# Integrating Coastal Earth System Science across Marine, Terrestrial, & Atmospheric Boundaries: The Interdisciplinary Science Potential of the GEO-CAPE Ocean Color Sensor

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## Objective:

Provide an overview of potential interdisciplinary science topics pertaining to coastal systems enabled by anticipated observations from the GEO-CAPE mission as a whole, with a particular focus on how the trade-space choices in planning for the ocean color sensor specifically will affect approaches to coastal system interdisciplinary research.

## Key Points:

- Coastal ecosystems sustain nearly half the world's population and a commensurate portion of global economic activity
- Interdisciplinary approaches needed to capture coastal anthropogenic and biogeochemical processes for forecasting and policy development
- Geostationary remote sensing offers crucial capability for future research objectives to capture transient features and processes

## Abstract

Supporting nearly 50% of global economic activity coastal ecosystems are crucially important for sustaining human societies. The physical, chemical, and biological processes at work in these regions are integrated across aquatic, terrestrial, and atmospheric boundaries and subject to additional forcings by anthropogenic activities. Much scientific work remains to be done to observe and understand coastal processes to better manage and sustainably maintain these systems for current and future generations. This need is particularly acute with impending changes that will accompany future climate change such as sea level rise, ocean acidification, and altered patterns of precipitation and weather extremes. The importance of using interdisciplinary scientific approaches to study these systems and the utility of future geostationary sensors for such work are discussed, drawing on work conducted by the science working groups tasked by NASA to undertake initial planning for the GEO-CAPE (Geostationary Coastal and Air Pollution Events) mission recommended in the NRC 2007 decadal survey of Earth science for NASA. We describe the potential for future geostationary observations to advance Earth system science across several disciplines in coastal regions over the Americas and how they may be linked to international satellite missions and research activities around the globe. These future studies are expected to inform public policy development, contribute new data for management tools, and offer near real-time data to the public regarding water quality, air quality, and coastal indices analogous to weather conditions and forecasts that the public routinely relies on today.

## 1 Introduction

### 1.1 Coastal Ecosystems at the Interface of Traditional Disciplines

The necessity of interdisciplinary science to resolve various scientific questions in order to develop beneficial policies for the stewardship of the world's oceans and coastal ecosystems has been discussed in many reports over the last decade (e.g., *IOCCG* [2008, 2012], *Howard et al.* [2014], *NRC* [2015], *SOLAS* [2015], see the Appendix 1 for acronyms used in this paper). This is particularly the case for coastal oceans, which provide a fertile ground for interdisciplinary science due to their complexity, their regional variability, their proximity to terrestrial influences both natural and anthropogenic, their interactions with the atmosphere, and their increasing vulnerability to climate change including sea level rise and the severity of weather extremes.

Approximately 50% of the world's human population lives in coastal regions generating about 46% of global economic activity [*LOICZ*, 2014]. According to the Land-Ocean Interactions in the Coastal Zone (LOICZ)– a 20-year international program operated under the guidance of the International Geosphere Biosphere Program (IGBP) and the International Human Dimensions Programme (IHDP)– coastal regions are the most transformed and imperiled social-ecological systems on earth that are characterized by pervasive unsustainable practices. Further, they note the diversity of economic activities in the coastal zone including "business, finance, industry, transportation, communication, energy production, shipping, fisheries, and tourism".

There are myriad complex interactions among human activities (Fig. 1a), biogeochemical cycles (Figs. 1b and 1c), and the physical dynamics within coastal ecosystems (Fig. 1d), including:

- •ecosystem services provided by barrier islands and wetlands in buffering coastal storm impacts further inshore
- •ongoing real estate development and commercial enterprise (e.g., port development,

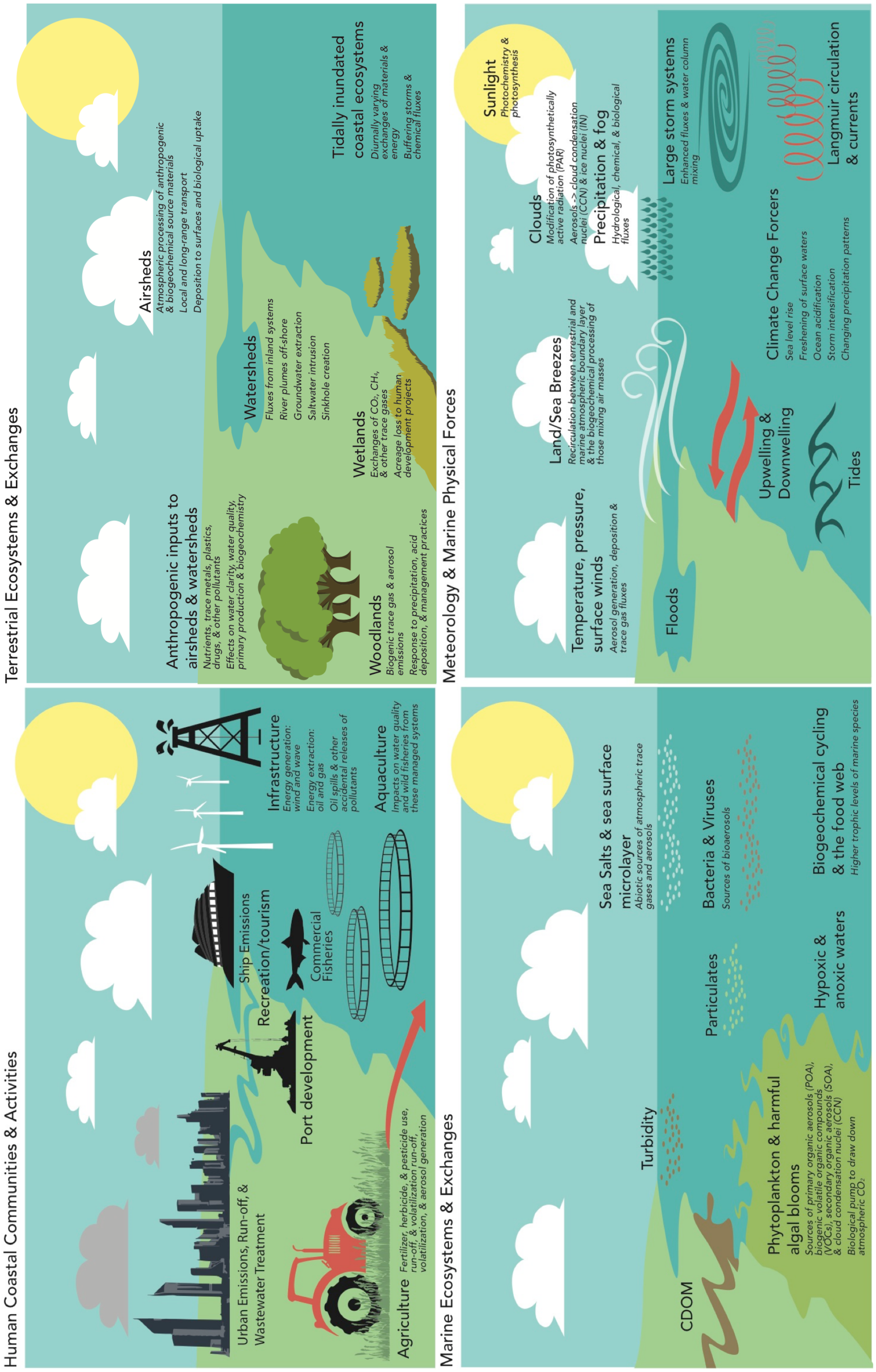

**Figure 1.** Schematic illustrating a) human activities in coastal regions, b) exchanges among terrestrial and aquatic ecosystems, and the atmosphere in coastal regions, c) components of coastal marine ecosystems that contribute to and are affected by exchanges with the atmosphere, terrestrial ecosystems, and human activities, and d) meteorological and marine physical forces that drive exchanges of materials and energy across atmospheric, marine, and terrestrial boundaries.

shipping, fishing, off-shore drilling, and energy generation) along increasingly urbanized coasts

- pressure on freshwater resources in developed coastal areas including increasing extraction of fresh groundwater for societal needs and saltwater intrusion potentially contaminating those resources
- inputs of nutrients and other chemical constituents (e.g., persistent organic pollutants, toxic trace metals, plastics) from upstream human activities and their effect on water clarity, water quality, aquatic photochemistry and biogeochemistry
- societal interests in coastlines for recreational activities both in-water and onshore
- sensitivities of coastal systems to sea level rise, ocean acidification, atmospheric pollution, and other climate change factors.

Given these diverse interactions, deeply integrated efforts across scientific disciplines, including social sciences, are needed to better understand the dynamics of coastal environments and how best to manage the resources they provide. In this white paper we focus on the interdisciplinary science topics pertinent to coastal regions to which the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission may be expected to make important contributions.

## 1.2 A Brief History of the GEO-CAPE Mission Envisioned in the 2007 Decadal Survey

Driven by the scientific need to characterize and understand the short-term dynamics of coastal systems, and to develop robust, predictive models of the effects of climate change and human activity on air quality and coastal ocean ecosystem structure and function, the National Research Council (NRC) recommended GEO-CAPE as a high priority mission in their decadal survey (DS), "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" [*NRC*, 2007], hereafter referred to as the 2007 DS. The need for interdisciplinary Earth Science observations is mentioned throughout the 2007 DS specifically noting for GEO-CAPE that '*coastal ocean ecosystems are under enormous pressure from human activities, both from harvesting and from materials entering the coastal ocean from the land and the atmosphere'*. Among the key ocean science objectives for GEO-CAPE in the 2007 DS were monitoring biotic and abiotic material in transient surface features, and assessing the importance of high temporal variability in coupled biological-physical coastal-ecosystem models. In addition to discussing science objectives for studies of coastal ocean biophysics and atmospheric-pollution chemistry, the NRC recommended exploring compatibility with objectives of the terrestrial biophysical sciences.

With GEO-CAPE the NRC combined into one mission research priorities that had been expressed by two separate communities (Tropospheric Atmospheric Composition and Ocean Color) for observations from a geostationary (GEO) platform. Observations from polar low earth orbiters (LEO) are typically limited to about once per day at low- to mid-latitude locations. However, present low earth orbit (LEO) ocean color sensors on average actually provide only one or two sets of valid products per week at these latitudes after discounting cloud-covered scenes and glint contaminations. This limited temporal coverage from LEO cannot capture the highly dynamic processes characteristic of coastal regions or the atmosphere. GEO offers an opportunity to greatly improve temporal coverage at these latitudes allowing for studies and forecasts on previously unattainable time scales for atmospheric and oceanic products. In addition to promoting a shared GEO platform for the now coupled missions, the NRC was also motivated by the need for atmospheric correction to obtain high quality ocean color retrievals.

Although the GEO-CAPE atmospheric composition and ocean color science objectives were initially conceived as interlinked and to be achieved from a shared platform, they were expected to have separate sensors for their respective measurements. This would allow for independent instrument optimization and scanning priorities. Hence, following the recommendation of the 2007 DS, NASA created two science working groups (SWGs) for GEO-CAPE to develop the mission requirements for each scientific discipline in parallel. As these efforts advanced, various alternative launch scenarios were entertained in order to explore avenues for cost reduction of the overall mission [*Fishman et al.,* 2012]. With the advent of hosted payload opportunities, where NASA sensors are hosted by commercial communications satellite platforms launched into GEO, significant cost savings could be achieved compared to a dedicated single NASA platform. This also presented the possibility that due to the reduced cost, the atmospheric composition and ocean color sensors could launch separately at earlier launch dates. At the GEO-CAPE open community workshop in 2011 the atmosphere and ocean science communities voiced their joint approval for the two sensors to launch separately as budgets and hosted opportunities would allow. The approach to assess and minimize the impact of this strategy on GEO-CAPE interdisciplinary science opportunities and ocean color atmospheric correction methods is discussed in more detail in §2. Even from separate platforms, the combination of high-quality atmospheric, oceanic, and terrestrial observations from a GEO orbit offers a unique opportunity to push the envelope in interdisciplinary science.

