EXOIS EXPLORING OCEAN IRON SOLUTIONS

Quantifying the Biological Carbon Pump with Tracer Budget Approaches

Yibin Huang[1,2,3]

Collaborators: Andrea Fassbender[1,2]

[1]NOAA's Pacific Marine Environmental Laboratory, USA

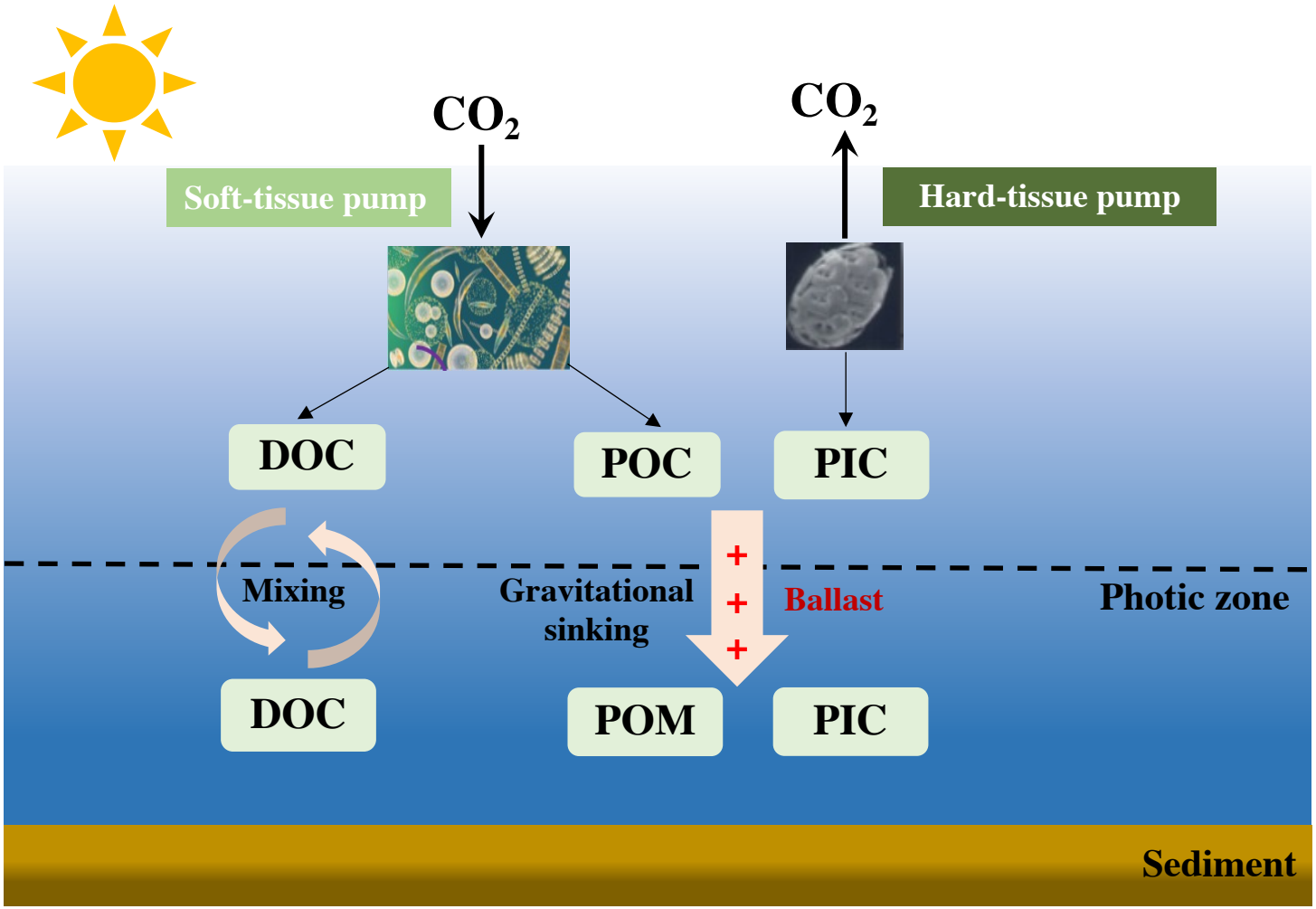
[2]Cooperative Institute for Marine and Atmospheric Research, University of Hawaii, Manoa, USA

[3]Department of Ocean Sciences, University of California, Santa Cruz, USA

February 20th, 2023

NOAA PMEL UNIVERSITY OF HAWAI'I UNIVERSITY OF CALIFORNIA SANTA CRUZ NSF NASA EXPORTS EXport Processes in the Ocean from RemoTe Sensing

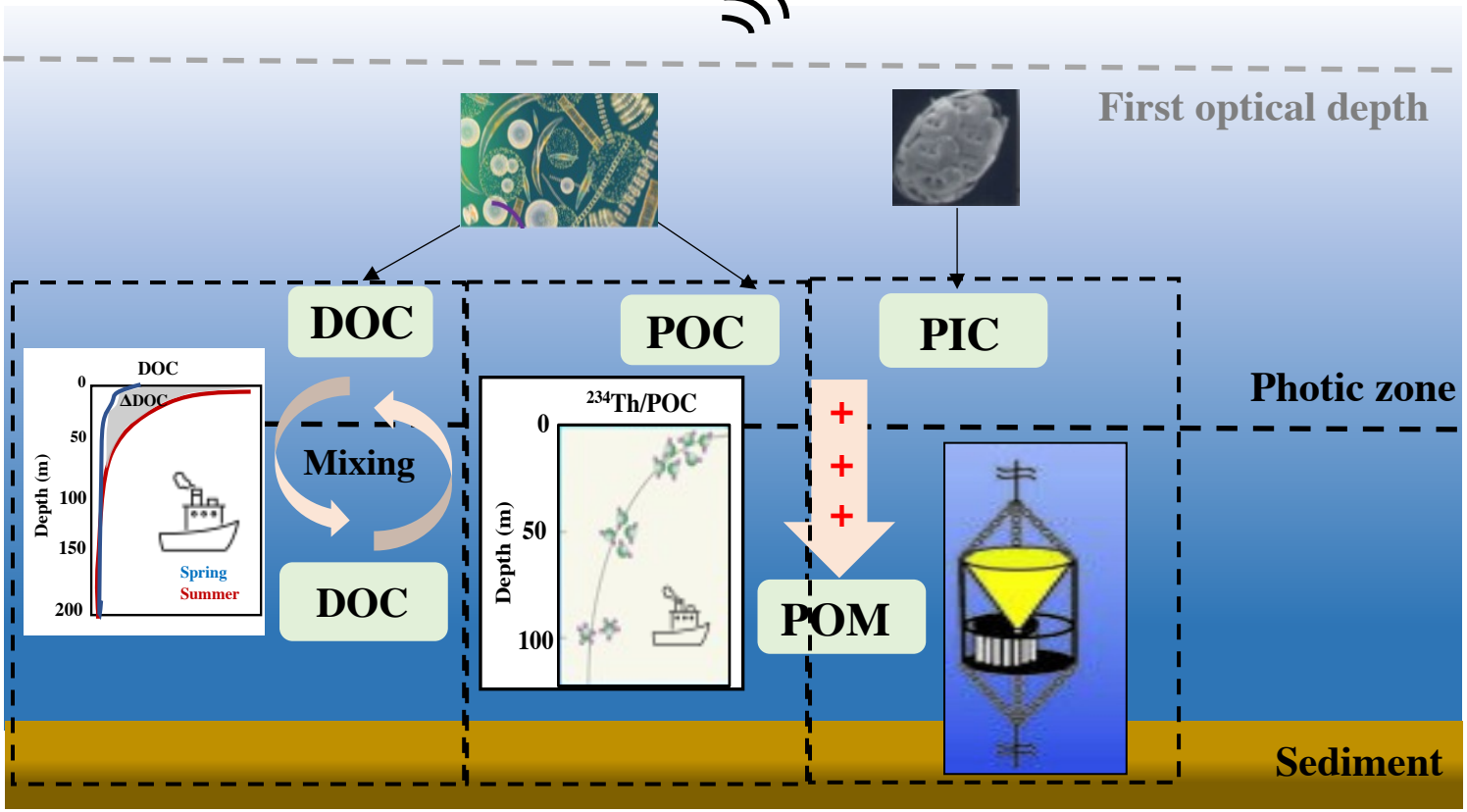
➢ Determine the biological pump functionally and oceanic CO_2 uptake



Buesseler *et al*., (2020): 10.1073/pnas.1918114117; Henson *et al*., (2009): 10.5670/oceanog.2009.109; Boyd *et al*., (2019): 10.1038/s41586-019-1098-2; Sarmiento *et al*., (2002): 10.1029/2002gb001919.

