An ocean health early warning system

A proposal to 100&Change MacArthur Foundation, October 3, 2016
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A. EXECUTIVE SUMMARY

(150 words)

The ocean provides critical services to all life on land, absorbing 93% of the heat from global warming and a quarter of human carbon dioxide emissions. Yet these services come at a price: ocean temperatures rise; pH and oxygen levels fall. This deteriorating ocean health bleaches corals, harms shellfish, changes where fish live and fishery yields. Scientists and policymakers are racing to understand and prevent irreparable harm to our largest global commons. However, we are flying blind. Until now, the prohibitive cost of obtaining observations left scientists unable to monitor ocean health. Our team has developed a new generation of robotic floats with cutting-edge sensors, enabling us to build the first real-time, high-resolution, ocean health early warning system. This system will finally allow us to track threats and provide critical guidance for climate policy and sustainable ocean management. All we lack is funding to implement this revolutionary system.

B. YOUR TEAM: WHO ARE YOU?

TEAM PURPOSE (150 words)

Our team of oceanographers and climate science communicators was formed 5 years ago by Jorge Sarmiento of Princeton University, to develop a global ocean health monitoring system based on robotic floats and chemical sensors, and to train a new generation of scientists in the use of this technology to study the ocean. Our motivations were principally: (1) to address a deepening concern about how oceanic chemistry and biology (*biogeochemistry*) have responded to the invasion of carbon dioxide, changes in climate, and increasing pressure on natural resources such as by fishing; and (2) to harness major technological developments which made it possible to envisage a float-based global network of sustained biogeochemical observations. A six-year $21 million grant from the National Science Foundation has enabled us to develop a prototype of the ambitious system we propose here.

TEAM STRUCTURE (200 words)

The project is directed by Jorge Sarmiento at Princeton University, which has full responsibility for implementation of the project. He will be advised by a Directorate, an Executive Board, and an Advisory Committee. The Directorate includes the Associate Director (Kenneth Johnson), a Project Manager, and a Business Manager. The Executive Board consists of the leaders of three teams that will implement the project:

Team 1, Observations (Lynne Talley, Leader, Stephen Riser & Kenneth Johnson, co-Leads), is responsible for acquisition, testing, deployment, data validation of the instrumented floats, and data management.

Team 2, Synthesis, Analysis & Evaluation (Jorge Sarmiento, Leader, Joellen Russell, co-Lead), is responsible for 1) production of global real-time estimates of ocean biogeochemistry, and 2) analysis of the observations through model experiments and algorithm development to assess ocean health.

Team 3, Outreach (Heidi Cullen, Leader), will engage with stakeholders to take the data and create a real-time ocean health early warning system.

Advisory Committee

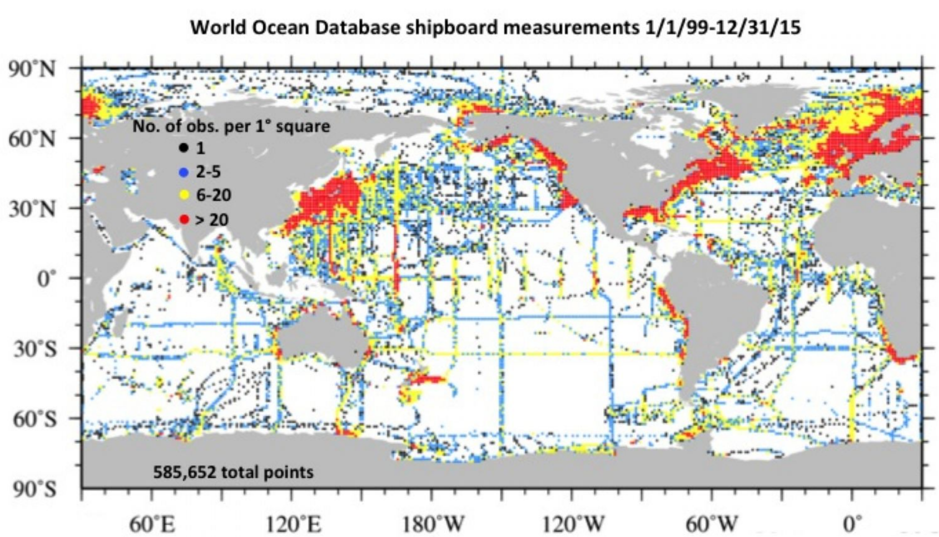
The program will be advised by a group of experts from the US, UK, France, Germany, Switzerland, Japan, and Australia with experience in climate, ocean biogeochemistry, robotic floats and biogeochemical sensors. This Committee will also advise on the global development of the program.

