EXport Processes in the Ocean from RemoTe Sensing

EXPORTS Implementation Plan

EXPORTS Science Definition Team

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1.0 Summary

The goal of the Export Processes in the Ocean from RemoTe Sensing (EXPORTS) field campaign is to develop a predictive understanding of the export and fate of global ocean primary production and its implications for the Earth's carbon cycle in present and future climates. EXPORTS builds upon decades of NASA-supported research assessing global NPP from space and is designed to deliver science of significant societal relevance by better characterizing the fate of organic carbon in the ocean.

EXPORTS' overall approach is to develop and validate ocean carbon cycle models from observations made over a range of ecosystem / carbon cycling (ECC) states. Observations of the fundamental NPP export and fate pathways as well as supporting data are required to develop satellite algorithms and numerical models that are valid over the global range of ECC states. Thus field data are needed from both intensive field campaigns, such as those detailed in the EXPORTS Science Plan, as well as previous results mined from the literature.

The goal of this document is to present an efficient strategy to implement the EXPORTS Science Plan that will successfully answer the EXPORTS Science Questions. This plan, the Goal Plan, is presented here along with a range of descoping options for the overall program. The draft Implementation Plan addresses the measurements and model activities needed to occur as well as notional cruise, project management, data management and partnership plans. A robust cost estimate for the Goal Plan is presented along with descoping options and an analysis of the balance between investment and success of descoping from the Goal Plan. Detailed planning documents are included in the supplemental materials section. This draft Implementation Plan is an attempt to find an *efficient* solution that optimizes *value to the agency*, *opportunities for transformable discovery* and *broad community participation*.

Implementation of the EXPORTS field campaign, if it were to occur, may look very different from the draft plan outlined here for many reasons. As such, we are soliciting comments from the community on this draft Implementation Plan and how it enables the EXPORTS Science Plan to be successfully conducted.

2.0 Introduction to the EXPORTS Implementation Plan

The goal of the Export Processes in the Ocean from RemoTe Sensing (EXPORTS) field campaign is to develop a predictive understanding of the export and fate of global ocean primary production and its implications for the Earth's carbon cycle in present and future climates. EXPORTS will test the hypothesis that the fates of ocean NPP are regulated by the state of the surface ecosystem, which links remote sensing science to oceanic carbon cycling processes. Developing a predictive understanding of the fates of global NPP and their roles in the carbon cycle is a NASA agency objective and builds upon decades of NASA-supported research assessing global NPP from space.

EXPORTS is designed to deliver science of significant societal relevance, representing a key component in the U.S. investment to understand Earth as an integrated system by better characterizing the fate of organic carbon in the ocean. The overall approach presented in the EXPORTS Science Plan is to develop and validate ocean carbon cycle models from observations made over a range of ecosystem / carbon cycling (ECC) states. Observations of the fundamental NPP export and fate pathways as well as supporting data are required to develop satellite algorithms and numerical models that are valid over the global range of ECC states. Thus field data are needed from both intensive field campaigns, such as those detailed in the EXPORTS Science Plan, as well as previous results mined from the literature. The Science Plan, this document and other supporting information is available at the NASA Carbon Cycle and Ecosystems webpage - http://cce.nasa.gov/obb/exports. A high-level description of the Science Plan is also available in Siegel et al. [2016].

The EXPORTS Science Plan has been through extensive community vetting, formal comments and a peer review panel (a detailed history of this process is included in Sections 11.4 to 11.7 of the EXPORTS Science Plan). In October 2015, NASA competed the formation of a Science Definition Team (SDT) to create an Implementation Plan that to guide EXPORTS' execution (see NASA's Charge to the SDT). This document is an initial draft of that plan. Service on the EXPORTS SDT has been entirely voluntary and no compensation was provided from NASA. The SDT will be disbanded after submission of this final plan. It is important to recognize that the SDT is only suggesting a potential implementation to NASA and does not have the authority to advise or direct the agency.

The goal of this document is to devise an efficient strategy to implement the EXPORTS Science Plan as proposed, vetted and approved by NASA. This required the SDT to devise a field, modeling and synthesis research program that will answer the EXPORTS Science Questions effectively. The SDT termed this plan the Goal Plan. To implement the Goal Plan, the SDT needed to understand and quantify many factors, including:

- The measurements & models required to answer the EXPORTS Science Questions,
- Efficient and effective cruise, project management & partnership plans,
- A robust cost estimate for the Goal Plan, and
- Suggestions for descoping options along with analysis of the balance between agency investment and program success.

This draft plan is the SDT's attempt to find an *efficient* solution that optimizes *value to the agency*, *opportunities for transformable discovery* and *broad community participation*.

At times, the Implementation Plan may appear prescriptive in its formulation. This approach was necessary to create a robust estimate of the required resources necessary to achieve the Goal Plan. Implementation of the EXPORTS field campaign, if it were to occur, may look very different from the implementation plan outlined here. Factors driving such differences would be available resources, the establishment of partnerships with U.S. or international agencies other than NASA, the results of competition for roles within the program, and the integration of new ideas into the planning of the field campaign.

Last, this document is only intended to provide NASA suggestions of how to implement the EXPORTS Science Plan as stated in NASA's Charge to the SDT. Hence, this document is not intended to provide guidance to individuals planning to propose to participate in EXPORTS nor does it describe how the competition process could occur. If EXPORTS is conducted, competition-specific instructions will come from NASA directly.

REQUEST FOR COMMUNITY INPUT:

The EXPORTS program does not yet exist and may not unless the ocean science community communicates that EXPORTS is an important priority. As noted above, the EXPORTS Science Plan has already been thoroughly vetted with the community. This document suggests an efficient strategy to implement the EXPORTS Science Plan.

The SDT is keenly interested in comments from the community on this draft Implementation Plan and how it enables the EXPORTS Science Plan to be conducted. We welcome comments on the suitability of the plans presented, but are especially interested in comments regarding:

- Alternative descoping options to those suggested in Section 5.2,
- Costing of the Goal Plan and the descoping options outlined Sections 5.1 and 5.2,
- Input on potential national and international partnerships and their interactions with the suggested timeline as outlined in Section 6,
- Proposed timeline and phasing of the Goal Plan program and the cruises (Section 4.1),
- Project and data management (Section 4.6) and
- Capacities not reflected in the plan that could make important contributions to the measurement suite and/or modeling (Sections 3.0 and 4.1).

Note that many of the details needed to actually conduct the Implementation Plan are expanded upon in the supplementary materials of this document (embedded URLs to these documents are provided in this document).

Prior to commenting, please be familiar with the EXPORTS Science Plan (see http://cce.nasa.gov/cce/pdfs/EXPORTS_Science_Plan_May18_2015_final.pdf) and/or the recent synopsis published in *Frontiers of Marine Science* (Siegel et al. 2016).

Please email your comments to: obb_comments@cce.nasa.gov by September 1, 2016

3.0 Science Questions to Requirements

By design, the EXPORTS measurement, modeling and synthesis program will deliver science of societal relevance. Figure 1 shows a conceptual diagram linking program resources and elements to societal benefits. EXPORTS is built on three Science Questions (SQ) whose answers provide major benefits to how we can monitor the export and fates of net primary production (NPP) in the modern ocean, but also how we predict change under future climates. To answer these questions, EXPORTS will examine the role of each of the five pathways of organic material transport from the surface ocean into the interior by measuring a suite of 80 observables that are grouped into 5 key Program Elements (Figure 1). PI-driven projects will address domain-specific science objectives as well as performing the syntheses needed answer the science questions. Resources include, but are not limited to, observations from oceanographic cruises, autonomous platforms and remote sensing as well as a range of numerical modeling efforts. The modular design of EXPORTS suggests that it can be easily augmented by national and international partnerships providing additional expertise and complementary science. Considerable preparation will also underpin EXPORTS through recently funded NASA projects focused on data mining and observing system simulation experiments (OSSEs). These efforts build a database of states from the literature, a knowledge base to inform the choice of locations and extend the dynamic range of states available, and OSSEs, to refine experimental planning (Figure 1).

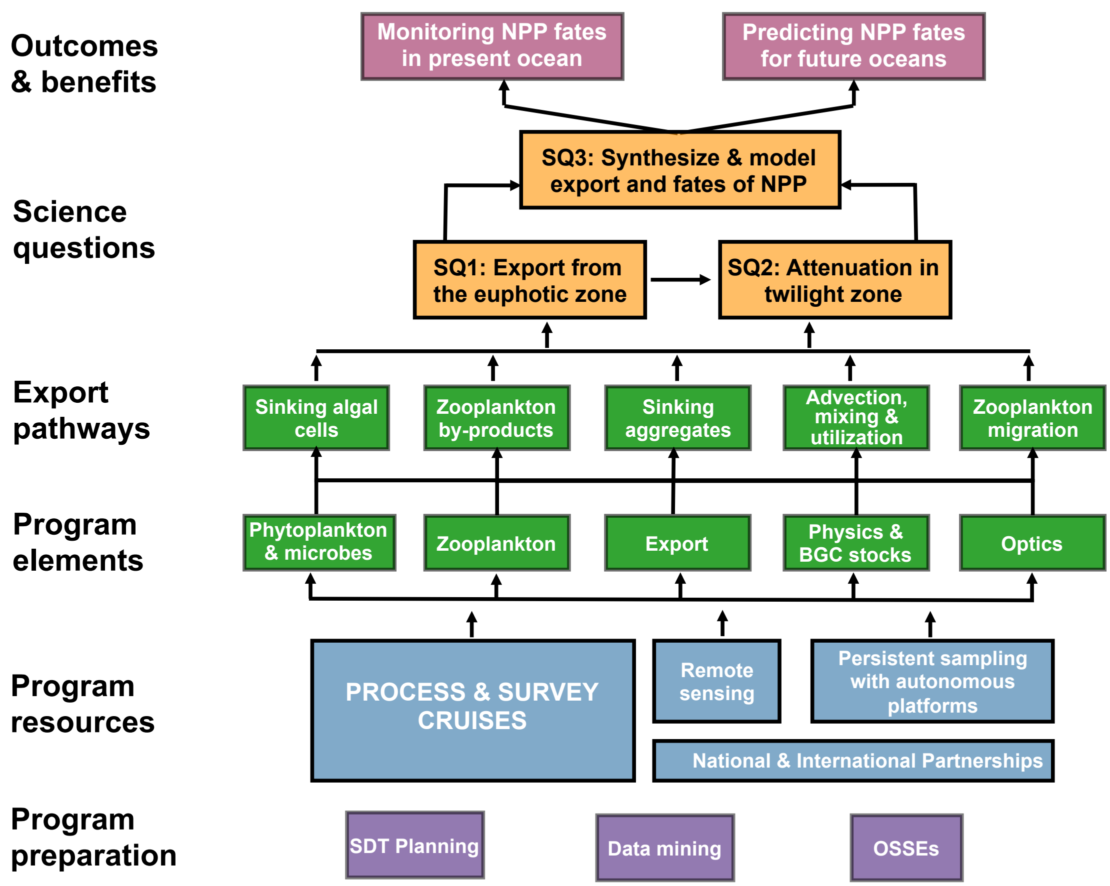

Figure 1 – The EXPORTS conceptual diagram linking program preparation, resources and elements via export pathways to science questions and societally relevant outcomes.

