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

Dave Siegel – UC Santa Barbara

Help from …

Ken Buesseler & Scott Doney – WHOI

Sevrine Sailley –Plymouth Marine Lab

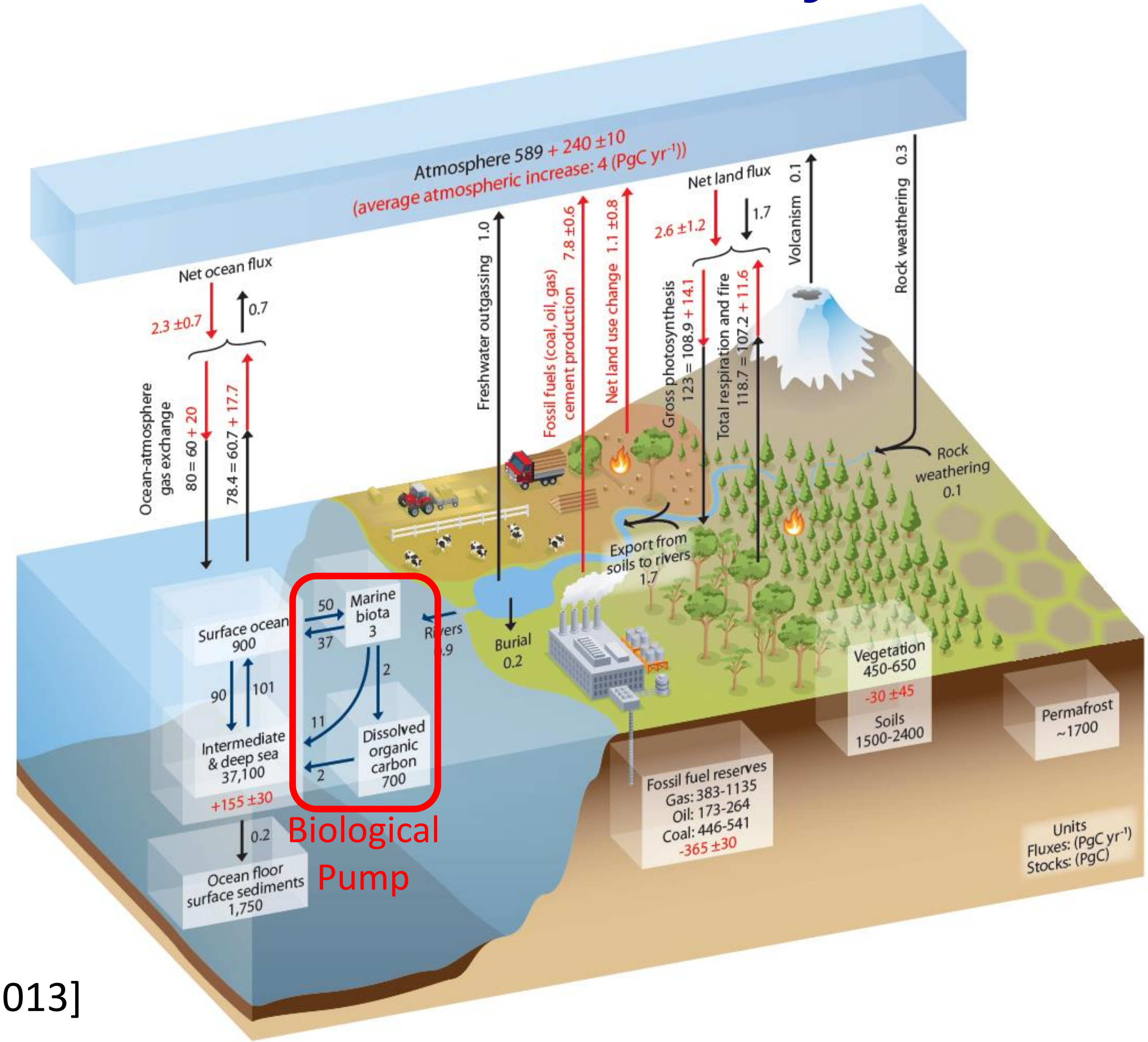
Mike Behrenfeld – Oregon State

Phil Boyd – Univ. Tasmania

Stéphane Maritorena, Norm Nelson & Erik Fields - UCSB

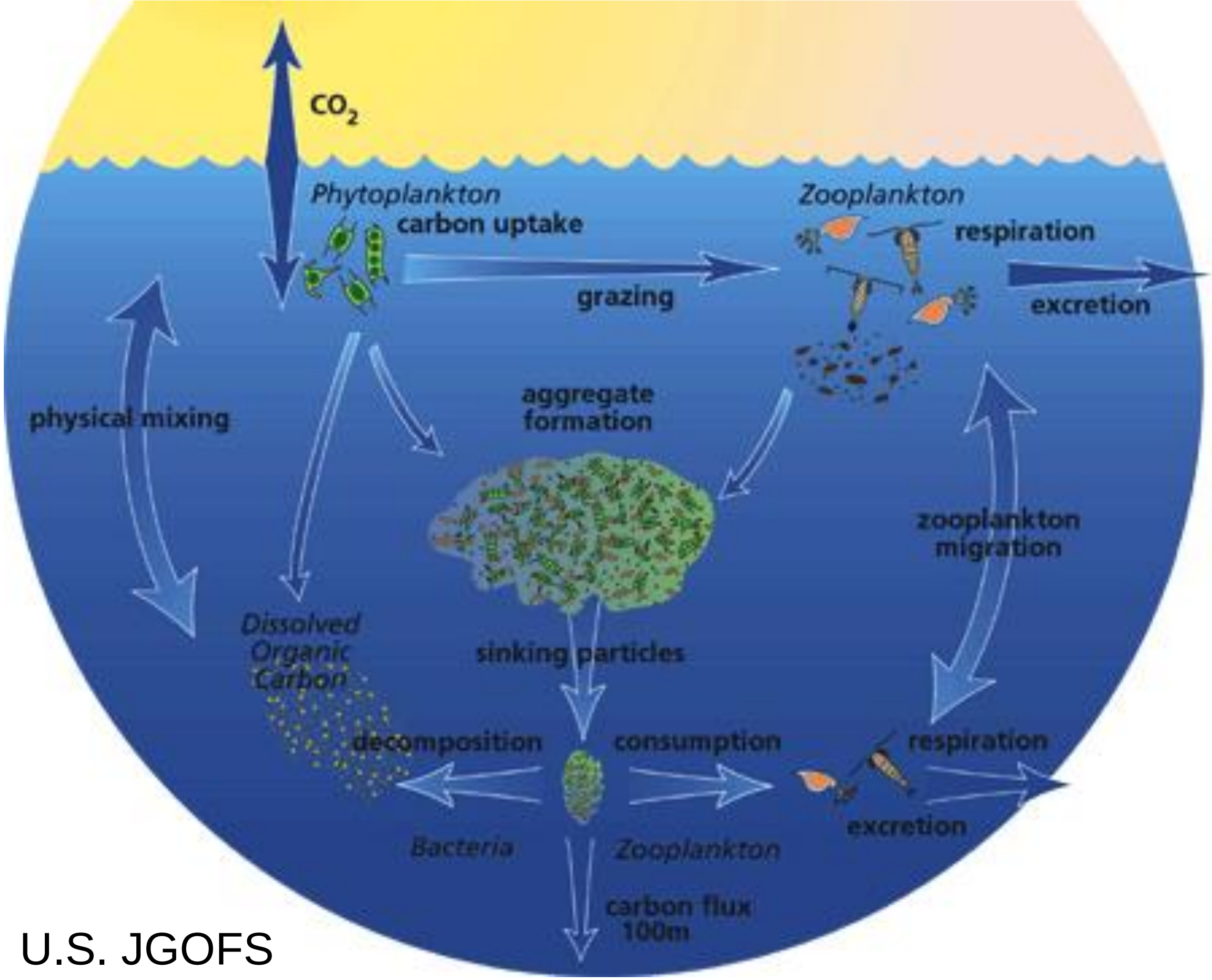
Support from NASA Ocean Biology & Biogeochemistry Program

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

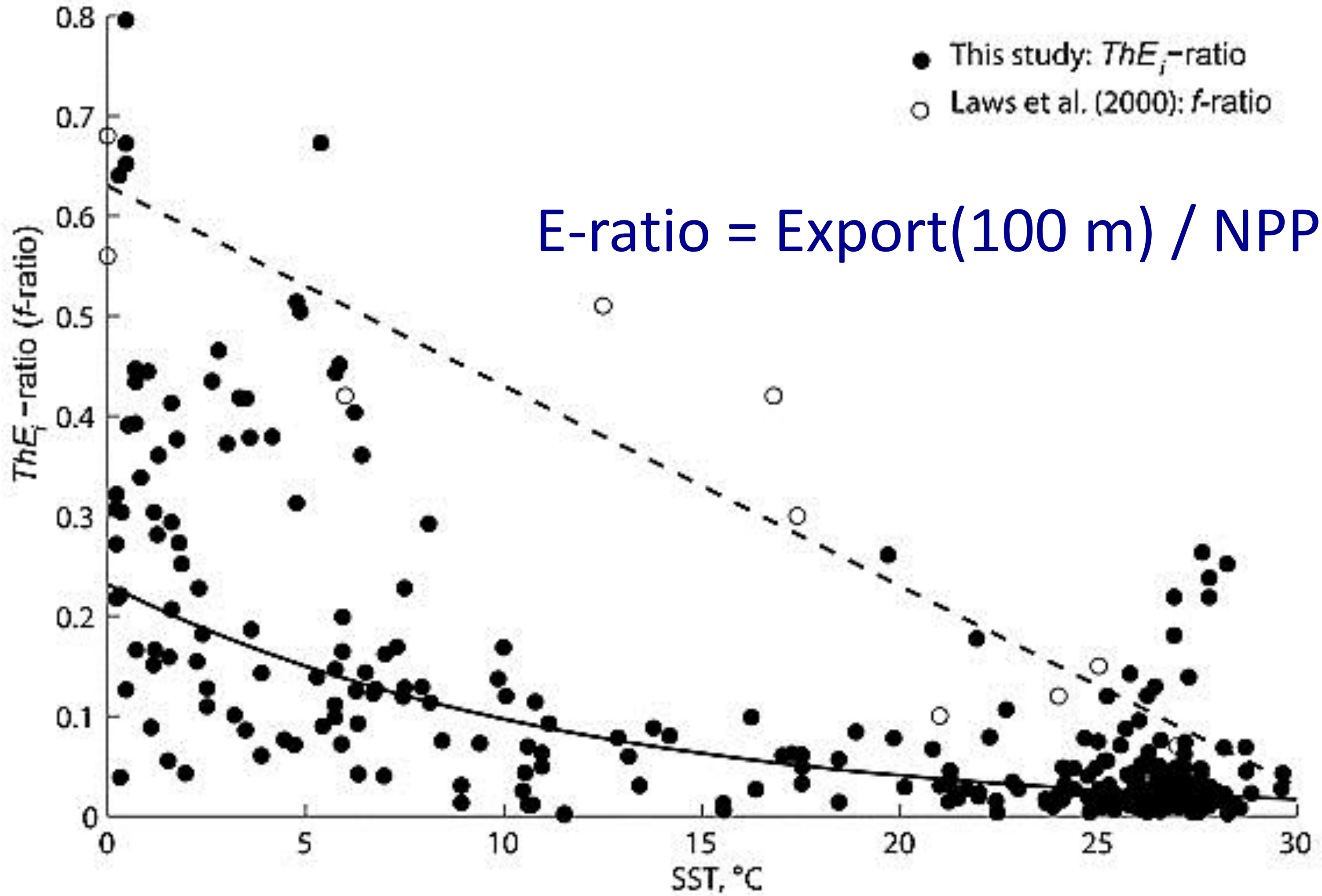
- Problems

  Not mechanistic

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

  Not very good…

E-Ratios vs. SST



Henson et al. GRL [2011]

Extrapolated Global Fluxes

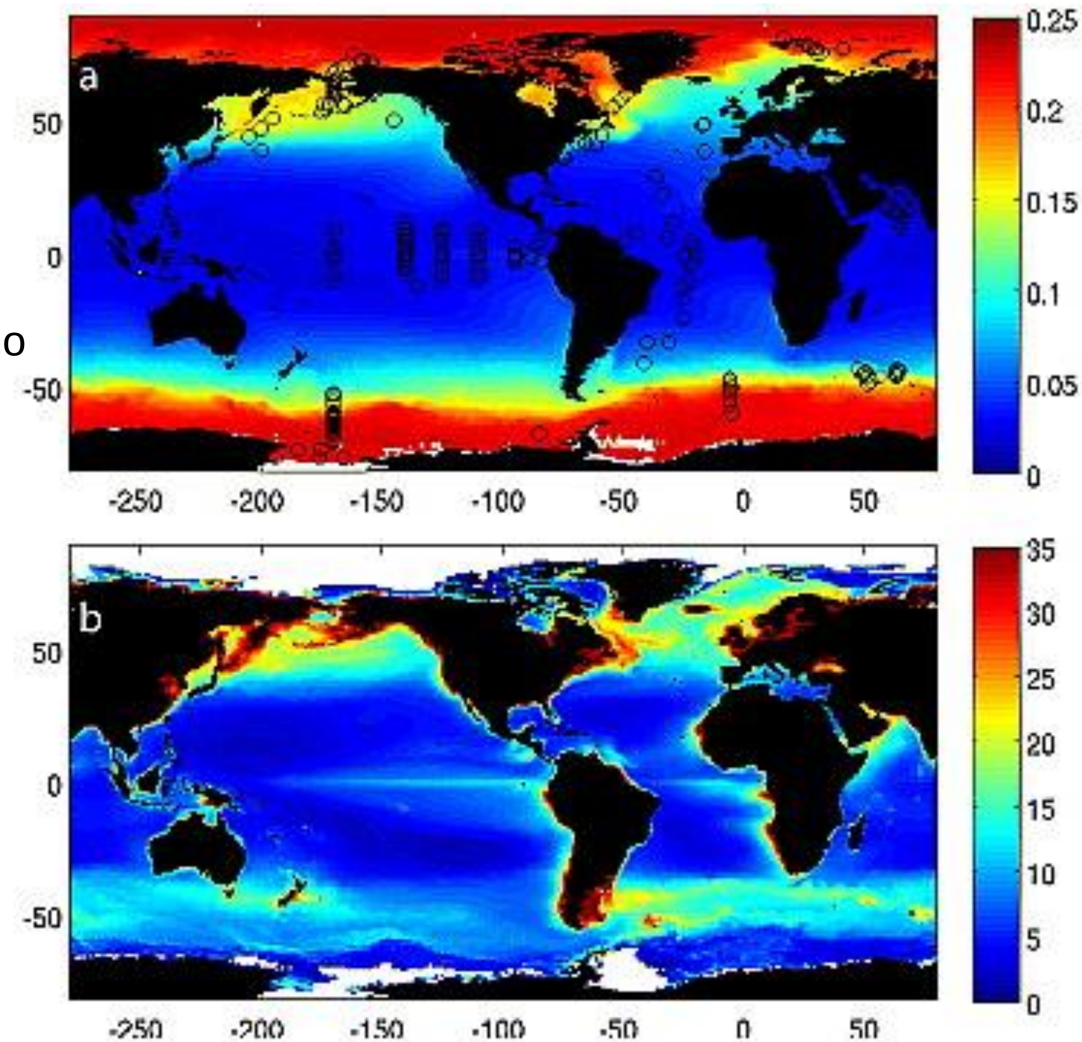
E-ratio @100m

>0.05 equatorward of 40^{o}

Export @100 m

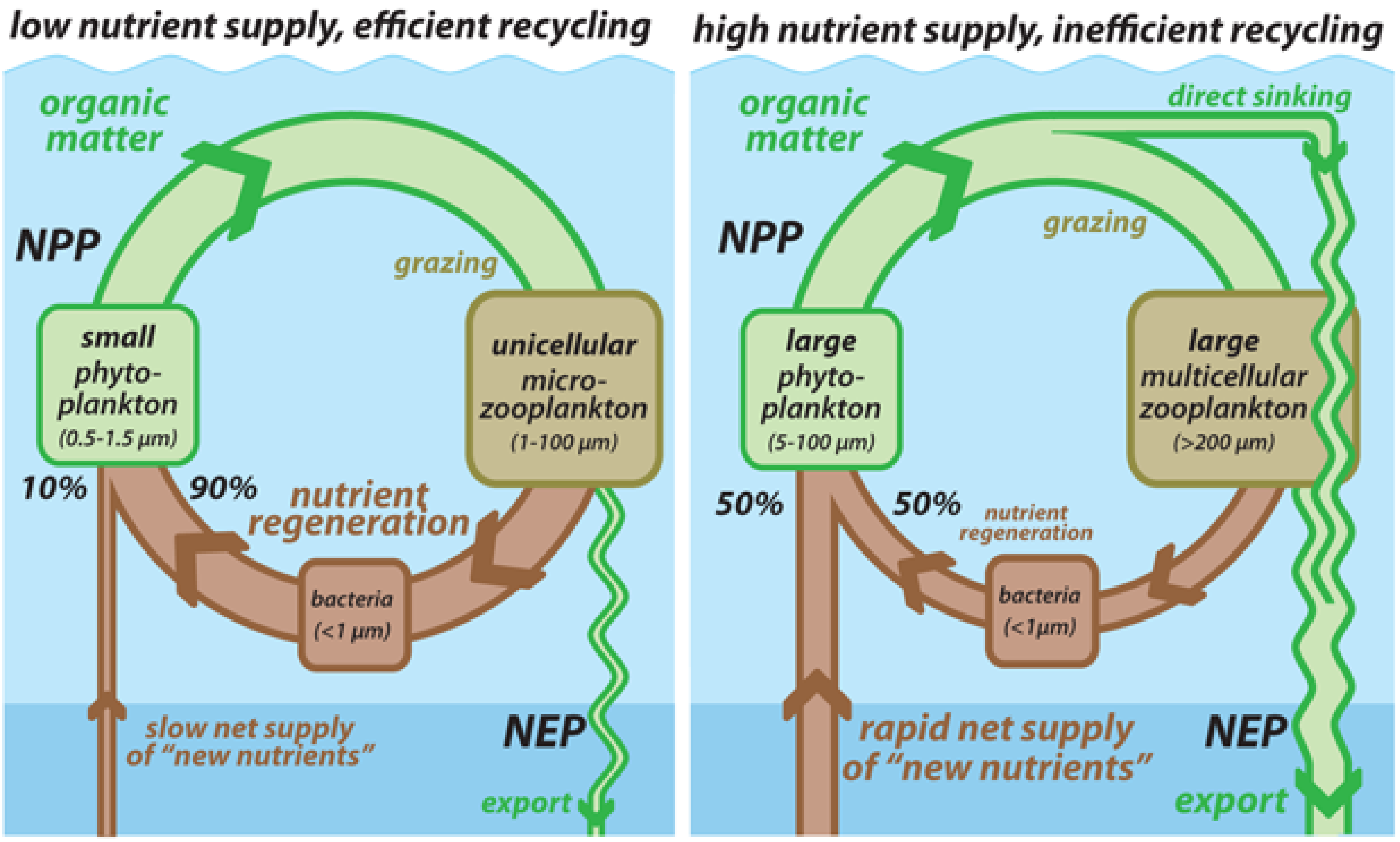
$(gC\ m^{2}\ y^{-1})$

Global Σ ~4 Pg C y^{-1}



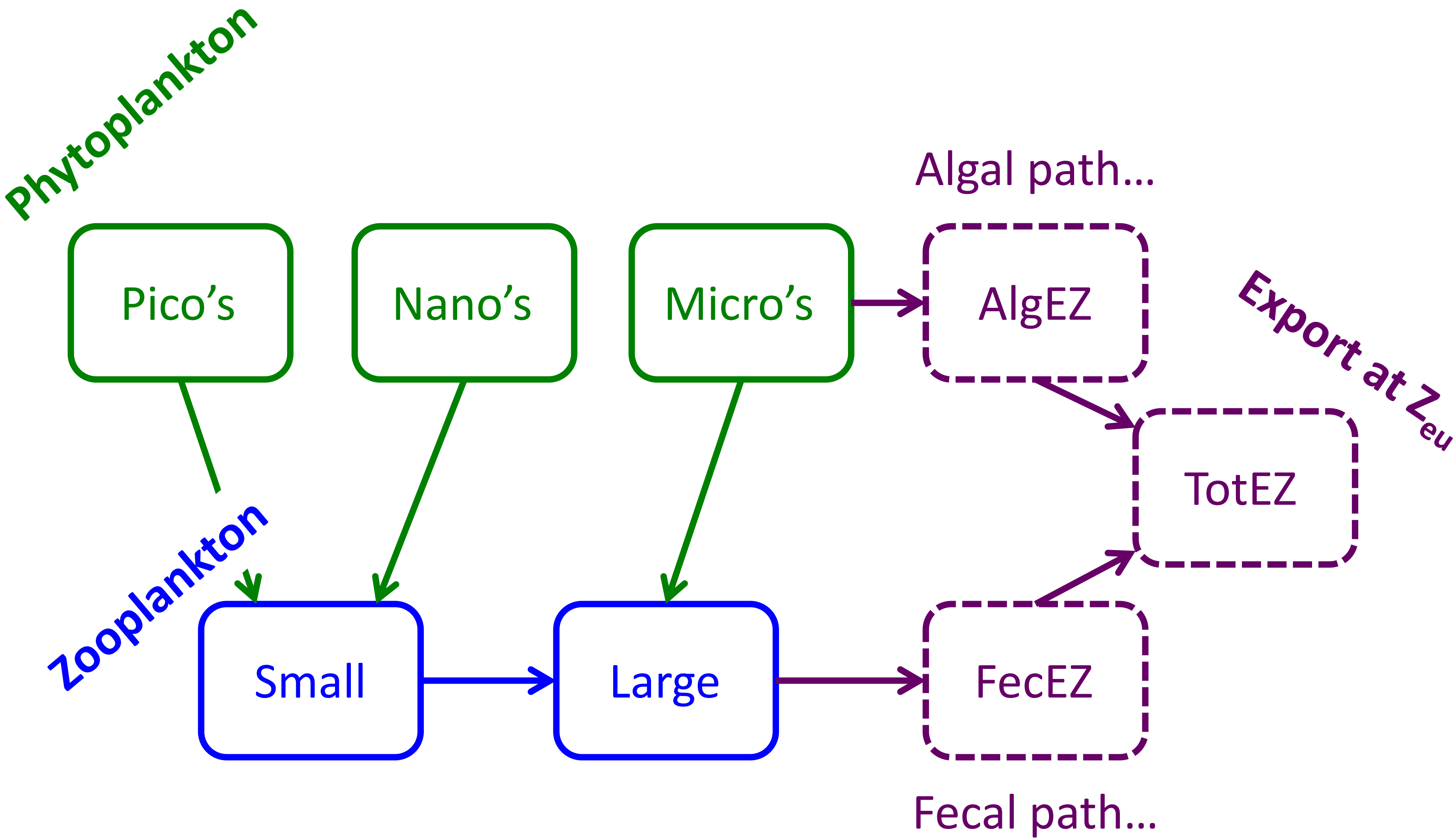
Henson et al. GRL [2011]