C. WHAT'S THE PROBLEM & HOW WILL YOU SOLVE IT?

<u>THE PROBLEM STATEMENT</u> (250 words)

Scientists are in a race to understand the ocean's role in our climate and marine life just as it undergoes rapid physical and biological change as a result of human activities. The principal drivers of life in the ocean are temperature, salinity, and ocean circulation; the supply of nutrients and light; and the carbon dioxide (and associated pH) and oxygen concentrations (IPCC, 2013). These properties shape the physiology of cells and organisms and determine the structure and functioning of ocean ecosystems. Every single one of these drivers is changing in response to climate change and acidification resulting from carbon dioxide uptake by the ocean. Scientists predict that such changes will cause major shifts in marine productivity, community composition, and ecosystem structure, with potentially devastating regional impacts on the marine food web and on fisheries that provide an important fraction of the animal protein consumed by humans.

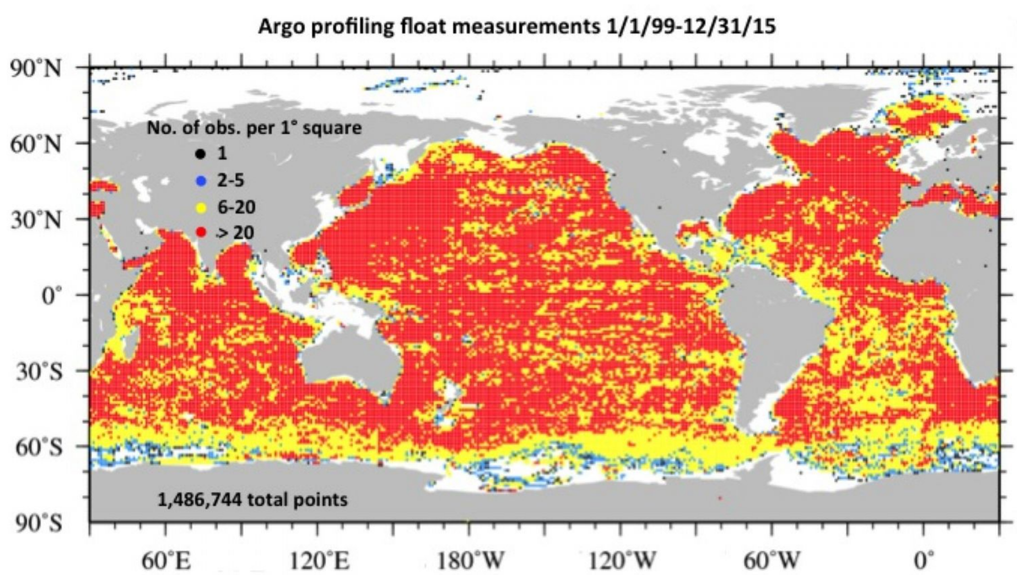
The problem is that our best efforts to slow climate change and its impacts on marine life are blunted by limited understanding. Traditional ship-based and mooring technology makes possible only the most coarse-grained decadal time scale observations of most of these drivers of life (see figure). Vast swaths of the ocean have never been studied, especially in the winter. Satellite observations have much higher resolution, but only for a few ecosystem variables, and only over the top few meters of the water column where light can penetrate. We are flying nearly blind, while the principal drivers of life in the ocean undergo massive changes.



Density of ocean observations made from ships 1999-2015.

YOUR SOLUTION (250 words)

The solution is at hand: the Argo global network of ~4000 robotic autonomous floats can measure heat and salinity throughout the ocean about once a week. We now have sensors for pH, oxygen, nitrate, chlorophyll, suspended particles, and irradiance, which, together with the Argo sensors, match, one-for-one, with the drivers of ocean life. We will use these new tools to build the first-ever open-source, real-time, biogeochemical monitoring system of the world's ocean, and transition the support to national and international agencies.



Density of ocean measurements made by Argo floats 1999-2015.

