Prediction of the Export and Fate of Global Ocean Net Primary Production: The EXPORTS Science Plan

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Abstract:

Ocean ecosystems play a critical role in the Earth's carbon cycle and the quantification of their impacts for both present conditions and for predictions into the future remains one of the greatest challenges in oceanography. The goal of the EXport Processes in the Ocean from Remote Sensing (EXPORTS) Science Plan is to develop a predictive understanding of the export and fate of global ocean net primary production (NPP) and its implications for present and future climates. The achievement of this goal requires a quantification of the mechanisms that control the export of carbon from the euphotic zone as well as its fate in the underlying "twilight zone" where some fraction of exported carbon will be sequestered in the ocean's interior on time scales of months to millennia. In particular, EXPORTS will advance satellite diagnostic and numerical prognostic models by comparing relationships among the ecological, biogeochemical and physical oceanographic processes that control carbon cycling across a range of ecosystem and carbon cycling states. EXPORTS will achieve this through a combination of ship and robotic field sampling, satellite remote sensing and numerical modeling. Through a coordinated, process-oriented approach, EXPORTS will foster new insights on ocean carbon cycling that maximizes its societal relevance through the achievement of U.S. and International research agency goals and will be a key step towards our understanding of the Earth as an integrated system.

Fate of Net Primary Production and the Ocean's Carbon Cycle:

Net primary production (NPP) by phytoplankton fix dissolved carbon dioxide and create organic matter. The fate of this fixed carbon is regulated through a variety of ocean ecosystem processes that control the vertical transport of carbon into the ocean's interior. Only a small fraction of the organic matter formed via NPP is exported from the surface ocean and in turn only a small fraction of that exported carbon is sequestered from the atmosphere on decadal and longer time scales. There are several pathways through which carbon flows within ocean food webs, each with different efficiencies that lead to significant differences in the vertical transport of carbon into the ocean interior. The predictive understanding of how these ecological, biogeochemical and physical oceanographic processes work together to sequester carbon on humankind-relevant time scales is critical for monitoring and predicting changes to the ocean's carbon cycle especially in a changing climate. The development of this predictive understanding is the goal of the EXport Processes in the Ocean from Remote Sensing (EXPORTS) Science Plan.

Unfortunately present abilities to quantify the export and fate of ocean NPP from satellite observations or to predict future fates using Earth system models are limited. In fact, current estimates of global carbon export flux from the well-lit surface ocean range from 5 to >12 Pg C yr^{-1}, an uncertainty range that is as large as the annual perturbations in the global carbon cycle due to human activities (e.g., Boyd and Trull, 2007; Henson et al. 2011). The exported carbon flux from the surface ocean is attenuated with depth, sometimes quite rapidly. Knowledge of the vertical transmission of export flux below the surface ocean is again limited with little predictive power either in space or in time (e.g., Buesseler and Boyd, 2009; Burd et al. 2009). This is particularly troubling considering that we know the global ocean is changing.

Figure 1 illustrates the ocean food web processes that drive the transformation and partitioning of carbon among the various particulate and dissolved carbon reservoirs (Figure 1). First, dissolved inorganic carbon (DIC) is photosynthetically fixed into particulate organic carbon (POC) by phytoplankton (and by some phytoplankton into particulate inorganic carbon [PIC]) in the euphotic zone (EZ). Phytoplankton carbon is in turn grazed upon by both micro- and macrozooplankton that respire much of the ingested organic matter back into DIC or release it as dissolved organic carbon (DOC). A fraction of that phytoplankton carbon is exported from the surface ocean either as sinking fecal pellets or as aggregates that are created from the pool of suspended POC and PIC by physical and food-web processes (e.g., Stemmann et al. 2004; Buesseler and Boyd, 2009). Zooplankton also contribute to export through their diurnal and seasonal migrations from the EZ to several 100 m's deeper into the twilight zone (TZ), where carbon consumed at the surface is subsequently respired as CO_2, excreted as DOC or released as fecal pellets (e.g., Steinberg et al. 2000; Bianchi et al. 2013; Jonasdottir et al. 2015). Further in the TZ, a host of remineralization processes driven by bacteria and zooplankton recycle sinking and suspended organic matter, further influencing the attenuation of the vertical carbon flux (e.g., Steinberg et al. 2008; Burd et al. 2009; Giering et al. 2014).

Physical processes also affect the fate of accumulated carbon pools in the surface ocean. For example, the transport of suspended POC and DOC from the EZ to the TZ via subduction, isopycnal exchange and seasonal convective mixing represents up to 20% of global carbon export from the EZ and provides another carbon source for TZ microbial communities (e.g., Hansell et al. 2009; Carlson et al. 2010). Further, intense upwelling and downwelling motions (several 10's m's per day) induced by the submesoscale (~1 to 20 km) flow field also have the potential to transport large amounts of organic matter to depth where some portion of it is remineralized resulting in a net export of carbon from the upper ocean (e.g., Lévy et al. 2013; Omand et al. 2015).

There are thus three important pathways that need to be quantified to develop diagnostic and predictive models for the export and fate of oceanic NPP. These are:

- Gravitational settling of particulate carbon as intact phytoplankton, aggregates and zooplankton byproducts,
- Vertical advection and mixing of suspended particulate and dissolved organic carbon to depth by physical oceanographic processes, and
- Vertical transport of organic carbon due to the diurnal and/or life cycle migration of zooplankton and their predators.

