Revised Executive Summary:

The Arctic-Boreal Vulnerability Experiment

Climate change in the Arctic and Boreal Region (ABR) is unfolding faster than anywhere else on Earth, resulting in a longer ice-free Arctic Ocean during summer, warming and thawing of permafrost, increases in the frequency and severity of climate-driven disturbances, and widespread changes to surface water extent, soil moisture, and vegetation structure and function. Amplification of climate warming in the ABR is particularly important as observations show that temperature variability and trends in this region tend to be larger than those for the Northern Hemisphere or the Earth as a whole. Arctic amplification is a forcing function that leads to multi-scale interactions and nonlinearities that are fundamental to understanding Arctic/boreal ecosystem processes and to constructing robust models and scenarios of ABR futures. In addition to producing significant and widespread climate providing critical feedbacks to climate, environmental change in this region is increasingly affecting society in a variety of ways, including impacts on forests from insects and fires, erosion of Arctic coastlines, changes to wildlife habitat and ecosystems that affect subsistence opportunities, as well as transportation infrastructure, oil, gas, and mineral development, and other economic uses. Long at the edge of our mental map of the world, environmental change in the ABR is rapidly becoming the focus of numerous policy discussions.

To more fully understand the evolving ABR environment and provide the information required to develop options for societal responses to the impacts of ABR climate change, the Arctic-Boreal Vulnerability Experiment (ABoVE) has been proposed as a NASA-sponsored field campaign. Previous and ongoing research sponsored by NASA has focused on developing the types of geospatial information products from remotely-sensed imagery and data that are critical for monitoring key environmental characteristics and processes. In addition, remotely-sensed data products are required to address scaling issues that are inherent in linking process-based research conducted at local scales over short time periods to modeling research that addresses a variety of spatial and temporal scales.

Research carried out as part of ABoVE would provide the opportunity to focus not only on key processes associated with changes to the land surface, but on important interfaces between the land and the coastal ocean and atmosphere as they interact with climate-mediated terrestrial processes. Through research that integrates and synthesizes geospatial data collected by airborne and spaceborne remote sensors with information obtained from field studies and ground-based monitoring, ABoVE would focus on addressing several key questions:

- ***What processes, interactions, and feedbacks control the vulnerability of Arctic and boreal ecosystems and landscapes to structural and functional changes in a changing Earth system?***
- ***How are people at local, regional, national, and global scales being affected by and responding to these changes?***
- ***How do changes to terrestrial processes in the ABR alter inputs to adjacent oceans?***

- ***How do changes to terrestrial processes in the ABR alter climate through exchanges of energy, water, gases, and particulate matter between the land surface and troposphere?***

The research conducted to address these questions would emphasize observations, analyses, syntheses, and modeling. This research would address questions critical to understanding the processes of climate and environmental change in the ABR, focusing on impacts to society and ecosystem services, changes to land surface processes, and interfaces with the adjacent coastal ocean and the overlying troposphere (see Figure 1). The studies conducted as part of ABoVE would provide the basis for improving the reliability of models required to predict how ABR terrestrial and coastal ecosystems and the troposphere are likely to change in the future based on different climate change scenarios. The output from these models, in turn, will provide decision makers, resource managers and other stakeholders with new information to aid in understanding the range of potential impacts on society and formulate decisions on how to respond to ABR environmental change.

ABoVE Study Plan

Research and analysis activities for ABoVE would be carried out in study sites located across western Canada and Alaska. Studies would be carried out over a range of spatial scales, including within different terrestrial ecoregions, within primary and secondary research areas, within discrete landscape units (such as a watershed or disturbance event), and within plots (at a scale of 10 m to 1 km). The exact geographic boundaries and location of study sites will be determined in the more detailed planning activities to follow, and will be influenced by collaborating programs and projects. An initial preparatory research phase would include dataset development, development of a modeling framework, and work to identify/secure/prepare needed field resources and infrastructure. The field phases of the research would be carried out during a multi-year intensive study period. The synthesis and integration phase would include final data analysis, modeling, and synthesis and integration studies making use of the data and information acquired during the intensive study period. The projects funded by NASA as part of the intensive study period would be involved in a variety of activities, focusing on the collection and analyses of airborne remote sensing data, development of new information products from remote sensing data, collection and analysis of field data, integrative analyses, and refinement, validation, and application of models.

