National Aeronautics and Space Administration

Arctic-COLORS
Arctic-COastal Land Ocean inteRactionS

A Science Plan for a NASA Field Campaign in the Coastal Arctic

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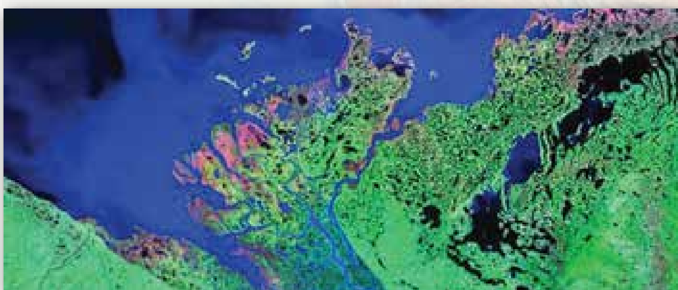

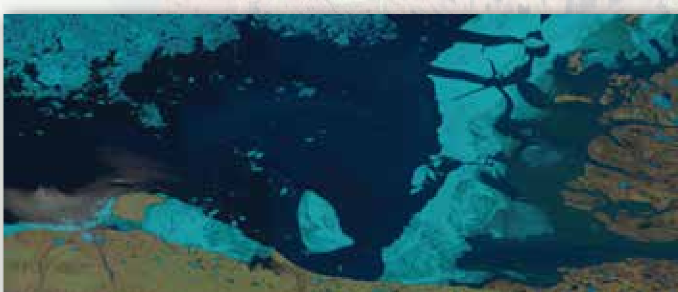
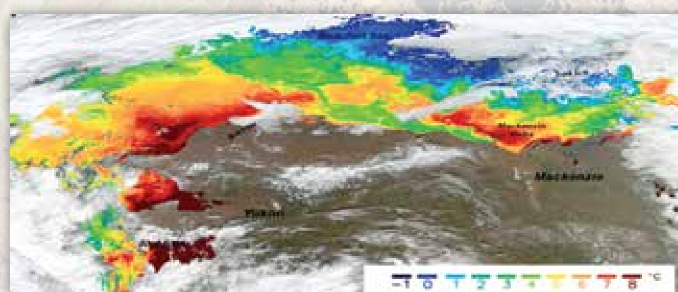
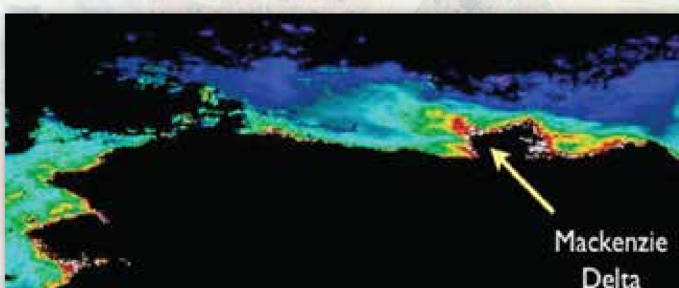

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Cover: NASA remotely-sensed imagery of Arctic physical and biogeochemical parameters:

a) Infrared satellite image of the Mackenzie delta (Landsat) [Credit: NASA Landsat/USGS, http://www.focusterra.ethz.ch/en/special-exhibitions/virtual-exhibition/Biogeoscience.html]
b) Phytoplankton bloom in the Bering Sea and Norton Sound on April 25, 1998 (SeaWiFS) [Credit: Norman Kuring]
c) Quasi true-color image of Mackenzie River delta June 16, 2014 (OLI, Landsat 8) [Credit: National Snow and Ice Data Center/USGS/NASA]
d) Sea-Surface Temperature (SST) for the Arctic-COLORS domain on Sept. 12–13, 2011 (MODIS) [Credit Muyin Wang]
e) Colored Dissolved Organic Matter absorption in the Western Arctic in July 2008 (MODIS-Aqua) [Credit Antonio Mannino]
f) The Mackenzie River Delta on Aug. 29, 2001 (MODIS-Terra), NASA Visible Earth [Credit: Jacques Descloitres]

Background image: Artist enhanced Landsat 7 ETM+ image of the Yukon Delta from September 22, 2002 [Satellite Image credit: NASA Earth Observatory].

Executive Summary

Over the past century, average Arctic surface air temperatures have increased at almost twice the global average rate and this rapid warming trend is expected to continue over the next century. Consequently, Arctic ecosystems have become an area of intense research focus, with specific emphasis on identifying compounding and exacerbating factors that can be critically important to our understanding and modeling of key biogeochemical processes. Short-term climate forcings and feedbacks that potentially accelerate local warming and environmental change in the Arctic are also increasingly affecting society in a variety of ways: from erosion of Arctic coastlines, to modifications of wildlife habitat and ecosystems that affect subsistence opportunities, to changes in transportation infrastructure, mineral development, and other ecological, socio-cultural, and economic uses of coastal ecosystem services. Arctic climate change has global implications, contributing to global sea level rise and affecting heat-flux changes, atmospheric circulation, and ocean circulation and dynamics beyond the Arctic region. The realization that changes within the Arctic have profound impacts on ecosystems and human populations across the globe has motivated greater attention by researchers, funding agencies, governmental policy makers, and non-governmental organizations. Recognizing the challenges associated with climate change and the emergence of a new Arctic environment, the White House released *The National Strategy for the Arctic Region* in May 2013. Included among the main principles highlighted in this strategy is: *"Making decisions using the best available information by promptly sharing – nationally and internationally – the most current understanding and forecasts based on up-to-date science and traditional knowledge".* **Yet major gaps remain in our understanding of the feedbacks, response, and resilience of coastal Arctic ecosystems, communities, and natural resources to current and future pressures. The biogeochemistry of the Arctic nearshore coastal zone, a vulnerable and complex contiguous landscape of lakes, streams, wetlands, permafrost, rivers, lagoons, estuaries and coastal seas, all modified by snow and ice, remains poorly understood.**

To improve our mechanistic understanding and prediction capabilities of land-ocean interactions in the rapidly changing Arctic coastal zone, our team proposed a Field Campaign Scoping Study called Arctic-COLORS (Arctic-COastal Land Ocean inteRactionS) to NASA's Ocean Biology and Biogeochemistry (OBB) Program. The goal of the project was to develop a scoping study report for NASA that describes and justifies the science imperative and design of an integrative, interdisciplinary oceanographic field campaign program that addresses high priority science questions related to land-ocean interactions in the Arctic. During the preparation of the scoping study report, our team consulted with the community to refine the high priority science questions for Arctic-COLORS, determine the study domain and research phases for the field campaign, and explore opportunities for linking to other field activities in the Arctic. Addressing the campaign's objectives will require multidisciplinary expertise, a coordinated engagement of regional authorities and local communities, and a combination of field studies, remotely sensed observations from various platforms (shipboard, buoys, gliders, ground-based, airborne, satellite, for example), process studies, and numerical modeling. This scoping study report does not describe a comprehensive field campaign activity in detail, but rather sketches out key aspects of a field campaign program including the study region, sampling approaches, critical measurements, remote sensing assets, and modeling activities necessary to address the science objectives.

What is Arctic-COLORS? Arctic-COLORS is a proposed NASA-funded field campaign designed to quantify the response of the Arctic coastal environment to global change and anthropogenic disturbances – an imperative for developing mitigation and adaptation strategies for the region. **The Arctic-COLORS field campaign is unprecedented, as it represents the first attempt to study the nearshore coastal Arctic (from riverine deltas and estuaries out to the coastal sea) as an integrated land-ocean-atmosphere-biosphere system** (Fig. ES1).

The overarching objective of Arctic-COLORS is to determine present and future impacts of terrigenous, atmospheric, and oceanic fluxes on the biogeochemistry, ecology and ecosystem services of the Arctic coastal zone in the context of environmental (short-term) and climate (long-term) change. **This focus on land-ocean**

interactions in the nearshore coastal zone is a unique contribution of Arctic-COLORS compared to other NASA field campaigns in polar regions. The science of our field campaign will focus on five key science questions:

1. How and where are materials from the land, atmosphere, and ocean transformed within the land-ocean continuum of the Arctic coastal zone?
2. How does thawing of Arctic permafrost—either directly through coastal erosion or indirectly through changing freshwater loads from upstream thaw—translate to changes in coastal ecology and biogeochemistry?
3. How do changes in snow/ice conditions and coastal circulation influence Arctic coastal ecology and biogeochemistry?
4. How do changes in fluxes of materials, heat, and buoyancy from the land, atmosphere, and ocean influence Arctic coastal ecology and biogeochemistry?
5. How do changing environmental (short-term) and climate (long-term) conditions alter the Arctic coastal zone's availability and use of ecosystem services?

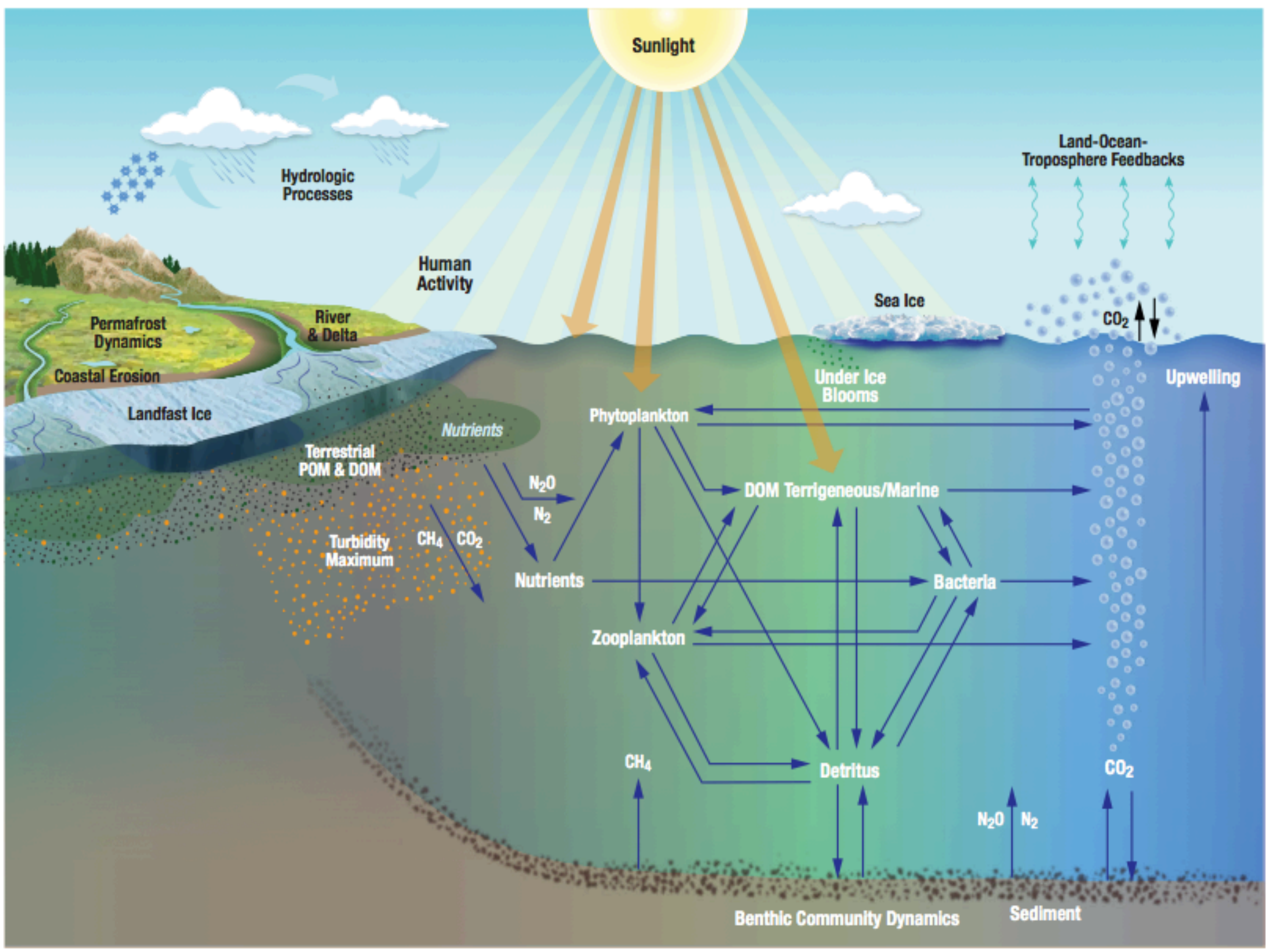

Figure ES1. Arctic-COLORS coastal dynamics linking the five overarching science questions. Processes represented by arrows as well as those labeled (permafrost dynamics, river and delta, coastal erosion, landfast ice, etc.) will be examined at the interface of river estuaries and deltas with the coastal ocean.

Science Plan and Implementation - The ecological and biogeochemical complexity of the land-ocean-ice interface in the Arctic coastal region will require an unprecedented integrative effort utilizing remote sensing to integrate across multiple spatial and temporal scales. Long-term remote-sensing time-series will also allow for hindcasting, which will assist in distinguishing between climate change and shorter term inter-annual variability. Ultimately, the models developed and improved by this research will provide a window into the future of the Arctic, with emphasis on identifying the most vulnerable components of the coastal ecosystem to change and the primary drivers that lead to those vulnerabilities. Such information will have great utility in planning for future management scenarios and contingencies in this region.

The geographical extent of this Arctic land-ocean exchange study is envisioned to extend from the Yukon River Delta (Alaska) to the Mackenzie River Delta (Canada), from the head of tidal influence to the coastal shelf (Fig. ES2). The proposed timeline for Arctic-COLORS (2019-2028) overlaps with the first several years of NASA's new ocean color mission PACE and coincides with NASA's Arctic-Boreal Vulnerability Experiment (ABoVE) field program (2015-2025), thus linking processes in the Arctic nearshore coastal region and terrestrial ecosystems. Intensive sampling and process experiments will be conducted from river mouths to the shelf of several large and small rivers from the Beaufort Sea, Chukchi Sea, and Norton Sound regions as well as at several coastal erosion sites.

Multiple cruises/deployments will be conducted each year throughout each of four consecutive years. To resolve the seasonal cycle associated with biogeochemical processes, intensive fieldwork and process studies will be conducted in different seasons, including March (end of winter/early spring), late May/early June (peak discharge, under ice blooms), July (high biological and photochemical activity), September (maximum open water, low river discharge, pre-conditioning for winter) and October/November (freeze-up periods for Mackenzie and Yukon, respectively). Multiple river mouth and shelf sites will be contrasted. Coastal erosion sites representative of exposed bluffs and lagoons will be sampled. Intensive field studies will be complemented by survey studies conducted across the study domain to: 1) assess spatial variability in the physical, biological, and biogeochemical state of different shelf regions; 2) determine interactions between the coastal ocean and the shallower shelf regions; 3) distinguish point sources versus distributed inputs; 4) evaluate model simulations across multiple temporal and spatial scales; and 5) design and evaluate

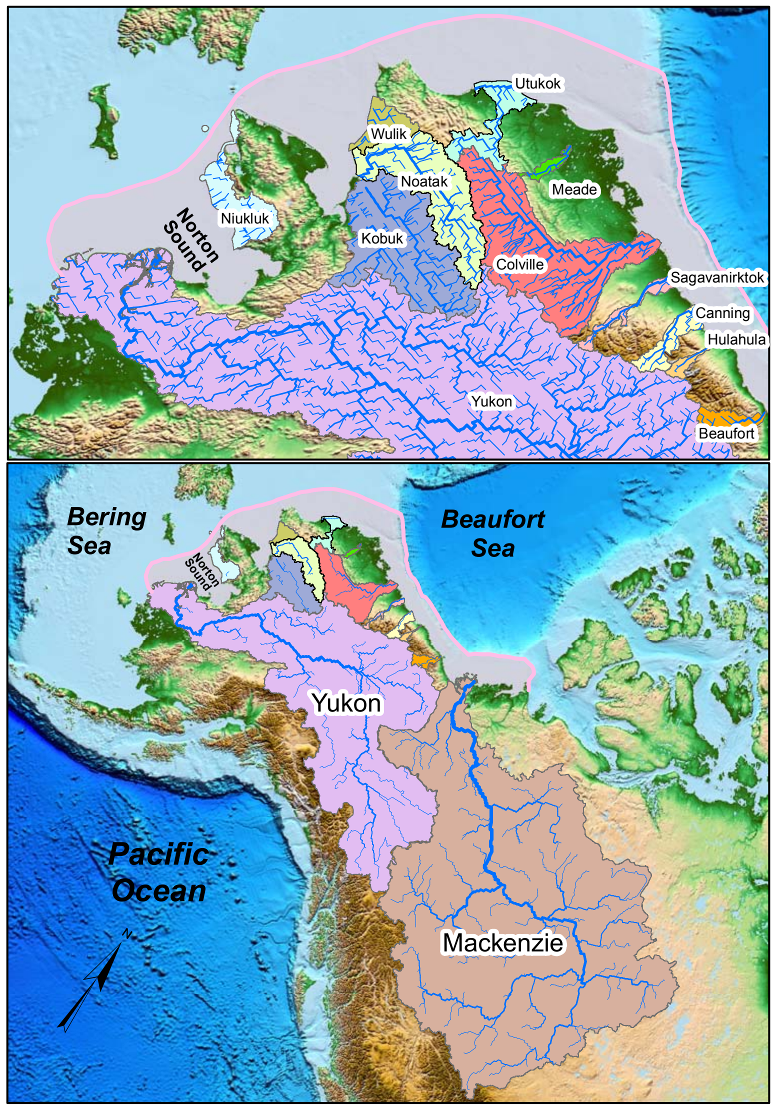

Figure ES2. Map of the Arctic-COLORS domain notated with pink shading along the coast in both panels. The domain includes the globally significant rivers Yukon and Mackenzie, as well as regionally influential watersheds across the continuum of coastline in between.

satellite algorithms across a range of environments, so that remote sensing satellite imagery can be used to scale up fluxes and processes.

In situ measurements collected during Arctic-COLORS will also provide a comprehensive dataset for evaluating and improving NASA satellite ocean color retrievals in the complex, coastal Arctic region, enabling the development of new applications for existing sensors as well as providing a robust preparatory dataset required to develop applications for the next generation of NASA ocean color missions. Through a combination of observational and modeling approaches and by integrating passive and active remote-sensing observations from various platforms, Arctic-COLORS will push the envelope of ocean color research and applications in high latitude areas.

Arctic-COLORS Outcomes – The objectives of Arctic-COLORS directly support the strategic goals and objectives of NASA's Ocean Biology and Biogeochemistry Program, and are fully aligned with the objectives of NASA's Applied Science, Terrestrial Ecology, Biodiversity, Carbon Cycle, Ecological Forecasting, and the Cryospheric Science Programs. Data analyses using information from multiple complementary satellite sensors that measure atmosphere, land, ocean and sea ice parameters are critical components necessary to better understand the nearshore coastal Arctic as an integrated land-ocean-atmosphere-biosphere system. The validation of remote sensing algorithms utilizing optical, biological and biogeochemical measurements from Arctic-COLORS will prove critical toward the development of NASA's new Climate Initiative mission PACE. Arctic-COLORS will facilitate high temporal-, high spatial- and high spectral-resolution field observations that contribute directly to current and future NASA ocean color validation efforts, and will enhance remote sensing capabilities *in one of the most sensitive regions to climate change, the Arctic.* Coastal zones, in general, are some of the most heavily impacted regions of the world by human activity, and will continue to undergo a high level of stress under the projected accelerated environmental change. As such, it is critical to develop remote sensing tools that are applicable to all coastal zones, and Arctic-COLORS will push those tools in new directions for ice-impacted regions.

Arctic-COLORS is a particularly timely opportunity to respond to the scientific and societal needs of developing an improved understanding of the coastal Arctic. The proposed field campaign will provide the necessary linkage between previous NASA field activities studying the offshore Arctic Ocean and on-going NASA field activities conducted in the framework of ABoVE that will measure Arctic land processes, river chemistry, and terrestrial fluxes. At the same time, Arctic-COLORS is highly synergistic and will leverage off other ongoing or upcoming U.S. and international research efforts and field activities in the Arctic, such as the Public Knowledge Canada program, the Canadian Sentinelle Nord program, and the North Pacific Research Board program in the Chukchi Sea. Understanding and predicting change in the Arctic during Arctic-COLORS will also respond to the recommendation by the National Research Council to link the terrestrial and ocean ecosystems of the Arctic (NRC, 2014). Further delays in establishing a comprehensive baseline in the coastal Arctic will hamper future assessments of Arctic climate change impacts. Arctic-COLORS will provide a critically detailed and accessible knowledge base for future research on ecosystem services, impacts assessment, emergency management, decision support, and social-environmental systems in the Arctic.

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1.0| Motivation for a NASA-OBB field campaign in the Arctic Ocean coastal zone

"The National Strategy for the Arctic Region" released by the Executive Office of the President in May 2013 sets forth the United States Government's strategic priorities for the Arctic. Among the major strategic priorities is the pursuit of responsible Arctic region stewardship, *"continue to protect the Arctic environment and conserve its resources; establish and institutionalize an integrated Arctic management framework; …**and employ scientific research and traditional knowledge to increase understanding of the Arctic."*** The foundation for U.S. Arctic engagement and activities rests primarily on the following principle, *"Making decisions using the best available information by promptly sharing–nationally and internationally–the most current understanding and forecasts based on up-to-date science and traditional knowledge."*

While there is a legacy of research on the nature and effects of climate change in the Arctic, major gaps remain in understanding the natural variability, vulnerability, response, and resilience of arctic coastal ecosystems (Goetz et al., 2011). **Most importantly, the Arctic coastal zone, a vulnerable and complex contiguous landscape of lakes, streams, wetlands, permafrost, rivers, lagoons, estuaries, and coastal seas—all modified by snow and ice—remains poorly understood**. Yet, the Arctic coastal ocean is one of the most critical areas for decision-making on issues related to marine living resources, energy resources, industrial development, transportation, security, and conservation. Additionally, many local communities depend heavily on these coastal Arctic resources and ecosystem services, which are currently in a state of rapid change.

The proposed NASA Arctic-COLORS field campaign is designed to quantify the response of the Arctic coastal environment to global warming and anthropogenic disturbances—an imperative for developing mitigation and adaptation strategies for the region. Using an integrative, interdisciplinary approach that combines detailed process studies, field surveys, advanced modeling tools, and enhanced remote-sensing retrievals from various platforms (ground-based, airborne, and space-based), Arctic-COLORS will address fundamental science questions in order to assess the impacts of natural and anthropogenic changes on coastal ocean biology, biogeochemistry, and biodiversity. **The Arctic-COLORS field campaign is unprecedented. It represents the first attempt to study the coastal Arctic as an integrated land-ocean-atmosphere-biosphere system, which is required to determine present and future impacts of changes in terrigenous, atmospheric, and oceanic fluxes on coastal ecology, biogeochemistry, and ecosystem services in the context of environmental (short-term) and climate (long-term) changes.**

Understanding and predicting change in the Arctic during Arctic-COLORS will benefit from a trans-disciplinary effort and from partnerships with ongoing U.S. and international efforts, such as the U.S. Bureau of Ocean Energy Management's (BOEM) Marine Arctic Ecosystem Study (MARES NOPP PARTNERSHIP), the Public Knowledge Canada program (POLAR) and its Canadian High Arctic Research Station (CHARS) [see letter of support by Dr. M. Raillard, §8.5], ArcticNET, and Sentinelle Nord programs [see letter of support by D. Brière, §8.5] as well as the upcoming North Pacific Research Board (NPRB) program in the Chukchi Sea. The campaign also takes full advantage of synergies with NASA's Arctic-Boreal Vulnerability Experiment (ABoVE), which aims to characterize drivers and consequences of environmental changes in Arctic terrestrial socio-ecological systems. Understanding and predicting change in the Arctic during Arctic-COLORS will also respond to the National Research Council's recommendation to link the terrestrial and ocean ecosystems of the Arctic (NRC, 2014). Furthermore, Arctic-COLORS will provide a critically detailed and accessible knowledge base for future research on ecosystem services, impacts assessment, emergency management, decision support, and social-environmental systems in the Arctic. Most importantly, however, the **Arctic-COLORS science objectives can only be achieved by using NASA's unique multi-platform, remote-sensing data assets and multidisciplinary data assimilation and modeling tools.**

1.1. Why the Coastal Arctic?

Historically, Arctic climate has alternated between cold and warm conditions, including a cooling trend of several degrees Celsius from 400–100 years BP (Jennings et al., 2002; McGuire et al., 2006). Such climatic trends have shaped the physiography, ecology, and human cultures in the Arctic. Yet, since the middle of the 20th century, the Arctic has experienced warming not observed since the early Holocene–warming that exceeds trends observed at lower latitudes. The importance of ice, snow, and permafrost to the Arctic environment and its human residents means that the local amplification of global warming will change the region and will re-shape ways of life. A warming Arctic may simultaneously result in new opportunities for mineral exploration and shipping as well as changes in traditional activities, all of which could cause further feedbacks, including significant impacts on global climate. These alterations include changes in carbon inventories (e.g., changes in sequestration and release of CO_2 and CH_4 stocks), as well as changes in global albedo, the hydrological cycle, and thermohaline circulation.

Although Arctic marine and terrestrial ecosystems have been the focus of much recent climate change research, **estimates of the biogeochemical processes, interactions and exchanges across the Arctic land-ocean interface are still poorly constrained.** Detailed studies have examined specific aspects of individual northern, high-latitude rivers including the Yukon (Dornblaser and Striegl, 2007; Spencer et al., 2008, 2009) and Mackenzie (e.g., Emmerton et al., 2008), yet only a few studies have examined how these riverine fluxes directly impact the Arctic coastal zone on regional scales (e.g., Dittmar and Kattner, 2003; Overeem and Syvitski, 2008). Such studies have been hampered by a number of factors, including inconsistent sampling and analytical methods across sites, poor coverage at low salinities, and lack of sufficient seasonal coverage (e.g., Holmes et al., 2012 and references therein). The lack of consistent sampling across coastal systems in the Arctic hinders efforts to scale up fluxes and processes and develop improved mechanistic models for the Arctic coastal ocean. The coastline in many Arctic regions is receding at an unprecedented rate due to coastal erosion, mobilizing large quantities of sediments and carbon. The impacts on coastal ecosystems from river deltas, to estuaries, to the coastal sea, remain unknown. **Clearly, a field program such as Arctic-COLORS is needed to provide a predictive understanding of the relative impacts of terrigenous, hydrological, atmospheric and oceanic fluxes on Arctic coastal ecology and biogeochemistry. Arctic-COLORS is a multidisciplinary, collaborative effort that aims to bring together observational, modeling, and remote-sensing investigators who cover a wide range of expertise and have experience working across a range of coastal environments (from lower latitude coastlines to polar regions) to address critical questions in the rapidly changing Arctic coastal ocean.**

1.2 Why NASA?

Field observations in the Arctic coastal zone are hampered by the vastness and remoteness of the region, the polar night, sea ice, and often-difficult weather conditions. Short-term research funding makes it challenging if not impossible to distinguish between inter-annual variability and true climate change phenomena. In many areas, economic hardship, high costs, and changing political priorities have resulted in a reduction in field monitoring and river gauging stations. However, the advent of satellite remote-sensing and the development of in-water and airborne autonomous vehicles have improved weather prediction, measurements of land change, snow cover, and sea ice extent. Modeling tools have also improved, with several fully coupled models focusing on the Arctic region. Understanding the Arctic requires multidisciplinary–terrestrial, oceanic, atmospheric, and now cryospheric–efforts that combine long-term observations, field campaigns with process studies, laboratory work, and modeling. Given the logistical complexities of sampling in the coastal Arctic (e.g., shallow waters, snow and ice cover, absence of terrestrial road network), orbital and sub-orbital remote-sensing, and coupled models are obligatory tools to understand, respond, and adapt to arctic environmental changes. Thus, Arctic-COLORS will address these inherent challenges by 1) using spatial-temporal products derived from NASA's remotely-sensed data to extend observations to larger spatial and longer temporal scales, and 2) integrating satellite and field observations with coupled physical-biogeochemical models. The former is particularly critical, as hindcasting using NASA remote-sensing data allows climate change trends to rise above the noise of inter-annual variability. The overall combination of competencies is a familiar strength for large, comprehensive NASA field campaigns and studies in support of satellite-based Earth System research.

In situ measurements collected during Arctic-COLORS will provide a comprehensive dataset for evaluating and improving NASA's satellite ocean color retrievals in the complex, coastal Arctic region, enabling the development of new applications for existing sensors as well as providing the robust preparatory dataset required to develop applications for the next generation of NASA ocean color sensors. Data analyses using information from multiple complementary satellite instruments that measure atmosphere, land, ocean, and sea ice parameters (e.g., OMI, OMPS, SeaWiFS, MODIS, VIIRS, Landsat, ASTER, Aquarius, ICESat2 [all acronyms are defined in Appendix 8.4]) are critical components that are needed to better understand the coastal Arctic as an integrated land-ocean-atmosphere-biosphere system. Several of these have sun-synchronous orbits and wide swaths, providing multiple observations per day over the Arctic. The rather wide swaths and thus moderate spatial resolution that such sensors sample will require the use of sub-orbital, airborne sensors with higher spatial resolution. *In situ* Arctic-COLORS data will also be used for developing new bio-optical algorithms and data analysis methodologies tailored to coastal arctic applications and in preparation for products that will be available from upcoming NASA missions (e.g., hyperspectral radiometry including UV capability, SWIR bands). Because the proposed timeline for Arctic-COLORS (2019–2028) will overlap with the first few years of NASA's PACE ocean color mission, the proposed field observations specifically will be particularly useful to PACE validation efforts, enhancing remote-sensing capabilities *in one of the most sensitive regions to Climate Change* (see §4.5), and benefitting the up-scaling requirements of Arctic-COLORS.