These pathways and their relationship with their sources in the surface ocean are illustrated in the EXPORTS conceptual diagram (Figure 1). EXPORTS will create a predictive understanding of both the export of carbon from the well-lit, upper ocean (or euphotic zone) and its fate in the underlying "twilight zone" (depths of 500 m or more) where a variable fraction of that exported carbon is respired back to CO_2. A predictive knowledge of the ocean carbon cycle is important societally for many reasons, including determining anthropogenic carbon sequestration, monitoring ocean deoxygenation and predicting the impacts of ocean acidification and future fisheries yields (e.g., Doney et al. 2009; 2012; Cheung et al. 2010; Keeling et al. 2010).

Here we present the results of a community planning effort aimed at developing a predictive understanding of the export and fate of global NPP (EXPORTS Writing Team, 2015). The EXPORTS Science Plan is a community vetted plan for a major field campaign sponsored by NASA. At the time of this writing EXPORTS is under consideration for implementation by NASA with potential involvement of additional partners. Our goal here is to present a high-level description of the EXPORTS science objectives, science questions, approach and possible implementation. We believe this approach is required for quantifying and predicting the export and fate of global oceanic NPP and understanding its roles in the Earth's carbon cycle.

EXPORTS Hypothesis:

The overarching hypothesis for EXPORTS is that …

> ***Carbon export from the euphotic zone and its fate within the twilight zone can be predicted knowing characteristics of the surface ocean ecosystem.***

The corollary to this hypothesis suggests that the importance of the export pathways should vary systematically among differing ocean ecosystem conditions. Together this implies that a comprehensive data set can be created to test this hypothesis by sampling NPP, export and fate among a range of ecosystem states. This focus on sampling a range of ecosystem / carbon cycling states is central to the EXPORTS experimental approach.

One way to visualize ecosystem / carbon cycling state differences is shown in Figure 2 (after Buesseler and Boyd, 2009). For each site and time, export efficiency can be quantified by the ratio of NPP to POC flux at the base of the EZ (Export ratio; Y-axis of Figure 2), and the transmission of export flux below the EZ defined by the ratio of POC flux 100m below the EZ to that at the base of the EZ (T_{100}; X-axis). The plotting of these two metrics permit both regional and seasonal variability in carbon cycling states to be characterized and related to differences in upper ocean characteristics.

It is instructive to examine two end-member sites; the North Atlantic spring bloom (efficient export and weak attenuation below the EZ; green circles in Figure 2) and the low-iron waters of the NE subarctic Pacific (inefficient export yet strong attenuation in the TZ, orange circles). During the spring bloom, about half of the NPP is exported out of the EZ and there is negligible POC attenuation in the first 100 m below EZ. The net effect is an extremely strong and efficient export of NPP with >40% of NPP found at 100m below the EZ relative to NPP (see contour lines). By the summer at the same site, however, the food web shifts to a more recycling dominated system, and <15% of the NPP is lost from the surface is exported depth with about 50% POC flux attenuation in the first 100 m below the euphotic zone. In the NE Pacific (Papa in Figure 2), we see a significantly lower export efficiency, with EZ export ratios of < 15%, and roughly 70% of the POC flux attenuated within the first 100 m below the EZ (orange circles). The food web at Station P is dominated by small phytoplankton < 5 μm that are under tight grazer control and thus do not lead to high export efficiencies (e.g., Boyd and Harrison, 1999). Other sites and times indicate that there will be a wide range of export flux efficiencies and TZ attenuation rates (Figure 2; see Buesseler and Boyd [2009] for more information).

The recent food-web model / satellite data synthesis by Siegel et al. [2014] is a useful example for how the overall EXPORTS hypothesis could be tested. These authors use available satellite observations of NPP, particle size and phytoplankton carbon to diagnose size-fractionated phytoplankton carbon budgets and to model sinking export using a simple food web model (Figure 3a). The resulting climatological fields of the carbon export from the EZ by sinking particles and export efficiency (= export/NPP) are shown in figure 3a and 3b, respectively. The model / satellite data synthesis results correlate well with available particle export estimates over a wide range of ecosystem / carbon cycling states ($r^2 = 0.75$ vs. available, regional-scale ^{234}Th determinations of export). The global carbon export summaries are also robust to large changes in food-web model parameters or choice of satellite data algorithms. Further the modeled spatial patterns in export and export efficiency have a realism not found in previous global summaries of export efficiency (see Siegel et al. [2014] for more details).

There are several significant, yet missing, processes in the Siegel et al. [2014] synthesis that EXPORTS must consider. First, the Siegel et al. [2014] results focus on sinking particle export and do not explicitly address the pathways for export due to the physical mixing and subduction of suspended particulate carbon or DOC. Similarly, the analysis does not include the carbon cycle impacts of vertically migrating zooplankton. The pathways and constants used in the food-web model do not respond to changes in the plankton community structure or environmental conditions (e.g., Silver and Michaels, 1989; Boyd and Stevens, 2002). Last, the fates of the exported carbon below the EZ are not addressed.

