

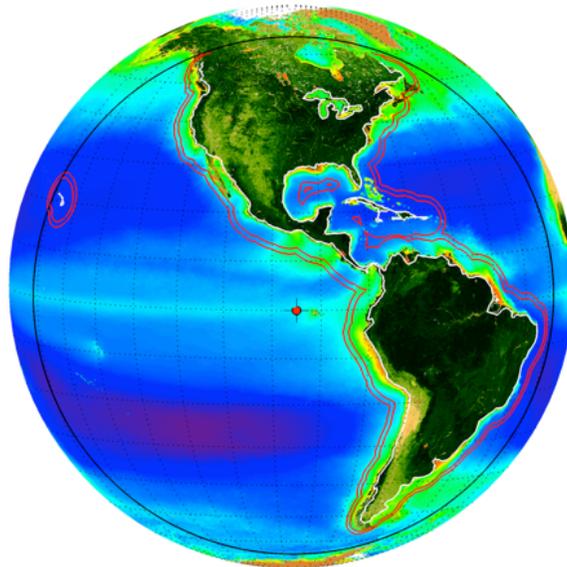
Rate Processes and Fluxes of Marine Biogeochemical Cycles, Ecosystem Functioning, and Natural Resources

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Executive Summary

Current space-based assets in low earth orbit are inadequate to constrain physical, ecological and biogeochemical fluxes and rates as well as variability in biogeochemical stocks within the marine environment at regional to global scales. Assets in low earth orbit (LEO) also fail to address many non-research applications requirements due to coarse spatial resolution and infrequent re-visit times. **Here we argue for the need and urgency of deploying advanced ocean color sensors to geostationary orbit (GEO) for constraining the magnitude and uncertainties in marine ecosystem climate change responses and feedbacks.**

Utility for Science and Applications— Processes that govern marine biogeochemical cycles, ecosystem function, health and biodiversity, and subsequently, marine resources that provide quantifiable services such as fisheries and water quality, vary on timescales from hours to weeks, in addition to the more well-studied seasonal and interannual timescales. Similarly, our decisions in responding to natural and manmade disasters will benefit from high-quality, high temporal resolution imagery, so that fast evolving features, like oil spills and harmful algal blooms can be monitored.

The science objective is to better constrain the magnitude and uncertainties in ocean primary production, surface-layer carbon cycle processes, and coastal ocean water quality in response to environmental (short-term) and climate (long-term) change. Constraining the magnitude and uncertainties of ocean primary production, carbon stocks, export production and phytoplankton community composition will be essential for enhancing climate model skills and forecasting capabilities, which will better inform the decisions of policy makers and other stakeholders. Application objectives include improvements of fisheries models such as operational ecosystem-based models and ecological forecast models, which will require these proposed measurements to assess model capabilities. Fisheries and other resource managers rely on these observations and models for optimal water resource management, risk assessment, decision-making, and financial planning.

This measurement capability is highly relevant to Decadal Survey **Theme III Marine and Terrestrial Ecosystems and Natural Resource Management** and has overlapping relevance to Theme IV Climate Variability and Change: Seasonal to Centennial and Theme I: Global Hydrological Cycles and Water Resources. Climate change, fisheries, ecological forecasting and hazards are clear application objectives of sub-diurnal ocean color-derived geophysical measurements enabled from geostationary orbit.

Type and quality of measurements— The minimum requirements are high-temporal measurements of top of the atmosphere radiances from 350-900 nm (minimum of 25 bands; SNR > 1000) plus 1240 nm (SNR >250) and 1640 nm (SNR > 180), a spatial resolution of 350 m at nadir, and an observation frequency of 3 hours or less.

Affordability— There are no technological limitations to implementing ocean color spectrometers or filter radiometers in geostationary orbit. Existing or planned atmospheric sensors on geostationary orbit will help mitigate the challenge of obtaining improved characterization of aerosols and trace gases for proper retrieval of time-varying ocean color observations. Current capabilities allow for spatial resolution and image stabilization for a nadir ground sample distance of ~200 m.

