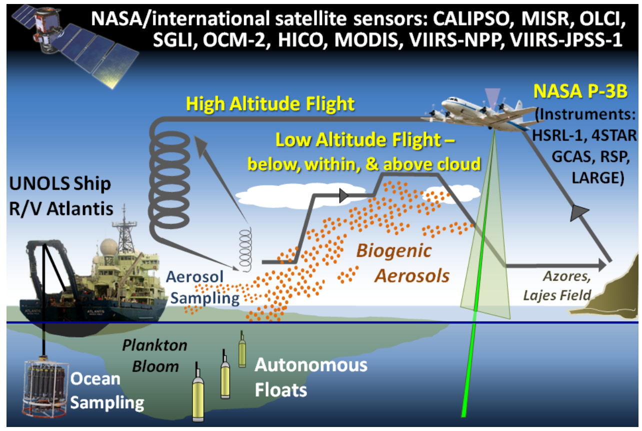
Executive Summary



***NAAMES** combines ship, aircraft, satellite, autonomous sensor, and modeling data to address knowledge gaps on ocean plankton and their biogenic aerosol emissions.*

Plankton ecosystems of the global ocean profoundly affect climate and life on Earth. NASA's ocean color satellite record tells us that these invaluable ecosystems are highly responsive to climate variability, with changes in ocean production impacting food production, uptake of atmospheric CO_2, and emission of climate-regulating aerosols. Intergovernmental Panel on Climate Change climate simulations suggest that surface ocean temperatures will warm by +1.3 to +2.8 °C globally over the 21^{st} century, with major consequences on physical properties of the surface ocean where plankton populations thrive. The pressing question is, how will these changes alter plankton production, species composition, and aerosol emissions? Today, even the sign of these potential changes remains unresolved. Our ability to predict Earth System consequences of a warming ocean and develop realistic mitigation and adaptation strategies depends on resolving conflicting hypotheses regarding factors controlling plankton ecosystems and biogenic aerosol emissions.

The **North Atlantic Aerosols and Marine Ecosystems Study (NAAMES)** is a high-impact, interdisciplinary investigation and the first Earth Venture Suborbital (EVS) mission focused on marine ecosystems. NAAMES is distinguished from all previous ocean investigations by its focus on observations over the complete annual cycle and by its critical integration of surface, airborne, satellite, and modeling data. The NAAMES design addresses fundamental measurement and knowledge gaps that currently restrict understanding of ocean ecosystem functioning, linkages to atmospheric aerosols, and implications on climate. NAAMES will improve predictive capabilities of Earth system processes and will inform ocean management and assessment of ecosystem change.

Goals and Objectives

NAAMES contributes to two overarching Earth system science goals:

- *Define environmental and ecological controls on plankton communities to improve predictions of their structure and function in a warmer future ocean*
- *Define linkages between ocean ecosystem properties and biogenic aerosols to improve predictions of marine aerosol-cloud-climate interactions with a warmer future ocean*

NAAMES focuses on characterizing ocean ecosystem and aerosol properties in the climate-sensitive North Atlantic, which is an ideal location for resolving key processes common to many other ocean regions. Specific NAAMES baseline science objectives are to:

- **Characterize plankton ecosystem properties during primary phases of the annual cycle in the North Atlantic and their dependence on environmental forcings**
- **Determine how primary phases of the North Atlantic annual plankton cycle interact to recreate each year the conditions for an annual bloom**
- **Resolve how remote marine aerosols and boundary layer clouds are influenced by plankton ecosystems in the North Atlantic**

NAAMES is important for achieving NASA's strategic Earth Science goal to understand and decipher causes of, and predict Earth system change. Specific NASA EVS science objectives met by NAAMES include advancement of Earth system Models, evaluation of Phenomena and Change, and investigation of Interdisciplinary Science issues.

Mission Overview

Four field campaigns constitute the core of the baseline **NAAMES** mission, with each campaign aligned to a specific event in the annual plankton cycle. Ship-based measurements provide detailed characterization of plankton stocks, rate processes, and community composition. Ship measurements also characterize seawater volatile organic compounds, their processing by ocean ecosystems, and concentrations and properties of gases and particles in the overlying atmosphere. These diverse data are extended over broader spatial scales through parallel airborne remote sensing measurements and in situ aerosol sampling. The airborne data provide the crucial link between local-scale processes and properties quantified at the basin-scale through satellite remote sensing. Satellite data and in-water autonomous sensor measurements create the sustained observational record for evaluating climate-ecosystem model results. Field campaign results further contribute to the testing and refinement of detailed processes captured by the model. Through this integration of ship, airborne, modeling, and sustained satellite and autonomous sensor approaches, conflicting hypotheses on system functioning are resolved and predictions of ocean ecosystem and aerosol changes in a future warmer ocean are improved. Threshold and baseline NAAMES science objectives are identical, but the threshold mission entails deployment descope options that increase reliance on independently funded in situ sensor assets and reduce airborne remote sensing aerosol data under thin cirrus.

NAAMES Platforms

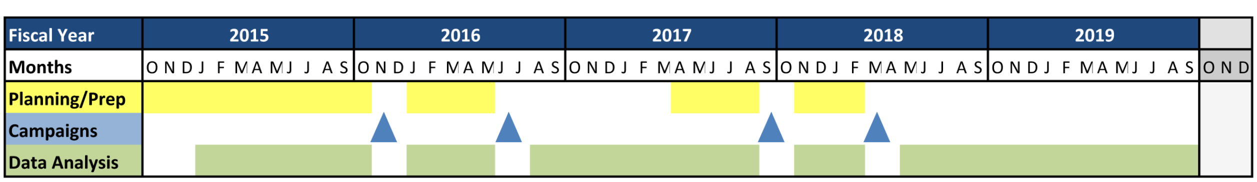
NAAMES ship-based measurements are conducted on the University-National Oceanographic Laboratory System (UNOLS) R/V *Atlantis* based in Woods Hole, MA. Airborne measurements are performed on the NASA P-3B aircraft stationed at Lajes Field, a U.S./Portuguese airbase in the Azores and home to the U.S. Air Force’s 65th Air Base Wing.

NAAMES Instruments

All **NAAMES** ship, aircraft, and autonomous in situ measurements are conducted using mature (TRL 9) instruments with extensive field deployment histories. Eighteen of these instruments are used for characterizing ocean ecosystems properties, while 25 are used to characterize aerosols and aerosol precursors. All NAAMES airborne remote sensing instruments are TRL 9 and have extensive deployment histories. These instruments are the NASA Langley Research Center (LaRC) High Spectral Resolution Lidar-1 (**HSRL-1**), the NASA Goddard Institute for Space Studies (GISS) Research Scanning Polarimeter (**RSP**), the NASA Ames Research Center (ARC) Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research (**4STAR**), and the NASA Goddard Space Flight Center (GSFC) GEO-CAPE Airborne Simulator (**GCAS**).

NAAMES Management Structure

Principal Investigator:	Michael Behrenfeld, Oregon State University
Project Scientist:	Chris Hostetler, NASA LaRC
Project Manager:	Mary Kleb, NASA LaRC
Science Data Manager:	Jeremy Werdell, NASA GSFC
Partnering Institutions:	Oregon State University; NASA LaRC; NASA GSFC; NASA ARC; NASA GISS; University of Maine; University of California, Santa Barbara; University of California, Irvine; University of California, San Diego; University of South Florida; Woods Hole Oceanographic Institution; Texas A&M University



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1 Science Investigation

The North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) is an interdisciplinary investigation resolving key processes controlling marine ecosystems and aerosols that are essential to our understanding of Earth system function and future change.

1.1 Science Goals and Objectives

Plankton ecosystems are composed of innumerable minuscule organisms that, for most of us, are 'out of sight and out of mind'. Yet, the annual net photosynthetic carbon fixation by planktonic plants, i.e., the 'phytoplankton', is equivalent to that of all terrestrial plants[1, 2]. This net production at the base of the aquatic food chain drives CO_2 exchange between the atmosphere and ocean and fuels carbon sequestration to the deep sea[3]. Plankton productivity therefore plays a vital role in Earth's coupled ocean-atmosphere system. Furthermore and in stark contrast to terrestrial vegetation, the entire global ocean phytoplankton stock is consumed and regrown every week[4]. This rapid turnover underpins ocean food webs and, hence, fish stocks and global food supply[5]. High latitude systems (roughly >40°) are particular 'hot spots' for this production, and many zooplankton and fish species have life cycles and migration patterns finely tuned to the historical timing of regional plankton blooms[6]. Consequently, these systems are particularly vulnerable to climate-driven changes in the phenology and strength of the annual plankton cycle[7-11]. Finally, the importance of plankton is not just about their overall abundance and productivity, but also their species composition. Some plankton communities are particularly efficient at supporting fish stocks, others have very high carbon recycling efficiencies, and some emit high levels of aerosol-forming compounds[12] that can affect cloud formation and alter Earth's radiative budget[13]. In short, while we may rarely give them any thought at all, ocean plankton profoundly affect climate and life on Earth.

If there is one overarching message that NASA's satellite ocean color record has conveyed it is that plankton ecosystems exhibit clear and pronounced responses to climate variability[2, 14-23] with associated changes in global ocean photosynthesis exceeding 2 Pg C y^{-1} [14]. However, basic mechanisms underlying these relationships remain unresolved. Climate change simulations conducted for the Intergovernmental Panel on Climate Change (IPCC) suggest that surface ocean temperatures will warm by +1.3 to +2.8 °C globally over the 21st century[24]. This warming impacts key properties of the surface ocean where plankton populations thrive, including the intensity and seasonality of water column stratification, surface mixing, and sunlight exposure[24].

The pressing question is, how will these changes impact plankton blooms, ecosystem species composition, and aerosol emissions? **Consensus is currently lacking on even the sign of these potential changes.** Unless conflicting views on factors controlling plankton ecosystem structure and seasonality are resolved, their diverging implications will undermine predictions of changing aerosol-cloud-climate interactions, ocean CO_2 uptake, and global food supply, and thus our ability to develop realistic mitigation and adaptation strategies in response to such changes.

Overarching Science Goals

- *Goal #1*: Define environmental and ecological controls on plankton communities to improve predictions of their structure and function for a warmer future ocean
- *Goal #2*: Define linkages between ocean ecosystem properties and biogenic aerosols to improve predictions of marine aerosol-cloud-climate interactions for a warmer future ocean

The North Atlantic Aerosols and Marine Ecosystems Study (**NAAMES**) is an interdisciplinary investigation addressing two key Earth system science goals essential to improve predictions of change for a warmer future ocean: (1) Define environmental and ecological controls on plankton communities and (2) Define linkages between ocean ecosystem properties and biogenic aerosols. Within these two broad Earth system goals, the NAAMES investigation focuses on identifying environment-ecosystem-aerosol interdependencies in the climate-sensitive North Atlantic. This ocean region hosts the largest annual plankton bloom in the global ocean and its impact on

Earth's radiative balance is particularly sensitive to biogenic aerosol emissions. Thus, the specific baseline science objectives of NAAMES are to (1) Characterize plankton ecosystem properties during primary phases of the annual cycle in the North Atlantic and their dependence on environmental forcings, (2) Determine how primary phases of the North Atlantic annual plankton cycle interact to recreate each year the conditions for an annual bloom, and (3) Resolve how remote marine aerosols and boundary layer clouds are influenced by plankton ecosystems in the North Atlantic. These objectives are accomplished by coupling autonomous in situ and satellite measurements sustained throughout the NAAMES investigation with short-term, coordinated ship and airborne campaigns that target critical events in the annual plankton cycle and focus on detailed system characterization. By integrating observations with a state-of-the-art climate-ecosystem model, a process-based foundation is created for resolving plankton dynamics in other ocean regions, accurately interpreting historical satellite records, and improving predictions of future change.

NAAMES Baseline Science Objectives

- *Objective #1*: Characterize plankton ecosystem properties during primary phases of the annual cycle in the North Atlantic and their dependence on environmental forcings
- *Objective #2*: Determine how primary phases of the North Atlantic annual plankton cycle interact to recreate each year the conditions for an annual bloom
- *Objective #3*: Resolve how remote marine aerosols and boundary layer clouds are influenced by plankton ecosystems in the North Atlantic

NAAMES is the first Earth Venture Suborbital (EVS) mission focused on marine ecosystems. It is distinguished from all previous ocean investigations by its complement of measurement and modeling approaches used to understand system functioning over the annual cycle. Urgency exists for conducting this investigation. The suite of satellite assets now available to support NAAMES are aging (e.g., MODIS, HICO, CALIPSO). NAAMES advanced suborbital measurements and algorithm development are also needed to prepare for three upcoming NASA missions: Aerosol-Clouds-Ecosystems (ACE) (http://dsm.gsfc.nasa.gov/ace/), Pre-ACE (http://decadal.gsfc.nasa.gov/pace.html), and GEOstationary Coastal and Air Pollution Events (GEO-CAPE) (http://geo-cape.larc.nasa.gov/). Finally, NAAMES leverages multiple independently funded U.S./international ocean assets to maximize investment payoffs, but these assets have a finite duration and may not be available at a later date.

1.1.1 Four Science Questions Drive NAAMES Objectives

Driving Science Questions regarding Ocean Ecosystems

- *Question #1*: How do environmentally-driven changes in phytoplankton growth rate and seasonal changes in ecosystem interactions create the spring bloom, and what does the relative importance of these two processes imply about future change?
- *Question #2*: How are seasonal changes in community composition linked to bloom formation?

The North Atlantic plankton bloom is among the most conspicuous biological events annually recorded by satellite ocean color measurements, yet even fundamental controls on the bloom's magnitude and interannual variability are controversial. The bloom climax is one event within an annual plankton cycle that essentially oscillates between a decreasing-biomass phase beginning in the summer and an increasing-biomass phase ending with the bloom climax, with two transition periods in between (in some years and locations, there may also be a secondary autumn bloom). This system, however, is highly non-linear, in that plankton properties at any given time reflect both current growth conditions (*reasonably well understood*) and processes occurring during past phases (*less understood*).

The traditional interpretation of the spring bloom focuses exclusively on phytoplankton responses to current growth conditions. It assumes that phytoplankton concentrations decrease in parallel with growth rate during autumn and winter and then attributes the bloom to rapid springtime phytoplankton growth rates driven by high nutrients, shallower mixing, increasing light, and warmer temperatures (**Figure 1-1, top**)[26, 27]. This view is so commonplace it is portrayed as a cornerstone concept in oceanography textbooks[28, 29] and is confidently explained in public media, such as the British Broadcasting Corporation's (BBC) *The Blue Planet* series. This traditional 'resource-based view' predicts that a *warmer surface ocean will yield larger and/or earlier blooms*[30-33], but is it correct?

A competing interpretation of blooms has recently emerged from analyses of NASA satellite ocean color data, autonomous sensor measurements, and ecosystem modeling[25, 34-37]. These studies suggest that the bloom actually begins in late autumn, when physical processes disrupt the balance between phytoplankton growth and losses (i.e., mixed layer deepening and lower temperatures impact zooplankton grazing more than phytoplankton growth rates). This disruption continues until the mixed layer stops deepening and temperatures begin to rise, after which the bloom is perpetuated by phytoplankton growth rates outpacing parallel increases in losses to grazers (**Figure 1-1, bottom**). According to this 'ecosystem-based view', harsher winter conditions (colder temperature, deeper mixing) cause stronger disruptions and yield greater phytoplankton biomass. Conversely, *milder winter conditions under a warmer future ocean will be associated with weaker blooms*[35, 37], with one recent assessment suggesting a potential decrease in peak phytoplankton stocks in the North Atlantic of 40% (range 10% to 66%) by 2100[37].