New developments suggest that these missing processes may be estimated using satellite remote sensing data. New remote sensing tools are being developed to use high-spectral resolution reflectance spectra to assess phytoplankton functional types on global scales (e.g., Bracher et al. 2009). Knowing phytoplankton size distribution and functional type together are first steps towards characterizing pelagic food webs (e.g., Michaels and Silver, 1989). It has been shown recently that the performance of the Siegel et al. [2014] export flux model improves substantially if the parameters are regionally tuned supporting the importance of food web structure (Stukel et al. 2015). Further, recent field data summaries show strong relationships between the vertical scales of sinking flux attenuation in the TZ and both phytoplankton community structure in the EZ (Guidi et al. 2015; Puigcorbé et al. 2015) and environmental conditions in the TZ (Marsay et al. 2015). The explicit testing of the EXPORTS hypothesis and development of modeling tools to diagnose carbon cycling processes will require an extensive data set of a wide range of ecosystem / carbon cycling states.

Science Questions and High-Level Objectives:

The EXPORTS Science Plan proposes three fundamental science questions relating the characteristics of plankton communities in the well-lit surface ocean to the predictions of the export and fate of global NPP. The three EXPORTS Science Questions are:

1. How do upper-ocean ecosystem characteristics determine the vertical transfer of carbon from the well-lit surface ocean?
2. What controls the efficiency of vertical transfer of carbon below the well-lit surface ocean?
3. How can the knowledge gained be used to reduce uncertainties in contemporary & future estimates of the export and fates of global ocean NPP?

Each science question has four sub-questions that together test the overall EXPORTS hypothesis. As the sub-questions are detailed in the EXPORTS Science Plan, they are not presented here (EXPORTS Writing Team, 2015).

Answering the three EXPORTS science questions will require new data and models that quantify the export and fate of global NPP. The EXPORTS Science Plan established a set of guiding objectives that must be achieved. The objectives are:

- Conduct a coordinated, multidisciplinary field campaign that will provide answers to the EXPORTS science questions,
- Improve our understanding of NPP export and fates and our abilities to monitor and predict their changes on regional to global scales,
- Develop an efficient, cost-effective plan through an integration of field and satellite observations and numerical modeling,

- Answer important high-level, agency science questions, such as those posed in NASA's Science Plan (NASA, 2014), and
- Provide a path for global carbon cycle assessments for NASA's up-coming Pre-Aerosol, Clouds and ocean Ecosystem (PACE) mission (http://decadal.gsfc.nasa.gov/pace.html).

These high-level objectives are aimed to help maximize the scientific output and address mission agency needs through the EXPORTS field campaign. In particular, EXPORTS will provide important algorithmic insights for the upcoming PACE satellite ocean color mission enabling the construction and validation of a new generation of carbon cycle satellite ocean data products.

Experimental Approach:

The EXPORTS Science Plan aims to quantify the underlying mechanisms that drive the export and fate of global NPP over a range of ecosystem / carbon cycling (ECC) states necessary to create the next generation of ocean carbon cycle models. Figure 4 presents the EXPORTS "wiring diagram" that illustrates the dominant pathways for carbon export from EZ and its fates in both the EZ and the TZ. The wiring diagram contains the expected components of a pelagic food web – autotrophic production in the EZ, micro- and macrozooplankton grazing and microbial loops in both the EZ and TZ and the formation and destruction of aggregates, which act to transform materials from the suspended to the sinking pools and back again. Although not explicitly represented in figure 4, an assessment of plankton functional types is also considered in the EXPORTS Science Plan. The flows of carbon from the EZ to the TZ are comprised of A) sinking particulate materials, B) the advection and mixing of DOC and suspended C stocks and C) active transport via migrating zooplankton as illustrated in figure 4.

The topology of the wiring diagram is expected to differ for different ECC states. This was illustrated previously in the export efficiency – vertical particle flux transmission plot shown in figure 2, but we now hypothesize that these differences alter NPP export and fate pathways. For example, the dominant pathways during the North Atlantic spring bloom emphasize rapid pathways for export associated with large phytoplankton and large zooplankton creating an efficient transfer of phytodetritus and aggregate materials to depth (Figure 5a). A very different case arises for summertime conditions in the Northeast Subarctic Pacific Ocean near Station P (Figure 5b). There, a more complex food web will be observed where smaller phytoplankton dominate NPP in summer resulting in a strongly recycled food web in the EZ. As such, this system is characterized by greatly diminished carbon export efficiencies both in the EZ and below (Figure 5b).

EXPORTS is designed to facilitate improvements in our predictive understanding of pelagic ecosystems and carbon cycling via the longitudinal comparison of observations collected across a realistic range of ECC states. It is therefore important that measurements of all the pools and pathways detailed in figure 4 be measured at the same time across all ECC states sampled. In particular, new automated microscopy tools have the potential to revolutionize oceanography by providing statistically meaningful descriptions of the underlying phytoplankton and zooplankton groups present (e.g., Sosik and Olson, 2007; Stemmann and Boss, 2012; Guidi et al. 2015). Further, supporting oceanographic observations needed for answering the science questions (which may include submesoscale physical oceanographic surveys) as well as measurements that link to satellite remote sensing products (e.g. water-leaving reflectance spectra, inherent optical properties, etc.) must also be collected. Last, the EXPORTS Science Plan requires the sampling of biogeochemical property profiles (O_2, NO_3, DIC, etc.) over long enough time scales (many months to years) so that changes in the integrated biogeochemical stocks can be compared with the summed pathway fluxes. These long-term stock measurements can be made from autonomous profiling floats or from periodic discrete water profiles taken from ships of opportunities (e.g., Emerson et al., 1991; Riser and Johnson, 2008).

