Satellites to the Seafloor:

Autonomous Science to Forge a Breakthrough in Quantifying the Global Ocean Carbon Budget

Study report prepared for The Keck Institute for Space Studies
Opening Workshop: October 7 - 11, 2013
Closing Workshop: February 4-6, 2014

Study Co-leads:
Andrew Thompson (California Institute of Technology),
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EXECUTIVE SUMMARY

Earth's climate depends critically on atmospheric concentrations of greenhouse gases, such as carbon dioxide (CO_2). The atmosphere exchanges carbon with the terrestrial biosphere and the ocean. Because the ocean is the largest of these reservoirs, over long periods of time, the primary constraints on atmospheric CO_2 are carbon concentrations in the ocean. Understanding how carbon concentrations in the ocean vary in response to natural and anthropogenic forcings is necessary to predict changes in Earth's climate and ocean sustainability.

Observations of the physical, biogeochemical, and biological processes governing ocean carbon fluxes are needed to improve our mechanistic understanding of the marine carbon cycle. However, these processes are distributed throughout the ocean over widely varying spatial and temporal scales. Ships and satellites offer only a partial view, limited either to short-term observations (ships) or by a lack of sub-surface coverage (satellites). Furthermore, the limited ability and availability of ships prevents operating in critical remote regions, such as the Southern Ocean.

In 2013-2014, the Keck Institute for Space Studies (KISS) conducted a study to investigate the premise that autonomous and coordinated groups of heterogeneous mobile robots, working in cooperation with remote sensing and shore-based data assimilation, could significantly advance our ability to obtain the observations needed to quantify the global ocean carbon budget. The study brought together 32 scientists and technologists from universities, space and oceanographic research institutes, and industry over two workshops. The KISS study focused on identifying the observational capabilities required to quantify the ocean carbon cycle; assessing the current capabilities in the ocean robotics, autonomous science, and satellite communities; determining the necessary advances to obtain the desired observations; and developing a collaborative research agenda aimed at solving these problems.

This KISS study, Satellites to the Seafloor, identified the vertical flux of carbon through the water column as a scientific focus, with an awareness that coupling between lateral and vertical fluxes also needs to be addressed. We determined that the understanding of three key marine carbon cycle processes would benefit from improved observational capabilities: (i) the export of carbon from the surface ocean, including its fine horizontal variability; (ii) the evolution of carbon through the "twilight zone" (sub-euphotic layer*)* where the bulk of remineralization occurs; and (iii) the flux of carbon through the seafloor and the identification of physical processes associated with its variability. Patchiness, or intermittency, which characterizes biogeochemical cycling, at least in the upper ocean (few hundred meters), and potentially throughout the water column, arose as a major theme of the study. Patchiness presents a major observational challenge, including matching robots and communication modalities to spatial and temporal scales.

The study developed a technical vision for a coordinated network of ocean robots and satellites that autonomously interprets data and communicates sampling strategies that lead to effective resolution of the coupling between physical and biogeochemical dynamics. The observational capabilities afforded by this paradigm will improve estimates of how patchy distributions contribute to larger-scale carbon cycle budgets. This vision formed the basis for focusing on three technology areas: (i) sensors, (ii) marine robotics, and (iii) information exchange. Implementation of the vision will require a large number of assets, each with individual requirements for re-tasking, data communication and assimilation, and health monitoring. Thus autonomy is a crucial part of the proposed vision. Autonomy will allow humans to focus on tasks they are uniquely suited for, such as data interpretation and high-level decision-making.

The study identified future technology areas that will be critical for arriving at the proposed vision. These include:

- Development of methods in which groups of heterogeneous mobile robots (e.g. autonomous underwater and surface vehicles) autonomously and adaptively obtain long-duration in situ measurements.

- Development of interaction strategies for in situ instruments that use remote sensing data and model output to optimize observations for information gain.

- Development of a dissolved inorganic carbon (DIC) sensor, suitable for deployment on mobile marine robots.

This vision builds on earlier efforts; however, an end-to-end implementation of long-term, large-scale adaptive autonomous ocean measurements has not been previously realized. Our approach complements, but is distinct from, existing observing systems, e.g. the Argo array and the Ocean Observatories Initiative (OOI), as it provides mobile, adaptable observing capabilities, specifically suited for diverse, remote and evolving environments. Robotic technologies are also germane to future space exploration missions. The goals laid out in this report are beyond the scope of a single future proposal; funding for a variety of projects from a diversity of sources, both public and private, will be required.

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CHAPTER 1. INTRODUCTION

Over the course of five months, the KISS study, *Satellites to the Seafloor*, brought together scientists who understand the imperative and scope of quantifying the global carbon budget with technologists who have the expertise to provide new solutions to this task. The scientists share an interest in the global ocean carbon budget, but consider various aspects of the problem, e.g. chemical, biological and physical processes, using different techniques, including remote sensing, in situ observations and numerical models. The technologists, from both ocean and space robotics communities, understand the possibilities and challenges of combining new robotic platforms with autonomous science to observe different environments. **We advocate that a significant advance in our ability to monitor the marine carbon, and other biogeochemical cycles, can be achieved through a coordinated network of ocean robots and satellites that autonomously interpret data and communicate sampling strategies.**

The core of this study is to identify the emerging technologies that will have the greatest impact on oceanographic and other space science investigations and to coordinate efforts between different disciplines that interact infrequently. In this chapter we provide a brief overview of the study motivation, focusing on both the importance and challenges of observing the marine carbon cycle and potential advantages of using autonomous robotics.

1.0 STUDY MOTIVATION

Understanding the global carbon budget and its variability is crucial to current and future life on Earth. The ocean holds roughly 94% of all the carbon in the Earth's three mobile reservoirs: atmospheric, terrestrial, and marine. Thus, ultimately, long-term changes in the global carbon budget, and its impact on global climate, reflect changes in the ocean's carbon content and cycling. In addition to physical processes that govern carbon fluxes at the air-sea interface, complex internal sources and sinks, including inorganic, geological, biological and microbiological processes also impact carbon distribution and storage. Thus, it is essential to observe and understand the system as a whole. This is a daunting task, as many of the processes are distributed throughout the ocean, laterally and vertically, over scales ranging from centimeters to thousands of kilometers. Ship and satellite observations both offer a partial view. Ships are typically limited to short-term, localized observations, whereas satellites provide greater coverage but suffer from limited spatial resolution, especially vertically. Ocean robots, such as deep-diving autonomous underwater vehicles (AUVs) and gliders, provide a platform from which persistent in situ observations of the seafloor and water column can be made; surface properties can be monitored by autonomous surface vehicles (ASVs). Presently, these assets are used disparately with each operating independently and requiring direct human intervention for data interpretation and mission re-tasking. This paradigm is insufficient for the task of obtaining the millions of in situ and remote measurements required to close biogeochemical budgets.

The central technology premise of this study – that groups of heterogeneous robots, including satellites, can autonomously operate in a coordinated fashion – has enormous potential to transform not only ocean sciences, but also future space science missions. Presently, space robots and satellites operate as individual assets that are supervised by humans. While low-level tasks may be carried out autonomously, high-level tasks, such as re-tasking, require human intervention. This paradigm is sufficient for single or small groups of robots; however future ocean and space missions, in which large numbers of heterogeneous robots are used to conduct autonomous science, will necessitate a reduced role for humans. Alternatively, there is a risk that human operators become saturated by the demand to efficiently interpret information and accordingly re-task assets. This need is further amplified if there is limited telemetry between robots and humans on shore or Earth. In this case, low-latency communications amongst a fleet of robots will be beneficial. The reduced cost, compared to space operations, of deploying diverse ocean platforms, e.g. gliders, AUVs, and ASVs, makes an oceanographic application a practical and cost-effective testing ground for the development of coordinated autonomous strategies.

Developments in four areas lead to the timeliness of this study.

(1) Constraining the ocean carbon budget has been identified as a key limitation (IPCC, 2007) in understanding Earth's changing climate. Ocean models point to the importance of physical processes characterized by high frequency variability and small spatial scales on regulating upper ocean carbon concentrations. Observations at these scales remain sparse.

(2) The increased presence, resolution and sampling rates of satellites make this data a potential source of information for real-time adaptive sampling strategies.

(3) Recent advances in ocean in-situ observing tools, including the increased availability of gliders, ASVs and AUVs, as well as the NSF-funded Ocean Observatories Initiative (OOI), provide ample opportunities for persistent, multi-scale ocean monitoring that is necessary to address our key science questions. The cost of these instruments will continue to decrease as they become more common tools for ocean research, paving the way for larger and more complex deployments.

(4) Recent advances in autonomous science for space exploration provide a foundation upon which solutions for the effective use of a fleet of assets can be based.

1.1 THE MARINE CARBON CYCLE

The ocean is the largest mobile reservoir of carbon in the Earth system. The ocean holds roughly 38,000 Petagrams of carbon (PgC) in both organic and dissolved inorganic forms. The importance of this number lies in its relative size compared to the other reservoirs: fossil fuels (5000 PgC), terrestrial (2000 PgC) and atmospheric (760 PgC). Thus, the ocean holds roughly 50 times more carbon than the atmosphere. Air-sea exchange at the ocean-atmosphere interface acts to reduce disequilibrium between atmospheric concentrations of CO_2 and the upper ocean partial pressure of CO_2. The size of the oceanic reservoir and the relatively slow time scales over which it changes means that upper ocean CO_2 strongly constrains atmospheric CO_2 concentrations (see Figure 1.1).

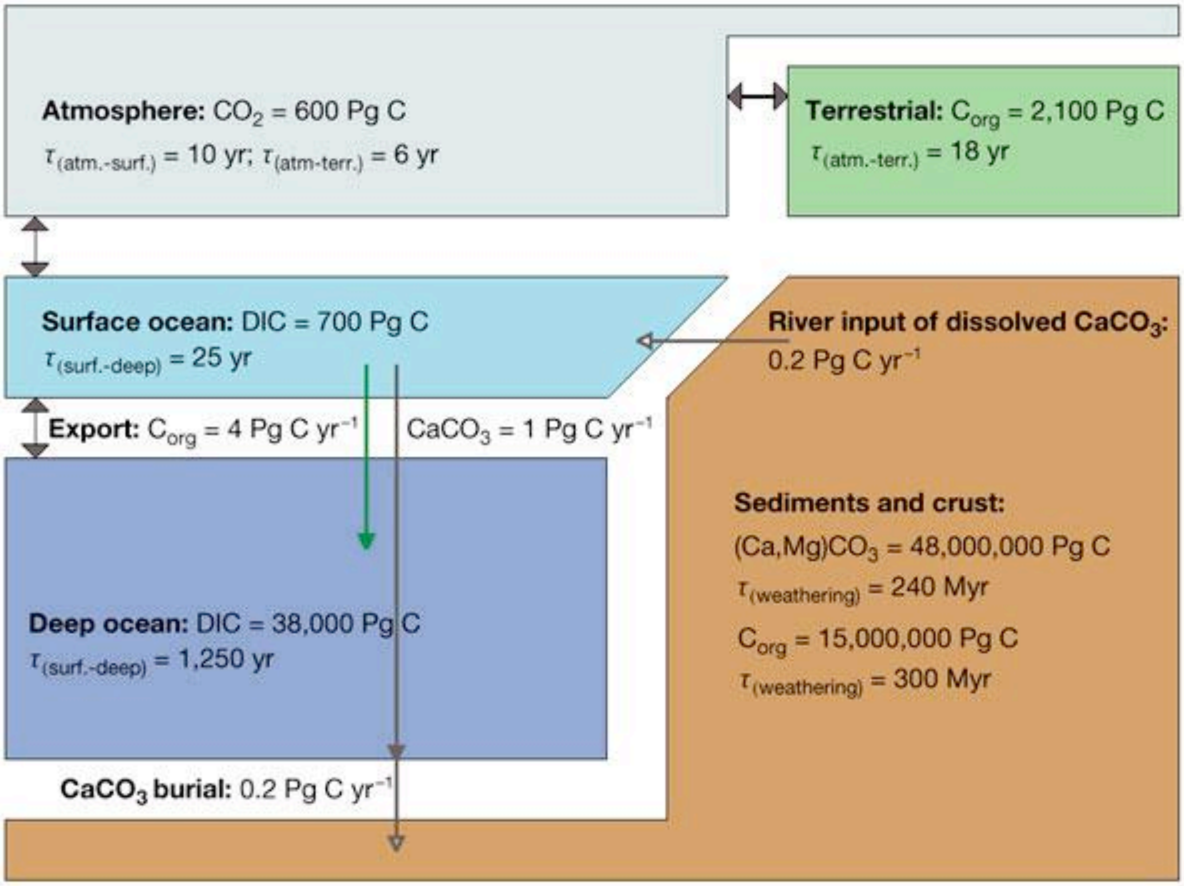


Figure 1.1: Global carbon reservoirs. Of the three reservoirs (ocean, atmosphere, and terrestrial) that experience relatively rapid exchange, the ocean by far holds the most carbon. (Sigman and Boyle 2000).

Changes in atmospheric CO_2 concentrations are tightly coupled to global temperatures due to carbon dioxide's behavior as a greenhouse gas, absorbing long-wave (infrared) radiation from the Earth's surface, but allowing the transfer of short-wave (visible spectrum) radiation from the sun. Atmospheric CO_2 levels are ultimately responsible for an essential negative feedback, involving the injection of CO_2 via volcanic eruptions and the removal of CO_2 from the atmosphere, via weathering, that has kept Earth's climate equitable for life over hundreds of millions of years. However, these feedbacks are believed to work over timescales that span many hundreds of thousands of years. On shorter timescales, and certainly over timescales relevant to policy makers, a high degree of variability in Earth's climate is possible. The current injection of anthropogenic CO_2 into the atmosphere represents a dramatic perturbation to Earth's climate system; it is critical to understand mechanistically how the ocean responds to these changes.

The global ocean has historically been a sink of anthropogenic CO_2. Uptake depends on ocean circulation as well as solubility, which depends inversely on temperature. Global warming is changing the ocean's ability to take up CO_2 by altering circulation patterns and decreasing solubility. Surface winds, heating, and precipitation changes are also modifying the input of momentum and buoyancy into the ocean. These changes are expected to accelerate in the future. A reduction in oceanic carbon uptake will influence atmospheric CO_2 concentrations with the strong possibility of a positive feedback that would further enhance global warming (Friedlingstein et al. 2006). The strength of these feedbacks depends on the complex interplay between physical and biogeochemical processes regulating the sensitivity of ocean carbon uptake to climate perturbation. Uncertainty in the fate of the oceanic carbon sink is a major source of uncertainty in understanding changes in future climate. **The challenge in resolving the large number of intricate processes that influence equilibrated CO_2 concentrations, covering a range of temporal and spatial scales, seriously limits our ability to predict and understand future climate changes**.

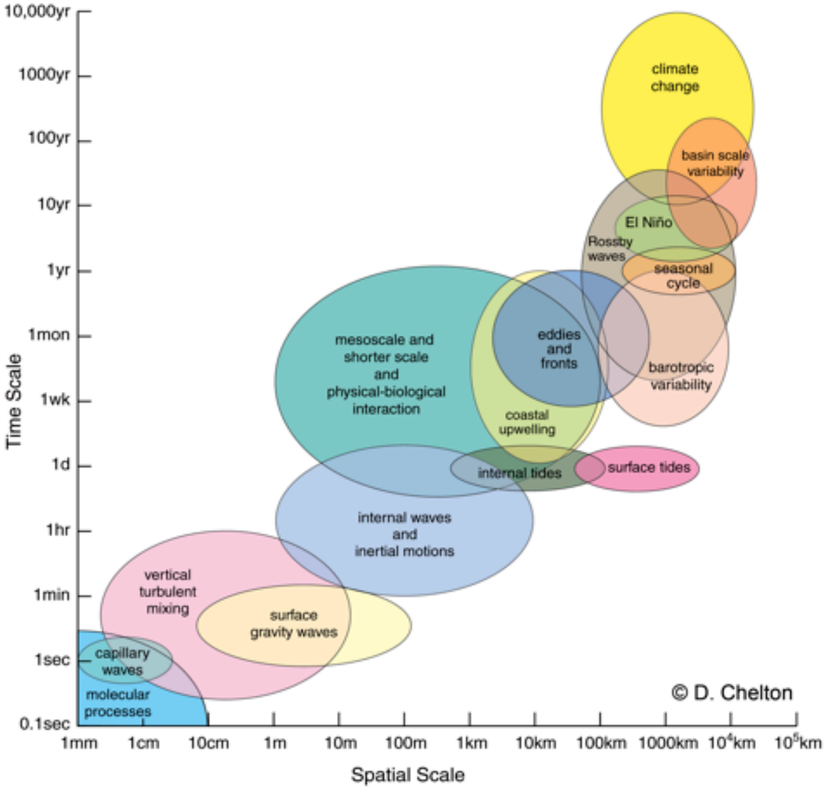
1.2 MARINE CARBON CYCLE CHALLENGES

The overriding challenge of monitoring, quantifying, and closing budgets related to the marine carbon cycle is that the ocean is massively undersampled in both space and time. The ocean is a challenging environment in which to make observations in any context. This situation is exacerbated by the fact that key carbon cycle processes involving physical, biological and chemical dynamics, span temporal and spatial scales that cover many orders of magnitude (Figure 1.2). Furthermore, ***biogeochemical cycling*** is intricately related to the physical circulation, making it difficult to separate physical, chemical and biological spheres. Significant advances in our understanding will require a multi-disciplinary approach.

To date, monitoring of oceanic biogeochemical processes has been dominated by two platforms: remote sensing via satellites and ship-based surveys. Satellites provide near global coverage of temperature, color, and geostrophic velocities - key ocean surface properties. Efforts have been made to infer interior distributions from these surface properties, but this remains challenging. Even essential upper ocean characteristics, such as the ocean mixed layer depth, currently require in situ measurements. Traditional ship-based sampling remains the primary method for achieving high quality measurements of key diagnostics needed to quantify and interpret the carbon cycle. These are time consuming and expensive efforts. Furthermore, in spite of the intense efforts to quantify oceanic CO_2 concentrations, ship-based surveys still provide a rather coarse view of these distributions. The global estimates of CO_2 fluxes, compiled by Takahashi et al. (2009), are an example. Large regions of the ocean, for example most of the Southern Ocean, remain almost completely unsampled (Takahashi et al. 2012).

These methods of observing the ocean would be sufficient if biogeochemical properties and dynamics were relatively homogeneous in the ocean. Both numerical modeling and observations suggest that this is far from the case (Clayton et al. 2013). Improvements in computational efficiency have identified a whole class of motions at scales spanning hundreds of meters to tens of kilometers, the ocean submesoscale (Section 2.1), that were previously under-appreciated. These motions likely have a strong influence on planktonic community structure in the upper ocean. In a fluid dynamical sense, the equations of motion are well understood, e.g. the Navier-Stokes equation. The ability to computationally resolve finer and finer scales reveals a greater range of physical behaviors that are believed to be properly represented; unresolved motions must still be parameterized. Unfortunately, biogeochemical models do not follow this same rule (e.g. Kriest et al. 2010). Parameterizations that produce realistic results when integrated with coarse circulation models may produce very different results when confronted with a greater diversity of dynamic features in higher resolution models. It is essential to have observations to validate and understand where these different models succeed and fail.

In addition to heterogeneity in a spatial sense, the ocean's carbon cycle also responds dramatically to individual events -- a temporal intermittency that also makes observations difficult. The most obvious example of this is annual spring blooms that happen predominantly near the boundary between the ocean's subtropical and subpolar gyres. In a period of just a few days, an intricate balance between surface heating, vertical nutrient fluxes and upper ocean turbulence triggers rapid growth in phytoplankton that completely changes carbon and nutrient concentrations/fluxes in localized regions of the ocean (e.g. Mahadevan et al. 2012). To better understand these events, and their impact on the global carbon properties, future observation systems will need to be responsive to individual events of this type.



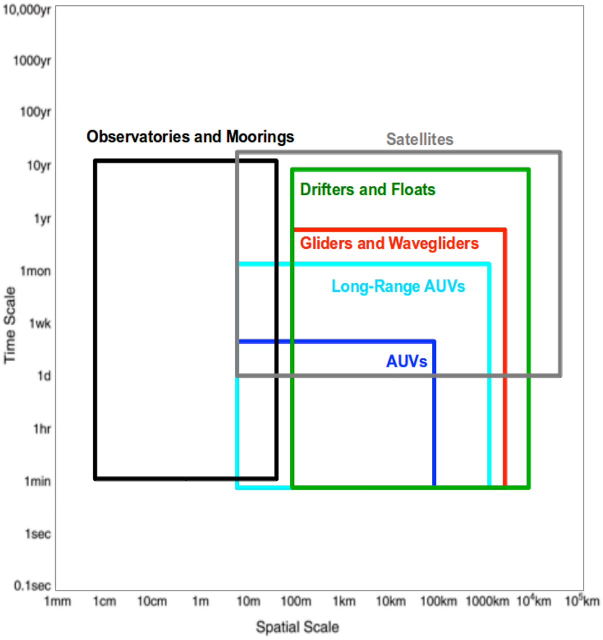


Figure 1.2: Top: Temporal and spatial scales of oceanographic processes (Chelton, 2001). Bottom: Range and endurance of various observation platforms. Figure created by KISS workshop based on a figure originally appearing in Dickey and Bidigare (2005).

1.3 OBSERVATIONS OF A HETEROGENEOUS OCEAN

The key limitation in bridging the gap between intermittent events that locally impact carbon fluxes and global carbon distributions is the lack of persistent observations at mesoscales- and submesoscales. The primary means of monitoring the upper ocean is remote sensing from satellites or in situ measurements from research vessels and, increasingly over the past two decades, gliders and floats. These methods, while powerful, have limitations. Remote sensing methods can provide measurements over large horizontal regions of the ocean but lack the spatial resolution and cadence of in situ measurements. Furthermore, the ability of remote sensing techniques to penetrate into the ocean is limited; it can only provide measurements of the ocean surface or, at best, the first few meters.

Improved resolution of the ocean's physical, biological, and biogeochemical properties in the vertical dimension require in situ measurements. In addition, in situ measurements validate remotely sensed observations. Ship-based oceanographic science remains the predominant means of obtaining ocean data especially in the biogeochemical domain. These expeditions are costly, on the order of 35,000USD per day. Furthermore, the endurance of these vessels is limited (60 days at most) as is their ability and availability to operate in remote regions, such as the Southern Ocean, where our need for measurements is the most acute.

Autonomous platforms have transformed our ability to obtain water temperature, salinity, and conductivity data in the upper 1000m of the ocean. Starting with the development of *Lagrangian* sub-surface floats in the 1950s – e.g., Swallow floats (Swallow, 1955, SOFAR (Rossby and Webb, 1970), ALACE (Davis et al., 1992), and ARGO (Roemmich et al., 2009) – and continuing with the development of gliders – first advocated by Henry Stommel (Stommel, 1989) and now in widespread use (Schofield et al., 2007; Eriksen et al., 2001) – physical oceanographers today benefit from the ability to more cost effectively obtain large amounts of basic physical oceanography data. Numerous studies have been conducted over the past two decades in which gliders, floats and moorings have been deployed, often for extended periods, to measure basic ocean physics properties. Activities range from individual PI efforts to large-scale, multi-year community efforts such as ITOP[1], SPURS[2], OSMOSIS[3] and MIZ[4].

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[1] https://www.eol.ucar.edu/field_projects/itop

[2] http://spurs.jpl.nasa.gov/SPURS/

[3] http://www.bodc.ac.uk/projects/uk/osmosis/project_overview/

[4] http://www.apl.washington.edu/project/project.php?id=miz

The advances in physical oceanography measurements afforded by floats and gliders are still insufficient for the task of fully observing the physical, biological, and biogeochemical processes associated with the marine carbon cycle. This lacuna is the result of five obstacles:

O1: The sensing capabilities for these platforms remain limited. Gliders and floats tend to carry simple sensing payloads, primarily focused on measuring physical ocean properties. While use of bio-optical sensors on floats is growing, coincident physical oceanography measurements and biological/biogeochemical measurements remain rare.

O2: Heterogeneity in the time and space dimensions applies not only to the science processes but also to the platforms used to investigate them. Figure 1.2 shows the range and endurance of various sensing platforms. When compared to the physical processes shown in the same figure, we see that gliders and floats are well-suited to the temporal and spatial scales of physical processes but are perhaps insufficient for the patchiness and rapid evolution scales of biological and biogeochemical processes.

O3: The capability for a mobile coordinated persistent presence, often in harsh, remote regions, remains nascent. Many of the most compelling questions, such as seasonal variability, require continuous measurements over months or even years. Furthermore, the patchiness of the processes requires a mobile capability. Significant progress has been made in the last decade on long endurance vehicles; however, extended deployments, especially in harsher environments, such as the Southern Ocean, remain rare.