Recent and current NASA field campaigns in the Arctic (Ice Bridge, ICESCAPE, and ABoVE) have or are focused on ice fields, the Pacific-influenced Arctic ocean ecosystem, and North American boreal forests, respectively. However, arctic warming is also causing changes to fast ice, permafrost, and hydrology in coastal systems, with significant impact to all drivers of coastal ecology and biogeochemistry. These shifts include changes in the timing and fluxes of riverine carbon/nutrients/heat/buoyancy and the timing and extent of sea ice formation and retreat, both of which will lead to changes in the timing and extent of microalgal blooms and coastal foodweb dynamics. **The importance of quantifying, in a timely fashion, how environmental and climate change are affecting the Arctic coastal ecosystem cannot be overstated. This focus on land-ocean interactions and the coastal zone is a unique contribution of Arctic COLORS compared to other NASA field campaigns in Polar Regions. A field campaign such as Arctic-COLORS that adequately captures the response of the Arctic coastal ecosystem to this change across a range of contiguous terrestrial/hydrological/estuarine/oceanic environments will take advantage of NASA's research leadership, strength, and assets.**

In addition, NASA has, and must continue to play, a leading role in social-environmental systems research via the application of fundamental Earth system science understanding and data. In the remote, riverine-influenced Arctic, climate change is resulting in losses to coastal communities with subsistence economies through fisheries degradation, species re-organization, and loss of habitat. Permafrost thaw and sea ice retreat exacerbate already high rates of coastline collapse, which threatens lives and infrastructure. At the same time, potentially positive changes include greater access for natural resources exploration, extended seasons for marine transportation, and stimulation of riverine and marine food webs. Arctic-COLORS offers a unique opportunity for NASA to dovetail with oil spill research, which has a direct application for emergency response within the Arctic, and collaborate with the Interagency Coordinating Committee on Oil Pollution Research. While local communities may be forced to adjust or move as subsistence harvesting of local food resources is negatively impacted, increased human immigration to the Arctic may still be the net outcome. The impacts of these interacting processes on the land/river/ocean biogeochemical interface (e.g., pollution, storm damage) and the human activities it supports are not yet known. NASA can contribute to these important questions by enhancing fundamental understanding of natural systems and providing expert data and knowledge support to social-environmental research programs.

1.3 Why Now?

Recent changes in the Arctic are unambiguous. Significant recorded changes now include: reduced sea ice extent and thickness (e.g., Barber et al., 2009; Stroeve et al., 2012; Overland and Wang, 2013; Lindsay and Schweiger, 2015); permafrost thaw (e.g., Frey and McClelland, 2009; Walvoord and Striegl, 2007); changes in hydrology (Rawlins et al., 2010, Parmentier et al., 2013) and ice breakup dynamics (Hutchins and Rigor, 2012; Nghiem et al., 2014); rise in water and air temperatures (Steele et al., 2008; Kay et al., 2008); changes in aquatic chemistry, such as pH, calcium carbonate saturation states; salinity; nutrients (Bates et al., 2006; Yamamoto-Kawai et al., 2011); and changes in ocean fresh water inflow (Woodgate et al., 2006; Proshutinsky et al., 2009; Steiner et al., 2015). Because of significant increases in Arctic river discharge in the past century, as well as in future projections (e.g., Peterson et al., 2002; Overeem and Syvitski, 2010), Arctic coastal ecosystems are among those most likely to experience an amplification of global change (e.g., Serezze et al., 2009). Hence, a comprehensive coastal study is of highest priority. Delays in establishing an inclusive baseline will hamper future assessments of Arctic climate change impacts, as well as any pro-active strategies for mitigation. **Arctic-COLORS will study processes across spatial and temporal scales (from diurnal to seasonal to inter-annual and inter-decadal).** Although observations collected during the Arctic-COLORS field campaign cannot be used in isolation to assess inter-decadal Arctic change, these new observations will be able to provide insight into past and future inter-decadal changes in the Arctic when used together with long-term satellite remote-sensing records and model simulations. Specifically, the long-term satellite record will allow for retrospective analyses, and newly developed high resolution models will generate past century simulations, thus enabling the separation of inter-annual variability from longer term trends.

Mitigation and adaptation to a warming Arctic requires new local, national, and international policies and significant resources. Policymakers and stakeholders need 1) more comprehensive data records from improved observational tools, accurate visualizations, and 2) a more quantitative understanding of how environmental (short-term) and climate (long-term) change affect present and future physical, chemical and ecological conditions in the coastal Arctic. It will take years to develop this new observational infrastructure to improve our understanding of current and future arctic processes and to develop and implement new policies.

As an example, Arctic-COLORS is well-timed and suited for providing baseline data that is critical for recent and future oil spill preparedness activities in the Chukchi Sea and other coastal Arctic waters. By integrating enhanced remote-sensing algorithms with new field observations and improved modeling tools, the Arctic-COLORS campaign has significant implications for improving oil spill emergency response in Arctic coastal waters. Undoubtedly, there is a strong urgency to increase national and international scientific efforts in the coastal Arctic. This urgency was recognized in the development of the National Strategy for the Arctic Region, as directed by the White House, which includes pursuing "our national interests in safety, security, and environmental protection" and calls for national and international response to arctic warming. Arctic-COLORS is a particularly opportune response to this need. Free and timely access to data and associated project reports will be a hallmark of the selected Arctic-COLORS teams.

As a coastal field-campaign Arctic-COLORS will not only build off of two previous NASA field campaigns focused on the offshore Arctic Ocean environment (ICESCAPE and Ice Bridge), but even more significantly, it will overlap with NASA's ABoVE field campaign that focuses on Arctic terrestrial ecosystems (Kasischke et al., 2012). With a start date of 2015 and a duration of 9 to 10 years, ABoVE will focus not only on key processes associated with changes to the land surface, but also on processes in major Arctic river basins (Yukon and Mackenzie Rivers). This provides a unique opportunity to link these activities with an integrative, interdisciplinary, estuarine/coastal oceanographic field campaign. The ABoVE effort includes a Water Group that will not focus on oceanic processes *per se*, but rather on the terrestrial ecological and hydrological processes that influence coastal ocean processes—particularly river chemistry and export (Kasischke et al., 2012). As highlighted in the ABoVE Science Definition Team Report, "*the terrestrial end-members relevant to ocean processes could be studied during ABoVE, thus informing studies of ocean processes, if suitable*

Figure 2.1. A map showing the Arctic-COLORS study domain (pink shading) located along the continental margin of North America.

partnerships can be established with one or more ocean research programs." This presents a unique opportunity for exploiting research synergies and for sharing resources that will increase the science return and increase efficiencies. Arctic-COLORS will strongly benefit from well-practiced Arctic logistics support at NASA, which provides a much needed linkage between previous NASA field activities studying the offshore Arctic Ocean and on-going field activities measuring Arctic river processes, chemistry, and fluxes. Furthermore, possible collaborations with, for example (see §5.4), the on-going BOEM/MARES NOPP PARTNERSHIP and POLAR field campaigns and the newly Canadian-funded Sentinelle Nord project have been identified and could provide ship-time, instrumentation, and other resources for NASA scientists thus increasing the impact of Arctic-COLORS efforts (see §5.4 and 8.5). This is particularly relevant to the objectives of several NASA programs (e.g., the Applied Science or the Interdisciplinary Science programs) and would provide an opportunity to coordinate activities with other Federal and state (and regional and private) programs addressing climate change and the human dimension in the Arctic.

2.0| Engaging the Broader Research Community

Successfully addressing the Arctic-COLORS science objectives will require a highly interdisciplinary approach, including investigators specializing in *in situ* observations, model simulations, and remote-sensing data. While some investigators will have extensive experience in the Arctic region, it is likely that other investigators will bring their lower-latitude expertise in land-ocean interactions to bear on the Arctic-COLORS science questions. The proposed field campaign will also require internationally coordinated observations from various platforms (e.g., satellites, aircrafts, over-the-snow/all-terrain vehicles, small boats, larger vessels, ground-based monitoring networks) across a range of temporal and spatial scales, as well as coordinated engagement of regional authorities and local communities. Reflecting these needs, this Arctic-COLORS science plan is the result of a collective effort by members of a broader science community who have been actively engaged in a series of research planning activities and have contributed to different stages of the proposed planning and design for this integrative, interdisciplinary (hydrological, riverine, estuarine, cryospheric, and oceanographic) field campaign in the Arctic coastal zone. At the same time, consultation with local communities early in the process of developing the Arctic-COLORS program is critical not only for successful implementation of the proposed activities but also for enhancing the broader impacts and realizing the societal benefits of the Arctic-COLORS scientific discoveries.

A bi-national group of researchers (United States-Canada)—many from local research and academic institutions in the study region that are well connected to the local communities—identified high priority science questions related to land-ocean interactions in the Arctic that underpin the planned integrative, interdisciplinary field campaign for Arctic-COLORS. This team of collaborators included individuals with extensive experience in Arctic field research and modeling who provided expertise across a wide range of disciplines. These experts included specialists in ocean optics, remote sensing of biological and biogeochemical processes, freshwater and marine biology and biogeochemistry, wetland biogeochemistry, aquatic ecology, terrestrial ecology, river plume dynamics, physical oceanography and Arctic circulation, sea ice dynamics, land-ocean-atmosphere interactions, Arctic air-sea and sea-ice exchanges, Arctic hydrology and meteorology, climate and climate change in the Arctic, coupled physical-biogeochemical modeling, and data assimilation. Two workshops defined the overarching science questions of Arctic-COLORS, determined the study domain and research phases for the field campaign, and identified requirements for a successful implementation plan. Early engagement of scientists from POLAR and members of the Science Definition Team for NASA's ABoVE project facilitated an exploration of opportunities to coordinate field activities in the Arctic region. They also discussed the Arctic-COLORS study-domain extent (Figure 2.1) and the processes linking Arctic ecosystems along the land-ocean continuum. The broader research community was also engaged in Arctic-COLORS planning at a number of scientific conferences and programmatic meetings where presentations were made. Town Hall meetings were conducted, and special Break-Out Sessions were convened (see §8.3) as well. Participation of members from both the research and applications communities in these outreach activities allowed the team to gain feedback from the broader international research community, further refine the project's overarching science questions for comprehensive coverage, balance among disciplines, and provide for a definition of the Arctic-COLORS spatio-temporal domain.

3.0| Overarching Objective and Science Questions of Arctic-COLORS

The overall objective of the proposed field campaign is to determine present and future impacts of terrigenous, atmospheric and oceanic fluxes on ecology, biogeochemistry and ecosystem services of the Arctic coastal zone in the context of environmental (short-term) and climate (long-term) changes in the Arctic.

Inherent in all aspects of this work will be the utilization of remote-sensing assets (ground-based, shipborne, airborne, and space-borne). Developing models at all scales will be critical for establishing a fundamental knowledge base for current conditions and evaluating climate-related impacts on availability and use of ecosystem services. The field campaign will require a systems approach that includes the study of feedbacks and linkages. Observations and models will be used to identify and understand the mechanisms and relationships between drivers and ecosystem processes, and predict which mechanisms are more vulnerable to environmental change. A specific goal of this research is the identification of likely adaptations of the Arctic coastal ecosystem in the face of multiple sources of change.

Given the variety and complexity of the Arctic coastal system, a broad range of coastal environments must be included in order to capture the relevant processes and fluxes to the coastal zone, as defined earlier (Figure 3.1). A central premise of this field campaign is that rivers form a primary conduit for transferring terrestrial materials to the coastal ocean and that these materials exert a strong influence on marine ecosystems and carbon processing. Indeed, ~80% of all Arctic freshwater inflow comes from the large rivers that enter the so-called “interior shelves.”

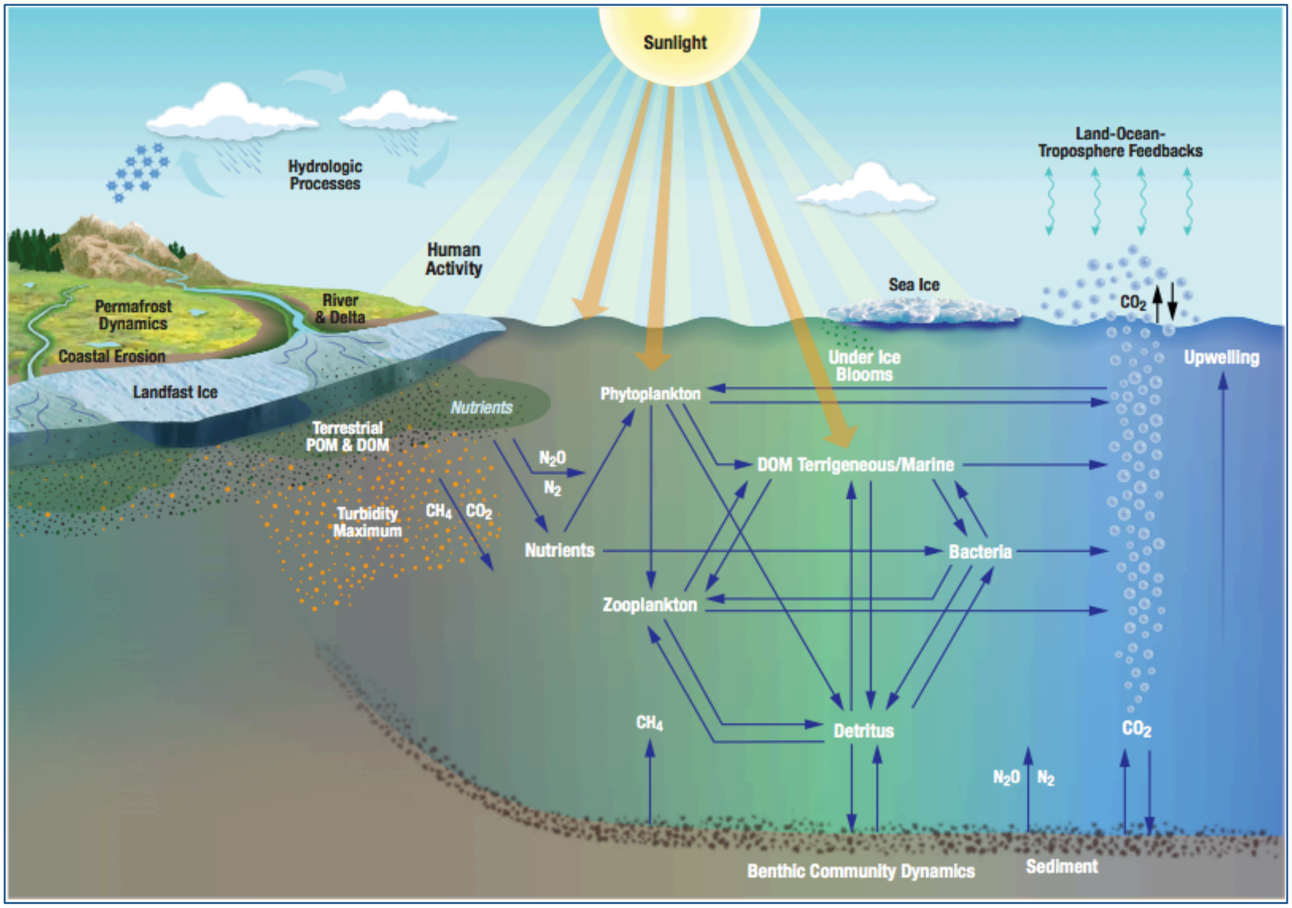


Figure 3.1 Arctic-COLORS coastal dynamics linking the five overarching science questions. Processes represented by arrows as well as those labeled (permafrost dynamics, river and delta, coastal erosion, landfast ice, etc.) will be examined at the interface of river estuaries and deltas with the coastal ocean.

Although there are some similarities in the major Arctic rivers, such as highly seasonal discharge and strong dissolved organic carbon signals (Holmes et al., 2012; Lobbes et al., 2000; Dittmar and Kattner, 2003), each has varying characteristics that hamper the scaling of single river systems to the broader pan-Arctic (e.g. Hernes et al., 2014). As such, we propose to characterize the impacts of both major and minor river flows spanning the North American Arctic coast, between the Yukon and Mackenzie Rivers. This strategy allows for a comparison between two major watersheds that primarily drain boreal forests (Mackenzie and upper Yukon Rivers) and numerous, smaller Arctic rivers that primarily drain tundra. The breadth of the study region also enables an assessment of diffusive groundwater exchanges along the shore and coastal erosion that is particularly prevalent along the northern shore of Alaska.

The concept of change is intrinsic to the Arctic-COLORS science, both at environmental (short-term) and climate (long-term) scales, as well as local and regional spatial scales. Seasonal and inter-annual observations will interact and be upscaled using model simulations to estimate how transformation processes may change in response to future conditions.

The science in our field campaign will focus on five overarching questions. Within these questions, "*materials*" refers to biogeochemical constituents such as sediment, organic carbon and nutrients and "*freshwater*" refers to water derived from rivers, groundwater, surface runoff, precipitation, and sea ice/ice/snow melt. The "*Arctic coastal zone*" includes the continuum of Arctic rivers, lagoons, estuaries, and the continental shelf.

1. How and where are materials from the land, atmosphere, and ocean transformed within the land-ocean continuum of the Arctic coastal zone?

2. How does thawing of Arctic permafrost—either directly through coastal erosion or indirectly through changing freshwater loads from upstream thaw—translate to changes in coastal ecology and biogeochemistry?

3. How do changes in snow/ice conditions and coastal circulation influence Arctic coastal ecology and biogeochemistry?

4. How do changes in fluxes of materials, heat, and buoyancy from the land, atmosphere, and ocean influence Arctic coastal ecology and biogeochemistry?

5. How do changing environmental (short-term) and climate (long-term) conditions alter the Arctic coastal zone's availability and use of ecosystem services?

3.1. Science Question #1

How and where are materials from the land, atmosphere, and ocean transformed within the land-ocean continuum of the Arctic coastal zone?

Delivery of riverine materials to the Arctic coastal zone has typically been assessed by sampling rivers above the influence of tides with the implied assumption of conservative transport through estuaries, deltas, and plume waters out to the coastal ocean. Similarly, atmospheric deposition has been measured mostly on land and far less on sea ice. However, these complex ecosystems at the land-ocean interface are highly reactive zones of biogeochemical exchanges and transformations. The first high-level science question in Arctic-COLORS derives from the need to quantify the many ways in which terrigenous, eolian, and marine materials are transformed across strong gradients at the Arctic land/ocean interface. Specific questions Arctic-COLORS will address include:

1.1 What are the specific roles of Arctic coastal wetlands, lagoons, estuaries and deltas as transformers of terrigenous, atmospheric and oceanic material transported to the coastal ocean?

1.2 What are the rates and magnitudes of biotic and abiotic processes such as flocculation, resuspension, dissolution, photooxidation, and microbial processing that affect biogeochemical transformations in the coastal zone?

1.3 How does the coastal snow and ice cover impact these transformations by controlling rates of transport/mixing, by modulating UV and visible radiation availability, by restricting atmospheric fluxes, and by receiving atmospheric deposition?

The Arctic Ocean is heavily influenced by inputs of terrestrial material via river discharge and erosion of coastlines, more so than in other oceans (e.g., Holmes et al., 2012). However, our understanding of how geomorphological, physical, photochemical, and biogeochemical processes in nearshore estuarine environments (e.g., deltas, lagoons, and plume waters) modify terrestrial inputs is still very limited, because of the fact that there are multiple processes occurring within these geographical features that have the potential to significantly transform materials transported to offshore waters. Seasonal differences in atmospheric circulation control the source region of eolian materials to the Arctic coastal zone—predominantly continental in winter and marine in summer, with very different chemical signatures. The concept of "transformation zones" in Arctic-COLORS is aimed at identifying the most significant areas and processes involved in altering material fluxes in Arctic nearshore regions. The functioning of transformation zones will change seasonally as a result of variations in physical factors such as temperature, solar radiation, river discharge, atmospheric circulation, and the distribution of sea ice. Transformation zone function also varies across the study region, following differences in catchment characteristics of rivers (e.g., size, vegetation types, permafrost coverage, and precipitation patterns), the presence and size of river-mouth deltas, and the morphology of the coastal zone into which terrestrial materials are released. As a result, the functioning of transformation zones must be quantified across seasons, and at multiple study locations (**Q1.1**).

In large river systems, deltas enable significant off-channel water storage and processing prior to discharge to the ocean (Lesack and Marsh, 2010). These deltaic systems flood during the spring high-water period (freshet), and then discharge water from distributary channels and connected lakes as water levels fall. The few published studies examining the effects of off-channel storage in Arctic deltas indicate significant particle deposition as water slows and is stored off-channel for the Mackenzie delta (Carson et al., 1999), unlike what may happen, for example, in the Colville (Walker et al., 2003; Schreiner et al., 2013). Off-channel storage also renders riverine materials susceptible to biological and photochemical processing as waters warm and become less turbulent, thus allowing sediments to fall out of suspension (e.g., Droppo et al., 1998; Febria et al., 2006; Tank et al., 2011). Such processes may lead to a decrease in the concentration of inorganic nutrients concurrent with increases in organics (Emmerton et al., 2008). However, much of what we know about in-delta processes in the North American Arctic comes from the Mackenzie system (Doxaran et al., 2015; Emmerton et al., 2007; Graydon et al., 2009; Lesack et al., 2014; Marsh and Hey, 1989), which differs significantly from other river-mouth deltas in this region. For example, the Colville delta is much smaller in size, and the geomorphology of the Yukon delta differs considerably due to its relatively young age and shallow Norton Sound (Walker, 1998). Although there are numerous biogeochemical studies of the Yukon River above the tidal influence, these same studies rarely extend below Pilot Station out to the delta and therefore little is known how Yukon River constituents might be altered during passage through the delta. How the various deltas in the study region behave relative to each other, how deltas vary in their function as transformation zones across years, and how complex physical, photochemical and biogeochemical processes (and their interplay) affect the overall flux and quality of dissolved and particulate materials to the coastal ocean remains largely unknown (**Q1.2**).

Beyond river-mouth estuaries/deltas, there are long stretches of coastline in the Arctic that may additionally function as focal areas for processing land-derived materials. For example, lagoon ecosystems that are prominent along the Alaskan Beaufort Sea coast receive substantial terrestrial inputs from runoff and coastal erosion each year. Water exchange between lagoon and open ocean environments varies as a function of seasonal sea ice dynamics and the geomorphology of barrier islands, but in general lagoons facilitate processing of terrestrial materials by trapping particulate material and increasing water residence and biogeochemical processing times. Previous studies have noted that productivity of lagoon ecosystems along the Alaskan Beaufort Sea coast is relatively high in comparison to productivity outside the barrier islands, and that the diets of consumers in these lagoons include substantial contributions from terrestrial organic matter sources (Dunton et al., 2006, 2012). In addition, processes that also occur within smaller estuarine plume waters—such as flocculation and the enhanced processing of organic matter where terrestrial and oceanic materials meet—can be expected to augment biogeochemical transformations in nearshore coastal regions (Bianchi, 2011; Fox, 1983; Sholkovitz et al., 1978) (**Q1.1 and Q1.2**). A recently proposed hypothesis suggests that all terrestrial freshwater runoff into the North American Arctic forms a narrow (<15 km) but "contiguous riverine coastal domain" (RCD) that flows clockwise along the coast (Carmack et al., 2015). In essence, the RCD would have characteristics of a highest order river that integrates all the lower order rivers or water sources that flow into it. Entrainment and mixing of freshwaters into the RCD would likely have a profound impact on the transformation of terrigenous materials.

Finally, submarine groundwater discharge (SGD) to coastal arctic waters is currently unknown, but recognized as a significant source of fresh water and terrigenous material world-wide (Moore, 2010). The composition of SGD differs from that predicted by simple mixing because biogeochemical reactions in the aquifer modify its chemistry.

In the polar environment, sea ice plays a critical role in altering how materials are transformed in the coastal zone. Sea ice properties impose many controls including: retarding the rates of transport and mixing within river plumes entering the coastal zone, modulating the availability of UV and visible radiation, introducing atmospheric materials deposited onto its surface (e.g., black carbon, organic and trace metal contaminants, sea salt), and dampening the exchange of gases between the atmosphere and water column. High spatial and temporal variability in Arctic coastal sea ice conditions are well-documented (Mahoney et al., 2012; Barnhart et al., 2014a), which results in a wide range of impacts on coastal material transformations across the study area and profound changes in processing rates between seasonal regimes. Long term changes in sea ice extent and properties are altering the role of ice by changing the synchronicity of seasonal cycling, reducing the duration of ice-impacted states and weakening the role of sea ice as an atmosphere-ocean barrier. While this question is primarily focused on biogeochemical transformations, coordinated observations of the biogeochemical processes associated with changing sea ice conditions will enable Arctic-COLORS to address the understudied relationships between ice, snow and coastal transformations (**Q1.3**). The role of sea ice in controlling and moderating atmosphere and ocean-forcing on the Arctic coastal zone is considered in more detail in Science Question 3.

3.2. Science Question #2

How does thawing of Arctic permafrost—either directly through coastal erosion or indirectly through changing freshwater loads from upstream thaw—translate to changes in coastal ecology and biogeochemistry?

Organic carbon stored in the Arctic permafrost exceeds the total carbon (as carbon dioxide) in the atmosphere. Permafrost thaw may increase loading of organic carbon and other constituents to the coastal zone. Quantifying the potential impacts of Arctic permafrost thawing on coastal ecology and biogeochemistry is the main objective of the second Arctic-COLORS science question. Specifically, Arctic-COLORS will address:

2.1 Are materials derived from thawing permafrost significantly increasing terrigenous fluxes relative to those delivered via historical riverine fluxes?

2.2 How do freshwater carbon and nutrient loadings to the coastal zone change as a result of permafrost thawing within the watershed?

2.3 What are the impacts of permafrost thaw on coastal ecology and biogeochemistry?

Permafrost thaw alters the movement of water through Arctic landscapes, modifying the export of water, carbon, and associated constituents to coastal margins. Frozen ground and large soil-based organic carbon stores are common throughout the pan-Arctic terrestrial system. Long-term, thawing permafrost is expected to impact coastal ecology and biogeochemistry by altering carbon and nutrient loadings to river and ground water systems as well as through coastal erosion, impacting land-sea and coastal air-sea fluxes (Vonk et al., 2015) (**Q2.1**). Currently, thawing permafrost has the potential to influence the quantity and timing of freshwater export from watersheds to the ocean. Discharge quantity may be altered by direct contributions (i.e. melting of ice in permafrost), while increased availability of subterranean flow pathways as the active layer deepens will alter discharge timing and potentially reduce evaporation. The most profound impact is likely to be a reduction in peak discharge and temporal lengthening of the spring freshet, which will have substantial impacts in the ability of rivers to carry constituents to the ocean, ultimately affecting estuarine stratification. The extent to which altered river discharge and timing can be captured in projections of future system changes is dependent on improved understanding of the relationships between various aspects of hydrologic cycling, rates and heterogeneity of permafrost thaw, vegetation cover and change, and the ability to anticipate non-linear responses over time (Haine et al., 2015; Tape et al., 2011). Simulations suggest that permafrost thaw is already contributing to increased winter baseflow and mean annual streamflow (St. Jacques and Sauchyn, 2009).

The multi-year thawing of permafrost not only impacts the timing and overall quantity of fresh water delivered from the land to the coastal ocean, it also impacts the chemical composition of this water. Much emphasis is placed today on the role of Arctic soils as a potential net source of CO_2 and CH_4 over the coming century (Schuur et al., 2008; 2015). The changes in chemical composition are largely associated with changes in water flow paths through soils as the active layer deepens (Frey and McClelland, 2009). Such water chemistry changes depend on the composition of the contacted soils, and the travel times through soils, which tend to increase as flow paths deepen. Shifting flow paths from organic to mineral soil layers increases the concentrations of some water-borne constituents, such as nitrate and weathering-derived ions (Ca, Mg, Na), and decreases the concentration of others, such as dissolved organic carbon (DOC) (MacLean et al., 1999), unlike the effect of certain deltaic processes examined in **Q1.2**. Similarly, catchments with lower permafrost extents may result in greater bicarbonate export (Tank et al., 2012a).

Permafrost thaw may also result in increased DOC concentrations when deepening flow paths pass through organic-rich peat deposits (Frey and Smith, 2005). Alternatively, if thawing and subsequent erosion continue to increase, they may result in a higher release of particulate organic carbon (POC) from the permafrost to rivers and further into the coastal zone. A significant fraction of this POC may escape degradation during river transport (e.g., Mackenzie) and be buried in marine sediments, where it has been reported to contribute to a longer-term, geological CO_2 sink (Hilton et al., 2015). Increased water travel times associated with deeper flow paths are likely to enhance microbial processing of DOC on one hand, while allowing POC to escape microbial processing on the other hand.

Ultimately, regional differences in how permafrost thaw impacts the chemistry of water flowing from land into the coastal ocean will depend on the strength of gradients in soil composition and microbial processing as water flow paths deepen (**Q2.2**). Changes in permafrost will also impact the seasonal phasing of freshwater discharge and associated biogeochemistry by controlling the onset and cessation of the percolation of ground water through the (frozen or thawed) soil and into the Arctic coastal zone. There may also be a dependence/difference associated with the size/area of the drainage basin. Larger drainage basins feeding the Mackenzie River extend far to the south and encompass a variety of vegetation, soil, and bedrock types whereas smaller rivers are typically associated with more unique, wholly Arctic drainage basins. Larger areas translate to potentially longer transit times. Variations in vegetation and soil types within larger drainage basins will also complicate the net effect of thawing permafrost on geochemical fluxes whereas smaller drainage basins may prove more predictable due to their simplicity. Permafrost thawing and erosion transcend the goals of Arctic-COLORS in relevance as the potential biogeochemical transformations and release of greenhouse gases through permafrost thawing, either to Arctic rivers, coastal zone or atmosphere, will have a global impact.