The EXPORTS experimental approach is dependent upon the assessment of an ecosystem / carbon cycling state. There are several constraints for defining an ECC state. For example, the length of time of sampling must be long enough to allow that all the measurements required to answer the science questions are collected. Further, the sampling duration should be long enough so the particles collected in traps at depth are sampled in the surface ocean. This corresponds to a time scale of roughly 10 days assuming a trap at 500 m is sampling slowly sinking particles (50 m d^{-1}). Recent work by Estapa et al. [2015] provides additional clues for the appropriate sampling period. These authors made simultaneous determinations of POC export (via ^{234}Th disequilibrium) and net community production (NCP; via O_2/Ar gas tracers) on ~2 km spatial scales over eight 30 to 40 km transects. Over long temporal and large spatial scales, determinations of export and NCP should balance. However on a point-by-point basis, Estapa and colleagues found little statistical correspondence between the two determinations. However when averaged over each transect, an excellent statistical correspondence was found between the transect-averaged NCP and export determinations. This supports a hypothesis that local-scale (or submesoscacle ≤ ~50 km) environmental processes leading to autotrophic particle production (NCP) are not necessarily collocated with those that remove particles from the surface ocean (aggregation and grazing). These results suggest that a multiday sampling over several 10's of kms is required to represent an ECC state for these biogeochemical fluxes. Taking into account the above considerations and the logistical issues required for sampling the diversity of required oceanographic observations, results in a time scale of about 10 days needed for sampling a single ECC state. One should expect that in a typical four-week cruise, two ECC state assessments could be completed.

The EXPORTS experimental approach is intended to be modular. Thus it is less important where and when the observations are made but rather that the entire measurement suite be sampled appropriately and that a wide enough range of ECC states are collected to enable robust model building and testing. The modular nature also makes it straightforward for any partner to contribute to EXPORTS independent of the formal program by sampling and sharing ECC state assessments. Further EXPORTS' modularity makes the experimental plan highly adaptable to resource de-scoping or re-scoping, which is expected for a project of this scale. In many ways the EXPORTS Science Plan provides a blueprint for future research aimed at improving models of ecologically-driven, biogeochemical processes.

The modular nature of the EXPORTS experimental approach also implies that there are oceanic regions that would be inappropriate for EXPORTS to expend resources to sample. For example, there are several biogeochemical time series sites with decades of observations (BATS, HOT, etc.) whose ECC state can be assembled from published accounts and databases. Thus the data mining of previous experimental results is an important part of the EXPORTS experimental approach. Further there are locations where it will be difficult to answer the EXPORTS science questions. These include places where intense persistent currents are found (western / eastern boundary currents, equatorial oceans, etc.) that will require a detailed accounting of large-scale horizontal fluxes. There may also be logistical advantages of the modular approach that will help reduce costs. For example, the U.S. National Science Foundation is implementing several Ocean Observatories Initiative (OOI) global nodes (http://oceanobservatories.org). Collocating an EXPORTS field expedition at an OOI site would provide useful background information and would reduce overall project costs. There are of course many other partnering opportunities to consider as well.

Numerical modeling is central to the EXPORTS Science Plan as improving predictions of the export and fate of ocean NPP comprise one of the science questions. Observing System Simulation Experiments (OSSEs) will be used to help plan the multi-scale sampling program while detailed process models will be developed and employed to understand many factors that are beyond present observational capabilities. These include, but are not limited to, understanding the importance of submesoscale physics on the sequestration of suspended carbon and DOC, the formation and destruction of sinking particle aggregates, and food web models to quantify the significance of species and functional group interactions. Advanced radiative transfer models are also needed to coupling observations of in-water optical properties with the novel abilities of the PACE mission (e.g. polarimetry and hyperspectral wavelength resolution). This will provide more information on the underlying particles and linking them to their signature that can be remotely sensed from space. Last, coupled Earth system models are needed to quantify the impacts of the EXPORTS discoveries on global scales and to forecast future responses to changes in ocean ecosystems and resulting carbon fluxes.

Answers to the EXPORTS science questions will result from a synthesis of the combined EXPORTS field program results, available ECC state assessments mined from previous studies and numerical modeling experimentation. Key to the EXPORTS experimental approach is the sampling of underlying mechanisms over a range of ECC states and the concerted efforts to link these observations to remotely sensed observables. Thus, ocean optics observations must be made simultaneously so the EXPORTS data are useful for developing advanced carbon cycle satellite algorithms.

Experimental Plan:

The EXPORTS Science Plan includes notional experimental and implementation plans to aid in elucidation of the overall experimental approach. The complexity of the sampling program requires multi-ship field deployments – each of at least 30 days duration. Field deployments are proposed for the Northeast Pacific (2 cruises to Station P) and the North Atlantic (2 cruises near the site of the Joint Global Ocean Flux Study [JGOFS] North Atlantic Bloom Experiment). The sites were chosen because of large differences in their ECC states and the ability to leverage on-going and planned activities (cf., U.S.'s OOI, Canada's Line P, EU's planned Horizon 2020). The four deployments to two ocean basins and the time needed to analyze and model results, requires EXPORTS to be a 5-year program.

It is proposed that each field deployment will be conducted in a Lagrangian frame following an instrumented surface float, while spatial distributions of oceanic properties surrounding the float will be resolved using ships, towed instruments, gliders, profiling and mixed layer floats and satellites. This requires two ships; a "Lagrangian" ship that samples the upper 500 m following the instrumented mixed layer float and a "Spatial" ship that makes surveys on scales up to 100 km. The major export pathways illustrated in figure 4 as well as supporting physical and optical oceanographic measurements can all be sampled from the two ships. In particular, carbon export and its vertical attenuation with depth will be measured by a host of approaches including drifting sediment trap arrays, biogeochemical and radionuclide budgeting, particle size and sinking rate determinations, and profiling optical sediment trap floats. OSSEs and monitoring of available satellite observations will be used to guide experimental plans.

