

# A decade of success in ocean remote sensing and a vision for the future

*A response to the 2015 Decadal Survey Committee Request for Information (RFI)*

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**DS-Q1:** What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

**Key ESS question:** How will climate change over the coming century impact global ecosystems, biogeochemical cycles, resource sustainability, and human welfare?

**Associated ESS challenge:** Conduct global remote sensing observations, linked to modeling and field measurements, that yield new insights on how the coupled Earth System responds to contemporary climate variations, thereby enabling improved predictions of future change that inform management and resource sustainability decisions.

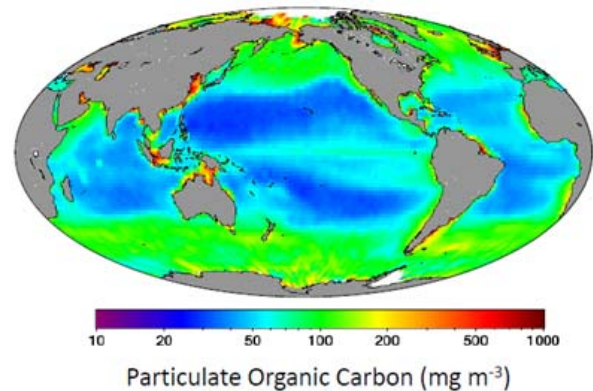
*Decade of Discovery* - This response to the Decadal Survey (DS) Request for Information (RFI) focuses on global ocean observations. Given that the DS committee charge is to recommend observational requirements for the coming decade, it seems appropriate to ‘set the stage’ by briefly recognizing some of the remote sensing achievements made over the past decade.

Since the 1970’s, the primary satellite tool available for globally observing ocean ecosystem properties has been passive ocean color measurements. With this technology alone, major progress has been made in addressing the above **ESS question and challenge**. We have discovered that ocean phytoplankton are responsible for roughly half of the annual net primary production on Earth [1] and that the globally-integrated response of the phytoplankton to climate variations can be notably stronger than parallel changes in terrestrial plants [2]. In the last decade, it has been further shown that these interannual changes in ocean chlorophyll are inversely related to sea surface temperature changes (i.e., a warming ocean exhibits decreased chlorophyll) [3]. Currently, these changes are driven primarily by natural drivers of climate variability (i.g., El Nino Southern Ocean (ENSO) cycle, Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO)) [4], but the relationship with SST nevertheless provides invaluable insights on potential future climate change impacts. Through the development of ocean color inversion algorithms [5,6], we are now also able to distinguish changes in phytoplankton biomass from changes in physiology [7]. With this new capability, ocean productivity models have become more mechanistically based [8], our understanding of the inverse chlorophyll-SST relationship has been greatly advanced [9, 10], improvements have been made in assessing the ocean biological carbon pump [11], and we have discovered that the largest annual plankton event in the global ocean, the North Atlantic spring bloom, results from physical-ecosystem relationships that are both very different than traditionally thought and directly impacted by climate [12,13]. Also in the past decade, field studies have revealed unique physiological impacts of iron limitation in phytoplankton that, in the equatorial Pacific alone, can cause errors in ocean productivity estimates on the order of  $2 \text{ Pg y}^{-1}$  [14, 15]. Building from this finding, satellite chlorophyll fluorescence retrievals by MODIS Aqua have allowed a global mapping of iron-limited plankton populations, including previously unrecognized regions [16]. Fluorescence data from the Geostationary Ocean Color Instrument (GOCI) have added to this understanding of phytoplankton physiological stressors [17]. These and many other ocean color-based discoveries over the past decade have greatly improved our understanding of ecosystem functioning and have provided important constraints for coupled ocean circulation – ecosystem models that allow improved predictions of future change. With the launch of NASA’s upcoming PACE mission, we can anticipate this record of discovery to continue.

