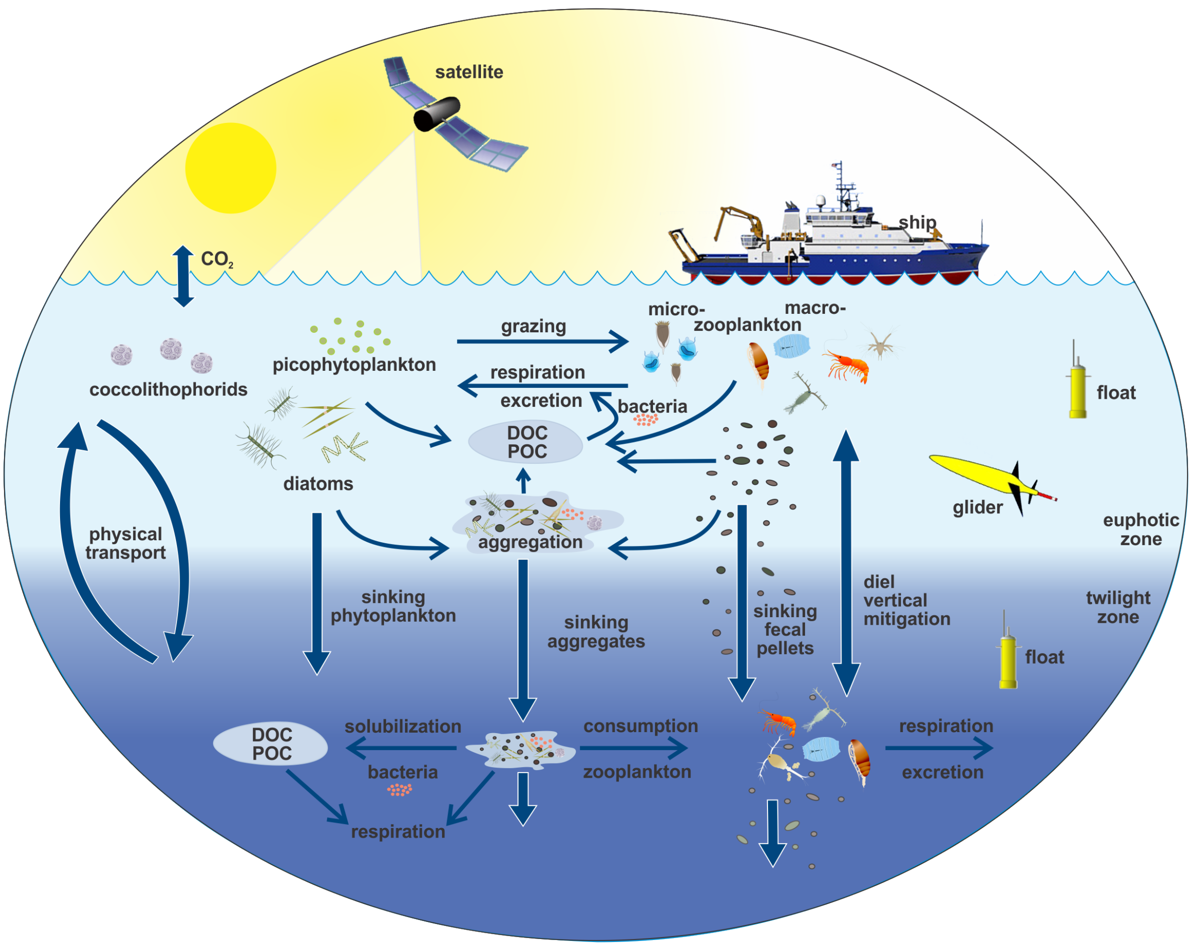
EXport Processes in the Ocean from RemoTe Sensing (EXPORTS)



A science plan for a NASA field campaign to quantify the state of the ocean's biological pump from satellite observations

June 3, 2014

EXport Processes in the Ocean from RemoTe Sensing (EXPORTS): A Science Plan for a NASA Field Campaign

Submitted by the EXPORTS Science Plan Writing Team

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Executive Summary

The Ocean's Biological Pump: Ocean ecosystems play a critical role in the Earth's carbon cycle through their fixation of organic matter from dissolved CO_2 in the well-lit, surface ocean and the vertical transport of this fixed organic carbon to depth. The combination of ocean food web and oceanographic processes leads to the export of organic carbon from the surface ocean to the ocean's interior, where that carbon may be sequestered from the atmosphere on time scales of months to millennia. The coupled ecological-oceanographic processes that mediate the vertical transport of organic carbon are referred to as the biological pump (Figure E1).

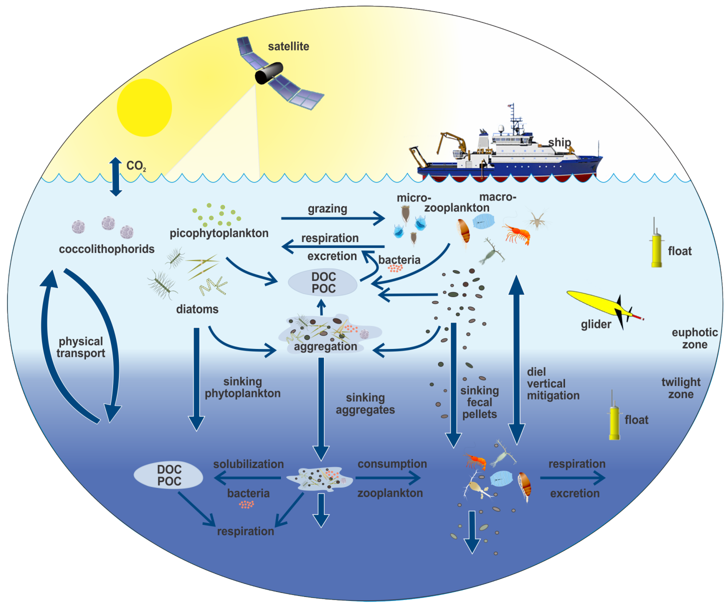

Figure E1 *– Illustration of processes controlling the fates of fixed carbon in the ocean's biological carbon pump.*

The spatial and temporal variations in upper ocean food web structure and circulation alter the efficiency of carbon sequestration by the ocean's biological pump. Only a fraction of the organic matter formed in the upper ocean is exported from the surface ocean into deep waters, where its sequestration depends on both the magnitude of the export flux and where that exported organic carbon is respired in the water column. Carbon flows in different paths through upper ocean food webs, moving fixed carbon with different efficiencies that lead to variations in carbon export and vertical transport. Present abilities to quantify the state of the biological pump from satellite observations or to predict its future state using Earth system models are limited. In fact, current uncertainties in global estimates of carbon export flux from the well-lit surface ocean are as large as the annual perturbations in the global carbon cycle due to human activities. Yet seemingly small changes in the efficiency of the biological pump in Earth system models can have profound effects on the global carbon cycle and predicted atmospheric CO_2 levels. Further, differences in the state of the biological pump reflect changes in ocean ecosystems that influence the many ecological services that the global ocean supports (e.g., fisheries, biodiversity, etc.).

Quantifying the Biological Pump from Satellite Observables: The oceanographic community is excited about NASA's upcoming advanced ocean color mission the Pre-Aerosol Cloud and Ecosystems (PACE) mission. PACE is designed to advance the quality, accuracy and breadth of satellite ocean color data products. Among the novel data products that PACE will retrieve are physiologically-driven assessments of net primary production, phytoplankton carbon concentrations, particle size distributions and phytoplankton community composition - all are required to quantify the biological pump.

One of the stated goals for NASA's PACE mission is to quantify the global ocean's carbon cycle, including quantifying the biological pump. This provides a new and exciting challenge for the NASA Ocean Biology and Biogeochemistry program and an opportunity to greatly improve current skill in predicting the state of the biological pump and thus the role of the ocean in regulating the Earth's carbon cycle and climate. To support PACE, an oceanographic field program is necessary to build mechanistic satellite algorithms that predict the state of the biological pump. Field data of the required type, focus and breadth have not yet been collected. The collection, analysis, synthesis and modeling of these observations are objectives of the planned EXport Processes in the Ocean from RemoTe Sensing (EXPORTS) field campaign.

What is EXPORTS? The goal of EXPORTS is to quantify the state of the biological pump from satellite observations. The mechanistic understanding gained through EXPORTS will inform predictions of how future changes in the biological pump will alter the global carbon cycle. Our underlying hypothesis is that carbon export can be predicted knowing the state of the biological pump as defined by the characteristics of the surface ocean plankton ecosystem. This builds on recent advances in satellite remote sensing as well as improvements in field research capabilities and the predictive skills of numerical models.

EXPORTS will take a fate-based approach to predicting the state of the biological pump. This approach requires that the fundamental export pathways be observed; the gravitational settling of particulate organic carbon to depth, the net vertical transport of organic carbon by physical processes (i.e., mixing & advection) and carbon transport mediated by the vertical migration of zooplankton (i.e. numbered arrows in Figure E2). The importance of the pathways will vary among ocean provinces and in time. These differences will drive systematic variations in the state of the biological pump.

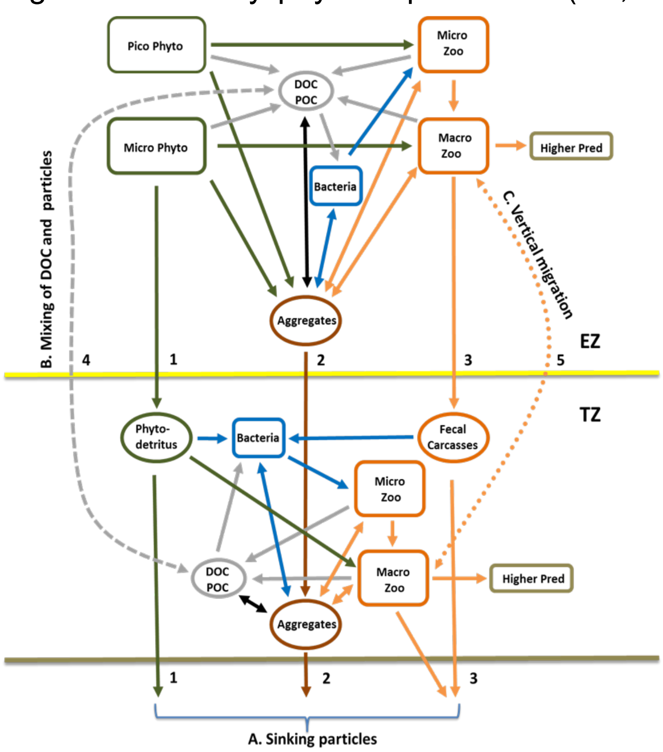

Figure E2 *- Illustration of the pathways regulating the biological pump and the flux of carbon from the euphotic zone (EZ) into the twilight zone (TZ).*

Understanding the fundamental export pathways is critical for 1) quantifying the carbon export leaving the well-lit surface layer, 2) assessing the vertical attenuation of that carbon flux below the euphotic zone where it is sequestered on time scales from months to millennia, and 3) predicting these carbon fluxes for present and future oceans. These three points constitute the science questions for the EXPORTS field campaign (science questions are listed in the Science Traceability Matrix; Figure

E4). EXPORTS will create a comprehensive database capable of answering its science questions as well as creating and validating novel satellite algorithms and numerical models that quantify present and future states of the biological pump.

***EXPORTS Science Plan**:* The EXPORTS science plan integrates ship, autonomous robot and satellite observations of the biological pump with data mining of previous observations and numerical modeling efforts all aimed at improving the predictability of the ocean's biological pump. The result of the EXPORTS field and data mining program will be a data set that spans the range of states of the biological pump. The modular nature of the EXPORTS science plan means that the exact location and sequencing of the field deployments are less important compared with other factors (cf., insuring a wide range of states are observed, logistical simplicity, leveraging existing resources and partnerships, etc.). The modularity of EXPORTS science plan also makes it easier to schedule field deployments, to de/re-scope the field campaign and to establish partnerships with international and U.S. research programs.

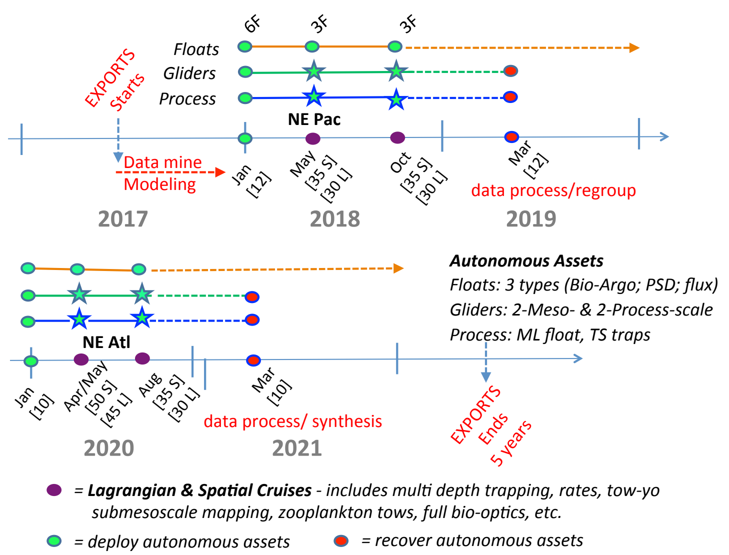

***Figure E3** - Proposed time line for the EXPORTS field campaign. The 5-year field campaign starts in 2017 and ends in 2022. Two major field campaigns with two ships and a pre and post cruise deployment/retrieval cruise are planned in the NE Pacific Ocean (2018) and in the NE Atlantic Ocean (2020). Section 6 discusses the EXPORTS field plan in detail.*

The EXPORTS field program will quantify export pathways during multi-ship field deployments – each designed to observe several states of the biological pump within a 30 to 45 day cruise. Field deployments are planned for the Northeast Pacific (2 cruises to Station P) and the North Atlantic (2 cruises to the NABE site). The sites were chosen because of differences in their food webs structure and the ability to leverage on-going and planned activities (cf., U.S.'s OOI, EU's Horizon 2020, Canada's LineP). The four deployments to two ocean basins and time needed to analyze and model the results require EXPORTS to be a 5-year program (Figure E3).

Each field deployment will be conducted in a Lagrangian frame following an instrumented surface float, while spatial distributions of oceanic properties about the float will be resolved using ships, towed instruments, gliders, profiling 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 about the "Lagrangian" ship. With the two research vessels, EXPORTS will sample all of the major export pathways illustrated in Figure E2 as well as supporting physical and optical oceanographic measurements necessary to link measurements back to remotely sensed observables. In particular, the carbon flux leaving the surface ocean 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 floats.

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 and their sensor outputs will be fully inter-calibrated with ship observations. 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 EXPORTS. Finally, ocean optics observations will be made to tie the EXPORTS results to PACE satellite ocean color measurements.

Numerical modeling is central to EXPORTS as prediction is one of EXPORTS' goals. Observing System Simulation Experiments (OSSE's) will be used to help plan the multi-scale sampling program while detailed processes 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 biological pump, the formation and destruction of sinking particle aggregates, and food web models to illustrate the significance of species and functional group interactions on the state of the biological pump. Last, coupled Earth system models are needed to quantify the impacts of the EXPORTS discoveries on global scales and to forecast future states of the biological pump.

***EXPORTS Implementation**:* A notional implementation plan is provided as part of the EXPORTS science plan and includes suggestions for timeline, technical readiness, data product development and management, project governance, partnership opportunities, and an estimate of resource requirements. Should NASA decide to support EXPORTS, a Science Definition Team will be competed to create a formal Implementation Plan.

***EXPORTS Outcomes**:* The goal of EXPORTS is to predict the state of the biological pump from satellite observations and to improve our predictions into the future. Achieving this goal is among the hardest problems in the Earth sciences, as it requires a predictive understanding of the combination of ocean ecological, chemical, and physical processes. 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 biological pump.

EXPORTS will create the next generation of ocean carbon cycle and ecological satellite algorithms to be used on 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. Last, the EXPORTS field campaign will 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.

***Figure E4** – The EXPORTS Science Traceability Matrix (STM) tracing the path (from left to right columns) from Science Questions to Approach & Science Plan to Measurements to Requirements.*

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 (≥ 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

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1. The Ocean's Biological Pump and the Global Carbon Cycle

Atmospheric levels of carbon dioxide (CO_2), an important greenhouse gas that modulates Earth's radiative balance and climate, have increased from a preindustrial value of 280 ppm to ~ 400 ppm at present (equivalent to an increase of ~240 Pg of carbon; 1 Pg = 10^{15}g = 1 Gt). Anthropogenic emissions via fossil fuel burning, land use change and cement manufacturing release ~9 Pg C y^{-1} in the form of CO_2 to the atmosphere. About half of the anthropogenic CO_2 released over the last two decades remains in the atmosphere while nearly 30% of the anthropogenic CO_2 emissions (2.5 ± 0.5 Pg C y^{-1}) have been taken up by the ocean over the last decade (Le Quéré et al., 2013). Thus, the ocean carbon cycle is a central component of the global climate system through its regulation of the uptake, storage, and release of CO_2 (and other climate relevant chemical species) to the atmosphere on annual to millennial time-scales (e.g., Falkowski et al. 2000; Fung et al. 2005).

Uptake and storage of CO_2 within the ocean are governed by the fundamental laws of physics, chemistry and biology (e.g., Sigman and Boyle, 2000; Sarmiento and Gruber, 2002). For example, the "solubility pump" refers to the uptake and transfer of CO_2 into the deep ocean as the result of deep water formation at high latitudes (evaporative cooling causes surface waters to increase in density and sink into the interior) and is the primary pathway by which the ocean absorbs anthropogenic CO_2 on time scales of ocean mixing (decades to millennia). The "biological pump" is the suite of biologically mediated processes responsible for transporting carbon against an inorganic carbon gradient from the upper ocean to depth (Figure 1). The biological pump includes processes that vary on daily to interannual time scales such as the export of organic and inorganic carbon via gravitational settling of particles, plankton and aggregates, diffusive and convective mixing of suspended particulate and dissolved organic carbon (POC & DOC), and active biological transport of organic and inorganic carbon derived from zooplankton daily migrations to depth.

Anthropogenic perturbations disturb the natural carbon cycle, altering the structure and function of marine ecosystems as well as the chemistry and circulation of the oceans (e.g., Sarmiento et al. 1998; Falkowski et al. 1998; Joos et al. 1999; Doney et al. 2012). These perturbations can impact the vertical gradient in inorganic carbon in the ocean, which in turn sets the magnitude and time scale of the ocean carbon sink. Approximately two-thirds of the vertical gradient in inorganic carbon can be attributed to the biological pump. However, estimates of the relative activity of the different pumps are poorly constrained (Sarmiento & Gruber 2002; Reid et al. 2009) and the range of uncertainties in global carbon export estimates is as large as the annual anthropogenic CO_2 emission rate (e.g., Henson et al. 2011; Siegel et al. 2014). Clearly a predictive understanding of the ocean carbon cycle and its response to human-induced stressors is critical.

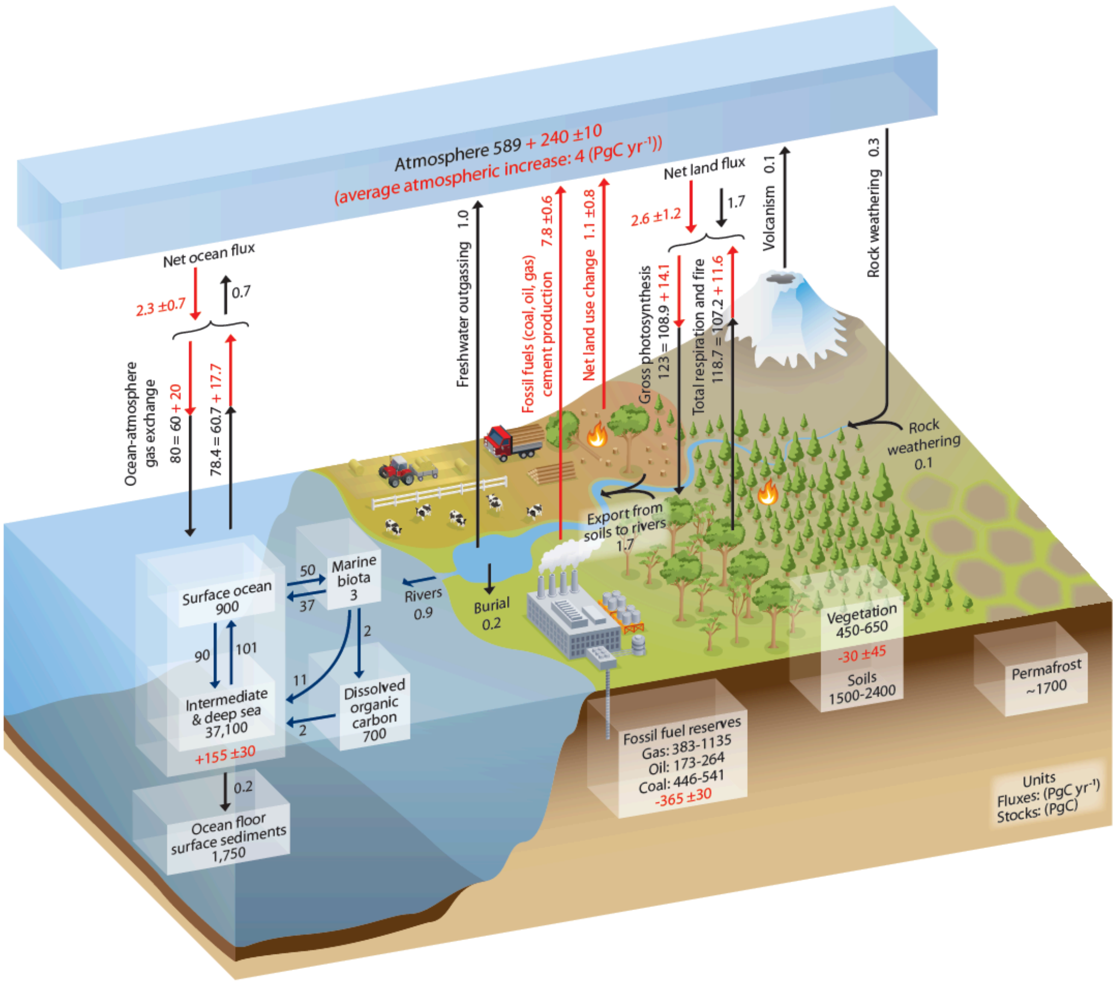

Figure 1 *The global carbon budget with black arrows and values reflecting the natural carbon cycle and red the anthropogenic perturbation (one billion metric tons of carbon or a Gt C is equivalent to 1 Pg C). In this depiction of the global carbon budget, the biological pump connects the stocks of "Marine biota" with the "Intermediate and deep sea" and "Dissolved Organic Carbon". Figure is from the 2013 IPCC report (AR5; Ciais et al. 2013).*

A predictive knowledge of the biological pump is important societally for many reasons including determining anthropogenic carbon sequestration, monitoring ocean deoxygenation and predicting the impacts of ocean acidification as well as future fisheries yields (e.g., Doney et al. 2009; 2012; Cheung et al. 2010; Keeling et al. 2010). The need for intensive research of the ocean's biological pump is well documented. For example, the white paper from the Ocean Carbon and Climate Change committee (OCCC, 2003) provided an implementation strategy for understanding the carbon cycle research for the United States' science agencies. This white paper delineated the types of investigations required to gain the required understanding of the physical and biological pumps. Similar national and international plan documents calling for research on the ocean carbon cycle are available (Ocean Carbon Transport, Exchanges and Transformations- OCTET; Ecological Determinants of the Ocean Carbon Cycle- EDOCC, Basin-scale Analysis, Synthesis, and INtegration- BASIN, etc.). Very few of these plans have been implemented into the programs they were intended to be. Hence, EXPORTS is responding to documented national and international needs and provides a new and globally important focus for satellite ocean color science.

EXPORTS (EXport Processes in the Ocean and from RemoTe Sensing) is a proposed NASA Field Campaign designed to quantify present and future states of the biological pump from satellite remote sensing, field observations and numerical models. Field observations of different states of the biological pump will be used to develop a mechanistic level understanding of how changes to planktonic ecosystems affect carbon transfer out of the well-lit surface ocean and the efficiency of its vertical transfer to depth. The underlying hypothesis is that the global ocean's biological pump can be quantified by observing the characteristics of surface ocean ecosystems as are measured by satellite ocean color instrumentation. Our understanding of these characteristics and the processes that control them allow predictions of oceanic carbon uptake and storage via the biological pump to be made on regional to global scales for contemporary and future oceans.

EXPORTS will address fundamental science questions relating the characteristics of plankton communities in the sunlit surface ocean to 1) the vertical transfer of carbon from the surface ocean to deeper waters, 2) the processes regulating the fate of exported carbon below the surface ocean, 3) the ability to extend this process-level understanding to predictions of the biological pump on global scales using NASA satellite observations, and 4) reduce uncertainties in contemporary and future estimates and models of the biological pump. The vertical transport of particulate and dissolved organic carbon from the surface ocean to depth we will refer to here as the ***magnitude of the biological pump*** while the fraction of the net primary production that is exported from the surface ocean and the vertical attenuation of flux with depth are both good measures of its ***efficiency***. Together we refer to the magnitude and efficiency of the biological pump as its ***state***. ***The satellite-based quantification and numerical model prediction of the state of the biological pump is the focus of EXPORTS***.

In the well-lit surface ocean, the characteristics of the plankton community have important controls on the rate of phytoplankton net primary production (NPP) and the efficiency by which this fixed carbon is exported from the surface ocean to depth. Much of the export of fixed carbon is by sinking particles and aggregates that gravitationally settle from the well-lit surface ocean. It is thought that the larger the phytoplankton that dominate the planktonic community, the more efficiently this fixed organic carbon is converted into exported carbon (e.g., Boyd and Newton, 1995; Boyd and Trull, 2007; Guidi et al. 2009; Siegel et al. 2014). Sinking particles transport not only organic carbon, but also inorganic carbon as biogenic mineral ballast that can influence the settling speed of particles (e.g. Ittekkot, 1993; Armstrong et al., 2001; De La Rocha and Passow, 2007). However, sinking particles are not the only process by which carbon is exported from the surface ocean via ecosystem processes. Others include its vertical transport by physical advection and mixing of labile and semi-labile suspended POC and DOC, and the daily vertical migration of zooplankton that consume organic carbon in the surface ocean and subsequently respire and egest it several 100's of meters below (e.g., Marra et al., 1995; Steinberg et al. 2000; Hansell et al. 2009; Buesseler and Boyd, 2009; Bianchi et al, 2013; Emerson, 2014).

The vertical attenuation of the exported carbon flux beneath the euphotic zone is also an important characteristic of the biological pump. Roughly 90% of the organic carbon exported from the surface ocean is remineralized in the mesopelagic or twilight zone (approximately 100 to 1000 m). The mesopelagic corresponds to the thermocline throughout much of the world's ocean and is ventilated on time scales of seasons to centuries. EXPORTS will focus on carbon fixation and export on these important sequestration time scales, rather than seafloor burial or millennial time scales. This vertical attenuation is key to these sequestration time scales because organic carbon remineralized deeper in the water column will typically remain sequestered from the atmosphere longer than carbon that is regenerated at shallower depths. All other factors held constant, the larger the fraction of carbon exported from the surface layer that survives transport to the deep sea, the lower the CO_2 content of the atmosphere. A complex array of physical and biological processes within the mesopelagic zone influence the efficiency of organic carbon regeneration. The sensitivity of these processes to changes in environmental conditions represents a major source of feedback to climate change.

Not surprisingly, significant effort and resources have been invested over the past few decades in understanding the processes that control the magnitude and efficiency of the biological pump (see reviews by Boyd and Trull, 2007; Buesseler and Boyd, 2009; Burd et al., 2010). While progress has been made on developing an understanding of the underlying processes, present predictive capabilities have lagged behind. For example, published ranges for the global export of POC from the surface ocean on sinking particles ranges from ~4 to > 12 Pg y^{-1} (e.g., Boyd and Trull, 2007; Henson et al. 2011). This range of global export estimates is roughly equal to present-day fossil fuel emission rates. Furthermore, our knowledge of the spatial and temporal patterns in global carbon export from the surface ocean is considerably less certain (e.g., Siegel et al. 2014). The EXPORTS field campaign is unique in its attempt to constrain all of the major biological pump pathways so that predictive satellite and numerical models can be built and tested.