Traditional Approaches to Constrain the Biological Pump

Laws *et al*., (2000 & 2011)
Henson *et al*., (2009)
Li and Cassar *et al*., (2016)
Dunne *et al*., (2005)

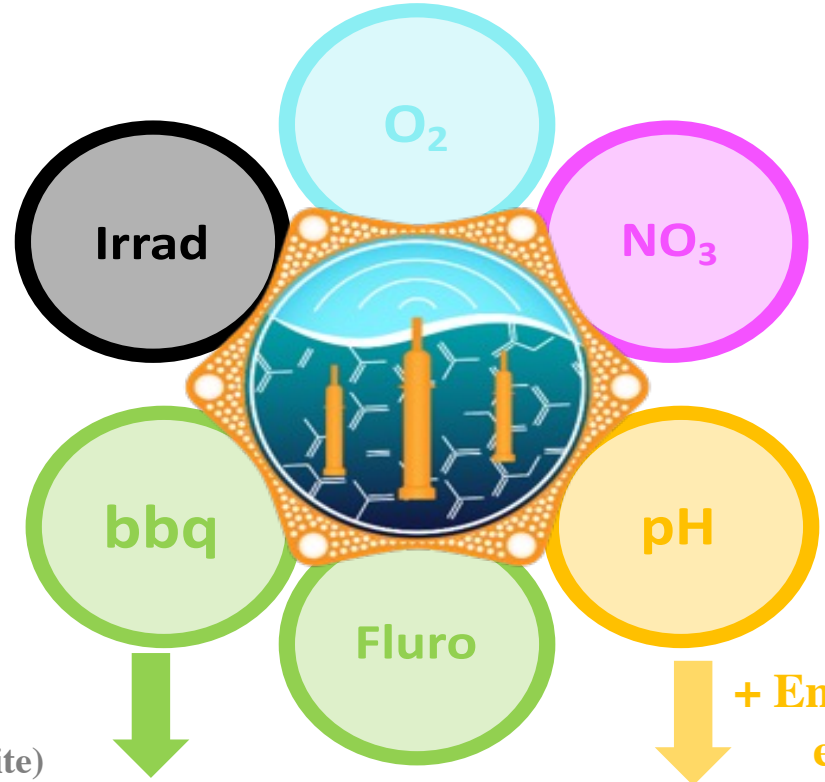


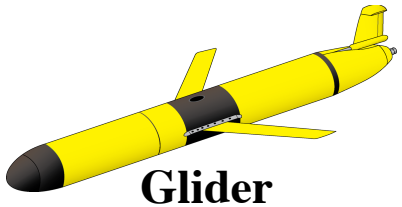
Repeated DOC sampling ^{234}Th-^{238}U deficiency Sediment trap

Stoichiometry of the Biological Production/Consumption

$$106\,CO_2 + 16\,HNO_3 + 1\,H_3PO_4 + 122\,H_2O \underset{\text{Respiration}}{\overset{\text{Photosynthesis}}{\rightleftharpoons}} (CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 138O_2$$

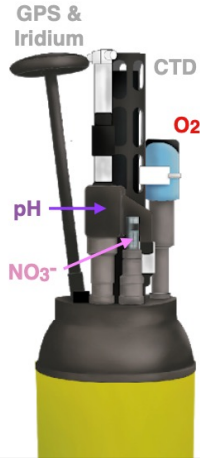
BGC-Argo





Glider

+radiometer



+ POC:PIC (satellite)

PIC_{bbp} ← POC_{bbp}

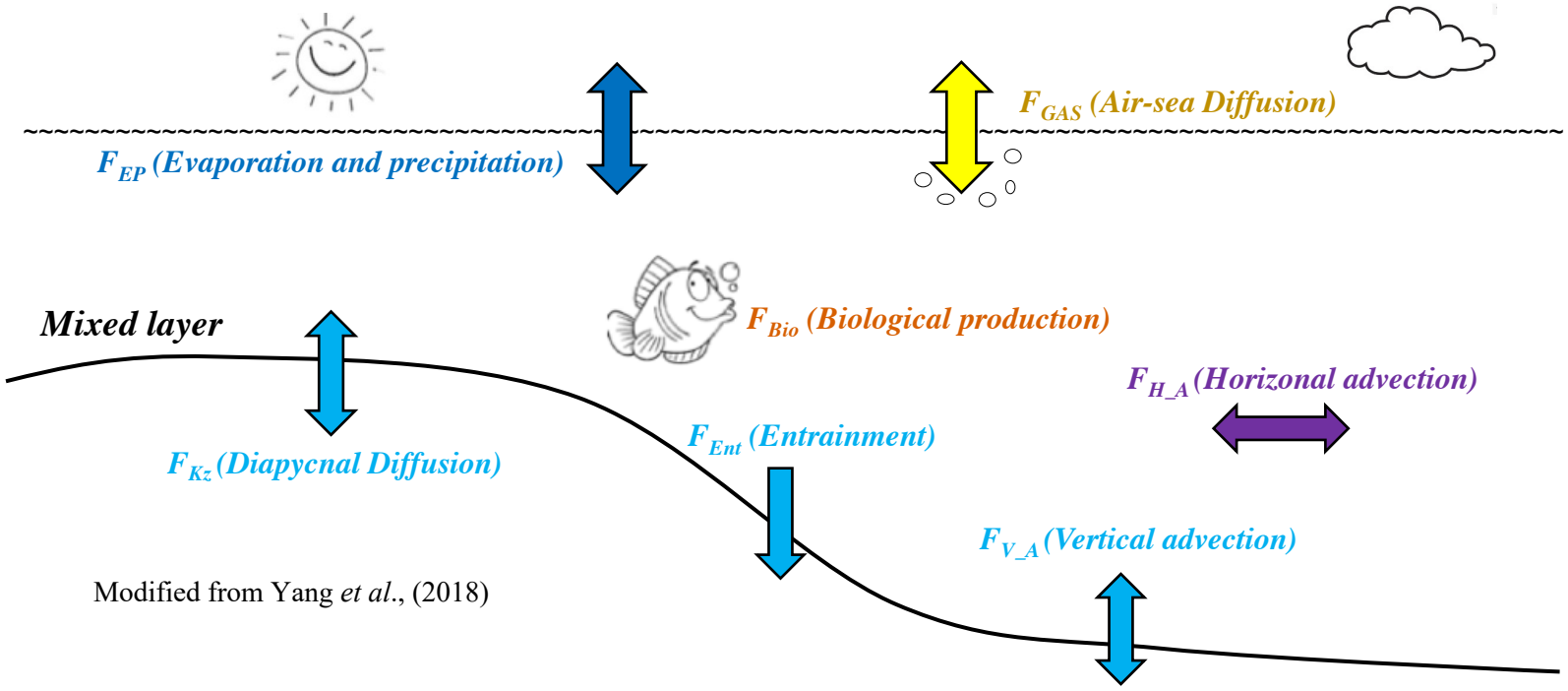
+ Empirical TA estimate

DIC, pCO_2

Johnson *et al.*, (2017): 10.1002/2017jc012838
Claustre *et al.*, (2020): 10.1146/annurev-marine-010419-010956

Slide adapted from Yui Takashita (MBARI)