Coastal erosion along the Beaufort Sea has been accelerating (Mars and Houseknecht, 2007; Jones et al., 2009; Wobus et al., 2010) with increased wave and storm surge exposure of the ice-rich coast to warmer ocean water (Overeem et al., 2011; Barnhart et al., 2014b), as much of the coastal zone now experiences longer open water seasons. Pan-Arctic analysis of satellite-based sea ice concentration specifically along the coast reveals that the length of the 2012 open-water season, in comparison to 1979, expanded by 1.9- to 3-fold (i.e., about a 10–30 percent decrease in ice season length) for the western Beaufort and Chukchi Sea sectors, respectively (Barnhart et al., 2014a), although eastern Beaufort sea ice has remained relatively unchanged (Steele et al., 2015). Frey et al. (2015) also found earlier sea ice retreat and later sea ice formation based on satellite observations, and increased variability in the recent decade of 2000–2012 compared to the 1979–2012 period. Current coastal erosion rates range up to 17–20m/yr in the most ice-rich exposed Beaufort Sea shoreline (Wobus et al., 2010; Barnhart et al., 2014b), whereas more protected or less ice-rich coasts have more dampened rates of 1.7m/yr as a long-term background rate (Gibbs and Richmond, 2015). Long-term coastal erosion rates along the Chukchi Sea were more modest at 0.3m/yr over 1940–2000, but have nevertheless been accelerating recently (Gibbs and Richmond, 2015). There is a high variability in soil properties and bank heights along these large stretches of permafrost shoreline, with coastal bluffs interspersed with sandy barrier islands protecting lagoons and large bays. Many sites consist of excess ice in the exposed bluffs and are rich in organic matter (Ping et al., 2011). Thus, coastal erosion processes release previously sequestered soil organic carbon and freshwater flux from melting interstitial ice into the shallow nearshore waters. Erosion rates are highest in late July and August, thus releasing most of the fluxes during a limited time in the summer when terrestrial discharge has largely subsided. It seems likely that storms during late September and October also may play a role in effectively mixing the newly introduced solutes, organic carbon, nitrate, and freshwater into the coastal zone, as is typical in sub-Arctic and temperate regions. Sediment and nutrient fluxes introduced from permafrost coastal processes increase in relevance along those stretches of coasts where riverine input is smaller, in contrast to the continental-scale estuarine/delta systems (the Mackenzie and Yukon Rivers) where the system may be dominated by the much larger riverine component (**Q2.3**).

While Arctic-COLORS Science Question 1 addresses the role that nearshore estuarine environments play in modifying biogeochemical fluxes between the terrestrial and offshore ocean domains (§3.1) and Science Question 4 addresses how land-derived inputs influence coastal ecology (§3.4), this second high-level Science Question addresses specific impacts of permafrost thaw and coastal erosion as they relate to the issues raised in both questions 1 and 4. Furthermore, Arctic-COLORS Science Question 2 will clearly benefit from interaction with the ABoVE research program in addressing, e.g., the relative importance of enhanced riverbank and thermokarst thaw leading to an increased active layer depth. To the degree that present inputs of inorganic nutrients and organic matter (from rivers as well as coastal erosion) support net biological production in nearshore estuarine environments, changes in these inputs as a consequence of permafrost thaw have the potential to alter total production as well as community composition and food web relationships. Thus, the relative magnitude of these processes must be evaluated and quantified at multiple spatial and temporal scales in the context of permafrost-driven change.

3.3. Science Question #3

How do changes in snow/ice conditions and coastal circulation influence Arctic coastal ecology and biogeochemistry?

As discussed above, the Arctic coastal zone experiences enormous physical pressures and gradients with forcings from the land (inputs of heat and buoyancy), the ocean (waves and currents), and the atmosphere (wind, heat fluxes, gas and particle exchange). Unlike land-ocean interfaces in temperate and tropical climates, the presence and retreat of sea ice in the Arctic acts as an additional constraint on the relative impact of these forces. Arctic-COLORS will assess and quantify the major physical forcings that impact coastal ecology and biogeochemistry, and will specifically address:

3.1. How does timing of sea ice formation/retreat, length of sea ice cover and ablation, snow accumulation, and morphology of the coastal ice zone influence coastal ecology and biogeochemistry?

3.2. What is the impact of changing freshwater fluxes, precipitation, wind intensity, tidal motions, stratification, upwelling, downwelling, heat budgets, and other atmospheric and oceanic physical forcings on coastal ecology and biogeochemistry?

Ongoing changes in average ice conditions are likely to have a large, quantifiable impact on ecosystem processes in the Arctic coastal zone and add a sense of urgency to characterizing these impacts now. The most recent state-of-the-art climate models from the Coupled Model Intercomparison Project, Phase 5 (CMIP5), predict that the open water duration will be extended from the current 1–2 months to 2–3 months in the southern Beaufort Sea by the 2030s due to loss of pack ice (Wang and Overland, 2015). Arctic-COLORS Science Question #3 examines how the ice and ocean, as affected by atmospheric processes, create and control major physical forcings important to coastal ecology and biogeochemistry. The work will prioritize changes in the ice-ocean system likely to alter availability of inputs that currently limit productivity or constituent processing in the coastal environment (e.g., light, nutrients, dissolved gases). Arctic-COLORS will take advantage of transitions in the seasonal cycle and variation across the study domain to assess variability in ocean and ice forcing and the sensitivity of coastal zone response to this variable forcing. In addition, impacts of changes in ocean and ice forcing will be investigated through the use of state-of-the-art, high-resolution numerical models that will have been evaluated with *in situ* observations collected as part of the field campaign as well as with longer term remote-sensing data time series. Such coupled biogeochemical-physical models have the ability to differentiate the relative impacts of multiple changing factors, such as freshwater fluxes, precipitation, wind intensity, stratification, and other ocean and ice forcing mechanisms.

Riverine plumes mix slowly because sea ice can partially inhibit wind momentum transfer. In addition, with the exception of some portions of the Eurasian shelves and Norton Sound, tidal energy is weak on Arctic Ocean shelves (Kowalik and Proshutinsky, 1994), leaving little mechanical energy to support mixing. Plume mixing with ambient waters is thus confined to the ice-ocean boundary layer. This has important implications on seasonal biogeochemical transformations (e.g., Bluhm et al., 2015). First, much of the suspended material carried by the buoyant plumes will likely settle in the quiescent waters beneath the landfast ice. Only after break-up occurs and the landfast ice becomes mobile will these materials be re-suspended and transported. Second, the shelf area influenced by the river plume is much broader than would be expected in the absence of ice. This suggests that the size of arctic "estuaries" will vary seasonally and may be altered in a changing climate. Third, it is not known how winds offshore of the landfast ice alter plume behavior, although models suggest substantial differences. Fourth, weak cross-shelf exchanges suggest that biogeochemical processes within the landfast ice zone are isolated from those of the outer shelf so that these processes may proceed quite differently between the two regions. Fifth, the winter baseflow of larger rivers (i.e., Mackenzie and Yukon Rivers) is small but significant and is typically associated with a different geochemical signature compared to the peak flows in spring and summer. This runoff enters the shelf at a time of thickest sea ice coverage and may spread along and across the shelf as far as the stamukhi (grounded ridges) zone allows (Macdonald et al., 1995; Reimnitz, 2002).

The seasonal transition between open water and landfast ice cover includes two particularly active shoulder seasons: break-up and fall freeze-up. Break-up coincides with peak river discharge and entails the melting and mobilization of the landfast ice and the accumulation of low-salinity waters from melting and runoff. Fall freeze-up coincides with strong fall storms that instigate vertical mixing, vigorous cross-shore exchanges, and along-shore transports. The wave field is generally the most energetic (and coastal erosion greatest) in fall, as ice cover is reduced and wind fetch is high. At this time, nearshore materials are most likely to be re-suspended and rapidly transported along and across the shelf and/or incorporated into forming ice. These seasonal milestones are anticipated to change in magnitude, timing, and synchronicity as the climate shifts.

In order to understand the transport, processing, and dispersion of terrigenous and eolian inputs to an Arctic coastal environment, we need to determine the roles of sea ice in four critical functions: 1) as a barrier to light, heat, mass, and momentum transfer between the atmosphere and the ocean, 2) as a barrier to lateral transfer and dispersal of freshwater and terrigenous constituents across the estuarine environment, 3) as storage for freshwater, nutrients, sediments, contaminants, and organic matter, and 4) as a control on sediment deposition, coastal erosion, and coastal bathymetry. The extent to which snow and ice serve as a barrier between ocean and atmosphere is determined primarily by snow cover depth, ice thickness, melt pond coverage, ice deformation, and the presence of light-absorbing particles within the ice. Snow on ice provides an important control on ice growth (Langlois et al., 2007), light transmission (Perovich and Polashenski, 2012), and biological productivity within and beneath the ice (Jin et al., 2006). Onset of melting conditions and later pond formation on the ice surface controls the surface radiative balance during summer as the ice thins (Grenfell and Perovich, 2004; Nicolaus et al., 2013; Polashenski et al., 2012). Stable landfast ice also suppresses momentum transfer from wind and the partial permeability of the ice to gas exchange may play a role in some gas availability (Loose et al., 2014). The dynamic opening and closing of shore leads can rapidly alter the continuity of this barrier in the coastal environment, placing tight controls on the transfer of momentum, heat, and mass.

The physical characteristics of the coastal ice relevant to these roles exhibit large inter-annual variability (Barry et al., 1979, Mahoney et al., 2007) and may now also exhibit long-term trends. Snow depths on land and ice appear to be decreasing (Webster et al., 2014) and there is evidence that the extent, stability, and duration of the landfast ice cover is also decreasing (Mahoney et al., 2007). Observation of sea ice in this ocean-atmosphere barrier role will be critical to the Arctic-COLORS mission and though techniques for local observation of these properties and processes are well developed, Arctic-COLORS will confront the need to address the enormous spatial and temporal variability in the coastal environment, which can only be done with NASA remote-sensing and modeling assets. Assessment of the controls that ice conditions impose on coastal productivity and processing will depend on quantifying ice properties throughout the annual cycle and placing current conditions in the context of historical observations. This is the key objective of Science Question 3.1 in Arctic-COLORS.

The role of ice as a barrier to lateral mixing is significantly less studied and is a key area for development in this program. Differing rates of processing in offshore versus inshore environments mean that the fate of the inputs from the terrestrial environment may be altered significantly by the impacts of ice on lateral exchange. Typical results (e.g., Garvine, 1974; Münchow and Garvine, 1993; Fong and Geyer, 2001) applicable to arctic continental shelves during the open water season are unlikely to hold in the presence of landfast ice, which interacts both dynamically and thermodynamically with the buoyant plumes generated by river discharge. The restriction of momentum transfer from wind alters wind-driven cross-shelf exchanges (Kasper and Weingartner, 2012), suggesting that waters within the landfast ice zone are renewed very slowly through winter. Riverine plumes can also be channeled or blocked by ice bottom topography (Macdonald et al., 1987; Macdonald and Carmack, 1991), or run both under and above the ice (Alkire and John, 2006), with significant impacts on the dispersal and mixing of buoyant plumes (Kasper and Weingartner, 2015). Stamukhi can completely cut off estuarine-ocean exchange in some areas (Carmack and Macdonald, 2002).

Ice formation in the estuarine system can lock up significant portions of the annual freshwater discharge from major Arctic rivers (Eicken et al., 2005), entrain substantial amounts of sediment (Stierle and Eicken, 2002), and transport terrigeneous organic matter with the ice (Eicken et al., 2003). Brine stored within the ice can be rejected episodically during ice growth or meltwater flushing (Weeks and Ackley, 1982). Sediment incorporated into ice during formation can be transported and dispersed on arctic continental shelves by ice drift and melt at times long after entrainment and over distances much greater than current velocities and settling times would ordinarily support, or may be re-deposited into the water column locally at times when material re-suspension would otherwise be unlikely (Pfirman et al., 1995; Darby et al., 2011). Understanding which materials are entrained in the ice is important for understanding this reservoir effect, so processes that lead to full water column convection and suspension of sea floor sediments into forming ice during autumn as well as processes that lead to formation and transport of fresh ice out of estuarine environments are of particular interest.

Over the Beaufort Sea, easterly alongshore winds foster shelf-break and coastal upwelling while downwelling occurs under westerly winds. Although upwelling winds occur more frequently and are, on average, stronger than downwelling winds in all seasons, wind-driven Beaufort shelf processes are event-like and generally last only for days. Upwelling and downwelling have different seasonal maxima and frequencies, as do storm winds (Lentz, 2004). If the shelf stratification is weak and the shelf is sufficiently shallow, the upwelled water may be rapidly mixed into the surface layers and support intense blooms (Pickart REF; Spall et al., 2014), enhancing overall biological production (Tremblay et al., 2011). Downwelling winds transport freshwater eastward in narrow, coastally trapped currents, which are bounded on their seaward side by a surface to bottom front. Mixing between the coastal current and ambient seawater is reduced in comparison to the upwelling case. The vertical structure of cross-shelf exchanges during upwelling events depends upon several factors including vertical stratification (Lentz and Chapman, 2004), bottom slope, and ice concentration/mobility (Pite et al., 1995).

For example, when subject to the same surface wind forcing, moderately heavy ice concentrations are far more effective in inducing upwelling (or downwelling) than open water due to ice-ocean stress. In contrast, heavy ice concentrations result in reduced ice mobility (or complete immobility in the case of landfast ice), so that transfer of momentum to the water column is impeded. Whether upwelling, onshore and cross-shelf transport, or sea ice brine rejection will become the dominant source of nutrient-rich water into the Arctic coastal zone on an annual basis is a major question for Arctic-COLORS; these processes have now been observed seasonally and regionally (Weingartner et al., 1999; Williams et al., 2006; Tremblay et al., 2011) and may become more important under a changing climate.

3.4. Science Question #4

How do changes in fluxes of materials, heat, and buoyancy from the land, atmosphere, and ocean influence Arctic coastal ecology and biogeochemistry?

Delivery of sediment and nutrients to the Arctic coastal zone has clear impacts on primary production, but less well-quantified are the impacts of terrigenous organic matter on microbial-to-fish and microbial-to-benthos foodweb dynamics. All constituents delivered to the coastal zone are expected to contribute to a unique physicochemical environment that will determine relative abundance and diversity of biological species. Obtaining a quantitative, mechanistic understanding of these processes and their impacts on coastal ecology and biogeochemistry (including organismal physiology) is the main objective of the fourth Arctic-COLORS science question. Specifically, Arctic-COLORS will assess:

4.1 How and why does coastal community diversity vary along the salinity gradient from land to ocean, and how do changes in diversity translate to functionality?

4.2 What is the impact of changing constituent fluxes on coastal food webs?

4.3 How will erosion of Arctic coastlines, changing estuaries, deltas, and coastal wetlands and associated changes in material transformations impact coastal ecosystems?

4.4 What is the impact of seasonal and inter-annual variations in the timing and magnitude of discharge and atmospheric deposition on the composition and functionality of coastal ecosystems?

Ten percent of the Earth's flowing fresh water discharges into the Arctic (Dittmar et al., 2003; Petersen et al., 2002), causing a salinity gradient in coastal waters ranging from ~0 salinity at the river mouths to higher salinities (32-33) found in the Canada Basin. River sediment plumes, clearly visible in satellite ocean color (e.g., Fichot et al., 2013) and L-band data, can have spatial extents > 10^5 km^2. Salinity serves as a tracer for several other biogeochemical properties—terrestrial organic material and inorganic nutrients as arguably the most important—that vary substantially in estuaries and that are well-known to impact organisms in low-latitude coastal systems. In particular, the species composition of heterotrophic and autotrophic microbial communities is known to vary substantially and systematically in low-latitude estuaries because of changes in salinity and other co-varying biogeochemical properties (Herlemann et al., 2011; Pan et al., 2011). Analogous variation in Arctic coastal microbial communities has also been observed in the Mackenzie River-Shelf system (Boeuf et al., 2014). Because remote-sensing has the capability to capture biological and biogeochemical stocks (separate from suspended sediments) and processes associated with salinity variability at unprecedented spatial and temporal scales, Arctic-COLORS will contribute significantly to our understanding of these issues at multiple locations and seasons.

The connection between salinity gradients and ecosystem functioning is not as well-understood, even in low-latitude estuaries. Phytoplankton cell size is known to vary with nutrient concentrations, which has quantifiable impacts on the structure of food webs in coastal systems—everything else being equal, smaller cells at the base of food chains eventually lead to less production at higher trophic levels, including marine mammals and fish. Low nutrient concentrations select for small phytoplankton, but whether this results from physiological or ecological changes is less clear. Previous work has demonstrated a decrease in algal cell size in the nutrient-poor Canada Basin during the period of 2004–2008 (Li et al., 2009). The decrease was correlated with a freshening of surface waters, suggesting that greater buoyant stability led to a decrease in mixing and lower nutrient inputs into these Arctic surface waters. Given that nutrients are likely to remain low in coastal waters, such changes may also occur in the coastal zone where Arctic-COLORS will focus.

The input of terrestrial organic material also impacts biological communities in Arctic coastal waters. As noted under §3.2, DOC and POC released by thawing soils and carried by rivers and groundwater may be sufficiently labile for use by microbial communities in Arctic coastal waters (Raymond et al., 2007; Shen et al., 2012; Vonk et al., 2013), though such terrestrial DOC may not reach the coastal zone (Spencer et al., 2015). A recent modeling exercise suggests that riverine dissolved organic nitrogen may increase Arctic Ocean bacterioplankton production by 26 percent and primary production by 8 percent (Le Fouest et al., 2015). Heterotrophic dinitrogen fixation in the Arctic has recently been reported (Blais et al., 2012; Diez et al., 2012) at rates comparable to other pelagic environments, which represents a source of “new” nitrogen. The importance of such detritus-based food webs versus food webs based on phytoplankton primary production or new sources of nutrients, for example, is unclear, but the rates of conversion could increase in the near future as warming of Arctic soils and coastal waters continues (**Q4.1** and **Q4.2**).

Comparisons between Arctic and low-latitude estuaries breakdown when seasonality is considered. Unlike low-latitude systems, export of organic carbon and inorganic nutrients is discontinuous over a few weeks to months. River discharge increases dramatically in late boreal spring as river ice melts. Shifts in the timing of river discharge in the spring would have large effects on the export of terrigenous material to the Arctic coastal zone. It is known that the largest impact of terrigenous material on ecosystem function occurs predominantly on interior shelves (e.g., Beaufort Sea), as opposed to inflow (e.g., Chukchi Sea) and outflow (e.g., Canadian Archipelago) regions (Carmack and Wassmann, 2006). Thus, such shifts will likely affect the timing of stratification and subsequent phytoplankton blooms and communities present in these waters (Hinzman et al., 2005). In turn, this could affect the growth and reproductive success of secondary producers through its effect on the relative timing of energy availability during early life stages (Cushing, 1969; Durant et al., 2007). The long-term stability of such food webs may in part depend on the ability of upper trophic level consumers to incorporate energy from multiple sources (McMeans et al., 2013). Indeed, isotopic data from amphidromous fish along the Alaskan Beaufort Sea coast suggest that up to half of their total dietary requirements could come from terrestrial sources (Dunton et al., 2006) (**Q4.2** and **Q4.3**).

Atmospheric circulation at sea level is also highly seasonal in the Arctic, dominated by a strong cyclonic (though asymmetric) vortex in winter that is replaced by a circum-Arctic easterly flow in summer. These modes promote differential transport of natural and anthropogenic continental aerosols that are present mostly in winter and spring (“arctic haze”—black carbon, dust, industrial pollution) and mostly absent in summer (marine, sulfate, organic aerosols). While these aerosols have direct and indirect climatic effects through scattering of solar radiation and cloud albedo, respectively, a small increase in summer aerosol loading can substantially enhance cloudiness (Mauritzen et al., 2011), potentially affecting aquatic primary production (Belanger et al., 2013). It is known that haze contaminants and N-containing compounds end up in arctic ecosystems (e.g., AMAP, 1997), but how and when is complex and not fully understood (Dominé and Shepson, 2002). Hence, it is highly likely that changes in the Arctic will also affect the atmospheric input of nitrogen and other biologically relevant compounds to terrestrial and marine ecosystems (**Q4.4**).

Beyond the obvious consequences of changing terrestrial inputs to the physicochemical environment in the coastal domain (e.g., increased light attenuation), terrestrial organic matter itself has the potential to change the base of the Arctic food web in coastal zone habitats by changing the dynamics between heterotrophic and autotrophic production (Le Fouest et al., 2014). For example, terrestrial dissolved organic matter is carbon (C) rich but nitrogen (N) poor with average annual C:N molar ratios of 30 and 45 for the Yukon and Mackenzie rivers, respectively (Holmes et al., 2008, 2012). Since these C:N ratios far exceed the Redfield ratio, additional N is required for bacteria to use the bioavailable C fraction, reducing the amount of nutrients available for phytoplankton growth (Tank et al., 2012b). Similarly, increased nitrate export (e.g., McClelland et al., 2007) and decreased DOC export (e.g., Striegl et al., 2005; Vonk et al., 2015) from Alaskan rivers and thawing permafrost (**Q4.1** and **Q4.2**) could lead to a shift in the balance between autotrophy and heterotrophy in the receiving estuaries and modify biogeochemical fluxes to offshore waters. This could ultimately lead to longer, less efficient energy transfer pathways to higher trophic levels. Changes in heterotrophic respiration, coupled with changes in alkalinity flux, can also be expected to affect aragonite saturation in the coastal Arctic Ocean (e.g., Tank et al., 2012c) with resultant biological and biogeochemical consequences (e.g., Steinacher et al., 2009). Furthermore, Arctic-COLORS can address how the transfer of terrigenous material through the RCD contributes to coastal Arctic food webs, biodiversity, and productivity.

A significant impediment to predicting the ecosystem response to the climate-associated changes occurring in the Arctic coastal zone is a lack of quantitative information on the role of microorganisms and nutrient inputs and cycling in the system. Microorganisms dominate biological biomass, production, and remineralization in marine systems, while large organisms and upper trophic levels primarily respond to, rather than set, the level of productivity. Microorganisms are also the major producers and consumers of CO_2 and other greenhouse gases. Our knowledge about the functioning of the Arctic marine food web is limited, especially for lower trophic levels (i.e., microbial systems; Dyda et al., 2009; Kirchman et al., 2009a; Sherr et al., 2009), though a complete evaluation in late summer over the Mackenzie/Beaufort coastal zone was recently completed (Forest et al., 2014). This scarcity of information, especially across seasons, is particularly problematic given that the accelerating changes underway in the Arctic are expected to affect the three primary parameters that control microbial production—temperature, nutrients, and light (Walsh et al., 2005; Grebmeier et al., 2009; Kirchman et al., 2009b)—all of which are directly impacted by inputs of terrestrial material to the coastal ocean and partially by atmospheric cloud cover (Bélanger et al., 2013).

3.5. Science Question #5

How do changing environmental (short-term) and climate (long-term) conditions alter the Arctic coastal zone's availability and use of ecosystem services?

The complexities of the Arctic coastal zone require an interdisciplinary approach that must include efforts to synthesize all characterized drivers of the system. One emphasis of the fifth Arctic COLORS science question is an evaluation of the relative stability of critical drivers/transformation zones/processes to changing conditions. The relative importance of Arctic coastal zones is tied to their value in terms of ecosystem services and as a source of livelihood for various stakeholders (e.g., subsistence fishing, fishing and ecological tourism, transportation, cultural use).

5.1 What is the most reliable current baseline that can serve to evaluate future changes (positive or negative) to nearshore ecosystem services in the Arctic?

Climate change-related risks to marine ecosystem services in the Arctic include ecosystem and fisheries degradation and damage (e.g., changes in habitat characteristics and dynamics, shifts in species biodiversity, altered productivity, ocean acidification), changes in biological resources (e.g., abundance, distribution and quality of subsistence fisheries including marine mammals, fish, shellfish), species reorganization and displacement (e.g., harmful algal blooms) (e.g., Hinzman et al., 2005; Macdonald et al., 2005; Parmesan 2006; Moore and Huntington 2008), and probably still other impacts yet unexpected. Climate-related changes in ecosystem services will vary greatly spatially and temporally among and throughout the Arctic regions and may result in both losses and opportunities. A recent risk-assessment report, published by Fisheries and Oceans Canada recently, enumerated these potential losses and identified opportunities for the western Arctic (DFO, 2013).

Negative changes may include loss of habitat, change in infectious disease transmission, contaminant pathways, species distribution and range expansion (introduction and/or spread of invasive or colonizing aquatic species displacing Arctic-adapted aquatic species) and an increase in other anthropogenic stressors (DFO, 2013). Permafrost thaw and increased coastal erosion (see §3.2) may affect shellfish fisheries as well as higher trophic levels that depend upon shellfish, e.g. bearded seals and walruses, through habitat alteration. Positive changes may include increased primary (phytoplankton) and secondary (zooplankton) production in spring (Wassmann and Reigstad, 2011), and perhaps locally even in fall (Ardyna et al., 2014), which may favor species at all levels in nearshore food webs, particularly in the short-term, by increasing foraging opportunities for some species. Alterations to riverine-borne constituent fluxes on coastal ecology, considered in detail in **Q2** and **Q4** (§3.2 and 3.4), may result in increased nutrient and allochthonous organic matter inputs into the coastal zone in some areas, stimulating processes at the base of the marine food web (Le

Fouest et al., 2015). These changes, combined with the longer open water duration, may result in extended access to and duration of national open-water fishing seasons as well as (inter)national open-water ecotourism and transportation in some regions. Increased water temperatures and declines in sea ice as a result of climate change may cause an increase in bacterioplankton respiration and growth. Increased bacterial production may result in a larger contribution of carbon and minerals to the estuarine and coastal food webs, both pelagic and benthic. This may be linked to potentially faster, temperature-driven growth and maturation rates and reductions in winter mortality for many Arctic species (e.g., anadromous fishes). Similarly, "microbialization" of the Arctic (§3.4) could lead to less carbon and energy passed on to fish and other higher trophic levels (Kirchman et al., 2009a). Arctic-COLORS will encourage research exploring which scenario is most likely to hold for the Arctic coastal zone in the near future.

Social-environmental systems research is particularly relevant to the objectives of several NASA programs (e.g., the Applied Science program and the Interdisciplinary Science program). Thus, Arctic-COLORS would provide an excellent opportunity to coordinate activities with other federal and state (and regional and private) programs addressing climate change and the human dimension in the Arctic. For example, the International Oak Foundation only supports human dimension research, and it has a focus for Alaska and Northern Territories in the Arctic. Consequently, Arctic-COLORS will provide a comprehensive and public knowledge base for future research on ecosystem services, impacts assessment, emergency management, decision support, and social-environmental systems in the Arctic.

Those who live in, work and engage with the Arctic have the most at stake in a rapidly changing environmental context. In order to access the critical expertise embodied by these groups, Arctic-COLORS researchers will seek support and engagement from key constituents. These may include local communities, Alaska Native and First Nations organizations, natural resource exploration and shipping companies, government agencies, and advocacy groups. Input will be sought early in the research trajectory to inform and refine critical research targets, and later in the process to ensure findings are communicated effectively to constituent partners. Concrete metrics for the success of these efforts will be sought from every research team.

3.6. Synthesis

The Arctic terrestrial/coastal interface is subjected to extreme physical, optical, chemical, hydrological, spatial, and temporal transitions; and the nature of these transitions are being altered under accelerated climate change. The Arctic-COLORS science questions encompass an integrated, interdisciplinary, holistic approach centered on the changing system with objectives of understanding relationships and feedbacks among all gradients and forcings. These science questions require a combination of new field data, state-of-the-art modeling approaches and remote-sensing techniques. NASA participation is key to this work because orbital and sub-orbital sensors allow investigation of gradients at various time and space scales. Remote sensing also allows data collection in regions and seasons inaccessible to conventional shipboard or land-based methods. For example, organic matter is a key constituent of the biogeochemical flux from land to the ocean. Terrestrial dissolved organic matter has a high proportion of colored dissolved organic matter, which can be remotely sensed (Fichot et al., 2013; Matsuoka et al., 2012; Nelson et al., 2010; D'Sa et al., 2015). Remote sensing can be a key tool for assessing inputs and transformations of total particulate matter within nearshore regions (Doxaran et al., 2012, 2015; Hudson et al., 2014), as well as capturing physical ocean features, coastal zone and sea ice dynamics. While detection may not be as sensitive as in tropical regions, the research community will likely find great value in remote salinity retrievals from L-band radiometers, whether sub-orbital or orbital like ESA-SMOS, NASA-SMAP or the no longer available NASA-CONAE Aquarius (Shutler et al, 2015) (see § 8.4 for acronyms). Clearly, most components of the Arctic-COLORS proposed science will not be possible without NASA assets, and therefore this project is not possible without NASA leadership.

The scientific community currently does not have the tools to anticipate the outcome of the changes discussed above. Regional ice-ocean models, for example, generally fail to reproduce landfast ice (e.g., Proshutinsky et al., 2007), so current models do not capture critical elements of shelf dynamics—particularly those having important implications for biogeochemical transformations and processes that control exchanges of river-influenced shelf waters with basin waters. Observation of thermohaline structure, nutrient fluxes, and terrigenous water mixing in the coastal ecosystem are limited enough to prohibit even a thorough understanding of current conditions, much less the mechanistic understanding needed to predict change. Through this proposed integration of new, coupled physical-biogeochemical models with comprehensive ship, ground-based and remote-sensing observations from different platforms and across a range of spatial and temporal (diurnal, seasonal, multi-year) scales, Arctic COLORS will provide a comprehensive opportunity to address these gaps in existing knowledge (see §4.6).

4.0| Science Plan

4.1. Arctic-COLORS Science Traceability Matrix

The Science Traceability Matrix (STM) developed for Arctic-COLORS shown on the following page summarizes the science questions, the approach to address these questions, and the required *in situ* measurements, remote-sensing observations, models, research platforms, and integration activities.