Instrument design studies supported by the NASA GEO-CAPE mission pre-formulation activity have suggested three viable classes of scanning instruments for meeting geostationary ocean color observations, they include (1) 2D step-and-stare filter wheel radiometers, (2) wide-angle pushbroom spectrometers and (3) multi-slit pushbroom spectrometers. The costs for these nominal sensor concepts were estimated by the Goddard Space Flight Center Instrument Design Lab and ranged from ~\$100 million to \$200 million (see summary of GEO-CAPE studies: http://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf). The success of the Korean Geostationary Ocean Color Imager (GOCI), which launched in 2010, has demonstrated the feasibility and utility of geostationary ocean color observations at a reported cost of ~\$36M.

IMPORTANCE:

Current or planned space-based assets in low-earth polar orbit (LEO) are inadequate for constraining physical, ecological and biogeochemical fluxes and rates as well as the variability in biogeochemical stocks within the marine environment at regional to global scales. This is a key issue for assessing the role of the oceans in carbon cycling because global ocean net primary production amounts to approximately 50 Pg C per year with an uncertainty on the order of ± 15 -20 Pg C per year. Climate change is altering marine ecosystems in multiple ways, most notably through ocean warming and increasing surface ocean $p\text{CO}_2$ that causes ocean acidification. Warming causes shoaling of the surface mixed layer, increasing the amount of light phytoplankton are exposed to, while decreasing the availability of nutrients. Both acidification and mixed layer are likely to reduce global ocean production. These climate change factors along with others are altering the geographic distributions of phytoplankton species and phytoplankton community composition (e.g., Walther et al. 2002; Rivero-Calle et al. 2015). Such changes can have cascading effects on the ocean's ecosystem functioning and carbon cycle. For example, a shift from diatom-dominated phytoplankton communities to those dominated by smaller cells will likely reduce the amount of marine biomass exported to depth, which will in turn reduce the amount of carbon sequestered by the global ocean within marine sediments. Thus, it is a scientific imperative to better constrain the magnitude and uncertainty in marine ecosystem variables: primary production, phytoplankton stocks, phytoplankton community composition, export production, and community metabolism in order to understand the overall response of ocean ecosystems to climate change and how these responses may contribute to positive or negative feedbacks to climate change.

Processes that govern marine biogeochemical cycles, ecosystem function, health and biodiversity, and subsequently, marine resources such as fisheries and water quality, vary on timescales from <1 hour to a few weeks, in addition to the more well-studied seasonal and interannual timescales. The diurnal cycle of solar irradiance engenders physical and biogeochemical responses within the surface layer of the ocean. Indeed, phytoplankton physiology and thus primary production responds to the fluctuation in solar irradiance throughout the day including varying light conditions imparted by clouds. Physical responses on daily time scales include heating of the surface ocean layer as well as fluctuations in wind intensity, surface currents, tidal cycles and changes in vertical mixing scales. Variations in environmental conditions on sub-diurnal to multi-day time scales influence phytoplankton physiology, growth rates, stocks and community composition and the metabolic balance of marine ecosystems. Other key processes include the impacts of diurnal wind variability on upper ocean processes, mixed-layer depth and subsequent influences on nutrient supply in the euphotic zone and particle dynamics in the mixed layer, photooxidation of organic matter, evolution of phytoplankton blooms, and the flux of carbon and nutrients through advection. While current space-based LEO assets have helped to elucidate the temporal and spatial scales of key ocean processes, they are inadequate by their sensor design and temporal coverage frequency to constrain physical, ecological and biogeochemical fluxes and rates as well as the variability in biogeochemical stocks within the marine environment at regional to global scales.

NASA's planned PACE satellite mission with its Ocean Color Imager (OCI), a passive hyperspectral UV-Vis-IR radiometer, will improve our capability to quantify phytoplankton stocks, production and community composition. However, with a revisit time of approximately 2-days, PACE will be limited in ocean coverage and frequency by clouds and its low-earth polar orbit that restricts clear-sky observations for any given location to about 10 measurements per month (IOCCG 2012a; Ruddick et al. 2014). Because of the highly dynamic nature of ocean ecosystems, much of the high-frequency temporal variability remains elusive in ocean color imagery from LEO, even with multiple LEO sensors. With PACE, sub-diurnal observations are only possible over polar regions where the OCI sensor swaths will overlap; however, this will be further restricted by the low percentage of clear sky conditions at high latitude areas. In addition, LEO observations may also contribute to biases in measurements because overpasses are confined to the same time of the day, generally the mid-day period, within temperate and tropical regions. The solution to these problems is a geostationary ocean color observatory yielding \leq bi-hourly data of PACE quality. Such high temporal frequency observations are necessary to understand the natural variability of oceanic and coastal ecosystems as well as anthropogenic impacts such as climate