O4: Adaptive surveying, which considers in situ and remote sensing data, a priori data, and models is crucial. The dynamic nature of processes constraining upper ocean carbon fluxes, combined with their heterogeneity in time and space, suggests a need for adaptive surveying. Adaptations should consider data not only from individual robots but also from other resources, such as remotely sensed measurements or models.

O5: Our present methods still require extensive human interaction. In general, oceanography and, in fact, most field robots continue to follow the mission cycle illustrated in Figure 1.3 in which only the mission execution step is highly autonomous. The other steps have significantly lower levels of autonomy (LOA) and are done almost exclusively by humans.

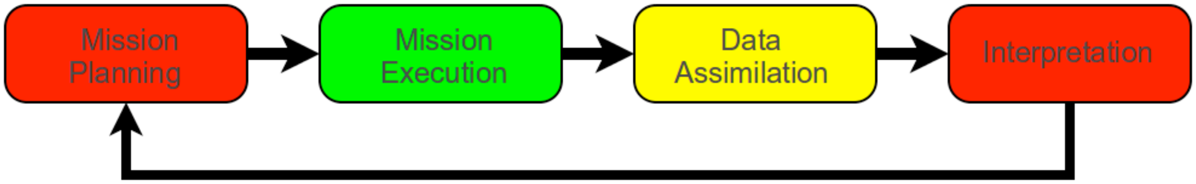

Figure 1.3: The conventional model for programming, executing, and analyzing missions and their results. Box color indicates the achieved autonomy – red indicates no autonomy; yellow indicates occasional low autonomy; and green indicates total autonomy. Total autonomy is routinely achieved only in the mission execution phase.

1.4 A VISION FOR OCEAN ROBOTICS AND AUTONOMY

A central concept that has emerged from our study is the use of fleets of mobile heterogeneous platforms working in a coordinated manner to obtain the observations over a broad range of temporal and spatial scales. Figure 1.4 illustrates a potential implementation of this proposed concept. The heterogeneous robots, which could include ASVs, AUVs, Long-Range AUVs (LRAUV), and gliders, communicate with each other via wireless communications (acoustic or optical methods for in-water telemetry; satellite communication for in-air) and with data assimilation efforts on shore. In situ data from these platforms, along with remote sensing data and models is assimilated on-shore and used to update estimates of scientific parameters and inform decisions about future sampling strategies. The outcomes of these decisions are goals for future observations, which are communicated to the robots. Based on these goals and the state of the robots and sensors (e.g., vehicle and sensor health, remaining power), the robots autonomously re-task and reconfigure themselves to achieve these goals. If the goals cannot be achieved, information is transmitted back on shore to allow humans to resolve the conflict between science goals and robot/sensor constraints.

Using heterogeneous robots has a number of advantages including the ability (1) to equip more sophisticated platforms with larger, more power consumptive sensors; (2) to match vehicles of differing performance characteristics (e.g., range and speed) to the temporal and spatial scales of different processes; and (3) allow smaller cheaper vehicles to obtain high density measurements and, potentially through the use of proxy measurements, serve as sentinels that inform larger, more capable vehicles.

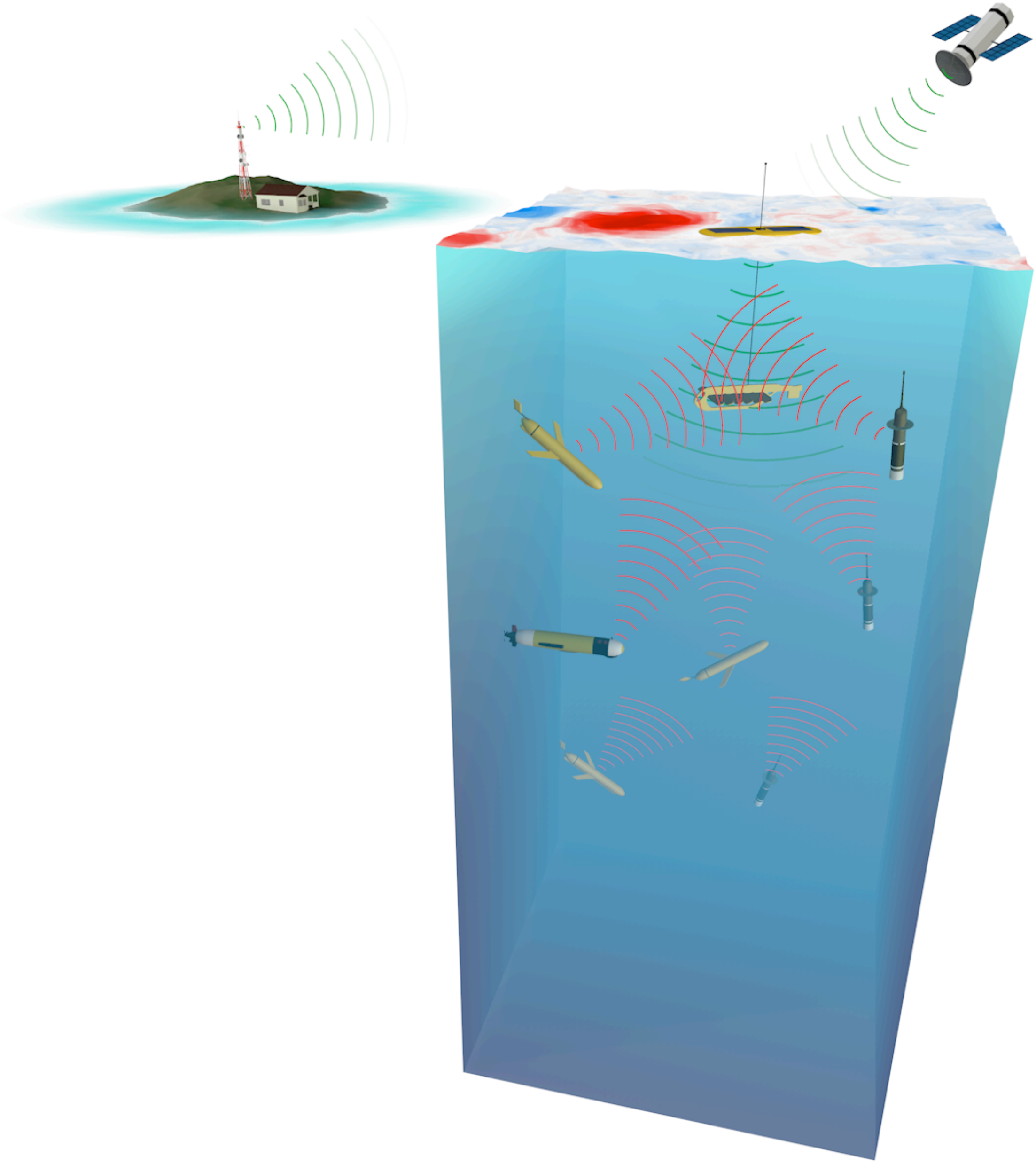

Figure 1.4: Illustration of a potential implementation of our vision of a multiple platform measurement fleet consisting of an ASV, multiple gliders, floats, and a LRAUV. Acoustic modems provide intra-vehicle communication and, via satellite, data is telemetered to shore for assimilation and human interpretation. Colors on the ocean surface indicate remotely-sensed diagnostics, such as sea surface temperature or ocean color. Image produced by WHOI Graphics with KISS funding.

Autonomy is critical for a number of reasons. First, the vast amount of required data – both science (necessary for data assimilation) and engineering (necessary for vehicle constraint information) – may exceed available telemetry bandwidth. Thus information needed to make decisions will reside at sea and require autonomous decision-making. This would allow more critical data, specifically, science data, to be transmitted ashore. Second, under the current paradigm illustrated in Figure 1.3, humans are still involved in most operations. As the number of robots grows, this approach will become unsustainable and requires autonomy to relieve humans of many tasks. This study does not seek to make this process totally autonomous; rather humans will focus primarily on tasks to which they are uniquely suited, such as interpretation of assimilated results and decision making. This vision is not entirely new --- seminal papers by Curtin et al., (1993) and Stommel (1989) spoke to the vision of large-scale, coordinated autonomous sampling nearly 25 years ago. However, an end-to-end implementation has yet to be achieved. Numerous efforts, both past and ongoing, continue to progress toward this goal and have advanced multiple technologies such as marine robots, in-water communications, and autonomy.[5]

1.5 SCHEDULE AND PROCESS OF THE STUDY

The study was organized as an opening workshop of five days, an interim period of virtual meetings, and a final three day workshop.

Opening Workshop (1), October 7-11, 2013

Day 1**.** To achieve workshop objectives and to be truly transformational, our approach has integrated many different disciplines. The workshop started with five presentations as part of a public short course. These lectures summarized advances and remaining challenges for the various disciplines involved and established a common language for communicating them. Topics from the short course included the marine carbon cycle, remote sensing of the oceans, oceanographic robotics and autonomy for space science and its applicability to ocean exploration. The titles of the talks and names of the presenters are given in Appendix F. Following the public short course, a group discussion of the KISS participants identified the main issues/challenges in Ocean Carbon Monitoring.

Day 2. The workshop was organized into three interdisciplinary breakout groups, which defined measurement goals. This was followed by the whole group prioritizing the required observations. The workshop participants then formed three different breakout

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[5] Section 4.6 elaborates on the differences between this work and previous efforts.

groups to identify the main challenges in different ocean environments, which were effectively successive vertical zones: (i) export from surface production in the euphotic zone; (ii) remineralization through the twilight zone and (iii) carbon exchange at the seafloor.

Day 3. Each of the three breakout groups worked to identify the technical challenges specific to their zone of interest for the first half of the day. In the afternoon there was a field trip to the Page Museum at the La Brea Tar Pits. This allowed an opportunity for demonstration of a JPL portable instrument for sensitive methane measurement. This demonstration illuminated the problems of integrating heterogeneous data, arising from different emissions and advection by the wind (an analog for ocean currents).

Day 4**.** The three breakout groups reported back to the whole workshop, which discussed the findings. The participants then re-organized again to populate three new technology solutions groups: (i) Resource allocation and adaptation, (ii) sensors, and (iii) modeling.

Day 5**.** The goals for the interim period and the second workshop were defined and articulated.

October 2013 through January 2014. There were virtual meetings of the three technology solutions groups.

Closing Workshop (2), February 4-6, 2014

Similar to the first workshop there were presentations on science and technology during the first two days.

Day 1**.** The three sub-groups organized the results of their work undertaken by virtual meetings since the first workshop and reported back to the whole group. This was followed by a group discussion to identify the crucial scientific questions about the fate of carbon in the oceans.

Day 2**.** There was discussion about closing the gaps in technology needed to address the science questions. Then, to focus the effort, the workshop split into breakout groups each of which was tasked with defining a hypothesis and an experiment to test that hypothesis. Although initially there were three experiments formulated, two of them were sufficiently similar to be amalgamated.

Day 3**.** The groups continued working on the details of the experiments and honed them in whole workshop discussion.

CHAPTER 2. FUNDAMENTAL SCIENCE QUESTIONS

The ocean's role in the global carbon cycle and its impact on Earth's climate is an enormous topic, about which much has been written (Archer 2010, IPCC 2007). We have not attempted an exhaustive review here of the marine carbon cycle. Rather, we hope to convey why this is a critical and challenging component of the oceans to observe. Having identified that persistent monitoring is a prerequisite, which in turn demands autonomy for effective implementation, we also seek to identify key components of the cycle amenable to study with ocean robotics.

Monitoring the marine carbon cycle is an inherently multi-disciplinary task. The circulation of the ocean and its variability strongly influence biogeochemical cycles, since the solubility, storage, and transport of the key chemical species are a function of the physical state of the seawater and its motion. Changes in the biogeochemistry of the ocean in turn affect the ocean's physical state by altering turbidity, aerosols, clouds, and **surfactants** that influence air-sea exchange.

Major goals of this KISS study were to identify gaps in our present understanding of the global carbon cycle and limitations in our ability to monitor these processes. Our approach to identifying technological advances that address these gaps and limitations started from an assessment of critical science questions. In this chapter, we summarize some overarching themes that address the following questions:

- What (temporal/spatial) scales are critical to accurately resolve the carbon cycling?
- What are the connections and feedbacks between ocean circulation and biogeochemical processes?
- What is the advantage of a multi-disciplinary approach?

2.1 WHAT SCALES ARE CRITICAL FOR THE RESOLUTION OF CARBON DYNAMICS?

A major theme running through the KISS study was the "patchiness," or intermittency, that characterizes biogeochemical cycling, at least in the upper ocean (few hundred meters), and potentially throughout the water column. Here we define key time and length scales that are believed to be of interest, including our ability to observe these directly in the ocean.

Turbulent convection (centimeters to meters; minutes to hours) is the most direct way of generating vertical motion in the water column. Convection arises from statically unstable distributions of density, i.e. dense fluid overlying light fluid. In the ocean this almost always arises due to surface forcing, such as cooling at the sea surface or strong evaporation that generates compositional (salt) convection. The non-linear equation of state may also be responsible for initiating convection, and the interaction with sea ice at high latitudes is another mechanism for generating strong convective motions. Direct resolution of turbulent motions typically requires sensitive measurements made from a microstructure profiler. However, turbulent dynamics are often inferred from "fine-scale" (order of a meter) measurements of temperature and velocity, which requires significant assumptions about background properties of the region. The applicability of these fine scale methods across different environments is not well understood.

Submesoscale motions (many tens of meters to kilometers; hours to days) represent a relatively new area of intense research in physical oceanography (Figure 2.1). These motions are associated with the breakdown of ***geostrophy***, which occurs when the time scale of fluid motion becomes comparable to or shorter than Earth's rotation rate, or, equivalently, the Rossby number becomes order one or greater. At larger scales, the combination of stratification and Earth's rotation tends to make the fluid "stiff" so that flow occurs predominantly in the horizontal plane. As this constraint weakens and the submesoscale regime is approached, stronger, vertical, ageostrophic motions are permitted. Submesoscale motions are often associated with the formation of sharp fronts. Intense vertical motions are generated to relax strong lateral density gradients associated with these fronts. Submesoscale vertical motions can play a key role in modifying mixed layer depths and delivering nutrients into the euphotic zone. Submesoscale motions also moderate the transfer of energy between small-scale turbulence and energetic mesoscale motions in the ocean. Ocean gliders and other AUVs are typically well suited for capturing the spatial scales of submesoscale motions. The evolution of these features can be rapid, happening over a period of a day or so, which can making tracking of features challenging for slower vehicles.

Mesoscale eddies (ten kilometers to a few hundred kilometers; days to months) arise from instabilities related to lateral gradients in ocean density. Eddies typically take the form of coherent vortices (Figure 2.1); however, the ocean mesoscale may encompass any variability that occurs at sub-basin scales but remains influenced by the Earth's rotation. Ocean eddies are similar in many ways to high and low pressure systems in the atmosphere, although the differing fluid properties of seawater and air means that mesoscale eddies are roughly an order of magnitude smaller than their atmospheric counterparts. An ocean basin may typically contain tens to hundreds of coherent eddies. In the context of this KISS study, eddies are efficient stirrers of upper ocean properties: temperature, salinity, and dissolved gases. In the presence of a front in tracer concentrations, these motions elongate boundaries and sharpen gradients. This acts to reduce the lateral scales of motion, catalyzing submesoscale dynamics, and also enhances mixing. Mesoscale eddy motion is also associated with a vertical deflection in subsurface *isopycnals* (surfaces of constant density). Cyclonic (anticyclonic) eddies experience an upward (downward) displacement of subsurface isopycnals. An upward displacement may bring nutrient rich waters into the sunlit upper waters (the euphotic zone) and thus stimulate local primary production (McGillicuddy et al. 1998, 2007). The surface signature of mesoscale eddies are generally resolved by remote sensing products: altimetry, ocean color, sea surface temperature and salinity, but interpreting the ocean's vertical structure from these signals is still an imperfect science. Coherent eddies may persist for many months and can be effective means of trapping and transporting properties or even ecosystem communities long distances.

Gyre circulations (basin scale; months to years) are responsible for large-scale distributions of surface chlorophyll and ecosystem communities. For instance, subtropical gyres are typically classified as oligotrophic regions (regions with low levels of nutrients) as wind forcing drives downward vertical motions (Ekman pumping) that suppress the supply of nutrients to the upper ocean. (Individual mesoscale eddies can oppose this effect as described above.) Subpolar gyres, where the wind stress curl changes sign, are associated with upward vertical velocities (Ekman suction) and are thus more biologically active regions when sunlight is in sufficient supply. Gyre circulations are also in part responsible for the size and structure of oxygen minimum zones in the eastern low latitudes of the Pacific and Atlantic basins. The **Antarctic Circumpolar Current (ACC)** is another large-scale circulation system that has a strong influence on the marine carbon cycle. The dynamics of this current are distinct from the gyres because it is zonally unbounded. In particular, a broad range of density classes outcrop at the surface making this an important region where interior water masses are exposed to surface forcing and atmospheric gas concentrations, a process known as "ventilation."

While processes have been discussed at discrete scales (gyre, mesoscale, submesoscale), there is intricate interaction across these scales that give rise to the full spectrum of ocean variability. For instance, mesoscale eddies arise from strong frontal regions associated with the gyres' western boundary currents and these in turn create straining fields that form submesoscale fronts. Submesoscale fronts can then transfer directly to small dissipation scales. These intricate interactions remain poorly understood.

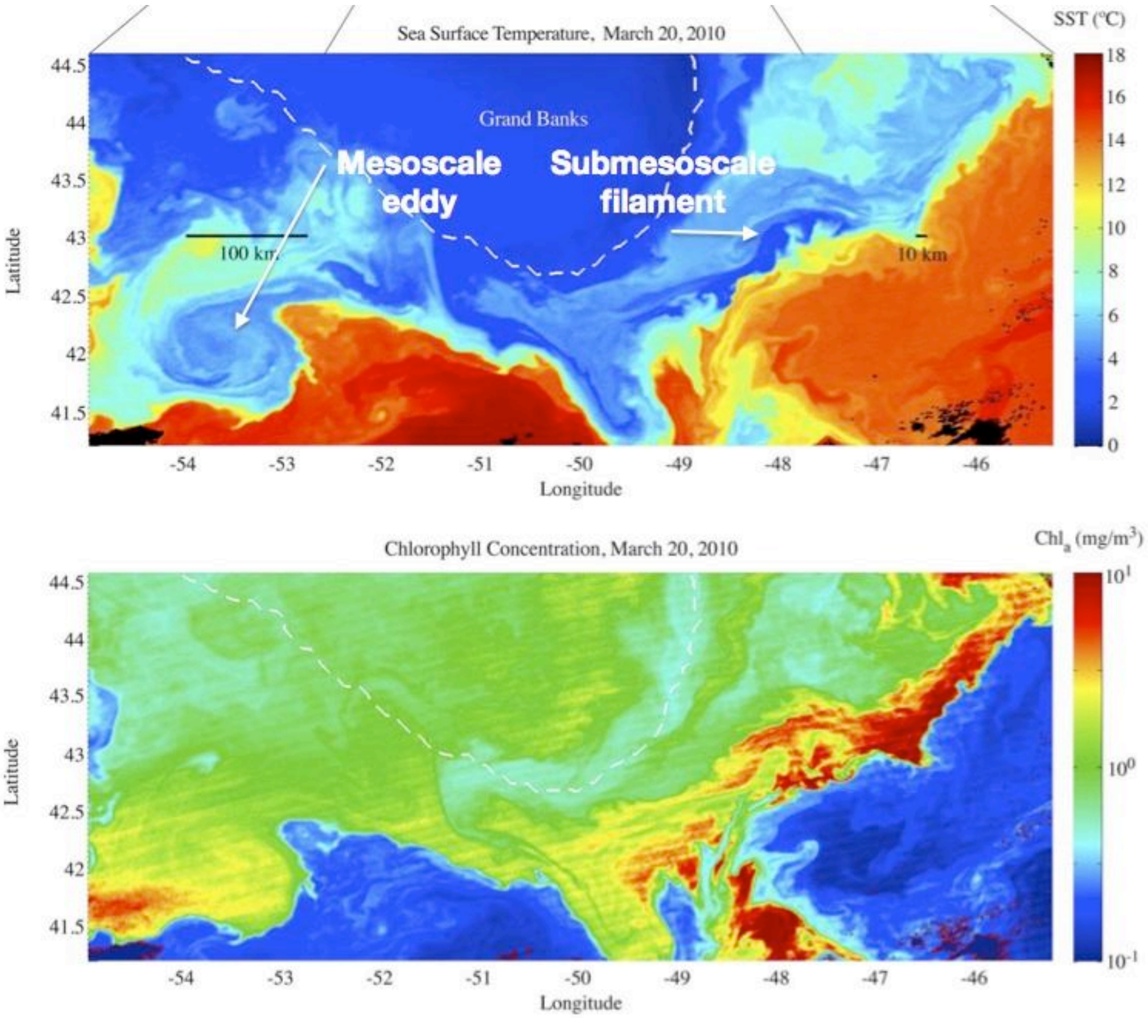
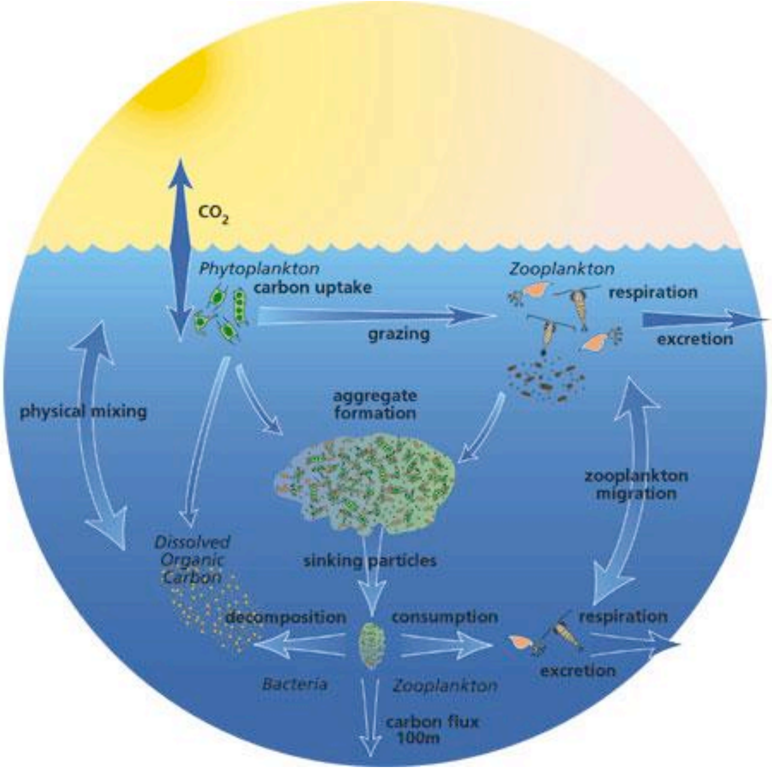


Figure 2.1. (Top) Snapshot of sea surface temperature from March 20, 2010 in the northern Atlantic Ocean. Coherent mesoscale eddies are apparent on scales of roughly 100 km, but the region also exhibits a large degree of submesoscale filaments and eddies. (Bottom) Snapshot of remotely sensed surface chlorophyll values for the same date. Peak concentrations are found to cluster around strong frontal regions. (Taylor and Ferrari 2011).

2.2 WHAT ARE THE CONNECTIONS AND FEEDBACKS BETWEEN OCEAN CIRCULATION AND BIOGEOCHEMICAL PROCESSES?

Carbon cycling in the ocean is intricately related to ocean circulation. Fluid motions carry dissolved gases and nutrients from one place to another and deliver essential nutrients required for primary production. Rotation, stratification and the ocean's small aspect ratio mean that ocean currents are predominantly horizontal, especially away from surface and bottom boundaries. This property challenges the notion that the vertical transfer of carbon from the ocean surface to the seafloor can be described with one-dimensional models. The ***advection*** of properties during their vertical transit also makes closing carbon budgets extremely difficult. In this section we point to a few key mechanisms that couple physical, biological and chemical properties in the ocean. This section reflects our discussion at the KISS meeting and is not meant to be representative of all the key processes in the ocean.



