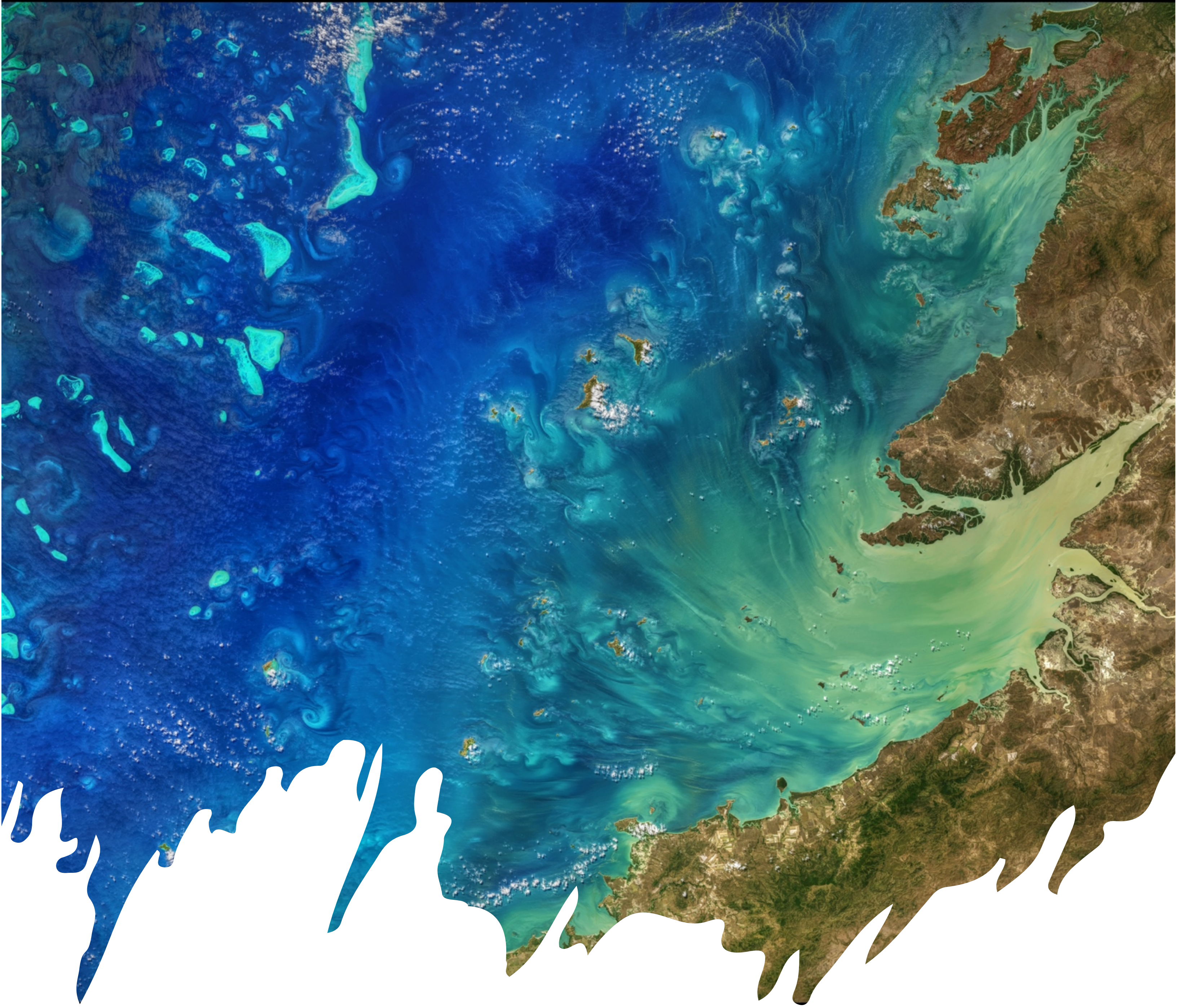

Earth's Living Ocean: Vast, Dynamic, Essential to Humanity

Dear Reader,

NASA supports state-of-the-art science, cutting-edge technological advances, and pioneering modeling ventures that seek to address some of the most pressing questions we have about the Earth system. NASA's Ocean Biology and Biogeochemistry (OBB) program goals include describing, understanding, and predicting the biological, ecological, and biogeochemical regimes of the upper ocean, as determined by observations of aquatic optical properties using remote sensing (satellite, aircraft, and other suborbital platforms), *in situ*, and Earth system model data. *Earth's Living Ocean: Vast, Dynamic, Essential to Humanity* is a document that identifies areas of opportunity for research that are essential for sustaining ocean health and our blue economy. It pursues pressing and open questions on which ocean sustainability hinges and addresses gaps in our understanding of ocean biological and biogeochemical processes for which advances in new observational technologies are necessary. This effort, led by members of our scientific community, provides critical input for charting the course of research for the current decade and beyond.

Ocean warming, acidification, deoxygenation, and sea level rise are but some of the consequences of the climate crisis that threatens ocean and human health. Understanding the changes that are happening within the ocean is critical because of its dominant role in climate regulation, and our intimate interdependence, at a global level, on the ocean for food, recreation, and commerce. The value of ocean provisions worldwide has been estimated at around $1.5T USD annually. This is our Blue Economy. Growing the Blue Economy relies on sustainability, ecosystem diversity, and maintenance of robust ocean health. Millions of jobs and livelihoods are linked to fisheries, aquaculture and tourism, and a stunning 80% of global trade by volume is carried out by sea. The ocean also provides 'intangible services' that are difficult to quantify in specific economic values, such as carbon dioxide sequestration. It is estimated that the ocean has absorbed over 25% of all carbon dioxide emissions since pre-industrial times, at a rate of 9 to 12 billion tons of CO_2 annually. This broad estimated range is a consequence of our current understanding about drivers and mechanisms of ocean carbon sequestration in the ocean's interior, the pressures these mechanisms are facing, and how these processes may change in the future. Improved understanding of ocean carbon sequestration and other biogeochemical cycles is essential for advanced climate modeling, which in turn provides decision makers with more accurate information to plan for future changes. The monetary value of accurate climate predictions, enabled through improved understanding of ocean carbon sequestration, is estimated globally at half a trillion US Dollars, in terms of better preparedness and mitigation of future damages associated with a warming climate.

Improved understanding of future changes our ocean will face have also a direct impact on the life it sustains, which is intrinsically connected to human livelihood. Sustained *in situ*, airborne or suborbital, and satellite ocean observations will continue to be critical for understanding how the ocean works, from the functioning of its ecosystems to their links with the physical environment, and their resilience to future change. Only through sustained observing of the ocean can we measure long-term trends in ecosystem states, understand the mechanisms underlying change, and discern anthropogenically-driven change from natural variability. Ocean ecosystems already face multiple stressors, and these are expected to be compounded by new stressors with continued climate warming. Better understanding of how the Earth functions as an interconnected system will enable our society to achieve a predictive understanding of future pressures, the resulting changes in aquatic ecosystems, and preparing humanity for the next decade and beyond.

Earth's Living Ocean: Vast, Dynamic, Essential to Humanity identifies five **Grand Challenges** that require our scientific community, and those that depend on our science for a variety of applications, to think beyond the conventional approaches and truly leap forward in our understanding of aquatic ecosystems. This Science Vision builds on the first OBB advanced plan published in 2007 and on the decades of heritage satellite missions and groundbreaking science that our community has led. Advancing understanding has never been more urgent, and investments in aquatic observing have never been more critical. Alterations in ecosystem composition and productivity will have direct impacts on the goods and services they provide us. An informed understanding of our living ocean will ensure its protection, recovery, and continued health in a sustainable blue economy.

The time for action is now. The ocean, its ecosystems, and the people that rely on them can't wait. The science that NASA provides now, and the vision presented in this document, will inform action in management and advance fundamental knowledge, create resilience of aquatic ecosystems and the people that depend on them, mitigate consequences of change through nature-based solutions, and find sustainable ways to navigate the evolving aquatic scape that spans the globe.

Sincerely,
Laura Lorenzoni, on behalf of all of those that have provided leadership to our community over the decades.

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Executive Summary

Over 96% of the water on Earth is in the ocean and in every drop of this water life exists. It truly is a *Living Ocean*. The foundation of most of this life is the photosynthesizing microscopic plants called 'phytoplankton'. At any moment in time, the number of living phytoplankton cells in the ocean is comparable to estimated number of stars in the universe. Yet, the phytoplankton are only one component of the complex marine food webs invaluable to humanity because of their provision of food, climate regulation, nutrient sequestration, and myriad other services, as well as intimate ties to human culture and lifestyle. The ocean is also the least explored environment on Earth, yet understanding its ecosystems, elemental cycles, habitats, hazards, and resilience is vital to human welfare and commerce.

The vast expanse of the ocean has historically been a key challenge for understanding its ecosystems, but NASA's oceanographic research from space has provided a path for meeting this challenge. The sustained satellite global ocean color record has now proven beyond any doubt that marine ecosystems are changing on timescales ranging from seasonal cycles to decadal trends. These discoveries have raised fundamental questions that require new technology to explore and new infrastructure and expertise within the science community to understand. Maintaining our existing monitoring capabilities and expanding research capabilities in the coming decade and beyond will help us protect the environment that surrounds us and our own health, ultimately contributing to our survival on the only planet where we know life exists.

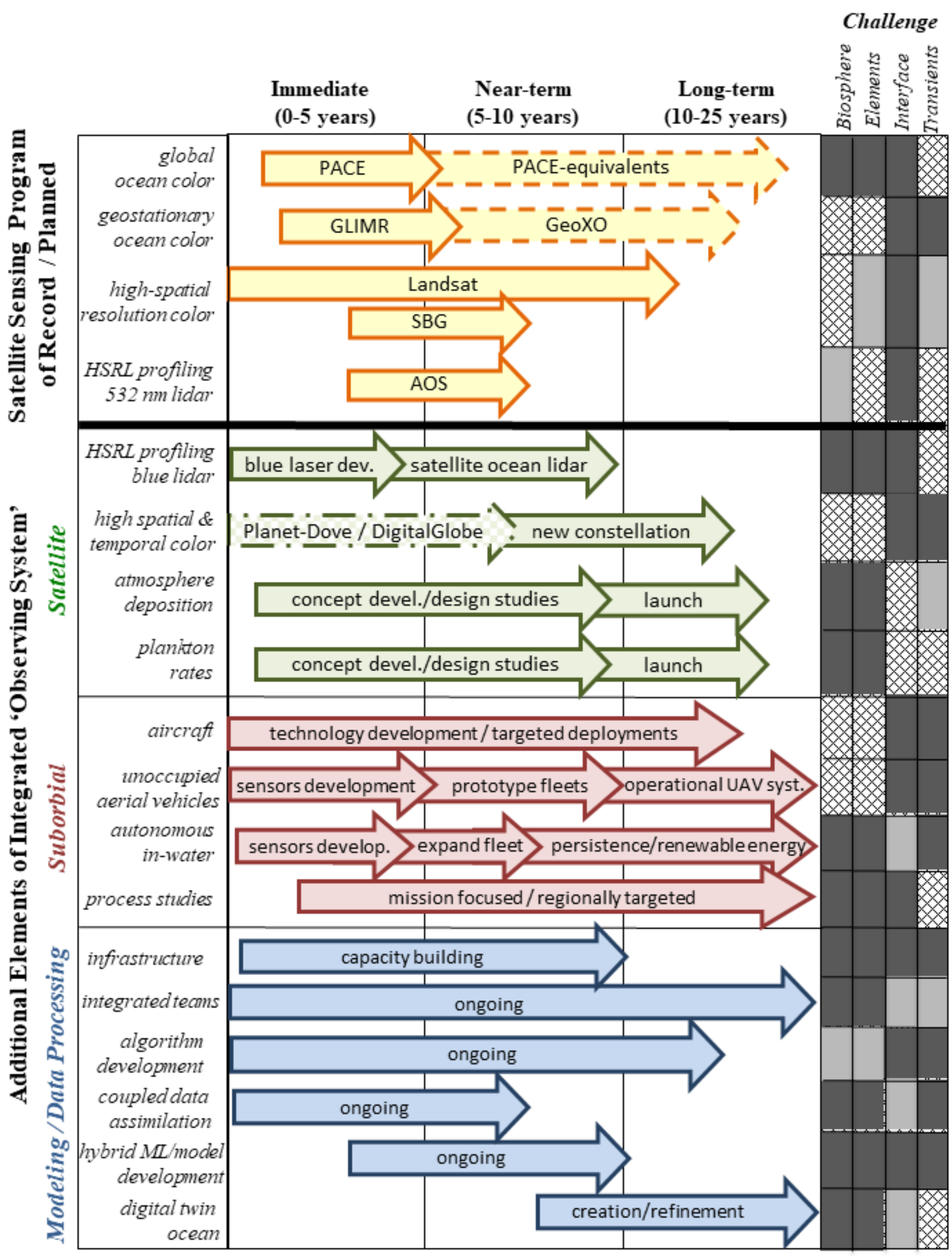
NASA's Ocean Biology and Biogeochemistry (OBB) Research Program is the centerpiece of the interdisciplinary, interagency, and international effort that advances knowledge on local- to global-scale processes and change in aquatic systems. To establish a forward path for the OBB Program, a working group was assembled to articulate current **Grand Challenges** in ocean science and identify strategies to address these challenges within the broader context of other national and international programs. This document is the outcome of that effort. It presents an integrated 'observing system' vision that entails a continuation of key heritage observations, development of new satellite observing capabilities, and a suite of suborbital (i.e., airborne, ship-based, and autonomous) and *in situ* measurements. The 'observing system' complements existing capabilities and includes significant advances in modeling to improve predictions and integration of data across observing platforms, investments in infrastructure to address growing 'Big Data' needs, and development of a scientific workforce that is inclusive of all peoples. The goal is to train a new generation in skills necessary to process and synthesize diverse data streams, develop engineering specifications for observational systems, provide solutions for management, and communicate new understanding to all stakeholders. Comments on this document were widely solicited across the research community and responses were incorporated into this final version.

A foundation upon which our strategy is built is the successful execution of satellite missions already in the Program of Record and continuation of these measurements into the future. These upcoming missions include global ocean color and polarimetry measurements from the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, high temporal-resolution ocean color measurements from the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR), and high spatial-resolution ocean color measurements from Landsat and NASA's Surface Biology and Geology (SBG) mission. Building upon this highest priority foundation, we identify additional immediate (1-5 year start date), near-term (5-10 year start date), and long-term (10-25 year start date) new satellite observing elements:

- (immediate) Global coverage, ocean-profiling lidar mission with advanced technology to directly separate in-water particulate absorption and scattering properties.
- (near-term) High spatial (1-10 meter) and temporal resolution, multispectral observations of global near-shore and interface (e.g., ice edge, current boundaries, etc.) environments, ecosystems, and biogeochemical fluxes.
- (long-term) Technological development allowing direct observations of atmospheric nutrient deposition to the ocean.
- (long-term) Characterization of global plankton physiological properties through high temporal resolution (1-2 hour) measurements of subsurface properties using a constellation of CubeSat/SmallSat lidar instruments or comparable approach.

Achieving the science objectives of these satellite systems also requires advances in data processing capabilities (e.g., atmospheric correction schemes for ocean color), suborbital observations, *in situ* measurements, and advances in modelling and these should be coordinated with other federal agencies, governmental partners, and industry. For brevity, this document does not include an exhaustive overview of non-US Earth observing satellite missions; however, the Grand Challenges and science objectives detailed herein represent a summons to the entire international science community that can only be effectively met through coordinated efforts. The parallel evolution of these 'observing system' elements will enable unprecedented 4-dimensional (3 spatial dimensions + temporal dimension) reconstructions of ocean ecosystems, greatly improve characterizations and monitoring of interface habitats, and provide a deeper understanding of coupled Earth system functioning that allows our Nation and the world to protect and nourish the *Living Ocean*.

Envisioned Observing System: Parallel development of diverse observing system elements allows ocean science **Grand Challenges** to be addressed. Program of Record missions are shown above heavy black horizontal line, with dashed outlines indicating planned but not yet funded missions. Additional new 'observing system' elements are shown below this line, with dash-dot outline indicating leveraging of commercial satellite programs. Modeling and data elements are indicated by blue arrows. Four **Grand Challenge** categories are shown on right, with importance of each *Observing System* element indicted by shading (Dark = essential; Light = important, Cross-hatch = contributing). The fifth **Grand Challenge**, 'Leveraging Ocean Data and Models', crosscuts and supports the other challenges and is represented in blue at bottom. See Table 1 for definitions of acronyms.



Introduction

The NASA Ocean Biology & Biogeochemistry (OBB) program is a research and analysis program under the Earth Science Division of the Science Mission Directorate. Its focus is to describe, understand, and predict the biological, ecological, and biogeochemical regimes of the upper ocean, as determined by observations of aquatic optical properties using remote sensing data, including those from space, aircraft, and other suborbital platforms. Overarching OBB programmatic goals include:

- Understanding and quantifying the impacts and feedbacks of Earth system processes, particularly oceanographic mechanisms, on the global and regional spatial and temporal variability of ocean biology, including phytoplankton and organisms from other trophic levels, and ocean biogeochemistry, including carbon sources and sinks and the fate of other chemical species or components in the ocean.
- Exploring beyond traditional ocean color products (e.g., phytoplankton chlorophyll a) by developing of new biological and biogeochemical observations from space-based assets, as well as furthering the climate research enabled by existing time series of climate observations (Earth system Data Records).
- Improving future climate predictions (impacts and feedbacks) by incorporating a dynamic understanding of ocean biology and biogeochemistry into global biogeochemical and ecological models to understand the ocean's role in the Earth system.

This science vision presented here, in support of the OBB program, has six primary sections. **SECTION 1** introduces five categories of **Grand Challenges** facing the Ocean Biology and Biogeochemistry community. Meeting these challenges is essential to the informed understanding and protection of a healthy ocean that is so vital to humanity. **SECTION 2** gives a brief historical overview of the ocean color Program of Record. In **SECTION 3**, we provide a brief contextual summary of the underlying science for each **Grand Challenge** and identify opportunities for forward progress. These opportunities are categorized in terms of timelines: ‘immediate’ = 0 – 5 years, ‘near-term’ = 5 – 10 years, ‘long-term’ = 10 – 25 years, and ‘continued’ = present activities sustained into the future. The material in each section is not exclusive of that in other sections but rather contributes to a complement of future capabilities that are interlinked. A synthesis of the overall portfolio is provided in **SECTION 4**. Additional details on observing system technological requirements and investment opportunities are provided in **SECTION 5**, while a ‘Benefits’ statement for the Nation and humanity is provided in **SECTION 6**. A table of acronyms, figure credits, and a reference list may be found at the end of the document.

1. Grand Challenges and a Sustainable Blue Economy

NASA's oceanographic research over the past four decades has revealed synoptic, seasonal to decadal changes in the biosphere. Satellite-based observations have advanced research to quantify links between surface and deep-sea ecosystems, established fundamental interactions between the ocean and atmosphere that influence climate and impact ocean health, and provided critical data to support management and policy objectives. These and a myriad of discoveries and applications create the scientific foundation defining a course of research for the future that addresses gaps in our understanding, advances new technologies, sustains our ocean's health, and better prepares all of humanity for a Blue Economy that ensures sustained services and welfare for future generations.

This document captures a science vision for NASA's Ocean Biology and Biogeochemistry (OBB) Research Program. It details observing-system strategies and technology development needs for addressing **Grand Challenges** in the realms of the **Global Biosphere**, **Climate and the Elements of Life, Interface Habitats**, **Transient Events,** and **Leveraging Ocean Data and Models.** *All five of these **Grand Challenges** are intimately linked to climate change, through its impact on ocean life, chemistry, and physics and the need to better predict and respond to future change.* Effectively addressing the **Grand Challenges** will enable improved assessment, adaptation to, and management of Earth system change. The vision outlined herein embraces a philosophy that an integration of approaches is necessary for groundbreaking advances wherein the requisite *observing-system* encompasses satellite, airborne, *in situ* measurements (both direct field-based and autonomously sampled), and computational assets and modeling. The approach takes advantage of 'Big Data' science. Within each of the five realms of investigation, linkages are defined between advanced science questions, new observing-system requirements, and the Program of Record. The five **Grand Challenges** are then synthesized into a single overarching vision with diverse opportunities for collaboration and coordination among programs and elements of NASA's Earth Science Directorate, as well as other national and international science institutions and programs.

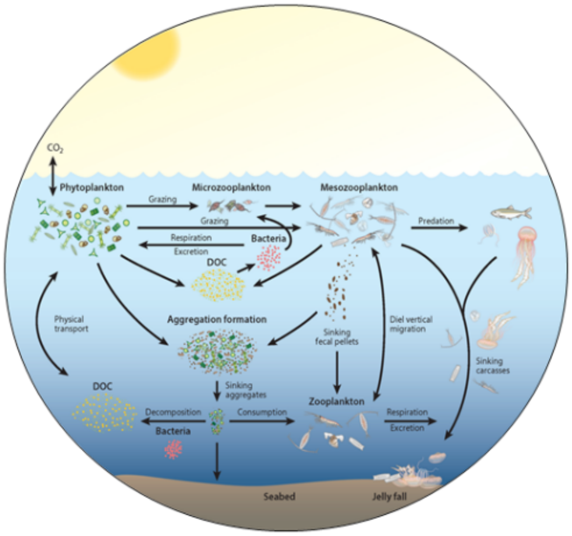
The 2007 OBB Advanced Science Plan illuminated science for over a decade of major advances in NASA's oceanographic research, resulting in groundbreaking *in situ* and remote sensing technologies, new frontiers in ocean research, and extensive collaboration and synergistic discoveries with federal, academic, private sector, and international partners. The current document presents a science vision for the next decade of research on Earth's living ocean to address issues of climate change and support sustainable management of ocean resources, which play an intimate and foundational role in the Earth system and for humanity. The science vision and opportunities outlined herein are in alignment with federal scientific priorities and with the National Academy of Sciences, Engineering, and Medicine (NASEM) Decadal Surveys, and are opportunities to inspire the next generation of explorers to result in a well-trained, interdisciplinary, climate- and biology-literate workforce. This science vision will directly impact the 21st century global economy and our Nation's role in advancing Earth system climate science that yields innovative solutions connecting exploration, discovery, and research with social science, management, and policy.

Global Biosphere

The 'living space' in Earth's biosphere is overwhelmingly dominated by the ocean, and the ecosystems that reside there are diverse, complex, highly productive, and fragile. Marine ecosystems need to be quantified and understood as the world around us changes, such that the resource and services they provide to humanity can be sustained. The diversity of ocean life is staggering, yet field observations of its biogeography and abundance are scarce. From the surface ocean to its underlying sediments, each layer of life is dependent both on its own abundance and diversity and that of the layers above and below it. Even at its upper interface, ocean life is influenced by (and influences) the overlying atmosphere. These interconnections allow inference on global ocean functioning, particularly through the conjunction of observations and coupled physical-ecological modeling. Because of the sheer magnitude of the ocean's expanse, satellite remote sensing revolutionized our understanding of marine ecosystem composition, distribution, and phenology in a manner beyond the reach of traditional field studies. They have provided observational data at spatial and temporal scales required for *global* model evaluation and development. These landmark advances have heightened awareness on the susceptibility of ocean ecosystems to change and simultaneously highlighted limitations of current observations and data analysis strategies essential for achieving robust predictions. **Challenge**: *Characterize how global ocean ecosystems will change in the future in the face of compounding stressors from natural variability, climate warming, and direct human impacts, identify which ecosystems are most vulnerable to these stressors, and quantify how changes in ocean life and biogeochemistry impact our planet as a system of systems.*

Climate and the Elements of Life

The ocean plays a dominant role in regulating Earth's climate, absorbing both anthropogenic carbon dioxide and nearly all the excess heat in the atmosphere it creates. Ocean life plays a fundamental role in this climate regulation through its interconnected cycling of greenhouse gases and other life-sustaining elements (Kwon et al. 2009; DeVries, 2022). The future role of ocean biology in climate regulation is uncertain, yet understanding this role is vital for prediction and management of climate change, the health of ocean ecosystems, and human welfare. The elements of life (carbon, oxygen, nitrogen, phosphate, iron and other microelements, etc.) constantly exchange between terrestrial, atmospheric, and surface-to-



deep sea pools (including geothermal vents and sediments). In the ocean, relentless processing of these elements by diverse marine organisms transitions them from one form of matter to another, while physical, chemical, and biological process together govern their distributions within the ocean and their residence times. Global satellite observations have had a 'game changing' impact on our understanding of elemental cycles in the ocean and associated repercussions to climate, but many fundamental aspects of ocean ecology and biogeochemistry are simply outside the realm of current and planned remotely detectable signals. Here, models must play a center stage role in our future *observing system*, providing a mechanistic framework for integrating satellite remote sensing, suborbital, and autonomous data with characterizations of phytoplankton community composition, ocean physics, biogeochemical, and climate processes. Models also will help quantify future global changes and explore different scenarios of Earth's past and future. **Challenge**: *Quantify how the role of ocean ecosystems in climate regulation and the biogeochemical cycling of elements will change in the future and what the ramifications of these changes are for the Earth's climate, the diversity of ocean life, resource sustainability, and human welfare.*

Interface Habitats

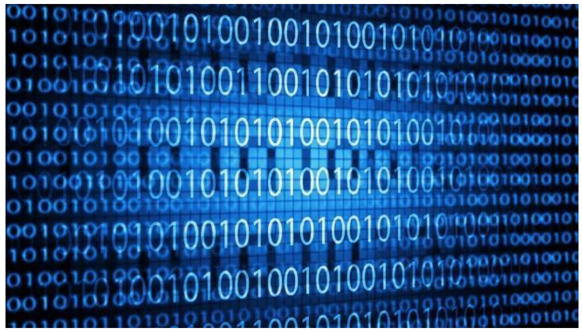
Interfaces between water and the solid Earth, soil, ice, and air represent highly dynamic spaces where physical, chemical, and biological processes are non-linear and take place across a range of temporal and spatial scales. These interface habitats host some of the most productive, diverse, and rapidly changing ecosystems on Earth. They also include areas of the ocean most closely linked to human activities. Because of this, interface habitats have experienced lasting shifts in community composition, productivity, and biodiversity resulting from climate warming (e.g., such as sea level rise) and human activities that can be proximal or occurring farther away, including inland. The reach of human impacts on interface habitats extends far beyond inhabited coastal zones and wetlands. These impacts now include ocean depositions from long-range airborne pollutants and nutrient transport, and climate change impacts on polar systems and the global water

cycle. Ensuring long-term health and vitality of such important interface habitats is essential, but the complexity of these habitats and the tempo of their variability presents unique observational and computational hurdles. In addition, understanding life processes at interface habitats on Earth can provide insight on the potentials for life on other ice-capped oceans worlds of our solar system and beyond. **Challenge**: *Establish how natural processes and human activities govern the diversity, function, and resilience of life in interface habitats such that the services and value of these dynamic systems to humanity can be safeguarded and sustained for future generations.*

Transient Events

Throughout human history, we have depended on the ocean for sustenance, transport, recreation, inspiration, and the regulation of weather and climate. In many cases, this relationship unfolds on time scales of seasons to millennia, but in other cases the link between humanity and the sea can be far more rapid. Transient events can take the form of rapid environmental changes leading to plankton blooms, ash deposition to the ocean from an erupting volcano, the passing of a hurricane, massive river outflow into the ocean, an oil spill, marine heat waves, or a myriad of other forms. Despite their transient nature, such events can have disproportionate impacts on ecosystems and human communities, and the frequency of these events may be increasing in parallel with the human population and with climate change. The unexpected nature of transient events, which are often localized, demands a unique and even mobile observational approach coupled to advanced modeling and prediction capabilities. Here, high spatial and temporal resolution satellite and suborbital assets may be particularly appropriate and, in the case of threats to humanity, enable targeted rapid response and monitoring for decision making by stakeholders and emergency workers. Extreme events happen and can evolve quickly, with impacts on aquatic ecosystems and human infrastructure. Observations enabling prediction and protection from threatening events are of national and international economic worth. **Challenge**: *Develop the knowledge base and infrastructure to detect, quantify, predict, and understand marine responses to transient events to enable preparation, mitigation, and recovery when these events affect communities.*

Leveraging Ocean Data and Models



A human genome contains around 3 billion DNA base pairs. How many 'base pairs' of information would we need to fully elucidate the functioning of life on Earth? The number is astronomical. Sources of data being collected to understand our planet include genomics, autonomous platforms, satellites, and global models. The rate of data flow rises exponentially every year. Collecting 'Big Data' is central to NASA's Earth Science programs, but equally important is investment in the infrastructure and workforce necessary to convert such data into new understanding and actionable science and applications. High Performance Computing, Artificial Intelligence and Machine Learning are all elements in the conversion of data to knowledge, filling gaps in knowledge and understanding and linking observations across vastly different scales. As the challenge of Big Data evolves, so too must our philosophy on data management and access. We need to be able to develop more complex and interactive models and be ready to handle, integrate, synthesize, and disseminate large global data volumes to understand life on Earth and to detail the impacts of climate change. We need to enable better management and decision support, integrate data-driven insights with mechanistic experiments and models, and connect exploration of the ocean with national economics. Investments are needed today to create large, regionally interconnected facilities that serve, manage, and share petabyte to exabyte data volumes and that support networks of researchers and professionals across disciplines. These investments will link communities of oceanographers with computational scientists and cyberinfrastructure professionals, working together to address basic questions and applied problems. **Challenge**: *Leverage advanced data harmonization, interoperability, synthesis, integration, and mining strategies and train next-generation scientists to maximize the value of satellite, suborbital, and modeled data streams to facilitate better understanding of life, ocean biogeochemistry, ecosystems, and their dynamic processes.*

The Bottom Line

Humanity depends on ocean ecosystems and the many functions they perform from local to global scales. Some marine ecosystems play a disproportionately large role in biogeochemistry, some support our largest fisheries, while others are particularly efficient at removing excess nutrients at land-ocean interfaces and greenhouse gases at the ocean-atmosphere interface. While fully quantifying the value of our ocean systems to humanity is impossible, as it would require assigning values to intangibles and non-market products such as climate regulation, carbon storage, global temperature, and human culture and lifestyle, assessments have been made of the ocean's global annual 'gross marine product' with respect to marketed goods and services. Even for this limited scope of benefits, estimates are on the order of a staggering >$2 trillion US dollars per year, with a total 'asset base' of at least $20 trillion US dollars (Hoegh-Guldberg et al. 2015). Climate change impacts on ocean physical and chemical properties cause additional wide-ranging ecosystem responses, including frequent harmful algal blooms, altered ocean plant growth, and reduction of fish stocks that, in many cases, are already either fully exploited or overexploited. These diverse climate change effects, along with other human impacts such as nutrient and plastics pollution, threaten foundations of marine food webs, putting whole ecosystems – and those who rely on them for food and jobs – at risk. In addition, humanity is now looking toward the global ocean for potential solutions to rising atmospheric CO_2 concentrations and consequent climate warming. Carbon Dioxide Reductions (CDR) schemes are being developed and discussed. If enacted, such intentional manipulations of the ocean add another dimension to ecosystem change that requires advanced observing systems to detect and quantify. For all these sources of stress and change, alterations in ecosystem composition and productivity will impact function, and function determines the human goods and services provided by the ocean. Understanding these dimensions of ecosystem change and function require an advanced set of future observing systems and a diverse next-generation workforce to create an informed understanding of our living ocean and to ensure its protection, recovery, and health in a sustainable Blue Economy.

2. Standing on Shoulders of Giants

This document is a forward-looking science vision for the NASA OBB program and identifies opportunities for groundbreaking advances in ocean science, applications, and management. The advanced 'observing system' envisioned herein builds upon decades of heritage satellite missions and *opportunities mentioned in subsequent sections presume that currently planned missions in the Program of Record will be successfully completed and that equivalent or improved observing capabilities will be sustained thereafter*. Here we provide a brief synopsis of key missions in the Program of Record most relevant to OBB's research objectives. Subsequent sections of this document largely focus on future opportunities for the OBB Program above and beyond this baseline.

