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Interface Habitats: An Integrated Observing Strategy for Earth's Most Dynamic and Consequential Aquatic Boundaries

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

Susanne E. Craig

Joaquim Goes, Abhishek Kumar, Chintan B. Maniyar, Deepak Mishra, Carina Poulin, Shaily Rahman, Corrine Rojas, Maria Tzortziou

Co-authors listed alphabetically.

Corresponding author: Susanne E. Craig, GESTAR II, University of Maryland Baltimore County, and Ocean Ecology Laboratory, NASA Goddard Space Flight Center — susanne.e.craig@nasa.gov

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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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Interface Habitats: An Integrated Observing Strategy for Earth's Most Dynamic and Consequential Aquatic Boundaries

A Multi-Platform Approach for the 2028–2037 Decadal Survey

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

NASA Earth System Science Research Sphere: Biosphere (Aquatic Ecosystems), with direct relevance to the Atmosphere, Cryosphere, and Hydrosphere spheres

Susanne E. Craig[1,2,*]

Joaquim Goes[3], Abhishek Kumar[4], Chintan B. Maniyar[4], Deepak Mishra[4], Carina Poulin[2,5], Shaily Rahman[6], Corrine Rojas[2,5], Maria Tzortziou[7,8]

Co-authors listed alphabetically. [*]Corresponding author: susanne.e.craig@nasa.gov

[1]GESTAR II University of Maryland Baltimore County; [2]Ocean Ecology Laboratory, NASA Goddard Space Flight Center; [3]Department of Marine Biology and Paleoenvironment, Lamont Doherty Earth Observatory at Columbia University; [4]University of Georgia; [5]Science Systems and Applications Inc.; [6]University of Colorado Boulder; [7]The City University of New York (CUNY), The City College of New York (CCNY); [8]Atmospheric Chemistry & Dynamics Laboratory, NASA Goddard Space Flight Center

Executive Summary

Interface Habitats – the dynamic boundaries where water meets land, the seafloor, the atmosphere, and ice, and where fronts, eddies, and filaments draw comparably sharp boundaries within the water itself – are among Earth's most productive, diverse, and rapidly changing ecosystems, and the site of most human interaction with aquatic environments. Coasts, estuaries, deltas, wetlands, coral reefs, kelp forests, seagrass meadows, continental shelves, polar ice edges, and open ocean fronts provide nursery habitat, cycle carbon and nutrients, purify water, and support the fisheries and aquaculture central to a global Blue Economy valued at an estimated $1.5 trillion annually. They are also the most heavily impacted by human activity - pollution, overfishing, coastal development, marine litter and plastics, and harmful algal blooms - even as warming and sea-level rise drive lasting change. This white paper presents the science case and a multi-platform observing strategy for characterizing, understanding, and predicting change in Interface Habitats. No single platform can resolve their spatial heterogeneity, temporal dynamism, and optical complexity. Meeting the challenge requires sustained hyperspectral, high temporal, and high spatial resolution ocean color observations in the Program of Record; operational processing of heritage Landsat- and Sentinel-2-class data; low-cost commercial constellations; an ocean-optimized profiling lidar extended to nearshore, benthic, and ice-edge applications; sustained suborbital and in situ observations; and data fusion and machine learning coupled with mechanistic modeling linking terrestrial, atmospheric, and cryospheric processes to the ocean. We recommend priority investment in each, with the infrastructure, interagency partnerships, and workforce needed to convert these data into decision-relevant products for the communities, resource managers, and policymakers who depend on healthy Interface Habitats.