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.*)

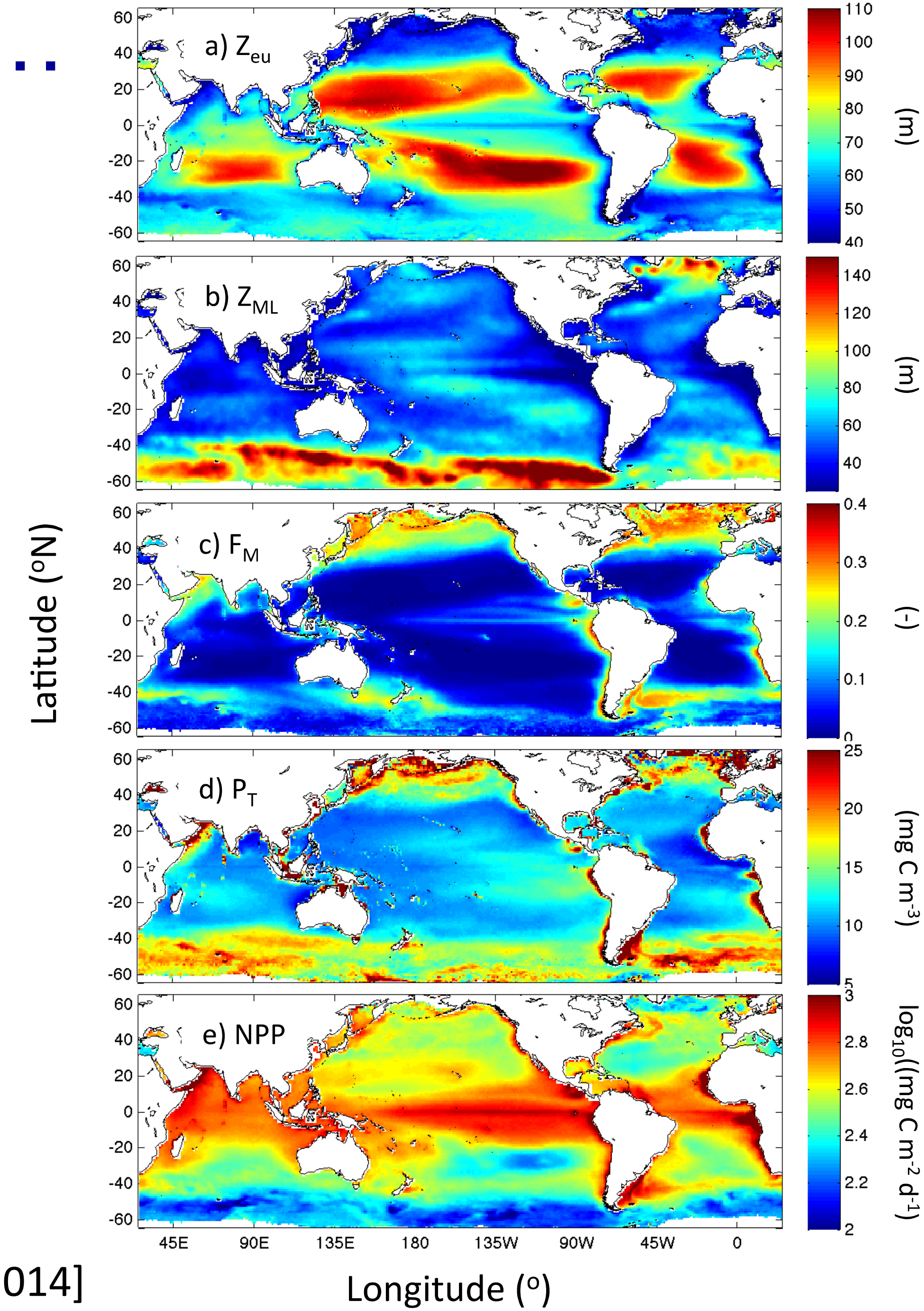
- Mass budgets for phytoplankton C stocks

  Enables upper layer grazing rates to be estimated

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

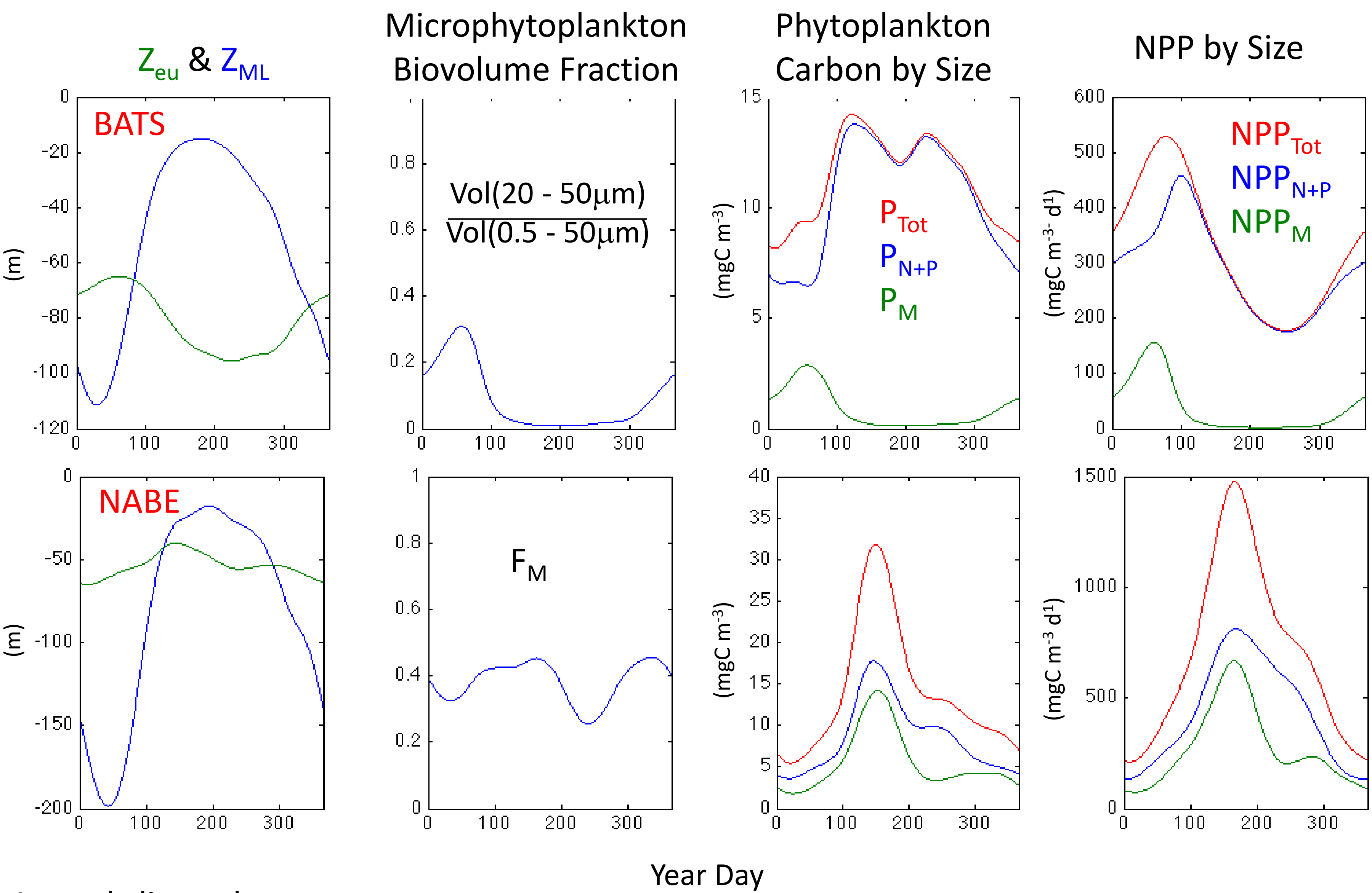
New Satellite Tools…

- 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



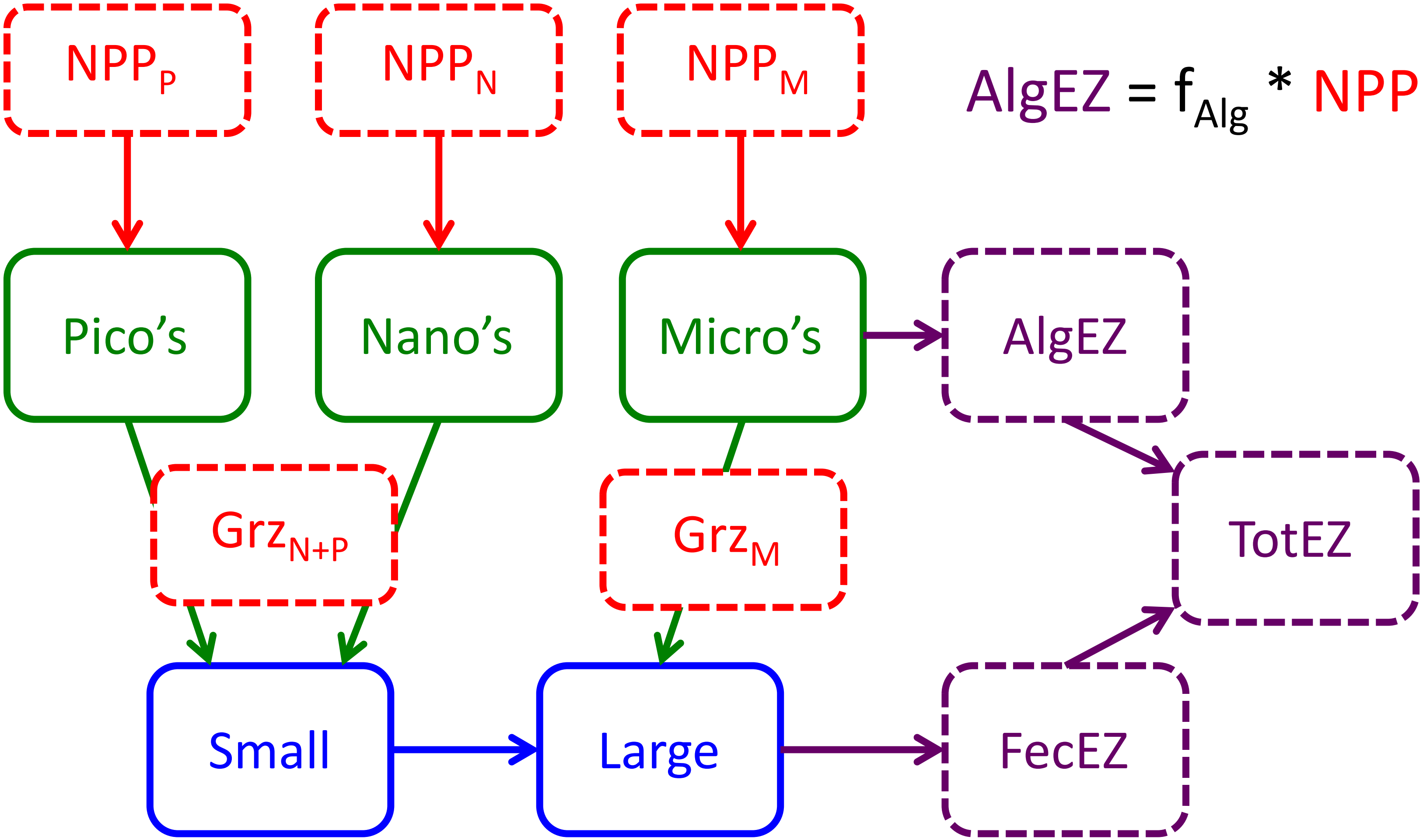
Annual Mean Distributions - Siegel et al. [2014]

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

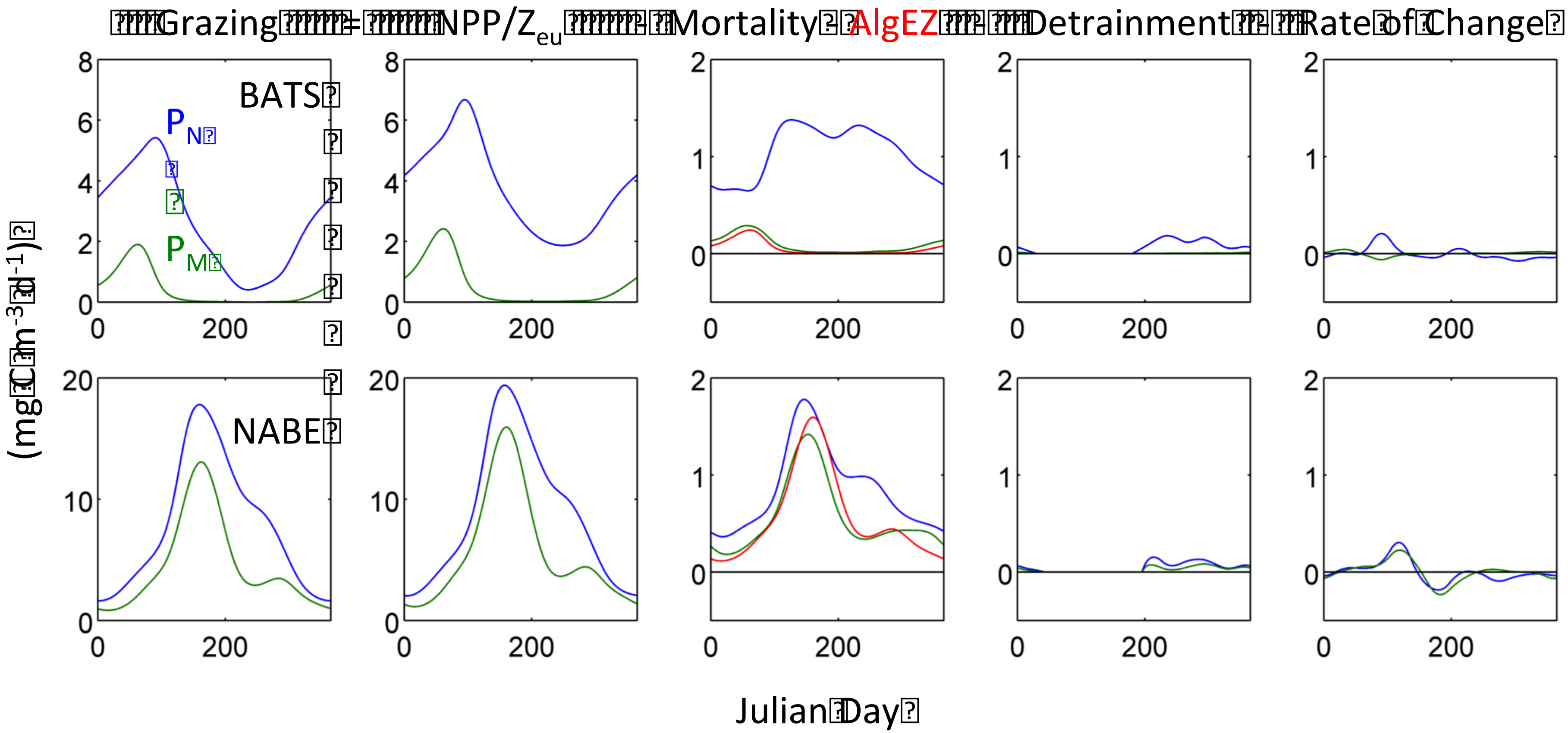
- Upper layer (Z_{ML}) phytoplankton biomass budget

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

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

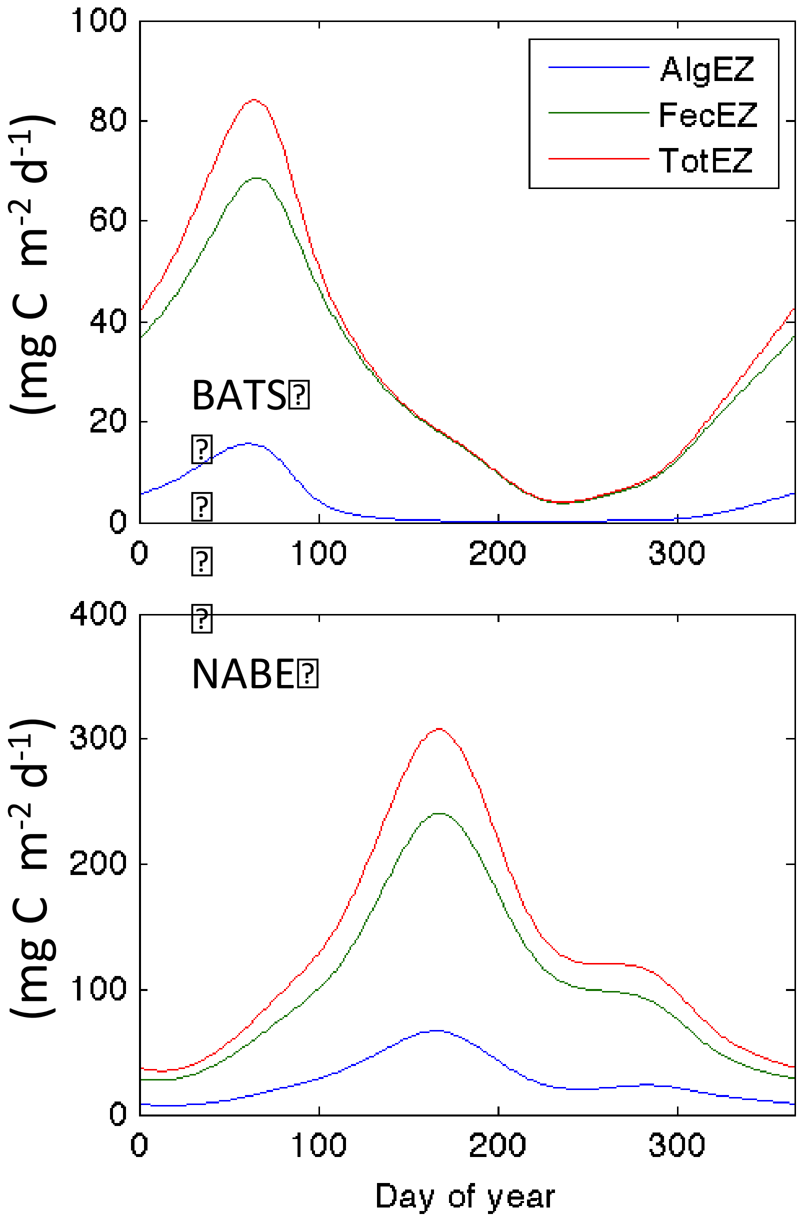
$$AlgEZ = f_{Alg} * NPP_M$$

$$f_{Alg} = 0.1$$

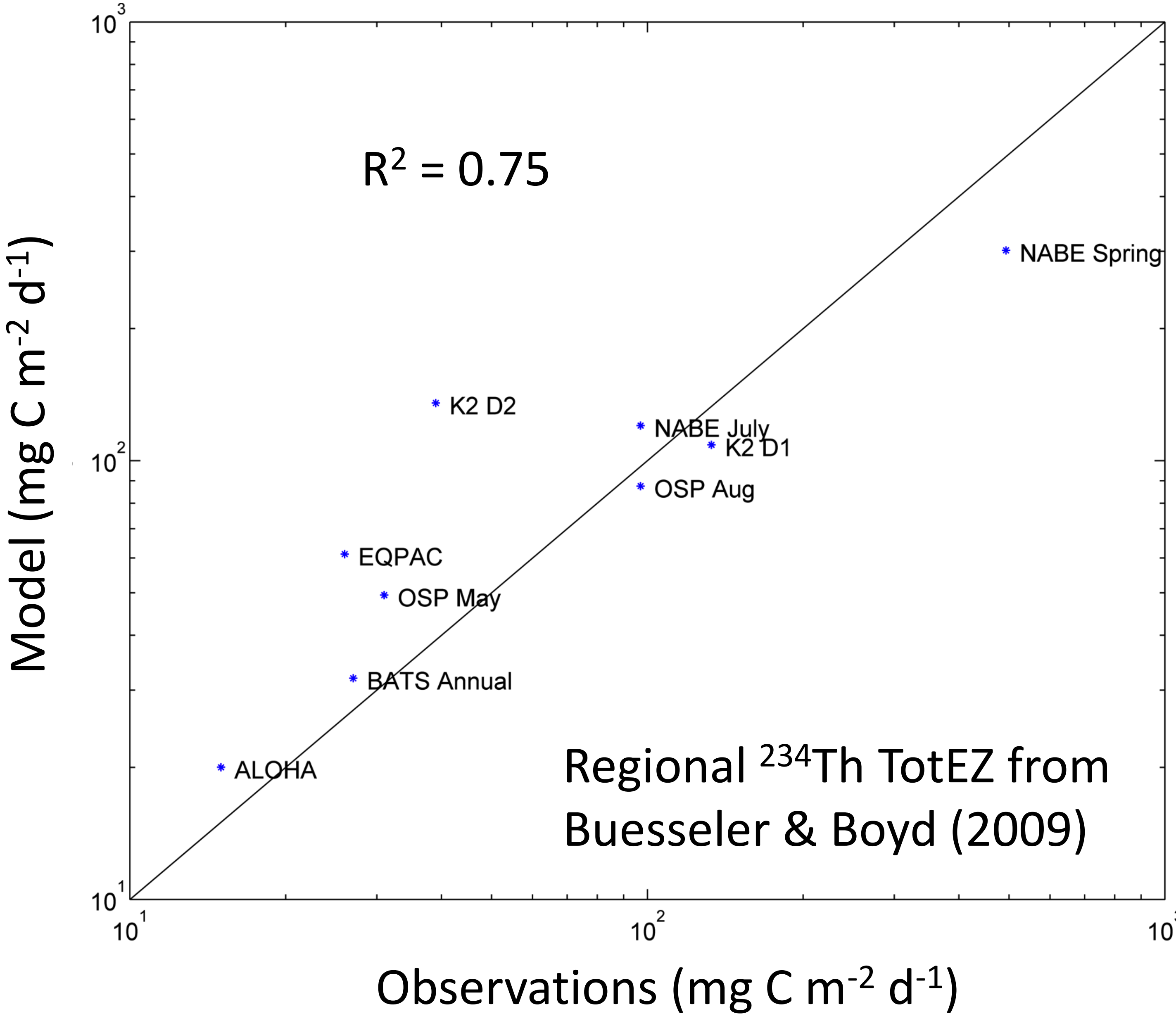
$$FecEZ = (f_{FecM} * Grz_M + f_{FecN+P} * Grz_{N+P}) * Z_{eu}$$