A key component of ABoVE would be the use of spatial-temporal information products derived from remotely-sensed data. Remotely-sensed information products would be used in several ways, including providing improved maps of key characteristics (i.e., ecological, hydrological, cryospheric, biogeochemical) of the land, ocean and atmosphere in the ABR, as well as providing the means to measure variations in these characteristics over time. In some cases, remotely-sensed data products would be the primary information source for studying specific processes. In others, these products would be used as key inputs for models or used as a basis for model validation.

A rich array of international satellite and airborne data would be utilized in ABoVE. In addition to the existing satellites and their successors, many new U.S. satellite sensors will be becoming available in the planned timeframe of ABoVE. Of

these, the following would be well-suited to contribute to the scientific goals of ABoVE: Soil Moisture Active Passive (SMAP), Orbiting Carbon Observatory-2 (OCO-2), Ice, Clouds and Elevation Satellite-2 (ICESat-2), and the Joint Polar-orbiting Satellite System (JPSS). Existing remote sensing and *in situ* airborne sensors, such as NASA's AVIRIS and UAVSAR as well as several new instruments now under development, would be available and are anticipated to make strong contributions to ABoVE's observational needs and scaling objectives. Especially noteworthy are 1) the instrumentation being used and data that will be collected in the NASA EV-1 Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) in Alaska in 2012-2014 and 2) the P-band SAR capability being developed through the NASA EV-1 Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) project.

An important activity that would occur during the research conducted is the development, refinement and validation of models based on the studies and analyses being carried out for ABoVE. In order to understand the impacts of the processes that are affected by climate change, or that affect climate change, requires that different process models be linked. A key element of ABoVE will focus on developing the integrated modeling framework needed to improve the representation of key processes and to provide the mechanisms for developing model linkages, particularly via scaling of local processes to regional and larger spatial scales using multi-scale, multi-sensor remote sensing. Compiling regional and global information products would be conducted as part of the activities associated with assessments using the integrated modeling framework. An additional activity for ABoVE would be to synthesize the results from research being carried out in other Arctic/boreal regions. The results from this synthesis would be used to make further refinements of the integrated models developed as part of ABoVE. These integrated models could then be used to conduct a pan-Arctic/boreal assessment of the impacts of climate change during the final synthesis and integration phase of ABoVE or as a follow-on activity.

The development of a data and information system would be another important component for ABoVE. The ABoVE Information System would serve the field campaign as a short-term repository and clearinghouse for all data sets collected and data products generated as a result of ABoVE research. It would provide access to other datasets that would be used during ABoVE that were generated from other ABR research projects, products from land management agencies, and from long-term monitoring efforts. The ABoVE Information System would provide access to the results and assessments being produced through modeling and other analyses to a wide range of end users, and would provide support for experiment planning during ABoVE. Representatives of end users who require information from assessments of the impacts of climate change would be involved in determining the products that would be generated during ABoVE and made available through the ABoVE Information System. Long-term archive of ABoVE data sets would transition to a NASA Distributed Active Archive Center (DAAC) or other appropriate archive.

During ABoVE, particular attention will be focused on those ecosystem processes and characteristics that are unique to the ABR. These include the widespread occurrence of natural disturbances, the presence of permafrost, and the existence of high levels of soil carbon in surface organic layers and frozen soils. At local scales, some Arctic and Boreal ecosystems are resistant or resilient to longer-term changes in climate

and episodic perturbations; however, ongoing climate change in the ABR may be crossing important threshold points that push or tip ecosystems and landscapes into new biophysical states. A key focus of ABoVE is to conduct the research necessary to identify factors that influence vulnerability, as well as to enable identification and understanding of potential tipping points that produce state changes in ecosystem processes and functional attributes.

Society and Ecosystem Services

The motivation for the research proposed for ABoVE is to provide scientific information needed by policy makers, resource managers and other stakeholders to develop policies and approaches that most effectively respond to the climate-driven environmental change in the ABR. While human land use activities are not as extensive as in other regions, a number of human activities directly contribute to environmental change in the ABR. Research on human activities would focus on activities related to the fire regime (human ignitions and fire suppression), oil, gas, and mineral resource exploration and development, and salvage activities in disturbed forests. Research on human impacts and responses would focus on developing an improved understanding of how climate change directly and indirectly affects society and the natural resources that it utilizes (including ecosystem services). This would include studies on the impacts of environmental change on the habitats (including food webs) for key fish, mammal, and migratory bird populations, the use of subsistence and recreational resources by native and non-native populations, harvesting of forest resources, and the impacts of permafrost degradation on resource development, coastal erosion, and human health. By design, research conducted on the impacts of environmental change on the society and ecosystem services will be integrated with research on other processes being affected by climate change. *As a result, all research carried out as part of ABoVE will be guided by the need to address questions of how society is affected by and responds to the impacts of environmental change in the ABR.*