EXPORTS must sample the appropriate ecological-oceanographic spatial and temporal scales of variability. The "Spatial" ship will be complemented by an array of autonomous gliders and profiling floats providing resolution of properties and processes from local (km's) to regional (100's km's) spatial scales and on synoptic (days) to seasonal (months) time scales. Gliders will be deployed to map out temporally evolving fields of bio-optical and biogeochemical quantities. Profiling floats will provide a long-term (>1 year) view enabling annual export estimates to be made for each study site. Satellite ocean color observations as well as physical oceanographic observations will be used to guide the sampling, interpretation, and modeling of the EXPORTS data set. Finally, ocean optics observations will tie EXPORTS results to NASA's upcoming PACE satellite ocean color measurements through the development of advanced satellite algorithms and predictive numerical models.

For more details of the EXPORTS Science Plan experimental plan, please see the complete science plan (EXPORTS Writing Team, 2015). At the time of this writing, NASA has formed a Science Definition Team (SDT) to develop implementation plans that will address the EXPORTS science questions (http://cce.nasa.gov/cgi-bin/cce/exports_sdt.pl). The EXPORTS SDT should complete its deliberations and present their recommendations to NASA Headquarters by the end of 2016.

Reflections and Considerations:

The development of a predictive understanding of the export and fate of global ocean primary production remains among the hardest problems in all of the Earth Sciences, as it requires a synthesis of ocean ecological, biogeochemical, physical and optical oceanographic processes over an extensive range of time and space scales. Answering EXPORTS' science questions will accelerate our knowledge of the role of the oceanic food web in the global carbon cycle and provide new models for understanding contemporary and future states of the ocean's carbon cycle and its influences on climate. These results will have tangible societal relevance, leading to advancements in our understanding of our changing planet and reductions in our uncertainties for monitoring its present conditions and for predicting its future state.

The focus on improved predictive understanding differentiates EXPORTS from previous large, multi-national/agency, ocean carbon science programs like JGOFS (Fasham et al., 2001). Although these programs provided much understanding of the regulating processes controlling the biological pump, JGOFS' focus was not on the creation of predictions of carbon cycling processes for present and future climate states. JGOFS also concentrated on surface ocean processes and considerably less attention was placed on the fates of NPP and it's processing in the TZ. EXPORTS will focus on resolving the underlying ecological and biogeochemical mechanisms so that useful predicative tools can be developed and then applied on global scales to monitor contemporary conditions using satellite remote sensing tools and to forecast future climates and ocean ecological states using Earth system models. Last, there are now many new tools that we can take advantage of from autonomous floats and gliders, to new genomic tools, for understanding plankton community structure and function and taking best advantage of advanced satellite observations with NASA's upcoming PACE mission.

EXPORTS will provide answers for many of NASA's science questions about how the Earth system is changing while creating the next generation of ocean carbon cycle and ecological satellite algorithms to be used for NASA's upcoming PACE mission. EXPORTS will improve our understanding of global ocean carbon dynamics and reduce uncertainties in our ability to monitor and predict carbon export and its sequestration within the ocean's interior, thus enabling PACE to address its global carbon cycle science objectives. The EXPORTS field campaign will further train and inspire the next generation of interdisciplinary ocean scientists working together on one of the hardest and most important problems in the Earth sciences.

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Figure Captions:

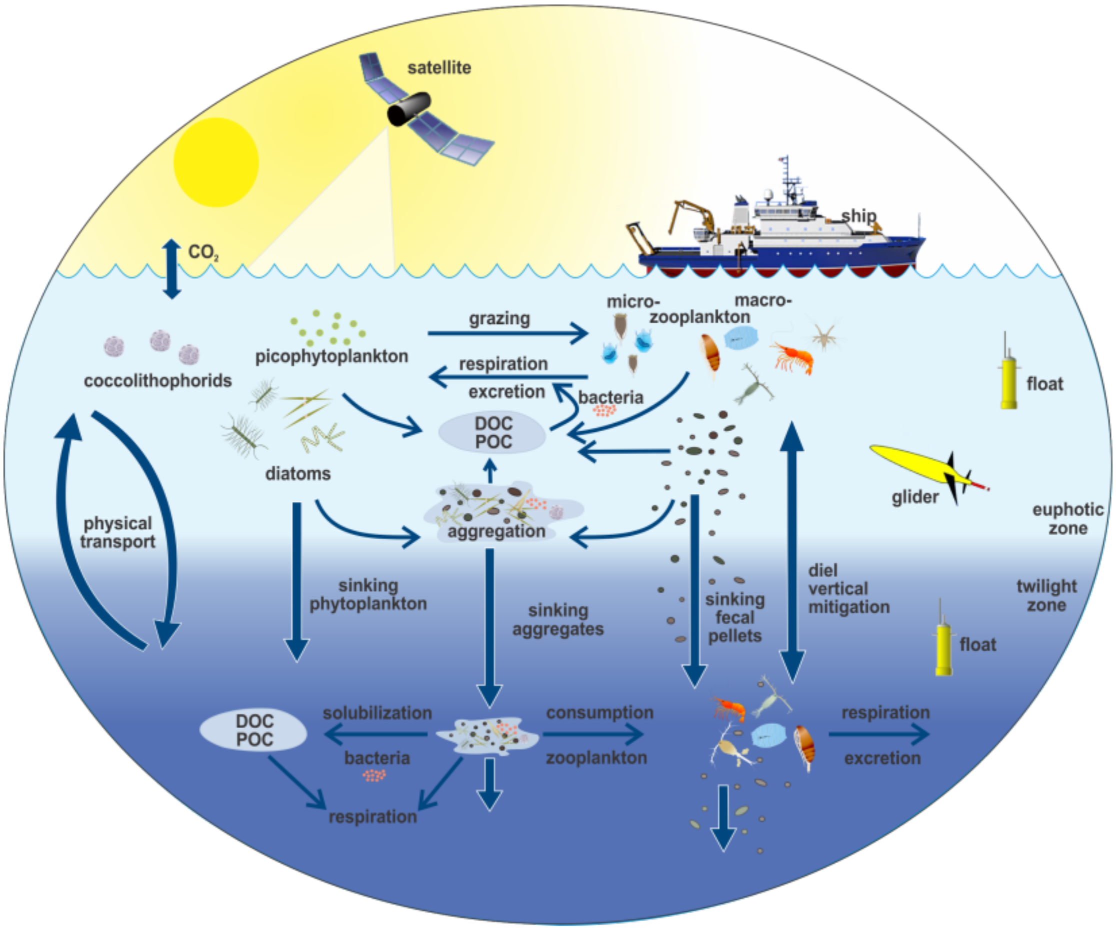
Figure 1: The EXPORTS conceptual diagram illustrates the links among the ocean's biological pump and pelagic food web and our ability to sample these components from ships, satellites and autonomous vehicles. Light blue waters are the euphotic zone (EZ), while the darker blue waters represent the twilight zone (TZ). Figure is adapted from Steinberg (in prep.) and the U.S. Joint Global Ocean Flux Study (http://usjgofs.whoi.edu/images/biological_pump.tif).

Figure 2: Graphical depiction of the export and fate of upper ocean net primary production (NPP) energy. For each site and time, the ratio of NPP to POC flux at the depth of the euphotic zone (Y-axis) is compared to POC flux transmission through the first 100m below EZ (X-axis). The area of the circle is proportional to NPP (roughly 1000 mg C m^{-2} d^{-1} at EQPAC) and the contour lines (1-40%) are the fraction of NPP that reaches 100 m below the euphotic zone. Figure is adapted from Buesseler and Boyd [2009] and focuses on POC flux at the EZ and first 100m below, as this is where sinking POC flux differences are largest.

Figure 3: Topology of a satellite-data driven food-web export flux model illustrating how NPP energy is routed to export either through sinking of large phytoplankton or as fecal material. b) Determination of annual export flux from the euphotic zone and c) export efficiency (=export/NPP). Figure is adapted from Siegel et al. [2014].

Figure 4: The EXPORTS wiring diagram illustrating the C flows from the euphotic zone (EZ) into the twilight zone (TZ) in the biological pump. The flow of C through the biological pump is comprised of A) sinking particles, B) the advective mixing of DOC and suspended C stocks and C) active transport via migrating zooplankton.

Figure 5: Conceptual wiring diagrams for (a) the spring bloom in the North Atlantic and (b) summer conditions in the North Pacific. These figures follow the organization of the EXPORTS wiring diagram presented in figure 4.



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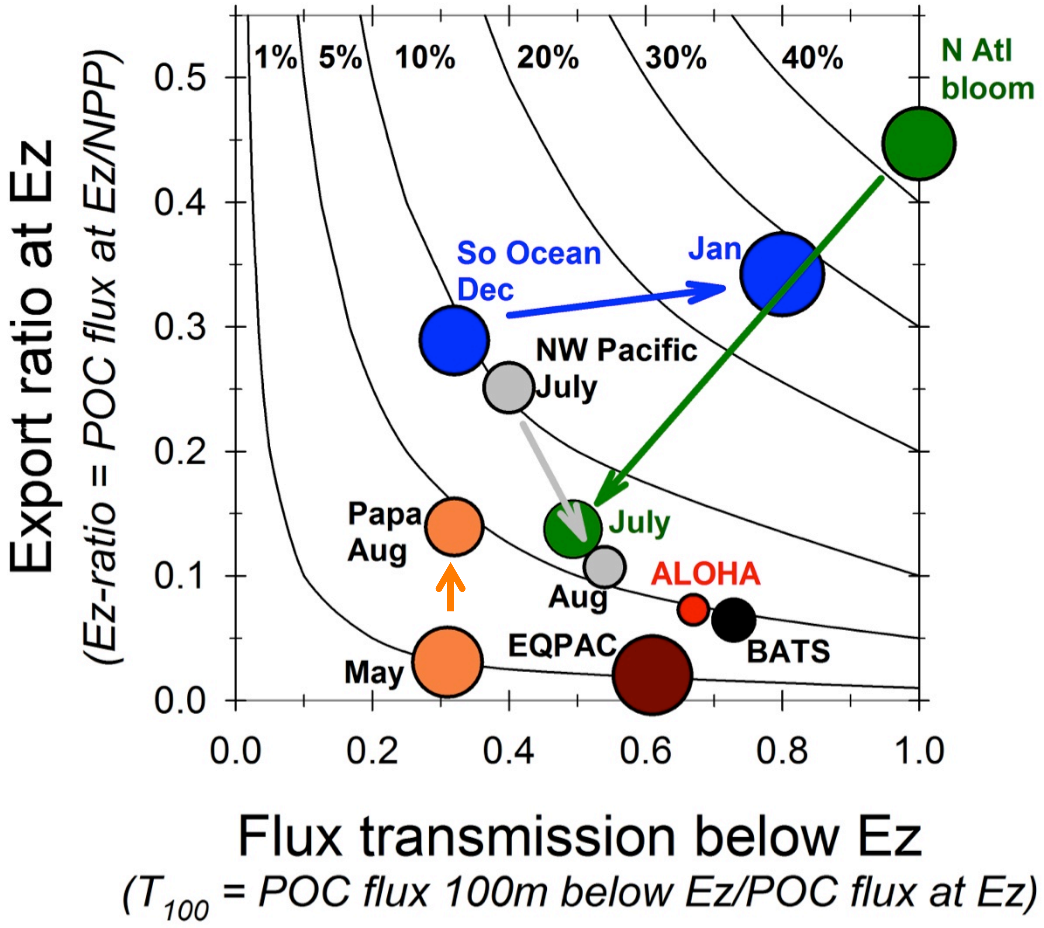