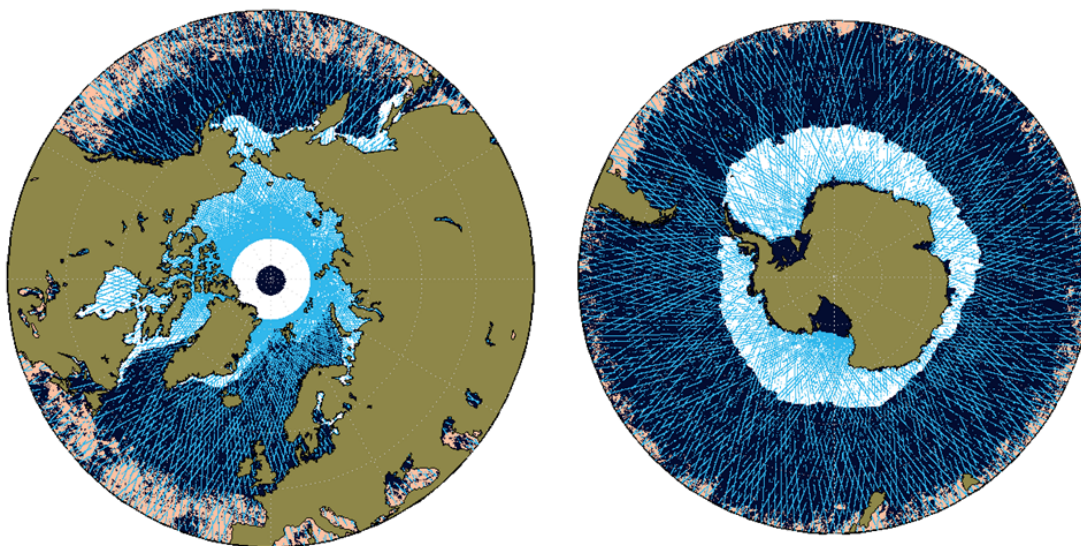
*New Era in Satellite Ocean Observations* – Ever since the Coastal Zone Color Scanner (CZCS) launched the modern satellite era of oceanography, fundamental limitations to this technology have been recognized. Specifically, the ocean color signal: (1) Emanates from only the first optical depth of the ocean (exponentially weighted toward the surface) and thus provides no information on plankton distributions over most of the photic zone, (2) Is not retrieved at low solar angles and under many patchy cloud conditions, which particularly limits observations of the polar ecosystems that are currently experiencing major impacts from climate change, and (3) Provides no information on plankton ecosystems during night, which again limits our understanding of plankton annual cycles in polar regions, as well as hinders new insights on global phytoplankton physiological conditions.

We are now in a position to address all of the above issues. For decades, the utility of lidar technology for vertically-resolving plankton properties has been demonstrated using airborne systems [e.g., 18]. However, the applicability of this technology from space was untested until recently. In 2006, NASA and the Centre National d'Etudes Spatiales (CNES) launched the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite as part of the A-train Earth Observing Sensor suite [19]. The primary instrument on CALIPSO is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor, and it has reliably collected global lidar measurements at 532 nm and 1064 nm for the past 9 years. CALIOP was designed for atmospheric, not ocean, applications and lacks the vertical measurement resolution for plankton profiling. Nevertheless, global distributions of phytoplankton carbon biomass and total particulate carbon stocks have been retrieved with CALIOP [20] (**Fig. 1**). Subsequent studies with CALIOP data have confirmed this new capability and demonstrate that we are ready for the next major step forward in the age of satellite oceanography. Modifying the CALIOP approach to capitalize on the technologically-mature High-Spectral Resolution Lidar (HSRL) technique, a new ocean-focused satellite lidar system is foreseeable in the immediate future that could provide global active retrievals of plankton properties with subsurface vertical profiling at 1 – 2 m resolution and down to 3 optical depths.

An HSRL-based ocean-profiling satellite lidar will allow more accurate quantification of plankton stocks throughout the year in climate-sensitive polar regions (i.e., the measurements are conducted both day and night) (**Fig. 2**), will improve global assessments of ocean productivity by allowing characterization of phytoplankton biomass distributions within the subsurface light environment, and will enhance our understanding of how ocean physical processes (mixing, advection, etc) structure ocean ecosystems. In addition, lidar measurements can retrieve plankton properties under patchy cloud conditions that prevent ocean color observations, are not susceptible to the significant atmospheric correction errors that ocean color data suffer from, and can be achieved to aerosol/cloud optical thicknesses up to ~1.0. Addition of fluorescence detection capabilities, which have already been demonstrated for airborne lidar systems, would also allow active measurements of phytoplankton physiological properties and an improved distinction of specific nutrient stressors. Inclusion of a UV wavelength (355 nm) on an ocean lidar could also provide accurate assessments of cDOM concentrations, which can then be used to refine ocean color inversion algorithms.



**Figure 1.** The first global retrieval of ocean particulate organic carbon concentrations from a space lidar [20]



**Figure 2.** High latitude coverage provided by CALIOP over a 16 day window in (left) January 2010 and (right) June 2010. Pink color = MODIS Aqua retrievals. Dark blue = No MODIS data. Light blue lines = CALIOP measurements at aerosol/cloud optical depths  $< 1$ . The ability of CALIOP to make measurements through cloud gaps and during darkness or low light has already yielded new insights on the early rise and late demise of high-latitude plankton blooms and their link to ocean temperature changes.