Systematic remote sensing of ocean color from space began with the launch of the Coastal Zone Color Scanner (CZCS) in 1978 (see McClain 2009 and McClain et al. 2022 for reviews of ocean color history). This sensor provided a first glimpse of what ocean color instruments could provide by generating a time-series of data at selected scenes. NASA subsequently launched the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) in 1997 that provided the first decade-long climate-quality imagery of the complete global ocean. Follow-on satellite ocean color instruments included the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua, and the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi-National Polar-orbiting Partnership (SNPP) and NOAA-20 platforms. Over a period now exceeding three decades, data from these satellite sensors along with similar international ocean color missions, coupled with *in situ* observations and numerical models, revolutionized our understanding of ocean processes, their complexity, and their interactions with other parts of the Earth system. These heritage missions also established fundamental guidelines for maintaining ocean color data of sufficient quality into the future to reliably detect temporal trends and spatial changes (National Research Council, 2011).

Continuous observation of ocean color is recognized as essential to satisfy operational, research, and societal needs. The [Global Ocean Observing System] and [Global Climate Observing System] have identified ocean color as an Essential Ocean and Climate Variable that supports monitoring of ocean health, fisheries, and other aspects of marine ecosystems and climate. To this end, an additional VIIRS instrument is included as part of the NOAA-NASA Joint Polar Satellite System (JPSS)-2 mission, as well as on future JPSS-3 and -4 missions in the 2028-2032 timeframe. VIIRS instruments, however, lack the radiometric quality and spectral coverage to enable advanced ocean science, including assessment of phytoplankton health through chlorophyll fluorescence monitoring, red-edge reflectance measurements for quantifying large plankton blooms, characterization of phytoplankton community composition, and the ability to distinguish living phytoplankton from detritus and colored dissolved organic matter (CDOM), particularly in coastal zones. Recognizing these limitations and to provide an observational record for scientific growth, NASA is executing, as part of the Program of Record, the Plankton, the Aerosol, Cloud, ocean

Ecosystem (PACE) Mission planned for launch in early 2024. PACE will deliver the most globally comprehensive, high quality, ultraviolet-to-shortwave infrared hyperspectral data set to date, along with global polarimetry measurements, for investigating Earth's integrated aquatic and atmosphere systems.

NASA has also recognized the fundamental importance of observing key short-timescale processes in aquatic ecosystems. Accordingly, it has included in the Program of Record the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR). GLIMR, scheduled to launch no earlier than 2026, is a high spatial resolution (300 m) ultraviolet-to-shortwave infrared hyperspectral sensor focusing on the Gulf of Mexico, southeastern United States coastline, and Amazon River plume. GLIMR adds to other international geostationary satellite missions viewing other regions of the global ocean. Sustaining geostationary GLIMR-equivalent measurements of ocean properties along both the east and west coasts of North America is the objective of the NOAA-NASA Geostationary Extended Observations (GeoXO) satellite system (https://www.nesdis.noaa.gov/GeoXO). The GeoXO mission represents a follow-on to the NOAA-NASA Geostationary Operational Environmental Satellite (GOES) Program that is expected to be enhanced with GLIMR-like instruments for the geostationary measurement of ocean color in the 2030-to-2040 timeframe. In addition to enhanced temporal resolution observations, many near-shore studies require finer spatial resolution data. Here, Landsat measurements have been particularly impactful, providing multispectral data at ~30-meter resolution since 1984. NASA's upcoming Surface Biology and Geology (SBG) mission will build upon this historic record.

Significant advances have also been made in active remote sensing utilizing lidar systems, which can complement passive, global ocean color missions. Most notably, CALIOP, which was designed for atmospheric science applications, has successfully been used as a proof-of-concept that ocean ecosystem properties can be measured with a space-based lidar (Behrenfeld et al. 2013, 2017, 2019, Churnside et al. 2013, Lu et al. 2016, 2021a,b, Bisson et al. 2021a,b). Additional ocean retrievals with a satellite lidar have also been conducted using the ICESat-2 sensor (e.g., Lu et al. 2020). These successes have demonstrated the value of satellite lidar measurements for advanced understanding of global ocean ecosystems and have established a >15-year baseline record of active ocean retrievals on which future ocean lidar mission can build.

3. Grand Challenges: Paths Forward

3.1 Global Biosphere

Characterize how global ocean ecosystems will change in the future in the face of compounding stressors from natural variability, climate warming, and direct human impacts, identify which ecosystems are most vulnerable to these stressors, and quantify how changes in ocean life and biogeochemistry impact our planet as a system of systems.

The health and productivity of ocean ecosystems are inextricably linked to the wellbeing of all life on Earth. Ocean ecosystems are changing around the world. Human activities are a major driver of this change. We need a quantitative understanding across the global ocean of key linkages between ocean ecosystem functioning and environmental forcing to reliably predict future change, enable effective ecosystem management, and safeguard the societal benefits of these ecosystems for generations to come.

Diversity of algal and animal communities and overall photosynthetic production are primary determinants of ocean ecosystem function. These key attributes are not independent, as highly productive systems tend to support communities with fewer trophic links between algae and apex consumers (e.g., fish, humans) than less productive ecosystems. In all cases, the structure, function, persistence, and resilience of aquatic ecosystems are intimately tied to variations in the physical-chemical environment. Mechanistically linking environmental disturbances to ecosystem responses remains a significant challenge, yet it is at the heart of robust predictions of future change.

The satellite ocean color era has had a profound impact on our understanding of global ocean ecosystems and their susceptibility to climate variations. These observations have provided unprecedented documentation of surface phytoplankton distributions and biodiversity (Alvain et al. 2005, Bracher et al. 2017), seasonal to interannual variability (Friedland et al. 2018), and insights on phytoplankton physiology (Behrenfeld et al. 2009, 2016; Kulk et al. 2020; Westberry et al. 2008, 2013) and biological responses to changes in ocean physical processes, including long-term trends (Behrenfeld et al. 2006; Henson et al. 2010; Mélin 2016; Gregg and Rousseaux 2019, Balch et al. 2022). Among many other accomplishments, the ocean color record has enabled significant improvements in global ocean productivity assessments (Silsbe et al. 2016), provided key insights on phytoplankton bloom dynamics and predator-prey relationships (Behrenfeld & Boss 2018), created an observational foundation for quantifying biological carbon sequestration (Siegel et al. 2014, 2021, 2022; Nowicki et al. 2022, DeVries & Weber 2017), and yielded observational data greatly improving numerical simulations of the global biosphere (Dutkiewicz et al. 2020; Gregg et al. 2017). Significant additional advances will be achieved with the upcoming PACE mission

(Werdell et al. 2019), which will provide new insights into phytoplankton biodiversity and productivity with coupled hyperspectral and polarization measurements across the global ocean. As described in **SECTION 2**, continuity of ocean color observations into the future is essential and a foundation upon which the advanced observing system described in the document is built. However, despite its resounding successes and future potentials, the passive satellite ocean color technique alone is inadequate for addressing the **Global Biosphere** science and applications challenges facing us in the coming decade and beyond. Meeting these new challenges requires a paradigm shift adopting a multifaceted *observing system* approach along with modelling activities.

A fundamental limitation of passive ocean color remote sensing is that it only detects signatures of plankton communities very near the ocean surface. But ocean ecosystems are three-dimensional entities evolving in time, with significant features below the surface that are known from routine ship-based, time-series, and BGC-Argo float measurements [e.g., Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program]. Communities at each depth-layer depend on and exchange materials with layers above and below them. These exchanges are facilitated by physical processes, dependent on community composition, and are a fundamental element defining how a given ecosystem responds to stressors. However, *in situ* measurements of depth-dependent plankton distributions remain sparse, so numerical models have been our primary tool for extrapolating measured surface properties to the three-dimensional ocean world. Without global observational constraints to inform and test these simulations, large uncertainties remain regarding contemporary ocean functioning and prediction of future change. In addition, the vertical distribution of many marine organisms changes between day and night. These movements are referred to as the diel vertical migration and they occur throughout the global ocean (Bianchi et al. 2013, Bianchi & Mislan 2016). Migrating animals, from zooplankton to fishes, vary in size and most of them spend the day light hours at depth and only come to the surface at night to feed. The diel migration is crucial for carbon export (Steinberg & Landry 2017), vital to fisheries, and the depth-dependent exchange of materials (~2 Pg C y^{-1}), but measurements of this migration are beyond the scope of passive ocean color measurements and significant discrepancies currently exist in estimates of its global spatial patterns (e.g., Bianchi et al. 2016, Aumont et al. 2018, Archibald et al. 2019, Behrenfeld et al. 2019). Complementing PACE and its equivalent follow-on missions with global day and night observations of plankton properties and vertical distributions and upper ocean physical properties (e.g., active mixing depth, stratification strength) will vastly improve our understanding of mechanisms structuring plankton stocks, vertical migrations, materials transfer within and below the sunlit surface layer, and the depth-dependent distribution of plankton stocks and production rates. This improvement will enable robust, process-based interpretations of observed changes in the **Global Biosphere** and, accordingly, improved predictions of future change. Achieving these objectives not only requires new observations, but also interdisciplinary collaboration of the science community to optimize the utility of new and traditional observations for Earth system modeling.

Plankton are an incredibly diverse group of organisms spanning bacteria, autotrophs, mixotrophs, and heterotrophs. Even within these trophic categories, there is a huge range of taxa that span several orders of magnitude in sizes and serve distinctly different biogeochemical and ecological functions. Differentiating different groups of organisms (e.g., diatoms and cyanobacteria) or size classes using heritage ocean color sensors has been a major thrust of research (IOCCG report 15, 2015), but remains a difficult task given the limited wavebands available, the sparsity of *in situ* data for verification, and a significant degree of autocorrelation between measurement wavelengths that prevents derived products from being truly independent (Bracher et al. 2017; Mouw et al. 2017, Cael et al. 2020, Kramer & Siegel 2019). In particular, the development of methods to identify specific species or plankton groups from remote sensing has been seriously hampered by the lack of *in situ* measurements of diverse communities (Lange et al. 2020; Dierssen et al. 2020; Kramer et al. 2022). PACE and subsequent hyperspectral remote sensing instruments will considerably improve assessments of diversity in surface phytoplankton communities, but fully understanding plankton ecosystems requires knowledge of their 3-dimensional structuring in the water column and how this structure changes with time.

Ocean color retrievals require sunlight, cloud-free conditions, and low atmospheric aerosol levels and, consequently, persistent data gaps exist for large ocean areas over extended periods where these conditions are not met. Polar and other high-latitude regions, as well as temperate upwelling systems, are particularly problematic in this respect, yet these regions are experiencing some of the most dramatic impacts of climate warming (Babin & Forget 2015). Indeed, polar night and persistent clouds can leave the entire north and south polar regions without any ocean color data for months. Unfortunately, dimly lit winter months of the polar seas are crucial in the development of the annual plankton cycle, setting the stage for blooms to come. In these regions, new observations of plankton properties and ocean physical properties at the surface and through the water column are needed that overcome limitations of the ocean color approach. Active remote sensing technologies may provide an approach for addressing this need. Such measurements could provide sustained records of ecosystem development throughout the annual cycle and links to their physical growth environment. Such data would be instrumental for quantifying changes in plankton stocks, understanding the ecological and physical factors governing these changes, and assessing their implications for carbon cycling and the productivity of fisheries that are amongst the largest in the global ocean.

Finally, it is desirable across all arenas of science to have independent, similarly scaled assessments of a common property to allow validation of derived properties and assessment of uncertainties in scientific conclusions. Historically, *there has simply been no independent data sources suitable for evaluating ocean color derived properties across the global ocean*.

Consequently, ocean color data have been validated using sparse, point-source field measurements, leaving significant potential for undetected large-scale biases in the satellite record. New global observations are needed that can be used to independently verify ocean ecosystem properties retrieved using ocean color data. Quantifying changes in the ocean biosphere requires robust assessments of sensor and algorithm uncertainties (IOCCG 2019)

Addressing the Global Biosphere challenge

NASA's satellite ocean color record has provided a phenomenal, *but 2-dimensional*, view of our global ocean biosphere. To address the **Global Biosphere** grand challenge, an area of opportunity is the *creation of an observing and modeling system allowing a 4-dimensional (3 spatial dimensions + temporal dimension) reconstruction and interpretation of global ocean ecosystems*. The first element of this vision is *ensuring an uninterrupted time-series of PACE-equivalent observations overlapping with previous missions*. Continuity of these heritage measurements is essential because modelling studies show that the time span of a record needed for robust trend detection (e.g., climate change impacts) is decades (Henson et al. 2010, Coles et al, 2012, Dutkiewicz et al., 2019) and is significantly lengthened if there are interruptions in that record. Moreover, advancements are needed to develop and refine algorithms to quantify the composition, abundance, distribution, and phenology of phytoplankton across the global surface ocean. Accurate assessments of the fractional composition of micro-, macro-, pico-sized phytoplankton (including cyanobacteria) and endosymbiotic algae across vast ocean provinces are foundational to understanding and modeling present and future changes to ocean ecosystems, along with information on functional types (e.g., calcifiers, silicifiers, nitrogen fixers). *An essential component of the **Global Biosphere** grand challenge will be to provide comprehensive, efficient, and effective laboratory and field programs to supply data for development and validation of algorithms to assess global phytoplankton community composition from remote sensing.*

As detailed below, the second key element for addressing the **Global Biosphere** grand challenge is coupling the sustained PACE-equivalent observations with new satellite technology, autonomous and ship-based *in situ* measurement, field process studies, and modeling. This integrated system will extend our understanding of the global ocean biosphere beyond the detection depth of passive ocean color imagery. These new opportunities are organized below into four overarching topics: (1) Plankton Communities in '4-D', (2) Observations in challenging regimes, (3) Mixing and stratification, and (4) Integrated global biosphere observing systems.

Plankton Communities in '4-D'

A particularly important addition to NASA's global ocean satellite observing portfolio that will enable depth-dependent quantification of plankton properties is an advanced satellite lidar system that builds upon the 'proof-of-concept' success achieved with CALIOP (see ***Section 2***). Although not designed for optimal ocean sensing, CALIOP demonstrated the capability of ocean observing with a space-based lidar and has yielded significant scientific results (Hostetler et al, 2018) including quantification of global ocean plankton stocks (Behrenfeld et al. 2013), detection of decadal-scale trends in polar ecosystems (Behrenfeld et al. 2017), and characterization of global patterns in diel vertical animal migrations

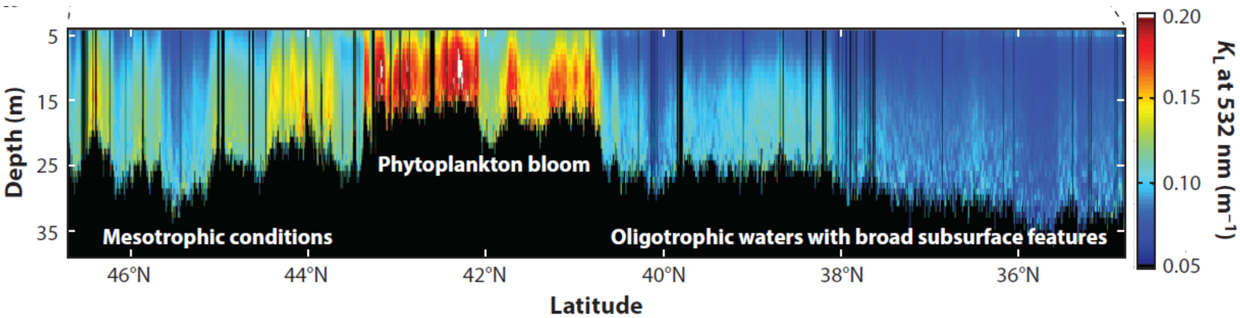


Figure 3.1-1: Example lidar 'curtain' of plankton vertical distribution measured with an airborne system during a flight track along the US eastern seaboard. K_L = lidar attenuation coefficient. (from Hostetler et al. 2018)

(Behrenfeld et al. 2019). A future ocean-optimized satellite lidar will enable more accurate and depth-resolved plankton observations. The ability to characterize depth-profiles of plankton communities with a lidar has been extensively demonstrated using airborne systems (Figure 3.1-1) and studies have shown that current space-qualified technologies can do so at meter-scale vertical resolution, with retrievals extending beyond 2.5 optical depths for a standard 532 nm emitting NdYAG laser (Hostetler et al. 2018).

For the above **Global Biosphere** observing system, we envision global coverage of vertically resolved subsurface lidar 'curtains', such as in Fig 3.1-1, but extended throughout the sunlit photic layer (~4.5 optical depths) with a blue-emitting laser. An additional desired capability for an ocean-optimized lidar is an ability to directly separate in-water scattering and attenuation.[1] One specific and highly mature example of such a technology is the High Spectral Resolution Lidar technique (HSRL). An HSRL lidar separates particulate and molecular signals by employing an additional filtered channel. This addition enables direct, independent, and calibrated measurements of particulate backscatter and attenuation and

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[1] While CALIOP bridged the critical gap between ground-based and space-based technology demonstration for ocean lidar, it provides only a simple elastic backscatter measurement that creates an 'ill-posed' problem with respect to ocean ecosystem retrievals (Hostetler et al. 2018). Specifically, the single directly measured property is dependent on both in-water backscattering and attenuation: i.e., one measurement, two unknowns. Accordingly, additional assumptions are required to isolate the signals of interest. A solution to this problem is to employ an advanced technology that enables direct separation of attenuation and scattering: i.e., a 'well posed' problem of two measurements for two unknowns (Hostetler et al. 2018). One approach is the High Spectral Resolution Lidar technique (HSRL), but other technological approaches to achieve the same ends may exist.

simultaneously improves the specification of particulate depolarization. Accurate, meter-scale vertical resolution plankton profiling with an airborne HSRL has been extensively demonstrated in the field [e.g., SABOR, NAAMES, Azores 2012 (Behrenfeld et al. 2013)]. Accordingly, a key addition to the ocean satellite missions currently in the Program of Record necessary to address the **Global Biosphere** grand challenge is *a baseline HSRL (or equivalent) instrument with a blue-emitting laser and polarized and depolarized channels* (see **SECTION 5** for addition technical specifications). Algorithm development will also be needed to ensure best use of the lidar data and for 'filling-in' both below and between lidar 'curtains' to achieve the desired 4-dimensional reconstruction of global ocean ecosystems. In addition to providing new information, a profiling lidar provides an independent global dataset to assess ocean color algorithms and uncertainties from passive satellite sensors (this cannot be done with other simultaneous passive missions as they are processed similarly). For example, CALIOP data revealed a previously unrecognized seasonal bias in ocean color products that can regionally exceed 40%, that impacts retrievals across all heritage NASA ocean color sensors and has been corroborated by available in-situ data (Bisson et al. 2021b). *Continuation of the global satellite lidar ocean record and expanding lidar capabilities for more accurate and vertically resolved retrievals of both particulate backscattering and absorption coefficients will thus be essential for addressing the **Global Biosphere** grand challenge*.

In support of the foundational ocean lidar satellite measurements, *an essential additional component of the observing system for the **Global Biosphere** grand challenge is suborbital observations from autonomously-profiling floats and airborne measurements*. These suborbital assets allow ground-based validation of satellite retrievals and model predictions, provide an essential linkage between *in situ* and satellite retrieval scales, and enable extension of observations to depths beyond those conceivably sampled from space (Haentjens et al. 2017; Claustre et al. 2020; Bisson et al. 2019; Dierssen et al. 2021; Behrenfeld et al. 2019; Siegel et al 2022). The envisioned observing system additionally relies on a sustained diversity of ancillary data sets characterizing key attributes of the surface-to-mesopelagic horizon, including physical mixing processes, ocean currents and mesoscale features, and sea-surface temperature, to name a few. *Process studies and ship-based surveys are also fundamentally important for linking new satellite observables to key ecological phenomena*, such as lidar-detected diel vertical animal migrations and multi-asset assessments of 4-D plankton biodiversity.

Developing the optimum 4-dimensional characterization of plankton stocks and movements for the **Global Biosphere** grand challenge will require extensive use of numerical models. A challenge here is in matching model entities with those that are directly observed. To incorporate the types of data provided by passive ocean color sensors, lidar 'curtains', and *in situ* measurements, *models need to be developed. These simulators should include optical characteristics of the ocean, including apparent (e.g., reflectance and diffuse attenuation) and inherent (e.g., absorption and scattering) optical properties as they are observed, following the paradigm of other modeling communities (e.g., the cloud ISCCP simulator)*. It would also be advantageous to include radiative transfer modules in these models to more closely link modeled products with ocean color products, such as water leaving radiances. Advanced models can be used for process studies to help understand observed phenomena, in hindcast mode to understand the natural variability at a range of timescales, and in future climate change scenarios to reveal potential changes to the **Global Biosphere**. Models can also help in designing sampling strategies and interpreting data from observational campaigns to ensure that the most relevant sites are sampled and to develop understanding for the spatiotemporal scales that individual measurements represent. Many types of numerical models can help address this challenge, from hindcast models investigating spatial and temporal sampling scales of the modern ocean (e.g., Kuhn et al., 2019) to climate change models exploring the timescales over which we detect trends (e.g., Henson et al., 2010; Dutkiewicz et al., 2019). Observing System Simulation Experiments (OSSEs) are a general category of modeling approaches that enable evaluation and design improvement of new observations and observational strategies. Concerted efforts to develop OSSEs in the climate community are already underway (e.g., at NASA/GMAO; Errico et al., 2013) and *it is of the utmost importance for the continued use of OSSEs as a key part of the new observing techniques, including lidar and AUVs*.

The 4-dimensional ocean ecosystem reconstruction goal of the **Global Biosphere** grand challenge can be expanded to include characterization of plankton community diversity. Because taxonomic information is difficult to determine through remote sensing, this expanded objective will necessitate sustained field observations detailing plankton functional types and size distributions, along with technology development allowing autonomous optical characterization of community composition. Current field approaches combine measurements from distinct instruments (e.g., flow-cytometry, FlowCytobot, FlowCam, LISST, and Underwater Vision Profiler) that span the plankton size domain. New information developments are needed to automate the seamless merging of such data and technological developments are needed to improve spatial and temporal *in situ* data coverage. Such advances in optical measurements, together with pigment data and the increasingly abundant 'omics' data (i.e., genomics, transcriptomics, proteomics, metabolomics, etc.), will be crucial for interpreting advanced ocean color (e.g., PACE) and lidar data in terms of spatially extensive 3-dimensional views of the plankton community structure over time. *Models specifically targeting marine ecology should be expanded to include increased diversity, size structuring, bacterial communities, trophic interactions, and diel vertical migrations.* Currently, most models (e.g., Séférian et al. 2020; Laufkotter et al. 2015, Gregg & Casey 2006, Fujii et al. 2007) include only a handful of representative groups, such as small and large phytoplankton, have minimal complexity of trophic interactions, and rarely consider vertical migration. Advances in modeling to include additional diversity (e.g., Ward et al, 2012; Dutkiewicz et al, 2020) and processes will support synthesis of disparate field observations, enable assessments on the importance of diversity in plankton communities and interactions within and across trophic levels, and provide 'laboratories' to explore potential changes to communities with climate change (Henson et al. 2010).

Observations in Challenging Regions

As noted above, a limitation of ocean color retrievals is their restriction to sunlit, cloud-free conditions, which yields large gaps in data coverage in particular regions and over extended periods. Polar systems are experiencing some of the most drastic and rapid alterations from climate warming and are in the spotlight of the **Global Biosphere** grand challenge, yet ocean color retrievals by current and planned sensors are limited in these regions due to persistent cloud cover, presence of sea ice, and extended dark periods during winter months (Fig 3.1-2, left panel) (Babin & Forget 2015). Here too, the advantage of pairing satellite lidar measurements with ocean color has been demonstrated using CALIOP (Behrenfeld et al. 2017), where lidar data collected between cloud gaps and during polar night greatly enhance coverage of polar plankton biomass, extending right up to the ice edge (Figure 3.1-2, right panel). Similarly, lidar measurements improve ocean retrieval coverage in other persistently cloudy regions of the global ocean (e.g., temperate upwelling zones). Thus, *an advanced ocean-optimized satellite lidar is a highest-priority addition to the global observing system and will yield new insights on ocean regions and times where clouds, aerosols, and sunlight conditions compromise the traditional ocean color approach*, in addition to the value of this technology for characterizing plankton depth-dependent structuring, as noted above. *Significant investment in BGC-Argo and other autonomous platform measurements will also be essential*, especially those platforms that can operate in polar regions around and under sea ice (Ardyna et al. 2020). To support this multi-faceted observing system*, continued studies are needed to improve synthesis of different data streams (e.g., Lidar, BGC-Argo, in-water optical) and enable more sophisticated visualization of the global ocean biosphere*. This need for improved synthesis and visualization capabilities applies across the other grand challenges as well and is discussed in detail in **SECTION 3.5**.

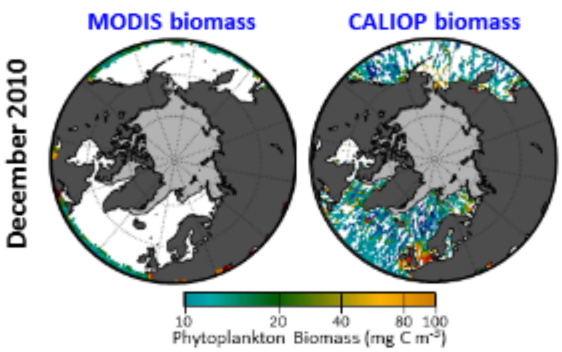


Figure 3.1-2: Phytoplankton biomass observations from (left) MODIS and (right) CALIOP poleward of 45ºN (white = no data) for December 2010 . Gray shading = ice cover. (from Behrenfeld et al. 2017)

Mixing and Stratification

The water column structuring of plankton communities and their temporal dynamics in part reflect ecological production-loss balances, but they are also strongly influenced by physical mixing and stratification. Across nearly all the open ocean, the surface-most layer is well mixed due to air-sea exchanges of buoyancy and momentum. Within this actively mixed zone, the vertical distribution of physical, chemical, and biological variables is usually uniform. Immediately below this active mixing layer (AML), these water column properties may or may not change depending on the recent history of mixing and ecological processes, but persistent deep chlorophyll maximum features are commonly observed in the tropical and subtropical ocean. Distinct water column features in density (i.e., stratification) are typically found at the base of the seasonal mixed layer (SML), which can vary spatially from several meters to many 100's of meters, with strong gradients in chemical and biological properties observed below the SML.

Knowledge of the active mixing depth, the SML, and the degree of stratification are all highly relevant to our understanding of the **Global Biosphere** and its evolution in time. For example, phytoplankton have a characteristic timescale for photoacclimation that is like or shorter than that for changes in the AML. This photoacclimation response includes an adjustment in cellular pigment concentrations in response to the median light level of the AML and must be accounted for to accurately assess ocean primary production rates (Westberry et al. 2008, Silsbe et al. 2016), interpret observed changes surface plankton properties with respect to climate variability (Behrenfeld et al., 2008, 2015), and quantify air-sea gas exchange. Understanding variations in the SML is likewise vitally important, as these changes influence plankton bloom dynamics (Behrenfeld 2010, 2014, Behrenfeld & Boss 2018), time-averaged exchanges of heat and momentum, carbon biogeochemistry (Dall'Olmo et al. 2016), and the distribution of evolved plankton ecotypes within the water column. Characterizing the strength of stratification at the SML horizon is important, since this layer 1) creates a physical barrier for materials exchange (e.g., organic material, nutrients) between surface layer populations and communities deeper in the photic layer, 2) defines energy requirements for mixed layer deepening, and 3) is expected to face further intensification due to climate warming.

Accurate, time-resolved global assessments of surface ocean mixing properties are clearly of high importance for addressing the **Global Biosphere** grand challenge, as well as the **Climate and the Elements of Life** (see **SECTION 3.2**). Today, these global data sets are provided by integrating physical ocean circulation models, satellite data [surface wind speed, surface topography (e.g., TOPEX/Poseidon)], and available *in situ* data (e.g., ARGO), but these latter data are of limited spatial and temporal coverage (Figure 3.1-3). *Validation of these contemporary products is challenging and would benefit greatly if approaches were identified for globally characterizing surface mixing properties directly from satellite remote sensing*. This opportunity may in part be addressed by the ocean-optimized profiling lidar described above. Specifically, this instrument will provide meter-scale vertical resolution

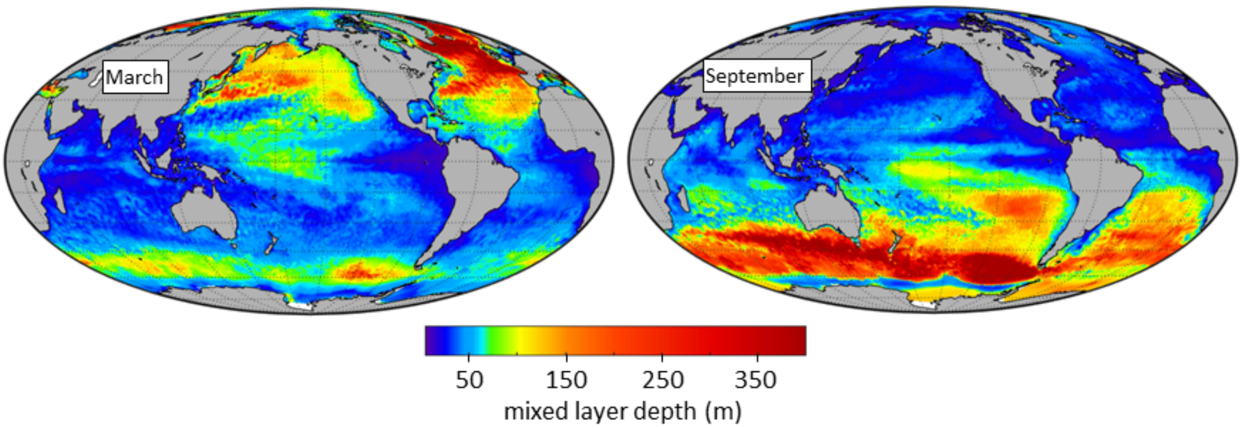


Figure 3.1-3: Example global seasonal mixed layer (SML) depths for March (left) and September (right) based on the data-assimilating HYCOM model, where SML is defined as the depth where the water density (sigma-theta) is 0.125 kg m^{-3} greater than found at a reference depth of 10 meters.

retrievals of particulate backscattering and attenuation coefficients, where the depth at which these properties first deviate from near-surface values can provide an estimate of surface mixing. A challenge here is that this biologically defined horizon may correspond to either the AML or SML (Zawada et al., 2003). In addition, this approach is susceptible to ecological processes giving rise to short-lived vertical features independent of physical mixing and it is unlikely to provide information on the strength of stratification. Alternative approaches should therefore also be investigated. For example, laser emission/excitation spectroscopy could be developed to determine upper ocean concentrations of rapidly evolving photochemical species. By knowing the light driven kinetics of a given chemical species and examining differences in its concentrations at different times of day, estimates of the SML may be derived. Active approaches may also be considered that allow detection of depth-dependent changes in water density, with the benefit here being the potential to assess stratification strength. Given the importance of upper ocean mixing properties to the grand challenges articulated herein, investment into technology design studies is clearly warranted.

Integrated Global Biosphere Observing System

Four-dimensional, pole-to-pole reconstructions of ocean ecosystems that extend from the air-sea interface through the mesopelagic can only be accomplished through an integrated observing system that entails satellite remote sensing, *in situ* observations, and modeling. A particularly important element in synthesizing ocean-observing data to achieve science objectives is their assimilation in models. Data assimilation refers to a collection of techniques where observations that are discrete in space and time are ingested into a modeling framework, such that the modeled state is forced to match observations to the extent possible, using algorithms to minimize a misfit cost function. There are several techniques that can be used for state estimation (e.g., 3DVar, 4Dvar, Ensemble Kalman filter, etc.). Data assimilation has been widely used and is relatively mature in physical oceanography, but biogeochemical data assimilation faces several unique challenges. Biogeochemical and ecological models employ representations of the sources and sinks of different constituents with varying degree of complexity. As discussed above, an avenue for improvement with respect to the **Global Biosphere** grand challenge is to include model variables directly linked to measured properties (e.g., spectral ocean reflectance or water-leaving radiance, particle backscattering, absorption). Studies suggest that assimilation of measured, rather than more derived, products (e.g., chlorophyll concentration), can provide an improved state estimate of ecosystem structure (e.g., Baird et al., 2015; Jones et al., 2017, Ciavatta et al, 2011). *Thus, investment in model development and data assimilation advancement with models that include spectral optical characterization and radiative transfer models is necessary*.