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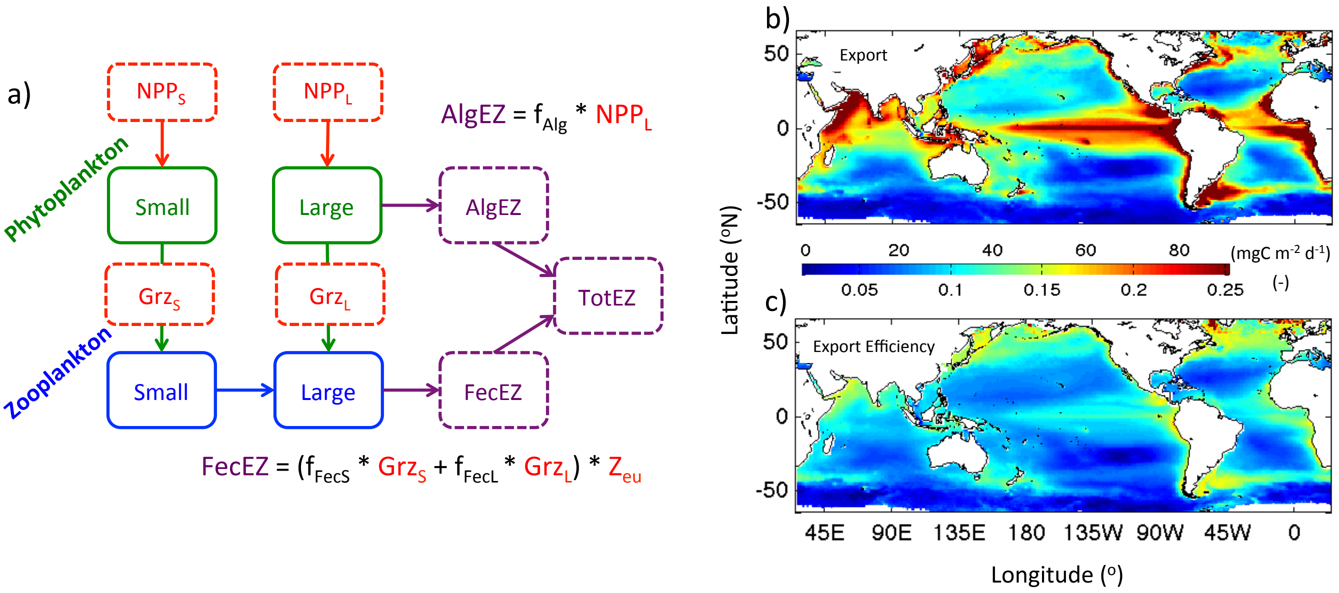