Land Surface Processes

ABoVE would provide the opportunity to conduct research on climate-driven processes that are forcing changes to ABR terrestrial and aquatic ecosystems and land surfaces, in particular changes to disturbance regimes, permafrost warming and thawing, and hydrologic processes. ABoVE research would focus on how changes to these processes are driving changes to ecosystem dynamics and the cycling of soil carbon. This research would also focus on connections, interactions, and feedbacks between the land and the near-shore coastal oceans and troposphere

Climate-driven, natural disturbances impact large areas within the ABR and their frequency has been increasing over the past two decades. Research on disturbance would focus on improving the understanding of controls on and impacts of natural disturbance regimes, including fire, insects, disease, and the formation of thermokarst and other land features associated with thawing of permafrost, and erosion of coastlines. Such research would include investigations on the responses of terrestrial ecosystems to changes in climate, disturbance regimes, surface hydrology and permafrost, including

changes to terrestrial and aquatic ecosystems, and soil microbial processes that drive heterotrophic respiration.

In areas with permafrost, the large reservoirs of soil carbon and hydrological processes are intrinsically linked. Studies of soil carbon would offer the opportunity to investigate the responses of carbon stocks in organic and mineral soil layers to the direct and indirect impacts of climate change. For land systems, research would focus on linking surface-based inventories of soil carbon stocks with land surface features that can be mapped using remote sensing (vegetation cover, locations of wetlands and peatlands, disturbance location and severity, surface hydrology, topography and microtopography) and that control variations in soil carbon, and carbon cycling processes. For permafrost, studies would focus on understanding how variations in climate, surface characteristics (e.g., topography, soils, vegetation type and structure, organic soil depth, surface hydrology) and disturbance history, interact to control the distribution of permafrost as well as the rates of permafrost warming and degradation.

Studies of hydrological processes are not only critical to understanding terrestrial and aquatic ecosystem processes and characteristics in the ABR, but also the processes controlling the exchange of water between the land and coastal oceans and troposphere (discussed below). Research on terrestrial hydrology would provide the opportunity to conduct investigations on the processes and factors controlling landscape and regional-scale variations in the patterns of surface and subsurface water (including soil moisture) over multiple time scales. Because permafrost and seasonal thawing of frozen grounds are important to surface hydrology, this research would be closely linked to research being conducted on permafrost. Studies on the factors controlling variations in water discharge from Arctic/boreal river systems as well as the amounts of suspended and dissolved matter being transported are important from several perspectives. First, these discharges provide inputs of sediments and nutrients to near-shore coastal waters, critical information for understanding coastal ocean processes. Second, water and sediment flow are important for the formation and maintenance of the large delta and estuarine ecosystems found on coastlines. Thus, research on factors controlling river discharges would be important to studies of coastal ocean chemistry and biological processes.

Research on coastal erosion would offer the opportunity to quantify the rates of erosion of Arctic coastlines, and to understand the processes that interact to mediate or intensify this erosion, including sea level rise, formation and loss of seasonal ice cover, coastal currents, storms, and changes to permafrost. Studies would also focus on processes controlling the growth and/or loss of land and changes to vegetation cover within major deltas, estuaries, and salt marshes in the ABR region (e.g., Yukon, Kuskokwim, and Mackenzie Rivers), including the role of river discharge, sea level rise, and increased wave energy resulting from changing coastal and coastal-zone ice cover and changing storm patterns.

Studies of land surface-atmosphere interactions would focus on improving understanding of the key feedbacks and linkages between the land surface/ocean surface and the atmospheric boundary layer/troposphere in the ABR. This research would include studies of factors controlling the reflectivity of the land surface in the ABR, in particular on how variations in snow, vegetation, water, and ice coverage

directly change albedo, as well as the role of disturbance in controlling variations in surface processes (e.g., vegetation, snow, and water dynamics) that influence land-surface reflectivity. In addition, this research area would include studies on how atmospheric deposition of soot and black carbon influences snow dynamics and snow albedo. The research would provide the opportunity to integrate research on the processes responsible for exchanges of carbon dioxide and methane between the land and coastal oceans and the atmosphere. This work could build upon the results from NASA's CARVE project. In a similar fashion, studies would also investigate how variations in vegetation cover, vegetation dynamics, permafrost, and surface hydrology regulate the exchange of water between the land surface and atmosphere. Results from disturbance studies would offer the opportunity to quantify the levels of emissions from wildland fires that are common across the ABR and that contribute to additions of aerosols and particulate matter to the atmosphere.