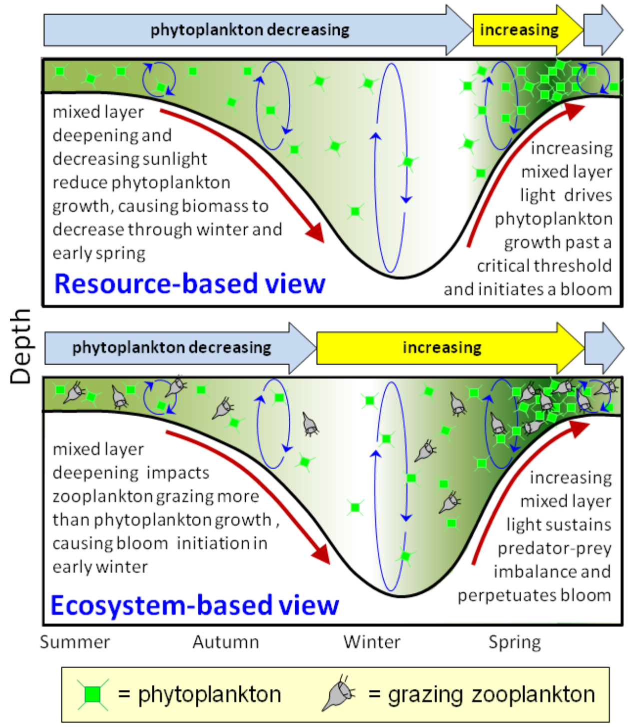

Figure 1-1. *NAAMES observations distinguish between the (top) traditional 'resource-based' hypothesis focused only on factors controlling phytoplankton growth, and the (bottom) 'ecosystem-based' hypothesis emphasizing disturbances in phytoplankton-grazer interactions. From Behrenfeld and Boss*[25]*.*

Without resolution, these contrasting hypotheses on bloom regulation (**Figure 1-1**) prevent consensus on even the ***sign*** of future change in ocean productivity, and thus the implications on seasonal atmospheric CO_2 uptake and fisheries. Importantly, the traditional 'resource-based view' has arisen largely from field studies, but a primary shortfall of these earlier investigations has been their nearly universal focus on final stages of the bloom without context to critical events occurring in previous seasons. In contrast, the 'ecosystem-based view' has arisen from analyses of model, satellite, and optical data covering the complete annual plankton cycle, but it lacks the mechanistic field studies necessary to demonstrate assumed key ecosystem processes and resolve the role of changing plankton community composition on bloom formation. **NAAMES addresses these major issues by providing the sustained observations, targeted field process studies, and advanced ecosystem modeling necessary to reconcile competing hypotheses and understand blooms as one element in a roughly repeating annual cycle.**

During NAAMES, water-column and surface layer ecosystem properties are continuously monitored over the entire investigation using autonomous in situ sensors and satellite observations. Guided by these and historical observations, NAAMES field campaigns provide detailed system characterizations targeting the increasing- and decreasing-biomass phases and the two transition events of the annual cycle. Prior to each campaign, ecosystem modeling provides predictions of plankton community properties and predator-prey relations based on current understanding of system functioning and observations from the autonomous sensors and satellites. These predictions are directly tested by ship-based measurements. Airborne remote sensing of plankton stocks and depth distributions provides essential data on spatial variability to address scaling issues from local measurement to satellite pixel scales. Results from each field campaign are integrated into a model-based forecast of change in the coming season(s), which is then compared to observations from the sustained in situ and satellite sensors. Thus, each field campaign is intimately connected to modeling and the sustained observations, but the four campaigns themselves are independent. This attribute provides exceptional flexibility to the NAAMES investigation, as the order in which these campaigns are executed is irrelevant. Through its successive integration of observational approaches and modeling, **NAAMES resolves the primary mechanisms linking plankton ecosystem structure between seasons and thus how these linkages ultimately recreate conditions for the annual spring bloom**. With this process-based understanding and iterative model refinement, primary drivers of observed interannual variability in plankton properties can be reconciled and uncertainties in future predictions reduced.

Driving Science Questions regarding Aerosols

- *Question #3*: How do ocean-ecosystem emissions alter remote marine aerosol burden, spatial distribution, and properties?
- *Question #4*: How do these biogenic aerosols affect cloud condensation nuclei abundance and, in turn, cloud microphysical properties?

Ocean ecosystem changes in a warmer future ocean will likely induce significant changes in the chemical, physical, and optical properties of aerosols within the marine boundary layer (MBL). However, these consequences remain highly uncertain. This is because marine aerosols consist of a complex mixture of sea salt, non-sea-salt sulfate, and organic species formed through a variety of production pathways (**Figure 1-2**). The relative contribution of each aerosol type changes across the particle size distribution and exhibits a strong seasonal association with ocean biological activity[39]. Understanding changes in the burden and properties of atmospheric aerosols is important because these aerosols can act as cloud condensation nuclei (CCN) to form clouds that alter the Earth's radiation balance and, hence, climate. In fact, the indirect effects of aerosols on clouds are the single largest uncertainty in current IPCC estimates of global radiative forcing since preindustrial times. Remote marine biogenic aerosols are especially important because the addition of CCN to these low CCN environments (order 10-500 CCN cm^{-3}) has a bigger relative impact on cloud droplet number and size than the same addition to CCN-rich environments (e.g., thousands of CCN cm^{-3} over land). This means that increases in local biogenic emissions can change both CCN concentrations (e.g., new biogenic particles) and/or composition (e.g., organic coatings on sea-salt particles). The addition of biogenic aerosol in remote marine environments can dramatically change the number and size of cloud droplets[13, 39, 40]. For example, satellite measurements over a Southern Ocean phytoplankton bloom showed that a doubling in cloud droplet number changed the local short wave radiative flux by -15 W m^{-2}, which is comparable to the aerosol indirect forcing near highly

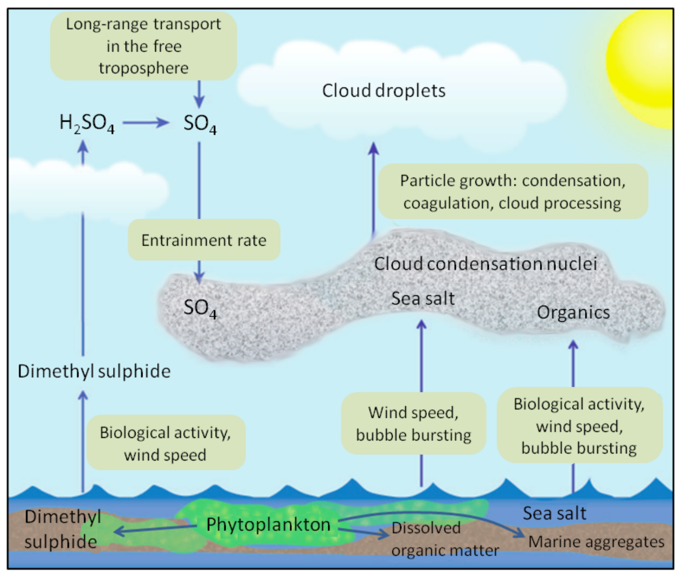

Figure 1-2. *NAAMES quantifies linkages between marine ecosystems, atmospheric aerosols, and clouds that are important, but highly uncertain, climate forcers. Adapted from Quinn and Bates*[38].

polluted regions[41]. Thus, changes in organic aerosols driven by ocean ecosystem changes can have a big effect on climate!

NAAMES focuses on the North Atlantic where models indicate particularly strong cloud albedo sensitivity to aerosol perturbations (**Figure 1-3**), making this an excellent test region for process-level studies on ocean ecosystem-CCN-cloud linkages that are relevant to other remote regions (e.g., southern oceans). Furthermore, the large spatial and temporal range in plankton stocks and species diversity in the North Atlantic improves distinction between biologically-impacted and non-impacted areas. This variability has contributed to previously observed correlations between phytoplankton chlorophyll concentrations and organic aerosol fraction transported to coastal measurement stations [12] and changes in remotely-sensed cloud albedo[41, 42]. However, a pressing need remains for interdisciplinary field campaigns that directly connect in situ measurements of ocean ecosystem properties to in situ atmospheric measurements with high spatial resolution. Only by doing so, can a mechanistic understanding be achieved of the ocean ecosystem-CCN-cloud relationships required for physics-based parameterization of Earth system models.

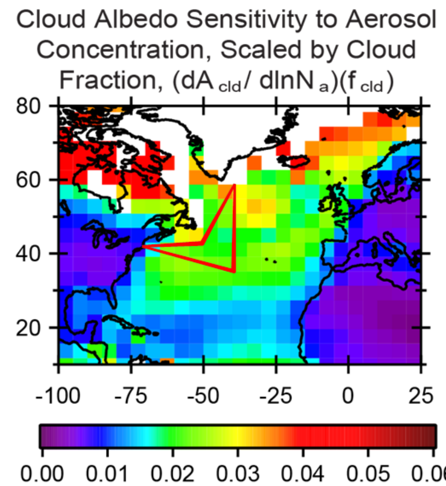

Figure 1-3. *The NAAMES study region (red line) is an area where cloud albedo is highly sensitive to biogenic aerosols but is not well constrained by models. Adapted from Moore et al.[40].*

From a recent consensus workshop of leading experts, Meskhidze et al.[43] highlighted in their recommendations report the pressing need for integrative field studies targeting regions with (1) minimal continental influence, (2) stable meteorology and a well-defined boundary layer, (3) predictable gradients and seasonality in large-scale biological features, (4) favorable logistics for simultaneous water, airborne, and remote sensing measurements, and (5) links to long-term land-based measurements. *One key location noted in this report as satisfying these requirements is the NAAMES study site of the North Atlantic* [43], which ties directly into the long-term aerosol measurement record at Mace Head, Ireland.

NAAMES perfectly aligns with the consensus criteria set out by this expert workshop and will provide essential information on how ocean ecosystem changes bring about changes in atmospheric composition that affect Earth's radiative balance and climate. This will be achieved through a combination of ship-based, airborne, and remote sensing measurements that characterize ocean ecosystem processes leading to aerosol precursors, emissions of ocean-generated aerosols and precursor gases, and subsequent atmospheric evolution and processing. NAAMES will quantify the relative contributions of primary organic aerosol (POA) that is directly emitted via wave breaking and bubble bursting, as well as secondary organic aerosol (SOA) that forms in the atmosphere from the oxidation of volatile and semi-volatile organic gases derived from ocean ecosystems[44, 45]. The relative contributions of POA and SOA are determined through Fourier transform infrared spectroscopy (FTIR) and mass spectrometer techniques, with particular focus given to novel approaches for quantifying biologic material using laser-induced fluorescence. Sea-air fluxes of volatile species are computed using measured interfacial concentration differences and bulk transfer coefficient parameterizations, thereby providing important constraints on SOA pre-cursor-emission estimates, which current models significantly underestimate[46]. In situ airborne and shipboard measurements are used to characterize MBL aerosol loading and microphysical properties, effects of cloud processing and entrainment of aerosols from the free troposphere via the presence of black carbon and non-sea-salt sulfate. Thus, *NAAMES quantifies the contribution of each aerosol component in **Figure 1-2** to the overall aerosol burden*.

NAAMES also quantifies the cloud-forming ability of MBL aerosols using in situ and remote sensing measurements. Cloud indirect effects drive climate uncertainties, and both POA and SOA likely contribute to marine cloud formation by changing droplet surface tension[47-51] and contributing solute that enhances CCN activity[12, 13].

There is currently no field-based measurement record that directly links remote ocean ecosystem changes and emissions to changes in cloud properties, despite the importance of these linkages to climate forecasting. NAAMES addresses this gap by providing a comprehensive airborne measurement dataset of aerosol size and composition, CCN number and hygroscopicity, and cloud droplet number and effective radius. Collocated measurements of meteorological state parameters (e.g., relative humidity, temperature, pressure, vertical wind speed) are used to control for seasonal variation in cloud dynamic drivers. These data place constraints on the remote marine aerosol burden, properties, and CCN activity that are highly uncertain and can be directly incorporated into new or existing model parameterizations. In addition, aerosol and cloud properties measured in situ will be compared to those from airborne remote sensors to evaluate and improve present and future (e.g., ACE lidar and polarimeter measurements) satellite retrieval algorithms for the particularly challenging humid environment in-and-around clouds.

1.1.2 NAAMES Value to NASA's Earth Science Goals and EVS-2 Objectives

NAAMES contributes directly to NASA's Earth Science goals to "Quantify, understand, and predict changes in Earth's ecosystems and biogeochemical cycles" and "Improve understanding of the roles of the ocean [and] atmosphere…in the climate system and improve predictive capability for its future evolution"[52]. Specific **EVS-2 science objectives** met by NAAMES are:

- Models: Integration of in situ and remote sensing measurements with Earth system modeling is a core component of NAAMES, with observations improving model performance and modeling used to inform interpretations of field and remote sensing data and forecast change
- Phenomena and Change: NAAMES resolves (1) climate-sensitive controls of ecosystem annual cycles, (2) food web interactions underlying plankton blooms, and (3) links between plankton ecosystem structure and biogenic aerosol burdens and characteristics
- Interdisciplinary: NAAMES investigation design, Science Team, and measurement suite reflect the interdisciplinary and inseparable nature of atmosphere and ocean processes
- Relevance: NAAMES science objectives are relevant to NASA's Carbon Cycle and Ecosystems, Atmospheric Composition, and Climate Variability and Change focus areas

Specific NAAMES attributes relevant to stated **EVS-2 preferences** are:

- Use and/or validate products from up to nine NASA/international satellite sensors (CALIPSO, MISR, OLCI, SGLI, OCM-2, HICO, MODIS, VIIRS-NPP, VIIRS-JPSS-1)
- Exploratory research on ecosystem-aerosol dependencies, including use of hyperspectral and lidar retrievals of plankton species composition and vertical structure, respectively
- Process studies, remote sensing, and algorithm development extremely relevant to NASA's upcoming PACE (ocean radiometer + polarimeter), ACE (ocean radiometer + polarimeter + lidar), and GEO-CAPE (hyperspectral ocean-aerosol radiometer) satellite missions.

1.2 Baseline Science Requirements

This section describes the science strategy and complement of observation and modeling approaches for achieving the baseline NAAMES science objectives. This baseline mission is summarized in **Table 1-1**.

1.2.1 NAAMES Study Site

The NAAMES mission focuses on the North Atlantic (**Figure 1-4**) because this region exhibits strong seasonal cycles in ecosystem and marine aerosol properties, is one of the largest ocean sinks for atmospheric CO_2[53-59], supports massive fisheries, and is expected to experience significant surface ocean warming over the 21st century[24, 37]. The North Atlantic also has the logistical advantage of being close to many U.S. assets (ports, flight facilities, labs) and has a long history of field measurements[25, 60, 61] that provide a rich scientific background for NAAMES.

Table 1-1. NAAMES science traceability matrix, *linking mission science goals and objectives to measurement, instrument, and investigation requirement.*

Science Objectives & Questions	Scientific Measurement Requirements	Instrument Functional Requirements	Investigation Functional Requirements
Science Objectives: • Characterize plankton ecosystem properties during primary phases of the annual cycle in the North Atlantic and their dependence on environmental forcings • Determine how primary phases of the North Atlantic annual plankton cycle interact to recreate each year conditions for an annual bloom ***Question #1****: How do environmentally-driven changes in phytoplankton growth rate and seasonal changes in ecosystem interactions create the spring bloom, and what does the relative importance of these two processes imply about future change?* ***Question #2****: How are seasonal changes in community composition linked to bloom formation?*	1. Continuous, mission-long plankton ecosystem properties from satellite ocean color data (e.g., VIIRS, MODIS, HICO, OCM-2, OCLI, SGLI) 2. Continuous, in situ mission-long plankton ecosystem properties through the water column at distributed locations in N. Atlantic 3. In situ measurements of mixed layer plankton concentrations, species composition, POC, cDOM, and phytoplankton growth, accumulation, total loss, and grazing loss rates 4. UV-to-NIR airborne radiometric measurements linking local-scale analytical data (item 3 above) to satellite remote sensing resolution 5. Field measurements in items 3 and 4 above conducted over a wide dynamic range in ecosystem properties and encompassing differences in seasonal timing of ecosystem annual cycle events 6. Field measurements in items 3 and 4 above conducted during contrasting stages of the annual plankton cycle	1. Autonomous measurements of water column optical and physical properties at 5 m vertical resolution and sustained over annual cycle 2. Ship-based ecosystem and optical measurements with the spatial-temporal resolutions and uncertainties specified in Table 2-2 3. Ship- and aircraft-based in situ aerosol, aerosol-precursor, trace-gas, and cloud measurements with the size range, temporal resolutions, and uncertainties specified in Table 2-3 4. Passive airborne remote sensing of mixed layer plankton and cDOM properties at spatial resolutions and uncertainties specified in Table 2-1 5. Active airborne remote sensing of subsurface particles at spatial resolutions and uncertainties specified in Table 2-1 6. Passive airborne remote sensing of column-averaged aerosol properties from surface to aircraft level at spatial resolutions and uncertainties specified in Table 2-1 7. Active airborne remote sensing of aerosols between surface and aircraft levels at spatial resolutions and uncertainties specified in Table 2-1 8. Active and passive airborne remote sensing of clouds at spatial resolutions and uncertainties specified in Table 2-1 9. Passive airborne remote sensing of spectral aerosol optical depth above the aircraft at spatial resolutions and uncertainties specified in Table 2-1	1. Four field campaigns targeting biomass increasing/decreasing phases and transition periods of the annual plankton cycle 2. Co-located ship and airborne measurements and long-range, transport-scale airborne measurements. 3. Field measurements of the subtropical to subarctic gradient in ecosystem and aerosol properties 4. Autonomous sensor deployment along latitudinal gradient to sustain in situ observations of annual cycle 5. Airborne transects including (1) long-range low-altitude (below-to-above cloud) sampling (Azores to ship), (2) match-up with ship samples, (3) 200 km along forecasted ship transect, (4) vertical profile sampling of lower troposphere and (5) long-range measurements at high-altitude (ship to Azores) 6. Basin-scale retrievals of aerosol and ecosystem properties from existing/upcoming satellites 7. Central data archive 8. Climate-ecosystem modeling to (1) optimize field campaign design, (2) understand mechanisms of observed ecosystem variability, (3) forecast change in ecosystem properties, with relevance to aerosols
Science Objective: • Resolve how remote marine aerosols and boundary layer clouds are influenced by plankton ecosystems in the North Atlantic ***Question #3:*** *How do ocean-ecosystem emissions alter remote marine aerosol burden, spatial distribution, and properties?* ***Question #4:*** *How do these biogenic aerosols affect cloud condensation nuclei abundance and, in turn, cloud microphysical properties?*	*Ecosystem and optical properties as in 1-4 above plus the following with spatial-temporal coverage as in 5-6*: 1. Measurements of surface air concentrations of aerosols (e.g., sea salt, POA, SOA) and trace gases (e.g., VOCs, DMS) 2. Measurements of aerosol concentration, size distribution, composition, optical properties and CCN activity below, above, and between clouds 3. In situ and remote sensing measurements of cloud droplet number density, size, and liquid water content 4. In situ measurements of seawater volatile organics and their production and consumption rates 5. Continuous, mission-long record of passive-sensor, satellite-derived aerosol and cloud properties		

In addition, NAAMES investigators Behrenfeld and Hostetler led a highly successful, Azores-based field campaign in 2012 involving coordinated ship, airborne, and satellite measurements in the North Atlantic, with many similarities to NAAMES deployments[62]. While science objectives of this 2012 study focused on subsurface ocean particle measurements with a lidar (Section 3.3.3) rather than plankton and aerosol annual cycles, it provided highly relevant experience that greatly reduces logistics risks to NAAMES.