Science Questions	Science Plan & Approach	Methods (observations and modeling)	Requirements
The overall objective of the Arctic-COLORS field campaign is to determine present and future impacts of terrigenous, atmospheric and oceanic fluxes on ecology, biogeochemistry and ecosystem services of the Arctic coastal zone in the context of environmental (short-term) and climate (long-term) changes in the Arctic. ***1-How and where are materials from the land, atmosphere and ocean transformed within the Arctic coastal zone?*** ***2- How does thawing of Arctic permafrost—either directly through coastal erosion or indirectly through changing freshwater loads from upstream thaw—translate to changes in coastal ecology and biogeochemistry?*** ***3-How do changes in snow/ice conditions and coastal circulation influence Arctic coastal ecology and biogeochemistry?*** ***4-How do changes in fluxes of materials, heat, and buoyancy from the land, atmosphere, and ocean influence Arctic coastal ecology and biogeochemistry?*** ***5-How do changing environmental (short-term) and climate (long-term) conditions alter the Arctic coastal zone's availability and use of ecosystem services?***	**Approach** Determine the role of Arctic coastal wetlands, lagoons, estuaries and deltas as transformers of terrigenous, atmospheric and marine material transported to the coastal ocean Quantify the rates and magnitudes of biotic and abiotic processes that affect biogeochemical transformations in the coastal zone Assess the impact of permafrost thawing, coastal snow, and ice cover on coastal fluxes and transformations Assess the significance of coastal erosion fluxes relative to riverine fluxes Quantify the impact of changing freshwater fluxes, precipitation, wind intensity, tidal motions, stratification, up/downwelling, heat budgets and other atmospheric and oceanic physical forcings on coastal ecology and biogeochemistry Determine the impact of seasonal and inter-annual variations in the timing and magnitude of discharge and atmospheric deposition on the composition and functionality of coastal ecosystems **Study Domain** Coastline from the Yukon River Delta (Alaska) to the Mackenzie River Delta (Canada), from the head of tidal influence to the coastal shelf **Measurement Approach** Combination of intensive high-resolution sampling and experiments to improve understanding of processes and development of new models and remote-sensing algorithms, with synoptic surveys of the core domain that will enable scaling up and extending results to a wider system, inclusive of a broad range of coastal Arctic environmental characteristics **Timeline** The proposed timeline (2019-2028) overlaps with NASA's new ocean color mission PACE, enhancing remote sensing capabilities in the Arctic. It also coincides with ABoVE, thus linking processes in the Arctic coastal oceans and terrestrial ecosystems	**Field observations and experiments** • Above and in water (and under ice) radiometry, IOP, AOP • Hydrological parameters (e.g., flow rates, water depth) • Fluxes and concentrations of biogeochemical variables (e.g., POC, Chl-a, DOC, DON, DIC, CDOM, SPM) • Chemical characterization (e.g., biomarkers, lignin, black carbon, $\delta^{13}C$, C:N, amino acids, ^{14}C, other isotopic tracers) • Optical characterization (absorption, fluorescence analyses) • Physicochemical properties (e.g., salinity, temperature, alkalinity, pH, DO, pCO_2) • Inorganic nutrients • Net primary productivity (NPP) and net community production (NCP) • Phytoplankton pigment composition • Phytoplankton taxonomic abundances • Pore-water/ ground water measurements • Possible tracer release experiments (e.g., rhodamine, SF6, 3He) • Community Respiration (CR) • Bacterial production (BP) • Micro-, meso- and macro-zooplankton abundances, taxonomy, and grazing rates • Quantum photochemical efficiencies • Microbial incubations • Possible tracer release experiments (e.g., rhodamine, SF6, 3He) • Atmospheric composition (aerosol optical depths, trace gas amounts), sun photometry **Remote Sensing** • Moderate-high resolution UV-VIS-NIR remote sensing measurement of ice cover, water inherent and apparent optical properties, and derived biogeochemical and geophysical products • Active remote sensing for atmospheric and ocean profiling • Remote sensing based monitoring and modeling of permafrost cover in river basins; remote sensing of vegetation cover; remote sensing based determination of fire frequency in river basins (in collaboration with ABoVE) • Remote sensing determination of coastal ice and snow cover (historic and through field campaign) • Remote sensing and field measurements of wind and current vectors • Remote sensing of atmospheric composition **Modeling** • Coupled hydrodynamic-photochemical-biogeochemical models • Link coupled biogeochemical models to foodweb/ecosystem-based models • Link modeling of permafrost dynamics and watersheds to coupled coastal biogeochemical models • Climate modeling	**Field platforms** • 35-80m length coastal research vessels with standard hydrographic equipment for coastal work (includes R/V Sikuliaq for light ice-breaking capability) • 6-15 m landing crafts for near-shore and in-river work. • 15-35 m length small research vessels for in-shore and river work. • Medium-to-large (75-130m length) icebreaker research vessels primarily for deeper shelf waters and during thick ice conditions. • Native hunter boats • Buoys, moorings, and gliders • Land towers for optical and atmospheric instrumentation. • Small planes/UAV, helicopters • Over-the-snow/all-terrain vehicles **Integration and Scaling** • Integration of existing field and remote sensing datasets and modeling products into the project (Phase I) • Integration across all disciplines, observational approaches and modeling efforts (Phase III) • Integration with current and future campaigns in the Arctic • Use modeling and remote sensing to scale up fluxes and processes in both temporal and spatial domains **Transdisciplinary efforts and partnerships** • Collaboration with other federal and state agencies and regional and private programs • Engagement of local communities • Coordination with ABoVE • Partnerships with ongoing U.S. and international efforts in the Arctic (e.g., Polar Knowledge Canada, ArcticNET, and Sentinelle Nord). • Coordination with other programs addressing climate change and the human dimension in the Arctic.

4.2. Study Domain: Core and Extended Regions

The geographical extent of the study domain will cover a core area from the Yukon Delta to the Mackenzie Delta, which includes the head of tidal influence (~2 salinity) on to the coastal shelf (Figure 4.1). The extent is driven by the main objective of Arctic-COLORS: to closely examine material and energy exchanges, interactions, and transformations at the land-ocean interface and impacts on coastal zone processes. Although not intended as an oceanographic program reaching into the deep basin, the influence of freshwater on ocean circulation; storage of freshwater in the Beaufort Gyre; and the varying influence of melted sea ice, local precipitation and runoff on water column stratification; alkalinity; biological productivity; biogeochemical processes; and ecosystem function should be recognized and linked to related, on-going work and new Arctic marine studies by MARES NOPP PARTNERSHIP (see §5.4 below). An extended domain that includes Victoria and Banks Islands in the Canadian Archipelago will be established through collaboration and coordination with monitoring and research programs of POLAR (Figure 4.1 lower panel; §8.5). An extended inland domain for land/river and permafrost transitions will be achieved through collaboration with ABoVE, as indicated earlier.

The geographical scope for our core and extended study areas will facilitate focused process studies of large, globally-significant rivers (Yukon and Mackenzie), regionally influential watersheds (e.g., Kobuk, Noatak, Colville), as well as smaller tundra rivers (e.g., Sagavanirktok, Kuparuk) where prior intense hydrological work provides insights on flow regimes, chemistry, and other hydrological features. This geographical scope will also facilitate studies of coastal lagoons, erosional bluffs that contribute organic materials and sediments to the adjacent shallow continental shelf, and barrier islands, which are common coastal geomorphic features along the entire study domain and border the Arctic coastal zone. The extent of the Arctic-COLORS domain will permit confirmation of the riverine coastal domain hypothesis.

Comprehensive, multi-disciplinary, high-spatial resolution, seasonal measurements will be performed in selected *"intensive study"* regions within the core study domain, as needed for developing new and enhanced coupled hydrodynamic-photo-biogeochemical models and designing appropriate remote-sensing, bio-optical algorithm retrievals for the Arctic coastal zone. In addition to these intensive studies, *synoptic surveys* of the core domain (see §4.3 and §4.4) will enable scaling-up and extending results to a wider system, inclusive of a broad range of coastal Arctic environmental characteristics.

A number of coastal villages are located within the study area, where subsistence hunting and food gathering are everyday activities (Figure 4.2). These include major communities with seats of governmental authority and transportation hubs such as Nome, Kotzebue, Barrow, and Inuvik, as well as small villages, including Alakunuk, Emmonak, Stebbins, Unalakleet, Brevig Mission, Wales, Teller, Shishmaref, Deering, Buckland, Kivalina, Point Hope, Point Lay, Wainwright, Nuiqsut, Kaktovik, Tuktoyaktuk, and Kugluktuk. Concerns of local residents include increasing coastal ship traffic, industrial development of oil and gas reserves, and the impacts of seasonal sea ice retreat, permafrost thaw and other aspects of climate change on subsistence hunting and gathering, and transportation.

Figure 4.1. Map of the Arctic-COLORS domain notated with pink shading along the coast in both panels. The domain includes the globally significant rivers Yukon and Mackenzie, as well as regionally influential watersheds (e.g., Kobuk, Noatak, Colville rivers) across the continuum of coastline in between.

Figure 4.2. This map of the study region shows the locations of large population centers and villages along the coast of the Arctic-COLORS study domain. The watersheds shown in Figure 4.1 are also outlined here in black.

4.3 Research Phases and Field Campaign Timeline

The notional start date for the Arctic-COLORS activities is mid- to late 2018. A ~10-year program, 2018-2028, is envisioned to address the science questions and objectives described in section §3 (Table 4.1). The proposed timeline for Arctic-COLORS fieldwork will overlap with the first two years of NASA's Climate Initiative ocean color mission PACE (expected to launch in March 2022), enabling application of the proposed field observations to PACE validation efforts, and enhancing remote-sensing capabilities in one of the most responsive regions to climate change (see §4.5). The proposed timeline will also result in significant overlap with NASA's ABoVE field program, providing a unique opportunity to link processes in Arctic coastal zone and terrestrial ecosystems, and leveraging on-going NASA funded field activities in order to get maximum return on NASA's investment in the Arctic region.

A **one-year Phase I activity** would precede the formal Arctic-COLORS field and modeling projects during which the program office or designated team will develop repositories of relevant field data sets, satellite products, airborne data sets, and model products.

Phase II will consist of two sets of 4-year funded projects (2019–2023 and 2021–2025) that accomplish fieldwork, satellite data analysis and modeling. The projects focused on field-based process studies and measurements would each conduct two years of field sampling activities (2019–2021 and 2021–2023), which provides for four years of dedicated field measurement activities for the duration of the program. Field sites and required measurements for the intensive process studies and field surveys are discussed further in section §4.4.

Phase III, a **2-year synthesis** will follow after the conclusion of the 4-year projects between 2026 and 2028.

Table 4.1. Notional Plan for the Arctic-COLORS Program.

Phase of Arctic-COLORS Program	Duration	Scheduled
Phase I: Pre-Arctic-COLORS	1 year	2017-2018
Phase II and III Duration	8 years	2019-2028
Phase II: Field and Modeling projects	Two 4 year intervals	2019-2023 & 2021-2025
Phase II: Fieldwork period	4 years	2019-2023
Phase III: Synthesis	2 years	2026-2028

4.4. Field Measurements Program

Satellites have been employed to study sea ice extent over the Arctic since 1979 but recently remote sensing has also been successfully utilized to study dynamic heights and freshwater content in the Arctic (e.g., Morison et al., 2012). As seasonal sea ice continues to decline, more extensive areas of open water are emerging for longer periods of time and allowing for even more diverse remote-sensing opportunities, including the study of biological and chemical parameters. Early studies (Doxaran et al., 2015; Fichot et al., 2013) have already begun to show the capability of remote sensing for tracking river plumes in the coastal Beaufort Sea as well as identifying fall phytoplankton blooms stimulated by storm activity on the Siberian shelf (Ardyna et al., 2014). However, certain limitations persist including the restriction of observations to the sea surface, polar night, typical heavy cloud cover, wide footprints prohibiting high spatial resolution, and the necessity for extensive calibrations and development of improved and regionally tuned bio-optical algorithms using field observations.

By combining extensive surveys over wide areas, more highly focused process studies (from the mouths of several large and small rivers to the outer shelf and also land-to-sea transects for four types of coastal erosion sites), and model simulations, the limitations of remote observations can be minimized or placed into an appropriate context. For example, Arrigo et al. (2012) reported that a highly productive phytoplankton bloom occurred underneath thin, first-year sea ice on the Chukchi Sea shelf at levels similar to what has previously been observed for open water or ice edge blooms; at the time, however, production in the open waters was much lower, likely due to nutrient limitation and/or intense stratification (Tremblay et al., 2015). The authors suggested that melt ponds occurring on the sea ice allowed for a greater penetration of light through the ice that was sufficient to stimulate a phytoplankton bloom (Lee et al., 2011). The results of this work and others (e.g., Matrai and Apollonio, 2013, Bergeron and Tremblay, 2014) illustrate two important points: 1) estimates of primary production in the Arctic Ocean based on satellite observations during the open water period represent significant underestimates, and 2) there are potential observations that can be completed using existing tools (e.g., areal extent of melt ponds, chlorophyll concentrations in the open water during the presumed post-bloom period) that may be used to improve primary production estimates. Extensive improvements can also be made to the bio-optical quantification of dissolved and particulate material transitioning and transforming through the Arctic coastal domain, as shown by the recent ICESCAPE and MALINA Arctic campaigns (i.e., special issues in *Deep-Sea Research* and *Biogeosciences*, respectively).

Using a multi-disciplinary approach and leveraging on-going, NASA-funded field activities in Arctic-boreal terrestrial and freshwater ecosystems, **Arctic-COLORS will create a uniquely comprehensive database of physical, optical, biological and biogeochemical variables across a range of spatial** (from the Yukon to the Mackenzie Rivers) **and temporal** (e.g., diurnal, seasonal, multi-year) **scales in the North American Arctic coastal zone**. This unique set of field measurements and observational approaches will facilitate:

- Improved ranking of complex processes across the Arctic land-ocean interface.
- Evaluation and refinement of remote-sensing retrieval capabilities in these challenging high-latitude waters.
- Model parameterizations of key biological, biogeochemical and biodiversity-relevant processes.
- Benchmark data sets against which model simulations can be evaluated.
- Improved predictability of the effects of continuing Arctic change on the terrestrial fluxes of dissolved and particulate materials to the coastal zone, their biogeochemical processing within rivers/estuaries/deltas and coastline in between, and their potential ecological impact.

4.4.1 Process Studies

Arctic-COLORS plans an interdisciplinary scientific program that includes collection of water, ice, and sediment samples from across the full estuarine salinity gradient. Measurements will be conducted in multiple seasons (late winter/early spring, late spring, early summer, and late summer/early autumn), including the spring freshet, during which the highest fluxes of the most labile materials occur, and the fall freeze up, a highly local source of dissolved organic and inorganic materials to the water column. The field data sets will be incorporated into physical and biogeochemical models to improve parameterizations of nearshore physical, geomorphological, chemical, and biological processes (productivity, grazing rates, etc.). These data will also be used to improve algorithms associated with satellite products, such as ocean color, dissolved and particulate matter, sea ice, microalgal functional groups and others, so that remote-sensing techniques may be more effective in a changing Arctic environment.

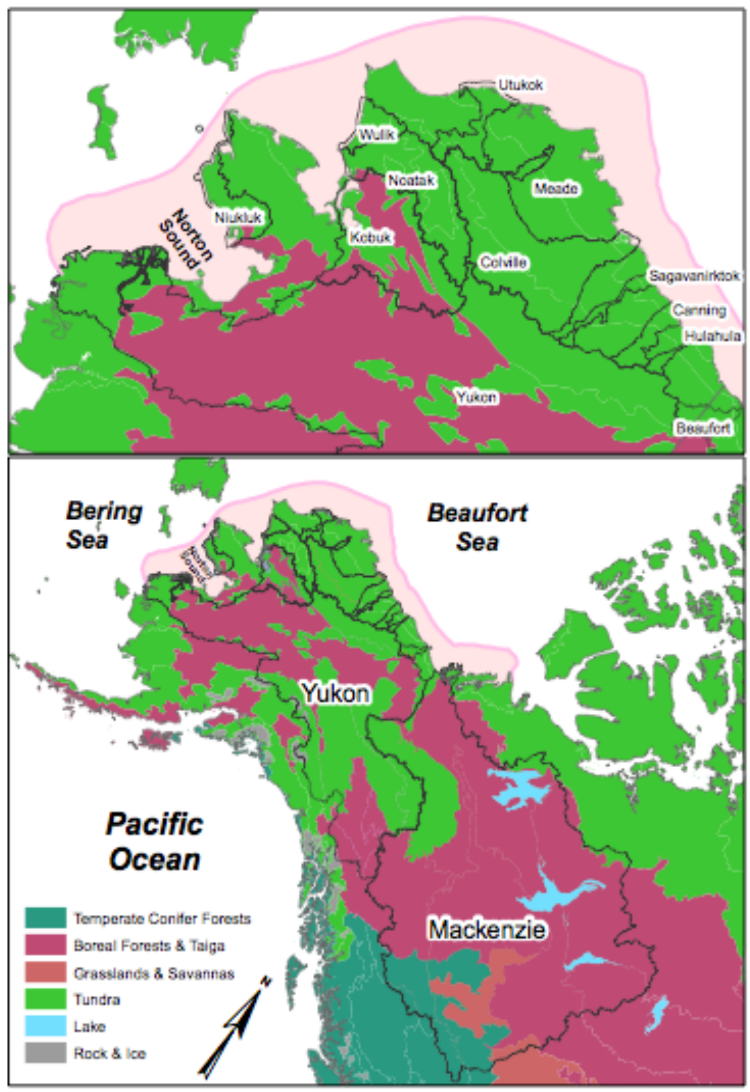


Figure 4.3. Map showing predominant vegetation and surface terrain for watersheds draining into the Bering, Chukchi and Beaufort Seas.

Fieldwork will be conducted within six or more estuaries adjoining different North American rivers and four erosion sites (Figure 4.1; Table 4.2). Examples of river mouth-to-shelf study areas that could be sampled as part of Arctic-COLORS include (but are not limited to) the Yukon, Mackenzie, Colville, Canning, Utukok, Kobuk, Noatak, Niukluk, Hulahula, Meade, or Wulik Rivers (Figure 4.1); the Kuparuk and Sagavanirktok (Sag) deltas are now part of an active oil field such that offshore sampling will require a collaboration with the private sector. These river systems will provide contrasts in terms of temporal freshwater discharge dynamics, particle dynamics, landscape type (boreal forest versus tundra soil types) (Figure 4.3), and resulting changes in coastal sea ice coverage. For example, the Colville River drains mountainous terrain in the Brooks Range whereas the Kuparuk River primarily drains low-lying tundra (Rember and Trefry, 2004). These differences in soil and rock compositions contribute to differences in loads of suspended sediment, nutrients, and dissolved organic and inorganic carbon. In addition, these rivers enter the coastline in areas with varying geomorphological features; for example, the Kuparuk and Wulik Rivers discharge into relatively shallow lagoons separated from the southern Beaufort Sea by chains of barrier islands whereas the Hulahula and Canning Rivers discharge into relatively open ocean waters. These different settings impact the residence time of river water in the estuaries and shelf exchange with the Beaufort Sea.

Table 4.2. Notional Sampling Regions for Arctic-COLORS Program.

Phase II Field Measurement Activities	**2019–2023**
Intensive studies river mouth-to-shelf	**Notional study sites**
Beaufort coastal region	Mackenzie, Hulahula, Canning, Sagavanirktok, Kuparuk, Colville, Meade Rivers
Chukchi coastal region	Utukok, Wulik, Noatak, and Kobuk Rivers
Norton Sound coastal region	Niukluk and Yukon Rivers
Seasonality of intensive studies	1 full season per field site plus a 2nd full season at select field sites: (1) March, (2) late May/mid June, (3) July and (4) September
Coastal erosion intensive sites	Four sites to be selected among exposed bluffs to the east of Barrow, AK and lagoon sites within the Chukchi and Beaufort coasts.
Seasonality of coastal erosion studies	Two full seasons per site: (1) July and (2) September/October
Synoptic Survey studies	Transit cruises extending across from Norton Sound to Chukchi Sea and Beaufort Sea shelf region.
Seasonality of survey studies	Two seasons per year during all four years of the field program: (1) July and (2) September/October

North American rivers such as the Mackenzie and Yukon drain much larger areas extending far southward and include a larger variation of rock and soil types within their watersheds compared to truly Arctic rivers with smaller drainage basins entirely within the Arctic Circle (Figure 4.1). As such, the smaller rivers tend to freeze entirely during winter months, and their drainage basins may be less diverse in terms of their mineralogical and vegetative content. These differences result in different weathering regimes that can contribute to geochemical diversity in the solute fluxes transported by the rivers to the coastal ocean. Individually, these rivers have a much smaller average annual discharge compared to the Yukon and Mackenzie Rivers; however, they are numerous. Their integrated contribution of both freshwater and a varying range of inorganic and organic materials may not only impact their local estuaries, and they may also affect the geochemical signature of North American Arctic river waters exported offshore to the Arctic Ocean and play a significant role in the net uptake or release of CO_2 to the atmosphere.

The measurements appropriate for these studies will focus on the chemical and biological processes modifying terrestrial materials delivered to the Arctic coastal zone (Fig. 4.4). Studies will focus on planktonic biodiversity, gross and net primary production, net community production, bacterial respiration, zooplankton grazing rates, photochemical degradation, organic matter inputs and transformations, nitrogen cycling, sedimentation, foodweb transfers up to fish and benthic fauna, and associated processes across the salinity gradient. In addition, common variables such as temperature, salinity, nutrients, DIC, TA, pCO$_2$, DOC, POC, PN, DON, chl-*a*, phytoplankton pigments, chlorophyll fluorescence, particle absorption, CDOM absorption and fluorescence, and scattering properties will be routinely measured to define the biogeochemical state of the system during the detailed process studies.

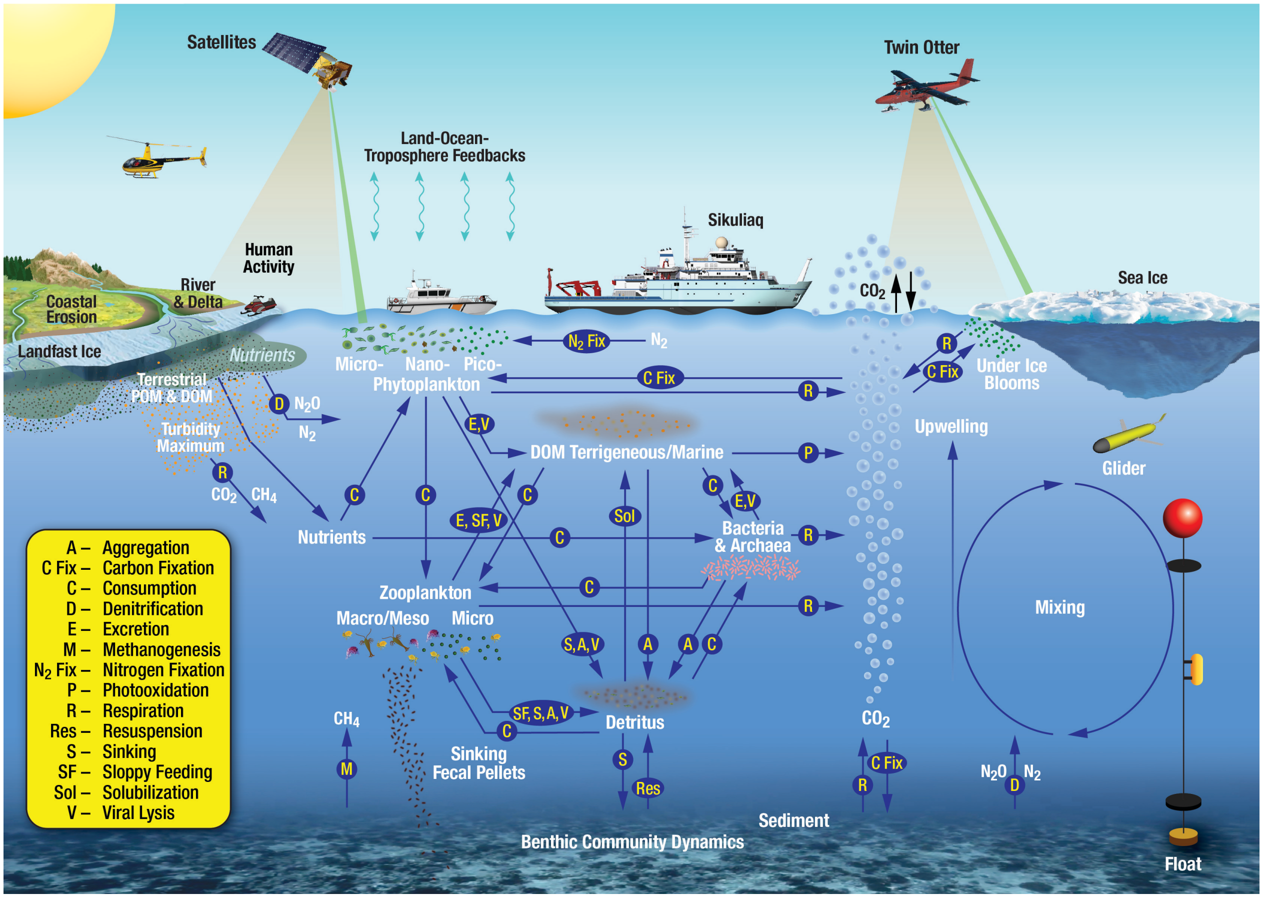


Figure 4.4. Schematic of the processes (including those labeled but with no arrows such as coastal erosion, landfast ice, and river and delta exchange with the sea) and constituents that will be measured and modeled for Arctic-COLORS at the interface of river estuaries and deltas with the coastal ocean and the necessary measurement (or transportation) platforms. A single satellite is shown to represent past and current remote-sensing observations from multiple satellites.

A particular emphasis will be given to sensor-based optical measurements such that potential improvements to calibrations and algorithms linking remote sensing data to state variables, biological functional groups, and biogeochemical processes may be improved. Sampling will take place in the coastal zone, focusing on shallow water depths (0–20 m, Figure 4.5), such that the full estuarine salinity gradient ($2 \leq S \leq 30$) and/or the effects of erosion will be observed and thereby capture the influence of biogeochemical transformations/modifications of terrestrial materials transitioning into the coastal ocean where they are further transformed. As the seasonal variability in Arctic river discharge and other inputs is very high and the seasonal formation and melting of sea ice greatly influences primary production and microbial succession via light limitation, timing of delivery of riverine/marine nutrients and organic substrates, and stability of the water column, it is necessary to collect samples throughout the annual cycle.

Fieldwork in four coastal erosion sites will include barrier island-lagoon systems, such as along the North Slope of Alaska, and bluff-type systems, such as east of Barrow, Alaska, with process studies conducted in July and September/October. Studies will include two full seasons per field site; the second full season will quantify a larger inter-annual variability within sites than between sites.

Winter/Early Spring Sampling will be conducted early in March (shortly after daylight returns to the Arctic but prior to substantial snow and ice melt and the spring freshet) in order to capture the end of winter condition in the target estuaries. Over-the-snow/all-terrain vehicles will be used to access the landfast ice. Access to the water column will be gained by drilling holes through the sea ice, which could be challenging due to its potential thickness. Canvas tents or other temporary structures can be erected and heated to keep instruments and samples from freezing after extraction. Through-ice moorings or buoys with a surface expression may be deployed to allow continuous monitoring; total or partial recovery can be done with helicopters. These winter-to-spring varying chemical and physical conditions control a changing microbial community, as recent observations in open and ice-covered waters indicate that winter and the polar night are not "biologically dead" periods (e.g., Leu et al., 2011; Falk-Petersen et al., 2015).

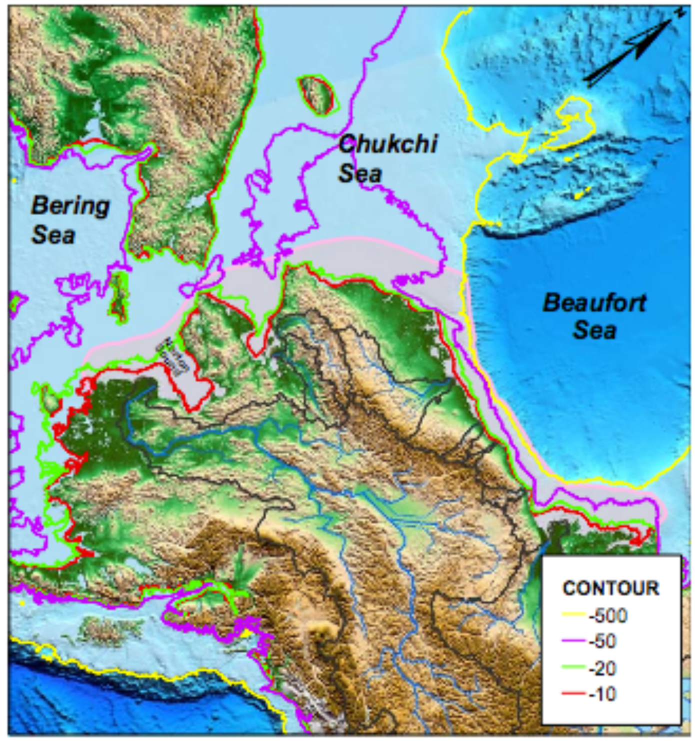


Figure 4.5. Map of the Arctic-COLORS study domain with bathymetry contours.

Late Spring Sampling will be conducted in late May/early June to coincide with the advent of ice algae, mixotrophic microalgae, or under-ice phytoplankton blooms that utilize nutrient and/or organic substrate concentrations reminiscent of the previous winter (remineralization and/or base winter flow supplies) as well as at the onset of the peak river discharge (during which >50% of the annual discharge of freshwater, suspended particulate matter, and DOC occurs over a period of weeks). Samples of river water will be collected during this period to characterize the geochemistry of the rivers during peak discharge.