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

$$TotEZ = AlgEZ + FecEZ$$

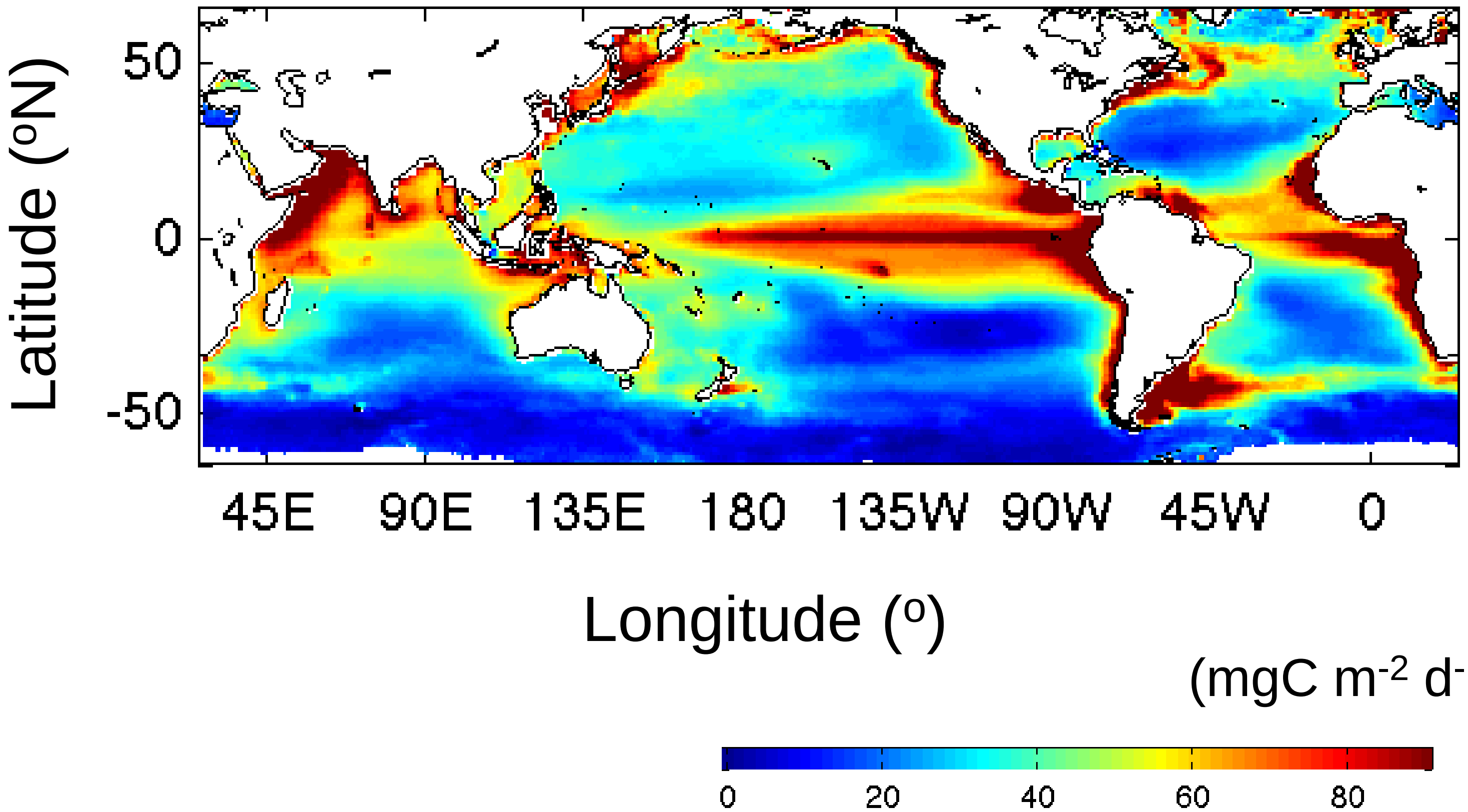


So, Does It Work??



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

Annual TotEZ



Total = 5.7 Pg C y^{-1}

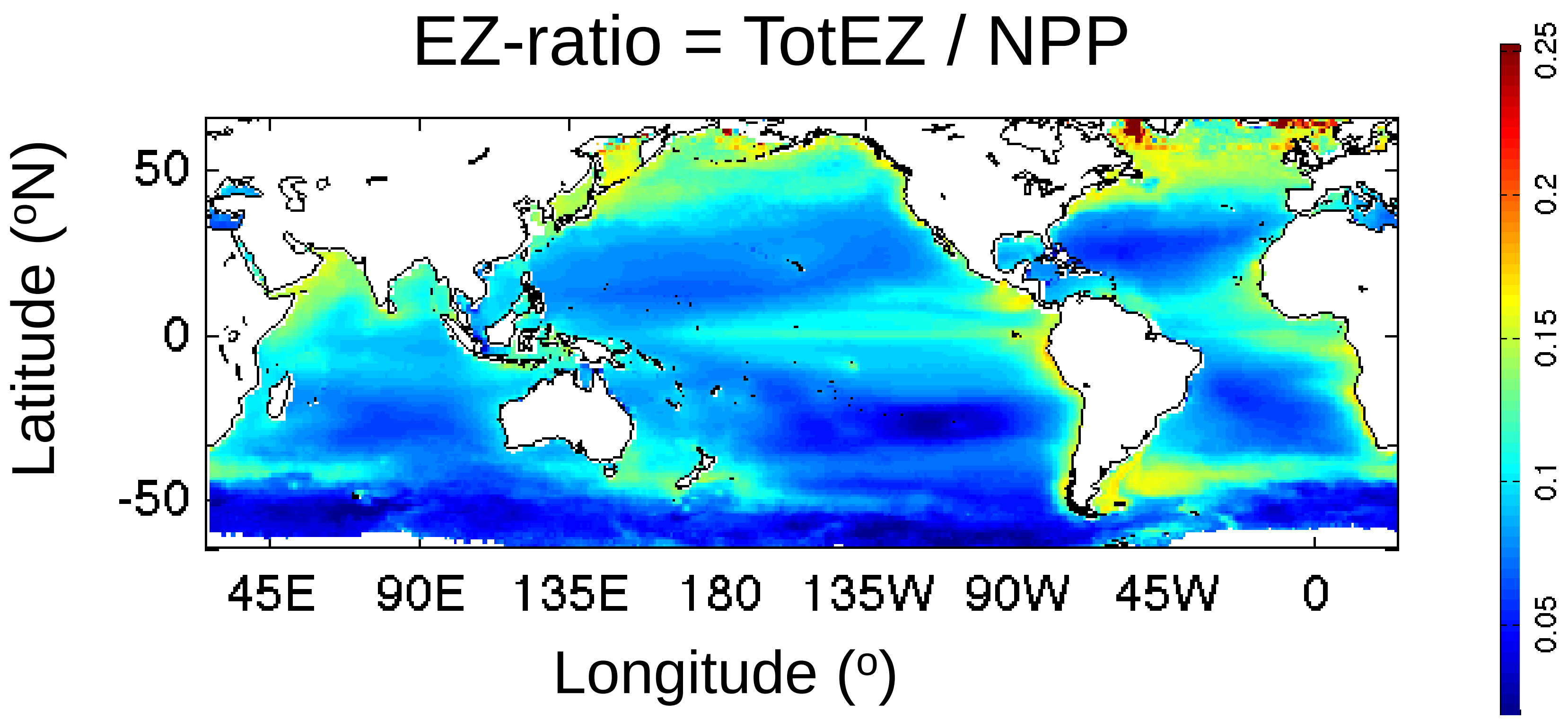
So, Is It Robust??

	f_{alg} (-)	m_{ph} (d^{-1})	f_{fecM} (-)	f_{fecN+P} (-)	Global TotEZ ($Pg\ C\ y^{-1}$)
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 $Pg\ C\ y^{-1}$

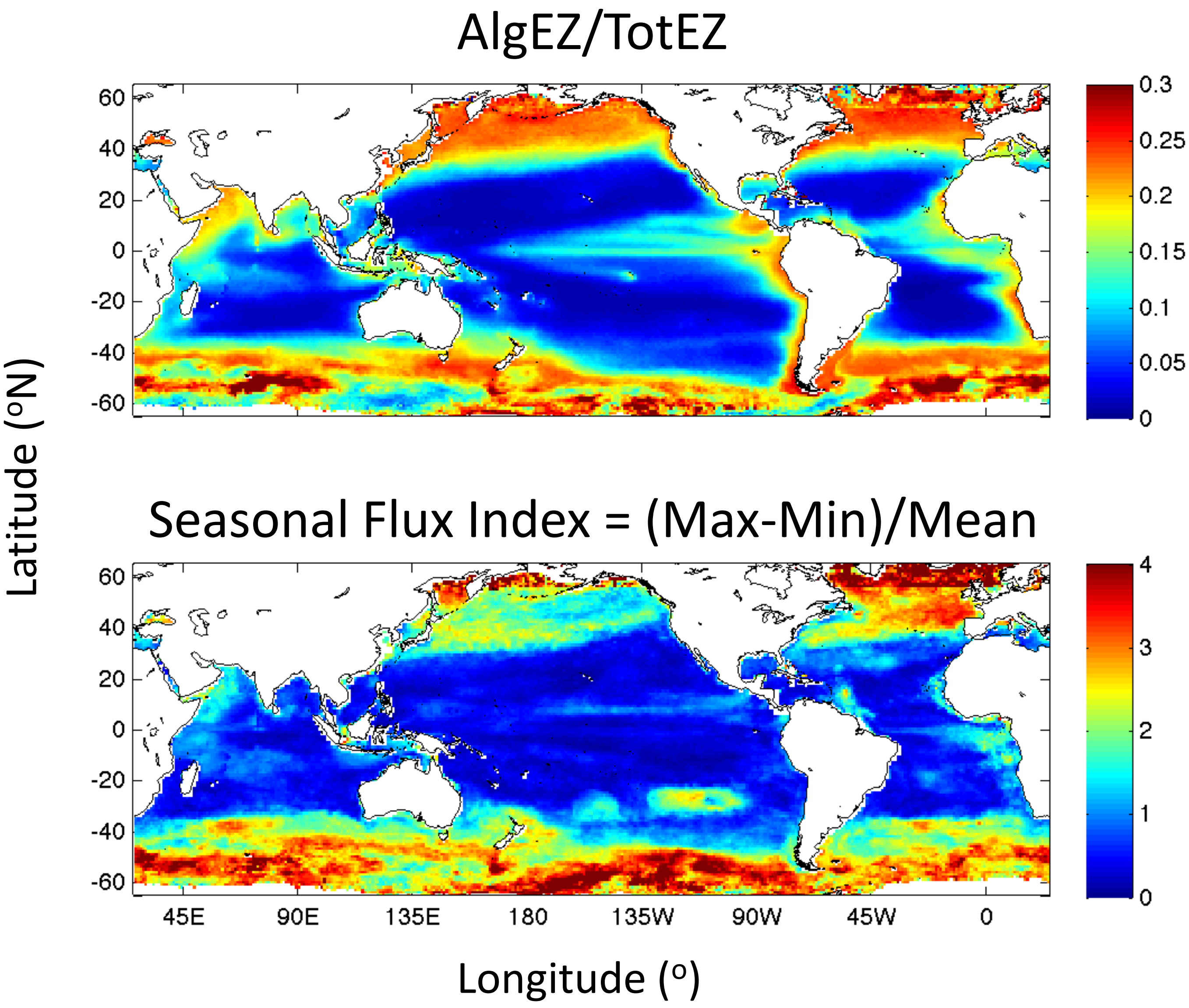
Using VGPM for NPP model, we get 5.4 $Pg\ C\ y^{-1}$

Export Efficiency

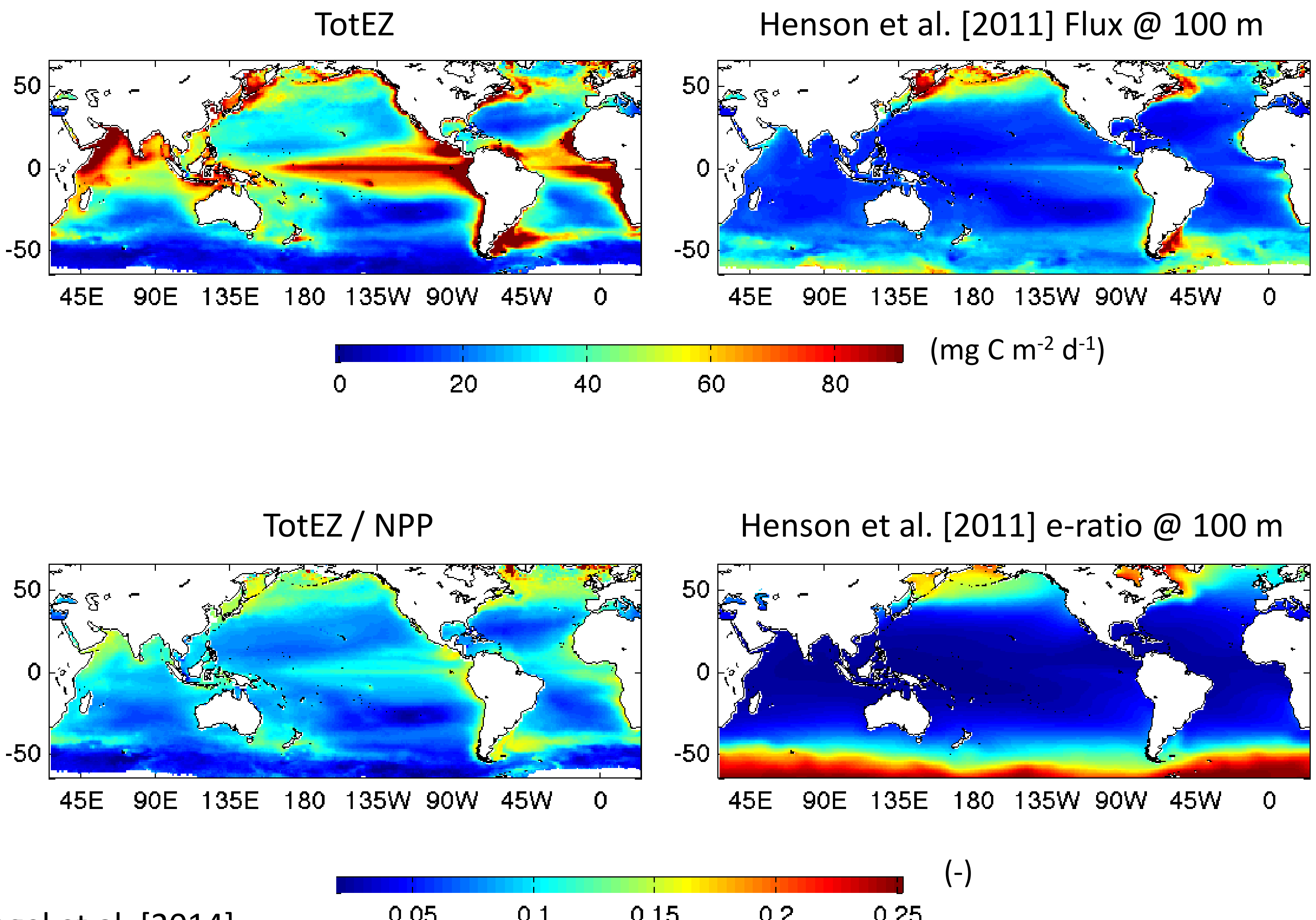


- EZ-ratio patterns have an "oceanographic logic"
- Global mean = 0.10 (± 0.05)

