# Next-Generation Ecosystem Experiments (NGEE Arctic)

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Oak Ridge National Laboratory
Brookhaven National Laboratory
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Next-Generation Ecosystem Experiments (NGEE Arctic)

Submitted to

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# ABBREVIATED TERMS

| | |
|---|---|
| 1D | one-dimensional |
| 2D | two-dimensional |
| 3D | three-dimensional |
| ACRF | Atmospheric Radiation Measurement Climate Research Facility |
| ARCHY | Arctic Hydrology model |
| ARCN | Arctic Network Inventory and Monitoring Program |
| ARM | Atmospheric Radiation Measurement |
| ASCEM | Advanced Simulation Capabilities for Environmental Management |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| ATLAS | Arctic Transitions in the Land-Atmosphere System |
| BAID | Barrow Area Information Database |
| BEO | Barrow Environmental Observatory |
| BER | Office of Biological and Environmental Research |
| BESC | BioEnergy Science Center |
| BGC | biogeochemistry |
| BNL | Brookhaven National Laboratory |
| CALM | Circumpolar Active Layer Monitoring |
| CAMS | Center for Accelerator Mass Spectrometry |
| CART | Cloud and Radiation Testbed |
| CARVE | Carbon Arctic Reservoirs Vulnerability Experiment |
| CASSM | continuous active source seismic monitoring |
| CDIAC | Carbon Dioxide Information Analysis Center |
| CESM | Community Earth System Model |
| CF | climate forecasting |
| CLM | Community Land Model |
| CMIP-5 | Coupled Model Intercomparison Project Phase 5 |
| CT | computerized tomography |
| CZO | Critical Zone Observatory |
| DAAC | Distributed Active Archive Center |
| DEM | digital elevation map |
| DIF | Data Interchange Format |
| DIN | dissolved inorganic nitrogen |
| DOC | dissolved organic carbon |
| DOE | US Department of Energy |
| DOI | digital object identifier |
| DOM | dissolved organic matter |
| DTLB | Drained thaw lake basin |
| DTS | distributed temperature sensor |
| E/CO | education and community outreach |

| | |
|---|---|
| EA-IRMS | elemental analyzer–isotope ratio mass spectrometry |
| ECD | electron capture detector |
| EEM | excitation-emission fluorescence spectroscopy |
| EESD | Energy and Environmental Sciences Directorate |
| EMSL | Environmental Molecular Sciences Laboratory |
| EO-1 | Earth Observing Mission 1 |
| ES&H | environment, safety, and health |
| ESG | Earth System Grid |
| ESH&Q | Environment, Safety, Health, and Quality |
| ET | evapotranspiration |
| FACE | Free-Air $CO_2$ Enrichment |
| FEHM | Finite-Element Heat and Mass Transfer |
| FGDC | Federal Geographic Data Committee |
| FID | flame ion detect |
| FLIR | forward-looking infrared |
| FTIR | Fourier-transform infrared |
| GCM | General Circulation Model |
| GCRG | Global Change Research Group |
| GHG | greenhouse gas |
| GIPL | Geophysical Institute Permafrost Laboratory |
| GLOBE | Global Learning and Observations to Benefit the Environment |
| GPP | gross primary production, productivity |
| GPR | ground-penetrating radar |
| GSP | Genomic Science Program |
| HDMR | high dimensional model reduction |
| HIGRAD | High-Gradient Applications Model |
| IL | institutional lead |
| IFRC | Integrated Field-Research Challenge |
| IfSAR | interferometric synthetic aperture radar |
| IPCC | Intergovernmental Panel on Climate Change |
| IR | infrared |
| IRMS | isotope ratio mass spectrometry |
| ISO | International Organization for Standardization |
| LAI | leaf area index |
| LANL | Los Alamos National Laboratory |
| LBNL | Lawrence Berkeley National Laboratory |
| LCC | Landscape Conservation Cooperative |
| LDRD | Laboratory Directed Research and Development |
| LGPL | lesser general public license |
| LiDAR | light detection and ranging |
| LLNL | Lawrence Livermore National Laboratory |

| | |
|---|---|
| LRD | laboratory research director |
| MAST-DC | ORNL Modeling and Synthesis Thematic Data Center |
| MASW | multichannel analysis of surface waves |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MSTC | Multivariate Spatio-Temporal Clustering |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NCEP | National Centers for Environmental Prediction |
| NDVI | Normalized Difference Vegetation Index |
| NEE | net ecosystem exchange |
| NEON | National Ecological Observatory Network |
| NetCDF | Network Common Data Form |
| NGA | National Geospatial-Intelligence Agency |
| NGEE | Next-Generation Ecosystem Experiments |
| NGO | nongovernmental organization |
| NIR | near-infrared |
| NMR | nuclear magnetic resonance |
| NOAA | National Oceanic and Atmospheric Administration |
| NSA/AAO | North Slope of Alaska/Adjacent Arctic Ocean |
| NSF | National Science Foundation |
| OAI-PMH | Open Archive Initiate—Protocol for Metadata Harvesting |
| OGC | Open Geospatial Consortium |
| OpenDAP | Open-source Project for a Network Data Access Protocol |
| ORNL | Oak Ridge National Laboratory |
| OTC | Open Top Chamber |
| PETSc | Portable, Extensible Toolkit for Scientific Computation |
| PFLOTRAN | A multiphase, multicomponent model of subsurface flow and reactive transport |
| PFT | Plant functional type |
| PI | principal investigator |
| PMI | Plant-Microbes Interface |
| POC | point of contact |
| POM | particulate organic matter |
| PyLith | computer code for tectonics deformation problems |
| QA | quality assurance |
| QC | quality control |
| RACM | Regional Arctic Climate Model |
| RASM | Regional Arctic System Model |
| REST | Representational State Transfer |
| RTM | River Transport Model |
| RT-PCR | quantitative, real-time polymerase chain reaction |
| SAB | scientific advisory board |

| | |
|---|---|
| SAMR | structured adaptive mesh refinement |
| SAR | synthetic aperture radar |
| SC | Office of Science |
| SDSU | San Diego State University |
| SIMS | Sample Information Management System |
| SIP | spectral-induced polarization |
| SIPRE | US Snow, Ice and Permafrost Research Establishment |
| SOM | soil organic matter |
| SPRUCE | Spruce and Peatland Responses Under Climatic and Environmental Change Experiment |
| STL | science team lead |
| TCD | thermal conductivity detector |
| TDR | time-domain reflectometry |
| T-FACE | Temperature and Free Air $CO_2$ Enrichment |
| THM | thermal-hydromechanical |
| THREDDS | Thematic Realtime Environmental Distributed Data Services |
| TOUGH | Transport of Unsaturated Groundwater and Heat |
| UAF | University of Alaska Fairbanks |
| UIC | Ukpeaġvik Iñupiat Corporation |
| UTEP | University of Texas at El Paso |
| UV-CDAT | Ultrascale Visualization-Climate Data Analysis Tools |
| VIC | variable infiltration capacity |
| WALE | Western Arctic Linkage Experiment |
| WaSim-ETH | Water Flow and Balance Simulation Model |
| WBS | work breakdown structure |
| WebGIS | ORNL DAAC data browser |
| WMO | World Meteorological Organization |
| WRF | Weather Research and Forecasting |
| YSI | YSI, Inc. (commercial vendor, formerly “Yellow Springs Instrument Co.”) |

# EXECUTIVE SUMMARY

An important challenge for Earth System models is to properly represent the land and subsurface and their feedbacks to climate. This can be problematic, yet failure to identify and appropriately account for complexities at the landscape scale can compromise climate predictions. The Next-Generation Ecosystem Experiments (NGEE Arctic) project will address this challenge for sensitive and rapidly changing ecosystems of the Arctic tundra through a combination of field and laboratory studies, observations, and multiscale model simulation. A focus on model-data integration and scaling based on geomorphological units will allow us to deliver **a process-rich ecosystem model, extending from bedrock to the top of the vegetative canopy, in which the evolution of Arctic ecosystems in a changing climate can be modeled at the scale of a high-resolution Earth System model grid cell (i.e., 30 × 30 km grid size).**

A distinguishing characteristic of the Arctic tundra, especially the coastal plains of the North Slope, is the existence of recognizable and quantifiable landscape units that are repeated over large domains and that occur at multiple spatial scales. These include active thaw lakes, drained thaw lake basins, and ice-rich polygonal ground consisting of low, high, and transitional polygons. Our scaling approach will build on the hypothesis that the transfer of information across spatial scales can be organized around these discrete geomorphological units, for which processes are represented explicitly at finer scales, with information passed to coarser scales through sub-grid parameterization of Earth System models. By extending an already well-established framework for fractional sub-grid area representations to allow dynamic sub-grid areas and hydrological and geophysical connections among sub-gridunits, we expect to be able to characterize permafrost dynamics and the influence of thermokarst at multiple spatial scales in Arctic tundra landscapes. Our fundamental scaling approach will be to identify processes likely to have the largest influence on climate, based on current knowledge of the Arctic tundra system, and then to define a connected (nested) hierarchy of modeling necessary to resolve those processes. This approach allows us to begin immediately to integrate new process knowledge into a climate-prediction-scale land model while establishing a quantitative framework connecting this scale to more process-rich models implemented at finer spatial resolution and over smaller spatial domains. Process studies and observations of hydrology, geomorphology, biogeochemistry, vegetation patterns, and energy exchange and their couplings will be undertaken to populate the hierarchical modeling framework and to achieve a broader goal of optimally informing process representations in a global-scale model. A central focus of this challenge is to advance process understanding and prediction of ecosystem-climate feedbacks and how climate-driven changes will control the spatial and temporal availability of water for biogeochemical, ecological, and physical feedbacks to the climate system. Field activities to inform model development will be carried out across a gradient of polygonal ground nested within a chronosequence of drained thaw lake basins near Barrow, Alaska. Geophysical characterization of these sites will be essential as we describe critical surface-subsurface variability and interactions, as will assessments of the fine-scale topography that controls local hydrology. Process studies and observations that have the greatest potential for reducing prediction uncertainty have been prioritized, including studies focused on improving the mechanistic understanding of permafrost degradation and its influence on water distribution, quantifying mechanisms and rates associated with organic carbon decomposition in Arctic soils, and developing response functions relating plant community composition and phenology to resource gradients created by high-centered and low-centered polygons and other thermokarst features. Insights generated from these studies will provide improved model algorithms and constraints to model algorithm parameterization, model initialization, and evaluation.

A key deliverable from NGEE Arctic Phase 1 will demonstrate the end-to-end functionality of our model-observation-experimentation approach for the Arctic coastal plain. Specifically, this means that new fundamental knowledge from field and laboratory studies will be integrated within appropriately scaled process-resolving models, a nested hierarchy of such models will be coupled to deliver improved parameterizations for climate-scale prediction, and quantitative metrics of prediction skill will be established on the basis of independent observations representing integrated system behavior at multiple

spatial and temporal scales. Our vision for Phase 1 is to advance all of the system components necessary to exercise one complete cycle through this integrated model-experiment approach, as a proof-of-concept for this new research paradigm. Having accomplished this demonstration, we expect to turn our attention in Phase 2 to the critical process of iteration through this cycle, resulting in more exact hypotheses, more penetrating field and laboratory investigations of processes relevant to the climate prediction problem, more complete and sophisticated integration of new process representations into models at relevant scales, and further improvement in model prediction skill as measured by independent metrics. We will continue our research in Barrow but will extend our multiscale modeling and process understanding framework to other regions of Alaska. Throughout our Phase 1 and 2 activities the NGEE Arctic project will implement innovative communication and data management strategies as we work both within a multidisciplinary team environment and with the larger scientific community to chart a course for an improved process-rich, high-resolution Arctic terrestrial simulation capability.