The EXPORTS Science Plan identifies 3 key interrelated questions concerning the fate of ocean net primary production (Table 1). Science Questions 1 and 2 focus on how processes in the surface and the subsurface pelagic control the export (SQ1) and attenuation (SQ2) of organic matter into the ocean interior. SQ1 and SQ2 are broken down into four sub-questions that identify the most significant current uncertainties in our understanding of those ecosystem characteristics that promote export of organic matter and controls on the efficiency of its vertical transfer into the ocean's interior.

Table 1: **EXPORTS Science Questions and Associated Sub-Questions**

SQ1	**How do upper ocean ecosystem characteristics determine the vertical transfer of organic matter from the well-lit surface ocean?**
1a	*How does plankton community structure regulate the export of organic matter from the surface ocean?*
1b	*How do the five pathways that drive export (cf., sinking of intact phytoplankton, aggregates or zooplankton byproducts, vertical sub-mesoscale advection & active vertical migration) vary with plankton community structure?*
1c	*What controls particle aggregation / disaggregation of exported organic matter and how are these controls influenced by plankton community composition?*
1d	*How do physical and ecological processes act together to export organic matter from the surface ocean?*
SQ2	**What controls the efficiency of vertical transfer of organic matter below the well-lit surface ocean?**
2a	*How does transfer efficiency of organic matter through the mesopelagic vary among the five primary pathways for export?*
2b	*How is the transfer efficiency of organic matter to depth related to plankton community structure in the well-lit surface ocean?*
2c	*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?*
2d	*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)?*
SQ3	**How can the knowledge gained from EXPORTS be used to reduce uncertainties in contemporary & future estimates of the export and fate of upper ocean net primary production?**
3a	*What key plankton ecosystem characteristics (cf., food-web structure and environmental variations) are required to accurately model the export and fate of upper ocean net primary production?*
3b	*How do key planktonic ecosystem characteristics vary and can they be assessed knowing surface ocean processes alone?*
3c	*Can the export and fate of upper ocean net primary production be accurately modeled from satellite-retrievable properties alone or will coincident in situ measurements be required?*
3d	*How can the mechanistic understanding of contemporary planktonic food web processes developed here be used to improve predictions of the export and fate of upper ocean net primary production under future climate scenarios?*

Science Question 3 asks how the answers to SQ1 and SQ2 improve current and future estimates of ecosystem / carbon cycling processes and their implications on larger time and space scales (SQ3). The dependence of SQ3 on SQ1 and SQ2 also suggests that EXPORTS can be implemented in two phases where Phase 1 tackles SQ1 and SQ2 together, while Phase 2 uses the resulting information (and data mined observations) to answer SQ3. Because of the dependency of SQ3 on SQ1 and SQ2, here we emphasize greater detail on Phase 1. Implementation of Phase 2 is discussed in Section 4.5.

Table 2: **Measurements Sorted into Program Elements Needed to Answer Science Subquestion 1C** (The Complete Measurement Table lists needs for all subquestions).

Program element	Platform	Methods	EXPORTS science question needs	Measurement types & examples	Questions Addressed		Survey cruise priority	Process cruise priority
					Q1	Q2		
Phytoplankton	CTD	FCM	Phytoplankton biomass proxies and diversity	flow cytometry (number, volume, groups); imaging cytometry	1abc		1	1
Phytoplankton	CTD	FCM	Phytoplankton biomass	sorting flow cytometry/imaging	1abc		no	1
Phytoplankton	CTD	FCM	Heterotrophic prokaryote concentration (cell number) and size/volume, including viral	e.g., flow cytometry with staining and epfluorescencei microscopy	1abcd	2abcd	1	1
Phytoplankton	CTD	FCM	Heterotrophic nanoflagellate and larger protist concentration (cell number) and size/volume	e.g., flow cytometry, digital imaging microscopy, inverted microscopy	1abc	2abcd	1	1
Phytoplankton	CTD	omics	Phytoplankton community composition	DNA-based community composition (genetic profiling) & microbial and phytoplankton metatranscriptomes	1abc	2abc	2	1
Phytoplankton	CTD	omics	Heterotrophic prokaryotic community composition	DNA-based community composition (genetic profiling)	1abd	2abcd	2	1
Zooplankton	nets	community	Zooplankton metazoan concentration (cell number) and	Net Tows - vertical	1abc	2abcd	1	1
Zooplankton	sensor	accoustics	Zooplankton metazoan biomass	Acoustics	1abc	2abcd	1	2
Zooplankton	nets	day/night tows	Zooplankton metazoan concentration (cell number) and size/volume	Net tows- day/night depth resolved with microscopic or digital analysis	1abc	2abcd	no	1
Zooplankton	nets	experimental	Fragmentation	Experiments with zooplankton impacts on particle size spectra	1c	2abcd	no	1
Export	trap	optics	Particle flux EZ & TZ- trap based	Optical flux gauges (on trap and/or independent float)	1abc	2abcd	no	1
Export	Multi	cameras	Aggregate PSD and flux derived from particle distributions	particle cameras (e.g., UVP, VPR, LOPC, etc.)	1abc	2abcd	1	1
Export	Multi	cameras	Zooplankton metazoan biomass	In situ camera (e.g. UVP, VPR)	1abc	2abcd	1	1
Export	CTD	experimental	Aggregation & disaggregation	Aggregation experiments	1c	2abc	no	1
Optics	Multi	sensor	PAR, above-water and subsurface	PAR	1abcd		1	1
Optics	CTD	sensor	Spectral particle absorption & attenuation	acs	1abcd	2abc	1	1
Optics	CTD	sensor	Spectral particle attenuation	acs	1abcd	2abc	1	1
Optics	Multi	sensor	Remote sensing reflectance (subsurface obs)	Ed (l) & Lu (l)	1abcd		1	1
Optics	ship	sensor	Water-leaving radiance (-->remote sensing reflectance) above water	Lw (l)	1abcd		1	no
Optics	ship	sensor	LIDAR	ship-mounted LIDAR	1abc		2	no
Optics	Multi	sensor	Single wavelength beam c and bbp (ie 650 nm)	acs/C-Star/C-Rover, transmissometers	1abcd	2abcd	1	1
Optics	CTD	sensor	Birefringent (calcite) particles	polarized beam c (WETLabs PIC/POC sensor)	1abcd		2	2
Optics	CTD	sensor/geochem	Total small particle size spectrum	e.g., Coulter Counter (bench), LISST (in situ) for small particles	1abcd	2abcd	1	1
Physics & Bulk Geoch	CTD	Rosette & sensors	CTD- see also physical processes	CTD- O2, T/S	1abcd	2abcd	1	1
Physics & Bulk Geoch	CTD	geochem	Chlorophyll fluorescence	in vivo chlorophyll fluorescence sensor	1abcd	2abc	1	1
Physics & Bulk Geoch	CTD	geochem	particle composition	HPLC pigments	1abcd	2abc	1	1
Physics & Bulk Geoch	CTD	geochem	particle composition	Chlorophyll incl. some size fractionated	1abcd		1	1
Physics & Bulk Geoch	CTD	geochem	Oxygen	O2 bottle (Winkler)	1abcd	2abc	1	2
Physics & Bulk Geoch	CTD	geochem	Carbonate System	e.g. TCO2, pCO2, Talkalinity, pH	1abcd	2abcd	2	1
Physics & Bulk Geoch	CTD	geochem	particle composition	biogeneic silica	1abc	2abcd	1	1
Physics & Bulk Geoch	CTD	geochem	particle composition	Lithogenic Si, Al	1abcd	2abcd	2	1
Physics & Bulk Geoch	CTD	geochem	Transparent Exopolymer Particles	Microsopy, Spectroscopy	1c	2abcd	2	1

In order to answer each of the EXPORTS science questions and subquestions, the required measurements were identified and tabulated. Table 2 shows an example of the measurements that were deemed necessary in order to answer SQ1C which examines the controls on particle aggregation and disaggregation and how they relate to upper ocean community composition. The Complete Measurement Table lists the measurement needs for all subquestions. An accompanying Measurement Footnote Document provides further details concerning each measurement entry.

Table 2 illustrates how measurements need to answer SQ1C are grouped into the 5 Program Elements: Phytoplankton & Microbes, Zooplankton, Export, Optics, and Physics & Bulk Geochemistry (see also Figure 1). Nearly all of the required measurements will be of value for answering a number of subquestions. In some cases, a measurement is listed under one program element for brevity, but is also a relevant measurement in another (for example, optical cameras in Export and Optics). A range of methods is required to build a detailed picture of the system and to balance the strengths and sensitivities of different approaches. In the SQ1C example, the methods span from genomics (for identifying phytoplankton and microbial communities that contribute to the composition of the aggregates) to experimental work (measuring aggregation and disaggregation rates). It is important to note that each measurement may include a number of different approaches for redundancy and closure (e.g., to measure the particle size distribution (PSD) of aggregates a variety of different camera approaches could be used).

Priorities are also assessed for each measurement in the Complete Measurement Table. A '1' indicates that the measurement is essential, a '2' if it is useful but not essential and 'no' for not necessary for answering one of the science questions. This priority assignment is done separately for each of the two ships that will be operating during each cruise (see next Section for details). For example, there may be reasons to focus a specific measurement following a target water parcel such that it is a priority for the Lagrangian-sampling process ship. Alternatively, it may be important to assess the spatial variability of a measurement on a broader, quasi-synoptic spatial scale by conducting the measurement on the survey ship.

The measurements considered necessary to address each of the subquestions in full are listed in the Complete Measurement Table in the supplemental materials section 7.2. The full table has more details of ship deployments and priorities. An accompanying Measurement Footnote Document also provides additional details concerning each measurement entry in the complete measurement table.

Measurements are grouped into the 5 Program Elements shown in Figure 1. Each Program Element will be comprised of several PI-driven Projects (Section 4.1), which will need to work together to provide the full suite of measurements in the Complete Measurement Table and synthesized EXPORTS data products (Section 4.4). Grouping the measurements into these Program Elements provides a means of assessing what will be needed and how the available resources may be best allocated. By grouping measurements in a way that reflects typical research group foci, the Program Element structure provides a clearer path for collaborators to contribute by allowing them to easily identify how their expertise maps onto and augments the required measurements, ultimately providing a richer context to answer the Science Questions.

4.0 Implementing the Goal Plan

The goal of EXPORTS is to develop a predictive understanding of the export and fate of global ocean primary production and its implications for the Earth's carbon cycle in present and future climates through an integrated program of field measurements, remote sensing and modeling. The SDT devised a Goal Plan that, in their opinion, will answer the Sciences Questions posed in the EXPORTS Science Plan. The Goal Plan is then used as the starting point for costing and descoping. Costing the Goal Plan requires estimating the number of research projects and associated costs, ship time, project coordination, data management, logistics and NASA-held contingency funds. The Implementation Plan is presented with the understanding that the actual EXPORTS program, if implemented, will likely differ from the plans presented herein.