change, pollution, resource exploitation, overfishing, and natural hazards. The NRC Committee on Ocean Infrastructure Strategy for U.S. Ocean Research stated, “many of the current changes and their impacts remain unreported, for lack of comprehensive global marine ecosystem monitoring efforts. In order to provide effective stewardship of the marine environment, infrastructure that can quantify ecosystem changes and manage human activities in response is a need for 2030” (NRC 2011). Indeed, there are significant synergies from the combination of an advanced LEO mission such as PACE and a geostationary ocean color mission in terms of enhanced global coverage across time and space scales as well as cross-calibration. LEO sensors contribute global observations as well as sub-diurnal measurements in polar regions. Observations from geostationary orbit (GEO) contribute high-frequency measurements across mid- and low latitudes (~60°S to 60°N depending on season). An additional benefit of GEO observations is the significant increase in valid pixel retrievals as greater temporal coverage enables the ability to fill in gaps of missing data as clouds move throughout the day. Monitoring of ocean ecosystems from geostationary platforms will be an essential component of a comprehensive observing system to detect and follow naturally and anthropogenically induced alterations in the next decade. GEO observations can provide the temporal frequency required for quantifying diurnal rate processes and stocks and will provide an improved capability for establishing a daily bio-optical mean. Thus, GEO observations will provide better constraints on global ocean net primary production.

Challenge: *Quantification of marine ecological and biogeochemical processes on regional and global scales, on sub-diurnal to weekly timescales to further constrain the magnitude and uncertainties in marine ecosystem climate change and shorter-term anthropogenically-driven responses and feedbacks.*

UTILITY: A Description of Science and Applications Objectives

Science: The science objective is to better constrain the magnitude and uncertainties in ocean primary production, surface-layer carbon cycle processes and coastal ocean water quality in response to environmental (short-term) and climate (long-term) change and other human impacts. This target is highly relevant to Decadal Survey Theme III Marine and Terrestrial Ecosystems and Natural Resource Management and also pertinent to Theme IV Climate Variability and Change: Seasonal to Centennial, and Theme I: Global Hydrological Cycles and Water Resources.

The ocean’s phytoplankton and other microbial biomass turns over on daily to weekly time scales, which is much faster than the turnover of biomass on land. Thus, the required observational time scales to study and understand ecosystems are quite different between ocean and land. Phytoplankton physiology and productivity varies with the diurnal solar irradiance cycle. Furthermore, phytoplankton and other microbes respond to ephemeral events that introduce nutrients into surface waters such as from storm-induced upwelling and atmospheric deposition of dust, aerosols, volcanic ash, etc. Such events impact the production and biodiversity of the microbial community as well as export production and standing stocks of carbon and nutrients. Climate change impacts on marine ecosystems such as rising temperatures, increased stratification (shoaling of the surface mixed layer), lower pH, sea level rise, shifts in ocean circulation patterns, etc. will alter biodiversity, primary production and functioning of marine ecosystems. High frequency observations (multiple times per day) are required to better constrain global ocean production, carbon stocks and biodiversity and to reduce their uncertainties and better understand the downstream feedbacks to climate change. For instance, photosynthetic production in surface waters and the export of this production to depth can influence the variability and trends in air-sea CO₂ fluxes and thus atmospheric CO₂ levels (Ciais et al. 2013). Ocean biogeochemistry is sensitive to sub-mesoscale (1-10 days, 1-10 km) physical processes (Levy 2008). However, this bio-physical coupling at sub-mesoscales is not yet accurately accounted for in global ocean biogeochemical models because high-resolution synoptic observations of biogeochemical quantities are still out of reach (IOCCG 2012a). Detection of seasonal to centennial impacts of climate variability and change requires that the magnitudes and uncertainties of the parameters of interest be adequately constrained through analysis of observations made available for modeling studies. Developing a predictive understanding of the response of marine

ecosystems to change (both short- and long-term) requires observations and models that can accurately capture variability and transformation rates across temporal scales.