Uncertainties in quantifying the rate at which the export flux decreases with depth below the surface ocean are even greater, as the field has not progressed beyond the so-called "Martin curve" established in the late 1980's (Martin et al. 1987). A predictive understanding of vertical export flux attenuation within the ocean interior is critical for assessing sequestration time scales for the biological pump and the air-sea partitioning of CO_2 (e.g., Kwon et al. 2009; DeVries et al. 2012). Yet while we now know that the shape of the flux attenuation curve is highly variable (Buesseler et al., 2007; Burd and Jackson, 2009; Henson et al. 2012; Estapa et al. 2013; Giering et al. 2014), the Martin curve estimates remain the backbone of most large-scale coupled ocean biogeochemical, circulation, and ecosystem modeling systems (e.g., Friedlingstein et al. 2006).

The response of the biological pump to the many consequences of climate change is largely unknown and currently even the sign of its change is unknown. EXPORTS will observe and model the biological pump's pathways from an extensive field program with the goals of improving our ability to monitor globally the state of the ocean's biological pump from satellite (and potentially field) observations and to predict its future states using numerical models. EXPORTS will observe a range of states of the biological pump from which satellite and numerical models can be built and tested. Thus, the EXPORTS experimental plan is modular enabling the number of observed states to be expanded or reduced depending upon resources as well as contributions from collaborative field programs and the data mining from previous results. In all, EXPORTS' modular approach will provide a wide range of variability in field observations of the biological pump's pathways that will be used to reduce uncertainties in its predictive understanding from satellite observations and numerical models.

The EXPORTS field campaign as planned here will begin in 2017. The initial efforts will be made in developing and testing numerical models for cruise planning and data mining previous results to expand the possible range of states of the biological pump available. The EXPORTS field component will conduct four major cruise deployments in two field years; the first year in the NE Pacific and second year of sampling in the NE Atlantic. The sites are chosen based on their likelihood to represent a range of contrasting states of the biological pump (see following sections). Before the major ship-based cruises, a well-instrumented mixed layer float, medium duration gliders, and an array of long-term profiling floats will be launched. During the main field operations, a two-ship sampling program is required. The "Lagrangian" (or process) ship will focus on rate determinations of dissolved and particulate pools of organic matter while a "Spatial" (or survey) ship will sample mesoscale and submesoscale biogeochemical and physical fields around the Lagrangian ship as well as supporting important flux measurements. The ship-based sampling will be supported by the deployment of array of autonomous assets that will provide resolution of properties and processes from local (km's) to regional (100's km's) spatial scales and from synoptic (days) to interannual (years) time scales. Detailed bio-optical measurements will be made that ground truth and supplement the satellite observations. Finally, throughout the EXPORTS campaign, coupled numerical models will be efforts to improved and validated over a variety of space and time scales. By the end of the field program in 2021, EXPORTS will have contributed vastly to our predictive understanding of the biological pump on a wide variety of space and time scales, allowing for its critical role in the global carbon cycle to be quantified.

EXPORTS' observational focus is on quantifying the mechanisms controlling the pathways of the biological pump. Mechanistic observations are essential for building and testing satellite and numerical models of the biological pump that will be able to stand the tests of time. There are other ways to quantify the biological pump including geochemical constraints that assess the total net community production over annual time scales (e.g., Jenkins, 1998; Riser and Johnson, 2008; Stanley et al. 2012; Quay et al. 2012; Emerson, 2014). The EXPORTS experimental plan includes multi-year Bio-ARGO profiles of O_2 and NO_3 that will be used to provide geochemical constraints that will be intercompared with mechanistic approaches focused on pump pathways. Thus, EXPORTS will embrace multiple observational approaches for constraining the ocean's biological pump.

Many new methodologies and approaches were developed in the last decade that can be applied for understanding ocean carbon cycling. In particular, we learned much about the upper ocean carbon cycling and the regional and seasonal variability in the export of organic matter from the surface ocean during the Joint Global Ocean Flux Study (JGOFS) program conducted from 1987 to 2003. However, JGOFS focused on the major ocean basins and were not conducted with a predictive goal in mind. Hence, the linking between the JGOFS process studies happened in a post hoc fashion, poorly resolving the relationships between sites and processes.

There have been many conceptual advances since the start of the JGOFS program in the late-1980's. We now know that a host of processes regulate the vertical attenuation of export flux below the surface ocean including zooplankton grazing, microbial degradation, mineral ballasting, organic carbon solubilization, vertical migration active transport, and aggregate fragmentation and reaggregation. We also now understand that the biological pump requires us to think beyond the black boxes for carbon stocks used in highly simplified P-Z-N-B-D models. Plankton community structure, DOC quality and the composition of the bacterial assemblage all are known to have important roles in the transformation of organic matter as part of the biological pump. Lastly, during JGOFS, little was known about the biogeochemical roles that submesoscale physical processes play in the biological pump. Thus there are many conceptual advances that make it ripe to conduct EXPORTS now.

Since JGOFS, significant advances have also been made in technologies to sample the ocean. This includes the development of in situ autonomous gliders, floats and other autonomous underwater vehicles (AUV's) as well genomic and video imaging tools for characterizing the structure and function of plankton populations. During JGOFS, quantitative satellite ocean color remote sensing was in its infancy, and many advances were made over the past decade in the use of satellite observations to constrain ocean biogeochemical rates and stocks. Further huge advancements have been made in marine bio-optics, and field measurements of inherent optical properties (IOP's) and remote sensing reflectance spectra have now become routine- making the link between field observations of ocean biogeochemical cycles and satellite ocean color remote sensing products possible. Using these new tools as part of carefully planned field studies, EXPORTS is designed to link the newly obtained field results with prior data to build a robust model with predictive strength on regional to global scales.

EXPORTS also contributes to NASA's upcoming advanced ocean color satellite mission; the Pre-Aerosol Cloud and Ecosystems (PACE) mission, which is scheduled to launch in 2020. PACE is designed to advance the quality, accuracy and breadth of satellite ocean color data products. Among the novel data products that PACE will retrieve are physiologically-based assessments of net primary production, phytoplankton carbon concentrations, particle-size distribution and phytoplankton community composition which are all key elements of the biological pump. Initial approaches for many of these retrievals have been made from existing satellite ocean color observations (see Section 3). The PACE mission is planned to have many on-orbit characteristics that will improve upon these retrievals as well as providing the in situ data which presently is lacking to build and improve these satellite algorithms. Importantly one of the stated goals for the PACE mission is to quantify the global ocean's carbon cycle, including the biological pump. The EXPORTS field campaign aims to provide field validated carbon cycle algorithms for application to the PACE mission – helping to achieve PACE's carbon cycle goal.

Lastly, EXPORTS will help train the next generation of highly interdisciplinary ocean scientists who will become the monitors and caretakers of our global oceans. Predicting the state of the biological pump is among the hardest problems in the Earth sciences, because it requires an understanding of ocean ecology, chemistry, physics and as well as the ability to retrieve these processes from satellite observations and to model them numerically. The multi-disciplinary, multi-tooled design of EXPORTS will require scientists that understand both the complex interactions of the physical ocean with the biogeochemistry and ecology of the sea as well as how to integrate observations across ship, autonomous and satellite platforms and a suite of numerical models of the ocean's biological pump. Involving the next generation of marine scientists as contributors to the EXPORTS field campaign will be essential. An important challenge of EXPORTS will be to train and mentor these new, young scientists with a broad yet deep understanding of the ocean, the processes regulating the biological pump, and the multi-scale tools that are required to assess it.

2. The Biological Pump and Oceanic Food Webs

Phytoplankton production of organic matter is driven by photosynthesis, and the growth of phytoplankton stocks is constrained to the well-lit surface waters where it is detectable from space. However, remineralization, which oxidizes organic matter back to CO_2 and inorganic nutrients, occurs throughout the water column, much of which is beyond detection from space. The biological pump is therefore the mechanism that spatially separates the biological production of organic and inorganic carbon in the surface from its remineralization throughout the water column. Because only some of the processes that are key to the biological pump can be remotely sensed, its global quantification requires the merging of satellite, field and model data. This complement of technologies is the core of EXPORTS.

The efficiency of the biological pump is driven primarily by the imbalance between production and respiration processes over time and space. As some measures of the biological pump's efficiency increase, so does the physical separation between organic matter production and its subsequent remineralization (i.e., the greater the remineralization length scale). The structure and functioning of the ocean's ecosystem plays an important role in determining the efficiency of the biological pump and thus the magnitude of fixed carbon exported from surface waters. Still lacking is a mechanistic understanding of how food web structure affects the partitioning of organic matter between particulate (sinking organic matter) and dissolved or suspended particulate organic matter, and how that affects the magnitude and efficiency of export.

The structure and function of pelagic food webs are key determinants of elemental cycles, playing a major role in the transformation and partitioning of carbon among the various particulate and dissolved organic and inorganic oceanic carbon reservoirs (Figure 2). First, dissolved inorganic carbon (DIC) is photosynthetically fixed into 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 macro-zooplankton that respire much of the ingested organic matter back into DIC or released as DOC. A fraction 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. Zooplankton also contribute to export through their diurnal migration from the EZ to several 100 m's deeper into the twilight zone (TZ), where organic carbon consumed at the surface is subsequently metabolized (respired, excreted) (e.g., Steinberg et al. 2000; Bianchi et al. 2013). A host of remineralization processes driven by bacteria and zooplankton recycle suspended POC and dissolved organic carbon (DOC) (e.g., Steinberg et al. 2008; Burd et al. 2009; Giering et al. 2014). An illustration of these pathways is shown in figure 2.

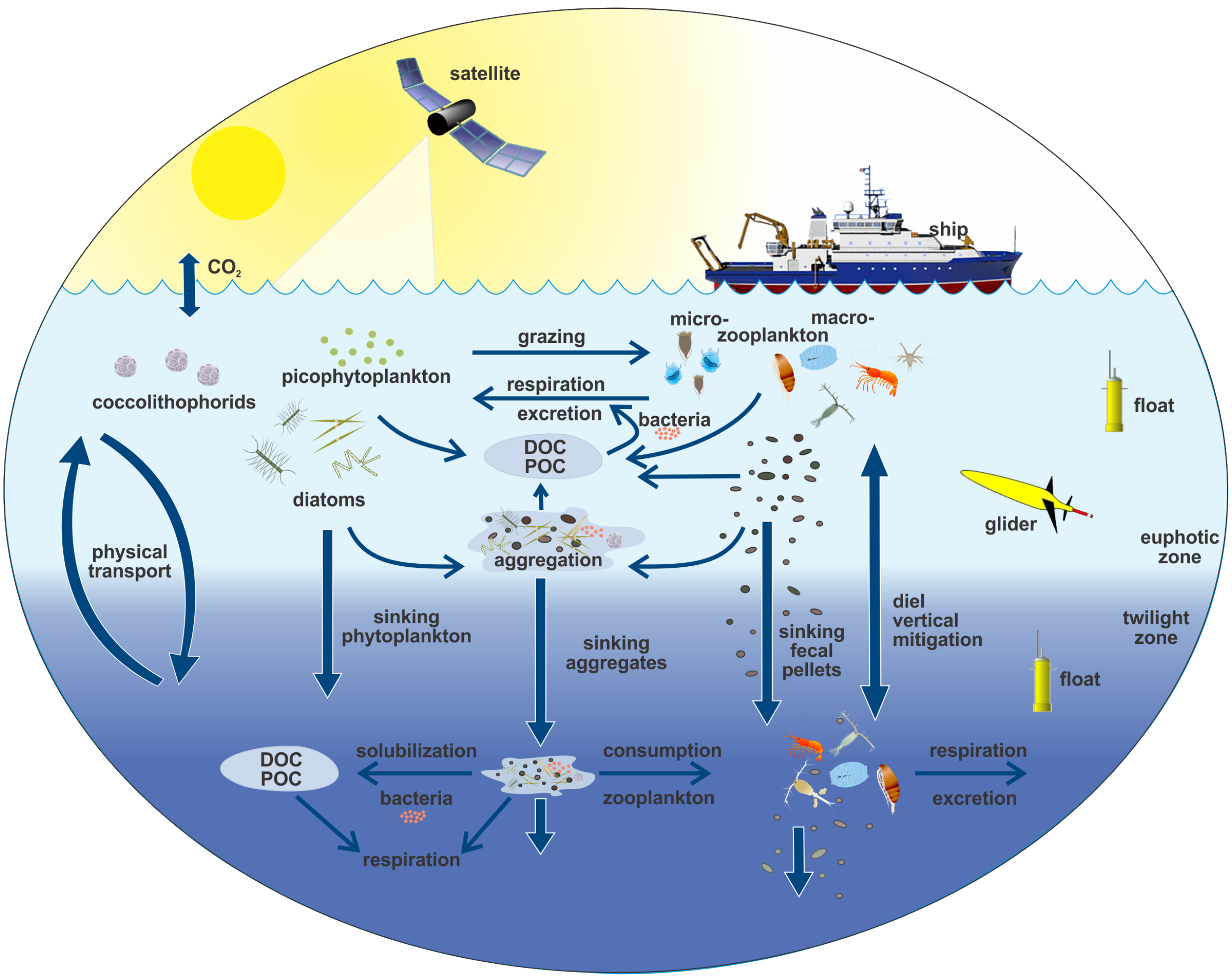

Figure 2 *Illustration of the links among the ocean's biological pump and pelagic food web and our ability to sample these components from ships, satellites and autonomous vehicles. Light blue waters are the euphotic zone (EZ), while the darker blue waters represent the twilight zone (TZ). Figure is adapted from Steinberg (in press) and the U.S. Joint Global Ocean Flux Study (http://usjgofs.whoi.edu/images/biological_pump.tif).*

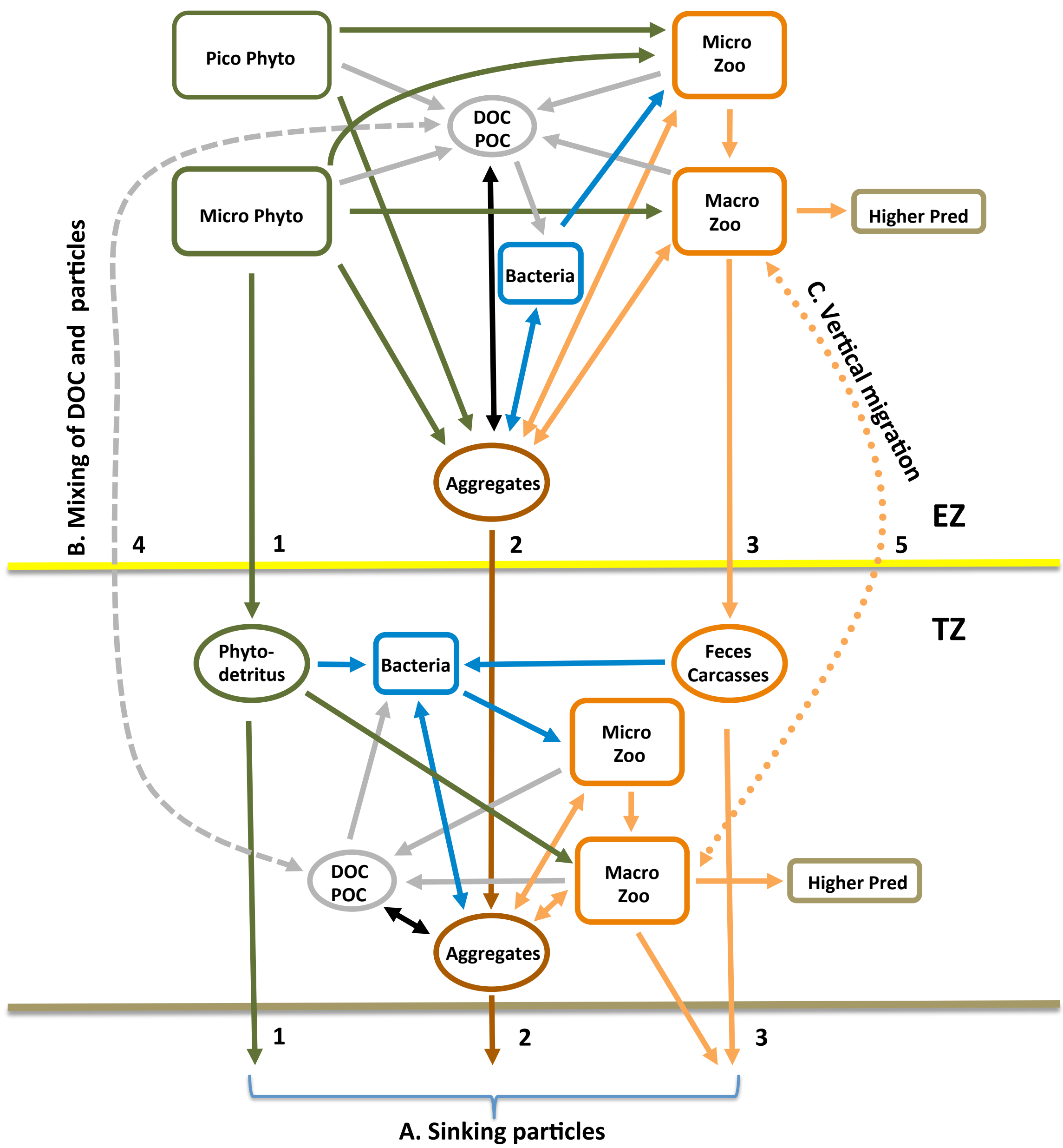

Figure 3 *The EXPORTS wiring diagram illustrating the C flows from the euphotic zone (EZ) into the twilight zone (TZ) in the biological pump. The flow of C through the biological pump is comprised of A) sinking particles, B) the advective mixing of DOC and suspended C stocks and C) active transport via migrating zooplankton. The text describes the five pathways that control the biological pump in more detail.*

Physical processes also affect the fate of accumulated carbon pools in the surface ocean. For example, the removal of suspended and dissolved fixed carbon from the ocean surface to its interior via seasonal convective mixing has been shown to be a potentially important contributor to the biological pump, representing ~20% of global carbon export (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 it is subsequently remineralized (e.g., Mahadevan et al. 2012; Lévy et al. 2012; 2013).

EXPORTS will focus on carbon flow via three classes of processes that constitute the biological pump (Figure 3). These are (1) export associated with gravitational settling of particles, (2) the vertical advection and mixing of organic carbon to depth and (3) the vertical migration of zooplankton and their predators.

The strength and efficiency of the biological pump can be related to a simple food web with 5 fundamental processes

1) Gravitational settling of phytoplankton as single cells or fragments of cells;
2) Sinking of aggregates comprising bacteria, phytoplankton, zooplankton and their byproducts;
3) Sinking of zooplankton byproducts and their carcasses;
4) Vertical advection and mixing of organic carbon to depth by physical oceanographic processes; and
5) Vertical transport of organic carbon due to the diurnal and/or life cycle migration of zooplankton and their predators.

The combination of these five fundamental vertical pathways quantifies the functioning of the biological pump.

The biological pump is conceptually modeled through a wiring diagram shown in Figure 3, which is partitioned into the euphotic zone (EZ-upper) and twilight zone/mesopelagic (TZ- lower). In Figure 3, squares represent living biota (phytoplankton, zooplankton and bacteria), circles represent stocks of non-living matter (POC, aggregates, fecal pellets, etc.), while arrows (one- and two-way) indicate carbon flow and key processes. Build up and physical processes carrying DOC and particles to the depth are confined on annual time scales to the depth of winter mixing, while active transport by zooplankton migrators often exceeds the depth of winter mixing depending upon local zooplankton species and physical conditions. It is important to note that aggregates can convert to the DOC/POC pool through physical aggregation and disaggregation (black arrows), and/or bacterially mediated processes (blue), and/or zooplankton feeding activities (orange arrows). Bacteria and viruses acting on living cells are not included in Figure 3 for simplicity. Plankton community composition (beyond size) is also omitted for simplicity from Figure 3 although it is recognized that community composition affects many processes including particle ballasting, grazing efficiency and many other food web processes.

The underlying hypothesis of EXPORTS is that changes in food web structure in the surface ocean that are observable using remote sensing (e.g., phytoplankton functional types, particle size spectra and carbon stocks), can be used to quantify the biological pump. EXPORTS will conduct field and modeling studies of different states of the biological pump, allowing us to quantify and predict the consequences of differences in planktonic ecosystem characteristics on the strength and efficiency of the ocean's biological carbon pump.

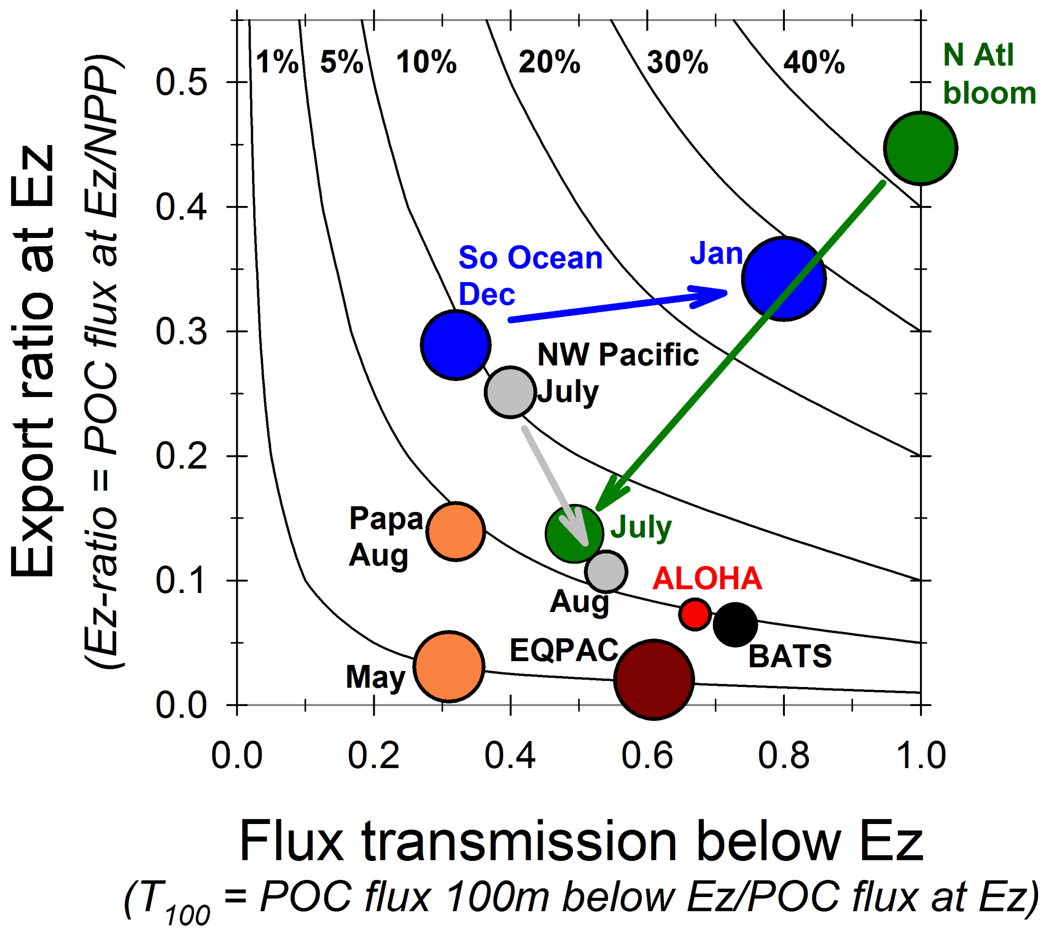

Figure 4 *Graphical depiction of the states of the biological pump. For each site and time, the ratio of NPP to POC flux at the depth of the euphotic zone (Y-axis) is compared to POC flux transmission through the first 100m below EZ (X-axis). The area of the circle is proportional to NPP (roughly 1000 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 differences are greatest in the biological pump efficiencies.*

EXPORTS will focus on observing contrasting states of the biological pump that can be used to monitor and predict the global ocean carbon cycle. There are many ways of doing this. Here we will define the state of the biological pump using two characteristics the export flux leaving the well-lit surface ocean and the vertical attenuation of that flux with depth. Again, we refer to the export flux from the EZ as a measure of the "strength" of the biological pump and its vertical attenuation as one measure of its "efficiency". One way to visualize the state differences is shown in Figure 4 (after Buesseler and Boyd, 2009). For each site and time, the strength of the biological pump is described by the ratio of NPP to POC flux at the base of the euphotic zone (Ez-ratio; Y-axis), and the transmission of C 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). Different states of the biological pump (i.e., the values of the Ez-ratio and T100) are likely related to seasonal or regional differences in the characteristics of the EZ and TZ plankton communities. When these metrics are plotted against each other they permit both regional and seasonal variability in the state of the biological pump to be clearly identified.

Two end-member sites for biological pump efficiencies are the North Atlantic spring bloom (strong and efficient pump; green circles in Figure 4) and the low-iron waters of the NE subarctic Pacific (weak and inefficient pump, orange circles). Both of these sites will be sampled in the EXPORTS experimental plan (See Section 6.2). During the North Atlantic spring bloom, about half of the NPP is exported out of the EZ and there is negligible POC attenuation in the first 100m below EZ. The net effect is an extremely strong and efficient biological pump with >40% of NPP found below EZ relative to NPP (see contour lines). This is consistent with work conducted during the JGOFS North Atlantic Bloom experiment (NABE) where Dam et al. (1993) found low mesozooplankton grazing (path 3 in Fig. 3) and most of the export could be attributed to the direct sinking of algal cells (path 1 in Fig. 3). By the summer at NABE however, the planktonic food web shifted, and <15% of the NPP is lost from the surface with about 50% POC flux attenuation in the first 100m below the euphotic zone. This is an example of a strongly seasonal biological pump.

At Station P in the NE Pacific (Papa in Fig. 4), we see a much lower biological pump efficiency, with EZ export ratios of <5 and up to 15% (May and Aug, respectively), and roughly 70% of the POC flux is attenuated within the first 100m below the EZ (orange circles, Fig. 4). The food web at Station P is dominated by small phytoplankton < 5 um (Boyd and Harrison, 1999) that are under tight grazer control (Landry et al., 1993). Hence, the processes that would lead to an efficient biological pump are not active. In addition, there are layers of particle-intercepting zooplankton just below the EZ (Dagg, 1993) that attenuate POC flux presumably through their grazing activities. Clearly conditions of high C fixation do not necessarily lead to high export when under such tight grazing controls.

For the other sites reviewed by Buesseler and Boyd (2009), a wide range of biological pump efficiencies are observed that are controlled by a variety of processes in the surface and subsurface layers. For example, in the NW Pacific there is a shift from high to low surface export efficiency at the end of a diatom bloom (grey circles in Figure 4). Another seasonal shift is seen from high to lower flux attenuation below EZ between December and January in the Southern Ocean (blue circles). This shift was postulated to be due to a decline in iron and increased silicification, yielding higher sinking rates at the end of this ice edge diatom bloom (Landry et al, 2002; Buesseler et al. 2003). Finally, sites like ALOHA and the Equatorial Pacific show less seasonality and consistently low surface export ratios, but there is only relatively modest POC flux attenuation below the EZ. Such settings are characterized by smaller plankton and enhanced recycling of carbon within a deep euphotic zone.

EXPORTS will focus on the two contrasting conditions represented by the NE Atlantic and NE Pacific. At each location, observations will be conducted at different times of the year to characterize a range of biological pump states and quantify the processes responsible for significant changes in the biological pump. The experimental plan we are designing can be applied to other sites and conditions as we build a better quantitative understanding of the variability and uncertainties in our assessment of the biological pump, including the strengths and weaknesses of the tools and models we have to assess these conditions.

3. Observing the Biological Pump

EXPORTS hypothesizes that the combination of food web structure and its spatiotemporal variability set the state of the biological pump. That is, the *characteristics of the planktonic ecosystem* reflect the spatial and temporal variations of the distribution of plankton and the structure and functioning of the open ocean food web. It is likely that the structure of both the upper ocean food web and its spatial and temporal patterns will be important for quantifying and ultimately parameterizing the strength and efficiency of the biological pump.