The initial discussions of potential interdisciplinary science from GEO-CAPE contemplated opportunities provided by the mission as a whole. However, the decision to separate the atmospheric composition (AC) and ocean color (OC) components into different hosted payloads required consideration of interdisciplinary science enabled by GEO observations of AC and OC separated in space and time. Hence, in this document we examine interdisciplinary science enabled by GEO-CAPE as a whole and by the GEO-CAPE OC sensor alone, as the hosted payload launches may not overlap.

### 1.3 GEO-CAPE Interdisciplinary Science Foci Areas

A subset of members from the two SWGs met via telecons for a series of discussions to consider the scope of topics that could be addressed by GEO-CAPE. A revised summary of interdisciplinary science questions identified by this group is provided in Box 1. The focus was initially narrower than that described in §1.1, with topics falling into three categories where atmospheric and oceanic observations would be beneficial to each other: 1) influences of meteorology on coastal waters and vice versa, 2) bidirectional fluxes of constituents between the atmosphere and coastal waters, and 3) contributions of in situ anthropogenic activities in aquatic environments to biogeochemistry. Subsequent efforts have expanded the list of topics to include those that integrate terrestrial ecosystems with atmospheric composition and ocean color dynamics (see Box 1, topic 4).

These topics are consistent with key science questions for understanding and managing coastal ecosystems in the 2007 DS as captured in the GEO-CAPE ocean color science traceability matrix (STM, see Appendix 2). All of the overarching science questions in the GEO-CAPE ocean color STM address processes across scales that will require collaboration across disciplines. The initial discussions of the interdisciplinary GEO-CAPE group that resulted in the first 3 topics shown in Box 1 were focused principally on questions 4 and 5 in the STM, related to airborne fluxes, episodic hazards, and contaminant loadings. These topics are also consistent with the priorities of the Surface Ocean - Lower Atmosphere Study (SOLAS), an

### *Box 1: Interdisciplinary Science Questions identified by GEO-CAPE SWG members*

***Influences of meteorology on coastal waters and vice versa***

a) role of coastal waters in land/sea breeze dynamics affecting transport and processing of atmospheric constituents
b) changes in atmospheric boundary layer height over estuarine and coastal waters with respect to that over their adjacent land masses and the subsequent effects on vertical distribution, transport, processing, and deposition of atmospheric constituents
c) influence of cloud cover and atmospheric composition/pollution on down-welling surface irradiance and light availability for marine photosynthesis and photochemical processing of other marine constituents such as CDOM (especially as they relate to changes in climate and coastal urbanization)
d) influence of precipitation, both direct and indirect via watershed runoff, on coastal sea surface height, temperature, salinity, acidity, buffering capacity, and delivery of nutrients, carbon and pollutants to coastal ecosystems
e) role of large storm systems (e.g., tropical storms and hurricanes) in:
    1) enhancing transfer of gases and aerosols from marine ecosystems to the atmosphere
    2) affecting turbidity of coastal waters and subsequent in-water processes
f) extent to which global synoptic patterns (droughts/floods, clear skies/cloud cover, average annual precipitation, snowmelt, etc.) coupled with coastal dynamics (e.g., tides, circulation, thermocline variability, salinity, etc.) influence community structure and dynamics of marine organisms, as well as the sensitivity of different ecosystems (e.g., Gulf of Maine, Chesapeake Bay, Gulf of Mexico, Monterey Bay, Great Lakes, etc.) to variability in those synoptic patterns
g) influence of fog on light availability and sea breeze formation; large scale meteorological effects on fog formation
h) effect of water density at water/air interface (i.e., fresh water plumes v. saline surface waters) on local meteorology, especially the role of the Amazon plume
i) influence of coastal aerosols on cloud formation and local structure of precipitation

***Bidirectional fluxes of constituents between the atmosphere and coastal waters***

Examine and *quantify* fluxes to coastal waters (dry and wet, direct and indirect), concentrations, bioavailability, toxicity, etc. to examine influences on biogeochemical cycling, productivity, water quality, biodiversity, etc. in the water. Explore how in-water constituents, dynamics, and processes in conjunction with meteorological conditions influence fluxes to the atmosphere; quantify the spatial and temporal variability of these fluxes and examine how that variability influences the atmosphere, marine and terrestrial ecosystems.

a) nutrient deposition from the atmosphere to the ocean and its influence on coastal marine ecosystem communities
b) pollutant aerosol deposition (e.g., black carbon, aerosol-associated trace metals, persistent organic pollutants, etc.) and subsequent biogeochemical cycling within marine ecosystems (e.g., biological cycling, deposition to sediments, resuspension, and potential recycling to atmosphere)
c) role of ocean-derived aerosols (inorganic, organic, and biological) in atmospheric chemical cycling, cloud formation and properties, and climate
    1) identify sources of organic and biological material and how fluxes vary with respect to sources, water temperature, and meteorology
    2) examine the effect of biological aerosols (e.g., plankton, viruses, microbial aerosols, pathogens) on coastal urban air quality, human health, climate (via their potential role as ice, cloud, and fog condensation nuclei). HAB (harmful algal bloom) aerosols are of particular concern, e.g. brevetoxin-contaminated aerosols have been shown to travel a mile inland from shore and have been shown to cause respiratory distress in susceptible populations
    3) explore transport of ocean-derived mercury
d) marine sources of IO and its role in aerosol nucleation in the atmosphere
e) exchange of VOCs (especially oxygenated and halogenated compounds) between coastal waters and the atmosphere
    1) coastal waters serve both as sources and sinks of such compounds via both biological and abiological chemical processing
    2) examine the influence of this exchange on marine ecosystems, atmospheric chemistry, and climate
f) influence of halogenated compounds from marine ecosystems on the oxidative capacity of the atmosphere
g) the influence of halogens on phytoplankton growth and vice versa
h) role of coastal ocean biology in $O_3$, CO, and $CO_2$ dynamics in the atmosphere
i) extent to which vertical migration of phytoplankton, grazing, temperature- and salinity-stress, existence and composition of sea-surface microlayer, and other in-water constituents and processes mitigate bidirectional fluxes with the atmosphere
j) chemical effects of fog ($SO_2$ and formation of sulfate aerosol, $HNO_3$ uptake and deposition to coastal waters, Hg) on coastal and inland waters

***Contribution of in situ anthropogenic activities in aquatic environments to biogeochemistry***

a) impact of ship exhaust plumes on atmospheric chemistry/photochemistry, climate forcing, nutrient supply to the oceans, and ocean biogeochemistry (these emissions include gases such as $SO_2$, $NO_x$, and hydrocarbons, as well as sulfate, black carbon, and organic carbon aerosols)
b) impact of oil spills related to off-shore drilling and shipping accidents within marine ecosystems and upon evaporation to the atmosphere
c) impact of aquaculture on ecosystems and water quality
d) impact of infrastructure development in watersheds or coastal waters (levees, wind farms and other off-shore energy production, etc.)

***Interdisciplinary Terrestrial Dynamics***

a) tidal influences on wetland energy and carbon balances to include carbon storage and albedo feedbacks
b) agricultural stresses in the terrestrial coastal zone to include diurnal water and nutrient stress and improved biomass estimations
c) flood monitoring and recovery over coastal zones to include sediment transport and vegetation recovery dynamics

international effort conducted over the past ten years to "achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, and of how this coupled system affects and is affected by climate and environmental change" [*SOLAS*, 2015]. They have recently released their 2015-2025 science plan [*SOLAS*, 2015] revolving around five themes:

1) greenhouse gases and the oceans
2) air-sea interface and fluxes of mass and energy
3) atmospheric deposition and ocean biogeochemistry
4) interconnections between aerosols, clouds, and ecosystems
5) ocean biogeochemical control on atmospheric chemistry

In addition to the science objectives laid out in this science plan, SOLAS also proposes to coordinate with international Future Earth (http://www.futureearth.org/) projects to advance science policy and sustainability.

As the work of the GEO-CAPE ocean color SWG proceeds, new interdisciplinary relationships are being explored with colleagues that study terrestrial ecosystems. These efforts will more fully develop an interdisciplinary approach to science questions 2 and 5 in the GEO-CAPE ocean color STM related to exchanges across the land-ocean interface, watersheds, and alterations of coastal habitats (e.g., topic 4, Box 1). Coastal wetlands (i.e., mangroves, tidal salt marshes, and seagrass beds) store carbon, principally in their thick underlying soils, that can be released to the atmosphere as $CO_2$ as these wetlands are degraded or converted to other uses [*Pendleton et al.,* 2012]. Called "blue" carbon, these coastal $CO_2$ reservoirs are not adequately quantified in terms of their carbon stocks, nor are their contributions to carbon sequestration and global carbon budgets well constrained [*Pendleton et al.,* 2012; *Howard et al.,* 2014]. Much more work is needed to understand these systems, their sensitivity to environmental changes such as sea level rise, as well as the role of human activities in altering these systems.

Within the ocean science community itself, the most recent decadal survey of ocean sciences for NSF [*NRC*, 2015] states, "most of the questions will require interdisciplinary research across the subdisciplines of ocean science". The decadal priorities set by the NRC identified "transformative" topics they considered to be "integrative, interdisciplinary, strategic research areas" [*NRC*, 2015]. Most of the 8 themes they identified are important for coastal waters and communities, whether related to sea-level change, geohazards, marine food webs, biodiversity and resilience to climate change, or the role of ocean biogeochemical and physical processes in climate and its variability. One theme specifically addresses coastal and estuarine oceans and how they are influenced by the global hydrological cycle, land use, and upwelling from the deep ocean.

### 1.4 Integrating GEO-CAPE Across Disciplines and Leveraging Partnerships

Achieving the science objectives of the GEO-CAPE ocean color STM in their broad interdisciplinary scope will require the integration of in situ observations, remote sensing, and modeling studies. These objectives align well with those of international efforts. GEO-CAPE could play an important role in international interdisciplinary efforts such as SOLAS, Future

Earth, and the Blue Carbon Initiative (http://thebluecarboninitiative.org/) by providing important atmospheric, oceanic, and terrestrial measurements at an unprecedented temporal resolution. Further, GEO-CAPE is intended to be part of an international effort to monitor atmosphere and ocean processes from GEO around the globe [*Fishman et al.,* 2012] with partner missions over Asia (GOCI, GOCI-II, and GEMS) and Europe (GEOCAPI and Sentinel-4). The regional data from these GEO orbiters are to be linked via global observations made from LEO platforms [*IOCCG*, 2012].

As the science of remote sensing advances, its utility for the broader policy community and public information is expanding. For many of these applications, integration of ocean color observations with atmospheric and terrestrial datasets is required to develop improved forecasting tools and warning systems. For example, interdisciplinary forecast tools are used to inform the public about swimming and air quality hazards related to red tides and other nuisance blooms along shorelines. Coupled terrestrial, oceanic, atmospheric models integrated with interdisciplinary satellite observations are needed to assess the implications of reductions in greenhouse gas emissions for carbon cycle science or evaluate the potential for managed restoration of wetlands to mitigate climate change impacts.

Improvements in spectral, spatial, and temporal resolution of ocean color sensors are required to make ocean color retrievals sufficiently quantitative for future applications [*IOCCG*, 2008]. Finer spectral resolution and new algorithmic approaches linking retrievals with in situ measurements and models will make possible the remote sensing of additional water quality metrics. Enhanced spatial resolution will be required for monitoring estuarine and coastal river systems at scales useful to coastal water managers. Greater temporal resolution is needed to monitor rates of various processes in coastal waters and would be especially useful in monitoring the response to short term perturbations such as from storms or spills.

