Assessment of Ocean Carbon Export From Satellite Data: New Approaches & A Plan for the Future

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Help from …

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Mike Behrenfeld – Oregon State

Phil Boyd – Univ. Tasmania

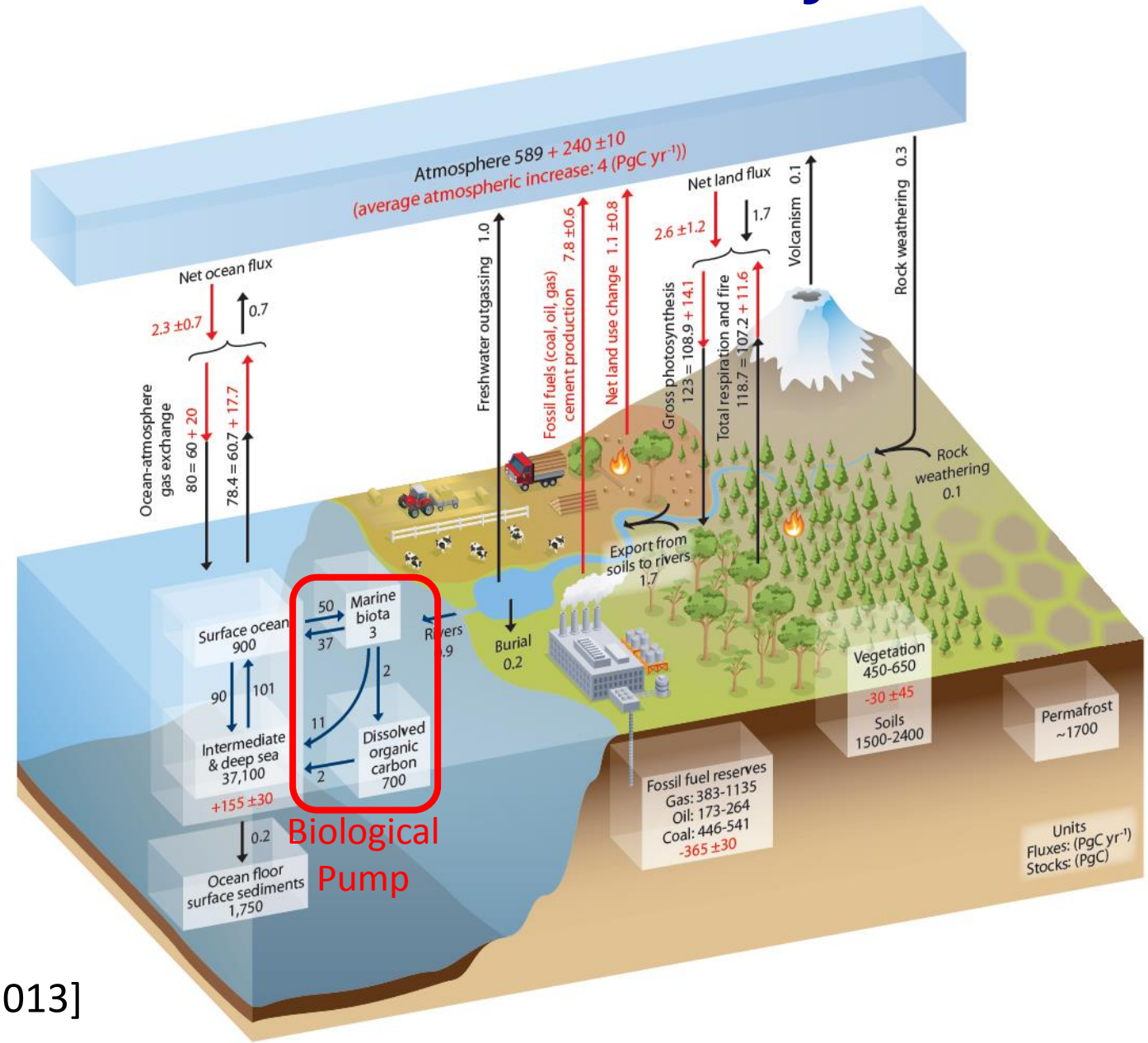
Stéphane Maritorena, Norm Nelson & Erik Fields - UCSB

Support from NASA Ocean Biology & Biogeochemistry Program

Outline

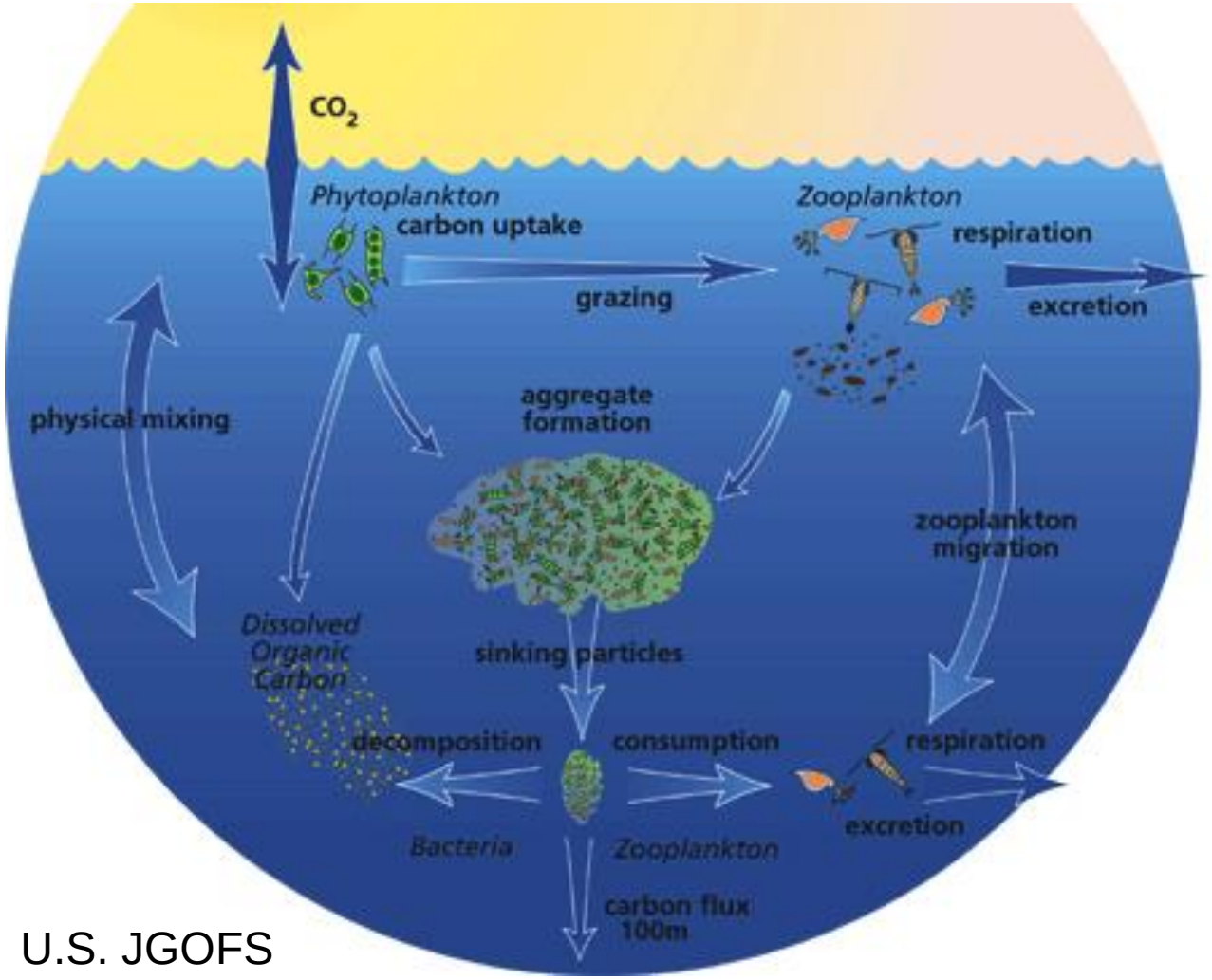
- Recap what we know about the ocean's biological pump
- Introduce a new approach for quantifying the biological pump using satellite data
- Assess the logical next steps in improving these models
- Introduce EXPORTS - a science plan for a future NASA major field campaign

Global Carbon Cycle



IPCC AR5 [2013]

The Biological Pump



U.S. JGOFS

Food web processes transfer organic matter to depth

pathway for rapid C sequestration

Quickly remove C from surface ocean

turn off bio pump & atm. CO_2 increases by 200 ppmv

Global C Export estimates range from 4 to 12 PgC y^{-1}

we must do better

Global Extrapolation of Carbon Export

- Export modeled as [e-ratio] * [NPP]

  We can estimate NPP globally - but need e-ratio

- Empirical modeling for e-ratio

  f(SST) - Laws et al. [2000] GBC; Henson et al. [2011] GRL

  f(SST & Chl) - Dunne et al. [2004] GBC

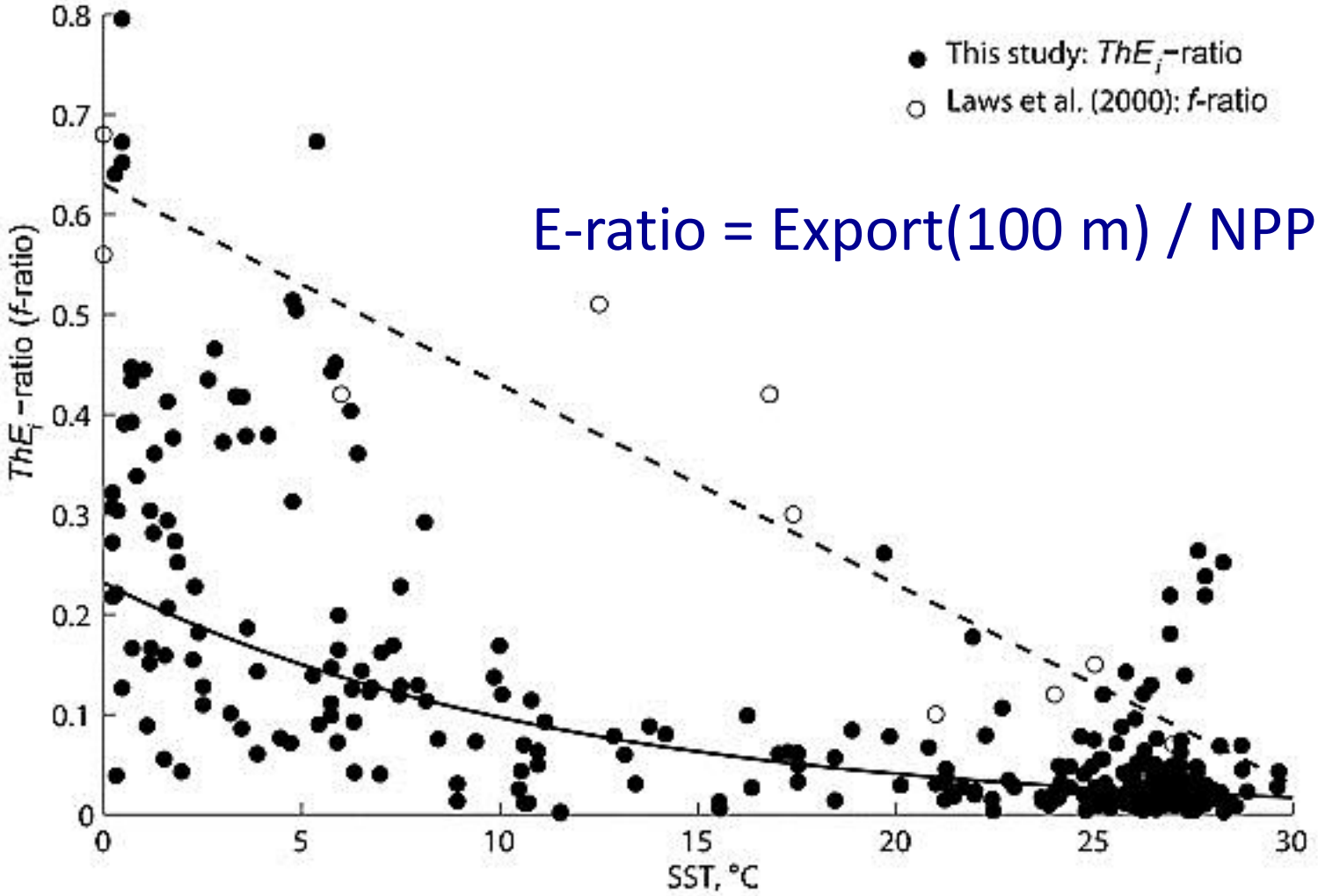
- Problems

  Not mechanistic

  Tuned for a single depth – not export at Z_{eu}

  Not very good…

E-Ratios vs. SST



E-ratio = Export(100 m) / NPP

Henson et al. GRL [2011]