It is both difficult and dangerous to sample the river and immediate nearshore regions just prior to ice break up (unstable ice) and during the spring floods. As such, the lower portion of the salinity gradient ($0 < S < 5$), where the majority of flocculation and adsorption/desorption processes take place, may be inaccessible as river water typically invades the estuaries both above and below the ice, preventing sampling via over-the-snow/all-terrain vehicles. Autonomous systems may be deployed in the ice earlier in March or from open water up to the solid sea or landfast ice, but broken ice, especially in shallow areas, is unforgiving to instrumentation. The rivers can be sampled from a safe distance via casting long poles and/or lines from shore or bridges (as available) that are attached to flow-through bottles (e.g., Niskin or other specially designed equipment). AUVs, airborne measurements, and stand-alone sensors can be deployed during this period. Over-the-snow/all-terrain vehicles will be used to access the landfast ice as conditions allow. Sleds that have flotation capability will be dragged behind the over-the-snow/all-terrain vehicles; these sleds will be primarily used for transporting equipment (ice augers, sample bottles, etc.). Helicopters offer highly desirable access to these regions that is at times almost impossible by any other way, but their flight costs and fuel needs may make them less accessible. It is most important to sample the rivers during this particular period as budgets can be constructed (and models applied) from a combination of the data collected during the late winter/early spring period (preconditioning of the estuary), influx of dissolved and particulate materials during the spring freshet (i.e., the river sampling), and sampling conducted within the estuary as allowed during the spring freshet and immediately (few days to a few weeks) afterward.

Early Summer Sampling in May to July (depending on the river system) will assess the rising biological activity as the snow and sea ice continues to thin, pond, break up, and melt out. As the sea ice cover disintegrates, the increased buoyancy flux stabilizes the water column and light limitation is alleviated, both of which initially stimulate phytoplankton blooms (Sakshaug, 2004). In addition, the decreased ice cover exposes dissolved organic matter to photochemical reactions that could release dissolved inorganic carbon and nutrients, further supporting primary production and net community production. The reduction and mobilization of the sea ice also allow for greater interaction between winds and the water column, potentially affecting local circulation/surface currents, the spread of the river plume, vertical mixing, upwelling, and air-sea exchange. River discharge also decreases during this period; inorganic nutrient concentrations tend to increase whereas dissolved organic substrates generally decrease, except when biological uptake is the dominant process in the large rivers (Holmes et al., 2012; McClelland et al., 2014). Thus, the supply of nutrients and organic matter changes remarkably between the spring and early summer periods and the nature and rapidity of these changes affect both biological production and microbial community composition. Field operations will be conducted via small boats deployed from shore (cautious of any remaining, wind-induced ice shifting) and overlap with wide-area surveys (described in the next section). Inflatable boats can also be deployed from ocean-based vessels to conduct clean sampling of the top five meters without disruption and mixing associated with the passage of a motorized vessel at higher speeds.

Late Summer/Early Fall Sampling will be conducted in September, the period of maximum open water and minimum sea ice extent and the widest spatial distribution of river runoff. Sampling will be conducted by small boats deployed from shore, nearly identical to the early summer survey and also in conjunction with wide area surveys conducted in late summer. The physical and biogeochemical state of the estuaries and coastal ocean during the late summer/ autumn period also preconditions the system for the onset of winter (Carmack et al., 2004). Preconditioning of the estuary and shelf regions helps determine to what extent densification through brine expulsion and vertical convection will occur during sea ice formation. Shelves receiving large quantities of river runoff during the spring and summer months are more likely to have a higher degree of stratification (depending on local circulation and wind forcing) and therefore are less likely to form dense water plumes. These plumes can increase the residence time of waters on the shelf bottom, lengthening interactions with shelf sediments and potentially accumulating nutrients and dissolved inorganic carbon. Plume formation may also carry higher nutrient concentrations, and perhaps dissolved organic substrates. from the upper water column downward, further limiting their availability for use by microalgae the following spring, unless reduced by biological uptake (Holmes et al., 2012).

The minimum areal extent of sea ice also maximizes the exposure of dissolved organic materials to photodegradation. Any materials not already degraded or modified by heterotrophic/bacterial activity may still be susceptible to photochemical reactions. Thus, sampling during this period may capture chemical transformations of materials previously inaccessible to biological processing. Such processes have the potential to stimulate secondary phytoplankton blooms and increase bacterial production. The potential impact of this process for initiating such blooms is not well-known, particularly the relevance of this mechanism compared to nutrient supply via vertical mixing, induced by autumn storms or upwelling events.

4.4.2 Synoptic Surveys

In addition to intensive process studies, a series of field survey studies will be carried out to help connect the shallower estuarine and river work conducted as part of the process studies with the deeper regions of the shelf and shelf break. For example, as an interior shelf, the Alaskan Beaufort Sea is associated with lower primary production compared to other shelf regions around the Arctic, such as the Chukchi and Barents Seas (Carmack et al., 2006). As such, biological production in this region is concentrated primarily along the ice edge and seasonal ice zone and is highly dependent upon nutrient inputs from rivers and vertical mixing of deeper nutrient reservoirs near the halocline. The interaction between the estuaries and inner shelves and the outer shelves/slope regions may therefore determine the balance between autotrophy and heterotrophy as well as the microbial community composition and succession in the southern Beaufort Sea. As the sea ice continues to decline and open water periods lengthen, winds are likely to play a larger role in the biogeochemistry of the estuary-shelf continuum due to their effect on the spread of the river plume, vertical mixing and upwelling of nutrients, and local circulation. Inter-annual variability associated with the transport of terrestrially derived materials and by-products of estuarine biological and chemical processing should increase, as will the support of community production on the outer shelf and slope. It is this exchange between the river/estuary/delta and the outer shelf that may be monitored on a large scale using remote sensing. Therefore, broad surveys will be conducted between the Yukon/Norton Sound and Mackenzie River mouths in addition to smaller scale process studies. These studies would:

- Gain an overall sense of similarities and differences in physical (e.g., temperature and salinity), biological (e.g., primary and secondary production, microbial biodiversity), and biogeochemical state of different shelf regions along the North American Arctic coast.
- Determine which areas of the coast can be treated as point sources versus distributed sources of freshwater and associated constituents.
- Determine the interaction/teleconnection between the coastal ocean and the shallower shelf regions occupied during the process studies, and consequently.
- Permit evaluation of the contiguous riverine coastal domain hypothesis (Carmack et al., 2015) (see §3.1).
- Assess the potential for satellite monitoring using optical sensors and collect necessary data for calibration and algorithm improvement.
- Address the spatial scaling issues for models and application of satellite products.

Surveys will be comprised of a series of transects (zig/zags) generally aligned such that they cross the shelf break (e.g., Beaufort Sea) or a pre-defined salinity (e.g., 30 psu). An ice-capable vessel will be used to traverse the study area both in early (July/August) and late (September) summer. Short-term deployments of a series of moorings as well as year-round moorings in some landfast ice will help to place data collected during both the small-scale process studies and large-scale surveys into context with respect to temporal variability. A standard CTD/Niskin rosette will be utilized to collect samples from the ship. The rosette will also be equipped with properly calibrated instrumentation (e.g., CTD, O_2 sensors, chlorophyll and CDOM fluorometers, beam-c, NO_3 sensors) to collect more highly resolved vertical profiles of biogeochemically-relevant variables, and concurrent profiles of inherent and apparent optical properties. Deployment of small boats (from shore or larger vessel) may be necessary to capture the physical, biological, and biogeochemical variability in areas too shallow to access safely by the larger vessel. Seagliders equipped with additional sensors will be deployed to gather supplemental information regarding the spatial variability over the study region, ice allowing. Buoys may be deployed at the northernmost stations within the perennial pack (as collaborative opportunities arise). Underway sampling of surface water parameters (e.g., salinity, temperature, O_2, pCO_2, NO_3, CDOM and particle absorbance, backscatter, VSF, CDOM and chlorophyll fluorescence, among others) will also help to characterize the larger spatial variability between fixed/discrete sampling stations. Alternatively, these studies could potentially be conducted on piggy-back research vessels transiting from the Bering Strait to the Mackenzie plume region with only modest ship-time costs to NASA. For example, the Canadian Coast Guard Service Sir Wilfrid Laurier, which transits each year from her homeport in Victoria, B.C., to the Canadian Arctic, has taken small teams of scientists aboard for sampling.

The surveys will comprise a number of “normal” sampling stations where the state variable measurements will be collected at nominal depths. In addition, a small number of stations will involve more intensive sampling of the biology (e.g., plankton and zooplankton net tows, incubations) and sediments (surface and cores). As these stations are more time-consuming, there will be a lower frequency of them spread throughout the study area. Although attempts will be made such that spring and summer surveys will be timed to coincide with process studies conducted during the associated season, the ship-based surveys will not be used to supply logistical support to the shore-based process studies. This will require more logistical resources but will save time and ensure both maximum spatial coverage by the surveys and detailed observations collected during the larger process studies.

4.5 Remote Sensing in the Arctic: Challenges and Capabilities

Scientific research in a fast-changing Arctic coastal ocean requires a well-balanced combination of remote-sensing, field, laboratory, and modeling efforts. Integration of multi-disciplinary remote-sensing observations from various platforms is a key component of Arctic-COLORS and, thus, one of the reasons why NASA can achieve the proposed field activities and science objectives. The number of international satellite and airborne sensors as well as the quality of remote-sensing products in existence today and planned over the proposed timeframe of Arctic-COLORS will provide a unique opportunity to monitor change in the Arctic coastal zone in a synoptic manner, as can only be done from orbital and sub-orbital remote-sensing platforms. Furthermore, the polar-orbiting satellites provide high-frequency daily observations due to their wide swaths. Thus, an advantage of satellite remote sensing in the Arctic is the potentially greater coverage in both time and space, notwithstanding continuous cloud cover. A diverse array of airborne sensors will be employed to remedy the challenges posed in applying satellite remote sensing due to pervasive cloud cover in the Arctic and insufficient spatial resolution.

Arctic-COLORS will require use of remote-sensing observations of ocean biology and biogeochemistry (e.g., pigments, organic carbon, primary productivity, suspended particulate matter) from ocean color sensors at various scales from river to ocean, observations of ocean physicochemical properties (e.g., sea surface temperature, sea surface height, salinity, ocean currents), cryology (e.g., snow cover and depth, sea ice extent and thickness, melt pond coverage), atmospheric processes and composition (e.g., aerosols, traces gases including ozone and NO_2, CO_2 and CH_4), meteorological measurements (e.g., atmospheric temperature, wind speed and direction), hydrology (e.g., precipitation, terrestrial water height, river discharge, erosion rates), and terrestrial observations (e.g., wetland area extent, NDVI, soil moisture, freeze/thaw condition, snow cover and land ice) (Table 4.3). These remote-sensing datasets will be used to 1) quantify processes and assess exchanges and interactions at the land-ocean and atmosphere-ocean interfaces across a range of spatial and temporal scales, 2) inform parameterizations in coupled, land-ocean-atmosphere-hydrodynamic-biogeochemical models and evaluate model simulations, and 3) improve and evaluate atmospheric correction approaches for ocean color retrievals in the coastal Arctic environment.

Ocean color remote-sensing provides a unique tool for monitoring changes in coastal ocean ecosystems at relatively low cost and across spatial and temporal scales, and as such, is central in Arctic-COLORS. Still, the use of space-based ocean color and other observations at high-latitude regions is hindered by a number of difficulties and intrinsic limitations. **Through a combination of observational and modeling approaches and by integrating passive (hyperspectral) and active (lidar) remote-sensing observations from various platforms, Arctic-COLORS will push the envelope of ocean color research and applications in high latitude areas.**

Sea Ice

The sea ice research community has relied intensively on remote-sensing data to provide mappings of sea ice concentration, sea ice extent and sea ice thickness. Accurate regional and local sea ice data will be an essential control to the Arctic-COLORS efforts, since sea ice impacts most of the Arctic environment, from ocean and nearshore circulation, to marine ecosystems, to coastal sedimentary dynamics.

The most commonly used Arctic-wide reconstructions of daily sea ice concentration now span 35 years and are assembled from passive microwave sensors, including the early instruments SSMR, SSM/I, and now SSMIS aboard the DMSP F17 satellite (Table 4.3). An improved version of this data product, as developed by NASA scientists and the National Snow and Ice Data Center, includes data input from the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) (Meier et al., 2008) and now AMSR-2. These sea ice concentration maps have a ~25 km spatial resolution and show drastic decrease in sea ice extent, particularly in summer time and early Fall (Comiso et al., 2008; Simmonds, 2015). Detailed analysis of sea ice concentration along the Arctic coastal zone showed that the median length of the 2012 open-water season, in comparison to 1979, expanded by 1.5- to 3-fold for different regions (Barnhart et al., 2014a).

Thickness of sea ice, specifically sea ice freeboard heights, has been derived from measurements of the Ice Cloud and Elevation Satellite (ICESat) data collection campaigns (Forsberg and Skourup, 2005). Sea ice has thinned dramatically over the last 50 years, as reconstructed from a combination of submarine measurements, ICESat data (Kwok and Cunningham, 2008), and SMMR, SSM/I bootstrap ice concentration estimates (Kwok and Rothrock, 2009). Detailed sea ice thickness records will be critical for ocean nearshore and ecological processes. ICESat-2, which is scheduled to launch in 2017, will provide greater coverage, smaller footprint and presumably higher quality data than its predecessor. Logistically, remote-sensing imagery of sea ice can be very useful for planning field-sampling events, providing up-to-date ice location and ice motion.

Arctic Rivers and Coastal Sediment

Major contributions of sediment, nutrients and freshwater to the Arctic coastal zone originate from its tributary rivers. A significant increase of nearly 10 percent in annual freshwater river flux has been observed in 13 major rivers throughout the entire Arctic region over the last 30 years (Peterson, 2002; Overeem and Syvitski, 2009); assessment of these fluxes to the coastal zone is a requirement for our understanding of nearshore and shelf processes. At the drainage basin scale, GRACE data provides insight in the Arctic water balance and freshwater flux (Frappart, 2011).

Observations at *in situ* river gauging stations are hampered by seasonal ice coverage, river break-up and freeze-up dynamics, and unstable banks; thus direct measurements are sparse for smaller river systems along the Chukchi and Beaufort Sea coasts. The paucity of river gauge data in the Arctic (Rawlins et al., 2006) has motivated development of satellite-based or aircraft-based techniques to quantify river discharge based on varying inundation of the river channel or measurements of water surface elevation, cross-sectional flow width, or bankfull depth (Smith and Pavelski, 2007; Brakenridge et al., 2007; Mersel et al., 2010; Overeem et al., 2015). Remote-sensing-based river discharge measurement techniques are employed using a variety of satellite sensors, including synthetic aperture radar (e.g. Smith et al., 1996), reflectance in the near-infrared band of MODIS (Overeem et al., 2015), Landsat (Hudson et al., 2014), and brightness temperature ratios from the passive microwave sensors AMSR-E and AMSR-2 (Brakenridge, 2012; 2014). The more-than-daily temporal sampling allows ice-out and ice cover establishment to be very accurately measured in time and over very large geographic areas or along long river reaches. Approaches to detect river ice break up in spring have been established also with MODIS and AVHRR (Pavelsky and Smith, 2002) and are now undergoing validation with AMSR-2 data.

Water density variations on arctic shelves are primarily influenced by salinity variability due to the generally low temperatures (<5^{o}C) and large range in salinities encountered due to river runoff, ice melt, and oceanic source waters. Hence, the dynamically important density gradients (stratification and fronts) are determined by salinity. Sea surface temperature (SST) maps are easily measured remotely from airborne or satellite platforms, but SST features may not be co-located with sea surface salinity (SSS) variations. High precision, multi-beam passive microwave radiometers capable of remotely sensing SSS exist. Indeed, satellite measurements of global salinity are now underway (Lagerloef et al., 2008) from the SMOS mission, but these may be of limited use in the Arctic coastal zone because of their coarse horizontal resolution (~50 km), reduced sensitivity in colder waters and land-water interference. Sub-orbital sensors will help cover this gap (see §4.5.3).

The use of spectral reflectance data (MODIS and Landsat thematic mappers) to assess nearshore suspended sediment concentration in estuaries and coastal regions is widespread (e.g. Nanu and Colette, 1990; Miller and McKee, 2004; Doxaran, 2012). River plumes and suspended sediment concentrations have been successfully mapped and related to river discharge and in-situ suspended sediment (e.g. McGrath et al., 2009; Hudson et al, 2014). Robust retrieval algorithms of suspended sediments within river plumes surrounding Greenland have been established (Chu et al., 2009; Hudson et al., 2014). Novel algorithms for processing of MODIS visible wavelength bands 1 and 2 have improved the detection of turbid water in imagery with low cloud cover (Hudson et al., 2015). Interestingly, sediment dynamics allow inferences of river dynamics and ice sheet processes (McGrath et al., 2009; Chu et al., 2009). Advances in these promising techniques will improve mapping of change and quantification of trends to allow better transformation of future climate response.

Table 4.3. Satellite Data Time Series and Sensor Characteristics

Note: The table does not include ocean color atmospheric correction input products such as aerosol properties, atmospheric trace gases (ozone and nitrogen dioxide), and water vapor. Non-Ocean Color and terrestrial products are identified in the ABoVE Science Definition Team report.

Sensor	Time Series	Product	Spatial Resolution	Technology	Global Coverage	Agency
AMSR-E	5/2002 to 10/2011	Sea ice concentration Sea surface wind vector	25 km 21 & 38 km	Microwave radiometry	1-day	JAXA/ NASA
AMSR-2	10/2010 to present	Sea ice concentration Sea surface wind vector	15 km 15 km	Microwave radiometry	1-day	JAXA
Aquarius	6/2011 to 6/2015	Sea surface salinity	150 km	Microwave radiometry (L-band)	Weekly	NASA/ CONAE
ASCAT	10/2012 to present	Sea surface wind vector	12.5 x 12.5 km	Scatterometer (microwave radar)	1-day	EUMETSAT
ATLAS (ICESat-2)	2017 launch	Sea ice thickness Sea surface height	10 x 0.7 m	Laser altimeter (photon counting)	Monthly	NASA
CALIPSO	5/2006 to present	Aerosol and cloud profiles TBD - ocean particle profiles	Aerosols: 5 or 40 km horizontal; 60 m vertical	Lidar (CALIOP; 333 m) and imaging infrared radiometer (1km)		NASA/CNES
Cryosat-2	4/2010 to present	Thick ice thickness (1.3cm resolution)	0.3-1.5 km	SAR/ interferometric radar altimetry	14 to 28 days	ESA
GLAS (ICESat)	2/2003 to 10/2008 intermittent	Sea ice thickness Sea ice elevation	70 x 170 m	Laser altimeter	15 campaigns	
GRACE	3/2002 to present	Ice mass balance Ocean currents Evapotranspiration Global water balance	1° x 1° 1° x 1°	GPS and microwave ranging	Monthly Monthly	NASA/ DLR
NSCAT (ADEOS)	8/1996-6/1997	Sea surface wind vector	25 x 25 km	Scatterometer (microwave radar)	1-day	NASA/ NASDA
OCO-2	8/2014 to present	Total column atmos. CO_2 CO_2 source/sink	2.25 x 0.1 to 1.3 km L3: 1° x 1° 4° x 5°	Infrared spectrometry	Monthly	NASA
SeaWinds on QuickSCAT on ADEOS-II	6/1999-11/2009 12/2002-10/2003	Sea surface wind vector	12.5 x 12.5 km 25 x 25 km	Scatterometer (microwave radar)	1-day	NASA NASA/ NASDA

Sensor	Time Series	Product	Spatial Resolution	Technology	Global Coverage	Agency
SMAP	1/2015 to present	Soil moisture Landscape freeze/thaw	10 km 3km	Radar[1]	2-day	NASA
SMOS	11/2009 to present	Sea surface salinity Soil moisture Thin ice thickness (0 to 50 cm) not useable during melt season	200 x 200 km 50 km 35 to >50 km	2D microwave imaging radiometer with aperture synthesis (L-band)	10–30 days 3-day	ESA
SMMR SSM/I SSMIS	10/1978 6/1987 11/2006 to present	Sea ice concentration	25 x 25 km	Microwave imager/ sounder		NASA DMSP DMSP
SWOT	2020 launch	Sea surface height Terrestrial water height Ocean circulation River discharge (w/ hydrodynamic models)	2 x 2 km 50-100 m ~10 – 200 km TBD	Ka-band radar interferometry	Twice in 21 days	NASA/ CNES/ CSA
TANSO (GOSAT)	2/2009 to present	Total column atmos. CO_2 and CH_4 Clouds and aerosols	10.5 km 0.5 to 1.5 km	FTS: Thermal and NIR UV-Vis-NIR radiometry	Monthly 3-day	JAXA/ MOE/ NIES
TOPEX/ Poseidon Jason-1 OSTM/ Jason-2 Jason-3	8/1992-1/2006 2/2001-7/2013 6/2008-present 2015 launch	Sea surface height Sea surface wind speed Wave height	310 km	Pulsed radar altimetry	10-day	NASA/ CNES + NOAA

[1] as of July 2015, the SMAP radar is no longer in operation. NASA is working on a solution to utilize data from the SMAP passive radiometer to provide these data products, albeit at a coarser resolution.

4.5.1 Improvement of retrospective analyses from legacy ocean color sensors

Quantifying biogeochemical processes in a rapidly changing coastal Arctic requires developing the best possible understanding of these processes as they have changed over the last several decades (Figure 4.6). Legacy ocean color instruments have provided continuous and mostly overlapping measurements from low-Earth orbit (LEO) from the last ~18 years (Table 4.4). Nevertheless, the coastal Arctic environment, like many other coastal areas, has optically complex waters with runoff from several distinct basins. The picture is complicated by strong seasonality in runoff, the formation and destruction of fast ice, and the movement of the ice pack. Above all, the remoteness of the region and pervasive cloud cover and fog result in a limited number of matchups between field measurements and satellite overpasses. The limited number of matchups affects the development and validation of derived products like chlorophyll and primary production (Matrai et al., 2013; Hill et al., 2013; Lee et al., 2015), and may mask changes and trends during the last decade. The

ICESCAPE and MALINA projects have provided invaluable bio-optical data for offshore waters of the Chukchi and Beaufort Seas. The Arctic-COLORS field campaign will measure the optical complexity of the coastal zone along the study area, improve our understanding about the relationships between ocean biogeochemical variables, inherent optical properties, and remotely sensed parameters, and acquire data to improve atmospheric correction of ocean color. Detailed information on atmospheric composition will allow for selection of the most appropriate approach for atmospheric correction (e.g., selection of appropriate aerosol models). Further improvements in atmospheric correction algorithms will be needed to resolve the impacts of high solar-zenith angles (thicker atmosphere, lower effective ocean signal) prevalent in the Arctic.

We expect that MODIS (albeit degraded), and VIIRS (on Suomi NPP and JPSS-1) will be collecting data during the Arctic-COLORS field campaigns. Data sets will then be applied to revise current algorithms and reduce and quantify the uncertainty in coastal retrievals. Multiple regional algorithms may be necessary to account for the variability in bio-optical conditions found in the Arctic Ocean. Given the high stakes of these measurements, we support the idea of multiple groups collecting similar measurements, and strongly suggest the collection of replicate samples.

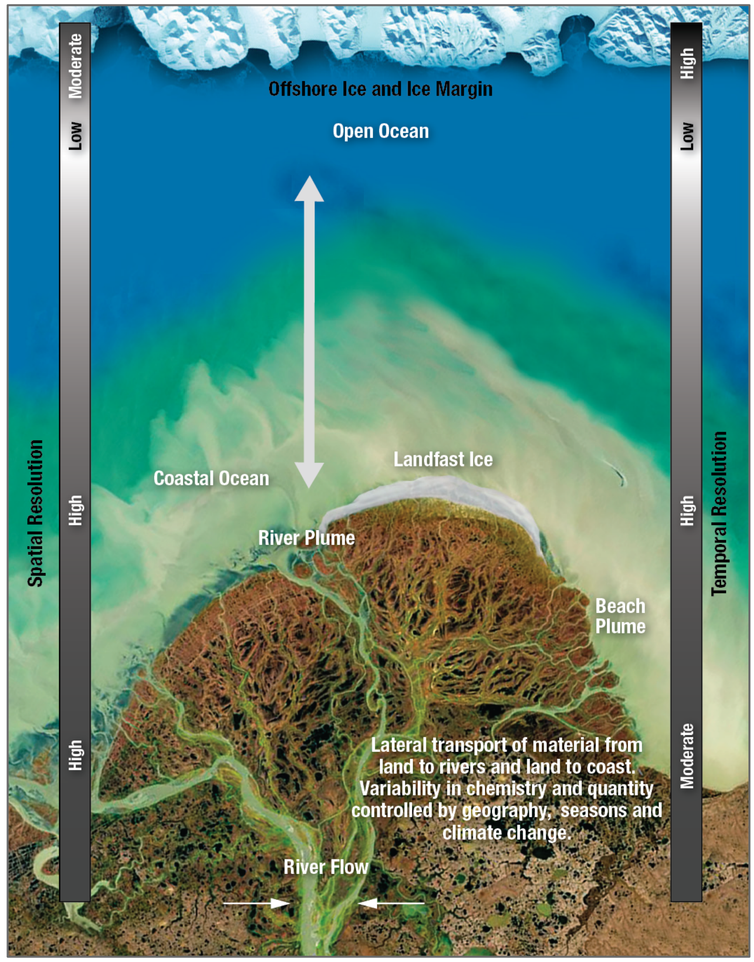


Figure 4.6. A biogeochemist's view on using remote sensing to study Arctic processes: from land to ocean, scientists hypothesize that thawing of the permafrost may result in changes to the quantity and quality of carbon export—including changes in optical properties. This requires simultaneous observations of changes in landscape and riverine properties through the seasons over extended periods at high (<100m) and moderate (<500m) spatial resolutions. Continuing with land-ocean interaction via runoff from rivers and beaches, with coastal processes requiring observation at high to moderate temporal resolutions (diurnal cycles to weekly composites) during process studies. Decadal analyses require monthly composites at lower spatial resolution (1–4 km). Significant advancements prescribe adoption of hyperspectral imagery. Graphic artist enhanced Landsat 7 ETM+ image of the Yukon Delta from September 22, 2002 [Satellite Image credit: NASA Earth Observatory].

4.5.2 Development of new remote-sensing approaches to exploit new and future capabilities

Beyond the refinements to current algorithms, ocean color research in coastal regions is limited by the spectral and spatial resolution of current sensors. Fortunately, three future ocean color sensors, ESA's OLCI, JAXA's SGLI, and NASA's PACE (Please see acronym list in Appendix 8.4], will offer improvements in spectral and spatial resolution and will overlap with the proposed Arctic-COLORS time-frame to provide unprecedented spectral coverage and signal-to-noise ratios (SNR) appropriate for ocean color measurements. ESA's OLCI sensor, slated to fly on Sentinel-3 (October 2015 for 3A and April 2016 for 3B), will provide extended band coverage at moderate spatial resolution (21 bands from 400 to ~1020 nm, at 300 m near the coast). The Second generation GLobal Imager (SGLI) planned for launch in December 2016 will extend into the UV with a 380 nm band and provide 250 m spatial resolution (Table 4.4). SGLI has several SWIR bands that would be useful for atmospheric corrections in highly turbid environments such as the Mackenzie River plume in addition to the heritage NIR bands. PACE is expected to have hyperspectral capabilities from 350–800 nm with several SWIR bands and a spatial resolution of ~1 km^2 or better.

The new generation of high spatial resolution optical imagers with improved spectral resolution and radiometric sensitivity offer new opportunities to monitor coastal, river and near-shore waters. In fact, Sentinel-2 (2A was successfully launched June 2015) and Landsat-8 (launched in February 2013) are anticipated to have capability useful for coastal and inland waters (Franz et al., 2015; Pahlevan and Schott, 2013; Vanhellemont and Ruddick, 2014; 2015) and, when combined, will have revisit frequency close to daily at high latitude. The sensors are particularly useful to map suspended particulate matter (SPM) at river mouths and along the coastline where coastal erosion is important. Both sets of sensors have NIR and SWIR capabilities. These sensors can be used in synergy with lower spatial resolution ocean color sensors to provide a continuum between land and ocean of key biogeochemical parameters. Quantification of CDOM absorption and/or phytoplankton pigments using Sentinel-2 and Landsat-8 remain to be assessed.

Table 4.4. Ocean Color Satellite Data Time Series and Sensor Characteristics. (Sensors with ocean color potential also listed).

Sensor	Ocean Color Data Time Series	Spatial Resolution at nadir	Ocean Color Spectral Bands (nm)	Global Coverage	Agency
SeaWiFS	9/1997 to 12/2010	~1 x 1 km	412, 443, 490, 510, 555, 670, 765	2-day	NASA/Geo Eye
MODIS-Aqua	6/2002 to present	~1 x 1 km	412, 443, 469, 488, 531, 547, 555, 645, 667, 678, 748	2-day	NASA
MODIS-Terra	2/2000 to present	~1 x 1 km	412, 443, 469, 488, 531, 547, 555, 645, 667, 678, 748	2-day	NASA
MERIS	6/2002 to 4/2012	300 x 300 m	412, 443, 490, 510, 560, 620, 665, 681, 709	2-3 day	ESA
VIIRS on Suomi NPP JPSS-1	~2/2012 to present Launch 2017	750 x 750 m across full swath	410, 443, 486, 551, 671	Twice/day	NOAA/NASA
OLI	3/2013 to present	30 x 30 m	443, 482, 561, 655	~16 days; ~5 days at ~73oN	NASA/USGS
OLCI	Launch 2015	300 x 300 m	400, 412.5, 442.5, 490, 510, 560, 620, 665, 681, 709, 754	2-3 days	ESA
MSI	6/2015 to present (Sentinel 2A) Launch mid-2016 (Sentinel 2B)	10 to 60 m	443, 490, 560, 665, 705, 740, 783	~10 days per sensor	ESA
SGLI	Launch Dec. 2016	250 x 250 m	380, 412, 443, 490, 530, 565, 670, 763	2-day	JAXA
PACE OCI	Notional launch March 2022	~1 x 1 km or better	Hyperspectral 350-800	2-day	NASA

The Arctic-COLORS field campaign will include efforts to develop regional algorithms specific to Sentinel-2 and Landsat-8 high spatial resolution (10 and 30 m respectively) and OLCI, SGLI, and PACE spectral capabilities, including possible expansion of the standard ocean color products to offer innovative approaches to the Arctic-COLORS research questions. In the case of OLCI, Arctic-COLORS will benefit from its satellite overpasses (~10/day with two satellites). Although a field campaign does not guarantee any number of matchups, coincidence with the satellite overpasses will be capitalized upon. As in the case of legacy sensors, new Arctic-specific algorithms and evaluation of atmospheric correction approaches for OLCI and SGLI in coastal environments will be essential. Issues regarding the applicability of low-resolution ancillary data to moderate resolution imagery will also be addressed. In addition, we note that the development of new optically-based algorithms during Arctic-COLORS will be applicable to measurements from a variety of *in situ* platforms, including ship-based, airborne, and autonomous, that will complement and enhance the observational capabilities of LEO sensors.