Developing a multi-faceted observing system to characterize the 3-dimensional spatial structure of planktonic communities, their diversity, and vertical migration, and synthesizing these data with sophisticated assimilation models is a significant undertaking and a major part of the **Global Biosphere** grand challenge. However, the challenge goes further in asking how global ocean ecosystems will change in the future and how these changes will impact our planet as a system of systems. Rising to this broader challenge, we need to understand the mechanisms controlling distributions of standing stocks, rates, and biodiversity. This understanding will allow us to make more accurate predictions and, potentially, mitigate **Global Biosphere** changes. *Of utmost importance will be field process studies and ship survey measurements linked closely with satellite measurements and observations considering the 3-dimensionality of the system, with the process studies targeting regions and mechanisms central to the interpretation of remote observing system data*.

Bottom-up (e.g., nutrients, light) and top-down (e.g., predators/grazers, viruses) mechanisms control plankton diversity and play a vital role in plankton bloom dynamics, nutrient recycling, and materials export potential (see **SECTION 3.2**). One approach to quantifying top-down factors is through satellite-observed differences between temporal changes in phytoplankton stocks and their growth rates (Behrenfeld et al. 2010, 2018). Hyperspectral PACE ocean color measurements will provide an important new avenue for improving characterizations of plankton community composition and environmental stressors (via chlorophyll fluorescence and phytoplankton chlorophyll-to-carbon ratios) (Werdell et al. 2019), but additional approaches are needed to better address trophic and non-trophic interactions through remote sensing and field observations encompassing a spectrum of organisms ranging from zooplankton to bacteria and viruses. *The use of models as an integral component of the observing system will be essential to aid in the interpretation of measurement data.* Of particular importance is advancing ecosystem models of the polar regions. To this end, the observing system envisioned herein will provide critical information on plankton depth distributions in under-observed locations that will be crucial for new model parameterizations and evaluation. Integration of these advanced marine ecosystem models into Earth system models (i.e., that include atmospheric, terrestrial, and ice components – e.g., Coupled Model Intercomparison Projects) will provide important insights on Earth system functioning.

Global Biosphere Summary

Global ocean ecosystems are faced with compounding stressors from natural variability, climate warming, and direct human impacts. Measured changes in today's ocean ecosystems provide key insights on potential changes for the future and their implications for the biosphere.

Areas of opportunity within the **Global Biosphere** grand challenge include:

1) Sustain and refine PACE-equivalent ocean color imagery to quantify global phytoplankton composition, abundance, distribution and phenology and associated uncertainty with new field measurement technology and algorithms (continued).
2) Enhance NASA's global ocean satellite observing portfolio to include an ocean-optimized lidar providing vertically-resolved retrievals through the sunlit surface layer to address key science issues beyond the capabilities of traditional ocean color sensing (immediate/near-term).
3) Develop technologies to directly assess surface ocean mixing properties and stratification through remote sensing (near-term/long-term).
4) Target a 4-dimensional reconstruction of ocean ecosystems by integrating time-resolved satellite remote sensing (1, 2) with sustained autonomous profiling measurements, airborne campaigns, and ship-based measurements (near-term/long-term).
5) Invest in model development and data assimilation, including models that link directly to satellite measured properties, such as reflectance and inherent and apparent optical properties (continued).
6) Develop technologies and expand 3-dimensional global ocean field characterizations and develop models of the diversity of pico-, nano-, micro-, macro-, and endosymbiotic algae and cyanobacteria, as well as the size and functional roles of these organisms in ocean ecosystem models (continued).
7) Support research to synthesize disparate observing system data (e.g., ocean color, lidar, BGC-Argo) and advance data assimilation modeling (continued).
8) Use models and OSSEs to optimize, inform, and evaluate the feasibility of observing system deployment and components identified in (1) – (3) above (near-term).
9) Integrate remote sensing data, modeling, targeted process studies, and ship-based survey measurements to improve interpretations of ocean ecosystem change and plankton community diversity (long-term).
10) Advance ocean color atmospheric correction capabilities through collaborations between the oceanographic and atmospheric science communities, supporting AERONET-OC type stations with enhanced sensors, and building upon/emulating cross-

sensor frameworks such as the Modern-Era Retrospective analysis for Research and Applications (MERRA; https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/).

11) Engage with the international community for seamless use of relevant data from all satellites and in-situ sensors (as in the Argo program).
12) Support science investigations and novel in-situ sensor development to advance the use of PACE polarimetry data for characterizing ocean particulate properties.

Remote sensing is a core component of NASA's OBB program for addressing grand challenges. For the **Global Biosphere**, these remote sensing observations are rooted in the heritage ocean color record. PACE will build upon this legacy and provide unparalleled global ocean color observations. Continuing and combining PACE-quality observations with new lidar observations will address fundamental limitations of the ocean color approach Technology readiness levels are high for an advanced ocean profiling lidar, and the potential for PACE and its follow-on missions to address the **Global Biosphere** grand challenge will be greatly enhanced by simultaneous vertically resolved satellite lidar data, *moving from a historical single-approach, two-dimensional view into a new active-passive remote sensing observing system* (Figure 3.1-4) *providing complete and continuous sampling of the upper ocean and enabling a 4-dimensional evaluation of ecosystem responses to environment change..* Advanced ecosystem modeling capabilities will also be needed to interpret changes observed from space and to advance forecasting and predictive skill for future change and ecosystem management, particularly to evaluate the implications of stock and rate changes at the remotely detected level of the plankton, assess carbon/energy transfer to higher trophic levels, and quantify export of carbon and other elements to depth. Additional supporting measurements are also needed for validating and informing model predictions beyond the satellite remote sensing observable realm. Thus, a third important element in the **Global Biosphere** observing system is investments toward a global array of autonomous platforms equipped with optical and geochemical sensors (Figure 3.1-4). Profiling floats, underwater gliders, Lagrangian floats, drifters and autonomous surface vehicles enable the targeting of a range of temporal and spatial scales from minutes-to-years and meters-to-ocean basins, providing simultaneous measurements of depth, temperature, salinity, oxygen, nutrients, bio-optics, partial pressure of carbon dioxide, and

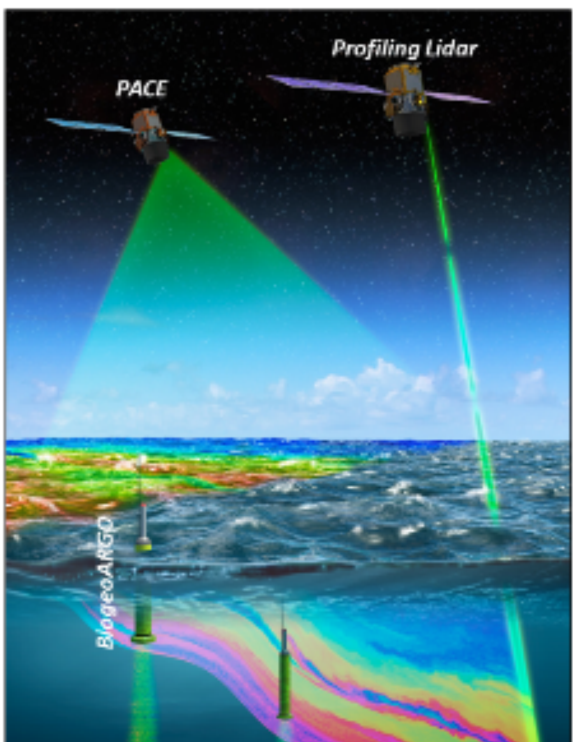


Figure 3.1-4: Artist's rendition of multiple elements in the **Global Biosphere** observing system. (from Hostetler et al. 2018)

ocean currents. Targeted airborne campaigns also provide remote sensing retrievals comparable to those measured *in situ* and from space, which can be valuable for integrating across disparate measurement length-scales, as well as developing and refining model parameterizations, data processing systems, and software workflows. Finally, implementing the **Global Biosphere** *observing system* will require developing a strategy for merging satellite, suborbital, process study, and numerical model data.

3.2 Climate and the Elements of Life

Quantify how the role of ocean ecosystems in climate regulation and the biogeochemical cycling of elements will change in the future and what the ramifications of these changes are for the Earth's climate, the diversity of ocean life, resource sustainability, and human welfare.

The distribution of life across the biosphere is an outward expression of the combined availability of life-sustaining energy and elements. A choreography of physical, chemical, and ecological processes continuously modifies this supply of resources (often termed 'biogeochemistry'), and, without exception, life responds accordingly. When human activities alter the flux of elements into and within the ocean, the physical systems distributing them, or the types of organisms supported by them, consequences ensue regarding ocean health, resiliency, and sustainability for humanity. *These changes in ocean biogeochemical cycles also lead to fundamental alterations in Earth's climate, including the rate and magnitude of contemporary climate change*. The future role of ocean biology in **Climate** regulation and the impact of climate change on ocean biology are uncertain. Improved understanding and associated improvements in prediction rely on advanced quantitative assessments of and process-oriented knowledge on the stocks and cycling of **Elements of Life** in the ocean.

The **Elements of Life** include carbon, nitrogen, oxygen, phosphorus, calcium, sulfur, silicon, and trace metals (e.g., iron, manganese, cadmium, aluminum). The concentration of these elements that are available to support ocean life is often inversely related with the energy available to utilize them. For example, surface nutrient concentrations are high during winter months at high latitudes, but low incident sunlight levels and highly coupled loss processes limit biological production. Conversely, the biomass sustained in surface waters of the central ocean gyres is limited by the availability of life's elements, despite an abundance of solar energy. Unique attributes of different elemental cycles also influence the relative availability of specific nutrients. For example, nitrogen distributions are controlled by competing rates of nitrogen fixation, recycling, deposition, denitrification, and remineralization. Likewise, dissolved iron levels reflect a balance between supply sources (e.g., dust deposition, sediments, ice melt, hydrothermal), biological uptake and recycling, and removal mechanisms (e.g., remineralization and scavenging at depth). The interplay of different elemental cycles dictates metabolic rates of marine organisms and, together with energy supply, determines responses to environmental stressors.

The cycling of carbon has been a major focus in ocean research, although there is still large uncertainty in global oceanic carbon fixation estimates. Phytoplankton utilize carbon dioxide in the sunlit layers of the ocean, producing particulate and dissolved organic carbon that feeds much of the marine food web. Historic bio-optical models for primary production are based on global distributions of the ubiquitous pigment, chlorophyll-a. However, new models are needed that incorporate different rates of carbon fixation by different groups of phytoplankton. Recent research has also demonstrated important linkages between phytoplankton community composition, physical processes, and carbon dynamics. For example, an evaluation of a 25-year time series of field measurements from the Western Antarctic Peninsula demonstrated how the air-sea exchange of carbon dioxide is influenced by different dominant phytoplankton, with blooms of diatoms contributing to much larger oceanic carbon dioxide uptake compared to blooms of cryptomonads and mixed flagellates (Brown et al. 2019). *An important research objective going forward will be to parameterize primary productivity models with data assimilation of phytoplankton community composition estimates from hyperspectral imagery.*

Understanding the fate of organic matter produced in the surface ocean has been an area extensive investigation for many years (Siegel et al. 2022) and a key to future improvements in these assessments is effectively linking models with satellite and *in situ* observations such that the dynamics of carbon biogeochemistry are characterized correctly. Some of the organic carbon produced by plankton is exported into deeper reaches of the ocean (a process called the 'biological pump'), where it may remain sequestered from contact with the atmosphere for months to millennia. The combination of planktonic uptake, the export of organic matter from the surface ocean, its remineralization back to inorganic carbon as it descends or is transported into the interior, the upwelling of carbon rich waters from depth, and differences in solubility of carbon with temperature leads to global patterns of release and uptake of carbon dioxide to the atmosphere (DeVries, 2022). Together, these processes determine the character of marine environments and have played a role in driving natural climatic fluctuations over geologic time. Today, a thorough understanding of ocean carbon cycling and its interdependence on other life sustaining elements is more essential than ever before, as escalating carbon dioxide emissions continue to drive climate warming. The direct and indirect effects of this warming threaten all life in the biosphere, human society, and commerce.

The ocean is a dominant sink for atmospheric carbon dioxide, but its effectiveness in sequestering carbon is changing in response to climate warming and other human impacts. These changes reflect alterations in physical-chemical processes, as well as impacts to biological stocks and rates resulting from changes in ocean carbon chemistry and climate warming. Currently, about one-third to one-half of the carbon emitted into the atmosphere by fossil fuel burning enters the ocean through solubility-driven gas exchange (Friedlingstein et al., 2021; Gruber et al., 2019). This has led to a decrease in the pH of the oceans (termed 'ocean acidification') that is profoundly affecting ocean life (Doney et al. 2020). Ocean life is also being impacted by anthropogenic eutrophication of near-shore water and expansion of oxygen minimum zones. Changes in ocean currents and vertical transport of nutrients is also driving shifts in the global distribution of plankton populations and the frequency and intensity of plankton blooms. The carbon cycle and other associated

Elements of Life are on a trajectory of dramatic future change that threatens the biodiversity, structure, and function of the ocean. *The capacity to predict future behavior in ocean elemental cycles relies on a mechanistic understanding that, in turn, requires comprehensive observations of key constituents and rate processes*. Improving these predictions is one of the grand challenges we face in the coming decade and beyond. *Future opportunities identified below regarding* **Climate and the Elements of Life** *will enable more accurate assessments of ocean biogeochemical cycles, in particular carbon cycling within the ocean and exchange of* CO_2 *across the air-sea interface.*

NASA's ocean color missions have had a major impact on our understanding of ocean elemental cycles by improving estimates of global ocean primary productivity (Westberry et al. 2008, Silsbe et al. 2016), addressing issues regarding carbon cycling in coastal zones and continental margins (Muller-Karger et al. 2005), and documenting basin-scale responses to climate variations (e.g., Behrenfeld et al. 2010, 2016; Siegel et al. 2014). These achievements have provided vital constraints for developing and evaluating important components of numerical models. Cutting-edge, contemporary ocean biogeochemical models express transformation rates as a function of environmental variables and yield prognostic source/sink terms of the **Elements of Life** (as indicated above) that are coupled to three-dimensional general circulation models enabling representation of ocean dynamics and tracer transport.

Models now include plankton ecological/size/biogeochemical functional types that allow assessment of community composition impacts on elemental cycles and transfer rates, as well as interrogation of mechanisms controlling phytoplankton distributions (e.g., growth-limiting elements and **Climate**). Additionally, there have been significant advances in the formal assimilation of data, including ocean color products, into models to provide extensive state estimates of ocean biogeochemistry (Jones et al, 2017; Carroll et al, 2021; Baird et al. 2020; Nowicki et al. 2022). However, the propagation of ocean color product uncertainties into models and the difficulty in relating model variables to the satellite products remains a significant challenge, similarly to the **Global Biosphere**. Additional model development is especially needed to fully utilize new sources of ocean observations, such as satellite lidar retrievals.

While the combination of heritage ocean color measurements and Earth system models has enabled a 'quantum leap forward' in understanding on the interconnected cycles of **Climate and Elements of Life**, confidence in model predictions relies on the fidelity of the underlying mechanistic formulations and in the quantification of rates with which elements transition between inorganic and organic forms. A grand challenge for **Climate and the Elements of Life** is thus to build upon the current foundation of measurements and models to create an advanced observing system and improved mechanistic understanding that enhances accuracy and reduces uncertainties in model characterizations, such that robust predictions can be made regarding the ocean's role in climate regulation and biogeochemical cycles.

Achieving this goal entails a variety of new approaches. For example, the elemental pathways and vertical patterns of carbon remineralization are not only impacted by the standing stocks of plankton, but also the taxonomic, or 'functional', composition and size distribution of communities (Guidi et al. 2015; Henson et al. 2022). Understanding the types of elements required by different planktonic groups and the rates with which they take them up is therefore crucial for forecasting changes in ocean ecosystems and associated impacts on the cycling of **Elements of Life**. *The short timescale of many of these processes are not captured by traditional polar-orbiting satellites but can to a degree be observed with satellite sensors in geostationary or other orbits*.

Elements of Life cycle through the biosphere in three-dimensional space, including deeper reaches of the ocean undetected by surface-only ocean color data. Physical and biological processes within the surface sunlit ocean (i.e., photic layer) create strong vertical features in plankton communities that reflect and influence the distribution of resources, with climate-critical polar systems and continental shelves exhibiting particularly strong water column structuring (Babin & Forget 2015). Ship-based and BGC-Argo measurements have documented, for example, significant depth-dependent variations in particulate organic carbon. Numerical modeling has expanded these observations to simulate global three-dimensional patterns but *profiling remote sensing observations of the photic layer are needed to assess the global prevalence of subsurface features and better inform model development*. Beyond the depth of the photic zone, opportunities for satellite remote sensing are limited, yet understanding biogeochemical processes within this 'twilight zone' and below is still essential to understand the fate and lifetime of elements transported from the productive surface to the deep sea and back again.

Elements of Life also exchange between the ocean and overlying atmosphere. New observations are needed to quantify the magnitude of these impacts as their role in **Climate** regulation, and ocean health is likely to change with climate warming. In the upward direction, organic matter produced by surface-layer ecosystems can be lofted into the atmosphere by bubble bursting and wave breaking and, once in the atmosphere, can have a substantial impact on aerosol and cloud properties (thus, Earth's radiative budget) (Gantt and Meskhidze 2013, Lewis & Schwartz 2004, O'Dowd et al. 2004, Facchini et al. 2008). Production of these compounds is linked to both the composition and physiological state (i.e., health) of planktonic communities. In the downward direction, wet and dry deposition from the atmosphere to the ocean can have significant impacts on marine ecosystems (Jickells & Moore 2015). Inland and coastal ecosystems, near the source of atmospheric emissions (e.g., urban pollution, fires), are often disproportionally impacted by wet and dry deposition of pollutants and thus are challenging for remote sensing (Loughner et al. 2016; Tzortziou et al. 2018). Remote sensing observations have yielded some of the most dramatic examples of plankton responses to major atmospheric inputs (Figure 3.2-1) (Hamme et al. 2010, Lindenthal et al. 2013, Westberry et al. 2019, Tang et al. 2012). However, *deposition events of lower magnitude are far more common and elicit subtle biomass and physiological* *responses that, when integrated over space and time, represent a major influence on ocean ecosystems but require advanced observing capabilities to monitor and quantify*.

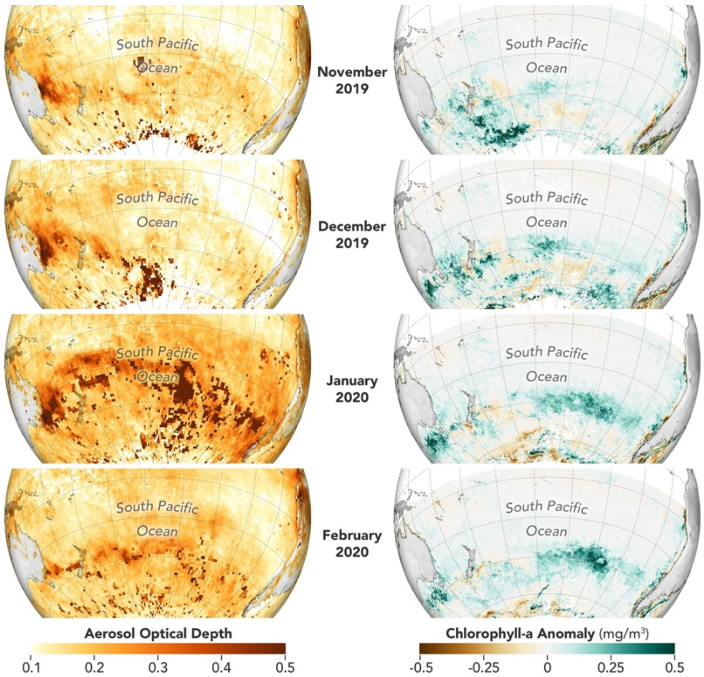


Figure 3.2-1. (left) Monthly aerosol levels and (right) chlorophyll anomalies from November 2019 to February 2020, following the summer 2019-2020 Australian fires. https://earthobservatory.nasa.gov/images/149039/australian-fires-fueled-unprecedented-blooms

Today, signatures of climate change are undeniable, and the growing recognition of this fact is stimulating plans for action. These actions fall into two primary categories: (1) reductions in climate-relevant emissions and (2) engineering strategies for carbon dioxide reduction. A wide range of potential carbon dioxide reduction solutions are currently 'on the table,' but approaches that enhance sequestration in the ocean are primary targets because such activities have the potential magnitude (i.e., billions of tons of carbon) to significantly impact atmospheric carbon dioxide levels. Example concepts being discussed include broad-scale iron fertilization schemes or purposeful changes in ocean alkalinity. While the potential ecological implications of such actions are of great concern, *NASA must nevertheless begin developing observational plans for documenting the impacts of carbon dioxide reduction manipulations*. Thus, a component of the **Climate and the Elements of Life** grand challenge is to identify remotely observable properties relevant to carbon dioxide reduction approaches and to improve our understanding of the potential implications of different candidate actions.

Climate and the Elements of Life Opportunities

To address the **Climate and the Elements of Life** grand challenge, *successful execution of upcoming ocean color measurements in the Program of Record (i.e., PACE, GLIMR) is of utmost importance, as are subsequent extension of equivalent measurements into the future, augmentation of these baseline observations with unique and complementary observing technologies that address limitations of the ocean color approach, and continued development of modeling capabilities*. Many of these opportunities overlap with those described for the **Global Biosphere** and **Interface Habitats** grand challenges (**Sections 3.1 and 3.3**), but here we focus on aspects of an observing system that are unique to the **Climate and the Elements**

of Life and emphasize that numerical modeling and *in situ* measurements play a particularly important role in understanding ocean elemental cycles and predicting future change because, for the most part, these elements are not directly observable from space. In the following subsections, new opportunities are organized into five overarching topics: (1) surface ocean properties and rates, (2) subsurface ocean properties and rates, (3) plankton rates, (4) ocean-atmosphere processes, and (5) carbon dioxide reduction.

Surface Ocean Properties and Rates

Quantifying, monitoring, and predicting changes in ocean elemental cycles and their interactions with atmospheric, terrestrial, and cryospheric systems requires information on stock sizes and key transformation rates. *Hyperspectral ocean color measurements are critical here as a baseline observing system requirement for addressing the* ***Climate and the Elements of Life*** *grand challenge*. These measurements, when collected from a polar orbiting satellite with 1-2 day repeat global coverage, provide global information on surface-layer plankton stocks, primary production, community composition, colored dissolved organic matter, particulate inorganic carbon, and rates of biomass growth and consumption on meaningful temporal scales. Global ocean color data also permit assessment of environmental stressors that are reflected by variations in phytoplankton chlorophyll fluorescence quantum yields and carbon-to-chlorophyll ratios. Spatio-temporal changes in these stressors play a pivotal role in elemental cycling rates. *Thus, global ocean color observations from the PACE mission and an uninterrupted continuation of these measurements from equally capable follow-on missions are essential to the* **Climate and the Elements of Life** grand challenge. However, the global perspective provided by an observatory in polar orbit still places limits on the temporal coverage of ocean color products for any given geographical location and many key aspects of elemental cycling occur on sub-daily time scales. For example, the physiological metrics noted above may integrated multiple simultaneous environmental stressors (e.g., light, nutrient, temperature), but the time scale of variations can differ between stressors and may be disentangled using high temporal resolution measurements. Accordingly, *the Program of Record geostationary GLIMR mission is an important complement to the PACE mission, providing ocean color observations at sub-daily time scales to capture temporal dynamics in ocean physical, biological, and biogeochemical processes in near-shore and continental margin habitats around North America*. Similar geostationary observations are underway or planned for observing other regions of the global ocean by international space agencies (e.g., Japanese

Figure 3.2-2: Artist rendition of the PACE observatory (from NASA's Conceptual Image Laboratory)

Himawari and Korean GOCI-II instruments), as well as the NOAA-NASA GeoXO program (see **SECTION 2**).

As an alternative to or complementing observations from traditional geostationary orbits, enhanced temporal resolution measurements of the global ocean may also be achieved from satellites positioned at Lagrange points, where the gravitational pull of the Sun and Earth equals the centripetal force of a satellite, causing the relative positions of the 3 objects to remain fixed. The first Lagrange point (L1) is at ~1.5 million km from Earth. From the L1 orbit, almost the entire sunlit face of the Earth can be regularly observed. Advantages of observing from L1 for ocean color are: 1) the entire sunlit oceans can be observed simultaneously at high temporal resolution from a single platform, allowing detailed temporal coverage of evolving phenomena, 2) atmospheric correction is facilitated by viewing at the same scattering angle but different zenith angles, 3) radiometric calibration, pixel-to- pixel uniformity, and long-term instrument stability are maintained by lunar observations whenever the Earth has a full moon, and 4) the thermal and particle radiation environments are 'quiet' (Frouin et al., 2022). The capacity to retrieve spatially- and temporarily resolved ocean color products from the L1 orbit has recently been demonstrated with the Earth Polychromatic Imaging Camera (EPIC) onboard the Deep Space Climate ObserVatoRy (DSCOVR), and preliminary analyses support the feasible of building a future sensor for the L1 orbit with hyper-spectral and polarimetric measurements spanning from the UV to NIR and with a spatial resolution of 1 km at the Earth's surface (Frouin et al., 2022).

In addition to ocean color, valuable information regarding **Climate and the Elements of Life** is provided through measurements of ocean polarization properties. The constitution of suspended particles impacts the functioning of marine food webs and biogeochemistry. Variations in surface-ocean particle types cause a change in the polarization characteristics of water leaving radiance, which can be detected by space-borne polarimeters. Satellite-based classification of ocean particle types was first demonstrated using the French POLarization and Directionality of the Earth's Reflectance (POLDER) sensor (Loisel et al. 2008). This capability will be extended by the PACE observatory, which includes two advanced multi-angle polarimeters for ocean and atmosphere microphysical property characterizations and improvements in atmospheric correction algorithms for ocean color retrievals (Werdell et al. 2019). *Continuation of equivalent polarimetric ocean measurements beyond the lifetime of PACE is needed*, noting here that polarimeters are currently planned for the NASA Aerosol Observing System (AOS; see **SECTION 5.4**) mission and European Organisation for the Exploitation of Meteorological Satellites' (EUMETSAT) MetOp Second Generation satellite series (https://www.eumetsat.int/our-satellites/metop-series). In addition, investments in new scientific analyses and field-based polarimetry technology are needed to ensure maximum use of satellite polarimetry data for ocean applications.

Active sensors can further improve our understanding of ocean **Elements of Life** by collecting information on plankton stocks and rates under conditions that prohibit the above noted measurements by passive sensors. Advantages of an ocean-optimized satellite lidar are detailed in **SECTION 3.1** and *the earlier-described baseline lidar should be augmented to include a chlorophyll fluorescence detection channel centered near 680 nm for assessment of environmental stressors and, potentially, to include an additional near-ultraviolet laser emission wavelength for assessments of CDOM concentrations and spectral slope of particulate backscatter (a measure of the particle size distribution)*. In coastal waters, CDOM concentrations can be highly correlated with the total mass of dissolved organic matter (DOM), thus providing a remote sensing proxy for this dominant pool of carbon. In open ocean waters, CDOM and DOM are often poorly correlated, but remote sensing measurements of CDOM are still critical. Specifically, the spectral absorption of light by CDOM is like that of phytoplankton pigments and inaccurate separation of these two absorbing components can lead to large errors in assessed ocean productivity and carbon cycling (Siegel et al., 2005). These advanced capabilities will be particularly valuable for addressing the **Climate and the Elements of Life** grand challenge in polar and persistently cloudy ocean regions, as well as for characterizing subsurface properties.

Subsurface Ocean Properties and Rates

Accurate quantification of global elemental stocks and transition rates requires observations beyond ocean color because physical and ecological processes create subsurface features that deviate substantially from the near-surface properties detected by this traditional remote sensing approach. As detailed in **SECTION 3.1**, major advances in the 4-dimensional characterization of global ocean stocks and rates within the photic zone can be achieved with a vertically-profiling blue-emission satellite lidar. *This addition to NASA's ocean observing system suggested for* **Global Biosphere** *applications should also be considered as a high-priority for addressing* **Climate and the Elements of Life** grand challenges.

A major challenge with respect to **Climate and the Elements of Life** goals is mechanistically linking photic layer properties observable from passive and active satellite sensors to elemental cycling (e.g., carbon) within, and materials transfer to, the mesopelagic and below. Numerical Earth system models provide a means for quantifying this linkage, but *in situ* observations are required to inform and evaluate model simulations. Autonomous observational platforms, such as profiling floats, gliders, and wire-walkers, can provide important high-frequency, depth-resolved, broad coverage measurements in a relatively cost-effective manner. *Deployment of these*

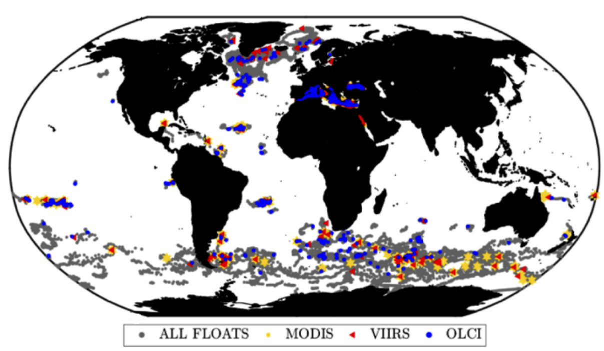


Figure 3.2-3: Global distribution of BGC-ARGO float locations with backscattering measurements. Gray = all data. Colors = matchups with ocean color retrievals (see key at bottom of figure). (from Bisson et al. 2019)

autonomous assets should be continued and expanded into the future and additional investments made to enhance measurement capabilities.

Biogeochemical floats (BGC-Argo, Figure 3.2-3) provide measurements of ocean pH, nitrate and oxygen concentrations, pressure, salinity, and temperature, along with optical measurements of particulate backscattering (a proxy for phytoplankton biomass and total particulate carbon biomass), chlorophyll fluorescence (a proxy for chlorophyll concentration and phytoplankton biomass), PAR, and spectral radiance and can yield sustained, high-frequency measurements of the water column over years. Particularly compelling for ocean color applications is the potential for integration of hyperspectral radiometers that would dove-tail with hyper- and multispectral measurements from satellite and suborbital assets (Organelli et al. 2021). These platforms are excellent tools for persistent, broad coverage and *an expansion of the programs that build, deploy, and distribute data from these floats is needed, along with development of new technologies that expand observables related to biogeochemical cycles (e.g., sinking flux measurements)*. However, even the upcoming 500 float fleet expansion through the National Science Foundation's GO-BGC program will leave major gaps in spatial and temporal coverage, particularly on 'process-study' scales that examine dynamics over meso- to submesoscale. Here, navigable tools such as gliders and autonomous underwater and surface vehicles are essential. These platforms enable high resolution observations in space and time and, when combined effectively, can together resolve processes over the mesoscale and smaller. Lastly, Lagrangian (water-following) or pseudo-Lagrangian tools can offer a novel perspective that eliminates or at least minimizes variations induced by advection, thereby isolating local sources and sinks of the **Elements of Life** tracer of interest. Wire-walkers, for example, can be a particularly effective pseudo-Lagrangian platform as these systems can accommodate a large payload of instruments, deriving the energy required for profiling from the surface wave field. Targeted wire-walker deployments can be envisioned as particularly useful for intensive process studies, though the power demands of a large or complex payload may presently preclude feasibly creating a long-term *in situ* observing array. *Thus, investments in* in situ *'green' technologies that expand deployment duration and persistence through harvesting energy from waves (e.g., wire-walkers, wavegliders), wind (e.g., Saildrones), solar (e.g., drifters, buoys, surface vehicles), or even ocean thermal gradients (e.g., SeaTrec SL1-Powered Profiling Float) will provide great scientific return in the future*.

Additional measurements of food web processes, community composition, and a broader array of nutrients and other elements can also be envisioned for these platforms, although technological developments are still needed. In addition, a variety of optical approaches are currently deployed from ships to characterize the composition of living and non-living particles (e.g., underwater video profiler, hyperspectral scattering sensors), but further work is needed to achieve necessary reductions in instrument size and power requirements. To this end, progress is already being made in developing BGC-Argo-compatible underwater video profiling sensors. Autonomous sensor data are already a critical asset for quantifying depth-resolved biogeochemical cycling using inverse models, but the above opportunity for expansion of measurements will substantially improve assessments on food web processes, elemental stocks, and community composition.