# ABSTRACT

Characterized by vast amounts of carbon stored in permafrost and a rapidly evolving landscape, the Arctic has emerged as an important focal point for the study of climate change. High-latitude ecosystems, particularly those of the Arctic tundra, are sensitive to environmental changes, yet the mechanisms responsible for those sensitivities are not well understood and many remain uncertain in terms of their representation in Earth System models. Increasing our confidence in climate projections for high-latitude regions of the world will require a coordinated set of investigations that target improved process understanding and model representation of important ecosystem-climate feedbacks. The Next-Generation Ecosystem Experiments (NGEE Arctic) seeks to address this challenge by quantifying the physical, chemical, and biological behavior of terrestrial ecosystems in Alaska. Initial research will focus on the highly dynamic landscapes of the North Slope, where thaw lakes, drained thaw lake basins, and ice-rich polygonal ground offer distinct landunits for investigation and modeling. The project will focus on interactions that drive critical climate feedbacks within these environments through greenhouse gas fluxes, changes in surface energy balance associated with permafrost degradation, and the many processes that arise as a result of these landscape dynamics. The overarching goal of the NGEE Arctic project is to reduce uncertainty in climate prediction through improved representation of Arctic tundra processes. A focus on scaling based on process understanding and geomorphological units will allow us to deliver a *process-rich ecosystem model, extending from bedrock to the top of the vegetative canopy, in which the evolution of Arctic ecosystems in a changing climate can be modeled at the scale of a high-resolution Earth System model grid cell (i.e., 30 × 30 km grid size).* This vision includes mechanistic studies in the field and in the laboratory; modeling of critical and interrelated water, nitrogen, carbon, and energy dynamics; and characterization of important interactions from molecular to landscape scales that drive feedbacks to the climate system. A suite of climate-, intermediate- and fine-scale models will be used to guide observations and interpret data; process studies will serve to initialize state variables in models, provide new algorithms and process parameterizations, and evaluate model performance. The NGEE Arctic project will also develop innovative communication and data management strategies as we work both within a multidisciplinary team environment and with the larger scientific community to chart a course for an improved process-rich, high-resolution Arctic terrestrial simulation capability.

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# I. BACKGROUND AND JUSTIFICATION

The Arctic may be the most climatically sensitive region on Earth. High latitudes have experienced the greatest regional warming in recent decades and are projected to warm twice as much as the rest of the globe by the end of the twenty-first century (Allison et al. 2009). These areas are uniquely characterized by the presence of permafrost, defined as ground that has been continuously frozen for two or more years. Observations suggest that permafrost degradation is now common in high-latitude ecosystems (Jorgenson et al. 2006) and is expected to drive changes in climate forcing through biogeochemical and biophysical feedbacks. Biogeochemical feedbacks are dominated by the potential to release a large amount of currently stored carbon back into the atmosphere as $CO_2$ and $CH_4$ (Zimov et al. 2006, Schuur et al. 2009), whereas biophysical feedbacks include terrestrial energy budgets that are changing in response to warming in high-latitude ecosystems (Chapin et al. 2005, Euskirchen et al. 2009). These feedbacks will take place in an environment undergoing dramatic geomorphic change and landscape reorganization (Rowland et al. 2010, Grosse et al. 2011). Thawing of ice-rich permafrost can lead to subsidence and deformation of land surfaces that range from localized depressions to deep and extensive thermokarst events. These landscape features, along with thermal erosion, gully formation, and drainage network expansion, are dramatically changing topography, surface hydrology, and vegetation structure on time scales of years to decades.

Coupled climate-carbon models project that the northern high latitudes will serve as a substantial land carbon sink during the twenty-first century because both climate warming and elevated global [$CO_2$] favor increased productivity and carbon uptake in the region (Friedlingstein et al. 2006, Qian et al. 2010, Sitch et al. 2008). However, these models lack many of the key processes governing high-latitude ecosystem behavior, and the magnitude of predicted permafrost thaw and subsequent amount of carbon made available for decomposition (release of $CO_2$) or methanogenesis (release of $CH_4$) varies widely among modeling studies. In contrast, results based on incorporating all of the major factors controlling the high-latitude carbon budget in uncoupled, process-based model simulations generally suggest that the net effect of increasing temperatures over the Arctic is a positive feedback to climate warming (McGuire et al. 2010, Hayes et al. 2011). Models that have projected permafrost carbon losses estimate a substantial, but highly uncertain, magnitude of cumulative emissions to the atmosphere over the next 100 to 200 years (Koven et al. 2011, Schaefer et al. 2011, Schneider von Deimling et al. 2011, Zhuang et al. 2006). Fewer negative feedbacks have been identified, and they may not be large enough to counterbalance the large positive feedbacks (Euskirchen et al. 2010). These feedbacks are generally most pronounced at the regional scale and amplify the rate of regional warming.

Multiple carbon, water, and energy feedbacks that occur in response to permafrost degradation must be resolved if we are to improve model prediction of climate. Permafrost soils store almost as much organic carbon (approximately 1670 Pg; Tarnocai et al. 2009) as is found in the rest of the world’s soils. Because of widespread permafrost thaw (Schuur et al. 2009), much of this soil organic matter may be vulnerable to rapid mineralization. Surprisingly little is known about the vulnerability of permafrost and how the landscape would evolve in the future. Key questions are the extent to which permafrost carbon is stabilized by processes other than cold temperatures and the extent to which the active layer becomes thicker as well as saturated and anaerobic. This is largely a function of how the landscape will evolve over time as a result of strong surface-subsurface interactions and impacts on local to regional hydrology. Anaerobic processes slow the rate of decomposition and favor production of $CH_4$ rather than $CO_2$, thus increasing the climate impact of carbon release because of the higher global warming potential of $CH_4$ (Figure 1). There is evidence of old carbon mineralization upon permafrost thaw (Nowinski et al. 2010, Schuur et al. 2009, Mack et al. 2004), indicating the high vulnerability of the organic matter previously stored in permafrost. Understanding the turnover times of carbon released due to thawing permafrost is critical for modeling the decomposition of organic matter. Moreover, accelerated decomposition may increase nitrogen availability, which promotes vegetation growth and may promote further microbial activity (Nowinski et al. 2008). However, the dynamics and mechanisms of plant response to changes in

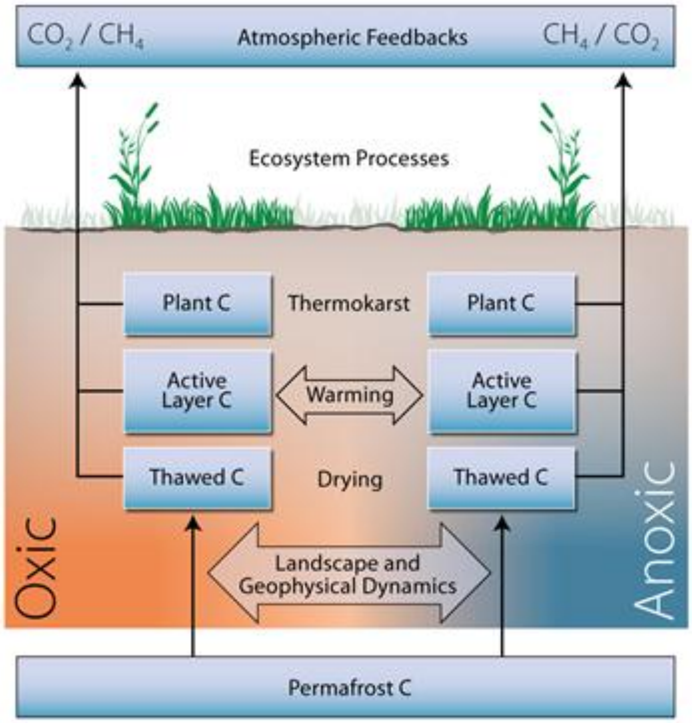


**Figure 1. Conceptual diagram showing the effect of permafrost thawing on climate.**
Permafrost carbon, once thawed, can enter ecosystems that because of local topography and hydrology have either predominantly oxic or anoxic soil conditions. Soil oxygen status determines the rate and form of C loss to the atmosphere. Decomposition primarily releases $CO_2$ in oxic soils, whereas $CH_4$ is primarily produced in anoxic conditions. Adapted from Schuur et al. (2008).

nitrogen availability are limited to only a few experiments. Furthermore, relatively little is known about the feedbacks that arise due to different forms of nitrogen released upon decomposition of labile vs recalcitrant carbon pools, thus further impeding model assessments (Xu et al. 2011).

While existing representations of land surface processes in Earth System models describe some interrelationships that exist among vegetation, biogeochemistry, and climate, many of the coupled arctic system properties and processes related to permafrost degradation are not currently explicitly represented. The presence of ice wedges, for example, and their influence on surface topography appear to be critical drivers of plot-scale processes but cannot be resolved at even the highest resolutions presently conceived for global-scale climate models. Subsurface geochemical conditions that influence greenhouse gas (GHG) emissions can vary laterally on the order of meters due to interactions between surface water and microtopography induced by thermokarst features or polygonal ground (e.g., Zona et al. 2011). Similarly, the formation, erosion, and drainage of thermokarst lakes (Walter et al. 2007) may provide important feedbacks to climate in high-latitude systems because of their role in the surface energy balance and $CO_2$ and $CH_4$ emissions. Accurately representing these dynamics in Earth System models is difficult, although progress has recently been made to introduce these processes into the Community Land Model (Subin et al. 2011a,b). There is a need for improved high-resolution Arctic terrestrial simulation capabilities that allow explicit representation of properties and processes at the spatial and temporal scales where they occur. Such high-resolution modeling can only be achieved through synthesis of new knowledge and understanding of Arctic system processes emerging from mechanistic studies carried out in the field and in the laboratory.

# II. SCIENCE GOALS AND OBJECTIVES

Increasing our confidence in climate projections for high-latitude regions of the world will require a coordinated set of investigations that target improved process understanding and model representation of important ecosystem-climate feedbacks. **Our goal for NGEE Arctic is to reduce uncertainty in climate prediction through improved representation of critical tundra processes**. Initial research will focus on the highly dynamic landscapes of the North Slope of Alaska. We will address, for these complex terrestrial ecosystems, how permafrost degradation in a warming Arctic and how the associated changes in landscape evolution, hydrology, soil biogeochemical processes, and plant community succession, will affect feedbacks to the climate system.

Two objectives will be particularly important as we undertake studies in the Arctic:

- Identify processes likely to have the largest influence on climate, based on current knowledge of the Arctic tundra system, and define a connected (nested) hierarchy of modeling scales necessary to resolve those processes.
- Develop a quantitative scaling framework that provides effective migration of new knowledge gained through process studies and observations to inform model representations and to improve prediction of Arctic ecosystem dynamics and interactions with climate at the global scale.

One of the most difficult challenges we face in accomplishing these objectives is the problem of how to optimally inform process representations in a global-scale model with knowledge and understanding gained through direct observation and process-resolving simulation at smaller scales—we call this “the up-scaling problem.” Of similar importance and just as daunting is the problem of how to provide appropriate large-scale context to guide strategies for direct observations and fine-scale simulation, allowing interpretation of results that can be meaningful at larger scales—what we refer to as “the down-scaling problem.” These two problems are clearly interrelated: appropriate large-scale context provided to guide measurement and process-resolving simulation is fruitless if no mechanism is in place to migrate new fine-scale knowledge to larger scales, while the up-scaled information itself is likely irrelevant if not conditioned in advance by the large-scale context. It is necessary, then, to solve the up-scaling and down-scaling problems together—referred to in tandem as “the scaling problem.”