Biological pump. Ocean biology primarily impacts the marine carbon cycle through the biological pump (Figure 2.2), a process that sets the leading order balance between net primary production by phytoplankton and ecosystem respiration. The biological pump is initiated at the surface by the production of fixed carbon in the upper, sunlit layer of the

Figure 2.2. Schematic of the biological pump. Plankton fix CO_2 as organic carbon during photosynthesis and also form shells from calcium carbonate. Through aggregation, sinking and vertical mixing, marine snow carries both of these forms of carbon away from the atmosphere and surface waters to reservoirs in the deep oceans and ocean sediments. The efficiency of this pump strongly influences surface ocean, and thus atmospheric, CO_2 concentrations. Source: © United States Joint Global Ocean Flux Study.

ocean via photosynthesis (see discussion of the mixed layer below for coupling to physical processes). Phytoplankton use carbon dioxide, nitrogen, phosphorus and other trace elements to produce organic carbon in the form of carbohydrates and proteins; this is known as the soft-tissue pump. A comparable process occurs amongst some plankton that use calcium and dissolved carbonates to form a hard, protective shell composed of calcium carbonate ($CaCO_3$). Following these processes, organisms may remain in the euphotic zone and become part of the regenerative nutrient cycle via respiration.

Alternatively, organisms may sink out of the euphotic zone and begin their descent to the seafloor. The sinking of this surface matter is a fascinating subject. Rather than falling passively, the particles tend to aggregate, which increases their mass and density, and thus their sinking rates. This process of aggregation is poorly understood and difficult to observe. An increase in sinking rates leads to a higher probability of sinking organic matter escaping predation and reaching the seafloor. This continuous shower of organic detritus falling from the upper ocean is often referred to as marine snow. During the sinking phase of the biological pump there are two possible fates for the fixed carbon. It can be decomposed by bacteria either in the water column or on the seafloor; in this case the organic matter is remineralized and becomes available for new primary production. The second possible end point is that the carbon reaches the seafloor and is buried by sediments before consumption by bacteria. Once the carbon is shielded in this manner, it has been removed from the marine carbon cycle (but not the global carbon cycle). The burial rate is roughly 0.2 PgC per year (Figure 1.1). In the absence of additional sources to the atmosphere, this removal of carbon from the oceanic reservoir will lead to a reduction in atmospheric CO_2 concentrations.

Solubility pump. Carbon chemistry also contributes to the vertical transfer of carbon (in its dissolved inorganic form) in the ocean, predominantly through the solubility pump. This transfer relies on two factors: (1) solubility of carbon dioxide is inversely proportional to temperature; and (2) the communication between surface and interior waters is promoted at the poles, where surface buoyancy forcing leads to the formation of colder, denser water masses that sink via convective processes into the interior. The link between sinking and temperature means that water with higher concentrations of dissolved inorganic carbon are preferentially “pumped” from the surface into the ocean interior. This also implies that as deep water upwells CO_2 will outgas into the atmosphere. This balance is of particular significance in the Southern Ocean, where a broad range of density surfaces outcrop across the Antarctic Circumpolar Current.

Mixed layer depths. Growth of phytoplankton in the upper ocean depends on access to both light and nutrients. Seawater is relatively opaque to electromagnetic radiation, which means that light penetrates to rather shallow depths (the euphotic zone), typically a few tens of meters. Light levels decay exponentially from the surface, and are strongly dependent on local properties of the water, for instance the amount of organic and inorganic material suspended in the upper ocean. Nutrients, on the other hand, are largely delivered from below, where large reservoirs are present at depth due to the remineralization of sinking organic matter (see discussion of the biological pump). The delivery of these nutrients into the upper ocean largely depends on physical processes that “upwell” water from depth towards the surface. Upwelling may depend on turbulent mixing, surface wind forcing (especially near the coast), mesoscale eddies or large scale circulation patterns. The vertical migration of mobile plankton may also impact nutrient supply. At the interface between upwelling nutrients and incoming solar radiation is the ocean mixed layer. This is a region extending from the ocean surface to a depth that varies between 10 m and many hundreds of meters, in which properties are homogenized due to the action of turbulent mixing.

Mixed layers have a distinctive seasonal cycle throughout most of the ocean, being shallow in summer months when surface heating acts to stratify the ocean, and deepening throughout the winter in response to wind-driven mixing and convection caused by surface cooling. The mixed layer is also, for the most part, the region where phytoplankton are passively cycled by these turbulent motions. Thus phytoplankton exposure to both light and nutrients is critically set by local mixed layer depths. For example, in areas of shallow mixed layers, phytoplankton are exposed to light more frequently than in deep mixed layers, and therefore tend to grow more rapidly, assuming nutrients are replete. When mixed layers deepen, nutrients may be in greater supply due to entrainment from below, but light levels are reduced. Phytoplankton growth is optimal in situations where neither light nor nutrients are limited. This is dramatically demonstrated in the North Atlantic during the spring, when phytoplankton populations “bloom.” At this time of year, wintertime deep mixed layers have enriched the surface with nutrients. Increased springtime solar radiation both provides more light for photosynthesis and shoals the mixed layer via heating. The result is a period where the environment becomes suddenly favorable to primary production leading to an exponential increase in surface chlorophyll levels over periods as short as a few days.

This relationship between mixed layer depth and phytoplankton growth is known as the critical depth hypothesis and dates back to Sverdrup’s seminal work in 1953. Recently this paradigm has been challenged by a number of observations, particularly ones that show active primary productivity in winter months during periods of deep mixed layer (e.g. Behrenfeld 2010). Other explanations for bloom events have identified the importance of intermittent mixed layer shoaling due to mixed layer instabilities (Taylor and Ferrari 2011) or a balance between phytoplankton and zooplankton populations (the “Dilution Hypothesis”, Behrenfeld 2010).

Surface export. The rate of photosynthesis in the sunlit ocean, the rate of recycling by respiration, and the export of unrespired organic particles to deeper waters is a logical starting point for thinking about biogeochemical cycles in the ocean. Among other effects, export removes carbon, nutrients, and trace metals from surface waters, leading to their depletion near the sea surface and thus lower rates of primary production. Export transports organic debris to depth, where it is respired and released as dissolved constituents. This process is the main source of chemical variability in the ocean. Export also suppresses the atmospheric CO_2 concentration, because the incorporation of CO_2 into biomass, followed by sinking, lowers the CO_2 partial pressure (pCO_2) of the surface ocean and the atmosphere as well. Finally, the growth of phytoplankton in the surface ocean establishes the base of the food chain leading to fish, shellfish, other sources of protein, and the oceanic megafauna.

The sunlit ocean is particularly relevant to this KISS study as it is the one oceanic domain observable by satellites. These observations characterize the surface water temperature, salinity, color and wind stress. They also characterize biological properties that affect ecosystems and respond to the physical environment: iron limitation, chlorophyll concentration, particulate organic carbon concentration, and derived properties including primary production and carbon export. Planned missions will make more detailed observations of bio-optical properties from space, leading to improved characterization of functional and taxonomic properties.

Understanding upper ocean carbon fluxes involves characterizing the relationship between these fluxes; the physical environment; the availability of the critical nutrients N, P, Si, and Fe; and the ecosystem. Autonomous underwater vehicles have extraordinary potential for improving our understanding of upper ocean ecosystems. They can characterize the structure of the upper ocean water column (measuring temperature and salinity), the nutrient concentration, bio-optical properties constraining rates of primary production and the daily metabolic cycle, chemical properties constraining these same rates, and particle dynamics and the sinking flux. Hence they can be used to understand a wide spectrum of influences on upper ocean carbon fluxes.

Remineralization in the twilight zone. Photosynthesis in the surface ocean produces approximately 100 gigatons (Gt) of organic carbon per year, of which 5 to 15 percent is exported to the deep ocean (Laws et al. 2000). Once this organic carbon sinks outside of the euphotic zone, it may be converted into CO_2 by heterotrophic organisms at depth. This conversion impacts the ultimate storage of oceanic carbon. Remineralization is particularly active from the base of the mixed layer / euphotic zone to a depth of roughly 1000 m. Due to respiration, vertical fluxes of particulate organic carbon (POC) may be reduced by one to two orders of magnitude in this region, sometimes referred to as the twilight zone.

It has proven difficult to close the budget between carbon sources at the surface and carbon sinks in the twilight zone (Boyd et al. 1999, Burd et al. 2010). Details of this remineralization process is complicated by a number of things: the array of organisms involved -- zooplankton, microbes, etc.; the sensitive dependence of sinking rates on particle size and aggregation; and ocean currents that may carry particles laterally large distances from the site where they exited the euphotic zone. Models indicate that variations in how the vertical POC flux decreases with depth can lead to changes in atmospheric CO_2 of up to 200 ppm (Kwon et al. 2009), implying a coupling between biological activity in the ocean interior and oceanic storage of CO_2. Estimates of POC flux are typically two orders of magnitude less than estimates of community metabolism at depth. A recent paper (Giering et al. 2014) argues that this gap may be closed by invoking a synergy between zooplankton and microbes. The larger zooplankton are able to access larger, faster sinking particles, but their feeding also breaks up particles that stimulate deep-ocean microbes (prokaryotes). This study was carried out in a specific location (the Porcupine Abyssal Plain site) and it is unclear whether this same balance is active elsewhere.

Seafloor Processes and the Global Carbon Cycle. Recent studies have begun to focus on the role that fluid flow from the deep ocean floor might play in the global carbon cycle. For example, SCOR/ InterRidge Working Group 135 studied the role of submarine hydrothermal systems and their role in regulating global Carbon budgets[6]. That work progressed in parallel with this KISS Seafloor study, resulting in a model that draws together results from prior global-scale estimates of iron inputs to the ocean and results from process-oriented studies at specific vent fields, into a coherent whole. That work has found that the net effect of hydrothermal cycling is likely to be one of removal in which dissolved organic carbon is sequestered into hydrothermal plume particles, either through microbial activity or through abiotic processes, with total removal estimated at 0.015 to 0.046 Gt C yr-1 (German et al., submitted). While these values are small compared to the predicted export flux of 5 Gt Cyr-1 for particulate organic carbon exiting the sunlit surface ocean, those fluxes attenuate markedly in the mesopelagic and bathypelagic zones with only 0.4-0.7 Gt Cyr-1 predicted to reach 2000m depth. The new study concludes that if photosynthetically-derived POC fluxes arriving at the seafloor only represent a fraction of the flux that reaches as far as 2000 m, hydrothermal plumes might represent the dominant mechanism for organic carbon removal to sediments globally. For cold seep fluid flow at ocean margins, our understanding of carbon fluxes is much less mature. While much recent attention has focused on the potential for future release of methane direct to the atmosphere from shallow submarine gas hydrate fields, (e.g. Shakhova et al., 2005), the majority of global methane release from the seabed along with associated CO_2, occurs much deeper, along active and passive ocean boundaries. Until recently, the scientific research community lacked a technological approach with which to investigate the release and fate of these important greenhouse gases but in the past 2-3 years, with the advent of high-resolution mapping approaches (Brothers et al., 2013), the abundances of known cold-seep activity along the US

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[6] http://www.scorint.org/Working_Groups/wg135.htm

seaboard alone have increased by approximately two orders of magnitude, from a few identified sites to a few hundred such systems. While these systems remain of compelling scientific interest and new lines of inquiry are continuing to be pursued (including a NASA Astrobiology Institute proposal that has been initiated and successfully developed past pre-proposal to full proposal during the lifetime of the KISS Seafloor project), the consensus of the majority of the participants in the first KISS Seafloor Workshop was that these systems were not thought to be of sufficient first-order importance to global carbon cycles to merit continued discussion between the workshops and onward into the second Workshop deliberations.

2.3 HOW IS THE CARBON CYCLE CHANGING (ANTHROPOGENIC CARBON)?

There exist two “flavors” of CO_2: natural carbon, which will have concentrations that vary inversely with temperature and dissolved oxygen; and anthropogenic carbon, which depends critically on the exposure history of the ocean to changing atmospheric CO_2 concentrations over the last 200 years. The signature of anthropogenic carbon is strongly correlated with water mass age, and is positively correlated with temperature, reflecting an increase in global temperatures following an enhancement of the atmosphere’s greenhouse gas content. Anthropogenic carbon represents the uptake of excess CO_2. This uptake is typically thought of as a perturbation to the “steady-state” pre-industrial air-sea CO_2 fluxes, assumed to be in an equilibrium determined by physical and bigeochemical controls, some of which are described above. As atmospheric CO_2 increases, the ocean must equilibrate, causing CO_2 sinks to become stronger and regions that were traditionally sources of CO_2 to the atmosphere to become weaker. Ocean biology does not directly drive excess CO_2 uptake, as carbon is not a biolimiting element in the ocean. However, increased CO_2 uptake does feedback on biological properties and ecosystem dynamics.

Roughly 50% of the CO_2 that has been released by mankind is now dissolved in the oceans; however, detecting where this excess CO_2 is in the ocean remains complicated. Particularly in the deep ocean, the signature of anthropogenic CO_2 can easily be masked by natural variability, due to biological modifications, circulation changes or mesoscale variability. Even direct comparisons of observed CO_2 concentrations at the same location taken decades apart do not reveal a clear increase. Numerous techniques have been applied in the efforts to estimate the anthropogenic increase. One promising technique is to use tracer proxies, for example short-lived CFCs, which via a transfer function can be related to carbon concentrations. However, there are still caveats: not all tracers are good analogs of carbon and typically proxy methods are unable to account for changes in ocean circulation over time. Considering maps of anthropogenic carbon concentrations, there is substantial variability amongst estimates using different methods, yet the bulk of anthropogenic CO_2 enters in the high northern latitudes, such as the Labrador Sea and is being carried into the interior along the pathway of North Atlantic Deep Water. In the southern hemisphere, the change is predominantly seen along the northern boundary of the ACC, related to the formation and subduction of Antarctic Intermediate Water (AAIW).

Since the 1990's the leading order question was "How much excess (anthropogenic) carbon is there in the ocean and where is it?" Great strides have been made in addressing this question, although there is still significant uncertainty in under-sampled regions of the ocean, e.g. almost the entire Southern Ocean. The depth distribution of the anthropogenic carbon inventory is also poorly constrained. Nevertheless, the community is moving beyond the purely inventory stage to address new questions including: Is it possible to identify and attribute changes in atmospheric CO_2 growth rates on timescales useful for carbon-management assessment (e.g. land-ocean partitioning)? How will ocean uptake change in the future? For these questions, it is critical to identify and understand carbon uptake in the upper ocean, its spatial and temporal variability, and its sensitivity to change.

2.4 SCIENTIFIC QUESTIONS

Mixed layer depths (MLD). We are particularly intrigued by the influence of water column stratification and the light field on upper ocean ecosystems and carbon fluxes. At least since Sverdrup (1953), it has been understood that, when the mixed layer is shallow, phytoplankton grow rapidly because they spend their life in a high-light environment. On the other hand, when the mixed layer is deep, phytoplankton spend a lot of their time in an environment where light has been attenuated to a low value. The depth of the mixed layer explains much of the variability in open ocean productivity. For example, in wintertime, surface waters are cold and dense; they mix with underlying waters, and mixed layers are deep. In summer, a relatively thin layer of warm water floats on colder waters below, and mixed layers are shallow. Productivities in the summertime ocean are generally much higher than in wintertime. Furthermore, during spring and summer, there is a strong link between mixed layer depth in particular oceanic regions and upper ocean carbon fluxes.

While there is strong evidence that productivity is higher when mixed layers are shallower, a major question remains about the role of MLD variability within seasons. In some domains, MLD is very stable, ecosystems are likely to approach steady state, and carbon fluxes are probably fairly constant. In others, wind stress from storms will cause mixed layers to deepen. In these areas, the ecosystem response may be slow, in which case again the biota and the fluxes may be rather stable. Alternately, the ecosystem may respond rapidly, in which case productivity may diminish during storms, as mixed layers deepen, and gradually increase as mixed layers warm and shoal in the aftermath. These two scenarios imply very different relationships between physical forcing and the biological response, but which is more representative in most oceanic domains remains an open question.

This background suggests approaches to the study of upper ocean ecosystems based on AUVs. These studies might be centered on observing the effects of mixed layer depth on ecosystems, but would be carried out in a context that would advance our understanding of the broader problem of upper ocean ecosystems and carbon cycling. Bermuda is the site where the links between physical forcing and the biogeochemical response are best characterized. Using an instrumented mooring, Dickey et al. (2001) made continuous observations of temperature and chlorophyll (among other properties) during much of the period from 1995-1998. In 2004-2005, four cruises were mounted to study the effects of changes in the wintertime mixed layer on production (Lomas et al., 2009; Maiti et al., 2009; and Krause et al., 2009). The 2004-2005 studies identified about 4 events associated with storms and eddies, and showed that the injection of nutrients into the euphotic zone led to increases in biomass and export fluxes. Autonomous vehicles, operating more or less continuously, could observe the sequence of physical, biological, and chemical changes associated with a large number of events, and lead to an understanding of their role in carbon fluxes.

Understanding the euphotic / twilight zone transition. The transition between the euphotic and twilight zones marks a biological regime shift. Within the euphotic zone, primary production is possible and in a steady state, comes into balance with cycling occurring within the sunlit layer and export out of this region. Below the euphotic zone, remineralization is the dominant process. Interestingly, this vertical regime shift also mirrors a dramatic change in the structure of ocean currents. Near the surface and especially in regions where the mixed layer is deep, submesoscale motions readily develop and intense vertical velocities are common. At greater depths, the effects of Earth's rotation become more important and both the temporal and spatial variability of the flow moves to larger scales.

It is now known that export from the euphotic zone is not a purely one-dimensional process. It depends sensitively on lateral flows that can drive tracers out of the mixed layer if spatial gradients in the mixed layer depth exist. The synergy between transitions in the euphotic/twilight zone and submesoscle/mesoscale regimes have not been explored in detail. AUVs are suitable platforms for tracking and observing these dynamic boundaries that are thought to evolve on daily time scales. An interesting science question is the degree of coupling between physical (mixed layer depth / submesoscale depth) and biogeochemical (euphotic zone) boundaries over a full seasonal cycle.

A number of efforts are presently under way to better understand these processes. The NSF funded Ocean Observatories Initiative (OOI) will be providing the oceanographic community with continuous measurements of upper ocean processes off of New England, the Northwestern Continental United States, and at deep-ocean moorings in the Gulf of Alaska, the Northern Atlantic Ocean, and off Western South America (Kelley, et al, 2014). The Ocean Observatories Initiative (OOI) is constructing a networked infrastructure of science-driven sensor systems to measure the physical, chemical, geological and biological variables in the ocean and seafloor. Greater knowledge of these variables is vital for improved detection and forecasting of environmental changes and their effects on biodiversity, coastal ecosystems and climate. These fixed assets will not only provide long-term measurements but can also serve as valuable “proving grounds” for the mobile methods we propose in this report.

In the Southern Ocean Seasonal Cycle Experiment (SOSCEx), five autonomous Seagliders were deployed in the Southern Ocean between September 2012 and March 2013 (Swart et al, 2012). The gliders explored the SAZ region of the SE Atlantic-Southern Ocean while being navigated remotely via satellite communications by glider pilots in Cape Town. During the experiment, the gliders collected over 5000 profiles of the water column between the surface and 1 km depth, while covering a total horizontal distance of 7000km.

CHAPTER 3: TECHNOLOGICAL ADVANCES FOR SCIENTIFIC PROGRESS

3.1 INTRODUCTION: THE “PATCHINESS” PROBLEM

In the previous chapter we isolated the export of carbon from the upper mixed layer and its subsequent remineralization in the upper 1000 meters (the twilight zone) as a topic that would benefit from observations collected using autonomous ocean robotic platforms. In Chapter 3 we identify conceptual experiments and technological advances that address the scientific challenges covered in Chapter 2.

This KISS study identified ocean “patchiness” as perhaps the key challenge in monitoring the marine carbon cycle. Patchiness refers to the broad range of spatial and temporal scales, spanning many orders of magnitude, which contribute to global carbon budgets. Over a distance of a few kilometers, or even a few hundreds of meters, physical, chemical and biological dynamics can be very different. A goal is to link surface properties that can be remotely sensed, e.g. sea surface temperature, sea surface height and ocean color, to subsurface dynamics such as particulate fluxes, mixed layer depths and vertical nutrient fluxes responsible for the transfer of carbon from the surface ocean to the ocean interior.

Observational strategies that address the patchiness problem require the combined development of autonomous vehicles, autonomy and focused science questions. The direct connection between surface properties and subsurface dynamics is tenuous due to slow sinking rates and the predominance of lateral currents in the upper ocean. The seafloor and deep ocean are not completely de-coupled from surface dynamics, but there is a considerable gap in our understanding of remineralization of sinking organic matter through the upper ocean. Of particular interest is the region extending from the surface through the base of the euphotic zone and the upper dark ocean, roughly 500 to 1000 m depth. This region marks a transition between the submesoscale-dominated motions in the mixed layer and larger, slower mesoscale motions at greater depths.

In this chapter, we present candidate field programs that address these physical processes on synoptic to seasonal timescales with an emphasis placed on the response of ecosystem dynamics and associated carbon fluxes in the upper ocean to changes in forcing or physical regimes. There is evidence that mesoscale and submesoscale processes have considerable control on biogeochemical budgets. Specifically, physical features such as fronts, meanders, eddies, and filaments induce intense vertical and horizontal velocities. Vertical velocities can both upwell nutrients, which enhance phytoplankton production, and subduct water masses, which can export organic matter. Similarly, horizontal stirring can amplify phytoplankton aggregation or lead to modifications of the upper ocean stratification by generating dynamic instabilities. The relative importance of these features and processes on larger-scale global budgets remains poorly constrained as observations are limited and these scales are often unresolved in numerical models.

To address the patchiness problem, an observational system must be responsive to evolving physical and ecological dynamics. This suggests a Lagrangian-type “patch experiment,” in which a patch of seawater is tracked, typically by labeling with a dye tracer, while biogeochemical properties in the patch are continuously monitored (e.g., Hamme et al., 2012). Alternatively, rapid deployment capabilities may be required. At present, experiments of this type are limited by both cost and infrastructure. However, AUVs and gliders may provide the persistent and responsive sampling required to meet the goals discussed below. The vehicles, equipped to measure fluorescence properties of phytoplankton, O_2, dissolved inorganic carbon, nitrate, POC, and other bio-optical properties, could repeatedly characterize the evolution of ecosystem biogeochemistry in response to changes in physical forcing or possibly independent biological events. Similarly, one could use AUVs to characterize circulation in eddies and understand the role of eddies in nutrient transport and production.

Our two concept experiments address intermittency in the temporal and spatial sense. The first focuses on the transient response of upper ocean biogeochemical properties to an abrupt forcing, such as a storm. The second focuses on the ubiquitous filamentary structure of the upper ocean and attempts to track its influence on upper ocean biogeochemical evolution. Both concepts were found to have similar sampling and sensor requirements, which are discussed later in this chapter.

In both experiments the physical, biological and chemical components of this system are integral to understanding the temporally- and spatially-evolving dynamics. Physical properties measured on AUVs include salinity, temperature, microstructure (turbulence) and surface winds. Biological properties that can be measured autonomously, now or in the near future, include many bio-optical properties. Modes of phytoplankton fluorescence reflect the chlorophyll concentration of seawater, the nature of the autotrophic community, and iron sufficiency. Other bio-optical properties allow one to access the particulate organic carbon, photosynthetically active radiation (PAR), and the extinction coefficient of the water column. Chemical properties constraining the mass balance include pCO_2, nitrate, dissolved inorganic carbon, and O_2. Measuring these properties would allow us to characterize the evolving nature of the ecosystem as well as primary production and carbon export.

3.2 CONCEPT 1: TEMPORAL INTERMITTENCY

STORM CHASER: EVOLUTION OF CARBON EXPORT FROM TRANSIENT MIXED LAYER CHANGES

The goal of Concept 1 is to determine the localized impact of atmospheric storms on upper ocean biogeochemical cycling. A mechanistic understanding of these processes would be used to estimate global impacts of transient perturbations of mixed layer depths. Concept 1 seeks to answer the following questions:

1. What is the role of synoptic variability in the mixed layer depth and the role of episodic events in this variability?
2. What is the empirical relationship between primary production, carbon export and the mixed layer depth?
3. What controls Southern Ocean meridional nutrient gradients, Si depletion, summertime nutrient drawdown variability, and biological productivity?

Observational plan

Figure 3.1 illustrates the experiment. The experiment design consists of 5 moorings deployed along a meridional transect spanning Antarctica to Tasmania. The moorings would be approximately 300 km apart along a line that is orthogonal to atmospheric storm tracks in that region. The moorings would be deployed up to a period of 5 years in order to track the forcing and consequences of storms on mixed layer properties and bioproductivity on annual to interannual time scales.