Leveraging assets across disciplinary programs, national funding agencies, international partnerships, and public-private strategies will be necessary to maximize scientific achievement and societal benefit within the anticipated cost constraints [*NRC*, 2015]. This view is consistent with those expressed by the international community (e.g., IOCCG, SOLAS, Future Earth, etc.). GEO-CAPE will be an important piece of an integrated, interdisciplinary, international and inter-agency effort to advance earth science and policy. Mission planning requires consideration of how to incorporate GEO-CAPE as seamlessly as possible within this broader framework.

## 2 Challenges of Remote Sensing in the Coastal Zone

### 2.1 Spectral complexity & GEO-CAPE OC sensor spectral range and resolution design choices

Coastal waters are optically complex environments where strong biological production, terrestrial sources of highly absorbing dissolved organic matter, as well as absorbing and scattering organic and inorganic particles affect the light field within the water column and hence, remote-sensing reflectance. For instance, the spectral characteristics of phytoplankton vary with wavelength by taxonomic composition, according to pigment composition, pigment packaging and physiological state [Bricaud and Morel, 1986; Bricaud et al., 1988; Bricaud et al., 1995; Ciotti et al., 1999]. Absorption from CDOM and non-algal particles (NAP) decreases exponentially with increasing wavelength. In shallow coastal waters benthic flora (including macroalgae seaweeds and sea grasses) can additionally absorb and scatter sunlight, which adds further complexity to the ocean color signal [*IOCCG*, 2000; *Mouw et al.,* 2015]. This complexity requires enhanced measurement capabilities to resolve the contributions of many different and non-covarying components to the top of the atmosphere (TOA) signal measured by an ocean color sensor.

The first OC sensors on LEO platforms relied on a few spectral bands (colored bars, Fig. 2) with the full-width half-maximum (FWHM) of the bands on the order of 5-20 nm capable of discerning broad spectral OC features that span several to tens of nm (black curves, Fig. 2). Coincidentally, atmospheric aerosol spectra also exhibit spectral features on a similar scale making OC sensors suitable for remote sensing of atmospheric aerosols as well as OC. In contrast, atmospheric trace gases absorb light at a much finer spectral resolution (e.g., Fig. 3, see §2.2.2). The GEO-CAPE OC STM (Appendix 2) offers two sets of sensor specifications both of which will dramatically expand spectral range and resolution from the early remote sensors as shown in Fig. 2 in order to expand the set of OC products that can be retrieved (see Appendix 3).

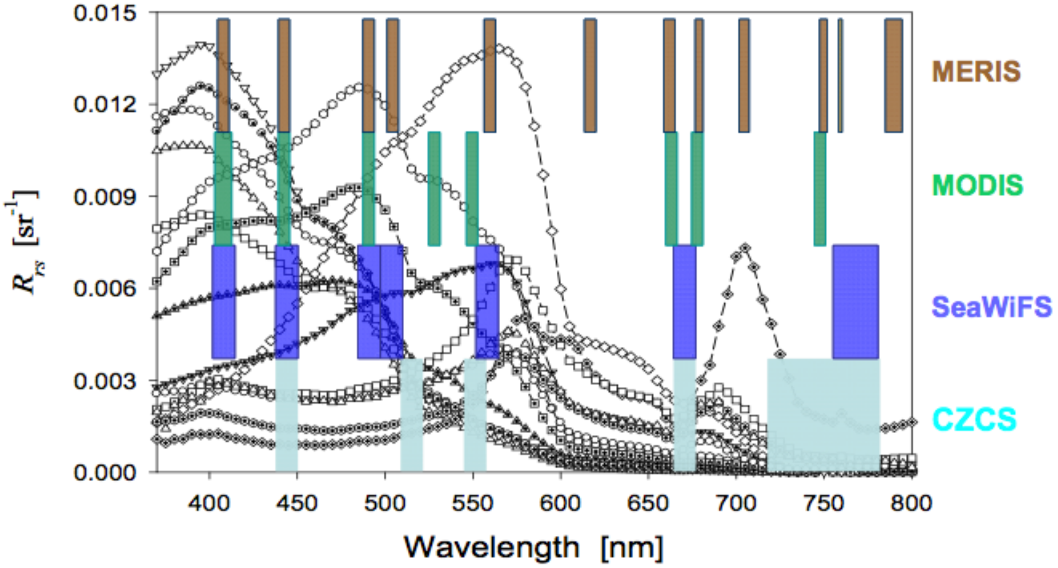

**Figure 2.** Example $R_{RS}$ (sr$^{-1}$) from a set of 384 spectra (~350-900 nm, ~3 nm resolution) collected during cruises over a 12-year period from a broad range of open ocean and coastal environments with spectral bands from four ocean color satellites overlaid from *Lee et al.* [2007].

The baseline instrument requirements specified in the STM are the target requirements that will provide the measurements needed to achieve all of the scientific objectives determined by the OC SWG. The threshold instrument requirements allow for a more cost constrained alternative that will still deliver on the mission critical science. The threshold requirements under consideration (Table 1) include a multiband sensor option that expands on the number of bands (e.g., 50 bands, Appendix 4) from those shown in Fig. 2 as well as a hyperspectral sensor option with spectral resolution of 2-5 nm over the ultraviolet-visible-near-infrared (UV-Vis-NIR). Both options offer greater flexibility in algorithm development for coastal ocean products (Appendix 3). They are both also sufficient for NIR aerosol atmospheric corrections to the ocean color products. Between these choices, a hyperspectral sensor offers the greatest flexibility in developing algorithms for optically complex coastal waters in order to discriminate among various phytoplankton functional types (which can be thought of both in terms of size distributions, e.g., pico-, nano-, and microplankton, or groups of organisms with shared traits, e.g., nitrogen fixers, calcifiers, silicifiers, etc. [*IOCCG*, 2014]). Hence, the baseline (preferred) instrument requirements envision a hyperspectral sensor with sufficient spectral resolution to retrieve not just OC products and atmospheric aerosols, but atmospheric $NO_2$ as well (a critical measurement required for atmospheric correction of OC retrievals).

**Table 1.** Baseline and threshold requirements as specified in the GEO-CAPE ocean color STM, along with revised requirements under consideration in 2016.

| | *Spectral Range (nm)* | *Spectral Resolution (nm) sampling & resolution* | *Spatial Resolution (m) at nadir* |
|---|---|---|---|
| *STM [Fishman et al., 2012]* | | | |
| Baseline | 340-1100 | ≤0.25 & ≤0.75 | 250 x 250 |
| | 1245, 1640, & 2135 | ≤20 - 50 | 250 x 250 |
| Threshold | 345-1050 | ≤2 & ≤5 (UV-Vis-NIR) | 375 x 375 |
| | 400-450 | ≤0.4 & ≤0.8 (for $NO_2$) | 750 x 750 |
| | 1245 & 1640 | ≤20 - 40 | 375 x 375 |
| *2016 STM Revisions (under consideration)* | | | |
| Baseline | 340-1050 | ≤1 & ≤2 (UV-Vis-NIR) | 250 x 250 |
| | 400-450 | ≤0.4 & ≤0.8 (for $NO_2$) | 750 x 750 |
| | 1245, 1640, & 2135 | ≤20 - 40 | 250 x 250 |
| Threshold | 50 bands*:<br>40 bands 350-715<br>7 bands: NIR<br>1020, 1245, & 1640 | FWHM<br>UV-Vis-NIR: 3-15 nm<br>SWIR: 20-40 nm | 375 x 375 |

*see Appendix 3

*Mouw et al.* [2015] have recently published a comprehensive review of the challenges of remote sensing of ocean color in inland and coastal waters. Two of the challenges discussed involve atmospheric correction and abrupt albedo changes at the land/water interface. The GEO-CAPE OC sensor design choice will determine how both of these challenges will need to be addressed and these choices will in turn affect the role GEO-CAPE will be able to play in interdisciplinary science studies. The challenge in accurate atmospheric corrections for coastal water OC products is due to the proximity to anthropogenic sources of highly variable absorbing trace gases such as $NO_2$ and $O_3$, along with absorbing aerosols such as black and brown carbon (discussed in §2.2). The challenge posed by the land/water interface (discussed in §2.3) arises from differing albedos of land and water surfaces and the role that difference plays in retrievals. Typically, different retrieval algorithms are applied over land vs. water leading to discontinuities in products complicating efforts to study transboundary fluxes for example. Given the implications for interdisciplinary science possibilities, the rest of this section will discuss these two issues in more detail.

## 2.2 Atmospheric Correction for Coastal Ocean Color

There are two key spectral range and resolution choices to be made for GEO-CAPE for atmospheric correction aimed at ocean color products in the coastal zone, one involves the shortwave infrared (SWIR) and NIR bands and the other, the spectral resolution in the UV and near-visible parts of the spectrum.

### 2.2.1 SWIR versus NIR bands for Aerosol Atmospheric Correction of Aerosols

In the NIR water is such an efficient absorber of light, it is assumed that the remote sensing reflectance, $R_{RS}$(NIR), approaches zero in open ocean waters, such that all of the signal measured by a satellite sensor comes from the atmosphere. Based on this assumption, past ocean color sensors have included spectral bands in the NIR to detect information of the aerosols and subsequently remove its contribution in the visible bands [*IOCCG*, 2010; *Mouw et al.,* 2015]. The assumption of $R_{RS}$(NIR) ~ 0 is not valid, however, for highly turbid coastal waters. By shifting to longer SWIR wavelengths the assumption of $R_{RS}$(SWIR) ~ 0 holds even in the presence of extremely high turbidity, resolving the problem. However, extrapolating the aerosol signal measured at SWIR wavelengths to the rest of the spectrum can be problematic, leading to the need to use additional UV bands for aerosol correction [*IOCCG*, 2012]. The baseline recommendation for GEO-CAPE includes three SWIR bands at 1245, 1640 and 2135 nm (Table 1). Preliminary instrument assessments suggest the additional cost of the 2135 nm SWIR band may be significant [*IOCCG*, 2012; *Mannino et al.,* 2016, hence, the threshold requirement is just for the first two SWIR bands.