1. Introduction: The Science Question and Societal Challenge

The most productive and diverse aquatic habitats on Earth occur where water meets another element of the Earth system [1,2]: land (coasts, estuaries, deltas, rivers, lakes, and wetlands), the seafloor (continental shelves and benthic communities), the atmosphere (a boundary explored further in the companion Carbon and the Elements of Life white paper [3]), and ice (polar sea ice and its marginal zones). Deltas stand apart: their rivers deliver roughly half of the fresh water and 40% of the particulate material entering the ocean [4], and their wetland soils are among Earth's most intense carbon sinks [5,6]. A second family of interfaces forms within the water column itself, where fronts, mesoscale eddies, and filaments impose gradients as sharp as any coastline and organize pelagic communities into distinct, mobile habitats. The ocean has long been partitioned into biogeochemical provinces on this basis [7], though those boundaries are dynamic and migrate and deform seasonally and interannually [8,9]. What unites the two families is the steepness of the gradient rather than the materials on either side: properties change over meters to kilometers and hours to days, a scale mismatch that places their characterization beyond any single observing platform. These Interface Habitats support complex biological communities; serve as essential nurseries for invertebrates and fish, and as foraging habitat for birds, amphibians, and marine mammals [10]; drive the biogeochemical cycling of carbon and nutrients [6]; and purify both fresh and salt waters [11]. They are also where marine litter and debris (>80% plastic) is most abundant [12].

Interface Habitats have attracted human settlement and use since the dawn of civilization. They are sites of massive materials exchange, receiving and transforming carbon, nutrients, and pollutants delivered from land and atmosphere, and burying some fraction of these materials in wetland soils and marine sediments. Understanding and quantifying these processes, and the communities that drive them, is essential to safeguarding the resources Interface Habitats provide. This central role in both ecological function and human welfare defines the challenge motivating this submission. We must:

> *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.*

This challenge has taken on new urgency. Many coastal and fisheries dependent communities are centered on Interface Habitats already degraded by pollution, habitat loss, and overfishing, both along the coast and far inland. Blooms of toxic or noxious phytoplankton and macroalgae are increasingly documented, with substantial health and economic consequences [13–15], although part of the apparent global increase reflects intensified monitoring [16], and the aggregate global footprint of coastal aquaculture on the marine environment remains poorly quantified [17,18]. Industry is increasingly eyeing the deep seafloor for mineral extraction, which threatens to mobilize manganese, nickel, copper, and other metals through sediment tailings [19] and inject them into the mesopelagic zone, the natural entry point for mercury into oceanic food webs that support fisheries destined for human consumption [20]. At the poles, the ice-water interface is undergoing some of the most rapid change on the planet, with cascading consequences for the food webs of the Arctic and Southern Oceans [21–23]. River deltas are an acute case: upstream damming starves them of sediment that once offset subsidence, so many of the world's most densely populated deltas are losing land faster than sea-level rise alone would explain [24]. These pressures frequently manifest as compound extreme events (e.g. intense riverine runoff coincident with coastal storm surges [25,26]) against a backdrop of continuing sea-level rise, salt-water intrusion, population growth, varying precipitation trends, and expanding coastal development. Thus, they sit at the center of the United Nations Sustainable Development Goals and Blue Economy initiatives [27,28].

Interface Habitats also provide the closest available analogs for assessing the habitability of ice-covered ocean worlds elsewhere in the solar system. Ice-water and seafloor-water boundaries on Earth, including hydrothermal systems, are benchmarks against which habitability on worlds such as Europa and Enceladus is assessed [29], and many of the platforms and sensing approaches developed to study Earth's Interface Habitats are being matured for that exploration [30,31]. Europa Clipper, launched in October 2024, reaches Jupiter in 2030 [32]. Because Interface Habitats sit at the intersection of the ocean, land, ice, and atmosphere, this submission is inherently cross-cutting. It complements parallel white papers addressing the Atmosphere, Cryosphere, and Hydrosphere spheres, and is the third in a linked series addressing the Grand Challenges of NASA's Ocean Biology and Biogeochemistry (OBB) Research Program [33], following companion submissions on the Global Biosphere [34] and Climate and the Elements of Life [3].