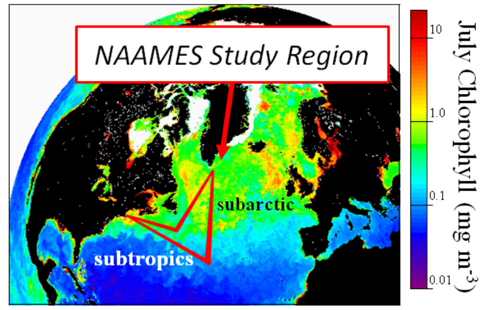

Figure 1-4. *NAAMES measurements span the subtropic to subarctic North Atlantic, this area is expected to have significant ocean warming. (Red line = ship transect)*

1.2.2 NAAMES Targeted Field Campaigns

Four field campaigns are conducted during NAAMES to validate remotely sensed properties, evaluate scaling issues between in situ and satellite data, and, most importantly, characterize ocean ecosystem and aerosol processes and properties critical to the interpretation of satellite and model results. Each of these campaigns targets a specific event in the annual plankton cycle.

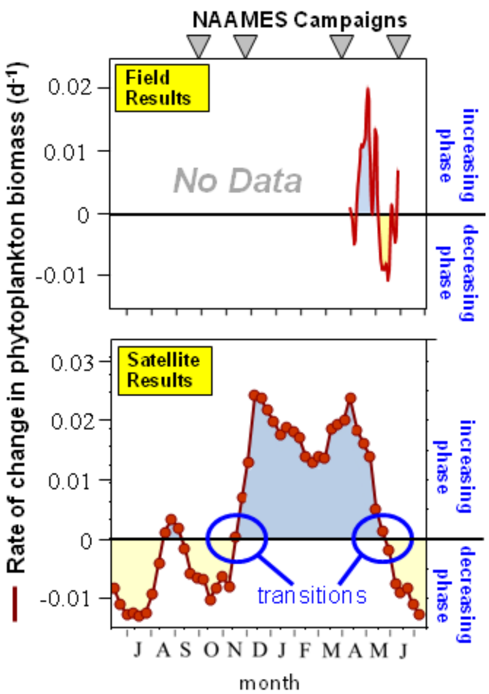

Figure 1-5. *NAAMES campaigns characterize ecosystem properties and processes during increasing and decreasing biomass phases and transition periods. (top) NAB-08 field results. (bottom) Satellite data for a 5° latitude by 10° longitude bin in the subarctic Atlantic. y-axis = specific rate of change in biomass [i.e., ln (biomass change)/time change][25].*

Figure 1-5 shows time-courses of phytoplankton biomass accumulation rates for (**top panel**) the 2008 North Atlantic Bloom field study (NAB-08)[63] and (**bottom panel**) satellite observations (note the x-axis begins with July on the left). In these figures, blue-shaded areas identify periods of increasing biomass and yellow-shaded areas show decreasing biomass. Typical of historical field studies, the NAB-08 measurements were confined to the late spring, with no in situ observations during previous seasons. This study was interpreted as demonstrating bloom initiation in April and thus providing support for the traditional 'resource-based' hypothesis (Section 1.1.1). However, satellite data in the bottom panel of **Figure 1-5** tell a strikingly different story. Here, the 10-year mean annual cycle from SeaWiFS satellite ocean color data indicate a prolonged blooming phase (blue shading) between November and early June, and a decreasing biomass phase (yellow shading) from late June through October. These results are consistent with the 'ecosystem-based' hypothesis. NAAMES field campaigns, together with modeling and sustained satellite and autonomous in situ sensor measurements, will not only resolve which of these views is correct, but also will characterize key ocean ecosystem properties that create the necessary conditions for each successive phase of the annual cycle.

Two of the NAAMES field campaigns are dedicated to characterizing system properties during the increasing and decreasing biomass phases, while the other two campaigns target the transition periods (**Figure 1-5**). These four events correspond to contrasting states in the balance between phytoplankton growth and losses. The biomass increasing- and decreasing phases reflect conditions that permit a sustained (multiple months) imbalance between growth and loss. The transition periods represent conditions causing a change in the sign of this balance (i.e., growth overcomes losses, or losses overcome growth).

Incomplete understanding of the mechanisms responsible for these events is the basis for the conflicting bloom hypotheses (**Figure 1-1**).

Importantly, the four stages of the annual plankton cycle also correspond to contrasting aerosol conditions[39, 64]. During the winter transition period, biogenic aerosol emissions are at a minimum. During spring, accelerating phytoplankton growth and turnover and rapid shifts in species dominance are paralleled by increasing, but variable, aerosol emissions. Peak phytoplankton concentrations occur at the late-spring/early summer transition period, which also marks the period of maximal biogenic aerosol concentrations. During autumn, aerosol emissions are again variable, corresponding to intensifying weather, changes in phytoplankton species dominance, and grazing and bacterial breakdown exceeding phytoplankton growth.

An important additional point needs to be made regarding **Figure 1-5**; these results are for specific subsections of the North Atlantic. While qualitatively similar patterns may be observed throughout the bloom-forming region (>40° N), significant quantitative differences are seen across latitude and longitude[35, 37]. In particular, transition periods occur one to two months earlier nearer the subtropics (~40° N) than at higher (~60° N) subarctic latitudes[35, 37, 65]. This difference is highly advantageous for the NAAMES investigation. As detailed in Section 2.1.2, each NAAMES field campaign entails measurements from ships and aircraft, which have to be scheduled a year or more in advance. However, the timing of the transition events unpredictably varies from year to year (within a window of ~1 month) at any given location. By conducting measurements from the subtropics to subarctic (**Figure 1-4**), *the NAAMES investigation design takes advantage of the latitudinal differences in bloom timing to ensure that the transition events are indeed captured during their targeted campaigns.* For example, if a campaign is conducted during a year when the blooming phase starts early (relative to the long term average), then the transition event will be encountered at higher latitudes of the NAAMES measurement region. Conversely, if the event is late, it will be best captured by the more southerly measurements.

1.2.3 NAAMES Integrated Measurements and Modeling

1.2.3.1 Science Strategy Addressing NAAMES Ocean Ecosystem Objectives

As soon as the NAAMES mission is selected under EVS-2, work will begin on compiling monitoring data and refining the timeline of basic ocean ecosystem properties. Initially, ocean color data will be available from four satellite sensors (OCM-2, HICO, MODIS, and VIIRS-NPP). Later in the investigation, additional observations are provided by OCLI (2015 launch target), SGLI (2016 launch target), and VIIRS on JPSS-1 (2017 launch target). Ecosystem properties retrieved from each ocean color sensor include chlorophyll concentration, phytoplankton pigment absorption, phytoplankton carbon, total particulate carbon, the rate of biomass change (i.e., from temporal changes in stocks), and absorption by colored dissolved organic material (cDOM). Having multiple sensors providing these products for NAAMES improves daily coverage of the North Atlantic (i.e., multiple observations at different times of the day increase the likelihood of observing the ocean through clouds) and reduces risk to the mission if one or more of these sensors fail during the investigation. A major advantage of the satellite data is that they provide basin-wide coverage of ocean ecosystem properties.

The second source of monitoring data that is immediately available to NAAMES is from autonomous in situ sensors already deployed in the North Atlantic, including physical properties from the ARGO program (http://www.argo.net/) and bio-optical measurements from the U.S. NSF-funded Ocean Observatories Initiative (OOI) Irminger Sea long-term monitoring site (http://oceanobservatories.org/infrastructure/ooi-station-map/irminger-sea/) and the BioArgo consortium (http://www.oao.obs-vlfr.fr/bioargo/floats.html). Data from all these sensors are freely available and include water temperature and pressure, chlorophyll concentration (from fluorescence), phytoplankton and total particulate carbon, and rates of biomass change. As demonstrated in the North Atlantic analyses of Boss et al.[66] and Boss and Behrenfeld[36], major advantages of these in situ measurements are that they provide continuous observations under clouds and characterize vertical structure in each property through the water column. However, these autonomous floats have typical lifespans of 1 to 3 years. Thus, three additional bio-optical profiling floats are deployed during each NAAMES field campaign (12 total) to ensure that these in situ monitoring data are sustained throughout the investigation.

Constructing a timeline of ecosystem properties from satellite and in situ data available early in the investigation serves multiple purposes. First, it allows rapid development and testing of the NAAMES data archive (see Section 2.2.5). Second, comparisons can immediately begin between the consolidated ecosystem products distributed through the archive and modeled properties. The Biogeochemical Element Cycling-Community Earth System Model (BEC-CESM) is the central model for NAAMES because it reliably reproduces bulk ocean ecosystem properties observed from space, while also providing the critical mechanistic framework for understanding factors governing the evolution of ecosystems over time[37]. It is a fully coupled Earth system model including an ocean ecosystem module integrated into a 3-dimensional physical ocean model[67-69]. The BEC-CESM generates bulk ocean ecosystem properties equivalent to those derived from the satellite and autonomous in situ sensors, but it also provides more detailed information on plankton community composition (e.g., abundance of different phytoplankton groups) and ecosystem interactions (e.g., balance between phytoplankton growth and loss rates). Throughout the NAAMES investigation, sustained satellite and autonomous sensor data allow repeated evaluations of model performance, in terms of reproducing plankton seasonal and interannual variability. *This approach to data analysis and modeling offered by NAAMES is consistent with recommendations of the 2012 NRC document, "A National Strategy for Advancing Climate Modeling"*[70]. Importantly, the NAAMES field campaigns provide detailed new observations to further evaluate this model framework and improve its predictive capabilities.

While the BEC-CESM is a state-of-the-art model, its resolution of ocean ecosystem composition and functioning is still relatively coarse. If the model reproduces the seasonal ecosystem patterns recorded by the monitoring sensors, is this success based on the correct parameterization of key processes? If model and monitoring results diverge, what drives this difference? Which aspects of the model most need to be refined to improve performance and predictions? These questions are answered by the NAAMES field campaigns by, first, comparing predicted and observed ecosystems states for the four stages of the annual cycle and, second, by using results from each campaign to improve forecasts of subsequent ecosystem changes recorded by the satellite and autonomous sensors. Required ship-based measurements include characterization of bulk plankton stocks, community species composition, colored dissolved organic matter (cDOM) concentration, in-water optical properties, and the physical environment (e.g., mixing depth, temperature). These data are essential to assess 'who and what is in the water', evaluate conditions of the mixed layer growth environment, and validate remote sensing products. Ship-based measurements are also needed that quantify biological rates and ecosystem interactions. Key properties include phytoplankton photosynthesis and growth rates, grazing losses, and rates of biomass accumulation. These observations, particularly when differentiated between major plankton taxonomic groups, are fundamental to understanding ecosystem dynamics, forecasting changes in the upcoming season(s), and evaluating mechanisms of modeled plankton properties.

Finally, a long-standing challenge for understanding ocean ecosystem variability has been the disconnect between spatial resolutions of field and satellite data. *A critical attribute of the NAAMES campaigns is that this gap between observational resolutions is bridged through airborne remote sensing.* This is accomplished with an airborne high-spectral-resolution ocean color sensor (GCAS), a high-vertical-resolution lidar (HSRL-1), and an advanced polarimeter (RSP), all of which have measurement capabilities that meet the science requirements in **Table 1-1**. GCAS and RSP data allow detailed characterization of surface-layer plankton stocks, species composition, and cDOM. The HSRL-1 measures vertically resolved plankton distributions. HSRL-1 and RSP data also provide detailed aerosol retrievals that reduce uncertainties in GCAS retrievals caused by atmospheric attenuation. Together, the NAAMES airborne sensors permit evaluation of whether the characteristically high spatial heterogeneity of the North Atlantic has compromised earlier satellite-based interpretations of ecosystem annual cycles. They also have measurement capabilities that far exceed those of current space assets, thereby providing a path for developing algorithms for ocean ecosystem properties in preparation for NASA's upcoming PACE, ACE, and GEO-CAPE missions.

1.2.3.2 Science Strategy Addressing NAAMES Aerosol Objectives

Activities described above characterize key features of plankton ecosystems in the North Atlantic. Building from this foundation, NAAMES ship and airborne measurements also allow these ecosystem properties to be connected to trace gases, aerosols, and cloud properties in the atmospheric marine boundary layer. Ship-based measurements of volatile organic compounds and dimethylsulfide are used with wind speed-based bulk mass transfer parameterizations to estimate the sea-air fluxes of these aerosol precursors, while direct aerosol emissions are characterized in terms of their number, size distribution, chemical composition, and optical properties. These ship-based measurements capture the lowest portion of the atmosphere with very high temporal and spatial resolution and establish a direct connection between the ecosystem changes occurring in the upper layer of the ocean and the broader, regional-scale aircraft-based in situ and remote sensing measurements.

As they are taken up into the atmosphere, these aerosols and aerosol precursors have direct radiative impacts (e.g., absorption and scattering) and indirect radiative impacts by interacting with water and clouds. The NAAMES airborne payload addresses these impacts through both in situ measurements and remote sensing retrievals of aerosol burden and properties. An important first step is establishing whether the aerosols sampled in the marine boundary layer derive from the sea surface or from entrainment of free tropospheric air masses. Vertical profiling measurements with an airborne lidar (HSRL-1) are used to detect the presence of aerosol layers in the free troposphere, to delineate boundary layer and mixed aerosol layer heights, and to evaluate the likelihood of entrainment. In addition, the presence of human-emitted combustion aerosols and gases (black carbon, CO, NOx) and/or non-sea-salt-sulfate are used to detect and quantify these free tropospheric influences. In situ airborne measurements of aerosol number, size distribution, chemical composition, and optical properties permit direct traceability to the ship-based measurements, while also capturing aerosol variability and trends over the much wider spatial scale relevant for clouds and climate.

A key challenge of marine aerosol composition measurements is quantifying the contribution and mixing state of biogenic organic species amongst a background aerosol population consisting predominantly of sea salt. This is especially true during periods of low ocean ecosystem stocks. However, the NAAMES aircraft payload is specifically optimized to overcome these difficulties through a number of complementary composition measurement techniques and will be able to distinguish between the sea salt and organic-sulfate aerosol modes. These techniques include volatility-based separation followed by number size distribution measurements that exploit the higher volatility of organics and sulfate versus sea salt, which remains in the aerosol phase at the denuder temperature of 350 °C. Additional spectrometric techniques capture the total and water-soluble organic mass fractions, SO_4 mass loadings, and the presence of large, fluorescing bioaerosols (among other species). *These composition measurements underpin the attribution of aerosol changes to ocean ecosystem drivers and will clearly distinguish when the aircraft is sampling organic-rich aerosols that have been influenced by ocean biota and when it is not*.

The next challenge is quantifying how the presence of these biogenic organics changes the overall aerosol optical properties (direct radiative effect) and CCN activity and cloud properties (indirect radiative effect). To address this issue, in situ measurements of aerosol absorption, humidified scattering, and dry sub- and super-micron scattering are conducted during below-cloud and above-cloud aircraft legs to capture the direct radiative effects. Measurements of CCN activity over a range of water vapor supersaturations are also conducted in these clear-air aircraft legs to quantify the cloud-forming tendencies of these aerosols (i.e., aerosol hygroscopicity and CCN spectra that feed directly into current model parameterizations). These optical and microphysical aerosol parameters are *the inputs* needed by global models to predict the climatic effects of ocean ecosystem-influenced aerosols. **Since NAAMES captures these aerosol parameters as a function of changes in ocean ecosystem stocks, community composition,**

and rates of plankton production and turnover, NAAMES provides global modelers with the information they need to predict how future ecosystem changes will affect climate through aerosol-cloud pathways.

NAAMES also provides key observational constraints on model outputs and on the ability to detect ecosystem-aerosol-cloud linkages from space-based remote sensors. High spatial resolution profiles of aerosol extinction, backscatter, and aerosol type from HSRL-1 connect ship measurements to vertically resolved atmospheric properties below aircraft flight altitude. Meanwhile, an aircraft zenith-viewing sunphotometer (4STAR) and nadir-viewing polarimeter (RSP) provide column-integrated views of spectrally-resolved aerosol and cloud properties. Critical cloud properties, such as droplet number concentration (CDNC) and size distribution, are measured in situ and derived from RSP observations to provide robust, cross-validated observations against which future model predictions can be assessed.