What are the spatial and temporal scales of the biological pump? The pelagic food web is embedded in an ocean with physical scales from cm’s to 100’s m’s in the vertical and from 100’s of m’s to 100’s of km’s in the horizontal (e.g., Lévy et al. 2012; 2013). However, the relationship between biological and physical scales of variability is not simple. While variance in physical properties is dissipated at small scales by molecular processes, biological fields contain variance at both larger and smaller scales. At the larger spatial scales, biological and biogeochemical variability and patchiness is linked to physical processes (e.g. fronts and eddies), while at small scales process associated with the collective behaviors of individual organisms introduce variance (e.g., swarming of zooplankton, association of high productivity with small scale physical nutrient injections). Planktonic biological systems respond on time scales of days to weeks to secular physical or chemical perturbation (e.g. iron seeding experiments) while physics is strongly modulated on inertial and synoptic time scales.

The diverse components of open ocean food webs also introduce a wide range of observational issues. The sizes of marine organisms depicted in figure 3 range from about a micrometer for bacteria to more than several cm's for some of the larger zooplankton. Thus a wide variety of approaches are needed to sample a size range of more than 5 orders of magnitude over the required space and time scales. Typical abundances of these food web components range from 10^5 to 10^7 per ml for bacteria to less than 1 per m^3 for most zooplankton creating a range of spatial separations among organisms that span nearly 6 orders of magnitude (from 10's of micrometers to 10's of meters; Siegel, 1998). This will create observational challenges for making measurements of plankton stocks required to quantify the pathways controlling the state of the biological pump.

Ship-based sampling will be the backbone of the EXPORTS experimental plan as ships are the only platform where all of the pathways illustrated in figure 3 can be determined. Many of the biological pump's pathways can only be sampled using ships because seawater and particulate matter needs to be collected and analyzed in a laboratory setting. However ships are not useful observing tools for globally monitoring the state of the biological pump because they are both slow and expensive to operate. Global monitoring is best accomplished using satellite-based synoptic imaging or via the analysis of arrays of autonomous underwater vehicles such as the ARGO array. In particular, ship observations are essential for correctly interpreting autonomous bio-optical signals (e.g., Cetinić et al. 2012). In the following we will address what we can see from satellite observables and autonomous underwater vehicles as a step towards including these tools in the EXPORTS science plan.

What can we see from satellite observables? Over the past decade, there has been important progress in applying ocean color observations for use in a wide variety of data products. These include but are not limited to:

- Net primary production (NPP) rates (Longhurst et al. 1995; Behrenfeld and Falkowski, 1997; Behrenfeld et al. 2005; 2006; Westberry et al. 2008),
- Suspended POC concentrations (Stramski et al., 1999; 2008; Mishonov et al, 2003),
- Phytoplankton carbon biomass (Behrenfeld et al. 2005; Behrenfeld and Boss, 2006; Siegel et al. 2005; 2013; Dall'Olmo and Westberry, 2009; Brewin et al. 2012),
- Identification and quantification of phytoplankton functional type (e.g., Alvain et al. 2008; Nair et al. 2008; Bracher et al. 2009; Hirata et al. 2011),

- Determinations of the particle size spectrum and relative phytoplankton size (Ciotti and Bricaud, 2006; Kostadinov et al. 2009; 2010; Mouw and Yoder, 2010; Bricaud et al. 2012; Roy et al. 2013),
- Phytoplankton loss rates (the sum of the horizontal green arrows in figure 5; Behrenfeld, 2010; Behrenfeld et al. 2013; Siegel et al. 2014), and
- Rates of export flux from the EZ using satellite data (Laws et al. 2000; Henson et al. 2011; Siegel et al. 2014).

Also, satellite observations can quantify upper ocean particulate inorganic carbon (PIC) and particulate silica (opal) concentrations as well as dust deposition rates when satellite observations are assimilated into numerical models (e.g., Balch et al. 2005; Bracher et al. 2009; Mahowald et al. 2005). Both of these determinations should be useful for constraining the modeling of sinking aggregate ballast (e.g., Berelson, 2001; Armstrong et al. 2001).

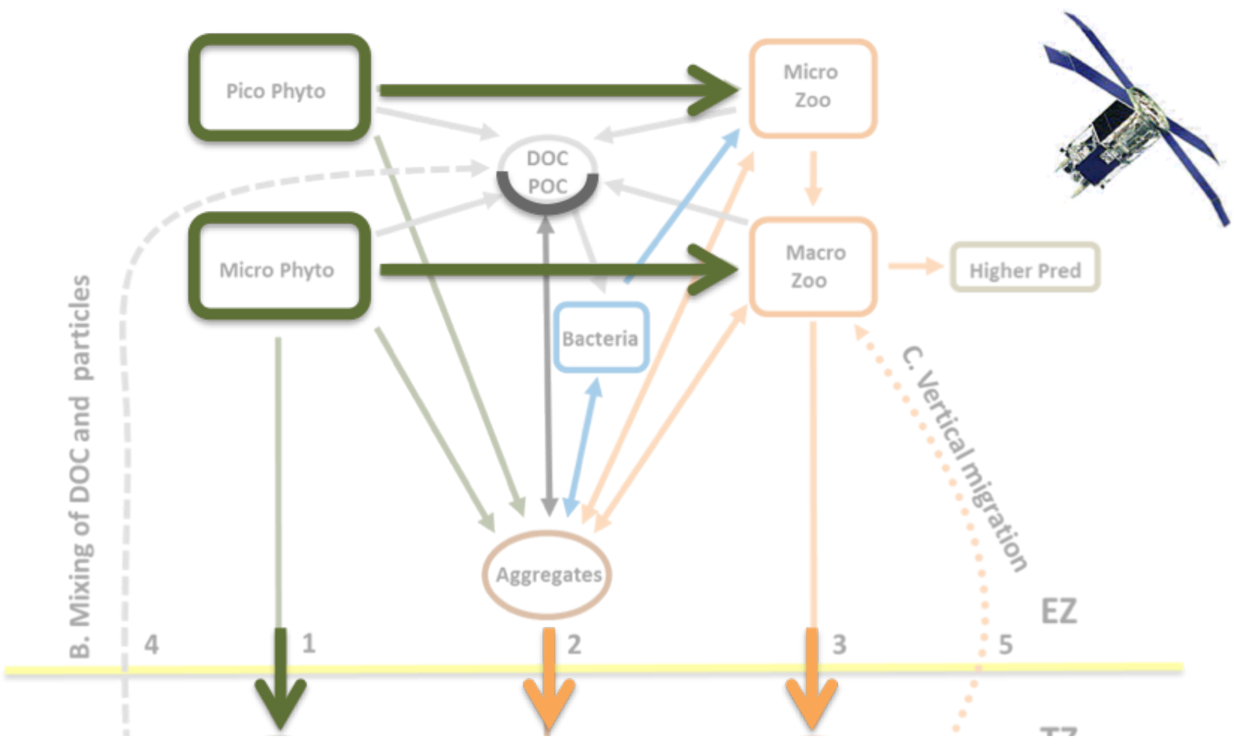

Figure 5 *Parts of the EXPORTS wiring diagram that can be assessed from satellite observation (in bold). Note that only the POC portion of the suspended DOC/POC pool can be estimated from satellite observations at this time outside of the terrestrially influenced coastal ocean.*

Even with this great deal of progress, satellites only resolve a limited subset of the food web components identified in the diagram above (Figure 5). This raises the question of how well the biological pump can be quantified knowing only a limited amount of information on the pathways that create flux.

What can we see from autonomous vehicles? Autonomous vehicles can sample at times and locations when and where research vessels are not available and provide a cost effective means to obtain certain properties for which low energy, stable sensors exist. In conjunction with ship-based observations, their measurements provide these properties in support of those done on the ships and, in addition, could be used to estimate spatial gradients in measured properties (e.g., constraining uncertainties in 1-D models).

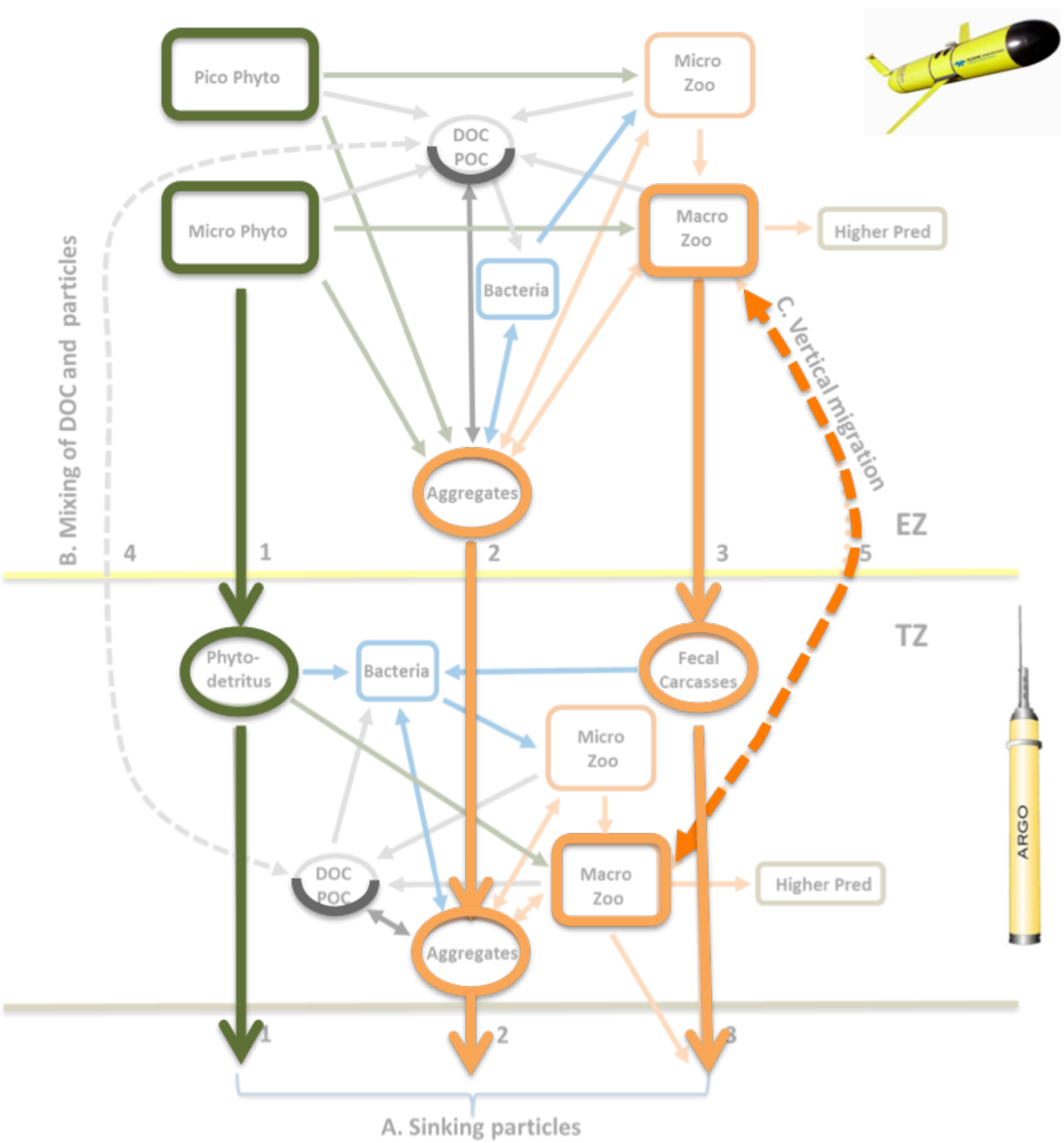

Figure 6 *Parts of the EXPORTS wiring diagram that can be assessed from autonomous sampling devices.*

Significant progress has been made in the last decade in autonomous platform technology (gliders, floats, and AUVs) both in terms of mission length and sensor suites. In addition to CTDs, sensors routinely measure irradiance, oxygen, nitrate, beam attenuation, optical backscatter, chlorophyll and CDOM fluorescence. Concentration estimates can be made by constructing proxies for phytoplankton pigments (Boss et al., 2008), POC (Bishop et al., 2002; Cetinic et al., 2012), PIC (Bishop and Wood, 2009), CDOM (Xing et al., 2012), and aggregates (Briggs et al., 2011) as well as estimates for mean phytoplankton and particle size (Briggs et al., 2013). Net primary productivity can be modeled from phytoplankton and light (Bagniewski et al., 2011), net community production (NCP) from temporal change in oxygen and nitrate (Riser and Johnson, 2008; Alkire et al., 2012) as well as proxies for particle export flux as functions of time and depth (Bishop et al. 2002; 2004; Martin et al. 2011; Estapa et al. 2013). By the time of the EXPORTS field campaign we expect that new approaches will be available to quantify macro-zooplankton abundances and type from autonomous platforms using both acoustic and optical imaging techniques based upon recent progress (e.g., Checkley et al., 2008; Sieracki et al., 2009; Picheral et al., 2009, Powell and Ohman, 2012). We expect that these newly developed techniques will provide measurements of mesozooplankton abundance and will help guide estimates of the zooplankton vertical migration and their effects. As pH sensors become more robust, they will also provide redundant estimates of carbon consumption in the twilight zone. An illustration of which pathways can be quantified by the autonomous assets is shown in Figure 6.

Autonomous platforms extend the vertical reach of satellites and extend both the spatial and temporal reach of ship measurements. Data from autonomous vehicles (e.g. the Argo array) are assimilated to models and have been used for process studies, for example linking upper ocean processes with the flux of particles to depth (e.g. Bishop et al., 2002, 2004, Briggs et al., 2011; Estapa et al. 2013). In turn, the optical variables measured need specialized attention as they provide proxies for biogeochemical variables. It is therefore important to constrain those proxies with in-situ measurements and to carefully cross-calibrate sensors on all platforms to ensure the best fidelity between in-situ measurements and the intended proxy.

What will EXPORTS do? Currently, data limitations prohibit progress on predicting the state of the biological pump from satellite observations. EXPORTS will provide a mechanistic assessment of the processes comprising the biological pump, elucidating the strengths of the various pathways that determine the state of the biological pump. Our inability to understand the underlying operations behind the biological pump's myriad pathways is in large part due to lack of a concentrated field campaign where food web, carbon cycle and bio-optical observations are made simultaneously on the relevant time and space scales. This field program with associated numerical modeling and satellite data analysis are the core elements of the EXPORTS field campaign.

EXPORTS aims to make improvements in remote sensing data products and autonomous sampling capabilities.

4. Objectives and Goal for EXPORTS

The objectives for EXPORTS field campaign are to…

- Conduct a field campaign that will provide critical information for quantifying the biological pump from satellite observations,
- Accomplish science that will greatly improve understanding, satellite monitoring and numerical prediction of upper ocean carbon cycle & the state of the biological pump on regional to global scales,
- Develop an efficient science and implementation plan that addresses the science questions by integrating field and satellite observations as well as numerical modeling, and
- Provide a path for global carbon cycle assessments for NASA's up-coming Pre-Aerosol-Clouds-Ecosystem (PACE) mission.

The goal of the EXPORTS field campaign is…

… to quantify & predict the consequences of ocean ecosystem characteristics on the state of the biological pump.

Assessment of the strength and efficiency of the ocean's biological carbon pump is important for many problems including understanding the roles of changes in marine ecosystems on atmospheric CO_2 levels and their feedbacks to the Earth's climate, as well as predicting the impacts of fossil fuel CO_2 emissions on marine ecosystems and biogeochemical cycles. Many of the characteristics of marine plankton communities are already changing in likely response to changes in the ocean's physical climate changes. A critical missing piece of information is the predictive understanding of the interactions between changes in the characteristics of pelagic ecosystems and the functioning of the ocean's biological pump. This is the goal of the EXPORTS program. These changes will impact fisheries through alterations in marine food webs and changes to geochemical conditions, such as ocean acidity and deoxygenation, which themselves affect ocean productivity and carbon sequestration. It should finally be noted that observing the functioning of the biological pump is central to the rationale for NASA's upcoming Pre-Aerosol, Clouds and Ecosystems (PACE) mission.

Now is the time to improve our predictive understanding of the biological pump. New remote sensing and in situ observing technologies have been developed that extend our observational capabilities beyond bulk measurements of a few surface ocean properties. Coupling these new observational capabilities with numerical models will enable us to move from local to global predictive understanding on how changing plankton ecosystems impact the functioning of the biological pump. The EXPORTS field program aims to links these approaches improving our abilities to quantify and predict the consequences of differences in planktonic ecosystem characteristics on the strength and efficiency of the ocean's biological carbon pump.

5. Science Questions

Our underlying hypothesis is that the global ocean's biological pump can be quantified by observing the characteristics of surface ocean ecosystems, thereby linking the biological pump to remotely sensible ecosystem properties. To test the hypothesis, we propose to address three fundamental science questions relating the characteristics of plankton communities in the well-lit surface ocean to 1) the vertical transfer of organic matter from the surface ocean, 2) the processes regulating the fates of exported organic matter below the surface ocean, and 3) the ability to extend this process-level understanding to improve predictions of the biological pump from regional to global scal*es.*

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

a. How does plankton community structure regulate the magnitude and efficiency of export of organic matter from the surface ocean?

b. How do the five pathways that drive export (cf., sinking of intact phytoplankton, aggregates or zooplankton byproducts, vertical submesoscale advection & active vertical migration) vary with plankton community structure?

c. What controls particle aggregation / disaggregation of exported organic matter and how are these controls influenced by plankton community composition?

d. How do physical and ecological processes act together to export organic matter from the surface ocean?

Why NASA?

- New remote sensing tools enable the diagnosis of phytoplankton community structure, particle size spectra, phytoplankton carbon and NPP on local to global scales that remain largely inaccessible from conventional sampling methodologies.
- Answers to Question 1 and its 4 sub-questions provide a path for estimating carbon export from the surface ocean using satellite observations including the up-coming PACE mission.
- Answers to Question 1 and its 4 sub-questions also provide validation data that can be used to build the next generation of Earth system models that forecast future states of the biological pump and its role in the Earth's climate system (Question 3 below).

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

a. How does transfer efficiency of organic matter to depth vary among the five primary pathways for export?

b. How is the transfer efficiency of organic matter to depth related to plankton community structure in the well-lit surface ocean?

c. How do the abundance and composition of carrier materials in the surface ocean (cf., opal, dust, PIC) influence the transfer efficiency of organic matter to depth?

d. How does variability in environmental and/or ecosystem features define the relative importance of processes that regulate the transfer efficiency of organic matter to depth (i.e., zooplankton grazing, microbial degradation, organic C solubilization, vertical migration active transport, fragmentation & aggregation, convection and subduction)?

Why NASA?

- Quantification of temporal and spatial scales of sequestration of carbon exported from the surface ocean is important for many science and policy reasons.
- Answers to Science Question 2 and its 4 sub-questions provide a path for predicting rates of sequestration of carbon exported from the surface ocean using satellite observations (question 3 below).

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

a. *What are the key plankton ecosystem characteristics (cf., food-web structure and environmental variations) that are required to be observed to accurately model the biological pump?*

b. *How do these key planktonic ecosystem characteristics vary across states of the biological pump and can they be assessed knowing surface ocean processes alone?*

c. *Can the biological pump be accurately modeled from satellite-retrievable properties alone or will coincident in situ measurements be required?*

d. *How can the mechanistic understanding of contemporary export processes developed here be best used to improve predictions of the biological pump under future climate scenarios?*

Why NASA?

- The 2014 NASA Strategic Plan has one of its goals to "Advance our understanding of our home planet and improve the quality of life".
- Parameterizing the impacts of changing plankton characteristics on the strength and efficiency of the ocean's biological carbon pump is a missing piece in our understanding of the Earth as an evolving system.
- The remote quantification of the biological system supports NASA's upcoming Pre-Aerosol, Clouds and Ecosystems (PACE) mission.

The EXPORTS science plan will provide answers to these critically important questions for our science and for the nation. The next section (6) provides a description of this science plan. A narrative for how the science plan will deliver answers to the EXPORTS science questions is presented in section 7 below. Notional plans for implementation are provided in section 8 and 9 that follow.

6. Science Plan

6.1 High-Level Objectives

The EXPORTS field campaign is focused on resolving contrasting states of the biological pump. In essence, satellite-based methods and numerical models of the biological pump need to be developed over a range of conditions. This requires multiple observation phases each capturing different states of the biological pump. It is not important that these observations are made in a particular sequence such as bloom initiation, maturity, succession and demise. Rather we need discrete states of the biological pump to be observed so that satellite-based methods and numerical models of the biological pump can be developed and validated. This modular nature of the

EXPORTS science plan makes it easier to extend these analyses, as it is the number of complete states of the pump that is important for the modeling.

The EXPORTS field campaign will collect up to eight independent states of the biological pump (2 for each intensive field effort; see estimate below) to develop these models. We aim to supplement this relatively small number of states of the biological pump by conducting an intensive data-mining effort scouring the literature for additional examples from the past 30 years of oceanographic observations. The data for these additional states will not be as complete as the EXPORTS observational suite and will likely be missing some important variables or spatial/temporal scales of variability. However the data-mining exercise will enable us to expand the range of observations of states of the biological pump, which will be very useful for model building and testing.

For each ecosystem state we will conduct field campaigns to quantify the pathways that operate the biological pump (Figure 3) that are required to answer the EXPORTS science questions. This requires intense oceanographic cruises to measure export carbon flux partitioned into appropriate pathways as well as environmental variables needed to establish context. Detailed bio-optical measurements are also required for developing and testing ocean color remote sensing algorithms. Further, many of the autonomous sampling devices measure proxies versus direct measurements (cf., light scattering is used a proxy for particulate organic carbon). Thus the simultaneous observation of proxy and direct measurements are required.

Each cruise needs to be long enough to sample at depth the sinking particles that are earlier created and observed in the surface ocean. Assuming a nominal particle sinking rate of 50-100 m per day and a 500 m depth range needed to resolve export flux attenuation as a function of depth, an on-station duration of at least 5-10 days would be required. Accounting for the time required to sample the upper ocean conditions at the chosen site appropriately, a 10-15 day sampling time interval is needed for assessing a single state of the biological pump. This means that we should expect to observe at least two "states" of the biological pump during each month long field deployment.

The ocean is a turbulent environment. Both mesoscale (roughly 50 – 200 km) and submesoscale (1 – 50 km) oceanic flow structures (i.e., eddies, fronts, jets, meanders, etc.) can alter their character in a mere matter of days. Further Lagrangian (water-following) parcels can be transported several 10's of km in just a day. Hence, the sampling order needs to account for this source of variability. Multiscale sampling using biogeochemical proxies to sample submesoscales (floats, gliders, ship & satellite) on multiple scales from short to long-term (seasons) to observe changes in processes will be conducted, requiring both ships and autonomous platforms. Spatial observations from the submesoscale to the mesoscale are necessary. Two ships are required to cover both proper spatial scales and process work simultaneously.

The EXPORTS campaign will integrate numerical modeling from the beginning. In fact, observation system simulation experiments (OSSE) are an essential component of the experimental planning for the EXPORTS field campaign. The third set of EXPORTS science questions focuses on how the EXPORTS field campaign will advance our predictive understanding of contemporary and future states of the biological pump, which requires regional to global-scale models to answer. There are simply too many complex processes that can only be resolved with a numerical model. For example aggregation / disaggregation is one process where its end products (size distribution) will be measured but the detailed rate processes of aggregate formation and destruction are likely to be resolved with a model. Last, only a model can be used to forecast future states of the biological pump – a major outcome for EXPORTS.

EXPORTS must advance satellite-based capabilities for understanding the ocean's carbon cycle. First satellite observations will be needed to conduct and interpret the field program. Importantly EXPORTS observations must help the development and validation of advanced satellite ocean color algorithms for carbon cycle stocks and rates. This is particularly important for making the link between the EXPORTS field program and future NASA satellite missions such as the Pre-Aerosol Cloud and Ecosystems (PACE) advanced ocean color satellite mission. Although it clearly is desirable, it is not necessary to conduct EXPORTS simultaneously with the PACE (or other advanced ocean color mission) as long as all in situ measurements are linked to observations of remote sensing reflectance spectra. With these new and improved algorithms, the EXPORTS field results can be extrapolated to regional and global scales.

The experimental plan must also balance scientific returns with project efficiency, which includes cost as well as logistical complexity and risk, while still answering the stated scientific questions. Some of this will be through the development of a plan with identified de-scope and re-scope options which still optimize the scientific returns while enabling cost / complexity / risk options to be considered (see Section 8.7 below). Leveraging on-going programs and establishing new partners both nationally and internationally will be an integral component of project efficiency (Section 8.6). Again, the modular nature of the EXPORTS science plan makes this easier to achieve.

The EXPORTS field program will be a large national investment that requires a large-scale data management structure. This includes the documentation of all measurement protocols and uncertainties, the open publishing of the composite data products and a plan for the long-term management of the EXPORTS data set (see Sections 6.7 & 8.3).

6.2 Locating the Field Program

There is a continuum of states of the biological pump over the global ocean. Figure 4 attempts a two-dimensional illustration of this continuum and encompasses specific historical measurement programs that range from relatively stable, permanently-stratified sites (HOT, BATS), to an equatorial upwelling system (EQPAC), and to multiple high-latitude regions (Southern Ocean, Ocean Station P, North Atlantic bloom). The EXPORTS data mining activity will collect and synthesize previous field and satellite measurements spanning the ecosystem-export continuum depicted in Figure 4. Exploiting the modular nature of EXPORTS will help to make our results truly global.

The EXPORTS intensive field campaigns could be conducted in many locations. However resources are limited and our high-level objectives are addressed in the previous section (6.1). After much deliberation, it was concluded that EXPORTS should focus on two high-latitude ocean basins the eastern subarctic Pacific (noted NE Pacific in the following) and the subarctic Northeast Atlantic (NE Atlantic). Multiple criteria guided this selection of field measurement locations:

- Long-term monitoring programs have already been established at the BATS and HOT locations, providing ample data diversity and coverage for characterizing the end-member condition of stable oligotrophic systems.
- Highly advective sites are avoided with the goal of simplifying the experimental design. Sites that will not meet this criterion include western and eastern boundary currents as well as equatorial oceans and much of the coastal ocean. Marginal seas with complicated source-sink relationships will also be avoided.
- Temporal variability in low-latitude, open-ocean productive regions, such as the equatorial Pacific, is dominated by interannual cycles (e.g., El Niño/La Niña transitions) and is thus both less predictable for field campaign planning and requires a longer funding cycle to ensure capture of extreme export conditions. Spatial variability in these systems is also low, which reduces the diversity of conditions that can be characterized within a 1-month field campaign.
- While biogeochemically important, EXPORTS campaigns (involving deployment of autonomous platforms and coordinated measurements with two ships) in the Southern Ocean would be logistically challenging and expensive.
- High latitude sites poleward of 60^{o} latitude were not considered as there are frequently neither clear skies nor enough solar illumination to acquire satellite ocean color observations.
- The North Pacific and North Atlantic sites have a long history of oceanographic measurements and are current sites for long term in situ sensor systems (e.g., OOI sites at Station P and Irminger Sea, PAP, Line P, etc.), which provides a rich historical context and complementary measurements in support of EXPORTS. However, these past and present measurements provide an incomplete

characterization of ecosystem links to carbon export processes. Thus EXPORTS is critical for understanding carbon pathways in these important ecosystems and for the interpretation of historical and concurrent in situ measurements.

- The North Pacific and North Atlantic sites both exhibit strong seasonal cycles in plankton stocks. This spatial-temporal variability maximizes the diversity of biological pump states that can be characterized within a given basin by paired month-long campaigns separated in time by only a few months (e.g., spring and summer).

- While located within the same latitudinal band, ecosystem structure and dynamics and dominant carbon export pathways are highly divergent between the North Pacific and the North Atlantic sites (see Figure 7 below).

- The North Pacific and the North Atlantic sites are in close proximity to U.S. field support assets (laboratories, ships, etc.) providing major logistical and cost benefits to EXPORTS.

- There are substantial long-term international research interests in the North Pacific and the North Atlantic sites providing excellent opportunities for partnering.

- Northern high latitude ocean regions are anticipated to experience major physical and ecological changes in the coming century in response to altered climate forcing. Understanding the current functioning of these systems is critical for improving forecasts of their future roles in carbon sequestration-biogeochemistry and provision of goods and services to humanity.