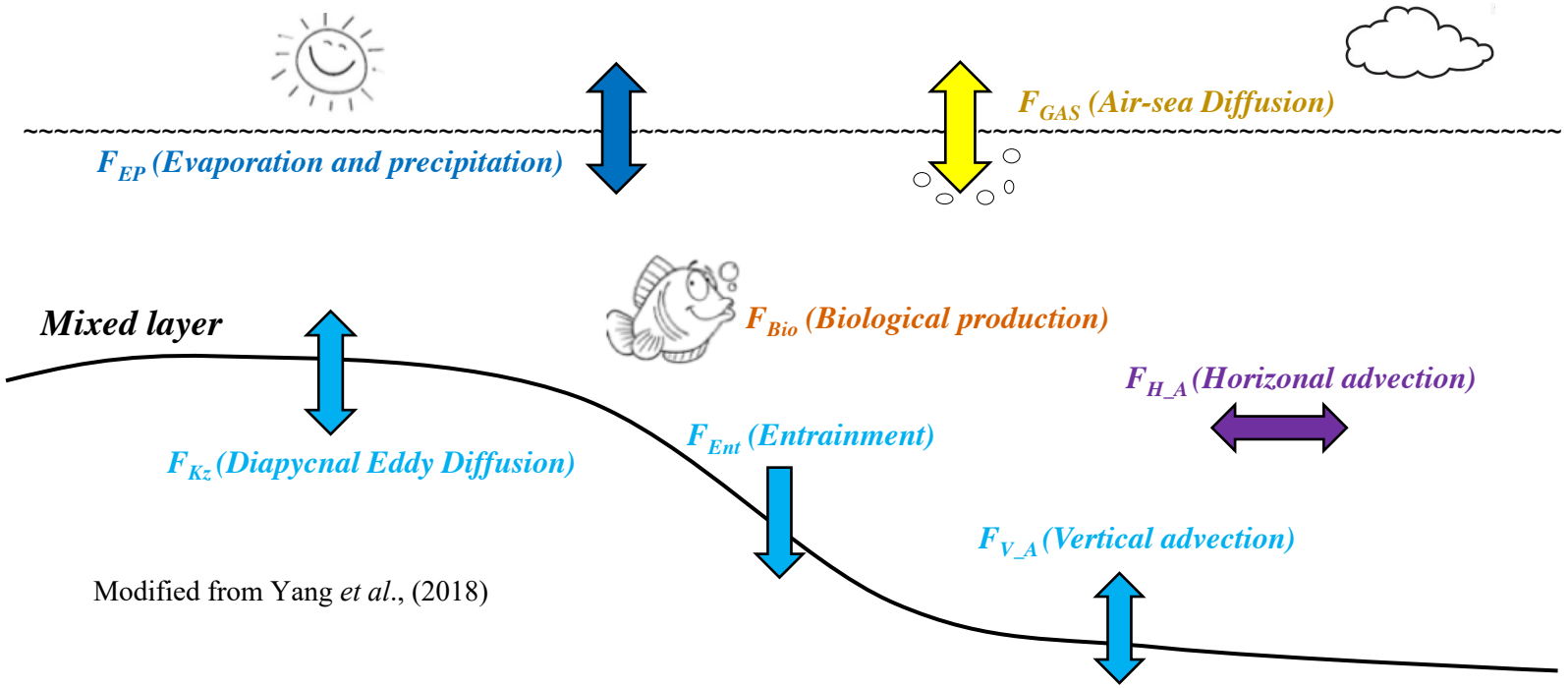
Main Processes Influencing the Change of Tracers in the Seawater



Modified from Yang *et al*., (2018)

Tracer	Biology	Mixing	Advection	EP	Gas
DIC	√	√	√	√	√
TA	√	√	√	√	
NO_3^-	√	√	√	√	
POC_{bbp}	√	√	√	√	
O_2	√	√	√		√

Main Processes Influencing the Change of Tracers in the Seawater



Modified from Yang *et al.*, (2018)

(Under the steady-state)

Export ≈

DIC: $F_{Bio} = F_{Obs} - F_{Mix} - F_{H\text{-}A} - F_{EP} - F_{GAS}$

TA: $F_{Bio} = F_{Obs} - F_{Mix} - F_{H\text{-}A} - F_{EP}$

NO_3: $F_{Bio} = F_{Obs} - F_{Mix} - F_{H\text{-}A} - F_{EP}$

O_2: $F_{Bio} = F_{Obs} - F_{Mix} - F_{H\text{-}A} - F_{GAS}$

POC_{bbp}: $F_{Bio} = F_{Obs} - F_{Mix} - F_{H\text{-}A} - F_{EP} -$

Parameterizations of Abiotic Terms

1. 1. Diapyncal diffusion: $\mathrm{Kz}\left(\frac{\mathrm{d[DIC]}}{\mathrm{dz}}\right)$

1. 2. Entrainment: $\frac{\mathrm{dh}}{\mathrm{dt}}\Delta[\mathrm{DIC}]_{\mathrm{h1}}$

1. 3. Vertical advection: $\mathrm{V_{ek}}\int_0^h \frac{\mathrm{d[DIC]}}{\mathrm{dz}}$

3. Evaporation and *precipitation*: $\frac{DIC}{Sal}_{t0} \times \frac{\partial \mathrm{Sal}}{\partial t}|_{EP}$

$$F_{Bio} = F_{Obs} - F_{Mix} - F_{H\text{-}A} - F_{EP} - F_{GAS}$$

2. Horizontal advection: $V_{hor} \times \nabla[\mathrm{DIC}]_{\mathrm{hor}}$

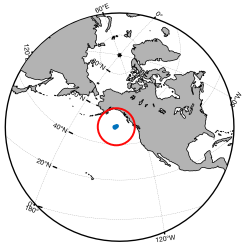
4. Gas exchange: $\mathrm{K_s} \times (p\mathrm{CO_{2\,sea}} - p\mathrm{CO_{2\,air}})$

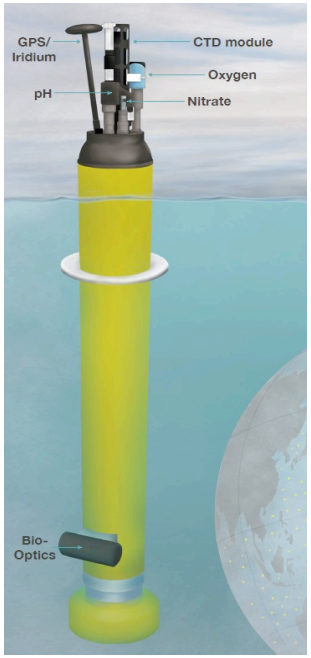
Ancillary parameters:

1. **Meteorological variables**: wind speed, wind stress, water current, air pressure, and air $x\mathrm{CO_2}$ (satellite or earth system model);
2. **Horizontal gradient**: $\mathrm{O_2}$ (GOBAI_$\mathrm{O_2}$), $\mathrm{NO_3}$ (WOA2018) and SODA_EHTZ (DIC and TA)

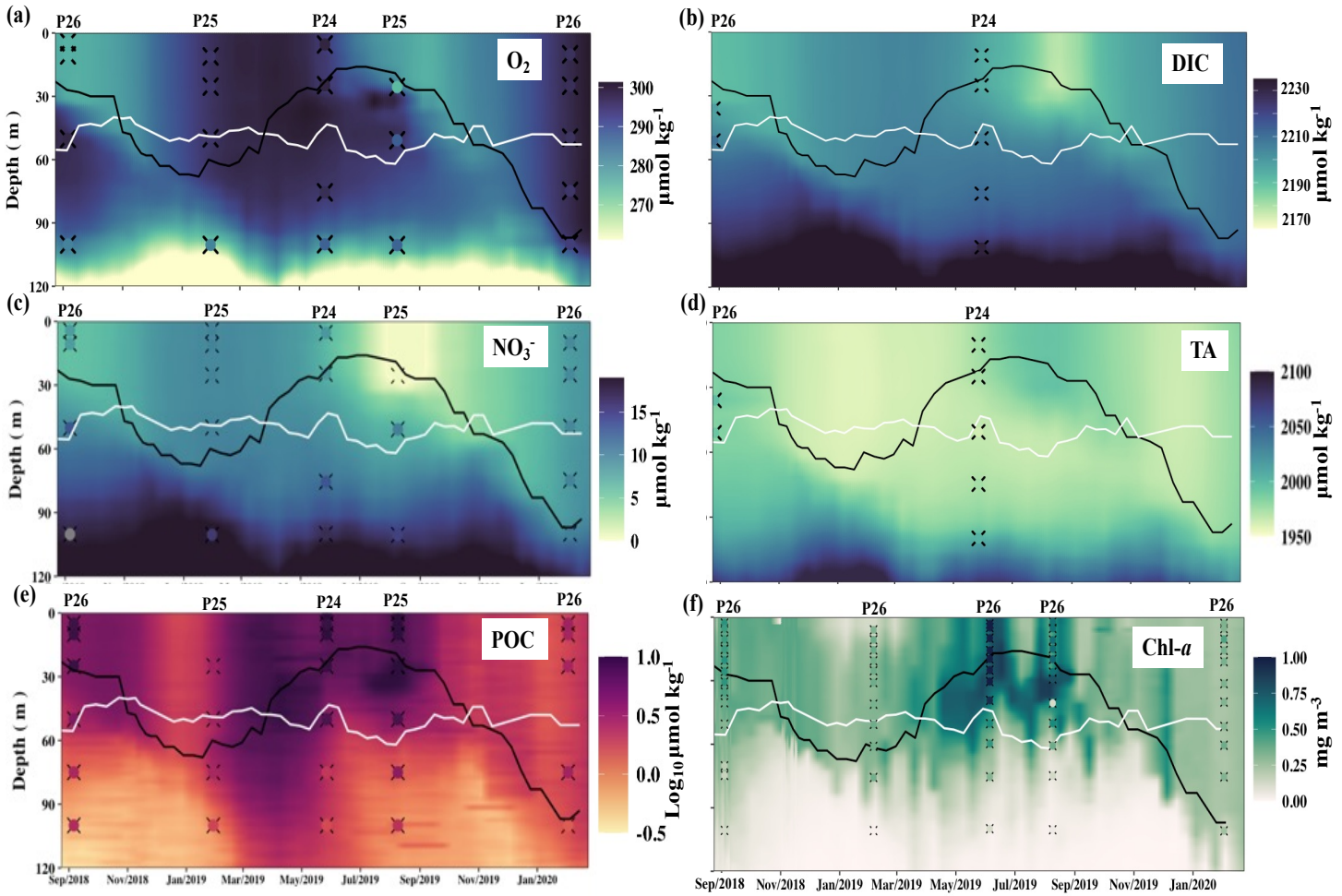
Emerson and Stump, (2010): 10.1016/j.dsr.2010.06.001; Bushinsky and Emerson (2015): 10.1002/2015gb005251
Fassbender *et al*., (2016): 10.1002/2015GB005205; Huang *et al*., (2022): 10.1029/2021GB007178.