Additionally, NAAMES provides data critical to assessing ecosystem-aerosol-cloud linkages inferred from satellite remote sensing data. Using combined CALIPSO/MODIS observations, Hu et al.[71] derived global statistics of CDNC over the ocean and noticed the similarity of regional and seasonal variations of CDNC and chlorophyll concentrations. The more capable HSRL-1 and RSP instruments will provide proxies for CALIPSO and MODIS data for assessing these retrievals against in situ cloud measurements from the Langley Aerosol Research Group Experiment (LARGE) instrument suite (detailed in Section 3.3.3.1) and provide transport-scale data sets for comparing to satellite climatologies. The 120-m spatial scale of the RSP polarized radiances and the similarity to relevant VIIRS spectral bands is of particular value for evaluating and improving satellite cloud droplet size retrievals, thereby improving their utility for studying ecosystem-aerosol-cloud linkages in other relevant ocean regions (e.g., southern oceans[72]).

Thus, the airborne sensor measurements represent an important integrator between NAAMES in situ observations and the satellite climatological record, which are used to 1) determine the amount of ecosystem-aerosol-cloud variability captured by satellite sensors, 2) place the NAAMES deployments within the context of observed seasonal-to-interannual variability recorded over the 5-year study, and 3) relate NAAMES observations of ecosystem-aerosol-cloud interactions to satellite-only studies in other global regions[41]. Finally, ongoing airborne remote sensing algorithm evaluation and development using NAAMES data will inform parallel efforts for existing satellite sensors and future space-based sensors (e.g., ACE, the Cloud-Aerosol Transport System (CATS)[73] lidar, and the Atmosphere Lidar (ATLID) on EarthCARE[74]).

1.2.4 Threshold Science Requirements

NAAMES threshold science objectives are the same as the baseline objectives, but the threshold mission involves three specific descope options (see Section 4.3) that increase risk by (1) placing a stronger reliance on independently funded in situ assets, (2) increasing science uncertainties by decreasing geographic coverage of field measurements, and (3) reducing the number of retrievals from GCAS and RSP when thin cirrus are present (see **Table 4.2** in Section 4).

2 Science Implementation

NAAMES is a low-risk, high-impact investigation with exceptional field deployment flexibility, a highly experienced team, and mature instrumentation.

A highly successful, scaled-down version of a NAAMES-type campaign was conducted in 2012 by Behrenfeld and Hostetler, with primary science objectives achieved and published in less than a year after deployment[62]. NAAMES investigators have been heavily involved in the successful DISCOVER-AQ investigation (an EVS-1 mission), which coordinated airborne measurements with GEO-CAPE ship measurements. NAAMES investigators have conducted successful autonomous in situ sensor measurements in the North Atlantic[36, 66] and have previously merged satellite and BEC-CESM data in analyses of North Atlantic plankton properties[37]. All NAAMES field science leads have decades of experience with ship-based and/or airborne studies. *This wealth of experience and history of collaboration means that the NAAMES team fully* *understands the challenges of and has the resources necessary for conducting successful large scale field campaigns, thus greatly reducing risk for NAAMES.*

All NAAMES airborne sensors have flight heritage. All NAAMES ship-based in situ sampling involves mature instruments with long histories of field deployment. The BEC-CESM employed for NAAMES is a state-of-the-art, mature Earth system model. *Technology readiness levels (TRL) of 9 for all NAAMES instruments and a mature modeling approach means that the NAAMES mission is conducted with minimal technology risk.*

NAAMES campaigns can be conducted in any order because field data are compared to model results and observations from sustained in situ and satellite sensors, not subsequent field campaigns. The timing of plankton annual cycle phases varies by one to two months over the NAAMES study site, so precise dates of each campaign are not critical. Finally, the ship transect route can be modified in real time, airborne measurements have schedule margin and adjustable flight patterns, and many ship-based measurements can be conducted without overboard deployments. *These attributes of the NAAMES mission convey exceptional deployment flexibility to accommodate schedule conflicts with other suborbital programs and reduce risks associated with inclement weather conditions without compromising science.*

2.1 Science Investigation Profile

2.1.1 Three Phases of the Investigation

NAAMES is a 5-year mission with three primary phases (**Figure 2-1**). Publications on NAAMES results will occur throughout the investigation. ***Phase 1*** (~13 months) involves project initiation, the first Science Team meeting, compilation and archive of available satellite and autonomous in situ data (see Section 1.2.3), initial BEC-CESM model runs, and website development. ***Phase 1*** also includes airborne instrument integration/characterization, field systems preparation, and deployment logistics coordination for the first field campaign.

The four field campaigns are conducted in ***Phase 2***, with an ~11 month period between the second and third campaigns allowing detailed measurement-model comparisons and time for the Science Team to evaluate successes of the first campaigns, identify unforeseen measurement gaps, and determine remedies (**Figure 2-1**). The first campaign is scheduled for November-December and the second campaign in June-July. Within the study region, these times will encompass the two 'transition periods' according to the 'ecosystem-based' hypothesis, and a 'biomass-decreasing phase' and 'transition period' according to the 'resource-based' hypothesis (Sections 1.1.2 & 1.2.2). The third campaign is scheduled for September-October and the fourth for March-April, which encompass the 'biomass increasing/decreasing phases' according to the 'ecosystem-based' hypothesis, and the 'decreasing phase' and combined 'increasing phase and transition period' according to the 'resource-based' hypothesis, respectively. Field sample analyses and data archival/analyses commence upon completion of each campaign (**Figure 2-1**).

The primary focus of ***Phase 3*** (~11 months) is final analyses, model refinement and forecasting, synthesis, publication, data archival, and close out. ***Phase 3*** also provides schedule flexibility to accommodate any delayed field deployment should schedule conflicts arise.

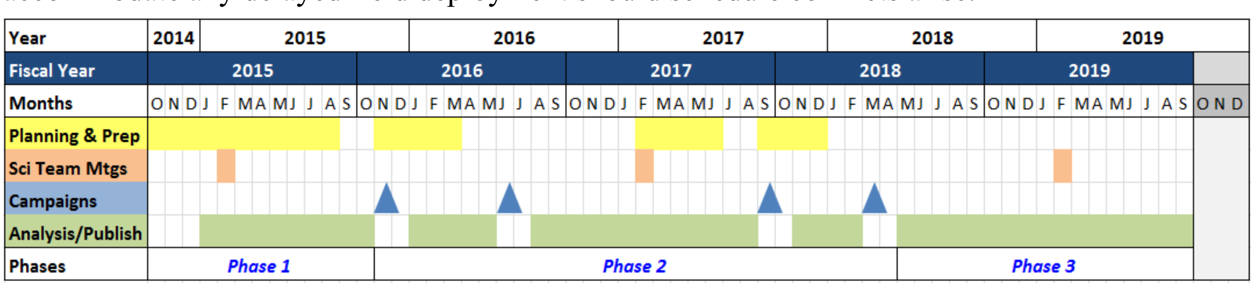

Figure 2-1. *NAAMES Investigation Profile of primary phases, activities, and field campaigns.*

2.1.2 Field Campaign Observing Profiles

All four NAAMES campaigns share a common observation profile (**Figure 2-2**). Ship-based measurements are conducted on a University-National Oceanographic Laboratory System (UNOLS) vessel departing from Woods Hole, MA. Airborne measurements are conducted from the NASA Wallops P-3B (or equivalent) aircraft stationed at Lajes Field, a U.S./Portuguese airbase in the Azores and home to the U.S. Air Force's 65th Air Base Wing. UNOLS ship scheduling has been submitted for all four campaigns, with the Global Class Research Vessel (R/V) *Atlantis* (or equivalent) selected for its provision of ample science berths for all investigators, required deck space for radioisotope and aerosol laboratory vans, and appropriate sea-worthiness. The crew of the R.V. *Atlantis* has extensive experience with winter-time operations under inclement weather conditions of the North Atlantic.

Each field campaign involves a 26-day, roughly triangular-shaped ship transect with turning points at ~35° N, 40° W and ~57° N, 40° W (**Figure 2-2**). The high-latitude turning point is near the OOI Irminger Sea time-series station, thus providing additional annual cycle context for NAAMES. Assuming continuous cruising at the *Atlantis* speed of 11 knots, the minimum transit time necessary to complete the full ~4700 nautical mile transect triangle is 19 days. The scheduled additional 7 days provide contingency for foul weather (i.e., slower cruising speed) and ample time for twice-daily overboard water-column profiling stations. Under particularly good weather conditions, these contingency sea days will be used for additional process studies at 24-hour occupation stations.

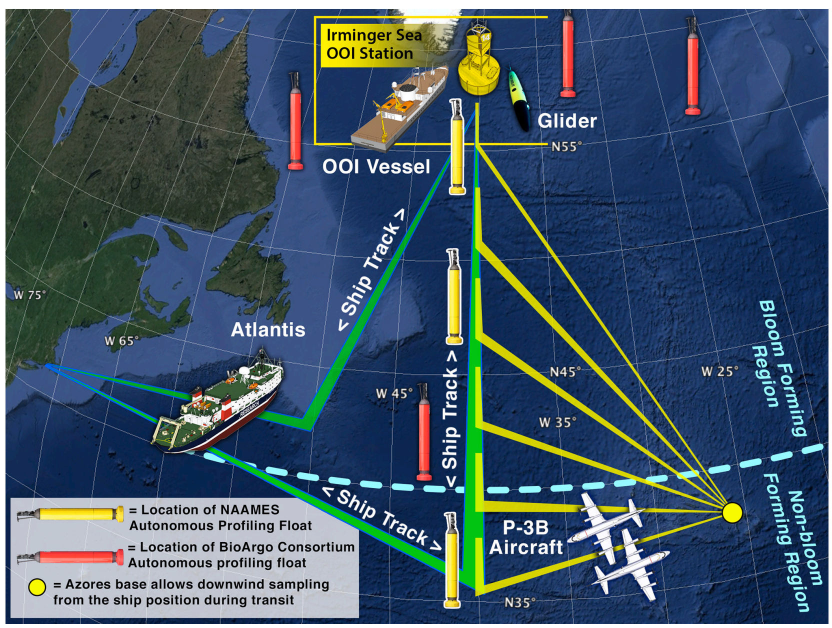

Figure 2-2. *NAAMES field campaign observing profile and independent supporting U.S. and international in situ measurement assets.*

The ship's direction around the transect triangle is scientifically irrelevant, which reduces risk to the mission by allowing real-time adjustments based on prevailing and forecasted weather conditions and sea-states. Assuming a counterclockwise direction, the ship proceeds from Woods Hole to the turning point at 35° N (**Figure 2-2**). During this outbound leg, underway sampling is conducted, but not overboard deployments. Following the turn northward, the full complement of ship-based measurements begins and continues for up to 13 days and the turning point at ~57° N is reached (**Figure 2-2**). During this leg, daily operations include dawn and noon station occupations for water-column sampling, incubation sample collection, and over-board optical measurements (**Table 2-2**). However, many of the ship measurements can be conducted using the ship's flow-through clean seawater supply system, so a successful field campaign can still be achieved under weather conditions too severe to allow overboard operations. For the return leg to Woods Hole, underway ocean and aerosol sampling is again continued. This return route includes a turning point at ~42° N, 50° W (**Figure 2-2**) to confine sampling to international waters and minimize sampling over the continental shelf. For each campaign, concurrent satellite ocean color data will be regularly consulted to identify nearby features of interest (e.g., fronts, bloom patches) and fine-tune the ship track to maximize the range of properties encountered.

Three autonomous profiling floats are deployed between 35° N and 57° N at three locations targeting contrasting ecosystem conditions (three floats per campaign x four campaigns = 12 total deployments). Each profiling float is equipped with temperature, density, subsurface light, chlorophyll, and particulate backscattering sensors. Over the course of the mission, data from >30 additional bio-optical floats deployed in the North Atlantic (red floats in **Figure 2-2**) will be available from other U.S. and international programs (http://www.oao.obs-vlfr.fr/bioargo/floats.html) (see support letters). These data complement the 12 NAAMES deployments, broaden the geographic coverage of sustained in situ measurements in the North Atlantic, and allow immediate in situ-satellite-model data comparisons (see Section 1.2.3.1).

Airborne deployments during each campaign begin with an 8-hour P-3B transit from the NASA Wallops Flight Facility (WFF) to the Azores. Although this high-altitude flight will not overpass the ship, measurements will be conducted with the airborne remote sensing instruments (Section 2.2.1). The following two days are dedicated to logistics and planning at Lajes Field, with no flights conducted. Primary science flights begin on day four and continue through day 17. This 14-day window is centered on the ship track between the northern-most and southern-most turning points (**Figure 2-2**), but also includes overflight opportunities during the outbound and return ship transects. Following the primary science flight days, a no-flight day is scheduled at Lajes Field for departure logistics. The transit day back to WFF occurs on day 19, during which high-altitude remote sensing measurements are again conducted.

The operations profile is essentially identical for all primary science flights, with only minor modifications reflecting maximum flight duration and distance to the ship from the Azores. A flight profile begins with remote sensing measurements along a high-altitude transit to the ship. Real-time analyses of sensor data during this transit allow mapping of aerosol heights and aerosol/ecosystem spatial features that will later guide sampling during the return flight. Upon arrival at the ship, in situ measurements are conducted during a spiral decent to ~500-foot altitude to obtain fine-scale resolution aerosol vertical structure. The aircraft then proceeds along its first low altitude flight for 200 nautical miles along the projected ship track, followed by an upward spiral and high altitude return to the ship. After a second descending spiral to ~500 feet, a second low-altitude flight is conducted over the return flight to the Azores. During the two low-altitude legs, the flight pattern follows the repeating sequence: (1) 5-minutes of below-cloud, marine boundary layer (500 feet) aerosol sampling, (2) 5-minutes of in-cloud droplet number, density, and size measurements and between-cloud aerosol measurements, and (3) 5-minutes of above-cloud measurements of background aerosol in the free troposphere and aerosols processed by clouds.

2.2 Science Data

2.2.1 Airborne Remote Sensing Measurements

The airborne remote sensing payload includes the GSFC GEO-CAPE Airborne Simulator (GCAS), the GISS Research Scanning Polarimeter (RSP), the LaRC High Spectral Resolution Lidar-1 (HSRL-1), and the ARC multi-channel sunphotometer (4STAR) (see Section 3.3.3 for instrument details). Measured properties, derived geophysical products, measurement specifications, and instrument leads are summarized in **Table 2-1,** while instrument descriptions are provided in Section 3.3.3. The sub-pixel spatial resolution data and advanced vertical/spectral resolution of these measurements compared to satellite data satisfies requirements for NAAMES science objectives. Airborne instrument investigators have extensive experience with all of these sensors, with recent deployments including HSRL-1 and RSP measurements during the 2012 Azores Campaign[62] and HSRL-2 and GCAS measurements during the DISCOVER-AQ mission. For this latter study, NAAMES investigator Chuanmin Hu was the lead ocean color data analyst for GCAS. During NAAMES deployments, preliminary 'quick view' products will be generated for each instrument within 24 hours, and final data products will have a maximum latency of 6 months. Data volumes for each instrument are well constrained by their extensive deployment history, with a combined total anticipated data volume for the full NAAMES mission of 8.4 TB.

Table 2-1. *NAAMES Airborne Remote Sensing Measurements*

Instrument and Relation to Objectives	Geophysical Products	Resolution	Uncertainty§	Algorithm, Calibration References	Lead Co-I
GCAS • Hyperspectral ocean color products • Atmospheric trace gas measurements • Relate ship-scale to satellite-scale measurement • GeoCAPE prototype satellite instrument	Chlorophyll-a concentration	10m x 150m†	30%	75-77	Janz
	CDOM absorption (440nm)	10m x 150m†	30%	77, 78	
	Particulate backscatter coeff. (440nm)	10m x 150m†	30%	79	
	Diffuse attenuation coeff. (Kd490)	10m x 150m†	30%	80	
	Euphotic depth	10m x 150m†	30%	79	
	Slant column atmospheric NO_2	1km x 1.5km†	4E14 molec. cm^{-2}	81	
	Slant column atmospheric O_3	1km x 1.5km†	3E16 molec. cm^{-2}	81	
HSRL-1 • Aerosol and cloud properties • Ocean properties • Relate ship-scale to satellite-scale measurements • ACE prototype satellite instrument	Aerosol backscatter (532/1064nm)	30m/150m*	0.2 $Mm^{-1}sr^{-1}$	82	Hair
	Aerosol extinction (532nm)	150m/1.5km*	0.01 km^{-1}	82	
	Aerosol & cloud depolarization (532/1064nm)	30m/150m*	1%	82	
	Ocean diffuse attenuation coeff. (532nm)	10m/500m*	Varies with depth	62	
	Ocean particulate backscatter coeff. (532nm)	5m/500m*	Varies with depth	62	
RSP • Aerosol and cloud properties • Ocean properties • Relate ship-scale to satellite-scale measurements • ACE prototype satellite instrument	Aerosol optical depth for each mode of a bimodal distribution	100m x 600m†	0.02/7%	83	Cairns
	Aerosol size: effective radius	100m x 600m†,‡	0.05μm/10%	83	
	Aerosol size: effective variance	100m x 600m†,‡	0.3/50%	83	
	Aerosol Single Scatter Albedo	100m x 4km†,‡	0.03	83	
	Cloud top effective radius	100m x 600m†,‡	1μm/10%	84	
	Cloud top effective variance	100m x 600m†,‡	0.05/50%	84	
	Cloud mean effective radius	100m x 600m†,‡	20%	85	
	Cloud optical depth	100m x 600m†,‡	10%	85	
	Liquid Water Path	100m x 600m†,‡	25%	85	
	Cloud Thickness	100m x 600m†,‡	15%	86	
	Cloud droplet number concentration	100m x 600m†,‡	25%	86	
	Water Leaving Radiance	100m x 120m†,‡	5%	87	
	Chlorophyll concentration	100m x 600m†,‡	<100%	87	
	CDOM absorption (410nm)	100m x 600m†,‡	<50%	87	
	Ocean particulate backscatter coeff.	100m x 600m†,‡	<50%	87	
4STAR • Facilitate RSP and GCAS retrievals	Spectrally resolved aerosol optical depth (350 to 1000nm) above the aircraft for constraining nadir-viewing RSP and GCAS retrievals.	NA x 150m†,‡	0.01-0.02	88	Rede-mann

§ Uncertainties, which represent a combination of measurement precision and accuracy, are presented for typical measurement conditions
* "*x* m / *y* m" indicates *x*-m vertical resolution and *y*-m horizontal resolution. HSRL-1 resolution greater than past experiments due to replacement of laser transmitter in 2013 with one having >20X more power.
† Cross-track by along-track. ‡ Non-imaging: along-track product with single cross-track elements for RSP and 4STAR.