Other Export Metrics

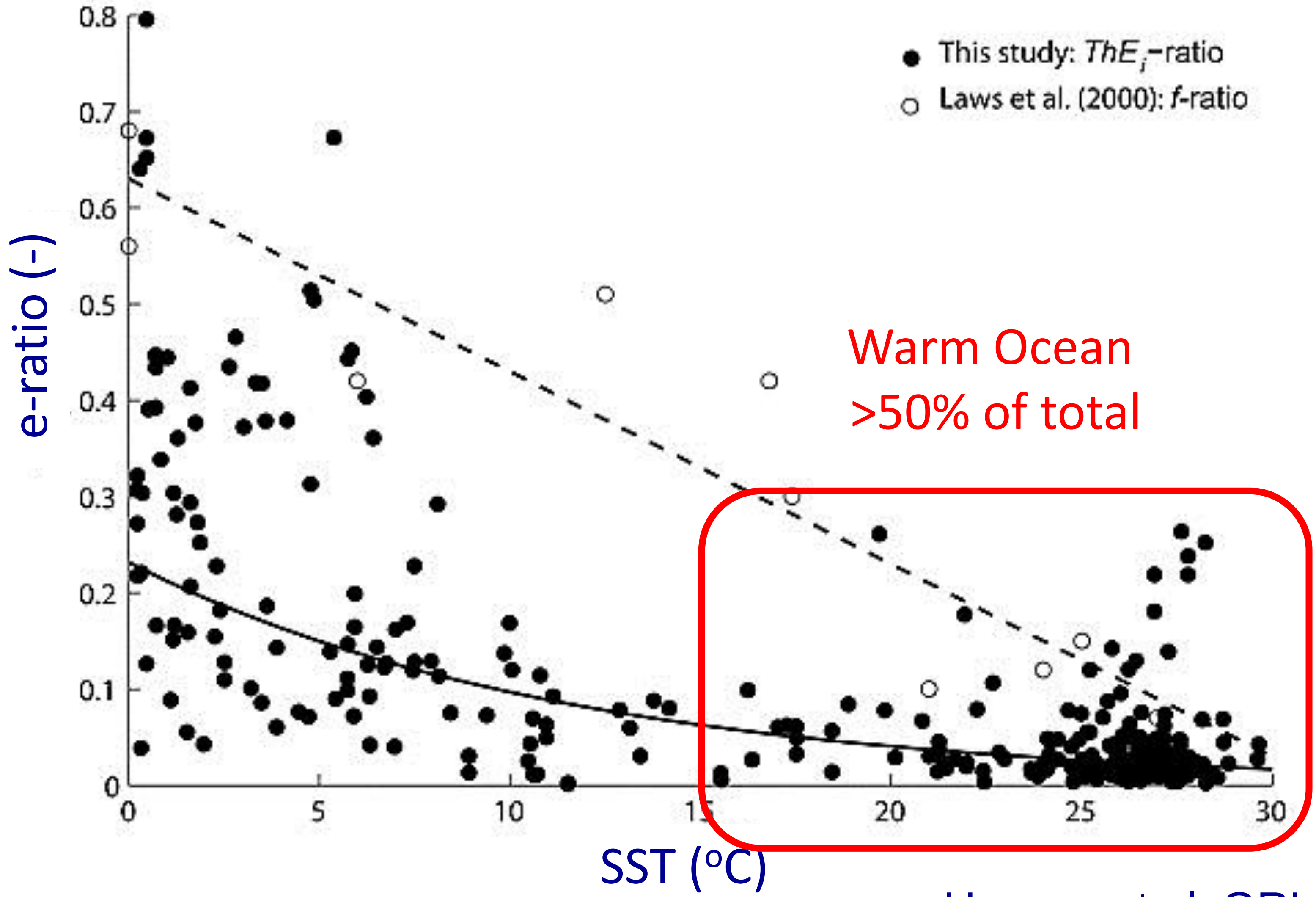


Comparison to Previous Approaches



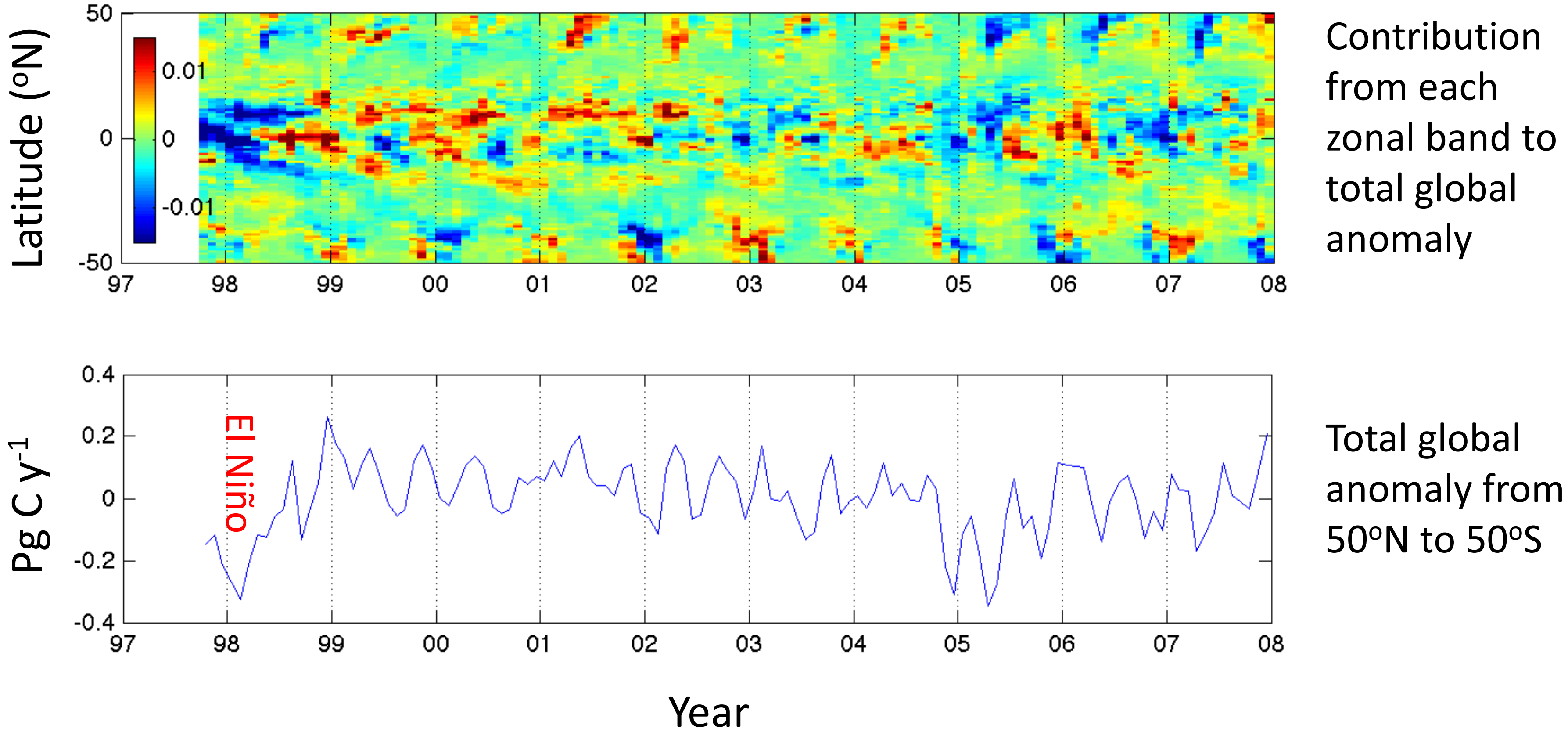
Siegel et al. [2014]

Comparison to Previous Approaches



Henson et al. GRL [2011]

Interannual Changes in TotEZ Anomalies



- 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

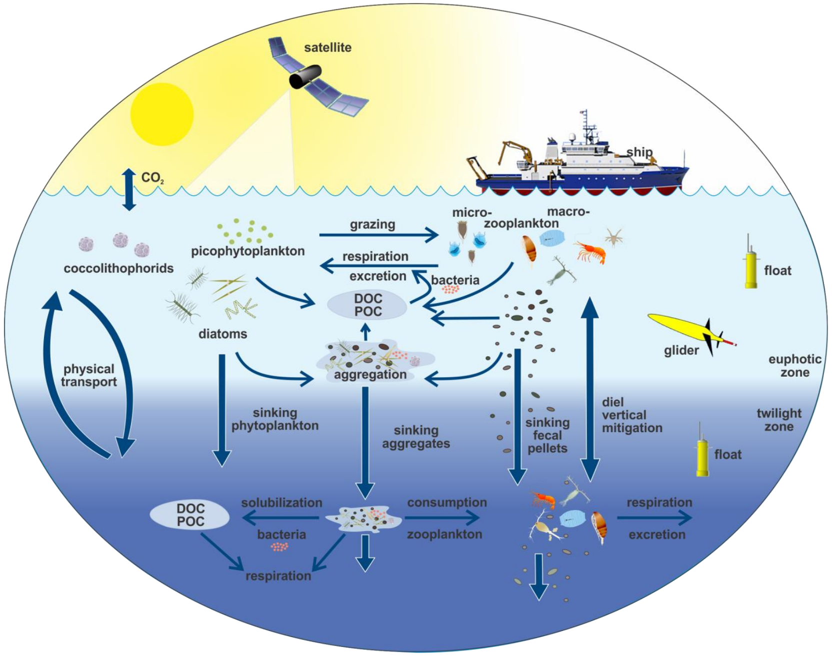
- Interannual variations are observed for both global TotEZ and EZ-ratio

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 Processes in the Ocean from RemoTe Sensing



Dave Siegel (UCSB) & Ken Buesseler (WHOI)

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

What is EXPORTS?

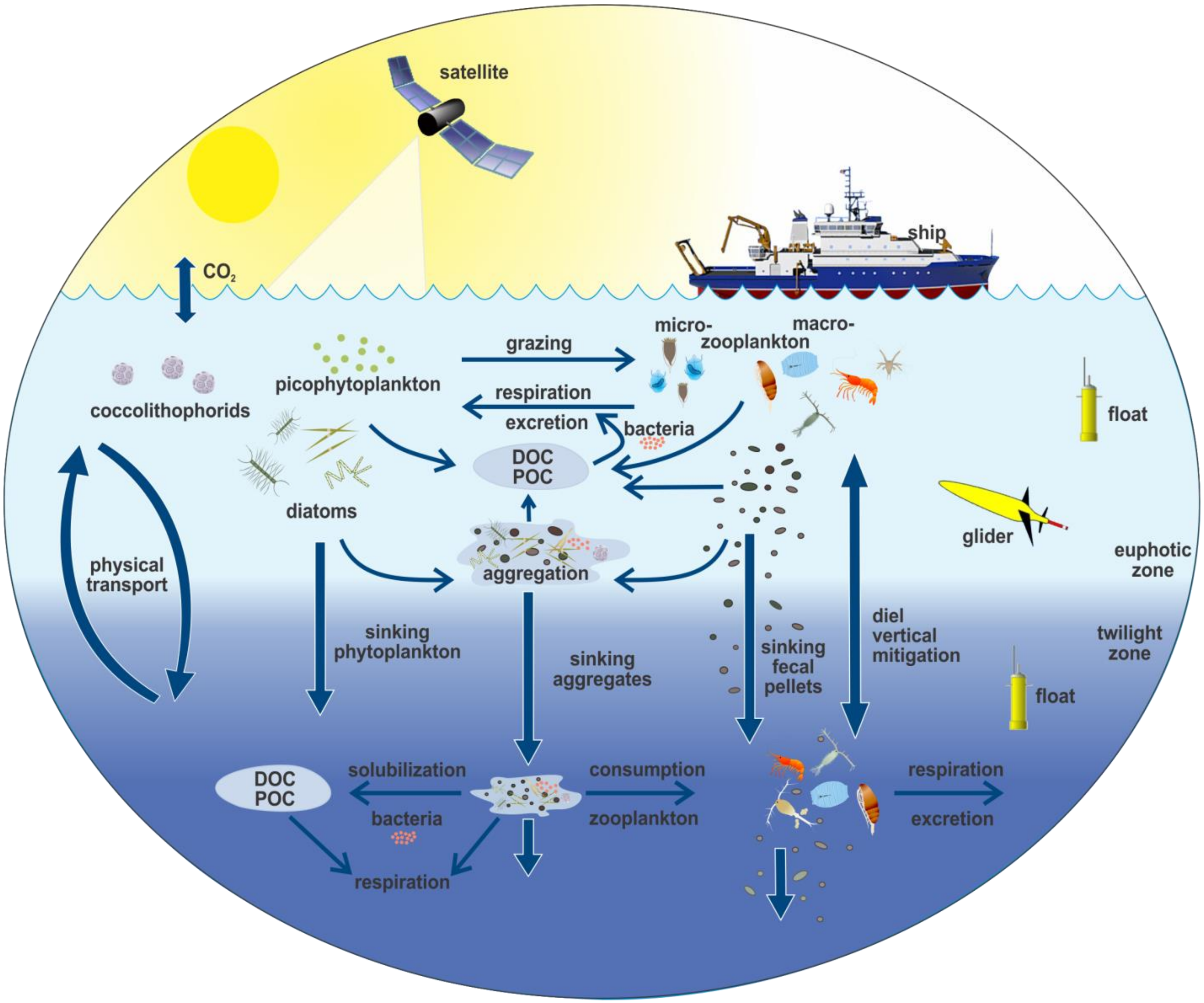
A community-vetted science plan for a NASA field campaign

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

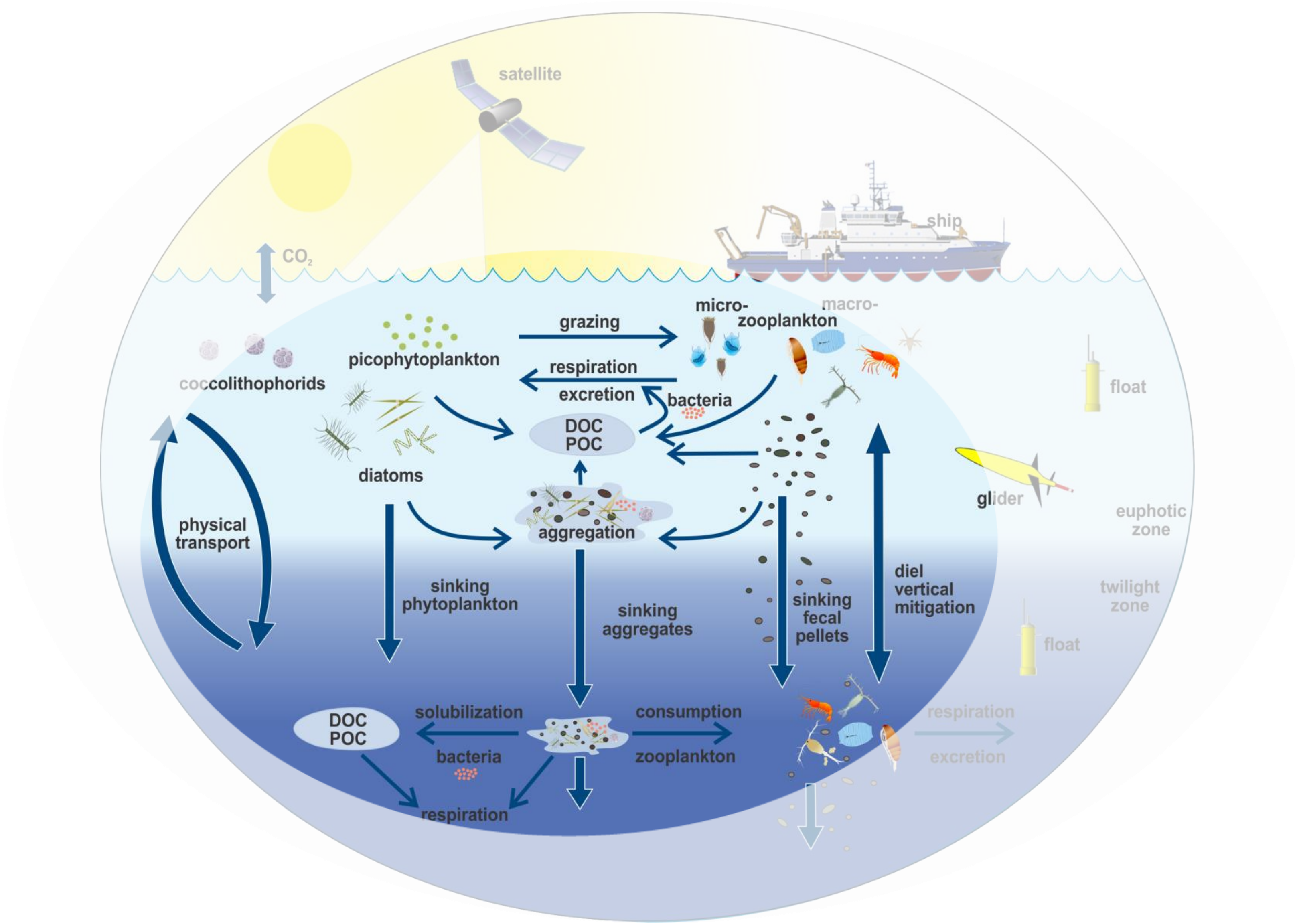
Final Science Plan Submitted: June 2014

Projected start date: 2017 (if approved)

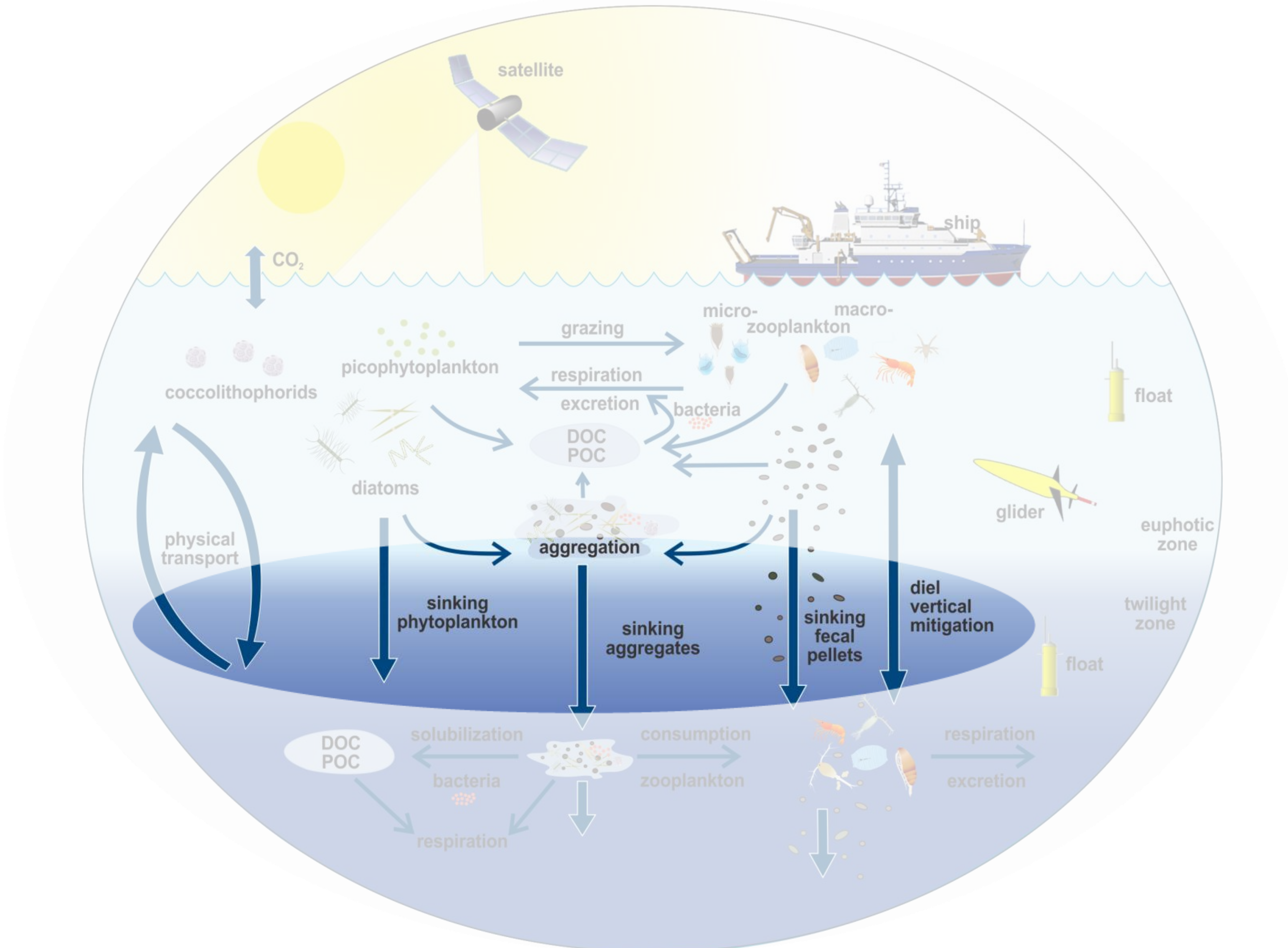
Why EXPORTS?


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

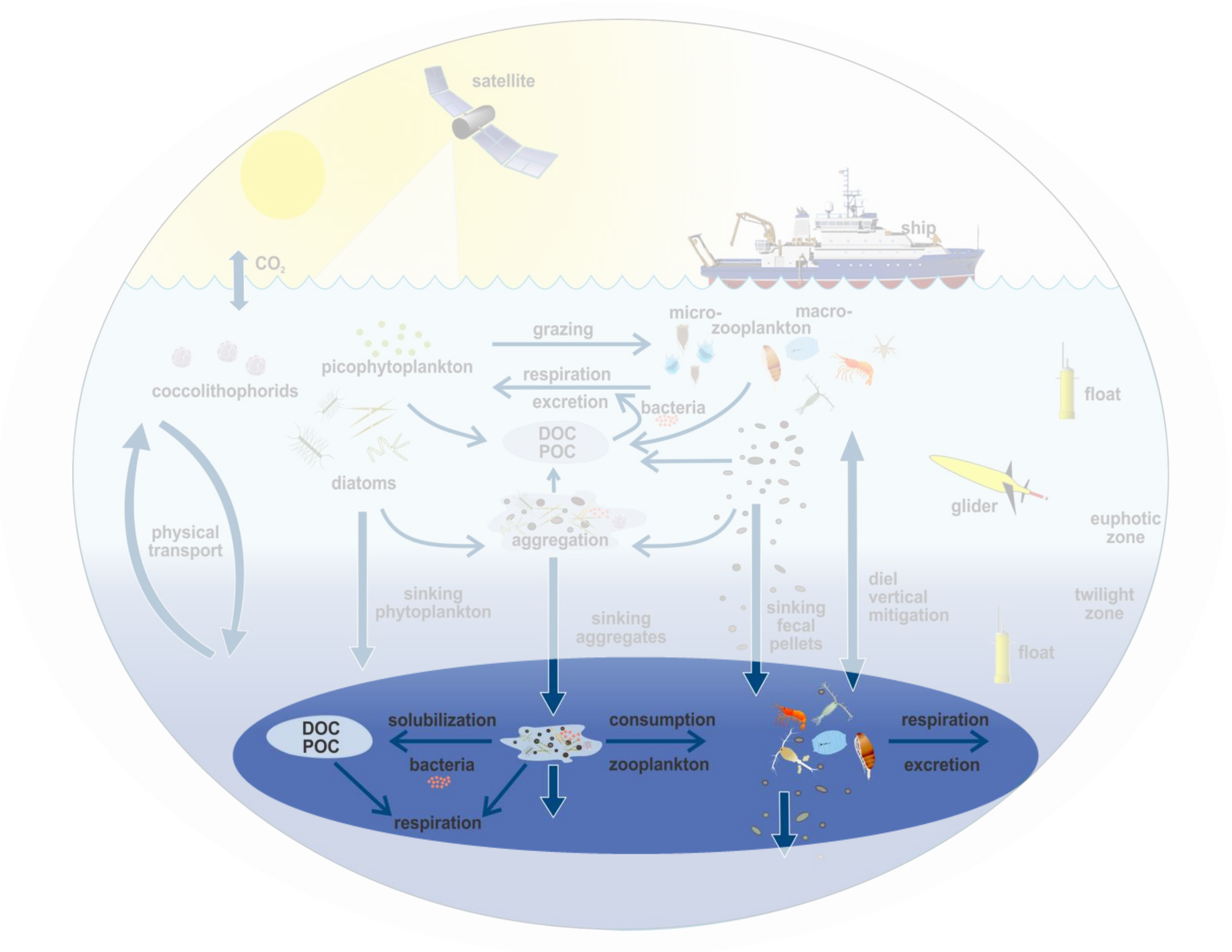
Why? Need to understand, quantify & predict how ecosystem processes transfer organic matter to depth



