Arctic Coastlines – Frontlines of Rapidly Transforming Ecosystems (FORTE)

FORTE EVS-4 Mission
Investigation White Paper

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1. Scientific/Technical Plan

1.1 Science Goals and Objectives

1.1.1 Motivation and Goals

The Arctic of today is a rapidly evolving environment, warming faster than any other region on the planet [1–6]. In the ocean, sea ice is shrinking [7–10], freshwater content and temperature are increasing [11–15], and water is acidifying [16–18]. On land, snow cover and river ice thickness are declining [19,20], ice-free periods in rivers and lakes are lengthening [20,21], permafrost is thawing [22–24], coastlines are eroding [25–27], and river flows are increasing [28–31].

These changes in the Arctic have both local and global environmental, economic, and social implications, motivating intensive research and major field campaign programs focusing on different components of the complex Arctic System. Programs such as NASA's CARVE (Carbon in Arctic Reservoirs Vulnerability Experiment; 2012-2014) [32], ABoVE (Arctic Boreal Vulnerability Experiment; 2015-2025) [33,34], and NGEE (Next Generation Ecosystem Experiments)-Arctic (U.S. Department of Energy (DOE), 2012-2018) [35] have generated rich datasets that transformed our understanding of the response of terrestrial social-ecological systems to the changing hydrology, land-atmosphere exchanges, permafrost dynamics, and disturbance. Oceanographic expeditions and monitoring programs such as the Western Arctic SBI (Shelf–Basin Interactions, 1998-2009) [36], the Distributed Biological Observatory [37], ICESCAPE (Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment, 2010-2011) [38], and MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate; 2019-2020) [39], have substantially increased our understanding of the impacts of environmental change on physical and ecological processes and feedbacks in Arctic marine systems. **Critically, the progress in observing and modeling Arctic marine and terrestrial ecosystems has also highlighted that the need for research connecting processes between the Arctic land and Arctic Ocean has never been greater.**

Hydrological and biogeochemical exchanges between these two interconnected systems —the land and the ocean—shape a 'new Arctic' that is quickly moving toward critical tipping points [5,40]. **Yet, the Arctic land-river-ocean aquatic continuum, one of the most critical areas on Earth for energy resources, transportation, security, subsistence, biodiversity and cultural heritage, is yet to be thoroughly characterized and assessed in the face of global change.**

Compared to other ocean basins, the Arctic Ocean is disproportionately affected by freshwater runoff and associated terrestrial nutrients and organic matter [41]. While it encapsulates only ~1% of the global ocean volume, it receives over 11% of global riverine discharge, resulting in estuarine gradients as a defining feature not just in the near-shore but throughout the Arctic Ocean [41,42]. Arctic permafrost coasts account for almost 34% of the Earth's coastlines and are rapidly collapsing [40]. Coastal erosion, at rates as high as 25 m yr^{-1}, results in an annual release of up to 46.5 Tg of organic carbon, a flux of similar magnitude as annual CO_2 emissions from the much vaster terrestrial permafrost [43,44]. Freshwater inputs influence ocean salinity, heat budgets, ocean albedo, sea ice formation and recession, and dense water formation. Large-scale ocean circulation is also impacted, affecting weather patterns as widespread as the American, African, and Asian monsoons [45–47]. Yet, the changing hydrological cycles, biogeochemical fluxes, competing transformation mechanisms, and seasonal transitions across this transforming coastline remain poorly constrained. As a result, our ability to model the various biogeophysical forcings and ecological responses, such as changes in phytoplankton production and diversity (which cascade up the food web), is severely limited [48–52]. To address this gap, programs that focus on improved predictions and long-term surface *in situ* observations in the coastal Arctic have been established, including the National Science Foundation

Beaufort Lagoon Ecosystem Long Term Ecological Research (BLE-LTER) [53] and the DOE-supported Interdisciplinary Research for Arctic Coastal Environments (InteRFACE) programs [54]. Yet, *in situ* sampling in the Arctic is inevitably restricted, spatially and temporally, in large part due to logistical challenges and dynamic, compressed seasons. **Airborne remote sensing observations provide an unparalleled capability to capture the hydro-biogeochemical connectivity of land-ocean ecosystems, at scales not feasible with field-based monitoring alone. Nowhere is this more profoundly true than in the remote and difficult to access coastal Arctic.**

FORTE (Frontlines **O**f **R**apidly **T**ransforming **E**cosystems**)** is the first EVS mission to apply the unique advantages (i.e., *"forte"*) of high resolution, ecosystem-scale, suborbital passive and active remote sensing observations to *explicitly link* hydrological, biogeochemical and ecological processes in Arctic land-ocean systems (Fig. 1). FORTE will fill a critical gap in our mechanistic understanding and modeling of environmental change impacts, by targeting the transitional continuum of Alaska's northernmost ecosystems – eroding coastlines, rivers, deltas, and estuaries – that connect land to sea: a dynamic continuum that can *uniquely* be captured from airborne platforms.