Each of these moorings would serve as the center of a study box in which an ASV, gliders, and a LRAUV would obtain mobile in-situ measurements in order to discriminate between spatial and temporal variability of physical and biogeochemical parameters. These platforms would be equipped with sensors listed in Table 4.2-2. The ASV would provide sea surface measurements and also serve as a communication relay for the submerged assets and provide external navigation aiding. The gliders, of which we envision there being on the order of 5, would concurrently obtain measurements of basic physical and biogeochemical measurements (e.g., salinity, temperature, fluorometry). The increased payload and available power of the LRAUV would allow it to carry larger sensors. Based on observations made by the gliders the LRAUV be re-tasked to acquire additional measurements in regions of interest.

The sampling of multiple mixed layer deepening and shoaling events during the experimental period would provide data that address questions 1 and 2. The meridional span of the moorings would provide a coarse measure of meridional nutrient gradients.

Modeling of the physics and biogeochemistry of the study region would be used to inform sampling strategies for the moorings and mobile sensors prior to the experiment using traditional pre-deployment Observation System Simulation Experiments (OSSEs). As the data becomes available, they would be used to evaluate the numerical models and adjust and/or improve subgrid-scale parameterizations. They would also be assimilated in the numerical models in order to obtain a more complete space-time reconstruction of mixed layer physics and biogeochemistry. This improved model representation could additionally be used to inform adjustments to mission sampling strategies allowing robot re-tasking accordingly.

Location

The ultimate goal of this experiment is to answer these questions during multi-year experiments in the Southern Ocean; however, developing and validating the methodologies will require a “scaled-up” approach in which we conduct shorter experiments with only a few assets at more accessible sites of scientific interest, such as Bermuda or George’s Bank. In subsequent years, longer deployments will be carried out at harsher, more remote sites such as Station Papa in Gulf of Alaska and eventually the

Southern Ocean. This approach will allow validation and refinement of our methods and, as we gain confidence, will allow an increase in the number of assets and their duration.

These studies are relevant wherever transient physical forcing plays a role in upper ocean biogeochemical processes, which is basically everywhere. Areas of interest include the subtropics, as discussed above with respect to Bermuda; the Subarctic, where shoaling of the mixed layer leads to blooms; the tropics, where upwelling has a big influence on the mixed layer; the Southern Ocean, where arguably the leading unanswered biogeochemical question is centered on the role of storms in production; and marginal seas, where productivity can be exceptionally high when the light field is favorable.

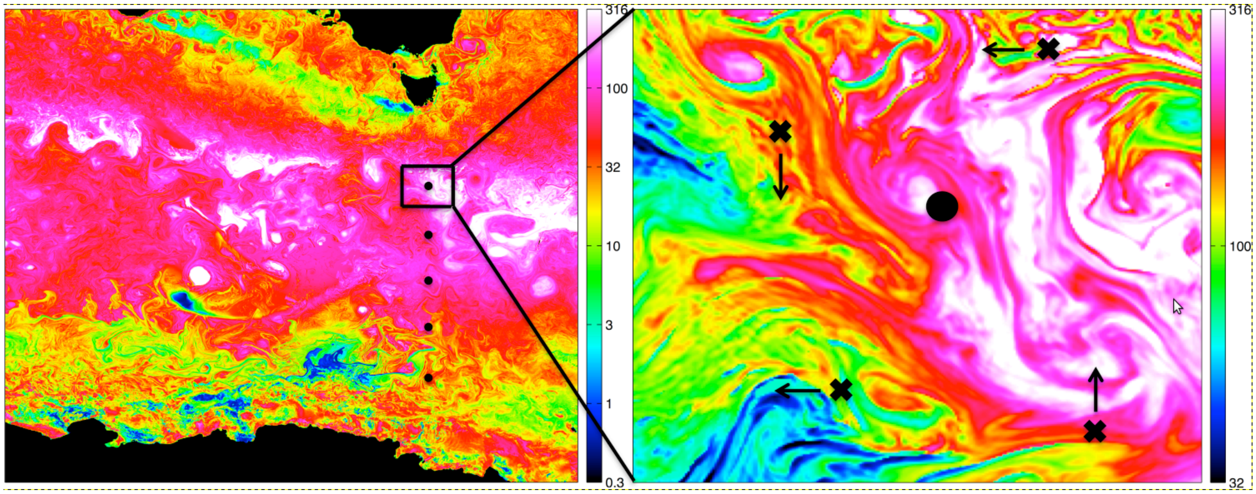


Figure 3.1: The figure illustrates the concept for experiment 1. Five moorings (represented by black dots) are deployed along a meridional line from Tasmania to Antarctica. Each mooring acts as the fulcrum of a suite of mobile assets (e.g., ASV, gliders, and LRAUV, represented by black crosses and arrows in right panel). The figure background displays simulated mixing layer depth in m on November 27, 2011, from a global ocean and sea ice simulation with 1/48th-degree horizontal grid spacing. The simulation illustrates the stunning variability of ocean mixed layer processes and the need for deployment of mobile assets around each mooring in order to separate space-time components of physical-biological interactions.

3.3 CONCEPT 2: SPATIAL INTERMITTENCY

SURFACE TO SINKING: LATERAL VARIATIONS IN CARBON EXPORT FROM THE UPPER OCEAN

The goal of Concept 2 is to gain a mechanistic understanding how submesoscale filamentation influences the upper ocean carbon cycle. Additionally, this proposed experiment addresses the question of whether carbon export has a surface signature that can be exploited using satellite instrumentation to provide insight into deeper processes related to carbon export. Concept 2 seeks to answer the following questions:

1. What is the role of upper ocean processes on the local carbon export from the euphotic zone?
2. Is it necessary to resolve filamentous processes in the upper ocean to adequately close the export flux budget in the upper 1000 meters?

Carbon budgets in the upper ocean are intrinsically linked to the exchange between atmospheric and oceanic reservoirs. However, estimates of carbon export from the upper ocean are poorly constrained. This is due to the intricate biological and physical processes dominating the remineralization and flux of carbon out of the euphotic zone and into the twilight zone, accompanied by a lack of sustained spatial and temporal scale observations. This experiment aims to elucidate the role of upper ocean processes on the local carbon export from the euphotic zone through a nested network of autonomous vehicles. This work will improve on previous observational efforts through the enhancement and development of 1) novel sensor and asset deployment strategies, 2) new data management-model interaction pathways and 3) new platform/sensor networks that allow for sustained observations on a variety of spatial and temporal scales. Understanding the processes controlling export from the upper ocean is integral to placing a more accurate constraint on global carbon budgets.

Observational Plan

A fleet of monitoring platforms will collect data and continuously monitor for the onset of a feature of interest (e.g., submesoscale eddy, filament, etc.). This fleet includes satellites and long duration in situ assets such as gliders, wave gliders, and floats. The controllable in situ assets will default to operating back and forth along parallel linear trajectories over regions of interest (10 km^2 or submesoscale eddies). Detection of the onset of an event (i.e., formation of an eddy or filament) may be based on direct measurements compared to preset thresholds or by comparison of measurements to one or more models. Upon detection of an event (feature), a set of additional assets with increased measurement capability will be deployed for the duration of the feature. The experiment timeline is envisioned to be on the order of an annual cycle to fully capture seasonal variability.

Decision making on the glider is described in detail in the Information Exchange component of Chapter 4. The novelty of this proposed experiment is to achieve a high degree of autonomy, which includes both feature detection, revision of sampling strategies as well as deployment timing and locations. A major advance would involve the removal of human intervention from the process of re-tasking assets. The current state of the art typically uses sub-optimal sampling strategies and is exceedingly time consuming. For instance, field programs often employ a fixed sampling strategy without regard for evolving features in the study area, or alternatively require near constant attention to re-tasking of assets. Manual re-tasking is feasible for a small number of instruments in the water over reasonable time periods, perhaps up to one year. However, even in this case, it likely requires a dedicated team with previous experience piloting the instrument. The obvious first step is the introduction of human-assisted situation awareness, or automated decision making. Ultimately the long-term goal is to remove humans from the loop.

Location

Two locations are envisaged for this Concept: the U.S. West Coast and the Southern Ocean. The first location, the U.S. West Coast is more accessible and better understood. Due in part to accessibility, there have been numerous observations and a variety of continuous sampling experiments in the region. The campaign in this region would leverage prior studies and assets in place. The Southern Ocean, despite its significant impact on global processes, is much less observed. Individual models show a great range of variation in how they handle upper ocean processes, often related to how they parameterize sub-grid-scale dynamics. Process studies designed to resolve these dynamics are needed to improve or develop new parameterizations.

3.4 GERMANE TECHNOLOGIES

A number of technology capabilities were identified as germane to the concepts described in sections 3.2 and 3.3. First, persistent, in situ observations are essential. Measurements are required over weeks and months (and in some cases years) in order to distinguish internal variability, seasonal trends and intermittent events. The need for inexpensive, low-power biogeochemical sensors was also identified as critical to both concepts. The patchiness aspect of these experiments requires multiple heterogeneous platforms working in a coordinated fashion. The number of required platforms combined with the extended observational periods necessitates improvements in autonomy both at the scale of individual robots and in the larger work flow from sensing and data assimilation to eventual decision making and response. Chapter 4 more finely delineates these requirements and presents the results of technology-based discussions during this KISS study.

CHAPTER 4. TECHNOLOGY REQUIREMENTS, GAPS, AND SOLUTIONS

The experiments discussed in Chapter 3 – along with other physical, biological, and biogeochemical experiments throughout the ocean – **require adaptive monitoring of upper ocean physics and biogeochemistry with multiple assets over extended periods in remote and harsh locations.** Achieving this vision requires that we move beyond our current paradigms of oceanographic measurements and develop new methods. The following requirements were identified as crucial to enabling these experiments:

- **R1: A persistent mobile presence** is required in order to capture processes occurring over different space (ranging from 1-1000km) and time (weeks to years) scales.
- **R2: The present sensing suite for autonomous platforms needs to be expanded** to include more biological and biogeochemical sensors. Where necessary, these sensors should be adapted for inclusion on smaller, longer endurance platforms such as gliders, LRAUVs, and smaller ASVs.
- **R3: Multiple coordinated heterogeneous assets are required** for two reasons. First, payloads range from small and lower power sensors (e.g., CTDs, fluorometers) that provide high-spatial resolution measurements to larger high-power sensors (such as flow cytometers or mass spectrometers) that make less frequent measurements. Second, the varying time and spatial scales of key processes implies that diverse vehicles will be required to capture all dynamics.
- **R4: The ability to adapt to changes is crucial** in both the science mission (as defined from shore) and to vehicle health (as observed by the vehicles themselves) such as battery power, maneuverability, and vehicle health.
- **R5: Increased autonomy is essential.** Efficient human interaction with an emphasis on using humans only for supervisory or interpretive tasks is required in order to sustain multi-vehicle experiments over long time periods.
- **R6: A “scaling-up” capability** is necessary in order to develop and test these technologies and to allow us to adapt these methods to future experiments.

These requirements were identified at the first workshop and served as the basis for discussions at the workshops and in the interim period on the necessary enabling technologies.

At the first workshop, we identified three technology areas – (i) resource allocation and adaptation, (ii) modeling, and (iii) sensors – on which to center our discussions during the interim period. Groups worked to further specify requirements, identify gaps in our present capabilities, and began suggesting engineering R&D efforts to overcome our current limitations. During these interim discussions, the scope of the modeling and resource allocation and adaptation technology areas was refined and the technology areas renamed to information exchange and marine robotics, respectively.

The three technology areas (with the requirements they address in parentheses) are:

- **Sensors** (R2) – addresses how we improve the ability to quantify in situ the ocean environment.

- **Marine Robotics** (R1, R3, R4, R5, and R6) – considers the required platforms, intelligence, and communication (both in-air and in-water).

- **Information Exchange** (R4, R5, and R6) – focuses on combining in situ sensor data with models and both remote sensing and a priori data to improve understanding of key physical and biogeochemical processes and to inform decisions about re-tasking assets.

This chapter focuses on the specific requirements, technology gaps and, where possible, specific R&D efforts identified during this KISS study. First, an overview of our vision is presented in Section 4.1. Sensing, Marine Robotics, and Information Exchange are discussed in Sections 4.2, 4.3, and 4.4, respectively. Autonomy is ubiquitous throughout these areas. All three of the technology areas both benefit from autonomy and contribute capabilities that advance autonomy; thus a separate discussion appears in Section 4.5.

4.1 TECHNICAL VISION

This study envisions fleets of coordinated, heterogeneous marine robots adaptively obtaining physical, biological, and biogeochemical measurements that are provided to shore-based data assimilation efforts. These in turn inform decisions about future surveys and how the robots will respond. Autonomy is required for this approach to be feasible (or for large fleets of robots to even be possible). Figure 1.4 illustrates our concept, which consists of a variety of heterogeneous marine robots working together. These vehicles have heterogeneous capabilities as shown in Figure 4.1.

Achieving this vision also requires improving how humans obtain data from and interact with robots – specifically increasing autonomy. In Section 1.3 we discussed that while the mission execution stage is presently highly autonomous, mission planning, data assimilation, and interpretation stages remain human intensive. The present state of autonomy must be advanced for our vision to be realized.

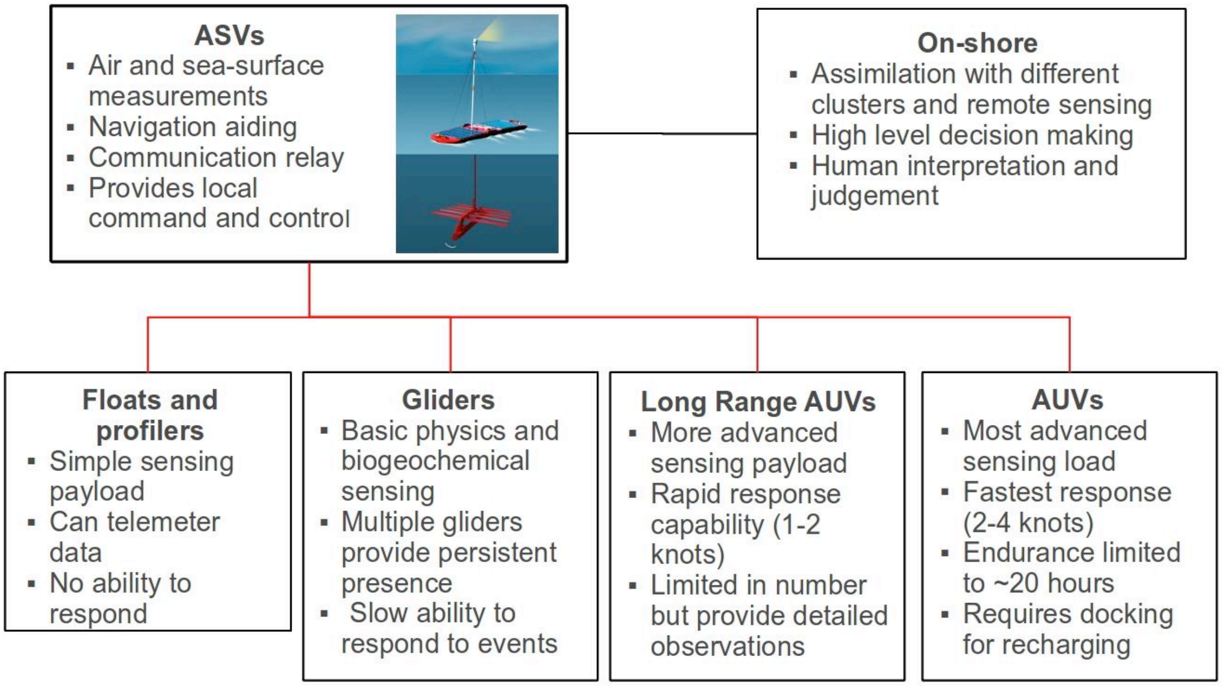


Figure 4.1: The marine robots we envision being included in the proposed architecture. Each possesses different sensor payloads, range and endurance, and ability to rapidly respond to changes in the environment. Individually, each robot is incapable of providing measurements at the necessary temporal and spatial scales; however, this study proposes that in a coordinated manner these vehicles could help address this issue. The submerged assets communicate with an ASV, such as a WaveGlider, that provides command and control functionalities for the fleet such as re-tasking based on goals received from shore and vehicle health state.

Many definitions of autonomy exist – one common definition is executing the cycle illustrated in Figure 4.2 with reduced, minimal, or no human intervention. The degree to which the process is autonomous is defined as the Level of Autonomy (LOA) – a frequently cited LOA scale is defined by Sheridan (Sheridan, 1992; included in Appendix B) in which LOA 10 has no human intervention and LOA 1 is done exclusively by humans As shown in Figure 1.3, autonomy in present ocean observation robots remains limited – i.e., the mission execution step is LOA 10 while the other steps are LOA 1-2. In the context of the decision making cycle defined in Figure 4.2, the sensing phase is commonly automated, the data assimilation stage less frequently, and, except for some demonstrations, the decision making and response stages are entirely done by humans. We seek to achieve a LOA between 3 (where autonomy narrows down the decisions to a select few) and 5 (in which autonomy selects an action and executes it after human approval). Numerous other autonomy cycles (e.g., vehicle health status processes, low-level mission planning) will likely possess higher LOAs thereby relieving humans of the mundane tasks. Increasing the overall LOA from its present state of 2 or less to the 3-5 range would be a major advance in marine robotics and oceanography.

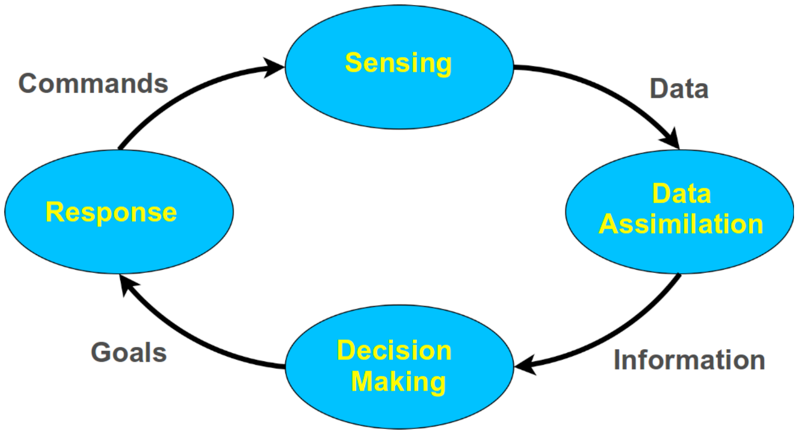


Figure 4.2: A flow chart of the decision cycle as applied to oceanography. Sensors obtain data, which is in turn assimilated into information from which decisions are made and new goals set. These goals dictate the response and subsequent commands to robots and sensors.

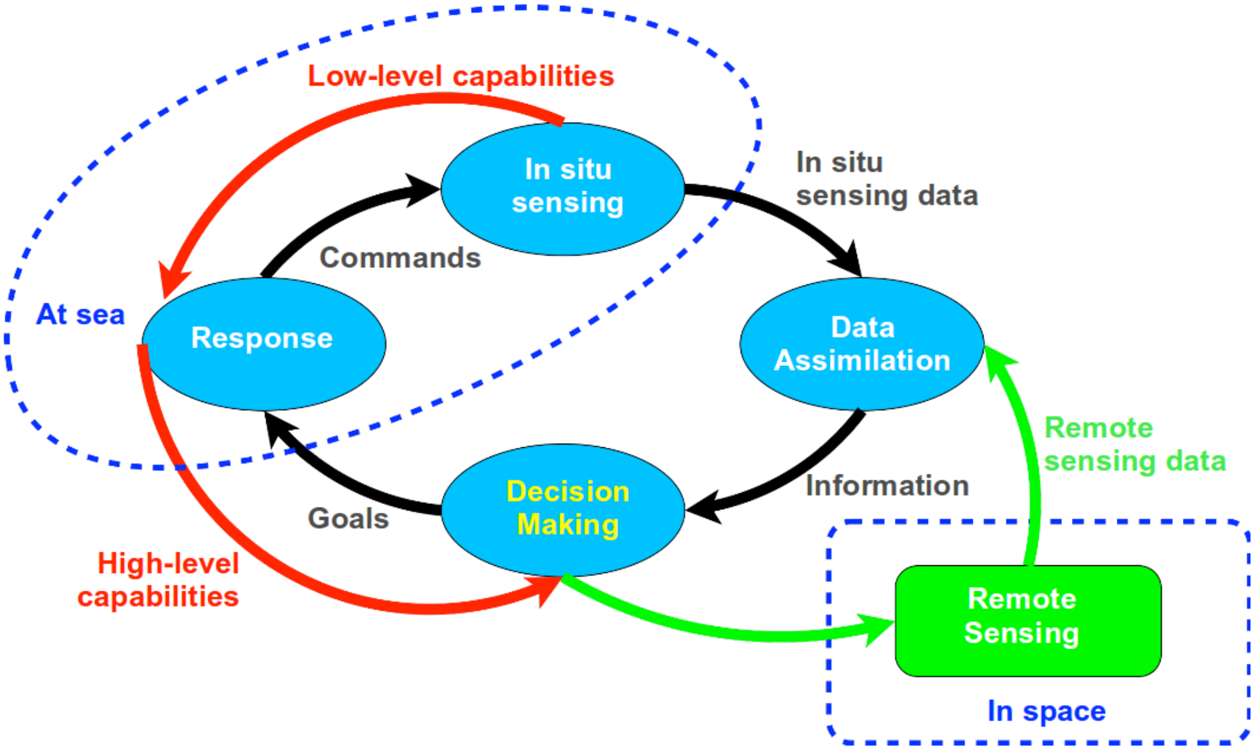


Figure 4.3: Illustration of an envisioned work-flow cycle for oceanographic missions. The core work flow (Figure 4.2) is illustrated by the blue circles and progresses from in situ sensing to data assimilation and decision making, and finally responses. One possible implementation of this cycle has data assimilation and decision making occurring on-shore, ideally in a largely autonomous fashion with human capabilities being focused on interpretation of results and high-level decision making. The subsequent response — i.e., detailed mission planning that considers vehicle capabilities — would be carried out at sea by a coordination computer on an ASV.

Figure 4.3 shows our proposed autonomy architecture for our concept including where we envision different elements residing. Sensors on gliders, AUVs, and ASVs at sea obtain **in-situ data** that is telemetered ashore for assimilation with **remote sensing data**. **Information** from the data assimilation process is used to inform decisions about sensor and platform re-tasking. The outcome of these decisions are **goals** that are relayed to a command platform at sea, which decides on responses and issues **commands** to specific platforms and sensors. This step can be iterative with sensors and platforms providing information about their specific **low-level capabilities** that informs what is achievable. If platform or sensor limitations preclude achieving the goals then **high-level capabilities** information is relayed ashore to allow for revised decision making. The study envisions the human being primarily involved in the decision-making stage; the other stages would be highly-autonomous.

Figure 4.4 shows how the Study's three core technology areas map to the decision making cycle shown in Figure 4.2.

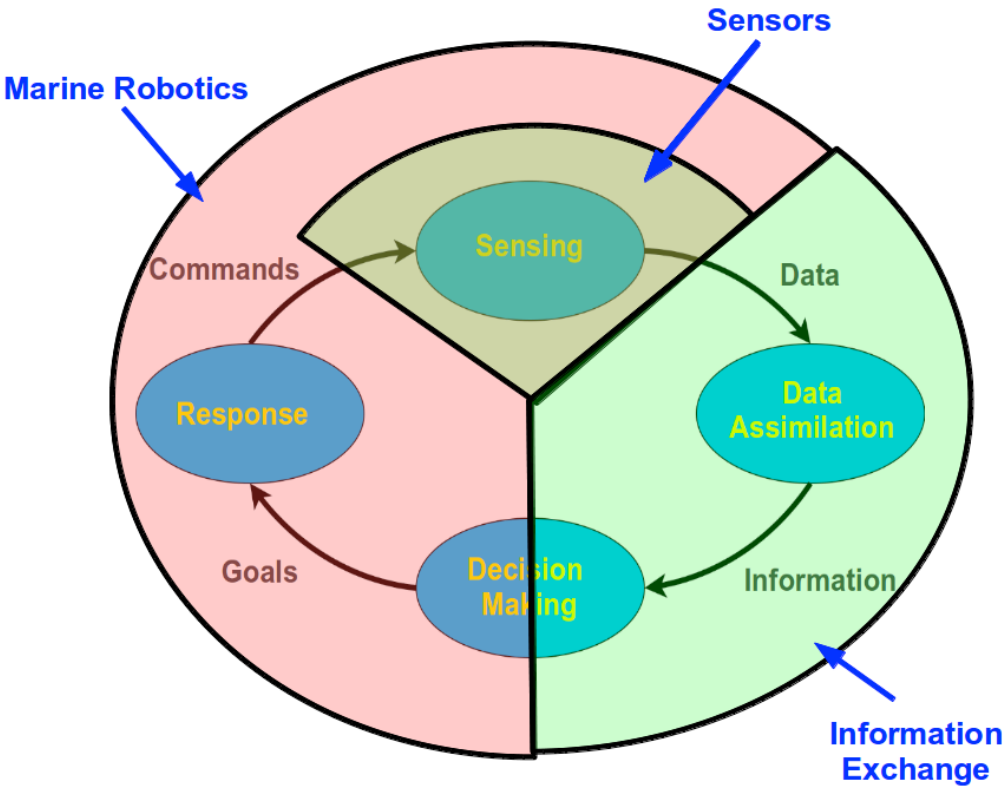


Figure 4.4: How the technology focus areas in this KISS study map to the decision making cycle (Figure 4.2).