Previous landscape-scale classification efforts using remote-imagery have identified active thaw lakes and drained thaw lake basins, and ice-rich polygonal ground as three common landscape units that occur over large parts of the Arctic. Our scaling approach will build on the hypothesis that the transfer of information across spatial scales can be organized around these discrete geomorphological units for which processes are represented explicitly at finer scales, with information passed to coarser scales through sub-grid parameterization of Earth System models. A focus on scaling based on process understanding and geomorphological units will allow us to **deliver a process-rich ecosystem model, extending from bedrock to the top of the vegetative canopy, in which the evolution of Arctic ecosystems in a changing climate can be modeled at the scale of a high-resolution Earth System model grid cell (i.e., 30 × 30 km grid size).** This vision includes mechanistic studies in the field and in the laboratory; modeling of critical and interrelated water, nitrogen, carbon, and energy dynamics; and characterization of important interactions from molecular to landscape scales that drive feedbacks to the climate system. A suite of climate-, intermediate- and fine-scale models will be used to guide observations and interpret data while process studies will serve to initialize state variables in models, provide new algorithms and process parameterizations, and evaluate model performance.

A key deliverable from NGEE Arctic Phase 1 will demonstrate the end-to-end functionality of our model-observation-experimentation approach for the Arctic coastal plain. Specifically, we will demonstrate that new fundamental knowledge from field and laboratory studies can be integrated within appropriately scaled process-resolving models, that a nested hierarchy of such models can be coupled to deliver improved parameterizations for climate-scale prediction, and that quantitative metrics of prediction skill can be established on the basis of independent observations representing integrated system behavior at multiple spatial and temporal scales. Our vision for Phase 1 is to advance all of the system components necessary to exercise one complete cycle through this integrated model-experiment approach. Having accomplished this demonstration, we will turn our attention in Phase 2 to the critical process of iteration through this cycle, resulting in more exact hypotheses, more penetrating field and laboratory studies of processes relevant to the climate prediction problem, more complete and sophisticated integration of new process representations into models at relevant scales, and further improvement in model prediction skill as measured by independent metrics.

In the following sections we provide a brief overview of current understanding of Arctic landscape processes relevant to the scaling problem and then outline a scaling philosophy that is consistent with this knowledge (Section III, "Approach"). We summarize the scaling approach currently employed in the land component of the Community Earth System Model (CESM) (Section III.1) as a demonstration that the community has some relevant experience in solving the scaling problem, and as a way to highlight the deficiencies of the existing approach for process scaling in the Arctic tundra landscape. We next define the physical basis for our proposed scaling approach, which relies on a representation of the landscape as geomorphologically distinct landunits connected by surface drainage networks and subsurface flow paths (Sections III.2 and 3). We describe the nested hierarchical modeling framework proposed to enable NGEE Arctic up-scaling and down-scaling followed finally by a comprehensive description of how model parameterization information will be derived and passed between scales.

Having developed this framework, we describe the breadth of Phase 1 activities that target multiscale modeling and process studies (Section IV, "Research Plan"). These plans will show how we intend to closely integrate modeling, observations, and experiments for improved prediction of climate at the scale of a high-resolution Earth System model grid cells.

# III. APPROACH

Our fundamental scaling approach is to identify processes likely to have the largest influence on climate, and the landscapes in which those processes take place, and then to define a connected (nested) hierarchy of modeling scales necessary to resolve those processes. This approach allows us to integrate new process knowledge into a climate prediction-scale land model while establishing a quantitative framework connecting the climate scale to more process-rich models implemented at finer spatial resolution and over smaller spatial domains.

The scaling problem for NGEE Arctic is bounded at large spatial scales by the need to represent the global pan-Arctic land mass and its interactions with the atmosphere, oceans, and sea ice in coupled Earth System climate prediction simulations. The significance of new process knowledge for global coupled climate prediction depends on the area (and time span) over which the process is relevant. Simply stated, the larger the region and longer the duration of influence for a process or phenomenon, the greater its potential impact on the coupled global system. An important challenge for our team is to assess the Arctic tundra environment at large spatial scales and over climate-relevant time spans, producing metrics of representativeness, impact, and uncertainty that can direct observation and process-resolving simulation to the most relevant regions in a vast and remote landscape.

Our scaling approach builds on the hypothesis that the transfer of information across spatial scales can be organized around discrete geomorphological units for which processes are represented explicitly at finer scales, with information passed up to coarser scales through sub-grid parameterization. A distinguishing characteristic of Arctic tundra landscapes is the existence of recognizable landscape units that are repeated over large domains, that occur at multiple spatial scales, and that are strongly correlated with vegetation assemblages. Previous landscape-scale classification efforts have identified thaw lakes, drained thaw lake basins, and polygonal ground as common landscape units that occur over large parts of the Arctic tundra (Figure 2).

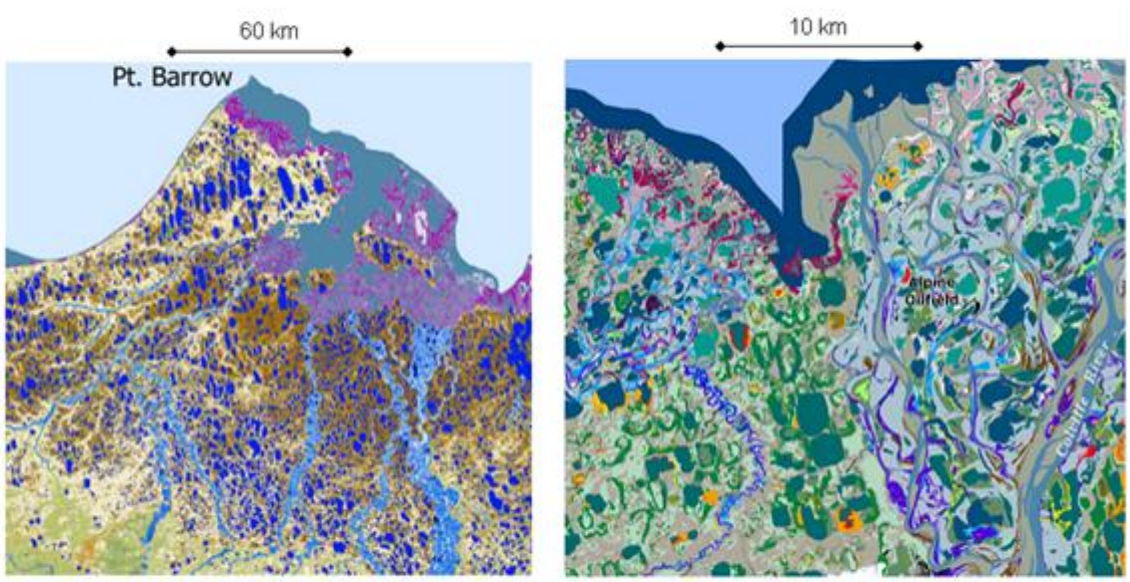


**Figure 2. Subsets from two recent remote-sensing efforts to map geomorphological units across the Alaskan North Slope region.**

Left: from Jorgensen and Heiner 2003. Right: from Jorgensen et al. 2005.

By extending an already well-established framework for fractional sub-grid area representations to allow dynamic sub-grid areas and hydrological and geophysical connections among sub-gridunits, we expect to be able to characterize permafrost dynamics and the influence of land surface deformation associated with thermal erosion and thermokarst formation at multiple spatial scales in Arctic tundra landscapes. We further hypothesize that hydrologic storage and connectedness control both structure and dynamics of the Arctic tundra and that our scaling approach accommodates two-way (up- and down-scale) hydrologic interactions. One consequence of two-way hydrologic interactions in tundra landscapes is that cross-scale iterative solutions are required to arrive at optimal coarse-scale parameterizations. Our approach implements this iterative solution as a progressive refinement, allowing us to make immediate progress toward process integration at the climate scale while the more advanced process-resolving model scales are fully constructed and tested.

## III.1 EXISTING SCALING FRAMEWORK IN THE COMMUNITY LAND MODEL

The current land model component of the CESM, the Community Land Model (CLM), already includes a sophisticated spatial scaling framework, the most advanced of any land model component in the current generation of Earth System models. The CLM grid cell is the geographically referenced unit in the model; that is, it has a known geographic center and fixed geographic extent. Grid cells can vary somewhat in size over the entire simulation grid, but the sizes and areas for each grid cell are fixed for the duration of a simulation. Each grid cell is composed of multiple sub-grid fractional areas. These sub-gridunits are not explicitly geographically referenced: they have a known area, and so a known fractional area representation within a grid cell, but the model has no explicit information about what part of the grid cell each sub-gridunit occupies. In this sense the sub-gridunits are considered to be statistical representations of the sub-grid heterogeneity, as opposed to explicit representations. CLM Version 4’s (CLM4’s) sub-grid information is derived from spatial datasets having (generally) a higher spatial resolution than the final model grid resolution. Sub-grid fractional units can therefore be prescribed to represent geo-referenced sub-grid variability. For example, a map of vegetation types (plant functional types, or PFTs) is one of the input layers used in defining a CLM4 grid and its sub-gridunits, and this map is based on 1 $km^2$ resolution remote-sensing data. Given a CLM4 grid cell of, say, 0.5 resolution, explicit geographic information regarding the sub-grid distribution of PFTs falling within the grid cell is converted to a statistical representation of the sub-grid area represented by each PFT.

The concept of sub-gridunits occupying fractional area on a grid cell is implemented with one more level of complexity in CLM4, by representing the grid cell as a nested hierarchy of three sub-grid types, (Figure 3). The first type below the grid cell is the “landunit,” and its intended purpose is to represent sub-grid variability that presents itself as geomorphologically distinct regions. For example, the current CLM4 sub-grid uses the landunit level of the hierarchy to represent the differences between lakes, crops, natural vegetation, wetlands, glaciers, and urban areas. Each grid cell can be composed of one or more landunits. Each landunit is composed of one or more soil “columns”. The purpose of the column is to represent the state variables and conservation equations for energy, water, carbon, and nitrogen within a multilayer soil, including the potential for multiple layers of overlying snow, and also including a mean representation of state variables for any vegetation existing on the column. Each column is composed of one or more (usually several) PFTs, each of which has a defined fractional area on the column. The purpose of the PFT level of the hierarchy is to represent the water, carbon, and nitrogen state of physiologically distinct vegetation types and their interactions with each other and with the column state variables, such as soil nutrient, water, and temperature distributions.

A final aspect of the existing CLM4 architecture is relevant here: a mechanism is already developed in the model to allow mass and energy conserving changes in sub-grid fractional areas represented at the PFT level, and with a few caveats also at the soil/snow column and landunit levels. With a little additional development work to eliminate these caveats at the higher levels in the hierarchy, our NGEE Arctic scaling approach will be able to put the existing scaling architecture in CLM4 to productive use.

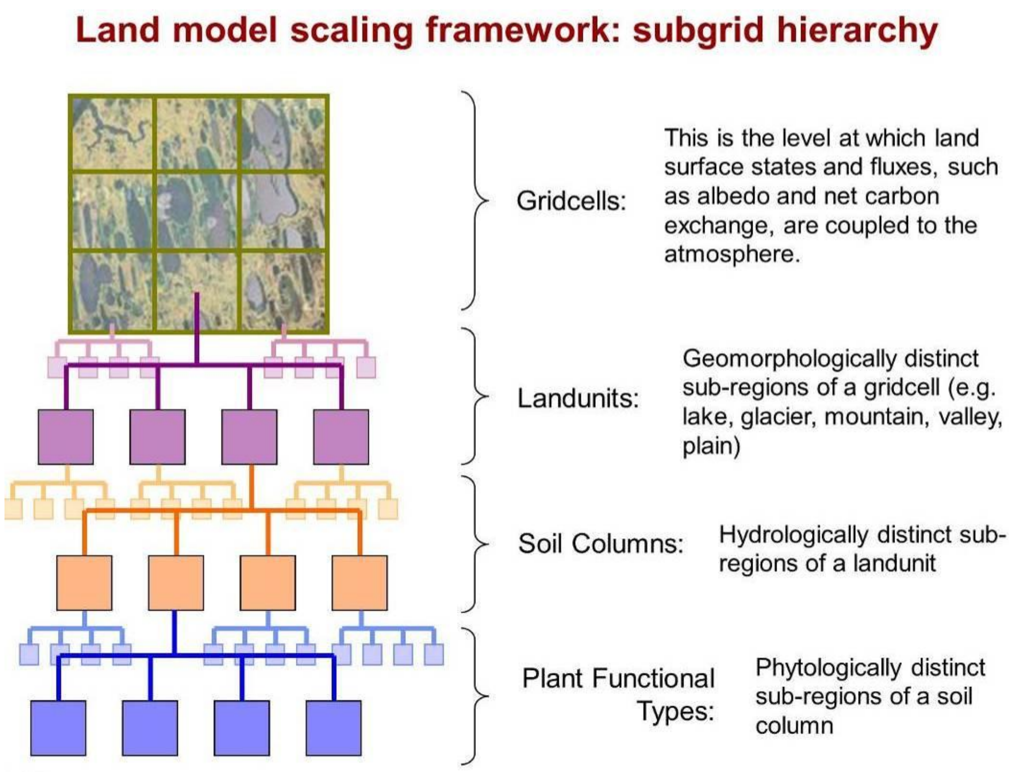


**Figure 3. Land model scaling framework: sub-grid hierarchy.**

The current version of the CLM includes a sophisticated and flexible representation of sub-grid heterogeneity, making use of a nested hierarchical arrangement of sub-grid types. This approach facilitates a mechanistic approach to process representation. The NGEE scaling framework will take full advantage of the existing CLM sub-grid hierarchy, with carefully designed expansions necessary to capture Arctic ecosystem processes.