### 2.2.2 UV-Vis Spectral Resolution for Atmospheric Correction of $NO_2$

The motivation for the UV-Vis spectral resolution in the current GEO-CAPE ocean color STM for the baseline requirement (Table 1) of 0.25 nm sampling and 0.75 nm resolution is driven by the possibility of simultaneous trace gas retrievals, particularly the retrieval of $NO_2$. $NO_2$ is a strong absorber in the UV-Vis range (Fig. 3), which can confound ocean color retrievals [*Tzortziou et al.,* 2014]. Unlike aerosols, trace gases have very fine, narrow band absorption features. Because many spectral regions contain a large number of simultaneous absorbers, retrievals of trace gases involve fitting those fine spectral features over certain wavelength intervals using a DOAS (Differential Optical Absorption Spectroscopy) approach. Hence, finer spectral resolution is required. The focus here on $NO_2$ versus $O_3$ for atmospheric correction derives from the greater spatial and temporal heterogeneity of the former [e.g., *Tzortziou et al.,* 2013] as illustrated in Fig. 4. Data from the four deployments of DISCOVER-AQ (in Baltimore, Houston, Denver, and the San Joaquin Valley of California) were collected at high spatial resolution from an aircraft, then binned to larger pixel sizes relevant to the TEMPO (Tropospheric Emissions: Monitoring of Pollution) instrument. It is clear that small spatial-scale $NO_2$ maxima are more sensitive to binning than $O_3$ maxima (Fig. 4). As a result, the need for coincident, high spatial resolution observations is

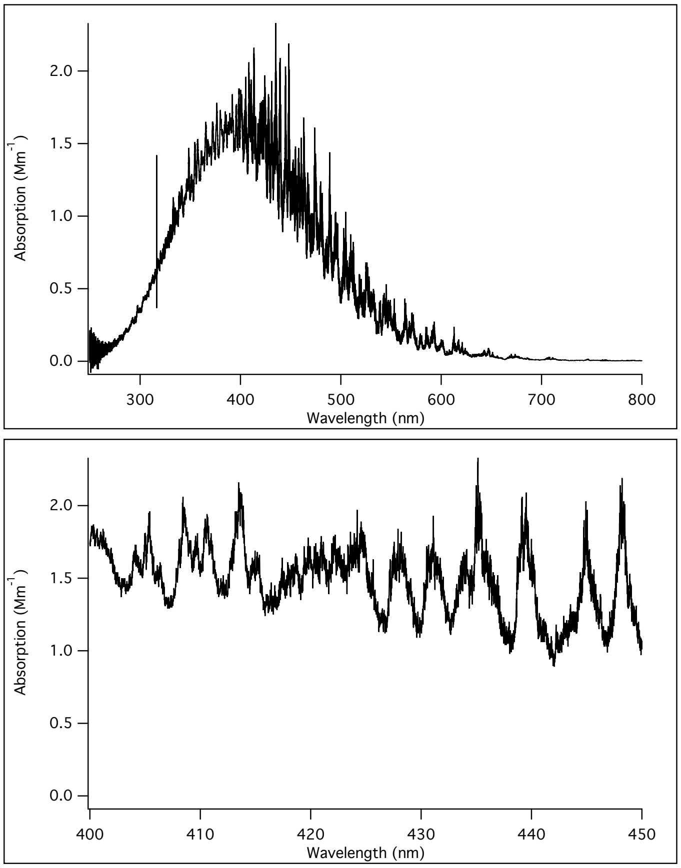

**Figure 3.** $NO_2$ absorption (Mm$^{-1}$) spectrum for a concentration of 1ppb from 250-800 nm (top) and from 400-450 nm (bottom).

higher for $NO_2$, while using coarser spatial resolution $O_3$ retrievals from ancillary sources for atmospheric correction will introduce less uncertainty to the ocean color retrievals.

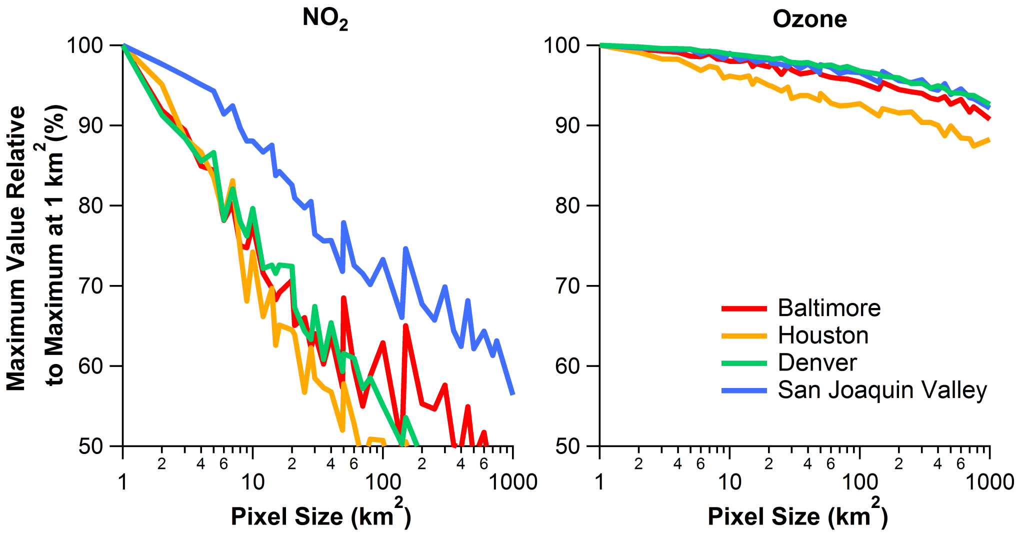

**Figure 4.** Comparison of the reduction in maximum values observed as fine spatial-scale features are binned to larger areas to illustrate the effect of pixel size on remotely sensed atmospheric constituents: $NO_2$, and $O_3$. The individual curves in each panel correspond to one of the four DISCOVER-AQ deployments, thereby capturing regional variability influencing the binning relationships.

In many coastal regions strong anthropogenic emissions of $NO_2$ and meteorological processes that influence the circulation and accumulation of atmospheric pollutants at the land/water interface result in highly variable $NO_2$ concentrations, both spatially and temporally. If not adequately corrected in satellite retrievals of ocean color, this atmospheric variability can impose a false impression of diurnal and seasonal changes in near-shore water quality and biogeochemical processes [*Tzortziou et al.,* 2014]. If unaccounted for, the $NO_2$ absorption

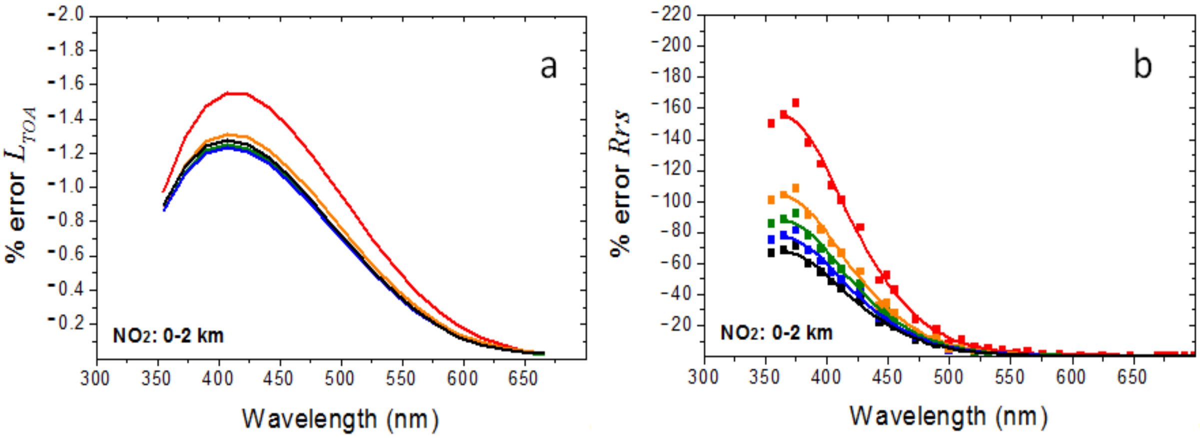

**Figure 5.** Percent error (or change) in (a) TOA signal $L_{TOA}$ and (b) coastal ocean $R_{RS}$ caused by a change of 1 DU of $NO_2$ (*Tzortziou et al.* [2014]). $NO_2$ was assumed to be homogeneously distributed within 0-2 km from ground. Results are shown for a look angle of 36° and solar zenith angles of 60° (red), 42° (gold), 30° (green), 18° (blue), and 1.5° (black).

results in an underestimation in retrieved ocean $R_{RS}$, with the maximum error in the 350-450 nm spectral region, wavelengths used for chlorophyll-*a* ($Chl_a$), CDOM, dissolved organic carbon, and other coastal ocean biogeochemical variable retrievals (Fig. 5). *Tzortziou et al.* [2014] reported that 0.7 DU unaccounted variability in total column $NO_2$, which is consistent with the spatial and temporal variability observed over the Chesapeake Bay watershed during the July 2011 DISCOVER-AQ field campaign, results in an error in coastal water $R_{RS}(412)$ as large as 40% at low solar zenith angles (SZAs, <30°), while it gets as large as 70–80% for larger SZAs expected from a geostationary sensor. The error in $R_{RS}$ gets larger at shorter wavelengths, larger solar zenith and look angles, and as the $NO_2$ is distributed at higher altitudes.

### 2.2.3 Climatological Approaches for Atmospheric Correction of $NO_2$

Recent instrument studies designed to help the ocean color SWG assess costs and trade-offs among various design parameters (spatial resolution, spectral resolution, spectral range, etc.) included comparisons between hyperspectral and multi-spectral sensors (e.g., Appendix 4). With multi-spectral sensors the ability to perform measurements at < 1 nm spectral FWHM will be lost, eliminating our ability to perform $NO_2$ retrievals. Hence, in the case of a multi-spectral sensor, some consideration will need to be given to how to correct the ocean color retrievals for $NO_2$ absorption. For open ocean retrievals, climatologies are typically used to correct for trace gases [*Mouw et al.,* 2015].

If the GEO-CAPE ocean color sensor lacks a companion instrument to measure $NO_2$ from GEO providing the diurnal variability required for the correction, perhaps new $NO_2$ climatologies that capture diurnal variability can be developed from TEMPO data. It will be necessary to assimilate such ancillary observations into models to rectify spatial and temporal offsets when applying ancillary data in the atmospheric correction processes. For example, the planned TEMPO field of regard (Mexico City to Alberta, Canada [*Zoogman et al., 2016*]) will miss regions of interest to the GEO-CAPE ocean color mission, especially the Amazon and Orinoco outflow systems in South America. Further, the spatial resolution of TEMPO is 4.4 km x 2.1 km compared to ≤ 375 m x 375 m at nadir for the GEO-CAPE ocean color sensor. Ground-based networks, polar orbiter observations, and models will need to be integrated to synthesize a suitable $NO_2$ correction at the appropriate spatial and temporal scales.

## 2.3 Abrupt Albedo Changes & the Need to Limit Discontinuities in Coastal Retrievals

Another coastal ocean color retrieval challenge described in *Mouw et al.* [2015] is that of stray light contamination due to abrupt albedo changes in the vicinity of brighter objects such as land, clouds, and ocean sunglint. Typically, ocean pixels adjacent to glint, clouds, or land are masked and not used for retrievals, with the last of these masks creating a particularly unfortunate situation for a coastal ocean color sensor, where inshore water bodies are of interest. Similarly, atmospheric retrievals over especially turbid near-shore waters typically result in the rejection of such coastal pixels. These land/water boundary pixel problems are exacerbated by the fact that different approaches are used to retrieve products over land versus over water with the result that unphysical features appear in data that cross land-water interfaces (Fig. 6). In this example, there is clear evidence of a land-water discontinuity in the MODIS retrieved AOD (aerosol optical depth) averaged over 2001-2008 in spring. The discontinuity in this example is more distinct along the east coast of Korea, but retrievals along the west coast are likely affected as well (Fig. 6).

For a coastal sensor as envisioned for GEO-CAPE, developing retrievals that are consistent across the land-water interface will be important for addressing coupled ocean, terrestrial and atmospheric science objectives. For example, to address the problem illustrated by Fig. 6, work is underway to resolve coastal discontinuities in AOD retrievals by using the 2.1 µm SWIR band. The Multi-Angle Implementation of Atmospheric Correction (MAIAC) is one of the newer algorithms that use time series analysis and multi-pixel processing to improve cloud detection and advance the accuracy of aerosol – surface BRDF/albedo retrievals [*Lyapustin et al.,* 2011]. The characterization of spectral surface BRDF is achieved by accumulating multi-angle observations over time (see §3.2 for more details). This approach has been applied to select LEO sensors (MODIS, VIIRS, AVHRR) [*Schaaf et al.,* 2002, 2011; *Sütterlin et al.*, 2015] to produce BRDF/albedo. GEO-CAPE at 1 km spatial resolution has the capability to provide the high spatial resolution aerosol information needed in air quality research over urban regions. The temporal resolution that geostationary observations can provide offers a finer temporal resolution "natural" time series of measurements without additional gridding, which is an extra source of noise when working with LEO sensors (e.g., MODIS, VIIRS). The descope options for GEO-CAPE that eliminate the 2.1 µm channel would affect the current aerosol retrieval capabilities of both MAIAC and the Dark Target [*Levy et al.,* 2013; *Kotchenova et al.*, 2006; 2007] algorithms over land. For most aerosol types with a dominant fine mode fraction, the 2.1 µm channel is transparent and almost unaffected by aerosol variability at low-to-moderate aerosol loadings. This is used by MAIAC to characterize BRDF in this channel, and then establish a spectral relationship with the blue-red spectral region using the minimal reflectance approach. Once this relationship is established, aerosol retrievals are made. The lack of the 2.1µm channel will complicate surface BRDF characterization in visible bands and increase uncertainty of separating aerosol from surface variability.