Year-round observation in the Subarctic Northeast Pacific



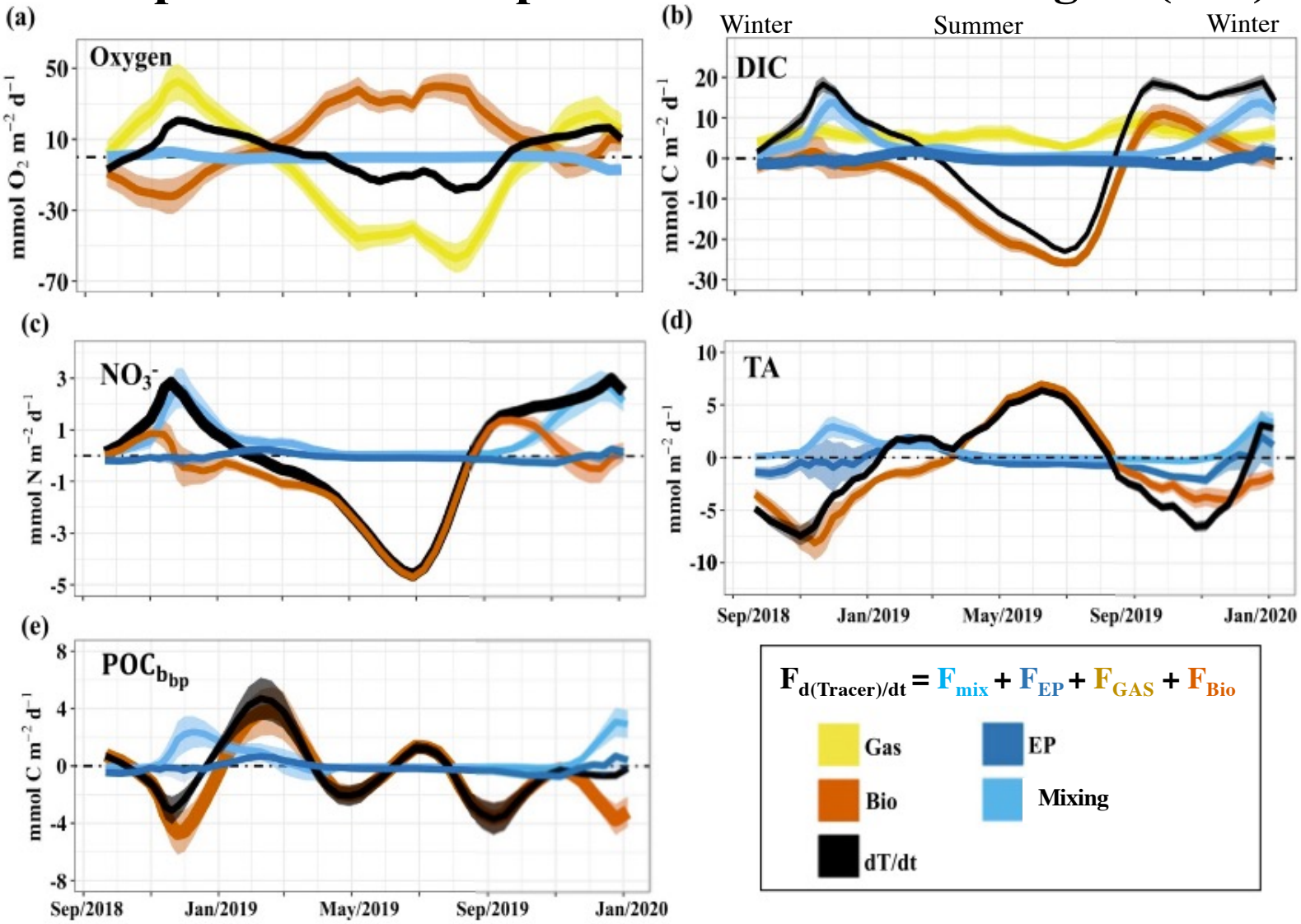


Fully-loaded BGC float



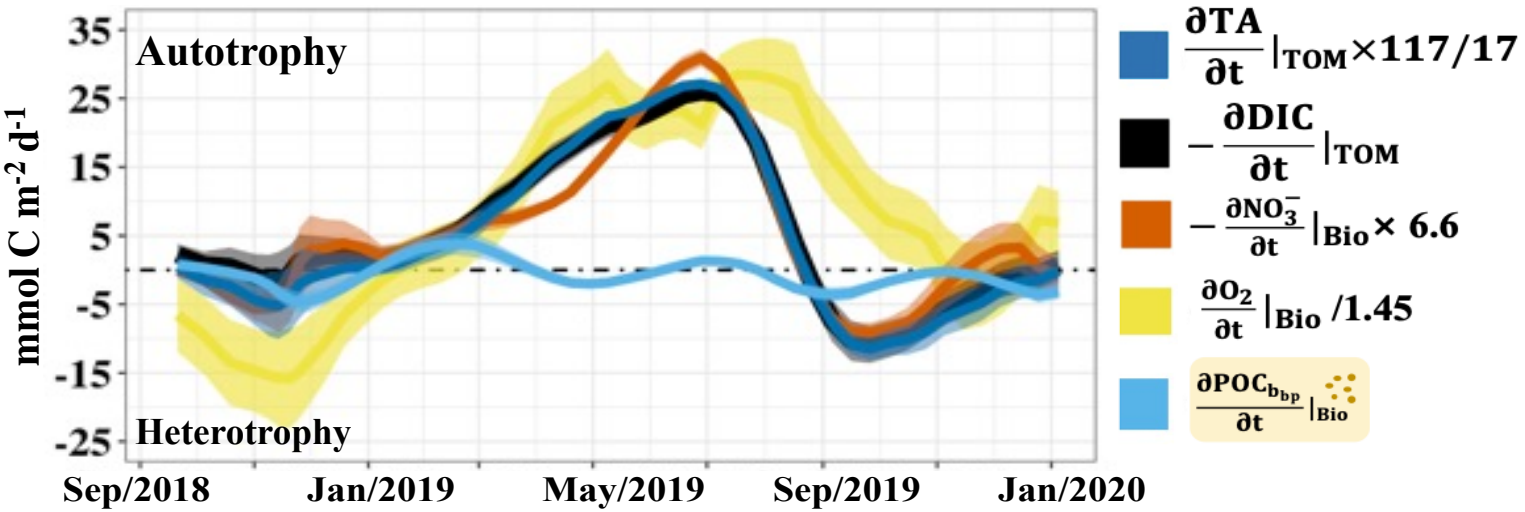
Huang *et al.*, (2022): 10.1029/2021GB007178

Multiple Fluxes in Euphotic Zone Tracer Budgets (1-D)