## III.2 DESCRIPTION OF NGEE ARCTIC SCALING FRAMEWORK

Our scaling approach depends on a conceptualization of sub-grid variability in a climate model as structured by a nested hierarchy of drainage basins and landscape elements within the basins. The realization of this idea depends very strongly on our ability to obtain high-quality topographic information at multiple spatial scales and to analyze those datasets to generate accurate depictions of the spatial and temporal dynamics of surface and subsurface water storage and hydrologic network topology. We also require process knowledge and high-resolution remote-sensing information to steer our interpretations of topography and topology toward effective model representations of landscape features and ecosystem behavior. Our process investigations are, at the same time, guided by a quantitative assessment of representativeness, optimizing the location of process studies and observations, and placing individual measurements and measurement campaigns in broader spatial and mechanistic contexts. In this section we describe the observations and process studies used to structure and quantify the NGEE Arctic scaling framework at the climate, intermediate, and fine scales.

### III.2.1 Climate Scale

Our treatment of the largest spatial scale in the NGEE Arctic modeling hierarchy is intended for application within a high-resolution coupled Earth System model. We consider that a few years from now, as we complete NGEE Arctic Phase 1 (i.e., initial three year scope of work), an operational land model resolution for a system such as the CESM will likely be in the range of 30 × 30 km to 10 × 10 km. We have constrained our approach to the scaling problem in Arctic landscapes by insisting that any methodology we adopt at the largest scale be integrated within the CESM framework and by insisting that the datasets used to define sub-grid variability at this largest scale be available globally.

We use the digital elevation model (dataset) derived from the National Aeronautic and Space Administration's (NASA's) Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER digital elevation map (DEM), available globally at 30 m resolution at no cost, as the climate-scale foundational dataset for delineation of hydrologic basins and recognition of surface drainage networks and network topology. Initial testing suggests that in the lowest relief regions of the Arctic, the data quality may not be sufficient for accurate drainage delineation. In such problematic areas we will supplement ASTER DEM with higher quality products such as airborne interferometric synthetic aperture radar (IfSAR) and other commercially available alternatives that exist at relatively low cost. As an example of our approach to structuring the scaling framework at the climate-model scale, we have used the ASTER DEM supplemented by IfSAR commercial data to map the large-scale drainage basins, drainage networks, and network topology in a region encompassing multiple 10 × 10 km high-resolution climate model grid cells near Barrow, Alaska (Figure 4).

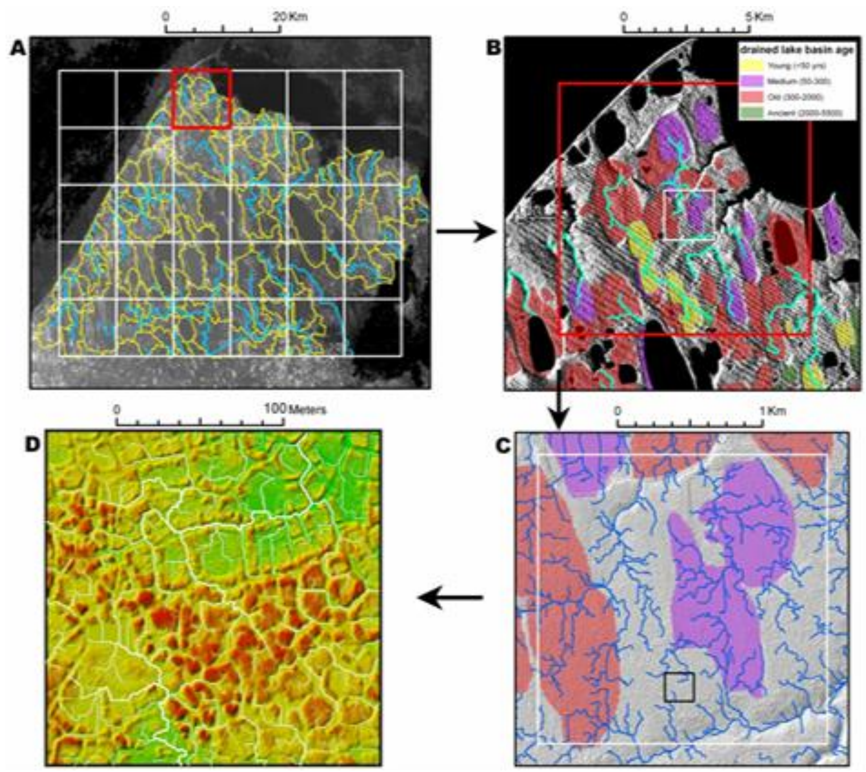


**Figure 4. Scaling of hydrologic and geomorphic features as a function of data resolution.**

At the scale of (A) high-resolution Earth System model (ESM), (B) a single ESM grid cell, (C) a 2 × 2 km domain of high-resolution Light Detection and Ranging (LiDAR) topographic data, and (D) polygonal ground. Yellow outlines in panel A show geomorphologically stable hydrologic basins, connected by stream channels (blue). Colored regions in panels B and C show multiple drained thaw lake basins within a single 10 × 10 km grid cell (B) or a 2 × 2 km domain (C), with progressively more detailed representation of stream channels (blue). Colors in panel D represent surface elevations from higher (red) to lower (green) for a fine-scale subregion, with very fine drainage features (white).Sources: C. Wilson, G. Altmann, C. Gangodagamage, J. Rowland (LANL); B. Bolton (UAF); C. Tweedie, LiDAR data (unpublished).

### III.2.2 INTERMEDIATE SCALE

Our current understanding of geomorphologic units in the Arctic coastal plain has guided us to implement an intermediate scale of simulation, with a domain size on the order of one to several climate-scale grid cells, and with spatial resolution of approximately 100 m (fine enough to represent explicitly the extent and dynamics of active thaw lakes as well as drained lake basins and regions of interstitial tundra). The North Slope of Alaska and lowland areas associated with major rivers throughout Alaska are characterized by thousands of thaw lakes and drained thaw lake basins (DTLBs). Thaw lakes are a primary mechanism of landscape modification as they grow and expand from small thermokarst ponds at the intersection of ice wedge polygons and coalesce, then eventually drain. Lake drainage can occur suddenly due to thermal erosion along a lake margin, ice wedge erosion, the headward expansion of a drainage feature, bank overflow, or coastal erosion. DTLBs are clearly recognizable features of the Arctic lowlands (Figure 4b). Once drained, the basins are subject to revegetation, organic matter accumulation, and ice wedge growth associated with aggrading permafrost in the unfrozen lake substrate. Polygonal ground develops over the time frame of thousands of years, and ponding in the evolving troughs between polygons, and the low centers within polygons may begin to a new cycle of thaw lake development. Many of the existing thaw lakes and DTLBs came into existence in the warmer early Holocene, around 10,000BP, apparently associated with regional thickening of the active layer.

We intend to use DTLBs of different ages to stratify our sampling and measurement approaches at the intermediate scale (Figure 4b). We also intend to use DTLBs of different ages as geomorphological types organizing the up-scaling approach from intermediate to climate scales. Additional geomorphological types resolved explicitly at the intermediate scale and represented statistically as sub-grid elements at the climate scale include active thaw lakes and patches of interstitial tundra between lakes and recognizable DTLBs. Estimation of DTLB age is currently a semiautomated process, depending on remote-sensing inputs, radiocarbon dating, and expert knowledge. A component of our Phase 1 effort will be to more fully automate this important analysis step.

Although DTLB age is hypothesized to be an effective metric for stratifying observations at the intermediate scale, our scaling framework depends also on explicit representation of hydrologic basins and basin connectivity across scales; we do not expect a simple and consistent correspondence between DTLBs and present-day inundation and drainage patterns. In order to derive accurate hydrologic patterns at intermediate and fine spatial resolutions in these very low-gradient landscapes, we require the best available quality digital elevation information, provided by LiDAR measurements. Taking the specific example of an intermediate-scale modeling region centered on the Barrow Environmental Observatory, we are able to use existing LiDAR datasets to distinguish the details of drainage networks as they interact with individual DTLB patches over the space of several kilometers (Figure 4c). This level of detail allows us to place results from the intermediate scale modeling in the climate-scale modeling context during up-scaling, and also provides a connection point for imposing boundary conditions such as water table height and stream channel flow from the climate scale model into the intermediate scale model in the down-scaling operation. We will commission LiDAR data collection with 1 m or finer resolution for subsets of all intermediate-scale modeling domains. As NGEE Arctic progresses and we address regions with greater topographic relief, we will use the hydro-geomorphic scaling approach outlined here but will focus our landscape classification and field observation design on a hilltop-to-river catena approach.

### III.2.3 FINE SCALE

As stratified by DTLBs and interstitial tundra, we will select representative subsets for fine-scale process studies, observation, and modeling. The LiDAR elevation datasets that provide accurate drainage patterns within and between DTLBs and surrounding tundra will also be evaluated to derive topographic connectivity and geomorphological classifications at the fine spatial scale (Figure 4d). While existing analysis tools show remarkable strengths in deriving accurate drainage patterns at the scale of flows within and between individual elements of polygonal ground, we expect that new tool development will be required to extend our representativeness analysis to recognize the landscape elements that we think structure landscape processes at these scales, such as polygon rims, troughs, high centers, and low centers.

## III.3 HYDROLOGIC STORAGE WITHIN, AND CONNECTIONS AMONG, GEOMORPHOLOGIC FEATURES IN THE ARCTIC LANDSCAPE

A fundamental aspect of our scaling approach is that information derived from high-resolution process-resolving simulation at small spatial scales must have a pathway for up-scale migration in order to properly inform the behavior of a larger-scale and more coarsely resolved model. To accomplish this we start with a conceptualization at the climate-prediction scale, our coarsest scale, which represents, for each climate model grid cell, multiple distinct sub-grid elements based on their geomorphology. These sub-grid elements correspond exactly with the CLM4 landunit scaling elements, but we will add a new layer of information for the NGEE Arctic scaling approach, maintaining not only sub-grid fractional area information, but also a description of the sub-grid topology in terms of a surface hydrologic network connecting multiple sub-gridunits.