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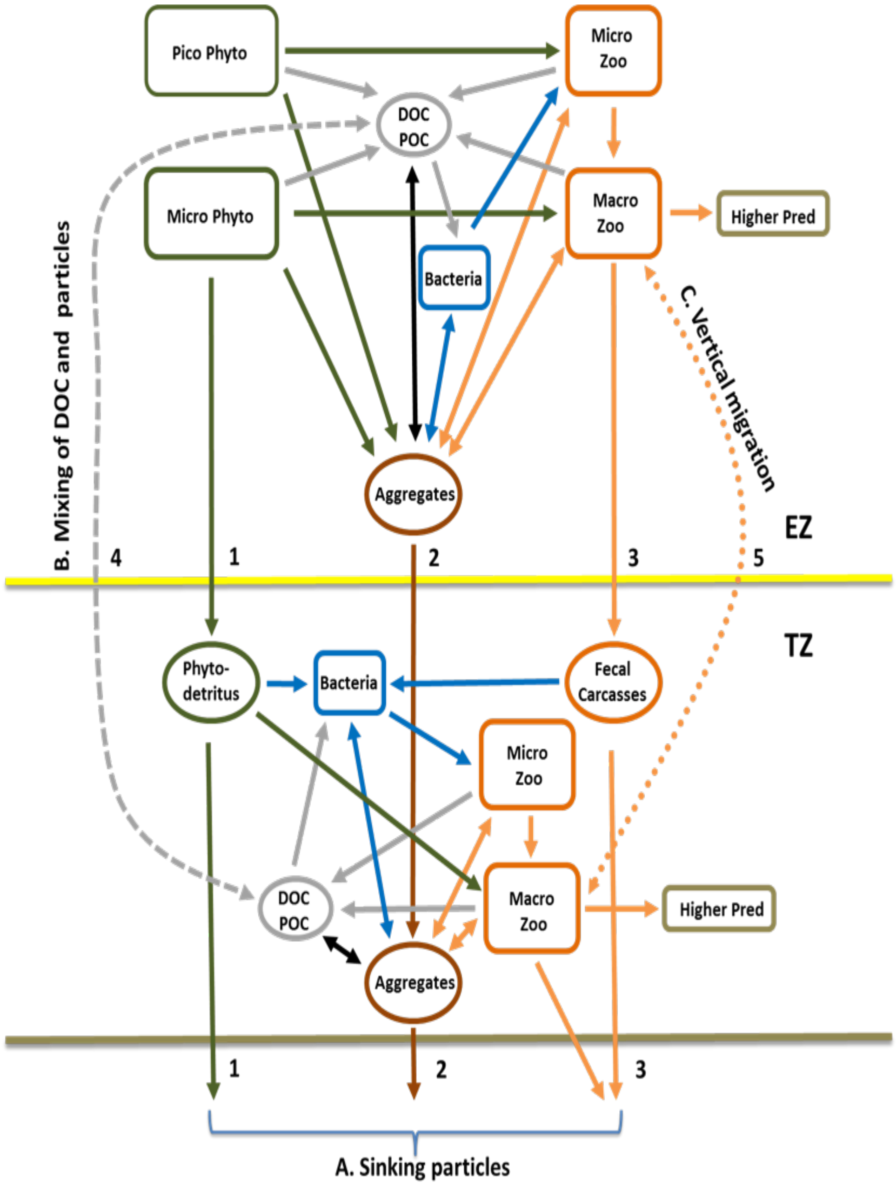

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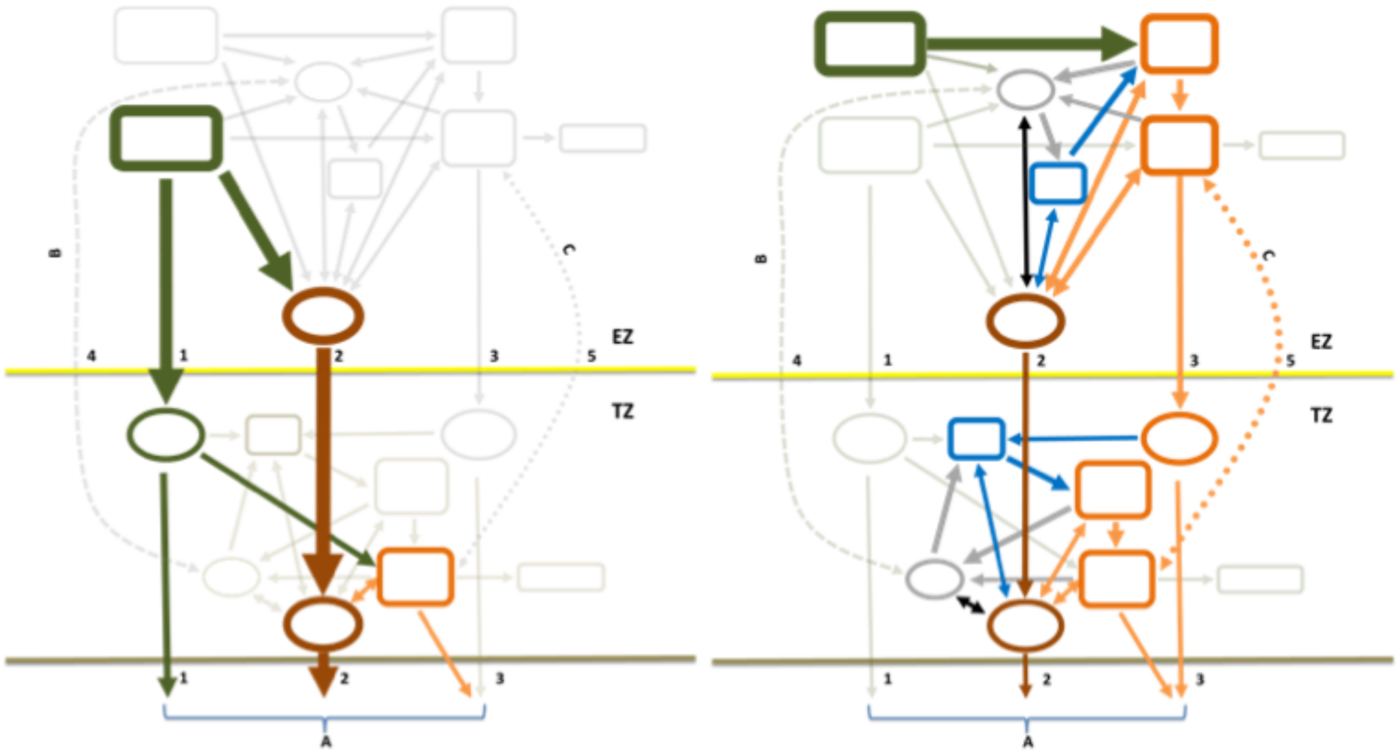

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