Extrapolated Global Fluxes

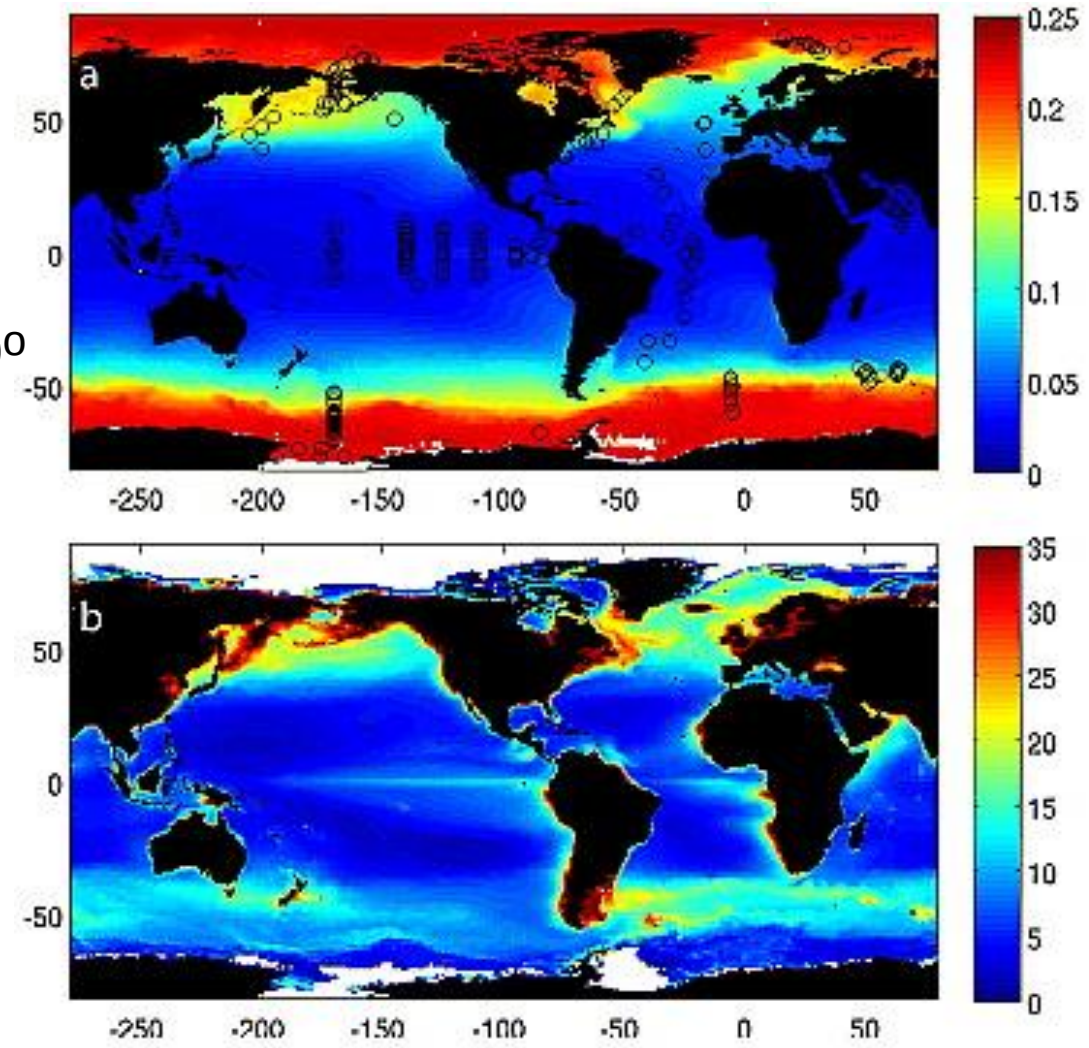
E-ratio @100m

>0.05 equatorward of 40^{o}

Export @100 m

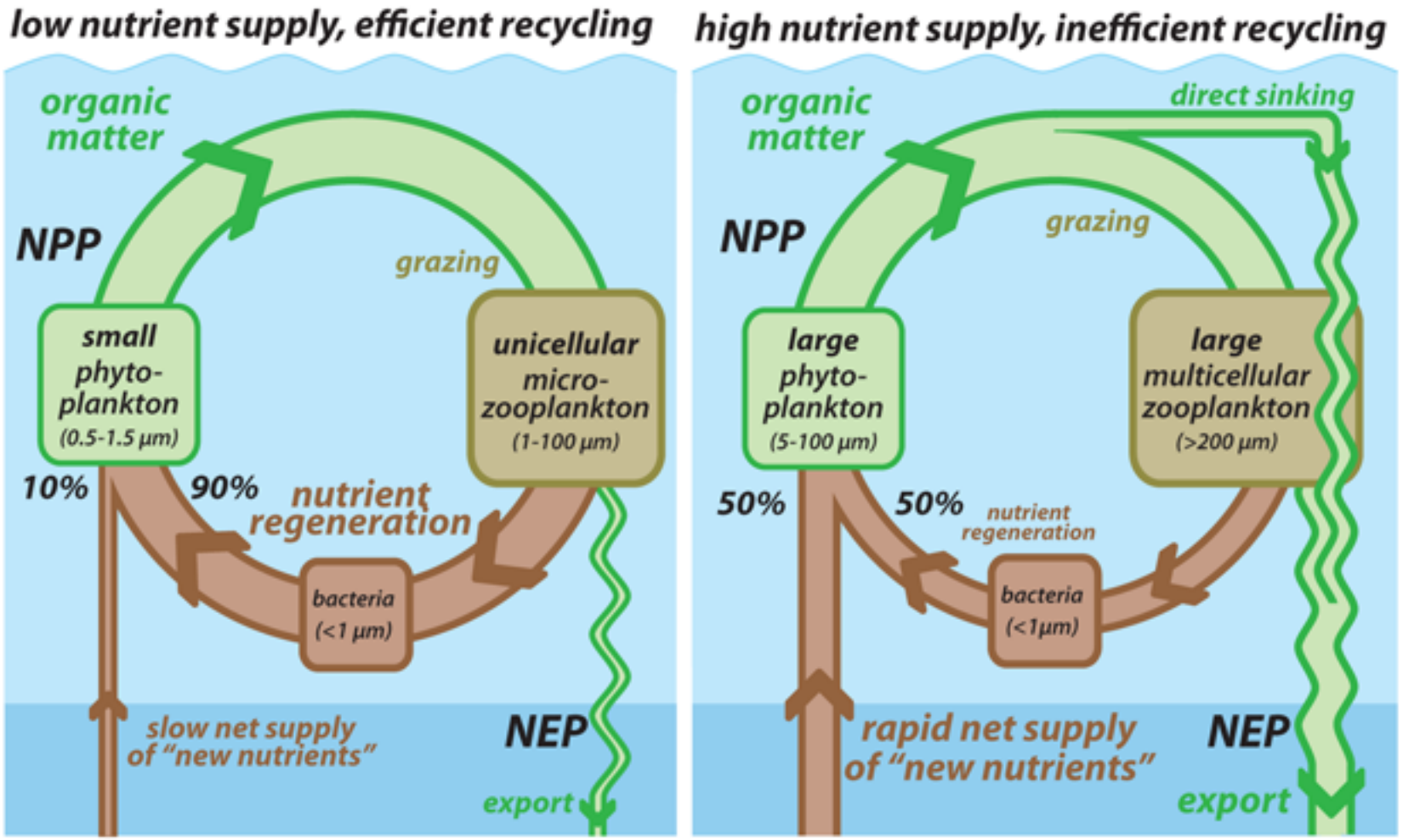
(gC m^{2} y^{-1})

Global Σ ~4 Pg C y^{-1}



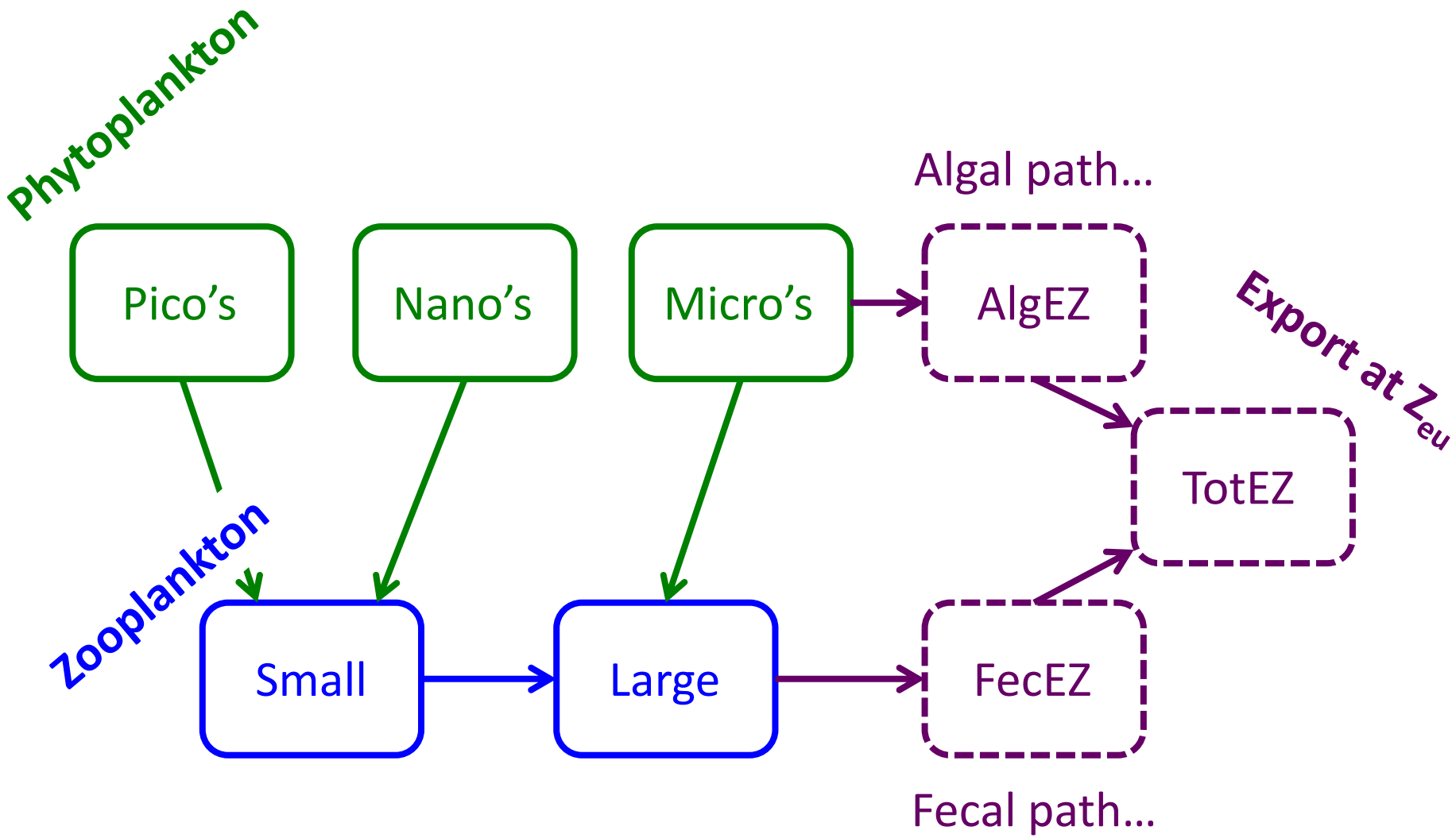
Henson et al. GRL [2011]

Food Web & Export



Sigman & Hain [2012] *Nature Education*

A Mechanistic Approach…



Following Michaels & Silver (1988), Boyd & Stevens (2002) & many more…

New Satellite Tools…

- Carbon-based NPP (CbPM)

  Phytoplankton Carbon & NPP using obs Chl:C ratio

  Behrenfeld et al. (2005; *GBC*) & Westberry et al. (2008; *GBC*)

- Particle-size distribution

  Partitioning of NPP & C stocks by biovolume fraction

  Kostadinov et al. (2009; *JGR*) & (2010; *Biogeosci.*)

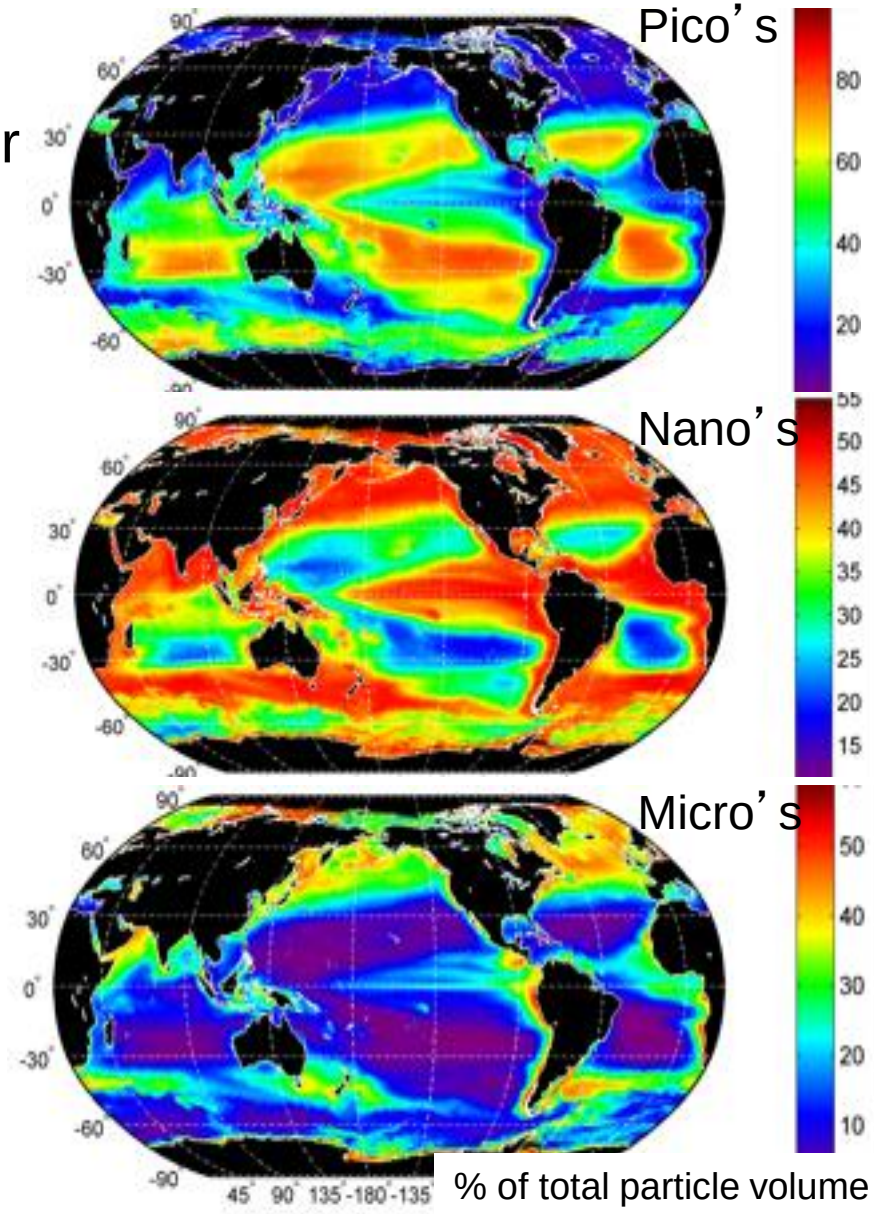
- Mass budgets for phytoplankton C stocks

