The Interdisciplinary Science of the Aerosol-Cloud-Ecosystem (ACE) Mission*

Arlindo da Silva[1], Michael Behrenfeld[3], Richard Ferrare[2] and Gerald Mace[4]
ACE Science Study Team

with contributions from
Robert Swap[5], Ralph Kahn[1], Lazaros Oreopulos[1], David Winker[2], Ali Omar[2], and Maria Tzortziou[6]

[1]NASA/Goddard Space Flight Center
[2]NASA/Langley Research Center
[3]Oregon State University
[4]University of Utah
[5]University of Virginia
[6]City University of New York

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1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

One of the most pressing contemporary Earth System Science questions is, incontrovertibly, how will life on Earth respond to climate change over the coming century? Global satellite measurements already provide among the greatest insights into this question by observing how today's ocean and terrestrial ecosystems respond to natural, and to some extent anthropogenic forms of climate variation. However, new and innovative measurement approaches are required to advance our understanding of the living Earth System. Current limitations are particularly acute for studies of ocean biology, for direct aerosol climate forcing, for cloud-aerosol interactions, and for precipitation-producing processes. For example, NASA's ocean color missions fail to observe high-latitude ecosystems over much of the annual cycle, yet these climate-critical ecosystems are experiencing the greatest rate of climate-driven change. Furthermore, heritage ocean color sensors only detect the plankton properties in a thin layer of the

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* This whitepaper response to the 2017 Decadal Survey RFI represents the umbrella of ACE responses for the mission's integrated science objectives. Additional responses to the RFI detailing ACE-related science questions within the different sub-disciplines are being submitted separately:

1) Ocean Biology and Biogeochemistry Community Initial Input Towards the Next Decadal Survey. (Lead author: *Anastasia Romanou*)
2) Characterizing Aerosol Processes and Properties for Reducing Uncertainties in Aerosol Radiative Forcing. (Lead author: *Richard Ferrare*)
3) The Link Between Climate Sensitivity Uncertainty and Understanding Cloud-Aerosol Interactions. (Lead author: *Gerald Mace*)
4) Addressing Major Earth Science Challenges in Cloud and Precipitation Processes. (Lead author: *Gail Skofronick-Jackson*)

ocean's surface, leaving major uncertainties in our understanding of ocean productivity, biomass distributions, and interactions between biological stocks and rates, and related physical forcings that will be strongly altered by a changing climate.

Within this grand Earth System Science Challenge of understanding how the biosphere will respond to climate change are two primary subquestions: (1) How will these responses of the biosphere feed back on atmospheric factors controlling climate? and (2) To what extent and where will changes in climate forcing impact the physical environment in which the biosphere exists? With respect to this latter subquestion, one particular uncertainty supersedes all others: aerosol-cloud interactions and the impact of clouds and aerosols on global radiation, hydrological, and biogeochemical systems. Indeed, the Executive Summary of Chapter 7 in the 2013 IPCC's states that "*clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget*" (p. 573). The underlying issues are further clarified by noting that "*…until sub-grid scale parameterizations of clouds and aerosol–cloud interactions are able to address these issues, model estimates of aerosol–cloud interactions and their radiative effects will carry large uncertainties*." (p. 574). It is also widely recognized that the treatment of meteorological influences on clouds and aerosols is an equally important subject that needs to be concurrently addressed.

These outstanding issues from the most recent IPCC assessment point to a series of unanswered questions regarding the roles of aerosol, clouds, and precipitation in Earth's changing climate system. These questions highlight the continued need for global observations allowing process studies addressing how the transfer and balance of energy in a changing climate are influenced by aerosols, clouds, and precipitation, and how the interactions between aerosols and clouds from their formation through their transition into precipitation systems influence the response of the Earth system to a rapidly changing atmosphere and ocean composition. Thus, to fully understand the threat that climate change poses to life on Earth in a quantitative manner, it is essential to relate observed changes in the contemporary biosphere to the magnitude of future change, which in turn requires process-level understanding of biological feedbacks on climate along with the details of aerosol-cloud and other interactions of the physical climate system.

In response to a similar set of questions posed by the Earth Science community, and recognizing the scientific and observational overlaps in ocean ecosystem and atmospheric sciences, the 2007 the NRC Decadal Survey recommended the Aerosol-Cloud-Ecosystem (ACE) mission. At the time, ACE was recommended as a Tier 2, pre-formulation mission focusing on observational requirements to advance understanding of ocean ecosystems, aerosols, and clouds and their interactions and feedbacks. (NRC Decadal Survey, 2007, pg. 4-4). As one of its fifteen recommended satellite missions, ACE represents the primary global mission to advance understanding of the climate-biosphere system. It brings together ecosystem, aerosol, cloud, and other Earth system scientists in a multiple-sensor, multiple-platform, low sun-synchronous satellite mission. The recommendation stresses that to achieve mission objectives active (primarily lidars and radars) and passive sensors need to be combined to observe the Earth at microwave, infrared, visible and ultraviolet wavelengths.