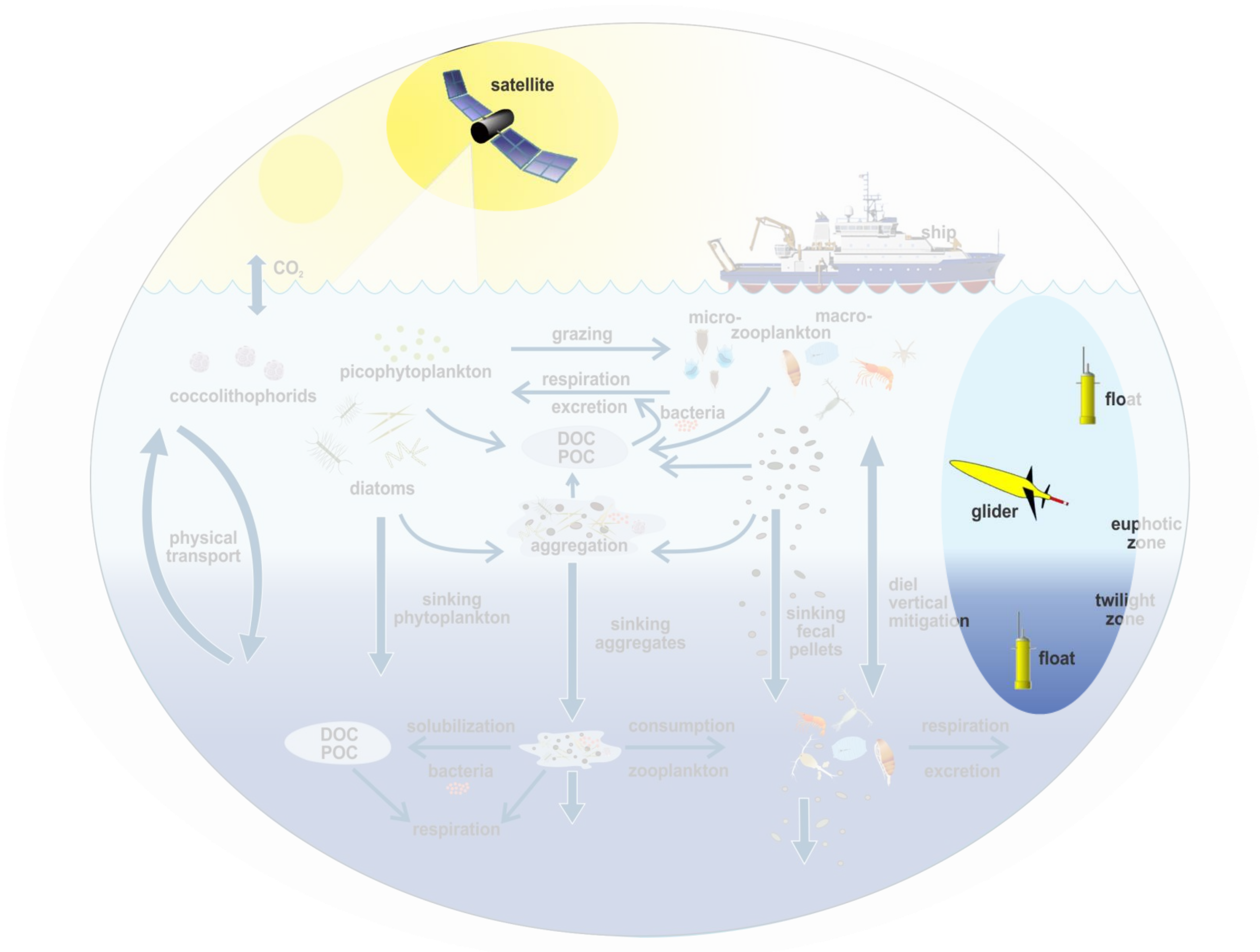
Why? Improve global estimates of carbon export from the euphotic zone (4 to >12 Pg C y^{-1})



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

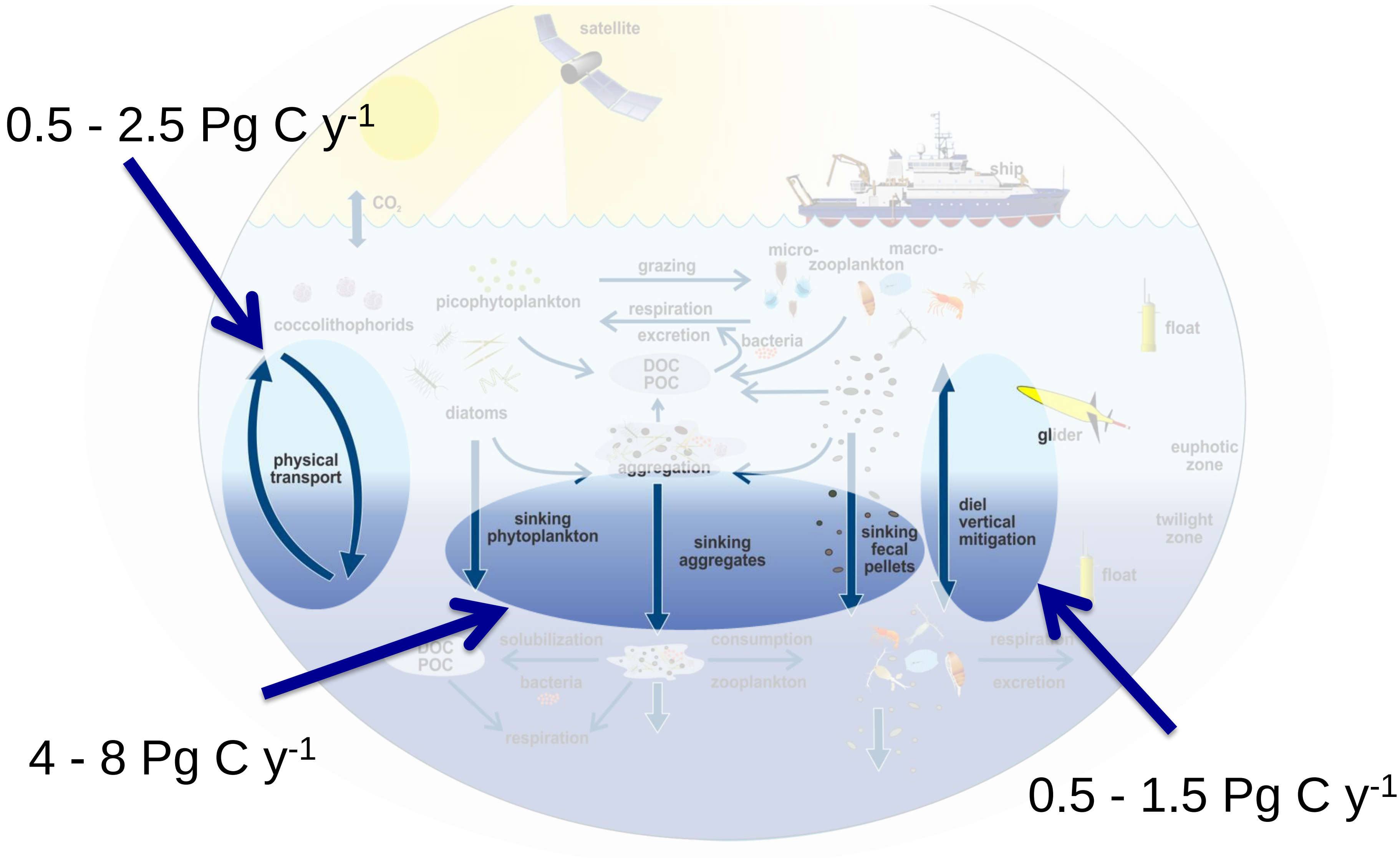


Why Now? Advances in remote sensing (PACE!!) & autonomous tools make it time!



EXPORTS: Focus on Pathways

Summing over the pathways gets 5 to 12 Pg C y^{-1}



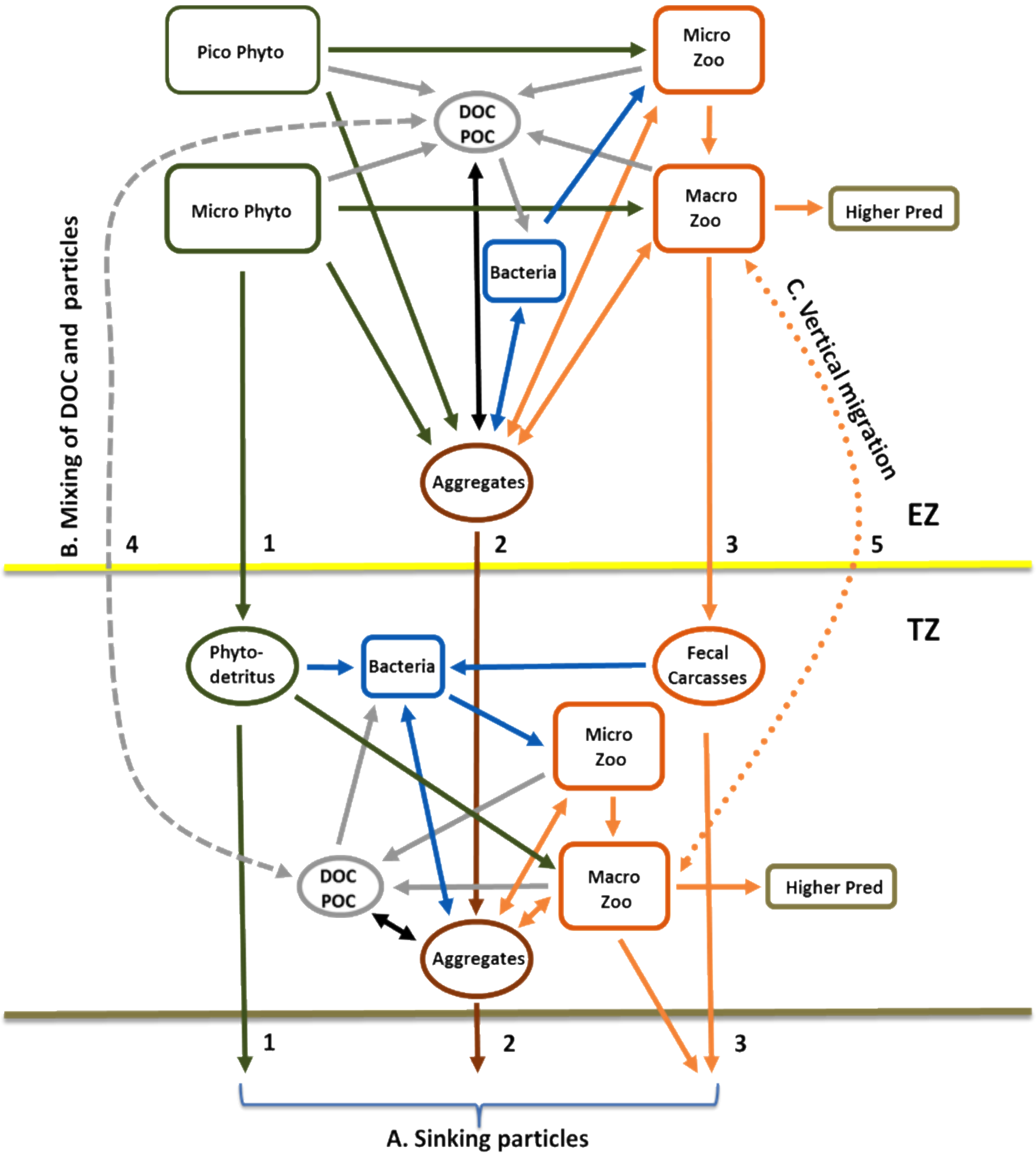
EXPORTS: Observing the Biological Pump's Pathways

Seek a **mechanistic understanding** of the **pathways** driving the biological pump

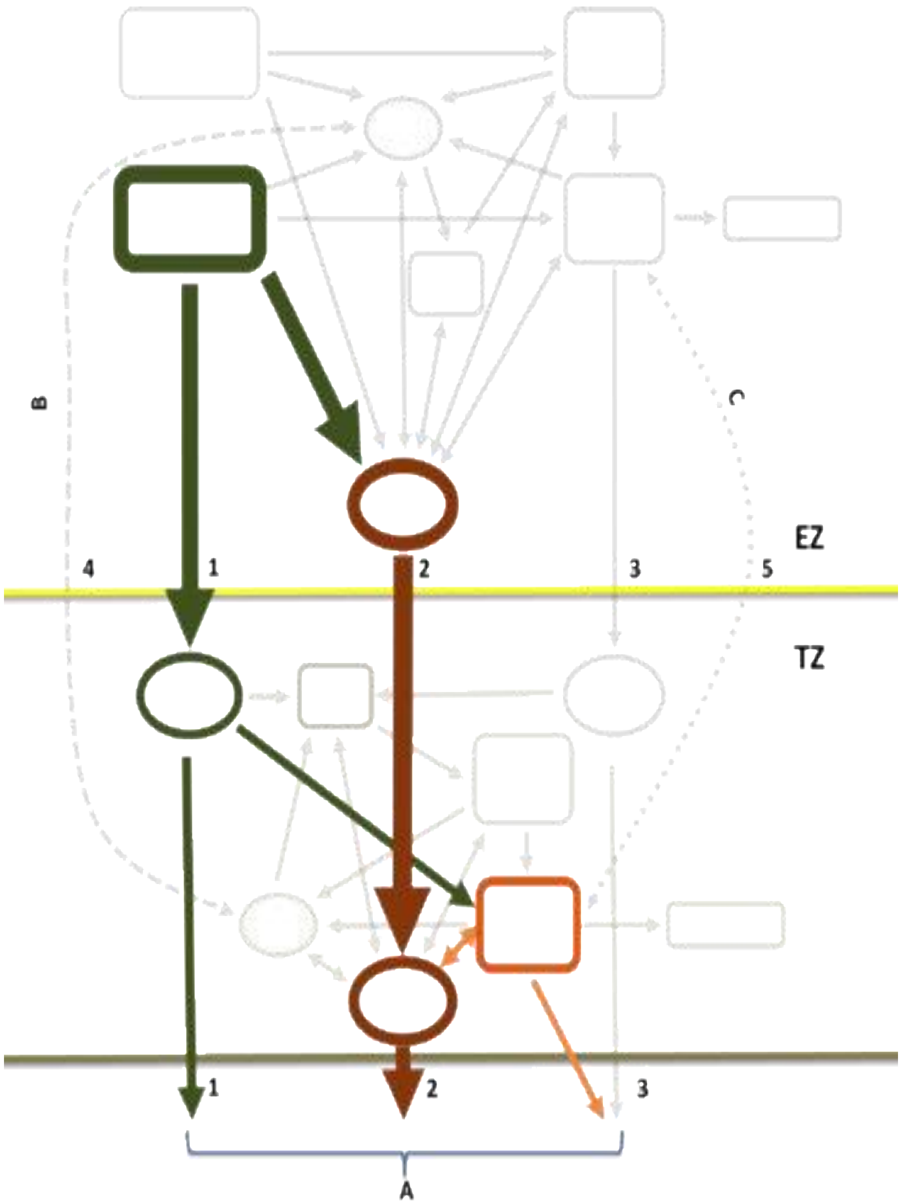
Needed for **building models and predicting** present & future states of the biological pump

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

EXPORTS: Focus on Pathways



Different Pathways for Different States



North Atlantic Bloom

Large phytoplankton

Large export flux from the Euphotic Zone

Weak flux attenuation in the Twilight Zone

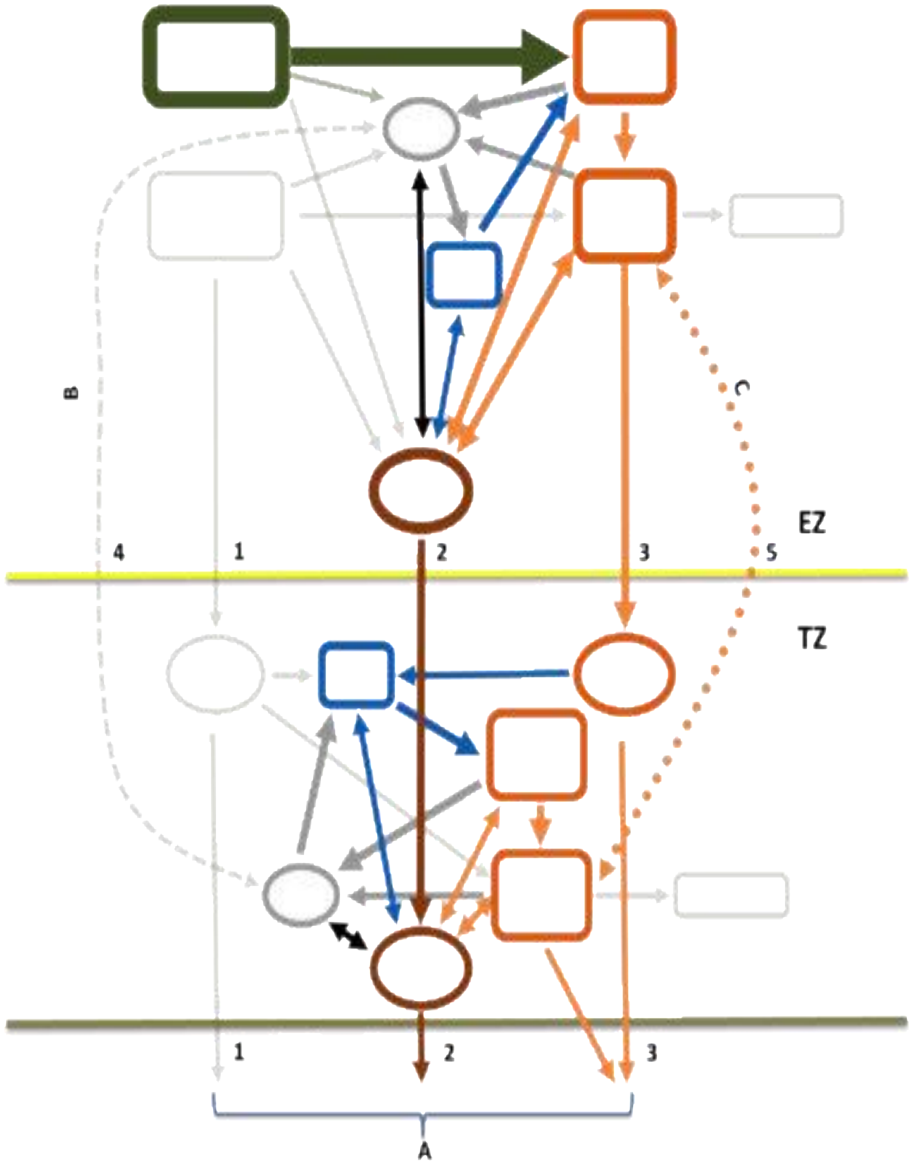
Different Pathways for Different States

Northeast Pacific Summer

Small phytoplankton & microbial loop dominance

Weak export from the Euphotic Zone

Strong flux attenuation in the Twilight Zone



EXPORTS: Three Science Questions

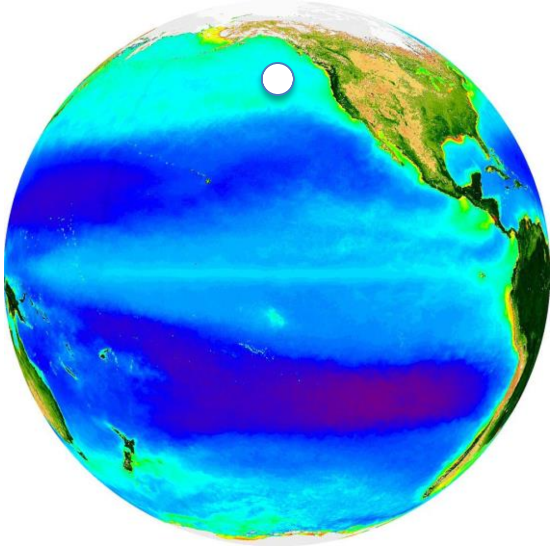
How do upper ocean ecosystem characteristics determine the vertical transfer of organic matter from the well-lit surface ocean?

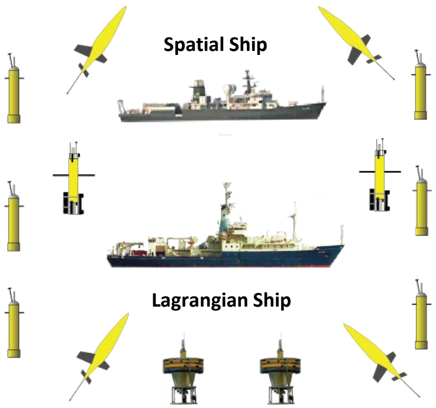
What controls the efficiency of vertical transfer of organic matter below the well-lit surface ocean?