The latter portion of the Arctic-COLORS field efforts will overlap with PACE, providing a unique opportunity to support future application of PACE for Arctic research. PACE offers unprecedented spectral resolution and extends into the UV. Of particular interest is the capability to separate the signals of CDOM and non-algal particles from phytoplankton pigments, needed to better estimate the composition and size characteristics of particulate assemblages, including phytoplankton functional types, and to determine stocks of total particulate matter and carbon (organic and inorganic). However, PACE has the significant challenge of extending water-leaving radiance measurements to 350 nm. Therefore, in- and above-water radiometric measurements should extend to this range. Similarly, improved atmospheric correction methods could allow for the exploitation of the hyperspectral UV-VIS bands.

4.5.3 Remote sensing from airborne platforms

Remote-sensing observations of the Arctic with UV-VIS-SWIR sensors from LEO are constrained by cloud cover and solar angle. The use of LEO sensors limits measurements to a few months around the summer, and the small number of consecutive overpasses at a fixed time limit the applicability of LEO sensors to study fast-paced coastal processes. Moreover, even moderate spatial resolution sensors (~300 m) may not offer enough resolution to study inland waters and processes near the ice edge. To address these challenges, Arctic-COLORS will deploy well-characterized and calibrated airborne hyperspectral systems (Table 4.5) with a minimal spectral resolution comparable to OLCI, and an optimal spectral resolution comparable to PACE. Signal-to-noise ratios should be appropriate for ocean color measurements. The airborne system should also produce data needed to calculate remote-sensing reflectance over water and make atmospheric corrections. Overpasses concurrent with field observations will be used to validate the airborne data, which in turn will be used to address Arctic-COLORS science questions. Clearly, the validation of the airborne data is not in itself a goal, but a means to extend remote-sensing coverage over the study domain during Arctic-COLORS.

In addition to passive radiometric sensors, airborne lidar will provide valuable data to address Arctic Colors objectives. For decades, airborne lidars have provided vertically resolved gradients of particulate scattering at very high vertical and horizontal resolution (for some systems, as high as 1-m vertical and 30-m horizontal resolution)(Churnside and Marchbanks, 2015). Advanced high spectral resolution lidars (HSRLs) optimized for ocean profiling provide the profile of diffuse attenuation coefficient (Kd) along with more accurate particulate backscatter. Gradients in Kd and particulate backscattering can be used to identify vertical and horizontal properties of river plumes and identify layers of low salinity water from ice melt over ocean water. A two-wavelength lidar sensor (355 and 532 nm) may provide some discrimination of particle size and the factors controlling attenuation (e.g., CDOM versus chlorophyll absorption). Polarization sensitivity may provide discrimination between plankton and sediments. In addition, the advanced HSRL instruments are capable of determining melt-pond depth and providing estimates of freeboard at ice edge and where leads exist. These advanced instruments also provide detailed characterization of the overlying atmosphere, including cloud vertical and horizontal distribution and optical depth for non-opaque cloud, aerosol optical depth, and vertically resolved information on aerosol type, layer optical depth by type, and microphysical properties (Burton et al., 2013; Burton et al., 2014; Mueller et al, 2014). This information can be used to determine boundary layer height (Scarino et al., 2014), discriminate between boundary layer and free troposphere aerosol properties, inform inferences of source attribution (e.g., pollution transport from Asia versus biomass smoke), and assess or improve the predictions of chemical transport models. Thus far, airborne lidar sensors have been deployed in the Arctic to measure landscape changes including coastal erosion, snow levels and permafrost. For example, Jones et al. (2013) applied repeat airborne lidar data from 2006 and 2010 along the Alaskan Beaufort coast and measured landscape changes (0.55 m change in landscape height) that could be attributed to permafrost degradation as well as erosion and deposition from river, delta, beach, and sand dune-related processes.

Table 4.5 List of Airborne Ocean Color Instruments in Consideration for Arctic-COLORS (not an exhaustive list).

Instrumen[1]	Spectral Range	Spectral resolution	# Spatial Pixels	FOV (degrees)	Mass (kg)	Volume (m^3)	Platform	Owner/ Operator	Notes
G-LiHT	420–950 nm	5 nm	1,000	50	20	0.5	Small plane	GSFC	System includes a canopy lidar and a thermal channel
PRISM	350–1054 nm and 2 discrete SWIR bands at 1.2 and 1.6 um	3.5 nm	1,000	31	20	0.5	Airplane	JPL	Two focal planes
GEO-TASO	290–388 nm; 412-650nm	0.36; 0.73nm	1,000	45	200	1.5	Airplane	GSFC	Two focal planes, push broom system
GCAS	300–490 nm; 480–900 nm	0.8; 1.6	1,000	45	40	0.17	Small airplane to UAV	GSFC	Two spectrometer, push broom system
Air-Shrimp[2]	300–900 nm	2.5 nm	11	5	10	0.25	Small airplane to UAV	GSFC	Multiple line scanning spectrometers

1 Other sensor technologies such as lidar among others should be included in the Arctic-COLORS program.

2 Air-Shrimp is a line scanner (collects data for a single spatial pixel along the flight track); all the other sensors are “pushbroom” type, meaning that multiple spatial pixels are imaged simultaneously across the flight track as the sensor moves along the flight track.

Airborne systems offer the advantage of flying under low cloud ceilings (given suitable flight ceilings), high spatial resolution, and flexible overpass schedules. Airborne lidar retrievals are immune to interference from atmospheric aerosols, can be made through tenuous clouds and between clouds, in regions dominated by pack ice (e.g., 90 percent ice coverage), and under any lighting condition including night. Therefore, airborne sensors can be used to complement process studies that require multiple observations through the day, at high spatial resolution to include measurement near land and the ice edge. Emphasis will be placed on the use of UAV-based sensors that may have the potential of extending measurements due to their high endurance and relatively low cost.

The physics of microwave remote sensing of sea surface salinity is well known and depends upon measuring the microwave emission (emissivity or brightness temperature) from the sea surface at a variety of wavelengths. Emissivity is a function of salinity (Klein and Swift, 1977) and temperature. By measuring microwave emission at several wavelengths (including within the infrared band) the temperature effects on emissivity can be determined and eliminated. Airborne microwave multi-channel radiometers provide a potential remote-sensing capability of SSS for the Arctic coastal zone that can fly below clouds and provide higher spatial resolution. Several of these instruments have been developed and applied successfully in a variety of mid- and low-latitude settings (Wang et al., 2007; Le Vine et al., 1998). Although the accuracy is relatively low (~1 salinity), the large range in surface salinities in summer (~10–30) suggest that the airborne

SSS sensor would be a valuable tool in mapping fronts and eddies in the Arctic coastal zone, especially when used in conjunction with in-situ measurements. However, high-latitude tests of the airborne SSS sensors have not been made and the accuracy of the instrument may be lower at the relatively low temperatures (-1°C to 5°C) typical of the Arctic.

Arctic-COLORS will require data from the following sensors and likely others, as new algorithms and products become available. Most products are available at no cost from NASA or ESA. These include medium resolution ocean color VIS-NIR; satellite SST (microwave, IR); high resolution mapping (e.g., IKONOS, Landsat-8); L-band salinity (e.g., SMOS, SMAP, Aquarius); altimetry; scatterometry; sea ice extent (SSMIS microwave, NSIDC); sea ice thickness (ERS altimetry, ICESAT-2); snow cover (AVHRR) and depth (NOAA SNODAS); melt pond fraction (MODIS); among others listed in Tables 4.3 and 4.4. While some imagery may be available daily, Arctic-specific factors such as the polar night, cloudiness, ice cover and snow solar angle reduce the frequency of truly useable imagery to weekly. One-day and 8-day imagery for ocean color-derived chlorophyll and primary production in Arctic Ocean open waters show significant agreement (Matrai et al., 2013). Sub-orbital sensors listed above in Table 4.5 will also generate data for all participating teams. We recommend an imagery data archive linked to the ABoVE data management system (see §5.3).

4.5.4 Remote-sensing science applications

Efforts associated with Arctic-COLORS should include explicit use of satellite imagery to address issues of both ecological importance and socioeconomic relevance, including coastal water quality, monitoring and assessment of risk of introducing invasive species through introduction of ballast water, perturbation of coastal food webs, and habitat change. Practical applications could also be extended to address key societal issues and needs in the coastal Arctic region, including coastal erosion, ice mapping and ship navigation, resource exploration and management, as well as identifying and monitoring areas of heightened ecological and cultural significance (Berkman and Vylegzhanin, 2012).

Arctic-COLORS research will address a wide range of applications areas of NASA's Applied Science program, including 1) climate, (2) ecological forecasting, 3) water resources, 4) human health and air quality, 5) ocean ecosystems and 6) disasters (http://www.nasa.gov/applied-sciences/). Specifically relevant to ocean ecosystems, ecological forecasting, and hazards, the proposed integrated modeling and observational approach would allow improved detection and tracking of harmful algal blooms, monitoring of oil spills, impacts of coastal erosion, flood detection, and post-storm assessments (Walsh et al., 2011; Berkman and Vylegzhanin, 2012). Remote-sensing datasets of sea ice, sea-surface temperature, sea-surface height, ocean color and retrievals of changes in chlorophyll distribution are all important parameters that, in combination with physical and ecosystem models, can provide predictions on zooplankton survival and distribution in the Arctic coastal zone. These, in turn, can provide information for assessing preferable habitats for many marine mammals, subsistence-harvestable fish, and the regional king crab fishery. Changes in environmental conditions are expected to result in substantial in and out migration of different marine species, affecting coastal food webs and ecosystem functioning; their quantification within foodweb studies is a key objective in Arctic-COLORS.

4.6. The Key Role of Advanced Modeling Approaches

4.6.1. General uses of models in Arctic-COLORS

Modeling is key to addressing the scaling, integrative, and predictive components of our science questions (Sect. §3) and, as such, a close linkage between data collection and model development will be required. Forecasting the future impacts of climate change, and isolating the impacts of anthropogenic forcing and natural variability requires the use of models. Nowhere is this more important than in the Arctic Ocean, where environmental change is occurring faster than anywhere else on the planet. Not only will data inform the models (e.g., improving model reliability necessitates adequate data being available to constrain parameter values in biogeochemical models), but these models will also inform the data analyses by providing context for field- and remotely-sensed measurements through synthesis and interpretation. Model evaluation and benchmarking heavily rely on independent data gathered during the campaign. It is important that priorities for model development and validation be identified early, so as to inform the collection of field data during the early years of the campaign. Consistent information and data exchange between modelers and observers will be required from the early fieldwork planning stages through the synthesis efforts in later years.

New, state-of-the-art, coupled Arctic models—including physical, biogeochemical, sea ice and riverine effects—developed and advanced as part of Arctic-COLORS will ultimately enable researchers to better understand mechanisms controlling the environmental gradients observed *in situ* and via remote-sensing platforms, with the ultimate goal of quantifying both contemporary and past/future conditions along the Arctic land-ocean interface. *In situ* observational data are sparse in both time and space in these remote Arctic regions, and frequent cloud cover limits satellite data. As a result, scientists must rely on numerical models to interpolate and extrapolate the available data in order to scale up from discrete observations to a whole-system view. Numerical models are also required to quantitatively constrain certain processes that are difficult to measure on the scales of interest to Arctic-COLORS, such as transport of biogeochemical constituents from their riverine sources to the coastal Arctic Ocean, and changes in microbial community composition and succession.

Although the need for models to address Arctic-COLORS science questions is clear, there are critical gaps in the abilities of current models to realistically simulate the land-ocean interface in the Arctic. First these gaps are identified below, then a description of how the Arctic-COLORS program will fill these gaps is provided.

4.6.2 Current gaps in Arctic land-ocean modeling

Most large-scale, coupled Arctic sea ice—ocean regional models include only the most rudimentary riverine input processes. Most commonly, this means that the only signature of river input to these models is dilution of salinity in the grid points closest to the river mouth, typically using climatological, monthly mean-river-discharge volume (Hibler and Bryan, 1987) and for only a subset of rivers. In addition, an "ungauged rivers" component is typically included as an extrapolated value distributed evenly along the coastline in order to account for both small rivers as well as groundwater discharge. Some models are even less sophisticated, and instead use a simple restoring term to climatological monthly mean-observed sea-surface salinity to capture river discharge (Karcher et al., 2007). However, land surface models can now estimate river discharge flux at sub-monthly, or even daily resolution for all major Arctic-draining rivers (al et al., 2009; Cohen et al., 2013). Used together, available river discharge data, numerical modeling, and hybrid approaches of remote-sensing data plus modeling will allow for quantification of suspended sediment and other constituent exports along the Arctic coastal zone.

Fully coupled climate models have their own hydrological model component that brings varying discharge to the ocean, but how that discharge is transferred into the ocean differs widely from one model to another. The most physically-consistent method is to transfer both volume and salt to the ocean, but while a numerical method considering these two aspects has been developed (Huang, 1993) and shown to impact Arctic circulation (Prange and Gerdes, 2006; Roullet and Madec, 2000), its implementation is still relatively rare. The transfer of heat from rivers into the ocean is also typically neglected, but can represent a critical source of heat in these regions (Nghiem et al., 2014). A new database of climatological river discharge and temperature to one-sixth of a degree (Whitefield et al., 2015) will likely improve future model estimates of water transport, sea ice formation and melt, and other fine-scale processes.

Several models have been employed to calculate coastal erosion of the Arctic coastal region (e.g., Ravens et al., 2011; Barnhart et al., 2014b). Coastal erosion processes certainly introduce an increased freshwater flux from melting interstitial ice, and importantly release soil organic carbon (solids and gases) previously sequestered in the permafrost into the shallow nearshore waters. Coupled climate models have not taken these fluxes into account yet, nor have they been set up with dynamically changing boundary conditions (i.e.

an evolving eroding coast). Identifying the relative strength/importance of these fluxes is one intended outcome of Arctic-COLORS.

Given the primitive numerical framework that many models use for the transfer of physical properties (volume, salt, and heat) into the ocean, it is not surprising that few models attempt to capture land-ocean biogeochemical and sediment fluxes. For example, none of the existing modeling frameworks currently transfer riverine sediment into the coastal ocean domain, despite evidence from satellite imagery that suspended sediment plumes dominate the shallow Arctic shelf waters during the summer season (Carmack et al., 2015) and profoundly change albedo and light availability. The development of large-scale, three-dimensional coupled biogeochemical-ocean-sea ice models of the Arctic seas is a relatively new development (e.g., Popova et al., 2014; Slagstad et al., 2011; Steinacher et al., 2009; Steiner et al., 2014; Zhang et al., 2010), with some including land/hydrology/ocean interfaces and month-to-month resolution (Maslowski et al., 2012). Although ongoing efforts to characterize these fluxes on a pan-Arctic scale, with annual to decadal resolution, appropriate for ocean modeling are bearing some fruit (e.g., Holmes et al., 2012), Earth System Models (ESMs) contributed to CMIP5 do not agree on the sign of future primary production changes (Vancoppenolle et al., 2013). This is despite the fact that all models report a decrease in available nutrients due to increased stratification and an increase in light availability due to a reduced sea ice cover. Moreover, most ESMs do not yet address Arctic biogeochemical processes in the nearshore zone, especially where large riverine inputs occur at local scales (but see LeFouest et al., 2013). Similarly, benthic processes (e.g., organic matter remineralization, nitrification, denitrification) that seem important in the wide and shallow Arctic shelves (e.g., Devol et al., 1997; Tanaka et al., 2004; Deal et al., 2014) are generally not yet included in these models.

While the typical ocean model does not include the properties of most biogeochemical land-ocean fluxes in the Arctic Ocean nor include parameterizations that are representative of Arctic coastal processes, modifications to address these issues seem feasible, given existing parameterizations from other regions and new data sets that are likely to be part of the Arctic-COLORS field campaign. Thus, this is an area where considerable progress can be made, given an appropriate investment in time and effort.

Advances in understanding near-shore biogeochemical processes will require model refinements in terms of how landfast sea ice at the coast impacts fluxes to the ocean. Many Arctic river drainage basins experience peak snow melt and river break-up while regional sea ice still covers the coastal ocean. For these river systems, the river drains into the landfast ice zone and the river plumes can drain partially under-ice, extending river water far offshore to the open channels that cross the landfast ice zone (Alkire and Trefry, 2006). Simplified model experiments with the Regional Ocean Modeling System (ROMS) show the profound impact of the frictional coupling of the sea ice on buoyant river plume dynamics (Kasper and Weingartner, 2015). Even more dramatic impoundment of river discharge is experienced in the spring via the presence of grounded sea ice ridges at the off-shore limit of the landfast sea ice (i.e. stamukhi), which creates an inverted dam effect (Carmack and Macdonald, 2002). These processes serve to concentrate river properties and delay their export to the open ocean; however, the impact of this delay on the evolution of the pan-Arctic sea ice pack and the underlying ocean ecosystem is presently unclear. Few models incorporate a parameterization for the landfast ice that includes stamukhi, although this is a topic of recent research (Itkin et al., 2015).

As described above, small-scale processes at the land-ocean interface are complex and are generally not captured in current coupled climate models. However, the necessary numerical methods are an active topic of current research; and with new data available from the Arctic-COLORS field component, resolving these processes will become increasingly feasible, as described below.

4.6.3. How will Arctic-COLORS advance modeling?

Arctic-COLORS is intended to lead to several significant modeling advances by allowing hydrological, coastal physical, biogeochemical, and sea ice model components to be evaluated against a comprehensive set of high-resolution observations that encompass the dominant dynamical processes at the land-sea interface. In addition, the modeling frameworks developed under Arctic-COLORS will serve to evaluate the adequacy of existing global and regional-scale models for providing consistent open boundary forcing for higher-resolution models in this region at monthly scales. The modeling component of Arctic-COLORS will use state-of-the-art community standards to assure open-source modeling practices. When possible, work will be conducted using sound protocols to standardize model parameter attributes to allow easy coupling between different model components, as are currently available in modeling communities such as the ROMS (Melsom et al., 2009), Regional Arctic System Model (RASM) (Maslowski et al., 2012), and Community Surface Dynamics Modeling System (Overeem et al., 2005). Nesting between different model grids and the incorporation of newly developed model components will be facilitated by adhering to best practices (e.g., Hutton et al., 2015) and will insure that the complex coastline, straits, and bathymetry of the coastal Arctic Ocean are well resolved.

One of the most unique challenges associated with the Arctic-COLORS modeling effort will be to realistically simulate the impact of riverine discharge (both physical and biogeochemical) on coastal ocean properties. High-resolution field and satellite observations collected during Arctic-COLORS will provide invaluable information to identify the proper modeling tools and configurations needed to resolve spatial and temporal variability at the land-sea interface. For example, nearshore surveys will provide information on whether regions of weaker and more evenly distributed river discharge can be reasonably approximated with a simplified line source approach in models. Similarly, physical, biological, and biogeochemical observations near the mouths of major rivers (e.g., Yukon, Mackenzie Rivers) will provide a basis for determining whether a "single" modeling approach is sufficient (e.g., coastal ocean circulation model extended into the river estuary/delta) or whether a combination of models is necessary (e.g., hydrological/terrestrial model coupled to coastal ocean circulation model). Both *in situ* and remote-sensing observations during Arctic-COLORS will provide critical information for scaling studies linking point measurements to processes at model resolutions necessary to capture spatio-temporal variability at the pan-Arctic scale.

Because of the strong seasonal variability and the significant challenges associated with resolving the spatial scales at which riverine inputs affect coastal ocean properties, it is expected that emphasis will be placed first on modeling intra-annual variability. The Arctic-COLORS field campaigns will provide reference datasets for evaluating model skill on these seasonal timescales, and in turn determine the level of confidence with which models can simulate inter-annual and inter-decadal changes in hindcast mode. Only then should these models be used in prognostic mode to make projections of the effects of future climatic changes and to distinguish between future impacts of natural and anthropogenic change on coastal ocean ecology, biogeochemistry and biodiversity. Such evaluation is a necessary step to understand the degree of complexity that models must include to adequately simulate the complex interplay between physical, biogeochemical and sea ice processes at the Arctic land-ocean interface, where riverine inputs significantly impact coastal biogeochemical variability.

4.7. Uncertainty and Error Analysis

All measurements and analyses will follow well-documented and peer-reviewed protocols. This will help insure consistency among measurements performed by different groups and with measurements obtained in the past. Historical climatologies of optical variables are extremely scarce for the Arctic, especially in the Arctic-COLORS domain. Thus, uncertainties in each measurement and model output will need to be defined and tracked.

There are a variety of sources of uncertainties, all to be taken into account and propagated appropriately; measurement uncertainties will be assessed from cross-instrument comparisons (>resolution), and uncertainties due to imperfect relationships between what we sense or measure and the proxy we are trying to obtain (e.g., POC from beam attenuation at 660 nm, nitrate from absorption in the UV). These require that we collect a sufficiently large set of measurements for comparison. We can use the limited data available from previous studies with care, because few exist for Arctic waters in multiple locations and seasons. Remote-sensing algorithms have their own uncertainties (propagated from measurements through a variety of models) that also require a significant number of independent match-ups to constrain them.

To minimize systematic errors in Arctic coastal waters, it is critical to revisit algorithms and assess and remove potential sources of bias (e.g., treatment of blanks, assumption about water properties in remote-sensing algorithm). Uncertainties in measurements should also be assessed with pre- and post-deployment calibrations, cross-calibration between similar sensors in the field and by cross-comparing variables that, while fundamentally different, should be related (e.g., carbon and chlorophyll in the upper ocean). With respect to measurements on autonomous platforms, cross-sensor inter-comparisons, measurements at depth and comparison to surface measurements (be it from a research vessel or remote sensing) will provide indication of sensor stability.

The numerical models developed and advanced as part of Arctic-COLORS will also provide a robust framework via which sources of uncertainty in in situ and remote-sensing observations can be evaluated. For example, ensemble calculations with different sets of forcing functions (e.g., winds) or biogeochemical parameters (e.g., growth and grazing rates) can prove useful to determine expected uncertainty in environmental properties at various spatial and temporal scales (Fiechter, 2012). Furthermore, such results could help focus attention for the field campaign on certain processes or rates that yield substantial uncertainty in model solutions.

4.8. Integration and Scaling

Integration across all measurements from different platforms, disciplines, scales, and environments is a key component of Arctic-COLORS and a critical aspect both in the proposed science and implementation plans. Synthesis and integration activities will take place throughout the duration of the field campaign. While we expect that funded researchers in Phase II will engage in integration activities with their natural cohorts, the Phase III synthesis effort is specifically included with a large enough time and funding investment to tap into larger integration efforts across all disciplines, while Phase I provides an opportunity to integrate previous work and existing field and remote-sensing datasets and modeling products into Phase II projects (Figure 5.1).

In order to facilitate integration, it will be necessary to include core measurements in most projects collected by agreed upon standard methodologies, ideally with links to past methodologies employed in Arctic research. Synthesis efforts and spatio-temporal extensions of datasets are significantly hampered by methodologies that are not easily compared or gaps in the data. Modeling will be key to addressing the scaling and integrative (as well as predictive) components of Arctic-COLORS (see § 4.6). Measurements collected during the proposed intensive and synoptic field studies will be used to improve and develop new parameterizations or new components for coupled Arctic models, which will then be applied to scale up fluxes and processes in both the temporal and spatial domains. Strong interaction between modelers and observers will thus be required from the early fieldwork planning stages (beginning of Phase II) through the synthesis efforts (Phase III).

In addition to integration efforts internal to Arctic-COLORS, a primary objective for the project should be integration with current and future oceanographic, terrestrial, and air-quality field campaigns in the region that are complementary. These are detailed in §5.4 below. This coordination and integration with international interdisciplinary field programs in the Arctic will not only allow to scale-up our findings temporally and spatially, but it will also extend the applications value of Arctic-COLORS observations and modeling tools.

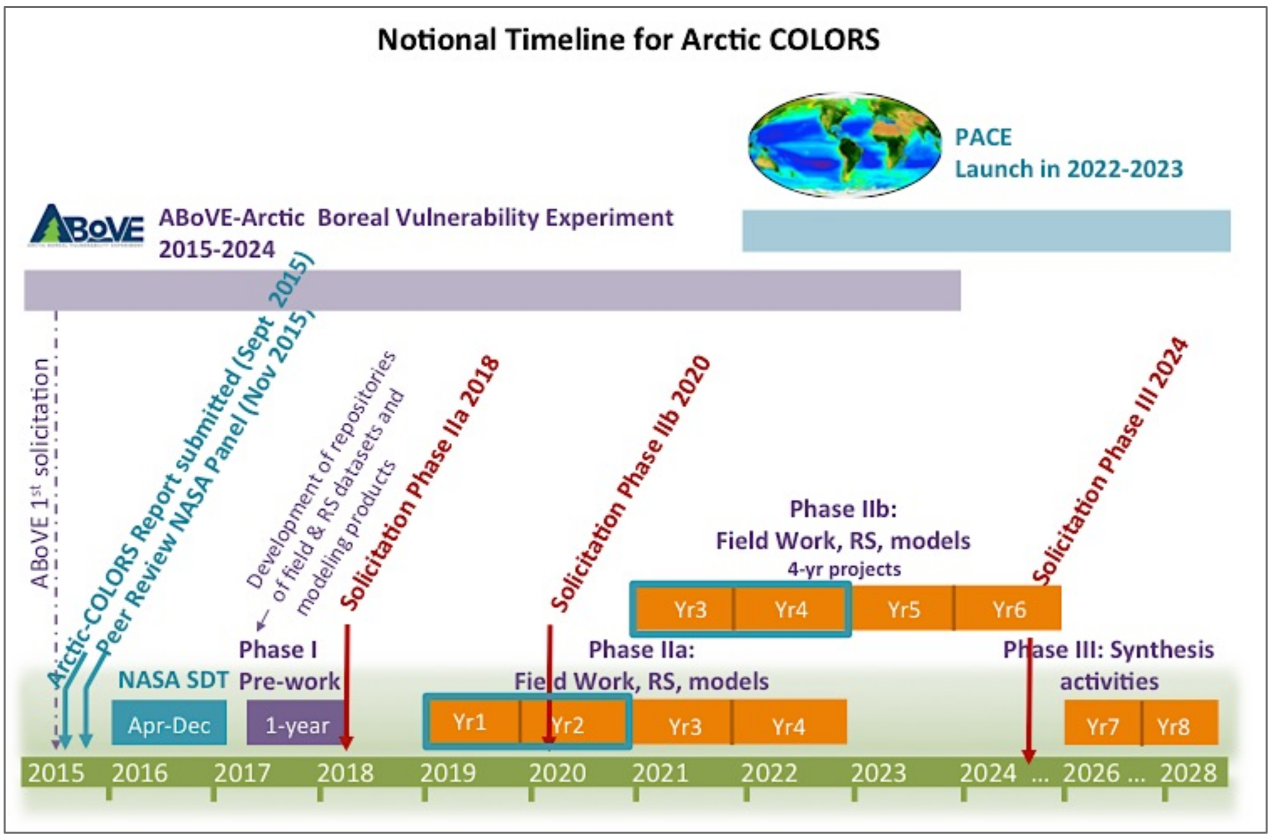
Finally, a key rationale for implementing this project through NASA is the ability to use past, present, and future remote-sensing data for scaling purposes. Calibration of data products with ground measurements enables both spatial and temporal scaling, which allows snapshot and seasonal sampling to address climate change, or synoptic and transect sampling to give continuous spatial coverage that can be utilized in regional process models and regional fluxes.

5.0| Implementation Plan and Project Management

5.1. Arctic-COLORS Project Timeline

The notional duration of Arctic-COLORS is nine years and includes three phases (Table 4.2 and Figure 5.1). Phase I involves a one-year pre-Arctic-COLORS activity to compile prior field and remote-sensing data sets. Phase II represents the main portion of the program and encompasses two sets of four-year research projects over a six-year period that overlaps in time between 2019 and 2024. These research projects will accomplish the primary science of the program including the fieldwork, model development and evaluation, and satellite data analysis. The field campaign duration would coincide with much of the ABoVE field program. Phase III will be a two-year synthesis period to complete the Arctic-COLORS program.

Figure 5.1. Notional timeline for the Arctic-COLORS program.



5.2. Required Resources: Planning and Funding

Arctic-COLORS will be a large multi-year, multi-disciplinary project with many deliverables and many participants charged with developing rich datasets and new technology. Successful implementation of Arctic-COLORS will require resources commensurate with the specific tasks to be completed. Requirements are expected to be modest in the planning and synthesis phases, and most demanding during the proposed Arctic fieldwork. During the fieldwork phase, funds will be required to ensure that all logistical considerations are met, including Arctic safety training, transport of personnel and equipment to and in the field, permits, and housing among others. Considerable resources will be required for ships, coastal vessels, land-based field stations and attendant logistics, sub-orbital platforms and their staging, and satellite data and model support. Personnel directly tied to NASA OBB or Headquarters (HQ) will also be needed to administer the program. Following the NASA process, a Science Definition Team will be selected who will finalize the scientific objectives and decide on the final experimental plan.

