APPENDIX A:
Science Measurement and Modeling Requirement Matrices

A.1 Science Measurement Requirement Matrices

Key airborne and shipborne measurements will be used to address FORTE hypotheses. Tables A1-A2 list these measurement requirements (geophysical variables), their priority ratings, and how measurements are linked to specific hypotheses. Priority ratings are expressed as: 1 = required, 2 = desired, 3 = useful. Priority 1 measurements include the most critical parameters needed to achieve FORTE's science objectives. Priority 2 (desired) and priority 3 (useful) measurements include additional parameters that could be integrated into FORTE depending on funding availability.

Table A1. *Science Measurement Requirement Matrix: Airborne measurements*

Scientific Measurement	Priority P	Hypothesis addressed
Aquatic spectral remote sensing reflectance, R_{rs} (380-1300 nm)	**1**	H1, H2, H3
Surface reflectance (380-2450)	**2**	H1, H2
Rayleigh corrected reflectance (R rc)	**2**	H1, H2, H3
Colored Dissolved Organic Matter (CDOM) absorption	**1**	H1, H2, H3
Chlorophyll-a concentration	**1**	H1, H2, H3
Turbidity/Suspended Particulate Matter (SPM) concentration	**1**	H1, H2, H3
Phytoplankton (Phyt) absorption	**1**	H1, H2, H3
Non-Algal Particle (NAP) absorption	**1**	H1, H2, H3
Particulate backscatter (b_{bp})	**1**	H1, H2
Diffuse attenuation coefficient (Kd)	**1**	H1, H2
Dissolved Organic Carbon (DOC) concentration	**1**	H1, H2
Particulate Organic Carbon (POC) concentration	**1**	H1, H2
Phytoplankton pigments	**1**	H3
Phytoplankton community composition (PCC)	**1**	H3
Coastal erosion-shoreline retreat	**1**	H1, H2, H3
Phytoplankton carbon (PC)	**2**	H3
Downwelling solar irradiance	**2**	H1, H2, H3
Coastal salinity	**2**	H1, H2, H3
Surface Temperature	**2**	H1, H2, H3
Surface freeze/thaw	**3**	H1, H2, H3
Soil moisture (200m)	**3**	H1, H2, H3

Table A2. *Science Measurement Requirement Matrix: Shipborne/surface in situ measurements and collection of samples for laboratory measurements/experiments*

Scientific Measurement	Priority P	Mode [a]	Hypotheses addressed
Surface measurements for validation of threshold airborne products			
Aquatic spectral remote sensing reflectance, R_{rs}	**1**	C, P	H1, H2, H3
Up/downwelling radiance & irradiance	**1**	C, P	H1, H2, H3
Colored Dissolved Organic Matter (CDOM) absorption	**1**	C, P	H1, H2, H3
Phytoplankton (Phyt) absorption	**1**	C, P	H1, H2, H3
Non-Algal Particle (NAP) absorption	**1**	C, P	H1, H2, H3
Particulate backscatter (b_{bp})	**1**	C, P	H1, H2, H3
CDOM and Chla fluorescence	**1**	A, C, P	H1, H2, H3
Dissolved Organic Carbon (DOC) concentration	**1**	P	H1, H2
Particulate Organic Carbon (POC) concentration	**1**	P	H1, H2
Suspended Particulate Matter (SPM) concentration	**1**	P	H1, H2
Phytoplankton (HPLC) pigments	**1**	P	H1, H2, H3
Phytoplankton abundance, size	**1**	C, P	H3
Phytoplankton community composition (PCC)	**1**	C, P	H3
Phytoplankton carbon (PC)	**1**	C, P	H3
Atmospheric trace gases (NO_2)	**2**	P	H1, H2, H3
Atmospheric trace gases (O_3)	**2**	P	H1, H2, H3
Aerosol optical depth, AOD (340-936 nm)	**2**	P	H1, H2, H3
Particle size distribution (PSD)	**3**	P	H3
Additional measurements needed for interpretation of airborne observations and model parameterization			
Nutrient concentration (NO_3^-, NH_4^+, H_4SiO_4, PO_4^3)	**1**	P	H1, H2, H3
Nutrient uptake	**2**	P	H3
Temperature, salinity, pH, dissolved oxygen, turbidity	**1**	A, C, P	H1, H2, H3
Net Primary Production (NPP)	**1**	P	H3
Gross Primary Production (GPP)	**1**	P	H3
DOM/POM photochemical reactivities	**1**	P	H2
DOM/POM microbial/biogeochemical reactivities	**1**	P	H2
DOM/POM flocculation	**1**	P	H2
Dissolved Inorganic Carbon (DIC) concentration	**2**	P	H1, H2
Amino acids, carbohydrate, lignin and lipid biomarkers (DOM, POM)	**2**	P	H1, H2
Water volume transport (Q)	**1**	C	H1
Ground water flux via radium or radon	**1**	P	H1, H2