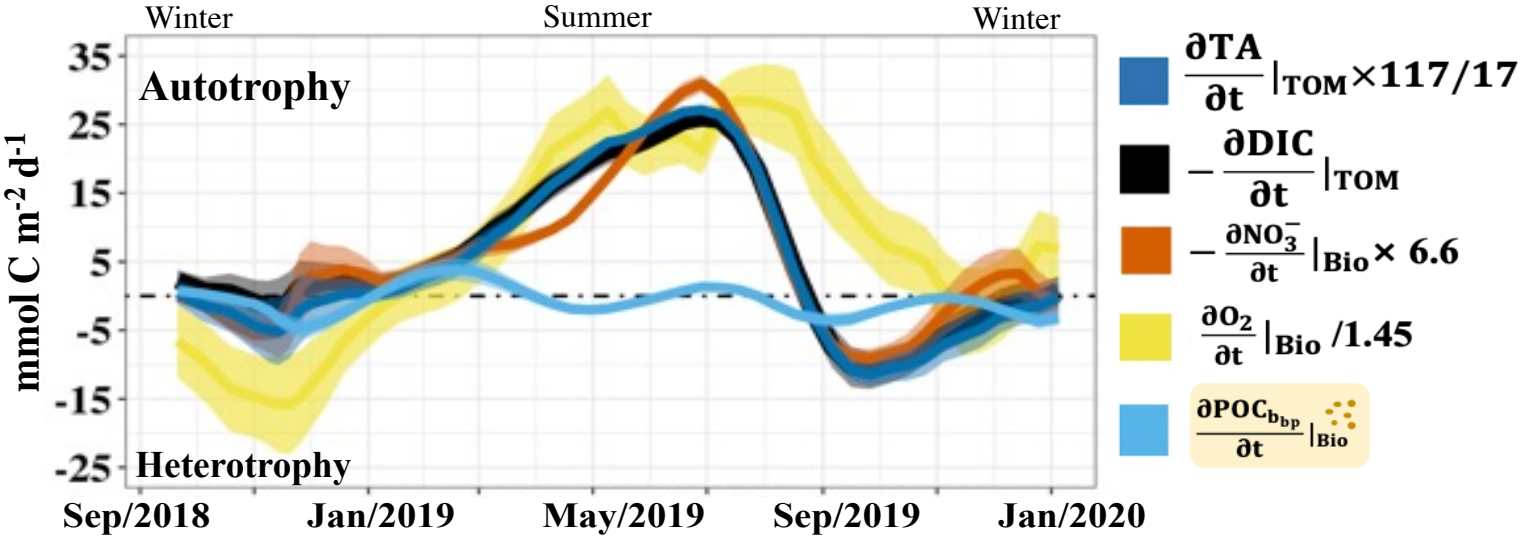
Huang *et al.*, (2022): 10.1029/2021GB007178

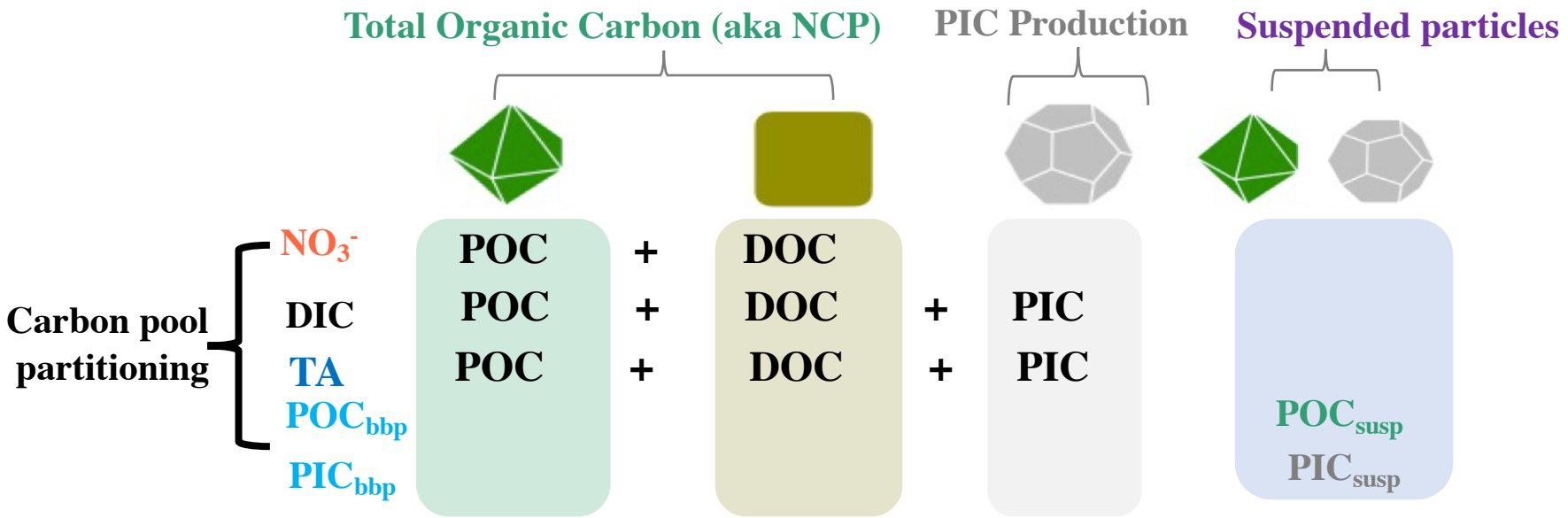
Net Biological Production Constrained by Multiple Tracer



Tracer	Sensor Limitations	Budget limitations
TA	No direct sensor (empirical estimate from T, S, and O_2)	➢ Vertical mixing parameterization ➢ Strong horizontal gradient ➢ Influence from external sources: N_2 fixation (for NO_3^-) and anthropogenetic carbon invasion (for DIC)
DIC	Derive from measured pH and empirical estimate of TA	
NO_3^-	Low accuracy in the subtropical ocean	
O_2	Calibration/quality control (many floats lack an air-calibration mechanism)	➢ Sensitive to sensor accuracy ➢ Bubble term parameterization (high wind) ➢ May miss some signals if the sampling frequency is greater than the residence time of O_2
POC_{bbp} PIC_{bbp}	Empirical estimate from b_{bp} and remotely sensed POC:PIC	➢ May miss particles that sink out of the euphotic zone between two sampling periods

Net Biological Production Constrained by Multiple Tracers

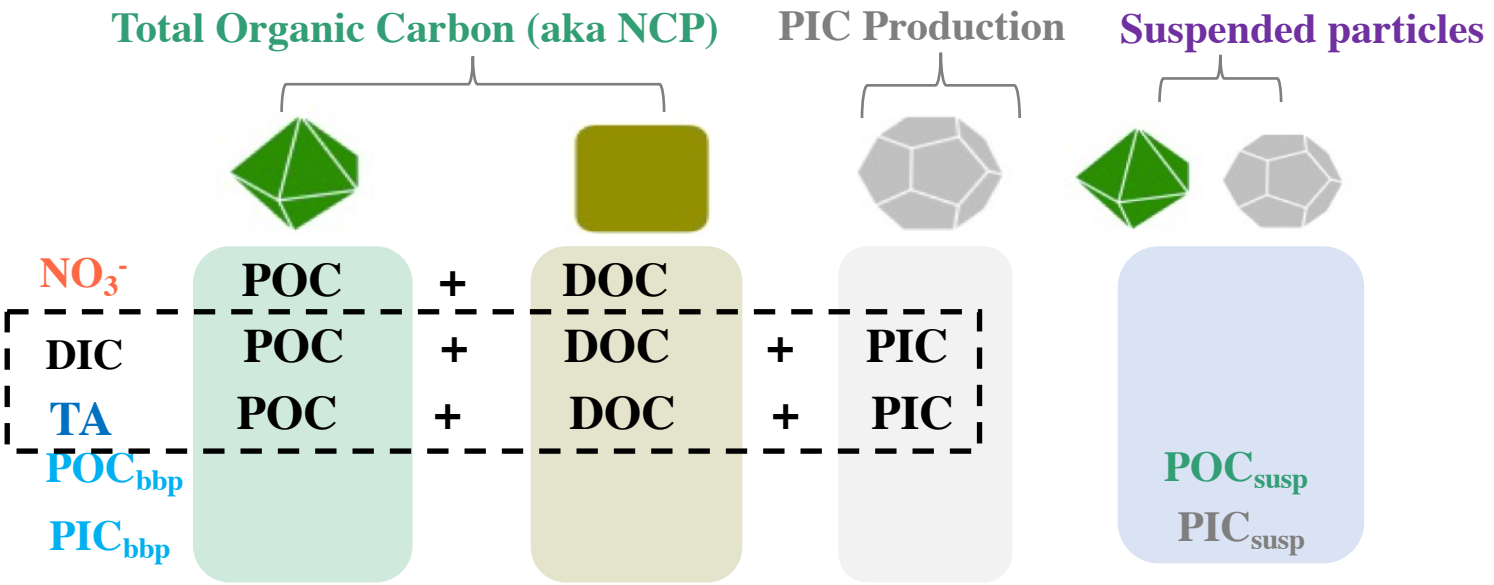




$POC_{susp} = POC - POM_{sinking}$

Alkire *et al*., (2012); Fassbender *et al*., (2016, 2017); Haskell *et al*., (2021); Huang *et al*., (2022)