Recent pilot efforts, including the 6-year, $21 million National Science Foundation funded Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Project led by Jorge Sarmiento, demonstrate the feasibility of our solution (http://soccom.princeton.edu). The first two years of SOCCOM data are in, and the results are stunning. The data and model-based analyses are leading to a dramatic revision of our estimates of the magnitude of the Southern Ocean uptake of human carbon dioxide emissions in areas that had previously been grossly under sampled due to harsh wintertime conditions; as well as providing our first ever observations of the carbon system under sea ice.

A biogeochemical float-based monitoring system would enable a transformative leap in our understanding of the role of the ocean in climate change, the global carbon cycle and marine life, and make it possible for scientists around the world to monitor the health and carbon uptake of the global ocean in real-time, providing early warning of ecosystem threats/changes and critical guidance for carbon policy.

YOUR TACTICS AND TECHNOLOGY (200 words)

Argo floats measure properties from 2000 meters depth to the surface, where data are broadcast to shore by Iridium. The system currently consists of ~4000 such floats, which repeat this cycle every 10 days for up to 7 years before their batteries die. Replacement floats and their deployment are covered by informal international coordination, with the US responsible for ~50%.

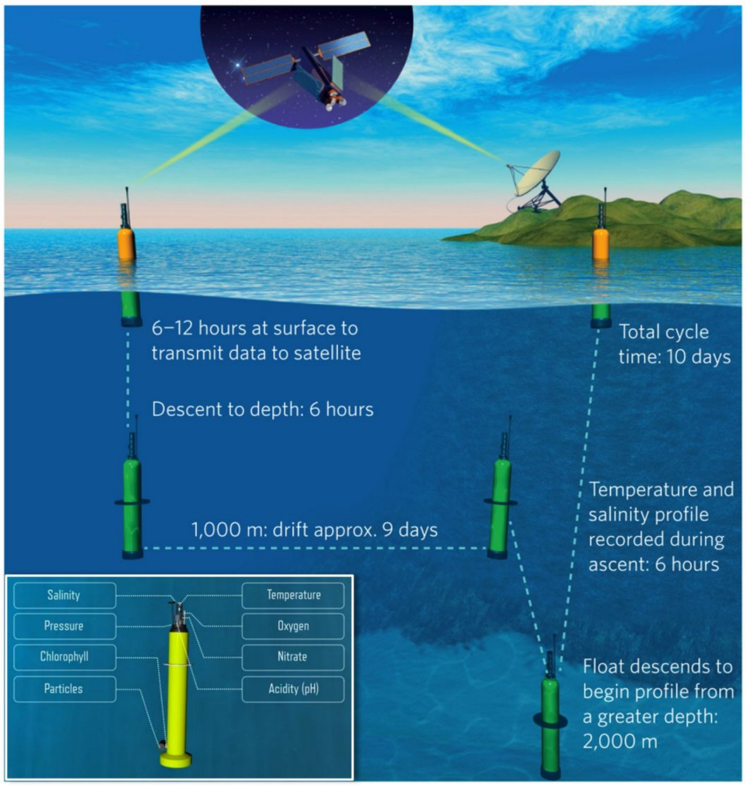


Illustration of Argo float operation and (inset) Argo float with biogeochemical sensors

Simulations of biogeochemical properties show that we need to add biogeochemical sensors to about one in four Argo floats for optimal results, so ~1000 in the world, with ~200 of these covered by SOCCOM. Installation of our proposed system would stimulate a rapid increase in industrial production of biogeochemical floats and close international collaboration. Our goal would be full installation after five years within a US and international framework that would lead to continued support of the system over the long term.

A Synthesis and Analysis component of our project will assimilate data into a high-resolution ocean model, enabling visualizations that will assess ocean health, including ocean carbon uptake, ocean acidification, and changes in marine productivity. We will communicate our findings through state-of-the-art visualizations on all platforms, so that the ocean can be viewed by the public, policymakers, and planners.

YOUR TIMELINE AND KEY MILESTONES (250 words)

Planning for a global array has already begun, with a meeting held in 2016 in France, with attendees from Australia, Canada, China, Japan, France, Germany, the United Kingdom, and the United States. The results of this meeting are described in the document "The Rationale, Design and Implementation Plan for Biogeochemical-Argo" (BATT, 2016). We propose the following schedule based on our estimate that development and maintenance of a fully operational 1000 biogeochemical float system would require ramping up to a continued supply of 250 floats per year.