As described in **SECTION 3.1**, numerical modeling is a 'platform' allowing synthesis of observational data, hypothesis testing, and projection of biogeochemical cycles across seasonal to centennial time scales*. Data assimilation models are the recommended method to draw together the multi-faceted observing system described above*. Such models can alter internal model parameters to bring model predictions more in line with available observations. A key component in this assimilation effort is defining a 'cost function', which is a measure of how far the non-assimilated model is from the observations. Cost functions commonly assign penalties to deviations in the absolute or relative difference of model and data magnitudes. Future work may benefit by designing cost functions that minimize the parameters of probability distribution functions (of model and data values), such that both the magnitude *and variability* of model predictions match that of the data. To adequately assess this cost function, knowledge is required on uncertainties associated with the observational data. This assessment is particularly complex for derived ocean color products, such as chlorophyll concentration, which are known to have large regional and seasonal variations in uncertainties and biases (Moore et al., 2009). *Further development of data assimilation models generating properties more closely aligned with directly observed ocean properties will be necessary*, as indicated for **Global Biosphere**. For instance, it has been shown that assimilating ocean reflectance or water-leaving radiance, with their relatively small uncertainties, leads to improved model performance compared to assimilation of the subsequently derived chlorophyll retrievals (Jones et al. 2017). More broadly, *prevalent development of assimilative models focused explicitly on inherent and apparent optical properties and radiative transfer will be needed*. This direction for future development is not without difficulty, however, due to its associated increase in model complexity, but several recent studies have already made significant progress to this end (Fujii et al. 2007, Gregg and Casey, 2007; Mobley et al. 2015, Dutkiewicz et al. 2015). Such models can provide valuable synthetic satellite-like products for mission planning (e.g., as for PACE, Gregg and Rousseaux, 2017).

Adequately capturing elemental fluxes and how these fluxes change over seasonal, interannual, and longer time scales associated with climate change-induced trends requires data assimilation models that conserve mass. Many techniques currently used to characterize the current state of the oceans (i.e., 'state estimates') modify, or 'nudge', model variables towards observations, at least within uncertainties of the data. Some of these techniques can artificially add or remove mass in the process. While these artifacts may not cause a significant issue for state estimates, they can cause problems when calculating trends. While climate models are required to conserve mass properties, many process models are not. *Therefore, enhanced efforts to develop models that take specific care to maintain mass should be pursued*. Such data assimilation methods (e.g., 4DVar) do not nudge model variables, but rather target the model parameters themselves to bring model output to better agreement with the observations. Numerical models (with or without data assimilation) provide insight into the mechanisms of ocean elemental cycles and can also illuminate physical-chemical-ecological linkages. *Investments to ensure continued model development, diversification, and testing of approaches are critical, as well as maintaining parallel evolution of modeling and observational capabilities over the coming decade and beyond*. These models provide a critical tool for assessing how cycles of carbon within the ocean influence the transport of CO_2 across the air-sea boundary. *Mechanistically based and mass-conserving models can also be used to provide constraints on satellite algorithms assessing key carbon cycle processes, such as net primary production and export.*

While the combination of advanced satellite remote sensing, *in situ* autonomous measurements, and numerical modeling will greatly improve understanding on **Climate and the Elements of Life**, robust model simulations and predictions also require investment in intensive field-based process studies to refine mechanistic formulations regarding links between community composition, food web structure, and elemental stocks and cycling rates. Additional tracer measurements of ocean circulation, mixing, and export processes are also needed to reduce uncertainties in the temporal length-scales of elemental sequestration. Simultaneous optical measurements (e.g., hyperspectral backscatter, beam attenuation, absorption) are required for high-resolution characterizations of plankton and abiotic stocks, while measurements using a variety of instruments/approaches are needed to provide detailed information on community composition across the organismal size spectrum. Hyperspectral measurements of ocean reflectance and/or water leaving radiance are also important for linking *in situ* observations to remote sensing, particularly ocean color. Research ships provide an appropriate platform for this extensive suite of observations, particularly given current capabilities for continuous collection of along-track optical properties, but ship-time can be prohibitively expensive. One successful and cost-effective approach has been the use ships of opportunity and international expeditions run by non-profit organizations (e.g., Tara Expedition) equipped with relevant instrumentation and enhanced water sampling. *Further opportunities should be sought for interagency partnerships*. For example, the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) could provide a basis for regular field deployments along repeated transects, but the current suite of measurement conducted during these campaigns would require significant augmentation to address **Climate and the Elements of Life** questions. Also, new University-National Oceanographic Laboratory System Regional Class research vessels will support several flow-through and profile measurements of bio-optical and biogeochemical properties Finally, coupling of ship-based measurements with airborne observations can provide critical links between spatial scales of *in situ* measurements and satellite remote sensing.

Plankton Rates

The ocean color signal detected by satellite remote sensing is the immediate product of the interaction of impinging light and the abundance (i.e., stocks) of dissolved and particulate material in water. The tempo with which the **Elements of Life** cycle within the ocean, however, is dependent both on standing stocks and *rate processes*. Relevant biological rates include photosynthesis, phytoplankton division, zooplankton and mixotrophic grazing, viral lysis, and migration, amongst other processes. Our ability to directly measure specific biological rates from space is limited, but not entirely devoid. For example, one metric of phytoplankton growth rate observable with satellite ocean color data is the ratio of phytoplankton carbon to chlorophyll (C:Chl) concentrations (Behrenfeld et al. 2005; Sathyendranath et al. 2020). Phytoplankton continuously adjust their C:Chl ratio in response to changes in their growth environment, particularly the availability of light and nutrients. With information on incident sunlight, active surface mixing depth (see **SECTION 3.1**), attenuation of light through the water column, and a robust physiological or bio-optical model, the influence of photoacclimation on observed C:Chl ratios can be removed to yield a quantitative assessment of nutrient limited growth rate (Behrenfeld et al. 2005, 2016, Westberry et al. 2008, Silsbe et al. 2016). Such assessments might be further improved with additional information on phytoplankton community composition, as may be provided through the upcoming PACE mission.

Another particularly important approach for assessing biological rates in the ocean from space is through the analysis of time-series data. For example, temporal changes in the surface concentration of phytoplankton at a given location (accounting for the influence of physical advection) is a metric of the balance between phytoplankton division and loss rates. This observed 'accumulation rate' (which can be either positive when biomass is increasing or negative when decreasing) can be dissected further using parallel information on phytoplankton division rate (see above) to quantify the summed (i.e., grazing, sinking, viral lysis, etc.) loss rate. Global evaluations of satellite-retrieved division, loss, and accumulation rates have been instrumental in elucidating mechanisms underlying phytoplankton blooms (e.g., Behrenfeld 2010, Behrenfeld & Boss 2018) and for assessing carbon export from the surface ocean to depth (e.g., Siegel et al. 2014).

While these developments have significantly advanced our understanding on **Elements of Life** in the ocean, as well as the **Global Biosphere**, uncertainties remain, particularly with respect to the phytoplankton that lie at the heart of marine food webs. Specifically, the C:Chl-based approached noted above is challenged by the unique influence of different forms of nutrient stress (e.g., iron versus nitrogen limitation) and photoacclimation strategies. *Alternative approaches are therefore needed to refine our understanding of phytoplankton physiology and growth rates to improve understanding of food web processes and biogeochemistry*. One potential opportunity to address this need is through higher temporal resolution satellite observations that span the full diel cycle.

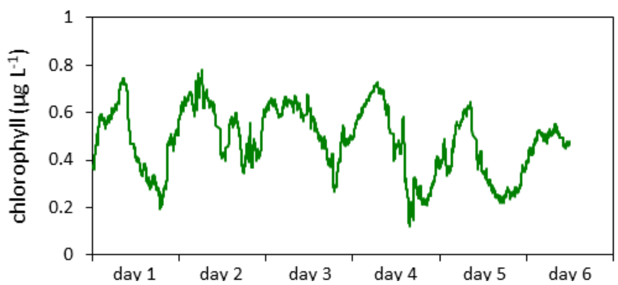


Figure 3.2-4: Example diel cycles in phytoplankton chlorophyll concentrations as observed during 6 day period of the NASA EXPORTS North Atlantic field campaign (data courtesy of Emmanuel Boss, University of Maine).

Diel cycles in plankton-related optical properties have been thoroughly documented during historical field campaigns, including variations in particulate backscatter, attenuation, chlorophyll (e.g., Figure 3.2-4), and fluorescence, that are associated with phytoplankton photosynthesis, division, and nutrient stress. Over the course of the diurnal period, the refractive and absorptive properties of cells change as phytoplankton photosynthesis results in an accumulation of intracellular organic matter and pigments. These changes are then reversed at night through cell metabolism and division. In addition, the chlorophyll fluorescence properties of phytoplankton exhibit strong diel cycles associated with nutrient stress and daytime photoprotection. Of particular interest regarding the former is the unique nighttime elevation in fluorescence quantum yields (i.e., fluorescence emitted per unit light absorbed) under iron limiting conditions (Behrenfeld & Milligan 2013, Feen et al. 2022). With respect to the latter phenomenon, the reduction in fluorescence yields during the day resulting from protective non-photochemical quenching mechanisms is dependent on the relationship between incident sunlight and the photoadaptive state of the mixed layer phytoplankton community. *Thus, routine global observations of these various diel cycles in optical properties can provide a critical direct link to key physiological properties essential to understanding and modeling global plankton communities*.

Obviously, passive ocean color observations will be ineffective at addressing the above noted opportunity because these measurements are limited to the daytime. Active measurements with a satellite lidar coupled with geostationary measurements, on the other hand, are well positioned to address this objective. The ability to detect day-night differences in subsurface particulate backscattering has already been demonstrated using CALIOP data (Behrenfeld et al. 2019) and the ocean-optimized lidar discussed in **Section 3.1** will expand upon this capability. Addition of a chlorophyll fluorescence detection band and multiple laser emission wavelengths on a lidar system would be a key requirement to advance understanding on phytoplankton diel cycles from space, or a separate mission of its own targeting these rich signals of phytoplankton physiology. For example, the diel timing of backscatter, absorption, and fluorescence peaks can be expected to vary from one ocean region to the next and seasonally. It would therefore be advantageous to consider a constellation of satellites flying in formation and providing 1 to 2 hour repeated coverage along identical orbit tracks. The objective of a physiology lidar would be to simultaneously retrieve all three optical properties. This objective imposes a limit on the required depth penetration for the lidar because chlorophyll fluorescence at 680 nm is strongly attenuated by water and thus the signal is restricted to the uppermost ocean. Accordingly, power requirements for lidar instruments will be greatly reduced compared to the ocean-profiling lidar detailed in **SECTION 3.1**, meaning that a physiology lidar may be compatible with CubeSat or SmallSat platforms. Trade studies will also be needed to evaluate the cost-science optimum for the lidar architecture. Specifically, HSRL-type systems would be preferable, given their enhanced capability to directly separate attenuation and backscatter signals, but lower-cost simple elastic backscatter lidar might also be acceptable (e.g., like the CALIOP approach). Space-demonstrated 532 nm emitting Nd-Yg lasers may also be adequate for a physiology lidar, as penetration deep into the water column is unnecessary. However, 532 nm light will be less effective at stimulating chlorophyll fluorescence than a blue emission wavelength. Another particularly important requirement will be a very accurate cross-calibration between instruments on the separate platforms, as the diel cycles of interest are of relatively small magnitude. Simultaneous geostationary ocean color measurements could augment the temporal coverage provided by a physiology lidar and expand spatial and spectral resolution of time-resolved data (albeit limited to daylight hours). While other technological considerations will need to be evaluated, a physiology lidar could provide an exciting and unique observatory for unraveling mysteries on the **Elements of Life** in the **Global Biosphere**.

Ocean-Atmosphere Processes

The organic composition of atmospheric aerosols can influence their direct and indirect effects on the Earth's radiative budget. Correlations have been observed at some locations between the organic mass of marine aerosol and plankton biomass or productivity (e.g., Mansour et al., 2020; O'Dowd et al., 2004; Sciare et al., 2009), but such relationships are not universally consistent (e.g., Bates et al. 2012, Frossard et al. 2014). The potential for ocean ecosystems to have a significant impact on atmospheric aerosols and clouds is greatest at higher latitudes, where non-marine aerosol loads can be extremely low and cloud droplet number is limited by aerosol concentration (Abbatt et al. 2019). Because of this potentially important influence, *continued suborbital research is needed to better constrain seasonal and geographic variations in ocean-to-atmosphere biogenic emissions, particularly with respect to oceanographic properties amenable to remote sensing and during the shoulder seasons*. To this end, one attribute of marine ecosystems that has been clearly linked to biogenic aerosol in the atmosphere is plankton community composition. For example, the climate-relevant gas dimethylsulfide in the atmosphere is often elevated where phytoplankton communities have large numbers of coccolithophorids or other *Haptophyta* species (O'Dowd et al. 2004, Andreae & Rosenfeld 2008, Sanchez et al. 2018). The PACE mission will provide global hyperspectral ocean reflectance retrievals that may significantly improve our understanding of phytoplankton community composition. Higher spatial- and temporal-resolution data from GLIMR or other sensors discussed in **SECTION 3.3** also have the potential to yield new insights on ocean contributions to atmospheric aerosol and mechanisms underlying these emissions. Applications of satellite data for understanding ocean-to-atmosphere processes still require significant investment in suborbital studies (including airborne and surface), however, because no direct remote sensing signal of ocean biogenic emissions has yet been identified.

In contrast to ocean emissions research, remote sensing has played a critical role in characterizing ocean ecosystem responses to atmospheric inputs. Atmospheric inputs to the ocean include wet- and dry-deposition of pollutants and nutrients and both wet- and dry-deposition of dust and ash. Heavy aerosol load can also influence the spectral quality of downwelling sunlight at the ocean surface through atmospheric absorption.

Significant increases in surface ocean chlorophyll concentrations have been observed in response to ash deposition following major wildfires (Tang et al. 2021) and volcanic eruptions (Hamme et al., 2010, Westberry et al. 2019). While these major events have clear signatures in ocean color data, monitoring ecosystem responses to the more prevalent low rates of deposition has been a challenge. Preliminary evidence that this background atmospheric flux influences ocean biology is provided in figure 3.2-5. Here, chlorophyll changes associated with the top ten dust deposition events are evaluated for each spatial pixel for the 2003 to 2016 timeframe. Despite being in the top ten events, in most cases, the actual mass of deposited material during these events is small (the range in deposition mass for these events exceeds 4 orders of magnitude). Nevertheless, the prominent response to these depositions is an increase in chlorophyll concentration relative to concentrations prior to the events (i.e., red colored pixels), although significant quantitative uncertainties remain in these assessments.

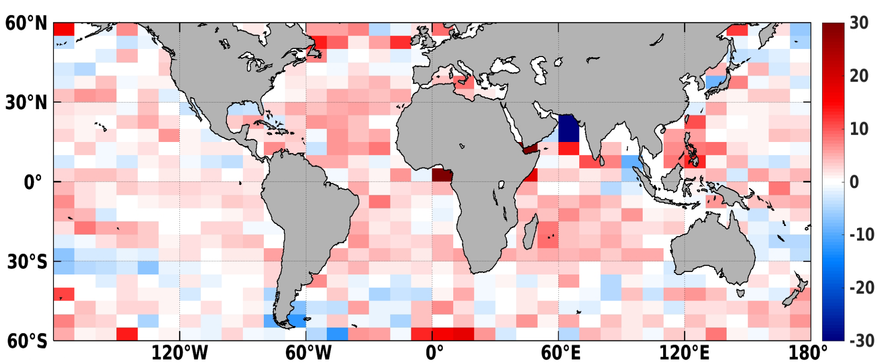


Figure 3.2-5: Mean chlorophyll change (%) following the top 10% GEOS-calculated dust deposition events for each location over the time 2003-2016. Chlorophyll change is the chlorophyll concentration immediately following dust deposition relative to the chlorophyll concentration immediately before the deposition. (from Westberry et al. in prep)

Detecting ecosystem responses to atmospheric inputs has the advantage that the impact of these depositions is largely restricted to the surface layer, making them ideally suited for ocean color remote sensing. A challenge here, however, it that the presence of aerosols can impact the accuracy of ocean color atmospheric corrects, potentially yielding inaccurate assessments of ecosystem responses. We anticipate that characterization of these responses will be significantly improved by the advanced observing capabilities of the hyperspectral PACE and GLIMR sensors in the Program of Record. The more significant challenge for characterizing atmosphere-to-ocean impacts is quantifying deposition.

Atmospheric aerosol loads have been routinely quantified using heritage NASA satellite sensors (e.g., MODIS, VIIRS, MISR, OMI, CALIOP, TEMPO), but aerosol load and aerosol deposition are two different things. To estimate deposition, satellite observations are ingested into atmospheric transport models (e.g., the NASA Goddard Earth Observing System model) and then deposition is determined from temporal flux divergences (i.e., deposition = flux into a model pixel – flux out of the pixel). Climate models, such as the NASA-GISS coupled climate model (Lerner et al., 2020; Ito et al., 2021) include interactive dust deposition and iron fertilization of the ocean that compare favorably to observations. Significant uncertainties exist in these assessments and the underlying processes and, therefore, *additional observations are required that will enable model refinement to link atmospheric inputs more quantitatively to ocean elemental cycles and ecosystem responses*. Key elements include process-oriented observations for testing model assumptions and measurements that allow distinction of different dust and aerosol chemical types. Ship-airborne deployments can also be particularly advantageous in this regard for conducting process studies addressing ocean-to-atmosphere biogenic emissions, as recently demonstrated during the NASA North Atlantic Aerosol and Marine Ecosystem Study (NAAMES; Behrenfeld et al., 2019).

To improve understanding of atmospheric deposition effects on ocean ecosystems, *studies should be developed to evaluate remote sensing options for augmenting heritage measurements of atmospheric trace gases (e.g., satellite measurements of NO2, linking to nitrogen deposition), dust, and aerosol loads to achieve quantitative, spatially- and temporally resolved assessments of mass deposition fluxes to the ocean surface*. In this case, the target of these new measurements may not be global monitoring of deposition, but rather a 'process' focus where the mass, rate, and composition of deposition are accurately quantified for enough specific events to improve global flux divergence calculations in simulation systems. While the details of such an approach require further evaluation, one possibility may include a constellation of CubeSats providing repeat scene observations separated in time, in such a manner that dust/aerosol losses to deposition are measured directly. Low-cost passive multi-angle polarimeters and/or shortwave infrared sensors on these CubeSats could provide not only information on atmospheric dust/aerosol loads, but also enable simultaneous retrievals of dust type and cloud type. In addition, multi-angle polarimeters could provide novel information on hydrosol (i.e., water-suspended colloids) microphysical aerosol properties that inform deposition studies. Low-power, low-cost simple elastic backscattering lidar systems might also be envisioned for this constellation, providing detailed information on temporal changes in dust and aerosol heights during periods of deposition, especially when coupled with atmospheric boundary layer and surface field observations.

Carbon Dioxide Reduction

It is becoming increasingly clear that controlling future Earth warming to well below +2.0C and preferably +1.5C, as is the aim of the 2016 Paris Agreement, will require large-scale technologies to be developed that can enact negative carbon dioxide emissions (IPCC, 2014, Rogelj et al., 2018). As such, there have been many suggestions of CDR strategies to provide negative emissions on global scales, including ocean-based CDR strategies (GESAMP, 2019; NASEM, 2021). These proposed CDR strategies range from techniques that either enhance productivity of (hence export of carbon from) the surface ocean (e.g., large-scale iron fertilization, artificial upwelling, large-scale farming of seaweed biomass that is then sequestered in the ocean interior) or increase the absorption of carbon dioxide by the surface ocean (e.g., large-scale addition of natural alkaline materials). The spatial scales of disturbance to ocean ecosystems necessary to provide the needed carbon dioxide removal and create negative carbon dioxide emissions are immense (NASEM, 2021,). *Hence there is a critical need for NASA observations to establish baseline records of biological pump functioning and to be ready to assess the environmental and ecological consequences of proposed CDR actions*. To a large degree, the NASA Program of Record (PACE, GLIMR), the NASA Surface Biology and Geology (SBG) mission, NOAA-NASA GeoXO Program, international satellite missions, and the above envisioned ocean-optimized profiling satellite lidar provide an appropriate complement of observations to address these challenges and would be a critical part of the required monitoring system if any of these ocean CDR strategies were to be implemented to scale. It might be envisioned that SmallSat satellites can help characterize specific CDR activities. Assessing the impact of carbon dioxide reduction actions also requires continued *in situ* measurements along with a quantitative understanding of carbon remineralization length scales (i.e., months, years, centuries), feedbacks on other elemental cycles, and implications for the ecosystems that these cycles nourish. This understanding requires accurate models with robust mechanistic formulations, as well as strong interdisciplinary collaborations between biological, biogeochemical, and physical oceanographic communities.

As noted above, one CDR approach being discussed involves large-scale fertilization of surface ocean ecosystems with iron (NASEM, 2021; ExIOS, https://oceaniron.org/wp-content/uploads/sites/54/2022/11/ExOISReportNov2022.pdf). Extensive field studies have demonstrated that iron-limited phytoplankton populations exhibit chlorophyll fluorescence properties that are distinct from other forms of physiological stress. Specifically, the quantum yield of fluorescence is abnormally high under iron stress, particularly at night. While there is some indication that this fluorescence diagnostic of iron stress is registered in an ocean color measurement at ~680 nm (i.e., the fluorescence emission band for chlorophyll-a) (Behrenfeld et al., 2009), this daytime signal is small and confounded by other physiological processes, most notably thermal de-excitation pathways (i.e., non-photochemical quenching). It might be envisioned that a SmallSat geostationary satellite specific for a CDR activity might help characterize such natural physiological processes, but a more effective approach may be to measure the iron stress signal at night. In **SECTION 3.1**, a baseline HSRL-type lidar is suggested, with a blue-emitting laser. During the day and night, penetration of this blue laser pulse into the surface ocean will effectively stimulate chlorophyll fluorescence and thus permit a global mapping of iron-limited plankton populations. Active measurements of chlorophyll fluorescence are also envisioned for the physiology lidar mission discussed above. *Therefore, augmentation of an ocean-optimized profiling lidar system to include a chlorophyll fluorescence detection band and execution of the physiology lidar concept have the potential to significantly advance ecological understanding and contribute to CDR monitoring.*

There is concern by stakeholders, scientists, and the public on the manipulation of ocean ecosystems on a global scale, its reversibility, and potential unintended geochemical and ecological consequences; however, engineering solutions are now being considered seriously as a course of action for mitigating climate warming. While this document is <u>not supporting</u> such manipulations by the above text, *it would be prudent for NASA to be engaged in these discussions and essential for the NASA OBB program to be proactive in considering the global observing system appropriate for studying such activities if conducted in the ocean*.

Climate and the Elements of Life Summary

Of all the ocean worlds in our solar system, only Earth receives enough solar energy to have a largely ice-free surface, prominent hydrologic cycling, strong ocean currents, and warm surface temperatures conducive to rapid enzymatic activity. These attributes drive massive biogeochemical cycles of life-sustaining elements and leave indelible signatures of biological activity in nearly every corner of our planet. *Human activities are having an unmistakable impact on life throughout the biosphere and Earth's physical-chemical environment. These impacts have unavoidable consequences on elemental cycles that threaten the health, sustainability, and human services of our living ocean. Understanding mechanisms driving elemental cycles in today's ocean dramatically enhances our ability to predict and prepare for future changes in a warming climate.*

Areas of opportunity within the **Climate and the Elements of Life** grand challenge include:

1) Sustain PACE-equivalent global ocean color observations to observe key ocean properties influencing elemental cycles and to inform numerical models (continued).

2) Sustain GLIMR-equivalent or other high temporal resolution remote sensing approaches (e.g., constellation of lower-cost hyperspectral low-Earth-orbit sensors) to characterize sub-daily fluctuations in plankton stocks and rates (continued).
3) Investigate technologies for global ocean color observing from the L1 orbit, building toward a future L1 ocean color satellite mission (long-term)
4) Augment the HSRL-type ocean-optimized and blue-emitting laser profiling satellite lidar with chlorophyll fluorescence and colored dissolved organic matter detection capabilities (immediate/near-term).
5) Sustain PACE-equivalent polarimetric ocean measurements for characterizing atmospheric aerosols and particulate matter and suspended ocean particle types (continued).
6) Expand global coverage of sustained autonomous and shipboard *in situ* measurements of key physical, chemical, and biological processes and rates. Invest in technology development that allows a more comprehensive assessment of food web processes, carbon cycling, community composition, and array of nutrients and other elements from autonomous platforms, drawing in some cases upon successful advanced measurements (e.g., radiometry) on international autonomous platforms (near-term).
7) Support research to synthesize disparate observing system data (e.g., ocean color, lidar, BGC-Argo), including development of data assimilation models explicitly resolving remotely detectable properties (e.g., water leaving radiances, inherent/apparent properties) (continued).
8) Emphasize mass-balanced model development, diversification, and testing to ensure parallel evolution of modeling and observational capabilities (immediate).
9) Conduct targeted field process studies and ship surveys to inform model development and enhance mechanistic interpretations of observed changes in ocean properties (near-term/long-term).
10) Continue suborbital research to better constrain ocean-to-atmosphere biogenic emissions (continued).
11) Explore remote sensing approaches to characterize diel cycles in spectral particulate backscatter, attenuation, and chlorophyll fluorescence (e.g., a physiology lidar)
12) Explore remote sensing approaches (e.g., CubeSat) to quantitatively measure mass deposition fluxes to the ocean surface and enable model refinements linking atmospheric inputs to ocean elemental cycles and ecosystem responses (long-term).
13) Consider in NASA's OBB program, the planning of observing and modeling capabilities that will be needed to monitor impacts of potential carbon dioxide reduction implementations in the coming decade and beyond (immediate).

Meeting the **Climate and the Elements of Life** grand challenge requires sustaining an unbroken record of remote sensing observations already in the Program of Record, as well as critical new observational capabilities. Many of the above opportunities are also relevant to the **Global Biosphere** (**SECTION 3.1**) and **Interface Habitats** (**SECTION 3.3**) science, but some are unique. These unique observations target specific processes linking elements, organisms, and food webs across depth horizons within the ocean and between the air-sea interface. The full suite of *observing system* elements outlined here fosters advanced numerical modeling, which is the cornerstone for quantitative assessment of elemental cycles. Accordingly, achieving **Climate and the Elements of Life** goals requires the parallel evolution of modeling and observational capabilities over the coming decade and beyond, supporting *in situ* measurements and process studies, and interdisciplinary and interagency collaboration.

3.3 Interface Habitats

Establish how natural processes and human activities govern the diversity, function, and resilience of life in interface habitats such that the services and value of these dynamic systems to humanity can be safeguarded and sustained for future generations.

The most productive and diverse aquatic habitats occur where water meets land (e.g., coasts, lakes, estuaries, and wetlands), the seafloor (e.g., continental shelf, seafloor), the atmosphere (e.g., phytoplankton blooms; see **SECTIONS 3.2** for its discussion), and ice (e.g., polar floating ice). These **Interface Habitats** support complex biological communities, serve as important nurseries for many invertebrates, fish, bird, amphibian, and mammal species, play important roles in the biogeochemical cycling of nutrients and carbon, and purify both fresh and salt waters. In addition, interfaces are also where marine litter and debris are particularly abundant, greater than eighty percent of which is plastics (Maximenko et al., 2019). **Interface Habitats** are where most of humanity's interactions with aquatic ecosystems occur and they provide social, economic, and ecological benefits that have attracted people across the Earth since the beginning of human history. **Interface habitats** are sites of massive materials exchange and transformations, including carbon, nutrients, and pollutants from the land and atmosphere and the fixation and burial of some of these materials in wetland soils and marine sediments. Understanding and quantifying these processes and the communities involved is essential for optimizing management strategies that safeguard the resources they offer. Finally, **Interface Habitats** are critical areas of investigation to inform exploration of ocean worlds on other planets (NOW 2021). Achieving this goal requires advances in remote sensing, modeling, and field measurements, but the spatial heterogeneity, temporal dynamics, and optical (and chemical) complexity of **Interface Habitats** requires unique capabilities that build upon and complement strategies outlined in **SECTIONS 3.1** and **3.2**.

Many coastal and fisheries-dependent communities are established around **Interface Habitats** that are already polluted and have suffered from habitat degradation, overfishing, and other harmful practices, both inland and along the coast. The aggregated global impacts of coastal fisheries and aquaculture on the marine environment are unknown and currently difficult to quantify. New and reoccurring blooms of toxic or noxious phytoplankton and/or macroalgal species have also become commonplace along **Interface Habitats**, with major health and economic impacts. Today, industries are also looking to the deep seafloor for large-scale mining opportunities, which will mobilize manganese, mercury, and other metals and redistribute them into the mesopelagic zone through sediment tailing. All these issues are at the core of the United Nations Sustainable Development Goals and Blue Economy initiatives. Comprehensive assessments of the status and trends in the extent, biodiversity, and biogeochemistry of **Interface Habitats** require development of new and synoptic observation strategies.

In extreme high-latitude environments, the interaction between ice and water creates unique **Interface Habitats**. The edge of the sea ice pack is a dynamic zone that moves latitudinally with the seasons. Melting sea ice in the spring can create stability in the water column that supports large plankton blooms and causes strong depth-dependent gradients in plankton concentrations. The timing, size, and type of ice edge blooms can define the success of a growing season and can control recruitment of invertebrate, fish, bird, and marine mammal populations. The composition of the food web in the Arctic Ocean and in the Southern Ocean near Antarctica depends on the seasonal extent of the sea ice-water boundary. These remote environments are difficult to explore by traditional means, yet their global and regional importance requires that we understand the interplay of physical, chemical, and biological processes that shape their associated ecosystems, particularly as these systems are witnessing some of the most extensive and rapid changes in our warming planet (Babin & Forget 2015).

Earth is the only planetary body in the universe that we know for certain is inhabited. On other ocean worlds in our Solar System, like Europa and Enceladus, permanent ice cover may prevent sunlight from penetrating to the liquid ocean below. Analogs for assessing habitable environments on these other ocean worlds include interfaces on Earth, such as ice-water and seafloor-water boundaries (e.g., hydrothermal systems) (NOW 2021). Much of the technologies developed to assess boundary habitats on Earth, including passive and active remote sensing techniques, can be harnessed to explore processes in these alien ocean worlds (NOW 2021).

In the face of projected human population increases, associated consumption of natural resources, a growing aquaculture industry, and accelerated environmental change, the need is escalating for improved understanding of ***Interface Habitats*** *regarding their ecological and biogeochemical functioning, their resilience, and the services they provide to humanity.* These attributes of **Interface Habitats** are directly tied to biodiversity and productivity. Biodiversity, or the variety of life in a habitat, ecosystem, or region, can now be measured in tremendous detail at very local scales through genome sequencing, but as the spatial scale of assessment increases the characterization of diversity tends to have less specificity. From a remote sensing perspective (and aside from a few unique organisms such as coccolithophorids and *Trichodesmium*), progress has been made in differentiating broad 'functional' phytoplankton groups by using multi-spectral ocean color data, but current approaches have largely been tuned to open-ocean conditions (Muller-Karger et al. 2018). For many **Interface Habitats**, a tremendous diversity of dissolved materials and particles of various sizes, shapes, and pigmentation, even sea ice, influence the amount and spectral nature of light leaving the water's surface and this optical complexity can compromise the accuracy of current algorithms for separating major phytoplankton groups, as well as algorithms for assessing primary production (Muller-Karger et al. 2018). Here, hyperspectral ocean color data can be particularly beneficial for classifying in-water constituents. It is anticipated that PACE observations will significantly advance understanding of **Interface Habitat** biodiversity over continental shelves and for other large water bodies where ~1 km spatial resolution data are sufficient. GLIMR will also provide continuous hyperspectral observations for studying biodiversity of near-shore waters around North America at the modestly improved spatial resolution of ~300 m. NASA's upcoming SBG mission will contribute significantly to the continuation and improvement of **Interface Habitat** studies through its expected continuous spectral coverage from the ultraviolet to shortwave near infrared with a 30-40 m spatial footprint.