2. State of the Science: Achievements and Limitations

Satellite remote sensing has transformed understanding of Interface Habitats over the past five decades. Landsat sensors, providing multispectral data at approximately 30 m resolution since the 1970s, together with the more recent Sentinel-2A/2B/2C constellation (10-60 m resolution), now enable a 2-3-day global coverage (and close to daily at the poles) sufficient to resolve fine-scale, highly dynamic processes in nearshore ecosystems, such as tidal carbon exchange across wetland-estuary interfaces [35–37]. These data have been fundamental for identifying and monitoring ‘foundational species’, i.e., key organisms such as mangroves, kelps, seagrasses, and reef-building corals and bivalves that nucleate stable, biodiverse habitat patches. Landsat, Sentinel-2 multispectral and airborne hyperspectral time series have characterized kelp canopy biomass [38], population dynamics [39,40], resistance and resilience to marine heatwaves [41], phenology [42], and physiological status [43], and have supported global maps of floating kelp, macroalgae, saltmarsh, and mangroves, which now show kelp forests facing intensifying marine heatwave threat with limited protection [44]. Spaceborne optical and synthetic aperture radar (SAR) observations enable precise characterization of tidal marsh inundation, providing critical insights into coastal hydrology, wetland carbon dynamics, and biogeochemical cycling [45,46].

Hyperspectral ocean color observations are poised to substantially advance Interface Habitat science [47]. PACE launched in February 2024 and has been returning science data since April 2024 [48], enabling new biodiversity characterization over continental shelves and other large water bodies at approximately 1 km resolution. GLIMR, now moving to commercial procurement with launch date to be determined, will provide continuous hyperspectral coverage of near-shore North American waters at approximately 300 m resolution [49]. The Surface Biology and Geology concept has been reformulated as EAGLE (Explorer for Artemis Geology Lunar and Earth), whose VSWIR element, targeted for 2028, retains the continuous ultraviolet-to-shortwave-infrared coverage at a 30-40 m footprint, a capability essential for resolving the fine-scale gradients and processes that characterize Interface Habitats [50]. Airborne hyperspectral, radar, and lidar systems have complemented these satellite records, providing detailed benthic habitat maps of algae, seagrass, and coral, along with shoreline elevation, bathymetry, wetland inundation, flooding extent, and vertical vegetation structure [51]. Deltaic dispersal systems, however, remain largely beyond reach: no current satellite combines the spatial resolution to resolve distributary channels and intertidal topset regions, the revisit frequency their tidal and fluvial dynamics demand, and the spectral fidelity their optically complex waters require, while many deltaic environments, tropical topsets among them, are inaccessible to ships. Deltaic biodiversity, the balance between net autotrophy and heterotrophy, and deltas' quantitative contribution to carbon cycling thus remain poorly constrained [52]. GLIMR and EAGLE will be major assets here, complemented by the multi-platform strategy below.

Physical context has proven equally important. Altimetry and high-frequency radar have been used to quantify surface advection and thereby delineate the physical drivers of observed ocean color variability [53–55]; to associate ecosystem features with mesoscale eddies and fronts [56,57]; to assess the role of Lagrangian coherent structures in shaping fisheries and ecological niches [58,59]; and to classify dynamic pelagic habitats [9,60]. These physical-ecological linkages are fundamental to larval dispersal [61] and to structuring phytoplankton [62], zooplankton [63], and higher trophic level communities [64,65]. In this functional sense, dynamic ocean boundaries can be viewed as Interface Habitats: like shorelines, they concentrate organisms, separate water masses and ecological communities, and move in space and time. This paper treats them as habitat-forming structures that help organize biodiversity, species distributions, and fisheries. Their role in setting carbon export efficiency is addressed in the companion Carbon and the Elements of Life white paper [3]. Species distribution models and mechanistic 'growth-advection' models forced by remote sensing data provide complementary tools for predicting community composition and informing resource management [53,66]. Despite these achievements, three fundamental limitations constrain the ability to characterize, understand, and predict change in Interface Habitats.

First, these systems are optically and physically among the most complex on Earth. A tremendous diversity of dissolved materials, particles, and even sea ice influences the amount and spectral character of light leaving the water's surface, compromising the accuracy of algorithms tuned to open ocean conditions for separating phytoplankton groups and for assessing primary production [47]. Mixed contributions from benthic and pelagic organisms further complicate retrieval of system level productivity, since bottom reflectance cannot be separated from the water column signal without explicitly solving for depth and substrate [67,68]. High loadings of dust, aerosols, and atmospheric trace gases common in coastal and continental margin settings degrade the atmospheric correction algorithms on which all passive ocean color retrievals depend [69,70].

