Table 2.1 ACE Aerosol Science Traceability Matrix

Themes	Focused Science Questions	Geophysical Parameters	Measurement Requirements	Mission Requirements
Sources, Processes, Transport, Sinks (SPTS)	Q1. What are key sources, sinks, and transport paths of airborne sulfate, organic, BC, sea salt, and mineral dust aerosol? Q2. What is the impact of specific significant aerosol events such as volcanic eruptions, wild fires, dust outbreaks, urban/industrial pollution, etc. on local, regional, and global aerosol burden?	Column: Q1 Q2 Q3 Q4 • $\tau_a(\lambda)$ • $\tau_{a,abs}(\lambda)$ • $m_a(\lambda)$ • $r_{eff\,a}(\lambda)$ • $\nu_{eff\,a}(\lambda)$ • Morphology Vertically Resolved: Q1 Q2 Q3 Q4 • $\tau_{a,abs}(\lambda)$ • $m_a(\lambda)$ • $r_{eff\,a}(\lambda)$ • $\nu_{eff\,a}(\lambda)$ • Morphology	High Spectral Resolution Lidar (HSRL) • Backscatter (355, 532, 1064 nm) • Extinction (355, 532 nm) • Depolarization (two wavelengths of 355, 532, 1064 nm) Imaging Polarimeter • Minimum 6 to 8 wavelengths spanning either UV or 410 nm to either 1630 nm or 2250 nm • Multiangle TBD, range ±50° • Polarization accuracy 0.5% • Combination polarized and nonpolarized channels • Resolution: 250 m in at least one channel	Integrated satellite, modeling, and data assimilation approach is required to meet science objectives. Expand high-resolution global and regional modeling capabilities to assimilate cloud and aerosol microphysical parameters such as number concentration and optical properties. Required ancillary data: • Land surface albedo map • Ground network $\tau_a(\lambda)$, shortwave and longwave F_d and F_{net} • Ground and airborne: column and vertically resolved $\tau_a(\lambda)$, $\tau_{a,abs}(\lambda)$, $m_a(\lambda)$ (2 modes), morphology, $P_{a,pol}(\theta)$ • Space measurements: Top of atmosphere shortwave and longwave F_u, collocated T(z), q(z), V(z), fire strength, frequency, location
Direct Aerosol Radiative Forcing (DARF)	Q3. What is the direct aerosol radiative forcing (DARF) at the top-of-atmosphere, within atmosphere, and at the surface? Q4. What is the aerosol radiative heating of the atmosphere due to absorbing aerosols, and how will this heating affect cloud development and precipitation processes?	Cloud Top: Q3 Q4 • τ_c • $\tau_{eff,c}$ • $\nu_{eff,c}$ • Thermodynamic phase		
Cloud-Aerosol Interactions (CAI)	Q5. How do aerosols affect cloud micro and macro physical properties and the subsequent radiative balance at the top, within, and bottom of the atmosphere? Q6. How does the aerosol influence on clouds and precipitation via nucleation depend on cloud updraft velocity and cloud type? Q7. How much does solar absorption by anthropogenic aerosol affect cloud radiative forcing and precipitation? Q8. What are the key mechanisms by which clouds process aerosols and influence the vertical profile of aerosol physical and optical properties?	Vertically Resolved: Q5 Q6 Q7 Q8 P1. N_a P2. $\tau_{a,abs}(\lambda)$ P3. $r_{eff,a}$ P4. N_c P5. LWC P6. Precip Cloud Top: Q5 Q6 Q7 Q8 P7. Cloud top height P8. Cloud albedo P9. LWP P10. τ_c P11. $r_{eff,c}$ P12. Cloud radiative effect Cloud Base: Q5 Q6 Q7 Q8 P13. Cloud base height P14. Updraft velocity	**Threshhold (i.e. minimum)** **HSRL:** P1 P2 P3 P10 **Imaging Polarimeter:** P1 P2 P3 **W band Radar:** P4 P5 P7 P13 P14 **Narrow swath High-Resolution VIS-MWIR Imager:** P9,P11 *Baseline* (additions to threshold): W + Ka Band Doppler radar P6 P14	