This plan is envisioned to occur in two Phases; Phase 1 includes multiple field campaigns and initial synthesis designed to answer SQ1 and SQ2, with a latter start for Phase 2's comprehensive synthesis and modeling activities to address SQ3. Two ocean basins would each be sampled twice during phase one, beginning in the North Atlantic with the spring bloom and late summer in 2018, followed by sampling near Station PAPA in the North Pacific in spring and early autumn 2020. This sampling strategy would allow EXPORTS to observe a wide range of ECC states required for the construction of globally applicable satellite and numerical models.

Each component of the Goal Plan field campaign would include two ships, a Process Ship and a Survey Ship. The Process Ship would operate in a semi-Lagrangian frame and a Survey Ship would sample over a wide range of spatial scales. Observations will also be made from an array of autonomous platforms (gliders and multiple types of floats) deployed in advance of the Process and Survey cruises and extending past their end. By operating over an annual cycle, the autonomous assets would provide persistent observations and temporal context for the ship-based observations. By sampling at a variety of spatial scales for long periods of time, they would identify important scales of variability necessary for scaling up process studies to the regional and global scales.

"Synthesis data products" will be created from measurements or "primary data products" collected during Phase 1 for use in synthesis and modeling in Phase 2. To answer SQ3, an integrated hierarchy of synthesis and modeling approaches will be required that are closely coupled to the analysis and interpretation of EXPORTS field data, remote sensing and other relevant ocean data sets. Phase 2 efforts will encompass a range of approaches, including coupled Earth System models, to forecast both present-day conditions and future responses of ecosystems and biogeochemical cycles under different climate scenarios.

Six descoping options are presented that reduce overall project costs through a combination of effort reductions. The descoped options are ranked qualitatively based upon the tradeoffs between prediction uncertainty (i.e., number of ECC states sampled) and measurement uncertainty (i.e., resolution of all export pathways).

EXPORTS aims to leave a legacy for years to come. The comprehensive nature of the data set to be collected is unprecedented, with deliberate oversampling of particulate materials for genomic and geochemical analyses, seawater for geochemistry, microscale video imagery, trap samples, in situ cameras, zooplankton net samples, etc. A key to success is the rigorous adherence to measurement protocols on both ships and rigorous cross calibration of sensors on all ships and autonomous platforms. The field measurements will be integrated with *in situ* optics and ocean color observations, providing invaluable data for algorithm development for NASA's upcoming Plankton, Aerosol, Cloud and ocean Ecosystem (PACE) mission, and for testing the hypothesis that the fates of global NPP are regulated by the state of the surface ocean ecosystem.

4.1 Determining Goal Plan Program Duration and Number of Projects

The framing of the EXPORTS science questions and the funding opportunities presented thus far suggest that a phased implementation would be an efficient way to conduct EXPORTS. In late 2015, NASA announced funding opportunities for conducting research in data mining and observational system simulation experiments (OSSEs) in support of EXPORTS planning and science (ROSES 2015 element A3). We expect that the Data Mining / OSSE funding will start in the third quarter of this year (Figure 2).

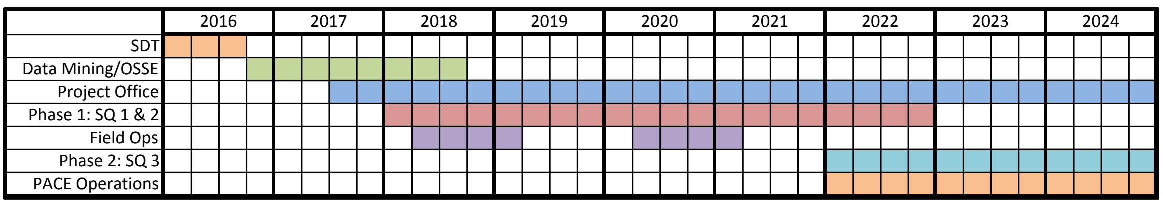

Figure 2 – Timeline by quarters for the Goal Plan.

A similar phasing of activities can be conducted with the Science Questions (Table 1) since the answers to SQ1 (What controls the carbon flux exiting the euphotic zone?) and SQ2 (What is the fate of that export flux in the twilight zone?) are required to address SQ3 (How can the knowledge gained reduce uncertainties in contemporary and future assessments of the ocean carbon cycle?). From an operational point of view, SQ1 and SQ2 require many of the same measurements, making it efficient to address them simultaneously.

The separation of EXPORTS into two phases suggests a staggered implementation for the Goal Plan. The first phase answers SQ1 and SQ2 using EXPORTS field observational record. We anticipate this be a five-year program, which will enable both domain-specific manuscripts to be published as well as the data synthesis and modeling required to answer SQ1 and SQ2. The second phase answers SQ3 and is three years in duration. Together we are suggesting that the Goal Plan be a seven-year program starting in 2018 with a staggered implementation of the two phases (Figure 2). The launch readiness date for the PACE mission is 2022. This timeline will enable advanced carbon cycling satellite algorithms that are developed and tested using EXPORTS observations to be used by PACE.

In order to obtain a total costing for the Goal Plan, the number of projects needed to answer the science questions must be estimated. A project is defined as a PI-led, five-year (Phase 1) or three-year (Phase 2) funded effort that addresses important domain-specific science questions that will directly contribute to answering the EXPORTS science questions and the EXPORTS measurement suite (if a Phase 1 project). It may be effective that a single project be made up of several PI investigators. All projects will also participate in synthesis activities to answer the three science questions. Phase 2 implements the knowledge gained in Phase 1 to reduce uncertainties in predictive and forecasting models and satellite algorithms. This is an agency goal for NASA. The two Phases are intricately linked and should not be considered autonomous elements (e.g., without Phase 2, SQ3 will not be addressed within the EXPORTS program).

Table 3: Estimated Program Elements and Number of Projects

Elements	Data Products	project #	Types of Measurements
Phytoplankton & microbes	biomass/comm structure	5	FCM, including sorting; omics; Fv/Fm; virus
	rates - intrinsic & C transforming		NCP, NPP, GPP, BP, dilution expts, nutrient expts; DOM; viral lysis
Zooplankton	biomass/comm structure	2.5	nets, incl. day/nigjt; bioaccoustics (incl fish)
	rates - intrinsic & C transforming		day/night; feeding/pellet expts; dilution expts/metabolic rates
Export/particles	Flux and attenuation particle abundance & size	5.5	traps (direct and optical), radionucludes, in situ pumps, cameras for PSD (CTD, AUVs)
	C transformation rates & processes		aggreg/dissag expts; in-situ incubations/drifters; sink rates
Optics	Links to remote sensing	3	Optical measurements to build optical models to link to satellites
	C proxy building		Optical measurements to lead to poxies of particle properties; LIDAR?
Physics and BGC	Hydrography- CTD	4	CTD/Rosette, O2, Flu, NO3
Stocks	Hydrography- towed		CTD, O2, Flu, nitrate, optics
	Site planning		pre/during/post cruises; remote sensing, all vehicles/hydrography, PO models, ADCP etc
	AUV team		Pre/post deployments and Lagrangian sub EZ float;al sensors & optics
Innovation	Novel methods, sensors, measurements, models	3	Novel approaches using materials/data collected on cruise
Phase 1 Total		*23*	Also need hydro / towyo / AUV ops teams
Phase 2 total		*8*	Assumes 2 projects per SQ3 subquestion

The number of Phase 1 projects needed was derived from the Complete Measurement Table (see Section 7.2). For each of the five program elements, the SDT judged how many field and modeling teams were required for Phase 1 of the staggered plan. This judgment was largely based upon the types of measurements required and the unique expertise that would be required on each ship. However, this activity was only utilized to derive cost estimates and was not aimed at prescribing the type or number of projects that will carry out the measurements. A few activities were deemed best conducted by competed measurement teams who deliver data products rapidly to the projects. Such efforts include the hydrographic CTD/rosette sampling, underway sampling, preliminary data processing and analytical work (nutrients, chlorophyll, particulate organic carbon, etc.), deployment and acquisition of data from the towed sled package on the survey ship and autonomous platform operations. The exact number of projects supported would be determined by NASA through proposal competition and consideration of available resources.

Twenty-three projects were estimated to be necessary to conduct Phase 1 of the Goal Plan to cover all program elements (Table 3). For the Phytoplankton and Microbes program element, the SDT estimated that a total of 5 projects were required, of which one is a modeling project. Similar estimates were made for the other program elements resulting in the number of projects listed in the third column of Table 3. Modeling projects were also considered to be important parts of Phase 1 and included in this total.

The SDT also felt strongly that in addition to the projects that contribute to the proposed EXPORTS measurement suite there needs to be resources set aside for highly innovative projects that help answer the EXPORTS science questions but may not be explicitly part of the EXPORTS measurement suite. A total of three innovation projects were suggested.

4.2 Goal Plan Ship Operations

Ship-based sampling in the EXPORTS Science Plan includes two major field deployments in two ocean basins with the aim of observing a wide range of ECC states. Each cruise will allow observation of up to three ECC states with 27 days on station (see details in the Notional Cruise Plan; Section 7.3). When considering the duration of sampling an ECC state, the SDT considered the time it takes for events in the surface ocean to influence particle fields at depths of 500 m given particle sinking rates of 50-100 m/d (5-10 days), although this is obviously an oversimplification. By conducting two seasonally-distinct cruises in each of two basins, EXPORTS aims to resolve up to 12 ECC states spanning a large dynamic range in conditions. This breadth, along with recently funded data mining efforts, increases the likelihood that the models created will be representative for other areas under similar regimes. In order to sample the full suite of measurements necessary to resolve all of the export pathways (Figure 1; Complete Measurement Table), two ships are required. This is due both to berthing space requirements, and to the fact that some measurements need to be made in a Lagrangian mode (Process Ship) while others are best collected in a spatially-distributed, quasi-synoptic fashion (Survey Ship). The most efficient sampling plan thus places the former group of measurements on the water-following Process Ship, and the latter group aboard the Survey Ship.

Briefly, drifting arrays, sediment traps, most net tows, and CTD casts deployed to collect material for shipboard experimentation are assigned to the Process Ship. Thus, most incubation-based biological rate determinations would be made aboard the Process Ship. Similarly, physical and geochemical measurements requiring distributed CTD sampling, large-volume in situ pumping, and towed profiler surveys are assigned to the Survey Ship. For example, this would include measurements required to assess downward mixing of dissolved organic matter. Specific ship assignments for all measurements are noted in detail in the Complete Measurement Table (Section 7.2). Measurements not clearly belonging to one of these categories were assigned to either or both ships after assessing interdependencies among the different measurements. For instance, most optical and imaging sensor-based measurements are included on both ships in order to link the Lagrangian-mode observations of the Process Ship to the larger, spatial context determined by the Survey Ship. A description of the platform requirements and sampling for the goal plan is provided in the Platform Requirements document in Section 7.4.