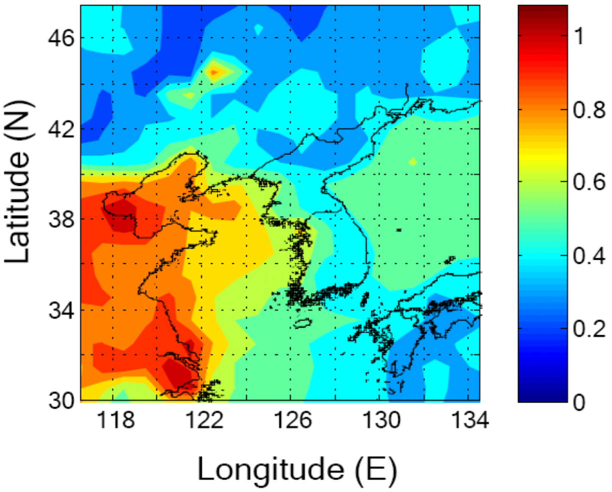

**Figure 6.** Evident land-ocean discontinuity in this MODIS AOD image over Korea, most likely due to errors in corrections of surface (land vs. ocean) reflectance.

## 3 The GEO-CAPE Mission

### 3.1 GEO-CAPE and TEMPO: Atmospheric Trace Gas and Aerosol Products

The planned GEO-CAPE atmospheric measurements are shown in Table 2, based on the information in the atmosphere science traceability matrix in *Fishman et al.* [2012]. *Fishman et al.* [2012] noted that at that time "spectral resolution requirements and their trade-off with measurement SNR requirements, are the subject of current studies". Hence, in Table 2 the GEO-CAPE spectral ranges are only shown in general terms. In November 2012, TEMPO was selected under the Earth Venture instrument program. TEMPO includes the majority of measurements planned for the atmospheric composition component of the GEO-CAPE mission (Table 2). In order to fit under the cost cap however, most of the infrared bands had to be dropped. As a result, the italicized products in Table 2 will not be measured from TEMPO, an instrument that uses an imaging grating spectrometer with two 2-D detectors that cover the spectral ranges 290-490 nm and 540-740 nm at 0.6 nm FWHM using 0.2 nm sampling [*Zoogman et al.,* 2016].

The TEMPO science traceability matrix offers greater specificity regarding the spectral bands needed for each trace gas and aerosol product. Comparing those spectral bands and resolution to the GEO-CAPE ocean color spectral options in Table 1, it is evident that $NO_2$ and glyoxal (CHOCHO) are retrievable from the current STM baseline and threshold, as well as from the 2016 suggested revised baseline (but not the potentially revised threshold). Hence, adoption of the 2016 suggested revised baseline will make no difference in terms of the GEO-CAPE ocean color sensor's ability to retrieve trace gases compared to the current STM. Further, the GEO-CAPE ocean color sensor will have the IR channels needed to obtain aerosol height information that was not included in the TEMPO design.

**Table 2.** Planned Atmospheric Composition observations from GEO-CAPE and TEMPO.

| | GEO-CAPE AC STM[*] | TEMPO[**] Band (nm) | TEMPO[**] Temporal Resolution |
|---|---|---|---|
| $O_3$: 0-2 km, FT<br>SOC, Total Col. | UV, Vis, TIR | UV: 300-345<br>Vis: 540-650 | 1 hr, 1hr<br>1hr, 1hr |
| $NO_2$ | Vis | 423-451 | 1 hr |
| HCHO | UV | 327-356 | 3 measurements per day |
| $SO_2$ | UV | 305-345 | 3 measurements per day |
| CHOCHO | Vis | 420-480 | 3 measurements per day |
| AOD | Vis | 354, 388 | 1 hr |
| AAOD | UV-deep blue | 354, 388 | 1 hr |
| AI (aerosol index) | UV-deep blue | 354, 388 | 1 hr |
| CF | | 346-354 | 1 hr |
| COCP | | 346-354 | 1 hr |
| *CO* | *SWIR, MWIR* | | |
| *$CH_4$* | *SWIR, TIR* | | |
| *$NH_3$* | *TIR* | | |
| *AOCH (aerosol hgt)* | *Vis-NIR* | | |

*Spatial resolution: GEO-CAPE 4 km x 4 km; TEMPO 2.1 x 4.4 km*
*[*]Fishman et al. [2012]; [**]Zoogman et al. [2016]*
*blue:also retrievable with GEO-CAPE ocean color sensor*

### 3.2 GEO-CAPE OC and Terrestrial Ecosystem Products

Ocean color remote sensing has been used to produce many useful products representing in-water constituents, with many more under development and planned for GEO-CAPE (Appendix 3) due to the advanced spectral characteristics described in §2. More importantly the high temporal resolution afforded by a geostationary orbit with its multiple views per day will allow for better constraints on rate calculations for various processes in coastal regions.

An exciting benefit of the planned specifications of the GEO-CAPE ocean color sensor at visible wavelengths (Table 1) will be remote sensing capabilities of surface reflectance of land surfaces that are used for monitoring processes in terrestrial ecosystems, e.g., surface albedo, vegetation indices, canopy chemistry and structure, snow cover, burned acreage, water indices, etc. [e.g., *Schaaf et al.,* 2002; *Román et al.,* 2009, 2013]. Surface albedo is a function of surface cover, topography and the view geometry and describes how energy is exchanged under varying atmospheric and terrestrial conditions influencing surface temperature, primary productivity, evaporation and transpiration, cloud formation, and precipitation [e.g., *Cescatti et al.,* 2012]. As such, it provides a link across various biogeochemical and physical processes crossing atmospheric, terrestrial, and aquatic domains. To compare surface albedos across time and space values need to be normalized to a specific set of illumination and viewing geometries (BRDF, are used to accomplish this). Therefore, to obtain high quality BRDF retrievals, data across a diverse set of illumination (solar) and viewing geometries are needed. For LEO sensors such as MODIS, data are typically acquired over 16 days [e.g., *Schaaf et al.,* 2002; *Ju et al.,* 2010]. A GEO sensor however, can accumulate the necessary geometries over the course of a single day [e.g., *Proud et al.,* 2014] (cloud cover permitting) enabling the acquisition of a much higher temporal resolution in albedo dramatically improving the ability to capture short-lived perturbations due to precipitation, spring leaf out, autumn senescence, fire, human activities, etc. For coastal ecosystems subject to tidal inundation under varying solar illumination conditions, high temporal resolution terrestrial retrievals would be especially valuable.

With the baseline spectral resolution extending from the visible range to 1100 nm there will also be an opportunity to retrieve fluorescence from terrestrial ecosystems as has recently been demonstrated by Joiner and colleagues [*Joiner et al.,* 2012 and 2013; *Guanter et al.,* 2015] using data with spectral resolution ≤ 0.5 nm over the 650-850 nm range where fluorescence exhibits broad peaks at 685 and 740 nm. As with ocean color retrievals, hyperspectral retrievals for terrestrial ecosystems have been shown to improve species discrimination, vegetation classification by functional types or species, nitrogen content of vegetation, and derivation of critical functional properties of wetlands across types and scales. However, 0.5 nm resolution is not necessary for these retrievals. Hence, the threshold requirement that relaxes the spectral resolution to ≤ 2 nm sampling and ≤ 5 nm resolution over the 345-1050 nm range, while preserving the $NO_2$ retrieval capability over the 400-450 nm range (Table 1) will not affect most terrestrial retrievals.

For the GEO-CAPE mission, the ocean color products (Appendix 3), atmospheric products (Table 2), and terrestrial products described in the preceding paragraphs form the basis of the direct observations that can be made for interdisciplinary science. These in conjunction with other remote sensors, in situ observations, and model representations are expected to provide wide-ranging benefit to advancing interdisciplinary scientific investigations and applications development for managers, policy makers, and the broader public.

## 4 The GEO-CAPE Mission Interdisciplinary Science Potential

The planned observations from TEMPO and the broader GEO-CAPE atmospheric composition component (Table 2) are expected to provide key atmospheric data that will enable near real time air quality forecasts, comparable to weather forecasts that the public has come to rely on in recent years. These observations are also expected to improve scientific understanding, model representations of atmospheric chemistry and physics, and to provide information needed for policy development related to improving and maintaining air quality, and preparing for climate change. Surface level ozone and aerosols directly affect air quality and human health. Oxides of nitrogen and sulfur are key precursors in the formation of ozone and aerosols, that also inform us about dominant atmospheric chemical cycles leading to products that contribute to acid rain, participate in cloud formation, and displace Cl from sea salt aerosols. Atmospheric deposition of N and S may also exacerbate $CO_2$-related ocean acidification in coastal waters [*Doney et al.,* 2007]. Formaldehyde (HCHO) is produced from most atmospheric chemical reactions involving volatile organic compounds (VOCs) and therefore provides a useful data point with which to trace VOC photochemistry from space. Glyoxal (CHOCHO) is an important oxidation product of isoprene, which makes it useful for observing regions where biogenic isoprene and photochemistry are important. Glyoxal also plays a role in secondary organic aerosol (SOA) formation, making this observation useful for relating aerosol observations to biogenic processes leading to SOA. Marine glyoxal from photooxidation of the sea surface microlayer suggests it may also be useful as a tracer for surface marine photochemical processes. Aerosol optical depth (AOD) and aerosol absorption optical depth (AAOD) are important observations related to climate and atmospheric photolysis rates. The aerosol index (AI) indicates the presence of absorbing aerosols (typically smoke and mineral dust). These key atmospheric remote observations are coupled to in situ data and models to advance our understanding of atmospheric science.

Similarly, the proposed GEO-CAPE ocean color products (Appendix 3) comprise a key subset of oceanic parameters that may be used to trace distributions and processes on basin to global scales. Remote sensing of functional/taxonomic groups of phytoplankton and plant pigments, especially in coastal waters, provides tools to characterize and distinguish regional and seasonal variability of biota in surface aquatic ecosystems, a crucial tool for monitoring change over time and in response to natural and anthropogenic perturbations. Coupled with euphotic depth and photosynthetically available radiation, it may be possible to discern how particular functional/taxonomic groups fill ecological niches. In addition, potential GEO-CAPE land products such as surface reflectance, albedo and vegetation indices will provide critical insight into biochemical and radiative processes of highly dynamic terrestrial systems at unprecedented temporal resolution.

The real power of the atmospheric and oceanic GEO-CAPE sensors lies in their ability to not just map the properties of the atmosphere, terrestrial and marine ecosystems but to observe short-term dynamics and rates of change. This promises to be exceptionally valuable in highly dynamic coastal environments where photochemical and biogeochemical transformations, along with physical forces result in strong spatial and temporal gradients.

Within the context of in situ data sets and models, remotely sensed data can be used to derive information on environmental parameters that cannot be directly retrieved. For example, ocean acidity (pH) cannot be observed directly by remote sensors. However, utilizing remotely sensed quantities such as sea-surface temperature and salinity, atmospheric $CO_2$, surface wind speeds, wave height, surface roughness, circulation, images of coral reefs, and ocean color products from a variety of space-based sensors, along with models for air-sea exchange and biogeochemical processes, algorithms can be developed to provide information on alkalinity and $pCO_2$ [*Salisbury et al.,* 2015]. Further, imagery of coral reefs and retrievals of coccolithophore blooms can reveal the effects of acidification on calcifying and silicifying organisms that are acutely sensitive to pH.