5.2.1 Required resources and budget estimate

To meet the goals set out, Arctic-COLORS requires a 10-year funding timeline and considerable resources for three phases (planning, fieldwork, and synthesis) that will require ship and aircraft time, over-the-snow/all-terrain vehicles, extensive and intensive logistical support, data management, project office costs, and most importantly, support for a wide range of scientists and their groups to participate in this study. Preliminary estimates were made for each program element. The total cost for Arctic-COLORS based upon this analysis is roughly $79.7M (see § 8.1 for details). The components and costs used in this preliminary budget estimate are summarized as follows.

Table 5.1. Summary of Costs for Arctic-COLORS. See § 8.1 for details.

Category	Cost ($K)
ROSES Awards to Science Teams	40,050
(Pre-Arctic-COLORS, Field Campaign and Modeling, and Synthesis)	
Ships, Helicopters, All-Terrain Vehicles	25,173
Airplane Remote Sensing	9,480
Project Management	5,000
TOTAL Costs of Arctic-COLORS	**79,703**

Ship time: Approximate day rates for small ($15K/day), medium (perhaps ice-enforced) ($45K/day), and large (ice-capable) ($55K/day) vessels were applied. For process studies, the expected days per year required are 56 for small, 60 for medium and 38 for large vessels, reflecting 2–4 cruises per vessel size (due to required seasonal coverage) in four different regions of the Arctic-COLORS study domain per year. For survey cruises, either small or large vessels will be used for 37 and 28 days per year, respectively, and repeated over three regions. Over four years of Arctic-COLORS fieldwork, these costs are estimated to total $23.2M or about 29 percent of the total.

Helicopter and all-terrain vehicles: Approximate day rates for helicopters are $5K/day for 120 days per year of field sampling (four regions and three seasons) for an estimated total of $1.8M. In addition, extensive use of over-the-snow/all-terrain vehicles (ATV) in winter and spring, given the terrain, will require approximately $200K. For the 4-year duration of the fieldwork, the combined total costs for helicopter and ATV time are estimated at $2M or about 2.5 percent of the total.

Aircraft remote-sensing time: Approximate day rates for airplanes of 15.2K/day for 50 days per year of field sampling (four regions and three seasons) and aircraft-specific logistics ($600K per season per year) for an estimated total of $9.5M or about 12 percent of the total cost. The airplane daily cost estimate is based on information provided by Glenn Research Center and assumes a Ken Borek Air Twin Otter aircraft (see §8.1 for further details).

PI costs: The largest costs for Arctic-COLORS are related to the scientists and labs conducting the study. The PIs will be responsible for the wide range of measurements, observations, modeling, remote sensing, and synthesis activities detailed above. We have tentatively estimated that roughly 49 percent of the budget, or about $40M, would be needed to support three research groups for one year each in Phase I; two groups of 14 research projects in Phase II for four years each in Phase II; and five research groups in Phase III for two years each. As might be expected in a field intensive program conducted in a remote location and often under inhospitable conditions, Arctic-COLORS costs would be higher on average for PIs and their labs during the field-oriented Phase II, and should be lower in Phases I and III. It is essential that the PI's (chosen through peer review) cover the full range of expertise needed to implement the five questions posed by Arctic-COLORS. The costs per group are not expected to be equal. Core groups would need to be supported in order to commit to a multi-year field program of this magnitude. When different scoping options are considered in order to build the strongest program, maintaining this range of PI skills will be paramount to the success of Arctic-COLORS.

Project Management: The Arctic-COLORS project office would coordinate the implementation of the project, including logistics; training activities; teleconferences, meetings, workshops for participants; and data management (including data repository). These tasks would be covered by the remaining 6 percent ($5M) of this budget.

Summary: When added, a preliminary estimate of the total funding of $79.7M would be needed for Arctic-COLORS. Alternatively, Phase 2 could be constructed as a single group of research projects with shorter field efforts and longer project duration; for example, 20 groups of investigations could be funded over a five-year period and encompass three years of fieldwork. Under this alternate scenario, ship-time, aircrafts, and helicopter requirements would be reduced by a third, yielding a total program cost of approximately $62M. Cost refinements will occur as Arctic-COLORS partnerships (Federal, international). Also, it is difficult to constrain accurate costs for aircrafts, ships, and logistics (including shipping costs). Operational and supply costs in the Arctic are significantly higher than in other regions. The scale of the resources needed to conduct the Arctic-COLORS field campaign as proposed is well within the bounds of previous multi-year, interdisciplinary NASA field campaigns (cf., ICESCAPE, Ice Bridge, ABoVE, etc.) in the Arctic region.

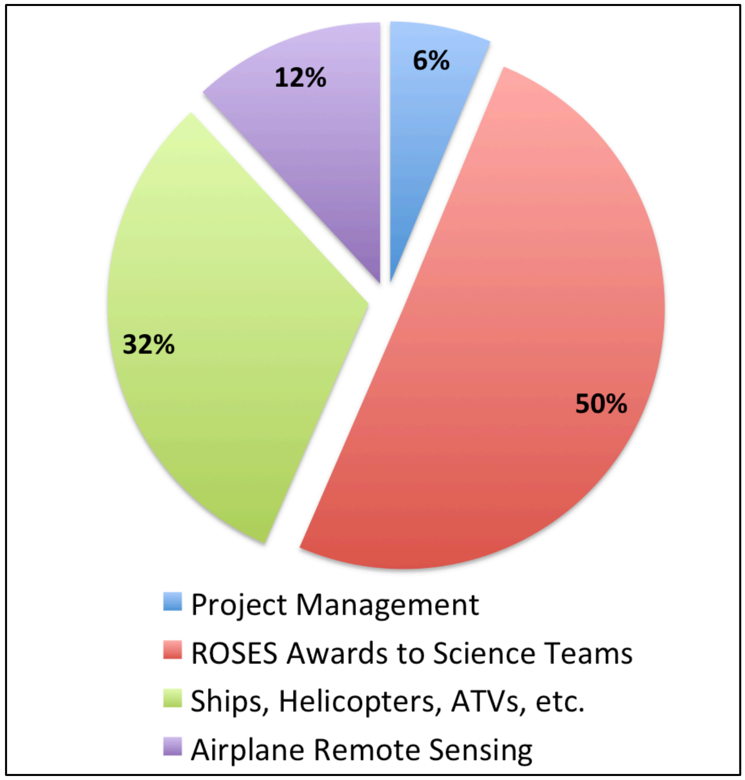


Figure 5.2. Proposed percentage of total cost by category for Arctic-COLORS. The total estimated cost for the project is $79.7M.

5.2.2 Logistical considerations

Safety protocols: Safety is a primary concern, and it is imperative that all personnel in the field be adequately trained for the unique hazards of the Arctic. Field scientists participating in the program should be given the opportunity to obtain appropriate training for the hazards that can be reasonably expected (e.g. cold weather, sea ice, river crossings, small boats, etc.) from commercial hazard training, such as Learn to Return, http://www.survivaltraining.com. NSF has been encouraging the development of formal training and risk management protocols (see http://rslriskworkshop.com/), especially in the context of small watercraft, over-the-snow/all-terrain vehicles, remote field camps, and aircraft and helicopter charters for transport in the field. Programs such as aviation land and water egress, wilderness first aid, and wilderness survival should be standard for any researcher working in these brutal environments. Such programs cannot replace experience in the field, however. An important component of any serious safety plan must include identifying and grouping individual researchers with the expertise needed to operate safely in these environments. This can be done by hiring local guides, pairing researchers new to Arctic fieldwork with more experienced field researchers or NASA logistics professionals, and hiring outside expertise from logistics service providers.

Personnel transport: In many cases, commercially scheduled air transportation will be adequate, although it is worth noting that west-to-east international scheduled air transportation is not available currently (e.g., between Alaska and Yukon/Northwest Territories/Nunavut). Airlines such as Alaska Airlines and Ravn Air provide service to major and minor communities in Alaska, respectively. In Canada, Air North Yukon, Canadian North, and First Air provide parallel south-north services that do not cross the international boundary.

As a result, contingencies should be allowed for chartering planes or helicopters to cross the international border if commercial schedules are insufficient for either freight or passengers, or if it is difficult to reach remote field sites. Several local air services readily provide fixed-wing aircraft for charter locally and across the border (i.e. RAVN, Wrights) Helicopter service generally requires ferrying aircraft from further south in Alaska or beyond. Logistical coordinators, such as Fairweather LLC and CH2M Hill Polar Services, could also provide science planning and coordination assistance to NASA. Individuals such as Andreas Heiberg of the University of Washington or services such as UIC Professional Services are notable resources with decades of science planning experience in Polar Regions. They too may be able to contribute significantly in planning the logistical efforts needed to implement Arctic-COLORS. These service providers are merely examples. NASA does not endorse any specific private service providers.

- http://www.alaskaair.com/content/route-map.aspx?lid =nav:planbook-routeMap
- http://www.flyravn.com/flying-with-ravn/route-map/
- http://www.flyairnorth.com/Experience/RouteMap.aspx
- http://www.canadiannorth.com/route-map-and-flight-schedule
- https://firstair.ca/book/routemap/
- http://www.fairweather.com/index.html
- http://cpspolar.com/
- http://www.apl.washington.edu/people/profile.php?last_name=Heiberg&first_name=Andy
- http://www.uicprofessionalservices.com/ services/category/uic-science/arctic-science-logistics-support/

Equipment transport: Air shipments are typically expensive and each team must budget accordingly. Typical transport rates into Alaskan villages vary between $0.50/lb and $1.5/lb, dimensional weight, for parcel size and shape objects, with considerably higher costs for large and irregular items. Large aircraft (e.g. 737 combi's) fly into Barrow, Kotzebue, Nome, and other larger towns in Alaska, enabling most parcels to be moved. However, aircraft size is typically limited to Cessna Caravans (208's) when flying into smaller villages, which substantially limits the maximum size of objects that can be moved to smaller villages. Northern Air Cargo provides jet freight service to larger communities such as Barrow, Nome, and Kotzebue. Several companies, including Northern Air Cargo and Evertts, specialize in bulk cargo, while RAVN and Alaska Airlines have priority parcel moving services. Services are typically available several times a week. Other transfer options include Arctic Air Alaska (http://arcticairalaska.com) and Air Arctic (http://www.airarctic.com/fbo/), which provide charter air services. Rental costs for vehicles are generally high in Arctic towns and villages. In smaller villages, obtaining a rental vehicle is quite difficult, as many towns do not have a dedicated business for renting equipment. In these instances, it is sometimes possible to rent personal vehicles and transport services. Several companies including Northern Transportation Company Limited (http://www.ntcl.com) also provide coastal and river shipping during ice-free periods in the Mackenzie River basin, which is a viable option for moving larger equipment to most small villages. If larger vessels are used, some cargo can be loaded at their homeports prior to the field season

Terrestrial field occupations: Much of the fieldwork requires setting up on land or ice. PIs must prepare for one of two approaches: 1) work at a sustained ice camp for a set period of time, or 2) establish a temporary occupation of stations on landfast or pack ice during sample collection with no sustained camp. Although it may be necessary to process samples in the field, the transport of necessary equipment to complete sample processing (i.e., power and refrigeration requirements) and the time spent on the ice are risks that require careful consideration (e.g., polar bear protection, sea ice breakup hazards, etc.). Landfast ice or the shear zone between landfast and pack ice can be dangerous during the spring months when river runoff is at its peak and the ice begins to break up. It may be necessary to develop a compromise that would allow for temporary preservation of samples before processing.

Ideally, fieldwork should be scheduled to minimize the transport time of samples to a moderately or well-equipped, climate-controlled laboratory that is centrally located, even if it requires multiple trips onto the ice to collect samples. Much can be accomplished with snowmobiles and sleds. For winter and spring sampling, over-the-snow/all-terrain vehicles can be used to transport sampling equipment (ice auger, drill strings, bottles, tubing, peristaltic pumps, and coolers) to a number of remote sites. Once on site, a hole can be drilled and samples collected within one to three hours (depending on complexity and number of samples collected). For colder temperatures or slightly longer sampling processes, a small canvas tent can be erected and a portable heater powered by a gas generator. This type of equipment is relatively easily to transport using sleds (assuming teams of two to three snow machines with four to six people). Options to purchase versus renting such vehicles must be considered as well as their fuel requirements, since researchers may need to bring their own fuel.

Local community involvement is critical to the success of this study. Local residents are well equipped to traverse the ice safely, anticipate weather and ice conditions, and provide safety from polar bears. Including local communities in the research, directly or indirectly, is highly encouraged when applying for various permits and licenses. Arctic sustainability is key to local survival. Erosion is an obvious concern for many communities, as well as changes to subsistence hunting, availability of wildlife and other country foods. Snowfall and stream flow supply drinking water, drive river chemistry, and modify contaminants from oil and gas exploration. In all cases, researchers should be prepared to allow free and timely access to data and associated project reports to the residents.

Researchers should be cognizant of the bureaucracy involved in obtaining permits and should be prepared to apply to numerous organizations and committees. As an example that covers Canadian requirements, a researcher working on Canadian Arctic rivers must obtain appropriate research licenses for Yukon, Nunavut, and Northwest Territories, including: Nunavut and Northwest Territories water board permissions, permits from Parks Canada and Environment Canada to enter national parks and bird migration sanctuaries, environmental screening of the project to mitigate impacts, land use licenses for the Inuvialuit Settlement region, letters of support from hunter and trapper organizations, and endorsements from community corporations in each of the locale visited. Each party may want detailed information about the project, including safety and mitigation strategies; potential environmental impacts requiring knowledge of the flora and fauna that be disturbed while sampling in the proposed area; and inventories of heavy equipment, fuel, or hazardous chemicals. The amount of time needed to properly address these applications should not be underestimated. Fees associated with permit applications are typically small. However, translation services may add up quickly. Standard translation fees are on the order of $0.50 per word, and researchers are typically required to translate documents into two languages. Bear monitors and field guides can also be expensive, around $1,000 per day. The web sites listed provide more details.

- United States: http://icefloe.net/community-primer
- North Slope Borough: http://www.north-slope.org/assets/images/uploads /Form_400_Study_Permit_Application_-_Instructions.pdf
- Yukon: http://www.tc.gov.yk.ca/fr/pdf/science_research_guidelines.pdf

- Northwest Territories: http://nwtresearch.com/
- Nunavut: http://www.nri.nu.ca

Housing: Some communities have hotels. However, in other villages, there is no hotel or only one hotel; during certain peak periods, finding housing can be a challenge. It is recommended that housing arrangements be made well in advance of field operations.

5.2.3 Ships

Arctic-COLORS will require access to small, midsize, and large vessels depending on the research question being answered. For example, small to midsize vessels include the Annika Marie and Ukpik based out of Prudhoe Bay or the larger Norseman II (http://www.norsemanmaritime.com/). Other ships have been used by the Office of Naval Research-funded Marginal Ice Zone project and are often procured by industry and others in the area. Alaska Clean Seas (http://www.alaskacleanseas.org/) can provide small boat rentals along the Beaufort Coast as well. Timing and scheduling are critical.

Table 5.2. List of Potential Research Vessels and Costs for Consideration

Research Vessel	Details	Cost US K$/day	Contact Information
Private vessels	32 ft (out of Barrow) 77 ft (out of Russian Mission) 132 ft (out of Prudhoe Bay)	$5.5 $8.8 $28	Able coastal vessels are available at a lower cost than the larger ice-capable vessels http://www.norsemanmaritime.com/ http://www.ntcl.com http://www.rvannikamarie.com/ Details on vessel, port and cost from C. Polashenski.
USCGC Healy	Berth space for 50 scientists	~$50	http://www.uscg.mil/pacarea/cgcHealy/)
UNOLS R/V Sikuliaq	Berth space for ~25 scientists	~$45	https://www.sikuliaq.alaska.edu/ Owned by the National Science Foundation and operated by the University of Alaska Fairbanks
CCGS Sir Wilfrid Laurier			http://en.wikipedia.org/wiki/CCGS_Sir_Wilfrid_Laurier
CCGS Louis S. St. Laurent			http://en.wikipedia.org/wiki/CCGS_Louis_S._St-Laurent
CCGS Amundsen		~$60	http://www.amundsen.ulaval.ca/
I/B Oden			http://en.wikipedia.org/wiki/Oden_(1988_icebreaker) and http://polar.se/en/om-oss/forskningsplattformar/fartyg/ Operated by the Swedish Polar Research Secretariat http://www.sprs.org
RV Araon			http://en.wikipedia.org/wiki/RV_Araon and http://eng.kopri.re.kr/home_e/contents/e_3400000/view.cms

A number of ice-capable ship platforms would be suitable for support of the Arctic-COLORS field program, such as the USCGC Healy and the new University Oceanographic Laboratory System (UNOLS) research vessel, Sikuliaq. Research scientists have also used Canadian Coast Guard vessels during the past few decades. These include the CCGS Sir Wilfrid Laurier, which annually supports the National Science Foundation (NSF)-supported Distributed Biological Observatory project in the Bering and Chukchi Seas (http://www.arctic.noaa.gov/dbo/); the Louis S. St-Laurent, which has provided support for the Beaufort Gyre Exploration Project (http://www.whoi.edu/beaufortgyre/); and the CCGS Amundsen, which has been supporting the Canadian ArcticNet program (http://www.arcticnet.ulaval.ca/). The Amundsen was specifically re-fitted for science operations with berths for large science parties. Similarly, the Swedish icebreaker, Oden, is also suitable for large science parties and has worked in the Arctic-COLORS core domain before, which included supporting small boats that surveyed coastal lagoons. The Korean icebreaker, Araon, has also provided sea-going support for U.S. scientists, most recently for the Marginal Ice Zone project in 2014 (http://www.apl.uw.edu/project/project.php?id=miz).

There are complexities with the use of foreign icebreakers, including the need for separate cooperative agreements. For example, Canadian Coast Guard icebreakers technically cannot be chartered. Access requires a collaborative effort between Canadian and U.S. scientists are required, typically with a Canadian national serving as the chief scientist.

5.2.4 Sub-orbital platforms

Arctic-COLORS will benefit from, and contribute to, the development of new technologies and emerging approaches for remote UV-NIR retrievals of ocean color, coastal lidar-based estimates of vertical structure and aerosol optical thickness, and high-resolution mapping of coastal features. Several sensors and platforms could be used. For example, a high-altitude Lockheed ER2 is capable of flying both a lidar and hyperspectral ocean color sensor, as could a Lockheed C130. Smaller aircrafts, such as the Beechcraft King Air and Twin Otter, are capable of hosting a number of hyperspectral ocean color sensors and have already flown them over the Chukchi Sea (e.g., Churnside and Marchbanks, 2015). There may also be a role for remotely operated drones or fixed dirigibles that could host low-mass sensors.

Suborbital campaigns will vary widely in cost. The cost of the ER2 is approximately $3.5K/hour. This includes both mission and transit times. A typical mission will last about seven hours, with an hour on the front side for achieving altitude. A campaign using a C130 is likely more expensive than one using a smaller aircraft, such as the King Air. Collaboration with other Federal agencies (e.g., BOEM, Coast Guard District 17) may allow access to flights in northern Alaska for opportunity-driven science at much lower cost. Budgeting must include contingencies such as long transit times, weather delays (with crew layover expenses), instrument integration, and data delivery costs. A single campaign with several overflights taking place during a one-week interval could cost $300–$700K.

This component will benefit greatly from collaboration with the NASA ABoVE field campaign to achieve research synergy and allow for resource sharing, both of which will increase the science return and decrease costs.

5.3. Data Management

Arctic-COLORS will provide a unique framework to study, for the first time, the Arctic coastal zone as an integrated land-ocean-atmosphere-biosphere system, and characterize present and future impacts of terrigenous, atmospheric and oceanic fluxes on coastal ecology, biology and biogeochemistry. Addressing this goal will require integration of oceanographic, hydrological, terrestrial, and social-ecological observations and data products across a large geographic domain that crosses international borders. Among the lessons learned from previous NASA field campaigns (BOREAS, LBA-ECO, ICESCAPE) are the hazards of having individual investigators use ad-hoc data management techniques, and the benefits of developing coordinated data and information management approaches that allow for the timely sharing, communicating and archiving of the results of scientific research. Moreover, the increasingly demanding requirements for the processing, integration, and analysis of field observations in combination with data from remote-sensing systems have driven the development of a novel approach for NASA's ABoVE campaign.

Briefly, proposals for ABoVE were solicited through ROSES-14, and the selection of a science team was announced in August 2015. ABoVE will integrate field-based studies, modeling, and data from airborne and satellite remote sensing. NASA HQ programs in High Performance Computing and Terrestrial Ecology have endorsed a partnership between the NASA Center for Climate Simulation (NCCS) and the NASA Carbon Cycle and Ecosystems Office (CCEO) to create a high performance science cloud for this field campaign. The ABoVE Science Cloud (http://above.nasa.gov/science_cloud.html) combines high performance computing with emerging technologies and data management with tools for analyzing and processing geographic information to create an environment specifically designed for large-scale modeling, analysis of remote-sensing data, copious disk storage for "big data" with integrated data management, and integration of core variables from in-situ networks and platforms. The ABoVE Science Cloud is a collaboration that promises to accelerate the pace of new Arctic science for researchers participating in the field campaign. Furthermore, by using the ABoVE Science Cloud as a shared and centralized resource, researchers reduce costs for their proposed work, making proposed research more competitive.

Arctic-COLORS will fully engage with the CCEO and the NCCS in the use of the ABoVE Science Cloud. Arctic-COLORS management should leverage the efforts of the CCEO in coordination of data management activities across NASA, its partners, and other data management and cyber-infrastructure efforts that are being carried out by other organizations in the shared study domain. Arctic-COLORS and the CCEO should participate in interagency and international efforts to promote, coordinate, and share Arctic cyberinfrastructure. Examples of complementary data management activities include the NASA SeaDAS (http://seadas.gsfc.nasa.gov), the Biological and Chemical Oceanography Data Management Office (http://www.bco-dmo.org), the National Snow and Ice Data Center (http://www.nsidc.org), the UCAR Earth Observations Lab (http://eol.ucar.edu). the Alaska Ocean Observing System (http://www.aoos.org), and the Polar Data Catalogue (https://www.polardata.ca) used by POLAR.

All data collected and science products generated during ARCTIC-COLORS will be managed following the NASA Earth Science Data and Information Policy (http://science.nasa.gov/earth-science/earth-science-data/data-information-policy). Data collected during Arctic-COLORS will be archived and distributed by NASA's SeaBASS (http://seabass.gsfc.nasa.gov), the ORNL DAAC (http://daac.ornl.gov), or other long-term archives.

5.4. Past and On-Going Programs Relevant to Arctic-COLORS

Arctic-COLORS will be undertaken in the context of an extensive suite of field studies that have been undertaken in the Chukchi and Beaufort coastal regions over the past several decades. Appreciation and consideration for the work that has been undertaken both on land and sea in the past, as well as on-going efforts will help inform the science questions and strategies to be addressed in Arctic-COLORS. The Pacific Arctic Marine Regional Synthesis (PacMARS; http://pacmars.cbl.umces.edu/ and http://www.nprb.org/arctic-program) is a recent project, supported through the North Pacific Research Board (NPRB), which was tasked to summarize and synthesize existing knowledge from past and on-going projects in the marine domain. The PacMARS report, now available at, http://www.nprb.org/assets/images/uploads/PacMARS_Final_Report_forweb.pdf, includes an extensive annotated appendix of coordinated and individual projects that have been supported by a wide variety of public and private entities, dating back to the 1970's. Included within this project inventory are links to relevant websites and data repositories.

A brief summary of the large integrated projects that have contributed to our knowledge of biological, biogeochemical and marine processes in the Arctic-COLORS study area include the National Science Foundation (NSF) supported Inner Shelf Transfer and Recycling Project (ISHTAR) in the 1980's that established understanding of the oceanographic processes in the northern Bering and Chukchi seas that contribute to overall high productivity, including the relatively small role played by rivers such as the Yukon. NSF also supported work from 2000–2008 during a three-phase Shelf-Basin Interactions (SBI) project that established much of our current knowledge on exchange of organic materials and water masses from the shelf to the deep basin of the Pacific-influenced Arctic Ocean, and subsequent potential impacts upon global ocean processes. Most recently NSF cooperated with the NPRB in implementation of the Bering Sea Project (http://www.nprb.org/ bering-sea-project) as an integrated ecosystem program that contributed to understanding ecosystem processes, particularly to the south of the study area envisioned for Arctic-COLORS. Other important work in the study area includes the Outer Continental Shelf Environmental Assessment Program that predated oil development, and much more recent work that has been supported by industry (Chukchi Sea Environmental Studies Program; https://www.chukchiscience.com/) and the Bureau of Ocean Energy Management (e.g., the Chukchi Offshore Monitoring in Drilling Area program; http://www.comidacab.org).

Canadian colleagues led the Canadian Arctic Shelf Exchange Study (2002–2004) (CASES; http://cases.quebec-ocean.ulaval.ca/welcome.asp) and the Circumpolar Flaw Lead Study (CFL; http://umanitoba.ca/faculties/environment/departments/ceos/research/cfl.html) near the Mackenzie River shelf. Both characterized multidisciplinary and seasonal, through-the-winter coverage of the region. The French-Canadian MALINA project (http://malina.obs-vlfr.fr/index.html) also focused on the southern Beaufort Sea and the shelf adjacent to Mackenzie river outlet in late summer. A new Canadian-funded project, Sentinelle Nord, linking Arctic biogeochemistry and human health, will be deployed over the next decade.

Despite this legacy of prior work documented in the PacMARS report, the orientation of Arctic-COLORS to the land-sea boundary is distinctive if not unique, and NASA is filling an ambitious role that most other arctic science sponsors have not been able to support in a coordinated manner. NSF supported a Study of the Northern Alaska Coastal System (SNACS) in 2005–2008 (http://www.arcus.org/arcss/snacs/index.php), but its five projects were only loosely coordinated and studied either terrestrial or marine systems, but rarely both. NASA's most recent Arctic marine research study, the Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment project (ICESCAPE, http://ocean.stanford.edu/icescape/) has shown that NASA is poised to make important contributions as a funding agency to understanding the changing Arctic system through studies of biological productivity that may be changing as light transmission through thinner sea ice increases. ICESCAPE was coordinated with the Canadian- and French-funded Malina (http://malina.obs-vlfr.fr/) that focused on the control by light of biodiversity and biogeochemical fluxes in the southern Beaufort Sea and the shelf adjacent to the Mackenzie River.

The Arctic Boreal Vulnerability Experiment (ABoVE) program, supported by NASA, will ideally dovetail with important terrestrial influences on the marine system, for example, permafrost thaw, hydrological, thermokarst, vegetation, and biogeochemical shifts and the resulting changes in fluxes of freshwater, nutrients, and organic carbon. Thus, it is timely for NASA to improve research coordination across the United States-Canadian border, treating the landscape and shorescape as a single entity with a focus on both terrestrial changes and the coastal zone. Arctic Observation Network projects such as the Arctic Great Rivers Observatory (http://www.arcticgreatrivers.org/) directly address runoff contributions from the two globally important rivers in the study area, the Yukon and Mackenzie. Arctic-COLORS will be contemporaneous with a number of other projects working in the Arctic marine system, and cooperation and synergies should be explored to maximize efficiencies of science funds and personnel. Among the on-going projects that are likely to be of importance to Arctic-COLORS include: the Russian-American Long-term Census of the Arctic (RUSALCA), the Arctic Marine Biodiversity Observing Network (AMBON; supported by the National Ocean Partnership Program), the Beaufort Gyre Observatory Project (supported by NSF), the Distributed Biological Observatory (DBO; supported by a number of agencies through the Interagency Arctic Research Policy Committee), the Department of Energy (DOE) Next Generation Ecosystem Exeriments (NGEE)-Arctic, and the new Marine Arctic Ecosystem Study (MARES NOPP PARTNERSHIP; coordinated by BOEM through the National Ocean Partnership Program). The NPRB is using the results of the PacMARS project as a basis for developing an integrated Arctic ecosystem project with other agencies focusing on the Chukchi Sea over a period of performance of 2016–2021, with most fieldwork slated for 2017–2018. The Canadian POLAR program will provide "baseline information preparedness for development, predicting the impacts of changing ice, permafrost and snow on shipping, communities and infrastructure, and underwater situation awareness" (§8.5). The newly Canadian-funded Sentinelle Nord project awarded to Université

Laval (~$98M between 2015-2022), a collaboration between academia, the public sector, and the private sector, will study the impact of climate change on the Arctic by looking at different facets of the environment, from animal populations to mining. Sentinelle Nord will develop tools to monitor human health and the environment, diagnostic models to mitigate human health or environmental disasters, and predictive decision-support models to realize sustainable ecosystems, human health and development of the Canadian Arctic/subArctic (Marbel Babin, personal communication). A key component of this program is support for the development of new technologies including a broad-range of optical instrumentation to monitor Arctic ecosystems from the ground, ships, in-water, airplanes, or drones. The European Commission Horizon 2020: Societal Challenges program in blue growth will be soliciting proposals on "the effect of climate change on Arctic permafrost and its socio-economic impact, with a focus on coastal areas" with a deadline of February 2017 (see http://research.uarctic.org/news/2015/9/h2020-bg-2017-call-for-blue-growth-demonstrating-an-ocean-of-opportunities-arctic-dimension/).