2.2.2 Ocean Ecosystem Measurements

NAAMES ecosystem measurements are summarized in **Table 2-2.** Multiple techniques (pigment-based, imaging, flow-cytometry, particle sizing, sequencing) are used to characterize community composition, with ribosomal RNA (rRNA) sequencing providing cost-effective assessments of phytoplankton and bacterioplankton diversity[89, 90] at a resolution critical for linking composition to ecosystem and aerosol processes[91]. Multiple approaches are also used to quantify ecosystems rates (net primary production, phytoplankton division, accumulation, total losses, and grazing), with differences between approaches providing measures of uncertainty. Measurements of optical properties provide critical data for linking ecosystem properties to remote sensing and for characterizing the underwater light environment experienced by phytoplankton. cDOM measurements are particularly important in the North Atlantic because unconstrained cDOM absorption is a primary source of uncertainty in ecosystem properties retrieved by remote sensing[92, 93]. As detailed in Section 1, current uncertainties in ecosystem processes and controversies between bloom hypotheses reflect historical inadequacies in the diversity of simultaneously measured properties and their coverage over the annual cycle, not the precision/accuracy of these measurements. All measurement uncertainties shown in **Table 2-2** thus meet or exceed requirements for achieving NAAMES science objectives. During each campaign, preliminary 'quick view' results from each optical instrument are provided within 24 hours, while final data products from all ecosystem measurements have a maximum latency of 6 months. The total anticipated data volume for these ecosystems measurements, based on the sum of all instrument specific data rates, is <15 Gb over the full mission.

Table 2-2. *NAAMES Ecosystem Measurements*

Geophysical Property	Instrument/ Measurement	Measurement Uncertainty§	Mode	Resolution		Lead Co-I
				Horizontal	Vertical	
Spectral absorption and scattering	WetLabs AC-S	±0.0005 m^{-1}	C P	500m 30 km	n/a 1 m	Boss, Siegel
Spectral backscattering	WetLabs bb-3 WetLabs ECO BBFL	± $1x10^{-6}m^{-1}$	C P A	500m 30 km n/a	n/a 1 m 1-50 m	Boss, Siegel
Spectral water-leaving radiance, up/downwelling irradiance	C-OPS, Satlantic PAR	≤3% ≤3%	P A	30 km n/a	0.1 m 1-50 m	Siegel Boss
Phytoplankton pigments	Turner 10AU fluorometer, HPLC, WetLabs ECO BBFL	±5% ±3% (50%)	C P A	500m 30 km n/a	n/a 20 m 1-50 m	Milligan Boss
Phytoplankton biomass	BD Influx/ Shimadzu TOCN	±1% ±5%	P P	30 km 30 km	20 m 20 m	Milligan
Particle size distributions	BD Influx, Coulter Counter	±3% ±3%	P P	30 km 30 km	20 m 20 m	Milligan
Colored dissolved organics	2m liquid waveguide spectrophotometer, WetLabs ECO-cDOM Wetlabs AC-S	<0.005 m^{-1} (30%) ±0.01 m^{-1}	P C C	30 km 500 m 10 km	20 m n/a n/a	Nelson Boss
Total particulate carbon	Exeter Analytical 440 CHN Analyzer	±5%	P	30 km	20 m	Milligan
Phytoplankton taxonomy	HPLC/CHEMTAX BD Influx TAG 16S/18S rRNA UVP/ IFCB	±3% ±3% ±0.01% ±20%	P P P P/C	30 km 30 km 30 km 30 km	20 m 20 m 20 m 20 m	Milligan Giovannoni Boss
Zooplankton abundance	UVP/ IFCB	±20%	P/C	30 km	20 m	Boss
Heterotrophic bacterial taxonomy	TAG 16S/18S rRNA	±0.01%	P	30 km	20 m	Giovannoni
Phytoplankton growth rates	dilution experiments NPP/biomass	±10%	P	30 km	20 m	Milligan
Net primary production	^{14}C uptake Biomass*division	±8%	P	30 km	20 m	Halsey Milligan

§ Uncertainties, which represent a combination of measurement precision and accuracy, are presented for typical measurement conditions

2.2.3 In situ Aerosol Measurements

Ship-based and airborne in situ aerosol measurements are summarized in **Table 2-3**. Airborne in situ measurements (1) allow detection and quantification of overlying and downwind ecosystem emissions and (2) link in situ aerosol characteristics to remotely observable properties. Ship-based in-water measurements characterize biogenic aerosol precursors and ecosystem processing. Ship-based above-water measurements of aerosol composition allow assessment/partitioning of aerosol sources (e.g., anthropogenic, biogenic, sea salt). An inherent challenge in detecting ecosystem imprints on atmospheric aerosols is the strongly divergent transport time-scales for the atmosphere and ocean. Trace gases in seawater reflect local processes, while atmospheric gases and aerosols integrate processes occurring upwind. For reactive trace gases, such as DMS, the time-scale for conversion to particulate material is on the order of a few days, while the lifetime of accumulation mode aerosols can be significantly longer. The NAAMES capability to study aerosol chemistry on a size-segregated basis is a key asset, as the composition of the finer submicron particles will reflect local processes and should be more closely linked to processes in the underlying seawater. The widespread nature of subarctic Atlantic blooms is also a great asset of NAAMES, as it provides large-scale features with significant atmospheric footprints. Preliminary 'quick view' results are provided within 24 hours for trace gases and particle size distributions, while final data products from all aerosols measurements have a maximum latency of 6 months. The total anticipated data volume for these aerosol-related measurements, based on the sum of all instrument specific data rates, is 6.3 TB over the full mission.

Table 2-3. *Summary of Airborne and Ship Aerosol-related Measurements*

Geophysical Property	Instrument	Platform	Size Range (μm)	Resolution	Uncertainty§	Lead Co-I
CO	LGR CRD	Aircraft	NA	1 s	2 ppbv	Anderson
NOx	LGR CRD	Aircraft	NA	1 s	0.1 ppbv	Anderson
Ultrafine CN Total, Nonvolatile CN	TSI 3025 (2) TSI 3772	Aircraft	>0.003 >0.01	1 s 1 s	10% 10%	Anderson
Aerosol Particle Size	TSI SMPS DMT UHSAS TSI 3321	Aircraft	0.01 -- 0.3 0.08 --1.0 0.5 -- 5	60 s 1 s 1 s	20% 20% 20%	Anderson
Nonvolatile Particle Size	TSI SMPS	Aircraft	0.01 -- 0.3	60 s	20%	Anderson
CCN spectra	DMT-CCN	Aircraft	<5	1 s	NA	Anderson
Scattering (450, 550, 700nm λ)	TSI 3563	Aircraft	<5	1 s	5e-7 m^{-1}	Anderson
Scattering humidity dependence, f(RH)	TSI 3563	Aircraft	<5	10 s	NA	Anderson
Absorption (467, 530, 660nm λ)	PSAP	Aircraft	<5	5 s	5e-7 m^{-1}	Anderson
Black carbon mass and size	DMT SP2	Aircraft	0.1 – 1.0	1 s	20%	Anderson
Water Soluble Organics	PILS/TOC	Aircraft	<5	15 s	0.5 $\mu g/m^3$	Anderson
Non-Refractory Aerosol Composition	HR-ToF-AMS	Aircraft	0.05 – 0.6	10 s	0.05 $\mu g/m^3$	Anderson
Bio-Aerosol Number, Size	DMT WIBS-IV	Aircraft	0.7 – 5	1 s	NA	Anderson
Cloud Particle Size	DMT CAPS	Aircraft	0.5 – 1550	1 s	20%	Anderson
Ultrafine CN	GRIMM 5.400	Ship	>0.003	5 s	10%	Brooks
Aerosol Particle Size	BMI SEMS TSI APS (3321) GRIMM 1.1.08	Ship	0.04 – 0.8 0.5 -- 10 0.3 -- 20	60 s 1 s 60 s	20% 20% 10%	Russell Russell Brooks
Nonvolatile Particle Size	BMI SEMS	Ship	0.04 – 0.8	60 s	20%	Russell
Scattering (450, 550, 700nm λ)	TSI 3563	Ship	<1, <5	5 s	5e-7 m^{-1}	Anderson
Absorption (467, 530, 660nm λ)	PSAP	Ship	<1, <10	15 s	5e-7 m^{-1}	Anderson
CCN Spectra	DMT CCN	Ship	< 10	27 mins	10%	Brooks
Black carbon mass	DMT SP2	Ship	0.1 – 1.0	1 s	20%	Russell
Non-refractory Composition	HR-ToF-AMS	Ship	0.05 – 0.6	300 s	0.05 $\mu g/m^3$	Russell
Organic composition	Filter/FTIR PILS/ESI/MS	Ship	<0.18, <1 <1, <10	4 – 8 hrs 60 -- 300 s	NA NA	Russell Saltzman
Gas-phase organics	PTR/MS	Ship	NA	10 s	10 ppt	Saltzman
Gas-phase DMS Seawater volatile organics	CIM Sequil./PTR/MS	Ship	NA	0.2 s	5%,10-100 pmol	Saltzman
Volatile carbon production/ consumption rates	PTR/MS	Ship	NA	< 5 s	5 -- 10 pptv	Halsey

§ Uncertainties, which represent a combination of measurement precision and accuracy, are presented for typical measurement conditions

2.2.4 Modeling

The BEC-CESM is a 3-dimensional, fully-coupled land, atmosphere, ocean, and sea-ice model[67] and a lead U.S. model used to support IPCC assessments. The model (1) includes three types of phytoplankton, (2) carries multiple nutrients for realistic, multi-faceted ecosystem interactions, (3) tracks phytoplankton biomass changes to zooplankton grazing and other loss processes, and (4) has been adapted for linking biogenic aerosols and trace-gas emissions to plankton ecology. The recent study of Behrenfeld et al.[37] demonstrated the skill with which the BEC-CCSM can closely reproduce many key plankton features observed by satellites in the North Atlantic.

During ***Phase 1*** of NAAMES, BEC-CESM simulations are compared to available satellite and autonomous sensor data to evaluate consistencies and discrepancies between measurement and model results. For consistent results, the model defines key physical processes and ecosystem interactions associated with different phases of the annual plankton cycle. When discrepancies are observed, model sensitivity tests are conducted to identify potential explanations. These model results during ***Phase 1*** are then tested during the field campaigns of ***Phase 2***. Prior to the field campaigns, the BEC-CESM is also used to refine field sampling strategies and locations based on observational design experiments that characterize the typical seasonal evolution over different phases of the North Atlantic Oscillation. During ***Phases 2*** and ***3***, high-resolution model-field data intercomparisons are conducted to inform model development and revise predictions of ecosystem evolution during the subsequent season, against which satellite and autonomous sensor data are compared and addition model refinements conducted if needed. During ***Phase 3***, model hindcast experiments are also conducted to facilitate analysis and interpretation of historical field and satellite data, while model forecast experiments provide a refined assessment of ecosystem changes to 2100 and, together with statistical relationships defined during the field campaigns, potential impacts on biogenic aerosols. Model improvements and full data sets are made broadly available through the NAAMES data archive.

2.2.5 Data Management and Archival Plan

The NAAMES Data Management Plan complies with the NASA Earth Science Data and Information Policy. Briefly, this Data Management Plan will ensure the public release of (1) all data within six months of each deployment and (2) all NAAMES related documentation, including instrument descriptions, cruise reports, and data processing algorithms and software. During the project lifecycle, all data collected from field, airborne, and satellite instruments will be archived and distributed through the existing infrastructure of the NASA Ocean Biology Processing Group (OBPG), which currently operates as the distributed active archive center (DAAC) for all NASA ocean color satellite data records and the permanent repository for all field data collected under the auspices of the NASA Ocean Biology and Biogeochemistry Program. The OBPG will host all data processing levels, from instrument primary output (Level 0 data) to derived higher-level data products and ancillary data. The OBPG will ensure that these data records meet all NASA data system and metadata requirements. Upon completion of the project, the OBPG will build a data transition plan with the HQ-assigned DAAC, verify the development of all required data product and file format descriptors, and ultimately transfer the NAAMES data to this DAAC for long-term preservation at no additional cost to the project.

The OBPG will generate ocean color data products from MODIS-Aqua and VIIRS to support NAAMES, as well as data products from available HICO, OLCI, OCM-2, S-GLI, and CALIPSO data. The OBPG will use its existing infrastructure and software to generate and deliver these data records, with no additional algorithm or software development required. The OBPG will archive and distribute shipboard and aircraft data using the SeaWiFS Bio-optical Archive and Storage System[94] (SeaBASS; http://seabass.gsfc.nasa.gov)[95]. The Co-Is are responsible for processing and submitting these shipboard and aircraft data products to the OBPG on schedule to support their public release within 6 months of each deployment. Summaries of data products are given in the science measurement Tables 2-1, 2-2, and 2-3. The OBPG will use the existing SeaBASS infrastructure and software to ingest and redistribute these data records, with no additional software development required. All NAAMES data products and metadata will be reported in the existing ESDIS-approved data formats. The shipboard data will adopt SeaBASS data formats (http://seabass.gsfc.nasa.gov). The aircraft data will use either ICARTT format (https://earthdata.nasa.gov/our-community/esdswg/standards-process-spg/rfc/esds-rfc-019-icartt) or HDF-5 format. The total shipboard, aircraft, and satellite data volume expected for NAAMES is <15 Tb. All data collected under the auspices of NAAMES will be permanently retained within OBPG facilities and the HQ-assigned DAAC. The OBPG facilities include approximately one petabyte of direct access, RAID-6 storage, with mirroring of all source data to ensure integrity. Minimal additional hardware (e.g., hard drives for physical data storage) will be required to augment the OBPG facilities in support of NAAMES.

2.2.6 Hardware Disposition and Investigation Close-out Plan

Surface and airborne instruments will be returned to their home institutions at the end of each field campaign. Investigation close-out includes development, posting, and archiving a summary document detailing NAAMES (1) goals and objectives, (2) organizational structure, with contact information for all key personnel, (3) disposition of all archived algorithms, raw data, and processed data, (4) lessons learned during each campaign and the full investigation, (5) recommendations for future efforts, including instrument improvements, algorithm development, and operational considerations, (6) links to published/presented papers, and (7) assessment of mission success. All data products created during the mission will be distributed by the DAAC.

2.3 Science Team

NAAMES is supported by a world-class Science Team with expertise covering all mission requirements and a long history of collaboration. Lead investigators for field campaign measurements are identified in **Tables 2-1** to **2-3**. Investigator roles and organizational partnerships are summarized in **Table 2-4**. Curriculum Vitae for each investigator are provided in **Section 6** that give details on related experiences and field deployment histories.

Table 2-4. *The NAAMES Science Team, Roles and Organizational Partnering*

Name	Role	Organizational Partner
Mission Science		
Michael J. Behrenfeld, PI	Principal Investigator	OSU
Allen Milligan, Co-I	Ship ocean ecosystem primary production	OSU
Toby Westberry, Co-I	Satellite remote sensing analyses, ship in situ optics	OSU
Chris Hostetler, Co-I	Project Scientist, Airborne Lead	NASA LaRC
Modeling & Analysis		
Scott Doney, Co-I	BEC-CESM modeling Lead	WHOI
Chuanmin Hu, Co-I	Data Analysis for GCAS	USF
Yongxiang Hu, Co-I	Ocean (CALIPSO) and cloud (CALIPSO, MODIS) satellite analyses	NASA LaRC
Airborne Science & Instruments		
Scott Janz, Co-I	Airborne Remote Sensing measurements, Lead for GCAS	NASA GSFC
Bruce Anderson, Co-I	In situ aerosol measurements, Lead for LARGE	NASA LaRC
Richard Moore, Co-I	Cloud microphysics and aerosol-cloud interactions analysis	NASA LaRC
John Hair, Co-I	Airborne Remote Sensing measurements, Lead for HSRL-1	NASA LaRC
Richard Ferrare, Co-I	Integrated aerosol science, HSRL-1 aerosol retrievals	NASA LaRC
Brian Cairns , Co-I	Airborne Remote Sensing measurements, Lead for RSP	NASA GISS
Jacek Chowdhary, Co-I	Data Analysis for aerosols and RSP	NASA GISS
Jens Redemann, Co-I	Airborne Remote Sensing measurements, Lead for 4STAR	NASA ARC
Shipborne Science & Instruments		
Stephen Giovannoni, Co-I	VOC Cycling, Ship community composition measurements	OSU
Kimberly Halsey, Co-I	Volatile aerosol precursor ecosystem processing	OSU
Emmanuel Boss, Co-I	Ship ocean optics, Lead for autonomous profiling floats	UM
David Siegel, Co-I	Marine bio-optics, satellite remote sensing	UCSB
Stephane Maritorena, Co-I	Satellite ocean color analyses algorithm development	UCSB
Norman Nelson, Co-I	Ship CDOM and bio-optics measurements	UCSB
Eric Saltzman, Co-I	In situ trace gasses, ship aerosol measurements	UCI
Lynn Russell, Co-I	In situ aerosol measurements	UCSD
Sarah Brooks, Co-I	Aerosols and cloud condensation nuclei	TAMU
Data Management & Archive		
Jeremy Werdell, Co-I	Data Manager/archive, ocean color	NASA GSFC
Bryan Franz, Co-I	Airborne/satellite ocean color analysis	NASA GSFC

3 Investigation Implementation

NAAMES will be implemented with proven measurement platforms, a highly coordinated and proven logistical approach, and an experienced team. All instruments are at TRL 9, thus minimizing risk and eliminating any development cost and schedule concerns.