CLM4 currently includes a surface hydrologic routing network, the River Transport Model (RTM), and static landunit types called lakes and wetlands, but we require a much more sophisticated representation. RTM does not include information on how sub-grid areas are connected with a drainage network, nor how they are connected with each other. Lake and wetland landunits do not account for the large and dynamic area of standing water associated with the microtopography of polygon centers, ridges, and troughs, yet fine-scale surface water features exert strong control on energy balance, vegetation, and subsurface biogeochemistry. Based on our hypothesis that warming will promote thermal erosion and thermokarst formation, and that these processes will lead to fundamental changes in the hydrologic organization of low-gradient Arctic tundra landscapes, we consider it crucial that our scaling approach accommodate the transfer of information regarding these hydrological reorganizations from the fine scale, at which the governing processes are resolved, up to the coarser scale, where interactions with the climate system can be realized. We will extend the surface hydrologic information content in CLM4 to include finely resolved delineations of dynamic inundation and of drainage networks and their associated catchments within individual CLM grid cells. This delineation depends on finely resolved digital surface elevation maps and automated polygon feature and drainage network and catchment delineation algorithms. We have some example surface elevation datasets for Arctic tundra landscapes, derived from airborne LiDAR measurements, and we are developing feature classification techniques and have performed tests using existing network and catchment delineation approaches to evaluate the ability of these datasets and tools to rapidly generate meaningful sub-grid hydrologic information. Initial results are encouraging (Figure 5), and we intend to pursue this approach with more extensive LiDAR retrievals and expert interpretation of the results of automated network delineation outputs as an immediate, high-priority effort at the start of NGEE Arctic Phase 1. We are especially encouraged to see that it is possible to estimate

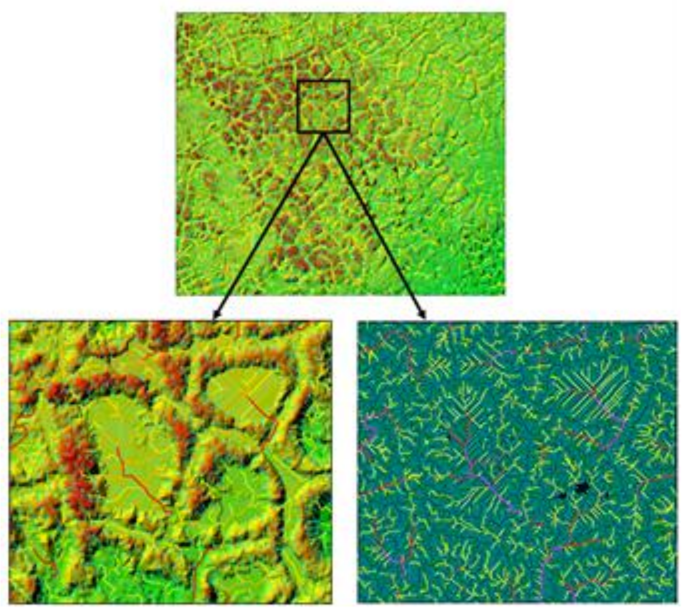

**Figure 5. Automated drainage delineation in a low-gradient landscape.**

From Bolton et al., unpublished data. LiDAR data provided by C. Tweedie.

connectedness among individual ice wedge polygons in this very low-gradient landscape, given a high-quality and high-resolution LiDAR elevation dataset.

The use of explicitly resolved sub-grid hydrologic storage and connectivity information is a critical element of our scaling framework, which makes possible the two-way iterative scaling approach that we hypothesize will lead to improved prediction skill at the climate-modeling scale. Our starting assumption is that at the scale of a high-resolution climate modeling grid cell (e.g., 30 × 30 km or 10 × 10 km resolution), it will be possible to delineate sub-grid catchments and drainage networks that can be considered fixed on century timescales, as constrained by the large-scale topographic gradients. Evidence from the ground suggests that even in these very low-gradient systems, there is enough large-scale topographic structure to organize the landscape into catchments that appear to persist on century time scales. Those catchments will form the CLM sub-grid landunits. Within those catchments, we further suppose that more finely resolved landscape units such as individual thaw lakes, individual ice wedge polygons, or polygon sub-units such as rims and troughs, can be resolved from LiDAR topography. In contrast with the larger-scale catchments and higher-order network elements, these fine-scale catchments and low-order networks are expected to have dynamic topologies under a warming climate, with thermal processes affecting surface elevations, leading to reorganized water storage and flow networks. It is precisely this sort of sub-grid reorganization which will be represented explicitly at the finely resolved modeling scales but implicitly, or through statistical parameterization, at coarser scales. Up-scaling of these processes requires the definition of a suitable parametric expression of the consequences of sub-grid inundation and flow reorganization in the coarse-scale model, the explicit representation of these same processes in the fine-scale model, and the summarization of model output from fine-scale simulations to optimize parameters in the coarse scale model that allow it to represent the behavior (variance) of the fine-scale processes with a quantifiable level of statistical completeness. These up-scaling activities will result in thermal-hydrologic response functions for sub-landunit hydrologic features and their associated responses to micrometeorological and climate forcing, analogous to dynamic plant functional types currently under development in CLM.

Arriving at the appropriate functional form for the parameterized process in the coarse-scale model, and connecting it with explanatory variables available as prognostic outputs or imposed boundary conditions in the coarse-scale model is a topic for focused new model development in the climate-scale model. Fortunately, this new development effort can begin in the absence of parametric input from finer scales, and the new coarse-resolution model can even be exercised by making informed guesses for initial parameter values. The consequence for NGEE Arctic implementation is that necessary development and model application efforts can begin immediately and in parallel for multiple modeling scales. This approach avoids the pitfalls of having to wait for completion of fine-scale models before commencing development of application of coarser scale models, and vice versa.

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# IV. RESEARCH PLAN

The following sections describe goals, rationale, and tasks for the implementation of NGEE Arctic Phase 1 research through coordinated modeling and process studies. High-level deliverables are summarized following each section, and specific deliverables are listed with expected dates of completion in the tables in Appendix XIV.1. These tables also indicate how specific modeling deliverables are linked to experimental and observational tasks. Together, the tasks related to models and measurements complement one another and demonstrate our commitment to model-data integration.

## IV.1 SCALING FRAMEWORK DEVELOPMENT

The scaling approach proposed for use in the NGEE Arctic project is one that requires the identification, quantification, and targeted study of processes within discrete geomorphic landunits. In Phase 1 we have already taken steps to identify distinct features that will direct our research in the Arctic coastal plain near Barrow, Alaska. However, additional work is required to complete our scaling framework for this area and to identify other areas of the Arctic for potential study in Phase 2.

Recognizing that logistical considerations often constrain candidate sampling sites in the Arctic, we propose a methodology that provides a quantitative framework for stratifying sampling domains, informing site selection, and determining the representativeness of measurements. The National Science Foundation's (NSF’s) National Ecological Observatory Network (NEON) adopted an objective, data-based methodology to define 20 optimal sampling domains across the conterminous United States (Keller et al. 2008, Schimel et al. 2007). An extension of that same methodology, applied to the state of Alaska at a nominal resolution of 2 $km^2$, was tested to demonstrate its utility for identifying distinct geographic domains, optimal sampling locations within those domains, and site representativeness. This and similar data-mining techniques can be applied at any spatial scale and offer a quantitative framework by which measurements may be scaled to larger domains or the entire Arctic.

**Scaling Framework Development Goal:** Investigate scaling strategies for biological and geomorphological measurements in the Arctic, to use this information to understand the representativeness of measurements, and to develop a scaling framework that will be applied to measurements and model parameters, integrating across the fine, intermediate, and climate modeling scales.

### IV.1.1 LANDSCAPE CHARACTERIZATION AND IDENTIFICATION OF GEOMORPHOLOGICAL FEATURES

Accurate characterization of the landscape and translation of data collected in the field and laboratory into useful datasets, process algorithms, and model parameters requires classification of the landscape into discrete units based on ecological, hydrological, and geological properties. Ecologists have long used the concept of ecoregions to provide a framework for visualizing, understanding, and managing complex environmental factors, plant and animal habitats, and ecosystem processes (McMahon et al. 2001, Omernik 1995, Omernik 1987, Bailey 1983). While ecoregions were traditionally based on human expertise, quantitative methods, combined with multivariate observational and remote-sensing data, have more recently been applied to produce custom-developed regionalizations for specific analytical purposes (Hargrove and Hoffman 1999, Hargrove et al. 2003, Hargrove and Hoffman 2004, Hoffman 2004), including analyses involving temporal changes in environmental factors (Saxon et al. 2005, White et al. 2005, Hoffman et al. 2005, Hoffman 2010). Similarly, geologists often classify landscape areas into geomorphological units based on their geophysical and hydrological features (Ulrich et al. 2009, Schneider et al. 2009, Jorgenson 2000, Jorgenson and Ely 2001, Jorgenson and Brown 2005, Gude et al. 2002). For NGEE Arctic, we propose to unify these two stratification concepts to produce biogeomorphic units at relevant spatial scales for landscape characterization, identification of ecological and geomorphological features, assessment of the representativeness of measurements, and provision of a framework for scaling measurements and model parameters to larger domains or the entire Arctic.

The development of landscape units relies on the fusing of plot-scale derived data with landscape-scale measurements obtained from towers, aircraft, satellites, and regional mapping. In published applications for the Arctic, such unit characterization incorporates a suite of landscape properties such as topography, hydrology, vegetation type and productivity, soil moisture and ice content, soil characteristics, and land surface age (Hinkel and Nelson 2003, Ulrich et al. 2009, Schneider et al. 2009). Characterization of the landscape using biogeomorphic units requires (1) a definition of unit characteristics, which will depend on the intended use of the unit classification and the availability of relevant data, and (2) determination of the spatial distribution of these characteristics through remote sensing or up-scaling of point measurements. In well-studied regions with extensive data on characteristics such as vegetation type, bioclimatic factors, above- and below-ground carbon content, geophysical feature age, and soil structure and composition, maps of biogeomorphic units may be constructed by developing relationships between the properties of interest and the spectral properties of imagery from satellites such as Landsat-7 and by classifying the landscape using a combination of supervised and unsupervised data-mining techniques (Hinkel and Nelson 2003, Ulrich et al. 2009, Schneider et al. 2009). In the case of areas with limited field data, development of biogeomorphic units will be an iterative process with the level of complexity varying depending on the intended application of the classification.

As an example, a preliminary landscape-scale regionalization was performed using model-derived bioclimatic and observed topographic factors for the state of Alaska at a nominal resolution of 2 $km^2$. A total of 37 characteristics, with model results averaged for the period 2000–2009, were included in the analysis. An unsupervised *k*-means algorithm, called Multivariate Spatio-Temporal Clustering (MSTC; Hargrove and Hoffman 2004), was applied to these data at various levels of division, yielding multiple maps of ecoregions for the state of Alaska. The map in Figure 6, shown in random colors, depicts the 20 most-different regions defined by MSTC. The North Slope, Brooks Range, central boreal forest, and

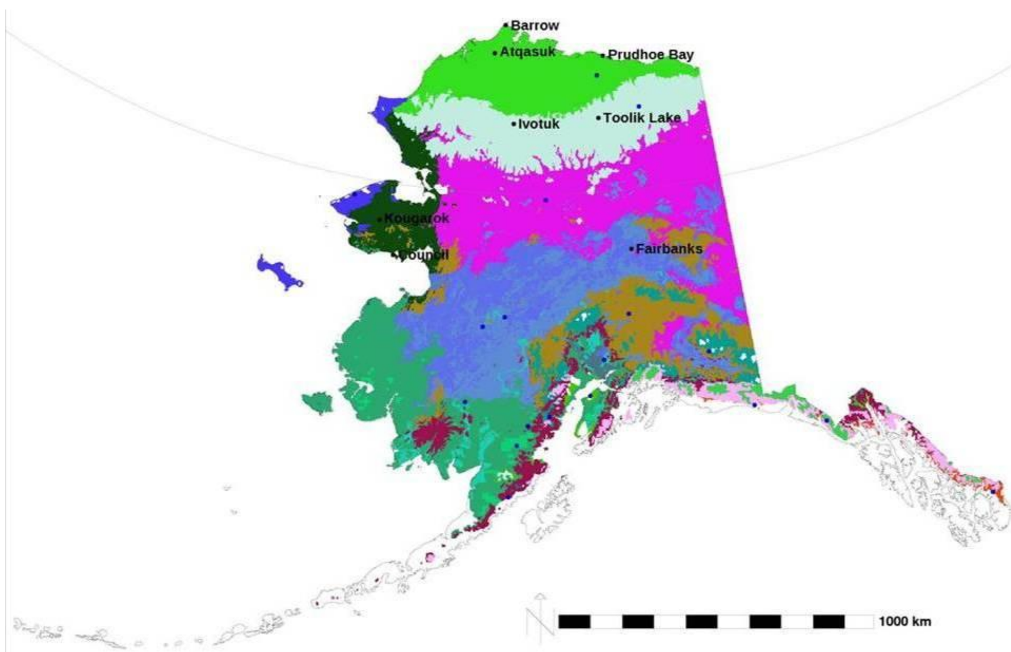



**Figure 6. Multivariate Spatio-Temporal Clustering (MSTC) of 20 regions in Alaska.**

Digital elevation map random colors; blue circles identify the locations that best represent the environmental conditions within each ecoregion.

other broad features in Alaska are clearly identifiable as distinct colors on the map. Blue circles on the map identify the geographic locations that best represent the mean combination of environmental conditions within each ecoregion. As such, these sites represent optimal sampling locations for each ecoregion. At a large scale, this technique is useful for delineating distinct broad regions and optimal measurement sites. However, this technique and similar methods—both supervised and unsupervised—can be applied at finer spatial scales, with inclusion of other geophysical characteristics and remote-sensing data, to inform measurement site selection within these broader ecoregions.