Proposed Milestones

Year 1

- Contract with industry to initiate production of a standard BGC Argo float
- Production and deployment of 100 floats
- Develop global state estimate model that assimilates float data
- Landscape analysis of the best available early warning systems

Year 2

- Production and deployment of 150 floats
- Evaluate performance of year 1 floats
- Begin synthesis and evaluation of scientific results
- Begin stakeholder surveys

Year 3

- Production and deployment of 220 floats
- Continue performance evaluation and publish data
- Build and test a prototype ocean health early warning system

Year 4

- Production and deployment of 200 floats
- Begin transition to long-term support by national agencies with initial 50/year float acquisition and deployment
- Build, test a prototype ocean health early warning system

Year 5

- Production and deployment of 150 floats
- National agencies ramp to 100 float acquisition and deployment
- Launch ocean health early warning system
- Broadly disseminate data products and collaborate with key stakeholders

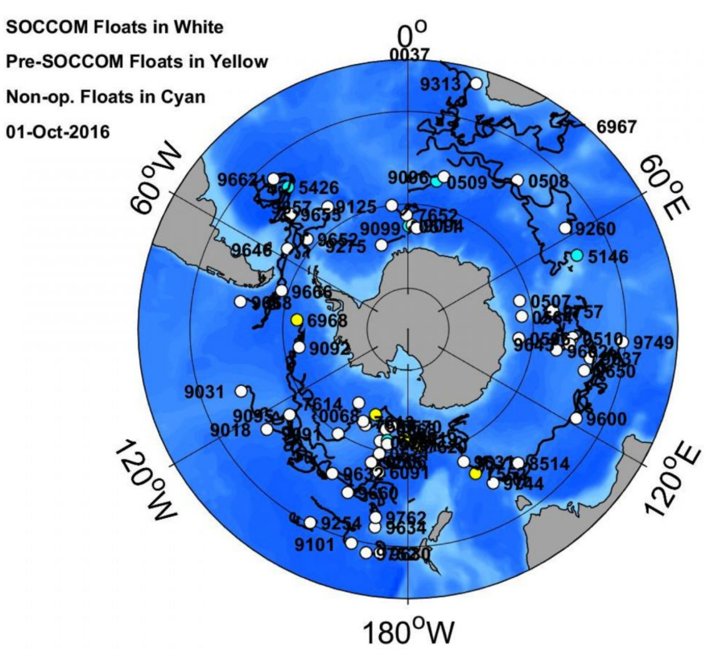
Year 6

- National agencies ramp to 250 float acquisition and deployment

D. WHAT'S THE EVIDENCE THAT YOUR SOLUTION WILL WORK?

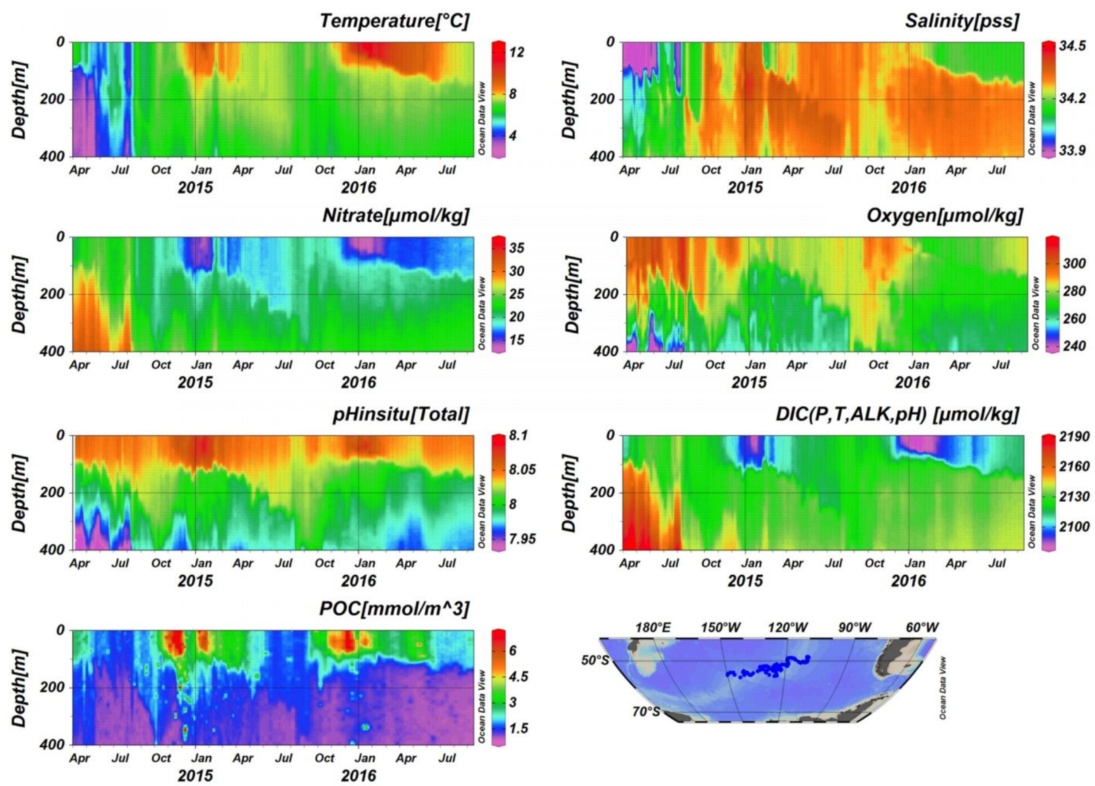
The effectiveness of robotic floats for measuring ocean properties and their evolution in time is strongly supported by the international Argo program of temperature and salinity floats which began in 1999. Over 2500 scientific papers have been published on these measurements, and Argo floats have been a crucial component in our ability to monitor the increasing heat content of the ocean and the global increase in sea level.

The evolution and effectiveness of biogeochemical sensors used in robotic floats are addressed in a number of publications, including an international planning meeting report and references therein (BATT, 2016). Our ongoing prototype SOCCOM research program is based on this new generation of Argo floats with biogeochemical sensors (Biogeochemical-Argo floats). In its first two years, SOCCOM has deployed more than 50 such floats into the Southern Ocean (see figure).



Map of SOCCOM biogeochemical floats (dots) currently operating in the Southern Ocean. Black lines indicate float trajectories since deployment.