3.1 Measurement Platform System Capabilities

3.1.1 Airborne Platforms

The Wallops Flight Facility (WFF) P-3B is the NAAMES baseline aircraft. With an endurance and ceiling of >8 hrs and >8 km and an approximate range of 4500 km, the P-3B optimally meets all requirements for NAAMES. The P-3B offers easy access for instrument installations and deployment tests, and has experienced support staff with which NAAMES researchers have worked closely in the past. It can be set up for experiments and deployed for a science mission in 3 weeks, has ideal ports for all NAAMES instruments, and can accommodate all required on-board analytical sampling. **Figure 3-1** shows Instrument locations on the P-3B.

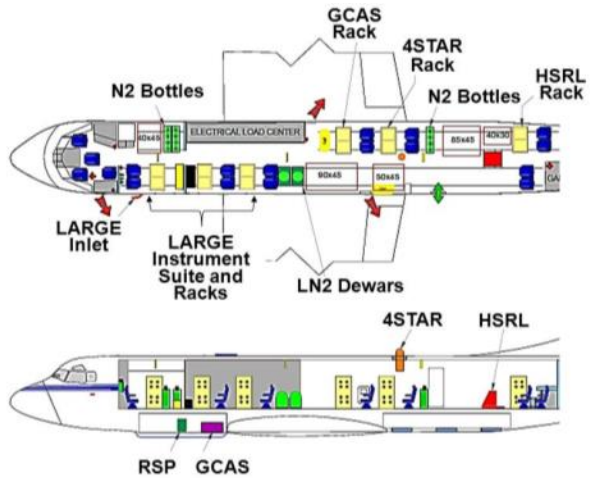

Figure 3-1. *NASA WFF P-3B provides ample space for NAAMES aircraft instrumentation, all rated TRL 9.*

NAAMES personnel have coordinated with WFF staff to review observing port requirements, space restriction, mounting approaches, and communication and navigation assets. Evaluations included safety, instrument power type and quality, instrument compliance requirements, operational limits (altitude, duration, speed), hangar laboratory for pre-integration instrument activities, and fabrication capability for adapting instruments to the aircraft. Advanced coordination with the P-3B pilots has been conducted to assure that all proposed flight sorties in each of the field campaigns are consistent with aircraft capabilities and meet all mission safety requirements, including capability to reach identified abort landing sites.

The Langley Aerosol Research Group Experiment (LARGE), HSRL-1, RSP, and an earlier version of 4STAR have already been flown on the P-3B. During DISCOVER-AQ, GCAS was flown on the NASA B200 aircraft in an unpressurized compartment, as it will fly for NAAMES on the P-3B. NAAMES personnel have discussed aircraft integration and operations planning with 4STAR and GCAS instrument leads to assure efficient and low-risk installations and operation on the P-3B. The investigation schedule includes planned pre-deployment test and check-out periods to ensure all concerns about installation and data collection are resolved without adverse impacts on science. A description of the airborne instruments is provided in Section 3.3.3.

In the unlikely event the P-3B is unavailable for any specific deployment, the Dryden DC-8 or WFF C-130 have been identified as suitable alternatives. With an approximate range of 8,000 km, ceiling of ~12 km, endurance of 10–12 hours, and a payload capacity twice that of the P-3B, the DC-8 easily accommodates NAAMES requirements. The C-130's payload capability exceeds that of the DC-8 and its 5,500 km minimum range capability also exceeds NAAMES requirements. Additional costs for using either of these aircrafts can be accommodated within NAAMES cost reserves (Section 5.3.2) and based on estimates from DFRC (DC-8) and WFF (C-130). NAAMES personnel have confirmed available flight hours on these aircraft and verified their capabilities to accommodate NAAMES instruments and support equipment as well as flight planning and operations at the Azores.

NAAMES investigators recently conducted a successful field campaign with the WFF P-3B from the Lajes Field during the 2012 Azores Campaign. Lajes Field meets all requirements for NAAMES, including runway length, fuel provision, aircraft ground equipment, emergency hangar availability, local availability of common compressed gases and liquid nitrogen, and facilities for plane operations on the ground and in the air. We have confirmed all personnel support requirements, such as billeting, messing, internet, telephones, transportation, office needs, and storage and repair space, and have discussed diplomatic procedures with government personnel for obtaining permission to enter the Azores including visa and customs processes. In the unlikely event that Lajes Field is not available for a campaign, St. John's International Airport in Newfoundland, Canada, is a suitable alternative that fully meets all requirements.

3.1.2 Ship Platform

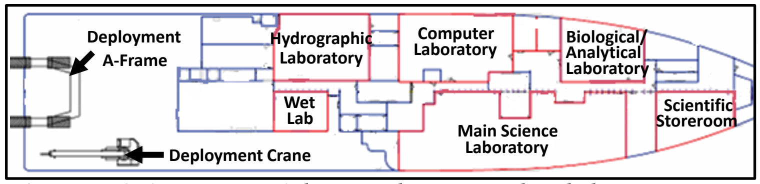

Figure 3-2. *R.V. Atlantis has ample lab space and deployment equipment for NAAMES ship measurements.*

As stated in Section 2.1.2, UNOLS ship scheduling is submitted for the Global Class R/V *Atlantis* for all campaigns, with departures from Woods Hole, MA. The *Atlantis* has the cruising speed and duration, wet- and dry-laboratory space (3,500 sq. ft; **Figure 3-2**), science berths, clean power supplies for science instruments, ultrapure water system for instrument calibrations, clean flow-through seawater system, shipboard computing capabilities, dynamic positioning system, and multiple communications pathways (HiSeasNet (email and web browsing), Iridium, and Fleet Broadband Voice) to fully support NAAMES. It also has the necessary over-board deployment assets (**Figure 3-2**) and adequate deck space for radioisotope and aerosol vans. In the event the *Atlantis* is unavailable for a specific campaign, several equivalent Global Class UNOLS ships have been evaluated and found to be fully capable of meeting NAAMES requirements. These ships include the *Revelle* (Scripps), *Thompson* (Univ. Washington), *Marcus Langseth* (Columbia University – Palisades, NY) and, until 2016, the *Melville* (Scripps). No additional charges are incurred by switching to these vessels as the *Atlantis* pricing estimates from UNOLS fully cover costs for use of any alternative vessel.

3.2 Logistics

The NAAMES field campaign schedule is described in Section 2.1.1 and a detailed description of the field deployment profile is provided in Section 2.1.2. The NAAMES team has many years of experience with ship and airborne deployments and a long history of successful collaboration. Several NAAMES investigators were involved in the coordinated ship-aircraft campaign from the Azores in 2012, are conducting another coordinated ship-aircraft campaign from the Gulf of Maine to Bermuda in 2014, and participated as instrument scientists, platform scientists, and Science Team members for the DISCOVER-AQ investigation. As such, the team has a thorough understanding of the logistical requirements for a highly successful NAAMES mission.

3.2.1 Prior to Each Field Campaign

The NAAMES team has reviewed all airborne instrumentation Payload Information Forms (PIFs) to understand instrument requirements onboard the P-3B and on the ground with respect to integration, deployment operations, de-integration, and transportation to and from these activities. This review defined requirements and needs for supporting equipment at WFF, on the P-3B, and in the Azores, along with capabilities required to transport these resources.

NAAMES P-3B instrument providers conduct functional and performance tests at their home facility prior to shipping to WFF. Integration of aircraft instruments onto the P-3B starts 3 weeks prior to departure at WFF where expert mechanics, machinery facilities, and experienced aircraft safety managers reside. Our experience with the WFF Aircraft Office and the P-3B team demonstrates that any installation challenges are quickly resolved. Ample time is allotted for cable and interface modifications, software changes, ground and flight testing, and packaging issues. Instrument mounting schedules are indicated in **Figure 4-2** (NAAMES Master Schedule). Existing WFF security assures access control for both the P-3B and instruments.

An aircraft team meeting occurs early in ***Phase 1*** for coordination and to identify potential installation or operations issues. Instrument integration and testing benefits greatly from LARGE, RSP, HSRL-1 and 4STAR predecessor AATS-14 all having flown on the P-3B. This experience gives high confidence for minimal integration issues. To avoid unnecessary delays or expense, the P-3B does not depart WFF for the Azores until shortly before the ship reaches the north-south transect between 35° N and 57° N (**Figure 2-2**). Project Scientist (PS) Chris Hostetler serves as the Aircraft Deployment Lead. Onboard the aircraft, LARGE PI Bruce Anderson serves as Airborne Platform Scientist. Both Dr. Hostetler and Dr. Anderson have previous experience in these roles.

Office, lab, supplies, security, hangar space, and additional support items as required during integration are provided by WFF. WFF is responsible for systems engineering to integrate instruments to the aircraft and reviews associated with aircraft integration and operations including Safety and Mission Assurance. As with the Azores 2012 Campaign, WFF is also responsible for securing clearances from Portugal and the Lajes Field base commander.

All ship-based instruments are highly platform independent, as they are readily setup and operated on any sea-going vessels (i.e., 'plug and play' instruments). Sea-going NAAMES investigators execute preliminary functional and performance tests at their home institutions prior to shipping equipment to WHOI. Once onboard the *Atlantis*, setup and final testing is completed in a few days prior to departure.

The NAAMES PI will serve as Chief Scientist (CS) on *Atlantis* and is the primary liaison between science and ship personnel. In the event the PI cannot serve this role during a specific campaign, Eric Saltzman or Dave Siegel will assume this responsibility. Drs. Behrenfeld, Saltzman, and Siegel all have experience in the CS role. The CS provides personnel forms for all Science Team members and coordinates laboratory, deck, and berthing layouts and assignments. The CS assures all science personnel are provided current versions of the *Research Vessel Operators Committee (RVOC) Safety Training Manual - Chapter 1* and *UNOLS Research Vehicle Safety Standards* and ensures adherence to guidelines and requirements.

3.2.1.1 Meeting Reviews

Following NPR 7900.3C, *Aircraft Operations Manual*, a Flight Readiness Review/Operations Readiness Review (FRR/ORR) is conducted prior to the start of each field campaign. The FRR/ORR focuses on flight operational safety and reviews operational requirements for each flight within the campaign, as well as the overall campaign. Personnel participating in FRR/ORRs include the Safety and Mission Assurance Office, mission manager and/or CS, Range Safety personnel, Flight Operations personnel, and the Aviation Safety Officer.

NPR 7900.3C requires a Mission Readiness Review (MRR) for campaigns using multiple aircraft. While NAAMES only utilizes a single aircraft, an MRR will still be conducted prior to each field campaign in recognition of requirements for aircraft and ship coordination. MRRs ensure that scientists and flight crews have made required arrangements to maximize operational safety and ensure mission success. MRR personnel include participants in the FRR/ORR plus designated GCV/WHOI representatives. While no formal reviews are required by UNOLS all science personnel will be required to go through an orientation regarding shipboard safety.

3.2.2 During the Field Campaign

Azores aircraft operations support is provided by Lajes Field (as in the 2012 campaign), including office/lab space, supplies, billeting, messing, internet, telephones, transportation, storage and repair, emergency hangar space, and access to consumables (e.g., liquid nitrogen for the RSP instrument). Aircraft fuel is secured through the military at the Government Contracted Rate. As with the Azores 2012 campaign, meteorological support at Lajes Field is provided by the Air Force meteorological office, with backup support from the NAAMES Flight Planner, Gao Chen (LaRC). The Flight Planner drafts the next day flight plan based on the weather data, satellite images, and model predictions, as well as input from PI, PS, and the science team. Weather and satellite data are updated to confirm that a scheduled flight can proceed.

Atlantis remains at sea for the duration of each campaign. Ship operations are self-contained and required supplies, support equipment, and spare instrumentation are onboard at the time of departure. The CS has authority to modify deployment schedules and cruise track to maximize science return, with concurrence from the ship's captain, P-3B Command Pilot, Airborne Platform Scientist, and the Flight Planner. The CS is responsible for assuring instrumentation and supporting gear are only deployed from the ship after direct consultation with the *Atlantis* Bridge. This includes all overboard deployable systems and the autonomous profiling floats.

A detailed description of ship and aircraft deployment profiles and coordination is provided in Section 2.1.2. A coordination meeting is held the morning of each flight to assure that all mission details are understood and agreed upon by all parties. While planned flight profiles are reviewed and approved by the P-3B Command Pilot, it is agreed that some deviation from the planned flight path is permitted in response to meteorological conditions and ecosystem conditions observed via quick-look instrument data. These changes are made at the direction of the Airborne Platform Scientist, to whom the PI delegates real-time decision authority and with the concurrence of the flight crew. Communications between *Atlantis* and P-3B will be conducted routinely during each campaign primarily using the aircraft and shipboard Iridium systems, although several backup communications paths also exist. Both the ship and P-3B will be in communication with designated mission support personnel in the Azores. Real-time changes to flight path and ship track may be coordinated via this communications leg.

3.2.3 Post-Field-Campaign Activities

The end of each campaign is defined as the point where the aircraft has returned to WFF from the Azores and the ship has returned to its home port. Post-investigation hardware dispositioning and data management and archival activities are detailed in Sections 2.2.5 and 2.2.6. Appropriate time has been allocated for evaluation of lessons learned following each deployment, thus providing guidance for subsequent field campaigns and investigations (see Section 2.1.1).

3.3 Instrumentation

3.3.1 Ship-based Instruments

Ship-based instruments are summarized for NAAMES ecosystem objectives in **Table 2-2** and aerosol objectives in **Table 2-3**, with all instruments at TRL 9 and having well established measurement protocols. There are three primary modes for ecosystem measurements: continuous, autonomous, and periodic (**Table 2-2**). ‘Continuous mode’ measurements involve platform-independent (i.e., they operate identically on any ship), bench-top optical instruments that are set up in the ship’s laboratory and plumbed into the clean, flow-through seawater system. This seawater system includes continuously operating temperature and conductivity probes recorded by the ship’s data system and is cleaned prior to each field campaign. ‘Autonomous mode’ measurements employ commercially-available optical instruments that are integrated into commercially-available profiling floats (see Section 3.3.2 for details). ‘Periodic mode’ includes all measurements requiring water column profiling, discrete water sample collection, sample incubations, or are limited to a specific period of the 24 hour cycle. Profiling optical measurements involve standard integration of commercially-available instruments onto the ship’s rosette sampling system or overboard deployment of a separate thruster powered system to avoid the ship’s shadow (Biospherical Instruments Compact Optical Profiling System (C-OPS)). Discrete water samples are collected from overboard castings of the CTD rosette system and from the ship’s clean flow-through seawater system. These samples are either processed immediately and stored for final post-cruise laboratory analyses (e.g., cDOM, phytoplankton biomass, HPLC, taxonomy, etc.) or are used for incubation experiments to quantity specific plankton rates (e.g., net primary production (NPP), growth rates, phytoplankton loss rates, etc). NPP measurements with ^{14}C require a separate radioisotope van on the ship. Above water measurements of incident up/downwelling irradiance are limited to daylight hours and conducted with deck-mounted sensors (e.g., Biospherical Instruments C-OPS multispectral shadow-band radiometer, LI-COR PAR sensor, Satlantic PAR sensor, Satlantic OCR503).

Aerosol and trace gas instruments for shipboard deployment (**Table 2-3**) are all commercially-available or mature instruments that have been previously deployed at sea by the investigators. These include particle sizing instruments providing continuous characterization of aerosol number distribution (10 nm - 10 μm), an aerosol mass spectrometer (AMS) that provides chemical composition (sulfate, ammonium, nitrate, and non-refractory organic compounds), and a proton transfer mass spectrometer (PTR-MS) that provides volatile organic trace gas measurements. These data will be acquired continuously and are made available real-time. Aerosol sample collection (filter, PILS) will be operated in the "upwind sector mode" to avoid stack emissions, using a condensation particle counter as the sensor. Post-cruise chemical characterization of aerosol particle filter and liquid samples for molecular functional groups and specific calibrated compounds will be completed after shipment to the PI's laboratories. Trace gas measurements on seawater utilize the ship's clean flow-through seawater system.