The sampling needs were partitioned between the two ships to assess all export pathways during each distinct ECC state assessment in as short of time period as possible. In each ECC state assessment, the Survey Ship will conduct a mesoscale CTD survey, towed profiler surveys at both meso- and submeso-scales, and large volume particle pump deployments at

3-day intervals. We define a mesoscale survey as achieving 5 km (CTD) resolution across a 50 x 50 km box, while a submesoscale survey will achieve higher resolution across a smaller target area (see Platform Requirements for further details on the planned sampling and platforms considered). On the Process Ship, each state will also require one set of approximately five-day sediment trap deployments, two consecutive, drifting experimental array deployments, two pairs of day/night MOCNESS deployments separated by 4-5 days, daily vertical net tows, and CTD casts 4 times per day. A detailed depiction of the timing details for the cruise sampling is given in the Notional Cruise Plan (Section 7.3). The plan also includes time for the Process Ship's sewage disposal away from the target water parcel. Tallying the time and berths necessary to make all measurements, one global-class Process Ship (35 berths) and one ocean-class Survey Ship (25 berths) will together be able to complete the assessment of one "state" of the biological pump in 8 days. Allocating two weather days per cruise and assuming actual operations achieve the efficiency detailed here; the goal plan thus achieves observations of 3 states during 27 ship days on site (see Notional Cruise Plan).

In addition to time on site, steaming time for each cruise needs to be considered. For the Atlantic cruises, steaming times are based on the distance from Woods Hole, MA to Porcupine Abyssal Plain (PAP); for the N. Pacific cruises the times are based on the distance from Seattle to Station P (details are in Notional Cruise Plan). The exact locations where the EXPORTS field campaign will be conducted will be decided after the program is initiated and depends on many factors (available resources, ship schedules, partnerships, etc.).

In order to achieve efficient operations and optimally-coordinated sampling across the program elements, the EXPORTS implementation plan assumes that CTD, towed profiler survey, ship's underway sensor system, and autonomous underwater vehicle sampling will be carried out by Project Office-directed operational teams. These ship- and shore-based teams will coordinate deployments and piloting with the management team and with appropriate project PIs. Data generated by the CTD, Underway, Towed Profiler survey, and Autonomous Platform Operations teams will be made available immediately for use in PI-led projects via the Project Offices' data management team.

Detailed water sampling requirements for nutrients, pigments, and other standard analytes are described in the Platform Requirements document in the subsection "Water sampling and minimum analysis set" (Section 7.4). Many of these analyses need not be carried out at sea and sample collections can be conducted using standard procedures by a technical team. These sampling efforts will also include deliberate overcollection for analytes such as filtered genetic material, which will be archived for later investigations as genomic libraries and analytical capabilities improve, and suspended and sinking particle samples for geochemical and isotopic analyses.

EXPORTS will also include a network of cross-calibrated biological, chemical, and optical sensors deployed across multiple platforms (ship underway, CTD, glider, float, and towed profiler). Requirements for these sensors are also given in the Platform Requirements document (Section 7.4). As with water samples collected by the CTD group, the plan includes over-collection of imaging, optical, and radiometric data for future reinterpretation and model development. In order to derive maximum value from these sensor-based measurements, it is important that all sensors be cross-calibrated frequently before, during, and after deployments. Therefore, the implementation plan advocates that dedicated personnel be assigned to coordinate intercalibration across platforms and manage the data processing streams from these sensors.

4.3 Autonomous Platform Operations

Roles of Autonomous Platforms in EXPORTS - Long-endurance autonomous platforms fulfill critical sampling needs, complementing and augmenting the intensive ship-based measurement program by providing:

- *Persistence*: Maintain a full year of sampling in each basin, beginning before the first process cruise and extending past the final cruise to provide temporal context for the intensive sampling periods and additional, if partial, characterizations of states at times not resolved by process cruises.
- *Spatial Context*: Distributed profiles collected by floats and longer (hundreds of kilometers) repeated sections occupied by gliders characterize variability at a range of spatial scales not resolved by ship-based sampling These measurements will identify the important scales of variability and provide information on the spatial distribution of processes resolved in detail by ship-based sampling. Autonomous platforms provide measurements at broad temporal and spatial scope to inform the upscaling of process investigations needed to understand basin-scale impacts.
- *Targeting*: Autonomous platforms return most of their measurements in near real time. Used in conjunction with satellite remote sensing, these observations will inform site selection for intensive, ship-based efforts and assist with day-to-day targeting of ship-based sampling. Guiding ships directly to features of interest increases efficiency and reduces risk associated with the adaptive approach employed by this plan.
- *Drifting Reference Frame*: A Lagrangian float defines a parcel-following reference frame for ship-based sampling. This eases interpretation by minimizing the impact of advection, allowing observed changes to be more readily interpreted as the result of biological and biogeochemical processes.
- *Adaptive Sampling*: Remotely commanded autonomous platforms provide flexible sampling that can be readily reconfigured to meet a range of needs, including opportunistic sampling of interesting events and optimization of coverage in response to failure of some elements of the observing array.
- *Large-Scale Biogeochemical Constraints*: The autonomous platform array will enable the calculation of net community production (NCP) via mass budgeting of the biogeochemical stock measurements on weekly to annual time scales. The resulting integrated measures of NPP fate will be very useful for comparing with the ship-based observations of NPP fate pathways.

The Autonomous Array - EXPORTS autonomous platforms operate in a nested system (Figure 3), with a persistent, Lagrangian array resolving kilometer-scale variability while drifting through a distributed array of Bio-Argo and Particle Flux floats designed to characterize scales of hundreds of kilometers. Long, repeat sections occupied by gliders provide persistent sampling that bridges the two scales and offers cross-calibration opportunities. Particle Size Distribution (PSD) Floats will be deployed for short periods during the process cruises.

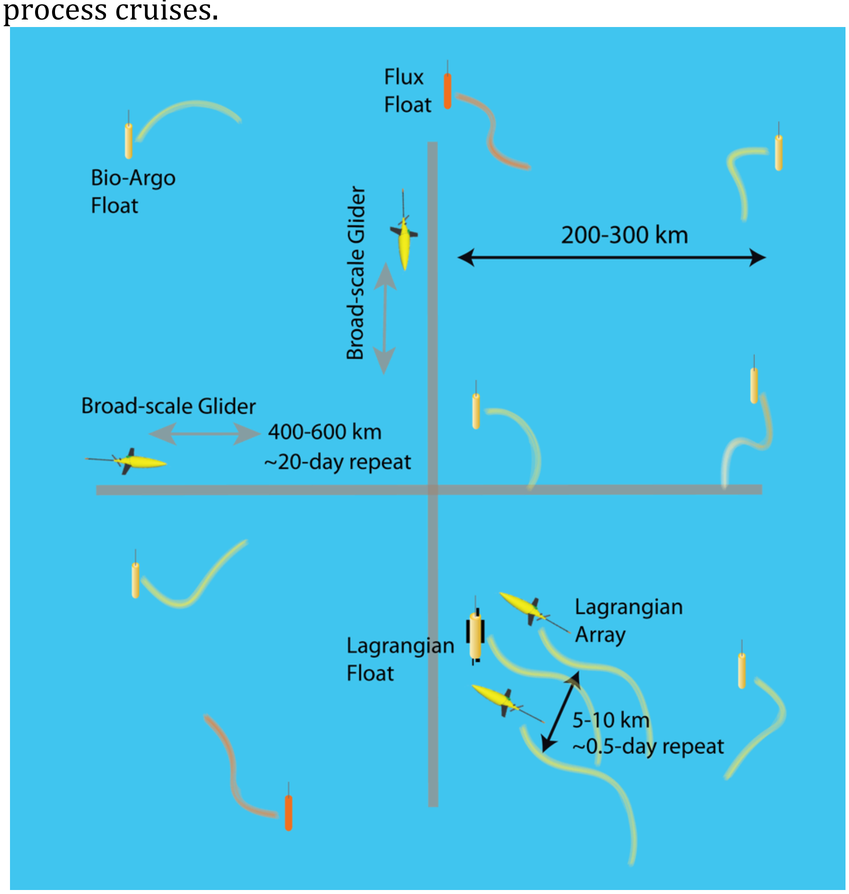

Figure 3: Autonomous platforms sampling schematic for the Goal Plan.

Drifting Float Array: A distributed array of Bio-Argo floats and Particle Flux floats (see Platform Requirements, Section 7.4) will be deployed with 200-300 km separation (selected so that each float represents an independent realization). The array will be deployed at least one month prior to the first intensive sampling period and maintained at eight floats (6 Bio-Argo and 2 Particle Flux) for the duration of the intensive sampling period. The eight-float array provides distributed coverage over a roughly 600 km by 600 km region (Figure 3). This represents a compromise designed to capture a broad range of oceanographic conditions across an operationally useful span (roughly two days for ships to traverse) with a minimal number of floats. Bio-Argo floats will profile from the surface to 2000-m depth at a timescale of 1-20 days, adjusted as needed to resolve target processes. Together, these floats will document the evolution of upper ocean stratification, establish a time-history of NCP and export fluxes on regional scales, and provide observations for assessing the representativeness of the process observations. The floats would also provide alternative targets, with known histories, for ship-based sampling, should the Lagrangian array (below) prove unsuitable.

Broad-scale Glider Repeat Sections: Two long-endurance gliders (Platform Requirements) will conduct long (300-400 km), repeated sections across the target domain, beginning prior to the first intensive sampling period and extending for a year. Gliders profile from the surface to 1000-m depth every six hours at roughly 3 km separation between dives. The resulting time series of sections will characterize spatial variability across a broad region and range of scales surrounding the process study sites, providing context for the intensive measurements, assisting in interpreting the profiles from the drifting float array and informing upscaling of process-level understanding to larger scaless.

Persistent Lagrangian Array: A system composed of a drifting Lagrangian float and two long-endurance gliders (Platform Requirements) will provide persistent sampling of small-scale O(1 km) variability in a parcel-following reference frame. The float quantifies evolution in the drifting (parcel-following) frame while gliders characterize spatial variability in the region (kilometers) surrounding the float. Small-scale, process measurements collected by the Lagrangian array will capture partial realizations of additional states, helping to assess the representativeness of ship-based observations and extending the record of NCP and export fluxes. During the periods of ship-based sampling, the Lagrangian array will provide targeting information and a drifting reference frame around which sampling strategies can be optimized.

Calibration and Proxy Building - Quantitative interpretation of autonomous biological and biogeochemical sensor arrays requires rigorous attention to calibration/cross-calibration and careful construction of proxies that convert observables to estimates of relevant biogeochemical parameters (e.g. fluorescence to chlorophyll concentration, optical backscatter and beam transmission to particulate organic carbon). EXPORTS calibration and proxy protocol should include:

- Laboratory calibration to common standards prior to deployment and (when appropriate) following recovery.
- Deployment calibration against collocated casts using reference sensors and/or analyses of samples.
- Calibration during intensive ship-based sampling against dedicated, collocated casts using CTD-based reference sensors on both ships and/or analyses of samples.
- Cross-calibration between autonomous sensors through both planned (e.g., gliders directed to visit floats) and chance encounters between EXPORTS platforms, and with instruments operated by other programs.
- Development and refinement of proxies at deployment, during intensive field periods, and though collaboration with other programs working in the region.
- Protocols for transparent, documented pathways from raw sensor output to final data product.