The wiring diagram shown in Figure 3 represents a generic overview of carbon flow within and between the euphotic zone and the twilight zone. Within this construct, the dominance of particular carbon pathways differs significantly from one ocean system to the next, and even from one season to the next at a given location. This variability of carbon flows for the biological pump is exemplified by the chosen NE Pacific and the NE Atlantic sites.

The NE Pacific has long been recognized as a region with relatively stable mixed layer chlorophyll concentrations and a dampened annual cycle in mixed layer depth compared, for example, to the Southern Ocean and the North Atlantic. Ecologically, we also now recognize the NE Pacific as a region where low mixed layer iron concentrations (1) provide a physiological constraint on growth rates of dominant phytoplankton species and (2) impact phytoplankton community composition (in particular, limiting diatom abundances). The current view is that the NE Pacific phytoplankton assemblage at Station P is dominated by smaller species that have growth rates closely matched by grazing losses to microzooplankton. The NE Pacific is also characterized by a population of large copepods (primarily *Neocalanus plumchrus and N. cristatus)*, which overwinter in the mesopelagic zone. Eggs laid at depth by adults prior to the spring bloom hatch and develop through their larval stages, arriving at the surface in spring as near adults (an 'ontogenetic', or life-cycle vertical migration) and poised to graze larger phytoplankton and microzooplankton. This tightly coupled cycle of increase in primary production and grazing by micro- and macrozooplankton does not allow for significant buildup of phytoplankton biomass.

The annual phytoplankton cycle in the NE Atlantic contrasts strongly with the observed phytoplankton cycle at the NE Pacific Site. In the NE Atlantic, winter mixing depths can exceed 100's of meters. During this time, the phytoplankton assemblage is dominated by small species that, as springtime increases in growth rates occur, are closely cropped by microzooplankton grazing. Diatom concentrations in winter are exceedingly low in the NE Atlantic, but during the spring a succession of dominant species emerge and then subside again to background concentrations. This succession eventually culminates into the late-spring, early-summer bloom climax. The demise of the spring bloom is due to nutrient depletion, phytoplankton aggregation and sinking, and grazing. In contrast to the NE Pacific however, a large part of the NE Atlantic bloom may be ungrazed and sediment out as phytodetritus, due to weaker predator-prey coupling. The dominant macrozooplankton grazer here, the copepod *Calanus finmarchicus*, also undergoes a life-cycle vertical migration as does its counterpart in the NE Pacific, but also has a second generation in late summer in the surface waters. However, due to a number of factors, the zooplankton community is not able to control the spring diatom bloom (e.g., higher susceptibility to metabolic losses of this smaller copepod species, a lag in feeding activity of the second generation copepods as adults mate and lay eggs, higher phytoplankton growth rates in early spring in the warmer NE Atlantic waters vs. NE Pacific).

Following the bloom peak in the NE Atlantic, the phytoplankton community exhibits additional major shifts in composition. Exhaustion of surface nitrate and iron again favors dominance of smaller species during summer. An abundance of haptophytes is often observed following the spring bloom climax, with concentrations of suspended particulate inorganic carbon in the form of coccolithophores regionally reaching levels sufficient for easy detection by satellite ocean color sensors. As noted above, PIC from coccolithophores represent one form of ballasting material for exporting carbon to depth. In some regions and particular years of the NE North Pacific, a secondary fall peak in chlorophyll concentration may be observed (i.e., the 'fall bloom').

Satellite measurements provide a basin-scale view of the contrasting annual cycles of surface layer chlorophyll concentrations for the NE Pacific and the NE Atlantic sites that have been documented for decades at specific sites by field measurements. Average late spring/early summer chlorophyll concentrations shown in Figure 7A illustrate the much higher bloom levels achieved at the NE Atlantic site compared to the NE Pacific, while the 8-day resolution time-series shown in Figure 7B contrasts the NE Atlantic spring bloom chlorophyll peak with the temporally stable values in the NE Pacific location. Satellite retrievals of phytoplankton biomass (C_{phyto}) levels, however, have recently added additional insight on annual plankton cycles for these two regions. Late spring/early summer C_{phyto} values shown in Figure 7C exhibit far greater similarity between the two basins than suggested by chlorophyll concentrations (Figure 7A). Moreover, the 8-day resolution time-series for C_{phyto} (Figure 7D) suggests that the North Pacific site can experience annual blooms in phytoplankton biomass that rival regions of the North Atlantic Site, albeit with a slower rate of biomass accumulation and a late summer/early autumn peak. EXPORTS will make direct measurements of phytoplankton carbon biomass that are essential for improving satellite estimates of C_{phyto} (e.g., Graff et al. 2012; Martinez-Vicente et al. 2013).

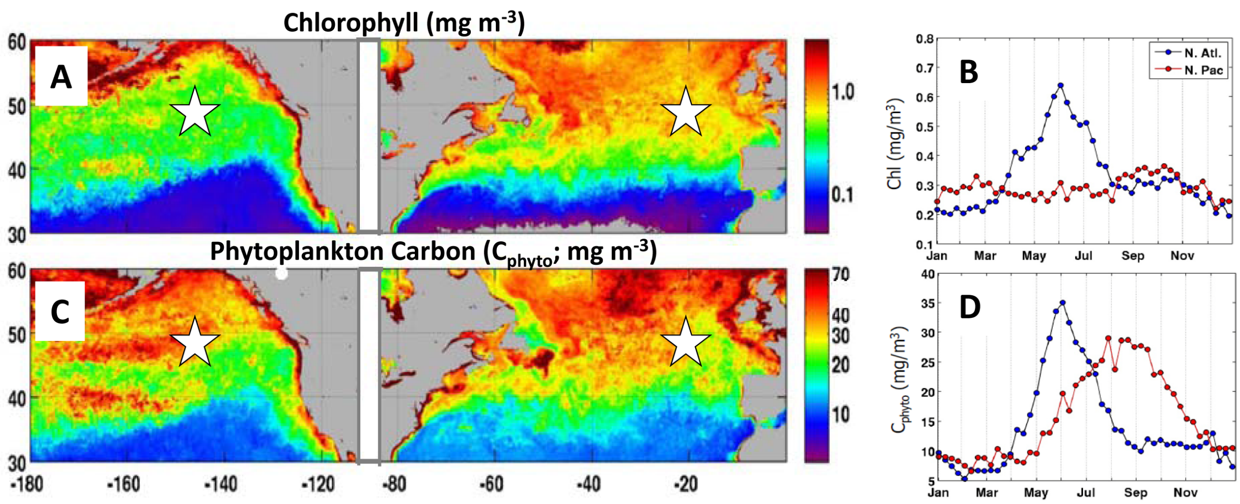

Figure 7 *Comparison of mixed layer chlorophyll and phytoplankton carbon concentrations between the eastern subarctic North Pacific and the subarctic North Atlantic sites. (A) Climatological average chlorophyll for May-July. (B) 8-day resolution mean chlorophyll time-series for the (blue) North Atlantic and (red) North Pacific locations identified by stars in panel A. (C) Climatological average phytoplankton carbon biomass (C_{phyto}) for May-July. (D) 8-day resolution mean C_{phyto} time series for the (blue) North Atlantic and (red) North Pacific locations identified by stars in panel A. All data are from the SeaWIFS mission (McClain, 2009; Siegel et al. 2013) and C_{phyto} values are estimated from particle backscattering coefficient satellite retrievals following Behrenfeld et al. [2005].*

Developments in open ocean trace metal studies and the availability of sustained, high quality satellite ocean color measurements have significantly advanced our understanding of subarctic plankton ecosystems over the past few decades. The NE Pacific is still viewed as a tightly coupled predator-prey ecosystem dominated by small phytoplankton species and microzooplankton, but temporal stability in mixed layer chlorophyll concentrations can now be viewed as reflecting light and iron stress driven spring-summer reductions in phytoplankton Chl:C ratios offsetting significant parallel increases in phytoplankton standing stocks (Figures 7C & 7D). Similarly, the NE Atlantic is also still recognized as the classic example of a springtime, diatom-dominated bloom, but the expression of this bloom in mixed layer chlorophyll concentrations also reflects springtime increases in phytoplankton biomass being accompanied by elevated Chl:C values associated with rapid division rates.

As illustrated in Figure 4, carbon export and flux attenuation below the euphotic zone in the NE Atlantic exhibits extreme variability over the annual cycle. For the NE Pacific location, the export ratio and flux attenuation are thought to be perpetually low (Figure 4). What are the mechanisms responsible for the divergent patterns between these systems? How will they change in the future? Notably, the differences in carbon export between the two sites occur despite similarities in the magnitude of annual phytoplankton peak concentrations (Figure 7D), suggesting the importance of top-down, zooplankton-mediated processes. This again highlights the importance of differing rates of change in stocks and contrasting community composition as fundamental drivers in export flux efficiencies.

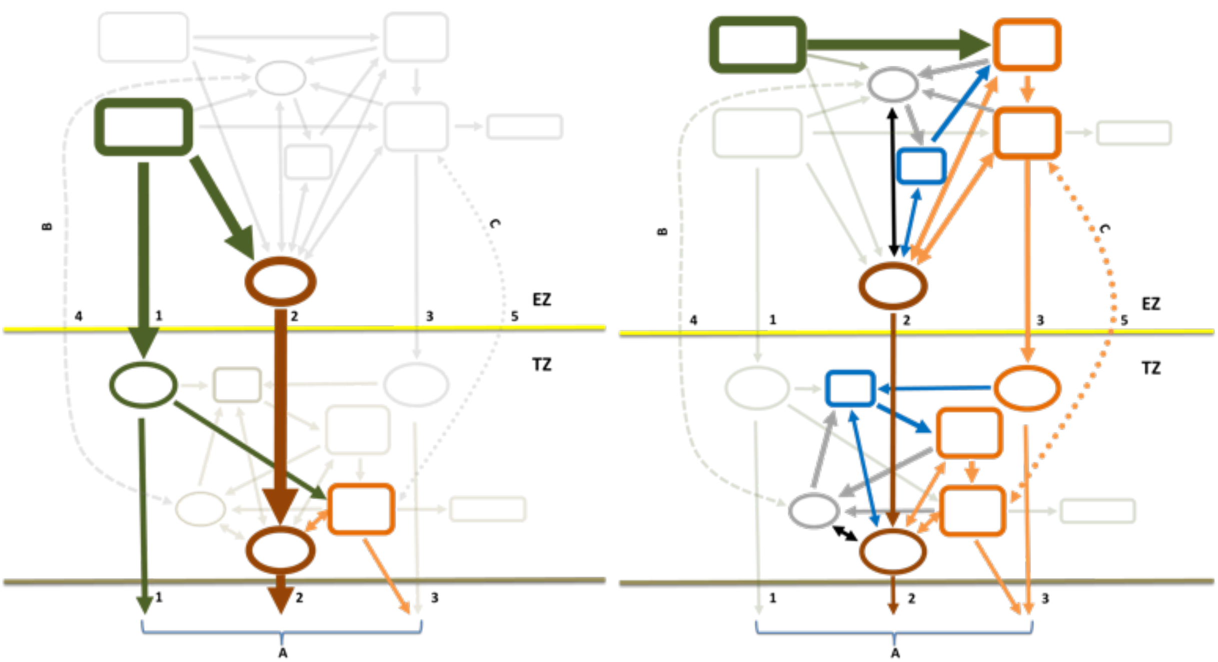

Figure 8 *Conceptual wiring diagrams for (left) the spring bloom in the North Atlantic and (right) summer conditions in the North Pacific. These figures follow the organization of the EXPORTS wiring diagram presented in figure 3.*

EXPORTS field campaigns target contrasting biological pump states during different seasons in both the NE Pacific and the NE Atlantic sites. As detailed below, a diversity of autonomous and ship-based measurements will be employed to characterize key carbon stocks and transformation rates. As a testable framework, a null hypothesis explaining differences between these two systems is summarized by the wiring diagrams in Figure 8. Here, the left hand diagram depicts a current view of carbon cycling in the NE Atlantic during the spring bloom that emphasizes rapid pathways for export associated with large phytoplankton. The right hand diagram summarizes the more complex food web dynamics thought to function in the NE Pacific during the summer and that result in diminished carbon export efficiencies.

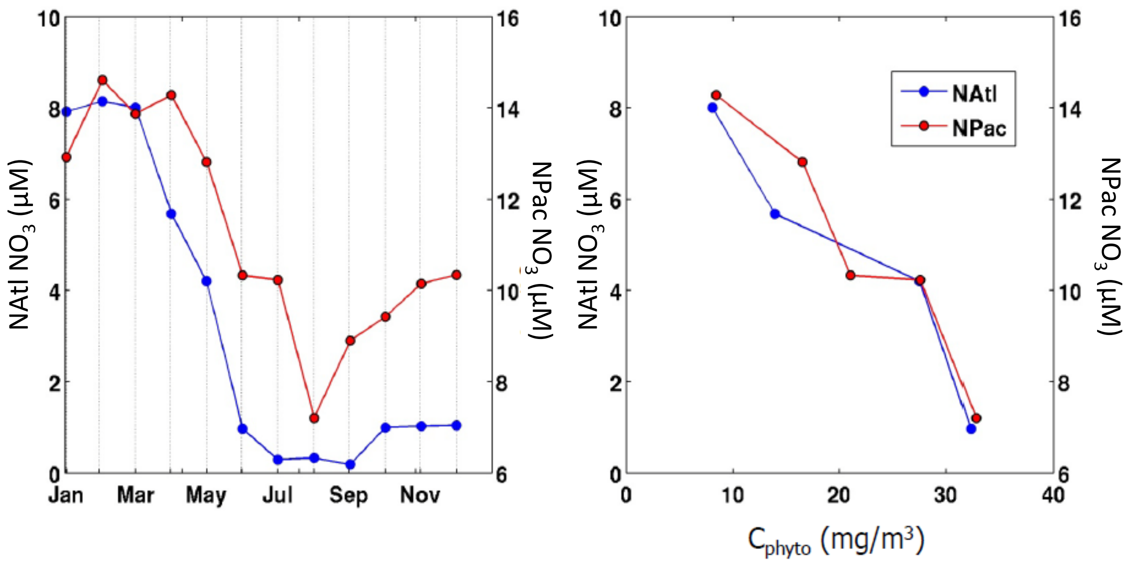

Figure 9. *Surface ocean nitrate drawdown in the (red) eastern Subarctic North Pacific and (blue) Subarctic North Atlantic locations. (A) Monthly nitrate concentrations from the World Ocean Atlas (left axis = North Atlantic and the right axis = North Pacific). (B) Nitrate concentrations during the seasonal phytoplankton bloom as a function of phytoplankton biomass (C_{phyto}).*

During each campaign, EXPORTS field measurements will quantify each linkage in the wiring diagram (Figure 3), not simply the dominant components anticipated for each system a priori (Figure 8). This end-to-end approach ensures consistent observations between system states, thereby informing model development and evaluation not only in terms of characterizing dominant processes correctly, but also accurately reflecting secondary carbon pathways that can be critical in other ocean regions.

With the EXPORTS observational approach, we anticipate that many new insights on system functioning will emerge. For example, Figure 9 shows the quantitative similarity in seasonal nitrate drawdown for the NE Pacific and the NE Atlantic sites. This loss of mixed layer nitrate should be reflective of net community production or carbon export, yet it is not immediately obvious how this apparent similarity in nitrate drawdown between the two sites is consistent with our current view of export processes and pathways illustrated in Figure 4 and Figure 8. The EXPORTS experimental plan also includes multi-year Bio-ARGO profiles of O_2 and NO_3 that will provide geochemical constraints on the proposed mechanistic approaches focused on pump pathways. Thus EXPORTS will enable a new synthesis of the biological pump using multiple observational approaches.

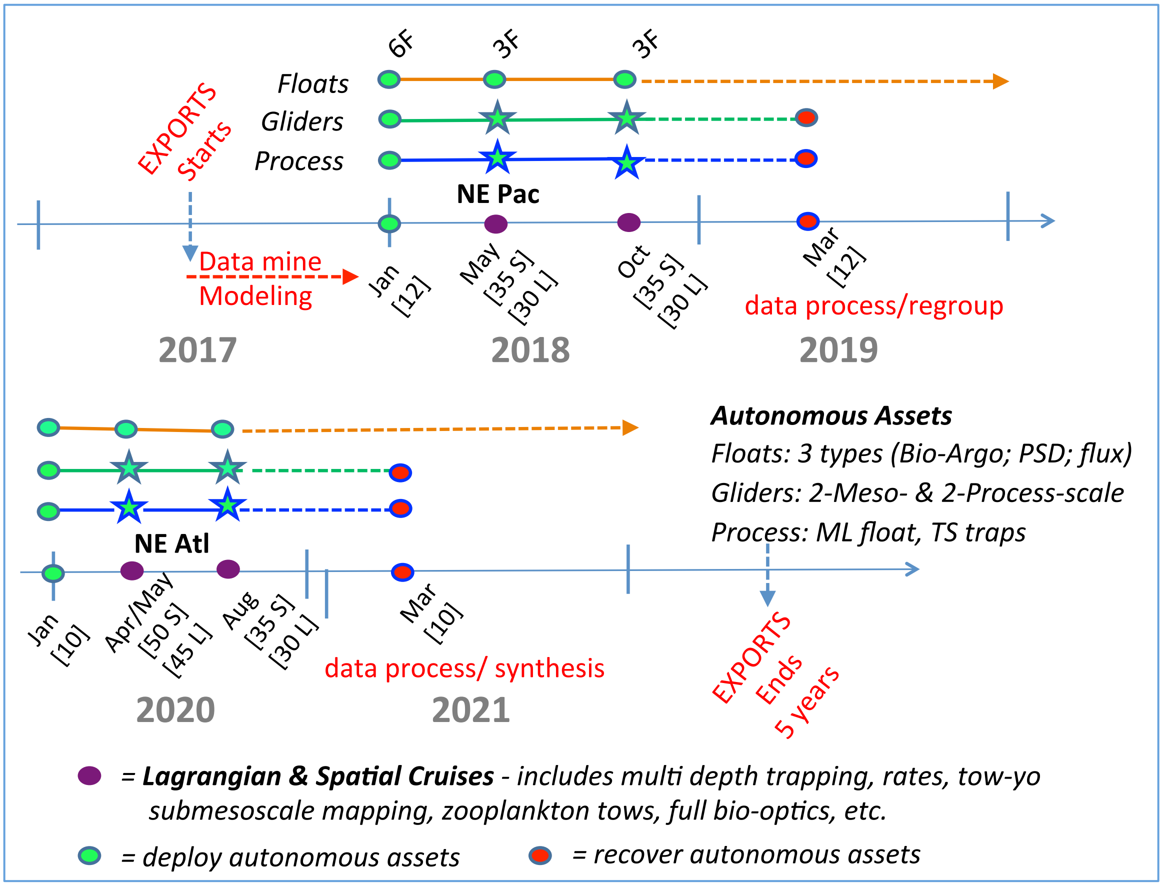

Figure 10 *Proposed time line for the EXPORTS field program. The 5-year field program starts in 2017 and ends in 2022. Two major field campaigns (stars) with two ships (S=spatial, L=Lagrangian) and a pre and post cruise deployment/retrieval cruise are planned for each the NE Pacific (2018) and the NE Atlantic (2020). Deployments of autonomous assets (F=floats and gliders) before and after the intensive field efforts are needed to provide a longer time baseline and resolve a wider range of spatial scales.*

6.3 Plan for Each Field EXPORTS Deployment

The field program of EXPORTS is designed to capture different states of the biological pump, which vary at any one site on a seasonal basis and differ between sites due to variations in physical forcing, the biogeochemical setting, and associated ecosystem responses. We have focused on the NE Pacific and NE Atlantic for scientific reasons (see Section 6.2) and because of the considerable effort that has gone already into studies at Station P in the NE Pacific and the NE Atlantic (OSP, PaP, NABE, NAB08, etc.). In addition, several ongoing programs are expected to continue at these sites, which will allow us to place our EXPORTS data from one field season in context of longer time-series. The continuing studies at Station P include among others, the global node for OOI (http://oceanobservatories.org/infrastructure/ooi-station-map/station-papa/) and seasonal sampling and long-term time series program at station P (Harrison, 2002). For the NE Atlantic, the UK continues to sample at the Porcupine Abyssal Plain (http://www.eurosites.info) and maintains regular time series moored trapping programs and cruises to the site (see Section 8.6 Potential Partnerships).

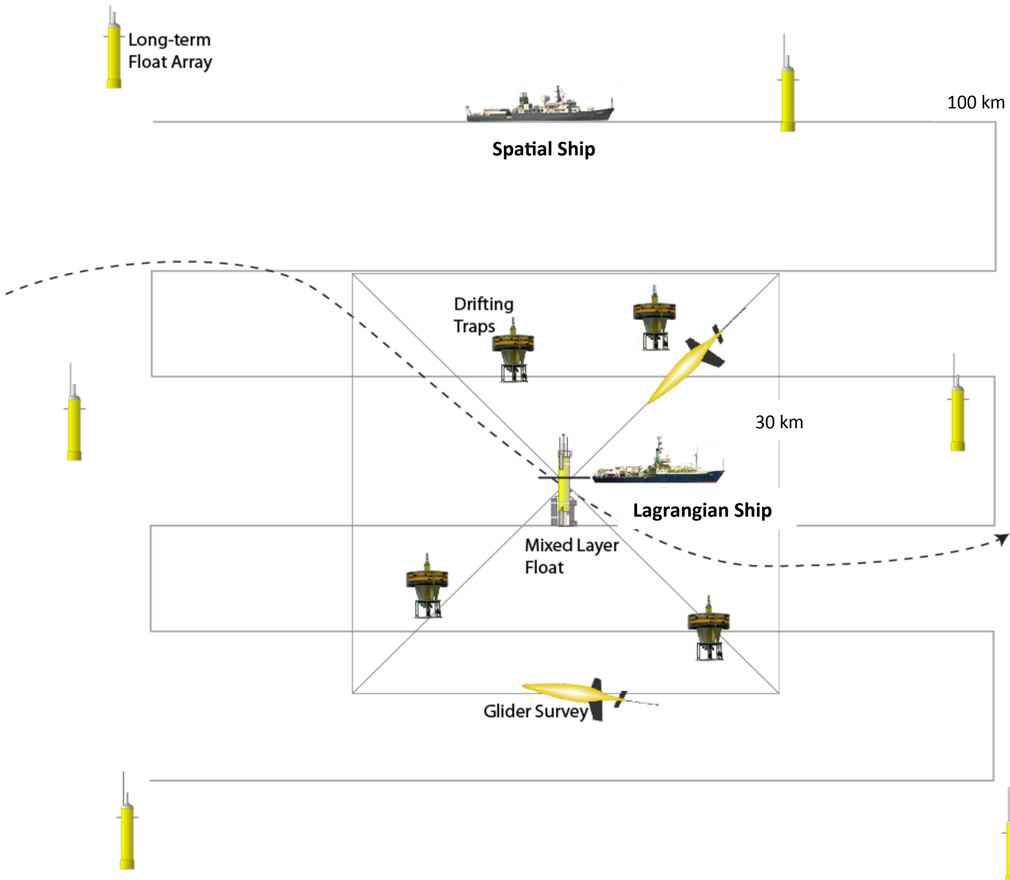

Figure 11 *Cartoon describing what a typical EXPORTS field deployment looks like. A Lagrangian ship measuring rates and time-series of stocks follows a mixed layer float. A spatial ship provides spatial information on biogeochemistry as well as performing submeoscale physical oceanographic surveys. The spatial ship spatial observations are supplemented with glider surveys about the Lagrangian ship and a suite of profiling floats. The floats also provide a long-term context for the experiments.*

Figure 10 shows a timeline for an efficient and practical experimental plan for each of the field programs to capture the states and variables required to answer EXPORTS key science questions. Each field program requires multiple ships (Lagrangian, spatial and vehicle launch/retrieval), and autonomous platforms (gliders and floats), conducted within a framework of remote sensing and modeling activities that begin well before and continue through and beyond the field year, extending to larger scales. The field year begins with a cruise that makes a limited survey of the predetermined study area, launching upstream from the intended central study area, deploying one well instrumented mixed layer float, an array of six profiling floats and 3 gliders, all of which are left behind for continuous measurement until the spring cruises. The mixed layer float will provide a central focus for the autonomous array, tracking the lateral motion of the water. Gliders will survey around the float on a 1-30 km scale (inner grid) and on larger scales (100 km outer grid). The profiling floats will operate in a larger region surrounding the outer grid. A cartoon showing the expected field deployment of the ships and autonomous instrumentation is shown in figure 11.

The autonomous platforms will measure water column properties through the mixed layer, euphotic zone and mesopelagic including, T/S, O_2 and NO_3 along with optical proxies for particulate organic carbon, particle size/abundance and particle flux. The gliders will cross-calibrate the sensors on different platforms using intentional co-located profiles with each other and the floats, thus ensuring a uniform calibration standard across the entire array. Absolute calibrations will be conducted at deployment, retrieval, and during the process, and spatial cruises will use intentional co-located hydrocasts from the ships.

The duration of the major sampling cruises is set by the desire to sample different states of the biological pump and to make observations on a time scale that relates to particle formation in both the euphotic zone and particle transfer through the transition zone (50-500 m, bottom set by depth of maximum winter mixing and/or diel and ontogenetic vertical migration). With a particle sinking speed from 50-100 m d^{-1}, sample time scales of 5-10 days are necessary and minimal occupation times for these Lagrangian time-series is set to 20 days. Many processes will be changing on much shorter time frames especially in the NE Atlantic spring. We thus expect to see large variations in daily rates. However, the longer observations will help constrain particle changes at depth that might be related to sources and processes in the surface that happened several days earlier (and later). A longer occupation also allows repeat experiments and observations at both the inner grid and larger outer grid on both ships (2-3 trap deployments, surveys, etc.). Each ship will have identical collection systems for key parameters, such as CTD-rosette/bio-optics/particle-imaging/hydrographic instruments aimed at providing samples and observations in the upper 1000m, and ideally a smaller CTD/multi-spectral bio-optical package (no bottles) for more rapid sampling of the upper 200-300 m only. Towed packages will provide periods of continuous observations focusing on along transect variability, which is the only way of sampling submesoscale features that cannot be adequately sampled with bottles.

At the end of each cruise, the long term floats and gliders will be redeployed by the spatial ship. Approximately 3-6 months after the final cruise, a smaller ship will be sent to retrieve the gliders (cheaper profiling floats may be left in-situ) and make a final survey of the site. This plan allows 18 months between the NE Pacific field deployments and start of field work in the NE Atlantic, though the retrieval of autonomous assets from one basin to redeployment in the other may be as short as 6 months (Figure 10). The NE Atlantic spring cruise is extended by two weeks to organize the sampling around the initiation of the spring bloom. While the position of the starting location can be changed to some degree, we don't want to move outside the mesoscale area already sampled by floats and gliders prior to the bloom cruise, and within any such area, the timing of the bloom can at best only be predicted to within a few weeks (e.g., Siegel et al. 2002; Behrenfeld, 2010; Mahadevan et al., 2012; Behrenfeld et al. 2013). As such, nominal times for Lagrangian ships are 30 days and 35 days for the spatial ships (longer as they leave early to retrieve in-situ assets and make initial surveys) in the NE Pacific, and 45 and 50 days for the spring and 30 and 35 days in the summer/fall again for Lagrangian and spatial ships in the NE Atlantic. For this calculation, a nominal ten days steaming time was used and will be adjusted depending upon ports. Here, we have assumed ports of Seattle for the NE Pacific work and a combination of Woods Hole and a UK port for the NE Atlantic work.

The exact determination of field sampling design will be guided by observing system simulation experiments (OSSEs) to set the frequency, depth, and spatial distribution of sampling parameters discussed in section 6.4. Likewise, during the field experiments several "operations centers" will be established in order to control the autonomous assets, collect available real-time satellite and model output, synthesize this information, distribute it to the ships, and coordinate the experimental activities. Thus high-speed communications and back-ups are essential between these land-based centers and both ships.

