GEO-CAPE

Geostationary Coastal and Air Pollution Events

Advancing the science of both coastal ocean biophysics and atmospheric pollution chemistry: A final report to the NASA Earth Science Division by the GEO-CAPE Team.

September 2018

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1. EXECUTIVE SUMMARY AND RECOMMENDATIONS

The 2007 Decadal Survey (DS) included the recommendation for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission to launch in 2013–2016 to advance the science of both coastal ocean biophysics and atmospheric-pollution chemistry. In 2009 the NASA Earth Science Division (ESD) initiated study activities for GEO-CAPE and 8 other near- to medium-term missions to help determine the readiness of these conceptual missions to begin the formulation phase. In FY15 the GEO-CAPE mission study team completed a white paper summarizing the results of the pre-formulation work accomplished to date: https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf The team was directed to complete a final report in FY18. This document, prepared as an addendum to the FY15 white paper, serves as the GEO-CAPE final report and focuses only on FY16-18 activities and on summarizing the final state.

GEO-CAPE fully matured during the 2010–2018 pre-formulation study activities. Early studies confirmed that the mission as recommended in the 2007 DS was at a high level of technology readiness, with launch feasible by 2015, but also found that the 2007 DS cost estimate of $550 million for a dedicated geostationary mission was low by a factor of 2 to 3. Therefore, the study team developed a novel mission implementation strategy featuring commercial hosting of GEO-CAPE instruments on one or more geostationary satellites. This strategy was estimated to reduce mission risk and potentially total mission cost, but most importantly to provide programmatic flexibility by allowing smaller components of the mission to be individually initiated as NASA funding profiles allowed. The team completed all other pre-formulation objectives (including developing science traceability matrices to express measurement requirements, conducting field campaigns and other science studies to affirm and refine these requirements, and maturing enhancing technologies) and advanced mission readiness via multiple synergistic activities with ESD research, applications, technology, and flight programs. In parallel, team members also started pursuing Earth Venture (EV) opportunities as the only means of initiating GEO-CAPE satellite observations in a constrained budgetary environment.

The selection of the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission through the EV Instrument (EVI) 1 solicitation is viewed as a step toward the GEO-CAPE distributed implementation strategy. TEMPO is likely to meet many of the GEO-CAPE atmospheric science objectives and is a pathfinder for the hosted payload mission strategy. The principal remaining atmospheric measurement objectives can be met by an instrument of comparable cost to TEMPO that makes measurements in infrared wavelengths, as defined in the GEO-CAPE atmospheric science traceability matrix, and use of data from the Advanced Baseline Imagers on the GOES-R/S series satellites. The GeoCARB mission selected December 2016 via the EV Mission 2 solicitation has potential to partially meet remaining GEO-CAPE atmospheric science requirements associated with infrared measurements, pending its final configuration and observing strategy, and also demonstrates an alternative partnering strategy for a commercial hosted payload mission. The coastal waters science objectives can be met by a variety of instrument concepts within an instrument cost range of $100–200 million. This statement is supported by the evaluations of the GLIMR proposal submitted to the EVI-4 solicitation. Full mission cost estimates for a hosted payload implementation strategy ultimately depend on the commercial market for hosting this class of instruments. At this time, it appears there are fewer geostationary launch opportunities in the 2020-2023 period for new satellites viewing the Americas than originally forecast, due to a combination of factors. It is unclear whether this is a secular business change or a shorter-term market fluctuation, but the TEMPO and GeoCARB experiences to date indicate that a hosted payload implementation strategy remains viable.

The 2017 DS contains clear statements of the ongoing importance of GEO-CAPE objectives and recommends accomplishing them via a range of existing and new missions. The importance of GEO-CAPE's atmospheric science goals is highlighted in 2017 DS "Weather and Air Quality" and "Climate Variability and Change" priorities. Air quality is a "Most Important" Science and Applications Priority (Table 3.3, Question W-5) and part of two other "Most Important" priorities (Questions W-1, W-2). Methane measurements similar to those of GEO-CAPE are part of the "Most Important" priorities for greenhouse gas measurements (Questions C-2d, E-3a, and E-4a). Disposition of Targeted Observables aligned with these priorities is via the Program of Record (including TEMPO, GeoCARB, MAIA, and partner space agency missions), the Designated Mission for aerosols, and Explorer missions for greenhouse gases and ozone/trace gases. Coastal ocean color is associated with three "Most Important" Priorities (Questions E-1b, E-1c, E-3a) reflected in the Aquatic Biogeochemistry Targeted Observable (TO). Though not presently allocated to a Flight Program Element, the Aquatic Biogeochemistry TO is well positioned for Earth Venture opportunities given favorable reviews of the EVI-4 submission.

Given the progress of GEO-CAPE and related projects, and the recommendations of the 2017 DS, the opportunity exists to fulfill all GEO-CAPE objectives in a cost-effective manner by completing NASA missions in the Program of Record (TEMPO, GeoCARB), investing in fused data products using observations from these missions and those of NOAA and international space agencies, and capturing future Earth Venture and Explorer opportunities. It has become evident that the value of GEO-CAPE observations will be amplified by being embedded within an integrated observing strategy featuring similar geostationary observations from missions over other parts of the globe combined with low Earth orbit observations to provide full global context. GEO-CAPE study team members remain key participants in international activities to implement this potential under the auspices of the Committee on Earth Observation Satellites (CEOS), and as members of mission science teams in Europe and Korea. Data harmonization activities featuring common validation strategies will be essential for providing truly interoperable data products from these satellite constellations. GEO-CAPE study activities have helped define and begin to build the modeling capabilities necessary for realizing these visions.

Specific recommendations follow.

1. Fulfill the Program of Record for the atmospheric composition missions in development (TEMPO, GeoCARB, MAIA) and maintain close coordination among them and partner missions in operation (GOES ABI, Sentinel-5 Precursor TROPOMI, S-NPP, JPSS, EPS) to meet the science and applications priorities expressed in the 2017 DS. In particular, ensure that measurements of CO and CH_4 consistent with GEO-CAPE science traceability matrix requirements are available from GeoCARB or other means.
2. Prepare to fully exploit these data for improved monitoring of air quality over North America by sustaining ongoing activities to improve retrieval algorithms, chemical data assimilation capabilities, inverse modeling capabilities for constraining emissions estimates, and integrated observing system frameworks (such as observation system simulation experiments). In particular, synergistic aerosol retrievals using geostationary observations from TEMPO, ABI, and potentially GeoCARB should be invested in.
3. Continue to support scientific investigations that exploit data from the Korean GOCI and GOCI-II sensors and collaborations with KIOST to advance NASA capabilities for accomplishing 2017 DS science and applications priorities (E-1a, E-1c, E-2a, E-3a, and C-2d) and Targeted Observable 3, Aquatic Biogeochemistry.
4. Remain receptive to opportunities to begin formulation of a coastal ecosystems mission to conduct GEO-CAPE coastal waters science, potentially through a targeted EV opportunity.
5. Continue collaborations with partners such as the U.S. EPA and regional air quality organizations to further implement and maintain long-term ground sites combining continuous *in-situ* and remote-sensing (Pandora, lidar) measurements many times per hour. Data from such sites are critical for validation of the geostationary measurements, science and applications data utilization, and stakeholder uptake of the satellite data.
6. Continue to mature mechanisms for engaging end-users to aid early adoption of TEMPO and other GEO-CAPE related observations, including participation in collaborative regional field campaigns.
7. Create formal Constellation Science Teams for Air Quality and Ocean Color, supported by stable funding for U.S. members, to collaborate with national and international partners in order to mature harmonized, consistent, well-validated interoperable data products from the constellations of geostationary and low-Earth orbit satellites now coming into existence.
8. Given that highly time-resolved observations are the next frontier of Earth science from space, build on the lessons learned from the communal GEO-CAPE study activities by continuing to work with all stakeholders to jointly identify priorities and develop advocacy for sustainable future highly time-resolved observations.

2. INTRODUCTION TO GEO-CAPE

The Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission was recommended by the 2007 National Research Council's (NRC's) Earth Science Decadal Survey (DS) to measure tropospheric trace gases and aerosols, coastal ocean phytoplankton, water quality and biogeochemistry from geostationary orbit, providing continuous observations within the field of view. In 2009 the NASA Earth Science Division (ESD) initiated study activities for GEO-CAPE and 8 other near- to medium-term missions to help determine the readiness of these conceptual missions to begin the formulation phase. In FY15 guidance was received from the ESD Associate Director for Flight Programs "to complete a white paper summarizing the results of the six years of pre-formulation work accomplished by the mission study team." The comprehensive 2015 report is available at:
https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

For FY18 the team was directed to complete a final report. This document is the GEO-CAPE final report, presented as an addendum to the FY15 white paper and focusing only on FY16-18 activity and summarizing the final state. The document layout is consistent with the 2015 report for ease in reading. Sections therefore address the specific topics originally requested, including science objectives and requirements, technology assessment, mission concepts, field campaigns, measurement algorithms, and coordination with other ESD elements. The public website communicating team accomplishments will be maintained for the foreseeable future:
http://geo-cape.larc.nasa.gov

The Science Working Groups (SWGs) developed realistic science objectives using input drawn from several community workshops (Table 2-1) and have performed extensive studies to refine requirements and reduce uncertainties, as described in Section 3. Section 3 is substantially updated from the 2015 report.

Table 2-1. Dates and Locations of GEO-CAPE Workshops.

Date	Type of Event	Location
August 2008	Open Community Workshop	University of North Carolina, Chapel Hill, NC
September 2009	Open Community Workshop	Columbia, MD
March 2010	Closed Team Meeting	University of South Florida, St. Petersburg, FL
May 2011	Open Community Workshop	National Center for Atmospheric Research, Boulder, CO
May 2013	Closed Team Meeting	NASA Ames Research Center, Moffett Field, CA
August 2015	Open Community Workshop	U.S. EPA, Research Triangle Park, NC
May 2018	Atmospheric Science Open Workshop	NOAA NCWCP, College Park, MD
August 2018	Ocean Science Open Workshop	NASA Goddard Space Flight Center, Greenbelt, MD

Section 4 discusses mission and instrument implementation considerations. This section is slightly updated with new developments since the 2015 report.

Section 5 describes Technology Assessment and Development efforts. This section is slightly updated with new developments since the 2015 report.

Section 6 summarizes GEO-CAPE mission development achieved through several field measurement campaigns. This section is substantially updated from the 2015 report.

Section 7 presents efforts that have advanced algorithms for retrieval and analysis of both ocean color and atmospheric data. This section is updated with new developments since the 2015 report.

Section 8 summarizes how GEO-CAPE development activities have been very well aligned and integrated with funded activities from other NASA ESD program areas. This section is updated with new developments since the 2015 report.

Brief closing thoughts and lessons learned are offered in Section 9.

References cited in this document are provided in Section 10 and acronyms are defined in Section 11.

Section 12 provides a complete listing of the 294 peer-reviewed publications produced to date with GEO-CAPE participation. Additional publications using data and information generated with GEO-CAPE funding are anticipated, in particular using data acquired in recent field campaigns (refer to Section 6).

3. MISSION SCIENCE REQUIREMENTS AND OBJECTIVES

3.1 Introduction

This addendum to the 2015 report includes only content that has changed since the 2015 report. The 2015 report is available at:
https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

During FY16-FY18 the GEO-CAPE study team invested significant resources, 40%-50% per year, to refine mission science requirements and demonstrate achievable mission objectives. Much of this funding was devoted to analysis of data acquired in GEO-CAPE funded field campaigns. Team members usually leveraged other sources of funding to efficiently complete these activities for GEO-CAPE. This section reports on accomplishments that have been published or otherwise publicly communicated.

3.2 Coastal Ocean Color

3.2.1 Coastal Ocean Color Accomplishments 2016-2018

Table 3-1 summarizes the major accomplishments of the Ocean Science Working Group (OSWG). The roughly 40 experts comprising the OSWG largely operated as a "committee of the whole" in which all members participated in all activities.

3.2.1.1 Evolution of Coastal Ocean Color Science Requirements

The accomplishments of recent years have produced many refinements to the Instrument Requirements articulated in the Science Traceability Matrix of 2015. The latest and final version of the Coastal Ocean Color STM can be seen in Appendix B.

During 2018, the OSWG conducted a detailed review of the Coastal Ocean Color Science Requirements and updated the Coastal Ocean Color STM shown in Appendix B. Previously the STM was last updated in July 2015. Two sets of studies conducted over the past three years provided the scientific basis for modifying the requirements. First, the OSWG continued data analysis through GEO-CAPE funded science studies from FY2015 to the present, including further analysis of the 2013 Gulf of Mexico field campaign datasets and the recent 2016 KORUS-OC campaign (Section 6.2.1). Second, the PACE mission has conducted science trade studies that are highly relevant to GEO-CAPE. The GEO-CAPE Coastal Ecosystem Imager continues to require high spatial resolution to resolve near-shore processes, fronts, eddies, and track carbon pools and pollutants. The OSWG has increased the baseline requirement to 200 m in coastal waters and maintained a spatial resolution of 1000 m for open ocean regions while maintaining a threshold coastal waters requirement of 375 m to optimize the science return versus cost (including the cost of achieving precision pointing).

Table 3-1. Ocean Science Working Group Activities and Accomplishments (2016–2018).

Activity	Objective	Accomplishment
Science Traceability Matrix (STM)	Define the high priority coastal ocean biology and biogeochemistry science questions, approach, measurement and instrument requirements.	§3.2.1.1 and §3.2.1.2; STM and white paper update; numerous publications
Science Studies	Advance the science of GEO-CAPE ocean biology and biogeochemistry	§3.2.1.2; publications
Interdisciplinary Science	Identify and describe topics of coastal ocean-atmosphere interactions.	§3.2.1.3; §6.2.1; interdisciplinary white paper
Applications and Event Monitoring	Identify applications that would benefit from GEO-CAPE ocean sensor capabilities	§3.2.1.4; publications
Communicating to a Broader Audience	Science communications to promote GEO-CAPE science and applications beyond the ocean color community and OSWG members	§3.2.1.5; publications
Field Campaigns	Reduce mission risk by collection & analysis of *in-situ* measurements to refine STM measurement and instrument requirements.	§6.2; §7.2; KORUS-OC
International collaboration	Korean Institute of Science and Technology; European science teams developing geostationary ocean color missions	3.2.2; Approval for NASA distribution of GOCI L1B obtained from Korean ministry; NASA OBPG is processing NASA L2 and L3 standard products for distribution by the OB.DAAC along with GOCI L1B; NASA OBPG incorporated GOCI processing capabilities in SeaDAS; recently performed GOCI vicarious calibration. Working towards a quasi-global constellation of geostationary ocean color sensors.

The OSWG has also invested significant effort in refining the spectral coverage and spectral resolution requirements to achieve ocean data products, including atmospheric NO_2 retrieval for atmospheric correction. The spectral range of the hyperspectral UV-Vis-NIR requirements was narrowed in the longer wavelength end of the spectrum (to 900 nm and 1000 nm for the threshold and baseline requirements, respectively) to allow for a wider range of detector substrate material. To compensate for the lack of a 1-micron band in the hyperspectral, the OSWG added a requirement for an additional standalone short-wave infrared (SWIR) band (band center at 1020 nm threshold and 1038 nm baseline). The band centers and bandwidths (full-width half maximum) for the SWIR bands were adjusted to match the recommendations from the PACE mission studies which minimized overlap with atmospheric gas absorption, primarily due to water vapor (Cairns 2018). The SWIR bandwidths were broadened, where possible, to maximize signal-to-noise (SNR) ratio (ibid). In addition, the spectral sampling and resolution requirements were modified to relax the threshold requirements and fine-tune the baseline requirements, to better match the science needs. The spectral requirement for NO_2 was retained in baseline but removed from threshold capability, which would rely on other satellite sensor data and a ground network of sensors such as Pandora in coastal areas near sources of NO_2 to permit atmospheric correction. Based on studies by OSWG team members and those from the PACE mission (Franz and Karaköylü 2018; Patt 2018), the SNR requirements and instrument polarization sensitivity were relaxed as these were thought to overly prescribe instrument performance with the exception that the baseline SNR in the 865 nm atmospheric correction band was increased On balance, these revisions to the requirements allow for a broader range of instrument solutions in terms of size, complexity and cost between the threshold and baseline requirements while accomplishing the full breadth of science objectives.

The temporal requirements did not change. The temporal resolution threshold of <2 hours will enable studies of harmful and non-harmful algal blooms, evaluation of the impacts of short-term physical processes (tides and eddies) on the biology and biogeochemistry of coastal waters, estimates of riverine and coastal fluxes of carbon, nutrients and sediments, estimates of phytoplankton primary production with lower uncertainties, estimates of surface oil films, tracking of the origin and evolution of hazardous events more effectively, and more precise assessments of impacts.

The observing strategy is envisioned as a combination of a Survey Mode (systematic observations) for evaluation of diurnal, seasonal and interannual variability in U.S. coastal waters and Regions of Special Interest and Targeted Observations modes for high-frequency and episodic events including evaluations of tidal and diurnal variability.

Two comprehensive synthesis studies from members of the GEO-CAPE team have been published this year. The current state of approaches and challenges for retrieving marine inherent optical properties (IOPs) from ocean color sensing has been reviewed by Werdell et al. (2018). IOPs are the spectral absorption and scattering characteristics of ocean water and its dissolved and particulate constituents. Because of their dependence on the concentration and composition of marine constituents, IOPs can be used to describe the contents of the upper ocean mixed layer. Muller-Karger et al. (2018) specify the spatial, spectral, radiometric and temporal characteristics required to observe Essential Biodiversity Variables (EBVs) that change rapidly with extreme tides, salinity, temperatures, storms, pollution, or physical habitat destruction over scales relevant to human activity.

Temporal advantages of geostationary monitoring are central to the GEO-CAPE mission concept. Three studies published since 2017 document the progress made in establishing the requirements and scientific value of sub-daily measurements. Arnone et al. (2017) characterized diurnal changes in ocean color in turbid coastal regions in the Gulf of Mexico using above water spectral radiometry from a NASA surface measurement site (Aerosol Robotic Network Ocean

Color; AERONET-OC) that provides 8 to 10 observations per day. Satellite capability to detect diurnal changes in ocean color was characterized using hourly overlapping afternoon orbits of the visual infrared imaging radiometer suite (VIIRS) ocean color sensor and validated with *in-situ* observations. The diurnal changes observed using satellite ocean color can be used to define the following: surface processes associated with biological activity, vertical changes in optical depth, and advection of water masses. VIIRS overlapping observations were also used by Qi et al. (2017) in their study of phytoplankton vertical migration in the NE Gulf of Mexico. They are able to infer phytoplankton vertical movement within a short timeframe, a phenomenon difficult to capture with other sensors as each sensor can provide at most one observation per day, and they caution that cross-sensor inconsistency may make interpretation of merged-sensor data difficult. These findings strongly support geostationary satellite missions to study short-term bloom dynamics. The 8 observations per day from GOCI allow additional temporal study, as reported by Qi et al. (2018), who studied diurnal changes of cyanobacteria blooms in Taihu Lake.

Two studies speak directly to the importance of studying coastal regions over a wide range of time scales. Jonsson and Salisbury (2016) present a satellite-derived proxy for net community production where simulated velocity fields are combined with satellite data to create a comprehensive accounting of spatial and temporal scales of biological production. The authors find that frequencies of rare events may be as important for biological production as seasonal averages, highlighting the need for additional datasets sampled at higher frequencies and shorter spatial scales. In very recent work, Salisbury and Jonsson (2018) report that rapid warming and salinity changes alter carbonate parameters and hide ocean acidification. Their analysis of a 34-year salinity, ocean color and SST time series (1981-2014) shows instances of decadal scale anomalies in temperature and salinity that perturb the carbonate system to an extent greater than that expected from OA, and thus it is imperative that regional to global models used to estimate carbonate system trends carefully resolve variations in the physical processes that control CO_2 on timescales from episodic events to decades.

