Carbon and the Elements of Life: Integrated Observing and Modeling of Marine Biological Carbon Cycles

A response to the Request for Information for the Decadal Survey for Earth Science and Applications from Space 2028–2037 (ESAS 2028)

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It is one of a series of five ocean biology and biogeochemistry white papers led by this author team.

The authors welcome feedback and comment; please contact the corresponding author.

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Carbon and the Elements of Life: Integrated Observing and Modeling of Marine Biological Carbon Cycles

A White Paper Submitted to the 2028–2037 Decadal Survey for Earth Science and Applications from Space (ESAS 2028) Request for Information

NASA Earth System Science Research Sphere: Biosphere with important linkages to the Atmosphere sphere

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Executive Summary

The global ocean acts as a massive reservoir for carbon dioxide, establishing ocean biogeochemistry as a primary driver of global carbon distributions [1-3]. This dynamic system is mediated by living organisms that cycle carbon and other elements through the ocean interior and air-sea interface, and is already being altered by warming, acidification, deoxygenation, and shifting nutrient supply [4]. Predicting how this role and ocean life will respond is a central unresolved challenge for Earth system science.

This white paper presents the science case and a phased, multi-platform observing and modeling strategy for the Climate and the Elements of Life grand challenge, following NASA's Ocean Biology and Biogeochemistry (OBB) Research Program science vision [5]. We recommend: (1) sustained hyperspectral and polarimetric ocean color resolving the mesoscale; (2) an ocean-optimized profiling lidar for subsurface elemental cycling and physiological state; (3) continued geostationary and, eventually, Lagrange-point observations; (4) an expanded autonomous and ship-based in situ network; and (5) mass-conserving biogeochemical models and assimilation fusing these into predictive estimates of carbon cycling and air-sea exchange.

Together, these elements would give the nation the capability to track how the ocean's biological regulation of global biogeochemical pathways is changing and to responsibly evaluate proposed ocean-based carbon management strategies before they are deployed at scale.

1. Introduction: The Science Question and Societal Challenge

Earth's ocean uniquely receives enough solar energy to sustain a largely ice-free surface, vigorous hydrologic cycling, and warm surface temperatures conducive to rapid biological and chemical activity. These attributes drive massive biogeochemical cycles of life sustaining elements, continuously modified by physical, chemical, and ecological processes, collectively termed ‘biogeochemistry.’ When human activities alter the flux of elements into and within the ocean, consequences ensue for ocean health and sustainability, feeding back onto the rate and magnitude of contemporary climate change.

The ocean plays a dominant role in regulating Earth's climate: it has absorbed nearly all excess heat added by anthropogenic greenhouse gases [3] and, since pre-industrial times, more than a quarter of all carbon dioxide emissions [5], presently about 12 billion tons annually. That sink has been roughly stagnant since 2016, reflecting climate variability including the 2023–2024 Northern Hemisphere marine heatwave [1]. Ocean life drives this regulation through the interconnected cycling of carbon, oxygen, nitrogen, phosphate, iron, and other elements [6,7]. In the upper sunlit ocean, phytoplankton fix carbon via photosynthesis and a fraction is exported to depth through the ‘biological pump’, remaining sequestered for months to millennia [7–11]. Remineralization of that flux consumes oxygen at depth, and oxygen minimum zones have expanded measurably as the ocean has warmed [12,13]. The strength of the ocean carbon sink depends not only on how much carbon is fixed but on which organisms fix it (e.g., cell size, mineral ballast, trophic fate), so comparable primary production can differ several-fold in export efficiency [14–16]. Much of this variability is organized at the mesoscale, where eddies and fronts concentrate distinct assemblages and drive vertical transport that basin-scale averages miss [17–19]. Marine heatwaves illustrate this: ocean color assimilated into a biogeochemical model shows chlorophyll rising in the Gulf of Alaska during the 2014 warm anomaly even as diatoms gave way to dinoflagellates, reducing export efficiency, and chlorophyll falling ~40% with near-total diatom collapse during the 2016 equatorial Pacific El Niño [20]. Vertically migrating zooplankton and fish also transport carbon below the mixed layer [21,22]. Escalating anthropogenic emissions drive acidification, deoxygenation, altered nutrient supply, and ecosystem disruption, threatening ocean life and human society [4].