Similarly, we expect novel uses will be made of GEO-CAPE atmospheric composition and ocean color retrievals to provide key insights into coastal marine and terrestrial ecosystems and their interactions with the atmosphere in ways that connect processes across disciplines. For example, air quality and climate models rely on accurate emission data of trace gases and aerosols to simulate the chemical and physical processes that determine the status and trend of air quality and climate. Many previous studies have derived marine emissions of trace gases and/or aerosols either from interpolating limited ground measurements or from LEO satellite data sets (e.g., Fig. 7) provided by missions that have been or are scheduled to phase out (e.g., SeaWiFS in *Gantt et al.* [2009], MODIS by *Palmer and Shaw*, [2005], or VIIRS by *Tong et al.* [2014]). To date, there is no well-validated marine emission data available to support real-time air quality forecasting and long-term climate assessment. As a result, marine emissions are either missing or represented in air quality, climate or Earth System models by prescribed monthly values empirically derived from sparse observations. There is a need in the air quality, climate and Earth System modeling communities to obtain more accurate emission estimation of these trace gases and aerosols through future satellite missions. GEO-CAPE promises to advance modeling efforts by greatly improving the temporal resolution of the available data, and by offering new products anticipated to improve on specificity of trace gas and aerosol emissions as a function of the phytoplankton functional groups, CDOM and NAP concentrations, etc. These novel data sets will help us understand how our planet functions and how our activities influence and interact within the Earth's deeply interrelated physical, chemical and biological processes.

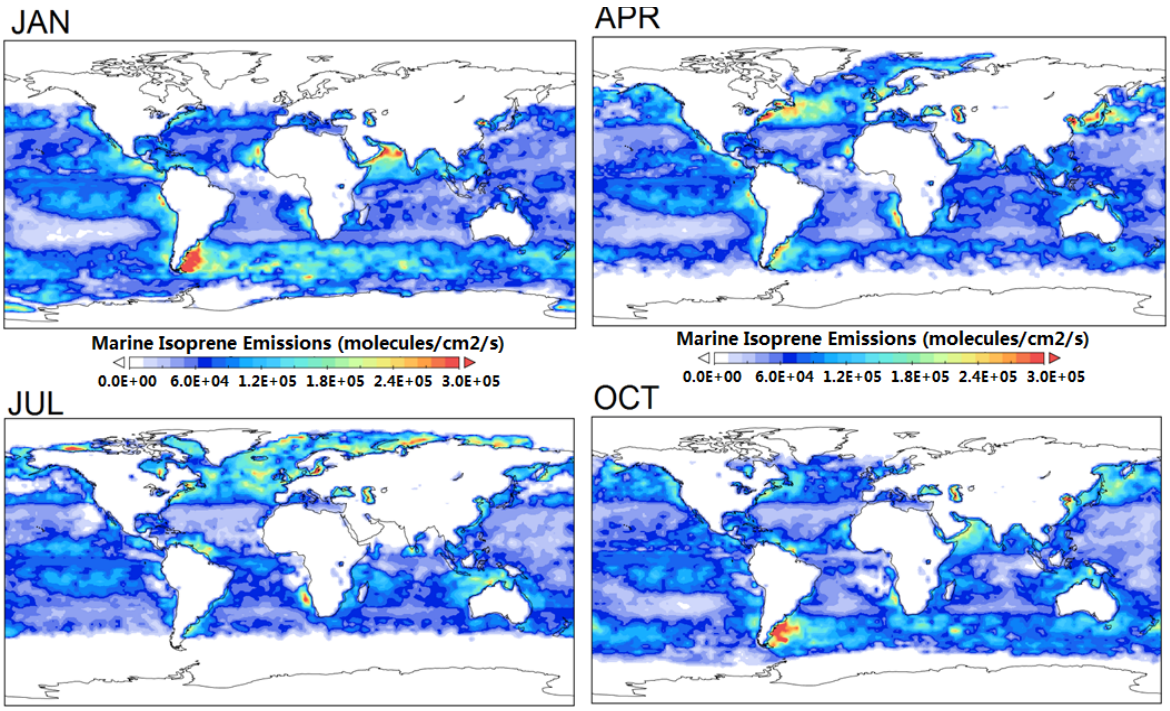

**Figure 7.** Spatial distribution of VIIRS estimated isoprene emissions over oceans in January, April, July, and October [*Tong et al.,* 2014].

## 4.1 Interdisciplinary Science from Linking Observations from Different GEO Sensors

With the separation of the atmosphere and ocean components of the GEO-CAPE mission to allow for hosted launches on communications satellites, and the selection of TEMPO for launch in 2020, it is possible that the GEO-CAPE atmosphere and ocean observations may not be coincident in time. However, if they are coincident (or at least overlapping), potential interdisciplinary science to be considered from the combination of observations include:

1) Monitoring $SO_2$ emissions, modeling their atmospheric chemical evolution, transport, participation in cloud processes including precipitation and deposition to terrestrial and marine ecosystems. Examine how natural and anthropogenic S emissions move through the environment affecting climate, clouds, precipitation chemistry and the effects of S deposition on

the receiving ecosystems. Of particular interest in coastal ecosystems is the role S deposition plays in the acidification of coastal waters.

2) HCHO and CHOCHO offer opportunities for studying marine sources of VOCs, however, the proximity of coastal ecosystems to terrestrial sources is likely to make it difficult to distinguish marine processes from the dominant terrestrial sources to the atmosphere from these two tracers alone. Although marine plants are likely to exhibit species-specific processes resulting in the release of VOCs analogously to their terrestrial counterparts, once they are released into the water column these VOCs may predominantly participate in biogeochemical cycling within the aquatic environment limiting emissions to the atmosphere. Ocean color observations that offer greater specificity of in-water organisms (e.g., plant functional types and/or pigments), along with remote observations of physical and chemical ocean processes that emit VOCs abiotically, with in situ measurements of air-sea exchange of VOCs are an essential first step in assessing the role of marine VOCs in atmospheric processes.

3) Coastal $O_3$ and $NO_2$ observations, along with surface wind and wave generation of coastal marine aerosols, offer a novel opportunity to examine the variability in coastal air quality related to land/sea breezes in high/low $NO_x$ environments and the role of halogen radical chemistry and sea-surface uptake in $O_3$ production and loss processes ultimately improving our understanding of coastal air quality. Monitoring harmful blooms will also be important for coastal air quality (as well as coastal water quality) and it would be interesting to investigate what impact the presence of such blooms have on these diurnal coastal air quality cycles.

These are only a few examples of a diverse array of interdisciplinary studies that are possible from joint GEO observations based on the current capabilities of TEMPO and the proposed capabilities for the GEO-CAPE ocean color sensor. These illustrate interactions of gases observed directly by TEMPO with coastal marine environments. However, the coupling of these trace gases to far more complex models and in situ measurements allows for the exploration of myriad aspects of the physical-biogeochemical coupling of the atmosphere to marine and terrestrial ecosystems.

Atmospheric observations planned for the GEO-CAPE mission include CO, $CH_4$, and $NH_3$. Although TEMPO will not be able to retrieve these gases, future GEO atmospheric sensors with IR bands would enable GEO-CAPE interdisciplinary studies related to:

1) Terrestrial combustion sources providing a gas-phase tracer (CO) to help discriminate absorbing black carbon (BC) aerosols from dust revealed in the aerosol index (AI) and then using meteorological information and models to examine atmospheric transport, chemical evolution, and deposition to terrestrial watersheds and marine ecosystems downwind and downstream. Ancillary data and models could offer guidance as to additional materials (i.e., trace metals, toxic substances, pollutants) likely to be co-emitted and transported with the soot. Ocean color products could then be used in conjunction with more detailed in situ measurements and models to examine aquatic ecosystem responses to these sources.

2) Maps of coastal ecosystem properties (both aquatic and terrestrial) and their diurnal cycles offer a powerful new tool to quantify coastal $CH_4$ sources to the atmosphere. In addition, clarifying OH and halogen radical chemistry in the coastal marine boundary layer could improve quantification of $CH_4$ photooxidation loss processes.

3) Atmospheric $NH_3$ observations could aid in monitoring fertilizer usage, deposition to watersheds and subsequent transport into river systems and coastal waters. Such data could be used to better differentiate coastal eutrophication due to anthropogenic activities and freshwater inputs from that arising from upwelling N sources.

## 4.2 Interdisciplinary Science from the GEO-CAPE Ocean Color Sensor

There will be many opportunities for interdisciplinary science from the GEO-CAPE ocean color sensor, alone, whether the hyperspectral or multiband designs are implemented. From an interdisciplinary point of view the main difference between these designs are the $NO_2$ retrievals that will be precluded from the multiband option. Terrestrial mapping is already available on finer spatial scales (e.g., 30 m Landsat) and for most retrieved products 5 nm spectral resolution is sufficient. What makes GEO-CAPE uniquely desirable for the terrestrial community is the high temporal resolution made possible by GEO. A key advantage of multiple revisits per day is the improvement in obtaining cloud free pixels. For the atmospheric aerosol community this reduction in cloudy pixels is further improved by the finer spatial resolution of the ocean color sensor ($\leq$ 375 m x 375 m at nadir versus TEMPO 4.4 km x 2.1 km resolution). Inland coverage expands interdisciplinary science opportunities with both the terrestrial and aerosol science communities. Sampling 100 km inland from the coast provides coverage of most U.S. megacities (population > 1 million), while 200 km inland will cover nearly half of the 100 largest cities in the U.S. These inland margins are comprised of approximately 30% forested lands, 20% herbaceous and woody wetlands, 17% agricultural land, and 10% developed land offering a wide variety of terrestrial ecosystems along the coasts and Great Lakes.

Among the interdisciplinary science questions involving ocean color, aerosols, and terrestrial ecosystems are:

1) What are the interactions among urban emissions, coastal meso-scale circulations, photochemical processing, upwelling, and fog formation on air quality and deposition along coastal margins?

2) What is the vertical distribution of aerosols over both water and land? Aerosol height measurements made by the IR channels on the ocean color sensor will allow for relating TEMPO aerosol optical depth measurements to ground-level aerosol loadings relevant to air quality.

3) What is the amount of aerosol imported into and exported from the North American continent? How does deposition from these distant- and local-source continental aerosols affect coastal marine ecosystems (e.g., nutrients from dust, volcanic ash, and anthropogenic aerosols, versus aerosol-borne pollutants)?

4) What is the influence of marine organisms on the composition and size distribution of aerosols? What role do marine aerosols (including bioaerosols) play in the vertical structure of the marine boundary layer, in cloud formation and properties, in long range transport, and deposition to terrestrial ecosystems?

5) What is the variability of optical properties of marine aerosols, does CDOM in surface waters provide a primary source of brown carbon (BrC, absorbing aerosols in the UV and near visible), if so is marine BrC chemically distinct from combustion-derived BrC and do these two classes evolve differently in the atmosphere? Do VOC emissions from marine organisms or photochemical processes provide sources for subsequent SOA formation, including secondary BrC?

6) Can same day assessments of water and nutrient stress in coastal agricultural systems improve management of irrigation and fertilizer usage such that downstream coastal water quality is improved?

7) Can revisits throughout the day increase the number of successful retrievals of tropical mangrove ecosystems resulting in better constrained carbon budgets for these important tropical ecosystems that sequester carbon and make important contributions to land-to-sea carbon flux?

8) Can we improve retrievals of tidally inundated ecosystems where the total reflectance signal is a non-linear combination of water depth and vegetation reflectances [*Turpie,* 2012] to better capture how inundation dynamics affect carbon fluxes and gross primary production in coastal ecosystems? Can we improve assessments of wetland productivity and terrestrial/atmosphere carbon exchanges in these systems where carbon flux dynamics are particularly complex due to tides, $CH_4$ generation in anaerobic soils and lateral material flux?