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

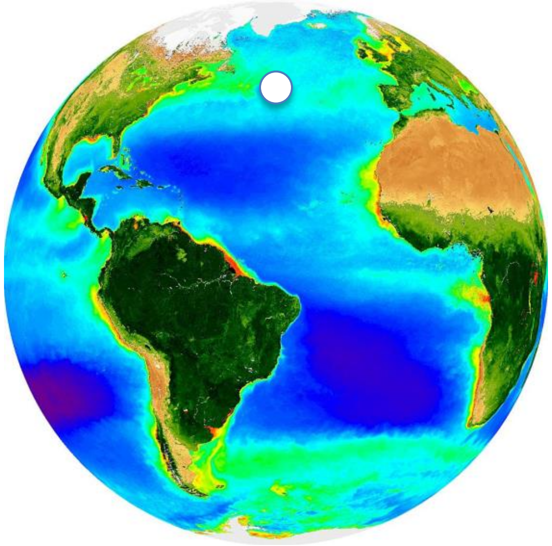
EXPORTS: Experimental Plan

Station P





North Atlantic

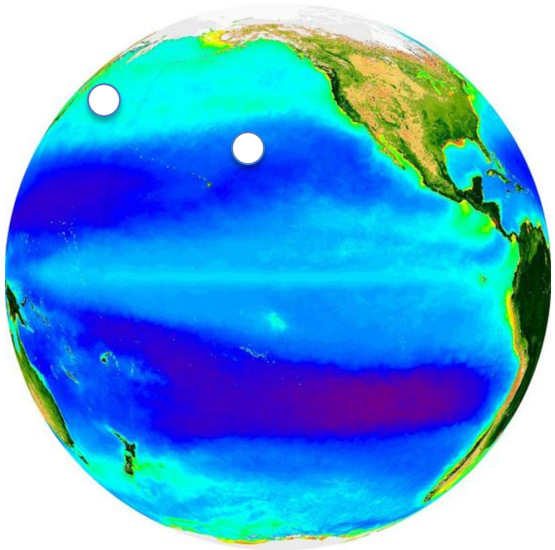


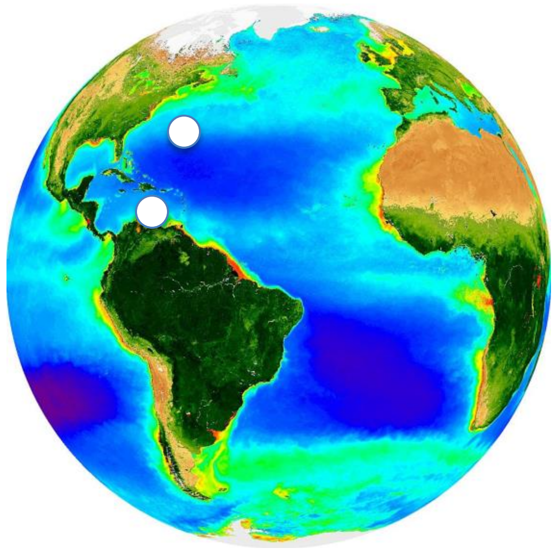
Cruise 1: April/May 30d
(40d survey)
Cruise 2: Aug, 30d
Leverage: OOI node, LineP

Bloom: April/May 45 d
Non-bloom: Aug, 30d
Leverage: PAP & other international partners

Will collect up to 8 states of the biological pump

EXPORTS: Experimental Plan





Data Mining

Compile secondary datasets of more biological pump states from other sites

Extends the number of “states” available for modeling building

Examples include:
BATS, HOT, CARIACO, VERTIGO, MAREDAT etc.

EXPORTS: Experimental Plan

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

Follow Particles
from production to trap
Measure stocks & fluxes from 0 to 500 m (over 10 d)

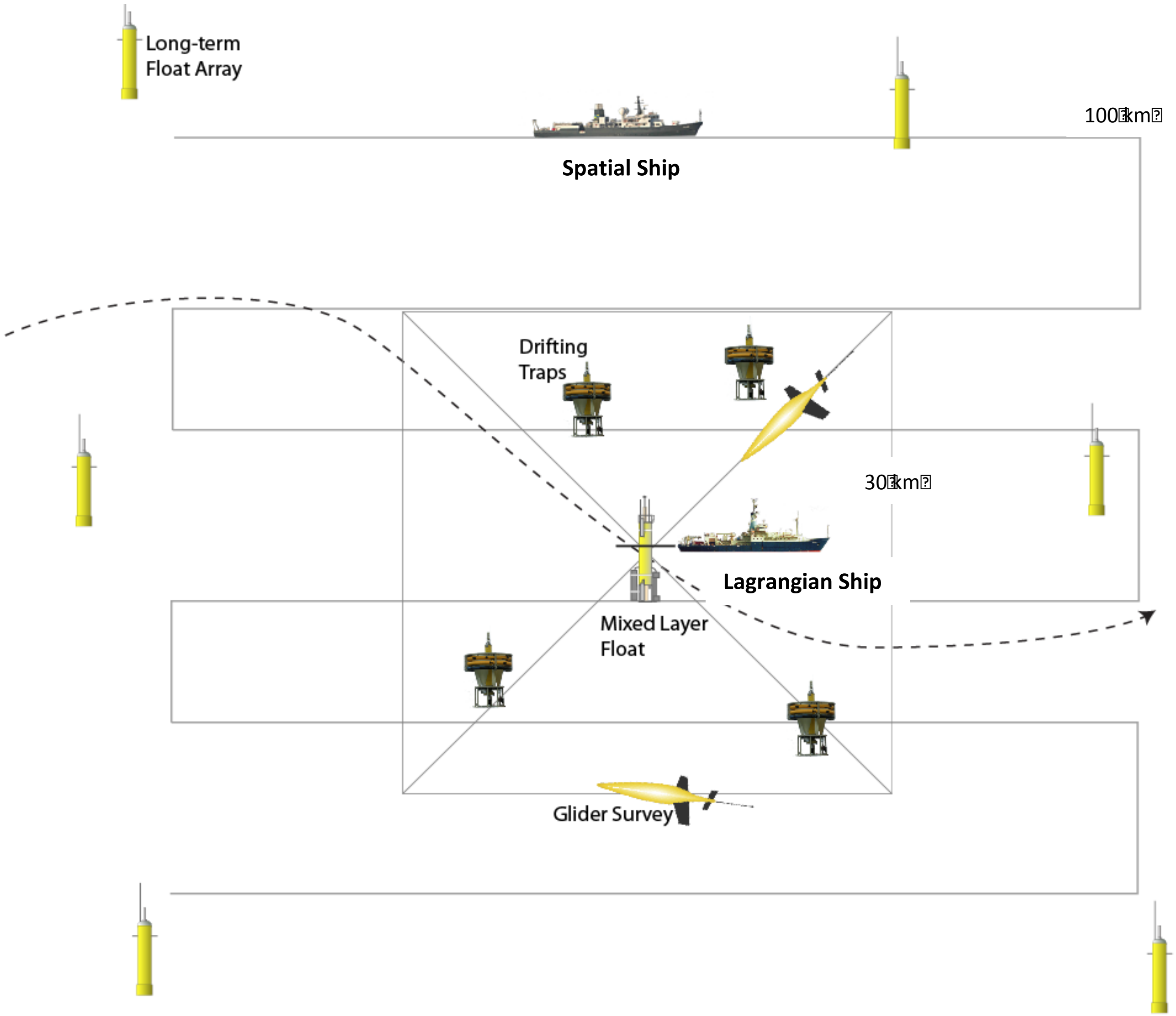
Lagrangian Ship
Measure rates & transformations

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 & more

EXPORTS: Experimental Plan



Two Ships

“Lagrangian”

“Spatial

Autonomous Array

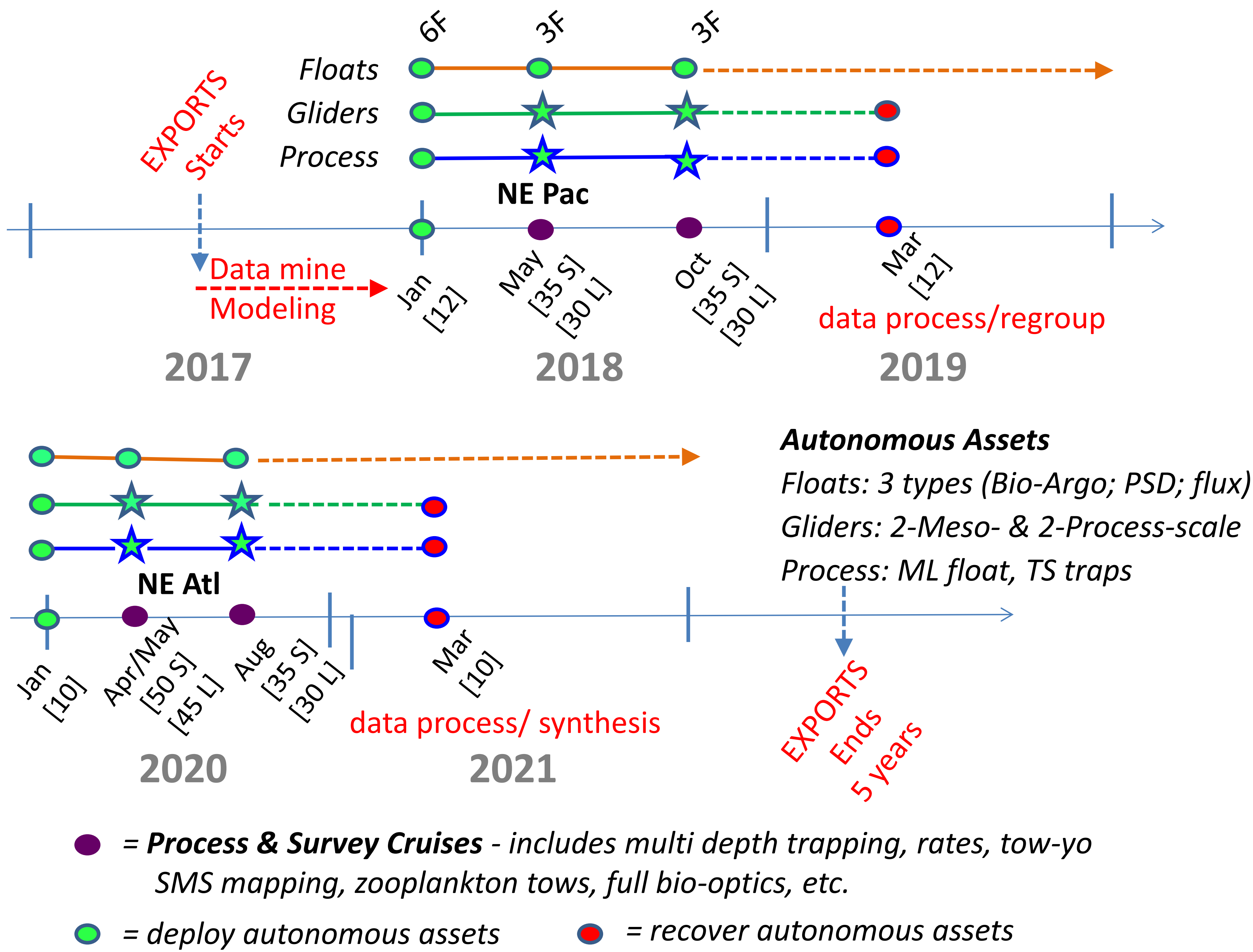
Mixed layer float

Glider surveying

Drifting traps

Multiple floats

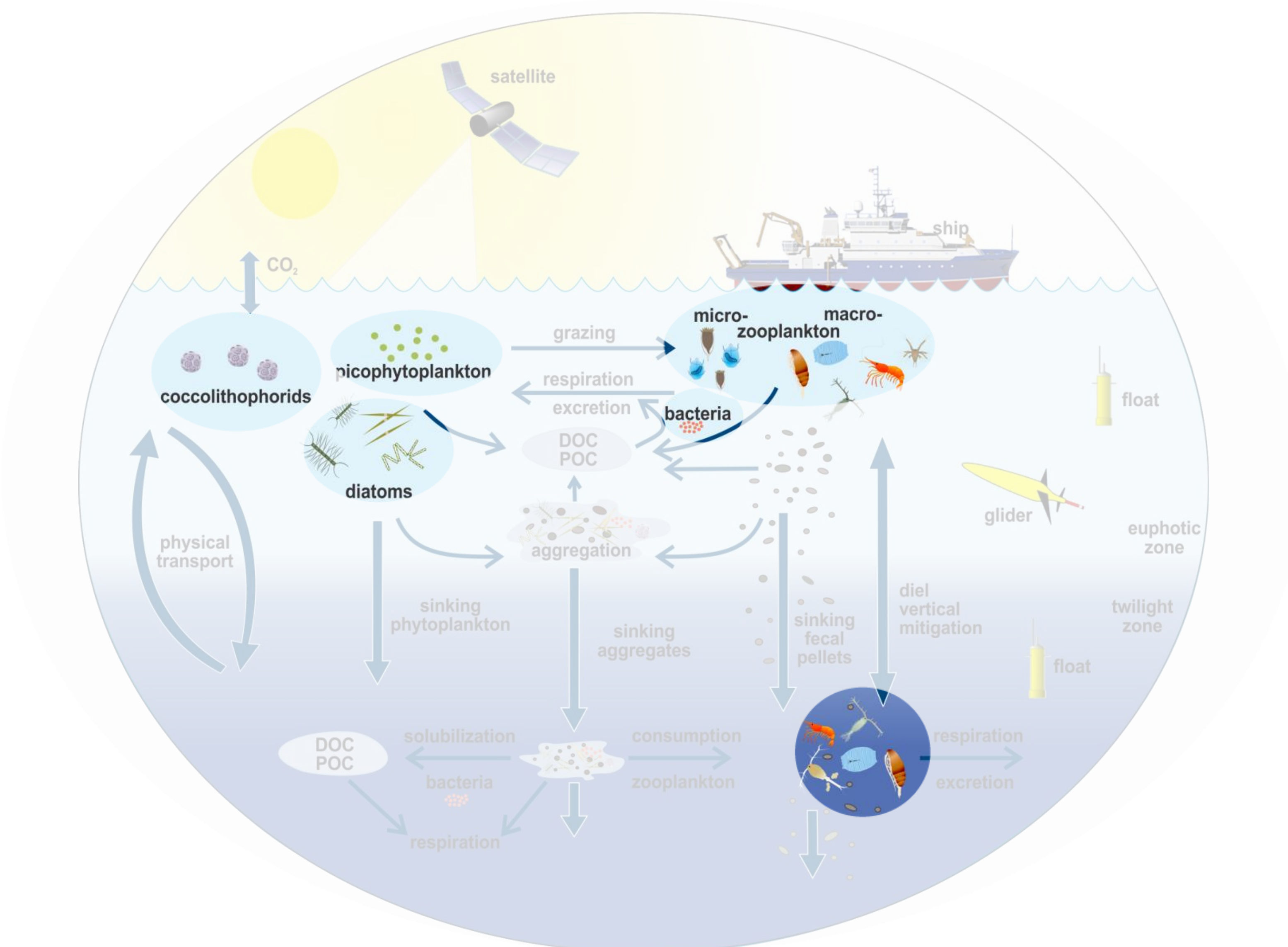
Bio-Argo, PSD, export



6F
3F
3F
Floats
Gliders
Process
EXPORTS Starts
NE Pac
Data mine
Modeling
Jan [12]
May [35 S] [30 L]
Oct [35 S] [30 L]
Mar [12]
data process/regroup
2017
2018
2019
Autonomous Assets
Floats: 3 types (Bio-Argo; PSD; flux)
Gliders: 2-Meso- & 2-Process-scale
Process: ML float, TS traps
NE Atl
Jan [10]
Apr/May [50 S] [45 L]
Aug [35 S] [30 L]
Mar [10]
data process/ synthesis
EXPORTS Ends 5 years
2020
2021
= Process & Survey Cruises - includes multi depth trapping, rates, tow-yo SMS mapping, zooplankton tows, full bio-optics, etc.
= deploy autonomous assets
= recover autonomous assets