Operational Approach - Autonomous platforms will maintain a persistent presence throughout the EXPORTS field year in each basin (Figure 4). The field program for each basin begins with a cruise dedicated to deploying the distributed Bio-Argo and Particle Flux float array, the gliders onto the broad-scale repeat sections and the drifting Lagrangian system (see below). Float deployment sites will be selected to cover the target region while maintaining the 200-300 km separation, with glider sections configured to traverse the target region, and thus the cloud of floats. Historical data and Observing System Simulation

Experiments (OSSEs) will guide selection of the Lagrangian array deployment site to maximize residence time in the target region.

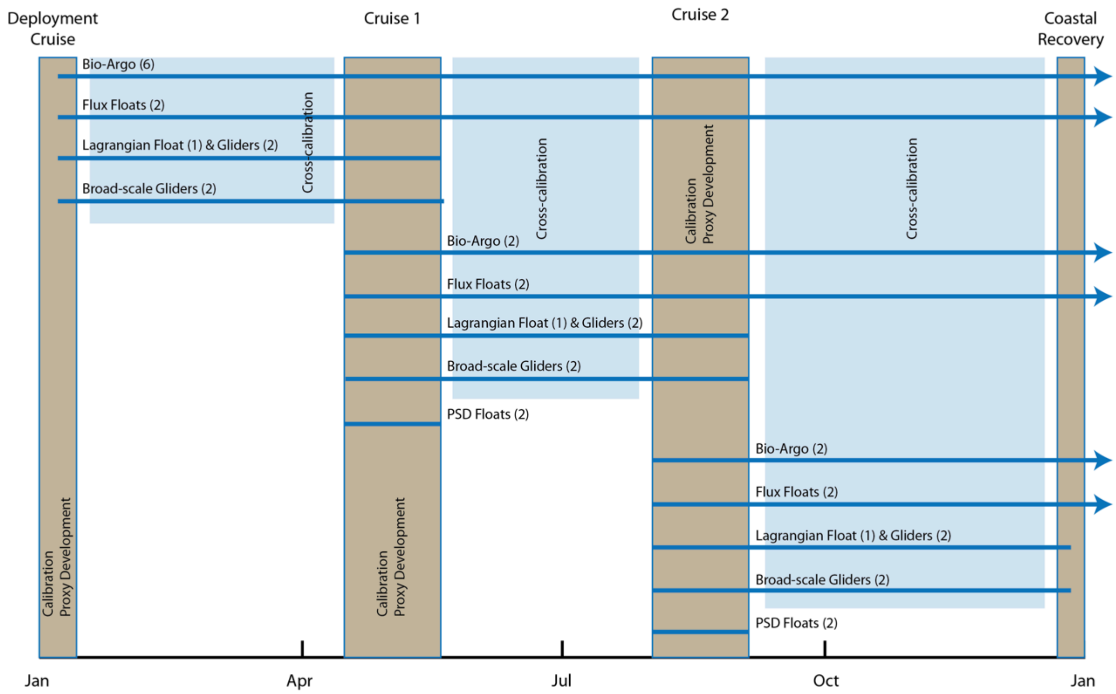

Figure 4: Timing chart for autonomous platform deployments, recoveries and operations.

Analyses of observations collected by the autonomous array will guide targeting of the two intensive, ship-based sampling periods. Gliders from both Lagrangian Array and Broad-scale Repeat Sections could be commanded to converge at the selected site to augment ship-based sampling during cruises, and to facilitate efficient recovery. During the first ship-based sampling periods, the Survey Ship will reseed a small number of floats into the distributed array filling spatial gaps and deploy four fresh gliders, the PSD floats and a Lagrangian float. Longer PSD float missions are desirable but will likely require development of onboard image processing. Ship-based process work can choose between the old and new Lagrangian floats when seeking a drifting reference frame, and will benefit from the survey capability of the combined fleet of eight gliders that results from deploying new gliders at the beginning and recovering old gliders at the end of the cruise. Ship-based sampling includes dedicated time for calibration and proxy building for autonomous sensors. At the end of the intensive sampling period, the ships will recover the four old gliders and, time permitting, the old Lagrangian float. Bio-Argo and Flux floats remain to sample until their batteries are expended. PSD floats generating data volumes too large to transmit will operate for short (days) deployments to provide information on suspended and sinking particles and for interpreting sediment trap observations, as a component of the ship-based observing effort.

The second intensive cruise also follows the sequence outlined above, with the full Bio-Argo/Flux Float array, four gliders and a Lagrangian float left behind to sample for the balance of the year. Bio-Argo and flux floats are not meant to be recovered and ship cost considerations make it impractical to devote a ship to mid-basin retrieval of gliders and Lagrangian floats at the end of the field program. Instead, gliders will be navigated to the nearest accessible coastal region, where surviving vehicles will be recovered using small, coastal research ships or charted vessels. Autonomous platforms that transmit their data back to shore should be considered quasi-expendable. Decisions to recover autonomous assets during all phases of the EXPORTS measurement program must weigh resource and opportunity costs against the value of the assets in question (including the need to reuse assets for additional EXPORTS deployments).

Logistics Needs - Initial deployment of autonomous platforms in the North Atlantic will require 18 days (5 days on site for deployments plus 13 days of transit), ideally from an Ocean Class vessel. Operations in the North Pacific will require 13 days (5 days on site for deployments plus 8 days of transit), also from an Ocean Class vessel. Time for deployment and recovery of floats and gliders is built into the Notional Cruise Plan.

Operations and Situational Awareness - Autonomous platforms will require monitoring and control throughout their missions. For example, float profiling frequency will be adjusted as dictated by science needs, gliders must be given waypoints and operating parameters, calibration opportunities must be identified and exploited, and all platforms monitored for system health. This will involve close internal (between floats and gliders) and external (with shipboard activities) coordination. These functions will be the responsibility of the highly experienced teams that compete successfully for these tasks.

More broadly, programmatic decisions about what and how to sample must be taken by the entire EXPORTS team. The EXPORTS autonomous platforms team will lead development of a situational awareness system to provide basic analyses and products aimed at informing the decision making process. This near real time information feed will support a wide range of operations, from glider piloting and selection of features for focusing sampling efforts, to the overarching choice of target region for each intensive field period. The EXPORTS measurement program relies on adaptive sampling to capture distinct features and states, making it imperative that all sources of real time information be captured and used in an integrative fashion to guide operations.

Operations Team - The EXPORTS autonomous platforms team will comprise all projects that compete successfully to conduct autonomous observations. Their day-to-day operations will depend on the nature of the successful proposals, but the need for highly coordinated operations leads the implementation plan to recommend that EXPORTS include a lead investigator for autonomous operations. This individual's responsibilities would include coordinating the diverse autonomous components, representing the autonomous platforms team on the EXPORTS Project Leadership Team (see Section 4.6) and planning of asset deployment, targeting and recovery. Similarly, the critical importance of sensor calibration and proxy building motivates the assignment of investigators to coordinate calibration of sensors across all platforms (autonomous and ship-based) and to lead the processing and delivery of data. These sensor leads would likely be drawn from the pool of EXPORTS investigators, identifying individuals with appropriate domain knowledge and a particular interest in the resulting data stream.

4.4 Assembling EXPORTS data products

EXPORTS will need to assemble measurements or "primary data products" from individual Phase 1 project teams into "synthesis data products" that can be used for answering SQ1 and SQ2 in Phase 1 of the Goal Plan, answering SQ3 in Phase 2 (Section 4.5) and for users beyond the EXPORTS program. The synthesis products from EXPORTS Phase 1 cruises, remote sensing and autonomous sampling will be a major legacy of the program, serving as a gold mine for future ocean mechanistic and modeling studies.

The specific form and organization of the EXPORTS synthesis data products should be determined by the Phase 1 project teams in conjunction with the EXPORTS Project Office's data management team. Broadly, synthesis data products should characterize the observed plankton ecosystem and carbon cycling in different states and quantify the five EXPORTS pathways in Figure 1. Table 3 in the EXPORTS Science Plan lists one approach and example of aggregated data products organized around processes, stocks, fluxes, and data types (e.g., productivity, export, particle size spectra, meso- and sub-mesoscale mapping, etc.). These data products may come from a single project team or more likely will need to be created using data collected from several project teams. Data products might 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 during a preparatory phase that will provide additional upper ocean ecosystem states, and these data also need to be organized into data products that are required to answer the EXPORTS science questions.

The EXPORTS Phase 1 synthesis data products will be compiled towards the end of Phase 1, and, as described in Section 4.6, the data products will be published and made publically available to all users through the EXPORTS Project Office in coordination with other oceanographic data repositories (SeaBASS, BCO-DMO, PANGEA, etc.).

4.5 Phase 2– Addressing EXPORTS Sub-Question 3

While a major component of the EXPORTS program will involve field campaigns to characterize different ocean states, the lasting impact of the project depends critically on how these observations are translated into better larger-scale constraints and uncertainty estimates for export and its subsequent fate from remote sensing, *in-situ* observations, and numerical models. EXPORTS SQ3 builds on the results from both SQ1 and SQ2 (Figure 1) and is divided into four sub-questions (Table 1). The expected SQ3 outcomes include synthesis products on carbon flows and mechanisms, diagnostic and prognostic state estimates of ocean export and carbon flows at broader spatial and temporal scales, identification of additional measurement needs, and better informed and tested models of varying complexity and hence more reliable future projections of the forced Earth System response. SQ3A-C specifically address estimates of contemporary biogeochemical processing in the euphotic zone and mesopelagic while SQ3D addresses projections of the ocean biological pump under potential future climates.

Addressing SQ3 requires an integrated hierarchy of synthesis and modeling approaches that are closely linked with the analysis and interpretation of EXPORTS field data and associated remote sensing and other similar ocean data sets, including the assembly of EXPORTS data products (Section 4.4). SQ3-related efforts should encompass a range of numerical approaches: statistical and diagnostic analysis of in-situ and remote sensing data; zero and 1-dimensional process-based representation of carbon flows in the upper ocean; state estimation and ocean observing system experiments (OSSEs) that can resolve the submesoscale to mesoscale regime; and 3-D prognostic regional and global-scale ocean biogeochemical models and coupled Earth System models that seek to forecast present-day conditions and future responses under different climate scenarios.

The Science Definition Team recommends that the majority of SQ3 related efforts be implemented during Phase 2 of the project in order to take full advantage of the observations collected for SQ1 and SQ2 in Phase 1. However some elements to address SQ3 are recommended to occur earlier, either before or during the field work in Phase 1. For example, the preparatory phase before EXPORTS (Fall 2016-Fall 2018; Figure 2) will likely include work on data mining of ocean ecosystem states that could contribute additional EXPORTS-related data products as well as OSSEs that could be used to guide EXPORTS mechanistic and mesoscale and sub-mesoscale sampling strategies. Phase 1 is envisioned in the Goal Plan to include some limited modeling linked to the ship, satellite and autonomous platform observations.