  Enables upper layer grazing rates to be estimated

  Behrenfeld (2010; *Ecology*) & Behrenfeld et al. (2013; *GBC*)

Assessment of Particle Size Distribution

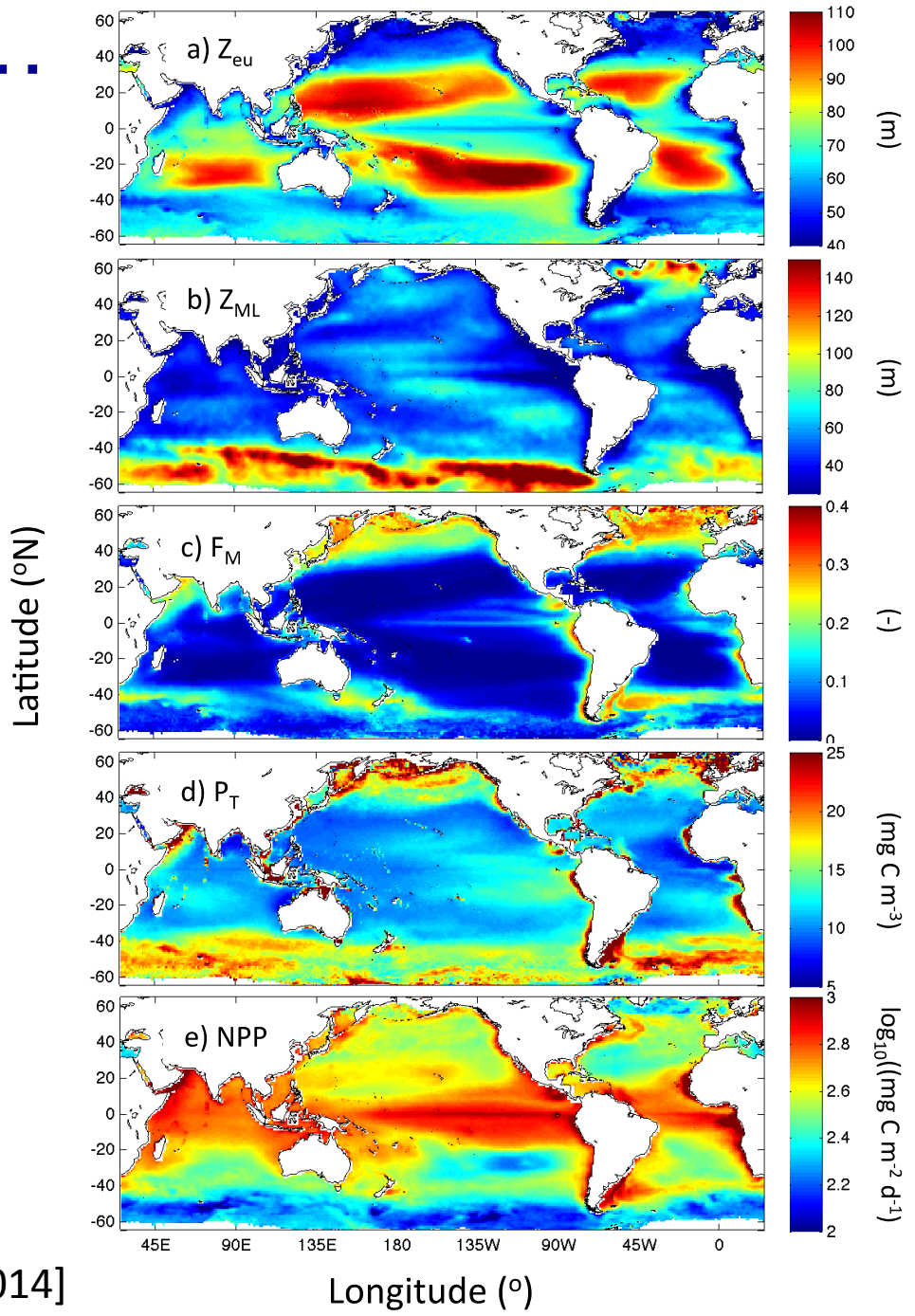
- Mie theory is used to model the PSD as a function of the backscatter spectrum
- Enables partitioning of biovolumes into pico-, nano- & micro-sizes
- Patterns follow expectations
  - Pico's dominate oligotrophic regions
  - Micro's are found only in high latitudes & upwelling regions
- Provides a new approach for assessing plankton functional types using satellite observations



Loisel et al. [2007] *JGR-Oceans*
Kostadinov et al. [2009] *JGR-Oceans*
Kostadinov et al. [2010] *Biogeosciences*

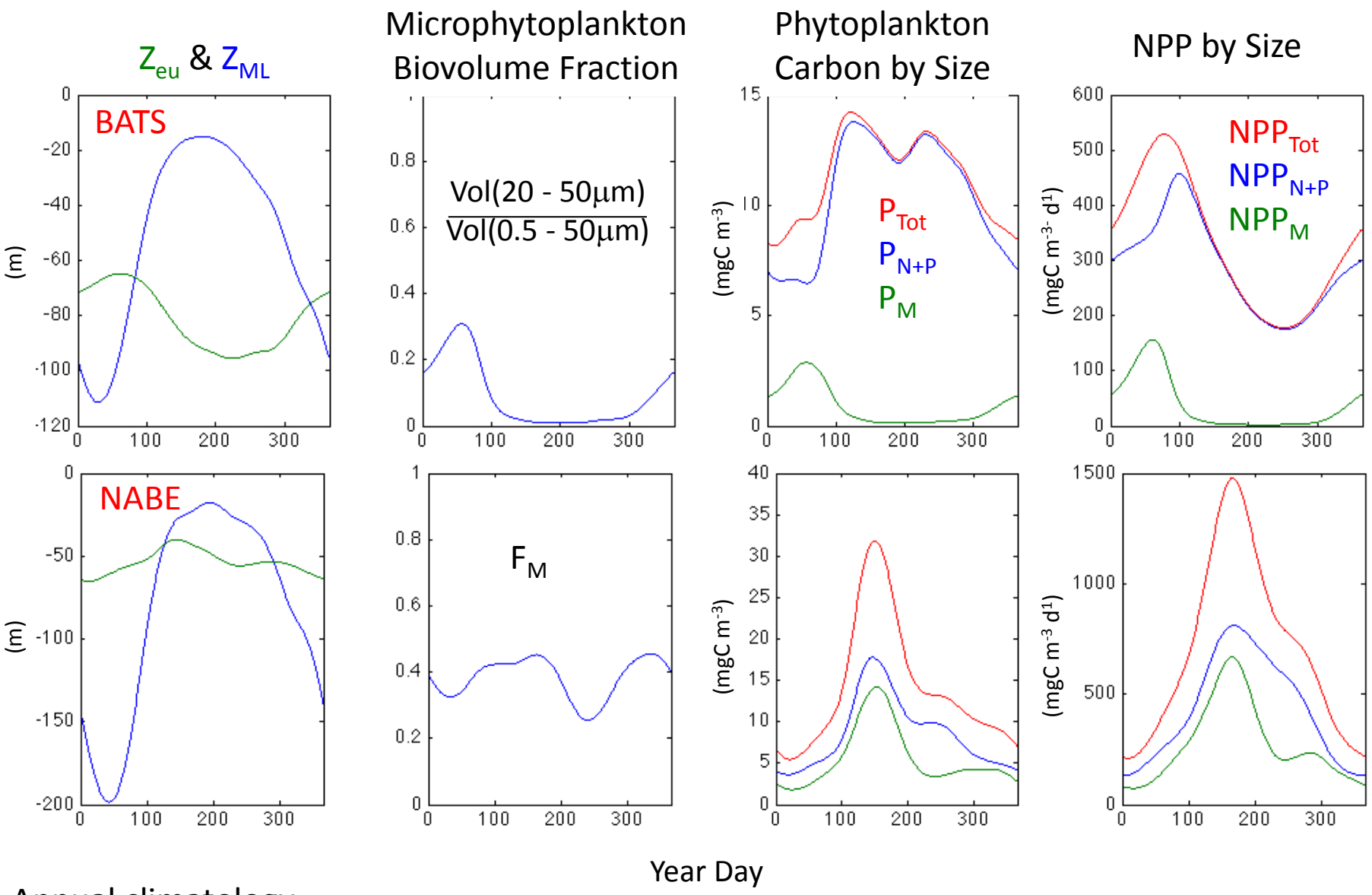
New Satellite Tools…

- Z_{eu} = Euphotic zone depth
- Z_{ML} = Mixed layer depth
- F_M = Fraction of micro-phytoplankton biomass
- P_T = Phytoplankton biomass
- NPP = Net primary production



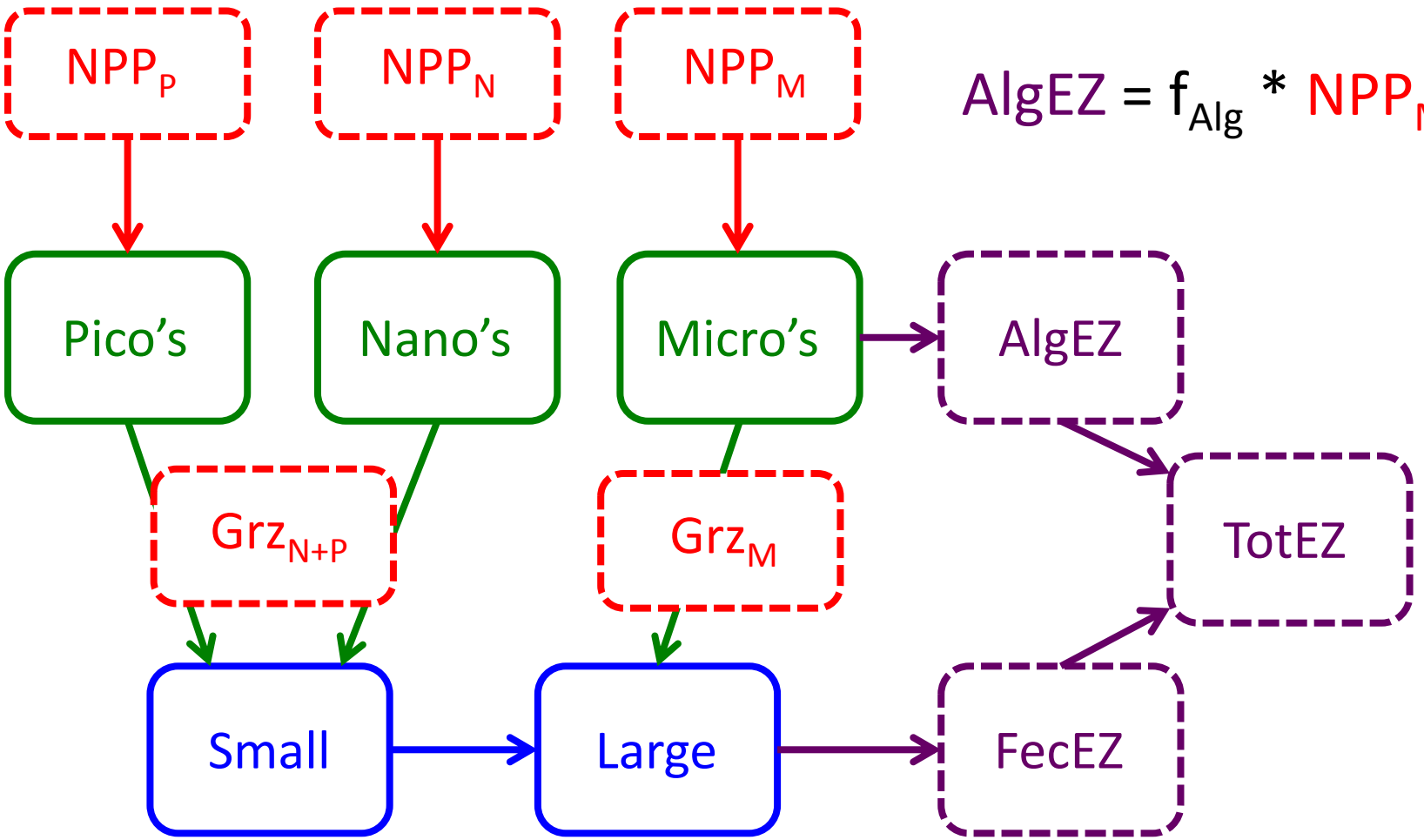
Annual Mean Distributions - Siegel et al. [2014]

New Satellite Tools…



Annual climatology

A Mechanistic Approach…



$$AlgEZ = f_{Alg} * NPP_M$$

$$FecEZ = (f_{FecN+P} * Grz_{N+P} + f_{FecM} * Grz_M) * Z_{eu}$$

Siegel et al. [2014]