6.4 In Situ Measurements

The biological and physical processes that influence the export of material from the surface ocean to depth occur over a wide range of temporal (hours to seasons) and spatial scales (submesoscale to the mesoscale). Thus, an effective sampling program combines both shipboard observations and autonomous platforms that link to satellite observations, which synoptically cover even larger spatial scales (see Section 6.3). Here, we have included a thorough, but not necessarily comprehensive, list of the types of measurements needed to address the Science Questions outlined in Section 5 and delineate the pathways outlined in Figure 3. Measurements are further delineated into the following subcategories Water Column Characterization, Food Web Structure, Carbon Flows, and the Five Paths of Export. Each of these categories can be characterized by both direct and indirect methods that balance specificity with the ability to rapidly collect data at different temporal and spatial scales. An abbreviated version of the EXPORTS measurement table is shown in Table 1. Further details regarding science platforms and specific method references are provided in Section 11.2.

Water Column Characterization is needed to define how biogeochemical dynamics within a specified physical regime drive changes in the amount and proportion of carbon that flows through the five major export pathways. Physical measurements include hydrography and circulation, using CTDs and ADCPs, to provide insight on vertical mixing (e.g., DOC and particles) as well as measurements of water column light and remote sensing reflectance spectra, a critical link to satellite measurements, and optical properties (e.g. fluorescence, absorption and scattering), which serve as proxies for phytoplankton pigment and particulate organic carbon concentrations as well as phytoplankton composition.

Ocean biogeochemistry must further include knowledge of the basic macronutrients (nitrate, phosphate, etc.) and in the case of the HNLC region surrounding station P, iron. Coupled measures of nutrient concentration and physics will help define nutrient supply and provide insight into whether the food web is subject to nutrient stress, which may subsequently influence elemental particle composition, stickiness and aggregation. In the same context, measurements of DOC and DIC define the vertical downward transport of dissolved carbon.

Table 1 EXPORTS Measurement Approaches and Platforms

Function	Subclass	Measurement	Platform
Water Column Characterization			
Hydrography	*Context*	CTD	ship/auto
		SST & SS salinity	satellite
Circulation		Horizontal Velocity (ADCP & Geostrophy)	ship/auto
		Vertical velocity (Omega equation from SMS surveys)	ship/auto
		Sea level & geostrophic surface currents	satellite
Light/Optics	*Ocean Color*	PAR	ship/auto
		Ocean color - LwN (wave) & light attenuation	ship/auto
		LwN - Daily PAR - Kd	satellite
Biogeochemistry	*Nutrient/C Stocks*	Nutrients (NO3, PO4, SiO4)	ship/auto
		DOC	ship
		DIC	ship
		Iron	ship
Food Web Structure			
Particle Size and Composition	*Collection (filtration)*	large volume (>1,000L) pumps for size classification	ship
		POC, PON	ship
		BSi, PIC	ship
		Organic Biomarkers, absorbance, fluorescence	ship
		Molecular techniques	ship
	Indirect (optics)	beam attenuation or backscatter spectra	ship/auto
		absorption spectra(ac-s or filter pad)	ship

		LISST (forward light scatter)	ship
		back scattering/total scattering ratio (organic/inorganic)	ship
		polarized beam attenuation (PIC)	ship/float
		POC, PIC & PhytoC concentrations	satellite
		PSD parameters	satellite
	Direct (optics)	Flow cytometry	ship
		Coulter Counter	ship
		In situ cameras (UVP, etc.)	ship
Bacterioplankton		Flow cytometry	ship
		microbial community structure (DNA)	ship
Phytoplankton community	*Indirect (optics)*	absorption spectra (acs or filter pad)	ship
		Flow cytometry	ship
		genomics	ship
	Functional types	HPLC	ship
		FCM/Microscopy/imaging	ship
		inverted microscopy	ship
		chlorophyll fluorescence	all
		extracted chlorophyll and chlorophyll size fractionation	ship
		CHN with sorting	ship
		cell plasma volume to carbon	ship
		PFT's & phyto biovolumes	satellite
Zooplankton community	*Indirect*	in situ camera (for larger microzooplankton)	ship/float
		towed & profiling camera systems (VPR, UVP, LOPC)	ship/floats
		acoustics	ship/auto
	Direct	nets & zooplankton size fractions	ship
		microscopy (of net contents)	ship
		zooscan (of net contents)	ship
		Trap ID work	ship (traps)
Carbon flows			
Phytoplankton Growth	*Total (indirect)*	Oxygen production (O_2/Ar)	ship/auto
		nitrate drawdown	ship/auto
		$p$$CO_2$ and DIC drawdown (NCP)	ship/auto
		diel cp	ship/auto
		NPP, phytoplankton growth rates	satellite
	Incubations	$H_2^{18}O$ bottle incubation	ship
		^{14}C (In situ; P vs. E bottle incubation)	ship
		phytop growth rate from microzoopl dilution	ship
Phytoplankton physiology		active fluorescence kinetics (Fv/Fm; PS parameters)	ship/auto
		molecular tools (Fe limitation, etc.)	ship
		Si limitation, N limitation	ship
		^{32}Si uptake - silicification	ship
		opal ballasting - cell specific silicification - PDMPO	ship
		sun stimulated fluorescence	satellite
Grazing		Cameras(flux vs. raptoral zoopl feeders) UVP5, etc.	ship/auto
		Microzooplankton dilution method (analyze changes in conc. with variety of methods)	ship
		zooplankton respiration (w/ food and w/o)	ship
		Grazing experiments	ship
		incubations/clearance rate	ship
		Size distribution, modeled, types of zooplankton	ship
		gut fluorescence	ship
		Grazing from upper ocean mass balance	satellite
Heterotrophic carbon demand	*Bacterial metabolism*	experimental DOM/ suspended POM remineralization	ship
		trap with incubation chamber, including in situ	ship
		Microbial decomposition of suspended & sinking POM (radiotracers and O2 measure)	ship
		hydrolytic enzyme activity	ship
		size-fractionated respiration	ship
		bacterial production (3H-Leu incorp)	ship
		Chemoautotrophy Mesopelagic	ship
	Zooplankton metabolism	Weight-specific metabolic rates	ship

Aggregation	*Radionuclide*	234Th, 228Th, size class	ship
	Experimental	Rolling tank experiments	ship
		TEP	ship
Five Paths of Export			
Particle Export	*Bulk (indirect)*	oxygen depletion	ship/auto
		nitrate (drawdown)	ship/auto
		pCO_2 and DIC drawdown	ship/mooring
		triple O_2 isotopes with O_2/Ar (GPP to NCP ratio)	ship
		$H_2{}^{18}O$ bottle incubation	ship
	Indirect (optics)	backscatter/ fluorescence	glider
		vertical transmissometer on floats	profiling float
		snow camera profiling (>200 µm)	ship
		e-ratio & food web modeling	satellite
	Indirect (model)	ADCP, model (for particle source regions)	moored
		Particle Camera (underwater vision profiler; > 1 mm)	ship/float
		snatcher/ snatcher with window	ship
	Indirect (radiotracers)	^{234}Th (Sinking flux days-week)	ship
		^{210}Po (Sinking flux month)	ship
		^{228}Th (Sinking flux year, aggregation/dis-aggregation)	ship
	Direct	Moored, drifting, neutrally buoyant traps	mooring/ship
		Attenuation with flux at multiple depths	traps/floats
	Sinking rates	Settling Velocity Traps & other in-situ experiments	trap
Aggregate Export	*ID and Size*	Polyacrilimide gel traps for ID and/or sinking rates	trap & gel
	ID and Size	trap with camera/optical imaging	ship
Zooplankton Carcass/Fecal Pellet Flux		fecal pellet production (incubations, assimilation rates)	ship
		pellet sinking rates	ship
		traps (also see Direct particle export and traps above)	trap & gel
Mixing of DOC and Particles		combines measures of circulation, DOC and POC	
Zooplankton diel vertical migration	*Zooplankton Migration*	nets & zooplankton size fractions, microscopy, cameras	ship
		acoustics	ship/auto
	Active transport	weight-specific metabolic rates	ship

<u>Food Web Structure</u> within the EZ and TZ requires knowledge of particle size structure and composition, bacterioplankton, and phytoplankton and zooplankton communities. Particle size structure and composition can be deduced using large volume pumps that fractionate particles into a variety of size classes that are then directly measured for their bulk elemental composition (e.g., POC, PN, BSi). Less common methods that should be included require larger amounts of material, but interrogate particle sources using a combination of biomarkers and molecular techniques. Techniques that collect particles will be augmented by systems aboard CTD rosettes and AUV's, greatly expanding the range of temporal and spatial scales of these observations. These measurements include beam attenuation, LISST, and back-scatter spectra that provide direct linkages between the direct measurements and remote sensing.

Bacterioplankton and phytoplankton community structure are directly characterized using flow cytometry, microscopy, and genomics. Phytoplankton functional type investigations include HPLC, extracted and size fractionated chlorophyll measurements, genomics and optical imaging systems. Indirect measures include chlorophyll fluorescence and absorption spectra that link to satellite measurements. Zooplankton community structure requires size-fractionated plankton tows coupled with optical zooscans and microscopy. Advances in camera systems (towed and profiling) and acoustics coupled with changes in particle spectra allow wider and more rapid coverage of zooplankton abundance and a first order understanding of taxonomic composition.

Carbon Flows are critical for linking food web structure within the EZ and TZ to export from each zone. These carbon flow paths include biological processes such as phytoplankton growth and physiological status, heterotrophic carbon demand and grazing, and physical processes, such as aggregation, which together provide a mechanistic understanding of net community production and particle size spectra. Phytoplankton growth rates can be measured using incubation and bottle experiments (^{14}C, $H_2{}^{18}O$ incorporation, dilution experiments) coupled with the observed drawdown of water column nitrate, pCO_2 and DIC and the production of O_2. Additionally, ratios of gas tracers, such as O_2/Ar to triple oxygen isotopes, are used to constrain the ratio of net community to gross production, a ratio that should be akin to the export ratio ("e-ratio") and that can be measured more precisely than either part separately. Phytoplankton physiological status can be monitored using active fluorescence kinetics, molecular techniques, and nutrient and trace element uptake and limitation experiments. Heterotrophic carbon demand focuses entirely on bacterial metabolism in both oxygen rich (EZ) and oxygen poor (TZ) environments, which can be measured by a variety of techniques that include hydrolytic enzyme activity, bacterial production rates, and experimental measurements of bacterially mediated DOM and suspended and sinking POM remineralization.

Grazing pathways require a combination of bottle experiments (microzooplankton dilution, incubation/clearance rates, and zooplankton respiration with and without food), with net collections (gut contents and fluorescence), camera systems, and models that incorporate zooplankton species and size distributions. Aggregation is difficult to quantify, but is a necessary component for understanding export. It should include assessment of compounds known to increase aggregation rates, e.g. TEP and TEP precursors, ship-based assays of particle aggregation potential, camera profiles of aggregate abundance and direct estimates of aggregate sinking rates and export (gel traps, in situ optical following) as well as indirect estimates of large particle export that rely on short-lived radionuclides (^{234}Th and ^{228}Th).

The Five Paths of Export shown in Figure 3 include three sinking particle pathways, physical mixing of DOC and suspended particles to depth, and zooplankton migration. Sinking particle pathways are characterized by 1) direct gravitational settling of phytoplankton as single cells or fragments of cells, 2) sinking of aggregates comprising bacterioplankton, phytoplankton, zooplankton and their byproducts, and 3) direct sinking of zooplankton byproducts and their carcasses. The complexity of these pathways and their importance to the overall goals of the EXPORTS Science Questions requires a suite of overlapping measurements that focus on various aspects of this dynamic and complex process.

Bulk measurements that bear upon all five paths of export include estimate of net community production (equal to net export over the proper space and timescales) determined as the seasonal drawdown of water column NO_3 or DIC, or the production of O_2 (also measured as O_2/Ar to correct for physical effects) which can be made using autonomously profiling floats. Importantly these geochemical determinations provide an integral constraint for the biological pump.

Sinking particle pathways are also characterized by using mass balances of short-lived radiotracers that span days to months (^{234}Th) with direct estimates of particle flux using sediment traps (free floating, moored, settling velocity) and indirect optical measurements (backscatter/ fluorescence, transmissometry, and cameras). Models further provide an estimate of the source region of these sinking materials.

Export can also be assessed by direct capture of particles in sediment traps (tethered, moored and floating). The composition of sinking particles informs the phytoplankton and zooplankton export pathways with the analysis of sediment trap samples for species composition, fecal pellets, ballast minerals and particle size using microscopy and molecular methods. The sinking aggregate pathway can be specifically determined using polyacrilimide gel traps, while direct sinking of zooplankton byproducts and their carcasses can be quantified by focusing on fecal pellet production from zooplankton incubations as well as close examination of fecal pellets found within the sediment traps.

Downward mixing of DOC and suspended particles and active C transport via zooplankton diel vertical migration have been shown to constitute important pathways in the export of material. Quantifying the magnitude of downward mixing relies on combined measures of mixing, DOC concentrations, and particle distributions. In some areas like the North Atlantic, this pathway may be dominated by seasonal convective mixing that transfers material to depth on large scales over relatively short time periods. These physical events can be captured via autonomous platforms (e.g. gliders) with subsequent ship observations defining the net effect on DOC and particle distributions. Zooplankton migration mediated export requires an integration of day and night size fractionated net tows, microscopy, and cameras with incubation experiments (e.g., weight-specific metabolic rates) and models of zooplankton excretion, defecation rates and mortality at depth. In addition, particular to our chosen sites, export associated with the mortality of ontogenetic vertical migrators will need to be assessed with stocks of mesopelagic copepods quantified.

Finally, it should be noted that it will be the differences between C flows determined by different methods that will help illuminate the times and depths where C is being actively recycled. For example NCP determined for the mixed layer using O_2/Ar is often greater than EP determined from ^{234}Th. This can be used, if sampled appropriately, to quantify the extent of remineralization directly below the mixed layer. Likewise contributions to EP from DOC mixing are not traced by ^{234}Th or traps, and when averaged over appropriate time scales, the imbalance in NCP and POC export is a measure of the importance of the mixing of DOC and suspended particles to the biological pump.

Links to a more complete version of Table 1 as well as a list of references for specific method are provided in Section 11.2 of this document.

6.5 Satellite Data Analysis Program

The satellite data analysis program will have three basic functions: 1) real-time analysis and support of the field program, 2) development and validation of satellite ocean color algorithms for carbon cycle stocks and rates, and 3) extrapolating EXPORTS field results to regional and global scales. All are required to make the link between the EXPORTS field program observational data set and future NASA satellite missions such as the Pre-Aerosol Cloud and Ecosystems (PACE) advanced ocean color satellite mission.

The EXPORTS field program requires the support of near-real time ocean color and other satellite data to be made available and shared with the field program. These data will be used to help situate the field observations and to help direct the autonomous platform operations. Ocean color data will be used to assess distributions of chlorophyll, POC, CDOM and other biogeochemical stocks as well as net primary production rates for the region surrounding the study site. We expect that ocean color imagery from both the Visible Infrared Imager Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (NPP) mission and the Ocean Color and Land Imager (OCLI) onboard Sentinel-3 mission will be available during the time of the EXPORTS field program (2017-2021). Ancillary satellite data sets include sea surface height (SSH) and sea surface temperature (SST), both of which should be available during this time. This work will be conducted at the on-land operations center, which will likely be a part of the EXPORTS Project Management grant (see below).

The second area of the satellite data analysis program is focused on the development and validation of advanced satellite algorithms for carbon cycle parameters. The EXPORTS field sampling program includes a full suite of high-quality ocean optical measurements to be made, including excellent observations of water-leaving reflectance spectra aimed at simulating observations to be made from the PACE satellite. The ocean optics field observations will be used to develop and test algorithms for carbon cycle parameters and to link the biogeochemical field observations to satellite data. Effort will be made for matching field measurements to the times and locations of satellite overpasses. This ship-satellite match up data set will also be useful for inter-calibrating bio-optical proxies across all platforms (e.g. autonomous and ship), which will maximize the number and quality of matchups opportunities. Data mined from existing databases (e.g. SeaBASS, NOMAD, BCO-DMO) will also be used to supplement the EXPORTS field sampling in developing bio-optical algorithms for additional states of the biological pump.

Last, the EXPORTS results will be used to understand the magnitude and efficiency of the biological pump on regional to global scales by implementing satellite data algorithms based upon EXPORTS results. This may be done using satellite data alone or through assimilating satellite data into Earth system models (see next section). Comparisons with field data collected as part of the data mining activity will be used to test whether the EXPORTS satellite algorithms are appropriate over a wide range of states of the biological pump. Thus, the scientific reach of the EXPORTS field program will extend far beyond the two study sites proposed here.

6.6 Modeling Program

Modeling is an essential component of the EXPORTS program. Supported modeling activities will contribute to the design of the field campaign (through OSSE), data synthesis and interpretation (e.g. through data assimilation and process models), and form the basis of answering Science Question 3 and its sub-questions. The five export pathways we have identified in the Science Questions involve physical and biological processes that operate on multiple spatial and temporal scales, all of which need to be represented in the supported modeling activities. This will possibly require a hierarchy of models differing in their level of detail, complexity and spatial/temporal resolution. Equally important will be the development and evaluation of more mechanistic parameterizations, often from more detailed high resolution or complexity simulations, that capture the sensitivity of export processes to ecosystem and environmental variations but that are computationally simple enough for incorporation into larger-scale biogeochemical models. The range of numerical models will include full 3D coupled biogeochemical and physical models on both regional and submeso-scales, as well as more specialized 0D or 1D models that can be used to explore effective parameterizations of individual processes (e.g. particle disaggregation, vertical migration). An example of the range of models suggested is given in Table 2.

Typically, ocean biogeochemical models concentrate on the surface layer, with progressively less (biogeochemical) detail below the euphotic zone. Simple models show that particle-organism interactions can strongly affect flux attenuation in the mesopelagic (Jackson, 2001; Jackson and Burd, 2002; Stemmann et al., 2004a,b;

Martinez and Richards, 2009). The model activities undertaken as part of EXPORTS necessitates appropriate means of extending the detail (including what level of detail is required) into the mesopelagic in order to incorporate the effects of vertical migration, particle processes etc. One of the goals of the EXPORTS modeling program is to provide that critical quantitative link between surface plankton processes and food web processes in the mesopelagic.

Table 2 EXPORTS Modeling Activities

Name	Purpose	Scale	Model Type	Timing
Observing System Simulation Experiments (OSSE)	Experimental Planning	Submesoscale	Idealized but with appropriate physics / BGC	During EXPORTS planning
Submesoscale Physics / BGC	To guide interpretation of the EXPORTS field results	Submesoscale	Process, Data Assimilation or Nested Models	During & After EXPORTS
Food Web	Address flows of C in EZ & TZ evaluating EXPORTS biological pump states	Zero-D or 1-D	Idealized Process	During & After EXPORTS
Particle	Address the formation & destruction of marine aggregates	Zero-D or 1-D	Idealized Process	During & After EXPORTS
Coupled Earth System	Testing EXPORTS parameterizations on regional scales & forecasting future states of the biological pump	Regional to basin	Realistic	During & After EXPORTS

Modeling in Direct Support of the EXPORTS Field Campaign There are two major uses of modeling in support of the EXPORTS field program. The first activity is to help develop sampling strategies for the field campaign. Existing physical, biogeochemical, and data assimilation models should be used as part of an Observing System Simulation Experiment (OSSE) that can be used to help assess different observational strategies (e.g., Arnold and Dey, 1986; Dickey, 2003). Model fields can be sampled and analyzed as simulated observed data fields to test how well the EXPORTS science questions can be answered given a particular observational strategy. In principle an OSSE can be used to optimize field program logistics helping to keep the field program's costs manageable. This work needs to be conducted in preparation for the EXPORTS field project.

The second approach is to use time-evolving, 3-D coupled models to address physical-ecological-biogeochemical couplings on the scales of the observations – roughly one to a couple 100 km's and hours to weeks. These modeling systems could be process models illustrating environments very similar to the observations (Lévy et al. 2012; Mahadevan et al. 2012) or data assimilation models that attempt to simulate the actual experimental conditions (Robinson and Lermusiaux, 2002; Ramp et al. 2009). Physical oceanographic field measurements and satellite data products (e.g., sea surface height) are essential in initializing and integrating simulations to replicate field experiments and can also be used to generate simple, yet useful, diagnostics of mesoscale and submesoscale ocean circulation. It is likely that these approaches will require a nested grid of models with different resolutions in order to capture the dynamics at submesoscales as well as the forcings on larger scales. These models will be very useful for filling in the gaps of the field campaign, including physical, biological, and particle properties and fluxes, constraining parameter values for empirical and mechanistic process models, and interpreting observed changes in the state of the ocean's biological pump.

Modeling of Specific Processes There are several modeling exercises that are needed to develop parameterizations of difficult to measure processes. These include but are not limited to models of the processes of particle aggregation and disaggregation and the functioning of the food web.

Particle aggregation and disaggregation processes operate on spatial scales of microns to centimeters. Existing models handle this range in one of several ways. Size-spectrum based models explicitly (Jackson and Lochmann, 1992), or implicitly (Kriest and Evans, 1999) utilize numerous (>20) size classes. Simpler, two size-class models have to be treated with caution because they do not accurately represent the reality of particle aggregation processes (Burd, 2013). The detailed particle size information being collected lends itself to the more detailed size-spectrum based models.

Simple disaggregation models exist and have been employed in conjunction with aggregation models (Jackson, 1995; Stemmann et al., 2004a,b). More detailed disaggregation models using a particle size-spectrum approach have also been developed (e.g. Hill, 1996; Burd and Jackson, 2009) but these involve parameters that are presently unknown for marine aggregates. Consequently, activities that further develop and experimentally verify disaggregation models need to be supported.

Supported modeling activities must include an examination of the incorporation of particle explicit aggregation/disaggregation models into food-web and larger scale models. Most existing aggregation models consider all particles to be essentially the same (though see Jackson and Burd, 2002). However, in distinguishing the various export pathways, different particle types (phytoplankton aggregates, marine snow, fecal pellets, etc.) will have to be considered; the problem being that doing this dramatically increases the computational complexity of the model. Consequently, effort needs to be put into alternative strategies for modeling aggregation and disaggregation and processes affecting the particle size distribution.

Particle based models will also need to access both the physical and the biological models for information such as fluid shears, particle production rates etc. Consequently, efforts to couple these different models should be supported.

Existing food-web models use plankton functional types to represent the different members of the biological community. The number and categories of plankton functional types used in these models might have to be changed and expanded once model results are compared with observational data to better isolate groups with similar characteristics relative to their imprint on the ocean biological pump. One specific problem with plankton functional type models is that they largely omit organism behavior such as vertical migration. Consequently, alternative models (e.g. 1D models with more explicit organism representations) should be supported with the aim that results from these models can be used to parameterize and inform changes in the plankton functional type models.

Given the type of problem being considered, it is entirely possible that novel types of models may provide better or different insight and predictive skill than existing model frameworks. Such efforts, if they arise, should be supported.

Forecasting into the Future Using Coupled Earth System Models The third EXPORTS science question asks how the results of the field program can lead to improved model determinations of present and future states of the biological pump. Coupled Earth System Models simulate ocean physical-ecological- biogeochemical interactions on regional to global scales for both contemporary conditions and under future climate change scenarios (e.g., Moore et al., 2013). Preliminary studies are examining how these models behave with respect to the variation of export flux and transfer velocity with respect to primary production, phytoplankton community composition, ballast material and zooplankton biomass (Laufkötter et al. 2013; Lima et al., 2014). The EXPORTS project needs to develop and test advanced parameterizations of the biological pump against the field data collected during EXPORTS as well as the historical data compiled during the data mining phase. In many cases these parameterizations will be derived from more complex mechanistic models that resolve processes and small time/space scales not captured in the full Earth System Model.

The next step is to incorporate these new, tested parameterizations into well characterized Earth System Models (for example the Community Earth System Model, the NOAA/GFDL Earth System Model), and EXPORTS needs to support an additional phase of model evaluation and sensitivity studies at the Earth System Model scale. These studies will address several specific questions How skillful are export parameterizations developed at the EXPORTS sites for other oceanographic regions? How do improved export flux parameterizations affect simulations of the overarching, inter-connected biogeochemical system (e.g., primary production; nutrient, oxygen and carbon distributions)? How does better, explicit treatment of export processes influence model projections for the future states of the strength and efficiency of the ocean's biological pump in response to climate change and ocean acidification? Given the importance of this work towards EXPORTS outcomes it is likely that several groups need to be working on these issues in collaboration with or as part of existing Earth System modeling groups.

6.7 Assembling EXPORTS Data Products

EXPORTS needs to assemble individual measurements into data products for each observed "state" of the biological carbon pump to answer the proposed science questions. These data products may come from a single measurement group or more likely will need to be created using data collected from several groups. Data products might also be constructed from a combination of autonomous, remote sensing and in situ data sets. The planned EXPORTS field campaigns will be supplemented by data mining activities that will provide additional states of the biological pump, and these too need to be organized into data products that are required to answer the EXPORTS science questions.

Table 3 lists examples of data products needed to answer the EXPORTS sub-questions. The data products will likely be measured by a host of different methods and disparate platforms. We plan to use the construct of integrated data products as a way of unifying the measurement and analysis teams towards the answering of the EXPORTS questions. It is likely that some centralized group will need to oversee their construction and dissemination, which will probably be a task for the EXPORTS project office.

The following lists obvious integrated data products needed to answer the stated science questions. It is likely that the exact description of these data products will change as EXPORTS matures as a program.

Export Flux - Each EXPORTS deployment needs a synthesized data set of export flux and vertical flux attenuation for each of the major constituents (POC, PIC, opal, etc.). This includes determinations of the component fluxes (mass, POC, PIC, opal, etc.) from the base of the euphotic and at fixed depths (for example 150, 300 & 500 m). Estimates are needed for each sampling epoch within each sampling cruise and if possible they will temporally resolve change within each EXPORTS cruise. Export data can be assembled by several means including sediment traps, biogeochemical mass budgets (POC, O_2, NO_3, ^{234}Th, etc.), autonomous optical flux proxies, etc. Importantly, each of the five export pathways (sinking of intact phytoplankton, aggregates or zooplankton byproducts, vertical submesoscale advection & active vertical migration) needs quantification. The EXPORTS sampling will be extended through a thorough combing of the literature to assess additional states of the biological pump.

Table 3 Examples of EXPORTS Data Products

Data Product Name	Brief Description	Use in Answering Sub-Questions
Export	Export flux, sinking rates & vertical flux attenuation	1A, 1B, 1C, 1D, 2A, 2B, 2C, 2D
Productivity	NPP, NCP & EP	1A, 1D
Plankton Community Structure	Phyto-/Zoo-plankton functional types, abundances, C content, etc.	1A, 1B, 1C, 1D, 2D
Particle Size Spectra	Particle size distribution of microbes through aggregates	1C, 2A, 2B, 2C, 2D
Aggregate Aggregation / Disaggregation Rates	Measurements of aggregate formation & destruction	1C
Meso- and Submesoscale Physical & Biogeochemical Mapping	Mapping of biogeochemical & physical fields on 5 to 200 km	1D
Partitioning of Organic Matter	Partitioning of POM and DOM	1D, 2A, 2B, 2C, 2D
Solubilization, Grazing and Remineralization	Processes regulating vertical flux attenuation	2A, 2B, 2C, 2D
Optics	Ocean color reflectance spectra & inherent optical properties	3A, 3C

Productivity - The Productivity data product is needed to address the efficiency of transfer of net primary production (NPP) to export – the so-called e-ratio (=export/NPP). This means that estimates of NPP are needed for each sampling epoch where export data products are available. NPP can come from many measurements (see Table 1). Export production, new production, and net community production will be measured using O_2/Ar, ^{234}Th and tracer mass balances (O_2, NO_3) determined from the shipboard underway water, autonomous instrumentation or from pumped water from a towed instrument. Primary production rates will be determined using in situ $^{14}C\text{-}HCO_3$ incubation methods, and/or the product of measured phytoplankton carbon biomass and division rates. By combining estimates of export production with primary production, we can obtain estimates of the efficiency of the biological pump at submesoscales.

Plankton Community Structure - Assessment of the phytoplankton and zooplankton community structure is needed from the surface waters of each deployment. Here, a summary of abundances by group, and if possible by species, and their vertical distributions is required. Estimates of the horizontal variability also need to be made following the mixed layer drifter. Data will come from net tows, in situ imaging, flow and imaging cytometers, chemotaxonomic phytoplankton pigment, absorption spectra, genomics, etc. Estimates from satellite ocean color remote sensing of phytoplankton functional types and size spectra will also be incorporated, especially for understanding the horizontal and temporal variability at the sites.