Second, no single observing platform can simultaneously provide the high spatial, temporal, and spectral resolution and radiometric quality needed to characterize Interface Habitats [47]. Landsat-class sensors provide the fine spatial detail needed to resolve benthic and shoreline habitats, but their revisit frequency is often insufficient to capture rapidly evolving conditions of these non-steady state systems. Geostationary missions, such as the future GLIMR instrument will provide hyperspectral observations at high temporal frequency but at coarser spatial resolution (300 m ground sampling distance) and, unless part of a global constellation, over a limited geographic region. Low-cost commercial constellations can provide high spatial and temporal resolution together but, currently, lack the radiometric stability, calibration and long-term consistency needed for quantitative environmental trend detection.

Third, observations of marine litter and debris, deep seafloor mining impacts, and the aggregate footprint of coastal aquaculture remain very sparse relative to the scale of the problem [12]. Mechanistic models linking terrestrial, atmospheric, and cryospheric processes to the ocean remain immature, in part because the relevant time and space scales rarely coincide across model components.

3. Proposed Observing and Modeling Strategy

Addressing the Interface Habitats grand challenge requires an integrated, multi-platform observing and modeling strategy that spans satellite, suborbital, and in situ measurement together with advanced data synthesis. It rests on six complementary elements (Sections 3.1–3.6), with Section 3.7 addressing their translation into decisions.

3.1 Foundation: Sustaining PACE, GLIMR, and EAGLE in the Program of Record

The successful execution of the PACE and GLIMR missions must be ensured, along with continuation of equivalent-quality observations into the future and continued development of NASA's EAGLE mission. Its final architecture must preserve the observational capabilities essential for observing aquatic Interface Habitats effectively. Together, these missions are the foundation on which this strategy depends.

3.2 Enhanced Capability: Operational Processing of Heritage High Spatial Resolution Data

An enhanced effort in the operational processing of heritage and contemporary high spatial resolution remote sensing data is required [37,71]. Producing operational ocean products from existing high spatial resolution satellites, particularly Landsat 8/9 and Sentinel-2 constellation, should be a near-term priority. Combining data from this multi-sensor constellation can provide nominal revisit intervals shorter than five days in many regions but doing so will require improved atmospheric correction algorithms and cross calibration among sensors [72,73]. Open-access, multidisciplinary products spanning the ocean, atmosphere, and terrestrial (including wetland) domains generated using AI and other innovative techniques will maximize the benefit of investments already made and provide a baseline against which future change can be evaluated.

3.3 New Capability: Low-Cost Commercial Constellations

Commercial remote sensing constellations offer an important, cost-effective complement to NASA's Program of Record. The Planet-Dove constellation, for example, provides imagery at ~3.7 m spatial resolution with near-daily global imaging opportunities from more than 150 satellites, and has already been used to classify benthic habitats with 82 percent validated accuracy (Figure 1) [74] and to generate a global-scale coral reef probability map [75]. Planet's Tanager-1, launched in 2024, extends this to hyperspectral measurement at 5 nm sampling from 400 to 2,500 nm and 30 m resolution, and has been compared against airborne imaging spectroscopy for live coral mapping [76]. Vantor, formerly Maxar/DigitalGlobe, pays greater attention to sensor calibration, geolocation, and documentation, making its data more amenable to quantitative trend detection. None yet fully addresses radiometric accuracy, sensor degradation, and inter-sensor calibration. Independent assessment of Planet's reflectance in coastal and inland waters remains poor outside turbid conditions [77]. Still, the data illustrate how low-cost constellations can extend coverage at meter-scale resolution and near-daily frequency. Work is needed to harmonize observations from these sensors, generate operational products, make them readily available to research and management communities, and train users in data access and applications.