Diagnosing Grazing Rates

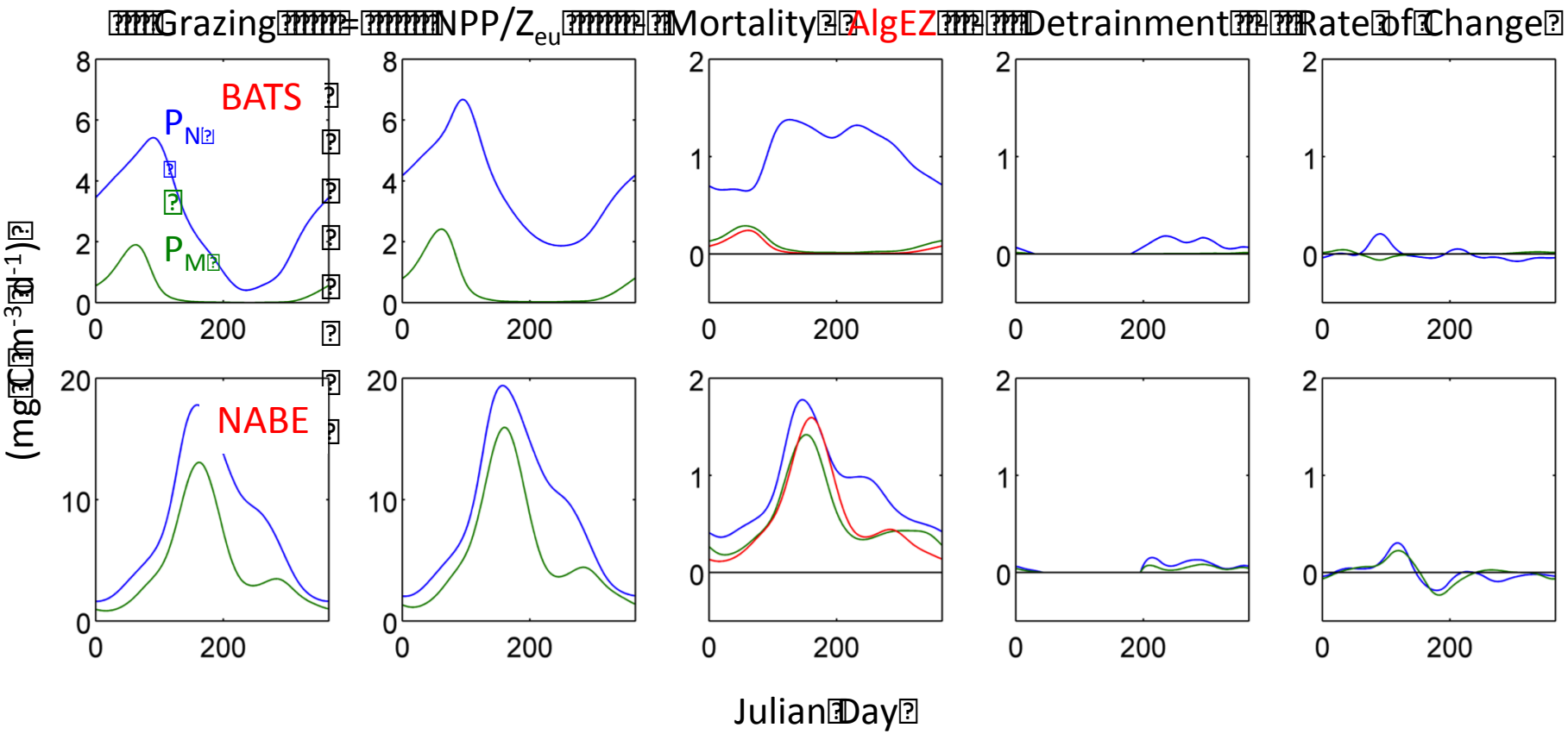
- Upper layer (Z_{ML}) phytoplankton biomass budget

$$\frac{dP_i}{dt} = \frac{NPP_i}{Z_{eu}} - Grz_i - m_i P_i - \frac{AlgEZ_i}{Z_{eu}} - Detrn(Z_{ml}, P_i)$$

unsteady | NPP/vol | grazing | mortality | direct sinking loss | detrainment

- Grz_i & $AlgEZ_i$ are the only unknowns
- Model $AlgEZ_M = f_{Alg} * NPP_M$ where $f_{Alg} = 0.1$
- Let $m_i = 0.1\ d^{-1}$ (non-grazing, biological losses)
- Solve for Grz_{N+P} and Grz_M

Diagnosing Grazing Rates



- NPP roughly balances grazing mortality
- All other terms are much smaller

Modeling Export Flux

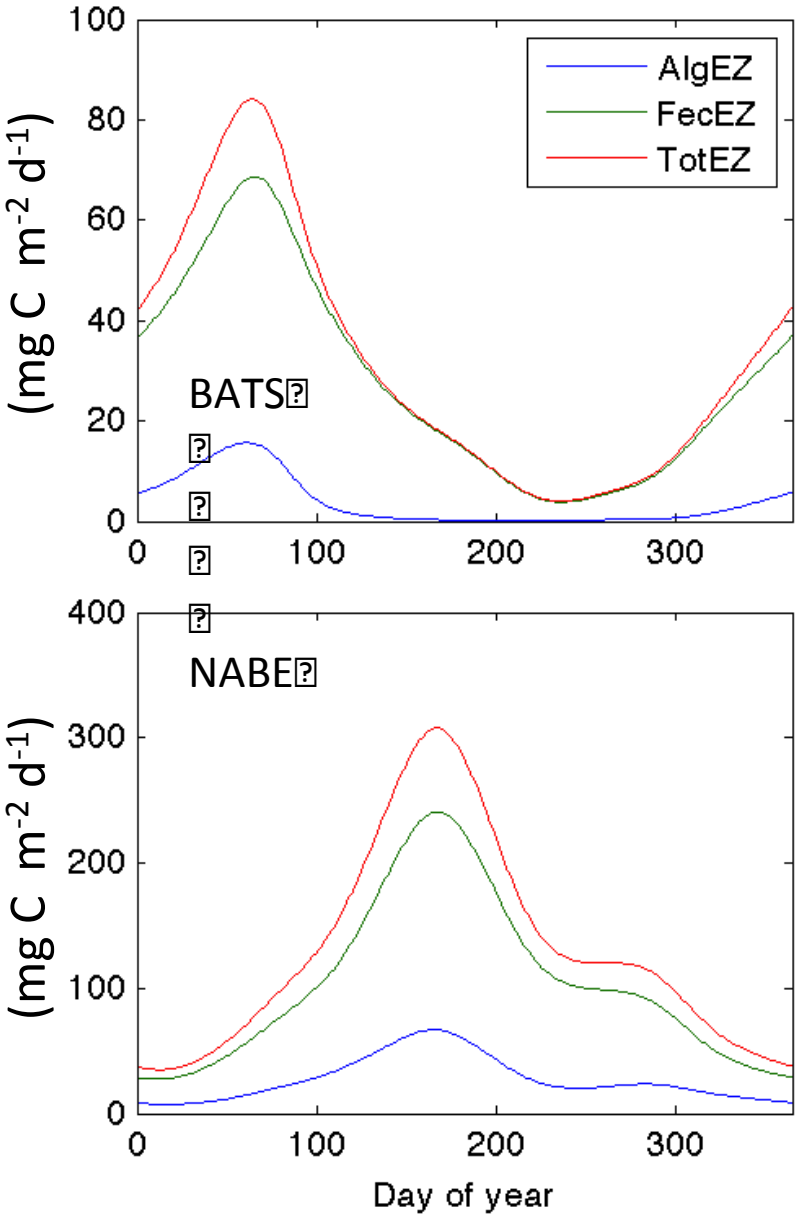
$$AlgEZ = f_{Alg} * NPP_M$$

$$f_{Alg} = 0.1$$

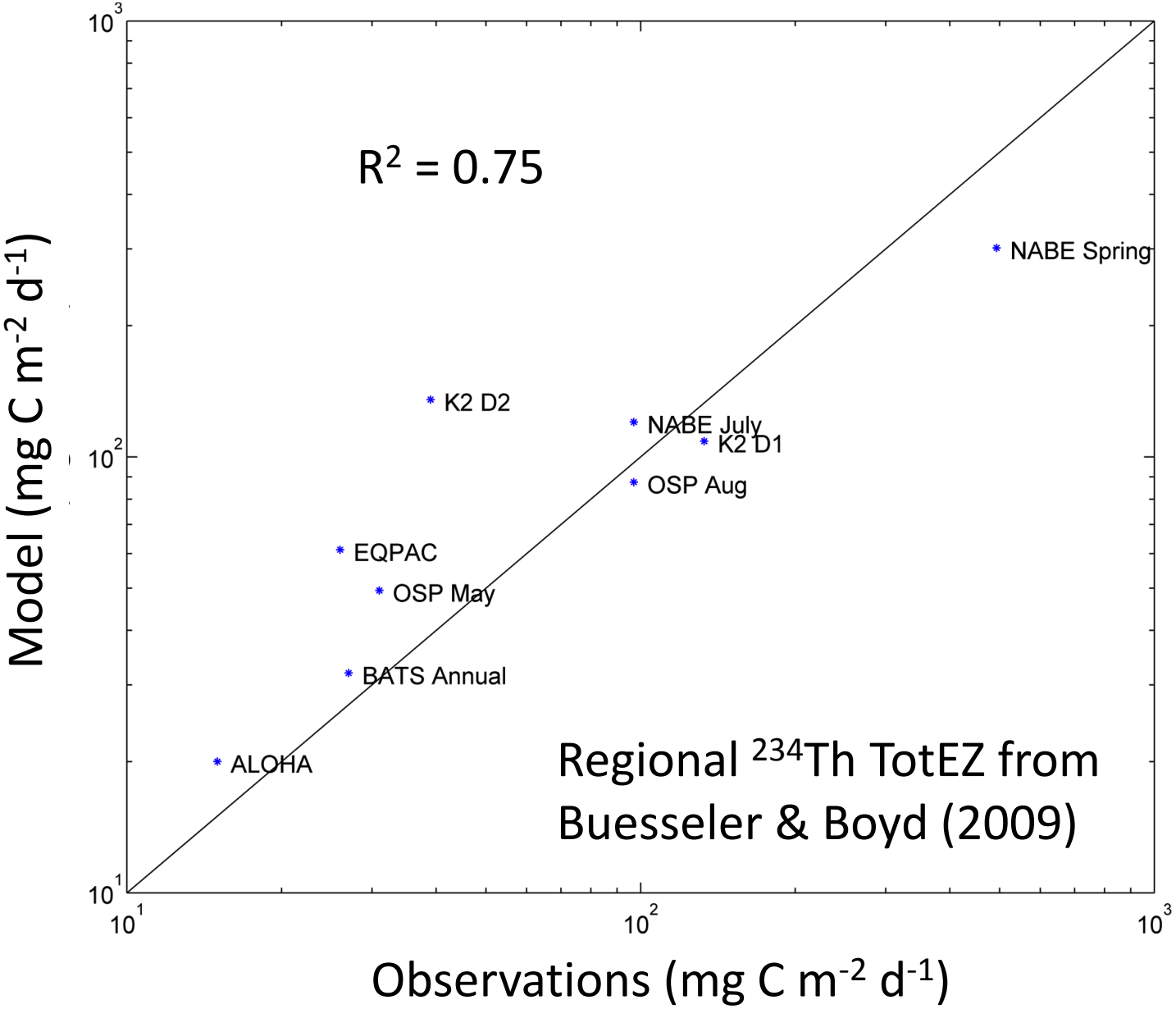
$$FecEZ = (f_{FecM} * Grz_M + f_{FecN+P} * Grz_{N+P}) * Z_{eu}$$

$$f_{FecM} = 0.3 \ \& \ f_{FecN+P} = 0.1$$

$$TotEZ = AlgEZ + FecEZ$$

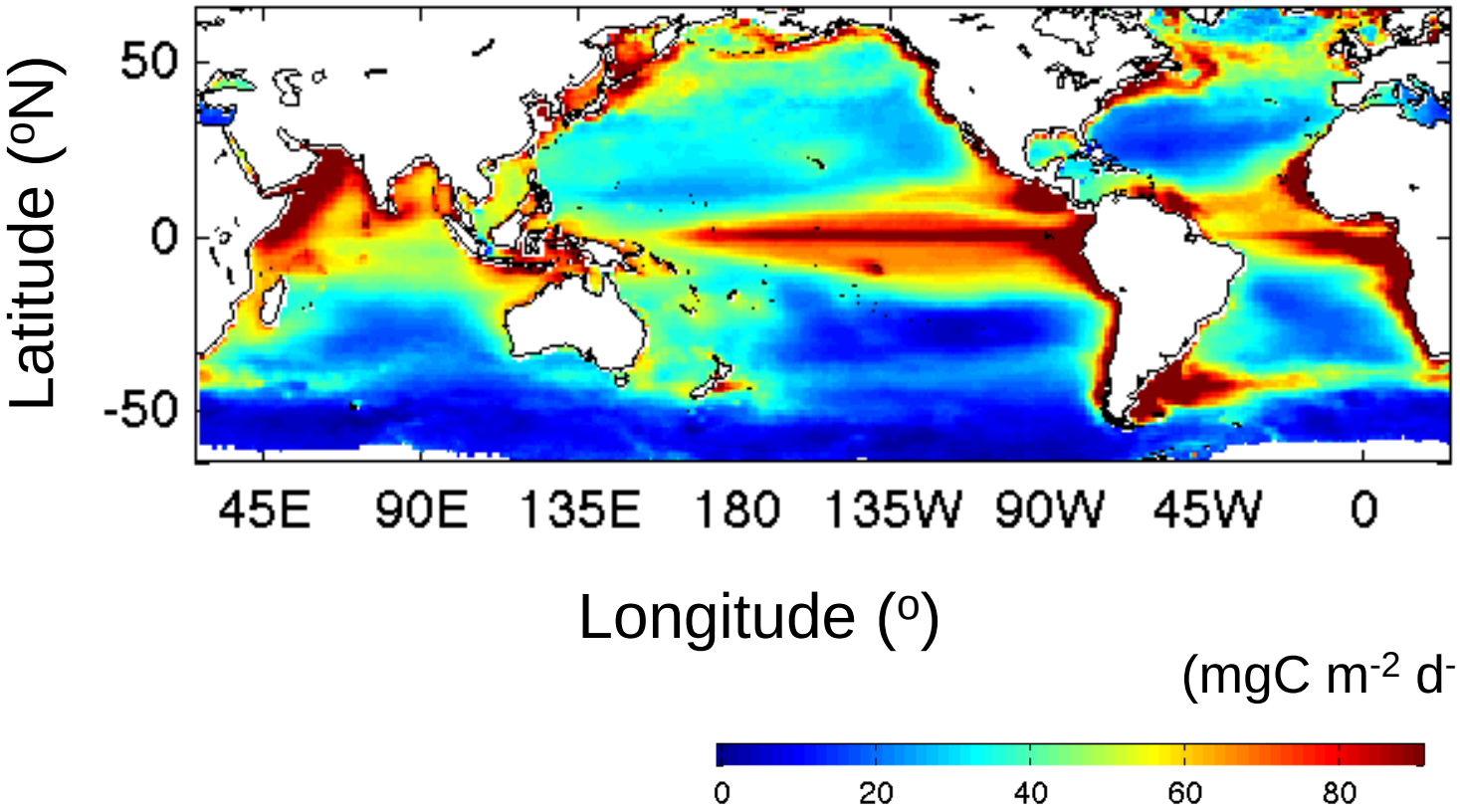


So, Does It Work??