FORTE tackles two interrelated and pressing Earth System science questions: ***How do nearshore Arctic ecosystems, from lower watersheds to coastlines and adjacent seas, respond to changes in the mobilization, magnitude, composition, and seasonality in land-ocean fluxes (freshwater, heat, carbon, sediment and nutrients), and what are the implications for larger scale ocean processes and feedbacks?*** These overarching questions drive three thematic research areas that address:

- The impact of warming and intensified Arctic River discharge on river plumes, coastal erosion, water quality, and **spatiotemporal transitions between sources and sinks of carbon and energy**.
- Changes in the relative importance and interplay of **coupled physical/biogeochemical processes in transforming land-ocean fluxes**, as environmental conditions change in the Arctic.
- The **response of phytoplankton populations** to a changing Arctic, also as relates to growing risk of harmful algal blooms and impacts on local marine resources and food security.

These accelerating changes – in coastal resources, water quality, subsistence activities, coastal erosion and infrastructure – are of key concern to Alaskan Native communities, industrial development, and economic prosperity in the region (55).

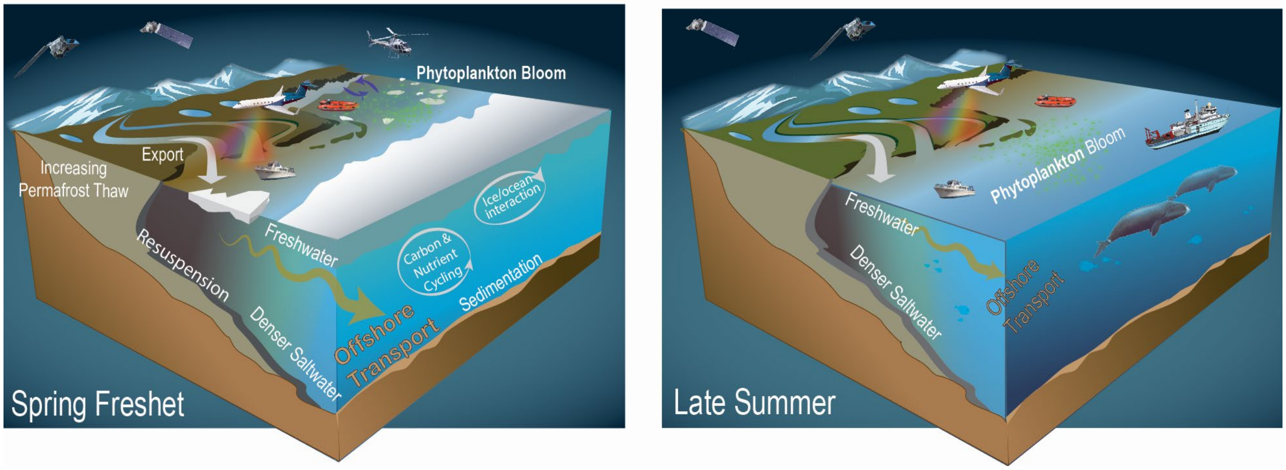


Figure 1: FORTE will apply suborbital observations from multiple platforms to capture hydro-biogeochemical connections across *the most dynamic segment* of the Arctic land-ocean continuum, and critical seasonal ecosystem transitions from the spring freshet (peak river discharge) and ice breakup (left panel) through the open water period (right panel).

1.1.2. Need for Sustained Suborbital Measurements

Airborne platforms offer a unique integrated perspective of the land-ocean continuum at a scale, resolution, and coverage that can neither be achieved by surface measurements (inevitably restricted in their geographic and temporal coverage) nor satellite sensors (currently too coarse in their revisit or spectral and spatial resolution). FORTE is driven by this unique perspective.

The primary driver of Arctic coastal function is seasonality and sharp temporal transitions that are compressed between May to October (Fig. 1). River systems flood during the spring thaw/high water period (freshet) and discharge water, heat, carbon, sediment, and nutrients into the coast. In summer and autumn, as freshwater flow decreases and temperatures rise, molecular composition of organic matter shifts altering the susceptibility to microbial and photochemical degradation [56–58], also allowing sediment to fall out of suspension [59,60]. The transfer of heat from rivers into the ocean is typically neglected in large-scale models but can represent a critical factor in the recession of coastal ice [61]. The sheer amount of freshwater input into the Arctic has significant consequences for coastal processes, as lower salinity waters extend much farther out into the Arctic Ocean relative to temperate and tropical oceans, extending the estuarine properties for tens of kilometers off and along shore. Differences in geomorphology are also critical. Large rivers can have extensive deltas that modify riverine inputs [62,63]. Indeed, much of what is known of Arctic riverine processes is from measurements in the six largest Arctic rivers (Mackenzie, Yukon, Kolyma, Lena, Yenisey, and Ob') that largely drain taiga catchments, and samples are generally collected well upstream of the large deltaic systems. Yet more than 40% of riverine discharge in the Arctic originates from smaller rivers that also make up a substantial portion of the increasing trend in total Arctic River flow [30]. **A sustained multi-year suborbital field campaign is needed to capture the spatial heterogeneity, sharp temporal transitions, and seasonal shifts that characterize the Arctic land-ocean continuum; specifically, its most dynamic segment spanning from river reaches and deltas to the nearshore coastal sea. Intensively studying this highly dynamic environment is the focus of FORTE.**