A recent NRC committee identified the target of “how will climate change influence cycles of primary production?” as a high priority (NRC 2011). This committee indicated that marine ecosystem responses to climate change would lead to nutrient limitation of primary production, shifts in phytoplankton community composition and modifications in zooplankton patterns. Alterations in surface ocean stocks, production and ecosystem composition affect the biological pump and influence the ocean’s potential to sequester carbon (NRC 2011). The NASA Ocean Biology and Biogeochemistry (OBB) Advanced Science Plan describes analogous high priority science questions: “How are ocean ecosystems and the biodiversity they support influenced by climate and environmental variability and change, and how will these changes occur over time? How do carbon and other elements transition between ocean pools and pass through the Earth System, and how do biogeochemical fluxes impact the ocean and Earth’s climate over time?” (NASA OBB Working Group 2007).

Applications: Ocean dynamics and societal benefits are inextricably intertwined. Improved prediction of ocean-climate feedbacks, changes in fisheries and biodiversity, enhanced ecological forecasting, and improved monitoring and response to hazards are now particularly urgent and require sub-diurnal, high quality observations from space to capture change across temporal scales. Constraining the magnitude and uncertainties of ocean primary production, carbon stocks, export production and phytoplankton community composition will be essential for enhancing climate model skills and forecasting abilities, which will better inform the decisions of policy makers and other stakeholders. Fisheries models such as ecosystem-based models and ecological forecast models require these measurements to assess and improve model skill. Fisheries and other resource managers rely on these observations and models to make management decisions. Studying the impact of climate change on fisheries is both an ecological (Brander 2010) and economic issue (Allison et al. 2009). Another important application for sub-diurnal ocean color observations is in data assimilation and state estimation models, which will benefit from the high frequency of measurements for improved assessment of model prediction skill. Furthermore, high frequency observations permit detection and evaluation of the impacts and response of marine ecosystems to disasters and hazards including hurricanes, harmful algal blooms, oil spills and seeps, biomass burning, and volcanic ash plumes. Current or planned U.S. capabilities do not allow for measurements at high enough frequency to capture the response of marine ecosystems to such events. To address the identified science and applications targets, sub-diurnal ocean color observations of the global ocean are required.

Utility of Measurements for Science and Applications Objectives

High-frequency (sub-diurnal) measurements of ocean color can be applied to quantify the rates of biological and biogeochemical processes including primary production, track inventories of biogeochemical constituents in time and space, and examine the impacts of physical processes such as upwelling, fronts, eddies, filaments, sub-/mesoscale processes, internal waves, surface currents and tides on the distribution, production, consumption and fluxes of ocean constituents (NRC 2011; IOCCG 2012a; Mouw et al. 2015). The NRC on Assessing Requirements for Sustained Ocean Color Research and Operations expressed that satellite ocean color observations provide the “capability to detect impacts of climate change on primary productivity. Therefore, it is imperative to maintain and improve the capability of satellite ocean color missions at the accuracy level required to understand changes to ocean ecosystems that potentially affect living marine resources and the ocean carbon cycle, and to meet other operational and research needs. To meet all these needs, a constellation of multiple sensor types in polar and geostationary orbits will be required” (NRC Ocean Color Requirements 2011). GEO allows for nearly continuous temporal coverage capability, and ocean color observations can resolve diurnal processes such as vertical migration of plankton, primary productivity, photooxidation of colored dissolved organic matter, phytoplankton physiology, growth and loss processes on the diurnal as well as multi-day time scales, impacts of diurnal wind variability on upper ocean processes, and particle dynamics within the

surface mixed layer. Continuous GEO measurements will enable timely information on *Sargassum* macroalgae rafts to provide early warning for ship navigation and beaching events, and thus improve adaptation strategies. They can also reveal daily to weekly variability in physical, biological and biogeochemical processes. Fluxes of carbon and other aquatic constituents between and within coastal ocean and open ocean areas can be determined. Such high frequency GEO observations will capture the evolution of phytoplankton blooms from space from onset, through growth, senescence and dissipation. Since phytoplankton blooms can initiate, grow and decay over the period of several days to a week, LEO sensors such as MODIS, VIIRS or PACE, individually or in combination, are sub-optimal for the observation of bloom evolution/decay, and are ineffective for tracking the temporal evolution of ocean ecosystems including plankton succession and biodiversity. Following such changes within moving features such as mesoscale and sub-mesoscale eddies, Ekman flow, large river plumes (Amazon) that extend for hundreds of kilometers into the ocean, western boundary currents (Gulf Stream), tidal circulation, and various other surface currents is a unique attribute of GEO observations. A complete global ocean assessment of net primary production, carbon stocks and fluxes requires both LEO and GEO ocean color sensors as well as information from other sources about the vertical distribution of phytoplankton, euphotic depth and mixed-layer depth. Assimilation of high-temporal resolution ocean color observations, which would provide daily ‘effective’ resolution, would help improve the accuracy and prediction capability of open ocean model at intra-seasonal and inter-annual time scales. The required measurements to meet science objectives are provided in Table 1 as well as the measurement frequency.