Step 1:Organic and Inorganic Carbon Partition



Stoichiometric Ratio

$$\frac{\partial DIC}{\partial t}|_{PIC} = 2 * \frac{\partial TA}{\partial t}|_{PIC}$$

$$\frac{\partial DIC}{\partial t}|_{NCP} = \frac{17}{-117} * \frac{\partial TA}{\partial t}|_{NCP}$$

Anderson and Sarmiento (1994): 10.1029/93gb03318

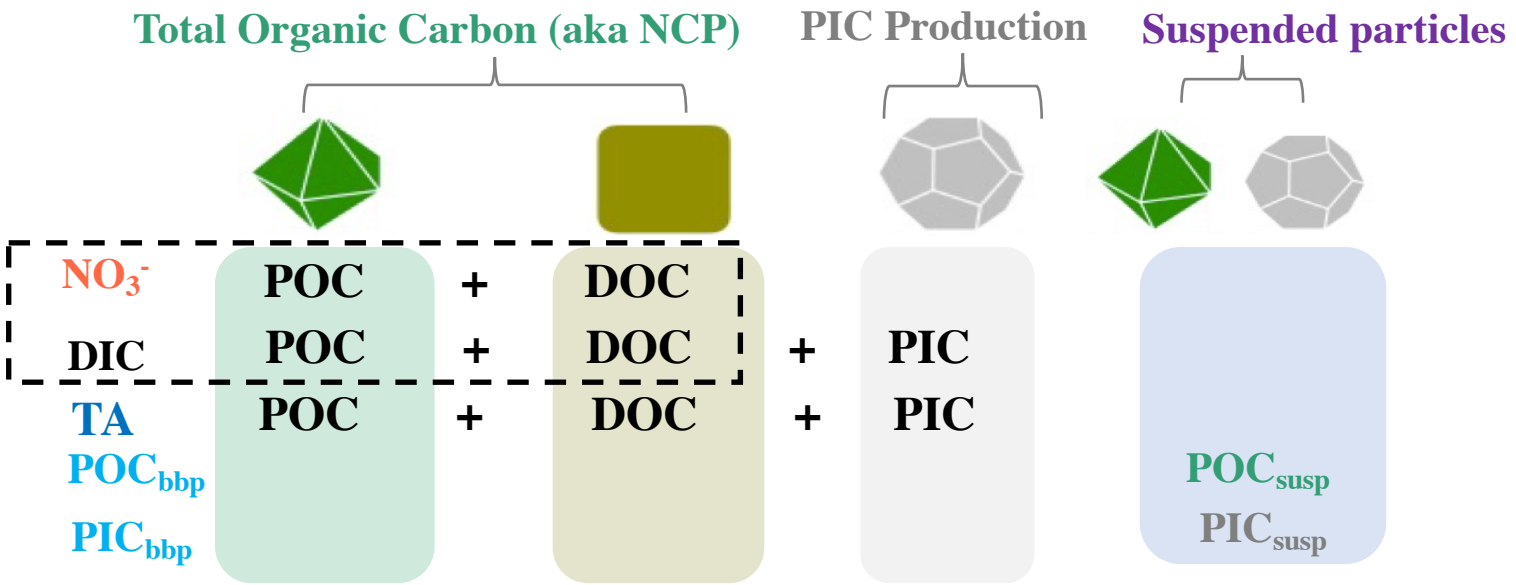
NCP and PIC Partitioning

$$\left.\frac{\partial DIC}{\partial t}\right|_{NCP} = \frac{\left.\frac{\partial TA}{\partial t}\right|_{Bio} - 2 * \left.\frac{\partial DIC}{\partial t}\right|_{Bio}}{2 - 17/117}$$

$$\frac{\partial DIC}{\partial t}|_{PIC} = \frac{\partial DIC}{\partial t}|_{Bio} - \frac{\partial DIC}{\partial t}|_{TOM}$$

Fassbender *et al.*, (2016): 10.1002/2015GB005205;
Haskell *et al.*, (2021): 10.1029/2020gb006599;
Williams *et al.*, (2018): 10.1029/2017jc012917

Step 2:POC and DOC Partition



Stoichiometric Ratio

$$\frac{\partial DIC}{\partial t}|_{POM} = C{:}N_{POM} * \frac{\partial NO_3}{\partial t}|_{POM}$$

$$\frac{\partial DIC}{\partial t}|_{DOM} = C{:}N_{DOM} * \frac{\partial NO_3}{\partial t}|_{DOM}$$

POM and DOM Partitioning

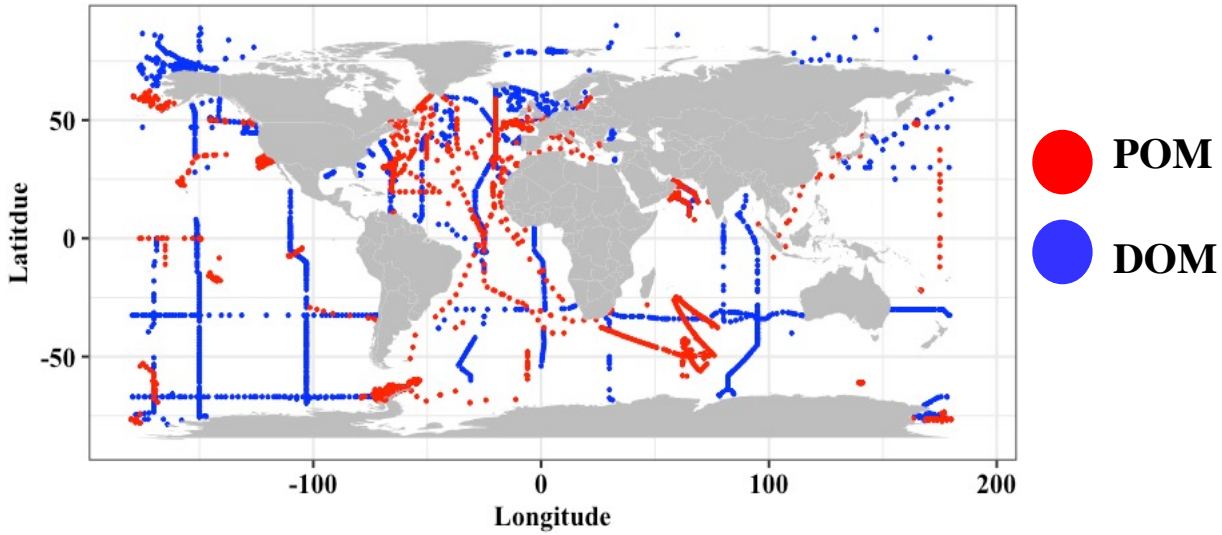
$$\frac{\partial DIC}{\partial t}\Big|_{DOM} = \frac{\frac{\partial NO_3}{\partial t}\Big|_{NCP} - \frac{1}{C{:}N_{POM}} * \frac{\partial DIC}{\partial t}\Big|_{NCP}}{\frac{1}{C{:}N_{DOM}} - \frac{1}{C{:}N_{POM}}}$$

$$\frac{\partial DIC}{\partial t}|_{POM} = \frac{\partial DIC}{\partial t}|_{NCP} - \frac{\partial DIC}{\partial t}|_{DOM}$$