*Not completely fair as model is a climatology and the observations are not

Annual TotEZ



Total = 5.7 Pg C y^{-1}

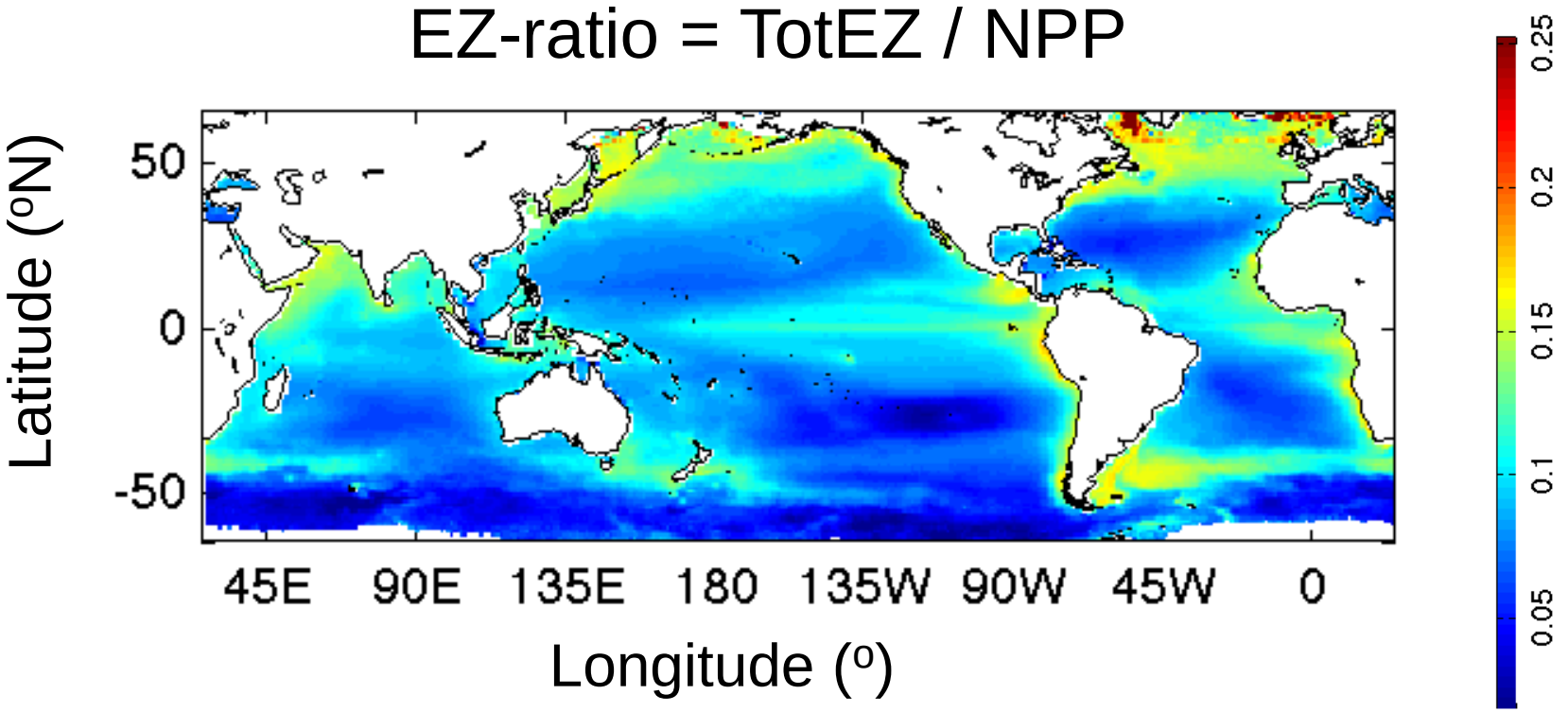
So, Is It Robust??

	f_{alg}	m_{ph}	f_{fecM}	f_{fecN+P}	Global TotEZ
	(-)	(d^{-1})	(-)	(-)	(Pg C y^{-1})
Baseline	0.1	0.1	0.3	0.1	5.69
Alter f_{alg}	0.2	0.1	0.3	0.1	6.20
	0.05	0.1	0.3	0.1	5.43
Alter m_{ph}	0.1	0.2	0.3	0.1	4.52
	0.1	0.1	0.2	0.1	5.16
Alter f_{fecN+P}	0.1	0.1	0.3	0.05	4.00
	0.1	0.1	0.3	0.2	9.07

Ensemble mean = 5.9 Pg C y^{-1}

Using VGPM for NPP model, we get 5.4 Pg C y^{-1}

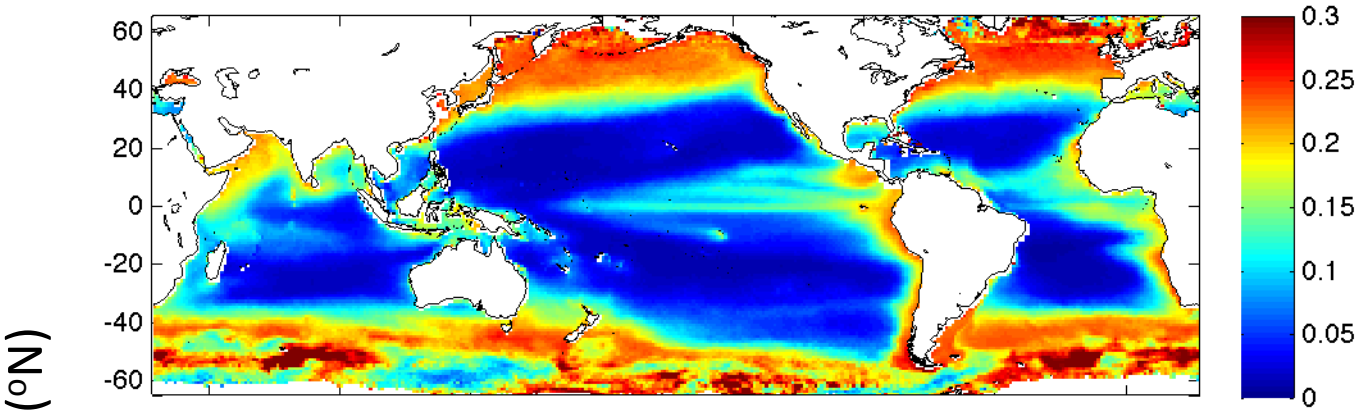
Export Efficiency



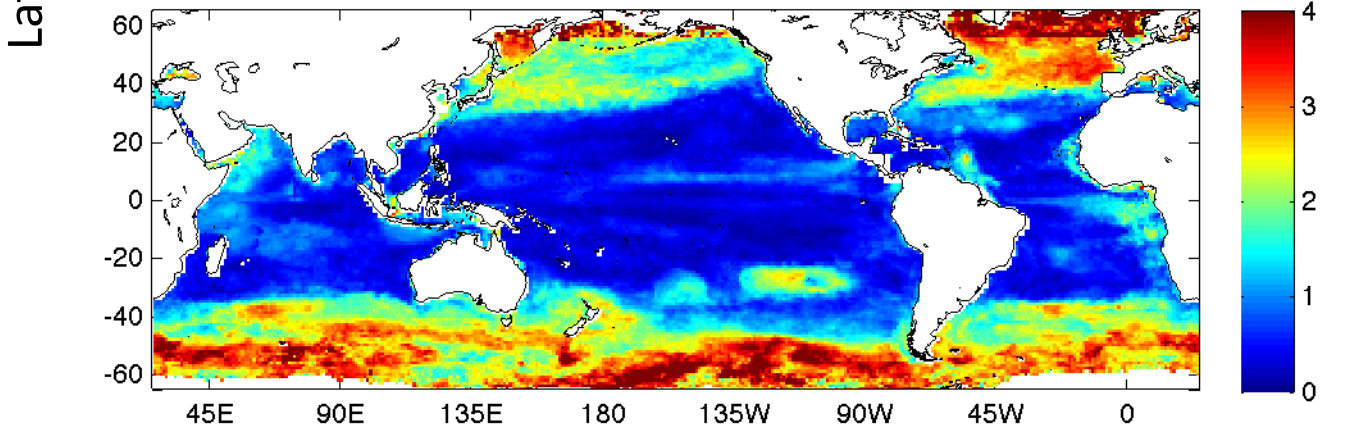
- EZ-ratio patterns have an “oceanographic logic”
- Global mean = 0.10 (± 0.05)

Other Export Metrics

AlgEZ/TotEZ



Seasonal Flux Index = (Max-Min)/Mean

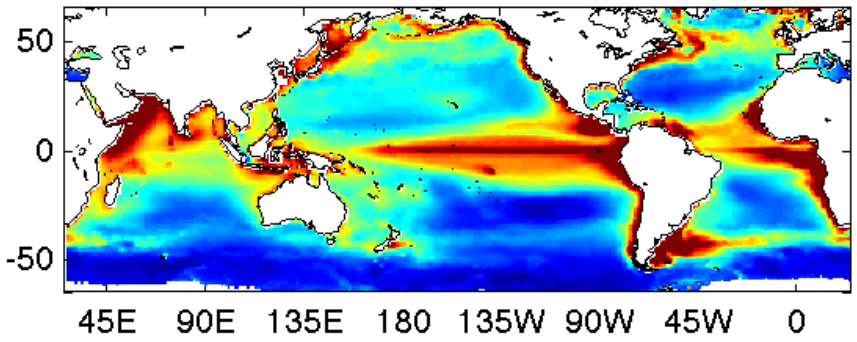


Latitude (°N)

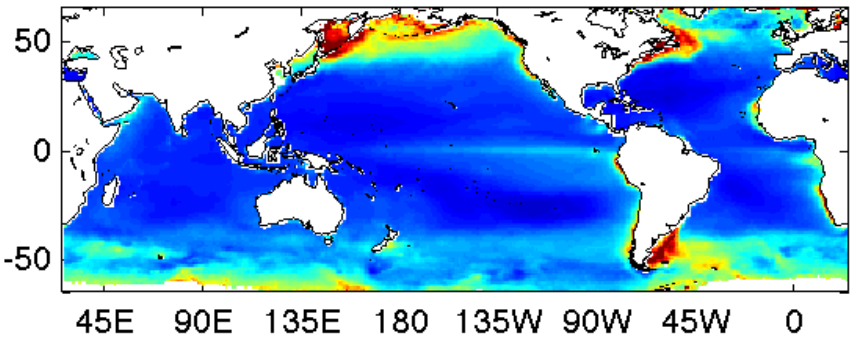
Longitude (°)