Radiometric requirements were also considered by the GEO-CAPE team. Ackleson et al. (2018) explored the impact of sensor noise, defined as the signal to noise ratio (SNR), on the retrieval of key coral reef ecological properties (bottom depth, benthic cover, and water constituent concentration) in the absence of environmental uncertainties. Parameter uncertainty was found to increase with sensor noise (decreasing SNR) but the impact was non-linear. They concluded that, while the definition of an optimal SNR is subject to user needs, a minimum SNR of approximately 500 (relative to 5% Earth surface reflectance and a clear maritime atmosphere) represents the threshold of sensor noise for a satellite sensor to be of high ecological value for coral reef remote sensing. The work of Pahlevan et al. (2014) gives insights into the radiometric sensitivity of the GEO-CAPE mission in identifying the changes in bio-optical properties at top-of-atmosphere (TOA), which aids in a more lucid understanding of the uncertainties associated with the surface products.

Spectral sampling frequency and uncertainty thresholds were explored by Vandermeulen et al. (2017), who found that a continuous spectrum of 5 to 7 nm spectral resolution is optimal to resolve the variability across mixed reflectance and absorbance spectra. The need for future geostationary and polar-orbiting ocean color missions to include highly sensitive SWIR bands (> 1550nm) to allow for a precise removal of aerosol contributions was addressed by Pahlevan et al. (2017) in light of engineering and cost constraints. The authors studied the sensitivity of a combination of bands centered at 1565 and 1675 nm to different aerosol conditions, calibration uncertainties, and extreme water turbidity. Further, they compared the present approach to that of all band combinations available on existing polar-orbiting missions.

Spatial requirements were articulated by Moses et al. (2016), who investigated the spatial scale of variability in optical properties of coastal waters using continuous, along-track measurements collected using instruments deployed from ships, aircraft, and satellites, highlighting the critical nature of complementary measurements. They found that, on average, at Ground Sampling Distances (GSD) greater than ~200 m most of the spatial variability due to small-scale features is subsumed within a pixel.

The dataset collected by Mouw et al. (2017) focuses on coincident observations of inherent and apparent optical properties along with bio-geochemical parameters in Lake Superior. They provide remote sensing reflectance, absorption, scattering, backscattering, attenuation, chlorophyll concentration, and suspended particulate matter over the ice-free months of 2013–2016, substantially increasing the optical knowledge of the lake.

Chesapeake Bay was the study site for both Rose et al. (2018) and Zhang et al. (2018). The former implemented a semi-analytical model to examine spectral, spatial, and temporal variability in the diffuse attenuation coefficient, identifying wavelengths most sensitive to long-term change, the seasonal phenology of long-term change, and the optical constituents driving changes and enabling insight into what types of long-term change in transparency have occurred over the long period of human impacts in the Chesapeake Bay watershed. In contrast, Zhang at al. (2018) focused specifically on the July-August 2011 CBODAQ campaign (see Section 3.2.2.2 of the 2015 Report) in their investigation of diurnal changes of surface remote sensing reflectance (Rrs) using airborne and shipborne sensors. They find that once airborne data are processed using proper algorithms and validated using *in-situ* data, they are suitable for assessing diurnal changes in moderately turbid estuaries such as Chesapeake Bay. The findings also support future geostationary satellite missions that are particularly useful to assess short-term change.

Kollonige et al. (2018) have evaluated several methods of estimating surface NO_2 over marine and terrestrial sites downwind of urban pollution using both satellite and ground-based remote sensing and compared them with *in-situ* measurements during field campaigns. The authors demonstrate that estimating surface NO_2 from satellite observations can be a challenging problem. The temporal and spatial resolutions of observations from current instruments, such as OMI, add difficulty to the analysis and validation process when limited by few co-located observations over a single specific site. This emphasizes the need for instruments with higher temporal and spatial resolution and indicates the need for the careful consideration of the location and coverage (i.e., networks) of ground-based instrumentation for validating satellites.

Three additional studies (Tzortziou et al. 2018, Martins et al. 2016, Loughner et al. 2016) have further explored the spatial and temporal variability of NO_2 in the coastal region, which is critical for proper atmospheric correction in polluted areas. Shipboard measurements of total column amounts of atmospheric trace gases across a range of environments, including Chesapeake Bay, Gulf of Mexico, New York coastal waters, and South Korean waters, highlight the impact of atmospheric variability on atmospheric correction of coastal ocean color observations (Tzortziou et al. 2014, 2018; Sullivan et al. 2018). Air-mass trajectory simulations explained the observed diurnal variability in coastal NO_2 and identified the influence of air mass origin on atmospheric composition over the coastal ocean. Polar-orbiting sensors do not provide the capability to detect these short-term changes, and if left unaccounted in atmospheric correction retrievals of ocean color, the observed variability in NO_2 would be misinterpreted as a change in ocean remote sensing reflectance, introducing a significant false variability in retrievals of coastal ocean ecological processes from space (Tzortziou et al. 2018).

3.2.1.2 Science Studies

In addition to refining Mission Requirements for future sensor development, many accomplishments of the Ocean Color Science Working Group used existing sensors and techniques to advance our understanding of the coastal ocean. Jenkins et al. (2016) enhanced the utility of satellite sea surface temperature and chlorophyll observations for mapping microscale features and frontal zones in coastal waters, while Goes et al. (2018) explored Green Noctiluca blooms in two monsoonal driven ecosystems. Lee et al. (2015b) provided overview of three primary strategies for modeling of primary productivity, as well as the nature of present satellite ocean-color products.

Community composition in the East China Sea was studied by Gomes et al. (2018), Zhu et al. (2017), and Xu et al. (2018) with a variety of approaches employing satellite and *in-situ* observations. Wei and Lee (2015) address the retrieval of phytoplankton and colored detrital matter (CDM) coefficients with remote sensing reflectance in the ultraviolet, finding that the separation of absorption coefficients due to CDM and to phytoplankton is highly dependent on the accuracy of the ocean color measurements and the estimated total absorption coefficient. Tzortziou et al. (2015) combined comprehensive measurements of the optical signature of colored dissolved organic matter (CDOM) with measurements of river discharges and water physicochemical and biogeochemical properties in the Eastern Mediterranean region, establishing that monitoring the CDOM fluorescence footprint could have direct applications to programs focusing on water quality and environmental assessment in this and other transboundary rivers where management of water resources remains largely ineffective.

Optical properties are fundamental to ocean measurements, and several GEO-CAPE studies made advances in this field. The transmittance of solar radiation in the oceanic water column plays an important role in heat transfer and photosynthesis, with implications for the global carbon cycle, global circulation, and climate. Zoffoli et al. (2017) assessed five models of transmittance of solar radiation in the visible domain and found that the IOPs-based model was insensitive to the type of water, allowing it to be applied in most marine environments, including coastal turbid waters. Wei et al. (2015) present the first measurements of the radiance transmittance (*Tr*) in a wide range of oceanic waters and report that the measured *Tr* values are generally consistent with the long-standing theoretical value of 0.54, with mean relative difference less than 10%. Another study that examines long-held practices is that of Lee et al. (2018b) who address empirical relationships that have been developed in the past nine decades to link the Secchi disk depth (Z_{SD}) with the diffuse attenuation coefficient, the euphotic zone depth, and chlorophyll concentration, where the latter two are important for the quantification and evaluation of photosynthesis in aquatic environments. Their results not only resolve the long-standing puzzles associated with these observations, but also unify the relationships published in the literature and provide strong support for using historical Z_{SD} data to study changes of phytoplankton in global oceans in the past century.

3.2.1.3 Interdisciplinary Science

As discussed in the 2015 report, the draft interdisciplinary science white paper prepared for the Science Working Groups had multiple objectives, including guiding GEO-CAPE planning and stimulating broader consideration of coastal interdisciplinary science topics among relevant scientific communities. It was refined throughout the pre-formulation period for the SWGs and is posted on the GEO-CAPE website in its most recent form as a record of the GEO-CAPE interdisciplinary science activities. An edited version is planned for peer-reviewed publication intended to foster future interdisciplinary collaborative research efforts in coastal studies.

Additional interdisciplinary activities during the 2016-2018 period were primarily focused on the KORUS-OC and KORUS-AQ joint field deployments in 2016, as briefly described in Section 6.2.1.

3.2.1.4 Applications and Event Monitoring

High temporal resolution observations of ocean color have many possible applications for societal benefit. Three in particular were explored by GEO-CAPE team members during the 2015-2018 period. Recurrent and significant *Sargassum* beaching events in the Caribbean Sea have caused serious environmental and economic problems, calling for a long-term prediction capacity of *Sargassum* blooms. Wang and Hu (2017) present predictions based on a hindcast of 2000 – 2016 MODIS observations, which showed connectivity between *Sargassum* abundance in the Caribbean Sea and the Central West Atlantic with time lags. Further work (Wang et al. 2018) provided the first quantitative assessment of the overall *Sargassum* biomass, nutrients, and pigment abundance from remote-sensing observations, thus helping to quantify their ecological roles and facilitate management decisions. Marechal et al. (2017) presented a simple, fast, and reliable method to predict Sargassum washing ashore in the Lesser Antilles, based on satellite imagery and numerically-modelled surface currents, combined with HYCOM current vectors.

Hu et al. (2018) estimated the surface oil volume during the Deepwater Horizon blowout in the Gulf of Mexico by combining synoptic measurements (2330-km swath) from MODIS and much narrower swath (~5 km) hyperspectral AVIRIS airborne observations. The study shows a significant limitation of MODIS in its spatial, spectral, and temporal resolutions, which can all be overcome with a dedicated geostationary ocean color mission.

Lastly, the works of Lee et al. (2015c, 2018c) propose and develop a methodology for continuing century-long monitoring of global water clarity. Through a combination of historical Secchi disk depth (Z_{SD}) records with continued field measurements and satellite products, a standardized global Z_{SD} data product can be developed to form a unique, century-long, Earth system dataset that links the past with the future and fills a key gap in assessing changes in water clarity in global seas and lakes. In addition, such a product can be valuable in supporting a positive economy as well as integrated water resources management.

3.2.1.5 Communicating to a Broader Audience

With its unique imaging capabilities and vantage point, the GEO-CAPE ocean color sensor would do for coastal science and applications what the Geostationary Operational Environmental Satellite system (GOES) has done for weather prediction. Members of the GEO-CAPE team have taken active roles communicating the importance of ocean color observations and science to a broader community of stakeholders, users and other interested parties:

- Tzortziou et al. (2017): Coordinating and communicating carbon cycle research
- Salisbury et al. (2016): Coastal observations from a new vantage point
- Salisbury et al. (2015): How Can Present and Future Satellite Missions Support Scientific Studies that Address Ocean Acidification?

3.2.2 Ongoing and Future Work

Coastal ocean ecology and biogeochemistry requirements for GEO-CAPE have continued to evolve to better fit within the cost and schedule constraints of NASA's programs. These efforts will continue under the auspices of Earth Venture opportunities.

To further constrain the measurement and instrument requirements from GEO, on-going and future studies that address high priority issues defined by the OSWG are needed. These high priority studies include utilization of GOCI and the follow-on sensor GOCI-II planned to launch in 2019 to examine the sensitivity of these sensors and current algorithms to detect short-term dynamics of physical, biogeochemical and bio-optical processes in the coastal and open ocean. Additional studies on atmospheric correction algorithms employing pseudo-spherical and spherical shell models of the earth as well as further characterization of the BRDF of coastal particles with varying solar angles. Completion of current studies and new studies will employ existing and new observations of high temporal resolution, high spatial resolution or high spectral resolution field data sets that have an abundant set of associated observations, as well as geostationary observations from GOCI or weather satellites, and observations from high latitude polar orbiters. A key advance provided by geostationary ocean color sensors, which will be evaluated through KORUS-OC, will be the capability to directly quantify diurnal and daily measurements of biological productivity from hourly GOCI observations. Further advances in the GEO-CAPE ocean color science objectives can be partially accomplished through sub-orbital programs such as EVS and other large-scale field campaigns.

3.3 Atmospheric Composition

3.3.1 Atmospheric Composition Accomplishments 2016-2018

During the final period of GEO-CAPE mission study activities, Atmospheric Composition efforts were largely focused in six areas: Emissions and Chemical Processes, Methane (including an assessment of the contribution of the GeoCARB mission to accomplishing GEO-CAPE science objectives), Aerosols, Global and Regional/Urban Observation Simulation System Experiment studies, and further application of the UV-Visible airborne simulator instruments (which is reported in detail in Section 6). The Atmospheric Composition science questions and science traceability matrix have remained unchanged since 2011, reflecting the progress being made in satellite mission implementation.

3.3.1.1 Emissions and Chemical Processes Working Group

The GEO-CAPE Emissions Working Group was formed to illustrate and understand the potential of geostationary remote sensing measurements to constrain emissions. The projects undertaken focus on aspects that require high temporal and spatial resolution and are thus novel with regards to going beyond the capabilities of existing measurement platforms to constrain emissions. GEO-CAPE observations potentially allow emissions from pollution sources in proximity to each other to be separately quantified, e.g., roads or point sources in densely populated regions, and estimation of source activity variation through the day, e.g. peak-demand electricity generation. These activities drew from existing data, e.g., GOME-2 and OMI, as well as measurements from field campaigns and monitoring networks that were conducted or available over small regions and/or time periods, affording a glimpse into the added value of geostationary measurements. Another approach adopted in several projects was to use CTMs to simulate observations from geostationary measurement platforms. Working group efforts also used forward and inverse CTMs to quantify the ways in which high space/time resolution emissions and observations result in predictions or analyses that differ from those using low space/time resolution inputs.

The activities of this working group are organized by considering the constraints of different types of geostationary measurements on emissions of different species. For short-lived reactive trace gases, several studies were conducted regarding NO_2. The reader is referred to Section 7 for accomplishments related to NO_2 retrievals and suggestions for retrieval algorithms and validation procedures for upcoming geostationary satellites.

Lightning is an important source of upper troposphere nitrogen oxides, however, there is high uncertainty in the amount produced from lightning. Upper tropospheric *in-situ* observations from the Deep Convective Clouds and Chemistry (DC3) experiment and global satellite-retrieved NO_2 tropospheric column densities were combined to constrain mean lightning NO_x emissions per flash. Using recent updates in upper tropospheric nitrogen oxides chemistry, Nault et al. (2017) decreased this uncertainty from a factor of 4 to less than a factor of 2 and showed that nitrogen oxide production from lightning should be higher. Guided by recent laboratory and field studies, Zare et al. (2018) developed a detailed gas phase chemical mechanism representing most of the important individual organic nitrates. This mechanism is used within the WRF-Chem model to describe the role of organic nitrates in nitrogen oxide chemistry and in comparisons to observations. They found the daytime lifetime of total organic nitrates with respect to all loss mechanisms to be 2.6 h in the model. The lifetime of the first-generation organic nitrates is ~2 h versus the 3.2 h lifetime of secondary nitrates produced by oxidation of the first-generation nitrates. The different generations are subject to different losses, with dry deposition to the surface dominant loss process for the second-generation organic nitrates, and chemical loss dominant for the first-generation organic nitrates. Lastly, Cooper et al. (2017) conducted a simulation study of the effectiveness of the commonly used mass-balance approach to developing top-down NO_2 emissions estimates, as compared to 4D-Var techniques. This paper develops an iterative, perturbation-based mass-balance inversion method that can achieve similar levels of accuracy as 4D-Var inversions for much lower cost, when the grid-cell size of the model used for the inversion is that of current global models (i.e. 100's of km).

Several projects considered the value of geostationary measurements of formaldehyde (HCHO). Bottom-up volatile organic compund (VOC) emissions in the Los Angeles Basin were studied by utilizing the model results and field observations during California Nexus of Air Quality and Climate Change (CalNex) campaign, including ground-based and airborne primary VOC and HCHO data. To support this activity, since studies of HCHO and O3 are inherently linked to the NOx budget, Kim et al. (2016) developed a new nitrogen oxide (NO_x) and carbon monoxide (CO) emission inventory for the Los Angeles-South Coast Air Basin (SoCAB), expanding the Fuel-based Inventory for motor-Vehicle Emissions and applied it in regional chemical transport modeling focused on the CalNex 2010 field campaign. Kim et al. (2018) then demonstrated the importance of fine spatial and temporal resolution *a priori* profile information on the retrieval, as described in Section 7. Using optimized model HCHO results in the Los Angeles Basin that mimic the HCHO retrievals from future geostationary satellites, the team illustrated the effectiveness of HCHO data from geostationary measurements for understanding and predicting tropospheric ozone and its precursors.

A new approach was developed for determining monthly updates of anthropogenic sulfur dioxide emissions from space, with applications for air quality forecasts (Wang et al., 2016). The approach's effectiveness was demonstrated for 14 months in East Asia; resultant posterior emissions captured a 20% SO_2 emission reduction in Beijing during the 2008 Olympic Games and improved agreement between modeled and *in-situ* surface measurements. Further analysis revealed that posterior emissions estimates, compared to the prior, lead to large improvements in forecasting monthly surface and columnar SO_2. With the pending availability of geostationary measurements of tropospheric composition, it may soon be possible to rapidly constrain SO_2 emissions and associated air quality predictions at fine spatiotemporal scales.

Lastly, a subset of emissions working group activities shed light on the potential of geostationary measurements to constrain long-lived greenhouse gases. These activities dovetailed with those of the CH_4 working group and many of the project findings are reported in Section 3.3.1.5. Within this topic lies challenges associated with inverse modeling. While geostationary measurements hold great potential for providing many more constraints on CH_4 emissions than currently possible with existing satellites, the nature of these constraints can be challenging to quantify. To address this challenge, Bousserez and Henze (2018) developed a dimension reduction approach for inverse modeling studies that allows for clear identification of the modes of variability in emissions that are constrained by the observations, as the singular vectors of the prior-preconditioned Hessian matrix. Further, their paper describes a computationally tractable way to compute these modes of variability using Monte Carlo methods. The results of this work facilitate inverse modeling and assimilation of large volumes of data with very high-resolution models, such as will be the case for using geostationary observations within regional emission estimation studies.

3.3.1.2 Aerosol Working Group

Many of the achievements of the Aerosol Working Group are reported in Section 7 (Measurement Algorithms). Achievements focused on Science Measurements and Objectives examined the possibility and challenges of using the daily and sub-daily aerosol observations from geostationary platforms for air quality applications (particularly the surface PM2.5 concentrations). By using several pairs of nearly collocated AERONET AOD and EPA PM2.5 measurement sites in the U.S., the team elucidated the relationship between these two quantities on sub-daily and daily time scales and addressed the feasibility of using geostationary observations of AOD for PM2.5 air quality applications under various environmental conditions. They have also used the GEOS-5 Nature Run to explain the variability of AOD and PM2.5. On a sub-daily time scale, for about 80% of the days AOD and PM2.5 are not significantly correlated or even anticorrelated over all sites examined, pointing out the challenges in using hourly AOD data for PM2.5. However, AOD and PM2.5 are better correlated on a daily-averaged basis or under well-mixed boundary layer conditions, although their relationship still varies with seasons. Major factors controlling the AOD-PM2.5 relationship include (a) atmospheric water vapor, (b) aerosol vertical profile (including PBL height, and (c) aerosol type.

3.3.1.3 Global OSSE Working Group

The GEO-CAPE Global Observation Simulation System Experiment (OSSE) Working Group was tasked with demonstrating the expected impact of GEO-CAPE atmospheric composition observations as part of a virtual constellation of geostationary Earth orbit (GEO) missions in concert with Low Earth Orbit (LEO) measurements. The CEOS Atmospheric Composition Constellation activity had previously identified joint OSSEs as a way to promote collaboration between the planned and proposed GEO missions from NASA GEO-CAPE/TEMPO, ESA Sentinel 4 and Korean GEMS.