In the proposed EXPORTS timeline (Figure 2), Phase 2 occurs during 2022-2024 and thus, importantly overlaps with final year of Phase 1 and assembly of data products to facilitate information exchange between the Phase 1 field and remote sensing project teams and the Phase 2 synthesis and modeling team. For costing purposes, 8 projects supported in Phase 2 for the Goal Plan were estimated, 2 projects per SQ3 subquestion (Table 3).

The expected Phase 2 outcomes will likely include additional synthesis data products and model products (e.g., code and model output). Similar to the data products from Phase 1, the Phase 2 synthesis and model products will be made publically available through EXPORTS data archive in coordination with the EXPORTS Project Office in coordination with other data repositories (SeaBASS, BCO-DMO, PANGEA, etc.; see Section 4.6).

4.6 Project Management

The EXPORTS SDT recognizes that there are a multitude of factors that will determine the effective governance structure for EXPORTS. Here, we outline various governance elements viewed by the SDT as important for effective execution of the Project. Many of ideas are based upon the SDT's experiences in large-scale, multi-PI research projects like the U.S. JGOFS process studies and time series sites, GEOTRACES, CLIVAR/Repeat Hydrography, NAAMES, Tara Ocean, etc.

It is recommended that governance of EXPORTS entail close coordination between agency Program Managers and a Project Leadership Team (PLT). It is envisioned that the PLT consists of (1) a Lead Scientist and a Deputy Lead Scientist, (2) a Science Steering Committee, and (3) an EXPORTS Project Office. In collaboration with the agency Program Manager(s), the PLT will be responsible for oversight and coordination of field campaigns, oversight of data management, and organization of outreach activities. To ensure program vitality while maximizing stability, it is recommended that the Lead Scientist and Science Steering Committee positions be rotated at strategic intervals throughout the program.

Lead and Deputy Lead Scientists and Science Steering Committee – If the 7-year EXPORTS Goal Plan program were implemented, it would be prudent to plan leadership rotation. One solution that retains consistency would be for the Lead Scientist to remain in office during Phase 1 of the Goal Plan (years 1-5) with the Deputy Lead Scientist assuming Lead responsibilities during Phase 2 (years 6 & 7). A new Deputy may be appointed at this time. The Project Leadership Team (PLT) should consist of the Lead Scientist, the Deputy Lead Scientist and a Science Steering Committee. The assembled PLT should be composed of no more than 7 members representing each of the primary research areas of the EXPORTS Project, including remote sensing, optics, modeling, autonomous sampling, biogeochemistry, export, food-web interactions, particle dynamics, and physical oceanography. The Science Steering Committee will work directly with the Lead Scientist and Deputy to advise Project Office activities, orchestrate the staging of all field activities, and facilitate and monitor partnerships and collaborations. Decisions will be made in conjunction with the PIs and funding agency representatives following a consensus process. Turnover within the Science Steering Committee may be staggered following the phases of the project, e.g., members rotate after Basin 1 & 2 investigations.

EXPORTS Project Office - The purpose of the Project Office is to provide 1) cruise planning and logistical support for cruises and deployments, 2) enhance communication among investigators and international partners, 3) direct the hydrographic, towed profiler and autonomous platform operation teams during cruises, 4) oversee data submission by PIs to central data archives, 5) construct and disseminate synthesized 'data products' (see below), and 6) organize public, community, and agency outreach activities, including EXPORTS' online presence. Essential to the success of EXPORTS, these Project Office activities will include organization of pre-cruise planning meetings and post cruise data-interpretation and synthesis meetings, as well as facilitation of communications among EXPORTS scientists and external collaborators (national or international). The Project Office as advised by the PLT will also direct the sampling conducted by the competed hydrographic, towed profiler and autonomous platform operation teams.

The Project Office will be responsible for conducting annual project team meetings. Face-to-face meetings are essential to ensure that the synthetic activities required to answer the science questions are conducted. The Project Office will also be responsible for communicating data submission requirements and timelines to the research team and coordinating data submissions with the EXPORTS data management and archive elements. It is expected that agency Program Managers will direct data submission to their established permanent archives, for example, SeaBASS for NASA and BCO-DMO for NSF. If multiple archives emerge as EXPORTS repositories, the Project Office will ensure consolidation and synergies of efforts, such as direct links to data via the EXPORTS Web site. The Project Office will also be responsible for communicating EXPORTS activities and findings to the public and policy stakeholders, which will involve routine communication with agency Offices of Communication. Project Office education and outreach activities will span from training programs for young scientists and K-12 curricula development to communicating EXPORTS concepts to the public and government officials.

Data Synthesis, Management, and Archiving - Science data created through the EXPORTS Project will include 'primary products', 'synthesized data products', and 'model products'. Primary products encompass all direct field measurement data. As noted above, the Project Office will provide guidance to EXPORTS PIs on data submission requirements and timelines. All primary product submissions will follow the NASA Earth Science Data and Information Policy (http://science.nasa.gov/earth-science/earth-science-data/data-information-policy/), requiring all PIs to submit all the data they have been funded to collect in designated public data repositories (following quality control), no later than one year following collection. The Project web site will provide updated links to all the data repositories where data have been submitted (SeaBASS, BCO-DMO, PANGAEA, etc.). Furthermore, all EXPORTS data will be archived within NASA's SeaBASS.

Synthesized data products are created through the integration of primary products and include properties such as export flux, productivity, plankton community structure, organic matter partitioning, etc. (see Section 4.4 above on EXPORTS Data Products and Table 3 in the EXPORTS Science Plan). These synthesized products are of central importance to answering the EXPORTS science questions and their construction and dissemination will be the responsibility of the Project Office. To this end, the Project Office will work with all PIs to coordinate field reporting and metadata standards. The synthesized data products will be submitted to the EXPORTS data archive and published in a scientific journal within one year after the last field campaign. A later submission of data will require the consent of the PLT. By publishing the EXPORT data products in a timely manner, 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.

The primary and synthesized data products are essential for EXPORTS synthesis and modeling activities. Output from these modeling activities will also be submitted to the central EXPORTS data archive, with these submissions coordinated by the Project Office in coordination with other data repositories (SeaBASS, BCO-DMO, PANGEA, etc.).

5.0 Estimating Project Costs

The goal of the EXPORTS Implementation Plan is to devise an efficient strategy to implement the EXPORTS Science Plan as proposed, vetted and approved. This includes a robust cost estimate for the Goal Plan ("Plan A", this section) and potential descoped plans ("Plans B-G", next section). The previous section (Section 4.0) lays out the SDT's suggestions for Goal Plan execution and (with the supplementary materials) provides many of the needed details. For various reasons, the eventual EXPORTS field campaign may look very different from this implementation plan, with project costs differing accordingly.

5.1 Costing the Goal Plan

There were many assumptions made in costing the Goal Plan. As described in Section 4.1, if implemented, the EXPORTS Goal Plan will be conducted in two phases, making it a 7-year program (Fig. 2). The first, five-year phase is aimed at answering Science Questions 1 and 2, and all field expenses are contained in Phase 1. A total of 23 projects were estimated to be needed to conduct Phase 1 (Table 3), each costed at $300K per year during the two field years, $200K per project per year during the analysis years, and $50K for capital equipment per project. Ship time is budgeted at published day rates for ships in the Global class (Process ship) and Ocean class (Survey ship and autonomous platform deployments/recovery/CTD ops). Ship time requirements are included in the Notional Cruise Plan (see Section 7.3). A total of 338 sea days are needed to achieve the Goal Plan.

Costs for the hydrographic team were made based upon at-sea labor during the cruise years for running the CTD and underway sampling systems on both the survey and process ships and the towed profiler on the Survey Ship (see Platform Requirements; Section 7.4). This includes at-sea analyses (fluorometric chlorophylls, dissolved oxygen, etc.) and collection of samples to be analyzed on shore (nutrients, particulate organic carbon, dissolved organic carbon, HPLC pigments, etc.) as well as samples to be archived for future analyses. Based upon the Notional Cruise Plan we assume that 1,000 samples will need to be collected by both ships per cruise, with an average on shore analysis cost of $300 per sample. We have assumed that not all depths will be sampled, and not all samples analyzed, with some archived for future analysis (e.g.,–omics, geochemistry, etc.). It is assumed that the Multiple Opening Closing Net and Environmental Sensing System (or similar) and the towed profiler system will be included in the UNOLS ship support for the program (see Platform Requirements; Section 7.4). Autonomous platforms will be purchased following the plan laid out in Section 4.3 and are considered expendable. Estimates of the operations costs required to produce useful data were made based upon past experiences of the SDT members. Logistics costs are for shipping/travel using a central NASA-like contractor, and data management and project office costs are included. A 10% contingency on the Phase 1 expenses will be held by the agency.

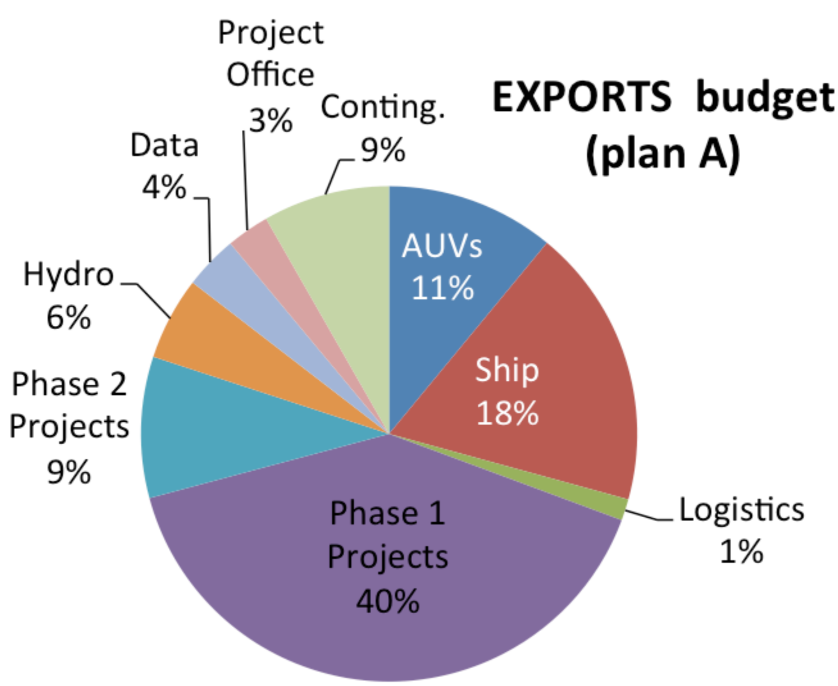

Figure 5 – Breakdown by category for the Goal Plan cost estimate (Plan A in the Science Plan Budget document).

Following the phasing suggested in Section 4.1, Phase 2 will be 3 years in duration and will start in Year 4 of the overall program (Figure 2). The Goal Plan assumes that there will be 8 Phase 2 projects (Table 3), each costed at $200K per year.

