	DS Science Question addressed by CALIGOLA [1]	DS Science/Application Objective addressed by CALIGOLA [1]	Priority
MARINE AND TERRESTRIAL ECOSYSTEMS AND NATURAL RESOURCES MANAGEMENT	***E-1.*** What is the structure of Earth's ecosystems, how and why are they changing?	**E-1a**. Quantify the distribution of functional types of marine biomass over space and time	**Very Important**
		E-1b. Quantify 3D structure of terrestrial vegetation and 3D distribution of euphotic zone marine biomass over space and time	**Most Important**
		E-1c. Quantify the physiological dynamics of terrestrial and aquatic primary producers	**Most Important**
	E-2. What are the fluxes of carbon, nutrients, and energy between ecosystems and the atmosphere, how and why are they changing?	**E-2a.** Quantify the fluxes of CO_2 globally between ocean ecosystems and atmosphere	**Most Important**
		E-2c. Assess ecosystem subsidies from solid Earth	**Important**
	E-3. What are the fluxes of carbon, nutrients, and energy within ecosystems, how and why are they changing?	**E-3a**. Quantify the flows of energy, carbon, and nutrients sustaining terrestrial and marine ecosystems	**Most Important**
		E-3b. Understand how ecosystems support higher trophic levels of food webs	**Important**
	E-4. How is carbon accounted for through storage, turnover, and accumulated biomass?	**E-4a**. Improve assessments of the global inventory of terrestrial carbon pools and their turnover rate	**Important**
		E-4b. Constrain ocean carbon storage and turnover	**Important**
	E-5. Are carbon sinks stable, are they changing, and why?	**E-5b**. Discover cascading perturbations in ecosystems related to carbon storage	**Important**

CALIGOLA Geophysical Observable [2]	Baseline and Threshold Measurement Parameters [3]	Coincident Synergistic Observations [4]
O1. Phytoplankton carbon and pigment concentrations through euphotic zone [**E-1b, E-2a, E-3a, E-4b, E-5b**] **O2.** Phytoplankton net primary production and biomass accumulation rates [**E-1c, E-2a, E-3a, E-3b, E-4b**] **O3.** Phytoplankton functional types (from depolarization to backscatter ratio) [**E-1a**] **O4**. Phytoplankton carbon:absorption ratio [**E-1c, E-2a, E-2c, E-3a**] **O5.** Diel vertically migrating (DVM) animal biomass and nighttime distribution in euphotic zone [**E-1b, E-2a, E-3a, E-3b, E-4b, E-5b**] **O6.** Ocean colored dissolved organic material concentration [**E-4b**] **O7.** Nighttime phytoplankton chlorophyll fluorescence [**E-1c, E-2a, E-2c, E-3a**] **L1.** Canopy height and vertical structure of terrestrial vegetation [**E-1b, E-3a, E-4a**] **L2**. Day and night vegetation chlorophyll fluorescence [**E-1c, E-3a, E-4a**] **A1.** Aerosol types and their vertical distribution [**E-2c**] **A2**. Aerosol column optical depths and profile [**E-2c**] **A3**. Aerosol particle size [**E-2c**]	**T1.** 532 nm co-polarized return [**O1-O5, L1, A1-A3**] **T2.** 355 nm co-polarized return [**O1-O5, L1, A1-A3**] **T3.** 532 nm cross-polarized return [**O1-O6, L1, A1-A3**] **T4.** 317 nm water Raman emission [**O1-O6**] **T5.** 405 nm water Raman emission [**O1-O6**] **T6.** 1064 nm co-polarized return [**A1-A3**] **B1.** 355 nm cross-polarized return [**O1-O6, L1, A1-A3**] **B2.** 680 nm chlorophyll fluorescence [**O7, L2**] **V1.** 450 nm water Raman emission [**O1-O6**] **V2.** 1064 nm cross-polarized return [**A1**] **V3.** 466 nm cDOM emission [**O6**] **V4.** 532 nm co-polarized and cross-polarized return with enhanced detector dynamic range [**O1**] 0.8 m vertical sampling from surface ocean to 2 optical depths (OD) [**T3**], 3 OD [**T1, B1**], and 4 OD [**T2/V4**] Depth-integrated return within first OD [**T4, T5, B2, V1, V3**] 0.8 m vertical sampling from terrestrial canopy to ground [**T1, T2, T3, B1, B2**] 90 m (low altitude) to 900 m (high altitude) vertical sampling of atmosphere [**T1-T3, T6, B1, V2**] 12° off-nadir lidar pointing [**All**] Global coverage with ~2 week repeat cycle [**All**] Day and night (>1 hr pre-sunrise) measurements [**T1-T6, B1, V1**] 10 nm bandpass detector [**T4, T5, B2, V1, V3**]	**E-1b** PACE, SBG VIIRS, Landsat, BioArgo (in situ) **E-1c** PACE, SBG **E-2a** PACE, SBG **E-2c** PACE, SBG Aeronet (in situ) **E-3a** PACE, SBG, VIIRS, Landsat **E-3b** BioArgo, ship-based observations **E-4a** SBG, Landsat **E-4b** PACE, VIIRS **E-5b** CALIOP baseline, Mesopelagic fishing records