OSSEs assess the impact of hypothetical simulated observations on a model analysis, forecast and/or inversion, and provide a means to generalize on the conclusions of limited case-studies. A typical OSSE consists of several components, each of which requires different expertise. The OSSE starts with a reference model field, or Nature Run, representing the “true” atmospheric system, atmospheric constituents of interest, their sources and sinks. The Nature Run is subsequently sampled by an Observation Simulator, corresponding to the sampling strategy adopted for potential observing system, leading to Simulated Observations. In parallel, a Control Run, preferably from a second model that is independent of the Nature Run model in terms of process description, meteorology etc., produces an alternate description of the atmospheric system. Finally, an Assimilation Run assimilates the Simulated Observations into the Control Run. The differences between the Nature Run and Control Run, compared to the differences between the Nature Run and Assimilation Run, then allows for an examination of the impact of the Simulated Observations in constraining constituents and processes.

Advances have been made across these OSSE components. The development of two global high resolution (7 km & 12 km) GEOS model Nature Runs representing aerosols and trace gases has allowed the extension of the OSSE concept beyond traditional weather forecasting applications (e.g. Hu et al. 2018). These Nature Runs have been subsequently evaluated against observational datasets, reanalyses, and other long-term model simulations. Leveraging the development of the Nature Runs, there has also been a focus on efficient Observation Simulator algorithms for generating simulated polarized top-of-the atmosphere radiances (e.g. Castellanos et al. 2018a). The simulated radiances for the GEO constellation were provided to other GEO-CAPE WGs to be used for algorithm development and evaluation. For example, in collaboration with the Aerosol WG, simulated radiances for the GOES-R sector, overlapping and synchronized with TEMPO, were used to quantitatively explore the synergistic capabilities of combining observations from the two instruments for detecting absorbing aerosols (Castellanos et al. 2018b).

Bringing together the OSSE components into a framework for evaluating the GEO virtual constellation and the role that GEO-CAPE instruments might play has also been investigated (e.g. Barre et al. 2015, 2016). This work has shown the value of upwind region measurements from one GEO in helping to constrain atmospheric composition in the downwind region covered by the next GEO member in the constellation. This is especially true for longer lived species, for example carbon monoxide and aerosol, where boundary conditions of the downwind region may be significantly impacted by upwind region extreme events, such as wildfires or dust storms. Running these large experiments has also motivated pragmatic approaches to reduce computational costs, especially for the data assimilation (e.g. Mizzi et al. 2016).

Through inverse modeling studies, research has also assessed the value of the virtual constellation of GEO and LEO sounders in improving the understanding and attribution of pollution. This has focused on three different studies: (1) the impact of non-local sources of emissions on local ozone; (2) the impact of long-range transport of ozone on local sources of ozone; and (3) the impact of changes in the chemical environment on the relationship between NO_x emissions and NO_x concentrations. Adjoint sensitivity analysis of both the global and nested (0.5 x 0.667) GEOS-Chem model has investigated these relationships, focusing in particular on mean surface ozone in the EPA09 region. This work has shown that over 35% of mean surface ozone in EPA09 comes from emissions outside EPA09. Chinese emission (2005-2009) contribution to mean column ozone is 70% of local emissions. Using OMI-derived NO_x emissions also found that increases in Chinese emissions in 2005-2010 largely offset local EPA09 emission reductions to mean surface ozone. These results showed that knowledge of Asian emissions from missions such as GEMS could improve knowledge of surface ozone in the Western US. To understand the role of long-range transport, the sensitivity of EPA09 surface ozone to ozone boundary conditions was computed, especially across the Western US edge. Using the difference between a TES ozone assimilation and a free-running simulation found that EPA09 surface ozone could change by up to 2 ppb. This result implied the LEO sounders such as CrIS or IASI as part of the constellation could improve surface air quality estimates. Lastly, computing the sensitivity of NO_x concentrations to ozone and other species has shown that the relationship between NO_x emissions and concentrations is sensitive to the chemical environment, pointing to the need for a multi-constituent approach.

Members of this working group co-organized the Second Atmospheric Composition Observation System Simulation Experiments (OSSE) Workshop in Reading, England in November 2016. This meeting was sponsored by the CEOS Atmospheric Composition Constellation, along with NASA Earth Science, the Copernicus project, and the European Centre for Medium-Range Weather Forecasts (ECMWF), and followed on from the first Workshop that took place at ECMWF in October, 2012. The first Workshop attracted 25 participants sharing OSSE expertise and experiments; for the second Workshop, interest had grown to more than 40 participants. An initial goal of these meetings was to define experiments to document the impact of individual GEO chemical observations over Europe, Asia and North America, and the value of the wider GEO constellation in conjunction with LEO assets. The Workshops reviewed OSSE experience from the Numerical Weather Prediction (NWP) community, discussed current methodologies for OSSE design, reported on individual OSSE activities and looked for synergies between these efforts to promote international collaboration. By the Second workshop it was clear that OSSEs were becoming an expected component of mission design, that the definition of "OSSE" was expanding to include other types of observation sensitivity study, and that research was moving to include research areas such as emissions and GHGs.

The OSSE WG studies have taken important steps towards quantifying the value of the virtual air quality constellation. They also point to the interplay of emissions, concentrations, and multiple species in advancing global air quality. Moving forward, it is vital that trace gas products from LEO sounders such as CrIS and TROPOMI be incorporated into this virtual GEO constellation. Furthermore, development of multi-constituent data assimilation is still in its infancy but will be necessary for fully harnessing the data across multiple platforms. Lastly, there is increasing interest in understanding the anthropogenic footprint of carbon and its relationship to chemically reactive gases. The synergy of these measurements will be important to understand and predict the trajectory of both short-lived and long-lived climate pollutants.

GEO-CAPE has played an important role in promoting the Science Traceability Matrix (STM) approach to mission design with Science Questions leading to Measurement Requirements and on to Instrument Requirements. This working group has shown OSSEs to be an important tool in quantifying expected mission performance for meeting STM requirements (e.g. Edwards et al. 2018), and OSSE framework capability now exists at several centers across the community.

3.3.1.4 Regional / Urban OSSE Working Group

The Regional/Urban Observation System Simulation Experiment (OSSE) Working Group was initiated in 2013 to assess the value of geostationary observations of ozone (O_3), nitrogen dioxide (NO_2) and formaldehyde (HCHO) over the continental US (CONUS) in addressing the scientific and applications objectives of GEO-CAPE. The main components of the Regional/ Urban OSSE (nature run, observation simulator, data assimilation system) are illustrated in Figure 3-1; the recommendations of Timmermans et al. (2015) were followed, providing a framework for the use of OSSEs for assessing the impact of satellite trace gas retrievals on air quality forecasts, including requirements for the individual components.

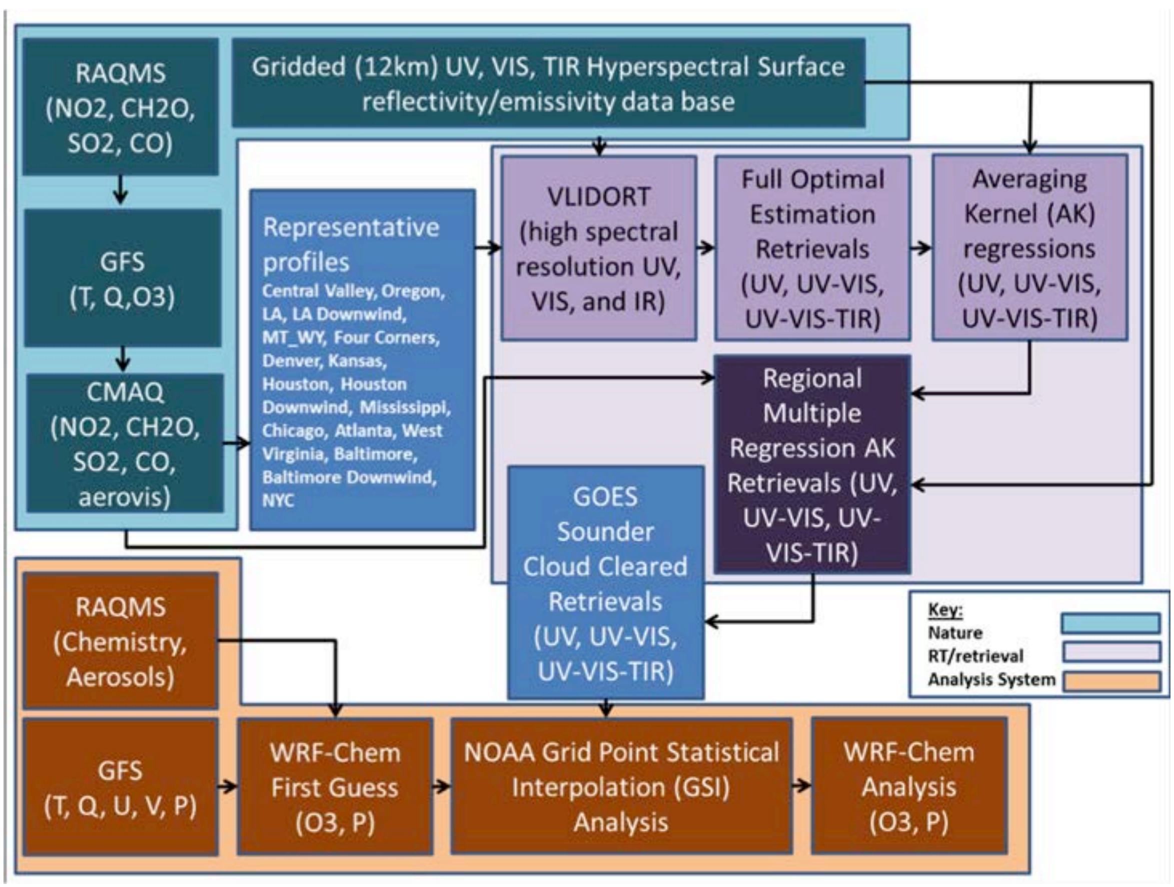


Figure 3-1: Components of the GEO-CAPE Regional/Urban OSSE: nature run (teal), observation simulator (purple), and data assimilation system (brown).

Development of the OSSE framework was based on three overarching goals: (1) the nature run must provide a reasonable representation of the real atmosphere; (2) the observation simulator must be able to produce synthetic "measurements" that account for the spectral resolution, signal to noise ratio, and averaging kernel (AK, sensitivity of measurement to true state) of the instrument being assessed; and (3) the model used within the data assimilation system should be different than the model used to generate the nature atmosphere. The first two years of the Regional/Urban OSSE activities are summarized in Table 3-3 of the GEO-CAPE 2009–2015 Summative White Paper and focused on completion of ultraviolet (UV), visible (VIS) and thermal infrared (TIR) radiative transfer (RT) modeling, generation of multi-spectral retrievals for a subset of CONUS profiles, and AK regression to extend the training set to all of North America for the O_3 OSSE studies.

The Regional/Urban OSSE Working Group activities resulted in several innovations. A hyperspectral surface reflectivity/emissivity database was created that combined GOME, MODIS and ASTER measurements with dual regression fitting for the spectral gap between the near-infrared and the thermal infrared. A multiple linear regression method was developed to provide O_3 retrievals over the entire CONUS region from selected full optimal estimation retrievals. Since NO_2 and HCHO have significantly more spatial and temporal variability than O_3, the fast 2S-ESS RT model was developed to avoid regression but instead perform full optimal estimation retrievals for every cloud-free grid point of the nature run. This approach resulted in a 200-fold speed increase compared to the full multiple scattering LIDORT RT model with negligible loss of accuracy. A new aerosol single scattering property database was created for six aerosol types (black carbon, dust, nitrate, insoluble and soluble organic carbon, sulfate) that spanned the entire ultraviolet to thermal infrared wavelength range and accounted for hygroscopic effects.

The regional O_3 OSSE was completed during this period. Results were presented at the Second Atmospheric Composition OSSE Workshop, hosted by the European Center for Medium Range Weather Forecasting in Reading, UK, 9–11 November, 2016. The GEO-CAPE Regional O_3 OSSE demonstrates systematic and significant increase in lower-to-mid-tropospheric correlations and reductions in root mean square (rms) errors and biases when hourly geostationary UV/VIS, and UV/VIS/TIR ozone retrievals are assimilated, compared to UV-only measurements. Results show improvements in lower tropospheric correlations and rms errors for all experiments, but the UV and UV/VIS experiments introduce higher biases. Comparisons of the nature run with data from US Environmental Protection Agency surface monitoring sites show that the overall positive impacts obtained with UV/VIS/TIR retrieval assimilation are due to reductions in nighttime biases, which highlights the importance of the TIR measurements in the multi-spectral retrievals. A manuscript describing the O_3 OSSE is in preparation ("Regional O_3 OSSEs for the GEO-CAPE mission," Pierce et al., to be submitted 2018).

The NO_2 OSSE has been completed and the HCHO OSSE is nearing completion. Using the 2S-ESS RT model, synthetic radiances have been generated for all cloud free gridpoints at hourly intervals for the full nature run time period (July 2011) utilizing the Supercomputer for Satellite Simulations and Data Assimilation Studies (Boukabara et al, 2016) at the University of Wisconsin-Madison Space Science and Engineering Center. Since NO_2 and HCHO are short lived species, assimilation of NO_2 or HCHO column retrievals does not lead to systematic changes in the concentrations of these species. Instead, the NO_2 and HCHO column retrievals must be used to constrain the emissions of these species. As part of the Regional/Urban OSSE working group activities during 2015–2018 we developed an offline approach to use satellite-based trace gas retrievals to constrain area and point source emissions. The approach involves calculating the sensitivity of the trace gas column to changes in emissions following Lamsal et al. (2011) and then using this sensitivity, combined with the monthly mean trace gas analysis increment, to adjust the emissions. The results of the NO_2 OSSE were presented at the Joint Committee on Earth Observation Satellites Atmospheric Composition-Virtual Constellation and GEO-CAPE Meeting, which was hosted by the NOAA Center for Weather and Climate Prediction in College Park, MD from May 2–4, 2018. The GEOCAPE NO_2 OSSE demonstrates significant adjustments in *a priori* NOx emissions using hourly TEMPO-like NO_2 retrievals compared to daily OMI NO_2 emission adjustments. However, the NO_2 OSSE results show low surface ozone sensitivity to changes in NOx emissions, possibly due to high urban NOx levels leading to VOC sensitive ozone production. The O_3, NO_2, and HCHO assimilation experiments were conducted using the NOAA gridpoint statistical interpolation (GSI; Wu et al. 2002; Kleist et al. 2009), which is a physical space-based 3-dimensional variational analysis. The observation operator for the O_3, NO_2, and HCHO profile retrievals was developed for GSI based on the approach used by Verma et al. (2009) for assimilation of ozone profiles from the Tropospheric Emission Spectrometer. This observation operator accounts for the AK and *a priori* used in the retrieval.

3.3.1.5 Methane Working Group

The GEO-CAPE Methane Working Group was initiated in 2015 to define the requirements and capabilities for geostationary observations of methane over North America as envisioned by the GEO-CAPE science traceability matrix. Methane was not identified as a high-priority measurement in the original concept of GEO-CAPE, reflecting the focus of that original design on air quality, but since then there has been growing interest in better understanding methane sources using satellite observations. This prompted the study team to direct attention to the methane observing capabilities from geostationary orbit and the potential role of GEO-CAPE. Observation of methane from space can be done in the same 2300 nm band as CO (a top priority of GEO-CAPE) or in an alternative SWIR band at 1650 nm. Methane is emitted by a large number of relatively small and often clustered point sources, posing a unique problem for satellite observations to quantify these sources.

The Methane WG had a number of accomplishments over its three years of operation. It contributed to the design of CHRONOS (Edwards et al. 2018) as an implementation of the methane-CO component of GEO-CAPE. CHRONOS was submitted three times to the EV program and always received high ratings, but was not selected. The Methane WG also contributed to the design of GeoFTS, a high-resolution geostationary implementation of GEO-CAPE for methane-CO-CO_2 (Xi et al. 2015). It facilitated the construction and deployment of CLARS-FTS as a GeoFTS ground-based imaging simulator operating on the top of Mt. Wilson and continually mapping methane and CO_2 emissions in the Los Angeles Basin. Observations from CLARS-FTS have been very successful in constraining methane emissions from the Basin and their seasonal variations (Wong et al. 2015, 2016). Additional details can be found in Section 6. Finally, the Methane WG produced OSSEs to determine the capability of different geostationary observing configurations to quantify methane emissions from regional scales down to temporally variable point sources. It was found that the GeoCARB mission selected by the EV program would deliver 70% of the original specifications of GEO-CAPE for observing methane on regional scales, and that improving GeoCARB measurement precision was more important than more frequent sampling (Sheng et al. 2018). It was shown that geostationary instruments such as GeoFTS can observe methane point sources down to the km-scale (Turner et al. 2018), and that detection of anomalously high sources ("super-emitters") can be enabled by the use of a L-1 norm in data inversion (Cusworth et al. 2018).

3.3.2. Ongoing and Future Work

The selection of GeoCARB was an important milestone for the GEO-CAPE Science Team. The specifications of GeoCARB (pixel resolution, precision, return time) are still in flux, and continued collaborations of the Methane WG with the GeoCARB Science Team would be useful to guide selection of an optimal configuration. Another area in need of further attention is the potential of geostationary observations to map emissions at the facility level using sub-km pixels. The general focus of geostationary methane missions so far has been to observe methane on continental scales, requiring compromises in pixel resolution and return time, but the Methane WG stressed the need for more work to define a geostationary mission that would view smaller domains but with finer resolution and continuous imaging. Such a mission has been recommended by the recent 2017-2027 Decadal Survey for Earth Science and Applications from Space (ESAS 2017) under its "Explorer" category, and the work done by the GEO-CAPE Methane WG will be highly relevant to its design.

Additionally, the Decadal Survey has designated priority satellite measurements to answer important questions related to Aerosols and Clouds, Convection, and Precipitation (A&CCP). The particular configuration of A&CCP, whether as a single mission or two component missions, is the subject of a NASA HQ-directed study commencing this fall. The OSSE framework and modeling capabilities developed for GEO-CAPE will be used as the basis for OSSEs needed to help guide Decadal Survey mission and instrument design.

Assessing the values of GEO-LEO constellation observations of aerosols with the current and near future satellites is particularly relevant in the CEOS framework and in the context of the new Decadal Survey. The LEO observations include TROPOMI, VIIRS, and PACE, and the GEO observations include GOES, Himawari, GEMS, Sentinel-4, and TEMPO.

As we move into an era of observations from geostationary satellites and applying the retrievals for operational monitoring and forecasting, it is important to analyze product performance and uncertainties on a sub-daily time scale. As aerosol changes due to chemistry and transport are captured at 5 – 60 minute time scales, accuracy and precision of these observations must be quantified on the same time scales. In particular, utilizing the suite of observations that will be available from the constellation should help reduce the difficulties of attributing satellite measured signal to surface and atmosphere over very heterogeneous and dry/arid regions.

GEO-CAPE studies have shown the important factors of water vapor, aerosol vertical profile, and aerosol type in determining the AOD-PM2.5 relationship. With more robust retrievals of AOD, AAOD, aerosol vertical profiles, aerosol type, and long-range transport characteristics from GEO-GEO and GEO-LEO synergy, the application of satellite observations for air quality can be better addressed with more confidence for user community.

3.4 Summary

The GEO-CAPE community reshaped the visionary but then-unaffordable notional 2007 DS mission by prioritizing the science set forth in the 2007 DS, by identifying separable instruments that could be fielded in a distributed implementation, and by actively responding to NASA Earth Venture opportunities to demonstrate that distributed implementation. NASA's 2012 selection of TEMPO and 2016 selection of GeoCARB represent first steps in delivering GEO-CAPE's compelling time-resolved science.

GEO-CAPE's objectives and associated requirements have remained remarkably stable over the last seven years of study team activities. GEO-CAPE funded activities have subsequently developed needed tools and demonstrated that the objectives are well able to be accomplished. As expressed in the 2017 DS, GEO-CAPE objectives are part of the current program of record and also associated with several of the future priorities. Tools and techniques developed via GEO-CAPE will continue to be useful for implementation of current missions and design of future missions.

4. MISSION AND INSTRUMENT CONCEPT STUDIES

This addendum to the 2015 report includes only content that has changed since the 2015 report. The 2015 report is available at:
https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

4.1 Mission Concept Studies

No changes.

4.2 Instrument Concept Studies

No changes.