3.4 New Capability: An Ocean-Optimized Profiling Lidar for Nearshore, Benthic, and Ice-Edge Habitats

Active remote sensing offers capabilities unavailable to any passive sensor. As detailed in the companion Global Biosphere white paper [34], an ocean-optimized, High Spectral Resolution Lidar (HSRL)-class profiling instrument is a high-priority addition to NASA's ocean satellite Program of Record. For Interface Habitats, ICESat-2 lidar data have already characterized phytoplankton properties below sea ice and along the ice-water interface [78,79], in regions and seasons where passive ocean color retrievals are entirely absent. Airborne lidar has an equally long history of application in Interface Habitats, beginning with the 2012 Azores proof of concept deployment and continuing through the SABOR and NAAMES campaigns [80–82]. This capability provides shoreline elevation and change detection, benthic habitat characterization, and vertical structure of intertidal vegetation such as mangroves [51]. A dedicated ocean-optimized HSRL is no longer hypothetical: China's ACDL aboard DQ-1 has returned the first spaceborne high spectral resolution retrievals of ocean particulate backscatter [83]. Continued development of spaceborne and airborne lidar, including expanded deployment on uncrewed aircraft, is essential.

3.5 Sustained Suborbital and In Situ Observation

Suborbital sensors on piloted aircraft, uncrewed aerial vehicles, and autonomous underwater vehicles provide measurements at centimeter-to-meter spatial scales and have been used to characterize coral, algal, under-ice, and other benthic habitat patches [84–86]. Recent advancements highlight this high-resolution capability, including centimeter-scale reef mapping from airborne fluid lensing [87],under ice robotic imaging of sea ice algal and benthic communities[88], and hyperspectral retrievals of organic carbon dynamics across rivers and coastal lagoons along the Arctic North Slope [89]. Airborne hyperspectral imagery has proven particularly valuable given the scattering and attenuation benthic signals experience through the overlying water column [90,91], producing detailed maps of fleshy and turf algae, seagrass, coral, and coral rubble that document changes in land use, coastal development, and reef connectivity over time. In situ monitoring and higher precision suborbital sensing remain essential for ground truthing satellite retrievals and for moving beyond broad vegetation classes toward finer taxonomic differentiation [92]. Continued investment in these assets, including expanded sensor deployment on drones, is a vital complement to the satellite elements of this strategy for regions that are difficult to sample at sufficiently high resolution.

3.6 Statistical and Mechanistic Modeling Linking Land, Ice, Atmosphere, and Ocean

Synthesizing these diverse observations into robust predictions of change requires parallel advances in modeling. Species distribution models, including machine-learning approaches, can identify factors correlated with species distribution but are often not process-based [66]. Mechanistic 'growth-advection' models forced by remote sensing data offer a complementary, process-based approach for reproducing observed patterns in key species [53]. High resolution regional, mechanistic, ecosystem models can incorporate land, wetland, riverine and sea ice inputs, including runoff and meltwater, to capture interface processes explicitly, though these models have not been developed for all Interface Habitats along the land-ocean continuum (e.g., deltas). However, linking model components across mismatched time and space scales remains an open challenge requiring sustained, interdisciplinary investment [52,93]. Model-based uncertainty assessments are most useful when modeled parameters are directly consistent with observables such as spectral reflectance and backscatter [94,95], reinforcing the need for tight coupling between the observing and modeling elements of this strategy.

3.7 From Data to Decisions: Operational Products and Interagency Partnership

The Interface Habitats Grand Challenge has an explicit human services dimension in supporting policy, decision-making, impact assessment, and management. This requires infrastructure for ingesting, processing, and integrating diverse data streams and assimilating them into operational models that support state, local, and tribal ecological forecasting and assessment [96]. The interagency Cyanobacteria Assessment Network (CyAN) is an excellent example of such a transition from data to decision support and delivers operational satellite bloom detection directly to water managers through the U.S. Environmental Protection Agency's (EPA) user-friendly platform [97]. New metrics are needed to characterize the health and condition of coastal foundational species and to detect ecosystem degradation [98], alongside advances in ecological theory and ecosystem valuation that link social and natural sciences [99]. This is most effectively addressed by partnering with the National Oceanic and Atmospheric Administration (NOAA), EPA, U.S. Geological Survey (USGS) and state environmental and conservation agencies to bring NASA data products to local users, gather feedback on their utility, and enable citizen science-based product validation [97,100].

4. Key Measurement Requirements

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

Ocean color continuity requires uninterrupted, PACE-, GLIMR-, and EAGLE-equivalent hyperspectral and high spatial resolution observations, sustained with inter-mission overlap and cross calibration to avoid record discontinuities and artifacts that could be mistaken for geophysical change [72,73].