Observable	A.D. Ref. [5]	Enabled Appl. [6]
O1	1-7	EA1- EA4
O2	6, 8-11	EA2- EA4
O3	7	EA2- EA4
O4	6-7, 12-14	EA- EA4
O5	15	EA2- EA4
O6	16-18	EA1, EA4
O7	19-23	EA2- EA4
L1	24, 25	EA1,EA5-EA18
L2	26	EA5-EA17
A1- A3	27-29	EA19-EA22

CLIMATE VARIABILITY AND CHANGE	***C-2.*** How can we reduce the uncertainty in the amount of future warming of Earth by reducing uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?	**C-2a.** Reduce uncertainty in low and high cloud feedback	**Most Important**	**A1.** Aerosol types and their vertical distribution **[C-2g, C-2h, C-5a, C-5b, C-5c, C-8g]** **A2**. Aerosol column optical depths and profile **[C-2g, C-2h, C-5a, C-5b, C-5c, C-8g]** **A3**. Aerosol particle size **[C-2g, C-2h, C-5a, C-5b, C-5c, C-8g]** **A4**. Aerosol layer top and base heights **[C-2g, C-2h, C-5a, C-5b, C-5c, C-8g]** **A5**. Aerosol optical depth above clouds **[C-2g, C-2h, C-5a, C-5b, C-5c, C-8g]** **A6**. Cloud thermodynamic phase **[C-2a, C-2e, C-2g, C-5b, C-5c, C-7a, C-8a, C-8b]** **A7**. Cloud top height **[C-2a, C-2e, C-2g, C-5b, C-5c, C-7a, C-8a, C-8b]** **A8**. Cloud optical depth and cloud water path **[C-2a, C-2e, C-2g, C-5b, C-5c, C-7a, C-8a, C-8b]** **A9**. Cloud droplet size, extinction coefficients, droplet number concentration, water content) **[C-2a, C-2e, C-2g, C-5b, C-5c, C-7a, C-8a, C-8b]** **A10**. Stratospheric aerosols and clouds **[C-2a, C-2g]** **A11**. Atmospheric temperature profile **[C-4c, C-6a, C-7a, C-7c, C8a, C-8c]** **A12**. Atmospheric wind speed 10 m above ocean surface **[C-3a, C-2d, C-4c]** **(Continued on next page)**	**T1.** 532 nm co-polarized return [**A1-A15, L1, S1-S4, O1, O2**] **T2.** 355 nm co-polarized return [**A1-A15, L1, S1-S4, O1, O2**] **T3.** 532 nm cross-polarization return [**A3 A6, A8-A15, L1, S1-S4, O1, O2**] **T4.** 317 nm water Raman emission [**A9, L1, O1, O2**] **T5.** 405 nm water Raman emission [**A9, L1, O1, O2**] **T6.** 1064 nm co-polarization return [**A1-A15, S1**] **B1.** 355 nm cross-polarized return [**A2-A11, A13-A15, L1, O1, O2**] **B2.** 680 nm chlorophyll fluorescence [**A1, L2, O7**] **B3.** 354 nm rotational Raman emission [**A2**] **V1.** 450 nm water Raman emission [**A9, O1, O2**] **V2.** 1064 nm cross-polarized return [**A1**] **V3.** 466 nm cDOM emission [**A1**] **V4.** 532 nm co-polarized and cross-polarized return with enhanced detector dynamic range [**S1-S4, O1**] Vertical sampling resolution, off-nadir pointing, global coverage, day and night measurements, and bandpass specifications as indicated under MARINE AND TERRESTRIAL ECOSYSTEMS AND NATURAL RESOURCES MANAGEMENT [**T1-T6, B1, B2, V1-V3**] 90 m (low altitude) to 900 m (high altitude) vertical sampling of atmosphere [**B3**]	**C-2g, C-2h, C-5a, C-5b, C-5c, C-8g** PACE, SBG VIIRS AMSR-3 **C-2a, C-2e, C-2g, C-5b, C-5c, C-7a, C-8a, C-8b** PACE, SBG VIIRS Sentinel 3, 4, & 5 Himawari 8 & 9 GOES 16, 17, 18 GOES-U
		C-2e. Reduce uncertainty in snow/ice albedo feedback	**Important**			
		C-2g. Improve understanding of upper troposphere and stratosphere (UTS) impact to climate feedbacks and change	**Very Important**			
		C-2h. Reduce total aerosol radiative forcing uncertainty	**Most Important**			
	C-3. How large are the variations in the global carbon cycle and what are associated climate and ecosystem impacts?	**C-3a** & **C-2d**. Quantify year-to-year variability by net uptake of carbon by terrestrial and ocean ecosystems	**Very Important / Most Important**			
	C-4. How will the Earth system respond to changes in air-sea interactions?	**C-4c.** Improve bulk flux parameterizations, particularly at high latitude regions	**Important**			
	C-5. How do aerosols, including interactions with clouds, affect Earth's radiation budget? How can we better quantify the magnitude and variability of aerosol emissions to better understand climate impacts?	**C-5a**. Improve estimates of natural and anthropogenic aerosols emissions	**Very Important**			
		C-5b. Characterize the properties and distribution of natural and anthropogenic aerosols, including impacts on clouds and radiation	**Important**			
		C-5c. Quantify aerosol effects on cloud formation, height, and properties, including semidirect effects	**Very Important**			