Shipboard surveys using underway flow cytometry and imaging techniques as well as towed camera systems will be used to determine the spatial variability in phytoplankton, zooplankton and aggregates. The shipboard measurements will be used to develop and tune optical and acoustical proxies that will then be used from autonomous platforms.

Particle Size Spectra - A data set combining size spectra and changes to the size spectrum with depth, combined with co-occurring information on community composition and water column physical characteristics will be analyzed. Particle sizes range from bacteria (0.5 μm) to sinking aggregates and mesozooplankton (~10's mm). This will allow for the study, from surface to mesopelagic, of biological and physical processes affecting aggregation and disaggregation and their impact on export flux.

Aggregate Aggregation / Disaggregation Rates - Rates will be quantified through laboratory measurements of (physical and biological) disaggregation of marine particles, including rates and daughter size spectra, for different types of marine particles. Temporal variation in particle size spectra may also serve as a proxy measure of mesopelagic fragmentation/ aggregation processes.

Meso- and Submesoscale Physical and Biogeochemical Mapping - Submesoscale variations in temperature, salinity and velocity will be measured using ship-based profilers and autonomous platforms. These will be merged with satellite altimetry measurements to map the physical variability and tune submesoscale models of this variability. Detailed measurements of macro- and micro-nutrients will be similarly made from the ships with a small subset (O_2, NO_3, pH, CO_2) made from the autonomous platforms. Mesoscale budgets of particulate and dissolved organic carbon, oxygen and other relevant biogeochemical metrics following the time-series mixed layer float will be assessed. Here we aim to examine the 4-D changes in organic carbon, dissolved oxygen, etc. following the mixed layer float. Data for this will come from the Lagrangian and Spatial ships as well as the autonomous assets that are deployed in the study. The Biogeochemical Budget data product will include all raw data, including the conversion of electronic signals to biogeochemical parameters, as well as objectively mapped fields of the same quantities (including error maps). It is also noted that high-resolution submesoscale surveys will also be needed to evaluate the role of submesoscale vertical motions on the biological pump (SQ1D; see more details below).

Partitioning of Organic Matter - Field measurements of POM and DOM concentrations allow for the calculations of net organic matter production and partitioning over the course of each field campaign. In addition direct measurements of organic matter production and partitioning between particulate and dissolved phases will be resolved with shipboard experiments conducted during the process study cruises. Measurements of particulate inorganic carbon (PIC) and its rates of formation are also important. Rate of particulate primary production as well as extracellular release rates will be measured directly for each primary production measurement. Rates of DOM production by meso- and microzooplankton will be measured directly in ship-based experiments conducted during varying states of the biological pump.

Field measurements of POM and DOM inventories as well as shipboard measurements of DOM production rates via primary production, micro and macrozooplankton and microbial conversion of POM to DOM via enzymatic solubilization will be measured in both the euphotic and mesopelagic zones on each cruise to assess the magnitude of organic matter partitioning. Field measurements of DOM and POM stocks over the seasonal time scale will be useful for constraining the seasonal scale advective export pathway. Subsequent microbial bioavailability assays as well as chemical characterization of DOM will be required to assess if the resulting DOM is rapidly used biologically or if it is resistant to decay, accumulates, and potentially available to export via mixing.

Solubilization, Grazing and Remineralization - Microbial production will be measured directly from all casts conducted in the field campaigns to determine how they change in time and space (depth and geographic space). Shipboard experiments will be conducted to determine the availability of DOM to microbes on time scales of days to weeks. These data will provide essential estimates of growth efficiency needed to estimate resource demand imposed by heterotrophic bacterioplankton growth and their associated remineralization rates. Both shipboard measurements and literature size/weight-temperature based algorithms of microbial metabolism and zooplankton grazing and metabolism will be utilized. The solubilization of POM to DOM will be assessed by measuring particle associated ectoenzyme activity rates in shipboard experiments. The remineralization of sinking particles will also be measured directly through tracer experiments and by mass balance experiments in which changes in organic matter and respiratory gasses are measured directly.

Optics - The link to satellite remote sensing is central to EXPORTS. All EXPORTS measurements will be conducted alongside measurements of remote sensing reflectance spectra optimally with a spectral range and resolution similar to that planned for the PACE mission (350-900 nm at 5 nm resolution; PACE SDT, 2012). These measurements may be made from free-fall profilers deployed from the ship, using above water spectroradiometers or another deployment strategy. Inherent optical properties (IOP's) are the path from ocean color reflectance to biogeochemistry and spectral measurements of the absorption, scattering and backscattering will be assembled. Absorption will be partitioned into dissolved (CDOM) and detrital and phytoplankton absorption spectra. A similar partition will occur for the scattering and backscattering spectra. Special efforts will be made to measure IOP's in the ultraviolet spectral range, whose remote sensing is a feature of the PACE mission. The IOP measurements too may come from a suite of autonomous and ship-borne platforms.

There are of course many more possibilities for data products that are needed to support EXPORTS science goals.

7.0 Answering the Science Questions

It is absolutely critical that the EXPORTS Science Plan answers the science questions posed previously. This section details how the EXPORTS field / satellite observational and numerical program will answer the EXPORTS science questions.

7.1 Science Question 1

The first high-level science question…

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

… has four associated sub-questions. The purpose of the four sub-questions is to provide facts that contribute to answering the high-level science question. The sub-questions are obviously interrelated where often one will logically lead to the following. For example, the first two sub-questions for high-level question one are…

SQ1A: How does plankton community structure regulate the magnitude and efficiency of export of organic matter from the surface ocean?

SQ1B: How do the five pathways that drive export (cf., sinking of intact phytoplankton, aggregates or zooplankton byproducts, vertical submesoscale advection & active vertical migration) vary with plankton community structure?

These two sub-questions relate export efficiency (SQ1A) and the five export pathways (SQ1B) to plankton community structure. Understanding the relationship between plankton community structure and export is central to predicting the export of fixed organic carbon from the surface ocean and the goals of the EXPORTS program. SQ1A focuses on links between plankton community structure and the efficiency of export of organic matter, defined as the flux of organic carbon leaving the surface ocean normalized to the rate of NPP in the surface ocean. Export efficiency is linked to plankton community structure through phytoplankton size, its role in contributing to export flux via intact phytoplankton composition (e.g. silica and calcite containing phytoplankton), the phytodetritus contribution to aggregates, the structure of the zooplankton community and its role in creating fecal pellets, active transport of carbon to depth via vertical migration, sinking of carcasses and fecal-dominated aggregates, and the role that phytoplankton community composition has on export.

SQ1B asks how the five export pathways described in figure 3 are related to plankton community structure. As denoted in figure 3, the relative importance of all three sinking particle paths (A; sinking phytodetritus, zooplankton byproducts, or aggregates) and the active transport by vertical migration (C) export pathways will clearly be functions of the phytoplankton and zooplankton community structure. More subtly, the vertical mixing and/or advection of suspended organic carbon pathway (B) should also vary with plankton community structure as surface layer food-web processes create the vertical differences in suspended organic carbon that are mixed and/or advected to depth. Details of how the active vertical migration and advective pathways are addressed are presented in answers to question 2 and sub-question 1D below.

The EXPORTS field program will collect data on both plankton community composition (both phytoplankton and zooplankton) and export from the surface ocean by several means aimed at answering Sub-Questions 1A and 1B. The EXPORTS field campaign will create integrated data products for **Export**, as well as **Plankton Community Structure** and **Productivity** needed to answer SQ1A (as described in Section 5.7). Quantification of the relative export pathways (part of the **Export** data product) is needed to answer SQ1B. The four EXPORTS field deployments will likely provide more than four complete snapshots of states of the structure and functioning of the biological pump. The collection and analysis of the states of the pump will be the major observational effort in EXPORTS. The intensive EXPORTS field campaigns will be supplemented by data mining activities that should provide additional states of the biological pump for our analyses.

To answer SQ1A, we will compare data products for **Export**, **Plankton Community Structure** and **Productivity** statistically. This work will provide parameterizations linking community structure and export and will be used as the basis for building and testing quantitative models, both analytical and statistical, for answering the question of how plankton community structure sets the magnitude and efficiency of export. The **Productivity** data product is needed to help address the efficiency question. Emphasis will be placed on how plankton community structure, not just total biomass or its productivity, regulates the export of organic matter from the surface ocean.

To answer SQ1B we will compare how the export pathways will vary as a function of plankton community structure statistically and use this understanding to build numerical models to test how the various export pathways change.

The **Export** and **Plankton Community Structure** integrated data products will also be used to test (and hopefully improve) existing satellite ocean color algorithms and ecological-biogeochemical models. These parameterizations are central for assessing the functioning of the contemporary biological pump on global scales and for predicting the future states of the biological pump.

SQ1C: What controls particle aggregation / disaggregation of exported organic matter and how are these controls influenced by plankton community composition?

This question is aimed at understanding what controls the aggregation pathway of export from the surface ocean. Aggregates are one of the main vehicles of export of organic material from surface waters (Figure 3). Aggregation packages small, slowly settling particles into larger, faster settling ones whereas disaggregation reverses this process. The combination of the two partly determines the particle size spectrum and the average settling speed of material, the latter affecting the remineralization depth of the exported material. Plankton community composition can affect aggregate composition and characteristics as well as rates of formation and destruction. Aggregates can be composed of primarily phytoplankton (e.g. diatom aggregates) or fecal material, or be a heterogeneous mixture of cells, fecal pellets and other detritus. Rates of aggregate formation and disaggregation in part depend on the number concentrations of constituent particles and their properties.

SQ1C asks how the plankton community structure affects the strength of the aggregate export pathway. Both biological and physical factors affect aggregate formation and disaggregation. Physical processes such as fluid shear cause particles to collide and break apart. Biological factors determine the abundance of colliding particles, the types of particles and their propensity to adhere once they have collided. We know that the relative strengths of the biological and physical processes regulating particle aggregation and disaggregation change through the water column (Stemmann et al., 2004a,b), with the relative importance of aggregation decreasing with increasing depth in the water column. Consequently, understanding the role of plankton community structure requires information on the planktonic community, the relevant physical and biological processes, and changes in the particle size distribution.

Existing models represent particle aggregation either by using theoretically detailed, but computationally expensive models, or by using simple parameterizations; disaggregation is rarely included. Currently, we do not know the dominant causes of particle disaggregation or the size distribution of daughter particles produced by different disaggregation processes. During EXPORTS, experimental measurements of disaggregation rates will be made to fill this gap. These measurements, combined with models and field measurements of particle size distributions made during the EXPORTS field campaign will greatly improve our understanding of the role disaggregation plays in regulating the aggregation export pathway.

The EXPORTS field program will collect data on **particle size distributions** and **fluxes** in conjunction with **plankton community structure** and abundance, and background physical variables. These, combined with **disaggregation experiments** will form the basis for the integrated data products that will be used in conjunction with detailed, process-based models to address SQ1C, and provide parameterizations to improve the predictive skill in large-scale models.

SQ1D: How do physical and ecological processes act together to export organic matter from the surface ocean?

There are two primary processes controlling how suspended and dissolved organic matter are exported below the well-lit surface ocean

- Advection of dissolved and suspended particulate organic matter by intense submesoscale vertical motions, and
- Seasonal convection of recalcitrant organic matter to depth where it may be utilized by a distinct mesopelagic microbial community.

Together these two processes provide a pathway by which suspended and dissolved organic matter is exported from the surface ocean (pathway B on figure 3).

Submesoscale (<10 km) variations have been frequently observed in distributions of chlorophyll, plankton abundance, and intriguingly in a few studies of export, net community production rates and community structure. This submesoscale patchiness (Figure 12) has been observed from *in situ* and remotely sensed data and predicted by numerical models that couple submesoscale physics and biogeochemistry to predict export rates. The high variability implies that measurements and models must resolve these small spatial and temporal scales of the biological pump and suggests new mechanisms coupling physical and biological variability.

Submesoscale physical variability can affect the vertical transport of organic matter through several different mechanisms. First, such motions can produce strong vertical downwelling that export organic material of all types (dissolved, suspended and sinking) into the mesopelagic and updrafts that bring this material, and nutrients, back into the euphotic zone. Second, they can create large variations in the various components of the food web (Fig. 3). Thus different nearby patches may have different relative concentrations of zooplankton and phytoplankton and thus a different community structure and different states and efficiencies of the biological pump.

The EXPORTS field campaign will produce integrated data products quantifying the **Export Pathways** caused by submesoscale vertical motions. The submesoscale variability of many of these data products can be resolved using shipboard, autonomous, and satellite data, albeit with reduced accuracy in some cases. These will be used to assess the importance of submesoscale variability on the biological pump.

EXPORTS will quantify the patchiness in the states of the biological pump, in vertical transport, and in physical conditions in several ways. First, we will determine the spatial and temporal scales of variability and covariability in the components of the food web will be determined and used to guide the sampling strategies (see for example Figure 12a & b). Second, examination of the variability in estimates of primary, net community and export production will be related to variations in the food web and the physical properties of the ocean. Third, EXPORTS measurements will be used to guide the creation of submesoscale-resolving biophysical simulations (e.g. Fig. 12c & d) that accurately mimic the physical flows, which will be used to diagnose the mechanisms by which the submesoscale physical variability affects the export fluxes. These simulations can then be used to assess the larger-scale effect of submesoscale variations. EXPORTS will create submesoscale-resolving data products measuring the variability in the biological pumps both directly and through the use of proxies. The proxies will be generated and calibrated by more detailed measurements during intensive cruises and then applied to shipboard underway, autonomous and satellite measurements. These different techniques will sample different space and time scales, with the shipboard underway surveys making a few highly detailed spatial maps, the autonomous measurements making repeated but coarser surveys over a much longer period of time, and the satellites making intermittent spatially detailed maps of surface properties.

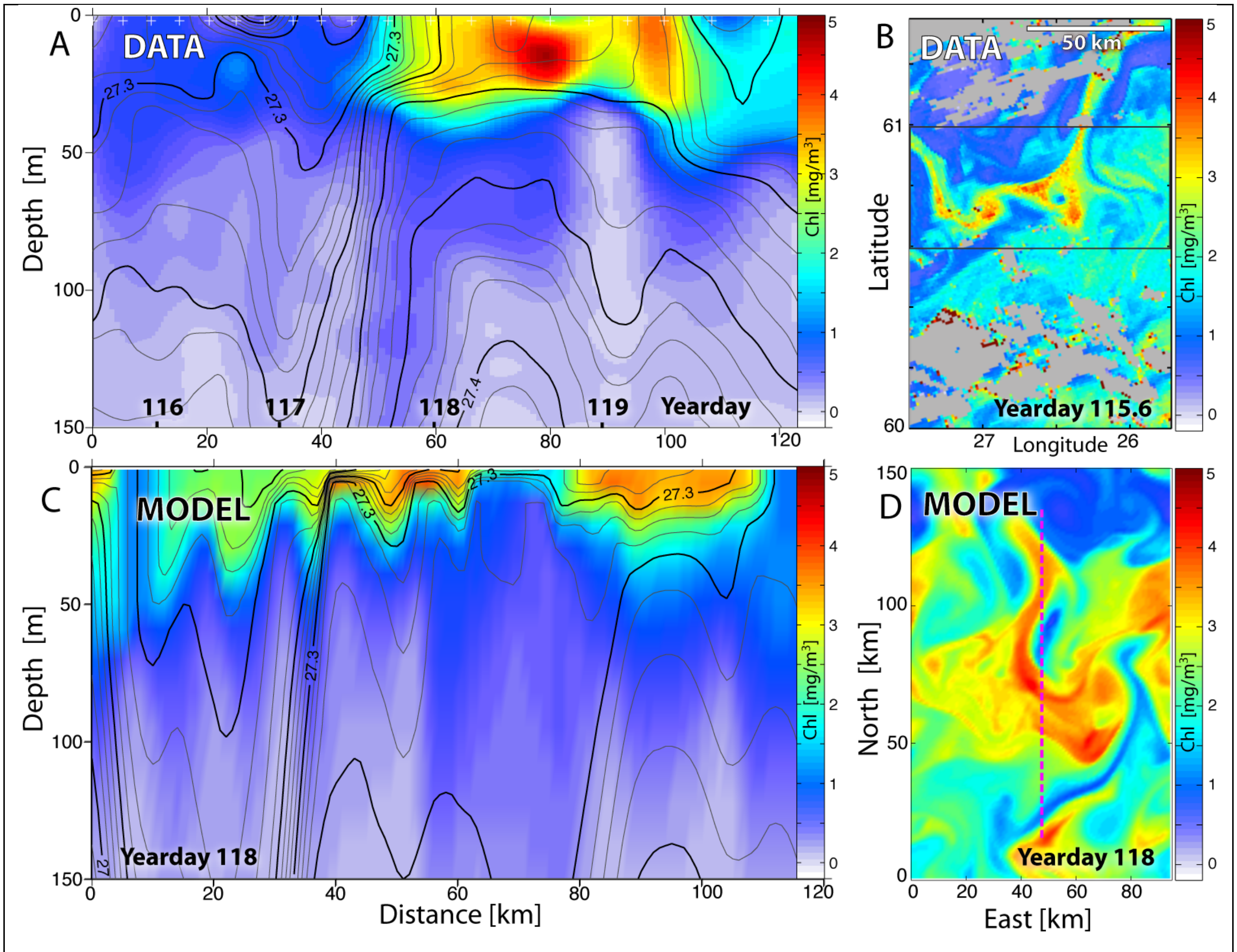

Figure 12*. Examples of the submesoscale structure of chlorophyll during the 2008 North Atlantic Bloom from both data (top row) and numerical models (bottom row). Measurements by both (a) an autonomous Seaglider and (b) the MODIS Aqua satellite chlorophyll show a factor of ~5 variability in chlorophyll over scales of less than 5 km in places. A high resolution coupled physical/biological model simulating the evolution of the bloom shows similar structures (c,d). The model predicts similar spatial variability in export rates (from Mahadevan et al. 2012).*

Seasonal convection of recalcitrant organic matter to depth is another mechanism where physical and ecological processes interact to export organic matter to depth. Biotic and abiotic processes can produce or transform DOM to recalcitrant (semi-labile) forms that create vertical concentration gradients in DOM (Fig 8a). In addition, the dynamics of DOM production can operate outside of the Redfield stoichiometry yielding a C-rich organic pool. The departure from Redfield stoichiometry means that for every new N and P atom introduced into the surface water, potentially more C can be stored in the DOM pool. Physical transport of DOM can be an important contributor to the biological pump if the seasonally produced DOM escapes microbial degradation in the surface waters long enough to be entrained to depth via convective overturn (Figure 13) or subduction along isopycnal surfaces. Geochemical models estimate that ~ 20% of the annual net community production is exported to depths > 100 m as DOC each year (~1.9 Pg C; Hansell et al. 2009). Once exported, the DOM and its remineralization byproducts travel along isopycnal pathways into the ocean's interior. Thus, although the magnitude of DOC export is less than that of passive particle flux it can be a highly efficient C export mechanism given the C-rich nature of DOM with global implications for the operation of the biological pump if it is mixed deep enough.

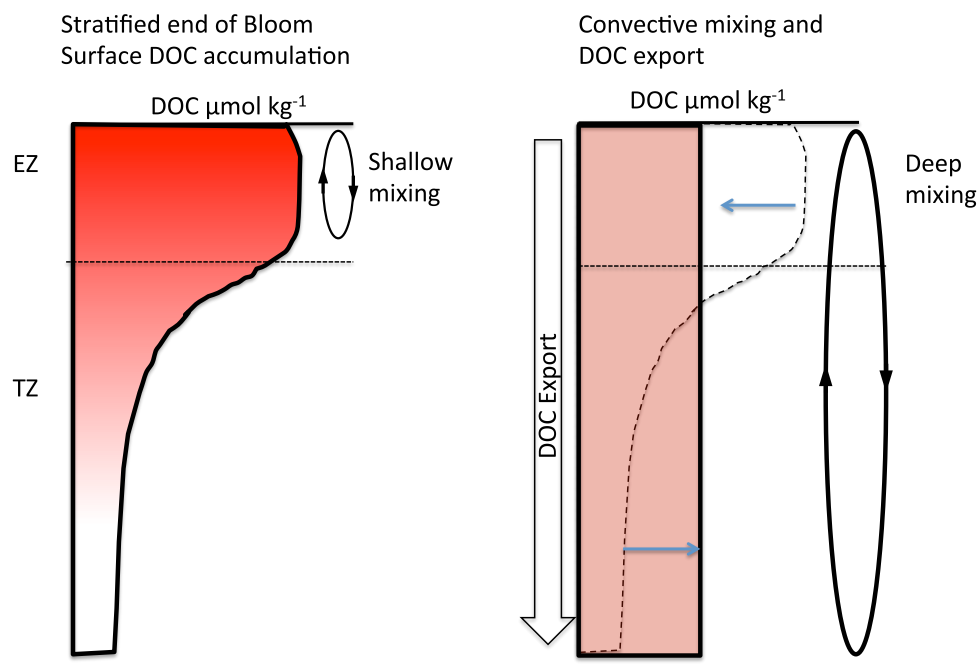

Figure 13 *Illustration of process exporting DOC and (implicitly) suspended POC (DOC/POC_s) from the surface ocean via convective mixing. The dark line represents DOC/POC_s profile in autumn (left) and during winter mixing (right). The dotted line on the right is the autumn profile superimposed on the winter profile. Horizontal arrows indicate dilution of DOC in the surface and enhancement of DOC in the TZ. The difference between the TZ column-integrated DOC in the winter from the vertically-integrated TZ DOC in autumn is the DOC export by convective mixing (Carlson et al. 1994, Hansell and Carlson 2001).*

The left hand profile in Figure 13 is the DOC and suspended POC (POC_s) left over after a bloom at the end of the season prior to deep mixing. The second profile is DOC/POC_s distribution during deep mixing. Export of DOC/POC_s = Integrated DOC/POC_s in TZ (winter)- Integrated DOC/POC_s in TZ (autumn).

The EXPORTS field campaign will produce integrated data products that allow for the quantification of the export caused by convective mixing. The cruise plan will enable collection of seasonal DOC/POC_s profiles during or shortly following convective mixing, during stratified spring/ summer periods and in autumn prior to deep mixing. Using a mass balance approach estimates export of DOC/POC_s via mixing can be determined by comparing the integrated stocks of DOC/POC_s within the upper mesopelagic (i.e., 140 – 500 m) during or shortly following convective mixing and that in autumn, prior to deep mixing via mixing. Export of DOC/POC_s = Integrated DOC/POC_s in TZ (winter)- Integrated DOC/POC_s in TZ (autumn).

The answering of this portion of SQ1D requires the measurement of stocks of DOC and POC_s over the seasonal cycle. The **Partitioning of Organic Matter** data product will need to include these measurements of DOC and POC_s inventories over the seasonal cycle. The EXPORTS science plan includes short deployment and recovery cruses that will enable the collection of DOC and POC_s inventories as well as other geochemical stocks over seasonal time scales (see timeline in Figure 10).

7.2 Science Question 2

Carbon exported from the surface ocean is only relevant to the global carbon budget if it remains sequestered from the atmosphere for a given time scale. The determination of that sequestration time scale is the subject of the second EXPORTS science question.

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

Differences in environmental and/or ecosystem features between regions will affect how fixed carbon mixed to or sinking through the mesopelagic zone is processed, and thus ultimately how much organic matter reaches depth. During downward transport sinking particles are transformed biologically by a number of processes that are influenced by regional environmental differences. For example, temperature structure of the water column will govern rates of metabolism and thus rates of heterotrophic processing of POM by mesopelagic bacterioplankton and zooplankton. Abundance and assemblage structure of the mesopelagic microbial and zooplankton community will affect how much sinking POM is consumed at depth, or to what extent organic matter originating in surface waters is introduced into the mesopelagic zone by migrating zooplankton. Differences in mixing depth and euphotic zone plankton community structure between regions (and seasons) will govern the amount and quality of organic matter (dissolved and particulate) available to mesopelagic consumers.

The first three sub-questions for question 2 relate to different aspects of how the efficiency of vertical transfer below the surface ocean is regulated by processes that create the sinking flux. Hence we will address the answers to these three sub-questions together as their data requirements are strongly interdependent. The last question addresses how environmental controls on the mesopelagic food web governs transfer efficiency through the mesopelagic via particle production and organic matter remineralization.

SQ2A: How does transfer efficiency of organic matter to depth vary between the four primary pathways for export?

SQ2B: How is the transfer efficiency of organic matter to depth related to plankton community structure in the well-lit surface ocean?

SQ2C: How do the abundance and composition of carrier materials in the surface ocean (cf., opal, dust, PIC) influence the transfer efficiency of organic matter to depth?

The production of organic carbon and PIC at the ocean surface ultimately drives the export of carbon at all ocean depths. This is because the transfer efficiency of organic matter to depth depends on the source and composition of the material produced by the overlying food web. This transfer can occur along several pathways in the biological pump. These include export associated with gravitational settling of several particles types, advection of organic carbon in dissolved and particulate form below the EZ, and vertical migration of zooplankton and their predators (Figure 3, pathways A, B, C). Each of these pathways may be further broken down into subcategories that differentially influence the quality of the sinking organic matter, and hence the depth dependent remineralization rate. Thus, the link between transfer efficiency below the EZ and processes that occur in surface waters are related to rates of net community production (how much organic C and PIC are produced), the composition of the EZ food web (e.g., recycling versus direct export influence content and quality) and the physical processes that mix both DOC, POC and PIC to depth on seasonal to annual time scales and physically aggregate and disaggregate particles between suspended and sinking phases. Active transport by vertical migration of zooplankton is triggered by light, seasonal availability of fresh organic matter, and the life cycles of zooplankton and their predators. The combination of these processes results in the largest attenuation of C flux in the upper 500-1000 m of the ocean, with highest remineralization rates just below the well-lit surface layer.

In its simplest form, the export efficiency of sinking particles and aggregates at any depth below the EZ should be proportional to the stock or concentration of a given particle type or size and its sinking rate (or Flux = Concentration * Sinking Rate).

Rapidly sinking large aggregates or fecal pellets transit the upper mesopelagic rapidly, which will reduce the amount of processing of these materials in the upper mesopelagic and the consequent loss of carbon to processes such as respiration or particle solubilization (see answers to SQ2D below). Other materials, such as small phytodetritus or small fecal pellets, sink slowly allowing ample time for subsurface food webs to process the associated carbon, decreasing the efficiency of export of these materials through the upper mesopelagic. Indeed, ballast materials such as bSi and PIC associated with these sinking particles are important, as they influence sinking speeds and possibly protect organic material from degradation. EXPORTS will determine flux, concentration and sinking rates of sinking particles and aggregates at multiple depths to look at variations in the control of these parameters in the mesopelagic.

The links between sinking particle attenuation and PC flux below the EZ, however, is quite complex, involving mid water zooplankton food webs tuned to feed on sinking particles, and bacteria that attach to aggregates and transform them into smaller organic or dissolved inorganic C components. In addition, surface food webs that export highly degraded or recycled material that sink slowly may have far less attenuation below the EZ than a food web that exports fresh and C rich particles, even if their sinking speeds are rapid, because of higher rates of heterotrophic degradation by mid water bacterial and zooplankton communities.

This leads to yet another pathway that has been the least studied relative to the others C export associated with the active migration of zooplankton to depth. Active transport of C by diel vertical migration of zooplankton that feed in surface waters during the night and return to their mesopelagic residence depths during the day occurs via respiration of CO_2 and release of DOC, the production of fecal pellets (POC), and zooplankton mortality, at depth (beneath the EZ). The magnitude of these various processes again depends on surface and mid water food web structure (short versus long food chain, biomass of migrating zooplankton) and has been shown to exceed the export of passively sinking particles depending on timing (bloom versus non bloom) and region (coastal versus open ocean).

The complexity of the biological pump’s mechanisms for the transfer of material from the surface ocean to depth requires that sampling moves beyond using simple strategies and platforms and instead employs a holistic approach that cuts across scales and methodologies. Using the measurements below, we will address the following integrated data products **Export, Particle Size Spectra**, **Partitioning of Organic Matter,** and **Solubilization, Grazing and Remineralization**.