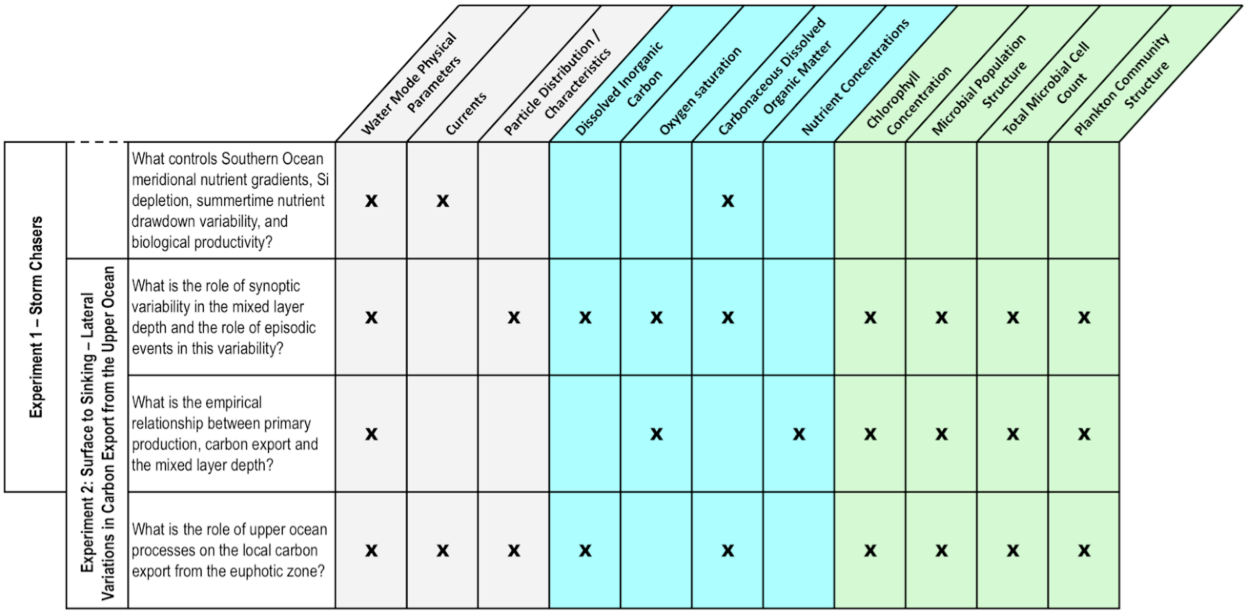
4.2 SENSORS

Observational oceanographic measurement data products were organized into the following six categories:

- Atmospheric Parameters
- Physical Oceanographic Parameters
- Dissolved Gases
- Chemical Parameters
- Nutrients
- Biological Parameters

Data products in these groups were ranked by the team based on importance to processes relating to atmosphere/ocean interaction, the euphotic zone, the mixed layer, and the deeper ocean (Appendix D). The ranking criteria were based on the desire for these measurements for experiments 1 and 2, both of which are focused on upper-ocean processes. Table 4.1 lists the most critical data products needed to address the experiment science questions.

Table 4.1. Traceability of science questions to data product families for experiment concepts 1 and 2. Major data products are highly similar between experiments and can be grouped into physical (gray), chemical (blue), and biological parameters (green). Complete list of associated physical, chemical, and biological data products included below (Appendix D).



			Water Mode Physical Parameters	Currents	Particle Distribution / Characteristics	Dissolved Inorganic Carbon	Oxygen saturation	Carbonaceous Dissolved Organic Matter	Nutrient Concentrations	Chlorophyll Concentration	Microbial Population Structure	Total Microbial Cell Count	Plankton Community Structure
Experiment 1 – Storm Chasers		What controls Southern Ocean meridional nutrient gradients, Si depletion, summertime nutrient drawdown variability, and biological productivity?	x	x				x					
	Experiment 2: Surface to Sinking – Lateral Variations in Carbon Export from the Upper Ocean	What is the role of synoptic variability in the mixed layer depth and the role of episodic events in this variability?	x		x	x	x	x		x	x	x	x
		What is the empirical relationship between primary production, carbon export and the mixed layer depth?	x				x		x	x	x	x	x
		What is the role of upper ocean processes on the local carbon export from the euphotic zone?	x	x	x	x		x		x	x	x	x

It was envisioned during this workshop that the potential deployment architectures would be highly similar for both Experiments 1 and 2. Both scenarios involve one or more "motherships," ASVs stationed permanently at surface, combined with numerous gliders and/or AUVs that can provide effective vertical profiling capabilities. The AUVs would also execute adaptive sampling capabilities based on autonomous direction from the mothership. The mothership would serve as a communication relay between shore and amongst subsurface assets, and include a payload for atmospheric measurement, drawing on high-TRL (Technology Readiness Level) heritage sensors available commercially for atmospheric investigations (see Appendix D). The atmospheric sensors are all high TRL due to their prevalence as lightweight deployable payloads used frequently in terrestrial and oceanographic field studies.

Differences in Experiment 1 and 2 architectures are summarized as follows. Experiment 1, the "Storm Chaser" configuration includes numerous platforms including fixed assets (moorings), ASV(s), Gliders and LRAUVs. The focus area for Experiment 1 will be a well-characterized region in which to examine the spatiotemporal transience, and ecological rebound, as a function of transient events such as storms. While both concepts include capability for mobility as a whole experiment (e.g. coordinated group movements to track interesting features), Experiment 1 maintains a discrete focus area centered around a well-characterized region. The Experiment 2 architecture represents a completely mobile experiment configuration where the mothership and mobile asset system can be deployed as a unit for long duration investigation of regions in the world's oceans that might exhibit complex physical, biological, and biogeochemical properties. This experiment configuration includes one or more motherships (envisaged as one or multiple Wave Glider platforms) complemented by sentries that can be commanded outside normal survey patterns to accomplish adaptive sampling of interesting areas. The completely mobile and completely autonomous sampling system advocated in Experiment 2 can be used to hold location to observe spatiotemporal stability of a particular region, or it can be commanded to follow a transient feature such as an eddy.

In order to summarize the differences in required platforms and instrument payloads, Table 4.2 reflects the instruments required for various experiment platforms including the payload for the mothership (ASVs), the fixed assets (e.g., buoy), and the mobile subsurface assets (AUVs, Gliders). The instruments required for each of these platforms are color coded based on current TRL for each experiment (□). For completeness, the TRL color-coding is also specified for those instruments not required for each experiment (O).

Apparent from this analysis is that many of the measurement objectives can be satisfied with commercial off the shelf (COTS) sensors (🟩), or in many cases by technologies that exist in advanced prototype or development stages (🟨). These types of prototype research sensors are typically at maturity levels for these experiments that can be considered for field deployment. A caveat is that these prototypes might not yet be appropriate for small platform deployment (e.g., glider or LRAUV). The TRL color-code also reflects those data products that are not yet achievable using in situ oceanographic sensing techniques, mainly due to lack of successful development efforts to make these into low-mass, low-power fieldable configurations. Future development based on the needs of the community will remedy this shortcoming. A few of these sensors are outlined in Table 4.2-2 are required for the experiment; however, the TRL of these sensors is low (for one or more platforms). These findings have been used to identify high priority recommendations for sensor development efforts, e.g. the Dissolved Inorganic Carbon (DIC) and nutrient sensors (besides nitrate). Furthermore, high priority is assigned to improving the technology readiness of biological sensors including the Environmental sample processor (ESP) and the Flow Cytometer (FC), both of which exist in buoy configurations but are desirable for mobile platforms.

Table 4.2. Traceability of desired data products for experiments 1 and 2 to availability of instruments that are appropriate in form, fit, and function for deployment on different platforms. Further information on sensors, including descriptions / vendor / performance characteristics, is included in Appendix D.

			Experiment 1 “Storm Chasers”			Experiment 2 “Surface to Sinking”	
Data Product Family	**Technology Example**		**ASV(s)***	**Mooring**	**Mobile Assets****	**ASV(s)***	**Mobile Assets****
Physical Parameters	Salinity, Temperature, Depth (CTD)		🟩	🟩	🟩	🟩	🟩
	Acoustic Doppler Current Profiler (ADCP)		○	○	○	🟩	🟨
	Particle Distribution (OBS)		○	○	🟩	○	🟩
Chemical Parameters	Dissolved Inorganic Carbon (DIC sensor)		🟥	⭕	🟥	⭕	🟥
	Oxygen Saturation (DO probe)		🟩	🟩	○	○	🟩
	Nutrients	Nitrate (UV-ABS)	○	○	🟩	🟩	🟩
		Phosphate, Silicate, Iron, etc.	⭕	⭕	🟥	🟥	🟥
	Fluorometer	CDOM (370 / 460 nm)	🟩	🟩	🟩	○	🟩
Biological Parameters		Chl-a (470 / 695 nm)	🟩	🟩	🟩	○	🟩
	Microbial Populations (ESP)		○	○	🟥	○	🟥
	Total Microbial Cell Count (FC)		⭕	○	🟥	⭕	🟩
	Plankton Community Structure (VPR)		○	○	🟨	○	🟩

Notes: Atmospheric payload assumed to be part of the ASV payload.
○ = sensor not required for experiment; ☐ = sensor required for experiment; color-code reflects maturity (TRL):: 🟥 = TRL 1-5; 🟨 = TRL 6-8; 🟩 = TRL 9 or COTS
*ASVs include a range of vehicles ranging from the Liquid Robotics waveglider to the larger classes of autonomous surface vehicles.
**Mobile Assets include the sentry vehicles such as AUV, LRAUV, and Gliders – selection of mobile assets for experiment determined by requirements for allowable payload, maneuverability, speed, response time, and duration, among others.
CTD = Conductivity, Temperature, Depth; ADCP = Acoustic Doppler Current Profiler; OBS = Optical Backscatter; DIC = Dissolved Inorganic Carbon; CDOM = Carbonaceous Dissolved Organic Matter, UV-ABS = UV-Absorbance Spectrometer; ESP = Environmental Sample Processor; FC = Flow Cytometer; VPR = Visual Phytoplankton Recorder.

Given the analysis above, it is possible to begin planning and integration efforts for these payloads. It is likely that the desire to include a variety of sensors on the mobile asset platforms to provide enhanced capability in a single mobile asset will exceed the limits for allowable payload with respect to mass and/or power. One way to deal with this is to have mobile assets that include different dedicated payloads instead of mirror image configurations. As the sensors all increase in TRL for small platform accommodation, driving towards lighter weights and lower power requirements, this envelope will broaden. Nevertheless, the capability to include sophisticated payloads on autonomous underwater vehicles (AUVs), long-range autonomous underwater vehicles (LRAUVs), and gliders is realizable now as a current capability and is well suited to making advancements in the field of Science Informed Robotics (SIR) in the near term to address critical science questions. Another consideration is that many of these sensors (e.g. CTD) are included as streamlined packages as part of standard issue robotics platforms. This high degree of integration being pursued by multiple manufacturers may increase the allowable payload for inclusion of these advanced sensors.

Findings

During evaluation of the available sensor payloads against desired in situ data products to satisfy experiment criteria, a number of critical findings were apparent. These include:

1. **Currently available sensors.** There is a wide range of physical and chemical sensors that are currently available for deployment on mobile asset platforms. These provide capability for sophisticated payloads on AUV, LRAUV, and gliders.

2. **Need for biological and chemical sensors.** There is an urgent need to advance capabilities for low mass, low power sensors, suitable for use on mobile assets particularly that satisfy the technology gap for biological and chemical in situ measurements. Many of these techniques will involve enhanced sample handling including reagent chemistry, hurdles that must be addressed through such techniques as microfluidics:

    - Environmental Sample Processor (ESP): Determines presence and abundance of pre-selected taxa in water samples. Process involves cell lysing, tagging of specific genomic sequences, and luminescent detection. Current capability includes;

    - Nutrients (expanding capability beyond nitrate).

3. **DIC sensor development** – in order to understand a linkage between the biological, physical, and chemical aspects of the carbon cycle, it is critical to understand the distribution of both organic and inorganic components. The oceanic inorganic carbon pool is the largest reservoir of carbon in the world's inventories and is the major sink for anthropogenic CO_2 emissions. Capability for in situ quantification of DIC is a critical technology gap for ocean science. Currently, there is an efficient instrument to perform this analysis (Fig. 4.5) but its mass and power requirements mean that it can only be deployed on a ship and furthermore needs to be fed with samples manually. Development of this sensor to a much smaller form factor, and thus capable for robotic monitoring on a glider,

would effectively close our gap in understanding of the oceanic carbon cycle and enable better investigations of air-sea CO_2 exchange, photosynthesis / respiration, and anthropogenic CO_2 penetration.

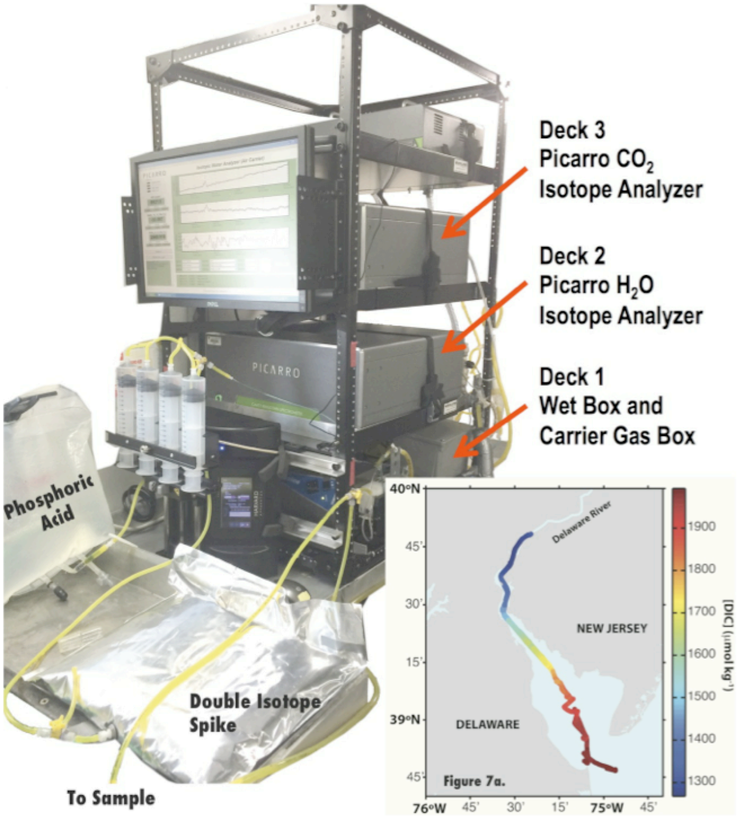


Figure 4.5: Princeton TRL6 dissolved inorganic carbon sensor version 2 and cruise data as inset (Figure: M. Bender and K. Huang). A unique isotope spike method and quantification of H_2O and CO_2 isotopologues provides extremely high precision of the field system (<0.03%). This DIC sensor has been deployed on multiple oceanographic cruises during which continuous operation was demonstrated.

4. **Simple Isopycnal Drifter (SID) sensor development** – A radical concept was envisaged in creating floats that provide capabilities for investigation of water mode physicochemical characteristics in a “dummy” **Lagrangian** payload. The Simple Isopycnal Drifter (SID) concept was envisioned to provide such capability in a low-cost consumable instrument package that can communicate from neutrally buoyant horizons in the ocean with a simple sensor and communication suite. Nutrient transport and the export of biomass from the ocean surface are key

components of the ocean carbon cycle process. These processes depend on mixed layer depth variability, motion along tilted isopycnals (density) surfaces, as well as diapycnal (cross-isopycnal) mixing. The simple isopycnal drifter (SID) recommended for development would be used in coordination with an AUV or ASV surface vessels to monitor upper ocean processes including: (1) turbulent mixing and vertical velocities in the upper ocean, (2) evolution of isopycnal surfaces and their gradients, and (3) eddy stirring on an isopycnal by potentially tracking temperature, salinity, and other property distributions. The vision is to deploy multiple drifters (possibly via an AUV, Figure 4.6) in a three-dimensional grid across an isopycnal surface and, through a simple communication protocol, track the SIDs in real-time to obtain physicochemical information about those regions of the upper ocean (e.g. temperature, salinity). Physical information on currents (horizontal and vertical) will be gleaned from the tracking capability accomplished using a mobile powered AUV asset. The SID design would ideally have endurance on the order of weeks with a depth rating of a few hundred meters (up to 500m). They will be "tuned" to ride at different isopycnals to provide a vertical grid. This technology provides the oceanographic community the ability to collect relevant scientific data for in-situ characterization of submesoscale processes such as filaments that play a prominent role in biogeochemical processes in the global carbon cycle.

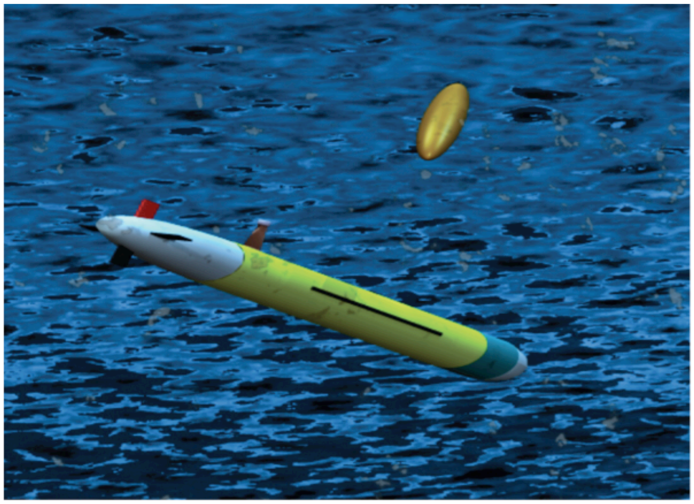


Figure 4.6: SID deployment from a REMUS100 AUV concept (Figure: T. Huntsberger).

4.3 MARINE ROBOTICS

Marine robotics is a key element of our proposed technical vision with a variety of robotic platforms being required including gliders, AUVs, ASVs, and long range AUVs. Communication – both in-air and in-water – between these platforms is also essential. This section reviews the state of the art in marine robotics including platforms and communication.

Platforms

Oceanography uses a wide variety of platforms to obtain measurements each with differing characteristics including endurance, sensing payload, communication bandwidth with other platforms and ship or shoreside operators, and available autonomy. This section reviews mobile autonomous ocean platforms both to provide an overall view of the present state of the art and to establish a common lexicon between different communities of researchers.

Range and endurance are important criteria in considering the suitability of platforms for the proposed experiments; the lower image in Figure 1.2 shows the range and endurance of different classes of vehicles. Vehicle power and speed are not shown but are equally important as they constrain the sensing payload and response time of the vehicle. For example, a conventional glider has a smaller suite of sensors and moves significantly slower than AUVs. Thus gliders may be poorly suited to tasks such as surveying large areas rapidly (as might be required for quickly evolving processes) or obtaining measurements with more power consumptive sensors. These tasks might be better suited to long-range AUVs. There is no “perfect” vehicle for these studies; rather we anticipate experiments requiring heterogeneous fleets of mobile drifters, gliders, ASVs, AUVs complemented by stationary assets such as moorings and observatories.

Gliders (Eriksen et al., 2001; Schofield et al., 2007) are long range autonomous vehicles that are passively actuated. They have matured into robust and stable platforms to perform profiling type missions with durations exceeding a year and ranges up to 1000s of kilometers in some cases. These ranges and durations are achieved through limiting the velocity of the platform and minimizing payload energy consumption. A typical glider mission operates with speeds of ~0.3 m/s and a payload power budget of less than several Watts.

Power Positive Gliders – A key technology for long duration ocean observation lies in the development of energy harvesting gliders and floats that can operate for 5 to 10 years at a time (Aintablian et al., 2012). These platforms rely on thermal phase change materials to create a liquid volumetric change that is converted into electricity through a hydraulic motor-alternator system. A SOLO float system developed in collaboration with Scripps Institute was deployed in the Pacific off the coast of Hawaii and was still operational after 18 months with little evidence of biofouling when it was recovered. The PCM system is power positive which will enable the use of low power CPUs onboard for science data analysis and autonomous operation (Jones at al., 2013). The system is being packaged into a Slocum glider and commercialized by Teledyne-Webb Research (Woithe and Kremer, 2009).

Hybrid underwater gliders (Claus et al., 2010) have been developed that integrate an auxiliary propeller-based propulsion system which may be turned on as needed to increase the velocity of the glider. These auxiliary systems are available as commercial add-ons to any G2 Slocum Electric underwater glider and increase the achievable velocity to 0.8 m/s at a cost of around 10 W of power. On an order of magnitude level these systems allow twice the velocity at four to five times the power, reducing the range of the vehicles by 200-250%.

Conventional AUVs (e.g., Griffiths et al., 1999; Allen et al., 1997; Yoerger et al., 2007) are propeller-driven autonomous underwater vehicles (AUVs) that have developed into high coverage rate inspection and survey type platforms. These platforms have much high power budgets on the order of 10s to 100s of Watts and operate at higher speeds on the order of 1.0 to 3.0 m/s. For persistent observations these platforms have seen limited use due to their limited endurance, on the order of hours to days.

Long-range AUVs (LRAUVs) are a special class of propeller-driven AUVs that carry a comprehensive suite of science sensors and navigation devices, run at high speed (0.5~1 m/s as compared with 0.25 m/s for gliders), yet over durations of weeks to months. MBARI Tethys LRAUVs are an excellent example [Bellingham et al. 2010]. The Tethys AUV's propulsion power consumption is minimized through designs of a low-drag body and a high-efficiency propulsion system. The AUV contains a buoyancy engine by which the vehicle can trim to neutral buoyancy and fly with zero attack angle, which further reduces drag. To cut down on power consumption, a power management scheme turns off sensors or control-surface motor controllers when not required to operate. Tethys AUVs' design range is 2000 km at 1 m/s speed, and 4000 km at 0.5 m/s speed (with some sensors turned off). One Tethys AUV has demonstrated 1800~km range (at 1 m/s speed) in a 23-day mission off the California coast (Hobson et al. 2012). UK's National Oceanography Centre is developing a long-range AUV of larger size --- Autosub Long Range, with a design goal of 6000 km range (Furlong et al. 2012).

Autonomous Surface Vehicles (ASVs) are designed for extended duration missions on the sea surface. A number of ASVs are now being used, including those being developed by ONR, DARPA, and commercial entities. These systems rely on a combination of technologies that include but are not limited to advanced onboard autonomy algorithms and integrated system health maintenance systems. For example, ONR and DARPA funded ASVs have autonomy systems that are designed to obey COLREGS (maritime rules of the road) and are thus suitable for safe use as a "mothership" in mixed initiative operations involving manned and unmanned systems. Launch and recovery systems for AUVs have been developed and demonstrated as well, which provides the vehicles with the onboard capability to deploy, monitor, and recover scientific payloads.

A significant commercial market for ASVs has emerged over the past decade. A notable entry is the Liquid Robotics Waveglider that is powered through a combination of wave and solar power and possesses endurance on the order of months. It has been used on a variety of persistent presence missions.

Communications

The experiments discussed herein require communication between field-deployed robotics assets that are obtaining measurements and shore-based efforts in modeling and human interpretation. Furthermore, the coordinated nature of some of our proposed experiments requires communication between robotic assets. Marine robotics presents unique communication challenges – specifically the communication will be subject to large variations in bandwidth and availability (Table 4.3). Increasingly sensor-rich robots are becoming less and less able to share significant fractions of their data with operators in real time. However, access to human perception remains important for data interpretation. For example, while gliders equipped with standard physical oceanography sensors (e.g., a CTD) can transmit all of their data through periodic iridium uplinks, AUVs with more sophisticated sensing loads (e.g., Sentry or Autosub) obtain hundreds of megs per hour of data – far more than can be communicated over iridium or acoustic communications. Assets in previous studies (e.g., Autonomous Ocean Sampling Network (AOSN)) have relied on iridium communications; however the last decade has seen the rapid evolution and maturity of in-water wireless systems including acoustic and optical communications. The dual restrictions imposed by bandwidth limitations and human cognitive capacity motivate the need for data-aware, and ultimately also mission-aware, selective communication between robots and their operators. This motivates new methods for data intelligent communication in which robotic assets in the field (a) autonomously evaluate in-situ data and decide what is transmitted and (b) intelligently respond to human requests for on-board data.