Airborne and other suborbital platforms in FORTE will be strategically integrated over multiple deployments capturing a wide range of states of the river-to-sea ecosystem for multiple seasons (from spring to fall). **Measurements will focus on the North Slope of Alaska, a region of increasing economic activity that is also characterized as a high priority area for coordinated monitoring of future environmental change across the Pan-Arctic** with projected increases in river discharge by >50% from 1961-1990 to 2061-2090 [1]. Aircraft (crewed and uncrewed) observations will be integrated with measurements from other suborbital platforms (research ships, small watercraft, and local boats), autonomous sensors, and satellites, to extend the restricted coverage of *in situ* sampling. High priority airborne observations for FORTE include measurements of hyper-spectral (UV-Vis-NIR) water remote sensing reflectance (R_{rs}) for retrievals of in-water constituents, including particle backscatter (b_{bp}) and absorption (a_p), chromophoric dissolved organic matter absorption (a_{CDOM}), particulate (POC) and dissolved (DOC) organic carbon, and phytoplankton pigments and community composition (PCC) at high spatial resolution (1-20 m); these airborne hyper-spectral measurements can also be used to retrieve land surface reflectance and characterize terrestrial habitat. Additional measurements of interest from airborne platforms include sea surface and land surface temperature, coastal sea surface salinity, soil moisture, and permafrost surface freeze/thaw state. **This integration of multi-platform observations will uniquely allow to capture and improve predictions of the biogeochemical and ecological response of the most dynamic and vulnerable segment of the Arctic land-ocean continuum to change** (Fig. 1).

1.1.3. Scientific Hypotheses and Approach

FORTE is the first EVS mission to apply ecosystem-scale, intensive suborbital measurements to capture the hydro-biogeochemical connectivity across the Arctic land-ocean continuum (Fig. 2). Our overarching approach entails: (1) **airborne remote sensing** during key observing periods that capture seasonal transitions from ice break-up and spring freshet in May/June to increasing biological activity later in summer; (2) **ship/boat-based sampling** of the lower reaches of rivers and nearshore sea; (3) **helicopter and/or surface vehicle based sampling** when ship/boat operations are not possible during spring-freshet due to hazardous conditions; (4) surface-water/groundwater sampling and **process-based experiments** from spring to fall. **Local community-based sampling** and measurements from **autonomous monitoring buoy systems/moorings** will extend the coverage and resolution of observations, continuously monitoring discharge, physicochemical parameters, and optical proxies of biological activity, to the extent allowable by river and sea ice (Table 1). Measurements from **uncrewed aerial systems** (UAS) (e.g., hyperspectral/optical and thermal sensors) collected between lower river reaches to outflow, will fill observational gaps and support algorithm validation.

Application and augmentation of satellite and modeling capabilities: The constellation of high spatial (10-60 m) optical sensors (e.g., Landsat-8/9 OLI and Sentinel-2A/2B MSI) with a combined revisit of 2-3 days, integrated with daily Sentinel-3A/3B OLCI retrievals, and SAR measurements (Sentinel-1, NISAR) obtained even under cloudy conditions, will contribute valuable data to augment intra-/inter-seasonal and inter-annual aircraft observations in FORTE (Fig. 2). At the same time, **algorithm development in FORTE will augment current satellite observational capabilities.** Legacy ocean color approaches have several limitations in coastal Arctic waters, due to high turbidity and absorption, unique polar phytoplankton physiology, bright target adjacency effects (ice), and limited information on appropriate atmospheric correction [64,65]. FORTE will