The future role of ocean biology in climate regulation and the impacts of a changing climate on ocean life constitute some of the most consequential open questions in Earth system science. To address it we must:

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

This challenge sits within the Biosphere sphere, given its focus on aquatic ecosystem biogeochemistry and biodiversity, but extends into the Atmosphere sphere through ocean-atmosphere gas and aerosol exchange, radiative forcing, and the global carbon budget. Addressing it is foundational to the Blue Economy, valued at an estimated $1.5 trillion annually, and to the roughly $0.5 trillion value of improved climate predictions from better carbon sequestration understanding [5]. Indeed, the biological pump alone has been valued at roughly $1 trillion annually [23]. This submission is one of a linked series of papers addressing the Grand Challenges of NASA's Ocean Biology and Biogeochemistry (OBB) Research Program [5].

2. State of the Science: Achievements and Limitations

NASA's satellite ocean color missions – from the Coastal Zone Color Scanner through SeaWiFS, MODIS, VIIRS, and now the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, operating since February 2024 [24] – have transformed understanding of ocean elemental cycles. These records have improved global estimates of primary productivity [25,26], revealed coastal and continental-margin carbon cycling [27], documented basin-scale ecosystem responses to climate variability [9,20,28], and constrained numerical biogeochemical models that increasingly resolve phytoplankton functional types and assimilate ocean color data into state estimates [8,29–31]. Despite this progress, four limitations constrain current capacity to predict how ocean biogeochemical cycling and its climate feedbacks will change.

First, the elements of life cycle through the ocean in three dimensions, but ocean color sensors detect only the near-surface optical signature of phytoplankton communities, in daylight and mostly clear skies. Physical and biological processes create strong vertical structure, particularly in polar systems and continental shelves [32,33], and the fate of carbon exported into the ocean's ‘twilight zone’ remains poorly constrained by remote sensing. Ship-based and BGC (Biogeochemical)-Argo measurements document substantial depth-dependent variation in particulate organic carbon and its flux [34,35], but profiling remote sensing is needed to assess it globally. Because interior oxygen is drawn down by that same remineralization, neither the respiration depth of exported material nor its imprint on oxygen minimum zone volume can be constrained from surface ocean color.

Second, the exchange of elements between ocean and atmosphere remains difficult to quantify from space in either direction. Two distinct pathways carry material upward. In the first, bubble bursting and wave breaking eject sea spray through the surface microlayer, lofting biogenic organic material that can influence aerosol and cloud properties [36–38]; yet remote ocean sea spray carries low organic content under weak biological control [39], and aerosol-plankton relationships remain inconsistent [40,41]. In the second, phytoplankton produce volatile organic compounds, including DMS and isoprene [42–44], which evolve across the sea-air interface whenever production outpaces bacterial consumption [44] and convert to secondary organic aerosols acting as cloud condensation nuclei, possibly governing marine cloud formation more strongly than sea spray [45,46]. Neither pathway yields a directly observable remote sensing signal, and their combined contribution to aerosol-cloud interactions – the largest source of uncertainty in global radiative forcing estimates [47] – remains unknown. In the other direction, atmospheric deposition of nutrients, dust, and pollutants influences marine ecosystems [48], particularly near urban and fire-related sources [49,50], yet low-magnitude events are harder to detect than episodic ones such as volcanic eruptions or wildfires, which leave a clear ocean color signature (Figure 1) [51–53].

Third, many elemental cycling processes, e.g., phytoplankton physiological responses to nutrient and light stress, diel metabolic changes, and diel vertical migration, operate on timescales not resolved by polar-

orbiting satellites, which revisit a location at most once or twice daily. Diel cycles in phytoplankton optical properties (Figure 2) are tied to key physiological processes [54], yet no routine global capability to observe them from space exists.