Marine litter and debris are a major human-induced problem that manifests at all **Interface Habitats**. Anthropogenic debris travels large distances and is ubiquitous. This debris floats-on and is submerged-in the water, on the seafloor, within sediments and sea ice, and along shorelines. Unfortunately, observations of its sources, composition, pathways, and distributions in the ocean are very sparse and inaccurate. Total amounts of plastics and other man-made debris in the ocean and on the shore, as well as degradation processes, vertical fluxes, and time scales, are largely unknown (Maximenko et al., 2019). Many different techniques have been proposed to detect and quantify marine debris (including plastics), including passive and active ocean color remote sensing from satellites, aircraft, and drones. Several national and international groups are actively evaluating approaches to assess marine debris more effectively. One such initiative is being led by the International Ocean Colour Coordinating Group (IOCCG). Its task force on Remote Sensing of Marine Litter and Debris aims to coordinate the advancement of current and future remote sensing technologies and techniques that have potential to provide observations of plastic litter over all aquatic environments.

In addition to in-water optical complexity, remote sensing of **Interface Habitats** can also be challenging because of mixed contributions from benthic and pelagic organisms to system-level primary production and influences of land, shallow water sediments, and sea ice on measured ocean color signals. In addition, high levels of dust, aerosols, atmospheric trace gases, and other pollutants can compromise ocean color atmospheric correction algorithms over interface regions. **Interface Habitats** also tend to be subject to enhanced physical mixing, upwelling, and tidal influences that result in small-scale heterogeneity in ecosystem attributes and challenge mechanistic interpretations of spatial and temporal trends in biodiversity and productivity. These physical influences can, at least in part, be characterized using altimetry and high-frequency radar data to quantify advection by surface flow fields and thus delineate underlying processes driving observed ocean color variability (Messié and Chavez, 2017; Matson et al., 2019; Catlett et al., 2021). By incorporating a variety of technologies, satellite remote sensing has also been used to associate ecosystem features with physical fronts and mesoscale eddies (Siegel et al., 2011; Gaube et al., 2014), assess the role of Lagrangian Coherent Structures in shaping niches and fisheries (Watson et al., 2018; Scales et al., 2018), and identify and classify dynamic pelagic habitats (Irwin and Oliver, 2009; Kavanaugh et al., 2016, 2018). These diverse interactions between ecosystems and ocean physics are fundamentally important to larval dispersal (Kuhn et al., 2019) and structuring phytoplankton (Schulien et al. 2020), zooplankton (e.g., Govoni et al., 2010), and higher trophic level communities (Della Penna & Gaube, 2020, Oliver et al., 2019).

As noted above, a key attribute distinguishing **Interface Habitats** from the systems discussed in **SECTIONS 3.1** and **3.2** is their enhanced spatial heterogeneity and rapid temporal dynamics. Effective observing of these systems thus requires a combination of observing platforms, as individually, capabilities in current platforms are either temporally limited or offer discontinuous coverage. Suborbital sensors on piloted aircraft, unoccupied aerial vehicles, and autonomous underwater vehicles provide measurements at the smallest spatial scales (i.e., centimeter to meter) and have been used to characterize patches and diversity in coral, algal, under ice, and other benthic habitats (e.g., Mayot et al. 2018, Monteiro et al., 2021; Cavanaugh et al., 2021). Satellite remote sensing has also provided meter-scale observations of **Interface Habitats** (e.g., SPOT), with Landsat measurements emerging as particularly impactful. Landsat sensors provide multispectral data at ~30-meter resolution with a 16-day repeated cycle. While specifications have changed between sensors, these data have now been collected for nearly five decades. With the constellation of Landsat 8 and 9, as well as Sentinel-2A/2B (at 10 to 60-meter resolution), a 2-3 day revisit can be achieved to study fine-scale features and highly dynamic processes in nearshore ecosystems (e.g., tidal carbon exchange in wetland-estuary interfaces; Cao and Tzortziou 2021; Pahlevan et al. 2019). A challenge with the Landsat time series is that few operational ocean products are generated, so additional focused efforts are needed to expand these products to ensure maximum utility of the record for studying **Interface Habitats**.

One of the important applications of Landsat data has been the identification and monitoring of 'foundational species.' Foundational species are key organisms that nucleate locally stabilized environments and create patches of complex habitat that increase biodiversity and provide refuge for reproduction and larval populations. In marine environments, foundational species include mangroves, kelps, seagrasses, and reef-forming groups, such as corals and bivalves. Foundational species have also been observed, in addition to satellites, through suborbital platforms, which include both *in situ* and airborne observing platforms. Airborne laser systems have provided detailed bathymetry and geomorphology measurements in **Interface Habitats** over spatial scales on the order of 100 km^2. Remote sensing of benthic habitats is complicated by scattering and attenuation of the overlying water column, making hyperspectral imagery particularly useful for accounting for these effects.

Airborne hyperspectral remote sensing has provided detailed benthic habitat maps of fleshy and turf algae, seagrasses, coral, and coral rubble. Time-series of such data have been used to evaluate changes in land use, coastal development, and reef connectivity. Emergent vegetation typically has a relatively strong reflectance signal and remote sensing has been used to create global maps of foundational species, such as floating kelp and macroalgae, saltmarsh, and mangroves. Remote sensing is also useful for documenting variability in these systems on large spatial scale. Landsat and airborne hyperspectral data have been used to characterize kelp canopy biomass (Cavanaugh et al., 2011), population dynamics (Bell et al., 2015a, McPherson et al., 2021), responses to ocean warming events (Cavanaugh et al., 2019), phenology (Bell et al., 2015b), and physiological status (Bell & Siegel, 2022) (e.g., carbon-to-chlorophyll, nitrogen, and sugar content). It is important to note that for all these remote sensing applications, traditional *in situ* monitoring and higher precision suborbital remote sensing are essential for ground truth and performance evaluation of satellite data and for moving beyond broad vegetation types (e.g., kelp, mangrove, or *Sargassum*) to finer taxonomic differentiation (McPherson & Kudela, 2022). It is also important to highlight that as the spatial resolution of satellite remote sensing data increases, temporal repeat coverage of measurements from a given sensor tends to decrease. As discussed later in this section, improved temporal coverage of high spatial resolution data can be achieved by integrated measurements from multiple platforms, such as a constellation of CubeSat platforms.

Species distribution modeling is an additional tool for understanding complex **Interface Habitats**. These models, which are also used in open ocean settings, can be used to identify the factors that correlated with the distribution of species. Species distribution models combine data on static features (e.g., bathymetry, seafloor rugosity, proximity to features such as coastlines and seamounts) with dynamic variables from remote sensing or regionally tuned models to predict community composition, sometimes including endangered species. Species distribution modeling can provide a basis for resource management and prediction of change. However, these models are often not mechanistic, and the employment of machine learning techniques can lead to the use of correlative relationships that are not process-based (see e.g., Bardon et al., 2021). Alternatively, mechanistic 'growth-advection' models have been developed that are forced by remote sensing data and reproduce observed patterns in key species (Messié and Chavez, 2017). Combining these more mechanistic models with species distribution models can provide an avenue for assessing uncertainties in predictions. Additionally, regional numerical models can be run at high resolution to capture interface regions (e.g., Regional Ocean Modeling System). Such models can include input from land or sea ice through runoff and meltwater and thus capture elements of interface habitats. However, linking different components of the Earth system in mechanistic models remains challenging, with time scales and spatial scales not always coinciding.

While significant advances have clearly been made in understanding and modeling **Interface Habitats**, the complexity of these systems and their invaluable services to humanity demand continued development of effective observing systems that entail satellite remote sensing, suborbital and in-water assets, process-based field studies, and advanced modeling. From the remote sensing perspective, tradeoffs need to be balanced regarding technologies targeting high spatial resolution, high temporal resolution, and high spectral resolution observations, as well as radiometric quality (i.e., signal-to-noise, electronic and spectral crosstalk, etc.) (Muller-Karger et al. 2018). As indicated above, *at present, there is no single approach that can achieve all these needs*. In addition, the **Interface Habitats** grand challenge has a particularly explicit element of supporting human services, policy and decision making, impacts assessment, and management. These goals require approaches for ingest, processing, and integration of diverse data streams and then assimilation into operational models aimed at improving state, local, and tribal assessments for management and enhanced ecological forecasting. Furthermore, a need exists to link remote sensing reflectance measurements to in-water properties of need at multiple scales for partners and stakeholders. Thus, continued development of data processing and distribution infrastructures is necessary, along with the development of an educated workforce capable of identifying key unknowns, processing advanced observational data, and applying new technologies and products for monitoring and applications. Additional progress is also needed in establishing effective links between research and decision-support tools for managers and policy makers. *The **Interface Habitat** grand challenge can be most effectively addressed by seeking partnering opportunities with National Oceanic and Atmospheric Administration (NOAA) and United States Geological Survey (USGS) to help bring NASA products into local hands, get feedback on their utility, and enable enhanced citizen science product validation*. Producing operational products from existing high spatial resolution satellites (e.g., Landsat 8/9, Sentinel 2A/B) should be a short-term goal that will significantly boost the data user community. Combining data from multiple sensors would yield a temporal resolution in coverage of better than 5 days, but efforts will be needed to improve atmospheric correction algorithms (see above) and cross-calibration of sensors.

Interface Habitats Opportunities

To address the **Interface Habitats** grand challenge, *it is critical that the successful execution of the PACE and GLIMR missions* in the Program of Record is ensured, as well as *continuation of equivalent-quality observations for both into the future (e.g., via GeoXO for geostationary), and continued support and development of the SBG mission*, including assurance that the final mission architecture entails technological capabilities supporting advances in aquatic **Interface Habitat** science. *In addition*, *an enhanced effort in the operational processing of heritage and contemporary remote sensing data* relevant to **Interface Habitat** research is required (e.g., Seegers et al. 2021). Open-access, user-friendly, multidisciplinary data products (including ocean, atmosphere, wetland, and other terrestrial) will greatly enhance their applications by the science community, thereby ensuring maximum benefits from investments to date and an increasing tempo of progress in addressing the **Interface Habitats** grand challenge. These heritage records provide an invaluable baseline against which future change can be evaluated. *Continuing this emphasis on operational processing into the future will be fundamental, as well as enhancing efforts on inter-sensor calibration among missions (both nationally and internationally) and characterizations of temporal changes in sensor performance* (Barnes et al. 2021, Franz et al. 2021). This latter point is essential for ensuring that detected spatio-temporal patterns in geophysical properties are robust and not simply reflections of within-sensor or sensor-to-sensor artifacts.

While Landsat and SBG type satellite observations will continue to play a critical role in observing global **Interface Habitats** because of their radiometric capabilities and spatial resolution, these sensors do not provide the temporal resolution of measurements necessary to characterize many key features in these dynamic systems without multiple similarly capable instruments flown in constellation, as is being pursued for the European Space Agency's (ESA) Sentinel-2 MultiSpectral Instrument (MSI) and discussed further below. Geostationary observations, such as GLIMR, can provide hyperspectral ocean color data at high temporal resolution, but at the cost of coarser spatial resolution (~300 m) to achieve sufficient signal-to-noise data and only for a limited region for a given satellite. An important new addition to these higher-quality data records that addresses the need for global daily-to-sub-daily resolution observations is a complement of low-cost, potentially lower radiometric quality measurements from a constellation of CubeSat-type sensors, as was introduced in **SECTION 3.2**.

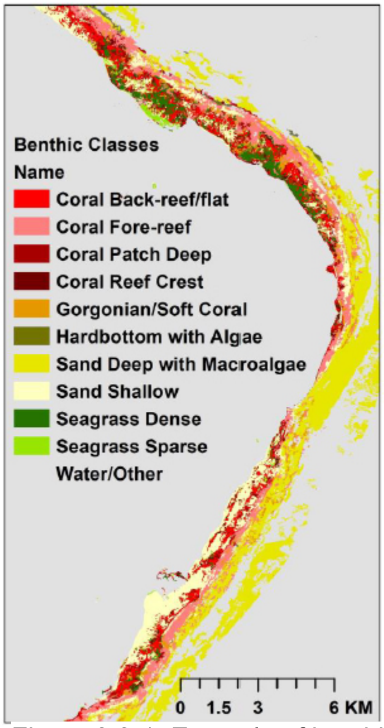


Figure 3.3-1. Example of benthic community classification using data from Planet-Dove. (from Li et al. 2019)

Commercialization of satellite remote sensing has resulted in the development of the Planet-Dove constellation. Each 'Dove' satellite provides 3.7 m scale imagery and over 150 instruments have already been launched into orbit, with many more planned for future deployments. A diversity of orbits within the constellation provides roughly daily observations of global **Interface Habitats**. An example application of Planet-Dove data is shown in figure 3.3-1, where a variety of benthic habitats were classified for a region of the eastern Dominican Republic (Li et al 2019). Validation of these retrievals with field measurements indicated an overall accuracy of 82%. Similar classifications were conducted for other reef systems (e.g., Catalina Island, Saona Island) by the authors and provide a basis for detecting temporal changes in these systems at high temporal and spatial resolution. These data have also been used to create a global-scale coral reef probability map (Li et al. 2020). Currently, the Planet-Dove program has not addressed a variety of concerns with the data, such as radiometric accuracy, sensor degradation, inter-sensor calibration, geolocation, documentation, and others, but it does provide a tantalizing proof-of-concept illustration on how constellations of low-cost sensors can provide an important complement to NASA research, analysis, and applications activities and potential synergies with NASA missions such as Ice, Cloud and land Elevation Satellite-2 (ICESat-2) and Global Ecosystem Dynamics Investigation (GEDI). Maxar/DigitalGlobe provides another example where commercialized low-cost satellite sensors have provided data complementing existing NASA research programs. In the case of Maxar/DigitalGlobe, greater attention has been paid to sensor calibration, geolocation, radiometry, and documentation, such that these data are amenable to detecting quantitative trends. *It is important that approaches such as those utilizing low-*

cost sensors be considered in the future as avenues for addressing important elements of the **Interface Habitats** grand challenge *not encompassed by the other higher-cost missions noted above*. To facilitate this, work is also needed to generate operations products from such sensor, make these data easily available for the research and management communities, and train users on data access and harmonization methods. These types of observations can provide a highly cost-effective solution for greatly improving coverage of coral reef, macroalgae, and oil slick mapping, understanding marine photosynthesis at meter-scale resolution, and quantifying the role of ephemeral water bodies on the hydrologic cycle, among many other potential applications. The high spatial resolution of these data is especially useful for mapping subtidal and intertidal habitats that are highly variable on small spatial scales (e.g., coral reefs, saltmarshes, estuaries, etc.).

In addition to passive satellite observations, active remote sensing technologies are also valuable for improved understanding of **Interface Habitats**. As noted in **SECTION 3.1**, recent advances in satellite lidar applications have demonstrated an ability to detect higher-trophic level organisms than those registered in passive ocean color data (Behrenfeld et al. 2019). High vertical resolution data from the ICESat-2 lidar have also been used to characterize phytoplankton properties both below sea ice and along the sea ice-water interface (Lu et al 2020, Bisson et al. 2021). *Re-emphasizing some of the opportunities identified in **SECTIONS 3.1 and 3.2**, the development of an advanced ocean-optimized satellite lidar is a priority for research on* **Interface Habitats**. In addition, airborne lidar measurements have a long history of applications in **Interface Habitats** (Hostetler et al. 2018) and can provide important observations on shoreline elevations and change, benthic habitats, and vertical structure of intertidal vegetation (e.g., mangroves) and near-shore communities. Similarly, airborne hyperspectral ocean color observations have been instrumental for validating and testing satellite remote sensing retrievals in **Interface Habitats**, as have measurements from in-water sensors and field monitoring programs. *Continued development of these suborbital assets, including the expanded use of sensors on drones, is thus suggested as a vital element in supporting advanced satellite remote sensing and for assessing critical properties and processes of* **Interface Habitats** *not amenable to space-based observations*. These enhanced observing capabilities also contribute to science objectives described for the **Transient Events** grand challenge detailed in **SECTION 3.4**.

The opportunities identified above create the foundation of an effective observing system for addressing the **Interface Habitats** grand challenge, but also essential to this system is parallel development of data processing capabilities, improvements in data analysis, and training of next-generation scientist in using data from new observing platforms (e.g., geostationary, CubeSat, etc.). Considerable advances are still needed in algorithmic approaches to more accurately separate suspended and dissolved constituents in optically complex waters and discern suspended constituents from submerged or emergent vegetation (Dierssen et al., 2020). Improvements are also needed in ocean color atmospheric correction strategies for the often-challenging conditions of **Interface Habitats** where nonmaritime aerosols, high amounts of atmospheric trace gases (e.g., NO2, ozone), and optically complex waters persist. New metrics are needed to characterize the health and condition of coastal foundational species to aid in the detection of ecosystem degradation. Advances in ecological theory, including impacts of interactions between organisms, and ecosystem valuation studies are needed, especially those linking social and natural sciences.

Synthesizing observational data, interpreting cause-and-effect, and making robust predictions of change will require advances in regional modeling. As noted above, modeling approaches for **Interface Habitats** may be statistical or mechanistic and *continued development of both is of utmost importance*. For mechanistic models, emphasis should be placed on improved transfer of information across model components (e.g., terrestrial and atmospheric modules to ocean module, sea ice module to ocean module), thus requiring interdisciplinary teams of scientists and sustained funding for model development.

Model-based uncertainty assessments are needed and, when compared to remote sensing data, are optimal if modeled parameters are consistent with direct observables (e.g., spectral ocean reflectance and backscatter) (Bell et al. 2020). Data products derived from these analyses need to be made readily accessible to managers and policy makers through the development of platforms where data can be viewed, analyzed, and downloaded. Finally, success in addressing the **Interface Habitats** grand challenge relies on the cooperative interagency effort of engineers, biogeochemists, ecologists, modelers, and the stakeholders who ultimately define application needs for ensuring sustainable and healthy ecosystems of our global **Interface Habitats**.

Interface Habitats Summary

For most people on Earth, our direct connections to aquatic ecosystems occur at **Interface Habitats**. These diverse, productive, and complex systems provide invaluable goods and services, but are also most susceptible to impacts of human activities. *The spatial heterogeneity and rapid tempo of change in **Interface Habitats** places unique demands on effective observing systems. Historical observations of **Interface Habitats** create a baseline record for documenting current and future change, while enhanced observing capability can provide new insights on system functioning that leads to improved predictions.*

Areas of opportunity within the **Interface Habitats** grand challenge include:

1) Sustain PACE- and GLIMR-equivalent ocean color observations into the future (continued).
2) Support SBG development and advocate technological capabilities supporting effective observations of aquatic ecosystems (immediate/near-term).
3) Enhance efforts on operational processing of heritage and contemporary higher spatial resolution remote sensing data (e.g., Landsat) and enhance efforts on inter-sensor

calibrations among these missions with medium resolution ocean color missions, as well as international high-spatial resolution ocean color missions (e.g., Sentinel-2) (immediate).

4) Evaluate potential lower-cost approaches (perhaps like Planet-Dove and Maxar/DigitalGlobe) for achieving higher spatial- and temporal-resolution observations than those provided by missions in the Program of Record (near-term).
5) Promote ocean-optimized profiling satellite and airborne lidars for characterizing plankton vertical structure in near-land and near-ice habitats (immediate/near-term).
6) Continue developing suborbital observing capabilities, including autonomous sensors on drones, floats, and similar, to support advanced satellite remote sensing and to characterize **Interface Habitats** properties not amenable to space-based observations (continued).
7) Support development of new approaches to derive meaningful geophysical quantities in optically complex waters at interface boundaries and in the presence of significant dust, aerosols, and pollutants (near-term).
8) Support research for synthesizing disparate observing system data and assimilating data into operational models that improve state assessments and ecological forecasting (see **SECTION 3.5**) (continued).
9) Sustain support of interdisciplinary modelling teams that link different components of the Earth system (e.g., land, ice, atmosphere) at increasing spatial resolution and enhanced detail (e.g., wet/dry deposition) to the ocean (continued).
10) Conduct targeted field process studies to inform model development and enhance mechanistic interpretations of observed changes in Interface Habitats (near-term/long-term).
11) Invest in advanced studies to improve atmospheric correction approaches applicable to the complex viewing conditions of **Interface Habitats** (continued).

Meeting the **Interface Habitats** grand challenge requires a complement of satellite and suborbital measurements, including and expanding upon those in the Program of Record, that together provide the needed spatial, temporal, and spectral coverage of observations. These data, along with supporting field studies, provide essential information for advanced ecosystem and operational modeling that improves scientific understanding of **Interface Habitats** and creates a foundation for improved forecasting, management, policy, and protection of these vital natural resources. In **SECTION 3.4**, additional opportunities are recognized regarding enhanced observational capabilities for addressing the **Transient Events** grand challenge. While those opportunities are less focused on sustained global data records than described above, their attention to high spatial resolution measurements makes them highly relevant to **Interface Habitats**.

3.4 Transient Events

Develop the knowledge base and infrastructure to detect, quantify, predict, and understand marine responses to transient events to enable preparation, mitigation, and recovery when these events affect communities.

Change brings both opportunities and risks to aquatic ecosystems, and sometime these changes are abrupt and extreme. Heavy rains over land can lead to rapid swelling of riverine systems and massive offshore materials plumes, and input of debris to coastal waters. Volcanic eruptions can deposit more ash-borne nutrients to surface plankton than they normally experienced over the entire year (e.g., Fig. 3.2-1). A spring storm may overturn a water column to 100's of meters depth, resulting in the disruption of predator-prey relations and enabling a plankton bloom. An oil spill can transform a pristine ecosystem into a toxic environment. These and many other forms of **Transient Events** can have disproportionally large impacts on the productivity, biodiversity, succession, and biogeochemistry of near-shore to off-shore communities, yet our ability to predict these outcomes is hampered because the unpredictable nature of these events challenges operational systems focused on routine observation. Indeed, the collection of key measurements before, during, and after a **Transient Event** may often be simply a matter of luck.

Transient Events in aquatic systems have occurred throughout the history of life on Earth. Mild environmental disturbances can enable the further proliferation of already dominant species. Modest disturbances can initiate successional sequences in dominance. Extreme disturbances can open new habitats for opportunistic, pioneer species. **Transient Events** can alter seascapes and coastlines, devastate habitats, and alter food web functioning. Today, natural **Transient Events** are coupled with new forms of disturbance associated with human activities, such as biological outbreaks of public health threats (e.g., harmful algal and bacterial blooms), coastal erosion, and anthropogenic disasters (e.g., oil spills, industrial chemical releases, etc.) that may threaten life, property, and commerce, and require immediate responses to mitigate impacts.

Biological outbreaks of certain phytoplankton and bacterial species can lead to high concentrations of potent neurotoxins in the water that adversely impact zooplankton, shellfish, birds, fish, marine mammals, and humans. Causes of these harmful blooms are complex and poorly understood, making them difficult to predict. Accordingly, routine monitoring is needed to detect early phases of these **Transient Events** and provide warning of toxin threats to water, food, and air. However, monitoring systems and forecasts are not fail-proof and 'false positives' can be costly because of unnecessary emergency responses or unwarranted application of regulations, such as closures of fisheries and beach access.

Petroleum and other hydrocarbon products are essential to modern society and must be transported considerable distances over land and sea. Ten to fifteen transfers are typically involved in moving product from the oil field to the final consumer. Many of these transfers occur on ships or through pipelines on the seabed. Oil spills to the marine environment can result from transportation accidents, pipeline leaks, controlled releases by shipping operators, and from oil production platforms. These spills can be dispersed in a matter of hours over large distances by wind, waves, and currents. Oil spills impact organisms ranging from microscopic phytoplankton to marine mammals, damage habitats, and compromise the livelihood of residents in coastal communities, often for many years into the future and particularly for communities based on fishing and tourism.

Effective observing systems are essential for understanding ecosystem responses to, and biogeochemical consequences of, **Transient Events**, and, in some cases, to minimize ecological and societal effects. While each type of **Transient Event** presents its own unique observational challenges, there are several attributes common across events that are key targets. First, an observable property must be identified that distinguishes a given anomaly from background, or 'normal', conditions. Next, the spatial extent of the anomaly and its dispersion or movement may need to be defined. If possible, it is also generally desired to know the severity or the concentration of the event or ecosystem response, recognizing here that these quantitative assessments are often difficult or impractical. Finally, the duration of the event must be characterized. With the above information, an evaluation can be made on the potential or realized impacts of a **Transient Event** on affected ecosystems and human communities. Over time, these observations can yield insights on the frequency and potential predictability of different types of **Transient Events**.

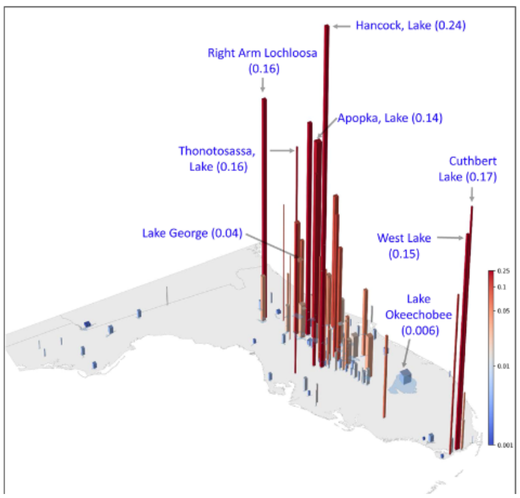


Figure 3.4-1. Magnitude of harmful cyanobacterial blooms in Florida lakes during 2011 as observed by the Medium Resolution Imaging Spectrometer (MERIS) satellite sensor. (From Mishra et al. 2019)

Satellite and suborbital remote sensing, including airborne and in-water autonomous platforms, have tremendous potential for **Transient Event** applications. Already, remotely sensed optical properties of aquatic systems are being used to assess and understand algal bloom responses (harmful or otherwise) to transient disturbances (Figure 3.4-1), track turbidity plumes and marine heat waves, characterize coastal flooding and susceptible lands, track oil spills and marine debris, and monitor shoreline erosion and change. However, the science and technology of **Transient Event** remote sensing is still in its infancy.

Transient Event Opportunities

Technologies for assessing **Transient Events** from space-borne, airborne, surface-based, and underwater platforms have advanced significantly over the last decade, with different platforms offering different advantages in terms of spectral, temporal, and spatial resolutions and merging data from a combination of platforms generally providing the most effective approach. From a satellite remote sensing perspective, *high spatial resolution and sub-daily observations are particularly relevant* to **Transient Events** monitoring. Medium resolution polar orbiting instruments with 2–3-day repeat coverage have contributed substantially to **Transient Events** monitoring (e.g., Mishra et al., 2019, Coffer et al., 2021), as have high resolution polar orbiters despite their individual ~16-day repeat cycle (Kuhn et al., 2019). Most current satellite instruments, however, are restricted in the types of **Transient Event** properties they can observe, due to limitations in spectral and temporal resolution. Detection of cyanobacterial outbreaks, for example, is best achieved using the combination of ~620, 665, 680, and 710 nm measurement wavelengths (e.g., Coffer et al., 2021), but this complement of spectral bands is not available from all high-spatial resolution satellite sensors. Geostationary sensors provide the additional advantage of hourly-resolution views of a fixed geographic location, which can enable temporal tracking of dispersing plumes or blooms and changes in flooding extent. Large fleets of CubeSats could also provide adequate temporal coverage and meaningful monitoring with properly assigned wavelengths (as introduced in previous **SECTIONS 3.2** and **3.3**). *Therefore, continuation of GLIMR-equivalent regional ocean color observations (via the NOAA-NASA GeoXO Program) is critical, as is the development of a low-cost constellation of CubeSat-type sensors with adequate calibration and spectral resolution for* ***Transient Events*** *applications*. Most space-borne measurements, however, generally have comparatively coarse spatial resolution relative to what is desirable for **Transient Events** monitoring (i.e., 10's to 100's of meters) and effective temporal coverage can be significantly compromised by cloud cover. For **Transient Events** applications, observations that can be successfully conducted under clouds and provide resolutions of a few meters or less are preferable, making suborbital platforms particularly attractive.

Portable sensors on aircraft and drones (e.g, Gray et al. 2022) have been used to support weather forecasting, hazard and coastal water quality assessment, inland flooding, coastline topography mapping, and harbor and shipping lane management. Hyperspectral imaging spectrometers covering visible and near-infrared wavelengths with a high dynamic range and signal-to-noise have been deployed on aircraft to monitor changes in coastal habitats, such as seagrasses and corals (Hill et al., 2014; Hedley et al., 2016, Joyce et al 2018), to identify concentrations and types of suspended particles in surface plumes emanating from rivers, seeps, or spills, and to delineate coastlines and water depth in flooded areas (Dekker et al., 2011). Examples of such instruments are the NASA Portable Remote Imaging SpectroMeter (PRISM), GEOstationary Coastal and Air Pollution Events (GEO-CAPE) Airborne Simulator, and Airborne Visible-Infrared Imaging Spectrometer-Next Generation

(AVIRIS-NG). An additional passive technique relevant for assessing impacts of **Transient Events** in shallow waters is 'fluid lensing'. Ocean wave fluid lensing uses time-dependent non-linear optical aberrations from the aquatic surface to magnify features on the seafloor (Chirayath and Earle 2016), thereby enabling robust imaging of underwater habitats (Figure 3.4-2). This technology has been applied to coral reef ecosystems to delineate three-dimensional reef features and, if a baseline record is established, could be used to evaluate habitat changes following a **Transient Event**.

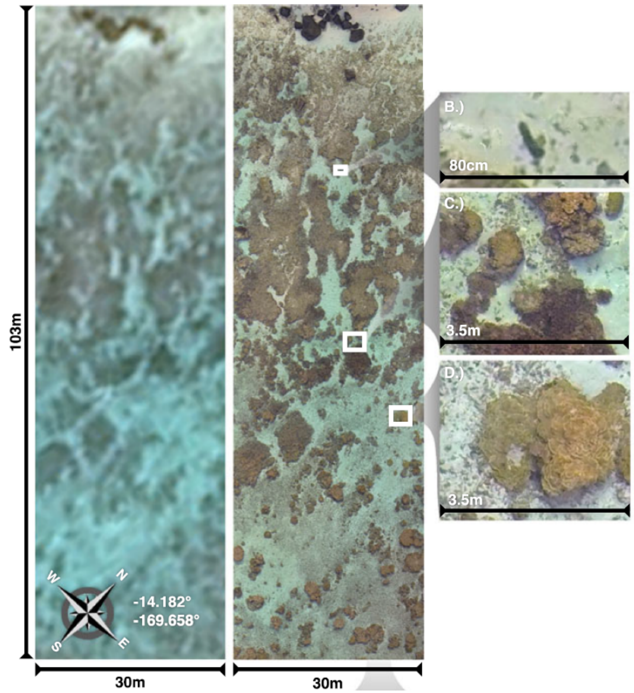


Figure 3.4-2. American Samoa example of benthic habitat imaging using fluid lensing. (left) Highest resolution satellite data. (middle) Fluid lensing retrievals using unoccupied aerial vehicle (UAV) data. (right) close-ups of fluid lensing resolution. (from Chirayath & Earle 2016)

Airborne lidars are also an important tool for addressing the **Transient Event** grand challenge. In the early 1970s, the first airborne laser fluorosensor was flown to map the extent of oil slicks (Brown & Fingas, 2003) and the technology has since been refined (Fingas & Brown, 2014). Fluorescence lidar can now be used for assessing phytoplankton standing stocks and physiology, as well as identifying and estimating the thickness of oil films at the water surface (Li et al., 2014). Active lidar systems are also the most effective means to map shallow water bathymetry (Dierssen & Theberge, 2012), with an elevation accuracy of 10–30 cm. Generally, two lasers are employed for this purpose: 1) an infrared laser (1064 nm) that does not penetrate water is used to detect the sea surface and 2) a green laser (532 nm) is used to penetrate the water column and provide a return signal from the seafloor (Quadros & Collier, 2010). In coastal waters, green light is the least absorbed and generally penetrates deepest into the water column, whereas a blue-emitting airborne lidar may be most appropriate for characterizing ecosystem responses to **Transient Events** in open ocean regions. Lidar measurements have been successfully used to map bathymetric features, beach erosion, coral reefs, and coastal vegetation. Multi-spectral lidar is a recently developed remote sensing technology that, when designed with fluid lensing compatibilities, can extend the depth range of mapped underwater features (Chirayath & Li 2019).