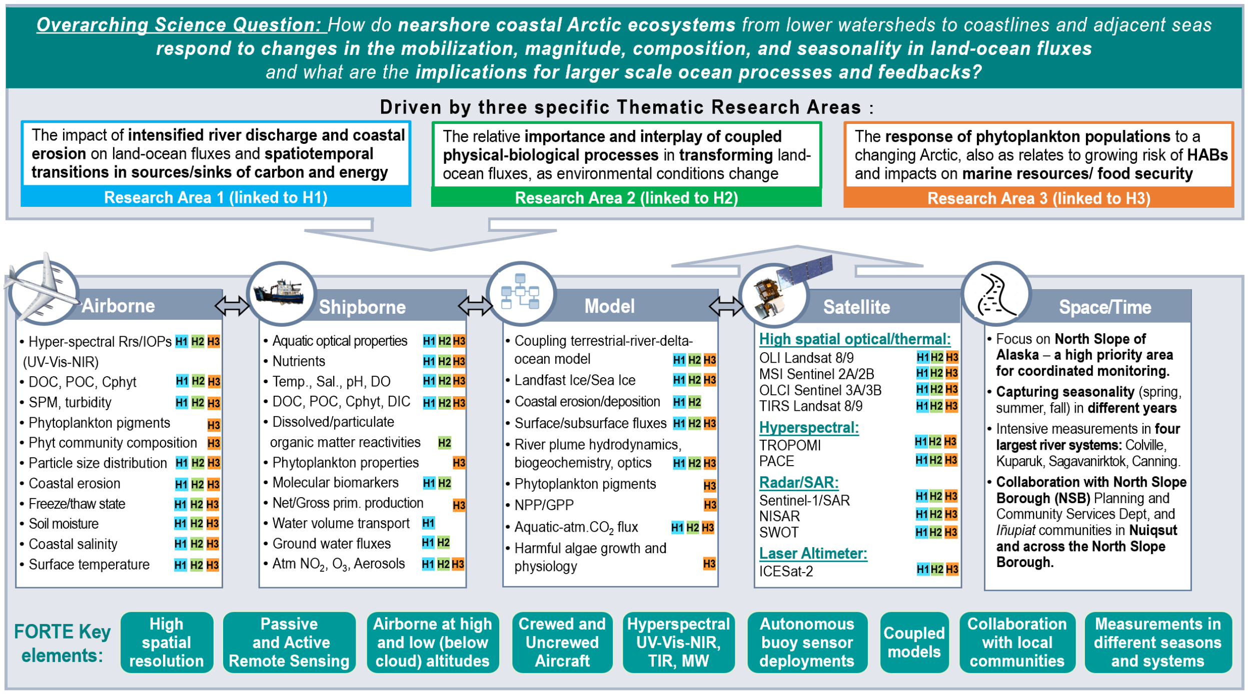


Figure 2: FORTE's research areas (linked to specific hypotheses H1-H3) and integration of multi-platform observations and models.

apply the collected suborbital datasets to develop multi- and hyper-spectral algorithms that are *optimized for the Arctic* and address these limitations. Moreover, FORTE's rich datasets will allow an unprecedented opportunity to couple existing Arctic regional hydrological-permafrost-coastal ocean models, develop critically needed new regional modeling components, and lay the basis to include dynamic Arctic coastal processes in Earth System Models (ESMs). Modeling processes that will be improved upon include the transport and reactivity of terrestrial organic matter as it enters the ocean, river and ice thermodynamic interactions and seasonality, landfast ice and sea ice optical properties and biogeochemistry, and phytoplankton growth and physiology. **FORTE will move the coastal Arctic modeling community beyond basic process representation and parameterization into dynamic land-ocean biogeochemical coupling and predictive capability from sub-seasonal to decadal timescales.** FORTE combines these *top-down* and *bottom-up* methods to holistically address three fundamental and testable science hypotheses:

H1: Intensified Arctic River discharge enhances the extent and influence of river plumes during freshet and throughout the summer, while increased warming and rainfall during summer enhances permafrost thaw and coastal erosion, increasing fluxes and shifting seasonal/spatial transitions between sources and sinks of carbon and energy.

H2: Transformations of land-ocean fluxes occur largely within river plumes during spring freshet, primarily through physical processes; whereas, during summer, transformations occur further landward, mainly within the lower river and deltas, dominated by photo-biogeochemical processes. The relative importance and interplay of these coupled processes will change as environmental conditions shift temporally and spatially in the Arctic.

H3*:* Phytoplankton populations are adapting to a changing Arctic. The timing and intensity of the spring freshet modulates the location and magnitude of phytoplankton blooms/growth events and phytoplankton community composition (PCC). Intensification of spring and summer river discharge and constituent fluxes is changing PCC with greater prevalence of opportunistic species (more abundant nano- and pico-phytoplankton than microplankton) and a growing risk of harmful algal blooms, with impacts on marine resources and food security.

1.2. Relevance to NASA Earth Science Goals and this Solicitation

FORTE's sustained and comprehensive suborbital observations across the North Slope of Alaska will uniquely advance our understanding of the biogeochemical and ecological response of the *most dynamic and vulnerable segment* of the Arctic land-ocean continuum to change. Thus, FORTE directly supports the objectives of NASA's Carbon Cycle and Ecosystems and Climate Variability and Change ESD Focus Areas, with a particular emphasis on (a) linking hydrological, biogeochemical, and ecological processes across Arctic ecosystems and (b) improving remote sensing and modeling predictive capabilities in the coastal Arctic (H1-H3).

FORTE supports NASA's Earth Science to Action Strategy by focusing on real-world challenges and opportunities relevant to coastal resources, water quality, economic growth and food security in the Arctic (H1-H3). Results from FORTE are expected to inform policy and decision making, and help coastal communities and industries prepare for the future*, in the Arctic and beyond.* FORTE focuses on sustaining strong collaborations with Alaskan Native communities who already experience enormous impacts on their livelihoods, culture, food security, physical safety, health, and social structure, and amplifies the value of Earth science through training, education, outreach, and "two-way" capacity sharing.

