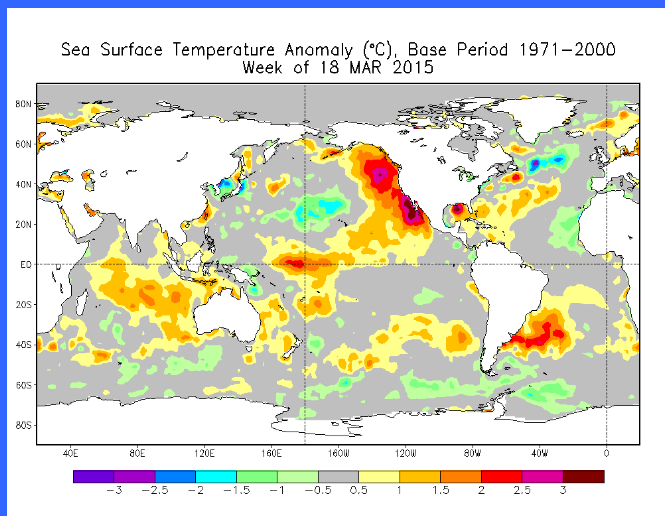

*Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016*




## Summary: Ocean Known Unknowns

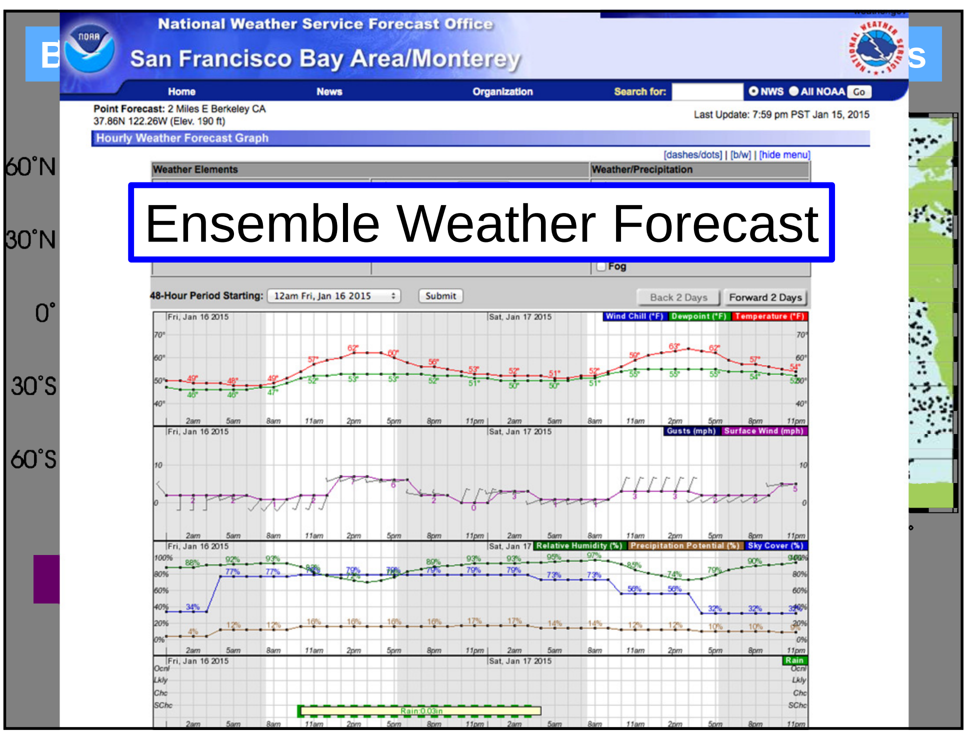
- Lack of prediction of Natural Ocean C Pump which moves 10 Pg C/yr.
- No way to assess OBCP stability without observations. Few last decade.
- Remote Sensing biomass to C Export not yet agreed on – even the sign of the trend with respect to biomass / primary production.
- Coastal Zone: Likely underestimated C export
- A Carbon-ARGO program/w. ensemble deployments of Carbon Explorer/ Carbon Flux Explorer robots in key ocean areas will lead to far better C Prediction.

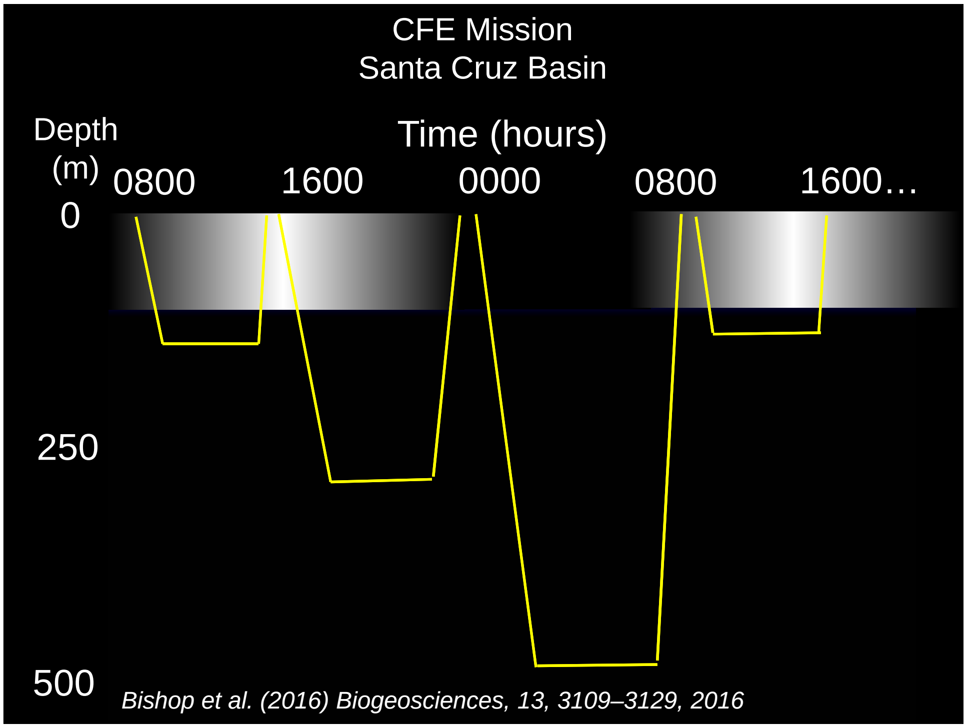
## Observations of Inter-annual Variability of C fluxes will lead to prediction of future BIOPUMP changes




Anomalous SSTs have lead to 2nd year of extreme drought in CA

http://www.ncdc.noaa.gov/teleconnections/enso/indicators/sea-temp-anom.php?




CFE Mission
Santa Cruz Basin
Depth (m)
Time (hours)
0800
1600
0000
0800
1600…
0
250
500
Bishop et al. (2016) Biogeosciences, 13, 3109–3129, 2016