To characterize these various influences on organic matter transport efficiency, depth profile measurements of bulk remineralization will be obtained using measurements of dissolved oxygen and nutrient profiles coupled with measurements of the elemental composition of sinking particulate organic matter and ^{234}Th profiles (**Solubilization, Grazing and Remineralization**). Specific components of gravitational settling will be interrogated using a combination of visual (cameras and gels) and *in situ* collection devices (traps and pumps) that can distinguish fecal pellets (pathway 1) from aggregates and phytodetritus (pathway 2) (**Particle Size Spectra**). The contribution of each of these components to depth attenuated organic matter flux can then be determined using direct biochemical measurements of the sinking organic matter and includes measurements such as elemental ratios and specific biomarkers (e.g., DNA) using new technologies (e.g., chemical separation, XANES, C and P NMR, nanoSIMS, fluorescence, etc.) (**Partitioning of Organic Matter, Solubilization, Grazing and Remineralization**). Vertical migration (pathway 2) will be interrogated using net tows and camera systems that include species identification coupled with onboard experiments to measure grazing and metabolism (**Solubilization, Grazing and Remineralization**). The remaining pathway, physical mixing of POC and DOC, will be determined using water column analyses coupled with ADCP measurements of vertical mixing (**Partitioning of Organic Matter**).

SQ2D: How does variability in environmental and/or ecosystem features define the relative importance of processes that regulate the transfer efficiency of organic matter to depth (i.e., zooplankton grazing, microbial degradation, organic C solublization, vertical migration active transport, fragmentation & aggregation, convection and subduction)?

Differences in environmental and/or ecosystem features between regions will affect how fixed organic carbon mixed to or sinking through the mesopelagic zone is processed, and thus ultimately how much organic matter reaches depth. During downward transport sinking particles are transformed biologically by a number of processes including remineralization by bacterioplankton or zooplankton, fragmentation of aggregates by zooplankton into slower- or non-sinking particles, solubilization of sinking POM to DOM via production of hydrolytic enzymes by attached bacterioplankton, and active transport of surface-derived organic matter by migrating zooplankton. In addition, physical processes such as deep convective mixing introduce DOM and suspended POM into the mesopelagic. Regional environmental differences will have profound effects on all these processes. Temperature structure of the water column will govern rates of metabolism and thus rates of heterotrophic processing of POM by mesopelagic bacterioplankton and zooplankton. Abundance and assemblage structure of the mesopelagic microbial and zooplankton community will affect how much sinking POM is consumed at depth, or to what extent organic matter originating in surface waters is introduced into the mesopelagic zone by migrating zooplankton. Differences in mixing depth and euphotic zone plankton community structure between regions (and seasons) will govern the amount and quality of organic matter (dissolved and particulate) available to mesopelagic consumers. Thus, this question will address how environmental controls on the mesopelagic food web governs transfer efficiency through the mesopelagic via particle production and organic matter remineralization.

To answer SQ2D we will analyze field data experiment products that address environmental/ecosystem controls on both biological and physical processes affecting organic matter transformations in the mesopelagic zone (see subquestions SQ2A-C). These include depth-resolved mesopelagic plankton community structure and metabolism in order to determine remineralization rates of sinking and suspended organic matter, and magnitude of active transport by migrating zooplankton. Measurement of the partitioning of organic matter between POM and DOM pools will help quantify the amount of organic carbon available for export through sinking vs. physical mixing. Regional comparisons of particle size spectra, combined with results from aggregation models, will address fragmentation and aggregation processes. Measurements of mixing depth and accumulated DOM bioavailability will address the efficiency by which DOM is entrained to depth via convective overturn or subduction along isopycnal surfaces into the ocean interior.

The answering of SQ2D requires integrated data products for **Export** and **Plankton Community Structure**, **Particle Size Spectra, Partitioning of Organic Matter**, and **Solubilization, Grazing and Remineralization**.

7.3 Science Question 3:

The third EXPORTS science question addresses the use of EXPORTS field observations in the prediction of the functioning of the biological pump. The third question asks…

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

Science question three has four sub-questions addressing how the EXPORTS data set can be best used to improve quantification of the biological pump. Clearly, the answer to question 3 and its sub-questions will come from numerical modeling and data synthesis aimed at addressing what really needs to be known (and how well) to quantify the biological pump. For example the first sub-question for science question three states…

SQ3A: What are the key plankton ecosystem characteristics (c.f., food-web structure and environmental variations) that are required to be observed to accurately model the biological pump?

The answer to SQ3A will come from two paths of inquiry. The first is a statistical analysis comparing the **Export** products to factors that are expected to drive changes in the magnitude and efficiency of export from the euphotic zone and its transmission to depth. There are many factors as discussed above that drive carbon export from the surface ocean. Integrated data products for these factors include **Plankton Community Structure**, **Particle Size Spectra**, **Aggregation / Disaggregation Rates**, and so on. A major overall synthesis effort for EXPORTS will be a multivariate statistical analysis of the roles of these factors on export, export efficiency and its attenuation with depth. This meta-analysis will be facilitated by the many states of the biological pump measured during EXPORTS as well as the results of the data mining exercise. This will provide assessment of what the key ecosystem characteristics are that regulate the state of the biological pump.

The second approach is to use coupled ecological/biogeochemical/physical models developed and tested using the EXPORTS data set. Here the numerical representation of particular processes can be altered and their influences on modeled solutions for changes in export flux, efficiency, and vertical attenuation can be evaluated. For this, idealized coupled ecological/biogeochemical/physical models will be used (addressed in section 5.6 above). A comparison between the results of the numerical modeling studies and the statistical meta-analysis described here will identify the key planktonic ecosystem characteristics that regulate the state of the biological pump.

SQ3B: How do these key planktonic ecosystem characteristics vary across states of the biological pump and can they be assessed knowing surface ocean processes alone?

Once these key planktonic ecosystem characteristics are identified, their variations across the EXPORTS data set can be addressed. Here the goal is to develop a parametric understanding of the key planktonic ecosystem characteristics across states of the biological pump and to assess whether knowledge of the surface ocean is sufficient in constraining these key characteristics needed to accurately predict the state of the biological pump. Again this is a case where both a meta-analysis of the EXPORTS data set and the use of coupled ecological / biogeochemical / physical models developed and tested using the EXPORTS data set will be useful. First the predictability of key ecosystem characteristics identified above will be explored statistically using EXPORTS observation from the entire water column and then using data only from the surface ocean. In this way we can answer the question of the degree of predictability of the key planktonic ecosystem characteristics across states of the biological pump.

Modeling approaches will include producing model simulations driven by varying amounts of data and comparing their output with the EXPORTS data set. For example, models will be run using data from surface data only and results will be compared with different metrics derived from the EXPORTS data (e.g. metrics for the strength of different export pathways and the effect and composition of the mesopelagic food web on flux attenuation etc.). Additional, non-surface components can be added to the models and the exercise can be repeated to learn the level of detail required to accurately predict the key ecosystem characteristics across the different states of the biological pump.

SQ3C: Can the biological pump be accurately modeled from satellite-retrievable properties alone or will coincident in situ measurements be required?

A goal of the EXPORTS project is to develop and validate advanced algorithms for observing the magnitude and efficiency of the biological pump from satellite data. The key points in achieving this goal is 1) an assessment of the degree to which the goal can be met and 2) what improvements can be made by simultaneously deploying autonomous assets over global scales. Again, both empirical and numerical modeling approaches will be useful to test the degree to which the states of the biological pump can be predicted from satellite observables alone and to the extent in which coincident in situ measurements (such as from autonomous samplers) are required. Here, Observing System Simulation Experiment (OSSE) models are likely to be especially useful.

SQ3D: What are the key plankton ecosystem characteristics (cf., food-web How can the mechanistic understanding of contemporary export processes developed here be best used to improve predictions of the biological pump under future climate scenarios?

This question needs to be answered using coupled Earth System Models that address marine ecological and biogeochemical changes on regional to global scales (e.g., Moore et al., 2013). The EXPORTS project needs to develop and test advanced parameterizations of the biological pump and to use these models to predict future states of the strength and efficiency of the ocean's biological pump. Research is needed to evaluate how to incorporate advanced process models such as those explained above and to make forecasts of future states of the pump.

8.0 Implementation Plan

The implementation plan presented here is not meant to be a complete blueprint of how the field campaign should be conducted. Rather, it attempts to list the major implementation issues that need to be resolved as the plan becomes implemented as a major NASA field campaign. A cost estimate is also developed for the proposed science plan with de-scoping and re-scoping options depending on budget and partnership realizations. Again this cost estimate is included as rough guidance and a more thorough analysis of implementation is required.

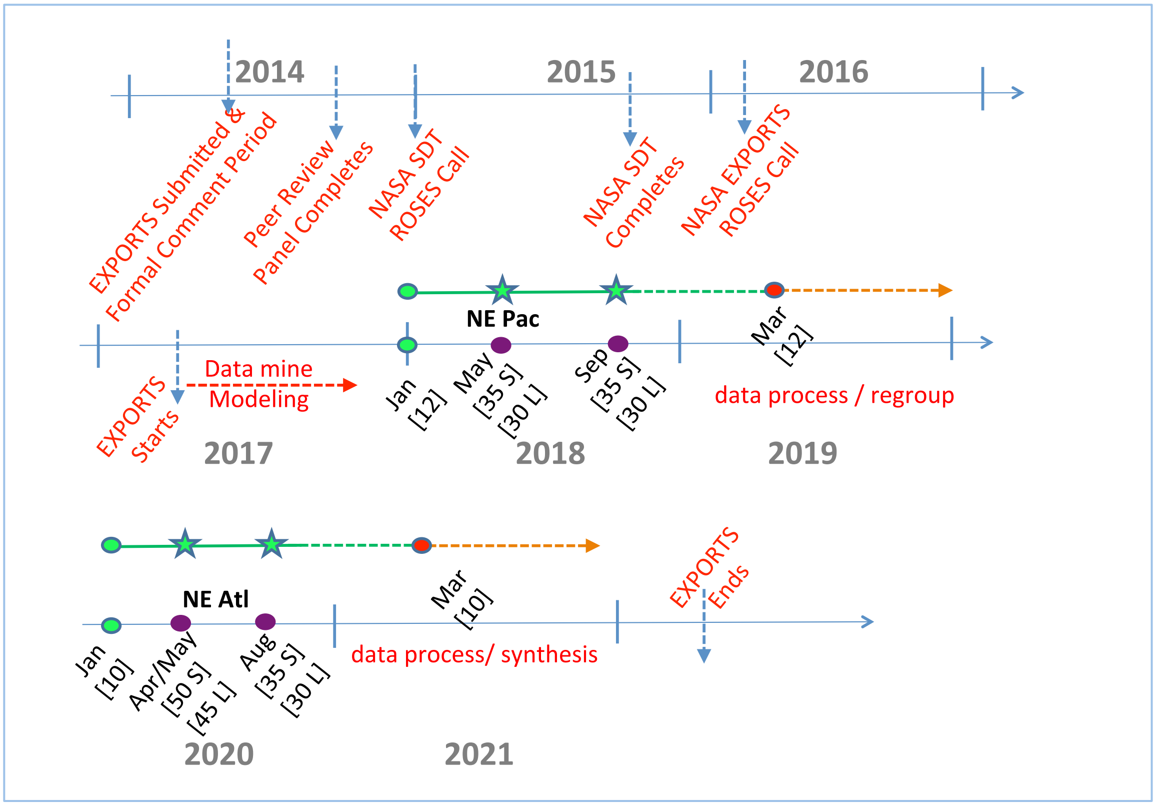

Figure 14 *Notional timeline for the EXPORTS implementation. See text for details. The timeline is notional and has not been approved by NASA. It is included here to illustrate the steps that the EXPORTS plan must go through before its first field season.*

8.1 Timeline Forward

The pathway for implementing the EXPORTS field campaign depends on many factors and an unofficial notional timeline forward from this point in time is presented in Figure 14. The planning history for EXPORTS up to this point is summarized in Section 11.4 of this document. The EXPORTS science plan has been submitted to NASA for its consideration. NASA will post the final report for a 60-day public comment period at the NASA Carbon Cycle and Ecosystems website (http://cce.nasa.gov/cce). A Peer Review

Panel set by NASA will review the final plan along with the public comments and make recommendations. With this information NASA will decide whether to go forward with the EXPORTS major field campaign plan or not. If the EXPORTS science plan is selected, NASA will solicit a call for proposals for a Science Definition Team (SDT) likely in early 2015. The SDT will be given a cost range and will build from the present science plan and propose an implementation plan for EXPORTS. Again if this is successful, a NASA grant solicitation for participation in EXPORTS will be released in 2016 with the EXPORTS program starting in 2017 (Figure 14). Keeping to the above timeline and the present science plan, fieldwork in the NE Pacific will commence in early 2018 and the NE Atlantic in early 2020. At the present time, 2020 is the expected launch readiness date for PACE and 2021 is the EXPORTS synthesis year.

8.2 Emerging Technologies and Technical Readiness

There are many emerging technologies that would benefit the EXPORTS field campaign. Some of these technologies will enable researchers a deeper understanding of the plankton community structure on unprecedented time and space scales while others would expand the suite of measurements that could be made from an autonomous platform. Still other advances in technical capacity would develop new numerical models that would allow the EXPORTS PI's to best design their sampling program. The goal here is to suggest where technical investments now would help improve EXPORTS (or similar) field program.

It must be stressed that EXPORTS will make fundamental advances in understanding the biological pump using present technologies. However advances are being made and it seems prudent to assess what will be ready in 2017 when EXPORTS starts. We might also be able to help identify markets for the developers of these technologies.

One area where technological advancements would help EXPORTS is in optical oceanography. There is a critical need to link EXPORTS field observations to the NASA's up coming PACE satellite mission. PACE is planned to be a UV-Vis-NIR hyperspectral (5 nm resolution) satellite sensor designed to quantify phytoplankton functional types and to accurately partition phytoplankton optical properties from colored DOM absorption (PACE SDT, 2012). Advances in optical field measuring systems are needed to provide the proper field observations for developing and validating algorithms for PACE. These include full spectral reflectance measurements and inherent optical property (IOP) sensors that operate in the ultraviolet spectral range. These technical advancements are needed for the PACE mission regardless if EXPORTS were to occur. Several reviewers of the draft report suggested the deployment of advanced aerial unmanned vehicles to map out surface chlorophyll distributions around the Lagrangian ship. This thought is intriguing considering the intense cloudiness of the two focal study sites.

Continued advancements in our ability to identify and quantify plankton communities would also be very useful for the ship-based sampling proposed for EXPORTS. Many of these ship-based tools are on the cusp of wide adoption by the oceanographic community including flow cytometric and image analyses tools, use of acoustics to assess zooplankton, and genomics approaches for a suite of planktonic organisms. Advances are also needed for ship-based methods for assessing the particle size spectrum from tenths of microns to centimeters and to make accurate measurements of phytoplankton carbon concentrations from the background of suspended POC. Similar improvements need to be made in our ability to quantify rates of particle sinking speeds as a function of size and type.

EXPORTS would benefit from the continued development of low-power, long-lived sensors to be deployed from autonomous platforms. This includes adapting many of the technologies, in particular imaging systems, suggested in the above paragraph to autonomous platforms. Further new sensors to measure dissolved inorganic carbon (DIC) concentrations from floats and gliders would be useful and another way of estimating export production via mass budgeting using autonomous measurements of dissolved oxygen and nitrate (e.g., Johnson et al. 2009). Another related need is the commercialization of neutrally buoyant sediment traps based upon profiling float technologies (e.g., Buesseler et al. 2000; Saw et al. 2004).

The development and application of Observing System Simulation Experiment (OSSE) modeling systems is one area where a small investment will greatly help the EXPORTS field program. These OSSE's need to include coupled physical-ecological-biogeochemical dynamics and must resolve submesoscale spatial scales (approaching 1 km in the horizontal) and processes. Use of such an interdisciplinary oceanographic OSSE would be used to optimize field program logistics helping to keep the field program's costs manageable. This development and experimentation needs to be conducted in preparation for the EXPORTS field project.

Last, the complicated nature of the proposed multi-ship / multi-autonomous platform sampling scheme proposed for EXPORTS means that upfront planning is needed for platform command and control as well as data integration. A capability is needed to coordinate the sampling of the ships and autonomous platforms driven by observations from the field site as well as available satellite and operational oceanographic model output. Satellite communication from ships-to-shore makes this possible. It is likely that this system will need to be operated by the EXPORTS project office. It can also provide ship-autonomous platform-satellite match-up data sets among platforms to assist in the intercalibration of the autonomous platform sensor data.

8.3 EXPORTS Data Product Creation and Data Management

The creation and use of integrated data products (section 6.7) are central to answering the EXPORTS science questions. The EXPORTS project office will coordinate the creation of the data products and will work will all PI's to set field reporting and metadata standards. The EXPORTS project office will likely create some of the integrated data products (see Section 8.5 below). However it is likely that the responsibility of many of the EXPORTS data products will be PI-led activities.

The EXPORTS data products will be published a year after the last field campaign in a special issue of a data journal, such as Earth System Science Data http://www.earth-system-science-data.net/). This will provide the essential EXPORTS data results to the wider community. These publications will include details of all the data collected as part of this project. In this publication, all the pertinent aspects of the data (methods of collection and analysis, QA/QC procedures, access) will be provided to maximize its use by the larger community.

EXPORTS will follow NASA's data policy, requiring all PIs to post all the data they have been funded to collect in a public data repository (following quality control), no later than a year following their collection. The project web site will provide updated links to all the data repositories where data have been submitted (SeaBASS, BCO-DMO, PANGAEA, etc.). All EXPORTS data will be archived on NASA's SeaBASS.

8.4 Uncertainty and Error Analysis

As with all NASA Ocean Biology and Biogeochemistry projects, all measurements and analyses will have well documented protocols collected at the project management office. This will help insure interoperability of data, etc. This includes the quantification of uncertainties for each measurement and the tracking of error propagations in the integrated data products.

Uncertainties come in many flavors, all of which will be taken into account and propagated appropriately; there are measurement uncertainties (no instrument measures perfectly) which will be assessed from cross-instrument comparisons (>resolution), uncertainties due to imperfect relationship between what we sense and the proxy we are trying to obtain (e.g. POC from beam attenuation at 660nm, nitrate from absorption in the UV). These require that we collect a sufficient set of measurement for comparison (and/or rely on previous studies). Remote sensing algorithms have similar uncertainties that require a significant number of independent match-ups to constrain.

While measurement uncertainty about the mean value can be reduced by averaging over many realizations of a phenomenon, this is not the case when a bias, or systematic error, exists. To minimize the latter it is critical to revisit algorithms and assess and remove potential sources of bias (e.g. treatment of blanks, assumption about water properties in remote-sensing algorithm etc.).

Uncertainties in measurements can be reduced by careful pre- and post-deployment calibration, cross calibration between similar sensors in the field and by cross-comparing variables that, while fundamentally different, should be related (e.g. different estimates of particle load). With respect to measurements on an autonomous platform, cross-sensor inter-comparisons, measurements at depth (~2000m) and comparison to surface measurements (be it from R/V or satellite) will provide indication of sensor stability.

8.5 Project Management & Governance

The EXPORTS field campaign is obviously a large project with many deliverables and participants as well as complicated logistics. To support these efforts, it is recommended that EXPORTS establish a dedicated project office over its lifespan. The project office will handle cruise planning, timeline management, logistics support for the cruise deployments, communication among investigators, data management, public and agency outreach, web presence, meeting logistics and many other project coordinating tasks both within the project and with external domestic and international partners. The project office will coordinate regular telecons, annual PI meetings, post-cruise data workshops and synthesis and modeling workshops. Coordination of the elements of the EXPORTS field program (ships, floats, gliders, modeling, etc.) will be performed by the project office and posted on the EXPORTS website. The success of EXPORTS requires adequate funding be set aside for project coordination, data management and post-cruise data, synthesis, and modeling workshops, all of which will substantially enhance NASA's investment in field and remote sensing measurements.

EXPORTS data management will need to be coordinated by the project office, and the project office will construct and serve a comprehensive project database that will be transferred to the appropriate data archive center at the end of the project. In particular, the EXPORTS project office will coordinate the creation of the data products, will work will all PI's to set field reporting and metadata standards and will serve the data set to all EXPORTS PI and the wider scientific community. The EXPORTS project office may also create some of the integrated data products (see Section 8.3). However the responsibility of many of the EXPORTS data products will likely be PI-led activities coordinated by the project office.

The EXPORTS project office should also coordinate training activities for young scientists. These include contributing to on-going summer school courses for graduate students (UMaine, IOCCG, etc.). EXPORTS might choose to conduct a summer school of its own focusing on the marriage of autonomous sampling, carbon cycle science, ocean optics and remote sensing, and numerical modeling that makes up the EXPORTS field campaign. Another area where the EXPORTS project office can help in the training of young scientists is to help them establish scientific leadership skills and credentials. This can be done by recruiting promising young scientists into leadership roles on the EXPORTS governing committee (next paragraph) or as junior chief scientists on the field deployments. We expect that one of the major outcomes of EXPORTS is the training of the next generation of interdisciplinary marine scientists.

A governing committee of no more than five participants will administrate the EXPORTS field campaign. The governing committee will include the EXPORTS Project Scientist who may or may not necessarily be the one administering the EXPORTS project office. The members of the governing committee must span the areas of research to be conducted by EXPORTS (remote sensing, modeling, biogeochemistry, autonomous sampling, food web, etc.) and may include promising young scientists. The governing committee will advise the EXPORTS project office, orchestrate the staging of all field activities and facilitate and monitor all established partnerships. The governing committee will also work closely with the chief scientists on each EXPORTS field deployment. All decisions by the governing committee will be made following a consensus process and working in conjunction with the PI team and NASA agency representatives. We expect the governing committee will meet via telecons on a regular basis and in person several times each year. It may be useful to constitute the governing committee before the final funding decisions on individual PI grants are made for EXPORTS.

Clearly, EXPORTS requires a diverse assortment of measurements and models to answer its science questions. The listed measurements (Section 6.4) and numerical models (Section 6.6) in this science document identifies which measurements and models will be useful for answering the EXPORTS science questions. One must expect that there will be funding limitations and not all useful measurements and models will be feasible to include in the field effort. A detailed discussion of which measurements and models are *essential* and which are *desirable but not essential* will need to be made as the implementation plan is drafted. This follows the measurement priority levels used in the CLIVAR/Repeat Hydrography and GeoTRACES programs. Hopefully the governing committee could contribute to these discussions before the solicitations are drafted for participation in the EXPORTS field campaign.

An EXPORTS core measurement team needs to be established that will perform the collection and analysis of basic state variables. This will allow more of the competed resources to go to science PI's rather than science infrastructure activities. Measurements to be coordinated by the core measurement team include many that can be outsourced to known laboratories. These include but are not limited to CTD profiling, macronutrients, HPLC phytoplankton pigments, stocks of DIC, PIC, POC, DOC, in situ primary production, etc. The parameters measured by the EXPORTS core measurement team need to be established in advance of the open competition for EXPORTS funding. One idea is to make the core measurement team a component of the EXPORTS project office, but other individual subcontracts arrangements are also possible. The goal is to make the highest quality and most cost-effective core measurements for EXPORTS science.

Another concern is that we need to ensure that all of the major pathways of the biological pump are sampled as part of the EXPORTS field campaign; yet there needs to be an open competition for the best science and required funding to make these measurements. Gaps in the suite of essential measurements will make it very difficult for EXPORTS to succeed. One path is to have PI's write individual proposals, sort out from the winning proposals what is missing and what is essential for EXPORTS' success and focus a second solicitation on the missing pieces. Another path is to solicit proposals for integrated data products as listed in Table 3. Then investigators would self-organize into groups and would propose to create the integrated data products. This would help ensure the creation of the data products and reduce the likelihood of gaps in the essential measurement suite. However, the measurement teams approach may be too complicated to conduct in an open solicitation of this type. Last, most EXPORTS principle investigators should be supported through the 5-year duration of EXPORTS. This will help insure the synthesis of all measurements and the answering of the stated science questions.

The comments here in section 8.5 on project organization, governance and investigator roles reflect considerations based upon prior experience of the Science planning group in large ocean and remote sensing campaigns as well as many comments from the draft science plan reviewers. This discussion is presented to help access the logistical requirements and thus costs for EXPORTS to succeed, and does not replace the need for a more detailed implementation plan that would happen if and when EXPORTS field campaign is approved by NASA.

8.6 Partnerships

Partnerships with up-coming U.S. and international research programs will be an important component for the implementation of the EXPORTS science plan. Partnerships bring logistical resources to a project, such as ship time and support for particular aspects of the overall science plan. Partnerships also expand the intellectual breadth of the program bringing the best scientists in the world to study important problems. There are many interdisciplinary marine science research programs being planned presently, which is rapidly evolving. These partnerships should be made once

NASA approves the EXPORTS science plan and begins its implementation. In the following we list a couple obvious partnering opportunities for EXPORTS. The listing is not meant to be exhaustive and we expect many other potential partners to emerge over the next couple of years.

Partnerships with on-going and planned satellite ocean color programs are natural partners with EXPORTS. For example, we have already described the links between the PACE mission and its science team with EXPORTS. Other upcoming satellite ocean color missions such as ESA's/EUMETSAT's Ocean Color and Land Imager (OCLI) and JAXA's Second-Generation Global Imager (SGLI) are two examples of potential partner satellite programs with EXPORTS. EXPORTS carbon cycle satellite algorithms and calibration / validation data will be useful for these mission data sets and the OCLI and SGLI ocean color data will be useful for interpreting and modeling the EXPORTS observations. There are other planned and ongoing satellite ocean programs from the U.S. and international participants (http://www.ioccg.org/sensors_ioccg.html), all of which are potential partners with EXPORTS.

The SeaWiFS Bio-optical Archive and Storage System (SeaBASS; http://seabass.gsfc.nasa.gov) is publicly shared archive of in situ oceanographic and atmospheric data maintained by the Ocean Biology Processing Group at the NASA Goddard Space Flight Center and is another potential partner for EXPORTS. The implementation plan for EXPORTS should bring the SeaBASS team into the data management project as early as possible to insure the wide use of the EXPORTS data set and the integration of carbon cycle science parameters into the SeaBASS archive. Other national and international data management projects (BCO-DMO, etc.) are also potential partners for EXPORTS (see Section 8.3 above).

There are several potential partnerships with on-going programs that were considered in the development of the EXPORTS Science plan. In particular, the two global node arrays in the Ocean Observatories Initiative (OOI; http://oceanobservatories.org), one in the North Pacific at Station Papa (50ºN, 145º W) and one in the subpolar North Atlantic in the Irminger Basin (60ºN, 39ºW) that can contribute to EXPORTS. The two OOI nodes should be operational by the end of 2015 and are considered as important assets for the EXPORTS science plan. Each array consists of a central mooring with a full suite of metrological sensors, 2 subsurface flanking moorings with oxygen, optical backscatter, chlorophyll and CDOM fluorescence at a fixed depth within the euphotic zone, and 3 to 5 gliders with chlorophyll fluorescence and optical backscatter. The arrays are to be operated as community resources, and can be re-tasked within certain constraints. The OOI is supported by the U.S. National Science Foundation. The OOI array at Station Papa supplements the long-standing Canadian Department of Fisheries and Oceans Line P program, and the NOAA Ocean Climate moorings with pH and CO_2, which would be useful partners for EXPORTS. The Station Papa OOI global node will be an important element to the EXPORTS implementation. The Irminger Basin OOI node is at 60ºN and therefore does not meet several of the site location criteria listed in Section 6.2.

There are several other potential partners that should be identified, including the recently NSF-funded OSNAP project (Overturning in the Subpolar North Atlantic Program; http://www.o-snap.org), with international collaborations in the U.K., Germany, the Netherlands and Canada, which will quantify the large-scale, low-frequency fluxes of mass, heat and fresh water associated with the meridional overturning circulation in the subpolar North Atlantic. By instrumenting two deep mooring lines, a west line spanning from Labrador to southern Greenland and an east line spanning from Greenland to Scotland, OSNAP will simultaneously measure surface ocean currents that carry heat northward toward the Arctic Ocean and deep ocean currents that carry cooler waters southward toward the equator. The collection of DOC and suspended POC profiles during OSNAP cruises will enable estimates of the sequestration of organic carbon via the global meridional overturning circulation.