Over 40 additional floats will be deployed in the coming austral summer and the array will build to near 200 floats over the next 4 years. With two years of data collected, a number of papers are already published and more are on the way, many based on measurements in regions and at times that have never been sampled before. The Southern Ocean is the most difficult place on the planet to carry out such work, and our success attests to the likelihood of success of an expansion to the entire global ocean.



Over two years of data from a SOCCOM biogeochemical float in the southern Pacific Ocean. Plots show top 400 meters of 2000 meter profiles for temperature, salinity, nitrate, oxygen, pH, DIC (dissolved inorganic carbon), and POC (particulate organic carbon) versus depth, from April 2014 to September 2016 along the float's trajectory (lower right).

RISK ASSESSMENT (200 words)

The major risks in operating a large biogeochemical sensor array have been mitigated by successful operation of the SOCCOM array. There are several remaining risk elements in a system scaled up to global coverage.

First is increasing production of floats from the current laboratory scale to an industrial scale. We are now working closely with manufacturers to further transition our technological developments and enable larger scale production, and have commitments from vendors that they can supply the floats needed.

A second risk element arises as we expand from deployments on international research cruises to ships of opportunity that may not be conducting biogeochemical research. SOCCOM is developing protocols for calibration that will mitigate this risk.

Finally, we must ensure that this program is followed up by national and international programs that support ongoing operations, which enable the decadal scale observations that link climate change and ocean health. The G7 Science Ministers' statement (Tsukuba Communiqué, 2016) demonstrates international consensus for the program. We are now in regular communication with NOAA, NSF, and NASA program offices about the transition of these technologies and capabilities. Support from the MacArthur Foundation would provide a critical accelerant to the development of a sustained international program.