Table 4.3: Current state of subsea telemetry

Method	**Bit Rate**	**Maximum Range**
Conventional Tether	multiple Gbits/s	<1km horizontal; <6km vertical
lightweight fiber-optic tether (Young et al., 2006)	multiple Gbits/s	<20km horizontal or vertical
Acoustic communications (Partan et al., 2007	100-30 kbit/s; latencies 0.1-10	Strongly linked to bandwidth and power. Typically several km.
Through-water optical comms (Farr et al., 2005)	1-10 Mbit/s	<150 m
Through-air wireless	up to 100 Mbit/s	10 km
Satellite Communications	~30 kbit/s	global, with some important gaps

The Changing Nature of "Autonomous" Vehicles

Advances in wireless in-water communication are changing how humans interact with supposedly "autonomous" vehicles. In the early days of AUV operations, humans would rarely interact with the robots because their ability to do so was limited to extremely low bandwidth telemetry with acoustic pings or occasional surfacing that allowed for satellite communications. Thus, once a mission was started, humans received minimal data and could do little, if anything, to intervene - i.e., the inability to communicate with the vehicle required that we develop suitable autonomy.

The emergence of acoustic modems over the last 5 years has radically altered how humans interact with these vehicles. The increased bandwidth afforded by acoustic modems, though low in comparison to in-air wireless communication methods, now allows humans to see realtime data and intervene in the mission. For example, new missions can be downloaded and vehicles even acoustically joysticked to obtain observations (e.g., Kinsey et al. 2011). This new ability, while powerful, possesses disadvantages. First, the limited bandwidth of the communication implies that humans rarely, if ever, have all of the data on the vehicle and thus risk making decisions on partial information. Second, the increased human interaction decreases the amount of autonomy provided by these vehicles with humans often intervening unnecessarily or being preoccupied by low-level tasks better left to autonomy. Third, the human is typically on a ship that is within acoustic range of the AUV and glider; this reduces the cost-efficiencies afforded by using autonomous vehicles. Thus these new communication methods can vitiate the autonomous nature of these robots.

The concept proposed by this study will rely heavily on new in-water communication methods. Furthermore, the range of effective acoustic communications tends to be shorter than the correlation distance of ocean processes, which implies that in-air communication modalities, such as iridium, will be crucial too; especially for communicating with shore-based data assimilation and control efforts. In order for these methods to truly transform how we use marine robots, we need to, in parallel, develop autonomy methods that exploit these advances while reducing the burden on humans.

Intelligent Data Communication

One of the most drastic changes over the last decade in marine robotics has been the emergence of new wireless in-water communication techniques - specifically acoustic and optical methods. As discussed in Section 4.3.2, these are enabling higher bandwidth telemetry over longer distances than has been previously possible. However advances in our ability to communicate between underwater robots are being outpaced by the increased data rates of sensors on-board those robots. Furthermore, these higher bandwidth communication modalities incur penalties in both power and range (e.g., an optical modem has a range of approximately 150 m). These competing criteria require that we selectively decide what is communicated and when the communication channel must be changed. These decisions typically must be based on data and information on the vehicle and, because of these communication limitations, must be decided on-board the robot, preferably with minimal human interaction.

A number of methodologies, of varying levels of autonomy, could be employed to transfer data from AUVs or gliders off-shore to shore-based assets. These methods include:

1. **Querying Queues** - The robot maintains a set of queues each containing different sets of information (e.g., health of the robot, data from different sensors) that can be queried by humans. This method is simple; however, it is human intensive as it requires the human to “drill down” into the queues to get data.

2. **Selective Data Return** - The robot autonomously decides what data to return based on on-board decision making. This method is directly coupled to autonomous science decision making (discussed in Section 4.5).

3. **Autonomous Data Processing** - Rather than returning large amounts of raw data, on-board processing reduces the data to a smaller set of information (e.g., a sensor or science based parameter) that consumes less bandwidth. One disadvantage is that it is difficult to generalize these methods across different sensors so a new sensor requires a new algorithm development effort.

4. **Establish a Higher Bandwidth Link** – Most of the time, submerged assets will only have low bandwidth links such as acoustic modems. However, events might warrant establishing a higher bandwidth connection. This can be achieved in a number of ways. First, the frequency of acoustic modem transmission can be increased or, if conditions permit, the bitrate can be increased. Alternatively, the robot could re-task itself to a higher bandwidth optical modem. Competing objectives such as power, bandwidth, and breaking off from the study site need to be considered.

Method 1 is mature (i.e., is presently used on a number of platforms) but possesses the least autonomy. The other methods require more autonomy and are less frequently done. Methods 2 and 3 have been demonstrated in the marine robotics but are not regularly used. Method 4, to the best of our knowledge, has not been demonstrated in the practice.

Docking

Docking potentially resolves a number of issues related to long duration missions using conventional UAVs. The most relevant constraint is the need to recharge the batteries in-situ and to transfer data. The traditional approach has been to dock the AUV and then autonomously "plug in" the AUV. However this requires wet-mateable connectors that often require high mating forces and are hampered by biofouling and limited mate/de-mate cycles. The need for a physical connection between the docking station and the AUV for data transfer is being increasingly diminished by emergence of optical modems – these systems allow for relatively high-speed wireless data transfers.

Recharging vehicle batteries in situ is more challenging. A number of solutions have been proposed and built to solve the limitations on the wet-mateable systems, including inductive (Heeres, et al., 1994; Gish 2004; Miller 2005; McGinnis et al., 2007) and acoustic (Shigeta et al., 2011; D'Amato 2011). The inductive systems use a matched set of coils and magnets, one on the charging unit and one on the UAV. These systems are typically within 2-5 mm of proximity (through a docking station) in order to mitigate losses in the water path. The acoustic systems typically use piezo-electric ceramic discs to convert the electrical signal into an acoustic one that is then transmitted to a battery charging circuit on the UAV that reverses the process. System performance in the lab has been demonstrated to 11.9% over a gap of 55cm. The acoustic charging systems eliminate the need for a docking station and are relatively low cost (<$350).

Self-health sensing and adaptation

Robotic systems possess varying degrees of complexity from gliders, which are actuated by buoyancy, to AUVs that possess multiple complex subsystems. While the complexity of a system can vary, they all suffer at times from failures. The nature of these failures can be mechanical, electrical, or software. Bowen et al., (2012) presents an analysis of the failures for two AUVs during ~370 dives over a 15 year period. The resilience of these systems can be improved through better design, manufacture and maintenance, and these improvements are often the result of lessons learned during extended use – e.g., a lasting contribution of the AOSN program is the improvements it made to glider technology.

While design improvements can yield significant advances in resilience, failures in the field will still occur and for the experiments we envision to be successful, robots will need to intelligently monitor their health and respond to these failures. We foresee the following areas to be crucial:

- Core vehicle systems (e.g., propulsion, battery systems, pressure housings) that directly affect a robot's ability to maneuver or remain in the field.
- Navigation and control systems that if degraded might affect our ability to estimate the vehicle position. For example, a vehicle with a poor navigation solution might be able to change trajectory to improve navigation.
- Sensing systems need to be monitored to ensure they are providing valid data.

Possible remedial actions vary from power cycling to self-calibration.

Findings

Vehicle technology is increasingly mature. Ten years ago, the challenges facing the ocean robotics community were developing and operating vehicles in the extreme ocean environment. The landscape has significantly changed over the past decade – gliders now stay out for months and ASVs have crossed oceans. Challenges (and risks) remain with respect to operating vehicles but an increasing amount of field research is in how to use the vehicles in novel ways.

- Communications are also evolving with acoustic and satellite iridium communications becoming increasingly mature and new modalities such as optical communications are providing new modalities. How the range of these communication modalities maps to the spatial scale of the studied processes is an important consideration in designing how we use these vehicles.
- Increased communication capabilities can inadvertently reduce our dependence on autonomy at a cost of increased human supervision.
- Our ability to intelligently use these new communication modalities is still nascent and research, especially in the context of field experiments, is required.

- Docking technologies continue to evolve.
- Fault tolerance, despite a mature field of research, is still primitive in marine robots. The long-duration deployments required for obtaining these measurements will result in vehicle failures. Failures to some degree can be accounted for in vehicle design (often at a higher vehicle cost) but real-time adaptive capabilities are also necessary.

4.4 INFORMATION EXCHANGE

Introduction

Physical and biological processes in the ocean and overlying atmosphere interact over a broad range of time and space scales. Numerical simulations can provide insight into ocean behavior on many scales. With a perfect model and unlimited observations, data assimilation methodology will reproduce the three-dimensional, time-evolving ocean state. Models can also forecast ocean behavior into the future. In practice, direct simultaneous measurements over all relevant scales are beyond the capabilities of even the most advanced observational tools. Computational cost and our limited knowledge of how to represent important physical and biogeochemical processes as equations also prevent us from resolving key dynamics, usually at relatively small spatial and fast time scales. It is therefore relevant to ask: for a given ocean region and a finite number of observational assets, how can these assets be utilized most effectively to produce the most accurate (i.e., least uncertain) current ocean state as well as forecast of future ocean conditions? This question was asked by the Autonomous Ocean Sampling Network (AOSN) field experiment conducted in 2003[7], and remains at the core of our proposed field experiments today. **A major goal identified by this KISS study is to develop techniques to exchange information between on-board or shore-based numerical models and in situ assets in order to maximize information gain**.

In this section we begin with a vision of the approach and architecture required to carry out this information exchange. We briefly describe the current state of ocean modeling that is most applicable to describing carbon cycling in the upper ocean. We emphasize that these techniques are adaptable to a range of different scientific questions, environments and numerical models. We then provide a specific example of carrying out

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[7] See the AOSN special issue in Deep-Sea Research II, Vol. **56**, page 61-259, 2009 and also section 1.4.

adaptive sampling in a multivariate environment. **This represents new research that has been carried out as part of the KISS study and is a potential topic for future technical development.**

General approach

The goal of implementing information exchange and adaptive sampling is to increase information return from a limited number of instrument resources. Ideally, this technique would be applied to a field program of sufficient duration to promote machine learning and adaptation over the course of the study. This architecture is applicable to both fixed-location (Eulerian) studies, e.g. a control volume that extends to a few hundreds kilometers on each side and to a depth of 1000 meters, or a patch-following (Lagrangian) study, e.g. a mobile region, advected by local currents, that follows the evolution of upper ocean physical, biological and chemical processes. The former scenario is suitable to regions where the background mean flow is weak and dynamics are relatively stationary. The latter case is applicable to areas such as the Antarctic Circumpolar Current, western boundary currents or eddies, which may carry an upper ocean ecosystem hundreds to thousands of kilometers over a life cycle (Lehahn et al. 2011).

The emphasis of this section is on extraction of the greatest amount of information from the available, deployed assets, which may require frequent re-configuration of the observational array, including spatial positioning and sampling frequency. Future work on this KISS study will focus on identifying metrics that will enable quantification of the benefits of adaptive sampling techniques. Realization of this goal will likely involve OSSEs of increasing complexity, in preparation for future field testing.

Architecture

The information exchange architecture consists of three cycles that act simultaneously (Figure 4.7). In brief these cycles are:

1) Ascribe goals to the assets based on adaptive sampling routines carried out on model output. This is termed the “planning” stage.
2) Rearrangement of assets according to local comparison of observation with fixed expectations from cycle 1.
3) Evaluate observations in the context of numerical predictions, which could result in a second round of asset re-arrangement and potential improvements to the models.

Cycle I. The first cycle begins with existing models, possibly informed by remotely-sensed or other observations, to design a deployment and sampling strategy that maximizes information (see specific discussion of Adaptive Sampling below). This can include number, position and spacing of AUVs, sensor requirements and sampling frequencies. This first stage does not involve communication between shore-based resources and the observing array. Models are assumed to be the truth and assets are re-configured to maximize comparison of observations with models.

During the experiment, the assets may or may not return data from observations. In the latter case, updates to the fleet are based on a forward-running model only, and information about rearrangement of the fleet can, in principle, be sent continuously. In the former case, observations can be incorporated into the model to improve prediction of future states. Data assimilation would require iterating on model solutions, which may limit the frequency at which updates to the array could be sent. Data merged from all members of the fleet and additional available data, e.g., remotely-sensed products, Argo floats, etc., is archived for further use as well as assimilated back into the model. The new model output is then used for planning the overall sampling strategy, as well as training the planning algorithm. This cycle continues throughout the duration of the field experiment.

Cycle II. This is a faster cycle, which does not involve communication via satellite to the shore-based model and planning components. This cycle represents the fleet's local planning capability. This cycle takes into account the data measured by the fleet and compares the measurements to its expectations based on the goals from cycle 1. It can be achieved in either a fully-connected network, where all agents have computing capabilities and communicate with one another, or a star network, where there is one central agent with superior computing capability that communicates with all the other agents.

Cycle III. The final cycle represents the evaluation and synthesis stage. This may be done at the conclusion of the experiment, or periodically during a longer field program. This cycle represents the science-based component, in which comparison of model and observed data is used to evaluate current knowledge (e.g. models, mechanisms) and improve both our physical understanding of the carbon cycling process and its representation, either directly or as parameterizations, in numerical models. An important component of this cycle is a well-defined set of metrics against which model output and observations can be compared. These will differ for specific experiments or even regions. This cycle requires human interaction and will ultimately result in new model parameterizations as well as lessons learned for future deployments.

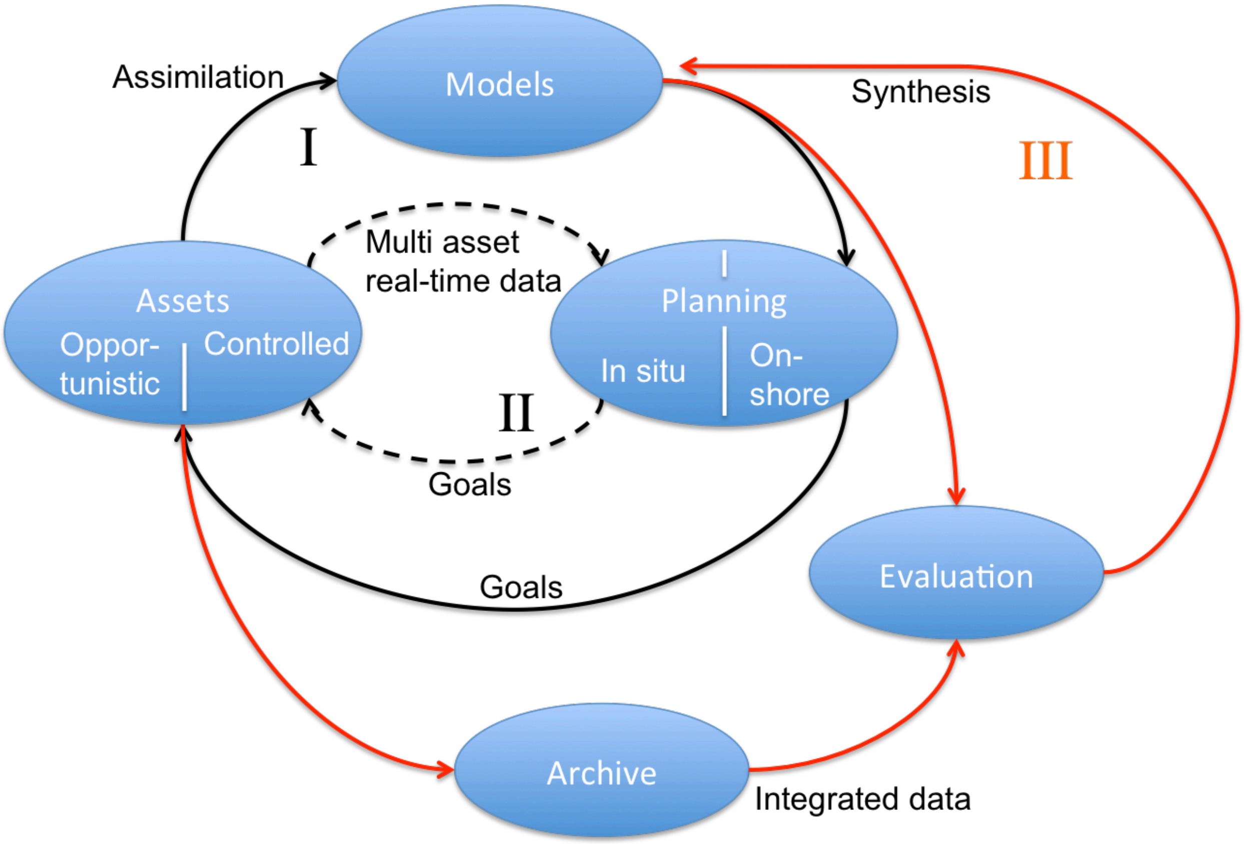


Figure 4.7: Overall architecture consists of three simultaneous cycles (see text for further description). Cycle I (solid black arrows) – model output is used by the on-shore adaptive sampling component to determine goals, which are given to the assets. Data collected is assimilated back into the models. Cycle II (dashed black arrows) – data collected by the experiment specific assets is used by their in situ planning component to adjust goals. Cycle III (red arrows) – synthesis cycle.

Models

The shore-based models employed for any given experiment will depend on the specific science questions being addressed by the study. However, focusing on spatial and temporal variability of upper ocean carbon cycling, an example of a relevant model would couple a high resolution physical circulation to a state of the art biogeochemical model.

Off the coast of California, a nowcast/forecast model based on ROMS (Regional Modeling System) has been developed and is running in real-time (http://www.cencoos.org/sections/models/roms/ca/). ROMS is a community-based model designed for regional applications. The model uses a vertical coordinate following the bottom topography. The model explicitly represents the time evolution of the free-surface and has an open lateral boundary condition to allow the exchange of information through boundaries. The ROMS data assimilation is based on a 3-dimensional variational data assimilation (3DVAR) method, which can assimilate both in situ and remote sensing observations including satellite and ocean current data measured by the land-based high-frequency (HF) radars. A biogeochemical ecosystem model based upon CoSiNE (Carbon, Si(OH)4, Nitrogen Ecosystem) has been coupled to the California coastal ROMS, and includes silicate, nitrate and ammonium, two phytoplankton groups, two zooplankton grazers, two detrital pools, TCO2. Oxygen is added to constrain remineralization processes in the model. Silicate regeneration is modeled through a similar approach but with a deeper regeneration depth profile, which reflects the tendency of biogenic silica to have higher preservation efficiency compared to other particulate organic matter.

Adaptive sampling in multivariate ocean environments

Adaptive sampling, or adaptive experimental design, involves designing measurement plans that maximize information obtained about an underlying physical process. We are particularly interested in spatial experimental design. This focuses on distributing one or more sensors spatially in an oceanic environment with dependences between measurement values and sampling location. The appropriate model depends on specific assumptions regarding the degree of spatial and temporal correlations, the properties of the sensors and their mobility, and the availability of prior information. Describing the phenomena under study with a probabilistic model allows one to calculate the information gain that is achieved by alternative measurement strategies. It is most typical to quantify information gain using the Shannon entropy, or simply entropy. This is a measure of uncertainty of the posterior distribution for variables of interest.The entropy H(X) is defined here, as in information theory more generally, to be the expected number of bits required to represent the realization of the posterior random variable X over its possible values x_i:

$$H(X) = \sum_i P(x_i)\, I(x_i) = -\sum_i P(x_i) \log_b P(x_i)$$

Since X represents the physical process under study, reducing the entropy H(X) equates to gaining certainty about the unknown ocean parameters. This in turn determines the optimal experiment for a specific model: it is that allocation of measurements which realizes the greatest expected reduction in entropy, given a finite budget for observations (Diggle and Lophaven 2006).

In the specific case of ocean carbon cycle investigations, the variables of interest are multivariate quantities that exhibit strong correlations both with each other and with respect to space and time. For example, the ROMS CoSiNE model contains over 14 observable quantities, some of which are physical oceanographic parameters (temperature and salinity) and others of which relate to biophysical phenomena (concentrations of phytoplankton and zooplankton). These quantities are correlated. As an example of adaptive experimental design, consider the problem of estimating biophysical parameters. These can be challenging to measure in the ocean, often requiring deployment of sensitive and expensive in situ sensing packages. On the other hand, physical oceanography parameters like salinity, currents and temperature are easier to model, predict, and sense remotely. Therefore, one potential application for adaptive experimental design would allocate sensors to an area of ocean to maximize the information gain with respect to the biophysical parameters, based on good knowledge of physical oceanographic parameters.

In the workshop we demonstrated this technique using a novel three-step analysis. In the first step, we decorrelated the biophysical target variables to remove redundant information. This involved a principal component analysis (PCA) and provided a handful of synthetic parameters, or indices, whose information gain was uncorrelated from each other. The information gain provided by measuring each of these new processes was additive, making subsequent analyses tractable. Figure 4.8 shows the first principal component. The left-hand chart shows biophysical variables and their coefficients for this index. It illustrates that the index is anticorrelated with zooplankton variables zz2 and zz1, and correlated with tco2. The right-hand plot shows the value of this variable at different locations in a gridded model of Monterey Bay during a typical simulation snapshot. This index is strongest near the shore, but is attenuated in deep water. By decomposing the biophysical variables in this way we can calculate information gain independently for each index during sensor placement.

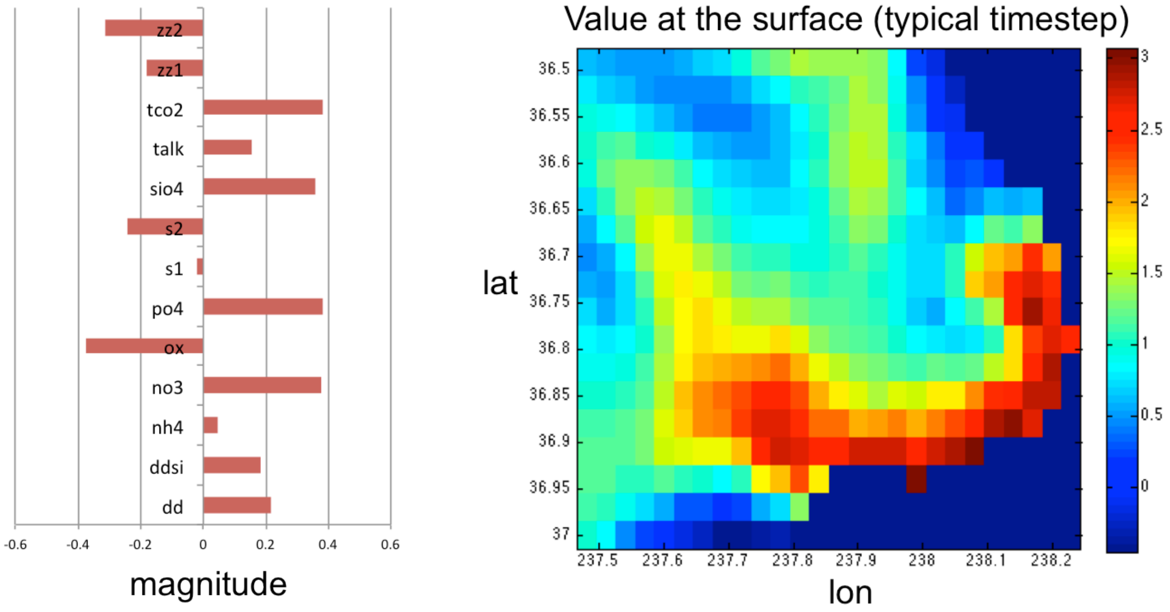
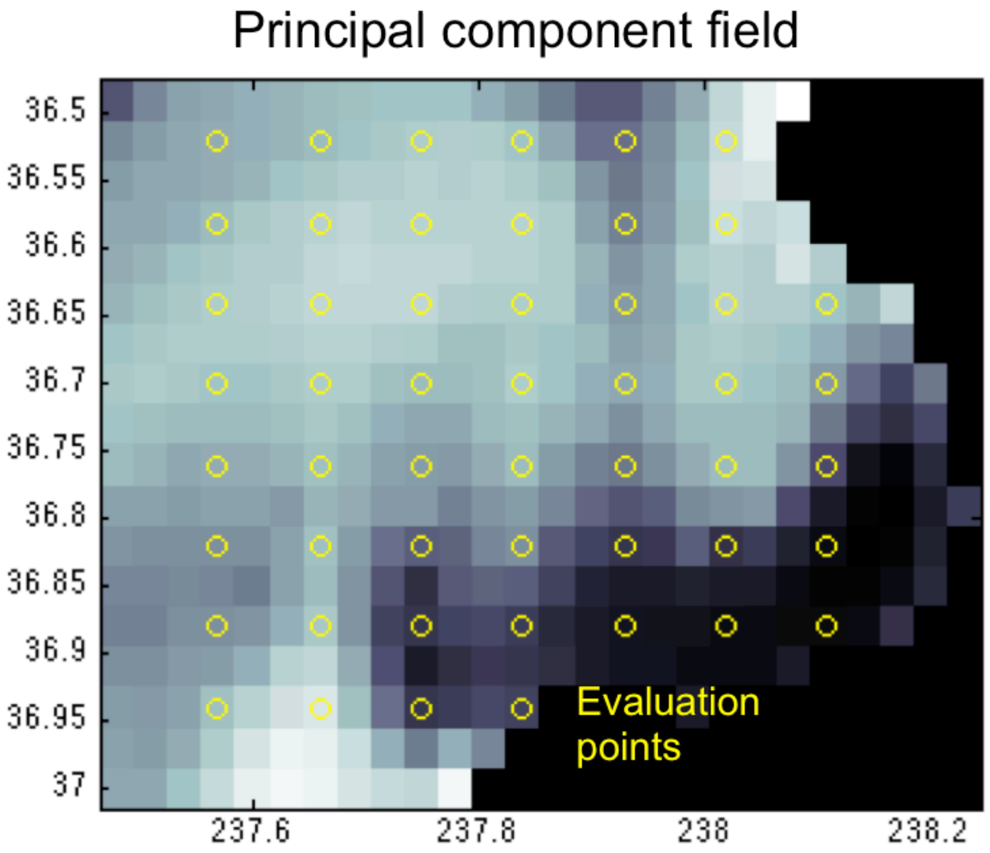


Figure 4.8: Principal component analysis of biogeochemical parameters in Monterey Bay, CA over the timespan of approximately 1 day. Left: loading factors in the first principal component for each of 13 different CoSiNE model parameters, indicating variables that are correlated and anticorrelated. Right: magnitude of the first principal component at the surface layer for a typical simulation timestep, showing spatial distributions of this component.