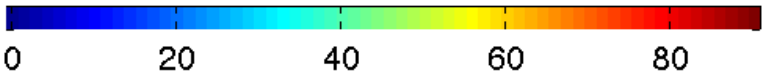
Comparison to Previous Approaches

TotEZ

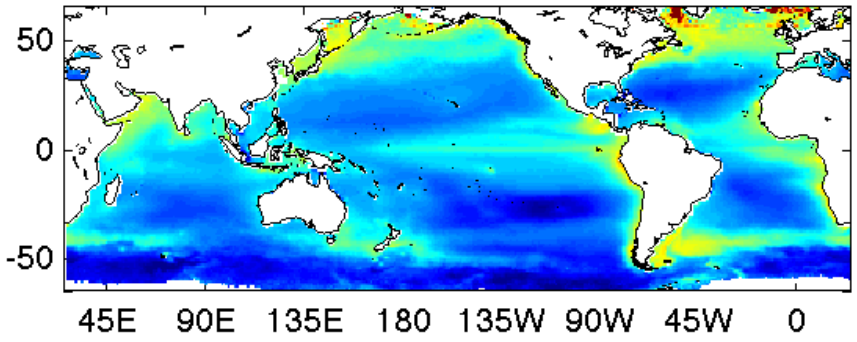


Henson et al. [2011] Flux @ 100 m

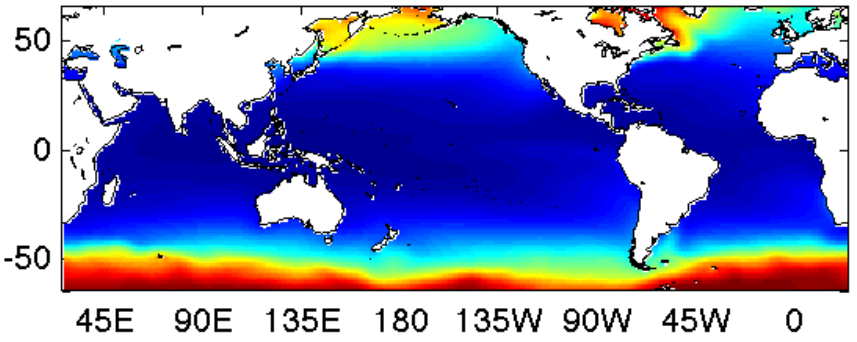


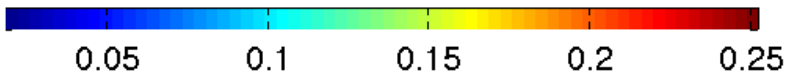


TotEZ / NPP



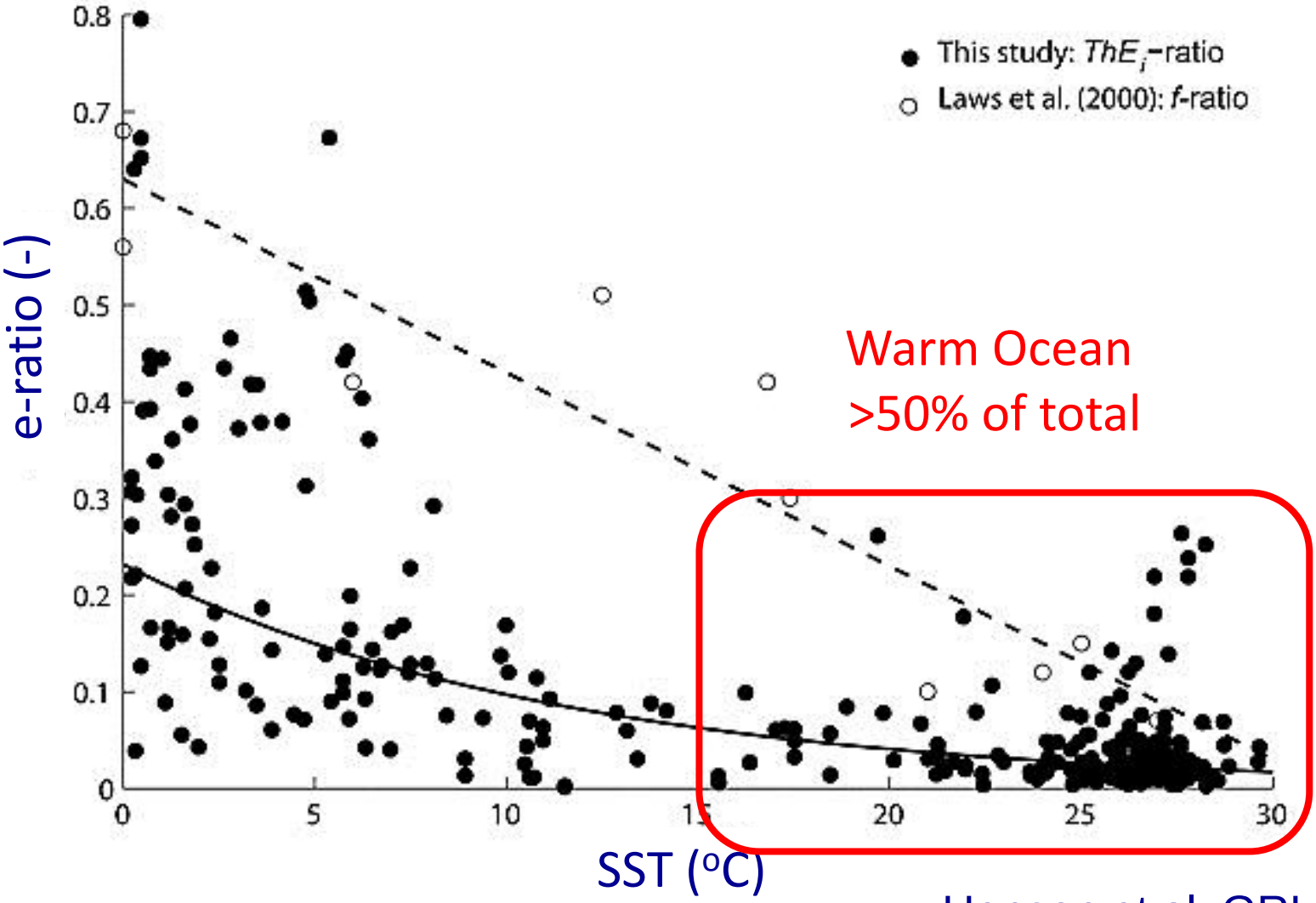
Henson et al. [2011] e-ratio @ 100 m





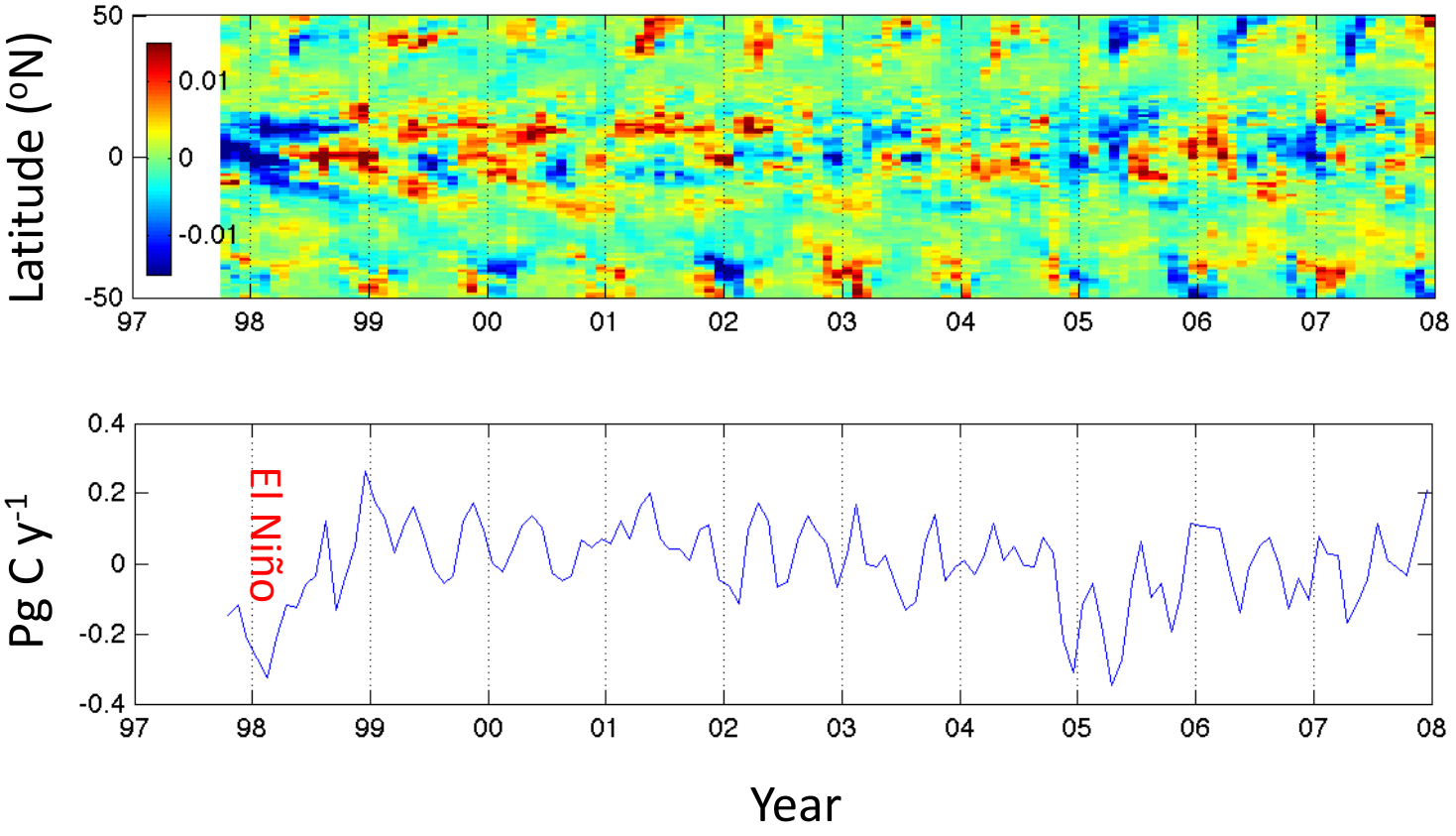
Siegel et al. [2014]

Comparison to Previous Approaches



Henson et al. GRL [2011]

Interannual Changes in TotEZ Anomalies



Contribution from each zonal band to total global anomaly

Total global anomaly from 50°N to 50°S

- Global variability is ~0.6 Pg C y^{-1} (~10% of climatological flux)
- Largest contributions in the tropical & subarctic oceans
- Insignificant trend over the SeaWiFS record

Summary of Results

- Mechanistic model for global C export on sinking particles from the euphotic zone

  Four parameters – make sense physically (at least to me)

  Model successfully recreates regional observations & is robust to large parameter variations

  Improvement over correlative methods

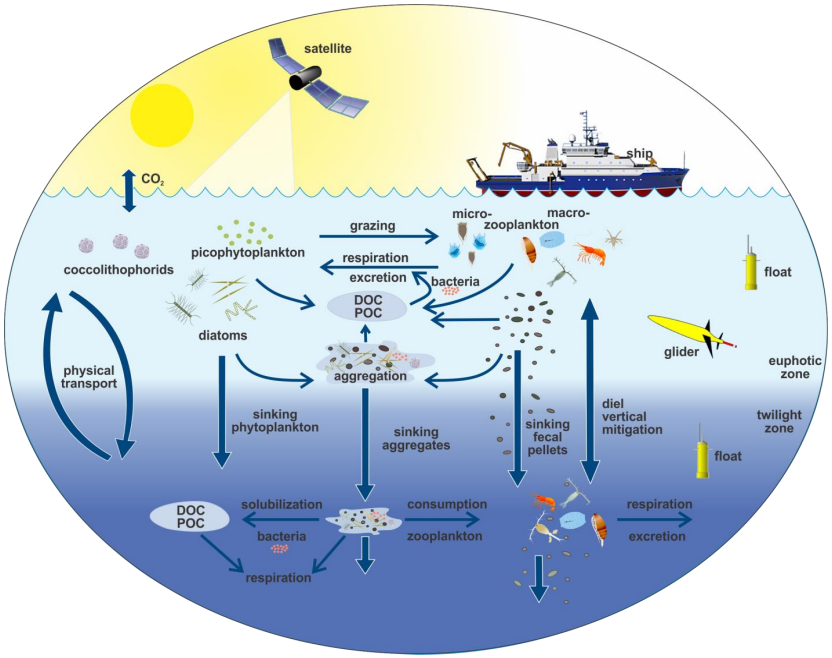
- Global TotEZ ~ 5.9 Pg C y^{-1} & EZ-ratio ~ 0.1
- Interannual variations are observed for both global TotEZ and EZ-ratio

Next Steps…

- Improve remote sensing data products
  - PhytoC, PSD, NPP, etc.
- Advance food-web modeling
  - What really are f_{AlgM}, f_{FecM}, f_{FecN+P}, etc.?
  - Is the food-web model framework used appropriate for all sites & times?
- Need field data...
  - Need simultaneous BGC/food_web/optics obs under differing “states” of biological pump
  - Then, models of the pump can be built & tested

EXPORTS

EXport **P**rocesses in the **O**cean from **R**emo**T**e **S**ensing



EXPORTS Writing Team: Mike Behrenfeld (OSU), Claudia Benitez-Nelson (USoCar), Emmanuel Boss (UMaine), Mark Brzezinski (UCSB), Ken Buesseler (WHOI), Adrian Burd (UGA), Craig Carlson (UCSB), Eric D'Asaro (UW), Scott Doney (WHOI), Mary Jane Perry (UMaine), Dave Siegel (UCSB), Rachel Stanley (WHOI), Deb Steinberg (VIMS)

http://cce.nasa.gov/cce/ocean.htm

What is EXPORTS?

A community-vetted science plan for a NASA field campaign

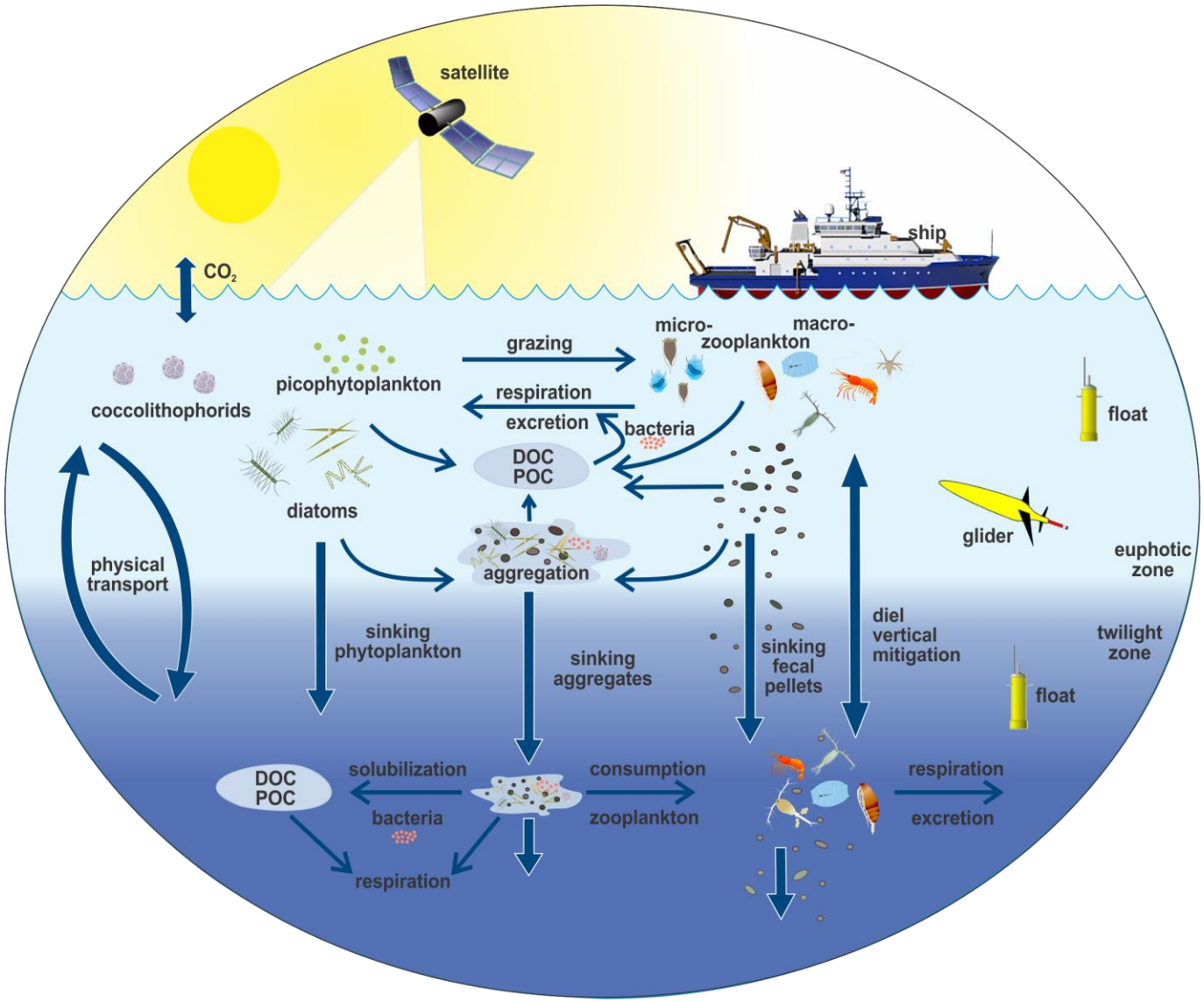
Predict the **state** of the biological carbon pump from satellite & other observations