Augmenting NASA investments in the Arctic, **FORTE presents a prime opportunity to explicitly link NASA's ongoing ABoVE (currently, in its final synthesis phase) and future Arctic-COLORS programs, providing the missing piece in capturing processes across Arctic's terrestrial-marine ecosystems**. ABoVE research (2017-now) has significantly advanced our understanding of the interactions and feedbacks between land-atmosphere carbon exchanges, hydrology, snow, permafrost, disturbance, and vegetation composition in Arctic Boreal ecosystems [33]. Observations gathered during the ABoVE campaign will be particularly useful for improving process representations of hydrological cycle dynamics in FORTE models. High-resolution data for soil organic properties [66] and biomass structure [67,68] can provide updated model parameterizations. Measurements of soil moisture and active-layer thickness [69,70] are key to model calibration and validation, and potentially assimilation in the model simulations. FORTE will allow to link these new findings from ABoVE to studies focusing on the changing biogeochemistry and ecology of nearshore aquatic ecosystems. Further into the ocean, Arctic-COLORS [71] addresses land-ocean interactions in the Arctic, yet it is conceptualized as a larger-scale oceanographic field campaign (from east of the Mackenzie River to the Yukon River in the northern Bering Sea) with a primary focus on improving satellite (rather than airborne) ocean color (primarily 1-km resolution hyperspectral) observations. It also has a broader scope with questions addressing changes in open ocean sea ice (e.g., using icebreakers), impacts on higher trophic levels and marine food webs, and longer-term (multi-decadal) projections over a much larger area. To understand the impacts of environmental change on the coastal ocean ecosystem, higher resolution observations – achieved only by using suborbital platforms, as proposed in FORTE – are needed to *solidify the connections between intertwined terrestrial and aquatic landscapes.*

1.3. Building Strategic Collaborations

The value and urgency of FORTE also stem from the timely opportunity it offers to foster interactions and collaborations across multiple agencies and organizations (e.g., NASA, NSF, DOE, NRL, NOAA, AWI) by augmenting ongoing and future data collection efforts with suborbital observations to obtain more comprehensive datasets at minimal additional costs. Specifically, there would be compelling value added to science from synergies between FORTE and the NSF BLE-LTER program, which has been collecting long-term datasets (2017-now) to assess how environmental change impacts near-shore food webs in the Beaufort Sea Lagoons. These existing datasets (at lower temporal and spatial resolution than FORTE's planned measurements but over longer timeframe) provide important context for FORTE's more intensive observational efforts and will allow modeling efforts to begin during the first year of the mission and to span multiple decades. In addition, FORTE provides opportunities to link to the DOE-supported InteRFACE and High-Latitude Application and Testing of Earth System Models (HiLAT) projects that continue to focus on large-scale ESMs. FORTE will further develop regional coastal ocean models, including the incorporation of satellite remote sensing data of coastal watersheds and seas. The US Navy has ongoing projects on Alaska's North Slope terrestrial and ocean domains, with complementary research goals that will be greatly enhanced by FORTE, resulting in a more comprehensive understanding of the coastal Arctic ecosystem. FORTE provides also opportunities to link to a Canadian-led field expedition in Arctic Canada in the summer of 2027, coordinated by the Arctic Pulse program, as well as airborne measurements over the Mackenzie River and into the Beaufort Sea region in 2027 planned by the Alfred Wegener Institute. **Such synergies and constructive collaborations maximize the scientific impact and cost-effectiveness of any single field campaign program and are, now, a necessity to capture, monitor, model, understand and respond to the rapidly occurring environmental changes in the coastal Arctic.**

1.4 Mission Science Requirements

<u>Spatial Domain:</u> Focus on the four largest river systems that drain North Alaska (Colville, Kuparuk, Sagavanirktok and Canning) and have different geomorphological and ecosystem characteristics. Surface measurements will focus primarily on the more accessible Colville, Kuparuk and Sagavanirktok Rivers, while measurements along the Canning River will be conducted from airborne (crewed aircraft and UAS) sensors and larger research vessels.

<u>Strong collaborations:</u> with the North Slope Borough Planning and Community Services Department and *Iñupiat* communities across the North Slope Borough.

<u>Temporal Domain:</u> Capturing seasonality is essential in FORTE. Multiple suborbital deployments per year, in mission years 2 and 3, and strong collaboration with local communities, will result in observations spanning multiple seasons (from spring to fall).

<u>Platforms/Measurements:</u> <u>Airborne observations</u> will include measurements of hyper-spectral (UV-Vis-NIR) surface (land and water) reflectance for retrievals of in-water constituents (optical, biological, biogeochemical properties) and characterization of terrestrial habitat; sea surface and land surface temperature; coastal sea surface salinity; soil moisture and permafrost surface freeze/thaw state. <u>Shipborne measurements</u> will include comprehensive atmospheric, biogeochemical, and ecological measurements (Figure 2). <u>Satellite observations</u> will augment suborbital measurements with retrievals of inland and coastal water biogeochemical and biological properties; river ice, landfast ice and sea ice properties; coastal erosion; permafrost dynamics; surface currents; and surface temperature (Figure 2).