Fourth, the biological control of the marine carbon cycle is exerted at spatial scales the current observing system resolves only intermittently. Mesoscale and submesoscale structures (one to ten kilometers) account for a disproportionate share of vertical carbon transport and impose sharp gradients in community composition, and critical carbon exchanges are concentrated at highly heterogeneous land-water interfaces whose dynamic fluxes and plumes demand higher spatial resolution. Persistent cloud cover often pushes the effective clear-sky revisit beyond a week, well past the timescale over which these features evolve, so eddies and fronts are sampled by chance and the composition–export relationship cannot be constrained at the scales at which it operates.

Meeting the Climate and the Elements of Life challenge for the coming decade requires addressing these four gaps through a coordinated observing and modeling strategy described below.

3. Proposed Observing and Modeling Strategy

Successful execution of the ocean color measurements in NASA's Program of Record, PACE and the future Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR, launch date TBD) is essential, as are future equivalent measurements augmented with technologies addressing current limitations and paired with continued modeling and data assimilation development. The strategy below is organized around properties and rates, ocean-atmosphere exchange, modeling and assimilation, and carbon dioxide removal (CDR) readiness.

3.1 Foundation: Sustained Hyperspectral and Polarimetric Ocean Color

Hyperspectral ocean color measurements, from a polar-orbiting satellite with 1-2 day global repeat coverage, remain the baseline observing requirement. These provide global information on surface layer phytoplankton stocks, primary production, community composition, dissolved and particulate organic carbon, and growth and consumption rates. New capabilities depend upon, not diminish, this baseline. Satellite polarization, pioneered by POLDER [55] and extended by PACE's polarimeters, additionally informs suspended particle composition and should be sustained beyond PACE, including through NASA's Falcon (Fleet for the Atmosphere Linking Commercial Observations with NASA) mission.

Two attributes warrant explicit specification. First, resolution and revisit must resolve the mesoscale. Pixel sizes near one kilometer with clear-sky revisit better than one week are needed to follow eddies and fronts. No single polar-orbiting platform can meet this in cloudy regions, motivating pairing of PACE-class continuity with the geostationary and constellation assets below. Second, hyperspectral information should be exploited to retrieve organic matter quality and phytoplankton community composition, since composition rather than biomass alone governs export efficiency, validated against coincident in situ flux measurements [56,57]; in EXPORTS, the diatom and Hacrobia content of sinking particles predicted particulate organic carbon flux magnitude [35].

3.2 High Temporal Resolution Geostationary and Lagrange Point Observations

Because many elemental cycling processes vary on sub-daily timescales, the geostationary Earth Venture Instrument (EVI) GLIMR is an important complement to PACE, providing sub-daily ocean color across near-shore and continental margin habitats around North America. Comparable capability should be sustained into the future to monitor transient biological pump dynamics and ocean carbon pathways. Satellites at the L1 Lagrange point could eventually offer high temporal resolution global coverage from a single platform, with advantages for accurate atmospheric correction and calibration [58], a concept demonstrated by the Earth Polychromatic Imaging Camera (EPIC) aboard the Deep Space Climate Observatory (DSCOVR). Investment toward a dedicated L1 mission is a long-term priority.

3.3 New Capability: An Ocean-Optimized Profiling Lidar for Subsurface Elemental Cycling

The highest-priority new technology is a vertically profiling, ocean-optimized satellite lidar, also a top priority in the related Global Biosphere Grand Challenge [59]. Active lidar can resolve vertical phytoplankton distribution, alongside broader particulate and dissolved carbon components, beyond the reach of passive sensors: passive systems 'see' only the first optical depth, whereas lidar reaches ~4.5 optical depths, depending on laser wavelength and water constituents [60,61], linking euphotic layer properties to mesopelagic material transfer. We recommend a High Spectral Resolution Lidar (HSRL)-class instrument with a 532 nm laser and both polarized and depolarized channels; unlike elastic-backscatter systems such as CALIOP, HSRL separates in-water particulate absorption from scattering directly. Heritage is substantial: CALIOP demonstrated the value of spaceborne ocean lidar [62,63], and China's ACDL instrument aboard DQ-1 has since returned the first spaceborne HSRL retrievals of ocean particulate backscatter [64,65]. This baseline should be augmented with a chlorophyll fluorescence channel near 680 nm to assess iron limitation and, potentially, a near-ultraviolet channel for CDOM and particle size. Resolving vertical CDOM distribution both prevents substantial errors in productivity assessments and traces the transport and microbial transformation of the marine dissolved organic carbon pool [66]. A parallel RFI submission by Collister and Hostetler [67] discusses the HSRL concept in depth and likewise recommends it as this Decadal Survey's highest priority.