**Task LC.1: Perform landscape characterization for site selection and data gap assessment.** In support of site selection and to establish a landscape-based framework for the assimilation of Year 1 data collected in the field and laboratory, an initial classification of landscape properties will be conducted to develop biogeomorphic units using published and unpublished datasets of climatology, topography, and other characteristics derived from existing remote-sensing data. These data sources may include

- basin ages (Hinkel and Nelson 2003);
- soil maps and vegetation indices [e.g., the Normalized Difference Vegetation Index (NDVI)] derived from high-resolution satellite imagery obtained from the National Geospatial-Intelligence Agency (NGA);
- polygonal ground topographic/geometric characteristics such as size, curvature, and geometric patterns (Gangodagamage et al. 2012);
- soil moisture from multispectral and/or radar data;
- NGEE Arctic-derived and prior study data on active layer thicknesses, such as the Circumpolar Active Layer Monitoring (CALM) Program;
- existing soil carbon inventories (e.g., Barrow Area Information Database (BAID) datasets; and
- topographic data such as slope, drainage networks, microtopography, and storage elements derived from the University of Texas-El Paso (UTEP) LiDAR dataset (Tweedie, unpublished data).

**Task LC.2: Incorporate field and laboratory datasets into spatially distributed datasets to project landscape properties.** As new datasets, such as thaw layer depths, ground ice content, thermal characteristics, and carbon and methane fluxes, are generated from field and laboratory work, they will be scaled up to larger domains by developing relationships between these properties and surrogate data. An example of this approach was documented by Hinkel and Nelson (2003), who developed the relationships between drained lake basin age (in the Barrow region) to remotely sensed observations of vegetation type, surface water ponding, degree of polygonalization, basin wetness, and texture. In NGEE Arctic, progress has already been made to correlate geophysical and subsurface data on thaw layer and snow depth thicknesses to topographic and vegetation characteristics (Hubbard et al. 2012; Wainwright et al. 2012, Gangodagamage et al. 2012).

**Task LC.3: Apply supervised and unsupervised clustering algorithms to classify the landscape based on observable, proxy, and mapped landscape properties.** A variety of agglomerative and divisive techniques have been applied to the general problem of classification, but data-mining methods for feature extraction and change detection that are designed to accommodate very large and complex datasets are being applied with marked success in the Earth sciences (Hoffman et al. 2011, Kumar et al. 2011). The *k*-means and similar approaches described by Hartigan (1975) have proven to be particularly useful for landscape characterization (e.g., Hargrove and Hoffman 2004) and detection of disturbance (e.g., Hoffman 2004, Hoffman et al. 2010). In addition to such established methods, novel unsupervised clustering methodologies using adaptive sparse representations (Moody et al. 2012) may offer promise as new techniques for characterizing the landscape and identifying unique assemblages of biogeomorphic properties at regional scales.

**Task LC.4: Develop model-specific landscape characterizations for model initialization and parameterization.** Not all surface and subsurface properties used to characterize the landscape into distinct biogeomorphic units determined in Task LC.3 may be directly relevant to models. Additionally, data needs and parameterizations will vary from high-resolution process resolving models to regional and global climate models. Therefore, a critical task will be the development of a suite of model-relevant landscape properties associated with mapped biogeomorphic units. Ideally, the biogeomorphic units developed in Task LC.3 will be associated with unique sets of model-relevant properties; however, revision and remapping of units will likely be required to capture the full range of inputs and parameterizations needed across modeling scales and platforms. A critical task in this process will be the identification of observable and proxy characteristics (such as from remote-sensing or surface geophysical measurements) for the mapping of model parameterizations. In many cases this will likely be an iterative process requiring field validation. As an example, ground ice content will likely be a critical subsurface attribute, but it is not directly observable. Direct field measurements will be required to test the relationships between the preliminary mapped biogeomorphic units from Task LC.3 and ice content. The need to identify these types of relationships also highlights the importance of landscape characterization in the site selection process.

### IV.1.2 REPRESENTATIVENESS AND SCALING

An important aspect of site selection and the up- and down-scaling approach to integration of models, observations, and process studies is the estimation of *representativeness*. The multivariate data-mining methodologies described above for landscape characterization offer useful metrics for indicating the representativeness of sites, measurements, and model parameters. Hargrove et al. (2003) described a technique for understanding the representativeness of a sampling network based on a suite of environmental gradients considered to be useful proxies for the characteristics being measured. Maps indicating poorly represented regions can be produced, suggesting where new measurements should be taken. While Hargrove et al. (2003) calculated representativeness in the context of customized ecoregions, this same approach can be applied to every map cell projected onto the hypervolume of environmental gradients (Hutchinson 1957) used to perform the cluster analysis that produced those ecoregions (Hargrove and Hoffman 2004), providing a continuously varying metric describing the representativeness of every location with respect to one or more than one sampling location.

As illustrated for the example landscape-scale regionalization in Figure 7, representative sampling sites can be determined for each region or sampling domain. These sites are the realized map locations that

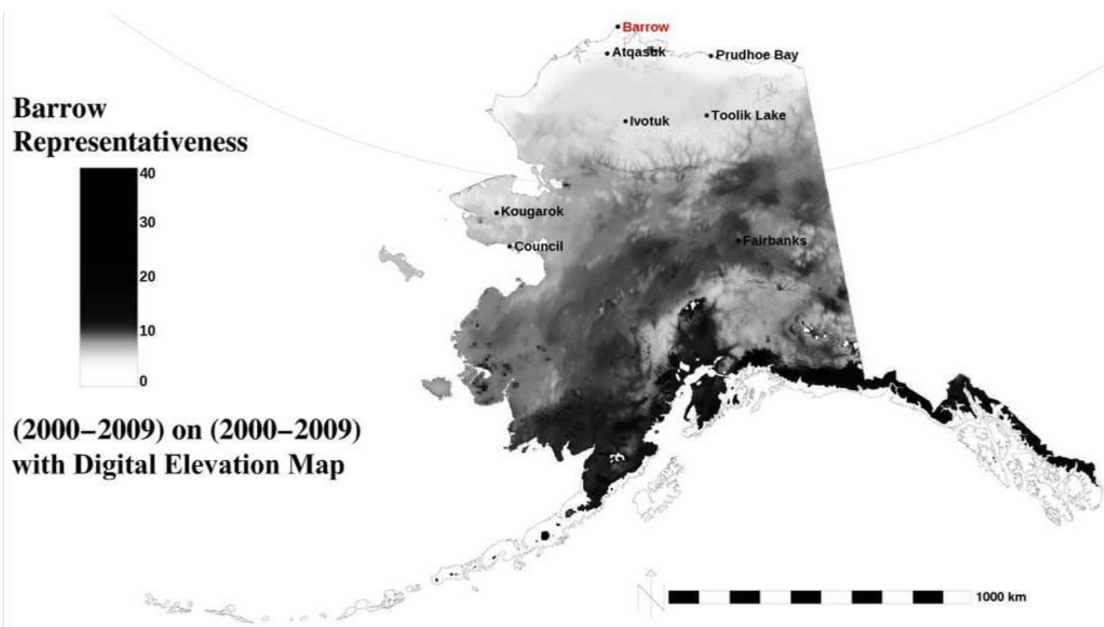



**Figure 7. Barrow representativeness, or "Barrow-ness," for the state of Alaska.**
Calculated as the Euclidean distance between Barrow (labeled in red) and every other map location in the phase space formed by the 37 characteristics.

most closely correspond to the idealized centroids of the clusters composed of member map cells in the 37-dimensional data space formed by the environmental characteristics. Similarly, the representativeness of any location selected a priori can be calculated for a sampling domain or across a larger region. Figure 7 contains a map depicting the representativeness of a location in Barrow for the state of Alaska. This unitless, relative representativeness metric is the Euclidean distance between every cell in the map and the Barrow location within the 37-dimensional data space. Therefore, low values imply high similarity and high values imply high dissimilarity between any location and Barrow. In this map, white to light gray land areas are well represented by the Barrow location; dark gray to black land areas are poorly represented by Barrow. If a field researcher were attempting to select one additional sampling location in order to provide optimal coverage of the environments within the state of Alaska, that next site should be chosen within the darkest land areas shown in the map. Once a new candidate site has been selected, a new map of representativeness can be generated with simultaneous consideration of both sites. Using this relative representativeness metric, optimal sampling locations can be chosen to maximize the coverage of environmental conditions for any domain at any scale for which sufficient data are available.

Because of a lack of data availability at a pan-Arctic scale, additional relationships between landscape characteristics and broadly observable features will likely need to be developed in order to assess the representativeness of the study area and to scale model parameters to the larger Arctic region. Moreover, statistical relationships between biogeomorphic units at different scales may be required to bridge observations across scales. This effort must be performed in concert with the data collection teams and the modeling teams.

**Task RS.1: Perform representativeness analysis within the Barrow domain to determine sampling locations and fine-scale measurement representativeness.** In support of fine-scale sampling and modeling, the biogeomorphic unit characteristics will be used to generate maps of representativeness for candidate and chosen sampling locations within the Barrow Environmental Observatory area and with respect to the larger Barrow region. This same framework will be applied to understand the representativeness of measurements and model results in support of up-scaling the observations and model parameters to the larger Barrow region. This task depends upon acquisition of field measurements and the landscape characterization tasks defining and mapping the biogeomorphic unit characteristics.

**Task RS.2: Define the relationships for up-scaling for fine-to-intermediate and intermediate-to-landscape or climate scales.** Representativeness analysis will be used to determine the most important environmental gradients at the fine, intermediate, and landscape/climate scales. These characteristics are likely to be the most significant in controlling processes at each of the scales. This analysis will use the biogeomorphic unit characteristics to inform the creation of the multiscale grids used in the fine-, intermediate-, and climate-scale models. In addition, this analysis will test a metric multidimensional scaling methodology for interpolating and extrapolating model parameters. This task depends upon the landscape characterization tasks defining and mapping the biogeomorphic unit characteristics and links to the fine- and intermediate-scale modeling tasks developing multiscale grids and interpolating and extrapolating model parameters.

**Task RS.3: Perform representativeness analysis for NGEE Arctic Phase 2 sampling and site selection.** Biogeomorphic unit characteristics acquired and computed at the landscape scale will be applied to perform representativeness analyses to determine optimal sampling and manipulation site locations. Maps will be produced showing the sampling network coverage offered by various candidate sites. This task depends upon the landscape characterization tasks defining and mapping the biogeomorphic unit characteristics.