EVALUATION (250 words)

Specific elements of our evaluation plan include:

EXTERNAL REVIEWS

1) An Advisory Committee will be appointed consisting of national and international members of the community. They will evaluate our Strategic Implementation Plan and our progress towards meeting our stated goals on an annual basis.
2) An external evaluator will be hired to provide an objective annual evaluation of the effectiveness of the program

TESTING & CALIBRATION OF INSTRUMENTS

3) Biogeochemical-Argo floats will be rigorously tested and calibrated before deployment.
4) In most cases, floats will be calibrated again at time of deployment, and all floats will be compared with historical measurements at 1500 m where the anthropogenic impact is still minimal. Algorithms based on historic ship data at 1500 m have been established (Williams et al., 2015; Carter et al., 2016) that enable a secondary, post-deployment check on the pH sensor.

DATA ANALYSIS (CROWD SOURCING)

5) Data, once uploaded, are publicly available within hours where anyone can check them and inform us of any perceived issues.
6) Assimilation of new data into a global state estimate produces fields that are compared to other observed data and provide a fuller picture of the global carbon cycle.

OTHER

7) Observing system simulation experiments assess the uncertainty associated with the array, provide metrics for model assessment, and help plan and refine deployment priorities of subsequent floats.
8) Our effort to visualize and disseminate our observations and analyses will be evaluated internally by common metrics available through social media and web access.

E. WHAT'S THE EVIDENCE THAT YOU CAN DO IT?

YOUR PREVIOUS PERFORMANCE (250 words)

Our experience with SOCCOM makes us uniquely qualified. Additional experience:

Prof. Jorge L. Sarmiento of Princeton University helped plan and participated in most major oceanographic observation programs of the past 4 decades, including in a variety of leadership roles. He has published 215 research papers and a leading biogeochemical oceanography textbook, and trained many of the current generation of biogeochemistry faculty members and research scientists.

Technical leadership is provided by Dr. Kenneth Johnson, Senior Scientist at the Monterey Bay Aquarium Research Institute, and Prof. Stephen Riser of the University of Washington. Johnson has made fundamental contributions to the development of nitrate and pH sensors, and had the vision for this project. Riser has built and deployed over 1400 Argo floats during the past decade, pioneering the addition of biogeochemical sensors, ice avoidance software, and Iridium communications to Argo floats.

Scientific leadership is provided by Prof. Lynne Talley at the University of California, San Diego, and Prof. Prof. Joellen Russell of the University of Arizona. Talley has led global oceanographic observational programs for three decades, and is a leading descriptive/observational oceanographer of her generation and author of a leading oceanography textbook. Russell is a climate modeler whose startling analyses of IPCC climate model performance in the Southern Ocean was one of the major motivations for SOCCOM.

Dr. Heidi Cullen is a co-founder of Climate Central, an award-winning journalism and data visualization non-profit. She is a globally recognized climate science communications expert.

YOUR ORGANIZATIONAL CAPACITY (200 words)

Our executive committee for 100&Change is the same as for our SOCCOM Project. SOCCOM is organized as a Strategic Implementation Plan, which has a structured framework for defining a I. Vision and II. Mission for the project, then performing a III. Situational Analysis of the strengths, weaknesses, opportunities and threats to the project; followed by IV. Goals, and V. Objectives, where goals are broken down into measurable terms and time frames; and VI. Strategies, where we define tools and approaches to achieve our objectives, and VII. Implementation Plan, where we lay out specific actions for the following year.

We now have more than two years' experience working within this structure and can easily scale it up. It helps us define our goals clearly and to adapt to new developments and surprises, including potential leadership changes, and it provides a clean way to evaluate our progress at annual meetings. Our 100&Change proposal anticipates any disruptions that may occur in scaling up SOCCOM by engaging a wide range of private manufacturers for floats and sensors, including additional administrative, technical, and scientific personnel, and having a stronger engagement of international colleagues

F. WHAT'S YOUR SOLUTION GOING TO COST?

BUDGET NARRATIVE (250 words)

The bulk of the 100&Change funding, ~$78 million, will be to fabricate or acquire 820 biogeochemical floats and ship them to the research vessels that will deploy them (see Budget Allocation table on next page). 120 of these floats will be fabricated at UW by adding BGC sensors to standard Argo floats; the remaining 700 will be purchased from vendors with experience producing biogeochemical floats, two of which have confirmed to us in writing that they can scale up their float-building capacity to deliver the number of floats required to create our planned observing system.