a. Mode refers to C=Continuous, A=Autonomous, P=Periodic mode

Satellite observations and missions relevant to FORTE are shown in Table A3

Table A3: *Satellite measurements and missions relevant to FORTE*

Sensor	Time period	Resolution	Revisit	Relevant Satellite Data Products
High Spatial Resolution Satellite Optical Sensors				
The constellation of high-spatial resolution satellite sensors shown below, will provide imagery that is particularly useful in FORTE for retrievals of advanced satellite aquatic biogeochemical and terrestrial products (see column on the far right). The spatial resolution afforded by these sensors (10-300 m) is critical for capturing processes and biogeochemical gradients in the coastal Arctic. Combined, the constellation of Landsat and Sentinel-2 sensors has a revisit of 3-5 days.				
OLI-Landsat 8/9	3/2013-now	30 x 30 m	~8 d (combined)	**Radiometric:** Water-leaving radiance (H1-H3) **Bio-Optical:** Chlorophyll-a, Kd, b_{bp}, CDOM absorption, NAP absorption, Phytoplankton absorption (H1-H3) **Biogeochemical:** POC, DOC, NPP, SPM (H1-H2) **Phytoplankton Characterization:** Phytoplankton community, Pigments, Phytoplankton Carbon, NPP (H3) **Terrestrial:** Land cover classification, Arctic tundra phenology (H1;H3
MSI-Sentinel 2A/B/C	6/2015-now	10 to 60 m	~5 d (combined)	
OLCI-Sentinel 3A/B/C	2/2016-now	300 x 300 m	1-2 d	
High Spatial Resolution Satellite Thermal Sensors				
Landsat 8/9 TIRS measurements would be useful for retrievals of sea surface temperature in coastal Arctic waters (at 100 m spatial resolution).				
TIRS-Landsat 8	3/2013-now	100 x 100 m	~16 d; ~5 d at ~73°N	**Physical:** Sea Surface Temperature (SST) (H1-H3)
TIRS-Landsat 9	9/2021-now	100 x 100 m	~16 d; ~5 d at ~73°N	
Satellite Atmospheric Sensors				
Measurements from hyperspectral air-quality sensors with fine spectral sampling, such as TROPOMI, can be used to provide information on atmospheric composition (aerosols as well as absorbing trace gases) in the coastal Arctic, which, combined with airborne atmospheric measurements, will be useful for enhanced atmospheric correction of satellite ocean color retrievals and airborne hyperspectral imagery.				
TROPOMI-Sentinel 5P	10/2017-now	~7 x 3.5 km	daily	**Atmospheric:** Aerosol (AOD), Atm. Trace gases (NO_2, O_3) (H1-H3)
Satellite Interferometry & Synthetic Aperture Radar (SAR)				
The recently launched Surface Water and Topography (SWOT) Ka-Band interferometer and altimeter provides estimates of river discharge in rivers > 100m width and water surface height including coastal waters. SAR measurements from Sentinel-1 SAR and the upcoming NISAR mission (beginning 2025) will provide a detailed record of changes in permafrost landscapes including surface deformation, surface vegetation, inundation, surface freeze/thaw state, lake and river ice, deformation of landfast ice, and ridge delineation, all of which are important parameters to address FORTE hypotheses. SAR can capture images day and night, even under cloudy conditions, giving consistent time series characterizations - a major advantage for monitoring processes in the coastal Arctic.				
Sentinel/SAR 1A (1C)	4/2014 (2024)	5 m x 5m	12 d	**Terrestrial:** Permafrost, Surface vegetation, Inundation, Soil moisture (200mx200m) Lake/river ice, Landfast ice (100mx100m), Landfast deformation, Ridge delineation, Coastal erosion (H1-H3)
NISAR	Launch in 2025	10 m x 10 m	12 d exact repeat	
SWOT	12/2022-now	70 m x 70 m	< 1 week in the Arctic	**Hydrology**: 70 m resolution to resolve water bodies > 100 m width **Oceanography**: sea surface height (2 km x 2 km)
Current and Future Hyperspectral NASA Satellite Missions				
Hyperspectral remote sensing observations from FORTE will be particularly useful for informing algorithm development for NASA's existing, recently launched and future satellite missions				
PACE	Launch in 2024	~1 x 1 km	1-2 d	Hyperspectral algorithms developed in FORTE for the airborne retrievals will be useful for application to satellite biogeochemical retrievals from PACE, PRISMA, and EnMAP, as well as preparation efforts for the SBG mission.
SBG	Launch in 2028	~30-60 m	~ 16 d	
PRISMA	Launch in 2019	~ 30m	variable	
EnMAP	Launch in 2022	~ 30m	variable	
Laser Altimeter				
Measurements from space lasers, such as ICESat-2, provide high-resolution surface elevation data that can be used for a range of cryospheric applications, including observations of surface height, ocean elevation, inland water elevation, land and sea ice, sea ice thickness.				
ICESat-2/ATLAS	11/2018-now	13 m footprint	91 days	Coastal/sea ice extent/thickness, landfast ice extent, coastal mapping