Table 2.2 ACE Cloud Science Traceability Matrix

Themes	Focused Science Questions	Geophysical Parameters	Measurement Requirements	Mission Requirements
T1. Morphology **Document occurrence, macroscale structure, and decadal scale changes of clouds and precipitation and their interaction with large-scale meteorological and thermodynamic forcing.**	**Q1. Climate Sensitivity** **What is the sensitivity of the climate system to cloud structure and variability? T1 T2 T3 T4** • *What is the role of natural and anthropogenic aerosol in modulating cloud system occurrence and properties?* T1 • **What microphysical processes dictate the lifecycle and coverage of clouds under various atmospheric conditions? T1 T2** • *What dictates the processes that cause and modulate precipitation in cloud systems?* T3	**GP1. Hydrometeor Layer Detection** Q1 Q2 Q3 Q4 GP2. *Simultaneously occurring* **Cloud and Precipitation Thermodynamics Phase profile** Q1 Q2 Q3 Q4 **GP3.** *Simultaneously occurring* **Cloud and precipitation microphysical properties profiles (Water Content, particle sieze, and number concentration)** Q1 Q2 Q3 Q4 GP4. **Precipitation Rate Profile in light** *and heavy (> 5 mm/hr)* **precipitation** Q1 Q2 Q3 Q4 GP5. **Profiles of Cloud Optical Depth,** *single scattering albedo, and asymmetry parameter* Q1 Q2 Q3 Q4 **GP6. Surface, TOA Cloud Radiative Effects** Q1 Q2 Q3 Q4 GP7. **Latent Heating Profile in light** *and heavy (> 5 mm/hr)* **precipitation** Q1 Q3 Q4 GP8. *Radiative Heating Profile* Q1 Q2 Q3 Q4 GP9. **Cloud-Scale Vertical Motion** Q1 Q4 GP10. *Aerosol/CCN number concentration profile* Q1 Q2 Q3	**Threshold Mission** **TM1. 2-Frequency (W- , Ka-bands), Scanning Doppler Radar (with radiometer channels)** GP1 GP2 GP3 GP4 GP5 GP6 GP7 GP8 GP9 TM2. **High Spectral Resolution Lidar** GP1 GP2 GP3 GP5 GP6 GP8 GP10 TM3. **Narrow Swath Vis Imager (0.6 microns, 1.6 microns, 2.1 microns)** GP2 GP3 GP5 GP6 GP8 GP10 *Baseline Mission* *BM1. 3-Frequency (W- , Ka-, Ku-bands), Scanning Doppler Radar (with radiometer channels)* GP1 GP2 GP3 GP4 GP5 GP6 GP7 GP8 GP9 *(replaces TM1)* *BM2. High Spectral Res. Lidar (HSRL)* GP1 GP2 GP3 GP5 GP6 GP8 GP10 *(replaces TM2)* *BM3. High Resolution Narrow Swath VNIR-SWIR Polarimeter* GP6 GP8 GP10 *(Replaces TM3)* *BM4. Narrow Swath High Freq. (183, 389 GHz) Microwave* GP2 GP3 GP4 GP5 GP6 GP7 GP8	We define the **threshold** ACE Clouds Mission as those elements of this matrix that are in **bold font**. We suggest that boldface science objective and questions in columns 1 and 2 could ultimately be addressed by the measurements listed as the Threshold Mission in the Measurement Requirements Column. Elements of this matrix in *italicized font* are defined as a *Baseline Mission* and designate important science questions that require a more aggressive set of coordinated measurements that are listed in italicized font. The set of baseline and threshold ACE clouds retrieval algorithms will be synergistic such that multiple measurements contribute to the retrieval of a geophysical parameter. For instance while microwave brightness temperatures cannot generally be used to retrieve cloud microphysics, when passive microwave is combined with multi frequency Doppler radar, the microwave brightness temperatures provides an important constraint on the retrieval algorithm.
T2. Microphysics **Document the microphysical properties of liquid, ice, and mixed phase clouds and precipitation with a specific focus on high latitude snow and light liquid precipitation (less than 1 mm/hr) at all latitudes that influences cloud morphology and lifecycle and ultimately radiative balance.**	**Q2. Climate Forcing – Solar (T4)** **How will shortwave cloud forcing change as the climate warms? T1 T2 T3 T4** • **Will the coupling between cloud occurrence and morphology with atmospheric motions and thermodynamic structure result in fundamental changes to the planetary albedo? T1 T2** • *What is the specific role of aerosol in modulating the properties of clouds and the planetary albedo under a changing climate? (T2, T3)*			
T3. Microphysical Processes **Identify the occurrence of microphysical processes that cause changes to profiles of aerosol, clouds, and precipitation properties.** *Concurrently quantify the process rates of important microphysical processes such as autoconversion and accretion in liquid and ice-phase stratiform and convective clouds.*	**Q3. Climate Forcing – Infrared (T4)** **How will longwave cloud forcing change as the climate warms? T1 T2 T3 T4** • **What is the coupling between thermodynamic structure convective processes and the properties of convective anvils in modulating the coverage and properties of tropical anvil cirrus T1 T2 T3** • *What is the role of aerosol in changing the microphysical properties of tropical anvils and modulating their coverage, persistence, and feedbacks to the water cycle in the upper troposphere?* T1 T2 T3			
T4. Energetics *Understand the maintenance of and changes to the energetic balance of the atmosphere and earth system due aerosol, clouds, and precipitation.*	**Q4. Water Cycle and Energy Transport (T4)** **What is the role of cloud processes (specifically mixed phase) in snow and rain production in middle and high latitude cloud systems? T1 T2 T3 T4** • **What role does the seasonal cycle of middle latitude cloud radiative forcing play in the poleward transport of heat and how is this radiative forcing partitioned as function of cloud genre? T4** • *To what degree do various microphysical processes when coupled with large-scale dynamics modulate the precipitation production within middle and high latitude frontal systems?* T2 T3 • **What is the role of convection versus large-scale dynamics in producing precipitation in the middle and high latitudes? T1 T3**			