4.3 Additional Studies

4.3.1 Studies in Support of Proposal Activities

In addition to studies funded as part of GEO-CAPE pre-formulation, the larger GEO-CAPE community invested in several high-quality peer-reviewed instrument concept studies, submitted to NASA as proposals to the Earth Venture (EV) Program. Most notable are the EV Instrument (EVI) 1 selection of the TEMPO investigation and EV Mission (EVM) 2 selection of the GeoCARB investigation. Several other GEO-CAPE Infra-Red Instrument (GCIRI) related concepts have been proposed to EV solicitations. Those that were evaluated as Category 2 (selectable) or better include 2011 EVM-1 Commercially Hosted spectRO-radiometer and New Opportunities for Science (CHRONOS), 2012 EVI-1 Geostationary Carbon Process Investigation (GCPI), 2013 EVI-2 CHRONOS, and 2016 EVI-4 TROpical Methane BiOsphere NASA Experiment (TROMBONE) and CHRONOS. Notably, the geostationary coastal ocean color Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR) mission was also proposed to 2016 EVI-4 and garnered favorable reviews for observational capabilities and science content, indicating the substantial progress made by GEO-CAPE team members to meet a majority of GEO-CAPE's science requirements at a fraction of the original cost estimates.

4.4 Summary

The conclusion from these studies is that GEO-CAPE remains ready for implementation. The phased hosted payload mission implementation strategy has provided flexibility to initiate new mission starts for components of the mission as funds have become available. Multiple instrument concepts are capable of achieving GEO-CAPE requirements with no new technology development required, and indeed two such concepts associated with GEO-CAPE atmospheric science (TEMPO and GeoCARB) are now in development. There remain other concepts that could complete GEO-CAPE atmospheric science should the need arise. Multiple instrument concepts are now capable of achieving the GEO-CAPE coastal waters science requirements within an affordable instrument cost range ($100M to $200M).

Full mission cost estimates for the distributed implementation strategy ultimately depend on the commercial market at the time of selection for each instrument. Over the past few months, it has become apparent that fewer host launch opportunities may be available than was forecast five years ago. This is due to a downturn in the market for new geostationary communications satellites, associated with increased longevity of existing satellites and still-pending standardization of next-generation telecommunications protocols. On the positive side, prospective hosts for TEMPO and GeoCARB have indicated that technical requirements are not an issue, and near-term host opportunities definitely exist. The challenge remains in synchronizing government procurement with the rapid approval-build-launch sequence that is standard practice in the communications satellite industry. It remains to be seen whether commercial payload hosting costs will change significantly from existing estimates.

5. Technology Assessment and Development

5.1 Introduction

The original technology readiness assessment for GEO-CAPE was provided in the 2007 DS:

"All the [GEO-CAPE] instruments have a low-Earth-orbit space heritage and are at a high level of technology readiness, and so launch would be feasible by 2015."

This addendum to the 2015 report includes only content that has changed since the 2015 report. The 2015 report is available at:
https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

5.2 Accomplishments 2016–2018

ESTO invested in a task with the Multi-slit Optimized Spectrometer (MOS) to add polarization (P) sensitivity measurement capability by adding polarization filters at different orientations over three of the slits. With GEO-CAPE funding, the resulting MOS-P configuration was added to the NASA King Air payload for KORUS-AQ/KORUS-OC and operated successfully during all flights over the 6-week period (see Section 6). While the performance evaluation of MOS-P with in situ measurements continues, with the polarization observations not as mature, an analysis of ocean remote sensing reflectance for the open slit appears quite good (Fig. 5-1).

One new activity was funded by ESTO and completed in this period: ATI-QRS-14-0009 for "COEDI Dual Slit Implementation." The objective was to develop a key technology for the Coastal Ecosystem Dynamics Imager (COEDI), a concept for a GEO-CAPE ocean color radiometer. The concept incorporates a dual-slit focal plane design, allowing smaller instrument aperture which results in a reduction in instrument volume. The project completed successfully in April 2018 with a starting TRL of 3 and finishing TRL of 4.

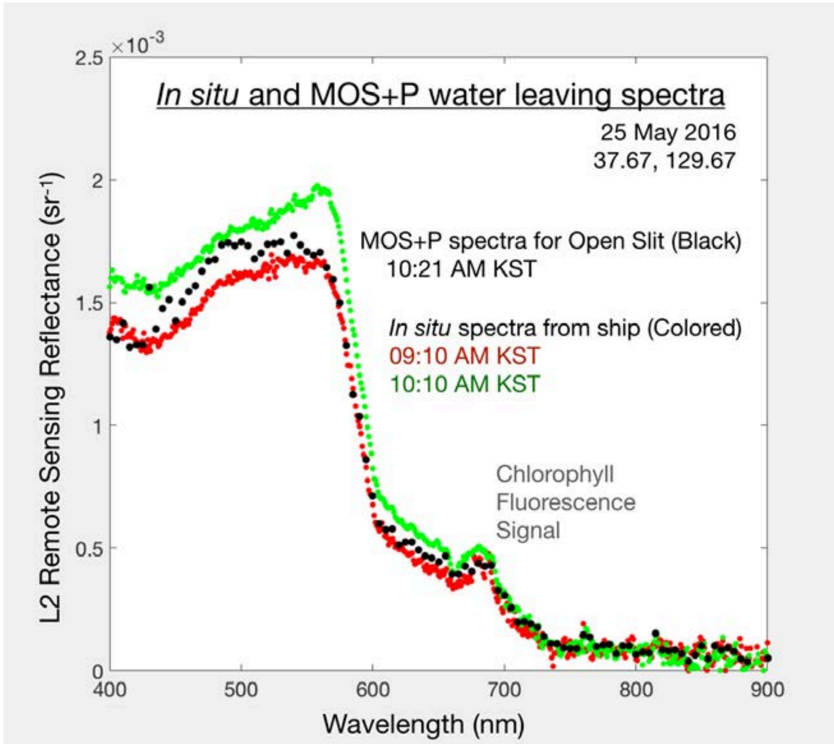


Figure 5-1. A comparison of KORUS-OC ocean remote sensing reflectance spectra ($R_{rs}(\lambda)$) from in situ measurements and MOS-P after atmospheric correction. A chlorophyll-a fluorescence signal (peak at ~680nm) is quite noticeable in both in situ and MOS-P data. MOS-P data represents an aggregation of 5x5 pixel array equivalent to a spatial resolution of ~ 225 m x 225 m at the sea surface. There is a small spatial offset between in situ and MOS-P observations due to sun glint contamination near ship. Figure courtesy of Nick Tufillaro, Oregon State University.

5.3 Ongoing and Future Work

The evaluation of MOS-P data products will continue through comparisons with observations from the ship, GOCI and GeoTASO.

Further technology development on the PanFTS instrument (see Section 5 of the 2015 report and Section 6.3.4 of this report) will mature the sensitivity and 2-D imaging of the instrument in preparation for the competed Decadal Survey 2017 mission opportunities.

5.4 Summary

GEO-CAPE studies started with several instrument concepts at high TRLs. ESTO investments during the early years of GEO-CAPE, particularly in IIP selections totaling $28M and ACT selections totaling $10M, resulted in robust high-performing instruments that are being used to collect GEO-CAPE related science data (see Section 6). ESTO assessments confirmed the maturity of multiple instruments and technologies presented for the GEO-CAPE mission.

6. FIELD CAMPAIGNS

6.1 Introduction

This addendum to the 2015 report includes only content that has changed since the 2015 report. The 2015 report is available at:
https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

The GEO-CAPE study team invested significant resources to conduct field campaigns during 2016-2018: 49% of total mission study funding in FY16, 32% in FY17, and 41% in FY18. In addition, up to 50% of annual resources were devoted each year to analysis of data acquired in GEO-CAPE funded field campaigns. The campaigns continued to serve the needs of both the ocean color and atmospheric science communities and to leverage major activities funded by other Earth Science Division program elements and also by federal and state partners. The data collected during these campaigns are publicly available from the Airborne Science Data for Atmospheric Composition portal, https://www-air.larc.nasa.gov.

6.2 Coastal Ocean Color Studies 2016-2018

6.2.1 Risk reduction measurements for GEO-CAPE: US-Korea joint field campaign in the East Sea and Yellow Sea

The Korea-United States Oceanographic (ocean color) Field Study (KORUS-OC) was an intensive ship-based field study focused on ocean color in the coastal waters surrounding the Korean peninsula, where the Geostationary Ocean Color Imager (GOCI) captures eight hourly images daily. Members of the GEO-CAPE OSWG and scientists from the Korea Institute of Ocean Science and Technology (KIOST) worked together to define, coordinate and accomplish the oceanographic field campaign. The basis for the NASA-KIOST collaboration on KORUS-OC is detailed in a Memorandum of Understanding (MOU). KORUS-OC was also developed in conjunction with the KORUS-AQ airborne and satellite observations (see Section 6.3.1), and the two collaborative studies integrated ship-based measurements with the airborne and satellite measurements to understand the dynamics of coastal water, gain insight into the limitations of satellite-based observations to retrieve ocean properties on diurnal time scales, correct satellite-based observations for atmospheric properties, and explore atmosphere-ocean interactions.

Biological and biogeochemical processes play critical roles in forming and modulating the ecosystems of both open ocean and coastal environments. Observing and monitoring the spatial and temporal changes of these environments are important for maintaining the quality of life for everyone on Earth. Decades of operation of CZCS, SeaWiFS, MODIS, and other sensors have demonstrated that Sun-synchronous ocean color missions can provide excellent observations on longer-term (weeks to years) biogeochemical processes, but are unable to detect/monitor short-term (diurnal to a few weeks) processes, such as the dynamics of algae blooms, tidal dynamics, and diurnal changes in photosynthesis. Due to the unique sampling strategy and sensor-target geometry, as well as the demand to address a wide range of challenging scientific questions, the radiometric sensor for GEO-CAPE cannot simply be a duplicate of the historical sensors such as SeaWiFS or MODIS. In addition to frequent sampling (every hour or better), the GEO-CAPE sensor is required to be able to provide high-spatial and high-spectral resolution measurements with high signal-to-noise ratios (SNR).

To facilitate the design of such a sensor, a series of field campaigns for risk-reduction purposes was performed in the Chesapeake Bay region (2011) and the northern Gulf of Mexico (2013). Please see details in the 2015 GEO-CAPE White Paper (available at https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf).

Because these previous campaigns did not include measurements from a geostationary platform, they were unable to address specific questions related to using such a sensor to study the dynamics of coastal waters, including:

a) Can the diurnal changes in sediment resuspension and settling be resolved with hourly satellite normalized-water leaving radiance (nLw) data?

b) Can the diurnal dynamics in organic carbon (dissolved and particulate) due to tidal exchanges at land-ocean interfaces be resolved in hourly nLw data?

c) How do particle size, shape and composition impact the ocean bi-directional reflectance distribution function (BRDF) and in turn the nLw signature at different view angles during a diurnal period?

d) Can diurnal changes in CDOM from production and photooxidation be detected with hourly data from a geostationary satellite?

e) How accurately do the atmospheric properties need to be estimated in order to obtain reliable diurnal nLw from a geostationary satellite?

f) How does BRDF variation in water-leaving radiance (Lw, w/m2/nm/sr) affect the GOCI hourly nLw retrievals?

g) Given the spatial and spectral specifications of GOCI how well can we address the diurnal variation of biogeochemical properties in the coastal oceans? What improvements are needed in future sensors to address coastal dynamics?

h) How do geostationary ocean color products compare with both polar-orbiting ocean color satellite products and with *in-situ* measurements?

i) To what extent can hourly geostationary data improve the estimation of primary productivity?

To address these questions that are important for characterizing a geostationary coastal ocean-color sensor, and to obtain important data for risk reduction of the GEO-CAPE mission, an 18-day field campaign with Korean scientists in the East and Yellow Seas was executed in May-June 2016 (Figure 6-1). These waters are directly under the field-of-view (FOV) of GOCI, the first ever geostationary-based ocean color satellite (launched in June 2009) in operation. Thus, we were able to obtain unique datasets that include both *in-situ* measurements and geostationary ocean-color satellite data to address various technique questions such as those listed above. Data from this field campaign are being analyzed to define the limitations of the present GOCI measurements regarding the retrieval of biogeochemical properties and to provide key information on satellite specific issues, e.g., impacts of atmospheric corrections, view angle, and diurnal solar radiance variability on the quality of satellite retrievals.

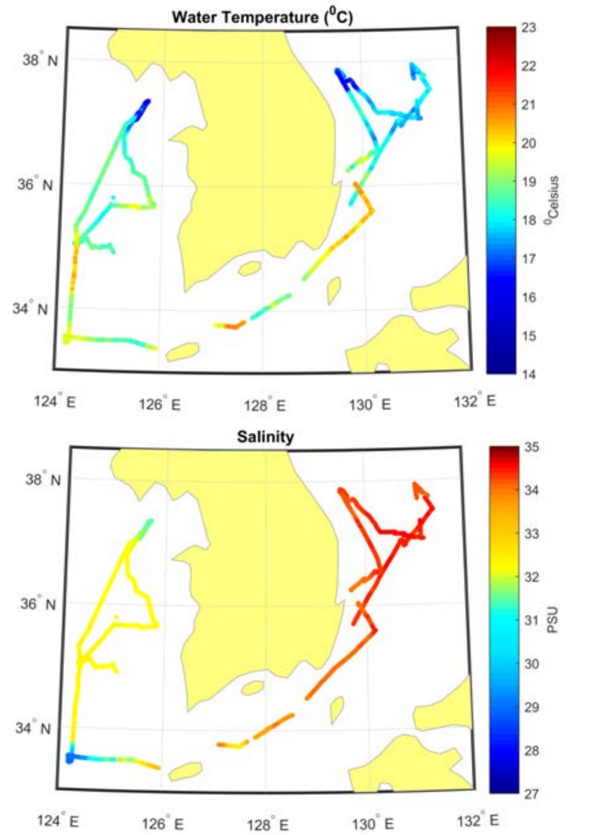


Figure 6-1. Map of the cruise track of the Research Vessel Onnuri, colored by observed (top) Sea Surface Temperature, and (bottom) Seas Surface Salinity. (Credit: J. Salisbury, UNH)

NASA and the Korean Institute of Ocean Science and Technology (KIOST) made ship-based observations on the KIOST research vessels Onnuri and Jang-Mok 1. The activities on Jang-Mok 1 (KOKOA) were sponsored by KIOST, which extended special invitations to U.S. and Canadian scientists primarily for instrument training purposes. Nevertheless, the science objectives and measurements were consistent with KORUS-OC. By comparing ship-based measurements with GOCI retrievals (Figure 6-2), we can examine retrievals throughout the day as a function of evolving conditions both in water and in the atmosphere, and collaborate with KIOST on optimizing retrievals from geostationary orbit in preparation for GEO-CAPE.

The GEO-CAPE team measured hyperspectral above- and in-water radiometry and in-water IOPs, phytoplankton taxonomy, pigments, primary productivity, respiration, carbon pools, and nutrients, along with ship-based atmospheric trace gases and aerosol properties. Such data will allow researchers to parameterize hyperspectral algorithms for phytoplankton functional groups, atmospheric corrections and primary productivity. A Pandora remote sensing spectrometer for trace gas column measurements was also part of the instrument complement on the R/V Onnuri, continuing the GEO-CAPE legacy of concurrently deploying multiple copies of this instrument in support of both atmospheric and ocean science. The capability for shipborne implementation has truly been an advancement. Further, the collaboration between ocean color and atmospheric scientists aboard ship provided an opportunity for novel application of measurement approaches across disciplines.

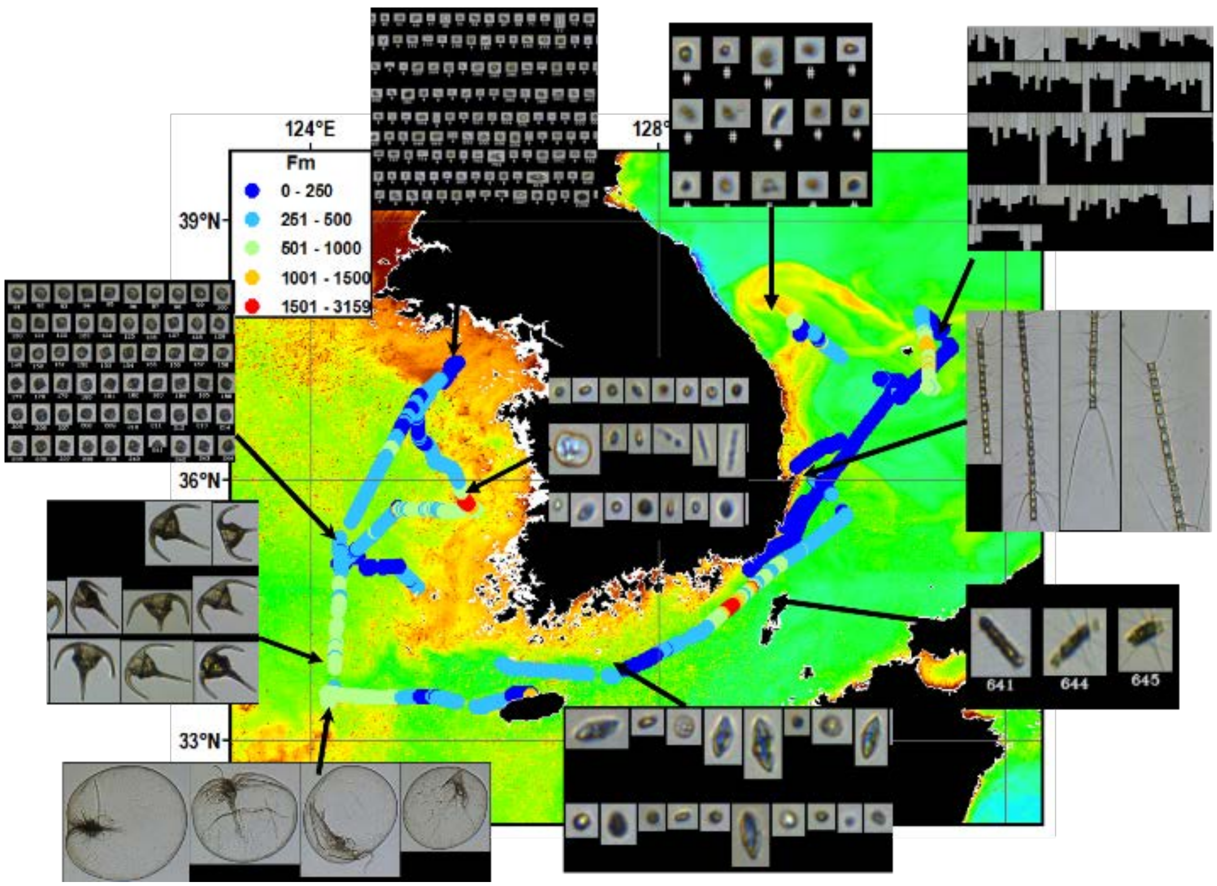


Figure 6-2. Results of a study of chlorophyll-a levels measured from a satellite using the Korean GOCI sensor, as well as both the chlorophyll-a maximal fluorescence (Fm) and the size, type, diversity, and amount of plankton in the research area measured using instruments on board the Onnuri research vessel. The base color image represents the difference in chlorophyll-a concentrations around the Korean peninsula and the colored discs represent the Chlorophyll-a Fm. (Credit: Joaquim Goes, Columbia University/LDEO)

NASA also collected airborne remote sensing ocean color and air quality measurements from the NASA King Air aircraft along the ship tracks using the hyperspectral airborne GeoTASO and MOS+P instruments, as well as DC-8 airborne measurements of atmospheric aerosols and trace gases as part of the complementary KORUS-Air Quality (KORUS-AQ) campaign (Figure 6-3). The trace gas and aerosol payloads on the R/V Onnuri provided a link to the KORUS-AQ data set by expanding its measurement domain to the surface over water. GEO-CAPE funded all costs associated with deploying the ESTO-funded MOS+P; the over-water data have been geo-registered and corrected for atmospheric effects, and are available for research.