3.4 A Physiology Lidar for Plankton Rates and Diel Cycles

Passive ocean color observations are limited to daylight hours, meaning they cannot resolve the diel cycles in phytoplankton physiology (i.e., division, photoacclimation, nutrient stress responses) essential for realistic modeling. Photosynthesis accumulates intracellular carbon and pigment by day, metabolism and division reverse those changes at night, and fluorescence yields are depressed by daytime photoprotective quenching but anomalously elevated at night under iron limitation [5,54]. A dedicated physiology lidar retrieving backscatter, attenuation, and chlorophyll fluorescence day and night would provide a direct global constraint on phytoplankton growth and stress that no passive sensor can supply [5]. Platform considerations differ from the profiling lidar (Section 3.3). Lidar-stimulated phytoplankton fluorescence is emitted over a band of wavelengths peaking at ~680 nm, where water absorbs strongly; the signal is therefore confined to the near surface, and only modest depth penetration and laser power are required, potentially opening the concept to CubeSat or SmallSat implementation. Because the diel timing of physiological processes varies regionally and seasonally, one solution is a constellation of SmallSats providing high temporal resolution coverage along identical orbit tracks, though the small amplitude of the diel signals would demand stringent cross calibration between platforms [5]. Trade studies are needed on the cost–science optimum, including HSRL versus simpler elastic-backscatter designs and space-proven 532 nm lasers versus blue wavelengths that stimulate fluorescence more effectively. Our strongest recommendation for the coming decade remains an HSRL-class lidar augmented with a 680 nm chlorophyll fluorescence channel; this should not preclude feasibility studies for a constellation-based physiology lidar.

3.5 Quantifying Ocean-Atmosphere Exchange

Additional investment is needed to quantify the two-way exchange of elements between ocean and atmosphere. On the ocean-to-atmosphere side, continued suborbital research, including process studies such as the North Atlantic Aerosol and Marine Ecosystem Study (NAAMES) [68], is needed to constrain seasonal and geographic variation in biogenic emissions and their link to community composition. Simultaneous ocean and atmosphere measurements from PACE, only beginning to be exploited to relate aerosol microphysics to primary production, should be sustained and enhanced. On the atmosphere-to-ocean side, deposition is more tractable: aerosol loads have long been observed by heritage NASA sensors (e.g., MODIS, VIIRS, CALIOP), but surface flux must be inferred from transport models, with significant uncertainty. Field studies (potentially via a CubeSat constellation) measuring deposition directly, would substantially improve these estimates.

3.6 Observing System Readiness for Carbon Dioxide Reduction Assessment

Controlling warming to well below the Paris Agreement targets will likely require negative carbon dioxide emission technologies [69,70], and ocean-based CDR strategies (e.g., iron fertilization, artificial upwelling, seaweed farming, ocean alkalinity enhancement) are under active discussion and field testing at scales that raise legitimate reversibility concerns [71]. The LOC-NESS project's August 2025 Gulf of Maine trial was the first EPA-permitted ocean alkalinity enhancement field test [72]. Independent of whether such interventions are pursued, NASA's Earth observing system is critical for establishing baseline records of biological pump functioning and assessing consequences of proposed CDR actions. The Program of Record missions, sustained high frequency and high spatial geostationary observations, a novel ocean-optimized profiling lidar, and the modeling capabilities above provide that foundation.