A satellite lidar ocean profiling capability will allow major advances in addressing the **ESS question and challenge** posed above, but will be particularly beneficial if coupled with the next-generation ocean color observations offered by the PACE sensor. In this scenario, the ocean color sensor provides information on spatial variability between lidar measurement lines. In turn, the lidar provides invaluable information on plankton vertical structure to complement the surface-only ocean color signal and provides ocean retrievals under light or cloud conditions that compromise PACE retrievals. The lidar data would also enable advancements in ocean color inversion algorithms by providing independent and active retrievals of ocean properties that are common to both sensors, such as the diffuse attenuation coefficient ( $K_d$ ) and the particulate backscattering coefficient ( $b_{bp}$ ), from which total particulate carbon and phytoplankton carbon stocks are assessed. Furthermore, the lidar would provide vertically-resolved atmospheric properties that can then be used to improve the accuracy of atmospheric corrections for the ocean color sensor by providing information on total atmospheric aerosol burdens, aerosol type, and aerosol vertical distributions.

The penetration depth for ocean lidar retrievals is limited by signal-to-noise to 3.0 optical depths for an instrument of practical size and power. Extending the characterization of plankton vertical structure beyond these depths is nevertheless desirable. This can be achieved through the simultaneous development of a BioGeoChemical Argo float array (BGC-Argo), such that a global distribution of profiling floats exists over the lifetime of the coupled lidar – next-generation ocean color missions. With this constellation of observing assets, the BGC-Argo array provides information on deep-water plankton structure and biogeochemical properties ( $\text{NO}_3$ ,  $\text{O}_2$ , pH) to extend the lidar retrievals and science, albeit at a coarser spatial resolution than the lidar. The combination of lidar and BGC-Argo data together provide the vertical context to the ocean color retrievals, which in turn provide the enhanced spatial coverage. *With this coordinated infrastructure, a global 3-dimensional reconstruction of temporally-evolving ocean ecosystems can be envisioned that would yield profound new insights on ocean biology, biogeochemistry, physical-biological interactions, and understanding of future climate change impacts.*

**DS-Q2:** Why are these challenges/questions timely to address now especially with respect to readiness?

The potential scientific advances that could be realized with a satellite-based ocean-profiling lidar have been recognized for many years, but only within the past decade have the major developments been made to demonstrate that this vision is now ready to become reality. These developments include:

1. Launch of the CALIOP sensor and demonstration of global ocean plankton retrievals
2. Development of the HSRL technique and airborne demonstration of its advanced capabilities for ocean retrievals and plankton profiling during 3 major field campaigns (Azores 2012, SABOR 2014, NAAMES 2015)
3. Validation of CALIOP and airborne HSRL plankton retrievals through comparisons with direct field measurements and MODIS Aqua matchups
4. CALIOP-based retrievals of complete annual plankton cycles for the Arctic and high-latitude Southern Ocean, demonstrating successful retrieval of phytoplankton biomass during low-light and polar night conditions and revealing new insights on phytoplankton losses and early bloom initiation that are undetected by ocean color sensors.

In addition to these technological and scientific developments, raising an ocean profiling lidar sensor to the status of a ‘top-tier mission’ DS recommendation is timely because:

1. Northern and Southern polar oceans are exhibiting some of the fastest rates of change in the natural world, yet we currently do not observe these systems from space over extended periods of each year
2. The two largest sources of errors in current ocean productivity estimates are uncertainties in phytoplankton distributions within the upper 3 optical depths and incomplete knowledge of phytoplankton physiological states. Lidar observations can address these issues
3. Technological readiness of the HSRL approach is sufficiently high that a lidar mission could be launched in the time frame of the upcoming PACE mission, with associated advantages of this pairing described above
4. BGC-Argo arrays are already being developed and deployed around the world’s ocean that could support a lidar mission (e.g., 200 floats from the NSF/NASA Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program; float lifetime ~7 years)
5. An HSRL satellite lidar with the profiling capabilities described herein would have major advantages for global cloud and aerosol sciences. Some of these advantages are detailed in the ‘ACE Mission’ whitepaper (lead: Dr. Arlindo da Silva) and the ‘Marine Aerosol-Cloud-Climate Interactions’ whitepaper (leads: Drs. Nicholas Meskhidze and Susannah Burrows) also being submitted in response to the current DS RFI.
6. Mission studies are currently underway for a future HSRL mission with ocean profiling capabilities at the NASA Langley Research Center and at CNES, with significant possibilities for an interagency collaboration.



**DS-Q3:** Why are space-based observations fundamental to addressing these challenges/questions?

The **ESS question and challenge** posed above requires new satellite ocean observations (lidar) coupled with advanced ocean color measurements (PACE). Space-based observations are the most effective tools for creating the globally-representative data sets needed for achieving new mechanistic insights on Earth System functioning that inform advances in coupled global climate-ecosystem modeling and improve predictions of future change. It is recommended here that for an evaluation of the above **ESS question and challenge** the Decadal Survey committee assemble a science panel with expertise in lidar technologies, ocean biogeochemistry, plankton ecology, ocean color remote sensing, atmospheric aerosols, and clouds.

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