**Task RS.4: Develop pan-Arctic representativeness analysis.** The development of biogeomorphic unit characteristics, scaling methodologies, and representativeness analyses will culminate in an initial pan-Arctic characterization that can be applied to understand important processes and vulnerabilities of current Arctic ecosystems. A pan-Arctic representativeness analysis will be performed to locate underrepresented biogeomorphic regions that may be critical to incorporate into future measurements or modeling activities. This same framework will be applied to scale existing measurements and to model results to the pan-Arctic domain. This task depends upon the landscape characterization tasks defining and mapping the biogeomorphic unit characteristics and the modeling tasks producing fine-, intermediate- , and climate-scale results.

**Scaling Framework Development Deliverables**

- Develop and apply network analysis and representativeness methodologies suitable for selection of sampling locations, scaling of measurements, and integration of model parameters across the fine, intermediate, and climate model scales.
- Develop maps of biogeomorphic characteristics and integrated field data for the Barrow region.
- Develop spatially distributed collections of model driver data, parameters, and model evaluation data for the fine, intermediate, and climate model scales.
- Publish results from investigations of scaling approaches, biogeomorphic characteristics data, and model driver and evaluation data.

## IV.2 MODEL DEVELOPMENT AND APPLICATION WITH LINKS TO PROCESS STUDIES AND OBSERVATIONS

Our NGEE Arctic modeling and model-scaling approach is founded on a simple concept that distinguishes between models at different scales on the basis of which processes are treated explicitly, which processes are treated as sub-grid parameterizations, and the model boundary condition requirements. This approach also provides a natural point of integration for new knowledge emerging from measurements, observations, and experimentation at multiple spatial and temporal scales. The ability to perform up-scaling depends on explicit representation of some process or processes at a finer scale, which are treated implicitly, or as sub-grid parameterizations, at a coarser scale. The ability to perform useful down-scaling depends on the existence of boundary conditions in a finer-scale model that can be assigned using outputs from a coarser-scale model.

To help clarify our model-scaling approach, we summarize the basic steps for the simple case of two models at different scales: a climate-prediction scale model, and a higher resolution process-resolving model (Figure 8). Initial model development is required for both modeling scales to accommodate the information passing and parameterization steps required by the scaling framework. As models are being developed in parallel, early model testing can begin without communication between them. A first scaling step is the up-scale coupling of information from the fine-scale model to inform parameterizations (set parameter values) in the climate-scale model. A second scaling step is to run the climate-scale model with new parameters and pass boundary constraints to the process-resolving model. This leads to subsequent simulations at fine and coarse scales in an iterative process through which final parameter estimates for the coarse scale model are expected to converge to their optimal values. The model-development and model-application phases shown here also represent periods during which integration of new process knowledge from observation and experimentation will occur.

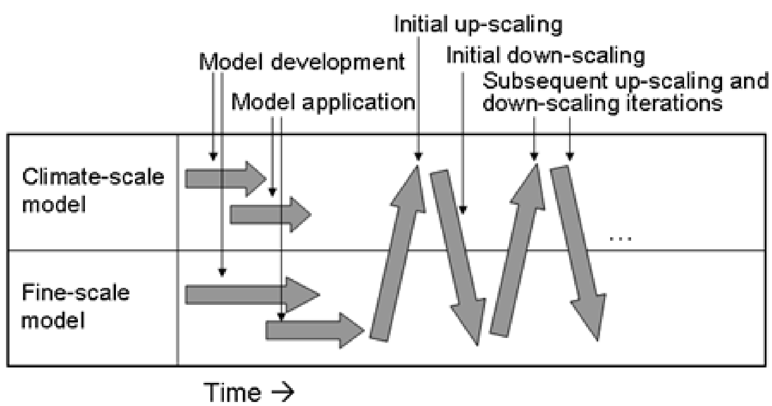



**Figure 8. Simplified representation of NGEE Arctic scaling approach: two-model case.**

As described in Section III, “Approach”, our scaling framework engages models at three spatial scales: the climate-grid scale, an intermediate scale, and a fine scale, with larger domain and coarser grid resolution for the climate-scale model and smaller domains and finer grid resolution for the intermediate- and fine-scale models. Observations, experimental results, and new process understanding will be integrated with modeling components at scales appropriate to the measurements and mechanisms. Our scaling approach assumes that the finer-scale modeling domains are nested within the larger-scale domains, and that these domains are centered on the NGEE Arctic study sites. Our initial implementation for NGEE Arctic Phase 1 will have a climate-scale domain on the order of 50 to 100 km ($x$ and $y$ horizontal dimensions), with grid resolution of approximately 10 × 10 km. Our intermediate model domains will consist of single climate-scale model grid cells with resolution of approximately 100 × 100 m, with the potential for several intermediate-scale domains within the climate domain. Our fine=-scale model domains will consist of single intermediate-scale model grid cells with resolution of approximately 1 × 1 m. We expect to have multiple fine-scale model domains represented within the each intermediate domain, to assess process sensitivity to variability in local topographic setting. In addition, at the fine-scale and intermediate-scale domain sizes, we will use both atmospheric models and subsurface modeling tools to characterize and quantify the coupled processes controlling the fluxes of mass species and energy.

Our climate-scale model will be derived from the current CLM4, and will share all of CLM4’s explicit process representations, including one-dimensional (1D) (column-based) mass and energy balance, permafrost structure, and active layer dynamics. New development will add thermokarst-driven changes in surface elevation as an explicit 1D process. Mass balance equations currently include explicit carbon and nitrogen biogeochemistry, and new plant functional types representing real Arctic vegetation will be introduced. The model will include an explicit representation of surface flow in a static drainage network, replacing RTM with a more sophisticated approach that maintains hydrologic connectivity information at the sub-grid scale (Section III.2.4). Sub-grid parameterized processes added to the model to accommodate the NGEE Arctic scaling approach will include overland flow across sub-gridunits and transport to the static drainage network as well as surface and subsurface flow between landunits, including dissolved-phase biogeochemistry and sediment transport. The distribution and dynamics of PFTs are handled as sub-grid parameterizations in the current CLM4, and this functionality will be retained. Shifts in sub-grid area from one type to another (e.g., polygonal ground to thaw lake, or thaw lake to DTLB) will be added as a new sub-grid process. Boundary conditions for the climate-scale model include near-surface weather and the imposed structure of the static drainage network and large-scale topography.

Our intermediate-scale subsurface model will be based on an existing three-dimensional (3D) `reactive transport model architecture [either PFLOTRAN or the Advanced Simulation Capabilities for Environmental Management (ASCEM) and Amanzi], using 3D finite volume computational methods for subsurface processes, and two-dimensional (2D) surface mesh representations for overland flow. All processes treated explicitly in the climate-scale model are also treated explicitly in the intermediate-scale model. Additional explicit processes include thaw lake dynamics, dynamic drainage network organization, and surface and subsurface lateral flow. The subsurface thermal hydrology processes will be represented at a level of detail appropriate for the spatial scale of interest and may thus consider approximate representations and sub-grid parameterization for some processes. Processes represented through sub-grid parameterization include polygonal ground and ice wedge dynamics as well as PFT distributions. Boundary conditions for the intermediate-scale model include near-surface weather and surface and subsurface water and energy inflow at domain boundaries. Regardless of the architecture selected, a substantial amount of new model development and integration of existing model components is required to arrive at a fully functional intermediate-scale model. Further details on model technical requirements and computational components will be developed early in Year 1 of the project.

The High-Gradient Applications Model (HIGRAD), an atmospheric hydrodynamics model, will be used to study the near-surface atmospheric dynamics at fine spatial scales. A critical aspect of HIGRAD is its capability to model the interaction between atmospheric flows and heterogeneous vegetation and topography, including aerodynamic drag and turbulence, energy exchange, and gas species transport. A variety of HIGRAD horizontal resolutions ranging from 0.1 × 0.1 m to 100 × 100 m will be used with appropriately scaled vertical resolutions in order to adequately understand the effects of resolving various atmospheric motions and landscape elements and to verify that sub-grid models of interaction with heterogeneities in topography and vegetation are capturing critical behaviors.

The processes treated explicitly for the intermediate-scale model will also be treated explicitly in the fine-scale model. However, a more mechanistic representation (Painter 2011) of thermal hydrology of freezing soil will be used. Additional explicit representations will include ice wedge polygons and dynamic microtopography. The need to model evolving microtopography associated with degrading ice wedges places considerably more demand on the computational meshing infrastructure than in the intermediate-scale case, requiring fully unstructured grids that can conform to features of interest such as material interfaces and, depending on the approach used to track material properties as deformation occurs (e.g., Lagrangian meshes vs Eulerian meshes across which material properties are advected), mesh movement and remeshing. Boundary conditions are formulated in the same way as for the intermediate-scale model. Finally, we expect that even for the fine-scale model we will not be able to resolve the explicit dynamics of individual plants as they grow, reproduce, and die, and so PFT dynamics will continue to be represented as a sub-grid parameterized process at this scale.

No existing highly parallel codes implement a freezing soil thermal hydrology model. Moreover, there are no existing codes that address the interactions among subsurface thermal hydrology of freezing/thawing soils, overland flow, and topographic evolution caused by mechanical deformation processes, which are the key process couplings at the fine scale. The proposed path forward is to evaluate the parallel subsurface flow/transport codes PFLOTRAN and Amanzi/ASCEM and select one of these codes, or a combination of the two, as the computational platform for the fine- and intermediate-scale modeling. This selection decision will be made by October 2012.

Given these three modeling scales, and following the general approach shown in Figure 8, we propose a more detailed research plan relating model development, parameterization, application, up-scaling, down-scaling, and integrative analysis across scales. Figure 9 provides a schematic for our more detailed plan, and describes dependencies among tasks at multiple modeling scales. The “time” axis can be roughly interpreted to cover all of NGEE Arctic Phase 1 and extending into Phase 2 as the iterative scaling process develops. Specific milestones and associated timelines are provided for each task in the following sections. The gray “Analysis” blocks represent the many points of integration with existing and newly collected measurements and observations from field and laboratory research. The orange “Initial Parameterization” blocks are additional critical points of integration between models and observations, where multiscale characterizations of the research sites from landscape-scale distributions of fluxes and geomorphological features down to the measured properties of individual permafrost cores or plant communities will be used to constrain models. In the following sections we describe the specific modeling tasks required to construct our scaling framework, apply that framework to guide observational and experimental strategies, and integrate new knowledge emerging from process studies in the hydrology/geomorphology, biogeochemistry, and vegetation dynamics areas. For clarity, we have organized these modeling tasks by scale, but these tasks are closely related across scales, as described above (see Appendix XIV.1).

### IV.2.1 Climate-Scale Modeling Tasks

A sophisticated sub-grid scaling framework already exists within the CLM4 architecture; however, significant modifications are required to accommodate the current best understanding of Arctic tundra processes and to accommodate connections to intermediate and fine-scale models with more explicit process representation. The following tasks define CLM4 development, application, and evaluation, which will lead us toward our goal of a process-rich ecosystem model in which the evolution of Arctic tundra can be modeled in the context of the coupled Earth System.