<u>Modeling:</u> The model setup will couple the terrestrial-hydrologic system with the river-delta-ocean system with mechanistic aquatic physics and biogeochemistry. River ice dynamics, landfast ice, and physics will be simulated, driving a biogeochemical modeling system that includes organic and inorganic carbon, nutrients, phytoplankton, sediment, optical properties, and coastal erosion. Simulations will include observation years and extrapolate back greater than 10 years to estimate interannual variability.

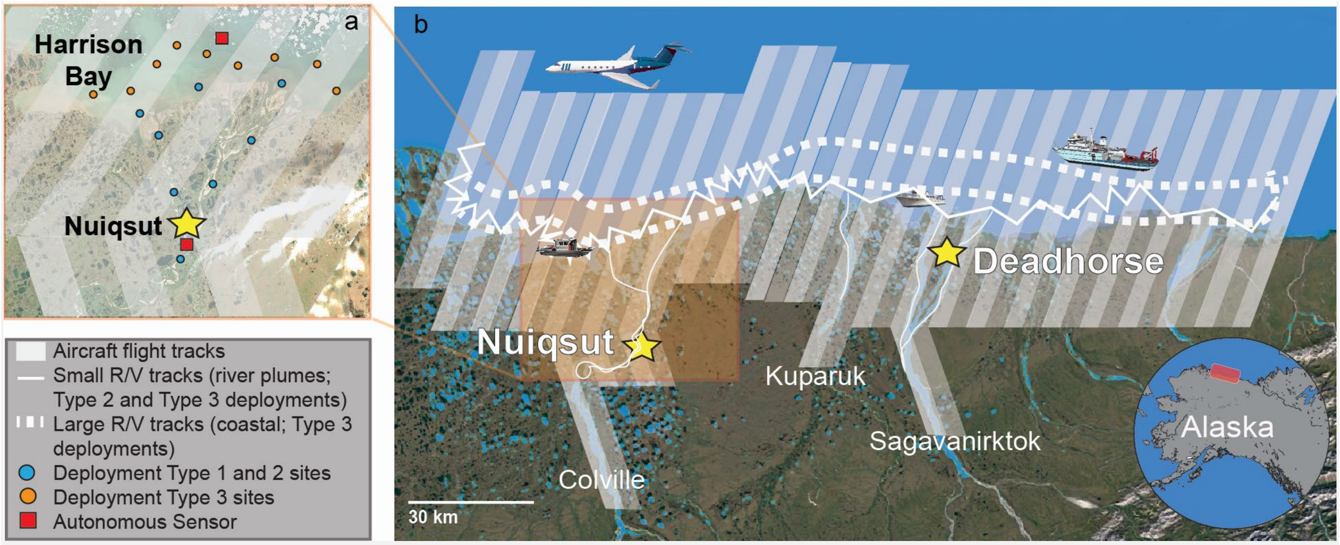


Figure 3: The FORTE observing profile showing: (a) example sampling locations in the Colville River for different deployment types (similarly, in other major rivers; overlain on July 2019 Sentinel-2 image); (b) the North Slope study region with the main rivers and example ship tracks and aircraft flight coverage.

1.5 Science Implementation

1.5.1 Study Domain and Observing Profile

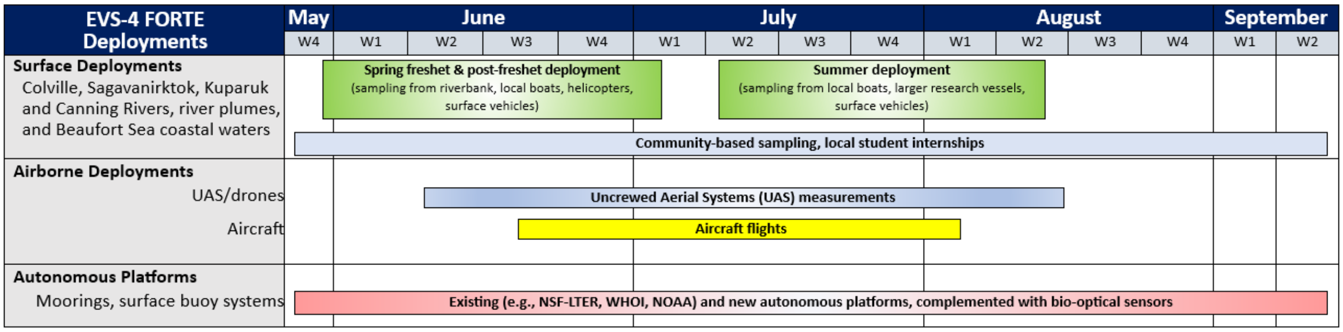
Study Domain: The FORTE study domain covers a range of coastal Arctic ecosystems along the North Slope of Alaska, as needed for addressing hypotheses H1-H3. The study region extends from Harrison Bay in the West (152ºW) to the Canning River (146ºW) in the East (Fig. 3). This area includes important river outflows (Colville, Kuparuk, Sagavanirktok, Canning), with different watershed and hydrographic properties (i.e., drainage basin areas, annual precipitation/discharge, elevation, slope, land cover) and varying levels of development and industrialization [72-74]. Shorelines in the vicinity of these rivers are eroding at rates as high as 25 m yr^{-1} [25,75,76]. This nearshore zone is relatively shallow, generally <20 m in depth, and includes the landfast ice zone and the edge of the sea ice zone of the coastal Beaufort Sea.