The total cost for the Goal Plan is $71.5M for 7 years. The spreadsheet illustrating the calculations is provided in the Science Plan Budget document (see tab "A" for the Goal Plan). Nearly one-half of the Goal Plan costs (49%) go to Phase 1 and 2 science projects (Fig. 5). Beyond that, 18% goes toward ship support, 11% toward autonomous platform purchases and operations (AUVs), 9% for contingencies (10% of the Phase 1 costs), 7% for project office and data management, 6% for the hydrographic team and sample analyses.

The SDT acknowledges that the Goal Plan cost estimate could be decreased by planning fewer projects or collection of fewer samples. However the charge to the SDT was to create a robust cost estimate for the Goal Plan. The process employed by the SDT is likely to have resulted in an estimate that is robust to minor omissions.

5.2 Descoping Options

Descoping options are required to help understand the trade space among project investment, risks to success, and scientific and agency rewards. The SDT considered many ways to pare down the Goal Plan, including fewer projects, cruises, AUVs deployed, number of ships, number of basins and combinations thereof. The descoping options presented below were costed similarly to the Goal Plan taking into account the factional decreases in each category from the Goal Plan. Details are provided in the Supplementary Materials (Section 7.4) and the Science Plan Budget document (see tabs B through G in the table).

Table 5 – EXPORTS Goal Plan and Descoping Option Costing

	Cruises	Basins	Ships	Projects in Phases 1 & 2	Years	Sea Days	Total Cost
A: Goal Plan	4	2	2	23 / 8	7	388	$72M
B: Goal "Lite"	4	2	2	20 / 6	7	388	$62M
C: Full Plan but 1 ship	4	2	1	18 / 8	7	196	$57M
D: 3 cruise, 1 basin, 2 ships	3	1	2	23 / 8	7	263	$58M
E: 2 cruise, 1 basin, 2 ships	2	1	2	23 / 0	5	164	$39M
F: 2 cruise, 1 basin, 1 ship	2	1	1	18 / 0	5	95	$30M
G: 1 cruise, 1 basin, 1 ship	1	1	1	18 / 0	4	50	$22M

A brief summary of the workable descoping options is given in Table 5, and illustrates the number of cruises, basins sampled, ships, projects, years and sea days, the existence of Phase 2, and the total project costs. Capacity to answer EXPORTS science questions diminishes as the project moves from the Goal Plan (Plan A in Table 5) to the 1 ship / 1 cruise descoping option (Plan G). In particular, Plans E, F and G will not have any Phase 2 projects and hence will not answer SQ3 within the EXPORTS program. The descoping options lying between Plans A and G provide different capabilities and constraints, and present varying risks to resolving the export pathways and NPP fates, and ultimately achieving overall program success.

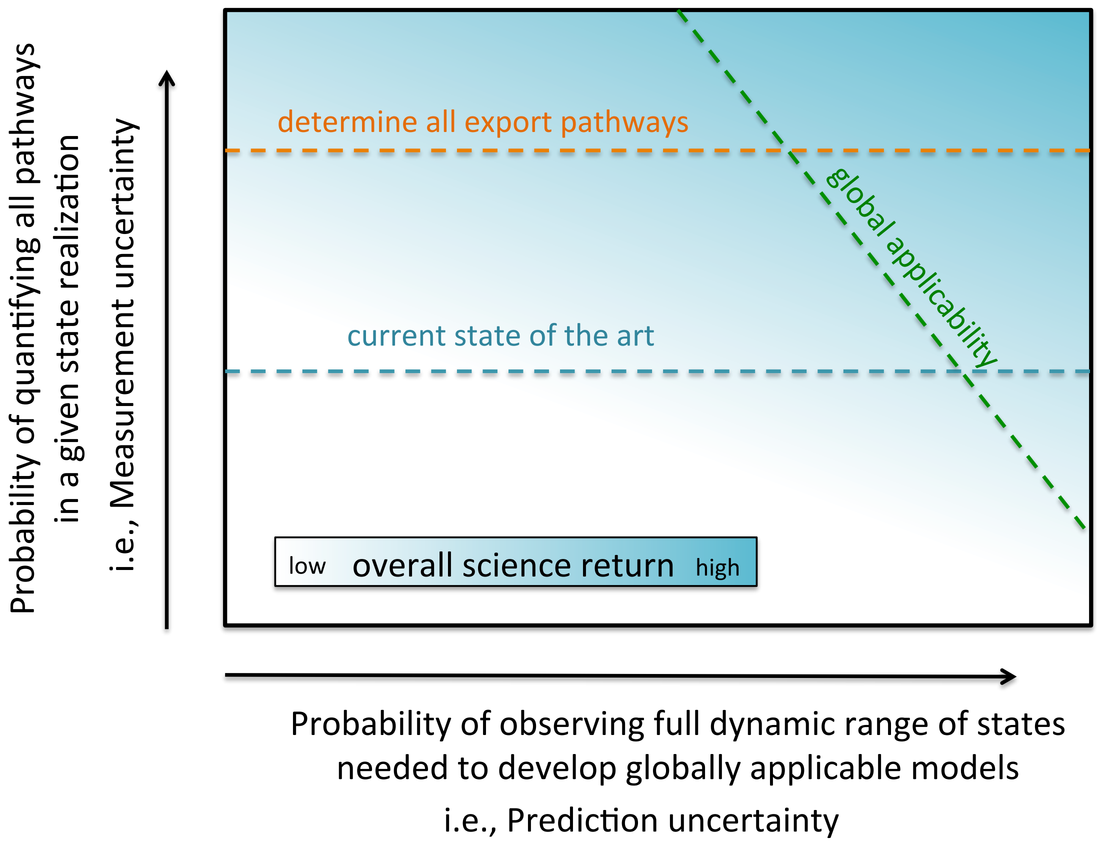

Figure 6 – Illustration of the trade space between "Measurement Uncertainty" (y-axis) and "Prediction Uncertainty" (x-axis). The dashed lines show the "current state of the art" (blue), the as-yet-unachieved simultaneous "determination of all export pathways" (orange) and the region in the upper-right corner of the trade space that optimizes the construction of "globally applicable models" (green).

The overall EXPORTS approach is to develop and validate ocean carbon cycle models from observations made over a range of ecosystem / carbon cycling states. This means that EXPORTS must observe the fundamental NPP export and fate pathways, as well as collect the supporting data that are required to develop satellite algorithms and numerical models valid over the global range of ECC states (from both the planned field work and the mining of previous results). Thus there are two variables, depicted as the axes in Figure 6 that must be considered when evaluating the trade space among the descoping options from the

Goal Plan. One axis (the vertical axis in Figure 6) relates how well the fundamental NPP export and fate pathways can be resolved by each of the descope options. We term this "Measurement Uncertainty" as it measures the probability that a given field campaign will be able to measure all of the export pathways. The other axis (the horizontal axis in Figure 6) illustrates how well the entire set of field campaigns can observe a wide enough range of ECC states to allow globally applicable satellite and numerical models to be developed and tested. This second variable can be thought of as the "Prediction Uncertainty".

The lowest risk – that is, the highest science returns – will occur in the upper right corner of the tradeoff space illustrated in Figure 6. In that region of the trade space, Prediction Uncertainty is lowest (i.e., many ECC states are sampled) and Measurement Uncertainty is lowest (i.e., all pathways are accurately resolved). Elsewhere in the tradeoff space, the measurements may only partially constrain the ECC state (lower on the vertical axis) or an insufficient number of ECC states may be sampled to create globally-applicable models (farther left on the horizontal axis). Importantly, Figure 6 illustrates the "current state of the art" (blue horizontal dashed line), the as-yet-unachieved simultaneous "determination of all export pathways" (orange horizontal dashed line) and the space that optimizes the construction of "globally applicable models" (green diagonal dashed line). To date, no field program has simultaneously measured all five of the export pathways and their transformations from the euphotic zone through the twilight zone needed to answer the EXPORTS science questions. Hence the "current state of the art" line lies far below the "determine all export pathways". By measuring all of the exports pathways in a comprehensive manner, EXPORTS has an excellent opportunity to advance new ground in how we understand and model global ocean NPP export and fate.

The different descoping options listed in Table 5 span the range of states of predictive and measurement uncertainty (Figure 7). The Goal Plan and the six descoping plans are plotted in the trade space based upon the SDT's best collective judgment. By design, the Goal Plan (Plan A) lies in the upper right corner of the trade space and will clearly do the best job among the various descoping options. The Goal Plan "lite" option (Plan B) will have fewer projects and hence will increase the measurement and prediction uncertainty levels, and likely not allow for "innovative" program elements (Table 3). The two ship plans with the same number of projects as the Goal Plan but reduced number of cruises/basins (Plans D & E) will achieve low measurement uncertainty but will not provide the same number of ECC states and thus will have higher prediction uncertainties.

The single ship options (Plans C, F & G) will not be able to sample all of the export pathways as there are simply not enough berths and wire time available. However, all three descoping options will provide state-of-the-art observations over a range of prediction uncertainty levels.

Similar options lie along the diagonal line illustrating global applicability. In particular there is some similarity in success among Plans B (Goal Plan "lite"), D (2 ships, 3 cruises and 1 basin) and C (1 ship, 4 cruises and 2 basins). Again, full details are provided in the supplementary materials (Section 7.4) and the Science Plan Budget document. While international partnering and data mining efforts will increase the number of states sampled, the inherent risks are greater and must be carefully managed (similar sampling protocols, standards, etc.) to ensure that the measurements are compatible.