As with the previous examples, addressing these questions will rely on remotely-sensed aerosol, terrestrial, and ocean color products combined with in situ information, measurements from other satellites, and models of physical-biogeochemical processes coupled across the oceanic and atmospheric domains at molecular, organism, regional, and global scales.

## 5 Concluding Remarks

Novel approaches are being developed to combine data sets in order to improve temporal, spatial, and spectral resolutions in final products. For example, 16 day Landsat 30 m imagery has been applied to daily MODIS 500 m surface reflectance in order to extrapolate the daily MODIS data to a 30 m scale and monitor land surface dynamic changes at finer scales [*Gao,* 1996; *Zhu et al.,* 2010]. The GEO-CAPE/TEMPO aerosol group is working to combine TEMPO, GOES-R, and possibly polar orbiters such as VIIRS to enhance retrievals. In particular, *Wang et al.* [2014] showed multi-platform observations enhance both spectral coverage, as well as viewing geometries. Retrievals that combine the hyper-spectral and high temporal resolution observations from the GEO-CAPE ocean color sensor with high spatial resolution ocean color measurements from a LEO orbit (e.g., similar to Landsat OLI and Sentinel satellites) would allow for unique applications in coastal waters, similar to the combined Landsat/MODIS daily product. These promising approaches suggest that whatever choices are made for the GEO-CAPE ocean color sensor design, improvements via multi-sensor retrieval algorithms and modeling approaches may improve on the nominal resolutions.

In their decadal science plan, *SOLAS* [2015] highlighted an observation from the *IPCC* [2013] that some of the largest uncertainties in forecasting the future of the global biosphere arises from inadequate understanding of the coupling of physical and biogeochemical processes between the ocean and atmosphere. Climate change introduces new forcings into an already insufficiently understood system leading to even greater complexity and posing additional challenges to fully characterizing this system and predicting future states. It will take an international interdisciplinary effort to resolve outstanding questions in Earth sciences that interconnect across aquatic, terrestrial, and atmospheric boundaries in ways that link physical, chemical, biological, and social sciences. This effort will require the development of new tools, a common language, and integration across spatial, temporal, and human scales.

Satellite remote sensing, both from LEO and GEO orbits, has a critical role to play to facilitate observing global ecosystems and helping to better understand their functioning, predict their future, and quantify observed changes. Remotely sensed surface sea-water observations from space need to be related to deep-water observations made possible by the Argo network and other autonomous sensors that can make observations below the euphotic zone [*NRC*, 2015]. New technologies for in situ and sub-orbital remote sensor measurements are expected to offer greater detail at a faster response that will provide the level of detail models need to examine biogeochemical coupling at the level of individual species and regional scales (from microbial composition to tracking migratory patterns of large mammals). For example, new techniques for in situ sampling and identification of bioaerosols may offer new tracers to the atmospheric community to distinguish marine sources from terrestrial sources of materials that enter and interact within the atmosphere. New interdisciplinary measurement techniques and collaborations, including international partnerships, will advance the state of the science relevant to atmospheric processes, ocean and terrestrial ecosystems. As we work in parallel to develop new remote-sensing tools, algorithms, and products with which we can observe and probe Earth's complex physical-biogeochemical systems, we can expect the field to advance and new questions to arise. GEO observations of our coastal environments promise to lead to exciting new scientific advances and applications as useful in our daily lives as the weather report.

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## Appendix 1 - Acronyms

| | |
|---|---|
| AC | Atmospheric Composition, here, tropospheric |
| AAOD | Aerosol Absorption Optical Depth |
| AI | Aerosol Index |
| AOD | Aerosol Optical Depth |
| BC | Black Carbon |
| BrC | Brown Carbon |
| BRDF | Bidirectional Reflectance Distribution Functions |
| CDOM | Colored Dissolved Organic Matter |
| CDR | Climate Data Record |
| $\mathrm{Chl}_a$ | Chlorophyll *a* |
| DISCOVER-AQ | Deriving Information on Surface Conditions from COlumn and VERtically Resolved Observations Relevant to Air Quality |
| DS | Decadal Survey |
| DU | Dobson Units |
| FWHM | Full-Width Half-Maximum |
| GEMS | Geostationary Environmental Monitoring Spectrometer |
| GEO | Geostationary orbit |
| GEO-CAPE | Geostationary Coastal and Air Pollution Events, recommended satellite mission |
| GOCI | Geostationary Ocean Color Imager, GOCI-II is the 2nd of this series of satellites |
| IGBP | International Geosphere Biosphere Program |
| IHDP | International Human Dimensions Programme |
| IOCCG | International Ocean Color Coordinating Group |
| IPCC | Intergovernmental Panel on Climate Change |
| LEO | Low Earth Orbit |
| LOICZ | Land-Ocean Interactions in the Coastal Zone |
| MAIAC | Multi-Angle Implementation of Atmospheric Correction |
| MI-II | Meteorology Imager - II |
| MODIS | Moderate-resolution Imaging Spectroradiometer |
| NAP | Non-Algal Particles |
| NIR | Near Infrared |
| NRC | National Research Council |
| NSF | National Science Foundation |
| OCAPI | Ocean Color Advanced Permanent Imager |
| $R_{RS}$ | Remote Sensing Reflectance |
| SeaWIFS | Sea-viewing Wide Field-of-view Sensor |
| SOA | Secondary Organic Aerosols |
| SOLAS | Surface Ocean - Lower Atmosphere Study |
| STM | Science Traceability Matrix |
| SWGs | Science Working Groups |
| SWIR | Shortwave Infrared |
| SZA | Solar Zenith Angle |
| TEMPO | Tropospheric Emissions: Monitoring of Pollution |
| TOA | Top of the Atmosphere |
| UV | Ultraviolet |
| VIIRS | Visible Infrared Imaging Radiometer Suite |

# Appendix 2 - GEO-CAPE Ocean Color Science Traceability Matrix (STM)

## GEO-CAPE Oceans STM

Draft v.4.7 - 30 July, 2015

| Science Focus | Science Questions | Approach | Maps to Science Question | Measurement Requirements | Instrument Requirements | Platform Requirem. | Ancillary Data Requirem |
|---|---|---|---|---|---|---|---|
| **Short-Term Processes** | **1 How do short-term coastal and open ocean processes interact with and influence larger scale physical, biogeochemical and ecosystem dynamics?** (OBB 1) | GEO-CAPE will observe coastal regions at sufficient temporal and spatial scales to resolve near-shore processes, tides, coastal fronts, and eddies, and track carbon pools and pollutants. Two complementary operational modes will be employed:<br>(1) survey mode for evaluation of diurnal to interannual variability of constituents, rate measurements and hazards for estuarine and continental shelf and slope regions with linkages to | 1<br>2<br>3 4 | Water-leaving radiances in the near-UV, visible & NIR for separating absorbing & scattering constituents & chlorophyll fluorescence<br>Product uncertainty TBD<br>**Temporal Resolution:**<br>*Targeted Events:*<br>• Threshold: ≤1 hour<br>• Baseline: ≤0.5 hour<br>*Survey Coastal U.S.:*<br>• Threshold: ≤2 hours<br>• Baseline: ≤1 hour<br>*Regions of Special Interest (RSI): Threshold: ≥1 RSI 3 scans/day*<br>• Baseline: multiple RSI 3 scans/day<br>*Other coastal and large inland bodies of water within ocean color FOR:*<br>• Baseline: ≤3 hours<br>**Spatial Resol. (nadir):**<br>• Threshold: ≤375 x 375 m<br>• Baseline: ≤250 x 250 m<br>**Field of Regard for Ocean Color Retrievals:**<br>60°N to 60°S;<br>155°W to 35°W<br>**Coastal Coverage*:**<br>width from coast to ocean:<br>• Threshold: min 375 km<br>• Baseline: min 500 km<br>**Scanning Priority:**<br>•Threshold:<br>1. Survey of U.S. Coastal Waters<br>2. Other coastal and large inland bodies of water<br>3. Open ocean waters within FOR | **Spectral Range:**<br>Hyperspectral UV-VIS-NIR<br>• Threshold: 345-1050 nm; 2 SWIR bands 1245 & 1640 nm<br>• Baseline: 340-1100 nm; 3 SWIR bands 1245, 1640, 2135 nm<br>**•Spectral Sampling & Resolution:**<br>• Threshold: UV-Vis-NIR: ≤2 & ≤5nm; 400-450nm: ≤0.4 & ≤0.8nm (for $NO_2$ at spatial resolution of 750x750m at nadir); SWIR resolution: ≤20-40 nm<br>• Baseline: UV-ViS-NIR: ≤0.25 & 0.75 nm; SWIR: ≤20-50 nm<br>**Signal-to-Noise Ratio (SNR) at Ltyp(70˚ SZA):**<br>• Threshold: ≥1000 for 10 nm FWHM (350-800 nm); ≥600 for 40 nm FWHM (800-900 nm); ≥300 for 40 nm FWHM (900-1050 nm); ≥250 and ≥180 for 1245 & 1640 nm (20 & 40 nm FWHM); ≥500 $NO_2$ band.<br>• Baseline: ≥1500 for 10 nm (350-800 nm); NIR, SWIR and $NO_2$ bands same as threshold; ≥100 for the 2135nm (50nm FWHM)<br>• Threshold: Aggregate SWIR bands to 2x2 GSD pixels to meet SNR; Baseline: No aggregation.<br>**Scanning area per unit time:** Threshold: ≥25,000 $km^2$/min; Baseline: ≥50,000 $km^2$/min<br>**Field of Regard:**<br>• Full disk: 20.8° E-W and 19° N-S imaging capability from nadir for Lunar & Solar Calibrations<br>**Non-saturating detector array(s) at Lmax**<br>**On-board Calibration:**<br>• Lunar: Threshold: minimum monthly; Baseline: same as threshold<br>• Solar: Threshold: none; Baseline: daily<br>**Polarization Sensitivity:** <1.0%<br>**Relative Radiometric Precision:**<br>• Threshold: ≤1% through mission lifetime<br>• Baseline: ≤0.5% through mission lifetime<br>**Mission lifetime:** Threshold: 3 years; Goal: 5 years | Geostationary orbit Threshold: 94°±2° W longitude; Baseline: 94°±1° W to permit sub-hourly observations of coastal waters adjacent to the continental U.S., North, Central and South America Storage (up to 1 day) and download of full spatial data and spectral data. | Western hemisphere data sets from models, missions, or field observations<br>**Measurement Requirements**<br>(1) Ozone<br>(2) Total water vapor<br>(3) Surface wind velocity<br>(4) Surface barometric pressure<br>(5) Vicarious calibration & validation - coastal<br>(6) Full prelaunch characterization<br>(7) Cloud cover<br>**Science Requirements**<br>(1) SST<br>(2) SSH<br>(3) PAR<br>(4) UV solar irradiance<br>(5) MLD°<br>(6) Air/Sea pCO2<br>(7) pH<br>(8) Ocean circulation<br>(9) Tidal & other coastal currents<br>(10) Aerosol deposition<br>(11) run-off loading in coastal zone<br>(12) Wet deposition in coastal zone<br>(13) Wave height & surface wind speed<br>**Validation Requirements**<br>Conduct high frequency field measurements and modeling to validate GEO-CAPE retrievals from river mouths to beyond the edge of the continental margin. |
| **Land-Ocean Exchange** | **2 How are variations in exchanges across the land-ocean interface related to changes within the watershed, and how do such exchanges influence coastal and open ocean biogeochemistry and ecosystem dynamics?** (OBB 1 & 2; CCSP 1 & 3) | open-ocean processes at appropriate spatial scales, and (2) targeted, high-frequency sampling for observing episodic events including evaluating the effects of diurnal variability on upper ocean constituents, assessing the rates of biological processes and coastal hazards.<br>*Measurement objectives for both modes include:*<br>(a) Quantify dissolved and particulate carbon pools and related rate measurements such as export production, air-sea CO2 exchange, net community production, respiration, and photochemical oxidation of dissolved organic matter. | 1 2<br>4 5<br>1 2 3 | | | | |
| **Impacts of Climate Change & Human Activity** | **3 How are the productivity and biodiversity of coastal ecosystems changing, and how do these changes relate to natural and anthropogenic forcing, including local to regional impacts of climate variability?** (OBB 1, 2 & 3; CCSP 1 & 3) | (b) Quantify phytoplankton properties: biomass, pigments, functional groups (size/taxonomy/Harmful Algal Blooms (HABs)), daily primary productivity using bio-optical models, vertical migration, and chlorophyll fluorescence.<br>(c) Measure the inherent optical properties of coastal ecosystems: absorption and scattering of particles, phytoplankton and detritus, CDOM absorption.<br>(d) Estimate upper ocean particle characteristics including particle abundance and particle size distribution. | 1 2 3 4 5<br>1 2 3 4 5<br>1 2 3 | | | | |
| **Impacts of Airborne-Derived Fluxes** | **4 How do airborne-derived fluxes from precipitation, fog and episodic events such as fires, dust storms & volcanoes affect the ecology and biogeochemistry of coastal and open ocean ecosystems?** (OBB 1 & 2; CCSP 1) | (e) Detect, quantify and track hazards including HABs and petroleum-derived hydrocarbons.<br>GEO-CAPE observations will be integrated with field measurements, models and other satellite data:<br>(1) to derive coastal carbon budgets and determine whether coastal ecosystems are sources or sinks of carbon to the atmosphere,<br>(2) to quantify the responses of coastal ecosystems and biogeochemical cycles to river discharge, land use change, airborne-derived fluxes, hazards and climate change, and | 5<br>2 3<br>1 2 3 4 5 | | | | |
| **Episodic Events & Hazards** | **5 How do episodic hazards, contaminant loadings, and alterations of habitats impact the biology and ecology of the coastal zone?** (OBB 4) | (3) to enhance management decisions with improved information on the coastal ocean, such as required for Integrated Ecosystem Assessment (IEA), protection of water quality, and mitigation of harmful algal blooms, oxygen minimum zones, and ocean acidification. | 3 5 | **Intelligent Payload Module** Baseline only: Near Real-Time satellite data download from other sensors (GOES, etc.) for on-board autonomous decision making.<br>**Pre-launch characterization:** Adequate to achieve the required on-orbit radiometric precision | | | |