Operational, high spatial resolution products require combined processing of Landsat 8/9 and Sentinel-2 constellation data to target sub-5-day nominal revisit at 10-30 m spatial resolution, together with atmospheric correction algorithms specifically validated for the non-maritime aerosols, elevated trace-gas concentrations, and optically complex waters characteristic of Interface Habitats.

Commercial constellation data should be evaluated and, where suitable, harmonized and integrated to provide near-daily global coverage at meter-scale spatial resolution. Priority should be given to establishing the radiometric calibration, geolocation accuracy, sensor-degradation characterization, and documentation needed to support quantitative, rather than purely qualitative, applications.

Dynamic interface tracking requires kilometer scale or finer resolution with clear-sky revisit better than one week, sufficient to follow fronts, eddies, and filaments as coherent features rather than encounter them at random. This is the same joint resolution and revisit requirement identified for mesoscale control of carbon export in the companion Carbon and the Elements of Life white paper [3].

The ocean-optimized profiling lidar described in the companion Global Biosphere white paper [34] should additionally provide day and night, under-ice-capable retrievals of particulate backscattering and attenuation at meter-scale vertical resolution, sufficient to resolve phytoplankton structure at the ice-water interface. From airborne platforms, vertical resolution should be sufficient to resolve shoreline elevation, bathymetry, and intertidal vegetation structure at sub-meter horizontal resolution over target areas on the order of 100 km^2.

Suborbital and in situ networks should provide centimeter-to-meter scale characterization of benthic and intertidal habitat patches, coordinated with satellite overpasses to support calibration and validation. These networks should be expanded to capture chemical and biological ground truth at temporal cadences ranging from single field campaigns to continuous, sensor-based monitoring.

Modeling infrastructure requires coupled terrestrial-atmospheric-cryospheric-oceanic model components capable of exchanging fluxes (e.g., freshwater, sediment, nutrients, and pollutants) at spatial and temporal resolutions relevant to interface processes. This should be implemented together with data assimilation systems capable of ingesting temperature, reflectance-, lidar-, and in situ-derived observations directly, rather than only products derived from them.

These requirements are interdependent. High resolution and commercial data depend on the hyperspectral ocean color foundation for context, the profiling lidar depends on suborbital and in situ networks for validation at ice edges and in turbid coastal waters, and all depend on models that fuse them into decision-relevant understanding.

5. Feasibility and Implementation within the Decadal Time Frame

The technology required to implement most elements of this strategy is mature or already in the Program of Record. PACE is operating, GLIMR and EAGLE are in development, and their continuity into the following decade is primarily a programmatic rather than a technical challenge.

Operational processing of Landsat- and Sentinel-2-class data requires no new sensor development. The principal investment needed is in algorithm development - particularly for atmospheric correction and cross-sensor calibration - and in the processing infrastructure to generate and distribute these products at scale. Commercial constellation data are already being collected at high volume. The near-term task is evaluation, climate-record standards of calibration, and integration rather than new technology development, making this among the most readily achievable elements of the strategy.

The ocean-optimized profiling lidar builds on two decades of heritage, from the CALIOP instrument operating since 2006 to the airborne HSRL campaigns described in Section 3.4, and on ICESat-2 retrievals already applied to sea ice-edge phytoplankton [78,79]. This combination places a dedicated instrument within reach of an immediate-to-near-term start, though extension to under-ice and optically complex nearshore waters will require algorithm development beyond the open ocean application described in the companion Global Biosphere white paper [34].

The principal implementation challenges are therefore not sensor readiness but algorithm development, interagency data infrastructure, and workforce capacity. Robust separation of suspended and dissolved constituents from submerged or emergent vegetation in optically complex waters remains an unsolved algorithmic problem [101], as does atmospheric correction under the non-maritime aerosol and trace-gas conditions typical of Interface Habitats - requiring targeted investments in physics-informed machine learning and Geo-AI frameworks. Realizing decision support potential will also require the interagency collaboration, international coordination, and workforce investment set out in Section 3.7.