QUALITY:

Ocean color remote sensing data quality has advanced considerably since the launch of the first sensor in 1978, CZCS, followed by SeaWiFS (1997-2010) and MODIS sensors on the Terra and Aqua. All aspects of data quality including on-orbit sensor calibration, vicarious calibration, atmospheric correction and bio-optical algorithms have advanced significantly culminating in the unprecedented quality requirements anticipated for PACE (PACE SDT 2012; IOCCG 2012b) and proposed for GEO-CAPE. These form the basis of the measurement quality requirements described herein (Table 2).

GEO offers unprecedented and virtually continuous temporal coverage of the Earth’s surface that has been the cornerstone for tracking and forecasting weather patterns from space. Meteorological satellites such as NOAA’s GOES, EUMETSAT’s SEVIRI and JMA’s Himawari 8 collect earth observations every 30, 15 and 10 minutes, respectively. Such high frequency measurements are essential for capturing atmospheric processes as well as daily variations in sea-surface temperatures. Much of the temporal and small-scale variability of ocean ecosystems remains elusive in ocean color imagery from LEO. Geostationary observations can provide the temporal frequency required to quantify diurnal rate processes and stocks for the open ocean and highly dynamic coastal environments.

AFFORDABILITY: Achieving Required Measurements in the Decadal Timeframe

There are no technological limitations to implementing ocean color sensors in GEO. Existing or planned atmospheric sensors in geostationary orbit would help mitigate the challenge of obtaining improved characterization of aerosols and trace gases for proper retrieval of time-varying ocean color observations. Current capabilities allow for spatial resolution and image stabilization for a nadir ground sample distance (GSD) of ~200 m. However, GSD increases with sensor viewing angle yielding a spatial resolution of ~400-500 m near the edge of the sensor field-of-view where data quality is still useful. While a nadir GSD of 500 m to 1 km will suffice for the open ocean, a higher spatial resolution on the order of ~250 m GSD is preferred for coastal ocean regions. GEO sensors maintain an orbit at a fixed longitude and latitude (at the equator). The extent of useful ocean color observations extends to $\pm 50\text{-}60^\circ$ north, south, east and west from nadir and dependent upon view angle and solar zenith angle (Fig. 1).

Instrument design studies supported by the NASA GEO-CAPE mission pre-formulation activity have suggested three viable classes of scanning instruments for meeting geostationary ocean color observations, they include: (1) 2D step-and-stare filter wheel radiometers, (2) wide-angle pushbroom spectrometers and (3) multi-slit pushbroom spectrometers. The costs for these nominal sensor concepts

were estimated by the Goddard Space Flight Center Instrument Design Lab and ranged from ~\$100 million to \$200 million (GEO-CAPE Team 2015). The success of the South Korean Geostationary Ocean Color Imager (GOCI), which launched in 2010, has demonstrated the feasibility and utility of geostationary ocean color observations at a reported cost of ~\$36M. GOCI is a 2D step-and-stare radiometer with an 8-band filter wheel and a ~360 m nadir GSD. The solid performance and modest cost of GOCI has prompted the Koreans to develop a 13-band follow-on sensor with Airbus called GOCI-II, which will launch in 2019. Other improvements in GOCI-II include a local GSD of 300 m over Korea (~200 m at nadir) and full-disk imaging capability. The NASA Ocean Biology Processing Group (OBPG) is collaborating with the GOCI team from the Korea Ocean Satellite Center in many facets to improve GOCI measurements. OBPG is now distributing hourly GOCI L1b products and NASA standard L2 products to advance the maturity and application of geostationary ocean color measurements.