Ocean Ecosystems STM

Goddard Space Flight Center

Category	Focused Questions*
Ocean Biology	1 What are the standing stocks, composition, & productivity of ocean ecosystems? How and why are they changing? [OBB1]
	2 How and why are ocean biogeochemical cycles changing? How do they influence the Earth system? [OBB2]
	3 What are the material exchanges between land & ocean? How do they influence coastal ecosystems, biogeochemistry & habitats? How are they changing? [OBB1,2,3]
	4 How do aerosols & clouds influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere and Earth system? [OBB2]
	5 How do physical ocean processes affect ocean ecosystems & biogeochemistry? How do ocean biological processes influence ocean physics? [OBB1,2]
	6 What is the distribution of algal blooms and their relation to harmful algal and eutrophication events? How are these events changing? [OBB1,4]

Approach	Maps to Science Question
Quantify phytoplankton biomass, pigments, optical properties, key groups (functional/HABS), and productivity using bio-optical models & chlorophyll fluorescence	1, 2, 6
Measure particulate and dissolved carbon pools, their characteristics and optical properties	2, 3
Quantify ocean photobiochemical & photobiological processes	2, 4
Estimate particle abundance, size distribution (PSD), & characteristics	1, 3, 2
Assimilate ACE observations in ocean biogeochemical model fields of key properties (cf., air-sea CO_2 fluxes, export, pH, etc.)	2
Compare ACE observations with ground-based and model data of biological properties, land-ocean exchange in the coastal zone, physical properties (e.g., winds, SST, SSH, etc), and circulation (ML dynamics, horizontal divergence, etc)	3, 4, 5, 6
Combine ACE ocean & atmosphere observations with models to evaluate (1) air-sea exchange of particulates, dissolved materials, and gases and (2) impacts on aerosol & cloud properties	4
Assess ocean radiant heating and feedbacks	5
Conduct field sea-truth measurements and modeling to validate retrievals from the pelagic to near-shore environments	1, 4, 2, 5, 3, 6