EXPORTS plan in public comments until **Aug 25**

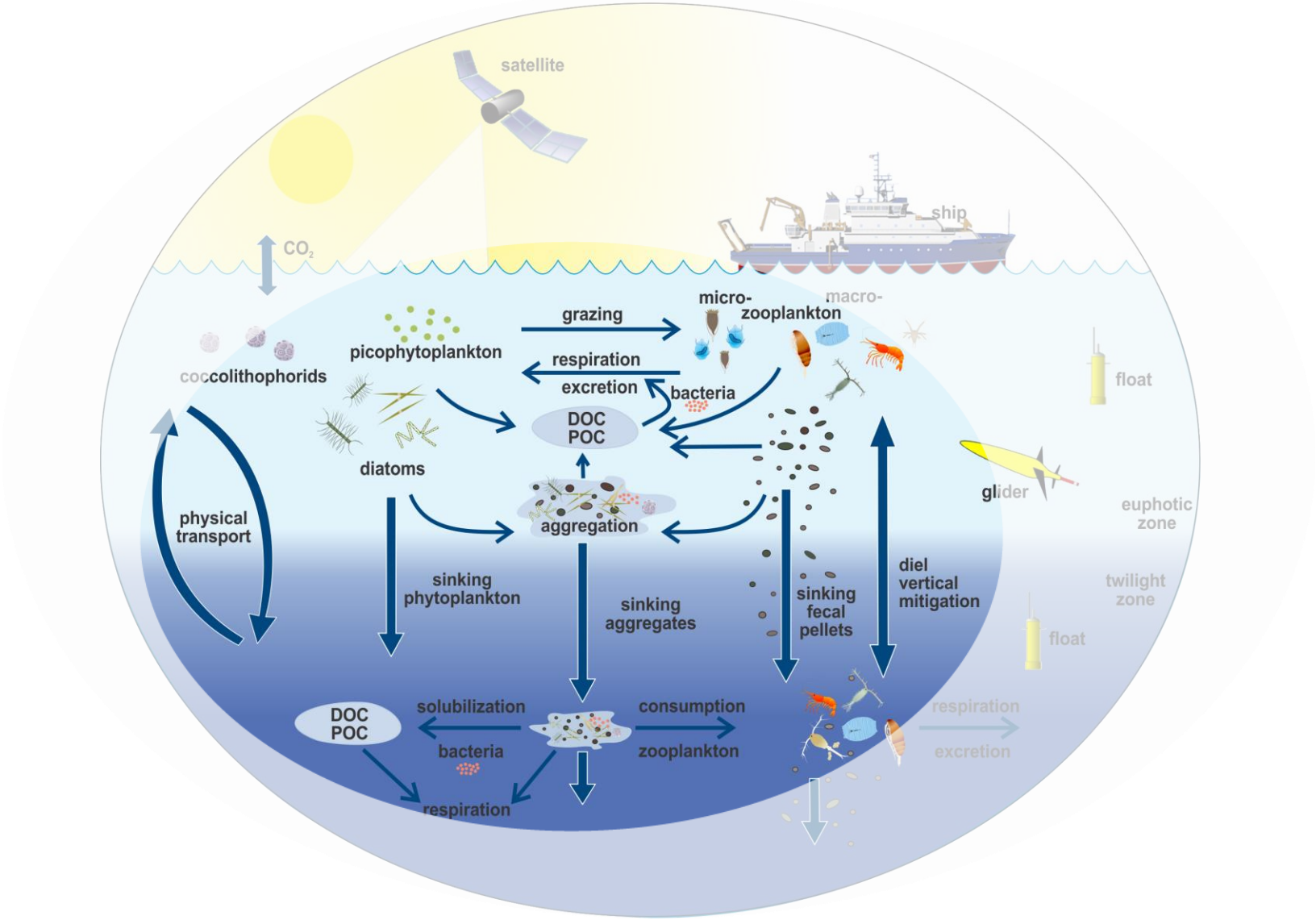
http://cce.nasa.gov/cce/ocean.htm

Projected start date (if approved): 2017

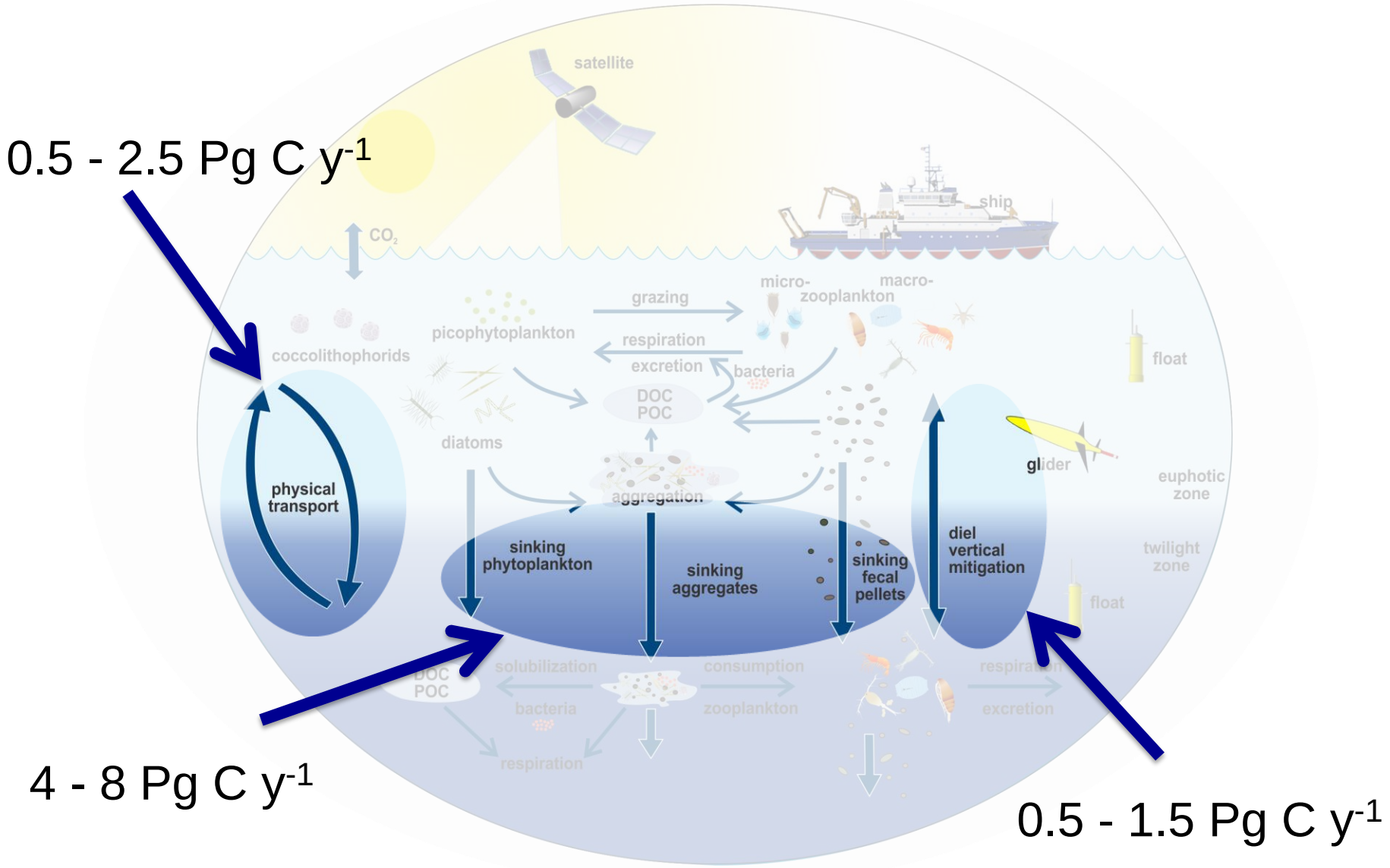
Why EXPORTS?


satellite
ship
CO_2
micro-
macro-
zooplankton
grazing
picophytoplankton
respiration
excretion
bacteria
coccolithophorids
DOC
POC
diatoms
float
glider
physical
transport
aggregation
euphotic
zone
sinking
phytoplankton
sinking
aggregates
sinking
fecal
pellets
diel
vertical
mitigation
twilight
zone
float
DOC
POC
solubilization
consumption
bacteria
zooplankton
respiration
excretion
respiration

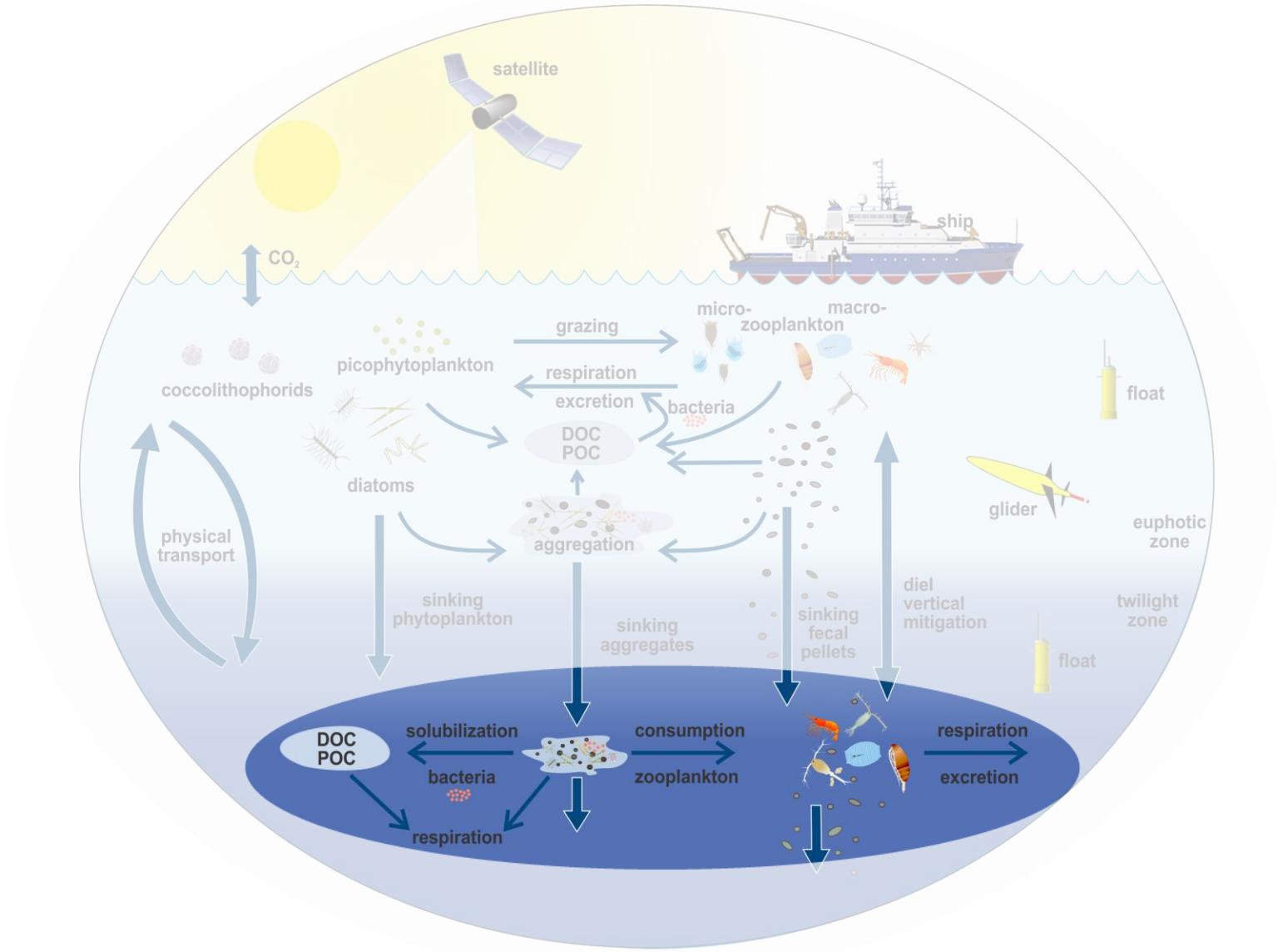
Why? Need to understand, quantify & predict how ecosystem processes transfer organic matter to depth