There is a strong possibility of leveraging geostationary observations from international partners to produce quasi-global geostationary ocean color products. The Korean GOCI-II sensor is already approved and will provide observations from the eastern Indian Ocean across the western Pacific (Fig. 2). A team at the French space agency, CNES (Centre National d'Etudes Spatiales), has proposed GEO-OCAPI (Ocean Color Advanced Permanent Imager) for a 2020/2021 launch. GEO-OCAPI will have similar capabilities to GOCI-II in terms of spectral bands (12-18) and spatial resolution (100-250 m coastal and 500 m for open ocean) with full-disk observing capabilities from the western Atlantic Ocean to the western Indian Ocean (Fig. 3). A single U.S. geostationary sensor at ~95° to 98° W along with GOCI-II and GEO-OCAPI would complete a quasi-global constellation of geostationary ocean color sensors (however, there will be no observations at high latitudes). Such a sensor would be capable of collecting high frequency observations from the eastern Pacific Ocean to the western Atlantic Ocean including coastal waters along North and South America and the Laurentian Great Lakes (Fig. 1a). Two geostationary ocean color sensors in orbit at similar locations as the GOES-East and GOES-West platforms (135° W and 75°W) would be ideal to meet the full breadth of measurement requirements including bi-hourly observations in the open ocean and coastal ocean (Fig. 1b), over major portions of both Atlantic and Pacific basins. Hosting GEO ocean color sensors as secondary payloads on commercial or government satellites will significantly reduce the cost since accommodation costs and hosting fees would be far less than for dedicated spacecrafts and launch vehicles (Fishman et al. 2012).

LEO and GEO ocean color observations provide the horizontal and temporal scales of variability for the ocean's first optical depth. The vertical structure of ocean phytoplankton and carbon stocks, currently unavailable from satellite sensors, is obtainable from models and *in situ* measurement systems. The nearly 4000 ARGO floats distributed throughout the global ocean provide vertical distributions of temperature, salinity and density for the upper 2 km of the ocean (<http://www.argo.ucsd.edu/>). Such information is essential to validate products from global ocean circulation models such as temperature and salinity and mixed layer depths. A current proposal to deploy 1000 Bio-ARGO (<http://www.ioccg.org/groups/argo.html>; <http://socom.princeton.edu/>), which are equipped with optical sensors to measure chlorophyll-a and particle backscatter can provide information on the vertical distributions of carbon stocks to constrain and evaluate coupled 3D global biogeochemical circulation ocean models.

SUMMARY: Current space-based assets are inadequate to constrain physical, ecological and biogeochemical fluxes and rates as well as variability in biogeochemical stocks within the marine environment. These variables are best addressed with sensors deployed in GEO. This orbit provides significant advantages for both research and operational needs due to possible moderate-to-high spatial and spectral resolution and the capability dwell over a region. There are no significant technological challenges to implement GEO ocean color measurements. Costs are within those of other Earth observing missions. The implementation costs for hosting science payloads on commercial satellites are a fraction of the cost than dedicated missions, which requires NASA and NOAA to bear the full cost of a spacecraft and launch. The first NASA Earth Venture Instrument project, TEMPO, is laying the foundation for a hosted GEO payload on a commercial satellite. Ocean color measurements from GEO offer substantial scientific and applications over the future decade, with benefits that far exceed the investment.

Table 1. Proposed input measurements and derived geophysical variables necessary to achieve the science targets.