| **Error** (as % of nadir pixel) | **Threshol** | **Baselin** |
|---|---|---|
| **Pointing Knowledge** | **<50%** | **<10%** |
| **Pointing Accuracy LOS** | **<100%** | **<25%** |
| **Pointing Stability LOS** | **<25%** | **<10%** |
| **Geolocation Reconstr.** | **<50%** | **<10%** |

GEO-CAPE Science Questions are traceable to NASA's OBB Advanced Planning Document (OBB) and the U.S. Carbon Cycle Science Plan (CCSP).

* Coastal coverage within field-of-view (FOV) includes major estuaries and rivers such as Chesapeake Bay, Lake Pontchartrain/Mississippi River delta and the Laurentian Great Lakes, e.g., the Chesapeake Bay coverage region would span west to east from Washington D.C. to several hundred kilometers offshore (total width of 375 km threshold).

## Appendix 3 - Mission critical & Highly desirable GEO-CAPE ocean color data products.

Mission critical products drive measurement and instrument requirements. Highly desirable products address mission science questions but are not critical because the retrieval algorithm and/or field/laboratory measurement are not mature. The maturity level shown (from *Fishman et al.* [2012]).

| Ocean products | Product maturity[a] |
|---|---|
| **Mission critical** | |
| Spectral remote sensing reflectances[b] | CDR[c] |
| Chlorophyll-a | CDR |
| Diffuse attenuation coefficient (490 nm) | CDR |
| Inherent optical properties and products:<br>colored dissolved organic matter (CDOM) absorption;<br>particle absorption and scattering;<br>phytoplankton and detritus absorption and scattering | CDR candidates |
| Euphotic depth | CDR candidate |
| Photosynthetically available radiation (PAR) | CDR candidate |
| Fluorescence line height (FLH) | CDR candidate |
| Primary production | CDR candidate |
| Suspended particulate matter (SPM) | CDR candidate |
| Particulate inorganic carbon (PIC) | CDR candidate |
| Particulate organic carbon (POC) | CDR candidate |
| Dissolved organic carbon (DOC; coastal) | Research |
| Phytoplankton carbon | Research |
| HAB detection and magnitude | Research |
| Functional/taxonomic group distributions | Research |
| **Highly desirable** | |
| Particle size distributions and composition | Research |
| Phytoplankton physiological properties (fluorescence quantum yields, etc.) | Research |
| Trichodesmium concentration | Research |
| Other plant pigments (carotenoids, photoprotective pigments, photosynthetic pigments, phycobilins, etc.) | Research |
| Beam-c | Research |
| Net community production of POC | Exploratory |
| Net community production of DOC | Exploratory |
| Export production | Exploratory |
| Petroleum detection, type, and thickness | Exploratory |
| Terrigenous DOC | Exploratory |
| Photooxidation | Exploratory |
| Detection of vertically migrating species | Exploratory |
| $pCO_2$ (seawater) | Exploratory |
| Air–Sea $CO_2$ fluxes | Exploratory |
| Respiration | Exploratory |

[a] CDR algorithms are the most mature followed by CDR candidate, research, and exploratory algorithms. Research products are those with validated algorithms discussed in the scientific literature. Exploratory products represent products for which algorithms are under development or have not been studied thus far.

[b] All other ocean products listed are derived from the remote sensing reflectances.

[c] "The NASA Earth Science Division has focused on data sets creation for particular Earth science research measurement needs, and has defined a term for data sets to be used these needs: Earth System Data Records (ESDRs), including Climate Data Records (CDRs). An ESDR is defined as a unified and coherent set of observations of a given parameter of Earth system, which is optimized to meet specific requirements in addressing science questions. These data records are critical to understanding Earth System processes, are critical to assessing variability, long-term trends and change in Earth System, and provide input and validation means to modeling efforts" (see http://science.nasa.gov/earth-science/earth-science-data/Earth-Science-Data-Records-Programs/).

## Appendix 4 - Threshold band set under discussion by GEO-CAPE ocean color SWG.

| | nm | nm | nm | nm | |
|---|---|---|---|---|---|
| | SNR Bin | Filter | SNR Bin | Resolution | |
| **Band Number** | **Nominal Band Center[1]** | **Nominal Band Center[1]** | **Bandwidth FWHM** | **Bandwidth FWHM** | **Application/Comments[1]** |
| **1** | **350** | **350** | 15 | 15 | Absorbing aerosol detecton |
| **2** | **360** | **360** | 10 | 10 | CDOM-chlorophyll separation; strong NO2 absorption |
| **3** | **380** | **377.5** | 10 | 5 | CDOM-chlorophyll separation; strong NO2 absorption; avoid precipitous drop in solar spectrum at 400 nm |
| **4** | | **382.5** | | 5 | |
| **5** | **400** | **397.5** | 10 | 5 | (Min. solar irradiance at 394nm; peak at 402nm) |
| **6** | | **402.5** | | 5 | |
| **7** | **412** | **409.5** | 10 | 5 | CDOM-chlorophyll separation; SeaWiFS (20 nm) & MODIS (15 nm) bands; strong NO2 absorption |
| **8** | | **414.5** | | 5 | |
| **9** | **425** | **422.5** | 10 | 5 | CDOM-chlorophyll separation, strong NO2 absorption |
| **10** | | **427.5** | | 5 | |
| **11** | **443** | **440.5** | 10 | 5 | Chlorophyll-a absorption peak; SeaWiFS (20 nm) & MODIS (10 nm) bands; strong NO2 absorption |
| **12** | | **445.5** | | 5 | |
| **13** | **460** | **457.5** | 10 | 5 | Assessory pigments & chlorophyll |
| **14** | | **462.5** | | 5 | |
| **15** | **475** | **472.5** | 10 | 5 | Assessory pigments & chlorophyll |
| **16** | | **477.5** | | 5 | |
| **17** | **490** | **487.5** | 10 | 5 | SeaWiFS (20 nm) & MODIS (10 nm) bands; chlorophyll band-ratio algorithm |
| **18** | | **492.5** | | 5 | |
| **19** | **510** | **507.5** | 10 | 5 | SeaWiFS (20 nm) band; chlorophyll-a band-ratio algorithm; strong O3 absorption |
| **20** | | **512.5** | | 5 | |
| **21** | **532** | **529.5** | 10 | 5 | Aerosol lidar transmission band; MODIS (10 nm) band; strong O3 absorption |
| **22** | | **534.5** | | 5 | |
| **23** | **555** | **552.5** | 10 | 5 | Bio-optical algorithms (e.g., band-ratio chlorophyll); MODIS-548 nm, SeaWiFS-555 nm; strong O3 absorption |
| **24** | | **557.5** | | 5 | |
| **25** | **583** | **580.5** | 10 | 5 | Phycoerythrin, strong O3 absorption |
| **26** | | **585.5** | | 5 | |
| **27** | **617** | **614.5** | 10 | 5 | Strong O3 absorption; bounded at 628 nm by water vapor absorption band |
| **28** | | **619.5** | | 5 | |
| **29** | **625** | **622.5** | 10 | 5 | |
| **30** | | **627.5** | | 5 | |
| **31** | **640** | **637.5** | 10 | 5 | Between O3 & water vapor absorption peaks |
| **32** | | **642.5** | | 5 | |
| **33** | **655** | **652.5** | 10 | 5 | Chlorophyll a&b, strong O3 absorption, weak water vapor absorption |
| **34** | | **657.5** | | 5 | |
| **35** | **665** | **662.5** | 10 | 5 | Fluorescence line height baseline, bandwidth constrained by water vapor absorption line & 678 band |
| **36** | | **667.5** | | 5 | |
| **37** | **678** | **675.5** | 10 | 5 | Fluorescence line height; band center offset from fluorescence peak by O2 absorption line |
| **38** | | **680.5** | | 5 | |
| **39** | **710** | **707.5** | 10 | 5 | Fluorescence line height baseline; HABS detection; terrestrial "red edge"; straddles water vapor absorption band |
| **40** | | **712.5** | | 5 | |
| **41** | **748** | **748** | 10 | 10 | Atmospheric correction-open ocean; MODIS band, between O2 A-band & water vapor absorption peaks |
| **42** | **752** | **752** | 5 | 5 | *Vertical aerosol layer height baseline (from O2 A-band)* |
| **43** | **760.5** | **760.5** | 3 | 3 | *Vertical aerosol layer height (from O2 A-band)* |
| **44** | **763.5** | **763.5** | 3 | 3 | *Vertical aerosol layer height (from O2 A-band)* |
| **45** | **765** | **765** | 40 | 40 | Atmospheric correction-open ocean; SeaWiFS band, O2 A-band absorption |
| **46** | **820** | **820** | 15 | 15 | Water vapor concentration/corrections. There are other water vapor absorption features that could be used. |
| **47** | **865** | **865** | 40 | 40 | Atmospheric correction-open ocean; SeaWiFS band (40 nm bandwidth); MODIS band-869 (15 nm bandwidth) |
| **48** | **1020** | **1020** | 40 | 40 | Atmospheric correction-turbid water |
| **49** | **1245** | **1245** | 20 | 20 | Atmospheric correction-turbid water; MODIS band; bandwidth constrained by water vapor & O2 absorption peaks |
| **50** | **1640** | **1640** | 40 | 40 | Atmospheric correction-turbid water; MODIS-1640 nm, moved to 1610 tobroaden bandpass & improve SNR |