From piloted aircraft, the above-noted sensors can be deployed repeatedly throughout the day with nearly unlimited repeat coverage. Aircraft provide a relatively stable platform that facilitates data geo-correction, accommodates instruments with considerable energy payloads, and provides ample space for supporting hardware (e.g., computers). In addition, these platforms allow flight lines and scanning geometries to be oriented in real-time to optimize retrievals (e.g., avoid sun glint, clouds), while their larger sampling domain allows for resolution of regional-scale features related to **Transient Events**. Disadvantages of aircraft are the considerable costs associated with aircraft maintenance and flight teams and the extended duration of field campaigns to accommodate inclement environmental conditions. Furthermore, the process of integrating, mounting, and calibrating the necessary instrumentation into aircraft may require too much time to observe certain **Transient Events**.

Given the above constraints, the use of small, unoccupied airborne vehicles (UAVs) drones has become increasingly common for conducting aerial surveys (Dierssen et al. 2021). These drones typically have preloaded flight plans, flight durations of 10-15 minutes, and a payload capacity of ~3-5 kg. In addition to simple photography, drones have been adapted with imaging instruments that are often gimbaled to minimize impacts of platform motion. Post-processing of drone imagery into high-quality, time-sensitive data for **Transient Events** responses will require additional investments in modeling and automation but provides a potentially tantalizing resource to capture such events. New drone capabilities that potentially collect samples of water autonomously could also prove useful for developing and validating algorithms for differentiating different types of blooms, toxin levels, and identifying floating materials. *Continued development and deployment of airborne passive and active sensors to observe **Transient Events** and inform responses to these events is of utmost importance.*

As part of the above opportunities and commensurate with those that are discussed in **SECTION 3.5**, attention is needed to ensure that *instruments are well calibrated and have rapid sampling capabilities, and that infrastructure for software development is in place for processing different types and potentially large volumes of co-located data streams* (see additional discussion in **SECTION 3.5**). For hazard-posing **Transient Events**, the more processing that can be conducted in real-time and transmitted back to a control center, the quicker appropriate response measures can be engaged. *Developing a capacity for adaptive sampling will also be advantageous*, such that platforms can be tasked with monitoring precise locations based on real-time data analyses and results.

New and improved in-water retrieval algorithms and ocean color atmospheric correction algorithms are also required. In-water retrieval algorithms are needed that can determine the composition, quantity, and extent of floating and suspended materials across diverse aquatic environments and to assess bathymetry and seafloor composition in shallow habitats. This algorithm development could include a compilation of spectral libraries of different algal types, dissolved constituents (e.g., organic matter, pollutants, toxins), benthic and floating vegetation, suspended sediment types, and other objects of interest. Developments in ocean color atmospheric correction algorithms are needed to accommodate the extreme conditions in water vapor, dust, and other aerosols often associated with **Transient Events** (see also **SECTION 3.3**).

In addition to airborne assets, autonomous *in situ* instruments can provide important observations during **Transient Events**. Sensors on remotely piloted underwater vehicles have been used for quantifying plankton stocks and rate processes, characterizing phytoplankton diversity, and habitat mapping. Imaging systems on underwater vehicles have usually involved digital photography, but sensor technology has advanced towards the ability to obtain high spectral- and spatial-resolution, georeferenced, and optically-corrected digital underwater maps of different habitats, minerals, substrates, and organisms. Laser profile imaging has also been used from an underwater vehicle to map detailed bathymetry of the seafloor (e.g., Roman et al., 2010). *It would be beneficial to continue studies to evaluate how underwater vehicle technologies can be most effectively used for monitoring **Transient Events** and characterizing their time-evolution and ecosystem and habitat consequences*. *In situ* profiling floats can also contribute to addressing **Transient Event** grand challenge. For example, BGC-Argo and similar floats can be equipped with a variety of physical, chemical, and bio-optical sensors which can then be deployed primarily in the open ocean. *Expansion of the* in situ *float array and other autonomous platforms is needed to improve coverage of observations in more inland waters.*

The technology for conducting underwater imaging requires *additional advances including underwater vehicle mechanical and control system design, navigation data processing, machine learning/artificial intelligence advances in adaptive sampling, sensor design, signal processing, image processing, and mapping algorithms*. *Algorithm development is also needed with respect to automatically discriminating, identifying, and quantifying targets of interest*. Adaptive sampling routines could also be optimized so that *in situ* vehicles are programmed to map the extent of targets of interest once they are identified. Finally, and particularly for hazards applications, *integrated modeling and data assimilation efforts will be required to develop predictions of where an event originated and the direction and speed with which its impacts are moving*. This may require incorporating *in situ* measurements and various remote sensing products, such as sea surface temperature, currents, and vector winds, and in the case of near shore events existing datasets on bathymetry and coastal morphology. Expanded model testing for different regimes and **Transient Event** types will be necessary to improve skill for future predictions.

Disturbance Responses: Improving the Odds

While transient hazardous events happen in aquatic environments (e.g., chemical spills, harmful algal bloom, flooding, etc.), the most common **Transient Events** are natural and typically not dangerous to humans. These events might be associated with a rapid increase in river flow to a continental shelf, dynamics from mesoscale eddies, melting of seasonal ice drifts, or passing of a weather system. In all cases, these events represent perturbations to marine ecosystems because they are associated with changes in the physical (e.g., mixing depth, temperature, strong benthic currents, high turbidity) and/or chemical (e.g., carbon, nutrients, hypoxia) environment. There is a long history of research on disturbance ecology, but much of it has focused on intertidal and terrestrial systems. Nevertheless, some of the same basic implications of disturbance may be anticipated for pelagic ecosystems, such as the disruption of predator-prey relationships, proliferation of opportunistic species, and the triggering of a successional sequence in community composition and biodiversity of both benthic and pelagic ecosystems. These, often short-lived, events can be enormously important to biogeochemical cycling and the trophic structure and composition of food webs. Acute restructuring of plankton communities following a **Transient Event** also challenges our ability to characterize biodiversity in the global ocean from satellite remote sensing. For example, one of the important justifications for retrieving hyperspectral ocean color data with the upcoming PACE mission is to improve assessments of phytoplankton community composition. While advances will undoubtedly be made to this end, a major improvement will not only require detailed measurement data on populations at a given time, but also information on the history of that population, including its disturbance history. We might observe two communities with similar hyperspectral signatures but different community compositions if those populations experienced different disturbance regimes that lead to contrasting successions. Unfortunately, our understanding of community responses to **Transient Events** is rudimentary, simply because they are difficult to predict and challenging to monitor directly.

Routine monitoring of pelagic and benthic ecosystems properties is essential to the science objectives of NASA's OBB program, but a mechanistic understanding of short-term variability is essential for interpreting observed properties. *Design studies are needed in the near-term to evaluate effective approaches for conducting detailed observations of disturbance responses in natural systems, followed by the appropriate asset development and deployment*. As an initial starting point, two basic approaches might be considered: (1) purposeful manipulation of an ecosystem that creates a measurable disturbance over scales of over multiple square kilometers or (2) a 'stand-by' deployment scheme that allows rapid mobilization of assets to observe natural disturbance events (here, OSSEs would be invaluable for optimizing such a system). In the case of the former, we might think of this approach as akin to previous iron-enrichment experiments (Coale et al. 1996, Chisholm 2000), but simulating different types of disturbances such as large-scale purposeful mixing of surface plankton populations with deeper plankton-poor waters or caging experiments to evaluate effects of biophysical disturbance and trophic interactions on benthic environments. With respect to the concept (2) above, this might be figurative thought of as the 'tornado chaser' approach, where research teams and deployment assets are prepared for rapid-response studies in regions with a record of frequent transient disturbances. Other approaches should also be considered along with how they might best capitalize on space-borne assets already in orbit or planned for orbit (e.g., the high temporal sampling of a geostationary satellite like GLIMR). Development of sub-seasonal to seasonal forecasting of ocean biology and biogeochemistry would contribute to such efforts. ***Transient Events*** *are a ubiquitous feature of marine systems, but their short-term and moderate-term implications have not been a significant focus of NASA research in the past despite their importance. Planning and investment are needed in the coming decade and beyond to address this issue as the likelihood is high that the nature and frequency of* ***Transient Events*** *influencing pelagic ecosystems will change under a warming climate.*

Transient Events Summary

Understanding responses to and monitoring impacts of **Transient Events** requires an effective and mobile observing system that can be deployed under challenging observing conditions and that employs a unique set of technologies focused on enhanced temporal and spatial resolution and often with fine detection limits. Development of such a system will yield new insights on the temporal dynamics of marine ecosystems and can aid in risk assessment, response planning, and predication in the case of potentially hazardous events. *While satellite remote sensing can support investigations of* ***Transient Events****, suborbital platforms (referring here to diverse approaches including manned aircraft, drones, ship, in-water autonomous vehicles, etc.) are particularly well suited for these applications and have already been demonstrated during a variety of specific events but require additional development and coordination for effective* ***Transient Event*** *monitoring and response support*.

Areas of opportunity within the **Transient Events** grand challenge include:

1) Develop and sustain sub-daily ocean color observations spanning all coastal and large in-land waters of interest (near-term/long-term).
2) Pursue continuity in GLIMR-equivalent regional geostationary ocean color observations (continued).
3) Develop a low-cost constellation of CubeSat-type sensors with adequate spectral resolution for **Transient Events** applications (near-term/long-term).
4) Develop and execute (an) approach(es) for improved understanding of disturbance event effects on marine ecosystems, perhaps involving field campaigns aimed at purposeful manipulations of marine systems or rapid deployments targeting natural events (near-term/long-term).
5) Continue development of airborne passive and active sensors, including unoccupied aerial vehicles with suites of sensors and potentially water sampling capabilities, to improve characterization of **Transient Event** impacts and response support (continued).
6) Continue development of autonomous *in situ* observing capabilities (e.g., piloted underwater vehicles, profiling floats) and develop a 'stand-by' asset pool for rapid response deployments (immediate/near-term).
7) Infrastructure development for rapid processing of large data volumes from disparate observing technologies (see also **SECTION 3.5**) (continued).

8) Support development of new approaches for deriving improved ocean properties under the often-severe observing conditions of **Transient Event**s (continued).
9) Integration of modeling and data assimilation approaches for improved tracking and adaptive sampling of **Transient Events** and their impacts (near-term/long-term).

Meeting the **Transient Events** grand challenge requires unique suborbital observing capabilities that are broadly supported by satellite systems. While airborne and in-water technologies have proven invaluable during specific past **Transient Events**, a coordinated asset pool, established deployment plan, data handling and synthesis system, and link to response and recovery programs has yet to be established. Capacity building is thus needed for the **Transient Events** grand challenge to realize important new insights, protect critical marine and aquatic ecosystems, and enable improved forecasting and mitigation efforts.

3.5 Leveraging Ocean Data and Models

Leverage advanced data harmonization, interoperability, synthesis, integration, and mining strategies and train next-generation scientists to maximize the value of satellite, suborbital, and modeled data streams to facilitate better understanding of life, ocean biogeochemistry, ecosystems, and their dynamic processes.

In recent years, there has been a significant increase in the amount of data available to the ocean biology and biogeochemistry community through expansions in remote sensing, *in situ* networks (e.g., BGC-Argo), and numerical models. MODIS on Aqua and Terra each generate ~30 TB of operational ocean color data each year and even these numbers will begin to seem small with the launch of new missions. For instance, PACE is projected to generate a total of 2.2 TB of data each day from its three-instrument observatory, amounting to ~800 TB each year. The Ocean Biology Distributed Active Archive Center (OB.DAAC; https://oceancolor.gsfc.nasa.gov) currently plans to store these data on physical servers at the NASA Goddard Space Flight Center, with data access through their website. However, parallel studies are underway at a NASA agency level to explore migration of data storage, hosting, and access to cloud-based resources. As additional new missions are approved and launched, there will be an explosion in data volume and data types. We have entered the realm of 'Big Data', where the amount, variety, and acquisition rate of data leads to streams that are too vast and/or complex for traditional data-processing software (Figure 3.5-1).

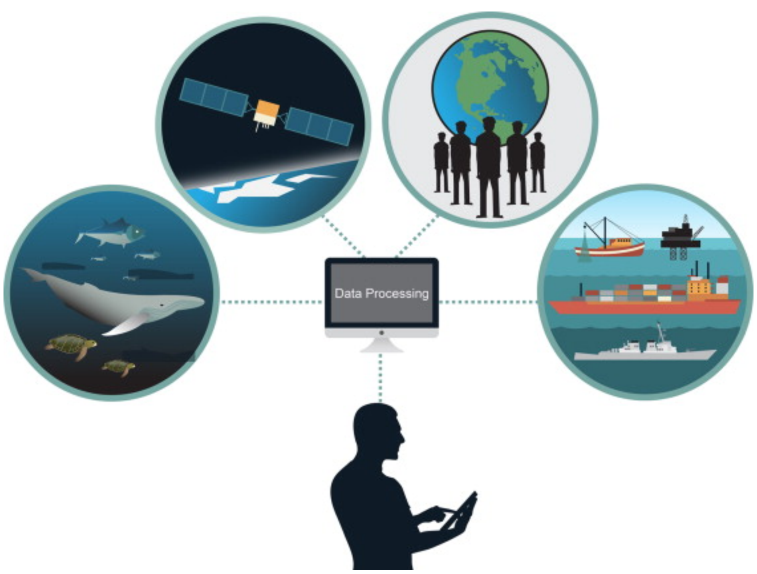


Figure 3.5-1. Multiple data types can be integrated in dynamic management, including biological, remotely sensed, and socio-economic data. (from Maxwell et al. 2015)

While this abundance of incoming data is a huge success in terms of innovation, technological advances, and logistics, *making the most of these data streams will require new techniques and expertise for capture, storage, sharing, usability, and analysis.*

Coincident with the increase in satellite data, there has been a large increase in data from airborne platforms, autonomous vehicles, genomic surveys, citizen science, and output from increasingly finely resolved numerical models. Combining the best attributes of different observational data streams and models will improve our understanding of marine ecosystems and biogeochemistry. Such syntheses will provide better 3-dimensional and temporal characterization of our oceans. Having many disparate data streams quantifying common properties (e.g., carbon biomass) will allow better assessment of uncertainties associated with each data source. *However, due to the heterogeneous nature of different data streams and their occasional incompatibility, it remains unclear how to use them together in an effective and systematic manner.*

Without a proactive vision for addressing the Big Data issue, the sheer volume, accumulation rate, and disparate nature of data streams and model output will significantly hamper our ability to address science goals in the coming decade for the grand challenges discussed in **SECTIONS 3.1** through **3.4**. Different data streams may be obtained through different agencies and from different countries. Additionally, software to process different data streams are not always publicly available. *As such, we deem **Leveraging Ocean Data and Models** as a grand challenge in its own right, with an urgent need for concerted and targeted research, technological advances, and workforce training to solve associated issues.*

Requirements for streamlined acquisition, quality control, synthesis, and data sharing are not new to the ocean color community. Maintaining continuous ocean color records as sensors are launched and others become decommissioned has required a dedicated team, the Ocean Biology Processing Group at NASA Goddard Space Flight Center, for the last three decades. However, the challenge to fully **Leverage Ocean Data and Models** will be even greater in the coming decade as we extend data merging to include additional data streams of established ocean color products (e.g., chlorophyll) from other sources (e.g., autonomous platforms, models) and other data types (e.g., nutrients, plankton species or functional-type composition). One element of this challenge will be evaluating uncertainty and inter-comparability between commonly derived products from different platforms (Figure 3.5-2). For example, chlorophyll concentration is derived from spectral ocean reflectance by passive ocean color sensors, from fluorescence on *in situ* platforms, and attenuated backscattering from lidar. For each approach, algorithms used to produce the chlorophyll product have an associated uncertainty. *Thus, each sensor has its own direct*

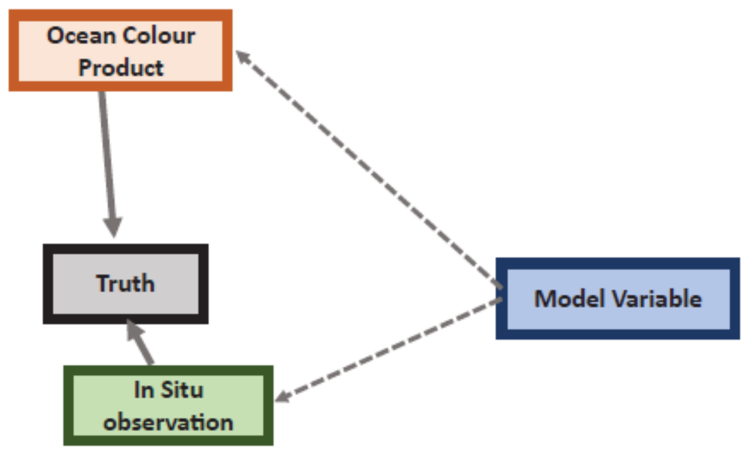


Figure 3.5-2. Schematic of uncertainties in in situ and ocean color products. Truth (e.g., the actual chlorophyll concentration at a location) can be measured in the field by several techniques (e.g., High-Performance Liquid Chromatography, fluorometry). Likewise, there are several ocean color based chlorophyll products (e.g., derived from reflectance ratios or semi-empirical methods). The length of solid arrows suggests the level of uncertainty of the product. Generally, in situ measurements are less uncertain than the ocean color products. Model variables can be compared to either in situ or ocean color products (usually both) (IOCCG 19, 2020).

observable that requires manipulation to derive a common property ('currency'), with the optimum approach for comparing and combining such data currently unresolved.

One way to **Leverage Ocean Data and Models** is through the synthesis involved in developing models of the oceans. Here we use the word "model" specifically for mathematical models considering for instance distribution of phytoplankton or cycling of carbon, and distinct from remote sensing "algorithms" (which themselves are models) that for instance estimate Chl-a from remotely sensed reflectance. Two particularly important types of such mathematical models are data-based statistical models and mechanistic models. Statistical models apply correlative relationships to spatially and/or temporally extrapolate sparse observations of an ocean property of interest (e.g., specific plankton cell abundances) using observed environmental properties with enhanced coverage (e.g., sea surface temperature). These so called 'Species Distribution Models' have been frequently used in the terrestrial sphere and have more recently been applied to provide an estimate of distributions of key plankton species from sparse data (Flombaum et al, 2020, Barton et al, 2016). However, care should be taken with respect to their ability to be extrapolated to regions with no data and to make future predictions (Bardon et al, 2021).

Mechanistic models use mathematical equations to define underlying processes. Such models use Navier-Stokes equations to represent the laws of physics, and other differential equations to represent the passage of matter and energy from inorganic nutrients through the marine food chain. Discretized forms of these equations can be solved using computers. These mechanistic models are by design simplified representation of reality but provide unique insight into an incompletely observed system by drawing upon a theoretical understanding of that system's functioning. They can be used as synthetic laboratories to help us understand the systems of interest (e.g., carbon cycle, marine food webs) and perturbations to them (e.g. warming). There exist many types of mechanistic models (see e.g., IOCCG report 20, Chapter 3) ranging in level of complexity and differ in the types of questions that they are designed to answer (including diagnostics). Relevant to this document these include simple idealized box models (designed to target specific processes, but simplifying the rest of the system), global ocean biogeochemical models (GOBM), Lagrangian models that follow water parcels, and coupled earth system models (ESM) which include land, atmosphere, and ocean modules and the feedbacks between them. The latter are used by the Intergovernmental Panel on Climate Change (IPCC) to explore the potential impacts of warming on the planet. Huge successes have been realized in the past few years regarding development of mechanistic models, bringing computational oceanography, particularly in terms of physical oceanography, to the forefront as an important subdiscipline (Haine et al, 2021). The synthesis of model and observational data can take the form of model evaluations or data assimilation, whereby observational data in the latter application are used to 'nudge' the model toward measured properties or to determine unknown parameters. Data assimilation is particularly advanced in physical oceanography and is becoming more widely used in biogeochemical modeling.

There exist many challenges in modeling ocean carbon and biogeochemical cycles. These include their lack of potentially important complexity (e.g., number of plankton groups, and higher trophic levels) and elements (e.g., micronutrients beyond iron), missing processes (e.g. many models do not include explicit bacteria and viruses, some only implicitly include sinking of organic matter), and often the crudeness of parameterizations. Parameterizations suffer where we have incomplete knowledge of processes and interactions. Models differ in their resolution; GOBMs and ESMs typically operate in the ¼ to 1-degree horizontal resolution while some regional models have much higher resolutions. Coarse resolution precludes capturing small scale turbulence and convective processes which are critical to ecosystem structuring. Such challenges limit the ability of models to capture for instance deep Chl-a maxima (e.g., Steiner et al., 2016) and oxygen deficient zones (e.g., Cabré et al., 2015; Duteil et al., 2021; Rixen et al. 2020). Differing complexity of models, a variety of parameterizations of similar processes, along with differences in the physical flows of the model leads to discrepancies in results. For instance, there remain large difference between the modelled alterations in net primary production due to climate change in ESMs (Tagliabue et al. 2021); these difference between models has not diminished between model intercomparisons conducted almost 10 years apart (Bopp et al., 2013 versus Kwiatkowski et al., 2020).

Carefully evaluation of models also has significant challenges. Model output are typically mean values over several km to 100km horizontally and meters vertically. Satellite data and *in situ* data have very different temporal and spatial coverage. There is no consensus on appropriate downscaling techniques, and to assess impacts on regional ecosystems (e.g., coral reefs, fjords). The common 'currency' issue noted above also applies to linking modeled variables with satellite or *in situ* observations. For instance, most mechanistic models of ocean planktonic communities are based in units of carbon concentration (or sometimes nitrogen), yet the most common 'currency' for comparing model and satellite data is chlorophyll concentration. Combined uncertainties from the interconversion of remotely sensed ocean reflectance-to-chlorophyll on the satellite-side and carbon-to-chlorophyll on the model-side can be large enough to make comparisons between model and satellite data difficult (Dutkiewicz et al., 2018). Such 'currency' issues, together with the volume and heterogeneity of data streams, hamper optimal **Leveraging of Ocean Data and Models**.

Leveraging Ocean Data and Models Opportunities

The abundance of incoming observational data and model output is a tremendous challenge to **Leverage Ocean Data and Models** most effectively. Associated issues include: 1) difficulties in processing the data volume and making it easily accessible in usable forms, 2) demands for new techniques and expertise to adequately diagnose and utilize large volumes of data from disparate streams, and 3) complications in synthesizing data streams of a heterogeneous nature. *This grand challenge requires, in collaboration with oceanographers, dedicated teams of scientists who understand the underlying data and span disciplines from* *computer science, statistics, machine learning, cyberinfrastructure, and other communities that may not have played key roles in OBB science in the past.* In the text that follows, approaches for addressing this grand challenge are organized into two categories: 1) Access and Utility of Ocean Observational Data, which focuses on enabling a scientific workforce that is well-equipped to process, understand, and visualize Big Data through advanced technologies, and 2) Numerical Models and Data Assimilation, which focuses on opportunities for advanced modeling and data assimilation.

Access and Utility of Ocean Observational Data

Data Access: Synthesizing data from ocean color, lidar, and other satellite sensors with in-water sensor data requires a steady growth in computational and storage capabilities at national facilities run by federal agencies. This housing of data, however, is only the first step in the challenge. Making the different data streams easily accessible to a large range of researchers will be crucial for its usability (the MERRA-2 project is an example from atmospheric sciences on how one might approach this challenge). One of the challenges here is to be able to either have fast enough connections for downloading vast quantities of data or have a tremendous increase in cloud-based computing. A second challenge is handling and serving data of vastly different sizes in such a way as not to overwhelm certain user groups. Enhanced growth in regional facilities is also needed to support modeling and analysis at multi-petaflop and multi-petabyte scales. *The development of a tiered hierarchy of networked computational and data facilities is suggested, to link a large community of oceanographers and aquatic scientists, computational scientists, cyberinfrastructure professionals, and the broader community of stakeholders.* Such centers should include not only the sharing of data, but also the tools for accessing and interrogating these data. Infrastructure development is needed to allow for true user-centric data access, process, and discovery. To be useful, this infrastructure must be fast, intuitive, and inclusive of a large group of end users.

Unique and important data streams will be produced by different agencies and from those in different countries. *Therefore, the development of improved international community data access and information sharing will be necessary*. Avenues such as international organizations (e.g., IOCCG) are needed to foster discussions on the importance of two-way data sharing and to ensure that the data are provided in a manner that can be utilized by the tiered hierarchy of networked computational and data facilities discussed above.

Skills: Data utility is an issue that requires not only the technological advances in making data available, but also the development and accessibility of tools and the training of researchers and other users enabling them to work with volumes of Big Data. *Developing advanced technologies in cloud-based computing, improving the synthesis of datasets, and enhancing expertise in machine learning* will be fundamental. Achieving this goal will require dedicated, transdisciplinary research with collaborations between oceanographers, computer scientists, and cyberinfrastructure specialists. It will also require course development and support for existing programs to train the next generation of OBB data users and stakeholders across the research, industry, and government communities to efficiently access, analyze, and synthesize vast and disparate data products.

Synthesis: A tremendous challenge that will remain even after the above infrastructure and skills development are established, is how to conduct meaningful syntheses and establish common currencies between diverse and multi-dimensional data types [e.g., satellite observations versus 'omics' data versus model output]. In general, a different set of skills is required to fully understand each of the different data streams or model output in terms not only on what they measure, but also on the level of uncertainties. As such, successful synthesis will require both the cross-training of scientists across disciplines and, perhaps more importantly, the establishment of teams including specialists in each data stream. Such teams require significant time to develop and begin speaking the same language, which is required to bring about a full ability to synthesize. To fully utilize data streams to address the **Grand Challenges,** *it will be important to establish and maintain multi-disciplinary teams across multiple-funding cycles to fully synthesize disparate data streams and model output.* Such teams might resemble in form, for example, a Science Investigator-led Processing System (SIPS), such as the University of Wisconsin MODIS Atmosphere Processing Group of the NASA Ocean Biology Processing Group, or a Center of Excellence providing, among other functions, leadership, recommendations of best practices, research, and support and training. *A legacy from these teams should be the development of tools that enable broader user communities to access and synthesize disparate data sets.*

Machine learning: Artificial intelligence refers to computer software that can learn, problem solve, and plan. Machine learning is a subset of artificial intelligence that is particularly directed at processing large volumes of data using algorithms that can adapt over time to be more effective. Machine learning has been particularly good at pattern and image recognition and has been very successful in language processing and video gaming. Machine learning is an important tool for dealing with Big Data because it can learn and become more efficient and effective. It is also a way forward in using multiple diverse ocean data streams, but naïve use of machine learning can lead to incorrect assessments and damaging science. To maximize the utility of machine learning to address the **Leveraging Ocean Data and Models** grand challenge**,** *enhanced investment in the teaching of machine learning techniques will be necessary, integrating machine learning specialists within OBB research groups, and embedding machine learning experts and statisticians in ocean biology and biogeochemical research groups.*

Numerical Models and Data Assimilation

Model Development: There remains a large discrepancy in the level of complexity between models, generally driven by the questions that they are developed to address. However, major discrepancies in results (e.g., estimates of change in primary production over the 21st century differ largely between ESMs, Tagliabue et al., 2021) require that we understand the impact of the variety of parameterizations. *Coordination between modelling groups is needed to ensure that model disparities are understood and reduced*. Major breakthroughs in modeling are possible in the near to mid-term future as more observational data and broader computational resources are available. Such breakthroughs should include *better representation of the physics, lights fields, and non-linear interactions at the sub-grid scale and identifying and parameterizing missing processes.* Missing and under-parameterized processes potentially include higher diversity of plankton groups and viruses, metabolic processes, production, and fate of particulate matter, resolving higher trophic levels, implication of transient and extreme events, and land-ocean and ice-ocean interfaces. *Such advances in models require better fundamental understanding of these processes, and as such strong interactions between modelers, theoreticians, and observationalists should be encouraged.* Further, ecosystems, tracers, pollutants, plastics are moved within water parcels. As more measurements become available from floats and gliders, Lagrangian (i.e., from the perspective of a moving water parcel) modeling is becoming a useful tool that supplements Eulerian representation of flows and transports. However, Lagrangian tracers/particles are not typically included (or coupled offline) with current biogeochemical models. *We need further understanding on how to parameterize systems and movement of matter (e.g., plastics) within a Lagrangian framework.*

Data Stream Uncertainties: A significant issue in linking models and data either through model evaluation or more formally through data assimilation is that better estimates of uncertainties are needed, particularly with respect to satellite remote sensing products, along with assessments of seasonal and regional biases in ocean observational data (Figure 3.5-3). For remote sensing data, pixel-by-pixel error estimates are challenging (Zhang et al. 2022), and *emphasis should be placed on better constraining uncertainties and better methods of articulating these uncertainties*. *In situ* data with quantified uncertainties can help here. In addition, an alternative approach to addressing these issues is to *promote model development such that the predicted properties are more consistent with the directly observable properties from remote sensing* (as discussed in detail in **SECTIONS 3.1 and 3.2**).

Coupled Data Assimilation: Assimilation of physical components of the ocean (e.g., temperature, salinity, sea surface height) is well advanced and used to provide important state estimates of ocean circulation. Biogeochemical and ecosystem data assimilation is also advancing substantially (see reviews in Baird et al. 2020) and includes data streams such as chlorophyll and nutrients. However, much less attention has been given to coupled data assimilation, such as the assimilation of both physical and biogeochemical components at the same time (though see Song et al., 2016) or assimilation across interfaces (e.g., land or ice to ocean). In this context, biogeochemical fields (i.e., nutrients) are rich in information that can help constrain the physical field, for example water mass distribution, while accurate physical circulation remains essential for characterizing biogeochemical fields. However, coupled data assimilation is particularly difficult and initial attempts often result in worse assimilation of either physical or biogeochemical fields. New techniques for coupled data assimilation will take dedicated teams of scientists and significant time investment before attaining successful results. *Thus, additional sustained investment should be made in* *combined physical and biogeochemical data assimilation*, taking advantage here of successes from other disciplines (e.g., atmospheric sciences).

Hybrid Modeling and Machine Learning: Fluxes of heat and salt and dynamical ocean processes are largely described by a set of well understood physical Navier-Stokes equations, and procedures for data assimilation into global circulation models are well established. Mechanistic equations that describe biogeochemical processes, on the other

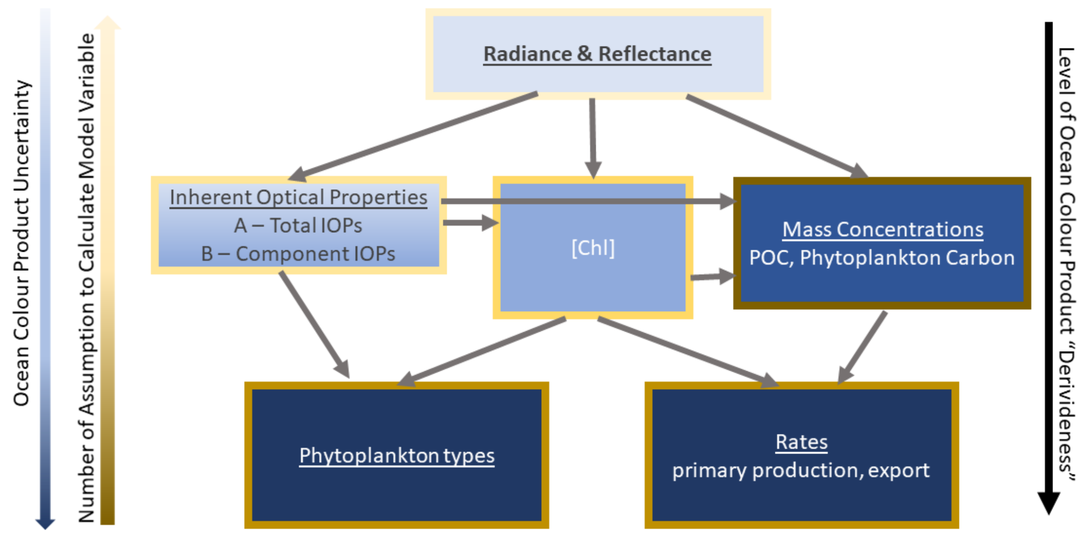


Figure 3.5-3. Schematic depicting uncertainties as products move from directly observed to increasingly derived. Uncertainty level is indicated by blue shading, with darker colors suggesting greater uncertainty. The vertical position (tier) of each box depicts how derived a product is, with radiance and reflectance being the least derived. Gray arrows indicate which products are used to derive other products. Brown colors surrounding boxes indicate how many assumptions needed to calculate variable in the model. Most models follow carbon, so phytoplankton carbon is one of the most basic variables. Inherent optical properties and reflectance require the most assumptions in the model to calculate. (from IOCCG 2019)

hand, are much less developed, and nonlinearities inherent in ecological and biophysical interactions (particularly under a changing climate system) can preclude reliable mechanistic modeling, even with vastly enhanced efforts. *The exploration of new, hybrid approaches that include mathematical equations for well understood processes and machine learning for processes that are less well understood or captured should be promoted*. For example, information theory and artificial intelligence can help guide researchers on how to include unknown processes, missing constraints, and help tune uncertain parameters. Such developments in ocean biology and biogeochemistry modeling will be important for inclusion in new Earth system models that can be used for robust projections of future states and change.