Input Measurements	Derived Precursor Measurements	Derived Geophysical Variable	Measurement Frequency	Interval	Latitudes	LEO Ocean Color	GEO Ocean Color
						Global	Quasi-Global ^e
Top-of-the-atmosphere radiances (UV-Vis-NIR); water vapor; aerosol properties <i>Ancillary:</i> total column atmospheric ozone and NO ₂ concentrations; surface pressure	Rrs(λ) ^a , a(λ) ^b , b _{bp} (λ) ^c , phytoplankton pigments	Phytoplankton Stocks	3 to 8 times per day	Diurnal, Daily	High	✗	✗
					Mid	✗	✓
					Low	✗	✓
			Daily	Daily; Weekly	High	✓	✗
					Mid	✗	✓
					Low	✗	✓
			2-day	Monthly; Seasonal; Annual	High	✓	✗
					Mid	✓	✓
					Low	✓	✓
	Rrs(λ) ^a , a(λ) ^b , b _{bp} (λ) ^c	Carbon Stocks	3 to 8 times per day	Daily; Weekly	High	✓	✗
					Mid	✗	✓
					Low	✗	✓
			2-day	Monthly; Seasonal; Annual	High	✓	✗
					Mid	✓	✓
					Low	✓	✓
	Rrs(λ) ^a , a(λ) ^b , b _{bp} (λ) ^c , phytoplankton pigments	Phytoplankton Community Composition	3 to 8 times per day	Daily; Weekly	High	✓	✗
					Mid	✗	✓
					Low	✗	✓
			2-day	Monthly; Seasonal; Annual	High	✓	✗
					Mid	✓	✓
					Low	✓	✓
	Rrs(λ) ^a , a(λ) ^b , b _{bp} (λ) ^c , phytoplankton pigments, PAR	Primary production; Export production; Net community metabolism	3 to 8 times per day	Daily; Weekly	High	✓	✗
					Mid	✗	✓
					Low	✗	✓
2-day			Monthly; Seasonal; Annual	High	✓	✗	
				Mid	✓	✓	
				Low	✓	✓	
Rrs(λ) ^a , a(λ) ^b , b _{bp} (λ) ^c	Current velocity vector	1 to 4 times per day	Daily to Weekly	High	✓	✗	
				Mid	✗	✓	
				Low	✗	✓	
			Monthly; Seasonal; Annual	High	✓	✗	
				Mid	✓	✓	
				Low	✓	✓	
	Fluxes of sediments, carbon stocks, oil and other pollutants	2 times per day	Daily to Weekly	High	✓	✗	
				Mid	✗	✓	
				Low	✗	✓	
			Monthly; Seasonal; Annual	High	✓	✗	
				Mid	✓	✓	
				Low	✓	✓	

^a UV-Vis Ocean Remote Sensing Reflectance

^b UV-Vis absorption coefficients of phytoplankton, colored dissolved organic matter and non-algal particles

^c Visible Particle backscatter coefficients

^d Spatial coverage is generally reduced due to cloud cover and reduced signal at high solar zenith angles

^e Global coverage at low and mid-latitudes requires multiple GEO sensors (3 minimum; 5 ideally; Ruddick et al. 2014)

Table 2. Measurement requirements and uncertainties.

	Minimum	Goal
Temporal Frequency (within 70° solar zenith angle)		
Open Ocean	≤3 hours	≤2 hours
Coastal	≤2 hours	≤1 hour
Spatial Resolution (ground sample distance at nadir)		
Open Ocean	1000 m	500 m
Coastal	350 m	200 m
Spectral Range	350-900 nm; 1240 and 1640 nm	340-1050; 1640 and 2130 nm
Spectral Resolution/Bandwidth		
UV-Vis-NIR	≤15 nm ^a	≤5 nm ^b
SWIR	20 and 40 nm	40 and 50 nm
Spectral Sampling		
UV-Vis-NIR	None	≤2 nm ^b
SWIR	None	None
Spectral Bands	≥25 multi-spectral bands ^c	Hyperspectral UV- Vis-NIR
SNR (based on typical top-of-atmosphere radiances within 70° solar zenith angle for 15 nm or 10 nm bandwidths and specified ground sample distance)	1000 (360-800 nm) 300 (at 350 nm) 600 (800-900 nm) 250 for 1240 nm 180 for 1640 nm	1500 (360-800 nm) 500 (<360 nm) 600 (800-1050 nm) 250 for 1640 nm 150 for 2130 nm
Uncertainties in Ocean Reflectance (by wavelength)		
<400 nm	≤20%	≤10%
400-600 nm	≤5%	≤3%
600-750 nm	≤10%	≤5%
Uncertainties in Geophysical variables	≤25%	≤15%

^a Bands for chlorophyll-a fluorescence line height should be 10 nm wide (665, 678 and 748 nm bands).

^b Near urban areas with variable tropospheric NO₂, it would be beneficial to retrieve total column NO₂, which would require a bandwidth of ≤0.8 nm and spectral sampling of ≤0.4 nm.

^c Nominal band centers equivalent to those identified in Appendix II of the PACE SDT Report