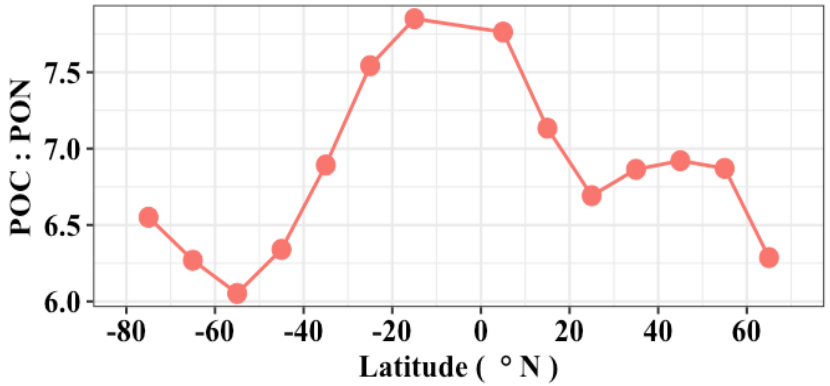
Haskell *et al.*, (2021): 10.1029/2020gb006599
Huang *et al.*, (2022): 10.1029/2021gb007178

End-member Nutrient Ratio for POM and DOM Production

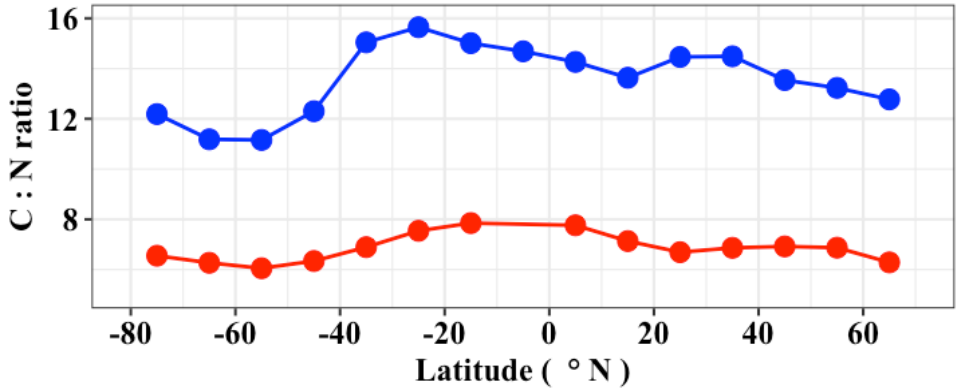
Global compiled dataset



POC:PON (above euphotic zone)

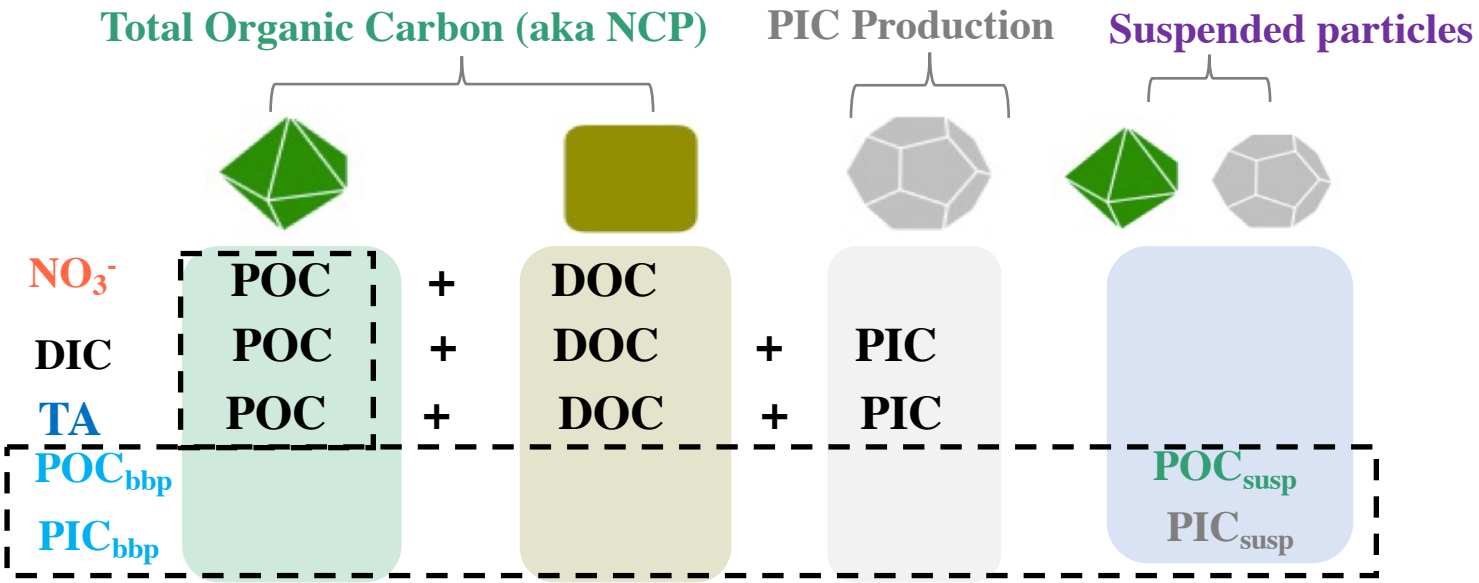


POC:PON & ΔDOC:ΔDON



POM dataset: Martiny *et al*., (2014, 10.1038/sdata.2014.48)
DOM dataset: Hansell *et al*., (2021, 10.2592/s4f4-ye35)
Seasonal DOM reconstruction: Baetge *et al*., (2020:10.3389/fmars.2020.00227)

Step 3:Particle Sinking Flux Partition

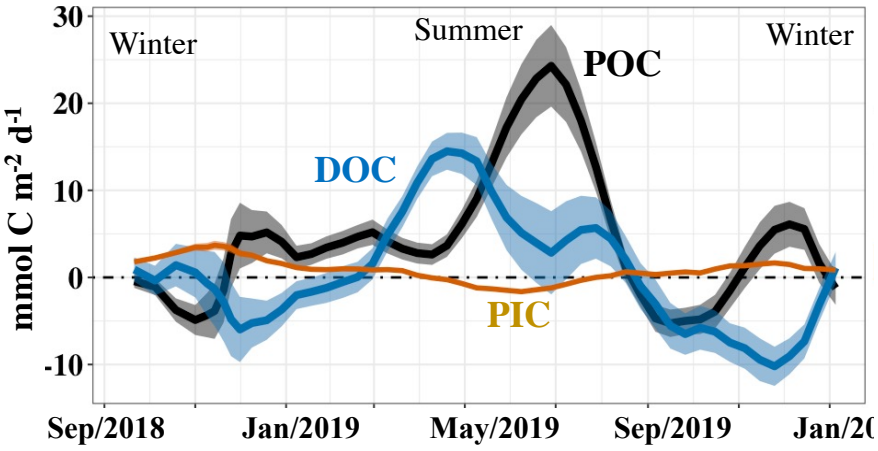


$$F_{POC\_sinking} = \frac{\partial DIC}{\partial t}\Big|_{POC\ (chemical\ tracer)} - \frac{\partial POCbbp}{\partial t}\Big|_{bio\ (bio\_optical\ tracer)}$$

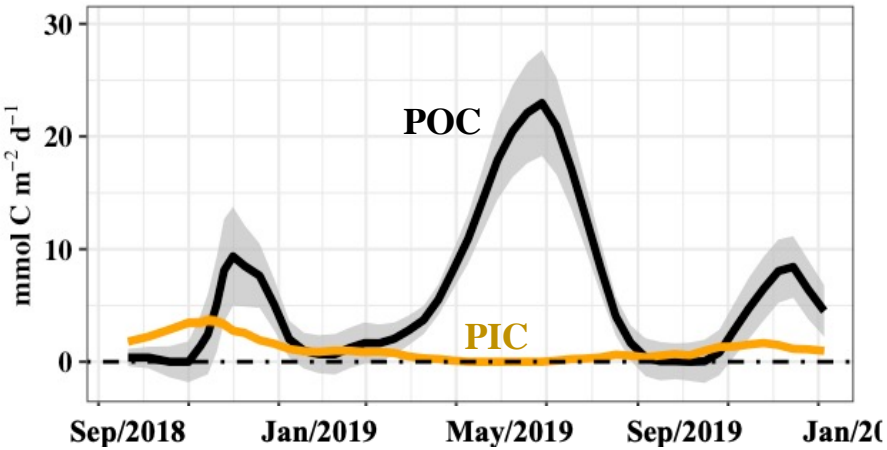
$$F_{PIC\_sinking} = \frac{\partial DIC}{\partial t}\Big|_{PIC\ (chemical\ tracer)} - \frac{\partial PICbbp}{\partial t}\Big|_{bio\ (bio\_optical\ tracer)}$$