In the next step we modeled the spatial distributions of each index using a Gaussian Process model. This representation, common in geostatistics, captures spatio-temporal correlations using a covariance function that describes how two measurements change as a function of distance in space and time. Critically, it allows calculation of posterior distributions given any set of input measurements. The input variables used to determine correlations were (1) the space and time of a measurement, and (2) the physical ocean conditions at that timestep. This allowed the system to represent the fact that rapid changes in physical ocean parameters could also cause changes in biophysical variables, increasing the information value of sampling in dynamic regions or across fronts.

In the final step, we optimized the information objective by distributing sensors in the environment and testing different configurations automatically. Information gain was calculated using a set of reference points – discrete locations on a grid where we would like to know the target variables' value. The yellow circles in Figure 4.9 (top) mark these locations. We used a "greedy" algorithm to optimize this objective. This was a heuristic approach and not guaranteed to be optimal, but it worked for a first prototype and provided reasonable sampling patterns for the ROMS-CoSiNE. Figure 4.9 (bottom) shows the resultant locations for a field consisting of four different time steps. We required the algorithm limit itself to a total of 20 sensor deployments. The system evenly spaced these sensors in space and time with some minor variations to account for patterns in the physical oceanography inputs. This proof of concept result demonstrates a flexible procedure that can be tooled to different environments or mobility constraints, and shows promise for future ocean sampling campaigns.



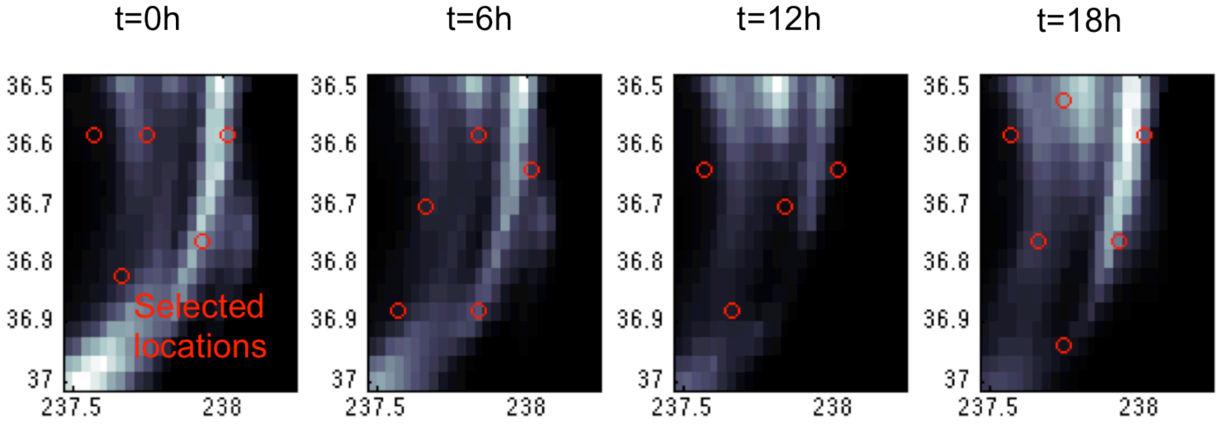


Figure 4.9: Adaptive sampling simulation. Top: evaluation points used for information gain calculations. The optimal experiment reduces posterior entropy at these locations, across all simulation timesteps. Bottom: optimal sensor measurement points selected for each of four timesteps. The adaptive sampling approach spreads its budget of 20 samples evenly to fill the spatiotemporal volume, with minor adjustments to account for local structures and heterogeneity.

Novelty

A quantification of improvements in measurement capabilities based on these adaptive sampling routines is essential and is the focus of on-going work in our KISS study. However, a few advantages can be enumerated:

1) As robotics become more prevalent in ocean research, larger and larger fleets of instruments will be deployed. Once the number of assets is on the order of ten or more, individual piloting, especially across diverse sensing platforms will be inefficient.

2) With many assets it will become difficult to assess the usefulness of acquired data on the timescales required to update sensing strategies.

3) Adaptive sampling provides a useful means to test intuition about physical processes as different adaptive sampling algorithms may be used to test different hypotheses about the physical processes being observed.

4) Lagrangian experiments may require predictive capabilities, even if only in the short-term, in order to adequately track evolving physical and biological processes in the ocean.

4.5 AUTONOMY

Achieving the vision outlined by this study will require autonomy at a variety of levels including on individual vehicles, within clusters of vehicles, and within the entire process. A number of autonomy concepts are salient to this study including mixed-initiative autonomy, on-board autonomy (i.e., autonomous decision making cycles that reside completely aboard a single vehicle), and distributed autonomy (in which decisions affecting multiple vehicles need to be made using data from multiple vehicles). This section reviews these autonomy concepts in both the marine and space robotics domains and how they might contribute to this study.

Mixed initiative autonomy will be a critical capability for developing and validating the Study's proposed vision. This capability enables the vehicle operators to interact with and direct the autonomy software. Operators will need to be able to adjust the autonomous behavior enabled on a vehicle depending on the current application scenario and on their level of trust in the onboard autonomy capabilities.

One important area of mixed-initiative systems is that they enable the operator to easily command and monitor the autonomy behavior. Interfaces to autonomy technologies should enable intuitive user interacting and enable the operator to have insight into why the autonomy software made certain decision. Mixed-initiative systems are also important for deploying autonomy capabilities in different stages. In the beginning, the autonomy might be very limited in its control over the vehicle. As the operator grows to trust the capability the level of autonomy can be dialed up.

Having the capability to dial-up or dial-down autonomy capabilities is also particularly important to deal with varying mission time and distance scales. For short-range missions, it may be beneficial to have human operators in regular contact with the vehicle, manually adjusting the plan and monitoring science data. For medium-term missions, vehicles will need to be more independent but still enable human operators to periodically contact them for guidance. Long duration missions will likely require the highest level of autonomy where interaction with human operators is minimal. Autonomy technologies will need to be developed to support different levels of onboard decision making to support these different mission scales.

On-board Autonomy for marine robots first focused on the automated execution and completion of pre-programmed missions. With the maturity of AUVs, the problem has shifted from autonomous execution to a variety of autonomy problems related to specific science problems. Extensive results – both in simulation and in experiment – exist; here we focus on work that has been tested in the field or on data obtained in the field.

Chemical plume tracing algorithms that have been implemented on robots or designed for them range from concentration gradient ascent, to biologically inspired algorithms (Farrell et al., 2005; Grasso et al., 2000; Kuwana et al., 1995; Nagasawa et al., 1999; Ishida et al., 2001; Consi et al., 1994; Lilienthal and Duckett, 2003a; Balkovsky and Shraiman, 2002), to model-based strategies that estimate source location along with other plume parameters (Ishida et al., 1998; Christopoulos and Roumeliotis, 2005a) or that build maps of probable source location (Pang and Farrell, 2006; Lilienthal and Duckett, 2003b), with some work also exploring multi-agent cooperative approaches either biologically-inspired (Hayes et al., 2002; Ferri et al., 2006) or model-based but with the advantage of distributed sensing (Christopoulos and Roumeliotis, 2005b; Zarzhitsky et al., 2004). Kowadlo and Russell (2008) provide an extensive overview.

An ocean front delineates the boundary between water masses distinguished by different physical, chemical, and biological characteristics. Ocean ecosystems are greatly influenced by the structure and dynamics of fronts (Ryan et al. 2010). For example, coastal upwelling brings cooler, saltier, and usually nutrient-rich deep water upward, replacing warmer, fresher, and nutrient-depleted surface water. The nutrients carried up by upwelling have significant impact on primary production and fisheries. The boundary between a stratified water column and an upwelling water column is called an upwelling front. Upwelling fronts support enriched phytoplankton and zooplankton populations (Ryan et al. 2010, Harvey et al. 2012), thus having great influences on ocean ecosystems. Detection and tracking of ocean fronts is important for investigating the formation, evolution, and interaction of ocean water masses, yet this is a very challenging task because fronts move and are often narrow. MBARI researchers have developed methods for AUVs to autonomously detect and track an upwelling front (Zhang et al. 2012a). The AUV distinguishes between stratified water columns and upwelling water columns based on their distinction in vertical homogeneity of temperature (temperature difference between shallow and deep depths in an upwelling water column is much smaller than that in a stratified water column). The Tethys AUV ran the algorithm to autonomously track upwelling fronts for several days in Monterey Bay, CA, providing high-resolution observations of the evolution of the frontal zone and revealing fine-scale mixing processes. The Dorado AUV ran a more advanced algorithm (based on the horizontal gradient of the vertical temperature difference between shallow and deep depths) to accurately locate the upwelling front and trigger water sampling within the narrow front (Zhang et al. 2012b).

Computer Aided Detection and Classification (CAD/CAC), a robust suite of efficient onboard algorithms for detection and classification of “interesting” objects and events, has been developed over the last 15 years for AUVs (Dobeck 2000; Ciany et al., 2003). These algorithms typically take any set of sensor inputs, analyze them to detect a desired signature, and fuse them into a coherent picture for classification. Although developed for specific military purposes, the CAD/CAC systems have now been used to close the loop with onboard autonomy systems in order to accomplish adaptive missions such as plume following, etc.

The space robotics community has developed technology for supporting autonomous science capabilities on space robotic vehicles that could potentially be leveraged for oceanographic studies. This technology typically enables the vehicle onboard software to make certain decisions based on data the vehicle has gathered and/or the current state of the vehicle itself. These capabilities have been field tested and/or demonstrated on a number of applications where the before mentioned benefits have been seen, such as relieving the human operator from mundane tasks and enabling the vehicle to gather higher quality science data. Examples of autonomous science capabilities that have been recently fielded on robotic hardware include:

- <u>AEGIS automated targeting system in use on the Mars Exploration Rover (MER) Mission</u>: AEGIS enables a Mars surface rover to automatically identify rocks in images and take additional observations of rocks that have certain properties. (Estlin, et al., 2012)

- WATCH atmospheric event detection in use on the Mars Exploration Rover (MER) Mission: WATCH enables a robotic vehicle to analyze images for certain dynamic events (such as Mars dust-devils) and if that event is detected, the containing images are downlinked with high priority. (Castano, et al., 2008)

- Autonomous Sciencecraft Experiment (ASE) on Earth Orbiting One (E01) Satellite: ASE enables the EO1 satellite to recognize dynamic events on Earth (such as flooding or volcanic eruptions) and acquire high resolution data on those areas automatically. (Chien, et al., 2010)

- Onboard data analysis and planning for research rover operations. A number of institutions have successfully tested autonomous-science capabilities on Earth research rovers. Applications include autonomous rover survey of large areas, recognizing key terrain features and acquire close-contact data on key features. (Fong, et al., 2008; Wettergreen, et al., 2008; Woods, et al., 2009)

Common capabilities provided by these systems include:

- Onboard data analysis for identifying environmental features of interest. Techniques can be applied to a variety of instrument data including visual images, spectral data, radar, etc.

- Data prioritization for determining what data should be downlinked at high priority.

- Data summarization which enables small summary products to be downlinked that inform operators about potential data content without requiring large downlink volume.

- Opportunistic science detection and response (especially at times where it’s difficult for the operator to be in the loop).

- Monitoring for rare dynamic events.

- Novelty detection for identifying novel or unique features in the environment.

- Representative data collection where a certain level of data is collected on all major feature types identified in the environment.

- Onboard planning and resource management where robot plans are created automatically onboard and task execution is closely monitored. This allows the operator to interact with the vehicle at a high level and enables the vehicle software to re-plan on the fly if something unexpected happens (including fault situation and/or fortuitous events).

These capabilities have been used on a variety of robotic platforms including mobile surface robots, spacecraft, Earth orbiters, UAVs, airships/balloons, etc.

For some applications, capabilities for autonomous science must also consider how to distribute and coordinate science activities among multiple agents. Common capabilities in an application that uses multiple vehicles include 1) distributing tasks among a team of robotic vehicles, 2) supporting coordinated observations where vehicles must work together in a loosely or tightly coordinated fashion to accomplish a science activity, 3) sharing data gathered with other vehicles and building a global data model, and 4) recognizing if a vehicle has failed or fallen behind and re-assigning its tasks to other vehicles.

Distributed Autonomy – While autonomy on individual platforms is important, a distributed approach is also required in order for data from multiple platforms to be assimilated and to make decisions about how to re-task these platforms. This challenge is complicated by the requirement that different types of platforms (i.e., heterogeneous) are required. Each platform will have different capabilities in terms of sensing, mobility and endurance. In light of these capabilities, each platform will need to be able to integrate itself into the larger observational plan. Drifters and non-mobile platforms will need to be capable of relaying their sensor data and state information such that their future states may be accounted when integrated into the larger model. Mobile platforms will need to be capable of receiving instructions, carrying out those instructions and modifying them if necessary according to the degree of autonomy required.

Due to the dynamics and multi-scale nature of the process to be sampled it may be necessary to integrate varying levels of adaptability into some of the sensors. Communications to subsurface platforms are intermittent and bandwidth limited such that platforms may need to decide when to sync with the larger picture and when something interesting is being observed.

Distributed autonomy among homogeneous vehicles – Significant work was done in this area within the context of coordinated glider trajectories. The 2003 and 2006 AOSN experiments demonstrated a number of results focused on gliders maintaining optimal survey patterns. These patterns were defined by humans a priori but once in the field, the gliders adaptively worked to maintain these trajectories using on board data, as well as data from other vehicles. Experiments during the 2006 AOSN experiments showed these methods to be an effective means of coordinating groups of gliders (Leonard et al., 2010; Paley et al., 2008); however, this work did not modify the vehicle trajectory based on realtime in situ or remote sensing data.

More recent work has considered how the coupling of realtime science data can be used to alter the trajectories of multiple gliders. Smith et al., 2010 present results that plan glider trajectories based on predictions from a regional ocean models (ROM) with the goal of locating and tracking features. These methods are tested in a two day experiment of the Southern California Bight with 2 gliders. A fixed glider sampling strategy for a 400 by 600 km box linked with a physical oceanography model was evaluated using OSSE experiments to determine the number of gliders needed (L' Hévéder et al 2009). Work towards merging satellite data with in-situ measurements has shown promise in propagating satellite measurements down from the surface (Alvarez et al 2012b).

Distributed autonomy among heterogeneous vehicles – The AOSN-II (2003) and MB2006 experiments involved coordinated networks of gliders, AUVs, aircraft, ships, moorings, floats and satellite information (Bellingham 2009); however the AOSN vision of these different assets working together in a largely autonomous manner remains unfulfilled. There is an increasing amount of theoretical and simulation work in this area. For example investigations into the combination of gliders and profiling floats or moorings has shown promise in de-correlating the spatially and temporally correlated data collected by slow moving platforms like gliders (Alvarez et al 2007; Alvarez et al 2012b). Petillo et al., 2013 considers the problem of a fleet of AUVs with different performance characteristics for plume tracking and shows simulation results.

Experimental results are rarer though a number of programs are underway. The concept of using an ASV as a tender for AUVs in support of long-term AUV operation is being pursued by a number of groups – e.g., Kinsey et al., 2013 and others. The Rapid Environment Picture (REP) project is an international effort conducting annual exercises aimed at advancing this area; the 2013 experiment included ASVs, AUVs, and UAVs. The GLINT '08 and GLINT '10 experiments demonstrated nested autonomy on four different classes of AUVs (Benjamin et al., 2010).

4.6 PUTTING IT ALL TOGETHER – CONTINUED PROGRESS TOWARD AUTONOMOUS OCEAN OBSERVING

The beginning of this chapter identified six crucial requirements for enabling the observational capabilities discussed earlier in this report. Over the course of this study, three technology groups investigated the state of the art and potential paths forward; these findings are discussed in Sections 4.2-4.5.

These technologies contribute to our larger vision presented in Section 4.1. The goal of completely autonomous data assimilation and re-tasking is not new to oceanography. The Autonomous Ocean Sampling Network (AOSN) as proposed by Curtin et al. (1993) is a conceptual framework to integrate autonomous mobile platforms and assimilative dynamical models to observe and predict dynamic ocean fields. Starting from the August 2003 field experiment, the AOSN initiative (Curtin and Bellingham, 2001) involved a series of field experiments in Monterey Bay, California, to develop new tools and methodologies to address the sparse sampling problem and reduce errors in ocean field estimation to enable hypothesis testing. Today, mobile sensors are operating reliably and persistently, and can be considered automated if not autonomous. In parallel with the maturation of hardware capabilities, assimilative models are now run routinely in real-time at the spatial resolution comparable to the observational data (e.g., 1 km). The 2003 AOSN field experiment in Monterey Bay demonstrated that individual elements as shown in Fig. 1.4 were mature enough to be operated as a collective system; however decision-making processes remain human intensive. As the observing and modeling system becomes more complex, synthesizing and interpreting the information become more challenging. Knowledge of the system includes scheduling of available assets, resource constraints, and key metadata for each observation. A variety of state variables are being extracted from a diversity of measurements on a heterogeneous mix of platforms. The priority assigned to observing depends on particular objectives. Thus the decision process encompasses a multi-dimensional space. This is the grand challenge to arrive at a truly autonomous system with minimum and ultimately no human in the loop of decision making.

A central goal of this study was to unite scientists and technologists - some of whom have worked on this problem before and others who have not but can contribute expertise: to develop methods specifically aimed at observing the physical, biological, and biogeochemical processes associated with the marine carbon cycle.

Achieving this vision, especially for multi-year missions in harsh remote regions, requires multiple technology development projects. Specific technology development efforts identified by this study include:

- Development of a dissolved inorganic carbon (DIC) sensor suitable for deployment on mobile marine robots.
- Development of a simple isopycnal drifter.
- Investigation of methods in which groups of heterogeneous mobile robots (e.g., AUVs, gliders, and ASVs) autonomously and adaptively obtain long-duration in situ measurements. Objectives would include: (1) developing an architecture that allows shore based models to communicate with robots in the field to receive science data and to provide high-level directives on future measurement strategies; and (2)

designing a framework in which a fleet of heterogeneous ocean robots can transfer high-level directives to vehicle specific commands, while considering robot health and sensing capabilities

- Development of an adaptive sampling methodology for the coordinated operation of mobile, heterogeneous Earth observing assets. A model-driven sampling strategy consisting of designing measurement plans that maximize information obtained about an underlying physical process is a compelling option.

These efforts will be important first steps toward the larger vision presented by this study. Subsequent efforts should focus on merging earlier efforts and begin to implement and assess these methods in the field during short to medium term deployments at sites of scientific interest near the Continental United States (e.g., George's Bank, Bermuda, or the California coast), before undertaking longer-term deployments in more remote regions such as the Southern Ocean. This resource deployment strategy is in line with the staged approach to autonomy adoption. Initial experiments will be structured and take advantage of existing assets and, as the methods are assessed and improved, gradually move to coordinated efforts in remote regions. Concurrently, both scientists and technologists will gain "trust" in these autonomous methods while in parallel obtaining scientific data. The increasing asset diversity will require an increase in autonomy complexity as well. Initially, a fixed sampling regime could be employed and require minimal autonomy. The degree of autonomy will increase slowly, sliding from the fixed regime to autonomous feature identification and eventually to autonomous capabilities such as online feature identification and re-tasking. Existing oceanographic programs such as SPURS2 and OOI, along with traditional oceanographic cruises, provide opportunities.

CHAPTER 5: CONCLUSIONS

Two workshops, funded by the Keck Institute for Space Studies (KISS), brought together a diverse group of scientists and engineers with expertise in physical, chemical, and biological oceanography, remote sensing, autonomy, and marine robotics. The purpose of the meeting was to discuss the observational challenges associated with understanding the marine carbon cycle and envision potential technological solutions to improve observational capabilities. The first meeting, held in October 2013, established a common lexicon, presented the current state of the art in our understanding of the science and present technologies, and identified the key challenges that limit our ability to constrain upper ocean carbon fluxes. During the interim period, science questions were refined and technological solutions explored. Our concluding meeting, held in February 2014, provided specific suggestions for coupling autonomy and autonomous ocean robots to resolve the patchiness associated with physical and biogeochemical processes in the ocean. These distributions have been difficult to resolve with traditional ocean observing techniques. The major conclusions of our study are:

1. Despite the imperative to understand the marine carbon budget and its key role in the global carbon cycle, our understanding of mechanistic processes that determine upper ocean carbon fluxes is limited. Progress has been made in identifying key physical processes, e.g. submesoscale dynamics that couple upper ocean circulation and biological dynamics. The impact of these dynamics on biogeochemical cycles is uncertain due to a lack of observational data and inability to express these interactions in numerical models. Improved representation of physical-biological coupling is needed to understand trends in global temperatures and ocean sustainability.

2. Observations of oceanographic physical properties have benefited substantially from the development of autonomous capabilities. Limitations remain in making coincident physical and biological measurements. This lacuna arises because: (i) sensing capabilities for autonomous platforms remain limited; (ii) heterogeneity in time and space applies to the dynamical processes we seek to measure as well as the platforms we use to investigate them; (iii) the capability for a mobile coordinated persistent presence, often in harsh, remote regions, remains nascent; (iv) adaptive surveying that can incorporate information from in situ and remote sensing data, a priori environmental knowledge, and numerical models is crucial but underdeveloped; and (v) present methods still require extensive human interaction. (Section 1.3).

3. A key scientific goal is to better observe and understand the vertical flux of carbon through the water column, with an appreciation that lateral transport can be significant. Within this framework, three important gateways were identified where further observational capabilities would improve understanding of the marine carbon cycle. These include (a) carbon export from the surface ocean, including resolution of its fine horizontal variability; (b) remineralization through the "twilight zone" (sub-euphotic layer) and (c) carbon fluxes through the seafloor, including physical processes associated with its variability. All three components are critical to marine carbon cycle. The export of carbon from the ocean surface and its transfer into the twilight zone was identified as the focus area of this study.

4. Patchiness in biological and water mass distributions, arising from stirring by ocean currents and eddies, is a key feature of upper ocean biogeochemistry and the primary feature we propose to resolve with ocean robots. The impact of patchiness on large-scale biogeochemical cycles is a difficult feature to reproduce in large-scale climate models.

5. A coordinated network of ocean robots and satellites that autonomously interpret data and communicate sampling strategies is required to observe and track this patchiness in the ocean. Improved observational capabilities will lead to greater insight into the larger-scale contribution from these patchy distributions to the global carbon cycle. Two conceptual experiments summarized this approach.