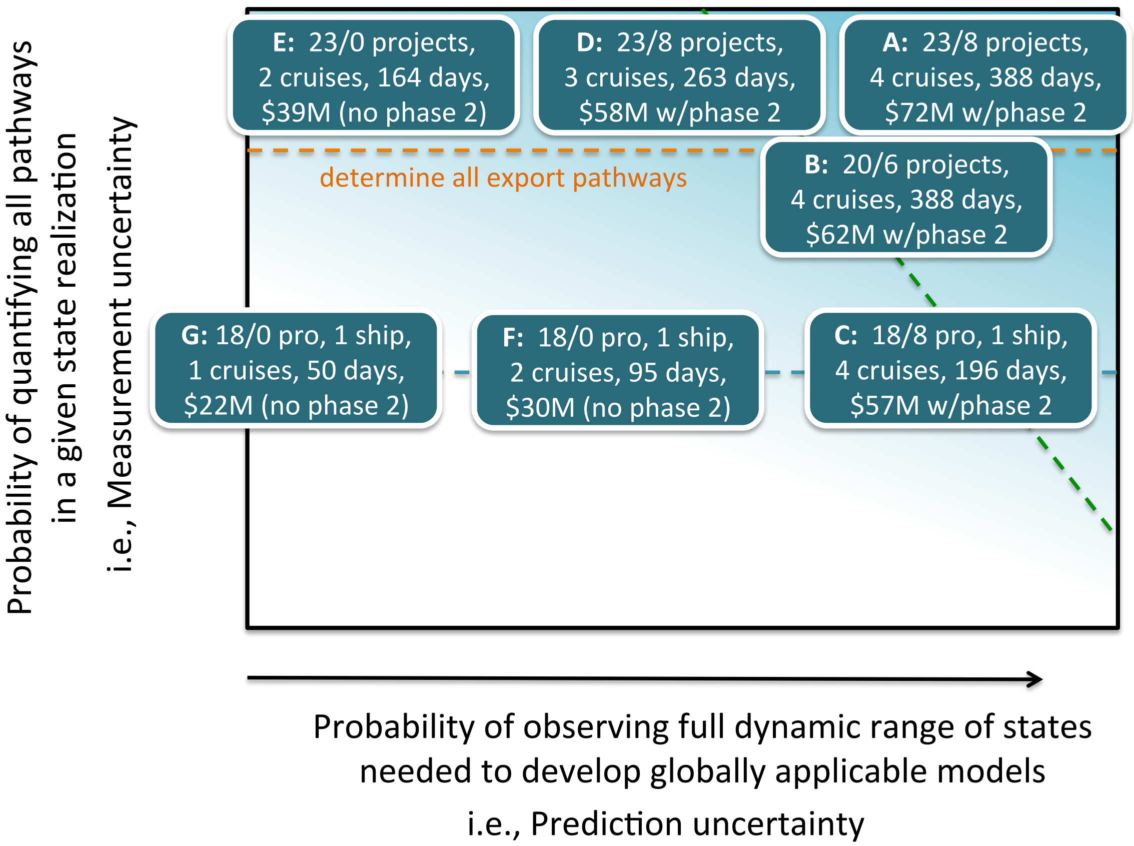

Figure 7 – Illustration of approximately where the Goal Plan and the six descope options lie in the trade space between "Measurement Uncertainty" and "Prediction Uncertainty".

6.0 Challenges going forward

While components of the carbon cycle have been addressed in the past, only through a comprehensive, highly coordinated program such as EXPORTS will the oceanographic community be able to quantify the key carbon exchange and export pathways and address the considerable uncertainties that exist to date. Reliable monitoring of contemporary and prediction of future ocean carbon cycling will depend upon data like those suggested here to build and validate numerical models and satellite algorithms. In addition, state-of-the-art technologies now at the community's disposal have never before been employed in such a coordinated fashion to answer carbon cycle questions.

There are challenges that a comprehensive, high-technology, and multi-partner field program such as EXPORTS presents. Striking a balance among discovery, innovation, broad participation, agency mission, and cost will be complicated. A strong partnership between the funding agencies, Project Leadership Team, and participating researchers will thus need to be in place to achieve the best possible outcome for EXPORTS for all parties. In order to accomplish the goals of EXPORTS (especially those relevant to NASA), we must also ensure that Phase 2 projects should be implemented so that SQ3 questions are answered. On the horizon already is OSSE development, funded under ROSES 2015, which will certainly improve the plans suggested here. Furthermore, the path forward must also include extensive data mining of previous results to reduce the risks in sampling too few ECC states.

The establishment of partnerships, within the U.S. and beyond, would greatly assist in the implementation of a highly interdisciplinary, comprehensive field, modeling and synthesis program like EXPORTS. There are clear partnerships with other national agencies that will benefit both the NASA EXPORTS program and reciprocally benefit partner agencies through the comprehensive biological, chemical, and physical framework that EXPORTS provides. One such example of potential partner agency leverage from EXPORTS emanated from an NSF-funded workshop on the "Biology of the Biological Pump" in February 2016. The goal of this workshop was to prioritize future research areas that are likely to make significant advances in our understanding of the biological processes regulating organic matter export and its consumption in the oceans. The broad research themes that resulted from this workshop (food web regulation of export, the dissolved-particulate continuum, variability in space and time) are directly relevant to the goals of EXPORTS. A draft report from that workshop was recently made available for broader community comment (http://www.us-ocb.org/publications/BioPump-v2.0.pdf). There are other potential collaborations, for example, with NOAA through the Galway Agreement or the NOAA climate office through the deployment of biogeochemical ARGO floats.

There are multiple opportunities for international partnering that span the continuum from direct collaboration in an EXPORTS field campaign to independent comprehensive EXPORTS-type field campaigns at other times of the year or in diverse locations that would increase the number of ECC states sampled. The table of Potential International Partnerships in the supplementary section of this document (Section 7.6) presents an informal, non-exhaustive list, introducing some such international programs, links and contact persons representing EU or national programs; some are funded, some are awaiting funding decisions, and others are in early planning stages awaiting decisions on EXPORTS implementation. Overall, the international response to the EXPORTS plan has been overwhelmingly positive, and a high degree of enthusiasm for potential collaborations was encountered. Existing international organizations, such as Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), Scientific Committee on Oceanic Research (SCOR), International Council for the Exploration of the Sea (ICES), North Pacific Marine Science Organization (PICES) and others should also be engaged.

One major challenge for partnerships is matching timelines for direct collaboration in field campaigns; this includes not only project funding, but also ship scheduling and personnel participation on other vessels. The EXPORTS timeline (Figure 2) is aggressive, and will require an intensive effort for coordination of methodologies, sensor calibration and cross calibration, sampling, and all aspects of data management from database structure to timing for data sharing. Sufficient person power and resources will need to be dedicated to international coordination and PI data workshops to fully take advantage of partnerships.

7.0 Supplemental Materials

7.1 EXPORTS SDT Membership

The EXPORTS Science Definition Team (SDT) was competed to create an Implementation Plan to execute the EXPORTS Science Plan. Details concerning the formation of the SDT and its charge are available at http://cce.nasa.gov/obb/exports/team.html.

The SDT members are David Siegel (Lead; UCSB), Barney Balch (Bigelow), Mike Behrenfeld (OSU), Ken Buesseler (WHOI), Craig Carlson (UCSB), Nicolas Cassar (Duke), Ivona Cetinic (NASA GSFC), Scott Doney (WHOI), Meg Estapa (Skidmore), Bethany Jenkins (URI), Ken Johnson (MBARI), Craig Lee (UW APL), Adrian Martin (SOC), Susanne Menden-Deuer (URI), David (Roo) Nicholson (WHOI), Uta Passow (UCSB), Mary Jane Perry (UMaine), Natassa Romanou (NASA GISS), Deborah Steinberg (VIMS), Andy Thompson (CalTech) & Jeremy Werdell (NASA GSFC). *Ex officio* SDT members are Paula Bontempi (NASA HQ), Quincy Allison (NASA ESPO), Peter Griffith (NASA GSFC) and Mike Sieracki (NSF).

Contact information is available at http://cce.nasa.gov/obb/exports/team.html.

7.2 Complete Measurement Table

The Complete Measurement Table groups the measurements needed to answer the EXPORTS science questions and subquestions. They are grouped by program element (column B), with shorthand for the platform, method, science needs and measurement types and purpose (columns C, D, E, F and G). Comments on each entry by row are provided in an accompanying Measurement Footnote Document. The measurements are further characterized by which of the first two Science Questions and sub-questions each would address (column H and I), and then a possible distribution of these measurements among a Survey Ship, Process Ship and Autonomous platform cruise (pre/post process cruises) is suggested (columns J-P). In making these suggestions, a priority was assigned for the need to be making each measurement on the different platforms, using a ranking of 1, for "essential" for addressing the science questions noted, or 2, for "useful". Finally, the measurements are further grouped by the EXPORTS data products (1e- primary, and 2e- secondary) as in the original EXPORTS science plan (Table 3; columns Q & R). The Complete Measurement Table is one way to assess the required measurements and needs across platforms and cruises and was used in this document to determine costs, cruise planning and scoping/descoping options, but it should not be seen as a final list of cruise activities or project elements.

Complete Measurement Table URL:
http://cce.nasa.gov/obb/exports/documents/Complete_Measurement_Table.xlsx

Measurement Footnote URL: http://cce.nasa.gov/obb/exports/documents/Complete_Measurement_Table_Footnotes.pdf

7.3 Notional Cruise Plan

The Notional Cruise Plan enables per cruise estimates of activities for costing the Goal Plan. Activities considered include the number of sea days required (27 on station), days needed to make a single ecosystem / carbon cycling state assessment (8 days), berths available to Phase 1 projects and the hydrographic and towed profiler teams (35 process and 24 survey ship), CTD casts (~80 process & ~200 survey), analytical samples to be run onshore (~1000 from both ships), towed profiler survey duration (~12 days total), MOCNESS casts (12 process ship), and more. The Goal Plan Notional Cruise Plan was constructed in 2 hr increments and the various activities required to measure the export pathways and NPP fates were placed on this matrix for both ships. Care was taken to account for any interdependencies among required measurements (detailed in the Complete Measurement Table).

Goal Plan notional cruise schedule URL:
http://cce.nasa.gov/obb/exports/documents/Notional_Cruise_Plan.xlsx

7.4 Platform / Sampling Requirements

The Platform Requirements document describes details for the measurements to be made and the sampling conducted in the EXPORTS Goal Plan implementation.

Platform requirements URL:
http://cce.nasa.gov/obb/exports/documents/Platform_Requirements.pdf

7.5 Goal Plan and Descope Options Costing

Science Plan Budgets were estimated for the EXPORTS Goal Plan (Plan A in the table), as discussed in Section 5.1, and for the various descoping options outlined in Section 5.2 (Plans B through G in the spreadsheet). A summary is also included to help compare the various options. For each scenario, these table include numbers of instruments (floats, gliders, traps), ship days for two types of ships- larger Process Ship (global class) and smaller Survey Ship (ocean class), also used for deployment of autonomous assets prior to the first process cruise (minimal CTD ops expected). A $100k allowance has been allocated for each basin to support potential coastal recoveries of mobile autonomous assets at the end of each field program. Also included based upon the measurements table are estimated number of multi-PI projects that might be included in Phase 1 and Phase 2 (not all options have both phases) including a budget for small amounts of "PI equipment" needed (for example camera systems, nets, filtration apparatus). A hydrographic team budget includes costs for analyses of samples to be collected and analyzed on shore (such as HPLC pigments, dissolved organic carbon, nutrients, particulate organic carbon and nitrogen, etc.) as well as the people on board to collect and process samples, including CTD operations and the operation of instrumentation on the towed profiler. Logistics costs are for shipping/travel using a central NASA-like contractor, and data management and project office costs are also broken down for each scenario, and scale to the number of projects and cruises. Descoping options include reduced number of samplings, basins, ships and projects, as well as deletion of phase 2 synthesis and modeling efforts as appropriate.

Science Plan Budget URL:
http://cce.nasa.gov/obb/exports/documents/Goal_Plan_Descope_Budgets.xlsx

7.6 Known international opportunities for partnerships

The table of Potential International Partnerships presents an informal, non-exhaustive list, introducing some such international programs, links and contacts representing EU or national programs; some are funded, some are awaiting funding decisions, and others are in early planning stages. Inputs to the table have come from conversations among SDT members and

Potential international partnership table URL:
http://cce.nasa.gov/obb/exports/documents/International_Partnerships.xlsx