3.3.2 Autonomous Profiling Floats

Three autonomous profiling floats (**Figure 3-3**) are deployed during each of the four field campaigns. Floats are commercially manufactured by SeaBird Electronics (Navis model) and include an integrated conductivity-temperature-depth sensor, dissolved oxygen sensor, chlorophyll fluorescence sensor, and an optical backscattering sensor, all of which are integrated to the floats topcap (constructed by WETLabs and SeaBird). Additionally, a Satlantic PAR sensor is integrated to the float. Floats can dive to 2000 m depth and, when at the surface, have two-way satellite communication capabilities allowing data transmission and adaptive sampling (change frequency and/or maximal depth of profiling). The float and sensors technologies are thoroughly tested and are TRL 9 (see quasi-real-time data from currently profiling floats at: http://navis.sea-birdscientific.com/). Since 2004, NAAMES investigator, Emmanuel Boss, and his collaborators have successfully deployed and analyzed data from more than fifteen profiling floats equipped with optical sensors. Each of these floats has provided hundreds of vertical profiles of optical properties and operated for several years (http://misclab.umeoce.maine.edu/research/bgcfloats/).

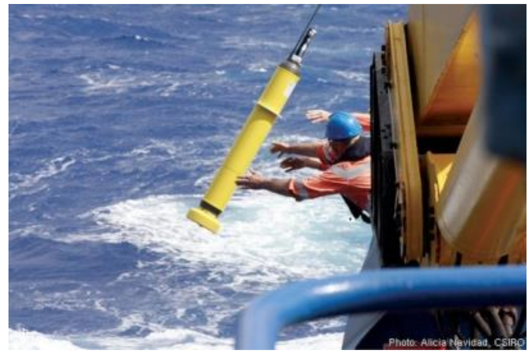

Figure 3-3. *Autonomous float being deployed from a ship. NAAMES floats provide sustained in situ observations throughout the mission.*

3.3.3 Airborne Instruments

3.3.3.1 LARGE

The LARGE suite of in situ aerosol and trace gas sensors comprise the "Aircraft" instruments in **Table 2-3**. These instruments sample from a common forward-facing isokinetic aircraft inlet with a well-characterized flow pattern [96] that has flown repeatedly on the WFF P-3B, most recently during DISCOVER-AQ. The inlet efficiently samples particles less than 5 μm in diameter at airspeeds up to 200 m s^{-1}. This transmission efficiency is optimal for submicron, marine biogenic aerosols.

The LARGE team has more than 20 years of experience making airborne measurements (recently NASA ACCESS, DC3, SEAC4RS, and DISCOVER-AQ), and has dedicated expert team members for instrument payload integration and plumbing, in-flight operation and troubleshooting, ground calibration and maintenance, data system design/implementation, and data analysis and archival submission. All LARGE instruments in **Table 2-3** have previously flown aboard the NASA P-3B, HU-25 Falcon, and/or DC-8, and most are integrated into a single data system allowing fast preliminary data processing and archival (< 24 hours post flight). This quick turnaround allows in situ measurement data to inform subsequent flight planning. Measurements are made using commercially-available instruments that have been modified for airborne operation by the LARGE team. Sufficient spare parts are readily available from both LARGE backup instruments and spares kits in the field or by direct shipment from the manufacturers.

The LARGE aerosol instruments in **Table 2-3** are optimized for measuring key NAAMES parameters, including aerosol concentration, size distribution, chemical composition, optical properties, and CCN activity. In addition, a wing-mounted Droplet Measurement Technologies

(DMT) cloud, aerosol, and precipitation spectrometer (CAPS) measures cloud droplet concentration and size distribution and cloud liquid-water content. Trace gas measurements complement these aerosol measurements for establishing air mass origin. Cloud updraft velocity is obtained from 20 Hz vertical wind speed measurements determined using a 5-hole pressure port system that is coupled to platform motion sensors.

3.3.3.2 HSRL-1

HSRL-1 employs the high spectral resolution technique[82] to independently measure extinction and backscatter at 532 nm and the standard backscatter technique[97] to measure backscatter at 1064 nm (**Figure 3-4**). It is also polarization sensitive at both wavelengths. HSRL-1 is one of the most quantitatively accurate aerosol lidars in existence, with calibration accuracies of 1-3% and retrieval uncertainties typically <10% at low-to-moderate aerosol loadings.

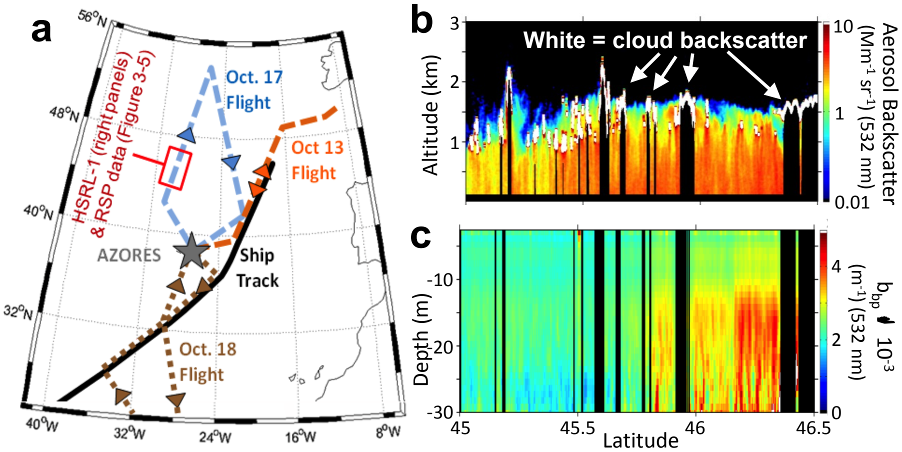

Figure 3-4. *Experience during 2012 Azores campaign reduces deployment risk for NAAMES. (a) Ship and flight track map (b) HSRL-1 aerosol backscatter. (c) HSRL-1 ocean subsurface particulate backscatter coefficients (b_{bp}).*

HRSL-1 has flown over 357 flights (~1200 flight hours) on the NASA B-200 during 22 field campaigns. Retrieved properties show excellent agreement with independent in situ and remote sensing data, even at very low aerosol loading levels[98]. Operational retrievals are applied to aerosol backscatter, extinction, and depolarization products to provide horizontally and vertically resolved curtains of Angstrom exponent, backscatter wavelength dependence, mixing ratio of spherical-to-nonspherical backscatter[99], aerosol type (e.g., marine, dust, pollution, etc.) and AOD partition by type[100], and aerosol mixed-layer height[101, 102].

The accurate profile products from HSRL-1 are used in conjunction with more detailed microphysical information from RSP (e.g., size distribution, refractive index, single scatter albedo) to infer aerosol composition and amount and to provide atmospheric correction for the satellite and airborne ocean color measurements.

In 2012, HSRL-1 was modified to provide high-vertical-resolution (1 m) ocean subsurface particle scattering profiles at 532 nm, and flew an ocean- focused campaign from Lajes Field on the P-3B in coordination with an oceanographic research vessel[62]. Ocean retrievals included diffuse attenuation and particulate backscatter coefficients up to depths of 50 m.

3.3.3.3 RSP

Two RSP instruments were built as airborne versions of the aerosol polarimetry sensor (APS) onboard the Glory mission to test polarimetric aerosol retrieval algorithms and to validate other (photometric) aerosol remote sensing retrievals (e.g.,[84, 103-110]) (e.g., **Figure 3-5**). To provide precise and accurate polarimetric retrievals of aerosol and cloud properties, RSP has been designed to cover a broad spectral range (412-2250 nm, see **Table**

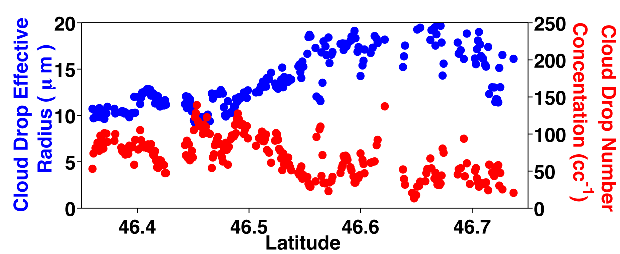

Figure 3-5. *RSP measured cloud (and aerosol) properties during 2012 Azores campaign, as in NAAMES.*

2-1), a broad angular range (152 viewing angles over ±60 deg from nadir), and to acquire Stokes parameters I, Q, and U simultaneously in all wavelengths for each angle (leading to an in-flight calibrated uncertainty of less than 0.2%).

Over the ocean, the validated ocean model of Chowdhary et al.[87, 111] will be used to account for photometric and polarimetric underwater light scattering contributions. RSP retrievals of aerosol properties over oceans are documented extensively in Chowdhary et al.[83, 87, 103, 112]. The approach separates atmospheric scattering contributions from underwater-light scattering contributions by using their differing impacts on angular and spectral properties of RSP total and polarized reflectance. HSRL-1 vertical extinction profiles provide complementary data to validate RSP assumptions made for aerosol vertical distribution and can be used to constrain retrievals and reduce uncertainties in retrieved aerosol imaginary refractive index.

3.3.3.4 GCAS

GCAS is an automated, imaging, hyper-spectral remote sensing instrument developed at NASA GSFC's Radiometric Calibration and Development Facility[113, 114]. GCAS provides UV/Vis/NIR measurements of spectral radiance using two, co-aligned Offner-style imaging spectrometers. Each spectrometer is absolutely calibrated using NIST standards for spectral radiance. It also acts as a GEO-CAPE prototype satellite instrument and provides a relationship between ship-scale and satellite-scale measurements. GCAS measures hyperspectral ocean color properties and trace gas slant column abundance below the aircraft using Differential Optical Absorption Spectroscopy (DOAS)[115] techniques (**Figure 3-6**). The spectrometers are designed to provide flexible binning schemes to address both high spectral resolution requirements of trace gas measurements and high spatial resolution requirements of ocean measurements. Native sampling provided by the 2-D CCD is 1000 cross-track pixels by 1000 spectral bins with a minimum of 0.6 nm resolution in the UV/Vis channel and 2.4 nm in the Vis/NIR channel. For NAAMES ocean color retrievals, native sampling resolution will be binned to provide approximately 600 10-m cross-track x 150-m along-track pixels from a nominal flight altitude of 8 km. Spectral binning is also configurable depending on the desired Signal-to-Noise (SNR) required for the retrieval of water-leaving radiances. For typical 10-nm binning, which provides 55 spectral channels across both spectrometers, GCAS meets or exceeds SNR requirements of 500:1 in the visible and 300:1 in the near-IR. GCAS flew 24 flights in September 2013 for DISCOVER-AQ on the NASA B200 along with the LaRC HSRL-2 instrument. Five of these flights focused on ocean color and were coordinated with ship-based measurements in the Gulf of Mexico. GCAS integrate easily into the P-3B bomb bay where it will operate in an unpressurized environment as on the B200. The GCAS team has flown similar instrumentation on the WB-57 and Global Hawk platforms.

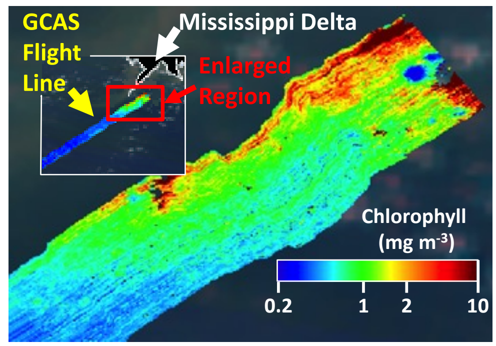

Figure 3-6. *GCAS provides hyperspectral ocean retrievals for NAAMES. Data shown here are early results from a 10 September 2013 Gulf of Mexico deployment.*

3.3.3.5 4STAR

4STAR was developed by NASA ARC. It extends the capabilities of ARC's AATS-14 airborne sunphotometer by adding the ability to measure the angular distribution of sky brightness (sky scanning) and by using a spectrometer in place of the discrete photodiodes and filters found in AATS-14 (wavelength resolution). The zenith-viewing 4STAR allows characterization of spectrally-resolved aerosol optical thickness above the aircraft. These data contribute to NAAMES science objectives by constraining ecosystem and aerosol retrievals from the nadir-viewing RSP and GCAS instruments, enabling retrievals for overlying cirrus+aerosol optical depths of up to 0.5. In summer 2012 and winter 2013, 4STAR successfully supported the DOE Two Column Aerosol Project (TCAP) missions. An early version of 4STAR has flown on the P-3B while performing intercomparison tests with AATS-14.

4 References and citations

1. Field, C.B., et al., *Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components.* Science, 1998. **281**(5374): p. 237-240.
2. Behrenfeld, M.J., et al., *Biospheric Primary Production During an ENSO Transition.* Science, 2001. **291**(5513): p. 2594-2597.
3. Takahashi, T., et al., *Climatological mean and decadal change in surface ocean pCO2, and net sea–air CO2 flux over the global oceans.* Deep Sea Research Part II: Topical Studies in Oceanography, 2009. **56**(8–10): p. 554-577.
4. Behrenfeld, M.J. and P.G. Falkowski, *Photosynthetic rates derived from satellite-based chlorophyll concentration.* Limnology and Oceanography, 1997. **42**(1): p. 1-20.
5. Chassot, E., et al., *Global marine primary production constrains fisheries catches.* Ecology Letters, 2010. **13**(4): p. 495-505.
6. Longhurst, A., *Ecological geography of the sea*. 2007, France: Academic Press.
7. Platt, T., C. Fuentes-Yaco, and K.T. Frank, *Marine ecology: Spring algal bloom and larval fish survival.* Nature, 2003. **423**(6938): p. 398-399.
8. Edwards, M. and A.J. Richardson, *Impact of climate change on marine pelagic phenology and trophic mismatch.* Nature, 2004. **430**(7002): p. 881-884.
9. Mackas, D.L., S. Batten, and M. Trudel, *Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific.* Progress in Oceanography, 2007. **75**(2): p. 223-252.
10. Koeller, P., et al., *Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic ocean.* Science, 2009. **324**: p. 791-793.
11. Kahru, M., et al., *Are phytoplankton blooms occurring earlier in the Arctic?* Global Change Biology, 2011. **17**(4): p. 1733-1739.
12. O'Dowd, C.D., et al., *Biogenically driven organic contribution to marine aerosol.* Nature, 2004. **431**(7009): p. 676-680.
13. Andreae, M.O. and D. Rosenfeld, *Aerosol–cloud–precipitation interactions. Part 1. The nature and sources of cloud-active aerosols.* Earth-Science Reviews, 2008. **89**(1–2): p. 13-41.
14. Behrenfeld, M.J., et al., *Climate-driven trends in contemporary ocean productivity.* Nature, 2006. **444**(7120): p. 752-755.
15. Behrenfeld, M.J., et al., *Global ocean phytoplankton.* State of the Climate in 2008, 2009. **90**(8): p. S68-S73.
16. Martinez, E., et al., *Climate-Driven Basin-Scale Decadal Oscillations of Oceanic Phytoplankton.* Science, 2009. **326**(5957): p. 1253-1256.
17. Vantrepotte, V. and F. Mélin, *Temporal variability of 10-year global SeaWiFS time-series of phytoplankton chlorophyll a concentration.* ICES Journal of Marine Science: Journal du Conseil, 2009. **66**(7): p. 1547-1556.
18. Yoder, J.A. and M.A. Kennelly, *Seasonal and ENSO variability in global ocean phytoplankton chlorophyll derived from 4 years of SeaWiFS measurements.* Global Biogeochemical Cycles, 2003. **17**(4): p. 1112.
19. Gregg, W.W., et al., *Ocean primary production and climate: Global decadal changes.* Geophysical Research Letters, 2003. **30**(15): p. 1809.
20. Gregg, W.W., N.W. Casey, and C.R. McClain, *Recent trends in global ocean chlorophyll.* Geophysical Research Letters, 2005. **32**(3): p. L03606.