3.7 Autonomous and Ship-Based In Situ Networks

Most elements of life are not observable from space, and mechanistic understanding must come from direct sampling. A complementary priority is therefore a permanent, standardized suite of ocean-optical and biological instrumentation aboard research and survey vessels operated by NOAA, the NSF-supported U.S. Academic Research Fleet, and U.S. Navy oceanographic programs. Operated continuously under common calibration, metadata, and quality-control standards, and extended through public–private partnership to ships of opportunity, these fleets would greatly expand high-quality satellite matchups and reduce uncertainties in satellite-derived products.

Biogeochemical profiling floats (BGC-Argo) provide sustained, high-frequency measurements of pH, nitrate, oxygen, backscattering, and chlorophyll fluorescence, and their oxygen records constrain oxygen minimum zone boundaries. The 500-float GO-BGC expansion, targeted for completion across 2021–2026, is welcome [73], but even the full 1,000-float BGC-Argo design averages fewer than one float per 300 × 300 km, leaving the mesoscale unresolved. Gliders, autonomous vehicles, and Lagrangian tools such as wire-walkers can fill these gaps, and investment in energy harvesting (solar, wave, ocean thermal gradient) would extend platform persistence.

3.8 Advanced Biogeochemical Modeling and Data Assimilation

Numerical modeling ultimately synthesizes these observations into predictive understanding of elemental cycles and their climate feedbacks. Continued investment is needed in models that explicitly represent optical properties via radiative transfer or machine learning analogues. Models that assimilate directly observed quantities, such as water-leaving radiance, outperform those using more derived products such as chlorophyll concentration, whose uncertainties vary regionally and seasonally [74,75]. Because climate-relevant flux assessments depend on long-term trends, assimilation should prioritize mass conservation, since common ‘nudging’ techniques introduce artificial sources or sinks that corrupt trends [76]. Investment is also needed in diverse modeling approaches, field process studies, and higher-resolution configurations resolving mesoscale export control.

4. Key Measurement Requirements

Achieving the observing and modeling strategy above requires the following capabilities, in approximate order of priority:

Ocean color continuity requires uninterrupted, PACE-equivalent hyperspectral and polarimetric global observations, with sufficient overlap between successive missions to avoid gaps in the climate data record.

Mesoscale sampling requires resolution of approximately one kilometer or finer with clear-sky revisit better than one week, achieved through a combined polar-orbiting, geostationary, and constellation architecture. Retrievals of carbon quality and phytoplankton community composition require hyperspectral products that discriminate the functional groups governing export efficiency, validated against coincident in situ flux measurements.

Geostationary and future L1 ocean color capability should sustain GLIMR-equivalent, or comparable constellation-based, high spatial resolution and sub-daily observations of near-shore and continental margin environments, while advancing technology toward a future L1 orbit global ocean color mission.

The ocean-optimized profiling lidar should be a spaceborne HSRL-class instrument with a blue-emitting laser, providing meter-scale vertical resolution retrievals of particulate backscattering and attenuation, augmented with a chlorophyll fluorescence channel near 680 nm, with global pole-to-pole, day and night coverage.

A physiology lidar, potentially implemented as a formation-flying CubeSat or SmallSat constellation, should provide 1-2-hour repeated coverage along identical orbit tracks, with cross-calibration between platforms sufficient to resolve the small-amplitude diel cycles in phytoplankton backscatter, attenuation, and fluorescence.

Ocean-atmosphere exchange measurement requires continued suborbital process studies of biogenic emissions and new remote sensing approaches to quantitatively resolve atmosphere-to-ocean deposition and ocean-to-atmosphere fluxes. This could potentially be achieved by CubeSat constellations, multi-angle polarimeters, and backscatter lidar.

The autonomous and ship-based in situ network should be an expanded global array of BGC-Argo floats, gliders, and related platforms with optical and biogeochemical sensors, providing depth-resolved measurements from minutes to years and meters to basin scales.

Modeling and data assimilation infrastructure requires mass-conserving, optically explicit ecosystem and biogeochemical models coupled to assimilation systems capable of ingesting reflectance-, lidar-, and float-derived observations, developed and tested in parallel with the observing system.