Of the remaining funding,

- $6.1 million will be spent on administration of the grant ($2.8 million for an administrative center at Princeton and $3.3 million in indirect costs)
- $8.5 million will be spent to support planning for cruises, float deployment, and data management and monitoring
- $5.0 million will fund evaluation of data quality and the creation of data products
- $2.4 million will be spent on data visualization and outreach to stakeholders

TOTAL RESOURCE REQUIREMENTS AND SUSTAINABILITY (200 words)

$100,000,000 would be sufficient to build and deploy the floats and develop support systems and audiences for the global biogeochemical observing network we are proposing. Sustaining the network over the longer term would require deployment and management of 250 floats per year at a cost of ~$25 million per year, a task that we envision will be taken over by existing international float programs as occurred with the original Argo program. Currently, the U.S. funds approximately half of the ~4000 floats in the Argo network, through the National Oceanic and Atmospheric Administration (NOAA). International partners fund the remaining floats and share responsibility for data management of the system. Because there is a precedent for a takeover of a pilot program in the original Argo programs, and because the BGC Argo program is aligned with the goals of the current agencies, we believe it is highly likely that our network will be adopted by national programs and sustained beyond the lifetime of the 100&Change grant. Our goal is to jump start a program that the international oceanographic community has already proposed, but has languished in the absence of a large-scale funding mechanism for this global project.

TABLE: Allocation of project funding by organization and task

Institution	Adminis-trative (million $)	Task 1 Observations (million $)	Task 2 Synthesis, analysis & evaluation (million $)	Task 3 Outreach (million $)	TOTAL (million $)
Princeton	2.8		1.6		4.4
Subcontracts					
U. Washington - Float purchase & operation		78.0			78.0
U. Washington - Other		1.0	1.0		2.0
UC San Diego/ Scripps Institution of Oceanography		0.5	2.0		2.5
Monterey Bay Aquarium Research Institute		7.0			7.0
Climate Central				1.5	1.5
U. Arizona			0.4	0.9	1.3
Indirect Costs	3.3				3.3
TOTAL	6.1	86.5	5.0	2.4	100

<u>OTHER CONSIDERATIONS</u> (200 words)

What we will be able to detect with our measurements:

- Changes in ocean photosynthesis (*nutrient, irradiance, chlorophyll fluorescence, particulate backscatter*)

    - Changes in ocean circulation and stratification, resulting in increased production in high latitudes, decreased in low latitudes, with associated changes in nutrient supply and transport.

- Changes in fisheries (O_2, *p*H, CO_2, *T and currents*)

    - Decreases in photosynthesis diminish the productivity of fisheries

    - Habitat extent and health diminish due to warming, changes in circulation, nutrient supply, acidification and decreasing oxygen.

- Carbon dioxide uptake by the ocean

    - CO_2 derived from pH sensor and interpolated Alkalinity, and winds derived from satellite observations

    - We will provide global coverage of CO_2 uptake on monthly time scale with ~twice the precision of current methods.

TABLE: Match-up of drivers of ocean life with sensors

Drivers of ocean life	**Corresponding sensor**	**Ocean Health Impacts**
Carbon dioxide	pH (estimate Alk, CO2 and DIC)	Acidification; Carbon uptake; Biological dissolution events;
Temperature	Temperature	Warming; Stratification; Decreased carbon solubility; Extent and health of habitats;
Salinity	Salinity	Ocean mixing and circulation; Precipitation;
Oxygen	Oxygen	Decreased oxygen solubility; Spread of anoxic and low oxygen zones;
Light	Irradiance	Changes in photosynthesis and productivity of fisheries
Nutrients	Nitrate	"

<u>TEAM STORY</u> (150 words)

We are a group of climate and ocean scientists alarmed by changes taking place in our ocean. The impacts of global warming are changing every ocean property, affecting where organisms live and how productive they are. The window to save this global commons is quickly closing.

We have a solution. Autonomous floats provide a tremendous opportunity to monitor ocean health in real-time. Our team has spent the last four years creating a prototype system for the Southern Ocean - the most poorly understood body of water on Earth. The prototype works and we are poised to take it global.

This grant is the best, and perhaps only, way to inspire governments around the world to take collective action and preserve ocean health. We have devoted our lives to understanding the ocean and its role in Earth's climate. We hope that this work to create a global early-warning system becomes our legacy.