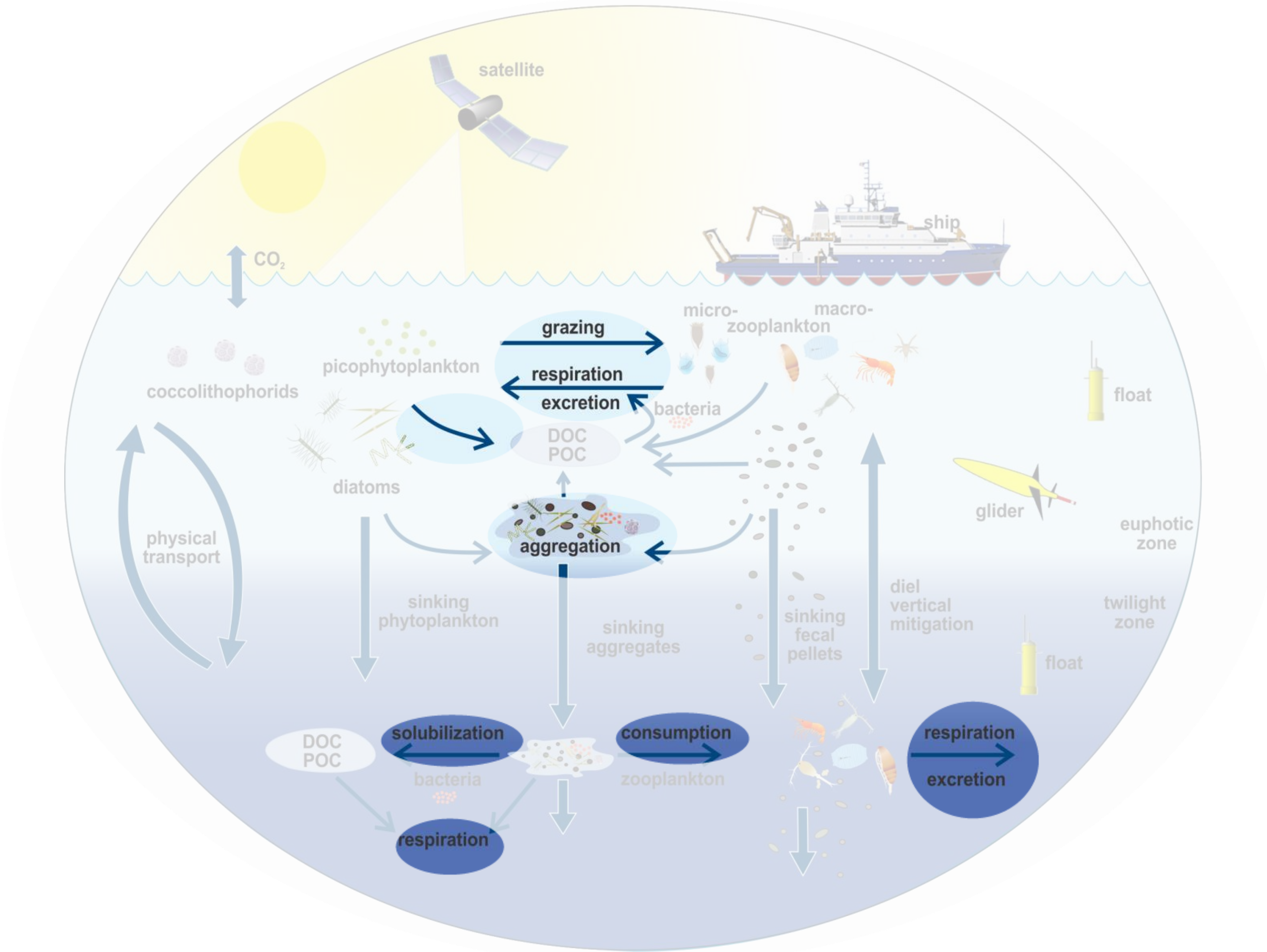
EXPORTS: Observables

Ecosystem Structure: Community Characteristics



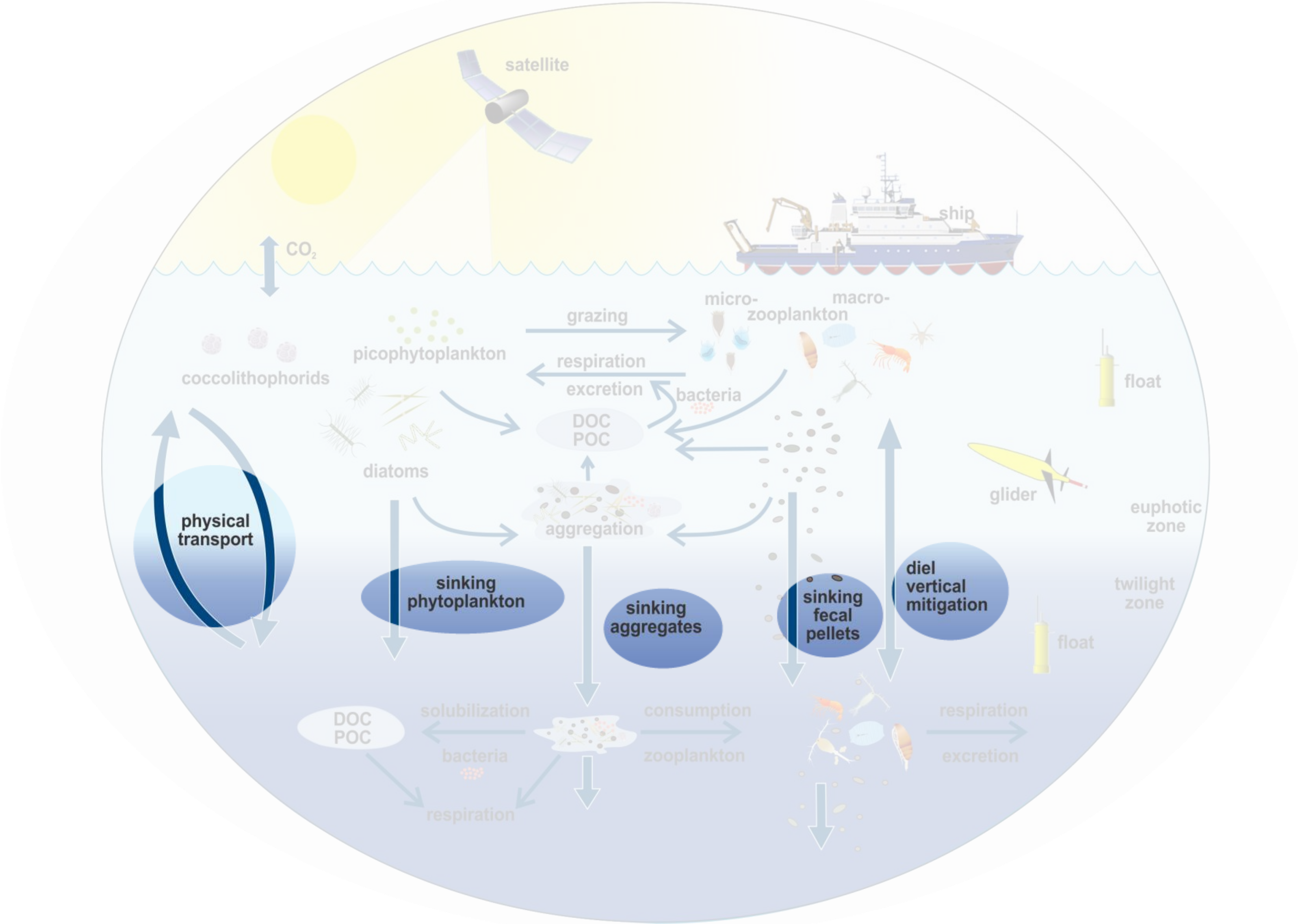
EXPORTS: Observables

Ecosystem Function: Physiology, rates, processes



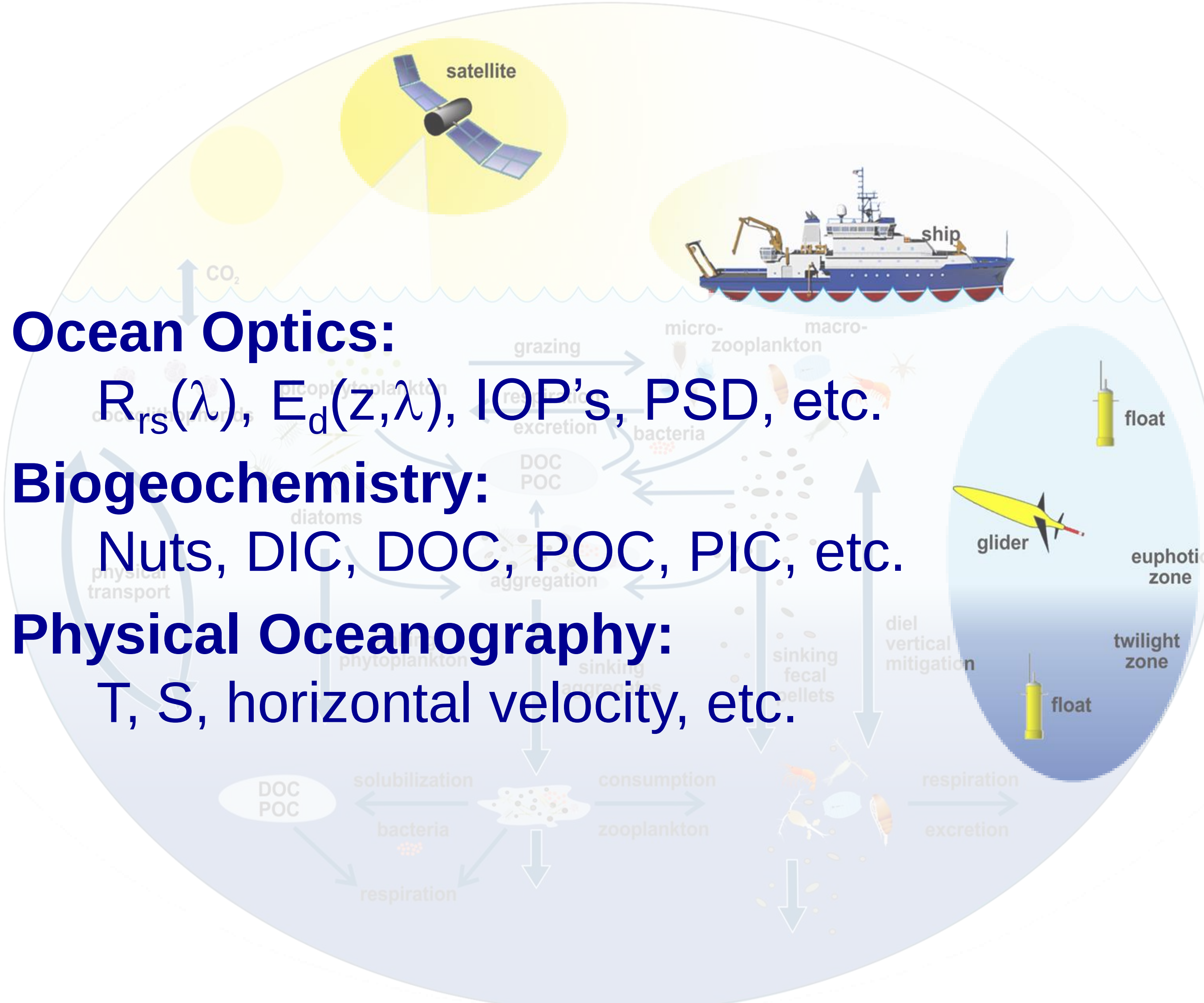
EXPORTS: Observables

Multiple paths to export & its attenuation with depth



EXPORTS: Observables

Water Column Characterization



Ocean Optics:

$R_{rs}(\lambda)$, $E_d(z,\lambda)$, IOP's, PSD, etc.

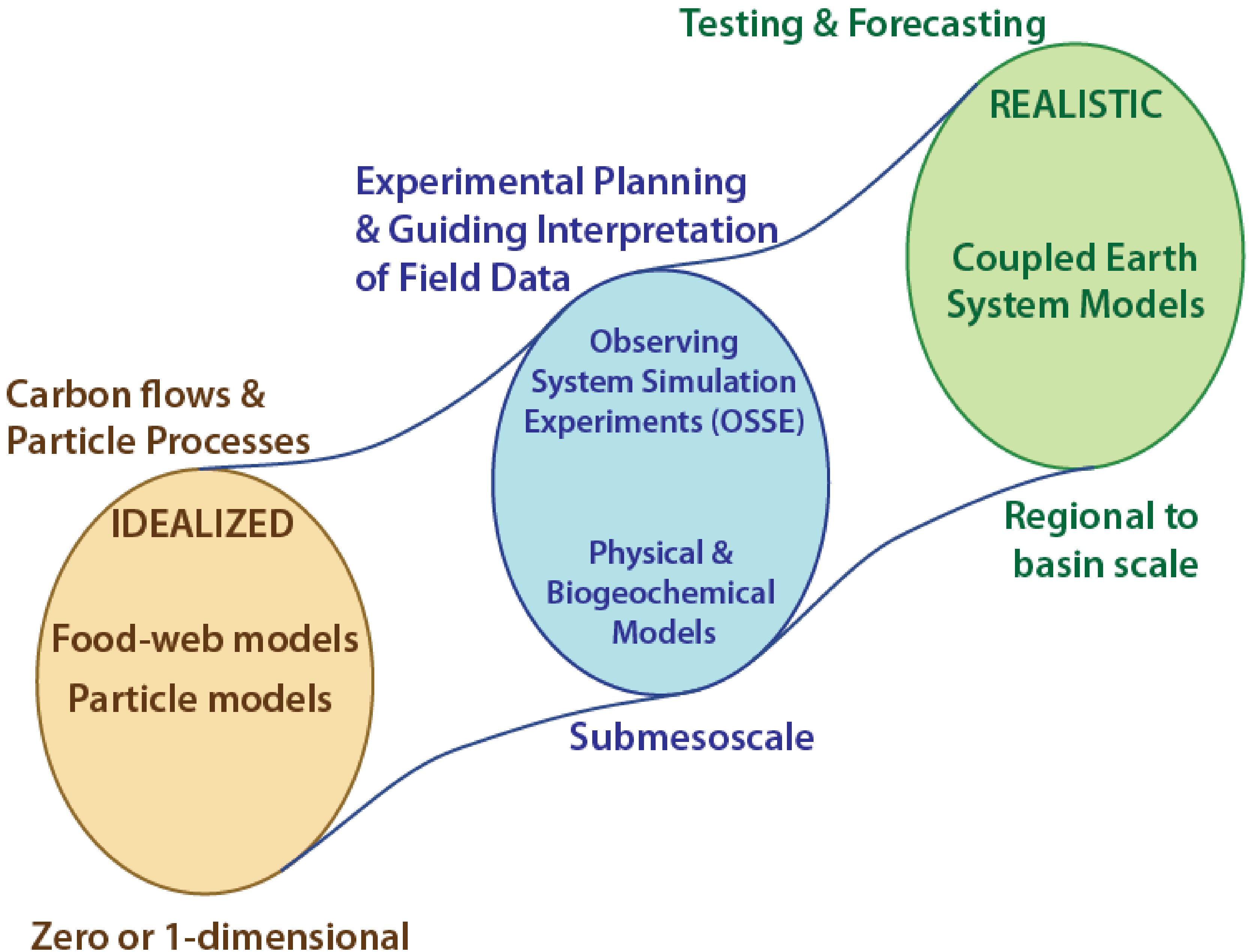
Biogeochemistry:

Nuts, DIC, DOC, POC, PIC, etc.

Physical Oceanography:

T, S, horizontal velocity, etc.

EXPORTS: Numerical Modeling



EXPORTS: Technical Readiness

EXPORTS **can** answer its science questions with present technology

Improvements that would be nice…

Experimental Logistics:
OSSE's & tools for coordinating sampling, etc.

Rapid Plankton Characterization:
-omics, imaging, acoustics, cell sorting, etc.

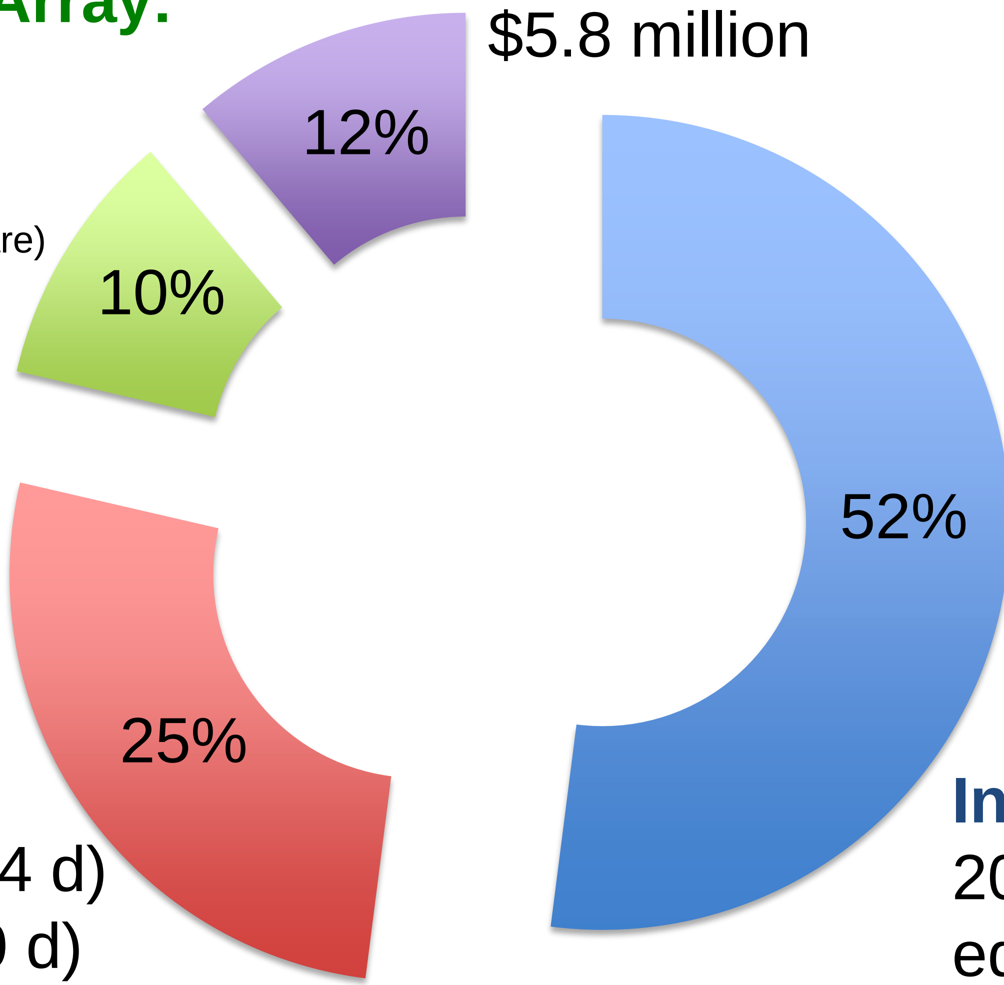
Sensors for Autonomous Platforms:
Zooplankton abundance/composition, DIC, DOC, PSD, etc.

Optical Instrumentation (aimed for PACE):
Hyperspectral reflectance, UV IOP's, etc.

EXPORTS Budget: $53M, 5 years

Other:
Logistics, project/data man, etc.
$5.8 million

Autonomous Array:
6 × 4 floats
6 gliders (4 spares)
2 ML floats (1 spare)
9 traps (3 spares)
$5.3 million



Ships:
NE Pacific (154 d)
N Atlantic (180 d)
$13.8 million

Investigators:
20 PI groups &
equipment
$27 million

EXPORTS: Budget

Yes, this is a large request. **BUT** $53 million is in line with most NASA field campaigns & U.S. JGOFS process studies

De-Re-scoping: Modularity of the EXPORTS science plan makes this easier & options will be proposed

Partnering will be critical: Within the U.S. & international EXPORTS is approved to go forward

EXPORTS: Next Steps

EXPORTS plan has been presented at many meetings, draft comments considered & final plan submitted to NASA

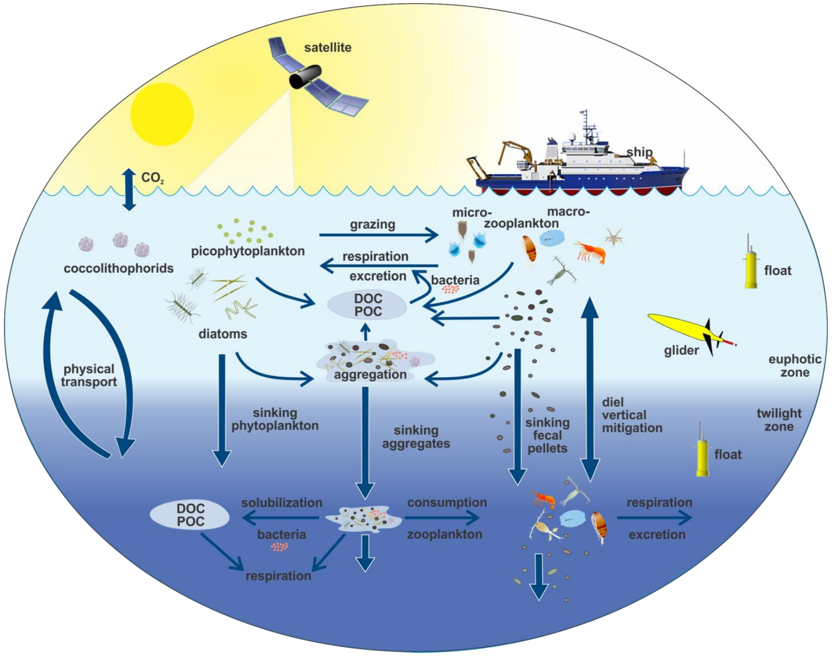
EXPORTS plan is available & comments are requested for NASA's review - **http://cce.nasa.gov/cce/ocean.htm**

If selected: A Science Definition Team will be competed (early-2015) to write the Implementation Plan with the EXPORTS field campaign starting 2017

Important: Every role in EXPORTS will be competed!!