Coastal Ocean Processes

The Arctic coastal oceans represent a key transition zone between the land and deep ocean basins, and thus are influenced by both terrestrial and oceanic processes. Arctic oceans may be heavily influenced by coastal erosion and by the water, nutrients, and particulate and dissolved organic and inorganic materials originating from river discharge. The terrestrial end members relevant to ocean processes could be studied during ABoVE, thus informing studies of ocean processes, if suitable partnerships can be established with one or more ocean research programs. Such studies could include the processes controlling rates of net ecosystem production (NEP) in the adjacent coastal oceans, in particular the role of ocean circulation and upwelling and nutrient availability; the role NEP plays on fluxes of carbon between the ocean and the atmosphere; and the marine food web. Studies of ocean acidification could examine factors regulating changes in dissolved carbon dioxide, which in turn, control the pH of coastal waters. Research could also be conducted on how changes to ocean acidity interact with ocean productivity to influence the marine food web. Studies could focus on factors controlling near shore circulation, including coastal currents, upwelling, and storms, and the relationship of physical oceanographic processes to permafrost warming, nutrient and sediment transport, and reshaping Arctic coastlines. Research could include studies on how patterns of ice cover influence coastal wave formation and propagation during storms, as well as processes controlling the formation and loss of shoreline ice cover during the spring and fall and interactions between ice cover and temperature-mediated processes in adjacent terrestrial ecosystems (e.g. tundra productivity).

Role of ABoVE in ABR Research

ABoVE would become a new contribution to an existing body of research on northern high-latitude systems and environmental change in the ABR. There is wide-spread recognition that climate change is unfolding faster in the ABR than anywhere else on the Earth, and there is growing appreciation of the imperative to understand its effects on Arctic and boreal systems and the consequences for society. It is also apparent that understanding interactions among major system components, across environmental boundaries and spanning multiple spatial and temporal scales, will be

major challenges in deriving understanding of change in the ABR and its consequences. It would provide the opportunity for coordination of research and monitoring activities on the impacts of climate change in the ABR and to catalyze synthetic and integrative studies building on the foundation of what is known and what is being learned.

A successful ABoVE field campaign will need to build partnerships with other programs, agencies, and nations conducting research in the ABR. NASA will need to leverage, coordinate with, and/or build upon recent and ongoing projects being sponsored by research and resource management agencies in other nations, especially Canada and Japan, as well as those in the U.S., both at the state and federal levels, and with non-government organizations. Within these organizations, there is a substantial amount of ongoing and planned research, monitoring, and assessment activities that focus on the questions and issues being addressed by ABoVE. Discussions with scientists and managers across a range of organizations in Canada, Japan, and the U.S. have revealed there is strong interest in ABoVE and in carrying out coordinated, collaborative research activities. These initial contacts have been made with the Department of Energy regarding their Next Generation Ecosystem Experiment (NGEE), the National Ecological Observatory Network (NEON), the National Science Foundation regarding the Study of Environmental Change in the Arctic (SEARCH), the Department of Interior, and several state and local organizations within Alaska. ABoVE has been discussed with representatives of the Canadian government involved in the Canada-Mexico-U.S. CarboNA program. Many other important contacts have yet to be initiated. A key activity for ABoVE would be to work with other organizations sponsoring activities focused on climate and environmental change in the ABR to develop an integrated approach to the sponsored research and create a management framework to facilitate data sharing, coordination of field activities, and collaborative analyses.

Equally important will be activities to broaden the disciplinary scope and build partnerships for coordinated multi-disciplinary research so that a full range of important ocean, land and atmosphere interactions can be addressed. In particular, to fully tackle research questions in the areas of coastal ocean dynamics and land-ocean-atmosphere feedbacks, partnerships with ocean- and atmospheric-oriented programs will be required.

Figure 1. Key Processes in the Arctic-Boreal Region that Provide the Focus for ABoVE Research