6. The conceptual experiments identified the following technology requirements: (i) a persistent mobile presence to capture processes occurring over different spatial (ranging from 1-1000km) and temporal (weeks to years) scales; (ii) an expansion of the existing sensing suite for autonomous platforms to include more biological and biogeochemical sensors; (iii) fleets of multiple, coordinated, heterogeneous assets; (iv) the ability to adapt to changes both for scientific reasons (as defined from shore) and for vehicle health, e.g. battery power, maneuverability, sensor functionality; (v) increased autonomy; and (vi) a "scaling-up" capability. The last point is critical to transition from the development of these technologies to applications in future experiments. (Chapter 4 Introduction).

7. Implementation of these technological advances is discussed in detail in Chapter 4 and summarized in section 4.6. Our KISS study focused on three areas of development: sensors, marine robotics and information exchange. Autonomy was an omnipresent theme in the robotics and information exchange group. Participants in the group are pursuing various opportunities to move forward with the techniques covered in this report.

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APPENDICES

APPENDIX A: TECHNOLOGY READINESS LEVEL DEFINITIONS

This study follows the technology readiness levels (TRLs) used by NASA and defined in (Mankins, 1996). The definitions have been modified to be generic to both the space and marine environments. For example, tested in the field could mean “space tested” or “ocean tested” depending on the application. This report occasionally reduces the TRL scale to a 3 level color-coded scale in which 🟥 = TRL 1-5; 🟨 = TRL 6-8; and 🟩 = TRL 9 or COTS.

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in the field
TRL 8	Actual system completed and “mission qualified” through test and field demonstration
TRL 9	Actual system “mission proven” through successful mission operations

APPENDIX B: LEVEL OF AUTONOMY DEFINITIONS

LOA 10 (High)	The computer decides everything, acts autonomously, ignoring the human
LOA 9	Informs the human only if it, the computer, decides to
LOA 8	Informs the human only if asked, or
LOA 7	Executes automatically, then necessarily informs the human, and
LOA 6	Allows the human a restricted time to veto before execution, or
LOA 5	Executes that suggestion if the human approves, or
LOA 4	Suggests one alternative
LOA 3	Narrows the selection down to a few, or
LOA 2	The computer offers a complete set of decision/action alternatives, or
LOA 1 (Low)	The computer offers no assistance: human must take all decisions and actions.

APPENDIX C: HIGH PRIORITY PARAMETERS TO MEASURE

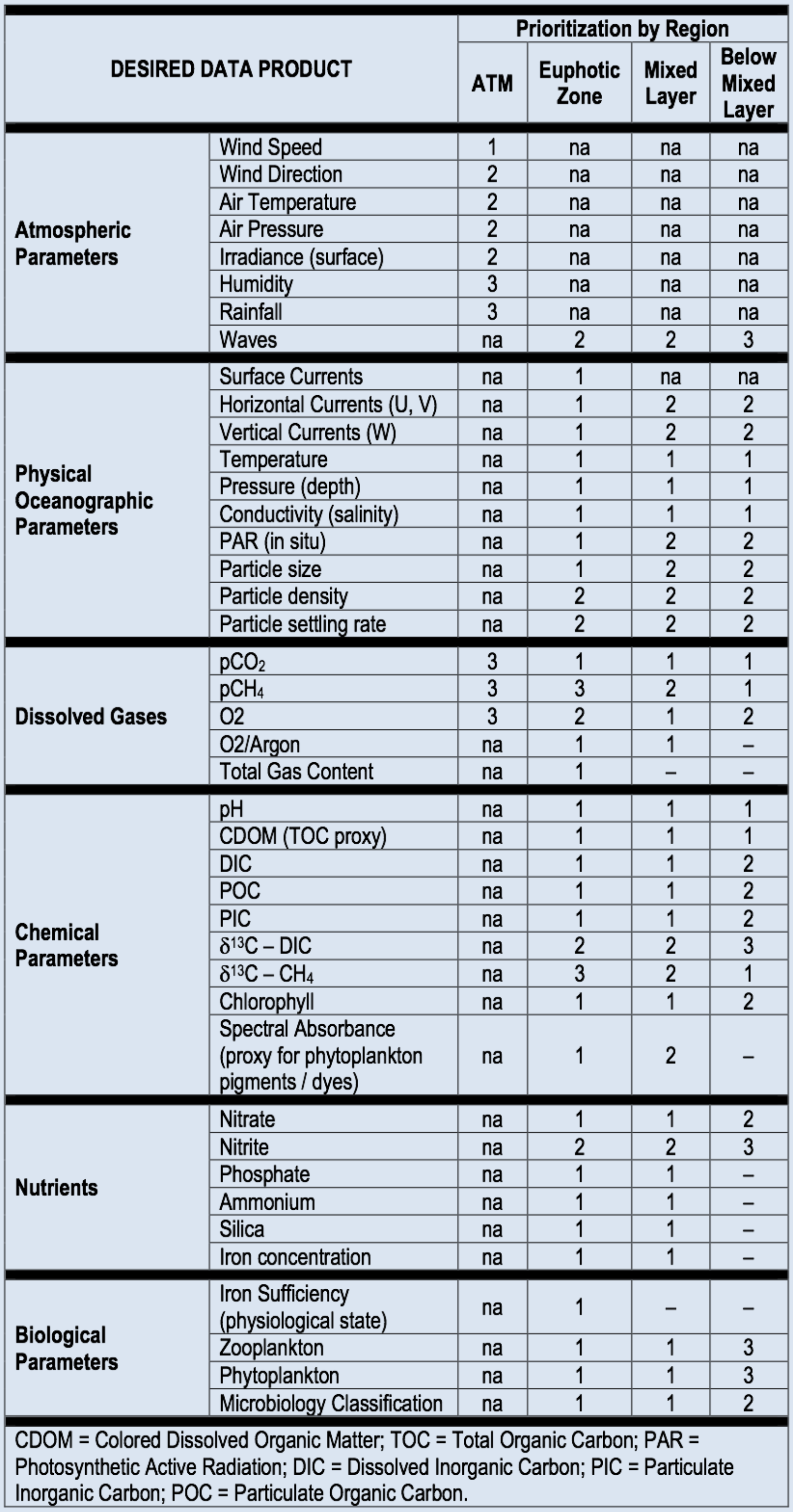
The team considered a comprehensive range of science data products and ranked these based on importance to processes relating to atmosphere/ocean interaction, the euphotic zone, the mixed layer, and the deeper ocean. This ranking was performed independently of assessing the TRL of currently available instruments that would be needed to generate the product.

The oceanographic measurement data products were organized categorically into the following groups:

- Atmospheric Parameters
- Physical Oceanographic Parameters
- Dissolved Gases
- Chemical Parameters
- Nutrients
- Biological Parameters

Each oceanographic in situ data product was ranked with respect to scientific relevance to the atmosphere, euphotic zone, mixed layer, or sub-mixed layer oceanographic regions. These rankings are shown in Table C.1.

Table C.1: Prioritization 1 is the highest priority.



DESIRED DATA PRODUCT		Prioritization by Region			
		ATM	Euphotic Zone	Mixed Layer	Below Mixed Layer
Atmospheric Parameters	Wind Speed	1	na	na	na
	Wind Direction	2	na	na	na
	Air Temperature	2	na	na	na
	Air Pressure	2	na	na	na
	Irradiance (surface)	2	na	na	na
	Humidity	3	na	na	na
	Rainfall	3	na	na	na
	Waves	na	2	2	3
Physical Oceanographic Parameters	Surface Currents	na	1	na	na
	Horizontal Currents (U, V)	na	1	2	2
	Vertical Currents (W)	na	1	2	2
	Temperature	na	1	1	1
	Pressure (depth)	na	1	1	1
	Conductivity (salinity)	na	1	1	1
	PAR (in situ)	na	1	2	2
	Particle size	na	1	2	2
	Particle density	na	2	2	2
	Particle settling rate	na	2	2	2
Dissolved Gases	pCO_2	3	1	1	1
	pCH_4	3	3	2	1
	O2	3	2	1	2
	O2/Argon	na	1	1	–
	Total Gas Content	na	1	–	–
Chemical Parameters	pH	na	1	1	1
	CDOM (TOC proxy)	na	1	1	1
	DIC	na	1	1	2
	POC	na	1	1	2
	PIC	na	1	1	2
	$\delta^{13}C$ – DIC	na	2	2	3
	$\delta^{13}C – CH_4$	na	3	2	1
	Chlorophyll	na	1	1	2
	Spectral Absorbance (proxy for phytoplankton pigments / dyes)	na	1	2	–
Nutrients	Nitrate	na	1	1	2
	Nitrite	na	2	2	3
	Phosphate	na	1	1	–
	Ammonium	na	1	1	–
	Silica	na	1	1	–
	Iron concentration	na	1	1	–
Biological Parameters	Iron Sufficiency (physiological state)	na	1	–	–
	Zooplankton	na	1	1	3
	Phytoplankton	na	1	1	3
	Microbiology Classification	na	1	1	2

CDOM = Colored Dissolved Organic Matter; TOC = Total Organic Carbon; PAR = Photosynthetic Active Radiation; DIC = Dissolved Inorganic Carbon; PIC = Particulate Inorganic Carbon; POC = Particulate Organic Carbon.

APPENDIX D: COMMERCIALLY AVAILABLE SENSORS

Table D.1: Examples of advanced in situ oceanographic sensors for physical and biochemical analyses. List is not comprehensive – in most cases only one vendor option was included. Glider capability evaluated based on estimated readiness for integration on a profiling glider vehicle.

Data Product(s)	Sensor	Maturity	Glider Capable	Depth Rating (meters)	Weight in Air (kg)	Volume (cc)	Power (W)	Sensitivity	Information
Conductivity Temperature Pressure Oxygen	Glider Payload CTD (GPCTD) / SBE 43F	**Commercial**	**Yes**	1500 m (CTD depth limit)	1.6	NA	0.28	0-90 mS/cm -5 to +42 °C 0-2000 dbar	http://www.seabird.com/glider-payload-ctd
Photosynthetically Active Radiation (PAR)	Satlantic PAR Sensor	**Commercial**	**Yes**	600 m standard (7000 m optional)	<0.65	94	<0.5	400-700 nm ± 5% (air)	http://satlantic.com/par
Particle Size Distribution (PSD)	Sequoia LISST-100X	**Commercial**	**Yes**	300 m	11	12,080	<2	<2.5 µm (<1 mg/L)	http://www.sequoiasci.com/product/lisst-100x/
pCO_2	CO_2-Pro (Mini-Pro CO_2 available)	**Commercial**	**Yes**	110 m	5.5	9,351	<7	0.01 ppm <600 ppm (hysteretic)	http://www.pro-oceanus.com/co2-pro.php

Data Product(s)	Sensor	Maturity	Glider Capable	Depth Rating (meters)	Weight in Air (kg)	Volume (cc)	Power (W)	Sensitivity	Information
pCH_4	Mini-Pro CH_4	**Commercial**	**Yes**	300 m standard (4000 m optional)	1	550	1.2	1 μg/L (hysteretic)	http://www.pro-oceanus.com/mini-pro-ch4.php
Colored Dissolved Organic Matter (CDOM)	WET Labs Eco-puck	**Commercial**	**Yes**	600 m	0.28	156	<1.5	NA (fluorescence)	http://www.wetlabs.com/eco-puck
Chlorophyll	Cyclops-6K fluorometer	**Commercial**	**Yes**	6000 m	0.6	260	0.3	0.025 μg/L	http://www.turnerdesigns.com/products/submersible-fluorometer/
Spectral absorption coefficients	In situ Integrating Cavity Absorption Meter (ICAM)	**Commercial**	**Yes**	200 m	15	20,000	25	0.001 m-1	http://www.turnerdesigns.com/products/submersible-fluorometer/
Spectral absorption coefficients	ac-s In-Situ Spectrophotometer	**Commercial**	**Yes**	500 m	6	6,700	10	0.005 m-1	http://www.wetlabs.com/ac-s
Nitrite	Ecolab 2 Multi-Channel Analyzer System Ecolab 2	**Commercial**	**No**	200 m standard (4000 m optional)	25	44,500	3	0.003 mg/L	http://www.envirotechinstruments.com/ecolab.html
Phosphate	Ecolab 2 Multi-Channel Analyzer System Ecolab 2	**Commercial**	**No**	200 m standard (4000 m optional)	25	44,500	3	0.003 mg/L	http://www.envirotechinstruments.com/ecolab.html
	Microlab Compact Nutrient Monitor	**Commercial**	**No**	200 m	10	15,500	3	0.003 mg/L	http://www.envirotechinstruments.com/microlab.html

Data Product(s)	Sensor	Maturity	Glider Capable	Depth Rating (meters)	Weight in Air (kg)	Volume (cc)	Power (W)	Sensitivity	Information
Ammonium	Ecolab 2 Multi-Channel Analyzer System Ecolab 2	**Commercial**	**No**	200 m standard (4000 m optional)	25	44,500	3	0.003 mg/L	http://www.envirotechinstruments.com/ecolab.html
	Microlab Compact Nutrient Monitor	**Commercial**	**No**	200 m	10	15,500	3	0.003 mg/L	http://www.envirotechinstruments.com/microlab.html
Silicate	Ecolab 2 Multi-Channel Analyzer System	**Commercial**	**No**	200 m standard (4000 m optional)	25	44500	3	0.003 mg/L	http://www.envirotechinstruments.com/ecolab.html
	Microlab Compact Nutrient Monitor	**Commercial**	**No**	200 m	10	15,500	3	0.003 mg/L	http://www.envirotechinstruments.com/microlab.html
Iron concentration	Microfluidic technology (Spectrophotometric Ferrozien technique)	**Prototype/ Early stage testing**	**No**	1700 m	NA	NA	0.05	NA	http://meetingorganizer.copernicus.org/EGU2012/EGU2012-4564.pdf
Zooplankton	Video Plankton Recorder	**Prototype**	**Yes**	350 m	NA	NA	NA	Zooplankton (0.1 mm to 1 cm)	https://www.whoi.edu/main/vpr
	In Situ Ichtyoplankton Imaging System (ISIIS)	**Prototype**	**No**	200 m	NA	NA	NA	Zooplankton (1 mm to 13 cm)	http://yyy.rsmas.miami.edu/groups/larval-fish/isiis website/isiispage1.htm

Data Product(s)	Sensor	Maturity	Glider Capable	Depth Rating (meters)	Weight in Air (kg)	Volume (cc)	Power (W)	Sensitivity	Information
Zooplankton (cont.)	Acoustic Zooplankton Fish Profiler	**Commercial**	**Yes**	600 m	<50 kg	23,000 cm^3	<5 W	NA	http://www.aslenv.com/brochures/AZFP-for-GLIDER-AUV-2013.pdf
Phytoplankton	Imaging Flow Cytobot	**Commercial**	**No**	40 m	~32 kg	54,127 cm^3	35 W (6 mos. continuous)	1 µm image resolution	http://www.mclanelabs.com/master_page/product-type/samplers/imaging-flowcytobot
Microbial Classification	Environmental Sample Processor (ESP) 2nd generation	**Commercial**	**No**	<50 m (Deep-Sea ESP in development)	~100 kg	312,000 cm^3	NA (3 mos. continuous)	Microorganism identification	http://www.mclanelabs.com/master_page/product-type/samplers/environmental-sample-processor
Iron Sufficiency (physiological state)	Fast Repetition Rate Fluorometry	**Commercial**	**No**	NA	16 kg	63,206 cm^3	16 W	NA	http://www.chelsea.co.uk/allproduct/marine/fluorometers/fast-ocean-system/fastocean-apd-profiling-system
		Research	**No**	NA	NA	NA	NA	NA	http://www.int-res.com/abstracts/meps/v353/p81-88/

NOTE: Ocean carbon measurement approaches not described thoroughly above – for detailed discussion, see reference: Schuster, U., Hannides, A., Mintrop, L., and Kortzinger, A. (2009) Sensors and instruments for oceanic dissolved carbon measurements. *Ocean Sci.* **5,** 547-558. URL: http://www.ocean-sci.net/5/547/2009/os-5-547-2009.pdf

APPENDIX E: WORKSHOP PARTICIPANTS

Name	Institution	Workshop	
		First	Second
Jess F. Adkins	Caltech Campus	X	X
Andrew Aubrey	JPL/Caltech	X	X
Ralf Bachmayer	Memorial University of Newfoundland	X	
Michael Bender	Princeton University	X	X
Rebecca Castano	JPL/Caltech	X	X
Nicolas Cassar	Duke University		X
Yi Chao	Seatrec Inc.	X	X
Steve A. Chien	JPL/Caltech	X	
Brian Claus	Memorial University of Newfoundland	X	X
Max Coleman	JPL/Caltech	X	X
John Delaney	University of Washington	X	X
Colin W. Devey	GEOMAR Helmholtz Centre for Ocean Research Kiel	X	
Tara Estlin	JPL/Caltech	X	X
Cedric Fichot	JPL/Caltech		X
Christopher R. German	Woods Hole Oceanographic Institution	X	X
Michelle Gierach	JPL/Caltech		X
Kevin Hand	JPL/Caltech	X	
Roger Hine	Liquid Robotics	X	X
Terrance Huntsberger	JPL/Caltech	X	X
Mike Jakuba	Woods Hole Oceanographic Institution	X	
Leah Johnson	University of Washington	X	X
James C. Kinsey	Woods Hole Oceanographic Institution	X	X
Tom Kwasnitschka	GEOMAR Helmholtz Centre for Ocean Research Kiel	X	
Ayah Lazar	Caltech Campus	X	X
Craig M. Lee	Applied Physics Laboratory, Univ. of Washington	X	
Dimitris Menemenlis	JPL/Caltech	X	X
Brendan Philip	University of Washington	X	X
Andrew F. Thompson	Caltech Campus	X	X
David R. Thompson	JPL/Caltech	X	X
Douglas W.R. Wallace	Dalhousie University	X	
Dana Yoerger	Woods Hole Oceanographic Institution		X
Yanwu Zhang	MBARI	X	X

APPENDIX F: SHORT COURSE SPEAKERS

The first workshop opened with a half-day short course entitled "Satellites, Ocean Robots and the Marine Carbon Cycle", Oct. 7, 2013. This short course discussed current problems associated with constraining carbon exchange pathways, as well as the state of the art in remote sensing, autonomous underwater and surface vehicles, including autonomy, co-robotics, and persistent presence. The course brought together experts in these diverse fields with a view towards identifying how a coordinated network of inter-communicating ocean robots and satellites can advance our ability to monitor the marine carbon cycle.

The speakers and talks are listed below. In electronic versions of this document, the blue text links to presentation slides and videos.

Douglas Wallace, Dalhousie University	The Ocean Carbon Cycle (2 MB pdf) (video)
Craig Lee, Applied Physics Laboratory, University of Washington	The Physical Dynamics of the Marine Carbon Cycle (49.3 MB pdf) (video)
Yi Chao, Remote Sensing Solutions, Inc.	The Future of Remote Sensing (12.4 MB pdf) (video)
Mike Jakuba, Woods Hole Oceanographic Institution	Autonomy in Robotics for Oceanographic Science: Successes, Challenges and Opportunities (2.9 MB pdf) (video)
Steve Chien, JPL / Caltech	Science-Driven Autonomy for Space Exploration and Parallels to Ocean Science (3.9 MB pdf) (video)

Advection
Transfer of heat, matter or tracers by the movement of a fluid, as opposed to by diffusion.

Bathypelagic
Inhabiting the deep ocean where the environment is dark and cold, approximately 1,000–3,000 m below the surface.

Biogeochemical cycling
Relating to or denoting the cycle in which chemical elements and simple substances are transferred between living systems and the environment.

Dissolved inorganic carbon / DIC
The sum of inorganic carbon species in a solution. The inorganic carbon species include carbon dioxide, carbonic acid, bicarbonate anion, and carbonate, all of which rapidly equilibrate with each other and are present to an extent governed by pH. Thus, DIC is a key parameter when making measurements related to the pH of natural aqueous systems and carbon dioxide flux estimates.*

Eddies
Eddies refer to deviations from the mean properties of the flow or tracer distributions. These anomalies often arise due to coherent, rotating motions known as vortices. Eddy transport or eddy fluxes refer to that component of the transport that is due to correlations between two eddy quantities such as velocity and heat. This contribution can often be as important or even more important than transport due to the mean flow.

Filaments
Features that are elongated in one direction, typically formed by turbulent stirring. A consequence of this elongation is that gradients become strong in the direction perpendicular to the filament. In the ocean, filament widths are typically less than 10 km.

Geostrophic velocity / velocities
A flow in which the principle balance is between pressure gradients and the Earth's rotation, or the Coriolis term. The effects of rotation cause large-scale atmospheric and oceanic velocities to move perpendicular to high and low pressure systems. This causes circular motion around storms in the atmosphere and mesoscale eddies in the ocean. Most flows in the ocean are in geostrophic balance.

Gyres

Large-scale, closed ocean flow patterns that result from wind forcing, buoyancy forcing, and the Coriolis acceleration. Since the Coriolis acceleration changes with latitude, gyre circulations are not symmetric and the flow on the western boundaries is stronger. Subtropical gyres are found in all the world's oceans at mid-latitudes and they have a clock-wise circulation in the northern hemisphere and counter clock-wise circulation in the southern hemisphere. Subpolar gyres have the opposite circulation and are found poleward of subtropical gyres. Recirculation gyres are flows associated with major ocean currents and consist of water that recirculates in a closed pattern around most of the ocean basin. Large-scale recirculation gyres are associated with fast western boundary currents; mesoscale recirculations are associated with meandering currents .

Heterotrophic

Organisms that consume organic or biochemical compounds in order to metabolize and grow as opposed to autotrophic ones that can synthesize organic nutrients from inorganic precursor compounds.

Isopycnals

A contour or surface of constant density in the ocean. Most ocean mixing takes place along isopycnal surfaces.

Lagrangian

A method of observing the flow that follows a fluid parcel. Mathematically this can mean how properties of a fluid change along the path of the fluid, or it may refer to flow-following instruments such as floats or drifters.

Meanders

Large-amplitude wave-like features seen in ocean currents.

Mesopelagic

Inhabiting intermediate depths of the ocean, approximately 200–1,000 m below the surface.

Mesoscale

A specific scale of feature that, which especially refers to eddies in the ocean. Length scales are on the order of many tens of kilometers to a few hundred kilometers and time scales span many days to a month. This scale is associated with motions that feel the effects of Earth’s rotation.

Ocean mixed layer

The mixed layer is that region of the ocean that extends from the surface to a variable depth over which properties such as temperature and salinity are well-mixed and homogeneous.

The mixed-layer owes its existence to the mixing initiated by waves and turbulence caused by the wind stress on the sea surface. Mixed layers can be as shallow as 10m (usually in the summer) and can extend to many hundreds of meters (usually in the winter).

Oligotrophic

A part of the ocean relatively poor in nutrients.

Remineralization

Conversion of organic compounds to inorganic species, usually mediated by microbial activity.

Rossby number

A non-dimensional number that compares the flow's advective timescale to the timescale associated with the Earth's rotation. When the Rossby number is small, which is typically is for currents with spatial scales greater than about 10 km, the Coriolis term dominates the advective term and the flow is in geostrophic balance: the Coriolis acceleration balances horizontal pressure gradients.

Solubility

The extent to which a substance can be dissolved in water.

Sub-euphotic layer

Below that depth of water in a lake or ocean that is exposed to such intensity of sunlight which designates compensation point, i.e. the intensity of light at which the rate of carbon dioxide uptake, or equivalently, the rate of oxygen production, is equal to the rate of carbon dioxide production, equivalently to the rate of oxygen consumption, thus reducing the net carbon dioxide assimilation to zero.*

Submesoscale

A scale of feature smaller than mesoscale (see above). Submesoscale motions are typically associated with a Rossby number that is roughly equal to one.

Surfactants

Compounds that lower the surface tension of water and therefore affect its ability to form droplets, which allow rapid exchange with the atmosphere.

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APPENDIX H: LIST OF ACRONYMS

AAIW	Antarctic Intermediate Water
ACC	Antarctic Circumpolar Current
ASV	autonomous surface vehicle
AUV	autonomous underwater vehicle
CDOM	colored dissolved organic matter
CTD	conductivity, temperature, depth
COTS	commercial off the shelf technology
DIC	dissolved inorganic carbon
ICAM	integrating cavity absorption meter
LOA	level of autonomy
LRAUV	long-range autonomous underwater vehicle
MLD	mixed layer depths
OSSE	Observation System Simulation Experiments
PAR	photosynthetically active radiation
PIC	particulate inorganic carbon
POC	particulate organic carbon
PSD	particle size distribution
ROMS	regional modeling system
SID	simple isopycnal drifter
SIR	science informed robotics
TOC	total organic carbon
TRL	technology readiness levels
UAV	unmanned aerial vehicle