Alkire *et al*., (2012); 10.1016/j.dsr.2012.01.012; Huang *et al*., (2022): 10.1029/2021gb007178

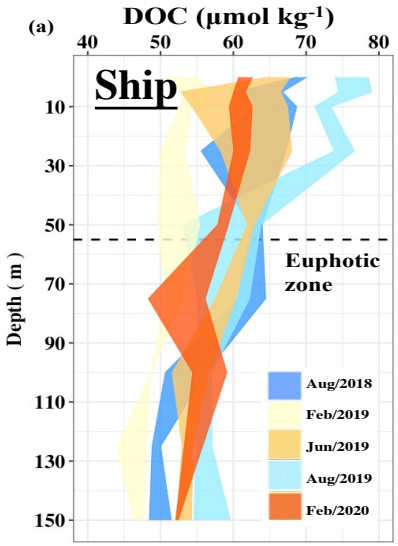
Export potential

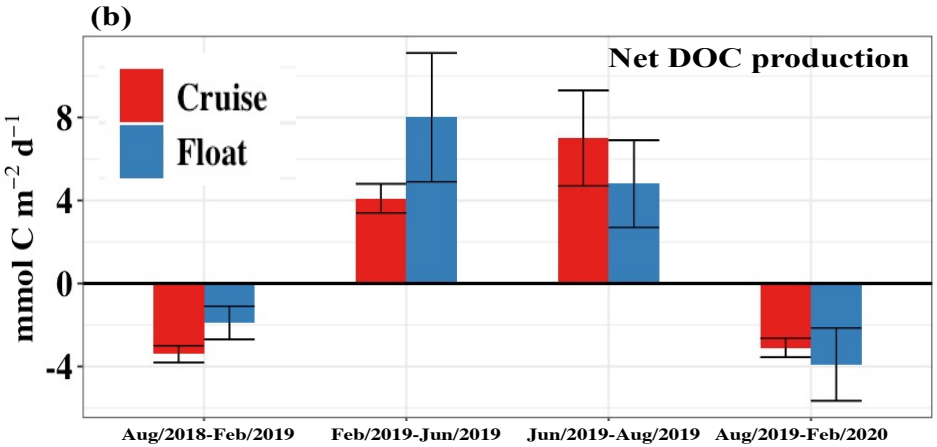


Sinking flux



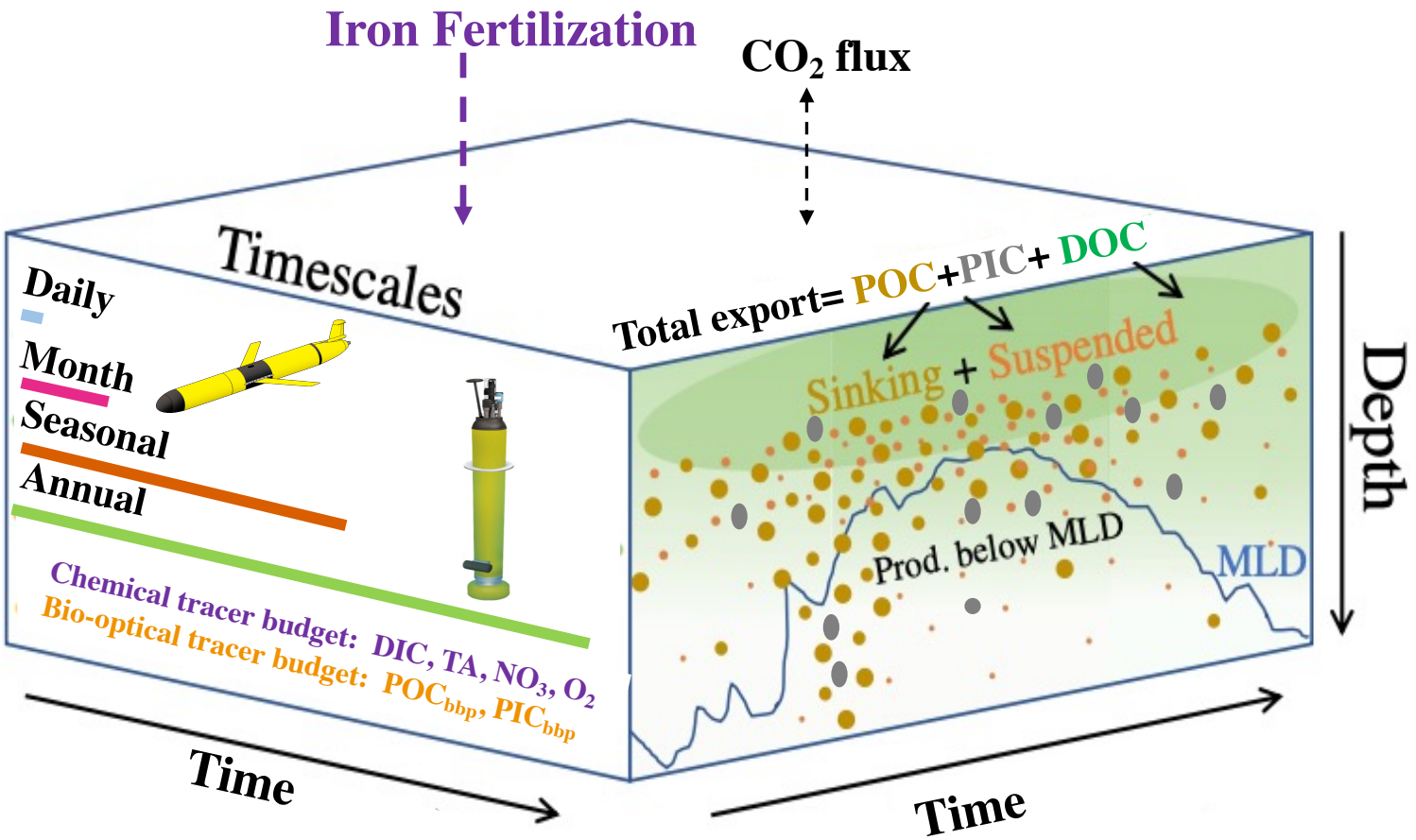
➢ **DOC production validation (float estimate vs ship)**





Huang *et al.*, (2022): 10.1029/2021gb007178

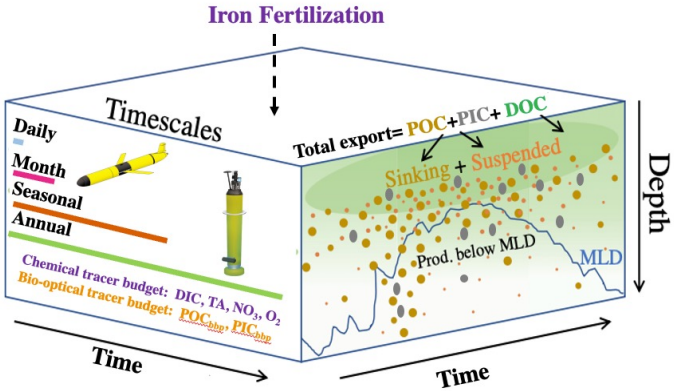
Toward persistent, autonomous observations of the export of distinct biogenic carbon pools



Modified from Haskell *et al.*, (2021)

Caveats and limitations

- Invalid TA estimate under the artificially enhanced TA condition
- Potentially modified nutrients ratio ($C:N_{POM}$ and $C:N_{DOM}$) in the bloom induced by iron fertilization



Best Practice in the Fieldwork

- **Instrument and Sensor configuration**

  Autonomous Platforms: BGC-Argo or seaglider

  Required sensors: CTD +pH+ O_2+ b_{bp}+ NO_3^-

  Desired/future sensors:

  1. Secondary carbonate parameter sensor (TA, Briggs *et al.*, 2017)
  2. Bio-optical PIC sensor (Bishop *et al.*, 2022)
  3. Microstructure profiler (diffusivity measurement, Roemmich *et al.*, 2019)

- **Shipboard samples collection**:

  1. **Sensor calibration/validation** (TA, DIC, pH, O_2, NO_3, POC, and PIC)
  2. **End-member nutrient ratio** (POC/PON/DOC/DON, or bottle incubation)

Thank You For Your Attention!