21. Polovina, J.J., E.A. Howell, and M. Abecassis, *Ocean's least productive waters are expanding.* Geophysical Research Letters, 2008. **35**(3): p. L03618.
22. Siegel, D.A., et al., *Regional to global assessments of phytoplankton dynamics from the SeaWiFS mission.* Remote Sensing of Environment, 2013. **135**(0): p. 77-91.
23. Behrenfeld, M.J., D.A. Siegel, and R.T. O'Malley, *Global ocean phytoplankton and productivity.* State of the Climate in 2007, 2008. **89**: p. S56-S61.
24. Bopp, L., et al., *Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models.* Biogeosciences Discuss., 2013. **10**(2): p. 3627-3676.
25. Behrenfeld, M.J. and E.S. Boss, *Resurrecting the Ecological Underpinnings of Ocean Plankton Blooms.* Annual Review of Marine Science, 2014. **6**(1): p. null.
26. Gran, H.H. and T. Braarud, *A quantitative study of the phytoplankton in the Bay of Fundy and the Gulf of Maine (including observations on hydrography, chemistry and turbidity).* Biological Board of Canada, 1935. **1**(5): p. 279-467.
27. Sverdrup, H.U., *On Conditions for the Vernal Blooming of Phytoplankton.* Journal du Conseil, 1953. **18**(3): p. 287-295.
28. Sarmiento, J.L. and N. Gruber, *Ocean biogeochemical cycles*. 2006: Princeton University Press.
29. Miller, C.B. and P. Wheeler, *Biological oceanography*. 2012: Blackwell.
30. Bopp, L., et al., *Potential impact of climate change on marine export production.* Global Biogeochemical Cycles, 2001. **15**(1): p. 81-99.
31. Boyd, P.W. and S.C. Doney, *Modelling regional responses by marine pelagic ecosystems to global climate change.* Geophysical Research Letters, 2002. **29**(16): p. 53-1-53-4.
32. Sarmiento, J.L., et al., *Response of ocean ecosystems to climate warming.* Global Biogeochemical Cycles, 2004. **18**(3): p. GB3003.
33. Henson, S.A., J.P. Dunne, and J.L. Sarmiento, *Decadal variability in North Atlantic phytoplankton blooms.* Journal of Geophysical Research: Oceans, 2009. **114**(C4): p. C04013.
34. Evans, G.T. and J.S. Parslow, *A Model of Annual Plankton Cycles.* Biological Oceanography, 1985. **3**(3): p. 327-347.
35. Behrenfeld, M.J., *Abandoning Sverdrup's Critical Depth Hypothesis on phytoplankton blooms.* Ecology, 2010. **91**(4): p. 977-989.
36. Boss, E. and M. Behrenfeld, *In situ evaluation of the initiation of the North Atlantic phytoplankton bloom.* Geophysical Research Letters, 2010. **37**(18): p. L18603.
37. Behrenfeld, M.J., et al., *Annual cycles of ecological disturbance and recovery underlying the subarctic Atlantic spring plankton bloom.* Global Biogeochem. Cycles, 2013. **27**: p. 526–540.
38. Quinn, P.K. and T.S. Bates, *The case against climate regulation via oceanic phytoplankton sulphur emissions.* Nature, 2011. **480**(7375): p. 51-56.
39. Gantt, B. and N. Meskhidze, *The physical and chemical characteristics of marine primary organic aerosol: a review.* Atmos. Chem. Phys., 2013. **13**(8): p. 3979-3996.
40. Moore, R.H., et al., *Droplet number uncertainties associated with CCN: an assessment using observations and a global model adjoint.* Atmos. Chem. Phys., 2013. **13**(8): p. 4235-4251.
41. Meskhidze, N. and A. Nenes, *Phytoplankton and Cloudiness in the Southern Ocean.* Science, 2006. **314**: p. 1419-1423.

42. Falkowski, P.G., et al., *Natural Versus Anthropogenic Factors Affecting Low-Level Cloud Albedo over the North Atlantic* Science, 1992. **256**: p. 1311-1313.
43. Meskhidze, N., et al., *Production mechanisms, number concentration, size distribution, chemical composition, and optical properties of sea spray aerosols.* Atmospheric Science Letters, 2013. **14**(4): p. 207-213.
44. Yassaa, N., et al., *Evidence for marine production of monoterpenes.* Environmental Chemistry, 2008. **5**(6): p. 391-401.
45. Sinreich, R., et al., *Ship-based detection of glyoxal over the remote tropical Pacific Ocean.* Atmos. Chem. Phys., 2010. **10**(23): p. 11359-11371.
46. Lapina, K., et al., *Investigating organic aerosol loading in the remote marine environment.* Atmos. Chem. Phys., 2011. **11**(17): p. 8847-8860.
47. Facchini, M.C., et al., *Cloud albedo enhancement by surface-active organic solutes in growing droplets.* Nature, 1999. **401**(6750): p. 257-259.
48. Nenes, A., et al., *Can chemical effects on cloud droplet number rival the first indirect effect?* Geophysical Research Letters, 2002. **29**(17): p. 1848.
49. Moore, R.H., et al., *Molar mass, surface tension, and droplet growth kinetics of marine organics from measurements of CCN activity.* Geophysical Research Letters, 2008. **35**(7): p. L07801.
50. Taraniuk, I., et al., *Surfactant properties of atmospheric and model humic-like substances (HULIS).* Geophysical Research Letters, 2007. **34**(16): p. L16807.
51. Ruehl, C.R., et al., *Strong evidence of surface tension reduction in microscopic aqueous droplets.* Geophysical Research Letters, 2012. **39**(23): p. L23801.
52. NASA, *2011 NASA Strategic Plan*, 2011: NASA Headquarters, Washington, DC 20546.
53. Takahashi, T., et al., *Seasonal variation of CO2 and nutrients in the high-latitude surface oceans: A comparative study.* Global Biogeochemical Cycles, 1993. **7**(4): p. 843-878.
54. Takahashi, T., et al., *Global air-sea flux of CO2: An estimate based on measurements of sea–air pCO2 difference.* Proceedings of the National Academy of Sciences, 1997. **94**(16): p. 8292-8299.
55. Takahashi, T., et al., *Global sea–air CO2 flux based on climatological surface ocean pCO2, and seasonal biological and temperature effects.* Deep Sea Research Part II: Topical Studies in Oceanography, 2002. **49**(9–10): p. 1601-1622.
56. Knox, F. and M.B. McElroy, *Changes in atmospheric CO2: Influence of the marine biota at high latitude.* Journal of Geophysical Research: Atmospheres, 1984. **89**(D3): p. 4629-4637.
57. Sarmiento, J.L. and J.R. Toggweiler, *A new model for the role of the oceans in determining atmospheric PCO2.* Nature, 1984. **308**(5960): p. 621-624.
58. Sarmiento, J.L. and J.C. Orr, *Three-dimensional simulations of the impact of Southern Ocean nutrient depletion on atmospheric CO2 and ocean chemistry.* Limnol. Oceanogr, 1991. **36**(8): p. 1928–1950.
59. Siegenthaler, U. and T. Wenk, *Rapid atmospheric CO2 variations and ocean circulation.* Nature, 1984. **308**(5960): p. 624-626.
60. Banse, K., *Grazing, Temporal Changes of Phytoplankton Concentrations, and the Microbial Loop in the Open Sea*, in *Primary Productivity and Biogeochemical Cycles in the Sea*, P. Falkowski, A. Woodhead, and K. Vivirito, Editors. 1992, Springer US. p. 409-440.

61. Ducklow, H.W. and R.P. Harris, *Introduction to the JGOFS North Atlantic bloom experiment.* Deep Sea Research Part II: Topical Studies in Oceanography, 1993. **40**(1–2): p. 1-8.
62. Behrenfeld, M.J., et al., *Space-based lidar measurements of global ocean carbon stocks.* Geophysical Research Letters, 2013. **40**(16): p. 4355-4360.
63. Mahadevan, A., et al., *Eddy-Driven Stratification Initiates North Atlantic Spring Phytoplankton Blooms.* Science, 2012. **337**(6090): p. 54-58.
64. Sciare, J., et al., *Long-term observations of carbonaceous aerosols in the Austral Ocean atmosphere: Evidence of a biogenic marine organic source.* Journal of Geophysical Research: Atmospheres, 2009. **114**(D15): p. D15302.
65. Siegel, D.A., S.C. Doney, and J.A. Yoder, *The North Atlantic Spring Phytoplankton Bloom and Sverdrup's Critical Depth Hypothesis.* Science, 2002. **296**(5568): p. 730-733.
66. Boss, E., et al., *Observations of pigment and particle distributions in the western North Atlantic from an autonomous float and ocean color satellite.* Limnology and Oceanography, 2008. **53**(5): p. 2112-2122.
67. Hurrell, J.W., et al., *The Community Earth System Model: A Framework for Collaborative Research.* Bulletin of the American Meteorological Society, 2013. **94**(9): p. 1339-1360.
68. Moore, J.K., et al., *Marine Ecosystem Dynamics and Biogeochemical Cycling in the Community Earth System Model [CESM1(BGC)]: Comparison of the 1990s with the 2090s under the RCP4.5 and RCP8.5 Scenarios.* Journal of Climate, 2013. **26**(23): p. 9291-9312.
69. Doney, S.C., et al., *Skill metrics for confronting global upper ocean ecosystem-biogeochemistry models against field and remote sensing data.* Journal of Marine Systems, 2009. **76**(1–2): p. 95-112.
70. *A National Strategy for Advancing Climate Modeling*. 2012: The National Academies Press.
71. Hu, Y., et al., *Global statistics of liquid water content and effective number concentration of water clouds over ocean derived from combined CALIPSO and MODIS measurements.* Atmos. Chem. Phys., 2007. **7**(12): p. 3353-3359.
72. Boers, R., J.R. Acarreta, and J.L. Gras, *Satellite monitoring of the first indirect aerosol effect: Retrieval of the droplet concentration of water clouds.* Journal of Geophysical Research: Atmospheres, 2006. **111**(D22): p. D22208.
73. *Cloud-Aerosol Transport System (CATS) lidar*. Available from: http://www.nasa.gov/mission_pages/station/research/experiments/1037.html.
74. Agency, E.S. *EarthCARE*. 2013; Available from: https://earth.esa.int/web/guest/missions/esa-future-missions/earthcare.
75. O'Reilly, J.E., et al., *SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3*, 2000.
76. Hu, C., Z. Lee, and B. Franz, *Chlorophyll algorithms for oligotrophic oceans: A novel approach based on three-band reflectance difference.* Journal of Geophysical Research: Oceans, 2012. **117**(C1): p. C01011.
77. Maritorena, S., D.A. Siegel, and A.R. Peterson, *Optimization of a semianalytical ocean color model for global-scale applications.* Applied Optics, 2002. **41**(15): p. 2705-2714.

78. Lee, Z., K.L. Carder, and R.A. Arnone, *Deriving Inherent Optical Properties from Water Color: a Multiband Quasi-Analytical Algorithm for Optically Deep Waters.* Applied Optics, 2002. **41**(27): p. 5755-5772.
79. Lee, Z.-P., K.-P. Du, and R. Arnone, *A model for the diffuse attenuation coefficient of downwelling irradiance.* Journal of Geophysical Research: Oceans, 2005. **110**(C2): p. C02016.
80. Lee, Z., et al., *Euphotic zone depth: Its derivation and implication to ocean-color remote sensing.* Journal of Geophysical Research: Oceans, 2007. **112**(C3): p. C03009.
81. Platt, U., *Air Monitoring by Spectroscopic Techniques*. Chemical Analysis Series ed. M.W. Sigrist. Vol. 127. 1994, New York: Wiley
82. Hair, J.W., et al., *Airborne High Spectral Resolution Lidar for profiling aerosol optical properties.* Applied Optics, 2008. **47**(36): p. 6734-6752.
83. Chowdhary, J., et al., *Retrieval of aerosol scattering and absorption properties from photopolarimetric observations over the ocean during the CLAMS experiment.* Journal of the Atmospheric Sciences, 2005. **62**(4): p. 1093-1117.
84. Alexandrov, M.D., et al., *Accuracy assessments of cloud droplet size retrievals from polarized reflectance measurements by the research scanning polarimeter.* Remote Sensing of Environment, 2012. **125**(0): p. 92-111.
85. Nakajima, T., et al., *Determination of the Optical Thickness and Effective Particle Radius of Clouds from Reflected Solar Radiation Measurements. Part II: Marine Stratocumulus Observations.* Journal of the Atmospheric Sciences, 1991. **48**(5): p. 728-751.
86. Bennartz, R., *Global assessment of marine boundary layer cloud droplet number concentration from satellite.* Journal of Geophysical Research: Atmospheres, 2007. **112**(D2): p. D02201.
87. Chowdhary, J., et al., *Sensitivity of multiangle, multispectral polarimetric remote sensing over open oceans to water-leaving radiance: Analyses of RSP data acquired during the MILAGRO campaign.* Remote Sensing of Environment, 2012. **118**(0): p. 284-308.
88. Shinozuka, Y., et al., *Hyperspectral aerosol optical depths from TCAP flights.* Journal of Geophysical Research: Atmospheres, 2013. **118**(21): p. 2013JD020596.
89. Segata, N., et al., *Computational meta/'omics for microbial community studies.* Mol Syst Biol, 2013. **9**.
90. Vergin, K.L., et al., *High-resolution SAR11 ecotype dynamics at the Bermuda Atlantic Time-series Study site by phylogenetic placement of pyrosequences.* ISME J, 2013. **7**(7): p. 1322-1332.
91. Treusch, A.H., et al., *Phytoplankton distribution patterns in the northwestern Sargasso Sea revealed by small subunit rRNA genes from plastids.* ISME J, 2012. **6**(3): p. 481-492.
92. Siegel, D.A., et al., *Independence and interdependencies among global ocean color properties: Reassessing the bio-optical assumption.* Journal of Geophysical Research: Oceans, 2005. **110**(C7): p. C07011.
93. Siegel, D.A., et al., *Colored dissolved organic matter and its influence on the satellite-based characterization of the ocean biosphere.* Geophysical Research Letters, 2005. **32**(20): p. L20605.
94. Werdell, P.J. and S.W. Bailey, *The SeaWiFS Bio-optical Archive and Storage System (SeaBASS): Current architecture and implementation*, G.S. Fargion and C.R. McClain, Editors. 2002: NASA Goddard Space Flight Center, Greenbelt, Maryland. p. 45.

95. Werdell, P.J., et al., *Unique data repository facilitates ocean color satellite validation.* Eos, Transactions American Geophysical Union, 2003. **84**(38): p. 377-387.
96. McNaughton, C.S., et al., *Results from the DC-8 Inlet Characterization Experiment (DICE): Airborne Versus Surface Sampling of Mineral Dust and Sea Salt Aerosols.* Aerosol Science and Technology, 2007. **41**(2): p. 136-159.
97. Fernald, F.G., *Analysis of atmospheric lidar observations: some comments.* Applied Optics, 1984. **23**(5): p. 652-653.
98. Rogers, R.R., et al., *NASA LaRC airborne high spectral resolution lidar aerosol measurements during MILAGRO: observations and validation.* Atmos. Chem. Phys., 2009. **9**(14): p. 4811-4826.
99. Sugimoto, N. and C.H. Lee, *Characteristics of dust aerosols inferred from lidar depolarization measurements at two wavelengths.* Applied Optics, 2006. **45**(28): p. 7468-7474.
100. Burton, S.P., et al., *Aerosol Classification of Airborne High Spectral Resolution Lidar Measurements – Methodology and Examples.* Atmospheric Measurement Techniques, 2012. **5**(1): p. 73-98.
101. Fast, J.D., et al., *Transport and mixing patterns over Central California during the carbonaceous aerosol and radiative effects study (CARES).* Atmos. Chem. Phys., 2012. **12**(4): p. 1759-1783.
102. Scarino, B., et al., *Retrieving Clear-Sky Surface Skin Temperature for Numerical Weather Prediction Applications from Geostationary Satellite Data.* Remote Sensing, 2013. **5**(1): p. 342-366.
103. Chowdhary, J., B. Cairns, and L.D. Travis, *Case studies of aerosol retrievals over the ocean from multiangle, multispectral photopolarimetric remote sensing data.* Journal of the Atmospheric Sciences, 2002. **59**(3): p. 383-397.
104. Waquet, F., et al., *Aerosol Remote Sensing over Clouds Using A-Train Observations.* Journal of the Atmospheric Sciences, 2009. **66**(8): p. 2468-2480.
105. Waquet, F., et al., *Polarimetric remote sensing of aerosols over land.* Journal of Geophysical Research: Atmospheres, 2009. **114**(D1): p. D01206.
106. Waquet, F., et al., *Analysis of the spectral and angular response of the vegetated surface polarization for the purpose of aerosol remote sensing over land.* Applied Optics, 2009. **48**(6): p. 1228-1236.
107. Knobelspiesse, K., et al., *Simultaneous retrieval of aerosol and cloud properties during the MILAGRO field campaign.* Atmos. Chem. Phys., 2011. **11**(13): p. 6245-6263.
108. Knobelspiesse, K., et al., *Combined retrievals of boreal forest fire aerosol properties with a polarimeter and lidar.* Atmos. Chem. Phys., 2011. **11**(14): p. 7045-7067.
109. Alexandrov, M.D., B. Cairns, and M.I. Mishchenko, *Rainbow Fourier transform.* J. Quant. Spectrosc. Radiat. Transfer, 2012. **113**: p. 2521-2535.
110. Ottaviani, M., et al., *Information content of aerosol retrievals in the sunglint region.* Geophysical Research Letters, 2013. **40**(3): p. 631-634.
111. Chowdhary, J., B. Cairns, and L.D. Travis, *Contribution of water-leaving radiances to multiangle, multispectral polarimetric observations over the open ocean: bio-optical model results for case 1 waters.* Applied Optics, 2006. **45**(22): p. 5542-5567.
112. Chowdhary, J., et al., *Retrieval of aerosol properties over the ocean using multispectral and multiangle photopolarimetric measurements from the Research Scanning Polarimeter.* Geophysical Research Letters, 2001. **28**(2): p. 243-246.

113. Janz, S., et al., *Uncertainties in radiance calibrations of backscatter ultraviolet (BUV) instruments.* Metrologia, 1995. **32**(6): p. 637.
114. Hilsenrath, E., et al., *Calibration and Radiometric Stability of the Shuttle Solar Backscatter Ultraviolet (SSBUV) Experiment.* Metrologia, 1993. **30**(4): p. 243.
115. Platt, U. and D. Perner, *Direct measurements of atmospheric CH2O, HNO2, O3, NO2, and SO2 by differential optical absorption in the near UV.* Journal of Geophysical Research: Oceans, 1980. **85**(C12): p. 7453-7458.