5. Feasibility and Implementation within the Decadal Time Frame

No element of the strategy requires fundamental scientific breakthroughs within the decadal time frame. Continuity of the hyperspectral and polarimetric ocean color record carries very high readiness, building on PACE and multi-decade heritage. The impending deployment of GLIMR establishes high technical readiness for sub-daily, geostationary tracking of rapid biogeochemical transformations. The principal risk is programmatic.

The core new satellite capability, an ocean-optimized profiling lidar, builds on two decades of heritage from CALIOP in orbit, repeated HSRL validation in airborne field campaigns, and, most recently, from China's ACDL instrument aboard DQ-1, the first ocean-optimized HSRL to operate in orbit [65]. Adding a chlorophyll fluorescence channel is a comparatively modest extension, within immediate-to-near-term reach. A dedicated phytoplankton physiology lidar constellation, and extension into ocean-atmosphere deposition assessment, are appropriately near- to long-term goals.

The autonomous in situ network builds on the mature, internationally coordinated Argo and BGC-Argo programs. Its principal challenges are expanding their payloads and sustaining funding and coordination, with funding for BGC-Argo set to expire during 2026-27.

Across the strategy, the principal implementation challenges are not sensor readiness but algorithm and model development, data synthesis, and workforce capacity. Robust discrimination of phytoplankton physiological state from hyperspectral and lidar data will require sustained field validation and scientists connecting remote sensing, in situ oceanography, and modeling. Mass-conserving, optically explicit data assimilation, mature in physical oceanography, remains underdeveloped for biogeochemistry.

6. Summary of Recommended Priorities

To address the Climate and the Elements of Life grand challenge, we recommend that the 2028–2037 decadal survey prioritize:

1. Sustain PACE-equivalent global hyperspectral and polarimetric ocean color observations at mesoscale-resolving resolution (~1 km) and sub-weekly clear-sky revisit, to track properties influencing elemental cycles and inform numerical models (continued).
2. Sustain GLIMR-equivalent, or comparable constellation-based, high-temporal-resolution remote sensing to characterize sub-daily fluctuations in phytoplankton stocks and rates (continued).
3. Add an ocean-optimized, HSRL-class profiling lidar with chlorophyll fluorescence and CDOM detection to the Program of Record, resolving subsurface elemental cycling and physiological stress (immediate/near-term).
4. Explore a dedicated physiology lidar constellation (CubeSat/SmallSat) to characterize diel cycles in phytoplankton backscatter, attenuation, and fluorescence (near-term/long-term).
5. Invest in technologies for global ocean color observing from the L1 orbit, building toward a future high temporal resolution global mission (long-term).
6. Continue suborbital research and develop remote sensing approaches to constrain ocean-to-atmosphere biogenic emissions and atmosphere-to-ocean deposition fluxes (continued/long-term).
7. Expand global coverage of autonomous and ship-based in situ measurement of key physical, chemical, and biological rates, investing in technology that broadens autonomous platform observables, and establishing a standardized ocean-optical and biological instrument suite aboard U.S. research vessels and ships of opportunity for satellite validation (near-term).
8. Emphasize mass-conserving, optically explicit biogeochemical model development, diversification, and testing at resolutions representing mesoscale export control, paired with field studies (immediate/continued).
9. Establish the quantitative link between phytoplankton community composition and carbon export efficiency by pairing hyperspectral composition retrievals with in situ flux measurements across contrasting mesoscale regimes (near-term).
10. Support research synthesizing disparate observing streams (ocean color, lidar, BGC-Argo) through advanced data assimilation modeling (continued).
11. Proactively develop observing and modeling capabilities to monitor environmental and ecological consequences of ocean-based CDR strategies, independent of NASA's deployment stance (immediate).

These priorities overlap with the related Global Biosphere [59] and Interface Habitats [77] challenges; the elements unique here target the mechanistic understanding needed to predict, not merely document, the ocean's changing role in climate.