Figure 6-3. The NASA DC-8, carrying a variety of aerosol measurement payloads as part of the KORUS-AQ experiment, samples over the Onnuri. The instrument pictured on the support structure near the bow of the ship is the HyperSAS instrument, which is composed of three hyperspectral sensors and an autonomous solar tracker used to analyze the sun-sky-water geometry for the KORUS-OC experiment. (Credit: Melissa Melendez, UNH)

A notable benefit of geostationary data over data from polar orbiting sensors is the ability to track ocean features and biogeochemical inventories at high temporal frequency. During the cruise the crew launched instrumented drogues designed to measure optical properties and the net dynamic behavior of oxygen over time, space and depth. These data coincided with shipboard IOP and AOP data and are being used to understand whether the accounting of the net behavior of biogenic stocks in time and space represents a fundamentally new means of estimating community productivity of carbon.

Ultimately, NASA and KIOST will use the results of KORUS-OC to help researchers understand the connections between ocean properties and ocean productivity, harmful algal blooms, oil spills, pollution, fisheries, and more. One tangible example of the interconnectedness of all human activities worldwide was the ubiquitous distribution of microbeads of plastics attached to detrital materials (Figure 6-4). Another is the distribution of nuisance and harmful algal blooms that were encountered in the Yangtze Plume and south of Korean Peninsula. Such algae could have a link to human activity such as aquaculture and discharge of waste.

An international constellation of geostationary sensors is envisioned from Asia to the Americas to Europe. Developing international partnerships and collaborations is essential to the success of a truly international global observing system, and this joint field campaign with our Korean partners was an important step in developing such collaborations.

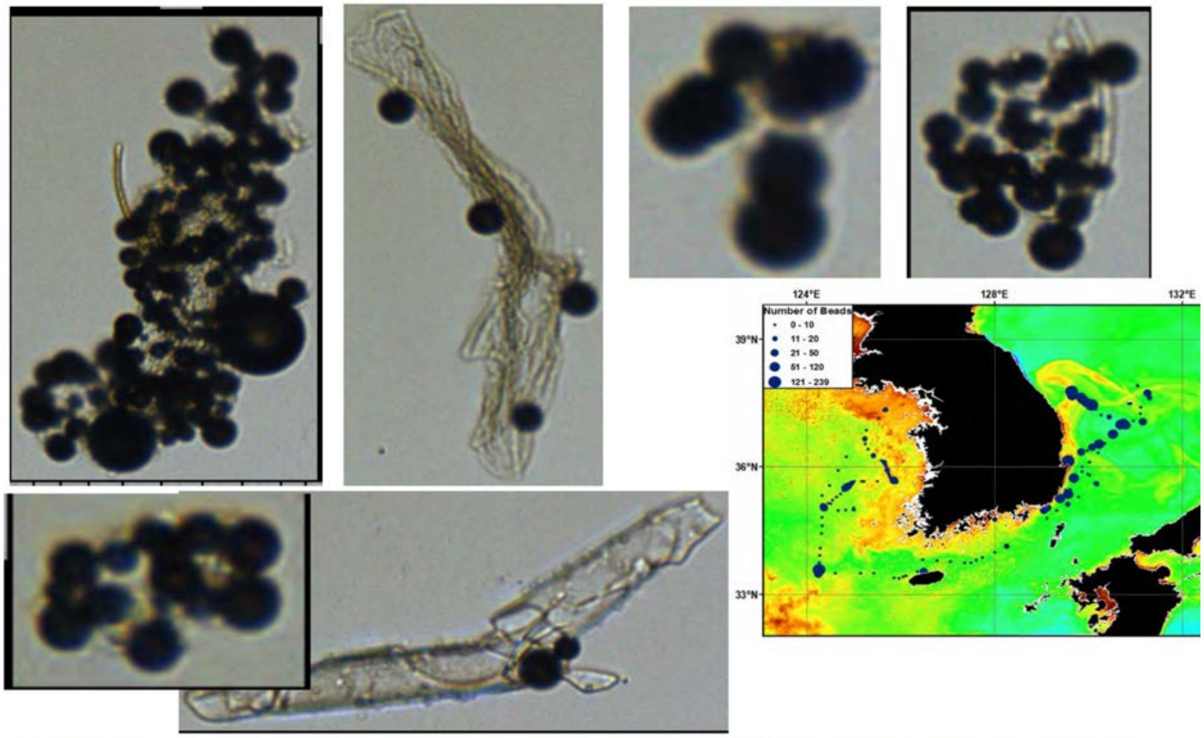


Figure 6-4. Microbeads adhering to detrital particles. The particles were ubiquitous, but concentrated near shore, in the East Sea and the Yangtze Plume. The particles ranged from ~5 - 60um, a size distribution which approximates the size of phytoplankton. Research is ongoing into the role of microplastics on optical properties and their role in ecosystem functioning.

6.2.2 Ongoing and Future Work

KORUS–OC data are presently being analyzed and the first manuscripts are expected to be submitted by year's end. In an effort to archive work relevant to the KORUS cruise, contributions have been solicited for a Special Issue of Remote Sensing entitled, "Remote Sensing of Short-Term Coastal Ocean Processes Enabled from Geostationary Vantage Point." Guest editors are GEO-CAPE SWG team members Nima Palevan and Steven Lohrenz as well as Yu-Hwan Ahn and David Antoine.

Future work will include presentations by US and Korean team members at the 2019 International Ocean Colour Science Meeting in Busan, Korea.

6.3 Atmospheric Composition Studies 2016-2018

As in previous field campaigns, a goal of GEO-CAPE's involvement in these field studies is improving the ability of the public to use air quality information from satellites, in particular the upcoming geostationary measurements from the Tropospheric Emissions: Monitoring Pollution (TEMPO) and its sister mission Geostationary Environment Monitoring Spectrometer (GEMS).

6.3.1 2016 Korea-US Air Quality (KORUS-AQ) Study

During May-June 2016, GEO-CAPE funded deployment of a NASA King Air to Seoul, Korea, to provide an airborne remote sensing platform for the KORUS-AQ campaign led by NASA R&A and Korea's National Institute for Environmental Research. The primary payload on the King Air was the Geostationary Trace gas and Aerosol Sensor Optimization (GEO-TASO) instrument previously developed under ESTO funding. GeoTASO is an airborne simulator for geostationary TEMPO and GEMS observations. GEO-CAPE funding allowed for 30 science flights in Korea, totaling 124 flight hours.

Korea was an excellent location for conducting geostationary air quality simulator measurements, given the linked development of the TEMPO and Korean GEMS instruments. These measurements fostered ongoing TEMPO/GEMS algorithm collaboration and harmonization and supported CEOS AC-VC Air Quality constellation objectives. As demonstrated during DISCOVER-AQ Denver, an optimal flight strategy for simulating geostationary observations is to conduct regular raster flights at constant altitude to map pollutant distributions across an area multiple times per day. The primary NASA aircraft in KORUS-AQ, the NASA DC-8, spent substantial flight time conducting vertical profiling with an in-situ payload. Flight plans for the two aircraft were closely coordinated, with the King Air and GeoTASO flying above the DC-8, in order to create an integrated set of observations. Deployment in concert with this campaign provided extensive correlative ground-based and airborne observations for evaluation of the TEMPO and GEMS data product retrievals. For the first time, a flight pattern that provided mapping 4 times through a day was executed (Figure 6-5), providing data for evaluating the diurnal air mass factor (AMF) calculation that will be critical for TEMPO and GEMS data products.

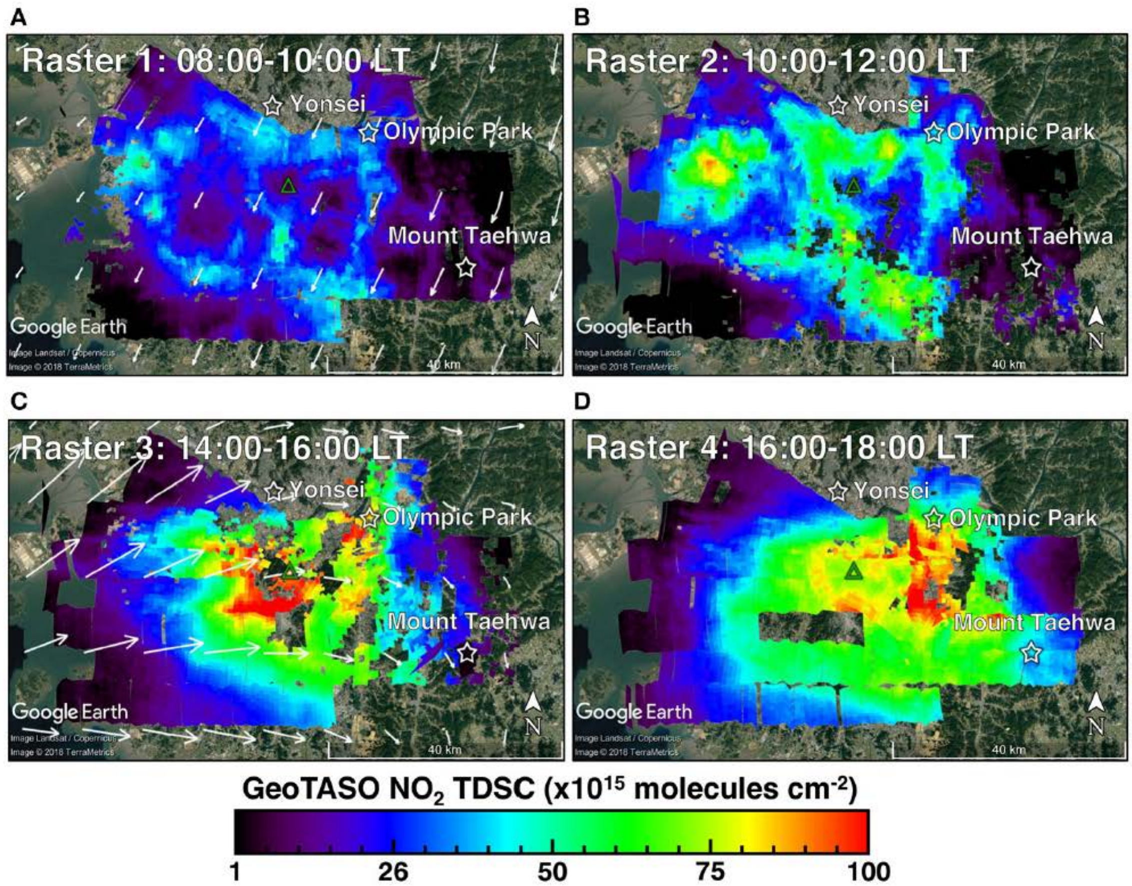


Figure 6-5. Maps of GeoTASO NO_2 tropospheric differential slant column (TDSC) over Seoul on June 9th, 2016 for (a) Raster 1 from 08:00-10:00 LT, (b) Raster 2 from 10:00-12:00 LT, (c) Raster 3 from 14:00-16:00 LT, and (d) Raster 4 from 16:00-18:00 LT. Pandora sites are labeled with white star icons. Rasters 1 and 3 includes wind vectors averaged through the lowest 500 m agl from the full resolution Global Data Assimilation System (GDAS) at (a) 00:00 UTC (09:00 LT) and (c) 06:00 UTC (15:00 LT). [Reproduced from Judd et al., 2018]

6.3.2 2017 Lake Michigan Ozone Study (LMOS) and Student Airborne Research Program (SARP)

The 2017 LMOS study started as a tiger team activity within NASA AQAST/HAQAST to work with state/regional air quality planners to demonstrate the usage of satellite observations in their development of implementation plans for attaining compliance with air quality standards in communities along the western shoreline of Lake Michigan. The GEO-CAPE team saw a clear opportunity to engage potential future users of TEMPO data in this region by again providing test-bed data sets with a TEMPO airborne simulator. A NASA King Air with Geo-TASO was deployed to Madison, WI, for 1 month and conducted 21 science flights totaling 100 local flight hours. Building on knowledge gained in previous campaigns, these flights provided raster mapping measurements multiple times per day over the two primary LMOS ground supersites and also over the Chicago metropolitan area, a major source of the pollutant emissions that can impact the LMOS study area. As in previous campaigns, ground assets (including a network of Pandora spectrometers) and high-resolution chemical modeling support provided by partners reflect the considerable leveraging attained in these community-initiated "grass-roots" studies. Preliminary results show that emissions from local large point sources (e.g., power plants) must be considered in addition to large upwind regional emissions (e.g., Chicago and Milwaukee) to address air quality concerns in this coastal environment.

After LMOS the King Air and GeoTASO team proceeded to Armstrong Flight Research Center to participate in the 2017 NASA SARP program. Flight plans were developed to conduct 3 separate flights each day over the Los Angeles basin (Figure 6-6), taking 2 different SARP students on each flight to provide 12 students with a hands-on research experience. NASA again worked with local air quality management organizations, this time to emplace Pandora spectrometers at 6 air quality monitoring sites across LA basin. These instruments were operated throughout the summer, providing longer term context for the two days of SARP measurements. Preliminary results from the summer 2017 campaigns show that TEMPO's spatial resolution will be able to capture the variability of column NO_2 observed across these two different urban regions in the US, which has not been possible with previous satellites [Judd et al., AGU 2017 and manuscript in preparation 2018].

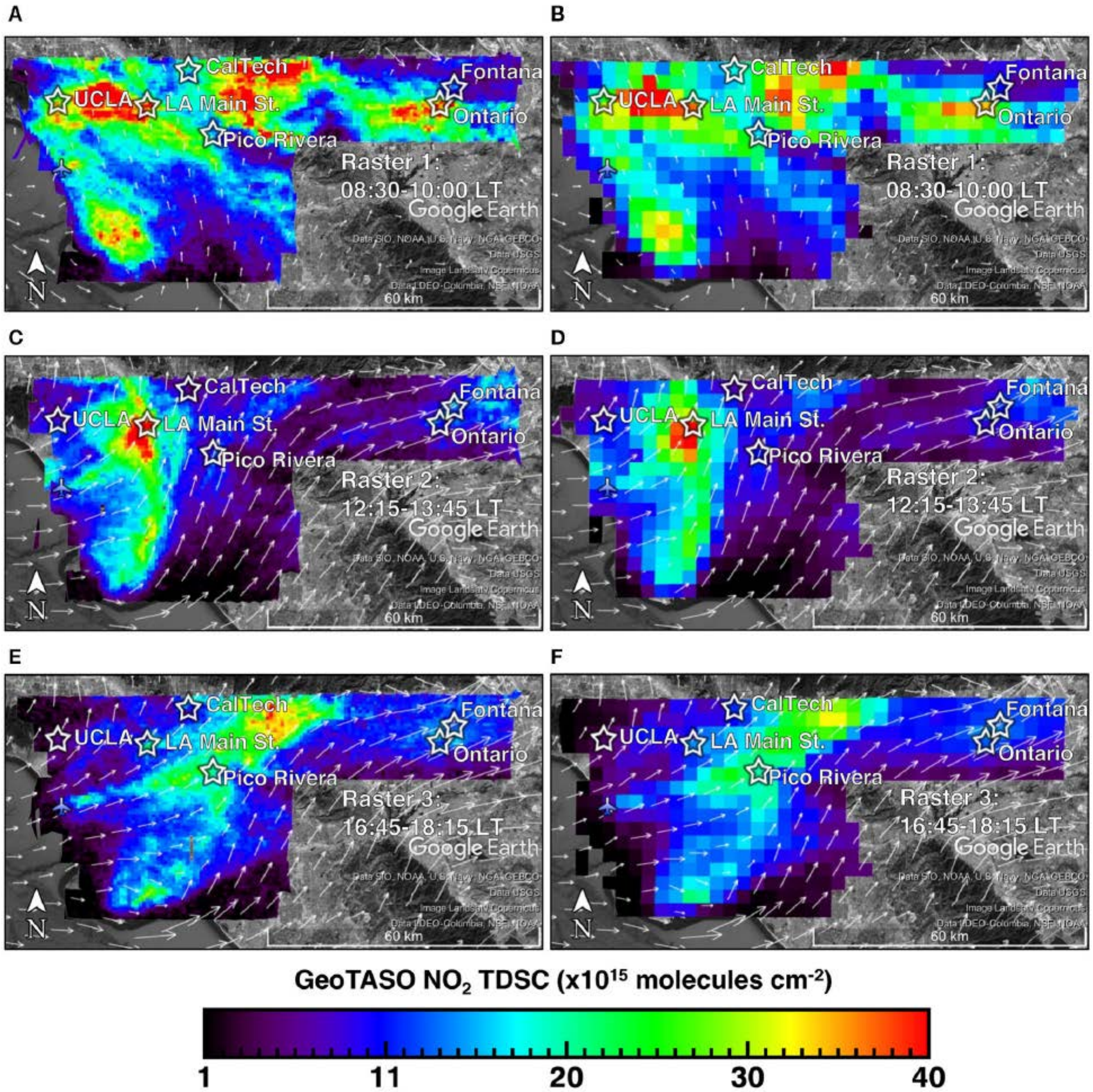


Figure 6-6. Maps of GeoTASO NO_2 TDSCs over the LA Basin on June 27th, 2017. Raster 1 from 08:30-10:00 LT is shown in a and b, Raster 2 from 12:15-13:45 LT is shown in c and d, and Raster 3 from 16:45-18:15 LT is shown in e and f. Panels a, c, and e are at 750 m x 750 m resolution, whereas b, d, and f are the TDSCs binned to 3 km x 3 km spatial resolution. Overlaid are the boundary layer averaged wind vectors from the NAM-CONUS 3-km nest analysis for 16:00 UTC (09:00 LT) in a and b, 20:00 UTC (13:00 LT) in c and d, and 00:00 UTC (17:00 LT) in e and f. [Reproduced from Judd et al., 2018]

6.3.3 2018 Long Island Sound Tropospheric Ozone Study (LISTOS)

In summer 2018, U.S. air quality stakeholders again pooled resources to conduct a field study with both science and policy aspects, LISTOS, noting that "the New York City (NYC) metropolitan area… continues to persistently violate both past and recently revised federal health-based air quality standards for ground-level ozone" [https://www.nescaum.org/documents/listos]. NASA's involvement included extensive airborne remote sensing measurements funded by GEO-CAPE, deployment and operations of two ground-based ozone lidar systems, ozone sonde launches, and support of a ground-based network of NASA-developed Pandora remote sensing instruments. Partners, including the Northeast States for Coordinated Air Use Management (NESCAUM) and their university partners, US EPA, and NOAA, provided continuous forecasting and analysis support, airborne in-situ measurements, and extensive measurements from ground sites, two mobile labs, and two ships.

The NASA LISTOS flights interchangeably used two instruments that are airborne simulators for TEMPO: GeoTASO and the GEO-CAPE Airborne Simulator (GCAS). A unique aspect of the LISTOS campaign was the ability to make measurements through the entire summer. By basing from LaRC and having flexibility to use either GCAS or GeoTASO on multiple aircraft, the team was able to conduct 30 flights totaling 140 flight hours during 15 sampling days from mid-June through mid-September while adapting to other scheduled usage of the aircraft. This flexibility allowed a wide range of weather conditions to be sampled through the summer, including classic heat waves resulting in unhealthy ozone throughout the region, other weather patterns resulting in more localized high ozone, and relatively clean background conditions.

The airborne GCAS and GeoTASO observations mapped the LISTOS domain up to 4 times per day, providing researchers and air quality managers with TEMPO-like data so they can improve preparations for using TEMPO data. LISTOS measurements are also being used to help with validation of data products from the new TROPOspheric Monitoring Instrument (TROPOMI) on the European Space Agency Sentinel-5 Precursor satellite launched last fall. Afternoon LISTOS flights were timed to coincide with TROPOMI overpasses on each flight day (Figure 6-7, Figure 6-8). While TROPOMI provides air quality measurements with a factor of 10 improvement in spatial resolution from previous satellites, its observations from low Earth orbit occur only once each day. Geostationary TEMPO observations will provide hourly measurements through the day at similar spatial resolution to TROPOMI.