Measurement Requirements	Instrument	Instrument Requirements
Water-leaving radiances in near-ultraviolet, visible, & near-infrared for separation of absorbing & scattering constituents and calculation of chlorophyll fluorescence Total radiances in UV, NIR, and SWIR for atmospheric corrections Cloud radiances for assessing instrument stray light	Ocean Radiometer	• 5 nm resolution 350 to 755 nm ▷ 1000 – 1500 SNR for 15 nm aggregate bands UV & visible and 10 nm fluorescence bands (665, 678, 710, 748 nm centers) ▷ 10 to 40 nm width atmospheric correction bands at 748, 765, 820, 865, 1245, 1640, 2135 nm • 0.1% radiometric temporal stability (1 month demonstrated prelaunch) • 58.3° cross track scanning • Sensor tilt (±20°) for glint avoidance • Polarization insensitive (<1.0%) • 1 km spatial resolution @ nadir • No saturation in UV to NIR bands • 5 year minimum design lifetime
High vertical resolution aerosol heights, optical thickness, & composition for atmospheric corrections Subsurface particle scattering & depth profile	Lidar	• 0.5 km aerosol vertical resolution • 2 m sub-surface resolution • < 0.3% polarization misalignment • 0.0001 $km^{-1}sr^{-1}$ aerosol backscatter sensitivity at 532 nm after averaging • < 4 ns e-folding transient response • Brillouin scattering capability; Receiver FOVs: 0-60 m; 0-120 m.
Broad spatial coverage aerosol heights and single scatter albedo for atmospheric correction. Subsurface polarized return for typing oceanic particles	Polarimeter	• Observation angles: 60° to 140° • Angle resolution: 5° • Degree of polarization: 1%

Supporting Field & Laboratory Measurements

- Primary production (NPP) measurement & round-robin algorithm testing
- Inherent optical properties (IOPs) instrument & protocols development, laboratory & field (coastal and open ocean) measurement comparisons
- Measure key phytoplankton groups across ocean biomes (coast/open ocean)
- Expanded global data sets of NPP, CDOM, DOM, pCO2, PSDs, IOPs, fluorescence, vertical organic particle fluxes, bio-available Fe concentrations

Ocean Biogeochemistry-Ecosystem Modeling

- Expand model capabilities to assimilate variables such as NPP, IOPs, and phytoplankton species/functional group concentrations.
- Improve model process parameterizations, e.g., particle fluxes

Platform Requir'ts

Orbit permitting 2-day global coverage of ocean radiometer measurements

Sun-synchronous orbit with crossing time between 10:30 a.m. & 1:30 p.m.

Storage and download of full spectral and spatial data

Monthly lunar calibration at 7° phase angle through Earth observing port

Other Needs

Global data sets from missions, models, or field observations:

Measurement Requirements
(1) Ozone
(2) Total water vapor
(3) Surface wind velocity
(4) Surface barometric pressure
(5) NO_2 concentration
(6) Vicarious calibration & validation **
(7) Full prelaunch characterization (2% accuracy radiometric)

Science Requirements
(1) SST
(2) SSH
(3) PAR
(4) UV
(5) MLD
(6) CO_2
(7) pH
(8) Ocean circulation
(9) Aerosol deposition
(10) run-off loading in coastal zone

* ACE focused questions are traceable to the four overarching science questions of NASA's Ocean Biology and Biogeochemistry Program [OBB1 to OBB4] as defined in the document: *Earth's Living Ocean: A Strategic Vision for the NASA Ocean Biological and Biogeochemistry Program*

** Specific vicarious calibration & validation requirements are defined in the ACE Ocean Ecosystem requirements document developed as part of ACE pre-formulation activities