Observing Profile: FORTE measurements will be strategically integrated over two types of deployments (per year), each involving a ~20-30 day intensive campaign and capturing very different states of the river-to-sea ecosystem (Table 1). The wide time window of each deployment is necessary and sufficient to account for non-optimal weather conditions (rain, clouds, fog). Community-based sampling led by FORTE's local partners will allow to link observations between deployments and extend datasets to late summer and early fall (Table 1; see also 1.5.2).

> Deployment type 1 (May-June): will target the spring freshet (median date of break-up at Colville Village is June 3, 1980-now), peak discharge, landfast ice breakup, and the response of the coastal Arctic as hydrological conditions dramatically change from peak to low river flow. Frequent measurements from airborne and surface platforms (including small local boats, helicopter-based sampling, UAS, and moorings) are critical to capture these highly dynamic conditions.
>
> Deployment type 2 (July-August): when sea-ice largely retreats from the coastal zone, measurements will be extended further into the coastal Beaufort Sea to capture the response of the coastal system as open water area increases, phytoplankton respond to light, nutrients, carbon inputs, rising temperatures, and as wind, wave action and increasing temperature influence erosion patterns. Measurements from medium-size research vessels will serve as the base of operations in the coastal ocean, to capture the Colville, Kuparuk, Sagavanirktok, and Canning River plumes and impacts on the Beaufort Sea coastal biogeochemistry and ecology.

Crewed aircraft will be based in Fairbanks, AK, and fly to the North Slope (<1 hr each way; 330-380 nmi) for each sortie/daytime science observations. UAS can be deployed from Deadhorse (or Ugnu-Kuparuk) and are ideally suited to cover the river deltas and estuaries.

***Table 1:** FORTE operational profile and notional timeline for Year 2 activities (similar for Year 3)*



<table>
<tr><th rowspan="2">EVS-4 FORTE Deployments</th><th>May</th><th colspan="4">June</th><th colspan="4">July</th><th colspan="4">August</th><th colspan="2">September</th></tr>
<tr><th>W4</th><th>W1</th><th>W2</th><th>W3</th><th>W4</th><th>W1</th><th>W2</th><th>W3</th><th>W4</th><th>W1</th><th>W2</th><th>W3</th><th>W4</th><th>W1</th><th>W2</th></tr>
<tr><td rowspan="2">Surface Deployments
Colville, Sagavanirktok, Kuparuk and Canning Rivers, river plumes, and Beaufort Sea coastal waters</td><td colspan="6">Spring freshet & post-freshet deployment
(sampling from riverbank, local boats, helicopters, surface vehicles)</td><td colspan="5">Summer deployment
(sampling from local boats, larger research vessels, surface vehicles)</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="15">Community-based sampling, local student internships</td></tr>
<tr><td>Airborne Deployments
UAS/drones</td><td></td><td></td><td colspan="9">Uncrewed Aerial Systems (UAS) measurements</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Aircraft</td><td></td><td></td><td></td><td colspan="7">Aircraft flights</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Autonomous Platforms
Moorings, surface buoy systems</td><td colspan="15">Existing (e.g., NSF-LTER, WHOI, NOAA) and new autonomous platforms, complemented with bio-optical sensors</td></tr>
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1.5.2 Strong Collaborations with Local Communities

FORTE incorporates strong collaborations with local Alaskan Native communities and other stakeholders. These include coordination and planning of activities with the village of Nuiqsut, and the North Slope Borough (NSB) Planning and Community Services Department that works closely with the Inupiat, Heritage, Language and Culture and Wildlife Departments to protect the North Slope of Alaska lands and subsistence lifestyle. Input from the NSB Comprehensive Plans that provide an overview of the eight local communities across the North Slope and their visions for their future has been considered as part of the FORTE design and implementation. Measurements led by local communities (also involving local youth) will cover the periods from end of June to mid-July and from mid-August to late September (Table 1). These collaborations are vital in FORTE to enable the sampling frequency and local knowledge needed for a successful project, especially to observe processes and seasonal changes between suborbital deployments and sustain observations beyond this project's lifetime.

1.5.3 Phases of Investigation, Key Milestones, and Notional Timeline

The FORTE investigation team will use the Mission Schedule (Table 2) to manage the required project milestones and safety reviews and ensure successful and timely implementation of planned activities. FORTE will include three phases of investigation. **Phase I** (year 1) will include initial model development, field systems preparation, instrument integration, deployment logistics coordination (e.g., securing permits and platforms), and training (i.e., field and safety (including polar bears), helicopter, anti-harassment trainings). **Phase II** (years 2-3) will focus on intensive sampling and model/algorithm development. Prompt data processing, analysis, and publication and frequent Science Team meetings will assess progress and optimize deployments in the 2nd fieldwork year to mitigate risks. **Phase III** (year 4) provides sufficient time for data synthesis, model/algorithm refinement, integration/synthesis of data products, publication and data archival/sharing, as well as development of a summary document detailing FORTE (i) science objectives, (ii) algorithms, data, and links to publications, and (iv) lessons learned and recommendations for future efforts.