The fundamental science questions that ACE addresses, and the fundamental approach to addressing those questions, have only come into sharper focus over the course of the pre-formulation activities. The mission concept continues to target collecting synergistic active and passive measurements that will aid understanding of ocean biological stocks, rates, and changes from pole-to-pole and from the surface to deep communities, along with the physical processes associated with the Earth's water and energy cycles. ACE activities involve participation from a broad segment of the Earth Science community, in particular from the ocean ecology and biogeochemistry, aerosol, cloud, precipitation, and radiation disciplines.

Since the ACE mission recommendation by the 2007 Decadal Survey Report, pre-formulation activities have made major advances toward refining its observational and science requirements. These developments have resulted in several reports. Most recently, the ocean science community has produced a very detailed description of requirements for the ACE advanced ocean color sensor as part of the Pre-ACE (PACE) Science Definition Team activities; the PACE Science Definition Team Report is available from http://decadal.gsfc.nasa.gov/pace-resources.html . In addition, guidance on numerous ACE-relevant objectives were provided in a recent NASA SMD community meeting (May, 2014, NASA Ames Research Center); recommendations from this workshop were published in a report entitled "*Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics, and Radiation for the Coming Decade*", available from https://espo.nasa.gov/home/content/NASA_SMD_Workshop. The radiation, aerosols, clouds, and convections sections of that report highlight questions and possible observational courses of action that pertain to the roles of aerosols, clouds, precipitation in the climate system. The novel observational approaches attend to significant shortcomings in our present observational systems for tackling the grand challenges in Earth science for the next decade.

ACE contribution to Applied Sciences. ACE also promises to increase the use of satellite measurements of the ocean-atmosphere system for applications of direct societal benefit. Improved characterization of aerosol optical depth, aerosol composition and aerosol height will significantly improve our ability to make informed policy decisions about air quality and aviation hazards. Science measurements of ocean color can detect and monitor harmful algal bloom, development of water-quality indices, and tracking of oil-spills. Applications user communities require products than can be rapidly delivered to users at a latency, spatial resolution and quality equal to or better than the Land, Atmosphere Near real-time Capability for EOS (LANCE) . This capability is needed to enable the generation of time-sensitive products such as the daily air quality or harmful algal bloom forecasts. The Volcanic Ash Advisory Centers (VAACs) and the Hurricane Center would benefit from next generation lidar and radar systems that can provide profiles of volcanic plumes, and storm characteristics, respectively, to inform public safety policy. Novel ACE observations are critically needed to improve understanding of ocean processes in Polar Regions and assess impacts of climate change on high-latitude biodiversity, fisheries, water quality, marine resources, ecosystem health, and human security. These observations are key to improving ecological forecasts and planning resource management strategies. ACE will contribute to the short-term assessment of carbon sources and sinks, knowledge needed to properly manage a carbon economy and understand impacts and feedbacks of the climate system.

2. Why are these challenge/questions timely to address now especially with respect

to readiness?

As the only mission identified by the 2007 Decadal Survey to focus on clouds, aerosols climate, ACE plays a significant role in continuing and extending the data record begun by previous passive and active sensors in the A-Train and upcoming missions such as EarthCARE. ACE is building upon experience gained from the current generation of Earth observing satellites, *e.g.* the NASA Terra, Aqua, TRMM, CloudSat, CALIPSO, SeaWIFS and GPM platforms. All of these previous missions had as their principal science objective to characterize the germane properties of the Earth's atmosphere and upper ocean. The goals of ACE are different, in that ACE aims not only to determine what is there, but to delve in more detail into why those properties exist as they do. This focus on physical processes distinguishes ACE from its heritage missions and responds to the science questions that will be pertinent in the coming decade and beyond. As such, enhanced coordination among satellite observations, suborbital measurements, and modeling is a key part of the mission concept. The ACE mission in its pre-formulation phase has made significant progress regarding mission requirements and instrument technical readiness on its way to becoming a fully-fledged free-flyer mission by using mission resources well. At the same time, ACE continues to leverage the advances in technical development and readiness of both instrument concepts (with support from NASA's Earth Science Technology Office, ESTO) and their related algorithm development (with ACE Decadal Survey Study support). The lidar, radar, polarimeter and ocean sensor technology that comprises ACE's core measurement suite is expected to reach a technological readiness level that will permit ACE to go in full formulation phase by the time the 2017 Decadal Survey Report is published.

3. Why are space-based observations fundamental to addressing these challenges/questions?

Although airborne and ground-based measurements are essential for calibration and validation of space-based sensors, for detailed study of isolated events, and to provide microphysical and chemical detail unobtainable from space, their spatial and temporal coverage are far from adequate to address the grand challenge of understanding global climate change and it implications to the biosphere. A comprehensive description of cloud, aerosol and ocean ecosystem processes, with full statistical and geographical coverage fundamentally necessitates global, multi-year, space-based observations capable of elucidating such processes, along with targeted suborbital measurements and models.