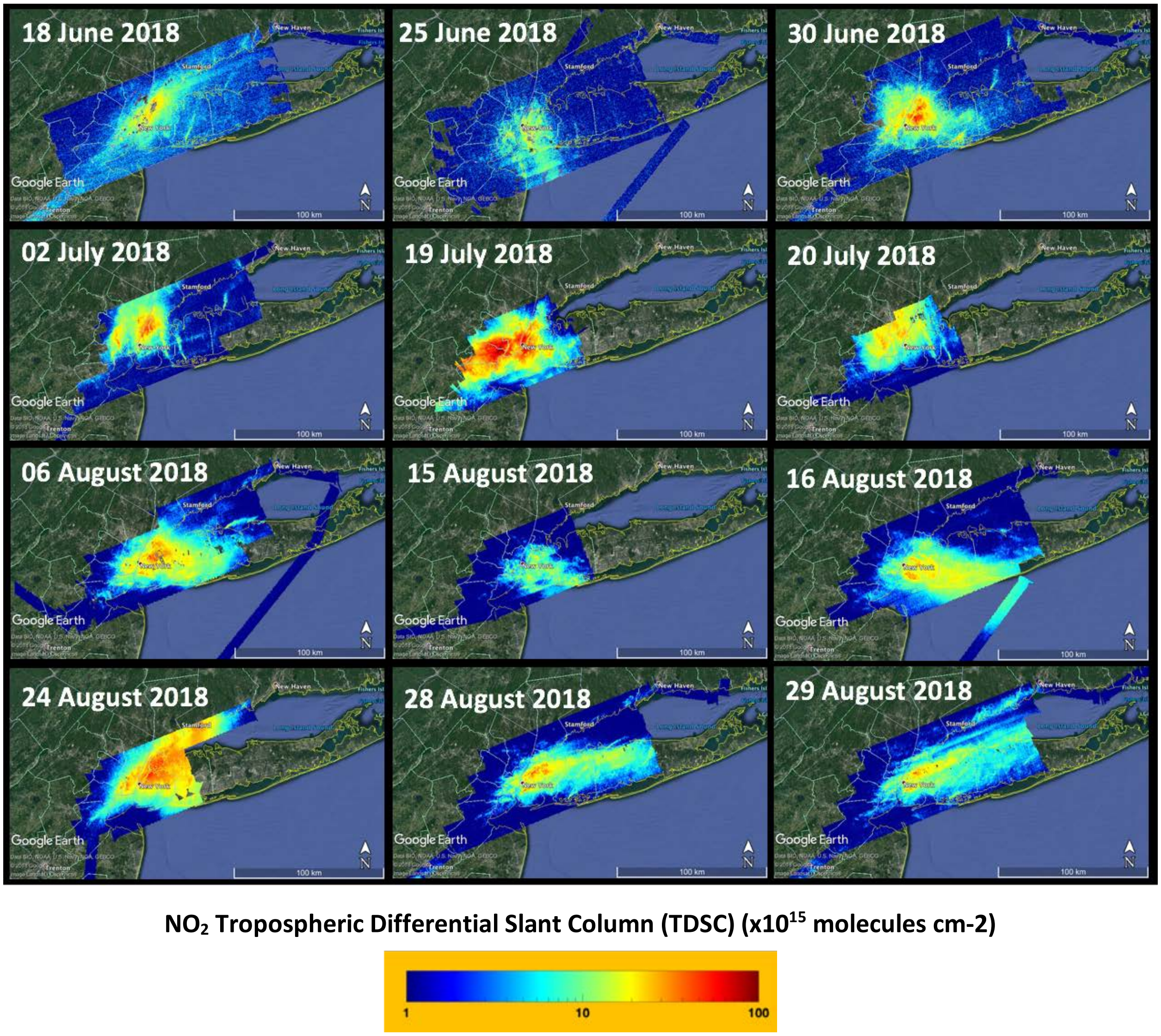
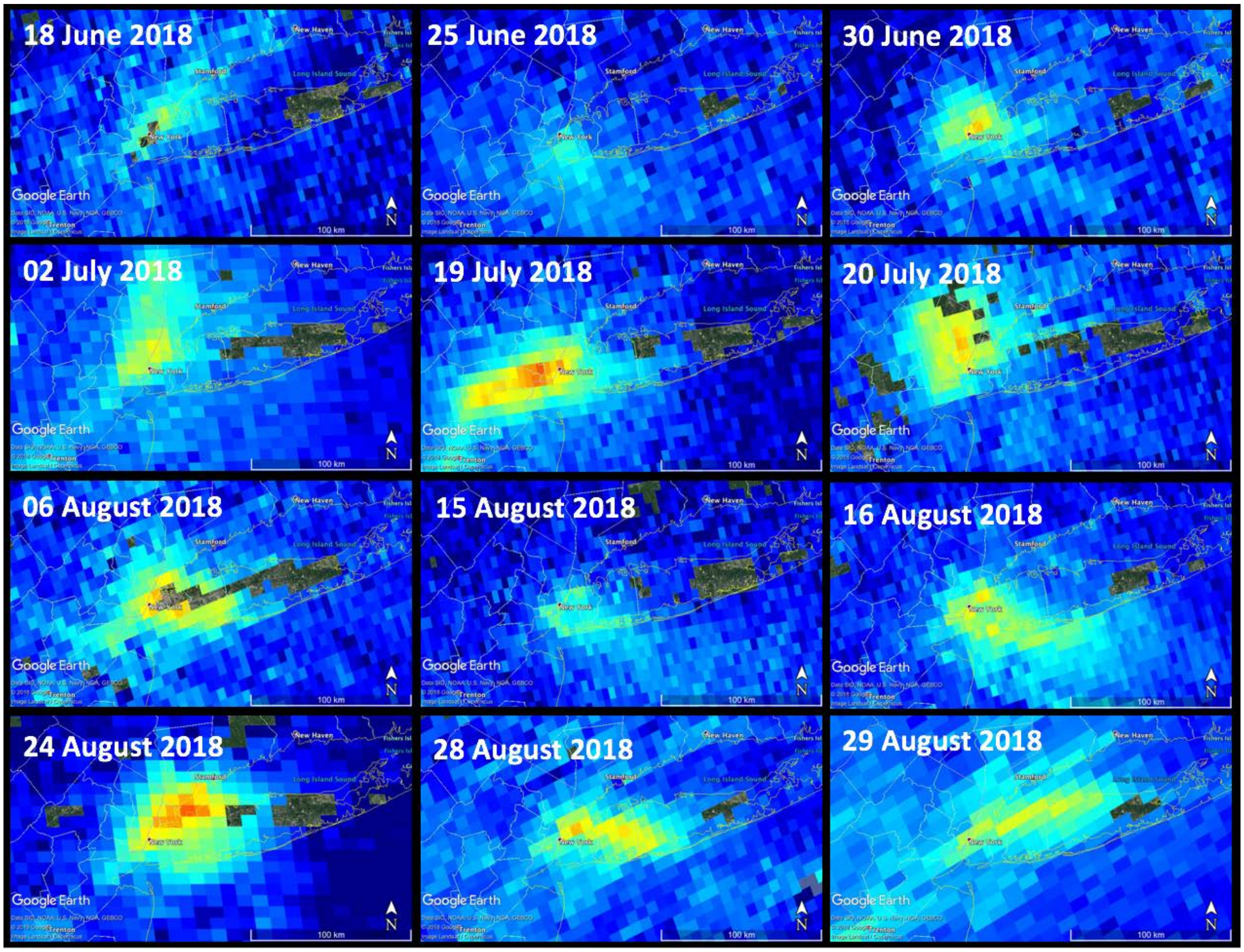


Figure 6-7. Maps of GCAS and GeoTASO NO_2 TDSCs over the Long Island Sound for afternoon flights during summer 2018 (through August) that include coincidences with TROPOMI overpasses.

Phase 1 of LISTOS, during June, used GeoTASO on the LaRC HU-25A Falcon aircraft. In addition to mapping the LISTOS domain, the range of the Falcon allowed these flights to also map pollutants in the Baltimore area in support of the OWLETS-2 air quality campaign (Sullivan et al., 2018). Phase 2, July through early September, used GCAS on the LaRC B-200 King Air aircraft. In addition to GCAS, the capability of the B-200 also allowed inclusion of the new High Altitude Lidar Observatory (HALO) instrument to provide information on aerosol vertical distribution and the mixing depth of pollutants. This information, critical for accurately inferring surface concentrations from the satellite remote sensing measurements, is also



NO_2 Tropospheric Vertical Column (x10^{15} molecules cm-2)

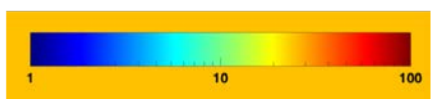


Figure 6-8. Maps of TROPOMI NO_2 tropospheric vertical column over the Long Island Sound on LISTOS flight days during summer 2018 (through August). Attribution: *"The presented work has been performed in the frame of the Sentinel-5 Precursor Validation Team (S5PVT) or Level 1/Level 2 Product Working Group activities. Results are based on preliminary (not fully calibrated/validated) Sentinel-5 Precursor data that will still change."*

especially helpful for analysis of air quality events in coastal regions such as Long Island Sound. Phase 3 of LISTOS, to occur in late September, will use the B-200 with GeoTASO and a new Multi-axis Optical Airborne Tracker (MOAT). MOAT will allow improved GeoTASO zenith measurements, providing data very useful for ongoing testing of new TEMPO algorithms for retrieving ozone vertical profile in the troposphere.

6.3.4 CLARS FTS activities 2016-2018

In the 2016-2018 time period, GEO-CAPE provided partial support for continuing operations of the CLARS-FTS and PanFTS-EM instruments at JPL's California Laboratory for Atmospheric Remote Sensing (CLARS) facility on Mt. Wilson, California. Overlooking the Los Angeles basin at an altitude of 5700 ft. ASL, CLARS simulates the observations that will be made from geostationary platforms: high spatial and temporal resolution, large field of regard, rapidly re-programmable concept of operations, and repeat cycles several times per day. Fourier transform spectrometers such as CLARS-FTS and PanFTS are ideally suited for geostationary observations, combining 2-D imaging with a square field of regard with a very wide spectral grasp for retrieval of multiple trace gases and aerosols.

6.3.4.1 CLARS measurements of CH_4 emissions trends

CLARS-FTS continued daily measurements (weather permitting) of CO_2, CH_4, CO, water vapor and O_2. The CLARS time series began in late 2011. These measurements were processed into maps of dry air column abundances for the three key trace gases four to eight times per day with a spatial resolution of 0.2-2 km. Measurements of water vapor in multiple spectral bands along with O_2 also provided retrievals of aerosol optical depth using a new method (Zeng et al., 2017). By combining the retrievals of CH_4 and CO_2 with a high-resolution bottom-up emission inventory of CO_2, spatially and temporally resolved CH_4 emissions were deduced over a 6-year time period for the Los Angeles basin (Figure 6-9). These results demonstrated that measurements from geostationary orbit can quantify the temporal and spatial variations of gaseous emissions that are important for air quality and climate, the first science question posed in the GEO-CAPE Science Traceability Matrix (STM).

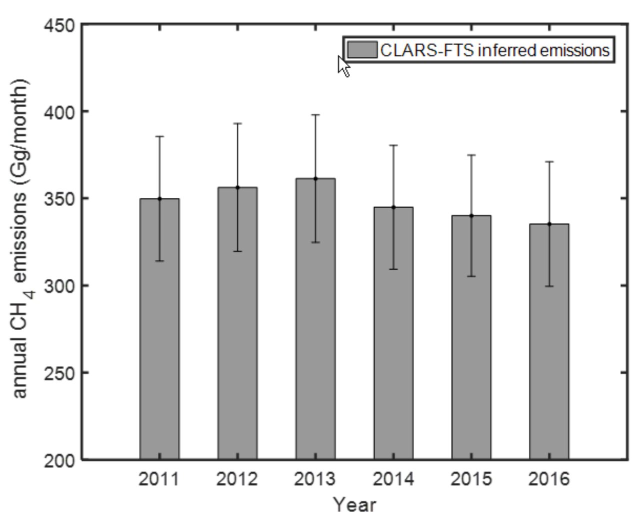


Figure 6-9. Annual CH_4 emissions for the Los Angeles basin inferred from CLARS-FTS measurements of XCH_4/XCO_2 combined with a bottom-up CO_2 emissions inventory. Data for 2017 and 2018 were acquired but not yet processed.

6.3.4.2 Mapping the Aliso Canyon natural gas blowout

In October, 2015, a very large natural gas storage well in Aliso Canyon, north of downtown Los Angeles, blew out, releasing ~100 Mt of processed natural gas into the atmosphere before it was capped in February, 2016. Daily CLARS maps of $XCH_{4,\ excess}$ revealed the spatial extent of the methane plume from the well blowout with CH_4 column abundances in the boundary layer occasionally exceeding 50 times their normal levels. A representative time series of the over 200

CLARS maps from the leak period is shown in Figure 6-10. Direct sampling and remote sensing of the near-source CH_4 plumes took place using aircraft instruments, but it required instrumentation with the high retrieval precision, and spatial/temporal resolution of the CLARS-FTS to map the area of elevated CH_4 far downwind of the source. Using these data, emissions estimates into the CLARS field of regard were calculated, showing the decrease in emissions over time as the natural gas storage well depressurized. These results demonstrated that measurements from geostationary orbit can determine how episodic events affect atmospheric composition and air quality, one of the science questions enumerated in the GEO-CAPE STM.

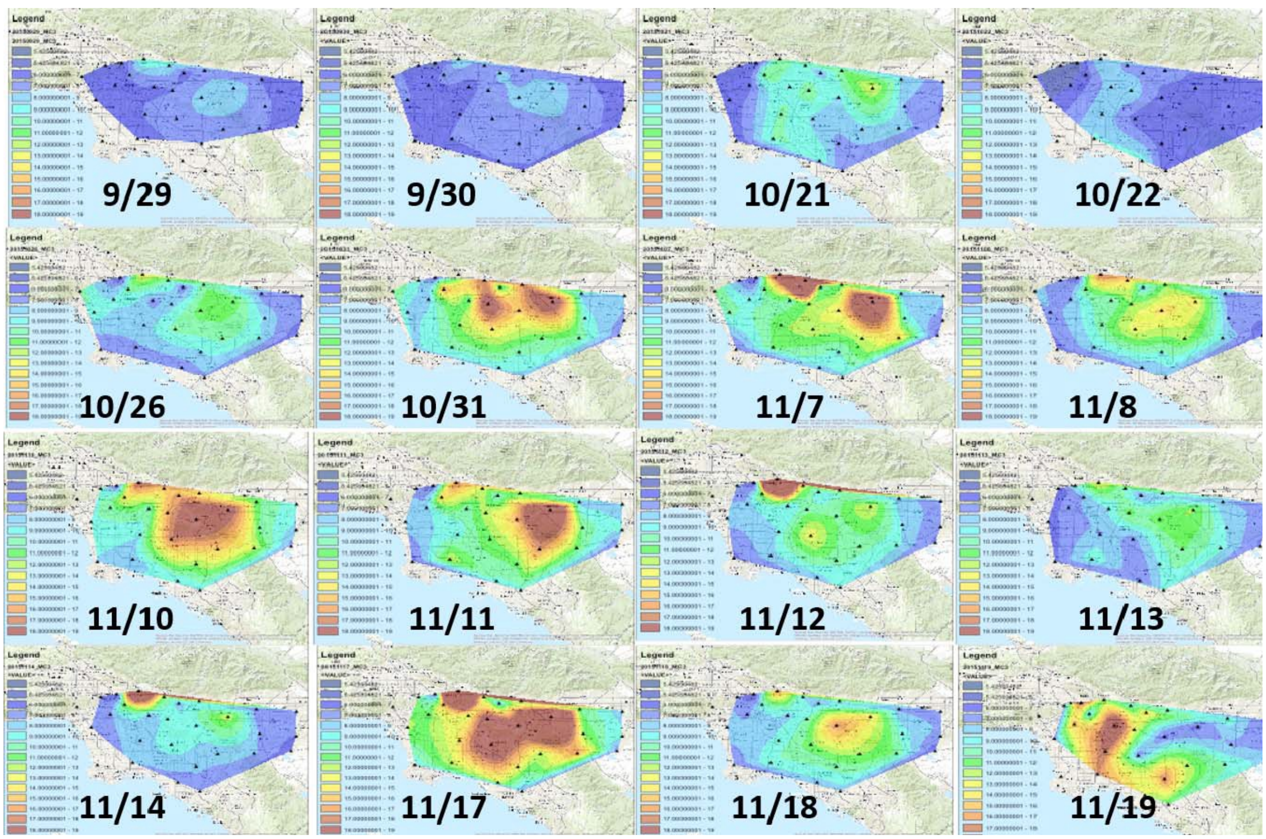


Figure 6-10. Sample maps during 2015 of $(XCH_4/XCO_2)_{excess}$ during the period of the Aliso Canyon natural gas well blowout. The maps from 9/29-10/22 are typical of conditions before the blowout, which occurred on 10/23/18. The site of the blowout was not visible from CLARS so only the CH_4 advected downwind could be observed. Observed conditions returned to normal in mid-February, 2016 following the capping of the well.

6.3.4.3 CLARS measurements of CO in the Los Angeles atmosphere

Carbon monoxide (CO) is an EPA Criteria Pollutant and a key target trace gas for GEO-CAPE. Ground-based *in-situ* monitoring instruments that are part of the South Coast Air Quality Management District's network have been monitoring CO surface concentrations for several decades. However, these instruments do not have high precision required to see small changes in CO. In addition there have been no previous time-resolved measurements of CO column abundances as would be measured from a geostationary mission such as GeoCarb.

In this work, we have used CLARS-FTS retrievals over several years to characterize the spatial and temporal variability of CO in the LA basin. Figure 6-11 shows XCO hourly averages from 0830-1630 during the month of June. The highest values of XCO in the morning are seen in the northwest part of the basin along the I-405 corridor where vehicular traffic is extremely high. As the sea breeze strengthens during the day, the high CO levels move progressively inland with the plume strengthening along the foothills of the San Gabriel Mountains to the north of the LA basin. The measurements also show a large weekend/weekday effect which has also been observed for other pollutants including NO_x. These data again show how measurements with high spatial and temporal resolution such as those that will be obtained from GEO-CAPE can reveal details of emissions processes that are not observable from LEO platforms.

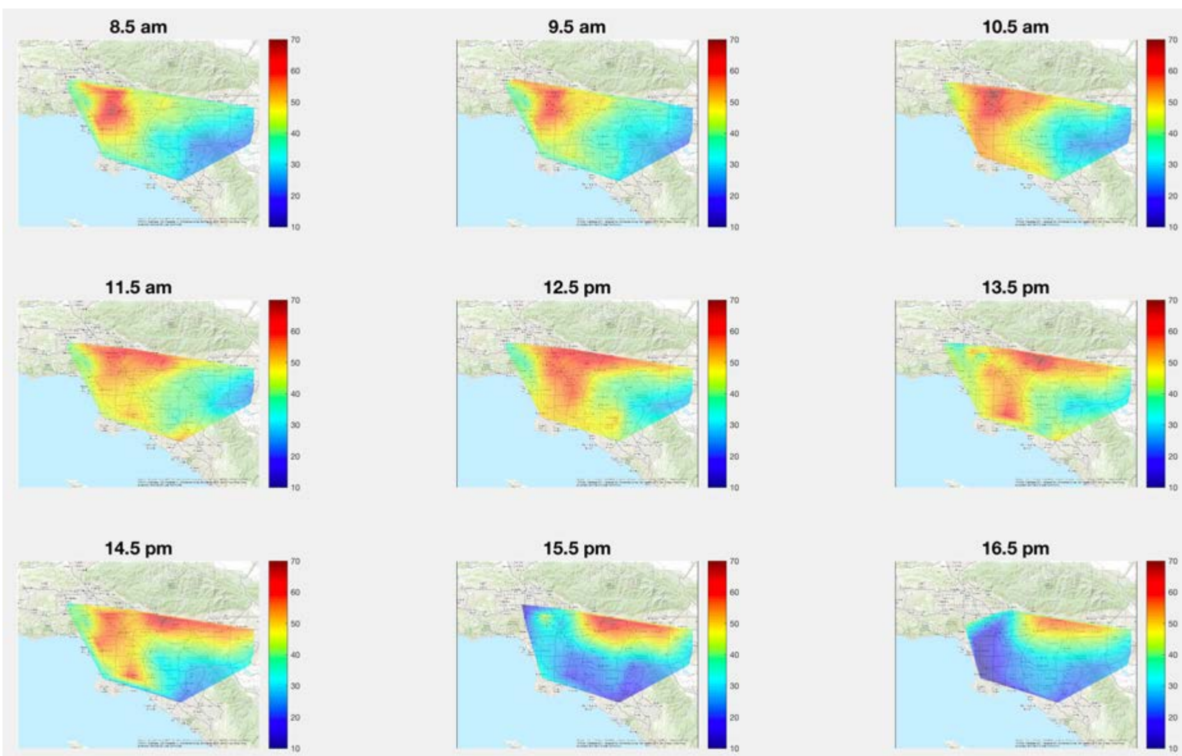


Figure 6-11. Hourly maps of CO distributions in the Los Angeles basin using data from CLARS-FTS.