6. Summary of Recommended Priorities

We recommend that the 2028 to 2037 decadal survey prioritize the following elements to address the Interface Habitats grand challenge:

1. Sustain PACE- and GLIMR-equivalent ocean color observations and support continued EAGLE development, ensuring its final architecture retains capabilities needed for Interface Habitat science (continued/immediate).
2. Enhance operational processing of heritage and contemporary high-spatial resolution data (e.g., Landsat, Sentinel-2), including inter-sensor calibration with medium- and high-resolution ocean color missions (immediate).
3. Evaluate and, where appropriate, integrate lower cost commercial constellation data (e.g., Planet-Tanager) to augment the Program of Record with finer spatial resolution and higher revisit (near term).
4. Add an ocean-optimized, HSRL-class profiling satellite lidar to the Program of Record, extended to resolve phytoplankton vertical structure in near-ice and nearshore habitats, and continue airborne lidar development for benthic and shoreline applications (immediate/near-term).
5. Continue developing suborbital observing capability, including autonomous sensors on drones, floats, and similar platforms, to support satellite retrievals and characterize properties not observable from space (continued).
6. Support new algorithmic approaches for separating suspended and dissolved constituents and submerged or emergent vegetation in optically complex interface waters, and for atmospheric correction under non-maritime aerosol and trace gas conditions (near-term).
7. Sustain interdisciplinary modeling teams linking land, ice, and atmosphere modules to ocean models at increasing spatial resolution (continued).
8. Conduct targeted field process studies to inform model development and mechanistic interpretation of observed change (near-term/long-term).
9. Support research synthesizing disparate observing-system data and assimilating it into operational models for state, local, and tribal ecological forecasting (continued).
10. Deepen interagency partnership with NOAA, USGS, and state agencies, and strengthen international coordination (e.g., IOCCG) to translate NASA data into operational products, decision support tools, and citizen science validation frameworks (continued).

7. Conclusion

For most people on Earth, the strongest connections to aquatic ecosystems occur at Interface Habitats, where land, water, atmosphere, and human activity converge. These diverse and highly productive systems provide invaluable goods, services, and societal benefits, yet they are among the most susceptible to the compounding effects of human activity and climate change, and their fine-scale heterogeneity and rapid tempo of change exceed any single observing system. By investing in these six elements, the 2028–2037 Decadal Survey can establish the sustained, integrated, and decision-relevant observations needed to understand, manage, and protect Interface Habitats, and to deliver the decision-support tools that coastal communities, resource managers, and policymakers require.

Figures

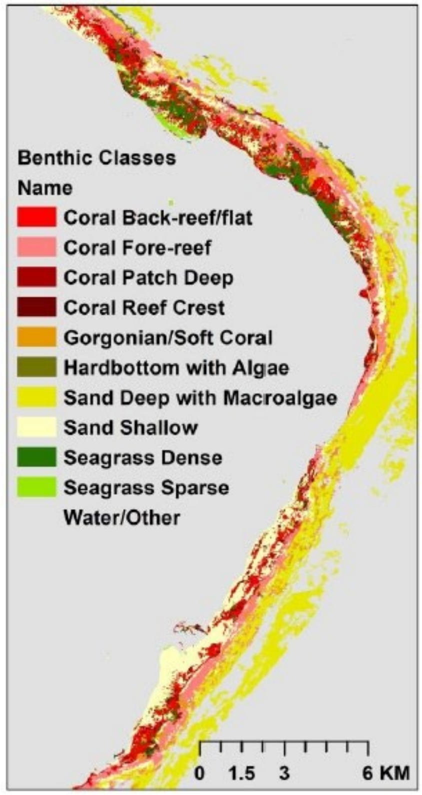

Figure 1. Example of benthic habitat classification (coral back-reef/fore-reef, coral patch, reef crest, gorgonian/soft coral, hardbottom with algae, sand, and seagrass) derived from 3.7-m Planet-Dove imagery for a reef system in the eastern Dominican Republic; validation against field measurements indicated an overall classification accuracy of 82 percent. Reproduced from Li et al. [74], as presented in the OBB Science Vision report [33].

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