A4	
30	EA19-EA21
A5	
31	EA20, EA21
A6	
32, 33	EA22
A7	
34	EA22
A8	
35	EA22
A9	
36, 37	EA22
A10	
38, 39	EA20, EA21
A11	
40	EA22
A12	
41, 42	EA22

CLIMATE VARIABILITY AND CHANGE (continued)	***C-6.*** Can we improve seasonal to decadal forecasts of societally relevant climate variables?	**C-6a.** Decrease uncertainty in quantification of surface and subsurface ocean states for initialization of seasonal-to-decadal forecasts.	**Very Important**	**A13**. Boundary layer heights and boundary layer temperature [**C-2a, C-2h**] **A14**. Tropopause heights [**C-2g, C-7a, C7-c**] **A15**. Cloud top temperature, pressure, and inversion strength [**C-2a, C-2e, C-2g, C-5b, C-5c, C-7a, C-8a, C-8b**] **L1.** Canopy height and vertical structure of terrestrial vegetation [**C-3a, C-2d, C-6a**] **L2**. Day and night vegetation chlorophyll fluorescence [**C-3a, C-2d**] **S1**. Snow Depths [**C-6a, C-8c]** **S2**. Snow Density, grain size and albedo [**C-6a, C-8c]** **S3**. Snow Water Equivalent [**C-6a, C-8c]** **S4**. Snow and ice cover and melting pond detection [**C-6a, C-8c]** **O1.** Phytoplankton carbon and pigment concentrations through euphotic zone [**C-3a, C-2d**] **O2.** Phytoplankton net primary production and biomass accumulation rates [**C-3a, C-2d**] **O7.** Nighttime phytoplankton chlorophyll fluorescence [**C-3a, C-2d**]			**A13** 43-45	 EA22
	C-7. How are decadal-scale global atmosphere and ocean circulation patterns changing, and what are the effects of these changes on climate and environmental processes?	**C-7a**. Quantify the changes in the atmospheric and oceanic circulation patterns	**Very Important**				**A14** 46, 47	 N/A
		C-7c. Quantify the linkage between global climate sensitivity and circulation change. Quantify Hadley cell extent.	**Important**				**A15** 48, 49	 N/A
	C-8. What will be the consequences of amplified climate change in the Arctic and Antarctica on carbon fluxes?	**C-8a.** Improve our understanding of the drivers behind polar amplification.	**Very Important**				**S1** 50, 51	 EA19, EA24
		C-8b. Improve understanding of high-latitude variability and midlatitude weather linkages	**Very Important**				**S2** 50, 51	 EA19
		C-8c. Improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea-ice cover, including sea-ice fraction, ice thickness, location of the ice edge, timing of ice retreat and ice advance	**Very Important**				**S3** 50, 51 **S4** 52-54	 EA19, EA23 EA19, EA25, EA26
		C-8g. Determine the amount of pollutants transported into polar regions and their impacts on snow and ice melt.	**Important**					