6.3.5 Ongoing and Future Work

Work is ongoing to produce final data products from the 2017 and 2018 airborne campaigns, in particular the retrieval of products other than NO_2 and the calculation of air mass factors

(AMFs) necessary to produce tropospheric vertical column densities (VCDs) similar to the satellite products. AMF calculation requires ancillary inputs including information from high spatial resolution chemical models. At present, our partners in these studies are committed to providing the model simulations, and a full-time NASA post-doctoral researcher will create and publicly archive the VCD products in FY19. Final level-1b data will also be publicly archived to allow other groups to conduct independent retrieval studies. Future work, potentially via NASA ROSES solicitations, will continue to analyze these rich datasets. The LISTOS data are being used to contribute to TROPOMI validation via participation in the ESA Sentinel-5 Precursor Validation Team. The data are also informing validation strategies that will be used for TEMPO. Preliminary work has shown excellent agreement of these airborne data with measurements from Pandora spectrometers, which will be the primary source of TEMPO validation data. Future work will help assess impacts of sub-pixel heterogeneity of TROPOMI, TEMPO, and similar satellite instruments.

CLARS measurements will continue with sponsorship of the California Air Resources Board and NASA ROSES programs. The primary objective will be to extend the 7-year continuous time series of CO_2, CH_4, CO, water vapor and aerosol measurements, and to further develop retrievals of solar induced fluorescence (SIF) from vegetation. New algorithms are being developed for aerosol retrievals to exploit the multi-angle and multi-spectral dimensions of the CLARS data. Further technology development on PanFTS will mature the sensitivity and 2-D imaging of the instrument in preparation for the competed Decadal Survey 2017 mission opportunities.

6.4 Summary

Field campaigns conducted with GEO-CAPE study funding have provided sample data that demonstrate the value of GEO-CAPE data products. These activities have provided data for affirming and adjusting GEO-CAPE science measurement requirements. The data are being used to test and refine retrieval algorithms for geostationary data products and to engage ultimate users of TEMPO and other satellite data products. The campaigns have very effectively leveraged activities within other ESD program elements and with national and international partners. Validation strategies that will be used for TEMPO have been demonstrated.

Via these campaigns, the GEO-CAPE team has engaged air quality scientists, practitioners, and managers in the regions experiencing the worst air quality in the US: Gulf Coast (Houston), Mountain West (Denver), Mid-West (Chicago), West Coast (Los Angeles), Mid-Atlantic (Baltimore Washington) and Northeast (New York and Long Island Sound). These survey activities have generated strong anticipation for GEO-CAPE data.

7. Measurement Algorithms

7.1 Introduction

At the beginning of GEO-CAPE studies, algorithms to derive data products from passive remote sensing radiances had mature heritage from low-Earth-orbit missions for both the ocean color and atmospheric composition disciplines. Mission study activities therefore generally focused on improvements to existing algorithms to adapt them to GEO-CAPE requirements. Examples include enabling accurate water data products in complex near-shore scenes and atmospheric data products at higher spatial resolution and at times of day other than the 2 satellite overpass times previously available from low-Earth orbit (LEO) missions.

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https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

7.2 Coastal Ocean Color Studies

7.2.1 Coastal Ocean Color Studies Accomplishments 2016-2018

Many of the algorithm improvements during the final period of GEO-CAPE studies expanded heritage (open-ocean) algorithms into optically complex coastal waters, or improved simplified inputs or parameterizations. Many of the studies reported here relied critically on significant quantities of high-quality *in-situ* data, highlighting the fundamental need for continued support and execution of oceanographic and airborne field measurement activities.

In turbid coastal waters, standard atmospheric correction algorithms often exhibit large inaccuracies that may lead to negative water-leaving radiances (Lw) or remote sensing reflectance (Rrs). Fan et al. (2017) introduced a new atmospheric correction algorithm for coastal waters based on a multilayer neural network (MLNN) method that it is robust and resilient to contamination due to sunglint or adjacency effects of land and cloud edges. The MLNN algorithm is very fast once the neural network has been properly trained and is therefore suitable for operational use. Fan et al. (2016) also applied neural network methods to correct bidirectional effects in water-leaving radiance. In Case 1 or chlorophyll-dominated waters, their neural network method produces corrections similar to those of the standard method. In Case 2 waters, especially sediment-dominated waters, significant improvement was obtained compared to the standard method. Lee et al. (2018) advocated for the application of models of the diffuse attenuation coefficient of downwelling irradiance (Kd) that are not only consistent with radiative transfer but also provide more accurate estimates, in particular for coastal turbid waters.

Results from Lee et al. (2016) indicate that it is necessary to use a more generalized Rrs–IOP (Inherent Optical Properties) model to describe the spectral variation of Rrs of high-sediment-load waters from the visible to the shortwave infrared region. These results will improve our understanding of the spectral signatures of Rrs in these conditions and subsequently improve the retrieval of IOPs from ocean color remote sensing, which could further help the estimation of sediment loading of such waters.

Yang et al. (2018) showed that the standard MODIS chlorophyll-a (Chl-a) algorithm, OC3M, underestimated Chl-a; the authors developed a new empirical switching algorithm based on the relationship between *in-situ* Chl-a and the blue-to-green band ratio, providing results with improved errors. Cao et al. (2018) used a rich dataset of field observations to develop and validate new CDOM (Colored Dissolved Organic Matter) and DOC (Dissolved Organic Carbon) algorithms that are broadly applicable to different estuarine and coastal regions, over different seasons and a wide range of in-water conditions. Application of these algorithms to multi-year MERIS satellite imagery over the Chesapeake Bay estuary allowed, for the first time, to capture the impact of tidal exchanges on carbon dynamics along wetland-estuary interfaces using composited images across a month for low tides and a high tide event, and resolved spatial gradients, seasonal variability, and year-to-year changes in estuarine carbon amount and quality associated with marsh carbon export, riverine inputs, and extreme precipitation events. Sub-diurnal observations from GEO-CAPE or comparable geostationary sensor is required to quantify the impact of tidal exchanges on carbon dynamics. Sahay et al. (2017) developed a new, regionally-tuned model of phytoplankton size classes, and comparisons with shipboard measurements of showed the superiority over parameterizations used in the predecessor model, capturing the seasonal cycle in the Arabian Sea.

Although highly variable in natural waters, in most remote sensing algorithms, the spectral slope of the absorption coefficient of colored dissolved and detrital material (Scdm) is either kept as a constant or empirically modeled with multi-band ocean color in the visible domain. Wei at el. (2016a) explored the potential of semi-analytically retrieving Scdm with added ocean color information in the ultraviolet (UV) range between 360-400 nm and showed that adding UV wavelengths to the ocean color measurements will improve the retrieval of Scdm from remote sensing reflectance considerably. Lee et al. (2015a) presented hyperspectral absorption coefficients of "pure" seawater in the range of 350–550 nm and obtained better retrievals of the phytoplankton absorption coefficient in oligotrophic oceans. Their findings will also provide better closure of remote sensing reflectance for the UV–visible domain.

A clever solution from Robinson et al. (2016) reduces the amount of cloud masking required for data collected from GOCI, thus increasing the available useful data. The length of time it takes to acquire all 8 GOCI bands for a given portion of a scene requires that cloud motion be taken into account, and inter-band correlations can be used to measure the amount of cloud shift, which can then be used to adjust the cloud mask so that the union of all shifted masks can act as a mask for all bands.

Diffuse reflectance in the visible, which is ignored in current glint algorithms, has been shown by Lin et al. (2016) to be important. Their new treatment of ocean glint reflectance and surface roughness in an optimized discrete-ordinate radiative transfer model (DISORT3) will help improve glint correction algorithms in current and future ocean color remote sensing applications.

Beyond improvements to heritage algorithms, some studies worked to increase the information content and application of existing data. Wei et al. (2016b) developed a novel quality assurance (QA) system that can be used to objectively evaluate the quality of an individual Rrs spectrum. The reference system includes Rrs spectra of 23 optical water types ranging from purple blue to yellow waters, and questionable or likely erroneous Rrs spectra are shown to be well identified. Application of this QA system to ocean color satellite data can improve the short- and long-term products by objectively excluding questionable Rrs data. Wang et al. (2017) showed that multi-spectral satellite remote sensing data can be decomposed to yield Gaussian curves, and the obtained chlorophyll *a* and phycocyanin concentrations from these Gaussian peak heights demonstrated potential application to monitor harmful algal blooms (HABs) and identification of phytoplankton groups from satellite ocean color remote sensing semi-analytically.

And yet gaps in our knowledge remain. The work of Moore et al. (2017) provides new insights into the optical properties of cyanobacteria blooms, and indicates that current semi-analytic models are likely to have problems resolving a closed solution in these types of waters, as many of their *in-situ* observations were beyond the range of existing model components. From a remote sensing perspective, this presents a challenge not only in terms of a need for new algorithms, but also for determining when to apply the best algorithm for a given situation.

The remote estimation of sea surface salinity (SSS) in coastal waters has been difficult because satellite sensors designed to "measure" SSS lack sufficient resolution, and higher-resolution ocean color measurements suffer from optical and biogeochemical complexity. Using extensive SSS datasets collected by many groups spanning > 10 years, coupled with MODIS and SeaWiFS reflectance data, Chen and Hu (2017) showed that SSS can be estimated from ocean color satellites, despite the significant limitation of lack of coverage due to clouds, stray light, and sun glint. A geo-stationary ocean color mission is expected to significantly enhance the capacity to estimate SSS in dynamic coastal regions, thus providing critical data to study coastal and estuarine ecology.

7.2.2 Ongoing and Future Work

In the coming years, GEO-CAPE field campaign datasets from KORUS-OC, GoMex and CBODAQ will be exploited further to improve coastal ocean color algorithms including atmospheric correction, BRDF effects, phytoplankton community composition, IOPs, DOC and POC, phytoplankton pigments, particle size distribution, net primary and net community production. Efforts will continue through GOCI data analysis to apply knowledge, algorithms and datasets obtained or developed with GEO-CAPE support to quantify coastal ocean productivity on sub-diurnal to multi-day time scales. Future work on the follow-on GOCI-II sensor, which will have a band in the UV and three additional bands in the visible spectrum, will undoubtedly make use of KORUS-OC, KORUS-AQ and other GEO-CAPE algorithms and datasets. Such rich datasets from GEO-CAPE will aid future PACE science teams, as well as Earth Venture geostationary sensor teams, in development of algorithms that employ UV hyperspectral field measurements and data taken at hourly time intervals to derive similar products for nearshore, coastal ocean and open ocean waters.

7.3 Atmospheric Composition Studies

7.3.1 Atmospheric Composition Studies Accomplishments 2016–2018

Accomplishments related to Measurement Algorithms were tightly linked to progress on the development of Mission Science Requirements and Objectives. Four efforts in particular are highlighted here, but the reader is encouraged to refer to the accomplishments reported in Section 3 as well.

The GEO-CAPE Aerosol Working Group was tasked with evaluating different retrieval techniques and exploring multi-platform synergistic approaches for retrieving aerosol total and absorption optical depth, aerosol type, and altitude information that will meet the measurement requirements to answer the GEO-CAPE science questions. In the 2016-2018 period, this group demonstrated synergistic retrieval of aerosol information from the two complementary geostationary satellite instruments on TEMPO and GOES-16. Specifically, they: ***a)*** demonstrated that the 2 km ABI cloud mask can be remapped to the TEMPO grid (4.7 km x 2.1 km) to screen for pixels contaminated with clouds prior to attempting aerosol retrievals; ***b)*** derived AOD, aerosol type, and aerosol height using the extended wavelength range combination from TEMPO and ABI (TEMPO: UV to VIS; ABI: VIS to IR) for smoke and dust separation; ***c)*** evaluated MAIAC AOD with correlative measurements from AERONET, VIIRS, and MODIS; ***d)*** demonstrated the capability of retrieving AOD and spectral AAOD with MAIAC from the extended spectral range (UV-IR) measured by the GLI instrument on the Japanese ADEOS-II satellite; and ***e)*** adapted MAIAC for retrieving AOD from the AHI-8 instrument on the Japanese geostationary satellite Himawari as proxy of GOES-16 and 17 retrievals. These studies have shown that the synergistic approach takes advantages of the capabilities from TEMPO and ABI to obtain additional key aerosol products of aerosol absorption and aerosol type, including the potential of identifying black carbon and brown carbon in smoke plumes.

Further efforts of the Aerosol Working Group explored retrieving aerosol layer height information. Three kinds of attempts have been made to estimate the aerosol layer height: (1) obtaining the AOD at UV by extrapolating the quality AOD at the visible wavelength (e.g., from ABI), then estimating the aerosol layer height using UV AOD and absorption information; (2) estimating the effective height of smoke plume from the brightness temperature contrast between the smoke plume and smoke-free background, assuming an average temperature lapse rate; and (3) using O_2-A or O_2-B bands under certain conditions. Each method has limitations and systematic validations to assess the errors, uncertainties, and feasibilities are still needed.

Additional improvements to measurement algorithms were accomplished by the Emissions Working Group, which was formed to illustrate and understand the potential of geostationary remote sensing measurements to constrain emissions. The projects undertaken focused on aspects that require high temporal and spatial resolution and are thus novel with regards to going beyond the capabilities of existing measurement platforms to constrain emissions.

NO_2 retrievals from OMI were conducted in Laughner et al. (2018a; b) that exploit higher resolution prior information than is used in current standard operational products, which will be a key aspect of developing NO_2 retrievals for TEMPO. The data details of the Berkeley High Resolution NO_2 retrieval are described in Laughner et al. (2018b). These were compared (Laughner et al., 2018a) against *in-situ* aircraft profiles, Pandora vertical column densities, and WRF-Chem simulation, finding that using daily NO_2 profiles improves the vertical column densities retrieved in urban areas relative to low resolution or monthly a priori by amounts that are large compared to current uncertainties in NO_x emissions and chemistry (of order 10% to 30%). Based on this analysis, suggestions are made for considerations when designing retrieval algorithms and validation procedures for upcoming geostationary satellites.

The importance of fine spatial and temporal resolution a priori profile information on the retrieval was determined in Kim et al. (2018), who conducted approximately 45,000 radiative transfer (RT) model calculations in the Los Angeles Basin (LA Basin) megacity. Their analyses suggest that an air mass factor (AMF, a factor converting observed slant columns to vertical columns) based on fine spatial and temporal resolution a priori profiles can better capture the spatial distributions of the enhanced HCHO plumes in an urban area than the nearly constant AMFs used for current operational products by increasing the columns by ~50% in the domain-average and up to 100% at a finer scale.

7.3.2 Ongoing and Future Work

The data collected during the summer 2018 LISTOS campaign (Section 6) will greatly aid further development of hyperspectral aerosol retrieval algorithms from geostationary observations (e.g., Hou et al., 2016, Hou et al., 2017). The repetition of flight tracks over multiple times of day and multiple days through the summer will allow accurate characterization of variations in surface reflectance, alleviating previous challenges associated with airborne hyperspectral retrievals.

Additional progress in aerosol retrievals can be made in producing systematically the synergistic (GEO-GEO and LEO-LEO) products of AOD, AAOD, aerosol type, and aerosol height using the UV-VIS-IR synergistic approach. Candidate combinations include: (1) TEMPO-ABI over the US, (2) GEMS-AMI-AHI over Asia, and (3) TROPOMI-VIIRS globally.

7.4 Summary

The refinements that the GEO-CAPE study team made to measurement algorithms will enable launch-readiness of high-quality coastal ocean color and air quality data products. Data acquired in field campaigns (Section 6) are allowing the algorithms to be tested and improved, while the modeling and OSSE frameworks developed (Section 3) will lead to broad use and application of the data products. Much of the progress is also directly applicable to data products from the EVI-1 TEMPO and PACE missions.

8. SUPPORT AND INVESTMENTS FROM OTHER ESD ELEMENTS

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GEO-CAPE development activities have continued to be well aligned and integrated with funded activities from other ESD program areas.

8.1 Flight

The EVM-2 Geostationary Carbon Cycle Observatory (GeoCARB) project has potential to partially meet the GEO-CAPE atmospheric science requirements associated with infrared measurements, depending on its final configuration and observing strategy, and also demonstrates an alternative partnering strategy for a commercial hosted payload mission. GeoCARB measurement capability may meet GEO-CAPE science traceability matrix (STM) requirements for a CH_4 product and would provide some information for CO but would not meet GEO-CAPE STM requirements for a CO product.

Ongoing Earth System Science Pathfinder Program activity to select a host satellite for the TEMPO mission continues to inform the GEO-CAPE strategy of utilizing geostationary commercial hosts.

8.2 Research and Analysis

The Korea-U.S. Air Quality (KORUS-AQ) study (see Section 6) was completed as a strong collaboration between the R&A Program and GEO-CAPE. While the R&A Program funded the majority of KORUS-AQ, including the GeoTASO instrument team on the NASA King Air, GEO-CAPE funded the flights of the King Air, the participation of the MOS instrument, and NASA's share of the companion ship-based Korea-U.S. Ocean Color (KORUS-OC) campaign. These campaigns, in the field of regard of the world's first geostationary ocean color mission, provided a wealth of data for evaluating and improving geostationary satellite retrievals.

The R&A Program is making sustained investments in the Pandora project to deploy a long-term network of ground-based spectrometers for acquiring column measurements of O_3, NO_2, and HCHO. These are the primary data products retrieved from air quality satellite instruments including TEMPO and TROPOMI, and Pandora measurements several times per hour will be the primary source of TEMPO validation data. Further, the R&A Program is partnering with the U.S. EPA to co-locate many of these instruments with reference *in-situ* measurements at long-term monitoring sites across the U.S., which will greatly increase the policy relevance of TEMPO observations.

The R&A Program continues to support ground-based tropospheric ozone profile measurements using lidar systems. The Tropospheric Ozone Lidar Network (TOLNet) includes systems at five institutions across the U.S. and one in Canada. Four of the systems are deployable to locations away from their home institutions. TOLNet data are providing an increasing database of the temporal variation of near-surface ozone at better than hourly time resolution. Because observations many times per day are fundamental to GEO-CAPE science, the TOLNet measurements are providing sample data sets that are useful for GEO-CAPE retrieval algorithm development.

8.3 Applied Sciences Program

The NASA Health and Air Quality Applied Sciences Team (HAQAST) was created in 2016 by the NASA Applied Sciences Program to serve the needs of U.S. air quality and public health management through the use of Earth Science satellite data, suborbital data, and models. They have the resources to carry out quick-turnaround projects responding to urgent and evolving needs of air quality management. HAQAST interactions led to the formulation of the 2017 Lake Michigan Ozone Study (LMOS) in a partnership between state, regional, and federal air quality management and research organizations. HAQAST interactions also helped lead to the 2018 Long Island Sound Tropospheric Ozone Study (LISTOS), a similar collaboration among state, regional and federal partners. Airborne TEMPO/GEO-CAPE simulator observations were a major component of both of these studies, familiarizing potential end users of TEMPO data with its capabilities. See Section 6 for additional details of these studies.

