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, Gabrielle Weiss, Imari Walker, Xiao Fu
and many more

Net Thermodynamic CO₂ uptake, aka “Solubility Pump”
quite well understood & empirically measured

The Ocean Bio-Carbon pump is fast, must be understood.
Is today’s pump (EXPORT, UPWELLING) in balance?
How do we find out?
Photosynthetically Active Radiation

SEa Surface Particulate (C, Ca, Si, N, P ...)

recycled nutrients
dissolved organic matter (DOM)

PHYTOPLANKTON
BACTERIA
MICROZOOPLANKTON

MACROZOOPLANKTON
(INVERTEBRATES)

active migration
excretion

DOM
dissolution
oxidation
respiration

Sinking
FECAL MATERIAL
MARINE SNOW

large particles

Sinking
FECAL MATERIAL
MARINE SNOW

Lateral (Fe...)

Upwelling
“New” nutrients
PO₄, NO₃, SiO₃ trace elements

sloppy feeding

active migration
excretion

Dust (Fe)

New Approach to Particle [ ] Dynamics:

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
   Bi-directional Iridium Satellite
   Telemetry & GPS

   Temperature, Salinity

3. Particulate Organic Carbon
   (digital 10 Hz, 14 bits)

4. Particulate Carbon Flux Index
   Scattering (analog)

5. Particulate Inorganic Carbon
   (digital, 10 Hz, 14 bits)

6. Mission life expected
   400,000 m of profiles

OCE 0964888
Challenges of Measuring Particle Fluxes

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

Surface Tethered Sediment Traps

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

Week averaged sample collection at 5 locations N Pacific Ocean during summer.

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\textsubscript{ATN} FLUX --- units: mATN-cm\textsuperscript{2} cm\textsuperscript{-2} d\textsuperscript{-1}

Birefringence (Cross Polarized Photon Yield)
Proxy for Particulate Inorganic Carbon.
(CaCO\textsubscript{3}) - shell materials that make aggregates sink
PIC\textsubscript{POL} FLUX --- units: ppm-cm\textsuperscript{2} cm\textsuperscript{-2} d\textsuperscript{-1}

Darkfield: (side illuminated reflectance)
Color of particles – Pigments – Fine structures – e.g.  Other modes possible.


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

Attenuance POC proxy

Cross Polarized PIC proxy (enhanced)

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. Thunell 1998)
San Pedro Channel (SPB)
(e.g. Collins et al. 2011)
CFE Mission
Santa Cruz Basin

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

ANSWER: NO
AVERAGE SAMPLE LOADING TIME SERIES POC$_{ATN}$ (mATN)

Sequential imaging of accumulated Particles over 1.6 hours followed by cleaning

Days Since Jan 1
0:00 [UTC]

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$^{-1}$

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$^{-1}$


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

In situ POC = 27°cρ

CARBON EXPORT - REMOTE SENSED BIOMASS Complex
Variability lower at high flux!

(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.

Twin OSR Instruments collect samples for calibration.

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 ...
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)

Source: Le Quéré et al 2013; CDIAC Data; NOAA/ESRL Data; Global Carbon Project 2013

Stability of Ocean Bio C pump not known but... can be known
CFE001 various depths 150 to 500 m

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 cm³

Dry weight Aggregate density 0.087 g/cm³
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 m²
Time days = 0.0766
⇒ POC Flux = 183 mmol C/m²/d
Vol Attn Flux = 66.2 ⇒ factor = 2.8
Merged 1 Km Chlorophyll from Modis Aqua/Terra and VIIRS

Uncorrected Merged Results.

Chlorophyll-a (mg m⁻³)

<table>
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<th>0.05</th>
<th>0.1</th>
<th>0.4</th>
<th>1.0</th>
<th>3</th>
<th>8</th>
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![Image of chlorophyll maps with study site indicated]

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.

![Graphs showing chlorophyll data over time]

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

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 7.6 cm). 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 cm²). 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!

46° N
48° N
50° N
52° N
54° N
56° N
58° N
60° N

Line P stations June 2013

CFE DEPLOYED @ P16
Bishop/UC-Berkeley

CFE 002
CFE003
Deployed
June 13 2013
Recovered
June 22 2013
Line P stations June 2013

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

MONTHLY COMPOSITE

CFE 003 at P16

MOST PIC FLUX IS ARAGONITE
Preliminary POC$_{ATN}$ Flux
mATN-cm$^2$ cm$^{-2}$ d$^{-1}$

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

Depth (m) | Time (hours)
---|---
0 | 0800 1600 0000 0800 1600...
250
500

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

CFE Mission
Santa Cruz Basin

Depth (m)

0 0800 1600 0000 0800 1600...

250

500