WEATHER AND AIR QUALITY	***W-1.*** What planetary boundary layer processes are integral to surface exchanges	**W-1a.** Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts.	**Most Important**	**A1.** Aerosol types and their vertical distribution **[W-1a, W-5a, W-6a, W-10a]** **A2**. Aerosol layer top and base heights **[W-1a, W-5a, W-6a, W-10a]** **A3**. Aerosol column optical depths and profile **[W-5a, W-6a, W-10a]** **A4**. Aerosol particle size **[W-1a, W-5a, W-6a, W-10a]** **A5**. Aerosol optical depth above clouds **[W-5a, W-6a, W-10a]** **A6**. Cloud thermodynamic phase **[W-2a, W-3a, W-9a, W-10a]** **A7**. Cloud top height **[W-1a, W-2a, W-3a, W-9a, W-10a]** **A8**. Cloud optical depth and cloud water path **[W-1a, W-2a, W-3a, W-9a, W-10a]** **A9**. Cloud microphysical properties (droplet size, extinction coefficients, droplet number concentration, cloud water content) **[W-1a, W-2a, W-3a, W-9a, W-10a]** **A11**. Atmospheric temperature profile **[W-1a]** **A13**. Boundary layer heights and boundary layer temperature **[W-1a, W-2a]** **A15**. Cloud top temperature, pressure, and inversion strength **[W-1a, W-2a, W-3a, W-9a, W-10a]** **S1**. Snow Depths **[W-3a]** **S2**. Snow Density, grain size and albedo **[W-3a]** **S3**. Snow Water Equivalent **[W-3a]** **S4**. Snow and ice cover and melting pond detection **[W-3a]**	**T1.** 532 nm co-polarized return [**A1-A9, A11, A13, A15, S1-S4**] **T2.** 355 nm co-polarized return [**A1-A9, A11, A13, A15, S1-S4**] **T3.** 532 nm cross-polarization return [**A3 A6, A8, A9, A11, A15, S1-S4**] **T4.** 300 nm water Raman emission [**A9**] **T5.** 405 nm water Raman emission [**A9**] **T6.** 1064 nm co-polarization return [**A1-A9, A11, A13, A15, S1**] **B1.** 355 nm cross-polarized return [**A2-A9, A11, A13, A15**] **B2.** 680 nm chlorophyll fluorescence [**A1**] **B3.** 354 nm rotational Raman emission [**A2**] **V1.** 450 nm water Raman emission [**A9**] **V2.** 1064 nm cross-polarized return [**A1**] **V3.** 466 nm cDOM emission [**A1**] **V4.** 532 nm co-polarized and cross-polarized return with enhanced detector dynamic range [**S1-S4**] Vertical sampling resolution, off-nadir pointing, global coverage, day and night measurements, and bandpass specifications as indicated above [**All**]	**W-1a, W-2a, W-3a, W-5a, W-6a, W-9a, W-10a** Sentinel 3, 4, & 5 Himawari 8 & 9 GOES 16, 17, 18 GOES-U **W-2a, W-3a, W-9a, W-10a** PACE VIIRS	As Above	As Above
	W-2. How can predictions of weather and air quality be extended to 2 months?	**W-2a.** Improve observed and modeled representation of interactions between large-scale circulation and boundary layer processes	**Most Important**					
	W-3. How do surface variations modify transfer among domains and influence weather and air quality?	**W-3a.** Determine how spatial variability in surface modifies regional cycles of energy, water and momentum.	**Very Important**					
	W-5. What processes determine the structure of air pollutants and their impact on human health, agriculture, and ecosystems?	**W-5a.** Improve understanding of the processes that determine air pollution distributions and their impacts on human health and ecosystems	**Most Important**					
	W-6. What processes determine the long-term variations and trends in air pollution and their impacts on human health, agriculture, and ecosystems?	**W-6a.** Characterize long-term trends and variations in global, vertically resolved speciated particulate matter	**Important**					
	W-9. What processes determine cloud microphysical properties and their connections to aerosols and precipitation?	**W-9a.** Characterize the microphysical processes and interactions of hydrometeors by measuring the hydrometeor distribution.	**Important**					
	W-10. How do clouds affect the radiative forcing at the surface and contribute to predictability at various time scales?	**W-10a.** Across scales, quantify effects of clouds on radiative fluxes (including boundary layer evolution) and determine the structure, evolution, and properties of clouds, including small-scale cumulus clouds.	**Important**					