8.4 Earth Science Technology Office

No changes from 2015 report.

9. CLOSING THOUGHTS

The 2007 Decadal Survey (DS) "Earth Science and Applications from Space" was a first for the NASA Earth Science Division (ESD). While the recommendations were broadly endorsed by the U.S. Earth science and applications communities, it became apparent that assumptions made in the 2007 DS regarding future ESD budgets were optimistic. Faced with this situation, ESD initiated an unprecedented strategy of funding all 9 of the so-called Tier-1 and Tier-2 missions to conduct mission definition studies to help guide planning and preparation for potential new mission formulation. This approach has proven exceptionally fruitful in the case of GEO-CAPE.

GEO-CAPE was a challenging fit in the ESD program, especially in a constrained budgetary environment, because of its geostationary orbit and notional payload of multiple instruments serving two very different sets of observing requirements. The study team leaders developed a strategy to engage the broadest possible range of stakeholders, including multiple NASA centers, federal partners, and universities. In addition to conducting the required concurrent-engineering design studies and technology assessments, study team funding provided effective seeds for building and maintaining broad stakeholder involvement. Team members were able to leverage other ongoing activities to support focused GEO-CAPE needs at low cost to the program, and in many cases contributed their efforts at no cost. After 2–3 years of study and vigorous debate, the team came to consensus that the best strategy for GEO-CAPE was to avoid scope creep, constrain costs, and remain as small and flexible as possible to enable most of the science of GEO-CAPE to be accomplished sooner rather than waiting until later to accomplish "all" the science. The EV-I TEMPO mission, EV-M GeoCARB mission, and multiple other well-rated proposals to the EV solicitations are fruitions of this spirit.

The 2017 DS reiterates the highest importance of GEO-CAPE atmospheric and coastal ocean science. The atmospheric observations are now largely being implemented as part of the Program of Record. Remaining components of GEO-CAPE, including aerosols, greenhouse gases, and trace gas vertical profiles, appear in recommended Designated and Explorer missions. It is gratifying to see that teaming lessons learned from the GEO-CAPE experience are apparently being adopted and improved upon for the 2017 DS mission studies. While the GEO-CAPE study team approach of funding many small competed activities succeeded in fostering broad community engagement, planning and managing this approach on an annual basis made it unnecessarily challenging to undertake activities requiring multiple years (for example the development of frameworks for observing system simulation experiments). The collaborative multi-Center, broad-stakeholder, multi-year approach being undertaken by ESD for the 2017 DS Designated missions appears promising for continuing to advance critical needs for Earth science and applications. The study team again expresses its thanks to ESD leadership for its vision in constructing these "first DS" study teams and sustainably funding them over a period of years. It is the team's belief that ESD obtained excellent value from its investment.

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11. ACRONYMS AND ABBREVIATIONS

A&CCP	Aerosols and Clouds, Convection, and Precipitation
AAOD	Absorbing Aerosol Optical Depth
ABI	Advanced Baseline Imager
ACAM	Airborne Compact Atmospheric Mapper
ACC	Atmospheric Composition Constellation
ACT	Advanced Component Technology
AC-VC	Atmospheric Composition – Virtual Constellation
AERONET	Aerosol Robotic Network
AERONET-OC	Aerosol Robotic Network Ocean Color
AHI	Advanced Himawari Imager
AIST	Advanced Information Systems Technology
AK	Averaging Kernel
AMF	Air Mass Factor
AOD	Aerosol Optical Depth
AOP	Apparent Optical Property
AOT	Aerosol Optical Thickness
AQAST	Air Quality Applied Sciences Team
ASP	Airborne Science Programs
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASWG	Atmosphere Science Working Group
ATBD	Algorithm Theoretical Basis Document
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BRDF	Bidirectional Reflectance Distribution Function
CBODAQ	Chesapeake Bay Oceanographic campaign with DISCOVER-AQ
CDM	Colored Detrital Matter
CDOM	Colored Dissolved Organic Matter
CEDI	Coastal Ecosystem Dynamics Imager
CLARS	California Laboratory for Atmospheric Remote Sensing
COEDI	Coastal Ocean Ecosystem Dynamics Imager
CEOS	Committee on Earth Observation Satellites
CH_4	methane
Chl-a	Chlorophyll-a
CHRONOS	Commercially Hosted spectRO-radiometer and New Opportunities for Science
CII	Common Instrument Interface
CLARS	California Laboratory for Atmospheric Remote Sensing

CO	carbon monoxide
CO_2	carbon dioxide
COAST	Coastal Ocean Applications and Science Team
CONUS	Continental United States
CrIS	Cross-track Infrared Sounder
CTM	Chemical Transport Model
CZCS	Coastal Zone Color Scanner
DC3	Deep Convective Clouds and Chemistry
DFS	Degreesof Freedom for Signal
DISCOVER-AQ	Deriving Information on Surface Conditions from COlumn and VERtically Resolved Observations Relevant to Air Quality
DISORT3	Discrete-Ordinate Radiative Transfer Model
DOC	Dissolved Organic Carbon
DOFS	Degrees of Freedom for Signal
DS	Decadal Survey
DT	Dark Target
EBV	Essential Biodiversity Variables
ECMWF	European Centre for Medium-Range Weather Forecasts
EPA	Environmental Protection Agency
EPS	EUMETSAT Polar System
ESD	Earth Science Division
ESTO	Earth Science Technology Office
ESTO-QRS	Earth Science Technology Office-Quick Response System
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EV	Earth Venture
EV-I	Earth Venture - Instrument
EV-M	Earth Venture - Mission
FOV	Field of View
FPA	Focal Plane Array
FR	Filter Radiometer
FTS	Fourier Transform Spectrometer
FY	Fiscal Year
GCAS	GEO-CAPE Airborne Simulator
GCIRI	GEO-CAPE InfraRed Instrument
GCPI	Geostationary Carbon Process Investigation
GDAS	Global Data Assimilation System
GEMS	Geostationary Environment Monitoring Spectrometer

GEO	Geostationary Earth Orbit
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GeoCARB	Geostationary Carbon Cycle Observatory
GEO-MAC	Geostationary Multi-spectral Atmospheric Composition
GeoSpec	Geostationary Spectrograph
GeoTASO	Geostationary Trace gas and Aerosol Sensor Optimization
GEOS	Goddard Earth Observing System Model
GEOSS	Global Earth Observation System of Systems
GLI	Global Imager aboard the Advanced Earth Observing Satellite-II
GLIMR	Geosynchronous Littoral Imaging and Monitoring Radiometer
GOCI	Geostationary Ocean Color Imager
GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GRIFEX	GEO-CAPE Readout Integrated Circuit Experiment
GSD	Ground Sample Distance
GSFC	Goddard Space Flight Center
GSI	Grid-point Statistical Interpolation
GTE	Global Tropospheric Experiment
HAB	Harmful Algal Bloom
HALO	High Altitude Lidar Observatory
HAQAST	Health and Air Quality Applied Sciences Team
HCHO	formaldehyde
HICO	Hyperspectral Imager for the Coastal Ocean
HoPS	Hosted Payload Solutions
HPL	Hosted PayLoad
HYCOM	HYbrid Coordinate Ocean Model
IDL	Instrument Design Laboratory
iFOV	instantaneous Field-of-View
IGACO	Integrated Global Atmospheric Chemistry Observations
IGOS	Integrated Global Observing Strategy
IIP	Instrument Incubator Program
IOP	Inherent Optical Properties
IR	Infrared
IRCRg	Infrared Correlation Radiometer
ISAL	Instrument Synthesis and Analysis Laboratory
JCSDA	Joint Center for Data Assimilation

JPSS	Joint Polar Satellite System
Kd	Diffuse attenuation coefficient of downwelling irradiance
KIOST	Korea Institute of Science and Technology
KORUS-AQ	Korea-U.S. Air Quality
KORUS-OC	Korea-U.S. Ocean Color
LaRC	Langley Research Center
LDCM	Landsat Data Continuity Mission
LEO	Low-Earth Orbit
LIDORT	Linearized Discrete Ordinate Radiative Transfer
LISTOS	Long Island Sound Tropospheric Ozone Study
LMOS	Lake Michigan Ozone Study
LMT	Lowermost Troposphere
LT	Local Time
LUT	Look-Up Table
Lw	water-leaving radiance
LWIR	Long Wave Infrared
MAIA	Multi-Angle Imager for Aerosols
MAIAC	Multi-Angle Implementation of Atmospheric Correction
MDC	Mission Design Coordination
MDCT	Mission Design Coordination Team
MDSA	Multi-Sensor Data Synergy Advisor
MERIS	Medium-spectral Resolution Imaging Spectrometer
MLNN	Multilayer Neural Network
MOAT	Multi-axis Optical Airborne Tracker
MODIS	Moderate-resolution Imaging Spectroradiometer
MOS	Multi-slit Optimized Spectrometer
MOU	Memorandum of Understanding
MSS	Multi-Slit Spectrometer
MWIR	Midwave Infrared
NAP	Non-Algal Particle
NESCAUM	Northeast States for Coordinated Air Use Management
NIR	Near Infrared
NO_2	nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWP	Numerical Weather Prediction

O_3	ozone
OA	Ocean Acidification
OB.DAAC	Ocean Biology Distributed Active Archive Center
OBP	On-Board Processing
OBPG	Ocean Biology Processing Group
OC3M	Ocean Chlorophyll 3 algorithm of MODIS
OMI	Ozone Monitoring Instrument
OSSE	Observing System Simulation Experiment
OSWG	Ocean Science Working Group
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PanFTS	Panchromatic Fourier Transform Spectrometer
PanFTS-EM	Panchromatic Fourier Transform Spectrometer-Engineering Model
PBL	Planetary Boundary Layer
PC	phycocyanin
POC	Particulate Organic Carbon
PFT	Phytoplankton Functional Types
PM2.5	Particulate Matter with diameter of 2.5 microns and smaller
PRISM	Portable Remote Imaging Spectrometer
QA	Quality Assurance
R&A	Research and Analysis
RFI	Request for Information
RGCI	Red-Green-Chlorophyll-Index
ROIC	Read Out Integrated Circuit
ROSES	Research Opportunities in Space and Earth Sciences
Rrs	Remote Sensing Reflectance
RT	Radiative Transfer
RU-OSSE	Regional and Urban Observing System Simulation Experiment
SARP	Student Airborne Research Program
Scdm	Spectral slope of absorption coefficient of colored dissolved & detrital material
SeaDAS	SeaWiFS Data Analysis System
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SEWG	Systems Engineering Working Group
SIF	Solar Induced Fluorescence
SIRAS-G	Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit
SoCAB	South Coast Air Basin
SO_2	sulfur dioxide

SOX	Sensor-Web Operations Explorer
S-NPP	Suomi National Polar-orbiting Partnership
SNR	Signal to Noise Ratio
SPM	Suspended Particulate Matter
SSA	Single Scattering Albedo
SSS	Single-Slit Spectrometer
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
STM	Science Traceability Matrix
SWG	Science Working Group
SWIR	Short Wave Infrared
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TES	Tropospheric Emission Spectrometer
TDSC	Tropospheric Differential Slant Column
TIMS	Tropospheric Infrared Mapping Spectrometers
TIR	Thermal Infrared
TO	Targeted Observable
TOA	Top Of Atmosphere
TOLNet	Tropospheric Ozone Lidar Network
Tr	Radiance Transmittance
TRL	Technology Readiness Level
TROMBONE	TROpical Methane BiOsphere NASA Experiment
TROPOMI	TROPOspheric Monitoring Instrument
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USPI	U.S. Participating Investigator Program
UV	Ultraviolet
VCD	Vertical Column Density
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS	Visible
VOC	Volatile Organic Compound
WAS	Wide Angle Spectrometer
WG	Working Group
WRF-Chem	Weather Research and Forecasting (WRF) model coupled with Chemistry
ZSD	Secchi disk depth

12. GEO-CAPE PUBLICATIONS

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A. GEO-CAPE MISSION SUMMARY: NATIONAL ACADEMY OF SCIENCES

This addendum to the 2015 report includes only content that has changed since the 2015 report. The 2015 report is available at:
https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

No changes to Appendix A.

GEO-CAPE Oceans STM

FINAL version 5.0 - 22 August, 2018

Science Focus	Science Questions	Approach	Maps to Science Question
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; ESAS E-1a,b, C-4)	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: (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 open-ocean processes at appropriate spatial scales,	1; 2; 3 4
Land-Ocean Exchange (land-river-estuary-coastal ocean-open ocean)	**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; ESAS E-2b, E-3a, E-4b, E-5b)	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. *Measurement objectives for both modes include:* (a) Quantify dissolved and particulate carbon pools and related rate measurements such as export production, air-sea CO_2 exchange, net community production, respiration, and photochemical oxidation of dissolved organic matter.	1 2; 4 5; 1 2 3
Productivity and Biodiversity: Impacts from 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; ESAS E-1a,b,c, C-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. (c) Measure the inherent optical properties of coastal ecosystems: absorption and scattering of particles, phytoplankton and detritus, CDOM absorption. (d) Estimate upper ocean particle characteristics including particle abundance and particle size distribution. (e) Detect, quantify and track hazards including HABs and petroleum-derived hydrocarbons.	(b) 1 2 3 4 5; (c) 1 2 3 4; (d) 5, 1 2 3; (e) 5
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; ESAS E-3a,)	GEO-CAPE observations will be integrated with field measurements, models and other satellite data: (1) to derive coastal carbon budgets and determine whether coastal ecosystems are sources or sinks of carbon to the atmosphere, (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	(1) 2 3; (2) 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; ESAS E-1a,c)	(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

Measurement Requirements

Water-leaving radiances in the near-UV, visible & NIR for separating absorbing & scattering constituents & chlorophyll fluorescence

Temporal Resolution:
Targeted Events:
- Threshold: ≤1 hour
- Baseline: ≤0.5 hour

Survey Coastal U.S.:
- Threshold: ≤2 hours
- Baseline: ≤1 hour

Regions of Special Interest (RSI): Threshold: ≥1 RSI 3 scans/day
- Baseline: multiple RSI 3 scans/day

Other coastal and large inland bodies of water within ocean color FOR:
- Baseline: ≤3 hours

Ground Sample Distance (nadir):
- Threshold coastal: ≤375m Open Ocean: ≤1000 m
- Baseline coastal: ≤200 m Open Ocean: ≤1000 m

Field of Regard for Ocean Color Retrievals:
60°N to 60°S;
155°W to 35°W

Coastal Coverage*:
width from coast to ocean:
- Threshold: min 375 km
- Baseline: min 500 km

Scanning Priority:
- Threshold:
1. Survey of U.S. Coastal Waters
2. Other coastal and large inland bodies of water
3. Open ocean waters within FOR

Instrument Requirements

Spectral Range: Hyperspectral
- Threshold: 350-900 nm; 3 SWIR bands 1020, 1250 & 1615 nm
- Baseline: 340-1000 nm; 4 SWIR bands 1038, 1250, 1615 & 2260 nm

Spectral Sampling / Resolution:

Threshold (nm)	Baseline (nm)
350-400: ≤10 / ≤15	340-400: ≤2.5 / ≤10
400-720: ≤5 / ≤10	400-450: ≤0.25/ ≤0.75
720-NIR: ≤10 / 10	450-NIR: ≤2.5 / ≤5
SWIR Resolution (FWHM nm)	
1020 (40), 1250 (30), 1615 (75)	1038 (75), 1250 (30), 1615 (75), 2260 (75)

Signal-to-Noise Ratio (SNR) at Ltyp(70° SZA):

Threshold SNR (BW)	Baseline SNR (BW)
350-360: ≥300 (15)	340-360: ≥500 (15)
360-400: ≥1000 (15)	360-400: ≥1200(10)
400-600: ≥1000 (10)	400-600: ≥1500 (10)
600-720: ≥800 (10)	600-720: ≥1200 (10)
720-760: ≥600 (10)	720-760: ≥700 (10)
820: ≥200 (15); 865: ≥600 (40)	820: ≥400 (15); 865: ≥700 (40)
1020: ≥250 (40)	1038: ≥300 (75)
1250: ≥200 (30)	1250: ≥250 (30)
1615: ≥150 (75)	1615: ≥180 (75); 2260: ≥100 (40)

Pointing Error (% of nadir pixel)	Threshold	Baseline
Pointing Knowledge LOS	<50%	<10%
Pointing Accuracy LOS	<100%	<25%
Pointing Stability LOS	<25%	<10%
Geolocation Reconstr.	<50%	<10%

Field of Regard:
- Full disk: 20.8° E-W and 19° N-S imaging capability

Non-saturating detector array(s) at Lmax

On-board Calibration:
- Lunar: Threshold & Baseline: minimum monthly
- Solar: Threshold: none; Baseline: daily

Polarization Sens.: Threshold: <2%; Baseline: <1.0%

Relative Radiometric Precision:
- Threshold: ≤1% through mission lifetime
- Baseline: ≤0.5% through mission lifetime

Mission lifetime: Threshold: 3 years; Goal: 5 years

Scanning area per unit time: Threshold: ≥25,000; Baseline: ≥50,000 km^2/min

Pre-launch characterization: Achieve the required on-orbit radiometric precision

Intelligent Payload Module Baseline only: Near Real-Time satellite data download from other sensors (GOES, etc.) for on-board autonomous decision.

Platform Requirem.

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 and South America.
Storage (up to 1 day) and full download of spatial data and spectral data.

Ancillary Data Requirem

Hemispheric data sets from models, missions, or field observations

Measurement Requirements
(1) Column Ozone
(2) Column NO_2 (threshold only)
(3) Surface wind velocity
(4) Surface barometric pressure
(5) Vicarious calibration & validation - coastal
(6) Full prelaunch characterization
(7) Cloud cover

Science Requirements
(1) SST
(2) SSH
(3) PAR
(4) UV solar irradiance
(5) MLD
(6) Air/Sea pCO2
(7) pH
(8) Ocean circulation
(9) Tidal & other coastal currents
(10) Aerosol deposition
(11) run-off loading in coastal zone
(12) Wet deposition in coastal zone
(13) Wave height & surface wind speed

Validation Requirements
Conduct high frequency field measurements and modeling to validate GEO-CAPE retrievals from river mouths to beyond the edge of the continental margin.

GEO-CAPE Science Questions are traceable to NASA's OBB Advanced Planning Document (OBB) and U.S. Carbon Cycle Science Plan (CCSP) and align with the NRC Earth Science Decadal Survey (ESAS 2017) most important (E-1, E-2, E-3), very important (C-3, C-4) and important (E-4, E-5) science and applications priorities and application themes (HABs, water quality, water clarity, fisheries, coastal recreation, water-borne diseases).

* 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).

C. Atmospheric Composition STM, SVM, and AVM

This addendum to the 2015 report includes only content that has changed since the 2015 report. The 2015 report is available at:
https://geo-cape.larc.nasa.gov/pdf/GEO-CAPE_2009-2015_SummativeWhitePaper.pdf

No changes to Appendix C.

D. POINTING STUDIES

This addendum to the 2015 report includes only content that has changed since the 2015 report. The 2015 report is available at:
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No changes to Appendix D.

E. GEO-CAPE STUDY TEAM MEMBERSHIP

The GEO-CAPE mission concept matured greatly between 2007 and 2018 because outstanding people engaged in the planning, discussion, and work of the mission study. The list of participants evolved over the years, and a sincere effort has been made to identify all contributors in order to recognize the value of their time. The authors extend apologies to anyone who may have inadvertently been left out, although their talent is certainly reflected in GEO-CAPE accomplishments. NASA ARC, GSFC, JPL, and LaRC collaborated on the pre-formulation of the GEO-CAPE mission. Inter-Agency partners EPA and NOAA engaged with NASA and made significant contributions to the definition of GEO-CAPE. Study team members from the National Center for Atmospheric Research, the Monterey Bay Aquarium Research Institute, and the Woods Hole Oceanographic Institution advanced the science of GEO-CAPE along with Study Team members from over 20 universities.

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