Table 5.1 Timeline of Ongoing and Upcoming Arctic Observing Programs

Project	**Region**	2016	2018	2020	2022	2024	2026	2028
AMBON	Chukchi	…	→					
DBO	Bering, Chukchi and Beaufort shelves	…	→					
RUSALCA	Chukchi- E. Siberian Sea	…	→					
Beaufort Gyre	Beaufort	…	→					
MARES NOPP PARTNERSHIP	Coastal Beaufort	…	→					
Arctic-COLORS	Coastal zone between Mackenzie and Yukon R.		←	—	—	—	—	→
ABoVE	Canadian Arctic and Alaska boreal and tundra	←	—	—	—	→		
NPRB	Chukchi	←	—	→				
Sentinelle Nord		←	—	—	→			

5.5. Science Communication during Arctic-COLORS

Coastal Arctic ecosystems are a vital part of the region's economy because of their importance for subsistence fisheries and as a foraging habitat for an extraordinarily rich and diverse habit of marine mammals and seabirds. Sea ice, for instance, is a critical platform for many species to access food and to complete critical components of their life cycle. In the past, climate change has induced major ecosystem shifts in some areas, and this could happen again resulting in radical unpredictable changes at the lower trophic level that could have cascading effects on the rest of the food chain. Arctic-COLORS will not only provide better information on productivity of coastal Arctic ecosystems, but will promote awareness of their vulnerabilities of Arctic communities to climate change.

Arctic-COLORS research questions will strive to achieve a balance between the scientific motivations to understand the arctic system and stakeholder concerns about ecosystem services and natural resources important to coastal communities. Arctic-COLORS will respect the needs and concerns of local residents during the planning and implementation of the program, which is likely to involve work within some of these communities, and also communicate plans and research findings back to local residents via meetings, distribution of posters, and by returning to villages to provide science results. Consultation with village leaders will be essential to highlight community needs that could be addressed by Arctic-COLORS research activities as well as to prevent any scheduling conflicts potentially arising from the proposed research activities.

Science communication plans will highlight the common science themes and discoveries of both ABoVE and Arctic-COLORS. Within this context, individual and joint training, education, and public outreach plans should be developed that provide formal educational opportunities through the selected PI's institutions and other institutions within the Arctic study domain. Institutional PIs and Arctic-COLORS management will be expected to participate in informal education and public outreach opportunities coordinated by NASA CCEO.

Arctic-COLORS communications efforts must be cognizant of the NASA Science Mission Directorate (SMD)'s desire to move from mission-by-mission products and services and towards aggregation of efforts into science-based disciplines aligned with the SMD Divisions. ABoVE and Arctic-COLORS should anticipate working within the new education structure(s) developed by NASA to accomplish education goals, and may need to allocate some funds to do so. There will undoubtedly be mechanisms for ABoVE and Arctic-COLORS science to be brought into educational activities that are funded via these initiatives, which requires awardees to work closely with NASA and other NASA-funded scientists. Missions are expected to provide scientific content and in some cases contribute funding to create mission-specific products. For ABoVE and Arctic-COLORS some important infrastructure activities include 1) The Science Visualization Studio at GSFC; 2) The Earth to Sky Partnership between NASA and the National Park Service; 3) GLOBE; 4) the Museum Alliance; and 5) The Earth Observatory. Additionally, ABoVE and Arctic-COLORS should anticipate working with the NASA Earth science communications team's Earth Right Now campaign to include Arctic research, even an Arctic theme. Finally, there will be opportunities to work together with close partners (see §5.4) MARES NOPP PARTNERSHIPin all these areas.

6. 0| Outcomes

The goals of Arctic-COLORS are fully aligned with the White House National Strategy for the Arctic Region, *"to protect the Arctic environment and conserve its resources; establish and institutionalize an integrated Arctic management framework; ...* ***and employ scientific research and traditional knowledge to increase understanding of the Arctic."*** In particular, Arctic-COLORS is focused on quantifying the impacts of rapid climate-driven changes that are bombarding sensitive coastal ecosystems from both the land and sea. The health of the Arctic coastal zone is critical to regional communities, while current change in the Arctic is likely a harbinger for future change in coastal zones at lower latitudes as well. The biogeochemical complexity of the land-ocean-ice interface in the Arctic region is unlike any other coastal zone in the world, and as such, will require an unprecedented integrative effort between multiple disciplines while utilizing remote sensing to integrate across multiple temporal and spatial scales. In addition to improving the quantitative understanding of Arctic coastal systems, the tools developed in the process of this research will be of great benefit to future studies around the globe.

Ultimately, the models developed and improved by this research will provide a window into the future of the Arctic, with emphasis on identifying the most vulnerable components of the coastal ecosystem to change and the primary drivers that lead to those vulnerabilities. Such information will have great utility in planning for future management scenarios and contingencies.

The objectives of Arctic-COLORS directly support the strategic goals and objectives of NASA's Ocean Biology and Biogeochemistry Program, and are fully aligned with the objectives of NASA's Applied Science, Terrestrial Ecology, Biodiversity, Carbon Cycle, Ecological Forecasting, and the Cryospheric Science Programs. The ground-truthing between biogeochemical measurements and remote-sensing algorithms from Arctic-COLORS will prove critical toward the development of NASA's PACE mission. Arctic-COLORS will facilitate high temporal-, high spatial- and high spectral-resolution field observations that contribute directly to PACE validation efforts, and will enhance remote-sensing capabilities *in one of the most responsive regions to Climate Change, the Arctic.* Coastal zones in general are some of the most heavily impacted regions of the world by human activity, and with rising sea level will continue to undergo a high level of stress. As such, it is critical to develop remote-sensing tools that are applicable to all coastal zones, and Arctic-COLORS will push those tools in new directions for ice-impacted regions. Arctic-COLORS observations will be particularly useful for informing measurement requirements and optimal remote-sensing design of future NASA sensors (e.g., GEO-CAPE, HyspIRI, ACE) while observing the Polar Regions, and mitigating risks while maximizing the return of NASA satellite missions.

Finally, Arctic-COLORS will give rise to a new generation of coastal researchers. Our planet faces daunting environmental problems, and there is a great need for inspired environmental scientists who are passionate about solving those problems, particularly in the Polar Regions. Arctic-COLORS will provide a platform by which young scientists can learn to work in an integrative environment with state-of-the-art tools while overcoming significant logistical challenges, all with the goal of improving the future prospects of the local communities and beyond.

7.0| References

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8.0| Appendices

8.1. Project Cost Estimation Procedure

A cost estimate for the Arctic-COLORS Field Campaign activity was prepared as shown in Table 8.1. A number of assumptions had to be applied to generate the cost estimate. For the purposes of the process/intensive cruises, the Arctic-COLORS study domain was sub-divided into four regions: Mackenzie Delta and adjacent shelf, other Beaufort river plumes and shelf, Chukchi river plumes and shelf, and the Yukon Delta and Norton Sound. Each of these four regions would be sampled over three years for each the seasons defined, though different river plume/shelf systems would be sampled over the four years of fieldwork. Thus, study sites and regions under investigation would be staggered across the 4-year period. Late winter (early March) sampling from river mouth to outer shelf would be conducted with the aid of over-the-snow/all-terrain vehicles and helicopters for transport to the landfast ice and sea ice-covered regions. Large icebreaker vessels would be used in late May/June to sample the mid- and outer-shelf regions. Over-the-snow/all-terrain vehicles and helicopters will be used in late spring as well to access nearshore areas that cannot be accessed by large icebreakers. The UNOLS R/V Sikuliaq (medium size, ice-capable) and various coastal ships and boats will be employed for summer (late July) and minimum ice extent (September) seasons for the process/intensive studies as well as helicopters in summer. Costs for small boats for PI-unique activities would be borne by individual grants. *In situ* buoys, moorings and gliders will be deployed and retrieved (as appropriate) from vessels planned for intensive process cruises. Some or many of these assets would presumably not be retrieved. Funds for buoys, moorings and gliders would be allocated to grants as a portion of the $2.8M in equipment budgeted (approximated as $100K per grant).

The survey cruises that will be conducted in July and the September/October timeframe will utilize coastal ships and boats and large icebreakers of opportunity. For example, the CCGS Sir Wilfrid Laurier transits each year through the Arctic-COLORS study area from its home port in Victoria, British Columbia, to the Canadian Arctic in July (eastbound) and in October (westbound) and has been "chartered" for a number of days during these transits. "As a Canadian government asset, it is not technically a charter vessel and requires a cooperative agreement and the involvement of Canadian scientists" (L. Cooper, pers. comm.). Regardless of whether such accommodations can be realized, large icebreakers will be operating within the study region for Arctic-COLORS process studies or other programs and can be scheduled for 28 days per year to conduct survey studies. For costing purposes, our assumption is that each region would be surveyed for only 3 years of the 4 total years of fieldwork planned.

Dedicated flight costs for airborne remote sensing are estimated by assuming an average of $15.8K/day for a Ken Borek Air Twin Otter aircraft (twin-engine aircraft; single engine aircrafts over water are prohibited by NASA), which includes non-flight days. The cost estimate was provided by Glenn Research Center to Christy Hansen for this report. This rate includes labor and travel costs for pilots, mechanics and instrument technicians. The cost estimates for airplane logistics include integration and testing of instrument payloads and transfer of airplane(s) to the Arctic region and assumed to be $600K per season (3 seasons/yr for 4 years). No cost-sharing is assumed with ABoVE or other airborne remote-sensing activities.

Project management includes data management following the ABoVE model and includes data management, safety and training, ship coordination, helicopter, airborne remote sensing and other field logistics, project meetings, etc. Our assumption is that an existing project office would be tasked to manage the activity to realize cost savings as opposed to establishing a new entity from scratch. Annual costs will vary depending on the level of the activity (low during synthesis phase but high during field years).

Ken Borek Air Twin Otter Aircraft Deployment for Arctic-COLORS

Assumptions

1. This captures approximate costs for one field deployment, at 10 days in the field.
2. It includes all costs for the aircraft, fuel, landing fees, per diems, and flight crew costs (3 flight crew)
3. It assumes 1 flight per day, each flight being 4 hours long
4. It includes the cost to get the aircraft from its home base in Calgary, CA, to a science base (Barrow), and back home again after mission ends.
5. It does not include any costs associated with engineering work to fit the instruments to the aircraft (this is part of the $600K per season cost estimate).
6. It does not include the travel costs and per diem costs for the science/instrument team.
7. It assumes take off and landing from same location each day once in the field (Barrow in this example).

Positioning Costs Breakdown

- 11.5 hours each way - Ferry (positioning flight) from Calgary to Barrow
- 400L/hr x 1.55/L x 23 hours = CAD $14,260 (Canadian dollars); Since Canadian dollars as the majority of positioning fuel will be uplifted in Canada.
- Twin Otter x 23 hours = USD $42,895.00
- Nav Fee: 89 x 2 = CAD $178.00; In Canada, we are charged navigation fees (CAD $89.00 per day for the Twin Otter). Goes to Nav Canada for air traffic control facilities and wages.
- Landing Fees: 95 x 6 = CAD $570.00; This fee is charged every time the aircraft lands. Estimated 3 landings between Calgary and Barrow and 3 landings on the return leg from Barrow to Calgary.
- Hotel (if applicable); Will only be charged for hotels if the crew has to overnight between Calgary and Barrow. It will be a long duty day; they will likely overnight in Inuvik.
- Total USD: $42,895.00
- Total CAD: $15,008.00 (USD $11,397.00)
- <u>Positioning Total: USD $54,292.00</u>

Operational Costs Breakdown

- Number of daily flight hours is not known so estimate is based on carrier daily minimum of 4 hours.
- USD $1,865.00 x 4 = 7,460; This is aircraft cost per hour, at a min of 4 hours per day.
- 7,460 x 10 operational days = USD $74,600.00
- <u>Operational Total: USD $74,600.00</u>

Incidentals: Operational Period Cost Breakdown

- Hotel: 250 x 3 x 10 days = USD $7500 arranged and paid for in advance by charterer
- Meals: 60 x 3 x 10 days = USD $1800 arranged and paid for in advance by charterer
- Nav: 89 x 5 operational days = Invoiced actual rate what is this? See above
- Landing: Invoiced actual rate
- Fuel: 400L/hr x 5 operational days @ 4 hours per day = USD $13,600
- <u>Incidental Total: USD $22,900.00</u>

Total Positioning and Operational Costs Summary (For Deployment 1)

- Positioning Total: USD $54,292.00
- Operational Total: USD $74,600.00
- Incidental Total: USD $22,900.00
- <u>Grand Total: USD $151,792.00</u>

Table 8.1. Basis of Budget Estimate for Arctic-COLORS Project

				# Ship Days per year			# days/yr	# days/yr	# days/yr
Process/Intensive Cruises	**Region**		**R/V Sikuliaq**	**Icebreaker - large**	**Coastal vessels**		**Airplane**	**Helicopter**	**All Terrain Vehicle**
	Mackenzie Delta and Shelf	3 years	16	10	14	3 years	10	30	60
	Yukon Delta and Norton Sound	3 years	12	10	10	3 years	10	30	60
	Other Chukchi coastal	3 years	20	10	20	3 years	20	30	120
	Other Beaufort coastal	3 years	12	8	12	3 years	10	30	90
Seasons: (1) early March, (2) late May/June, (3) late July, & (4) September			*3 & 4*	*2*	*3 & 4*		*2, 3 & 4*	*1, 2, & 3*	*1 & 2*
		TOTAL (days/yr)	**60**	**38**	**56**		**50**	**120**	**330**
Survey Cruises	**Region**								
	Norton Sound	3 years	0	4	7				
	Chukchi Sea	3 years	0	12	15				
	Beaufort Sea	3 years	0	12	15				
Seasons: (1) July & (2) September/October			*both*	*both*	*both*				
		TOTAL (days/yr)	**0**	**28**	**37**				
Total # days required			**180**	**198**	**279**		**150**	**360**	**990**
Cost ($K)/day			**45**	**55**	**15**		**15.2**	**5**	**0.2**
Total Cost/Project ($K)			**8,100**	**10,890**	**4,185**		**2,280**	**1,800**	**198**
						Airplane Logistics ($K)	**7,200**		

Cost of Science Teams						
Phase	**# Groups**	**$K/yr**	**Years**	**$K/1 time equipment**	**$K/project**	**TOTAL ($K)**
Phase I	3	200	1	0	200	**600**
Phase IIA	14	300	4	100	1,300	**18,200**
Phase IIB	14	300	4	100	1,300	**18,200**
Phase III	5	300	2	10	610	**3,050**
					TOTAL	**40,050**

SUMMARY	**$K**	**% Total**
Project Management ($500K/yr for 10 years)	5,000	6.3
ROSES Awards to Science Teams	40,050	50.2
Ships, helicopters, All Terrain Vehicles, etc.	25,173	31.6
Airplane Remote Sensing	9,480	11.9
TOTAL Costs of Arctic-COLORS	**79,703**	100.0

NOTES:

Assume large icebreaker costs for survey cruises based on usage of transiting icebreakers from Victoria/Seattle to Barrow or Canadian Arctic

small boat costs to be covered by individual grants

in situ floats, moorings and gliders will be deployed and retrieved from vessels planned for process/intensive cruises; some assets will not be retrieved; funds allocated to grants (portion of $2.8M equipment); assume some assets will not be retrieved

Airplane logistics include integration and testing of instrument payloads and transfer of airplane to Arctic region - assuming $600K per season (3 seasons/yr for 4 years)

Coastal Vessels: Coast Guard buoy tenders, Marty Bergman, Norseman, etc.

Project management includes data mngmt following ABoVE model (data mngmt, safety and training, ship coordination, other field logistics; project meetings, etc.); annual cost will vary depending on activity (low during synthesis; high during field years)

Phase II ROSES awards include field sampling, modeling, and remote sensing activities

8.2. Core Variables and Datasets

The Arctic-COLORS workshops (§2) concluded that it would be best for models to have complete datasets with biological/biogeochemical/physico-chemical rates at a few sites rather than lots of survey measurements without a complete set of rate measurements. Below is a list of core variables and non-core measurements that would be necessary to accomplish the objectives of Arctic-COLORS. This is not an exhaustive list and suggestions are welcomed.

Table 8.2. Planned Arctic-COLORS Field Campaign Core and Non-Core Measurements.

	Core Measurements	Non-Core Measurements
Aquatic Biogeochemical	Water column profiles of phytoplankton pigments, chlorophyll-a, POC/PN, DOC/DON, DIC, pCO2, TA, nutrients ($N0_3$, NO_2, NH_4, PO_4, $SiOH_4$), DO, SPM,	Profiles of size fractionated chlorophyll-a and POC/PN, POP and DOP, calcium, phytoplankton C and N Biomarkers and isotopic tracers: Lignin phenols, black carbon, petroleum hydrocarbons, other lipid biomarkers, amino acids, stable CNS isotopes, radiocarbon isotopes, water oxygen isotopes
Aquatic optics	Hyperspectral above-water (UV-Vis-NIR-SWIR) and in-water (UV-Vis-NIR) AOPs (Kd, radiometry) Profiles and surface underway IOPs: hyperspectral absorption attenuation; multi-spectral VSF, backscatter, and beam attenuation; chlorophyll and CDOM fluorometry; particle size spectra. Discrete particle and CDOM absorption	Profiles and surface particle size spectra Discrete CDOM excitation-emission matrices; particle size spectra and abundances
Aquatic Biological/ Biogeochemical/ Physical rates and processes	Profiles of gross and net primary productivity and respiration, Air-sea CO_2 fluxes	Micro- and meso-zooplankton grazing Particle sinking rates Photooxidation of DOM and particles Profiles of net community production,microbial productivity Air-sea CH_4 fluxes POC/PN and DOC/DON remineralization rates Flocculation of DOM Nitrification, denitrification, nitrogen fixation, ammonification, ammonox
Biodiversity	Phytoplankton taxonomic abundances and functional type (size or taxonomic classification) Coastal and sea ice phytoplankton taxonomy	Microbial community composition Zooplankton to higher trophic levels Benthic microbial community, meiofauna, macrofauna, and megafauna
Physical oceanographic	SST, SSS, profiles of temperature, salinity, and density, wave height, horizontal current velocities, vertical current velocities	Wave height, horizontal current velocities, vertical current velocities
Landfast and Sea Ice	Biogeochemical constituents and physical properties of ice, brine water, and melt-water: salnity, chlorophyll-a, POC/PN, DOC/DON, DIC, pCO2, TA, nutrients, SPM Ice thickness, temperature, areal extent, freeboard, other characteristics Under ice gross and net primary productivity Melt pond characteristics; above and in-water hyperspectral radiometry	Biogeochemical constituents and physical properties of ice, brine water, and melt-water: salinity, phytoplankton pigments, salinity, POP and DOP, black carbon, stable CNS isotopes, radiocarbon isotopes, oxygen isotopes Snow cover
Meteorological/ Atmospheric	Surface wind direction and velocity, temperature, humidity, pCO_2	Cloud cover, pressure, precipitation, albedo, surface heat flux, water vapor content, solar radiation

		Aerosol optical depth and vertical layer height and thickness Boundary layer CH_4 Total column ozone and NO_2 concentration
Sediment properties		SOC/SN, porewater DOC/DON, DIC, TA, pH, nutrients, DO, SPM, black carbon, lignin phenols, stable isotopes, seabed erodibility, acoustic scans of seabed to characterize sub-sea floor permafrost, etc.
Benthic rates and processes		Sedimentation and burial rates of SPM, POC/PN Oxygen respiration, denitrification, sulfate reduction, methanogenesis Sediment resuspension Benthic-pelagic fluxes
Hydrological		Freshwater discharge/ volume transport (river, groundwater, surface runoff)
Geomorphology		Coastal erosion fluxes of sediment load, POC/PN, IC, nutrients Bathymetry of channels at river head of tides
Airborne Remote Sensing	Hyperspectral radiometry (UV-Vis-NIR-SWIR) HSRL for in-water particle profiles, CDOM and chlorophyll absorption SST and SSS	HSRL melt pond depth, freeboard at ice edge, aerosol optical depth, aerosol type and microphysical properties Ranging lidar: coastal erosion, snow levels and permafrost.

8.3 Research Presentations

The broader research community became engaged in the development of the initial study design and implementation concept at a number of scientific conferences and programmatic meetings where presentations were made. Town Hall meetings were conducted, and special Break-Out Sessions were convened. These included the ABoVE Science Definition Team meeting (February 2014), the 2014 Ocean Sciences Meeting (February 2014), the NASA Ocean Color Research Team Meeting (May 2014), the Canadian Ocean Meteorological Society Meeting (June 2014), the Ocean Optics XXII Conference (October 2014), the international Arctic Change 2014 Conference (December 2014), the American Geophysical Union - AGU Fall 2014 Meeting (December 2014), the North American Carbon Program and AmeriFlux Joint Meeting (January 2015), the European Geophysical Union - EGU Spring 2015 Meeting (April 2015), the NASA Carbon Cycle & Ecosystem Meeting (April 2015), the Canadian Ocean Meteorological Society Meeting (June 2015), the International Ocean Color Symposium/NASA Ocean Color Research Team Meeting (June 2015), the 2015 Ocean Carbon and Biogeochemistry meeting (July), and planned for the 2015 Fall AGU meeting (December).

8.4 Acronyms

ABoVE	Arctic Boreal Vulnerability Experiment
ACE	Aerosol, Clouds and ocean Ecosystem
ADEOS	Advanced Earth Observing Satellite
AGU	American Geophysical Union
AMBON	Arctic Marine Biodiversity Observing Network
AMSR2	Advanced Microwave Scanning Radiometer 2
AOP	Apparent Optical Properties
Arctic-COLORS	Arctic Coastal Land Ocean Interactions
ARCTIC-STAR	Solution-oriented, transdisciplinary research for a sustainable Arctic
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLAS	Advanced Topographic Laser Altimeter System
AUV	Autonomous Underwater Vehicle
AVHRR	Advanced Very High Resolution Radiometer
BOEM	Bureau of Ocean Energy Management
BOREAS	Boreal Ecosystems-Atmospheric Study
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CASES	Canadian Arctic Shelf Exchange Study
CCGS	Canadian Coast Guard Ship
CDOM	Colored Dissolved Organic Matter
CFL	Circumpolar Flaw Lead study
Chla	Chlorophyll-a
CMIP5	Coupled Model Intercomparison Project, Phase 5
CONAE	Comisión Nacional de Actividades Espaciales (Argentine Commission on Space Activities)
CTD	Conductivity, Temperature, Depth
DBO	Distributed Biological Observatory
DIC	Dissolved Inorganic Carbon
DMSP	Defense Meteorological Satellite Program
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DOE	Department of Defense
DON	Dissolved Organic Nitrogen
EGU	European Geophysical Union
ERS	European Remote Sensing satellites (ERS-1, ERS-2)
ESA	European Space Agency
ESMs	Earth System Models
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
GCAS	GEO-CAPE Airborne Simulator
GEO-CAPE	Geostationary for Coastal and Air Pollution Events
GEO-TASO	Geostationary Trace gas and Aerosol Sensor Optimization
GLAS	Geoscience Laser Altimeter System instrument
G-LiHT	Goddard's LiDAR, Hyperspectral & Thermal Imager
GOSAT	Greenhouse gases Observing SATellite
HyspIRI	Hyperspectral Infrared Imager
ICESat	Ice, Cloud, and land Elevation Satellite
ICESat2	Ice, Cloud, and land Elevation Satellite-2
ICESCAPE	Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment
IOP	Inherent Optical Properties

IR	Infra-Red
ISHTAR	Inner Shelf Transfer and Recycling Project
JAXA	Japan Aerospace Exploration Agency
LBA-ECO	Large-scale Biosphere-Atmosphere Experiment in Amazonia - Ecology
LEO	Low Earth Orbit
MARES NOPP PARTNERSHIP	Marine Arctic Ecosystem Study National Ocean Partnership Program
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOE	Ministry of the Environment
MSI	MultiSpectral Instrument
NASA	National Aeronautics and Space Administration
NASA CCEO	NASA Carbon Cycle and Ecosystems Office
NASA HQ	NASA Headquarters
NASA NCCS	NASA Center for Climate Simulation
NASA SMD	NASA Science Mission Directorate
NASDA	National Space Development Agency of Japan
NDVI	Normalized Difference Vegetation Index
NGEE-Arctic	Next-Generation Ecosystem Experiments - Arctic
NIES	National Institute for Environmental Studies
NOAA	National Oceanic and Atmospheric Administration
NPRB	North Pacific Research Board
NRC	National Research Council
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
OBB	Ocean Biology and Biogeochemistry
OCI	Ocean Color Instrument
OCO-2	Orbiting Carbon Observatory 2
OLCI	Ocean Land Colour Instrument
OLI	Operational Land Imager
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
ORNL DAAC	Oak Ridge National Laboratory Distributed Active Archive Center
OSTM	Ocean Surface Topography Mission
PACE	Pre-Aerosol, Clouds, and ocean Ecosystem
PacMARS	Pacific Arctic Marine Regional Synthesis
PFT	Phytoplankton Functional Types
POC	Particulate Organic Carbon
POLAR	Public Knowledge Canada
PRISM	Portable Remote Imaging SpectroMeter
RASM	Regional Arctic System Model
RASM-mBGC	Regional Arctic System Model-marine Biogeochemistry
RCD	Riverine Coastal Domain
ROMS	Regional Ocean Modeling System
RUSALCA	Russian-American Long-term Census of the Arctic
RV	Research Vessel
SBI	Shelf-Basin Interactions
SDT	Science Definition Team
SEABASS	SeaWiFS Bio-Optical Archive and Storage System
SEADAS	SeaWiFS Data Analysis System
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor
SGD	Submarine Groundwater Discharge

SGLI	Second generation GLobal Imager
SMAP	Soil Moisture Active Passive
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SNACKS	Study of the Northern Alaska Coastal System
SNODAS	Snow Data Assimilation System
SNR	Signal-to-Noise Ratio
SPM	Suspended Particulate Matter
SSMIS	Special Sensor Microwave Imager/Sounder
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
STM	Science Traceability matrix
SWIR	Shortwave Infra-Red
SWOT	Surface Water Ocean Topography
TA	Total Alkalinity
TANSO	Thermal And Near-infrared Sensor for carbon Observation
TSM	Total Suspended Matter
UNOLS	University-National Oceanographic Laboratory System
USCGC	United States Coast Guard Cutter
UV	Ultraviolet
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS-NIR	Visible-Near Infrared
VSF	Volume Scattering Function

8.5 Letters of Collaboration

UNIVERSITÉ LAVAL

Cabinet du recteur

September 29 , 2015

Dr. Antonio Mannino
Ocean Ecology Laboratory
NASA Goddard Space Flight Center
National Aeronautics and Space Administration
Goddard Flight Center
8800 Greenbelt Road
Greenbelt, Maryland 20771
USA

Re: Sentinel North project in the framework of the Canada First Research Excellence Fund program

Dear Sir;

I am pleased to announce that the project submitted by our institution to the Canada First Research Excellence program was selected and awarded funding of nearly $100 million.
http://relationsmedias.ulaval.ca/comm/2015/juillet/subvention-historique-pour-universite-laval-3476.html?an=1

The Sentinel North program is based on a convergence of strategic research areas in which Université Laval provides national and international leadership: Arctic science, optics-photonics, cardiometabolic health and mental health.

In effect, Sentinel North is designed to map-out Arctic, subarctic and northern ecosystems and geosystems in the coupled human-environment in real time, using powerful, innovative and transdisciplinary scientific instrumentation.

Sentinel North also relies on partnerships with many organizations and communities like yours. These partnerships are critical to the success and relevance of our project.

On behalf of Université Laval, I want to thank you for the support you've provided to the Sentinel North project. We look forward to continuing and developing exciting collaborations with NASA in the future.

Sincerely yours,

Denis Brière
Rector

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September 27, 2015

Antonio Mannino, Ph.D.
NASA Goddard Space Flight Center
Ocean Ecology Lab
Mail Code 616
Building 22 Room 250
Greenbelt, MD 20771

Subject: **POLAR Letter of Support for NASA Arctic-COLORS Project**

Dear Dr. Mannino:

On behalf of Polar Knowledge Canada (POLAR), I am writing to express our support for the NASA-led Project – **"Arctic Coastal Land Ocean Interactions (Arctic-COLORS)".**

POLAR's mission is to be a world-class research station in Canada's Arctic that is on the cutting edge of Arctic issues (http://www.canada.ca/en/polar-knowledge/index.html), anchoring a strong research presence that serves Canada and the world, while advancing knowledge of the Arctic in order to improve economic opportunities, environmental stewardship, and the quality of life of Northerners and all Canadians. POLAR is also strongly committed to developing productive international partnerships that support its ability to meet its mandate and the Arctic-COLORS project is an excellent example of productive science cooperation on areas of common interest.

The proposed project is strongly supported by POLAR because:

- the area of interest is within the domain of POLAR research and monitoring activities;
- it directly supports three of POLAR's key science priorities, specifically, *Baseline Information Preparedness for Development*, *Predicting the Impacts of Changing Ice, Permafrost and Snow on Shipping, Communities and Infrastructure, and Underwater Situation Awareness";*
- it will build directly on land- and river-based research conducted under partnership with NASA and the ABoVE program, and;
- it strives to work with Northern communities, governments and Aboriginal organizations to ensure local engagement and relevant research that will benefit proactive climate adaptation and knowledge-based mitigation of industrial activities.

For these reasons, and because of the direct value the project provides in addressing key northern scientific questions, the POLAR S&T Team fully supports the Arctic-COLORS proposal.

POLAR has been a part of the development of the project to date and will continue to work with the Arctic-COLORS science team as the project evolves. In particular, POLAR will look for opportunities to coordinate the activities of Canadian partners e.g., federal and territorial departments, local co-management boards, and academics active in research and management in the Beaufort Sea and along the Beaufort Coast to Alaska. POLAR is also very interested in expanding the area of interest for the project to include the CHARS Regional Experimental and Reference Area in the Coronation Gulf area to the east – an area included in the study domain of the NASA-led ABoVE project, where POLAR is working with a wide range of national and international partners to invest in coastal research that directly overlaps with the objectives of the Arctic-COLORS science plan.

For all of these reasons, POLAR strongly supports the NASA-led Arctic-COLORS project and is strongly motivated to look for future opportunities for coordinated investments to support this research within the POLAR Domain.

Yours truly,

Alain Leclair for

Dr. Martin Raillard

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