Table 2: *FORTE operational milestones and notional timeline*

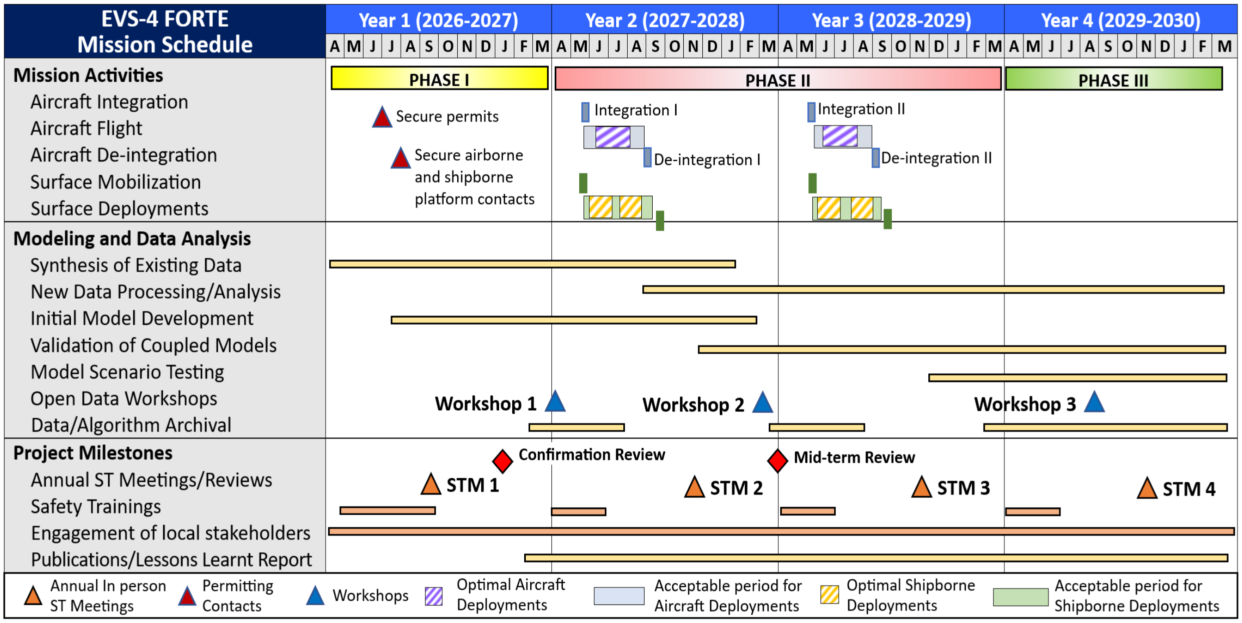

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***Table 3** Acronyms (in order of appearance)*

FORTE	Arctic Coastlines- Frontlines of Rapidly Transforming Ecosystems
EVS	Earth Venture Suborbital
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
ABoVE	Arctic Boreal Vulnerability Experiment
NGEE	Next Generation Ecosystem Experiments
DOE	United States Department of Energy
SBI	Western Arctic Shelf-Basin Interactions
ICESCAPE	Impacts of Climate on EcoSystems and Chemistry for the Study of Arctic Climate
MOSAiC	Multidisciplinary drifting Observatory of the Study of Arctic Climate
BLE-LTER	Beaufort Lagoon Ecosystems Long Term Ecological Research
UV-Vis-NIR	Ultraviolet-visible-near infrared radiation
SAR	Synthetic Aperture Radar
UAS	Uncrewed aerial systems
ESMs	Earth System Models
Rrs	Remote sensing reflectance
b_{bp}	Particle backscatter
a_p	Particle absorption
POC	Particulate organic carbon
DOC	Dissolved organic carbon
SPM	Suspended particulate matter
PCC	Phytoplankton community composition
E_d	Downwelling irradiance
NO_2	Nitrogen dioxide
O_3	Ozone
Temp	Temperature
Sal	Salinity
DO	Dissolved oxygen
DOM	Dissolved organic matter
POM	Particulate organic matter
NPP	Net primary production
GPP	Gross primary production
CO_2	carbon dioxide
OLI	Operational Land Imager (Landsat)
MSI	MultiSpectral Imager (Sentinel 2)
OLCI	Ocean and Land Colour Instrument (Sentinel 3)
TIRS	Thermal Infrared Sensor
PACE	Plankton, Aerosol, Cloud, Ocean Ecosystem
NISAR	NASA-ISRO Synthetic Aperture Radar
CDOM	Colored dissolved organic matter
NSF	National Science Foundation
NRL	Naval Research Laboratory
NOAA	National Oceanic and Atmospheric Administration