Horizon 2020 is the new European Union (EU) initiative to enhance European science competitiveness; two topics are relevant to EXPORTS are BG-01-2015 ("Improving the preservation and sustainable exploitation of Atlantic marine ecosystems") and BG-08-2014 ("Developing in-situ Atlantic Ocean Observations for a better management and sustainable exploitation of the maritime resources"). Both build on the recently signed Galway Statement on Atlantic Ocean Cooperation and anticipate collaboration with North Americans. The goal of BG-01-2015 is to deepen the understanding of the biogeographic patterns, biodiversity, biogeochemistry and ecosystem services in North Atlantic ecosystems. The ultimate goal of BG-08-2014 is to objective to deliver the knowledge base supporting the understanding of the Ocean Process at the level of the entire basin through establishment of an Integrated Atlantic Ocean Observing System (IAOOS). Within IAOOS is a heavy reliance on *in situ* observations, including floats and gliders, including integration of biological measurements. This activity should accelerate the efforts of individual national programs that are currently deploying a subset of ARGO floats with biogeochemical sensors. Additionally, partnering EXPORTS with the Bio-ARGO program should be very fruitful (http://www.argo.ucsd.edu/Bio-Argo_AST14.pdf).

To further collaboration in the subpolar North Atlantic-Arctic system among EU, Canada and US scientists, an invitational workshop was held in April 2014 in Arlington, Virginia, with agency representation from NSF, NASA, NOAA and the EU Commission. The intended outcome of this workshop is a framework for developing coordinated interdisciplinary projects, including biogeochemical fluxes and integrated food web processes (http://www.whoi.edu/website/NAtl_Arctic/). Abundant examples exist for time-series and processes studies carried out by individual organizations or nations (e.g., Porcupine Abyssal Plain, ESTOC, Iceland's quarterly cruises to the Irminger and Iceland Sea; see http://www.whoi.edu/website/TS-workshop/home for a list of time-series sites). A major challenge will be synchronization of funding opportunities across the various national entities.

Last it would be very useful if researchers would be able to write individual proposals to work along side or as part of the EXPORTS field campaign with support from U.S. and international science agencies in addition to NASA. This would greatly expand the scope of the research and the academic diversity of the EXPORTS team, as well as extending the NASA support for EXPORTS. Again these partnerships will need to be launched once a decision to support EXPORTS is made by NASA. One thing that would help with establishing individual partnerships is the overt effort to keep space open for investigators that are not part of the initial science plan. We urge that the implementation plan for EXPORTS keep a non-trivial fraction of the ship berths and wire time available for individual researchers to propose their own research that extends the scientific utility of the EXPORTS field program.

8.7 Required Resources and Budget Estimate

To meet the goals set out for EXPORTS requires a 5 year funding timeline and considerable resources for autonomous platforms, ship time, logistical support, data management, project office, and most importantly, support for wide range of scientists and their groups to participate in this study. To make an initial scaling of resource requirements we have taken the field program as outlined in 6.3 and Figure 10 and made estimates of the cost of each program element. The total cost for EXPORTS based upon this analysis is roughly $53M (the spreadsheet used is provided in Section 11.3).

The components and costs used in this budget estimate can be summarized as follows:

Ship time: Assume day rates of $50K/day, $40K/day and $20K/day for Lagrangian (L), spatial (S) and float (F) deploy/retrieval cruises, respectively. Days required are 60 (P), 70 (S), 24 (F) for NE Pacific field program and 75 (P), 85 (S) and 20 (F) for NE Atlantic field program. These costs vary of course with final ports and ship choices, and are scaled here to/from Seattle for NE Pacific, and from Woods Hole and in to Southampton (to reduce steam time) in NE Atlantic. These costs total $13.8 M over the course of EXPORTS or about 27% of the total, with higher costs in years 2 & 4.

Autonomous floats and gliders: We do not specify a specific current float or glider design, but use current floats and gliders to obtain an estimate of about $5.3 M for what is proposed here for the variety and number of in-situ platforms to be deployed during the two field programs. This is about 10% of the overall EXPORTS budget. As discussed in 6.3, the profiling floats are deployed before and during cruises, and are left behind for longer observations beyond the field year. Four of each type (Bio-ARGO; particle size; particle flux proxy) are budgeted here for each of the two field locations. Some of the autonomous platforms will be recovered and redeployed, so used in both field sites, and these include some type of mixed layer floats (2 per field site) and time - series mesopelagic sediment traps (5 depths). Gliders similarly will be turned around after each field year (3 for 30 km and 3 for 300 km inner and outer grids) and limited spares are included for the budget for gliders, ML floats and traps. For any given field year, there may be up to 30 of such devices in the water, allowing us to extend observations in space and time required to address the questions put forth by EXPORTS and relate these to the remote sensing observations and models. Because of the need to have these instruments in hand before the field years, the costs are higher in years 1, 2 & 3 when the majority of these platforms would be purchased.

PI costs: The largest costs for EXPORTS are related to the scientists and labs conducting the study. The PIs will be responsible for the wide range of measurements, observations, modeling and remote sensing activities as detailed in sections 6.4, 6.5 and 6.6. We have taken the measurement lists in Table 1 and assigned groups of PI's that might take on several tasks to reduce overall lab groups. By doing this and considering other program activities (such as modeling; shore operation centers, etc.) we expect that roughly 50% of the budget, or about $26M, would be needed to support 20 multi PI projects for 5 years. As might be expected in a field intensive program such as EXPORTS, costs would higher on average for PIs and their labs in the field years 2 & 4, and should be ramping down in year 5. It will be essential that the PI's, chosen through peer review, cover the full range of expertise needed for remote sensing, modeling, autonomous floats, gliders, particle cameras, sediment traps, optical instruments, field-based biogeochemical studies, etc. The costs per group would not be equal. Core groups would need to be supported to commit to a multi-year field program of this magnitude. In considering different scoping options (see below) and how to build the strongest program, maintaining this range of PI skills will be paramount to the success of EXPORTS.

Other essential elements: The remaining 15% of this budget we anticipate would be spend on data management ($2.5M or 5%), a Project Office ($2M or 4%), logistical assistance for field work ($1.25M or 2%) and initial equipment for the PI's that is dedicated to the project and required on shore or on the ship to complete the proposed measurements ($2M or 4%). While the breakdown may well vary, all of these are significant additional costs that are not included in the other funding estimates.

Summary: When added together, we reach an estimate of the total funding needed for EXPORTS on the order of $53M. Given the proposed time line, expenses would be highest in field years 2 & 4 and at the start of the program year 1, running roughly $10, 15, 8, 15, and 5 million dollars over years 1, 2, 3, 4, 5 respectively. What will need more refinement as EXPORTS planning progresses, is whether or not costs can be shared with other partners (federal, international, section 8.7), as well as whether additional funds are needed to enhance modeling and remote sensing analyses, as well as platform developments, especially prior to the launch of EXPORTS. Also, it is difficult to constrain accurate costs for ships and logistics (including shipping costs) without an actual cruise plan. However we feel that the relative ratio of each component would be on the order calculated here, with roughly 50% going to participants labs, 10% to instruments used in-situ (a key program element in EXPORTS) and 25% needed for the muti-ship operations with two main, two ship observation periods in each basin.

De/Rescoping Options: It is perhaps premature to discuss rescoping options for EXPORTS, but it should be noted that descoping options that would allow EXPORTS to address the fundamental questions are limited because the foundation of the program involves the unique combination of in-situ, ship-based and remote sensing observations and modeling of different states of the biological pump. Cutting out components of these simultaneous activities would mean opening gaps in the understanding of the flow of carbon between surface and deeper layers of the ocean and the processes that control them. Thus rather than remove specific research elements, a path to descope would include studying fewer than two states of the biological pump at two sites. Descoping is an area where partnering with additional agencies and/or international efforts might be very fruitful.

On the other hand, it is easy to see how to build upon the EXPORTS science plan, adding in components that are perhaps less NASA relevant and essential to our goals, but take advantage of the unique set of observations and models proposed here to study the biological pump. These might include studies that add additional emphasis and detail on the midwater food webs and ecology. Additional effort could also be added on those parts of the food web that are at both ends of the size spectrum of carbon reservoirs, and include biological processes that may respond to and by their activities impact carbon export and remineralization. At the smallest end, these include additional work on viruses and microbes and their impact on particle properties, biogeochemical cycles and community structure, and at the large end, fish or other predators that can move organic carbon in both the horizontal and vertical directions. Studies to augment EXPORTS that include measurements of these internal cycling rates and external inputs/export fluxes would enhance our understanding and add to the scope and costs of EXPORTS. In addition, one could argue that more states- either different settings or seasonal measurements will be required to extrapolate EXPORTS observation in the NE Atlantic and NE Pacific to other ocean basins. Given the ambitious nature of what is already proposed and budgeted, we anticipate that advances during EXPORTS would lead to further refinement of the tools needed to make these multi site and seasonal comparisons more efficiently and effectively, so they are not included here in the 5 year time line or budget. Finally, the state of the in-situ technologies is growing by leaps and bound, and additional support for sensor and glider/float enhancements should not only be encouraged, but is likely to be taking place during the planning period (see Section 8.3) and should be taken advantage of (and sensor development is not budgeted here).

8.8 EXPORTS Science Traceability Matrix

A Science Traceability Matrix (STM) links science questions to approaches for answering them to measurement requirements to additional needs. The EXPORTS STM (Figure 15) traces the path (from the left column) to Science Questions to Approach & Science Plan to Measurements to Requirements (in the right column). Specifically the EXPORTS STM address the Requirements needed to answer the stated science questions.

Figure 15 *The 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 (≥ 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

9. Outcomes

The goal of EXPORTS is to monitor the state of the ocean's biological pump from satellite observations and to improve predictions of its changes into the future. Achieving this goal is among the hardest problems in the Earth sciences, as it requires a predictive understanding of the ecology, chemistry, physics and optics of the oceans as well as the ability to model these processes numerically and assess them from satellite observations. Answering the EXPORTS' science questions will accelerate our knowledge regarding the oceanic food web's roles in the global carbon cycle and will provide novel satellite remote sensing approaches and new numerical models for predicting contemporary and future states of the biological pump. To achieve the goal of EXPORTS, many new observational and numerical modeling tools will need to be deployed and their results integrated and synthesized. Through its successful execution, EXPORTS will greatly advance our understanding and interdisciplinary knowledge of our global living oceans.

There are many societal reasons why this predictive understanding is important. This includes reducing uncertainties of the ocean carbon export and its sequestration within the ocean interior with the ultimate goal of implementing operational systems for monitoring the state of the biological pump. Changes in the ocean's biological pump also have important roles in future levels of global deoxygenation, hypoxia and ocean acidification. All of which have important impacts on ocean ecosystem services such as fisheries yields, nutrient recycling and maintenance of biodiversity.

EXPORTS will create the next generation of ocean carbon cycle and ecological satellite algorithms to be used on NASA's upcoming PACE mission. These will improve our understanding of global ocean carbon dynamics and reduce uncertainties in our ability to monitor of ocean carbon export fluxes and its sequestration within the ocean's interior. EXPORTS will help PACE achieve its goals of understanding and observing the ocean's carbon cycle.

Last, the EXPORTS field campaign will train and inspire the next generation of interdisciplinary ocean scientists working together on one of the hardest and key problems in the Earth sciences. It is the creation of our future ocean science leaders that we hope to be one of the lasting legacies of EXPORTS.

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11. Additional Materials

11.1 Acronyms

ADCP	Acoustic Doppler Current Profiler
ALOHA	A Long term Oligotrophic Habitat Assessment time-series station north of Hawaii
AUV	Autonomous Underwater Vehicle
BATS	Bermuda Atlantic Time-series Station southeast of Bermuda
BCO-DMO	Biological & Chemical Oceanography Data Management Office
BGC	Biogeochemical
BSi	Biogenic silica
C	Carbon
CDOM	Colored Dissolved Organic Matter
Chl	Chlorophyll
C_{phyto}	Phytoplankton biomass retrieved from satellites
CTD	Conductivity, temperature and depth sensors
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DSR	Deep-Sea Research
EP	Export Production
EQPAC	EQuatorial PACific -JGOFS project to study the upwelling zone of the equatorial Pacific.
EZ	Euphotic Zone.
Ez-ratio	POC flux at the base of the Euphotic Zone normalized by the NPP rate
FCM	Fluorescence Correlation Microscopy
GPP	Gross Primary Production
HNLC	High Nutrient Low Chlorophyll
HPLC	High Performance Liquid Chromatography
HOT	Hawaiian Ocean Time-series
IOP	Inherent Optical Property (absorption & scattering coefficients, etc.)
JGOFS	Joint Global Ocean Flux Study
Kd	Diffuse attenuation coefficient
LISST	Laser In Situ Scattering and Transmissometry (device to estimate the particle size distribution from forward light scatter)
LOPC	Laser Optical Plankton Counter
LwN	Normalized water leaving radiance
ML	Mixed Layer
MLD	Mixed Layer Depth
N	Nitrogen
NAB08	North Atlantic Bloom experiment 2008
NABE	JGOFS North Atlantic Bloom Experiment
NCP	Net Community Production
NMR	Nuclear Magnetic Resonance
NOMAD	NASA bio-Optical Marine Algorithm Dataset

NPP	Net Primary Production
OOI	Ocean Observatories Initiative
OCLI	Ocean Color and Land Imager
OSNAP	Overturning in the Sub-Polar North Atlantic Program
OSP	Ocean Station Papa
OSSE	Observation System Simulation Experiment
P	Phosphorus
PACE	Pre-aerosol, Clouds and Ecosystems satellite mission
PAP	Porcupine Abyssal Plain
PAR	Photosynthetically Active Radiation
PDMPO	2-(4-pyridyl)-5-((4-(2 dimethylaminoethylaminocarbamoyl)methoxy)phenyl)oxazole
PFT	Plankton Functional Type
PIC	Particulate Inorganic Carbon
PN	Particulate Nitrogen
PSD	Particle Size Distribution
POC	Particulate Organic Carbon
SeaBASS	SeaWiFS Bio-Optical Archive and Storage System
SIMS	Secondary Ion Mass Spectrometry
SMS	SubMesoScale
SSS	Sea Surface Salinity
SST	Sea Surface Temperture
SVT	Settling Velocity Trap
T/S	Temperature & Salinity
TEP	Transparent Exopolymer Particles
TS	Time-series
TZ	Twilight Zone (or mesopelagic zone)
UVP	Underwater Vision Profiler
VPR	Video Plankton Recorder
XANES	X-ray Absorption Near Edge Structure

11.2 Complete Measurement Table and References for Methods

Table 1 in the text lists the required measurements and approaches for the EXPORTS field campaign. Given the context of its presentation in the main text, Table 1 does not include typical methods for the required measurements. A complete list of measurements and method references are available online at the following URL's.

Table of measurements:
http://exports.oceancolor.ucsb.edu/system/files/documents/CompleteMeasurementTable_June03_2014.xlsx

Measurement references: http://exports.oceancolor.ucsb.edu/system/files/documents/MeasurementTableRefs_June03_2014.pdf

Please understand that the choices of references included in these tables are not meant to be restrictive and prescriptive. They are only provided to give examples and ideas of what is possible for the EXPORTS Science Definition Team to work from as they work on the implementation plan for EXPORTS.

11.3 Project Cost Estimation Spreadsheet

The project cost estimation details are presented in Section 8.7 of the EXPORTS science plan. Table 4 presents the spreadsheet used for these calculations, which includes additional details for how the ship time request was estimated as well as the annual resources required.

Table 4 EXPORTS project estimate spreadsheet

	In situ floats, gliders, traps						Glider	Glider		Ship Days	Ship Days	Ship Days
Cruise	**Bio-Argo**	**P Siz**	**Flux**	**ML float**	**TS trap**	**NBST**	**300km**	**30km**		**Lagrangian**	**Spatial**	**Deploy/retrieve**
NE Pacific												
Deploy	4	4	4	2	4	5	3	3		60	70	24
Recover	N	N	N	Y	Y	Y	Y	Y				
NE Atlanic												
Deploy	4	4	4	2	4	5	3	3		75	85	20
Recover	N	N	N	Y	Y	Y	Y	Y				
Min	8	8	8	2	4	5	3	3				
Spares	0	0	0	1	1	2	2	2				
total # req	8	8	8	3	5	7	5	5		135	155	44
unit cost	$100	$100	$75	$200	$100	$75	$150	$150		$50	$40	$20
total cost	$800	$800	$600	$600	$500	$525	$750	$750		$6,750	$6,200	$880
Total gear	$5,325							**Total Ship**		$13,830		
										Ports used for calc.		
Cost of Science Teams										**NE Pacific**	47.6N 122.3W Seattle	
# Groups	**$/y**	**year**	**1 time equip.**	**$/project**							50.7N 144.5W Papa	
20	250	5	100	1250								
										NE Atlantic	41.5N 70.7W Woods Hole	
SUMMARY											49 N 16.5W PaP	
Gear	**Ship Days**	**PI's (20)**	**PI Equip**	**Logstics**	**Data Man**	**Project Off**	**TOTAL**				back to	
$5,325	$13,830	$25,000	$2,000	$1,250	$2,500	$2,000	$51,905				50.8N 1.4W Southhampton UK	
10%	27%	48%	4%	2%	5%	4%						
* PI permanent equipment avg. $100/group; Logistics $250/yr; Data $500/yr; Project office/mtg $400/yr												
YEARLY BREAKDOWN (rough estimate)												
years	1	2	3	4	5	sum						
totals/yr	$10,000	$15,000	$8,000	$15,000	$4,000	$52,000						
%/yr	19%	28%	16%	29%	8%							
* assumes most of ship time in Yr 1 & 3; equip highest in yr 1; PI costs higher in field years, lowest in year 5												
All costs in $1K units												

11.4 EXPORTS Planning Process

The EXPORTS science plan was created to be a community consensus plan for understanding the biological pump from satellite observables. The process from submission of the initial proposal for NASA support of the planning process to the completion of the science plan took just more than two years. The initial proposal was submitted in response to the ROSES-2012 program element A.3, Ocean Biology and Biogeochemistry. The scoping plan proposal was for the planning of a NASA field campaign entitled “Controls on Open Ocean Productivity and Export Experiment – COOPEX”. The support for COOPEX was for a one-time experts meeting at the University of California, Santa Barbara (UCSB), communications and the final production of the science plan. David Siegel and Ken Buesseler are the co-PI’s of the COOPEX scoping plan proposal.

Table 5: Membership and Expertise of the EXPORTS Writing Team

Name	Organization	Expertise
David Siegel	UCSB	Co-PI; Remote sensing, ocean optics & modeling
Ken Buesseler	WHOI	Co-Pi; Biogeochemistry & export
Mike Behrenfeld	Oregon State	Phytoplankton & remote sensing
Claudia Benitez-Nelson	Univ. South Carolina	Biogeochemistry & export
Emmanuel Boss	Univ. Maine	Autonomous sampling, ocean optics & remote sensing
Mark Brzezinski	UCSB	Phytoplankton & biogeochemistry
Adrian Burd	Univ. Georgia	Modeling of export processes
Craig Carlson	UCSB	Microbial oceanography
Eric D’Asaro	UW	Physical oceanography & autonomous sampling
Scott Doney	WHOI	Earth system modeling, biogeochemistry & remote sensing
Mary Jane Perry	Univ. Maine	Phytoplankton, autonomous sampling
Rachel Stanley	WHOI	Biogeochemistry & geochemical techniques
Deborah Steinberg	VIMS	Zooplankton & biogeochemistry

The approach to creating the EXPORTS science plan was to develop community consensus through regular telecoms with a dedicated writing team, a one-time intense experts meeting at UCSB to set the science plans goals and questions and by informing the community and responding their feedback. Feedback came in the form of responses to presentations at national and specialist meetings as well as written comments submitted on the draft plan (dated Feb. 19, 2014). Agency feedback from NASA as well as NSF program managers was also considered in the planning process. In particular, this public vetting / feedback process for creating a science plan was new to the NASA Ocean Biology and Biogeochemistry program.

The composition of the writing team was set at the time of the writing of the initial scoping plan proposal. Members were chosen based upon their expertise and academic leadership in a particular area of the science and/or sampling of the ocean's biological pump as well as their enthusiasm for the task at hand and track record for working well as a team (Table 5). The writing team created the initial goals and questions for the experts meeting at UCSB, wrote the EXPORTS science plan and responded to community and agency feedback. The writing team started working together starting in the fall of 2013. Interactions among the team members have mostly been via telecons that occurred generally every other week with work by team members in between telecons.

Table 6: Attendees of the EXPORTS Experts Meeting at UCSB

Name	**Organization**	**Expertise**
Barney Balch	Bigelow	Phytoplankton & calcification
Mike Behrenfeld	Oregon State	Phytoplankton & remote sensing
Claudia Benitez-Nelson	Univ. South Carolina	Biogeochemistry & export
Paula Bontempi	NASA HQ	NASA planning
Mark Brzezinski	UCSB	Phytoplankton & biogeochemistry
Ken Buesseler	WHOI	Biogeochemistry & export
Craig Carlson	UCSB	Microbial oceanography
Dave Checkley	UCSD/SIO	Autonomous sampling & zooplankton
Curtis Deutsch	UCLA	Earth system modeling & biogeochemistry
Scott Doney	WHOI	Earth system modeling, biogeochemistry & remote sensing
Kim Halsey	Oregon State	Phytoplankton physiology
Debora Iglesias-Rodriguez	UCSB	Phytoplankton & calcification
George Jackson	Texas A&M	Particle aggregation & autonomous sampling
Ken Johnson	MBARI	Autonomous sampling & biogeochemistry
Mike Landry	UCSD/SIO	Zooplankton & biogeochemistry
Craig Lee	Univ. Washington	Physical ocean & autonomous sampling
Stephane Maritorena	UCSB	Remote sensing & ocean optics
Norm Nelson	UCSB	Ocean optics, remote sensing & biogeochemistry
Uta Passow	UCSB	Plankton processes & export
Mary Jane Perry	Univ. Maine	Phytoplankton & autonomous sampling
Paul Quay	Univ. Washington	Biogeochemistry & geochemical techniques
David Siegel	UCSB	Remote sensing, ocean optics & modeling
Heidi Sosik	WHOI	Phytoplankton & autonomous sampling
Rachel Stanley	WHOI	Biogeochemistry & geochemical techniques
Deborah Steinberg	VIMS	Zooplankton & biogeochemistry
Dariusz Stramski	UCSD/SIO	Ocean optics & remote sensing

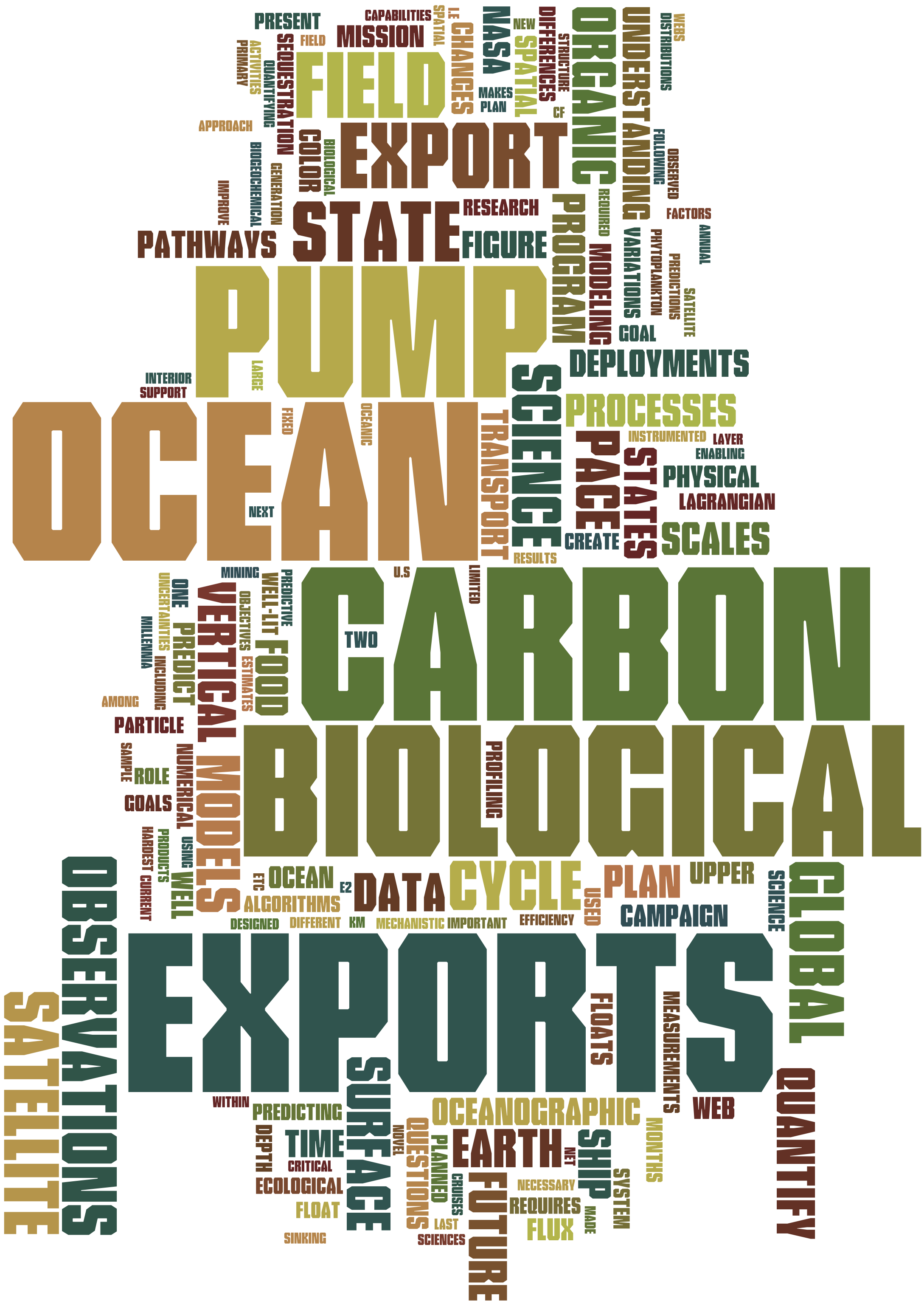
The experts meeting at UCSB was held June 3-6, 2013 focused on finalizing the overall goals and the science questions for the planned field campaign. The experts were invited from the community with focus on their expertise and representation of the many issues and institutions that potentially can contribute to EXPORTS (Table 6). Project goals and science questions were discussed at the experts meeting. Also a preliminary sampling plan was created.

Of particular significance, it was realized at the experts meeting that the original COOPEX plan, which required constraining both the production and the fate of fixed organic carbon, was too ambitious and the COOPEX plan was going to be very difficult to achieve because of budgetary (and berthing) limitations. At the meeting, it was decided that the biological pump field campaign should focus on the fates of fixed carbon and not its production (besides measurements required to improve remote sensing algorithms). It was there and then that the EXport Processes in the Ocean from RemoTe Sensing (EXPORTS) field campaign was born.

There have been many opportunities for community inputs to the EXPORTS science plan since the experts meeting. This includes the 2013 and 2014 Ocean Color Research Team (OCRT) meetings where the EXPORTS plan was presented orally and with a poster. The EXPORTS plan was also presented at the 2013 U.S. Ocean Carbon and Biogeochemisty (OCB) meeting with both oral and poster presentations. Also, there were many sidebar discussions at these meetings with the writing team members and these comments were synthesized and discussed as the writing team proceeded with the science plan. It is stressed that at each presentation, community inputs improved the EXPORTS science plan.

The major roll out of the EXPORTS science plan occurred at the 2014 Ocean Sciences Meeting (OSM) in Honolulu. The draft report was presented in a scheduled talk by Siegel, a poster by Buesseler, and an evening Town Hall discussion. Nearly every member of the writing team was at the OSM. All events were very well attended. Again community feedback was synthesized by the writing team and used in improving the science plan.

At the OSM, the draft report was made available via the EXPORTS website at UCSB (http://exports.oceancolor.ucsb.edu) for public comment. The EXPORTS writing team solicited written comments on the draft plan from February 25, 2014 to April 15, 2014. Nearly 100 downloads of the draft report were made and 25 written comments were either posted to the UCSB EXPORTS website or emailed to the exports email at USB (exports@eri.ucsb.edu). All comments were carefully considered and synthesized in the final submission (this document).



EXPORTS Science Plan Wordle…