EXPORTS

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



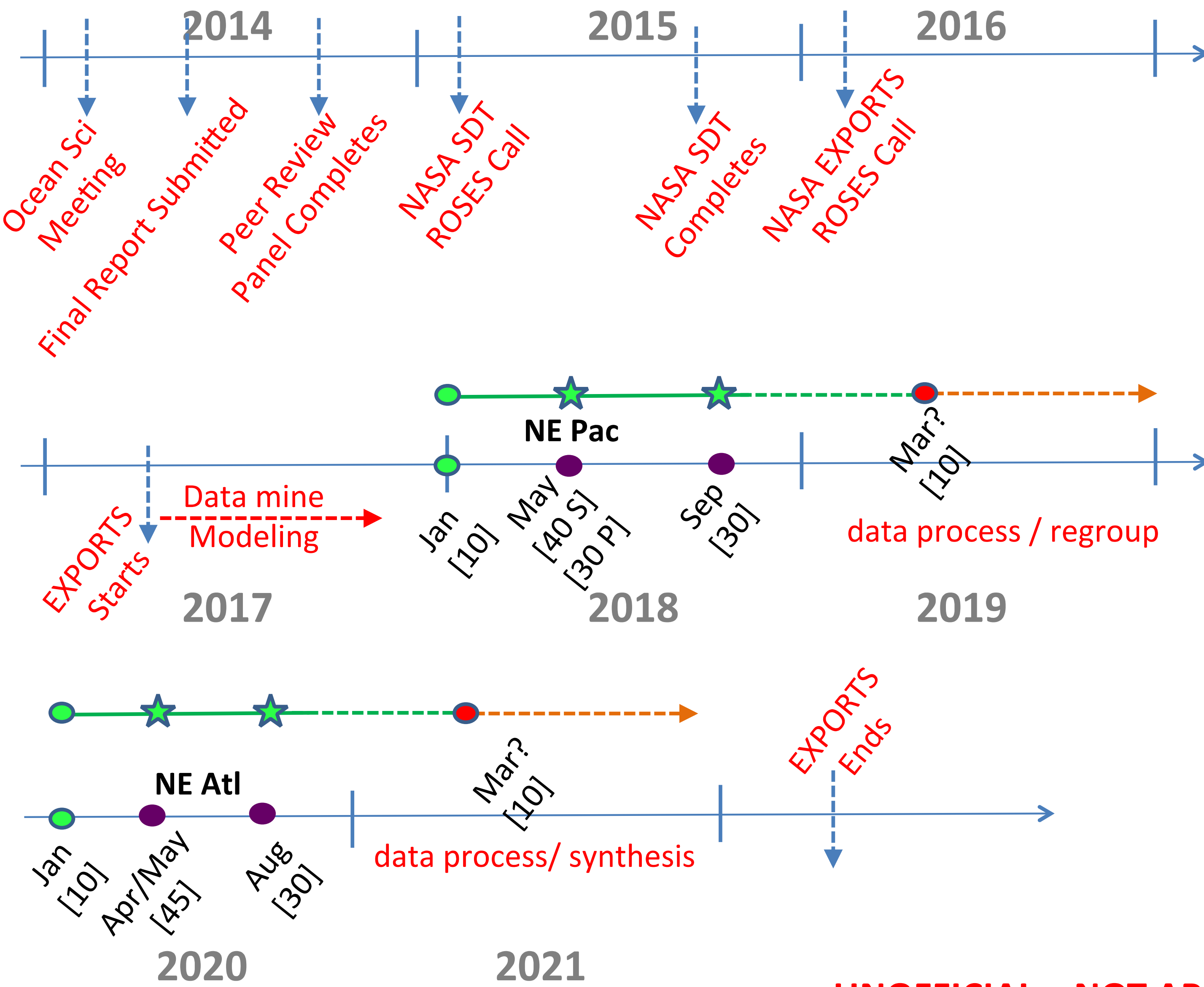
http://cce.nasa.gov/cce/ocean.htm

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

EXPORTS: Science Traceability Matrix

Science Questions	Approach & Science Plan	Measurements	Requirements
1. How do upper ocean ecosystem characteristics determine the vertical transfer of organic matter from the well-lit surface ocean? • How is community structure linked to export magnitude & efficiency? • How do export pathways vary with plankton community structure? • What physical and ecosystem factors control export particle aggregation/disaggregation? • How do physical & ecological interactions control surface export? **2. What controls the efficiency of vertical transfer of organic matter below the well-lit surface ocean?** • How do vertical export efficiencies vary between primary pathways? • How is vertical export efficiency related to surface plankton community structure? • How is vertical export efficiency linked to carrier abundance and composition? • How do environmental/ecosystem features define vertical export efficiency? **3. How can the knowledge gained from EXPORTS be used to reduce uncertainties in contemporary & future estimates of the biological pump?** • Which ecosystem properties are most important for modeling the biological pump? • How do key ecosystem properties vary biological pump states and can they be assessed from surface ocean processes alone? • Can the biological pump be accurately modeled from satellite-retrievable properties alone? • Can mechanistic understanding of contemporary export processes be used to improve predictions of the biological pump under future climate scenarios?	**OVERALL APPROACH** • Characterize the "state" of the biological pump over a range of conditions • Focus on the pathways regulating the fate of organic carbon fixed in the upper ocean • Conduct four major field deployments at two locations using two ships and autonomous sampling devices • Supplement the planned field work by data mining existing results • Use EXPORTS data products to improve satellite algorithms and numerical models of the ocean's biological pump **FIELD DEPLOYMENT PLAN** • During each deployment, a "Lagrangian" ship will quantify carbon stocks and rates of organic carbon formation, transport & transformations sampling in a 'parcel tracking' manner following a float • A "Spatial" ship assesses biogeochemical & physical properties over ~100 km scales to evaluate meso- & submesoscale variability & constrain physical pathways for vertical carbon transport • Sampling each pump state needs to be long enough to sample newly formed organic carbon at depth (to 500 m) • Autonomous gliders will extend spatial sampling and measure key physical, ecological & biogeochemical proxies • Profiling floats will provide long-term (≥1 year) vertical profiles of key physical, ecological & biogeochemical proxies • Key physical & biogeochemical properties will be sampled over seasonal time scales from ships of opportunity **SYNTHESIS & MODELING** • Synthesize field observations into a set of multi-platform data products needed to answer the science questions • Design the field deployments using observation system simulation experiment (OSSE) modeling • Apply 4-D coupled models to evaluate future changes in the ocean carbon pump	**SHIP-BASED MEASUREMENTS** *Water column characterization*: hydrography, circulation, optics, nutrients & carbon stocks *Food web structure*: particle size distribution and composition, plankton abundance & community composition, carbon content *Food web function*: net primary production, phytoplankton physiology, heterotrophic respiration & grazing, net comm. production *Export pathways*: Sinking particle flux, particle aggregation / disaggregation, dissolution & sinking rates, vertical zooplankton migration & associated fluxes and physical vertical carbon fluxes *Satellite observables*: Remote sensing reflectance spectra (at same spectral resolution as PACE) with supporting inherent optical property determinations **AUTONOMOUS MEASUREMENTS** Profiling floats for day to ≥ annual vertical & gliders for 1 km to 100 km variations Physical (T, S, u & v), biogeochemistry (O_2, NO_3) & optical proxies for organic carbon, particle size, abundance & type distribution and vertical sinking flux attenuation Water-following using a mixed layer float Cross-calibration of all sensor data and calibration to in situ data observations **REMOTE SENSING MEASUREMENTS** Satellite retrievals of chlorophyll, particulate organic carbon, phytoplankton carbon, colored DOM, net primary production, particle size, sea level height, and SST Near real time preliminary satellite retrievals of above properties during field deployments **NUMERICAL MODELING** OSSE's for planning field deployments Coupled physical/ecological/biogeochemical modeling at submesoscales for assessing relative importance of export pathways Detailed models for parameterizing particular processes (particle aggregation, etc.) Coupled Earth System models for hindcasting & forecasting states of the biological pump	**FIELD DEPLOYMENTS** Two 30+ day ship-based field campaigns in the Northeast Pacific performed sequentially in May and then October One 45+ day & one 30+ day ship-based field campaigns in the Northeast Atlantic performed sequentially in April and then August Each deployment requires a "Lagrangian" and a "Spatial" ship capable to work in demanding seas Autonomous profiling floats and gliders need to be deployed four months prior to and then replaced from a smaller "Deployment" ship Key physical & biogeochemical properties need to be sampled on seasonal time scales for both sites Basin-scale satellite retrievals of surface ocean physical properties and ecosystem properties from existing/upcoming satellites **SYNTHESIS & MODELING** Integration of field measurements into synthetic data products Data mining of existing results to extend the number of states of the biological pump Use synthetic data products to build & test numerical models & algorithms Coupled Earth system modeling to (1) optimize field campaign design, (2) understand mechanisms of physical-ecosystem-biogeochemical variability, (3) forecast impacts of changes in ocean biological carbon pump **PROJECT ORGANIZATION** Centralized project office, field event recording & project data management Teams of PI's work to create integrated data products Data mine to expand data set breadth Open meetings & berth availability to encourage partnerships

EXPORTS: *Notional* Timeline



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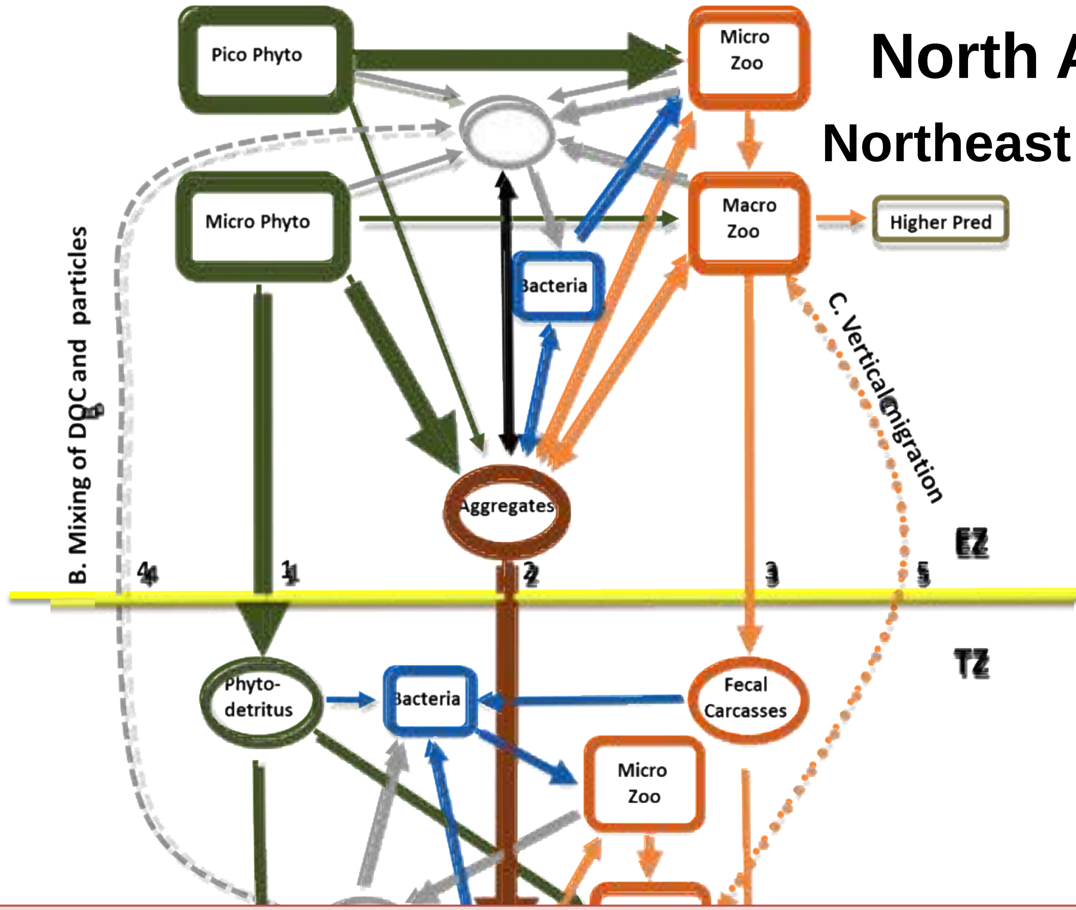
EXPORTS: Focus on Pathways

North Atlantic Bloom

Northeast Pacific Summer



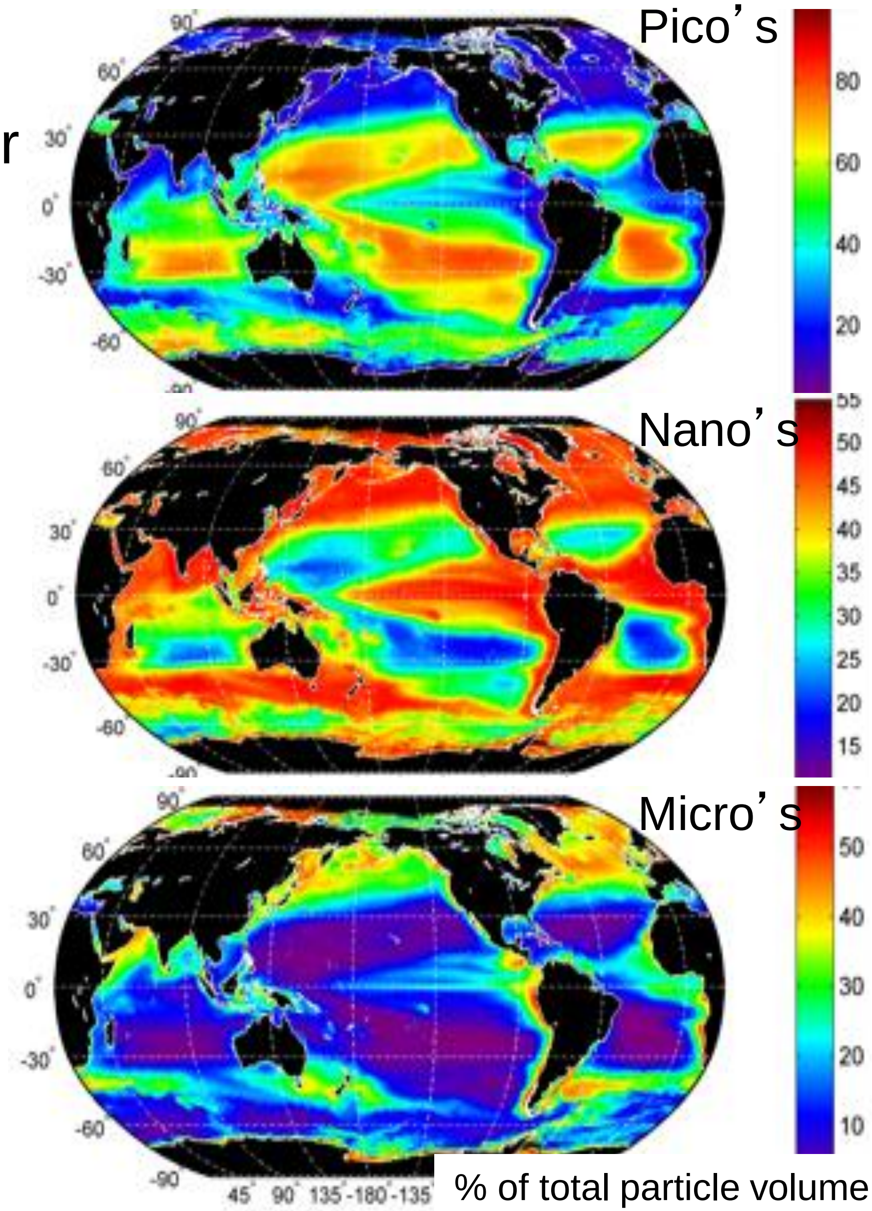
Goal: Predict the state of the biological pump given surface ecosystem characteristics

Assessment of Particle Size Distribution (PSD)

- 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

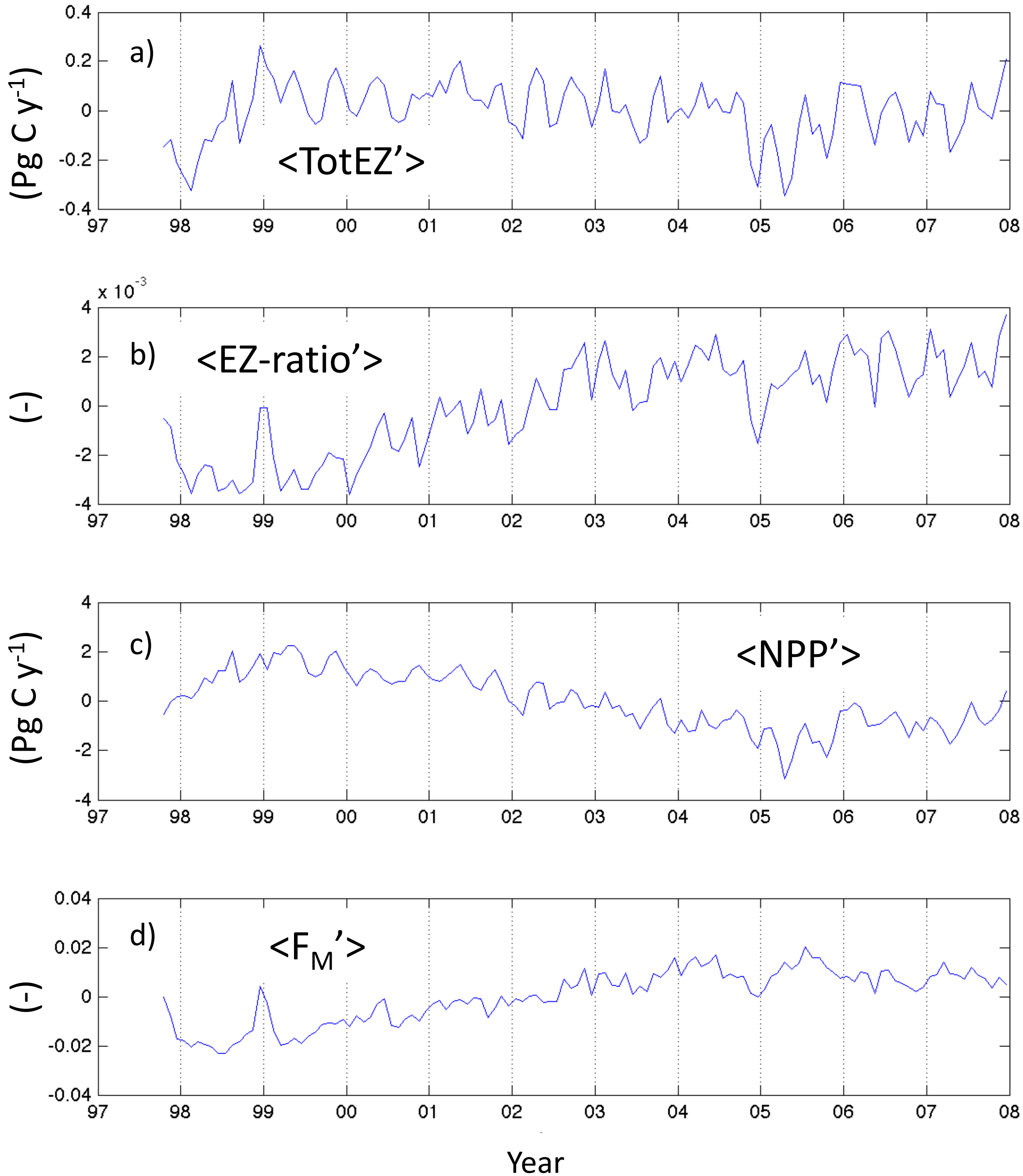
  Micro's are found only in high latitudes & upwelling regions
- Provides a new approach for assessing plankton functional types using satellite observations



Loisel et al. [2007] *JGR-Oceans*

Kostadinov et al. [2009] *JGR-Oceans*

Kostadinov et al. [2010] *Biogeosciences*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(Pg C y-1)
b)
<EZ-ratio'>
x 10-3
(-)
c)
<NPP'>
(Pg C y-1)
d)
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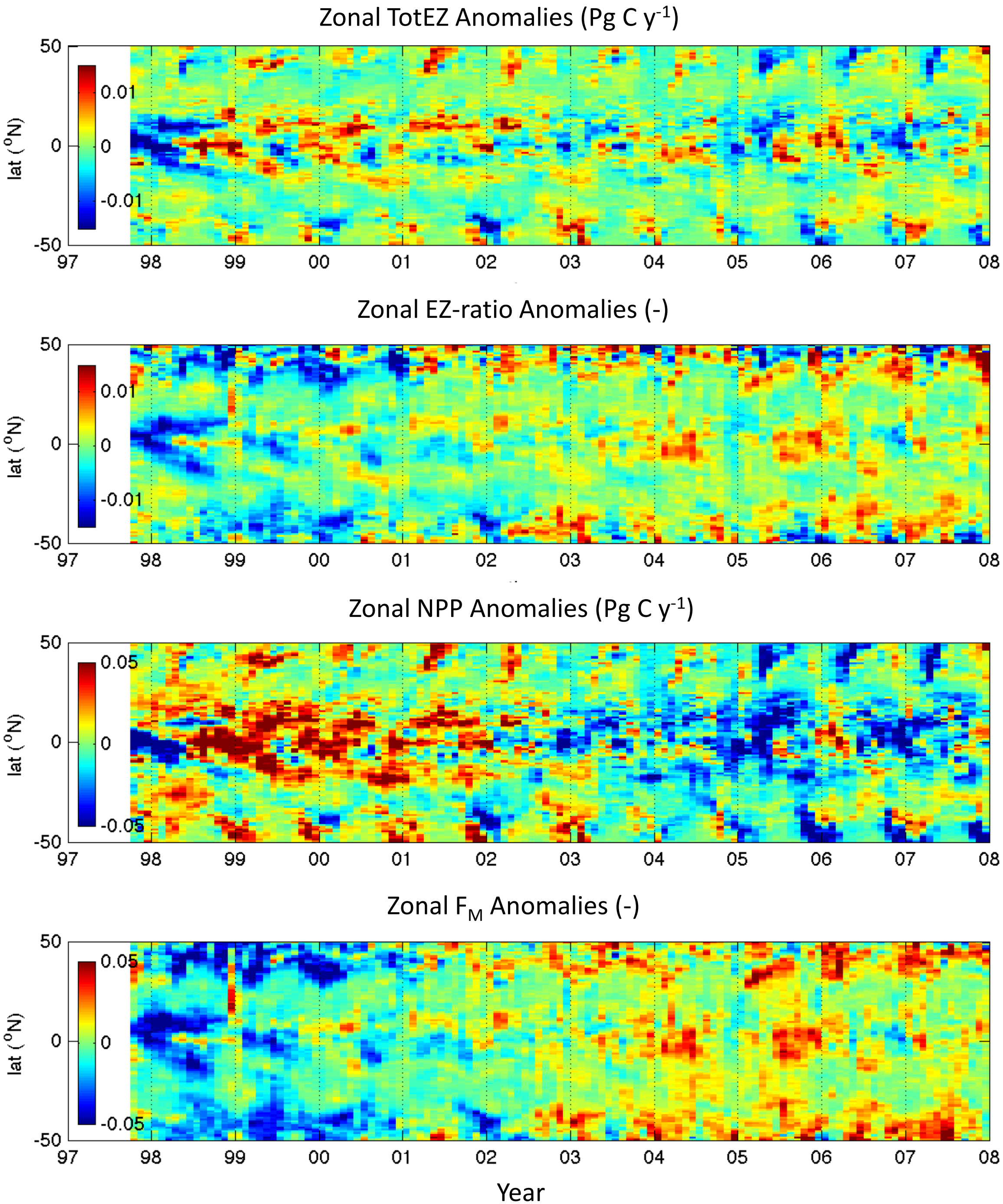
(-)
97
98
99
00
01
02
03
04
05
06
07
08
Year



Zonal TotEZ Anomalies (Pg C y-1)
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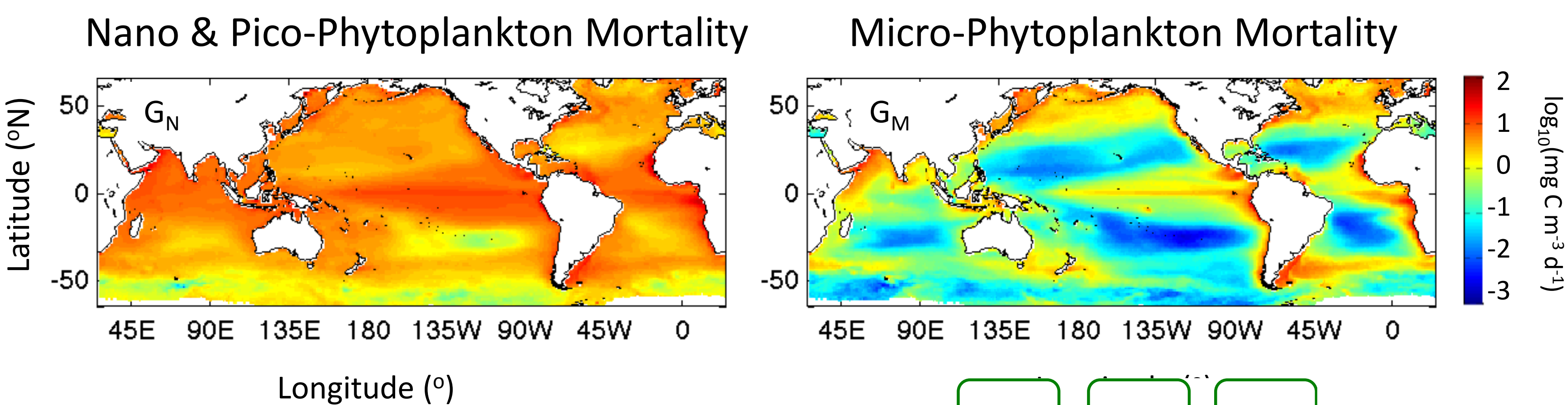
0
-0.01
Zonal EZ-ratio Anomalies (-)
0.01
0
-0.01
Zonal NPP Anomalies (Pg C y-1)
0.05
0
-0.05
Zonal FM Anomalies (-)
0.05
0
-0.05
lat (oN)
50
0
-50
97
98
99
00
01
02
03
04
05
06
07
08
Year

Grazing from Space??

- Global estimates of size-fractionated phytoplankton grazing mortality – could be useful…
- $G_M << G_{N+P}$ except when G_M is large, then $G_M \sim G_{N+P}$
- $G_M/G_{N+P} \sim$ f(fraction micro-phytoplankton biomass)



- Not zooplankton grazing rates