7. Conclusion

Ocean life is not a passive bystander in Earth's climate system but an active regulator, cycling carbon and other life-sustaining elements between the ocean interior, surface, and atmosphere. Satellite ocean color has provided a foundational but near-surface, passive view; meeting the demands of climate prediction, ecosystem stewardship, and the Blue Economy requires a more complete, vertically resolved, and process-explicit observing strategy. By pairing mesoscale-resolving hyperspectral ocean color with a profiling lidar, geostationary and eventual L1 observation, a sustained in situ network, and mass-conserving models, the decadal survey can close an observational gap that has limited mechanistic understanding of ocean biogeochemistry throughout the satellite era.

Figures

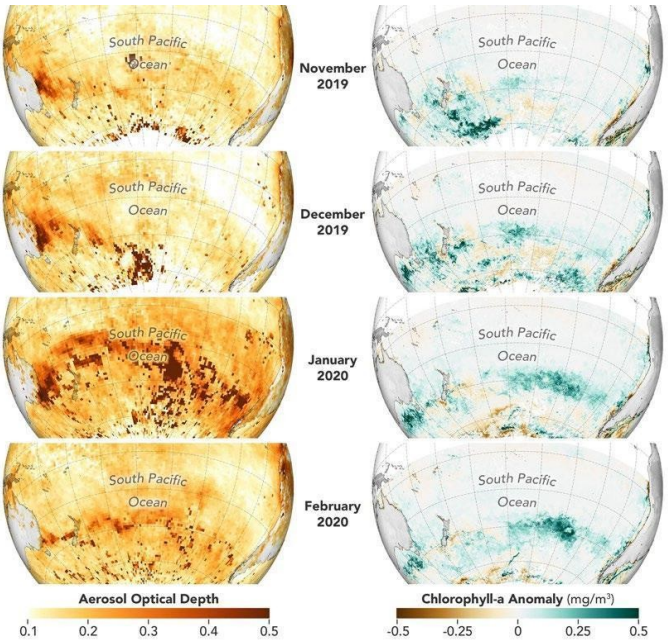

Figure 1. Monthly aerosol optical depth (left) and chlorophyll-a anomaly (right) across the South Pacific Ocean from November 2019 to February 2020, following the 2019–2020 Australian wildfires, illustrating a major, episodic atmosphere-to-ocean deposition event with a clear signature in ocean color data. Reproduced from the NASA Ocean Biology and Biogeochemistry Program Science Vision report [5] (Figure 3.2-1), based on Tang et al. [52] and NASA Earth Observatory imagery.

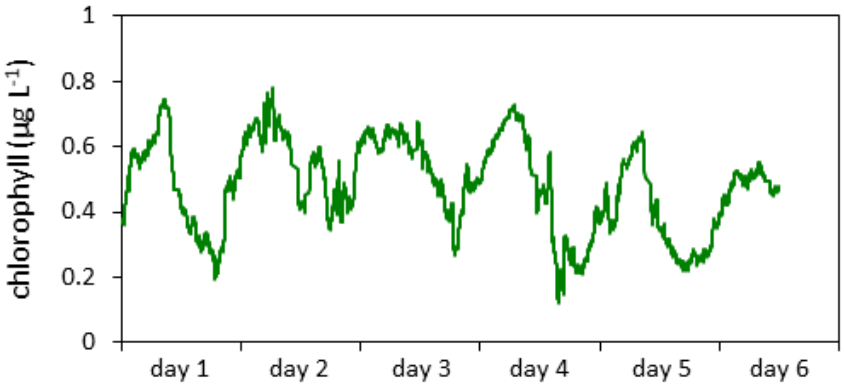

Figure 2. Example diel cycle in phytoplankton chlorophyll concentration observed over a six-day period during the NASA EXPORTS North Atlantic field campaign, illustrating the sub-daily physiological variability that current polar-orbiting ocean color missions cannot resolve. Reproduced from the NASA Ocean Biology and Biogeochemistry Program Science Vision report [5] (Figure 3.2-4), data courtesy of Emmanuel Boss, University of Maine.

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