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

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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 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 system, provide solutions for management, and communicate new understanding to all stakeholders. Comments on this document were

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widely solicited across the research community and responses were incorporated into this final version.

A foundation upon which this vision 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 and governmental partners, the international science community, and industry. 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*.

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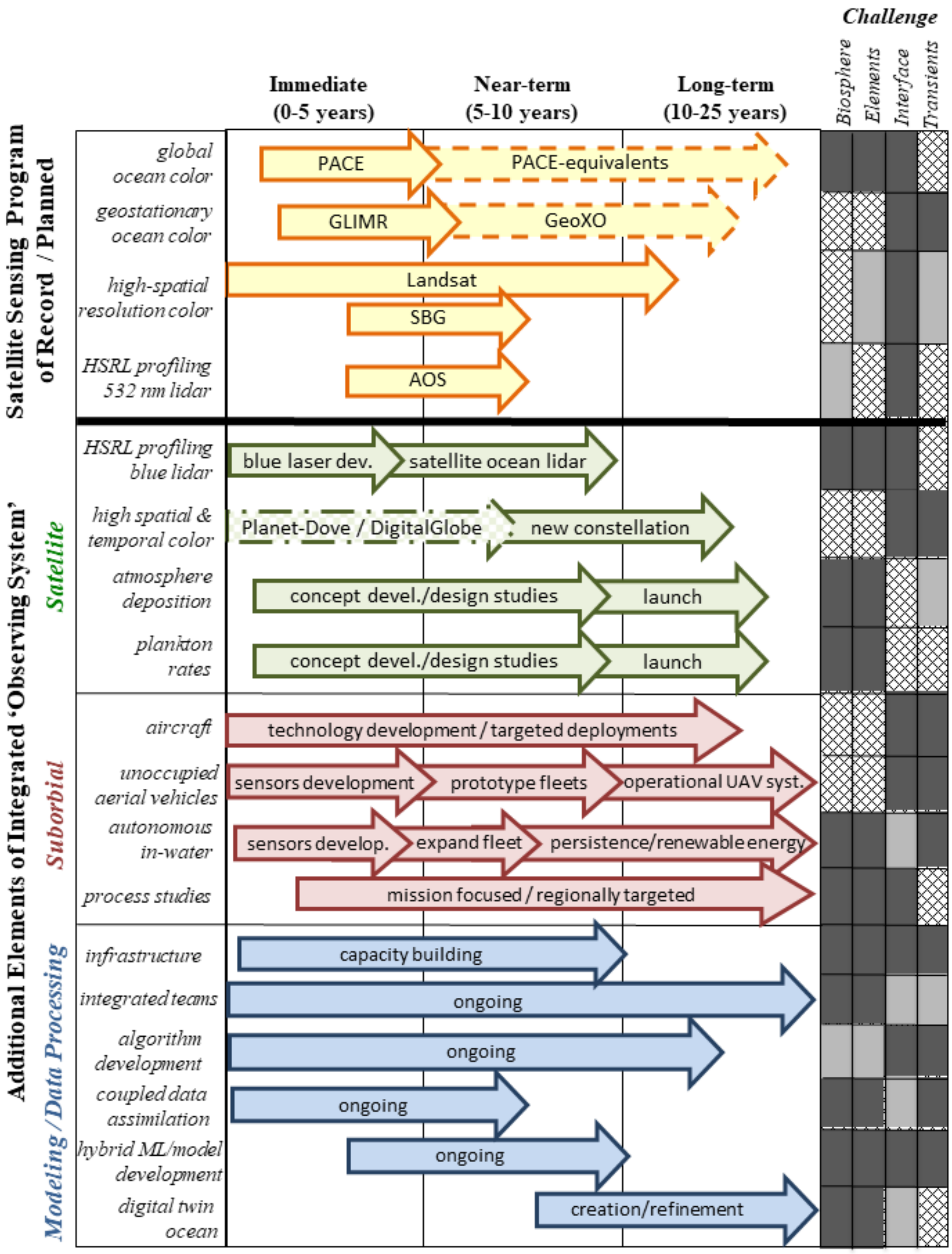
Envisioned Observing System: Parallel development of diverse observing system elements allows ocean science **Grand Challenges** to be addressed. Program of Record missions are shown above heavy black horizontal line, with dashed outlines indicating planned but not yet funded missions. Additional new *'o*bserving 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.

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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**, **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

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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.*

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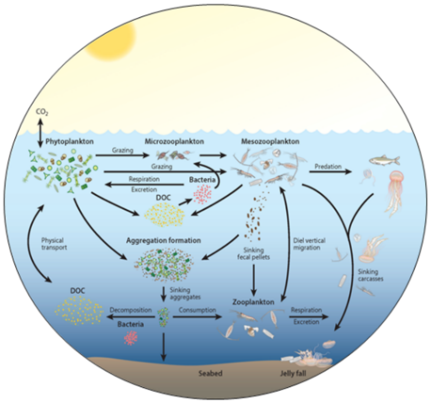
Elements of Life

The ocean plays a dominant role in regulating Earth's climate, including the rate and magnitude of contemporary climate change. 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). 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, 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, 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, and biogeochemical 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 process 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*

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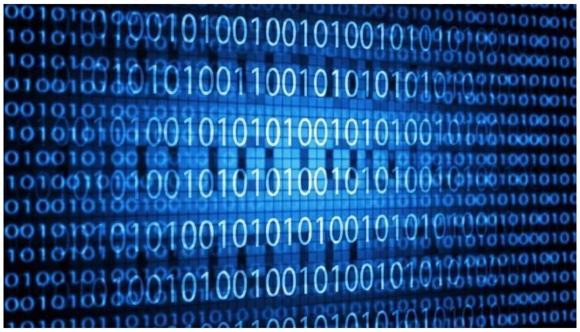
processes and human activities govern the diversity, function, and resilience of life in interface habitats such that the services and value of these dynamic systems to humanity can be safeguarded and sustained for future generations.

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



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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. 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

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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.

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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 (https://www.goosocean.org/) and Global Climate Observing System (https://gcos.wmo.int/en/home) 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 scheduled for launch in 2022 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

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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 been developing 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; https://sbg.jpl.nasa.gov/) 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.

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