Ocean Color Satellite Mission Emulators: As models more explicitly include inherent and apparent optical properties and radiative transfer, they become useful as emulators or simulators to help in ocean color satellite mission planning and continued successes. For instance, models have provided synthetic satellite-like products for PACE mission planning (Gregg and Rousseaux, 2017), estimated the tolerance of drifts in sensors (Dutkiewicz et al., 2019), and could be useful for ocean color algorithm (e.g. estimating Chl from remotely sensed reflectance) development (Dutkiewicz et al, 2018). These models could be used in Observing System Simulation Experiments (OSSEs) to enable mission design improvements and for developing new observational strategies. Though great strides have been taken in adding ocean color important properties to models, more development is needed in, for instance, including additional optical constituents (e.g. minerals, terrigenous material), missing optically-relevant processes (e.g. ramen scattering, fluorescence), and parameterizing the optics of the ocean floor. *We recommend the continued designing, improving, and maintaining of models which can be used as ocean color satellite mission simulators/emulators.*

Ocean Digital Twin: The model and data assimilation opportunities, as well as satellite mission emulators, outlined above are in line with the concept of the Earth Digital Twin (Bauer et al. 2021). The goal of this European project is to dramatically enhance data assimilative modelling, as well as synthesis of data products, to provide a system that can be used to provide actionable predictions, which is a goal recognized in the Earth Science Decadal Survey and the United Nations [Decade of Ocean Science for Sustainable Development](). The core of the Earth Digital Twin system would be a data assimilation model that ingests large numbers of different data streams in near real time, estimates parameter values, and assigns model structure uncertainty. To fully become an Earth Digital Twin, the model system must also account for human elements, such as pollution, economy, and policies. The "Digital Twin" concept is related to, but more advanced than Integrative Assessment Models that intend to inform policy making, particularly with respect to climate change. *The development of a NASA Digital Twin Ocean linking the four **Grand Challenges** discussed in **SECTIONS 3.1 to 3.4** is of the utmost importance.* In this Digital Twin Ocean, data streams from the observing systems discussed above for the other four **Grand Challenges** are fed to a sophisticated model. This model would need to be global in scale and include sufficient vertical resolution, complex interactions between components of the marine food web (**Global Biosphere**), and the cycling of elements (**Climate and the Elements of Life**). The model would also require sufficient resolution in near-shore environments to capture coastal features and essential links to terrestrial inputs and sea-ice dynamics (**Interface Habitats**). The Digital Twin Ocean would also need to digest data streams on fisheries, aquaculture, pollution events, and other anthropogenic stressors. Near-real-time assimilation and model output would be indispensable for addressing the **Transient Events** grand challenge.

Leveraging Ocean Data and Models Summary

In the coming decade and beyond, NASA's OBB program can make unprecedented contributions toward improved understanding of aquatic ecosystems and elemental cycling, informed policy making and event response planning, and the protection of our invaluable ocean resources. An expansion of observing system capabilities is one requirement for realizing these goals, but of equal importance is a parallel investment in enhanced data processing and modeling capabilities.

Areas of opportunity within the **Leveraging Ocean Data and Models** grand challenge include:

1) Organize dedicated teams of scientists from diverse disciplines to build upon previous successes (e.g., atmospheric sciences) and engage in the Big Data challenge of processing, synthesizing, and utilizing the ever-increasing volume and acquisition rate of ocean-relevant Earth system data. (immediate/near-term).
2) Identify and coordinate with end users to ensure maximum utility and application of data products and models, through for instance workshops and summer schools (continued).
3) Develop a tiered hierarchy of networked computational and data facilities to link cross-disciplinary science and applications. (near-term).
4) Enhance international community data access and information sharing and facilitate cross-pollination of modeling advances among communities. (continued).
5) Advance technologies for cloud-based computing and data synthesis. (immediate/near-term).
6) Invest in the teaching of machine learning techniques, integrate machine learning specialists in research groups, and embed machine learning experts and statisticians in ocean biology and biogeochemistry research efforts. (continued).
7) Develop models that explicitly resolve ocean properties that are directly observable through remote sensing. (immediate).
8) Invest in assimilation models that ingest both physical and biogeochemical data. (near-term).
9) Explore hybrid modeling approaches that combine mechanistic understanding of well-resolved processes with machine learning for more poorly constrained processes. (near-term).
10) Build toward a Digital Twin Ocean model utilizing the full suite of observations and supporting science objectives encapsulated by the grand challenges. (long-term).

The **Leveraging Ocean Data and Models** grand challenge emerges from the increasing observational demands and growing model complexity necessary to address science and applications needs of today and the coming decades (**SECTIONS 3.1 to 3.4**). The current acquisition rate of daily Earth observing data is increasing exponentially and will continue to increase as new, more capable sensors become operational. These increases in observational data are paralleled by vast amounts of model output. Infrastructure and personnel investments are needed to ensure that, as the flow of Earth system data continues to escalate, our ability to process these data, inter-compare and synthesize disparate data streams, and provide tools and products for a diverse user community keeps pace, thereby maximizing investment value and empowering the next generation of scientists.

4. Science Vision Synthesis

Vision: "The ability to think about or plan the future with imagination or wisdom."

In 2007, an Advanced Science Plan was presented to the community identifying directions for growth in NASA's Ocean Biology and Biogeochemistry Program. At the time of its writing, there were no new upcoming ocean-focused satellite missions in the Program of Record. The writing committee for that document envisioned a series of immediate, near-term, and long-term activities leading to an advanced ocean color mission, a geostationary mission, and progress on ocean observations with active (lidar) sensors. Over the ensuing decade, PACE and GLIMR were added to the Program of Record and data from CALIOP were used to demonstrate the feasibility and science value of a satellite lidar for ocean applications. Over this same period, tremendous progress was made regarding ocean ecosystem modeling and autonomous *in situ* measurement capabilities, and multiple major field process studies were conducted to better understand, among other topics, the submarine optical environment and ocean reflectance properties, phytoplankton blooms and ocean-atmosphere coupling, and surface-to-deep carbon export. As is typical in science, each new development led to new questions, creating a need for new approaches and new assets. Simultaneously, new, or intensifying concerns regarding ocean sustainability, climate warming, biodiversity, and a host of other issues have led to additional observing requirements to safeguard ocean ecosystems and the goods and services they provide. This current document is intended to synthesize many of these new opportunities for NASA's OBB Program and provide a science vision that inspires and serves upcoming generations.

Five **Grand Challenges** have been identified herein, and approaches for addressing them articulated in **SECTION 3**. These five **Grand Challenges** are unified under the single goal of *creating an integrated and accessible 'observing' system that encompasses elements of measurements, modeling, and workforce to advance understanding of aquatic systems that enables improved assessments, responses, adaptations, and management in the face of Earth system change*. A central element in this goal is the link between aquatic and Earth system changes. This linkage transcends disciplinary boundaries and implies that successful scientific advancement will be greatly accelerated through meaningful coordination, cooperation, and communication between NASA's OBB, physical oceanography (PO), cryospheric sciences, biodiversity, terrestrial ecosystems, astronomy, and atmospheric science programs, as well as other national and international partnerships. Enhanced integration of OBB and PO activities at the agency level is particularly important because changes in ocean biology and biogeochemistry are mechanistically driven by changes in ocean physics, and refining descriptions of these processes is essential for their improved parameterization in numerical models. Long-term success in addressing the five **Grand Challenges** requires investment into education and workforce training, attention to diversity, equity, and inclusion, as well as engagement with public audiences, data users, managers, and policy makers (see **SECTION 4.1**).

The integrated 'observing system' envisioned in this document encompasses a wide swath of temporal and spatial domains (see **SECTION 5** for additional detail on *Technical Requirements & Investments*). For the global domain, a forefront addition to observing capabilities is the pairing of PACE (or a PACE-equivalent follow-on mission) with coincident global observations from an ocean-optimized profiling satellite lidar capable of directly separating absorbing and scattering elements in the water column and penetrating to the depth of the sunlit photic zone. These satellite assets together create a framework around which a three-dimensional reconstruction of ocean ecosystems can be built that extends from the ocean surface through the mesopelagic, and to which geostationary observations can contribute. This reconstruction requires fleets of autonomous instruments (including profiling floats, gliders, wirewalkers, and others) to validate satellite products and extend observations to depths beyond remote sensing detection. It also relies heavily on the advancement of numerical models to interpolate findings over space and time and provide interpretation of observed patterns. Targeted process studies are needed to resolve mechanistic relationships for model parameterization and to link satellite signals to specific plankton properties and higher trophic levels, such as phytoplankton diversity and vertically migrating animals, respectively. The rapidly expanding capability and coverage of 'omics' measurements can further be envisioned here as a tremendous source of detailed information regarding community composition and physiological stressors (e.g., Ustick et al. 2021) and, with future developments in technology, something that might even be provided from autonomous platforms transferring data in real time through satellite links. Developing this three-dimensional observing system will create unprecedented opportunities for interdisciplinary collaborations, particular with NASA's PO program as, again, ecosystem spatial structuring and change are strongly tied to physical forcings. Data collected through this observational portfolio will likely also be relevant to other national agencies, such as the US Department of Defense, National Oceanic and Atmospheric Administration, and National Marine Fisheries Service, thereby promoting interagency collaboration and investments.

Coupling a sustained record of PACE-equivalent and ocean lidar global observations will also provide unprecedented new insights on polar systems, owing to the advanced spectral resolution of these ocean color data and the lidar's ability to observe ocean properties under conditions prohibiting passive retrievals. Integrating additional data from sensors such as ICESat and its follow-on missions will further foster opportunities for collaboration and coordination of OBB activities and those of NASA's Cryospheric Sciences Program, and lead to major advances in our understanding of these critical and rapidly changing **Interface Habitats**. Parallel investments in process studies, autonomous observations, and modeling will be crucial.

The coupling of atmospheric and ocean processes also presents many new opportunities for interdisciplinary science. The ocean observations outlined in this document will provide unprecedented data for further resolving the role of ocean emissions on atmospheric aerosols and clouds, thus the Earth's Radiative budget. Detailed global characterizations of phytoplankton community structure, informed by *in situ* observations ranging from process studies to autonomous 'omics' data, may be particularly important. New information on phytoplankton physiology and growth rates provided through a satellite constellation monitoring diel cycles in surface ocean optical properties will likely also be groundbreaking. In turn, new process-oriented observations from an envisioned CubeSat fleet measuring atmospheric depositions to the ocean will inform quantifications of important nutrient s(and possibly pollutants) flux to marine ecosystems. Close coordination of NASA's OBB and Atmospheric Science Program activities and investments will be critical for realizing these scientific advances in understanding our coupled Earth system. It will ensure that capabilities of future satellite missions serve both communities to the greatest extent possible, and that the atmospheric science community is engaged with the oceanographic community in addressing data analysis and processing challenges, such as achieving more accurate atmospheric corrections for ocean retrievals. The emergent new data sets from these activities will support applications of and foster interagency partnerships with the National Oceanographic and Atmospheric Administration, the US Environmental Protection Agency, and the National Weather Service, among other agencies.

The global 'observing system' envisioned in this document further creates a contextual basis informing parallel advances targeting **Interface Habitats** and **Transient Events**; however, additional capabilities with higher spatial, temporal, and spectral resolution observations are essential in this arena. Here, the 30+ year record of Landsat measurements provides an invaluable baseline against which future changes observed through missions such as the upcoming SBG can be compared. These high spatial resolution data are complemented by high temporal- and moderate-spatial-resolution data from geostationary platforms, beginning with GLIMR and continuing through the NOAA-NASA GeoXO program. Building upon successes of the commercial Planet-Dove and Maxar/DigitalGlobe experiences, a fleet of low-cost CubeSat sensors can be envisioned as contributing important high spatial and temporal resolution observations for target regions. Together, this full complement of regionally-focused satellite assets will enable the monitoring of ecosystem changes, an improved understanding of underlying drivers of these changes, and the mapping of interface habitats and 'foundational species'. Convergence of spatial and temporal observational requirements for addressing **Interface Habitat** and **Transient Event** goals with those for many terrestrial ecosystem science objectives presents significant opportunities for coordinated investments and activities between NASA's OBB and Terrestrial Sciences Programs.

Because of the tremendous spatial heterogeneity of aquatic ecosystems and elemental cycles often associated with **Interface Habitats**, their rapid tempo of change, the often-challenging observing conditions of these habitats, and the unpredictable nature of **Transient Events**, satellite remote sensing is only one element in an effective observing strategy. Airborne observations with, for example, ocean color and lidar instruments provide additional data from targeted deployments along **Interface Habitats**, having an advantage that such measurements can be conducted under conditions prohibiting satellite retrievals. Development of new suborbital assets, including sensors on drones, will engender more cost-effective approaches to such measurements compared to occupied aircraft. *In situ* observations from autonomous platforms (e.g., floats, gliders, wirewalkers, etc.), along with process studies and modeling are also essential elements of this 'observing system'. Products from these investments will serve, and thus provide opportunities for engagement with, the Environmental Protection Agency, the National Marine Fisheries Service, the National Park Service, Department of Interior, and other agencies and will be relevant to regional and local governmental agencies responsible for providing clean water, zoning development of coastal lands, hazard detection and mitigation, and maintenance of recreational uses of lakes, rivers, beaches, and coastal waterways.

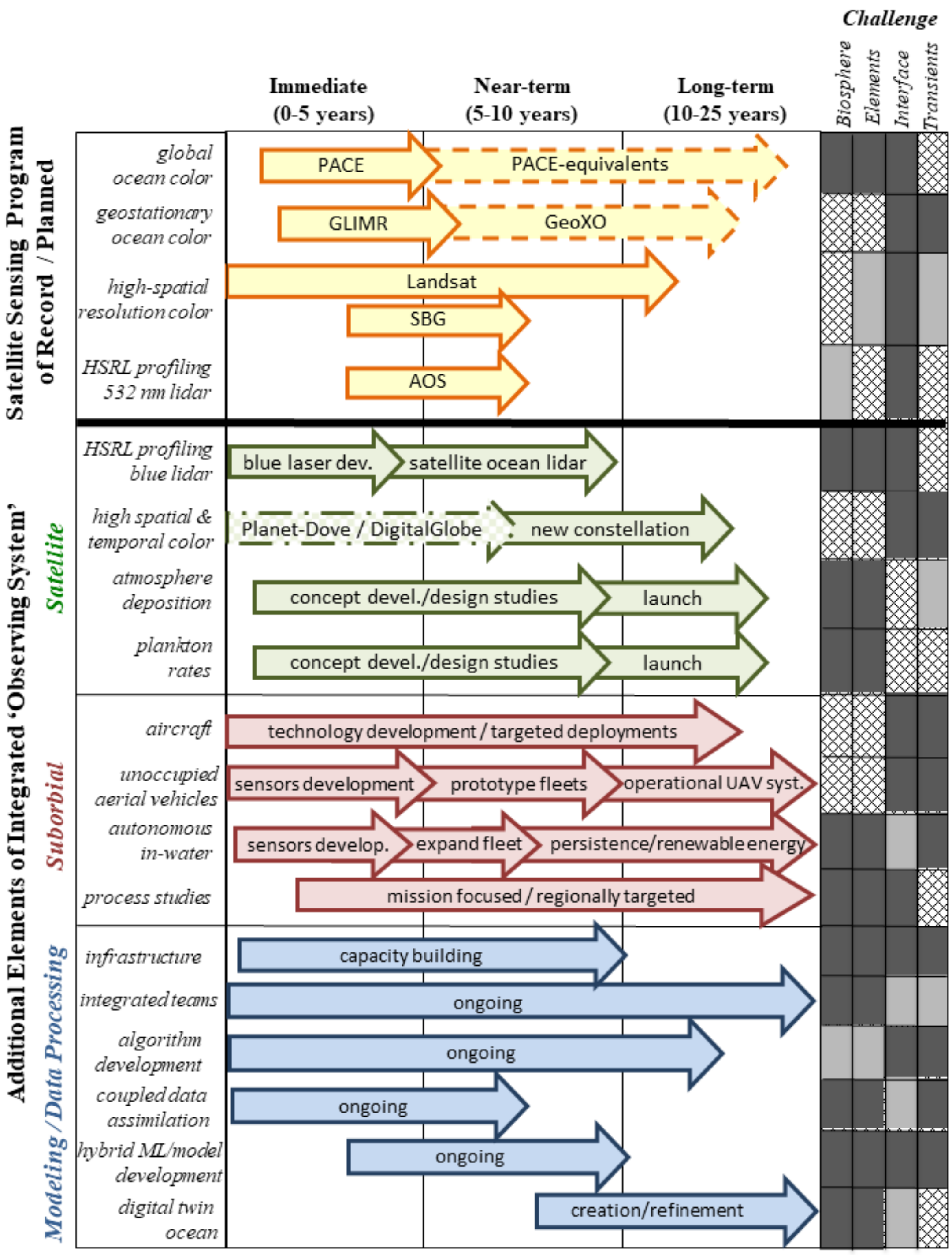
Mobility of the suborbital (including aircraft and *in situ* assets) observing system will be essential for addressing the **Transient Event** grand challenge. In the case of events threatening human welfare and infrastructure, a system with real-time coupling between measurements and modeling is needed to observe, track, and forecast impacts and ecosystem responses. Central to this capability are improved systems for the rapid ingest of disparate data streams, automated processing, and established communication links with early responders and decision makers. However, a mobile suborbital observing system is also of fundamental importance for understanding the role of **Transient Events** that are a natural part of the Earth system and occur from the shoreline, across continental shelves, and to the remotest reaches of the open ocean. These events can reshape aquatic communities, initiate species successional sequences, cause the proliferation of opportunistic organisms, or result in major biogeochemical shifts, yet we know comparatively little about these responses or how to incorporate them into models. A key challenge is that traditional long-term planning approaches for field campaigns is not compatible with the rapid response approach necessary to effectively capture **Transient Events**. A new observing approach is therefore required, involving mobile assets, a flexible real-time deployment plan, and informed by OSSEs. This same complement of mobile assets can also be used to monitor and observe purposeful large-scale perturbation experiments pertaining to **Climate and the Elements of Life** and **Transient Events** impacts on marine systems.

The vision presented here of a future OBB 'observing system' entails a rich assortment of systems that interlink 'omics' to satellites, the atmosphere to the mesopelagic, and transient events to long-term climate change. Realizing this vision will require coordination among NASA Earth Science Programs and engagement with national and international agencies and partners contributing individual elements, coordinating standards for calibration/validation strategies, sharing data, minimizing measurement gaps, and avoiding measurement redundancies. Of particular importance will be continued communication and coordination with the IOCCG to promote the development and application of satellite data and develop community consensus on radiometry and products. These diverse collaborations will ensure that necessary data streams for observational and forecasting systems are sustained and that the international community can develop and advance priority science questions, pursue partnerships in sensor development and measurement capabilities, and synergize field data collection and processing.

A foundation of our 'observing system' vision is the continuation of ocean-relevant measurements in the Program of Record (Fig. 4-1, top yellow arrows). Of particular importance is extension into the future of PACE's global, wide-swath, ultraviolet-to-shortwave infrared hyperspectral observations (Fig. 4-1, dashed yellow arrow). At the time of this writing, a plan for PACE-equivalent follow-on missions does not exist and this issue needs to be addressed. Building upon this foundation, we envision new satellite technologies (Fig. 4-1, green arrows) providing a suite of observations complementing and addressing limitations of current missions in the Program of Record. We expect that many, if not all, of these groundbreaking new missions will be compatible with SmallSat or CubeSat platforms, but design and engineering studies are needed to evaluate optimal science and technology approaches. Another key element in this document is the recurring theme in the **Global Biosphere**, **Climate and the Elements of Life**, **Interface Habitats**, and **Transient Events** grand challenges that success in these endeavors relies on the continued development and deployment of suborbital assets and process studies (Fig. 4-1, red arrows). Indeed, these suborbital activities may play a leading role in addressing the **Interface Habitats** and **Transient Events** grand challenges, with satellite remote sensing playing a supporting role and essential long-term monitoring. Accordingly, opportunities will be needed to facilitate these developments and activities, taking advantage of many potential partnerships across NASA's Earth Science programs as well as other national and international science programs and agencies.

In the time since the 2007 OBB Advanced Science Plan was released, an explosion has occurred in data collection and modeling capabilities. The **Leveraging Ocean Data and Models** grand challenge reflects these developments and recognizes the important Big Data leaps that have occurred over the past decade. Without a proactive vision for addressing the Big Data problem, the sheer volume, accumulation rate, and disparate nature of data streams and model output will significantly hamper our ability to effectively address these OBB science goals in the coming decade and beyond. The integrated 'observing system' envisioned herein will require the capture, storage, sharing, and analysis of an enormous quantity of data, necessitating the establishment of dedicated teams of scientists, including disciplines of aquatic sciences, computer science, statistics, machine learning, cyberinfrastructure, and others, a tiered hierarchy of networked computational and data

Figure 4-1. Immediate, near-term, and long-term elements of the integrated ‘observing system’ envisioned in this Science Vision Synthesis. Program of Record missions are shown above heavy black horizontal line, with dashed outlines indicating planned but not yet funded missions. Additional new ‘observing system’ elements are shown below this line, with dash-dot outline indicating leveraging of commercial satellite programs. Modeling and data elements are indicated by blue arrows. Four **Grand Challenge** categories are shown on right, with importance of each Observing System element indicted by shading (Dark = essential; Light = important, Cross-hatch = contributing). The fifth **Grand Challenge**, ‘Leveraging Ocean Data and Models’, crosscuts and supports the other **Challenges** and is represented in blue at bottom. See Table 1 for definitions of acronyms.



facilities, and improved international community data access and information sharing (Fig. 4-1, blue arrows). Cloud-based computing and machine learning will likely be key elements and will require enhanced workforce training in these areas. Potential opportunities should be explored for leveraging advancements in private industries (e.g., Google Earth Engine, Amazon Web Services, Microsoft Azure, etc.). A coordinated vision and investments will also be needed to constrain uncertainties in observational data and model predictions, evolve numerical modeling to generate products directly comparable to remotely detectable properties, improve coupled data assimilation and hybrid model capabilities, and integrate findings from field observations into mathematical model relationships (Fig. 4-1, blue arrows). Maturation of these diverse elements of modeling and data processing are integral to an effective 'observing system' and, with the incorporation of human elements (e.g., fisheries, aquaculture, pollution events, economy, policy), support the broader community's creation of a 'Digital Twin Ocean' that provides interpretations of observed changes and robust forecasts of future change that can inform decision makers.

The science vision presented here is organized around five **Grand Challenges** relevant not only to NASA's OBB Program, but interleaving diverse Earth Science Division research programs, including the NASA Earth Science Technology Office (ESTO), Applied Sciences, Flight, Earth Science Data System (ESDS), and other elements within NASA, as well as a diversity of national agencies, including the National Science Foundation, Department of Defense, National Weather Service, Environmental Protection Agency, National Oceanic and Atmospheric Administration, Bureau of Energy Management, Department of Energy, National Marine Fisheries Service, National Park Service, and Fish and Wildlife Service. Similar challenges are faced by many international science communities as well, as we all have a stake in safeguarding the future health of Earth's global aquatic environments and its Blue Economy. However, NASA's Ocean Biology and Biogeochemistry Program, with its enterprise spanning from cells-to-space and minutes-to-decades, is particularly well poised to function as the center-pole of the research umbrella necessary in the coming decade and beyond to rise to these **Grand Challenges**. In doing so, it will continue its legacy of scientific excellence, reveal new insights on our Earth system, enable new technology development, and inspire generations to come.

Science Theme	Timeline		
	Immediate (1 – 5 years)	*Near-term* (5 – 10 years)	*Long-term* (10 – 25 years)
Global Biosphere *Climate and the Elements of Life*	• **Ocean profiling blue lidar formulation** • **(PROGRAM OF RECORD) PACE, GLIMR** • Blue laser technology development • Lidar chlorophyll fluorescence/ CDOM detector development • Autonomous sensor development, including community composition, nutrients, and other elements • Conduct OSSEs to optimize assets • Data analysis infrastructure investment • Preparatory model development incorporating additional ecological diversity • Evaluation of mixed layer remote sensing approaches • Community evaluation of phytoplankton diel cycles remote sensing approaches	• **Ocean profiling blue lidar** • **(PROGRAM OF RECORD) PACE, GLIMR, AOS / PACE follow-on** • Blue laser technology development • Autonomous fleet deployment • Ship-based process studies • Mature data analysis systems • Model development and data assimilation • Suborbital deployments for ocean-atmosphere interactions • Explore remote sensing approaches to atmosphere mass deposition assessments • **Mixed layer remote sensing design studies and formulation** • **Phytoplankton diel cycles remote sensing design studies and formulation**	• **Ocean profiling lidar follow-on** • **PACE follow-on** • **Atmosphere mass deposition** • **(PROGRAM OF RECORD) GeoXO** • Sustained autonomous assets • Ship-based process studies • Integrated synthesis of ecosystem change, plankton biodiversity, and biogeochemistry • **Mixed layer remote sensing mission** • **Phytoplankton diel cycles mission**
Interface Habitats	• **(PROGRAM OF RECORD) PACE, GLIMR, Landsat, SBG** • **Commercial satellites** • Operational processing / inter-sensor calibration of heritage high-spatial resolution sensor data • Develop suborbital observing capabilities for habitat mapping • Algorithm development for optically complex retrievals • Data synthesis and operational model development • Interface (terrestrial-aquatic, ice-ocean) ecosystem/biogeochemical models	• **(PROGRAM OF RECORD) PACE, GLIMR, Landsat, SBG** • **Commercial satellites** • **High spatial & temporal resolution mission formulation** • Suborbital deployments targeting contrasting interface habitats • Observing system data synthesis and assimilation in regional models • Establish interdisciplinary science teams linking Earth system domains • Conduct process studies to reduce uncertainties	• **(PROGRAM OF RECORD) GeoXO** • **High spatial & temporal resolution satellite constellation** • Continued suborbital deployments • Continue process studies • Synthesis of observing system data and prognostic modeling for operational applications, management, policy
Transient Events	• **(PROGRAM OF RECORD) PACE, GLIMR, Landsat, SBG** • **Commercial satellites** • Operational processing / inter-sensor • Suborbital and autonomous sensor development • Data ingest and distribution infrastructure investment • Algorithm development for optically complex scene retrievals • Natural transient events impacts & responses assessment	• **(PROGRAM OF RECORD) PACE, GLIMR, Landsat, SBG** • **Commercial satellites** • **High spatial & temporal resolution mission formulation** • Establish suborbital and autonomous 'stand-by' asset pool • Model-data integration system for event tracking and impact assessment • Natural transient events impacts and responses asset development and early deployments	• **(PROGRAM OF RECORD) GeoXO** • **High spatial and temporal satellite constellation** • Continued suborbital deployments • Decision support system for event response based on model-data integration system • Additional deployments characterizing natural transient events impacts and responses
Ocean Data and Models	• Organize science teams for processing, synthesizing, and utilizing disparate Earth system data stream • Engage international data access and sharing • Invest in training of workforce • Develop explicit inherent and apparent optical property in models	• Develop tiered hierarch of networked computational and data facilities • Engage international data access and sharing • Invest in training of workforce • Develop physical-biogeochemical assimilation models and explore hybrid approaches	• Engage international data access and sharing • Invest in training of workforce • **Community development of 'Digital Twin Ocean Model'**

Bold Green Text = New satellite mission; **Bold Black Text** = Program of Record (PROGRAM OF RECORD) missions; **Bold Purple Text** = Integrated long-term modeling goal; Normal black text = all other observing systems elements for a given theme and timeframe.

4.1 Education and Engagement

The traditional passive ocean color approach has revolutionized our understanding of aquatic ecosystems and will continue to play a vital role in monitoring and predicting change. However, expanded observing technologies, data processing, and modeling capabilities are needed to address national and international science and applications that cannot be achieved simply through heritage ocean color approaches. The synergy between passive and active satellite remote sensing, enhanced suborbital assets, and suborbital process studies will create exciting new opportunities, as well as data handling and modeling challenges. To realize the full science and applications benefits of these advances, a significant and intentional effort is needed to engage product users and public audiences and to ensure the establishment of a next-generation workforce with necessary science, technology, engineering, and mathematics (STEM) skills. This responsibility is consistent with the agency's charge in the Space Act and with NASA's goals for outreach and engagement.

Complexities of the Earth system present unique opportunities for STEM education that transcend traditional disciplinary instruction. Earth system science at NASA, particularly in the face of intensifying climate change, also has strong links to societal benefits and stewardship of natural systems, demanding an integration of natural sciences with social sciences, traditional knowledge, computational sciences, informational technology, and policy, ensuring efforts are also focused on achieving environmental justice and diversity across gender, sexual orientation, race, ethnicity, and national origin. While defining a detailed approach for building the necessary transdisciplinary and STEM-literate workforce is beyond the scope of the current document, the OBB program and NASA in general should continue their long-standing engagement in promoting Earth system science at all levels of formal education, through active engagement of historically marginalized minorities, by incorporating traditional ecological knowledge (TEK), and with outreach and engagement opportunities for the public. A particular challenge for the ocean sciences is that many minority serving institutions in the US lack ocean science programs. Furthermore, many of the research-intensive institutes with robust ocean research programs do not have adequate support systems in place to retain under-represented, historically marginalized, and minority students.

A dynamic, agile education and engagement framework will need to target opportunities responsive to priorities in the Blue Economy and leverage Earth observations to address science and applications that inform policy, underpin sustainable resource management, and enable decision-making. This framework must be accessible with intuitive resources and tools that leverage NASA's technology and data holdings, presenting them in a usable and suitable context for a diverse audience of stakeholders ranging from teachers to students, policy makers, managers, and beyond. This framework must be accompanied by training and capacity development opportunities that truly go beyond the traditional to inspire the next generation of explorers and empower future innovators.

Increased outreach and user engagement should highlight the societal value and benefits of Earth observations, aquatic remote sensing, and Earth system modeling, to fully leverage NASA's science and technology investment. Generating knowledge and enhancing public awareness of the ocean and aquatic environments is an adequate first step. Truly effective engagement must generate active public participation in aquatic science, data, and technology to strengthen individuals' knowledge of and connections to the ocean. Hands-on participation by the public also creates more affective and experiential environment for learning about our home planet and climate change indicators and solutions, which can lead to more informed and effective management and policy decisions about our planet's changing climate.

One strategy for this type of public engagement is Citizen Science, which has been a staple in the sciences for over 2000 years; however, in the past decade, public involvement in scientific activities has significantly increased, which is transforming research. Achieving observational needs and improving societal connections to the environment are two powerful advantages that Citizen Science provides for Earth system science. The OBB **Grand Challenges** and open questions outlined in this document provide significant opportunities for increased and meaningful public engagement. For example, the public, through citizen science efforts, can help NASA explore and validate its data and enhance its research activities, provided the Citizen Science measurements are reliable and collected in a robust manner. To effectively engage the public and achieve this, open science will be critical.

Open science moves beyond open and accessible data, focusing on promoting free and intuitive access to knowledge, including methods and approaches, and science materials that support learning, including scientific publications and software, provided through transparent and collaborative tools. NASA is making a long-term commitment to Open-Source Science in which it seeks to further promote the open sharing of software, data, and knowledge (e.g., remote sensing algorithms, peer-reviewed publications, scientific documents, ancillary information) as early as possible in the scientific process. NASA is applying the principles of Open-Source Science to make publicly funded scientific data and research transparent, inclusive, accessible, and reproducible. Through the shift to open science and increased public engagement in scientific activities, observational gaps will be closed, and more innovative and alternative models of knowledge production and solution generation will be discovered.