HYDROLOGICAL CYCLES AND WATER RESOURCES	***H-1.*** How is the water cycle changing? How are these changes expressed in space-time distribution, frequency and magnitude of extremes such as droughts and floods?	**H-1a.** Evaluate an integrated Earth system analysis with observational components of the water and energy cycles and their interactions.	**Most Important**	**A1-A9, A11, A15.** Aerosol types and their vertical distribution / Aerosol layer top and base heights / Aerosol column optical depths and profile / Aerosol particle size / Aerosol optical depth above clouds / Cloud thermodynamic phase / Cloud top height / Cloud optical depth and cloud water path / Cloud droplet size, extinction coefficients, droplet number concentration, water content / Atmospheric temperature profile / Cloud top temperature, pressure, and inversion strength [**H-1a, H-2b**] **A12-A13**. Atmospheric wind speed 10 m above ocean surface / Boundary layer heights and boundary layer temperature [**H-1a**] **S1**. Snow Depths [**H-1a, H-1c**] **S2-S4**. Snow Density, grain size and albedo / Snow Water Equivalent / Snow and ice cover and melting pond detection [**H-1a, H-1c, H-2b,**] **L1**. Canopy height and vertical structure of terrestrial vegetation [**H-3a, H-3c**]	**T1.** 532 nm co-polarized return [**A1-A9, A11-A13, A15, L1, S1-S4**] **T2.** 355 nm co-polarized return [**A1-A9, A11-A13, A15, L1, S1-S4**] **T3.** 532 nm cross-polarization return [**A3 A6, A8, A9, A11-A13, A15, L1, S1-S4**] **T4.** 300 nm water Raman emission [**A9, L1**] **T5.** 405 nm water Raman emission [**A9, L1**] **T6.** 1064 nm co-polarization return [**A1-A9, A11-A13, A15, S1**] **B1.** 355 nm cross-polarized return [**A2-A9, A11, A13, A15, L1**] **B2.** 680 nm chlorophyll fluorescence [**A1, S2**] **B3.** 354 nm rotational Raman emission [**A2**] **V1.** 450 nm water Raman emission [**A9**] **V2.** 1064 nm cross-polarized return [**A1**] **V3.** 466 nm cDOM emission [**A1**] **V4.** 532 nm co-polarized and cross-polarized return with enhanced detector dynamic range [**S1-S4**] Vertical sampling resolution, off-nadir pointing, global coverage, day and night measurements, and bandpass specifications as indicated above [**All**]	**H-1a, H-2b** PACE VIIRS AMSR-3 Sentinel 3, 4, & 5 Himawari 8 & 9 GOES 16, 17, 18 GOES-U **H-1c, H-2b** AMSR-3 **H-3a, H-3c** PACE, SBG, landsat, VIIRS	As Above	As Above
		H-1c. Quantify rates of snow accumulation at scales driven by topographic variability.	**Most Important**					
	H-2. How do anthropogenic changes interact and modify the water and energy cycles?	**H-2b.** Quantify the anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt.	**Important**					
	H-3. How do changes in the water cycle impact freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?	**H-3a.** Develop methods and systems for monitoring water quality for human health and ecosystem services.	**Important**					
		H-3c. Determine structure, productivity, and health of plants to constrain estimates of evapotranspiration.	**Most Important**					

[1] DS Science Questions and Science/Application Objectives shown in the second and third columns of the above SATM are shortened from their original statements to focus on elements particularly relevant to CALIGOLA observations. Full text can be found in the 2018 NASEM Decadal Survey on pages 584-618.

[2] **O** = Ocean observable; **L** = Land observable; **A** = Atmosphere observable; **S** = Snow/Ice observable.

[3] **T** = Measurement parameters required for threshold CALIGOLA objectives; **B** = Measurement parameters required to achieve full baseline CALIGOLA objectives; **V** = Value added measurement parameters to enhance CALIGOLA capabilities.

[4] Coincident Synergistic Observations identify complementary satellite and ground-based observations to further address DS Science/Applications Objectives or are enhanced by coincident CALIGOLA. For **E-5b**, the objective is to discover cascading perturbations in ecosystems, with a particularly relevant example for CALIGOLA being the escalating international mesopelagic fishing efforts on ocean ecosystems and carbon sequestration. To evaluate these cascading impacts, CALIGOLA is informed by the baseline record of the global diel vertical migration provided by CALIOP and ground-based records on fish catch and efforts.

[5] A.D. Ref = Approach Demonstration References. Numbers refer to published manuscripts provided in **Appendix I** below that demonstrate the feasibility of CALIGOLA retrievals.

[6] Enabled Appl. = Enabled Applications from CALIGOLA observed geophysical properties.

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