A.2 Science Modeling Requirement Matrix

Table A4 lists the FORTE modeling requirements (modeling capability, resolution, frequency, time range for model simulations, and desired uncertainty), their priority ratings, and how these modeling capabilities are linked to specific hypotheses.

Table A4. *Science Modeling Requirement Matrix*

Scientific Modeling Capability	Priority, P	Model Specifications			Hypotheses Addressed
		Resolution[a]	Frequency	Time Range	
Spatially distributed surface and subsurface water flow	1	500 m to 1.5 km	Daily	10 years	H1, H2
Spatially distributed surface and subsurface aquatic carbon[b], nitrogen[c], and sediment[d] flux	1	500 m to 1.5 km	Daily	10 years	H1, H2, H3
River channel transport of water, carbon[b], nitrogen[c], sediment[d], and biogeochemical reactions	1	50 m to 2 km	Hourly to Daily	10 years	H1, H2, H3
River Plume and coastal ocean hydrodynamics (salinity, temperature, vertical heat flux, velocity)	1	10 m to 1 km	Hourly	1-5 years	H1, H2, H3
River plume carbon[b], nitrogen[c], sediment[d] concentration and biogeochemical reactions	1	10 m to 1 km;	Hourly	1-5 years	H1, H2, H3
Aquatic inherent and apparent optical properties[e] (IOPs and AOPs) and UV-Vis light propagation	1	10 m to 1 km	Hourly	1-5 years	H1, H2, H3
Phytoplankton concentration, carbon, and gross/net primary production in aquatic systems (river, delta, and ocean)	1	50 m to 2 km	Hourly to Daily	10 years	H2, H3
Coastal erosion and sediment deposition	1	50 m to 2 km	Hourly to Daily	10 years	H1, H2
Landfast Ice and sea ice area, thickness, and velocity	1	500 m to 25 km	Daily	10 years	H1, H2, H3
Coupling of terrestrial to river-delta-ocean model	1	50 m to 2 km	Hourly to Daily	10 years	H1, H2, H3
Aquatic-atmospheric CO_2 flux	2	10 m to 1 km	Hourly	1-5 years	H1, H2, H3
Harmful algae growth and physiology	2	50 m to 10 km or individual based	Hourly to Daily	1-5 years	H3

** Model accuracy can be quantified using various metrics and will be dependent on the measurement uncertainty and the inherent model uncertainty. All parameters and modeled quantities should be reported with associated uncertainty.

[a] Resolution ranges are provided with the expected highest resolution falling within the given range

[b] Carbon species to be modeled should include dissolved and particulate organic carbon (DOC and POC), dissolved inorganic carbon, carbonate system chemistry (e.g., pH and Alkalinity), and colored dissolved organic matter

[c]Nitrogen species to be modeled should include inorganic nitrogen (NO_3^- & NH_4^+), dissolved and particulate organic nitrogen (DON and PON); as needed other micro-nutrients may additionally be included such as phosphate, Silicate, and Iron.

[d]Sediment should include multiple classes of inorganic sediment that are related to source and physico-chemical properties such as size, density, and light absorptivity

[e] Inherent optical properties should include spectrally explicit CDOM absorption, non-algal particle absorption and particulate scattering, phytoplankton absorption, and the absorption due to water. Apparent optical properties will include the spectrally explicit diffuse attenuation and remote sensing reflectance.