Public participation in scientific activities creates a tighter connection between humanity and our lived environment. Communities who do not interact closely with the ocean may feel disconnected from its services, resources, and stressors. To achieve ocean sustainability, we must develop strategies that improve societal connection to the ocean. Involving social scientists (e.g., economists, anthropologists, sociologists) can lead to a more holistic understanding of aquatic resources and can help ideate novel solutions to address climate change. For example, increased collaborations between aquatic scientists and social scientists, such as psychologists, can provide insight into ways in which individuals and groups respond to risks and threats, including anthropogenic climate change. This can inform the development of adaptation and mitigation strategies that effectively inspire behavioral change.

There is a growing national movement to enhance diversity, equity, inclusion, and accessibility (DEIA) in the sciences to bring together different perspectives and life experiences and to empower a sense of belonging to spark unique questions and approaches to problem solving, which will lead to higher levels of scientific innovation. Each of these benefits will contribute and amplify the science goals outlined herein for the OBB program. We are a long way from achieving a diversity in the sciences, particularly at the doctoral and faculty levels and especially in the geosciences, which have the lowest level of diversity across the STEM fields. Earth observations provide a means to remotely connect humanity from across the planet with distant ecosystems, and NASA has a powerful opportunity to promote DEIA principles through its leadership in science, data, and technology.

TEK is a unique form of knowledge that takes into consideration the relationships between people and their environment. TEK has high intrinsic value yet can be difficult to quantify and often varies based on communities, their heritage, and their circumstances. To uphold and honor the value of TEK, co-production of knowledge and co-management of resources must be prioritized to address sustainability challenges. For example, as the understanding of the Earth as a system of systems is furthered, care should be taken to place scientific data in the proper context, and following this approach allows the connection of communities and their ecosystems to be recognized and placed in their proper historical and cultural context.

Recognizing existing shortcomings in STEM education, public engagement, environmental justice, and DEIA is a first step, but resolving them will be complex. Addressing the challenges described above will require circumspection, intentionality, and deliberate action across individual, institutional, and national levels. The new Earth observing technologies that will be available over the next decade, coupled with the OBB **Grand Challenges** to be addressed if we are to support and sustain a thriving Blue Economy, provide broad opportunities to strengthen and build a more diverse STEM workforce and to better engage individuals and communities. We have opportunities to address scientific gaps and promote meaningful involvement of all members of humanity by leveraging Earth Observations in combination with the rich historic information contained in traditional knowledge, working to co-develop scientific knowledge in a transparent and accessible manner, fully embracing open science.

5. Technical Requirements and Investments

The purpose of this section is to provide additional technical and developmental details regarding needed investments building toward the envisioned 'observing system' discussed in **SECTION 4.** In particular, the focus here is on specific measurement requirements for satellite and suborbital (including airborne and *in situ*) observations, identify where technology developments are needed, and overview investment needs to address data and modeling challenges over the next decade. Details on requirements for the satellite 'mixed layer mission' **SECTION 3.1**, 'atmospheric deposition' mission **SECTION 3.2** and 'plankton physiology' mission **SECTION 3.2** are not included here as development of these concepts is insufficiently mature and initial design and technology studies are needed to better define these missions. Also not included here are ancillary supporting measurements, such as sea surface temperature, sea surface height, ozone concentrations, etc., that have been sustained through the Program of Record and are assumed here to continue.

5.1 Global Passive Ocean Color Radiometry

This technology supports *all five* OBB **Grand Challenges,** but is particularly important for meeting the **Global Biosphere**, **Climate and the Elements of Life**, and **Transient Events** grand challenges. The PACE Ocean Color Instrument in the current Program of Record provides the basis for the following technical requirements to sustain PACE-equivalent ocean color observations, which are based on the PACE Ocean Color Instrument's design requirements and lessons learned during its formulation, design, and build.

- 1–2-day global coverage to solar and sensor zenith angles of 75^o and 60^o, respectively.
- A Sun synchronous orbit with a nominal equatorial crossing time between 11:00 and 13:00 local time.
- Continuous ultraviolet-to-near-infrared (UV-to-NIR; ≤340 nm to ~900 nm – noting here that extension of the UV bands to <340 nm can provide coincident information on ozone and nitrogen dioxide (NO_2) concentrations used for atmospheric corrections and potentially information on phytoplankton mycosporine-like amino acid concentrations) spectral coverage at a minimum of 5 nm spectral steps and a maximum of 5 nm spectral resolution.
- Select shortwave infrared bands at a minimum placed at approximately 940 (water vapor), 1038 (suspended sediments, atmospheric correction), 1250 (atmospheric correction), 1378 (cirrus cloud detection), and 1615 nm (atmospheric correction), plus a desired band at approximately 2130 or 2260 nm (atmospheric correction).
- Maximum 1 km^2 spatial resolution at nadir.
- A capability such as instrument tilt to avoid contamination by Sun glint.
- Monthly characterizations of instrument detector and optical component temporal stability, including lunar observations through the Earth-viewing port that illuminates all detector elements.

- Daily characterization of instrument detector and optical component changes using an independent, on-board capability that illuminates all detector elements.
- Instrument systematic artifacts that do not exceed 0.5% combined at the top of the atmosphere, inclusive of along-track and band-to-band image striping.

Technology Development

- High speed (~20MHz sample rate) silicon detector arrays (e.g., CCD or CMOS) in the UV-to-NIR (340-900 nm) for time-delay integration applications.
- High speed (~20MHz sample rate) Mercury Cadmium Telluride detector arrays in the shortwave-to-infrared (SWIR; 900-2300 nm) for time-delay integration applications.
- Improved optical gratings in the SWIR (900-2300 nm).
- Integrated, low power tunable Application Specific Integrated Circuits for bias and analog-to-digital converter sampling.

5.2 Ocean-optimized profiling lidar

This technology supports *all five* OBB **Grand Challenges**, but is particularly important for meeting the **Global Biosphere**, **Climate and the Elements of Life,** and **Leveraging Ocean Data and Models** grand challenges. The CALIOP sensor in the current program of record has served as a foundational proof-of-concept that measurements from an ocean-penetrating satellite lidar, in conjunction with passive ocean color data, can provide critical new information on ocean biology and biogeochemistry. However, as the CALIOP sensor was not designed for ocean applications, it only yields robust ocean properties for the upper-most sampling bin (i.e., a single 22 m deep bin just below the ocean surface), does not have the vertical resolution to retrieve essential information on plankton depth-structuring, and does not have the needed detector complement to directly separating scattering and attenuation elements of the retrieved signal. For an ocean-optimized profiling satellite lidar, HSRL or equivalent technology is needed to accurately quantify particulate backscatter and attenuation and a vertical sampling resolution of ~1 m is needed to characterize plankton structure through the water column. For a future ocean lidar, a blue laser emission wavelength is desired to allow retrievals to the base of the photic zone, although the 532 nm emission of the highly mature NdYAG laser might be considered as a threshold capability. Multiple ocean-penetrating laser emission wavelengths and chlorophyll fluorescence and Raman detection bands are also desired. Accurate retrievals of water column plankton properties have already been thoroughly demonstrated using multiwavelength airborne HSRL systems. The following provides a summary of desired capabilities:

- Global sampling from a Sun synchronous orbit with a nominal equatorial crossing time between 11:00 and 13:00 local time.
- Laser emission at blue wavelength (e.g., 486 nm).

- ~5 km along-track spatial resolution of derived near-surface properties, with horizontal resolution degrading with depth to account for reductions in signal-to-noise.
- Ocean surface pulse footprint diameter of ~50-100 m.
- HSRL or equivalent approach for direct separation of absorption and scattering.
- Geophysical retrievals with 2-to-3-meter vertical resolution, thus ≤ 1 m vertical sampling resolution.
- Polarized and depolarized channels for emission wavelength.
- Chlorophyll fluorescence detection band (~680 nm).
- Water Raman detection band.
- Day and night observations during all months.
- Minimum mission lifetime of 2 years, 10-year mission life goal.

Technology Development

- Maturation of blue laser technology.
- Maturation of detectors.
- Investigation of potential for deployable large aperture telescope.
- Continued development of HSRL receiver technology (i.e., interferometer).
- Studies investigating trades between platform size (SmallSat) and laser power enabling science capability (e.g., penetration depth, signal-to-noise).

5.3 Geostationary Satellites

This technology supports all five Grand Challenges, and especially the **Climate and the Elements of Life**, **Interface Habitats**, **Transient Events**, and **Leveraging Ocean Data and Models** grand challenges. The GLIMR instrument in the current Program of Record provides the basis for the following technical requirements to sustain geostationary ocean color observations across the river-estuary-coastal ocean-open ocean continuum. This list encompasses GLIMR design requirements as well as those currently being used to formulate the GLIMR-like ocean color instrument to be flown as part of the NOAA-NASA GeoXO program. Coordination with international agencies will be required to achieve near-global geostationary observations.

- 5-6 observations per day at approximately 60-to-90-minute intervals for priority science coverage regions between 60° N and 60° S within solar and sensor zenith angles of 75^{o} and 60^{o}, respectively.
- A geostationary orbit with a nominal longitude of 96° W ±4°; ideally, two geostationary sensors with one at ~75° W and other at ~145° W.
- Field of regard 20.8° North-South and East-West to enable lunar calibrations and Earth full-disk coverage.
- Continuous UV-to-NIR (~340 nm to ~900 nm) spectral coverage at a minimum of 5 nm spectral steps and a maximum of 5 nm spectral resolution.

- Select shortwave infrared bands placed at approximately 1038 (suspended sediments, atmospheric correction), 1250 (atmospheric correction), and 1615 nm (atmospheric correction).
- Maximum 300x300 m (8.4x8.4 microradians) spatial resolution at nadir; ideally, a minimum of four spatial samples per spatial resolution element.
- Image navigation and registration capability that provides a maximum geolocation uncertainty of ±60 m at nadir (1.68 microradians) and a maximum pointing line of sight stability of ±30 m at nadir (0.84 microradians).
- Monthly characterizations of instrument detector and optical component temporal stability, including lunar observations through the Earth-viewing port, which ideally illuminates all detector elements.
- Daily characterization of instrument detector and optical component changes using an independent, on-board capability that illuminates all detector elements.
- Instrument systematic artifacts that do not exceed 0.5% combined at the top of the atmosphere, inclusive of polarization sensitivity, band-to-band image striping, out-of-band response, crosstalk, and stray light.

Technology Development

- Fine pitch (4-5 microns) large format (6K x 3K) silicon detector arrays (CCD or CMOS) in the UV-to-NIR (340-900 nm) with low dark noise, deep wells, and high quantum efficiency.
- High-throughput optical gratings in the UV-to-NIR (340-900 nm) and SWIR (900-1700 nm) with <1% polarization sensitivity or compact prism with sufficient spectral dispersion in the UV-to-NIR range.
- Agile spacecraft or on-instrument field-of-view rotational scanning capability for efficient scanning of coastlines not oriented North-South or East-West.

5.4 Global passive multi-angle multispectral polarimetry

This technology supports the **Climate and the Elements of Life**, **Interface Habitats,** and **Leveraging Ocean Data and Models** grand challenges. Design requirements for the PACE polarimeters and those instruments being considered for AOS provide the basis for the following technical requirements to sustain multi-angle polarimetric observations. Note that the PACE Hyper-Angular Rainbow Polarimeter 2 (HARP2) and Spectro-Polarimetric Experiment One (SPEXone) are contributed multi-angle polarimeters and are considered proof-of-concept instruments. Both were designed primarily for aerosol and cloud remote sensing, but their characteristics are also valuable for ocean color atmospheric correction and have the potential for new ways of characterizing the optical state of ocean bodies. These requirements correspond to the recommendations of the Aerosol, Cloud, Ecosystems (ACE) study report (Da Silva et al. 2020). The instruments differ in some key characteristics. HARP2 has a wide cross track swath (±47°) and a hyper angle channel with 60 views in the along-track direction. This is intended for cloud remote sensing but will also be ideal for characterization of ocean reflected sun glint. SPEXone has a much narrower cross track swath (±4.5°) but is a 385-770 nm spectrometer that is valuable for understanding ocean properties. Characteristics shared by both instruments include:

- Simultaneous observation of the linearly polarized state with accuracy < 0.005 in the Degree of Linear Polarization (DoLP).
- Spatial resolution ≤3 km^2 at nadir.
- 5+ along track views spanning zenith angles from 57° forward to 57° aft.
- Spectral sensitivity at multiple visible-to-near infrared channels.

Technology development

- Class C flight components.
- Capabilities for spatial resolution ≤1 km^2 at nadir.
- Three or more SWIR (1000-2250nm) spectral channels.
- One or more UV (350-400nm) spectral channels.
- Synergistic retrieval algorithm development for measurements made alongside lidars and spectrometers.

These developments roughly correspond to the requirements of the upcoming AOS mission. While that mission's requirements are driven exclusively for aerosol and cloud remote sensing, *they could support all five **Grand Challenges** if efforts are made to ensure appropriate algorithms are developed*.

5.5 High spatial and temporal resolution ocean color observations

This technology supports the **Climate and the Elements of Life, Interface Habitats, Transient Events,** and **Leveraging Ocean Data and Models** grand challenges. The application of satellite observations can be limited by spatial resolution (km-scale pixel sizes for typical ocean color sensors) and temporal resolution (weekly to monthly revisit times). One of the key advances in the last decade has been the advent of commercial and open-access high spatial resolution satellites like OLI on Landsat-8, MSI on Sentinel-2, and commercial or CubeSat sensors and constellations with applications to aquatic remote sensing (e.g., Planet-Dove, Maxar/DigitalGlobe). By combining data from multiple high spatial resolution satellites, the amount of cloud-free imaging can be greatly enhanced in a location compared to any single satellite system and allow for better monitoring of dynamic processes across the aquascape.

- Spatial resolution meter to decameter scale.
- Visible red, green, blue (RGB) and NIR wavebands.
- <10 m positional accuracy on ground.

- Atmospheric correction approaches for limited band set (e.g., Vanhellemont 2020).

Technology Development

- Effective approach development for intercalibration of sensors between platforms (e.g., CubeSat constellations).
- Automated data fusion of imagery from different sensors both spatially and spectrally.
- Improved sensor intercalibration and NIR band performance.
- Aquatic algorithm development for RGB sensors across water types.

5.6 Suborbital Assets

This technology supports the **Global Biosphere, Climate and the Elements of Life, Interface Habitats,** and **Transient Events** grand challenges. Piloted airborne assets are particularly suited for high resolution sampling over larger regions, often away from shore, with high precision and sensor stability, but require considerable investment in personnel and aircraft technology and sampling is often limited to clear sky conditions. Smaller suborbital assets like unoccupied aerial and in-water vehicles, have applications that require very high resolution spatial (meter-scale) and temporal monitoring on (hours or more). For example, UAVs can be deployed under clouds and at short notice to detect hazards like the nuisance seaweed *Sargassum* sp. and oil spills in harbors and ports. As noted in Dierssen et al. (2021), advances in drone technology and sensor miniaturization will place sophisticated remote sensing capabilities into the hands of individual and commercial users and provide on-demand imagery tailored to research and management requirements. Development of sensor suites on autonomous profiling floats (e.g., BGC-Argo), and similar platforms, provides critical autonomous sampling in the vast world ocean with vertical resolution to validate satellite products and biogeochemical models. The technology development in autonomous instrumentation will also have applications to NASA’s exploration of other ocean worlds. Merging sensors on various autonomous platforms will allow for synergistic approaches to evaluating targets that merge passive and active techniques, as well as merging data from optical, thermal, and acoustical sensors.

- Piloted Aircraft.
- Unoccupied Aerial Vehicles (e.g., drones).
- Autonomous profiling floats (e.g., BGC-Argo).
- Remotely Piloted Underwater Vehicles.
- Underwater gliders (e.g., wavegliders).
- Fluid Lensing Imagers.
- Imaging Spectrometers.
- Bathymetric lidar instruments.
- Fluorescence lidar instruments.

- Multi-spectral lidar instruments.
- Linkages to acoustics, thermal sensing.
- Tech miniaturization (payloads/sensor fleets).

Technology Development

- Continued investment in sensor miniaturization with low payloads for autonomous deployments on a variety of platforms (moorings, floats, drones, etc.).
- Investment in technology and processing capabilities for data generated from suites of above- and in-water sensors, including both active and passive sensors and linkages to acoustics and thermal sensing.
- New techniques for intercalibration of sensors, 'Big Data' capture, processing, distribution and archival of data, including open-source data analysis software and automated quality control protocols.
- Development of prototype fleets of UAVs with portable sensors with onboard algorithms to track a variety of transient events including hazardous spills, storm surges, changes in critical coastal habitats, red tides, and marine litter and debris.
- Continued in investment in deploying autonomous profiling floats (e.g., BGC-Argo), and similar platforms, in the world ocean to monitor biogeochemical properties, phytoplankton composition, mixed layer depth, and other properties.

5.7 Data Processing and Synthesizing

A key component for all scientific challenges and as encapsulated in the **Leveraging Ocean Data and Models** grand challenge is developing the capability to store, process, synthetize and provide easy access to a significant amount of disparate data. The way data streams are organized should lead to an intuitive ability to utilize datasets from different data streams, synthesize these data, and enhance data utility and applications. Future efforts and investments should particularly focus on:

- Development of machine learning and significant increases in a machine learning educated workforce.
- Coordination of multi-and-interdisciplinary teams, including scientists in the oceanographic and optics sphere, together with data scientists, statisticians, and social scientists.
- Improvement of infrastructure to allow ease in accessing and working with multiple large datasets.

Technology Development

- A tiered hierarchy of networked computational and data facilities.
- Advances in Cloud-based computing and data synthesis.

5.8 Modeling

Models are a particularly useful tool for synthesizing many disparate datasets and for understanding global aquatic systems. Accordingly, improvements in modeling capabilities are essential for addressing all five OBB **Grand Challenges**. The needs outlined here include continued investment in developing/advancing a wider range of models, including hindcast/nowcast models dedicated to process studies, as well as data assimilation and the production of ocean biogeochemical and ecosystem state estimates, with a particular focus on:

- Incorporating inherent and apparent optical properties.
- Integrating radiative transfer components into models.
- Identifying and including additional necessary components and complexity (e.g., ecological diversity and interactions, intracellular and metabolic processes, additional micronutrients).
- Parameterizing of sub-grid scale processes.
- Including the land-ocean and ice-ocean continuum.
- Embedding mission simulators (e.g., PACE simulator) in appropriately designed coupled physics, biogeochemical and optics models.

Technology Development

- Coupled physical, biogeochemical data assimilation.
- Observing system simulation experiments (OSSEs).
- Lagrangian methodologies.
- Use of machine learning to advance model development for poorly constrained processes and parameters, as well as to build emulators.

6. Benefits for the Nation and Beyond

Benefits from the **Science Vision** outlined in this document for our nation, and all nations, extend far beyond the direct advances made to scientific knowledge and thread through global economies, national security, policy, human health, resource management, food security, navigation, weather, and climate prediction. Aquatic ecosystems provide 20% of annual animal protein to 3 billion people each year, with this value exceeding 50% in some countries. *The ability of aquatic systems to continue supporting such demands depends on scientifically sound management practices supported by advanced observations, such as those described herein*. The ocean also generates hundreds of millions of jobs in tourism, fishing, energy, shipping, biotechnology, and other sectors, ranking the ocean as the seventh largest global economy (Figure 6-1). *Advanced observational capabilities outlined in this report contributed to sustaining this vast ocean economy*. For the United States, the 30 ocean and Great Lakes coastal states comprise 57% of land area, but 82% of population and economy. Effective management, monitoring, and protection of marine systems are national priorities, particularly given that employment and population growth in coastal counties are the highest in the nation. The ocean currently generates the largest share of the United States natural resources economy (including farming, food production, oil and gas extraction, and forest products) and its share of U.S. employment is as large as that of all these other natural resource industries combined. *The security of this economy relies on the types of observational assets and research-based understanding uniquely provided by NASA and its OBB program*. Indeed, the economic value of such capabilities is substantial. As examples, harmful algal bloom events in coastal regions have an estimated cost impact of \$82 million per year in the United States alone and healthy coral reef systems provide

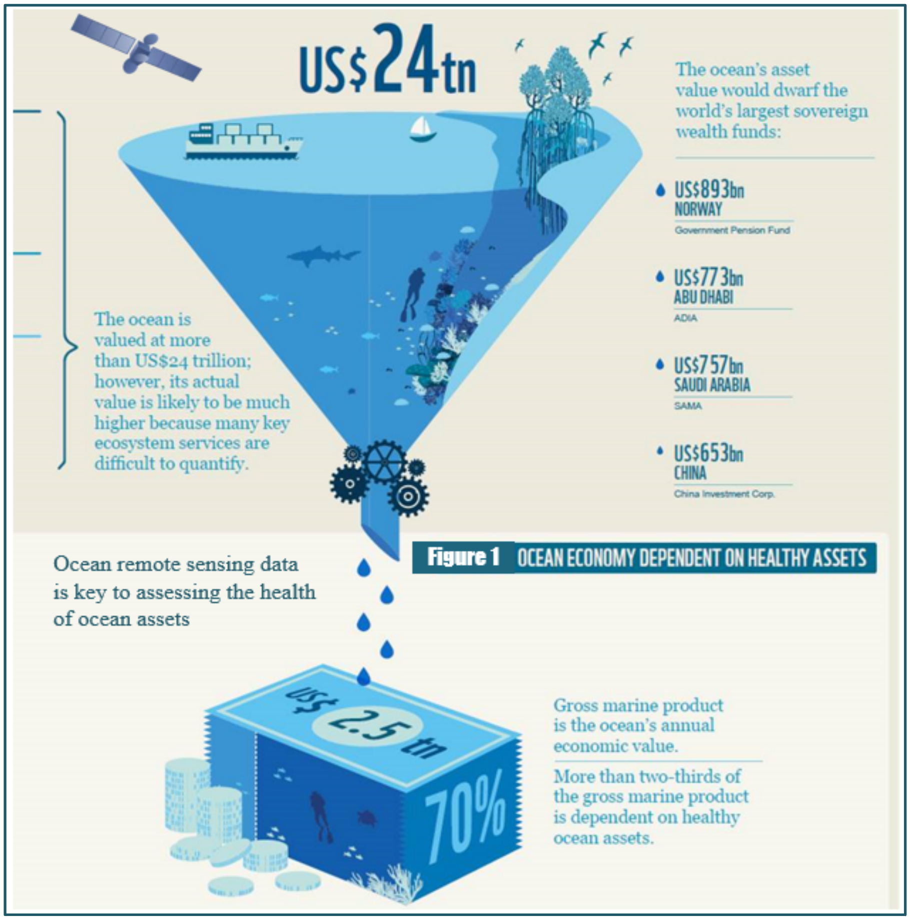


Figure 6-1: Valuation of ocean goods and services. (adapted from Hoegh-Guldberg et al. 2015)

billions of dollars to local economies through recreational industries, restaurants, and other associated businesses.

Observations outlined in this **Science Vision** improve ecosystem vulnerability assessments and enable improved management of fisheries resources. The value of these latter resources is staggering. United States commercial fisheries associated with coral reef systems alone are estimated at over $100 million and international trade in fisheries contributes $70 billion annually to the United States' economy. *By improving the spectral, spatial, and temporal resolution of ocean observations, significant advances will be realized in understanding spawning habitats and recruitment success, characteristics and changes in species environmental niches and life cycles, factors controlling ocean productivity and variability, and the planning for and impacts of coastal aquaculture*. Understanding controls on marine diversity and improving ecological forecasting are required scientific steps to realize the promise of better living for humans everywhere.

The portfolio of observations outlined in this document represents a path forward for assessing value, determining impacts, and detecting change in coastal and estuarine resources to global ecosystems. These capabilities allow monitoring of fisheries and water quality, mapping of sediment plumes, improving protection of sensitive ecosystems (e.g., seagrasses, corals), and developing advanced detection, forecasting, and early warning systems for aquatic threats that impact human health, including harmful algal blooms and aquatic pathogens (e.g., fecal coliforms such as *Vibrio* sp.). They directly address the major goals outlined by the Ocean Policy Committee and support its Ocean Climate Action Plan (OCAP) by providing high quality scientific information that will inform management and policy actions leading to the sustainable use of the ocean, thereby also contributing to the Sustainable Ocean Plan. The information garnered from embarking in these OBB **Grand Challenges** will be a critical baseline for ocean-based climate solutions and will inform strategies for developing more resilient communities living at aquatic interfaces.

Improved monitoring of ocean conditions and dynamics are also beneficial to emergency managers and community decision-makers faced with flood, hurricane, volcano, fire, oil spills, and other **Transient Events**. These capabilities have significant economic value. For example, the economic cost of the 2010 Deepwater Horizon explosion and oil release in the Gulf of Mexico is estimated at $50 billion and scientific investigations related to this disaster aided in assessment and recovery efforts. Satellite ocean observations of currents and sea ice extent have become increasingly valuable in the shipping industry for navigational purposes as well as developing fuel economy strategies. Satellite ocean observations have also played an important role in human safety, supporting search, and tracking assistance for over 8,000 rescued people in the United States since 1982.

While the science vision outlined in this document is largely focused on aquatic applications, it is important to note that the associated observations also contribute to atmospheric applications by providing improved or sustained measurements of clouds and aerosols. These data are needed by regulatory agencies, resource managers, weather forecasters, and first responders to allow for better assessments of local and regional air quality (a public health application) and better characterization of hazards for issuing disaster warnings (a public safety application). Air quality remains an important concern for human health, nationally and globally, and is degrading in many regions. In the United States, the accumulated economic value of the reduction in air pollution between 1990 and 2020 is estimated at almost $2 trillion. *Observational capabilities described herein will contribute significantly to understanding, monitoring, modeling, and predicting changes in air quality and weather*. In addition, these measurements have significant value to the aviation industry by providing observations of plume extent and trajectories following volcanic eruptions to allow for rapid adjustments in international aviation flight scheduling and routing.

The broad-reaching benefits of this science vision extend well beyond specific science targets. The execution of this plan will inspire exploration and discovery of our home planet. It will provide tangible benefits to the people of our nation and the world by providing data necessary to improve the quality of human life and contribute to job and economic security. Moreover, the technological advances required to achieve the proposed goals will be relevant to homeland security and will foster partnerships between businesses, state, and federal partners.

Figure Credits

Unnumbered figures in Chapter 1:

1. Global Biosphere: https://www.rgbstock.com/photo/mC2F1Dy/Sea+hemisphere
2. Climate and the Elements of Life: https://www.us-ocb.org/zooplankton-play-a-key-and-diverse-role-in-the-ocean-carbon-cycle/
3. Interface Habitats: https://www.eumetsat.int/melting-greenland-ice-sheet-cools-north-atlantic-ocean
4. Transient Events: https://www.theguardian.com/environment/2020/jan/04/lethal-algae-blooms-an-ecosystem-out-of-balance
5. Leveraging Ocean Data and Models: http://www.cantondataprint.com/data/
6. The Bottom Line: https://culturico.com/2019/07/05/humanity-is-a-cancer/

Figure 3.1-1 from
Hostetler, C.A., Behrenfeld, M.J., Hu, Y., Hair, J.W., Schulien, J.A., Spaceborne lidar in the study of marine systems. *Ann. Rev. Mar. Sci.* 10, 121-147, 2018.

Figure 3.1-2 from
Behrenfeld, M.J., Hu, Y. O'Malley, R.T, Boss, E.S., Hostetler, C.A., Siegel, D.A., Sarmiento, J., Schulien, J., Hair, J.W., Lu, X., Rodier, S., Scarino, A-J., Annual boom-bust cycles of polar phytoplankton biomass revealed by space-based lidar. *Nature Geosci*. doi: 10.1038/NGEO2861, 2017.

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Hostetler, C.A., Behrenfeld, M.J., Hu, Y., Hair, J.W., Schulien, J.A., Spaceborne lidar in the study of marine systems. *Ann. Rev. Mar. Sci.* 10, 121-147, 2018.

Figure 3.2-1 from
NASA Earth Observatory (https://earthobservatory.nasa.gov/images/149039/australian-fires-fueled-unprecedented-blooms)

Figure 3.2-2 from
NASA's Conceptual Image Laboratory (https://svs.gsfc.nasa.gov/12469)

Figure 3.2-3 from
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Figure 3.2-5 from
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Figure 3.5-2 from
IOCCG (2020) Synergy between Ocean Colour and Biogeochemical/Ecosystem Models. (ed. Dutkiewicz, S.) Dartmouth, NS, Canada, International Ocean-Colour Coordinating Group (IOCCG), 184pp. (Reports of the International Ocean-Colour Coordinating Group, No. 19), http://dx.doi.org/10.25607/OBP-711

Figure 3.5-3 from
IOCCG (2020) Synergy between Ocean Colour and Biogeochemical/Ecosystem Models. (ed. Dutkiewicz, S.) Dartmouth, NS, Canada, International Ocean-Colour Coordinating Group (IOCCG), 184pp. (Reports of the International Ocean-Colour Coordinating Group, No. 19), http://dx.doi.org/10.25607/OBP-711

Figure 4.1-1 created for this report by Michael Behrenfeld.

Figure 6-1 adapted from
Hoegh-Guldberg et al., Reviving the Ocean Economy: the case for action. *WWF International*, Gland, Switzerland, Geneva, 60 pp. 2015.

Table of Abbreviations & Acronyms

Acronym	Meaning
ACE	Aerosol, Cloud, Ecosystems
AML	Active mixing layer
AOS	Aerosol Observing System
AVIRIS-NG	Airborne Visible-Infrared Imaging Spectrometer-Next Generation
BGC-Argo	Biogeochemical Argo
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observatory
CDOM	Colored dissolved organic matter
CDR	Carbon dioxide removal
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DEIA	Diversity, equity, inclusion, and accessibility
DNA	Deoxyribonucleic acid
DoLP	Degree of Linear Polarization
DSCOVR	Deep Space Climate ObserVatoRy
EPIC	Earth Polychromatic Imaging Camera
ESA	European Space Agency
ESDS	Earth Science Data Systems
ESTO	Earth Science Technology Office
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GEDI	Global Ecosystem Dynamics Investigation
GEO-CAPE	GEOstationary Coastal and Air Pollution Events
GEOSS	Global Earth Observing System of Systems
GeoXO	Geostationary Extended Observations
GLIMR	Geosynchronous Littoral Imaging and Monitoring Radiometer
GMAO	Global Modeling and Assimilation Office
GO-BGC	Global Ocean Biogeochemistry
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GOCI	Geostationary Ocean Color Imager
GOES	Geostationary Operational Environmental Satellite
HARP2	Hyper-Angular Rainbow Polarimeter 2
HPLC	High-Performance Liquid Chromatography
HSRL	High Spectral Resolution Lidar
ICESat-2	Ice, Cloud and land Elevation Satellite-2
IOCCG	International Ocean Colour Coordinating Group
IPCC	Intergovernmental Panel on Climate Change
JPSS	Joint Polar Satellite System
MERIS	Medium Resolution Imaging Spectrometer

MERRA	Modern-Era Retrospective analysis for Research and Applications
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	MultiSpectral Instrument
NAAMES	North Atlantic Aerosol and Marine Ecosystem Study
NASA	National Aeronautics and Space Administration
NASEM	National Academy of Sciences, Engineering, and Medicine
NIR	Near-infrared
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
OB.DAAC	Ocean Biology Distributed Active Archive Center
OBB	Ocean Biology and Biogeochemistry
OLCI	Ocean Land Colour Imager
OMI	Ozone Monitoring Instrument
OSSE	Observing System Simulation Experiments
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PO	Physical oceanography
POLDER	POLarization and Directionality of the Earth's Reflectance
PRISM	Portable Remote Imaging SpectroMeter
RGB	Red, Green, Blue
ROMS	Regional Ocean Modeling System
SBG	Surface Biology and Geology
SeaWiFS	Sea-viewing Wide Field-of-View Sensor
SIPS	Science Investigator-led Processing System
SML	Seasonal mixed layer
SNPP	Suomi-National Polar-orbiting Partnership
SOCCOM	Southern Ocean Carbon and Climate Observations and Modeling
SPEXOne	Spectro-Polarimetric Experiment One
STEM	Science, technology, engineering, and mathematics
SWIR	Shortwave to infrared
TEK	Traditional ecological knowledge
UAV	Unoccupied aerial vehicle
USGS	United States Geological Survey
UV	Ultraviolet
VIIRS	Visible Infrared Imaging Radiometer Suite

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