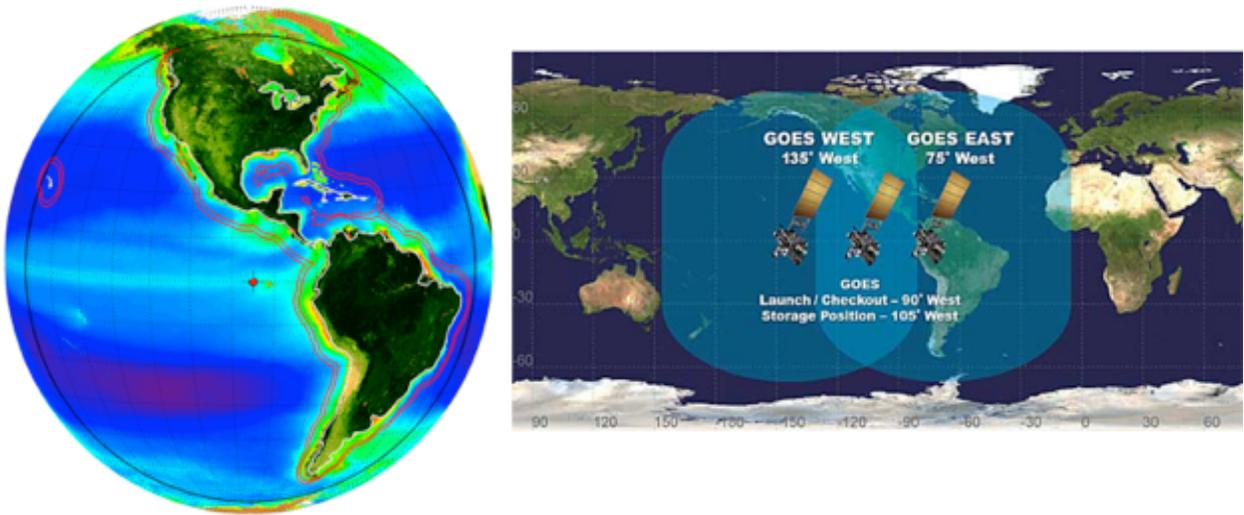


Figure 1. (a) Ocean color field of regard (black outer line; $\sim 67^\circ$ sensor view angle) for a satellite in geostationary orbit at 95°W . NOAA GOES (Geostationary Operational Environmental Satellites) satellite location and coverage for GOES-East and -West platforms (image from <http://goes-r.gov/mission/history.html>).

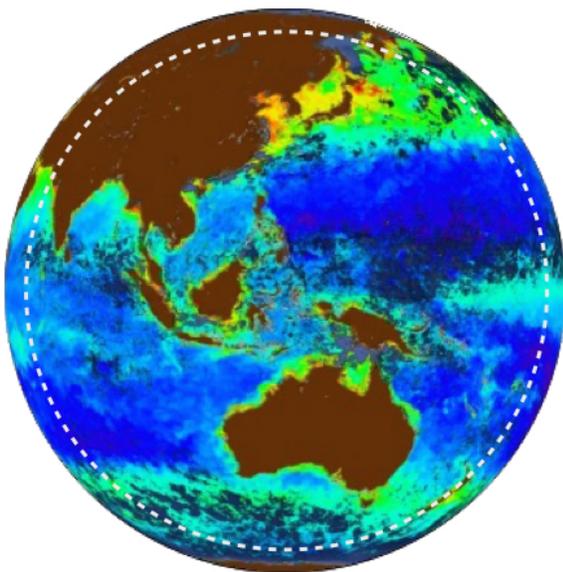


Figure 2. Ocean color usable field of view for the Korean GOCI-II sensor, which is scheduled to launch in 2019.

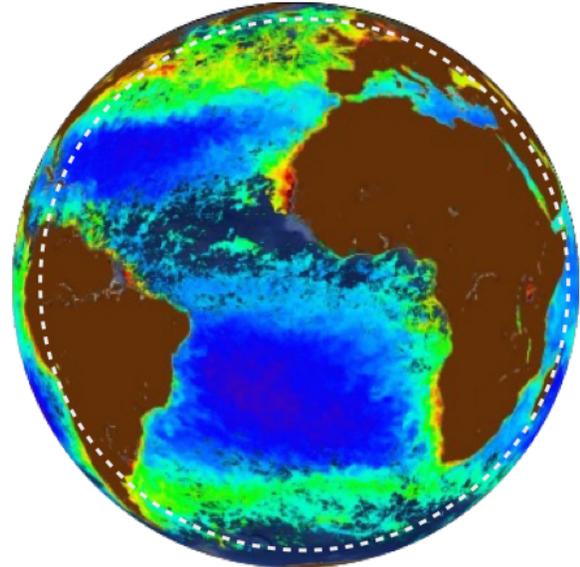


Figure 3. Planned European GEO-OCAPI ocean color sensor usable field of view. Proposal for GEO-OCAPI will be submitted to ESA in May 2016.

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