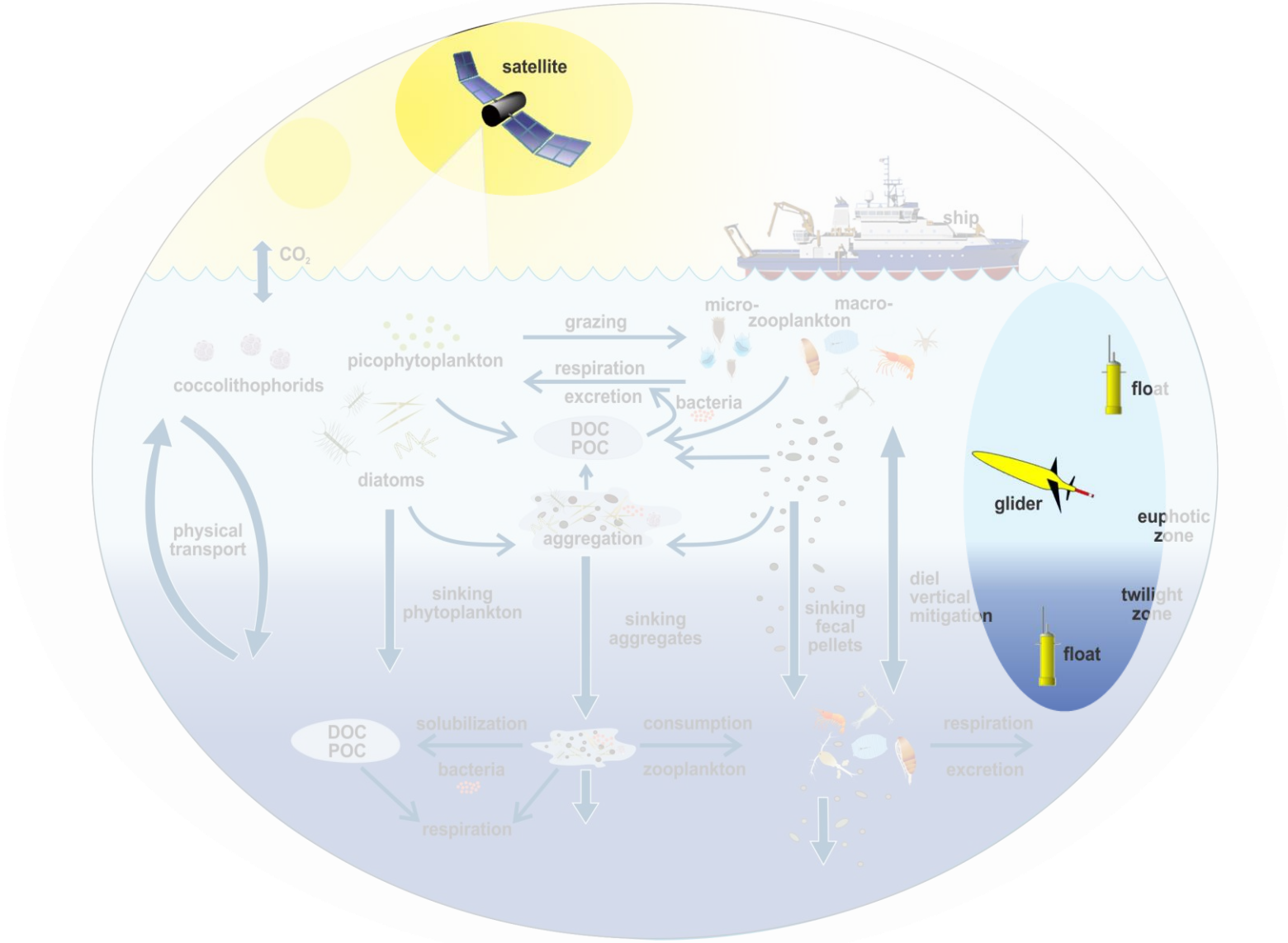
Why? Improve global estimates of carbon export from the euphotic zone (4 to >12 Pg C y^{-1})



Why? Need to quantify the attenuation of export below euphotic zone (the twilight zone)



Why Now? Advances in remote sensing (& PACE!!) & autonomous tools make it time!



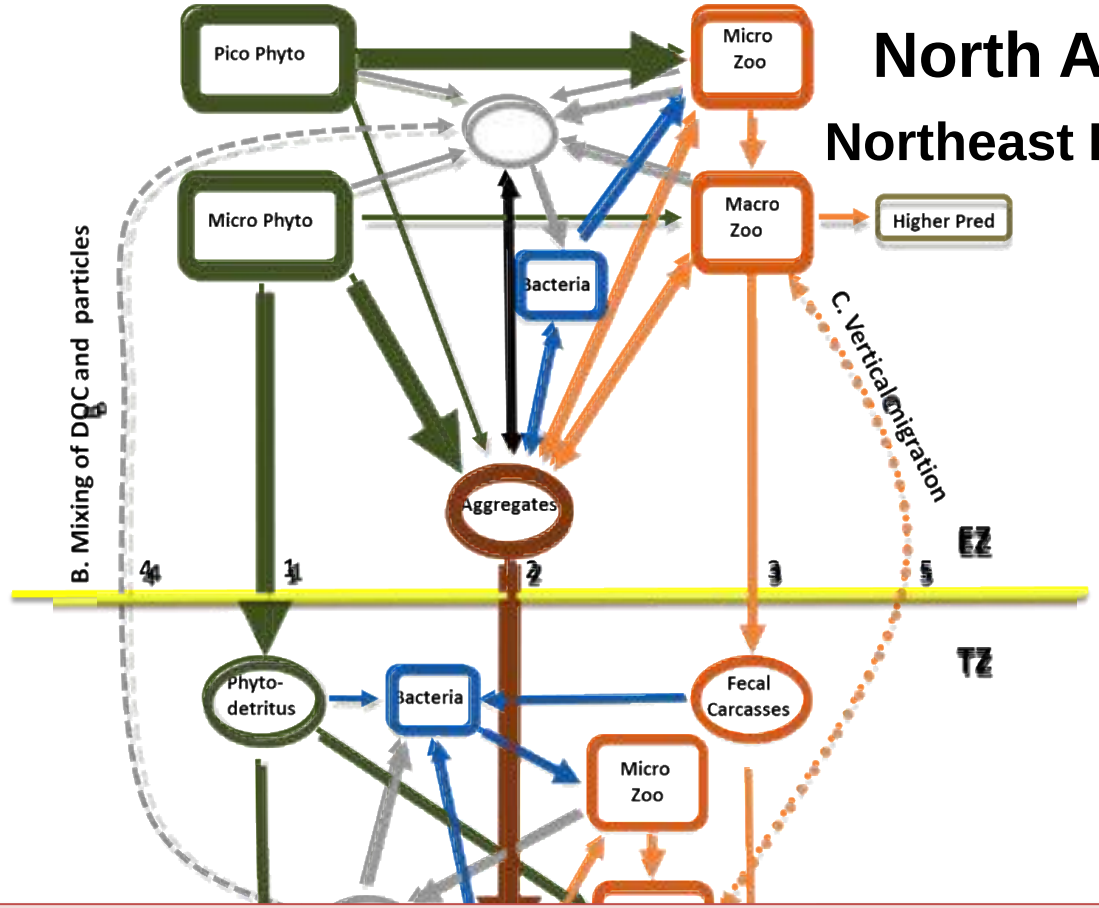
EXPORTS: Three Science Questions

How do upper ocean ecosystem characteristics determine the vertical transfer of organic matter from the well-lit surface ocean?

What controls the efficiency of vertical transfer of organic matter below the well-lit surface ocean?

How can the knowledge gained be used to reduce uncertainties in contemporary & future estimates of the biological pump?

EXPORTS: Focus on Pathways



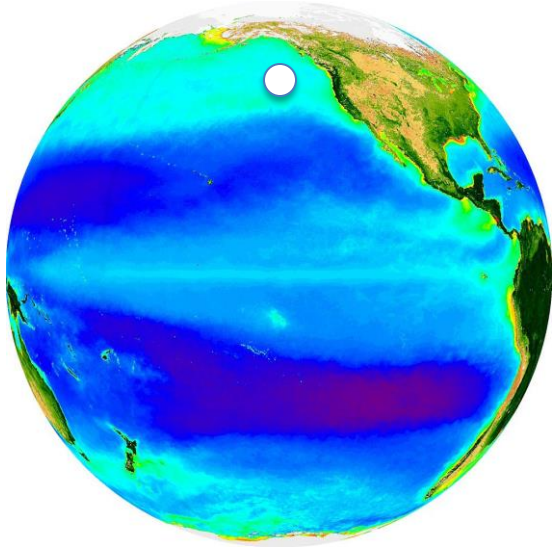
North Atlantic Bloom

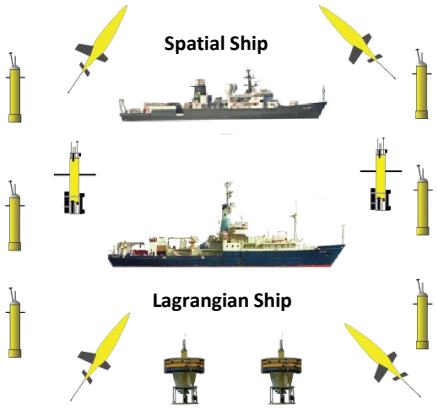
Northeast Pacific Summer

Goal: Predict the state of the biological pump given surface ecosystem characteristics

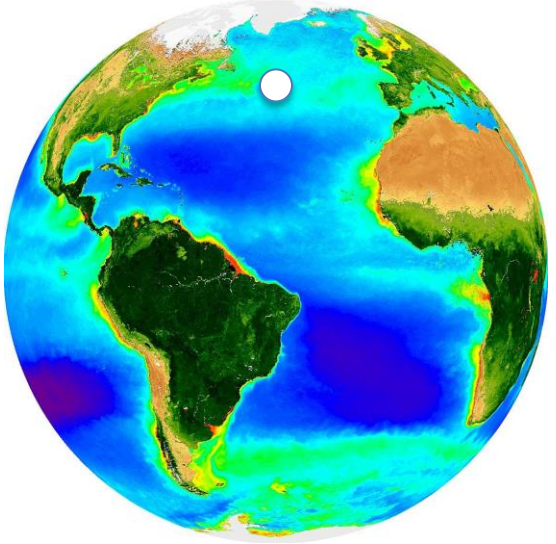
EXPORTS: Experimental Plan

Station P





North Atlantic



Cruise 1: April/May 30/45d
Cruise 2: Aug, 30d
Leverage: OOI node, LineP

Bloom: April/May 45 d
Non-bloom: Aug, 30d
Leverage: Internationals

Will collect ~8 states of the biological pump

Supplement by data mining existing results

EXPORTS: Experimental Plan

Water-Following
follow instrumented mixed layer float(s?)

Particle-Following
from production to trap
Measure C cycling fluxes from 0 to 500 m (over 10 d)

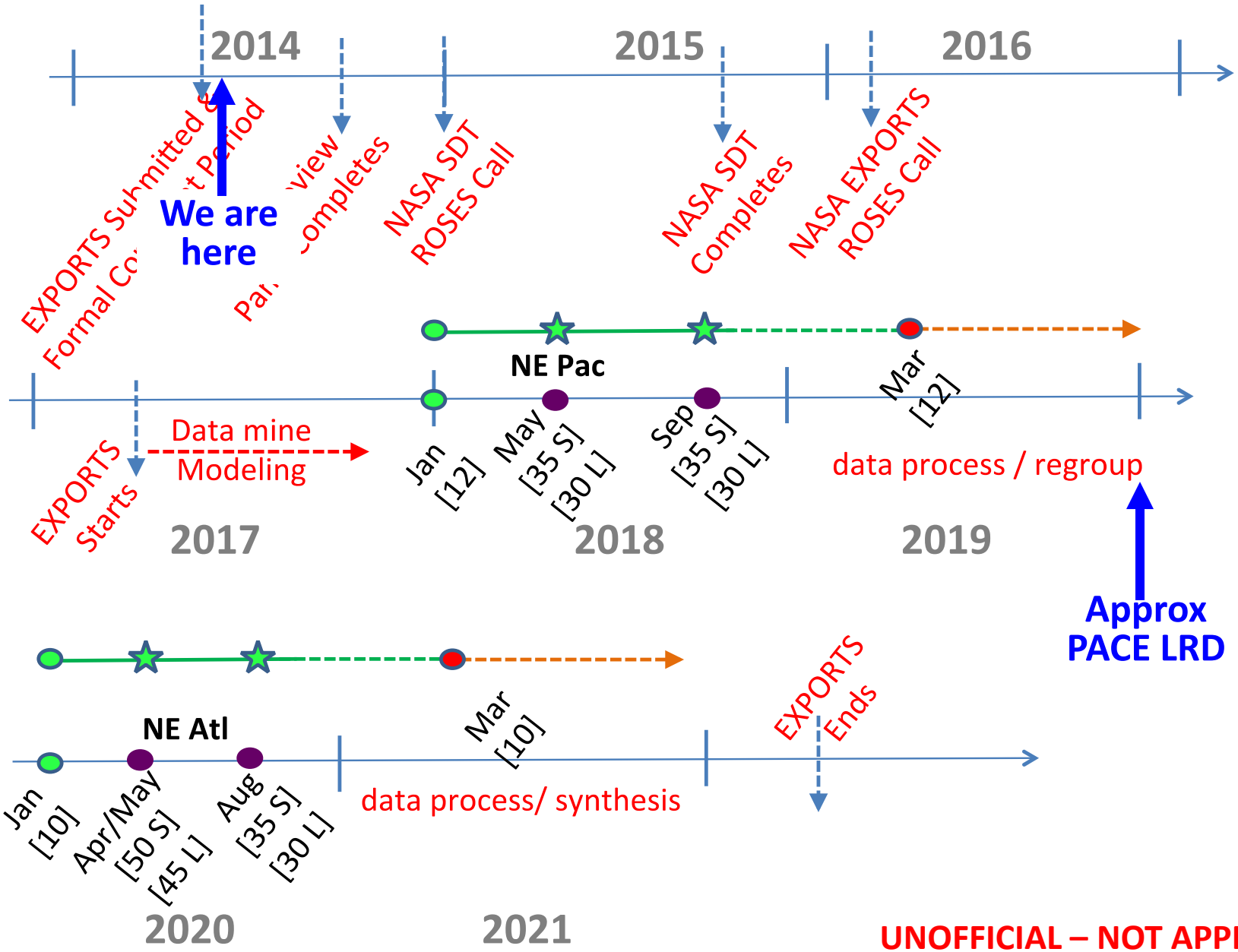
Lagrangian Ship
Measure rates & transformations

Spatial Ship
Submeso- & meso-scale surveys (5-200 km)
Deploy short-term assets

Long Term Presence
Profiling Floats & Satellites
BioARGO, PSD & export proxy
Annual BGC budgeting
O_2, NO_3, DOC, DIC, etc.

Optimize Spatial Sampling
Gliders surveying (5-100 km)
Bio-optical proxies
Satellite sampling
Ocean color & supporting info

EXPORTS: *Notional* Timeline



UNOFFICIAL – NOT APPROVED!!!

EXPORTS: Next Steps

The EXPORTS Science plan is under public comment until **Aug 25** - **http://cce.nasa.gov/cce/ocean.htm**

NASA will consider comments in a peer review panel to decide whether EXPORTS will be conducted

If selected: A Science Definition Team will be competed (end of this year?) to write the Implementation Plan & the EXPORTS field campaign would start 2017

Important: Every role in EXPORTS will be competed!!

Outline

- Recap what we know about the ocean's biological pump
- Introduce a new approach for quantifying the biological pump using satellite data
- Assess the logical next steps in improving these models
- Introduce EXPORTS - a science plan for a future NASA major field campaign

Thank You for Your Attention!!

Special thanx to the
NASA Goddard Ocean Biology Processing Group
NRC Committee on Sustained Ocean Color Obs, and
NASA PACE Science Definition Team