Aerosol-Ocean STM

Category	Focused Questions	Approach	Maps to Science Question	Measurement Requirements	Instrument Requirements	Platform Requir'ts	Other Needs
Aerosol-Ocean Inter-action	1 What is the flux of aerosols to the ocean and their temporal and spatial distribution	1) Identify microphysical and optical properties of aerosols, partition natural and anthropogenic sources, and characterize spectral complex index of refraction and particle size distribution	2, 3, 6	**Satellite** • Radiances & polarization at selected UV, visible and SWIR bands for aerosol types (dust, smoke, etc.), complex index of refraction, effective height, optical thickness, and size distribution with 2-day global coverage to resolve temporal evolution of plumes • Active (lidar) measurements of aerosol properties along orbit track to refine height distribution and composition • Drizzle detection and precipitation rates coincident with lidar & polarimeter data • Global phytoplankton pigment absorption, dissolved organics absorption, total & phytoplankton carbon concentration, ocean particle size distribution, phytoplankton fluorescence, Chl:C, and growth rate • Particle scattering & vertical distribution through active (lidar) subsurface returns **Supporting Field & Laboratory Measurements** • Dust chemical properties/solubility/ chemical transformation • Aerosol optical properties, heights, chemical composition, and partitioning of gas-derived and mechanically-derived contributions to total column load • DMS flux and dissolved concentration and precursors • Atmospheric boundary layer trace gases, NO_2 / SO_2 height distribution • Diffuse irradiance and in-water optics • Surface layer plankton species, phytoplankton carbon, fluorescence • observational network representative of global range in properties • process/mechanism oriented field and laboratory studies • sustain time series field measurements of key properties over active lifetime of mission **Modeling** • Conduct model tracer studies to determine sources, composition, and chemical attributes of aerosols • Model height distribution of NO_2 & SO_2 and dust chemistry • Use satellite data to constrain model aerosol source strengths • Model air-sea exchange rates and temporal variability, including sources of aerosols to atmosphere • Run coupled ocean biogeochemistry model to assess impacts and compare to observed response of ocean ecosystems	**Spectrometer** • requirements as stated in ocean STM **Polarimeter** • requirements as stated in aerosol STM **Lidar** • requirements as in ocean STM **Duel frequency Doppler radar** • requirements as stated in cloud STM	Orbit permitting 2-day global coverage for passive radiometer & polarimeter measurements Sun-synchronous orbit with crossing time between 10:30 a.m. & 1:30 p.m. Storage and download of full spectral and spatial data Monthly lunar calibration at 7º phase angle through Earth observing port Additional platform requirements for polarimeter, lidar and radar as detailed in Ocean, Aerosol, and Cloud STMs	**Supporting Global data** • Humidity profiles • Precipitation • Formaldehyde • Glyoxal • IO • BrO • NO_2 • SO_2 **Other Data** •Ground-based aerosol observational network
	2 What are the physical and chemical characteristics, sources, and strengths of aerosols deposited into the oceans?	2) Characterize dust aerosols, their column mass, iron content and other trace elements, and their regional-to-global scale transport and flux from events to the annual cycle	1, 2				
	3 How are the physical and chemical characteristics of deposited aerosols transformed in the atmosphere?	3) Conduct appropriate field observations to validate satellite retrievals of aerosols and ocean ecosystem features	1, 5				
	4 How do ocean ecosystems respond to aerosol deposition?	4) Use ACE space and field observations to constrain models to evaluate (1) aerosol chemical transformations and long range transport, (2) air-to-sea and sea-to-air exchange and (3) impacts on ocean biology	2, 5, 6				
	5 What is the spatial and temporal distribution of aerosols and gases emitted from the ocean and how are these fluxes regulated by ocean ecosystems?	5) Characterize aerosol chemical composition and transformation during transport (including influences of vertically distributed NO_2, SO_2, formaldehyde, glyoxal, IO, BrO) and partition gas-derived and mechanically-derived contributions to total aerosol column	2, 3, 5				
	6 What are the feedbacks among ocean emissions of aerosols and gases, microphysical and radiative properties of the overlying aerosols and clouds, aerosol deposition, ocean ecosystems and the Earth's climate, and how is humankind changing these feedbacks?	6) Monitor global phytoplankton biomass, pigments, taxonomic groups, productivity, Chl:C, and fluorescence; measure and distinguish ocean particle pools and colored dissolved organic material; quantify aerosol-relevant surface ocean photobiological and photobiochemical processes	4, 5, 6				
		7) Relate changes in ocean biology/emissions to aerosol deposition patterns and events	3, 5, 4				
		8) Demonstrate influences of ocean taxonomy, physiological stress, and photochemistry on cloud/aerosol properties, including organic aerosol transfer	1, 2, 3				