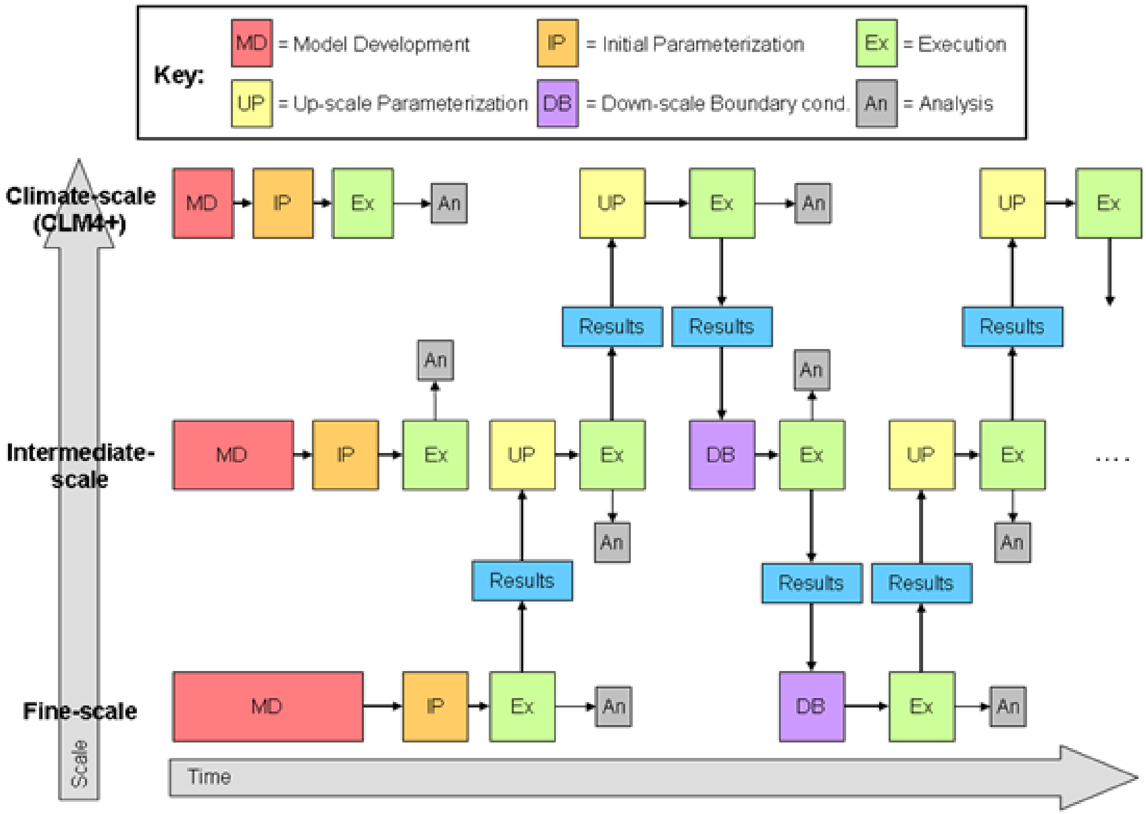



**Figure 9. NGEE Arctic model scaling and model-observation integration approach.**

**Task CM1: Baseline CLM4 simulations.** We will conduct a series of "baseline" simulations using the current operational CLM4 code, applied at high spatial resolution (10 × 10 km) over a region of approximately 100 × 100 km around the Barrow Environmental Observatory (BEO). These simulations will serve as a point of comparison as modifications are made, first to the CLM data structures and process representations, and later to CLM parameterizations as the result of up-scaling and down-scaling iterations. The series of simulations will include spinup to a pre-industrial steady-state and a transient simulation from 1850 to present with observed climate system forcings. We will also include a simple set of modeled manipulation experiments: enhanced $CO_2$, warming, and drought. The purpose of these simulated manipulations is to evaluate the influence of new model dynamics (see Task CM4) on predicted experimental outcomes, as a rapid feedback mechanism to observational and experimental groups.

**Task CM2: Structural modifications to CLM4 required for NGEE scaling approach.**
**Task CM2.1: Implement multiple vegetated landunits.** The NGEE Arctic scaling approach requires that CLM sub-grid elements be represented with explicit knowledge of spatial location and hydrologic setting, a departure from the current approach in CLM4, which ignores location within the grid cell and carries only fractional area information. The NGEE Arctic sub-grid treatment uses hydrologically distinct sub-basins to define landunits. This task generates the preprocessing code that defines the new landunits from sub-grid resolution DEMs, and modifies the CLM surface dataset file to carry new information on landunit geography and its relationship to hydrologic network topology.

**Task CM2.2: Implement improved surface and subsurface flow processes.** River-routing information in CLM4 is currently treated on a 0.5° × 0.5° grid, which is too coarse to accommodate the integration with intermediate- and fine-scale model outputs for the NGEE Arctic scaling approach. This task generates surface flow networks from digital elevation data at 50 m or finer resolution and provides network topology information that is incorporated in surface datasets to describe the hydrologic connections between landunits. One specific sub-task of CM2.2 is the introduction of a hydrologic head–

based formulation for subsurface hydrology, replacing the current volumetric water content–based scheme in CLM4. Subsurface processes in CLM4 are treated as 1D (only gravity driven), which is a major limitation for NGEE Arctic modeling. Thus, an additional sub-task of CM2.2 is development of new code to allow lateral flows between landunits. Since lateral flows will be largely determined by sub-landunit topography and subsurface frost table elevations associated with polygonal ground and DTLB depressions, response functions for sub-landunit lateral flows will be developed to generate partitioning of snowmelt and rainfall between on-site inundation and runoff available for lateral transfer between CLM landunits. This task is linked to the Hydro-Geomorphology tasks H1, H2, H3, and H4.

**Task CM2.3: Implement multiple vegetated soil columns per landunit.** The current CLM sub-grid scheme defines only a single vegetated soil column with a single landunit. The NGEE Arctic scaling approach requires multiple soil columns to coexist within a single landunit so that the full range of geomorphological types that are observed to occupy relatively small tundra regions can be represented. A primary mechanistic connection between climate-scale and intermediate- and fine-scale modeling will be the representation of a dynamic surface elevation for each soil column, which will be used to represent the influence of permafrost degradation on surface topography and associated changes in hydrologic state. A sub-task of CM2.3 is the introduction of new code allowing dynamic shifts in soil column area, which is currently implemented only for the plant functional type level of the CLM4 sub-grid hierarchy. These modifications to the column sub-grid level in CLM are necessary first steps that allow subsequent improvements in treatment of Arctic tundra biophysics (e.g., snow pack and snow albedo effects, surface temperature, and permafrost dynamics) and biogeochemistry.

**Task CM2.4: Implement realistic Arctic plant functional types.** Current arctic vegetation in CLM4 is represented by a small set of PFTs, with only bare ground, shrubs, and an “arctic grass” representing the complexity of arctic ecosystems. We will build on the existing CLM4 structures to add new herbaceous, woody, and bryophyte PFTs. This approach will involve more realistic representation of physiology, nutrient interactions (e.g., N fixation, organic N uptake), photosynthetic controls, subsurface interactions between roots and permafrost, and radiation/energy balance. We will begin exploring the plant competitive processes and environmental thresholds responsible for determining PFT distributions under a changing climate.

**Task CM3: Implement realistic Arctic biogeochemistry on soil column.** For climate-scale biogeochemical modeling in NGEE Arctic, we will build on CLM4.5, which is slated for release in December 2012. That model version will include vertically resolved belowground C and N pools; simplified representations of nitrification, denitrification, and leaching; and a $CH_4$ submodel. We will work with the modeling teams at the fine and intermediate scales and the biogeochemistry observations to improve climate-scale model representations of microbial community composition and function; aerobic and anaerobic C decomposition and carbon use efficiency; N mineralization, nitrification, and denitrification; plant inorganic and organic N uptake; exudation; mineral N competition between consumers; sorption impacts on C and N availability; impact of freezing on $CH_4$ ebullition; $CH_4$ oxidation; and vertical species transport.

**Task CM4: Incremental CLM simulations with NGEE Arctic modifications.** As new model versions are available from each of the climate-scale model development tasks (CM2, CM3), we will rerun the series of preindustrial, historical transient, and simple manipulation simulations (CM1), and evaluate the incremental influence of new model structure and new process representation on predictions of thermal and hydrologic dynamics, vegetation dynamics, and biogeochemical dynamics.

**Task CM5: Preliminary CLM scaling studies.**
**Task CM5.1: Preliminary CLM scaling study—hydrologic routing.** As a first demonstration of how the NGEE Arctic scaling framework interacts with the modified CLM sub-grid hydrologic routing scheme, we will evaluate the default CLM hydrologic outflow estimates against measurements of streamflow made at multiple locations within the BEO (observations described in Hydro-Geomorphology

tasks H5 and H6). We will then repeat these evaluations using the explicit sub-grid hydrologic routing framework introduced under Task CM2.2. We hypothesize that the explicit sub-grid treatment of hydrologically distinct landunits in a topologically connected network will lead to improved prediction of mean streamflow and seasonal variation, compared to the implicit routing scheme in the default CLM.

**Task CM5.2: Preliminary CLM scaling study—soil saturation state.** As an early demonstration of how the NGEE Arctic scaling framework interacts with modified CLM soil column representation, we will evaluate the default CLM water table height and soil saturation state against site level measurements taken in the BEO (observations described in Hydro-Geomorphology tasks H1 and H3). We will then repeat these evaluations using the multiple soil column implementation with dynamic surface height, introduced under Task CM2.3. We hypothesize that the explicit surface height and multiple soil column approach will improve prediction accuracy for depth to water table, soil saturation state above the water table, and estimates of fractional inundated area at the grid cell level.

**Task CM5.3: Preliminary CLM scaling study—soil biogeochemistry.** We will apply new climate-scale biogeochemical representations (Task CM3) within the modified CLM4 structure (Task CM2). We will evaluate the impact of new CLM sub-grid representation (CM2.1, CM2.3) on soil biogeochemistry dynamics, quantifying the effects of representing landscape units at finer spatial scales within CLM. We will assess the influence of new surface and subsurface hydrologic routing schemes (CM2.2) on net fluxes and transport of biogeochemical species. We will examine the interactions of new soil biogeochemistry representations with new Arctic plant functional types (CM2.4).

**Task CM5.4: Preliminary CLM scaling study—vegetation dynamics.** We will demonstrate the influence of new sub-grid hydrologic routing and soil column hydrology representations (Tasks CM2.2 and CM2.3) on vegetation transitions as predicted by new Arctic-specific PFT representations (Task CM2.4), including interactions with nutrient dynamics as predicted by a more mechanistic representation of soil biogeochemistry (Task CM3). We will evaluate predictions of vegetation structure and function from the default CLM against observations across multiple geomorphological types within the BEO. We hypothesize that the new PFTs and competitive process representations, coupled with improved hydrology and biogeochemistry boundary conditions, will result in improved predictions of vegetation structure and community composition when compared with the default CLM.

**Task CM6: CLM parameterization from finer-scale models (up-scaling).** We will use results generated by intermediate-scale modeling over subsets of the BEO (Task IM9) as training targets in the development of new soil-column and landunit parameterizations for CLM. Specifically, we will use intermediate-scale model predictions of surface height, water table depth, saturation states, and hydrologic outflow as data assimilation targets to define parameter settings in the soil column and landunit levels of the modified CLM sub-grid hierarchy. We expect that changes in surface elevation can be related empirically to changes in temperature, moisture content, and associated phase changes by depth in the soil column and that fractional saturated area, water table depth, and hydrologic outflow can be related in turn to changes in surface height. This hierarchical approach to parameter estimation will be supported by established data assimilation methodologies. New up-scaled parameter settings will be used to generate full CLM simulations over the BEO, and results will be compared with integrative observations (Task I1) to evaluate changes in prediction accuracy at the climate scale.

**Task CM7: CLM boundary conditions passed to finer-scale models (down-scaling).** We will use the up-scaling results of Task CM6 to provide updated boundary conditions to the intermediate scale model over subsets of the BEO, which will in turn provide more finely resolved boundary conditions to the fine-scale model over smaller subsets of the BEO spatial domain (tasks IM10 and FM10). Specifically, we will pass hydrologic outflow as predicted by the explicit sub-grid hydrologic routing component of CLM (Task CM2) as boundary forcing input to the intermediate model surface hydrology. We will also pass water table depth, soil water saturation state, and soil temperature from the CLM landunit level as additional intermediate-scale boundary conditions.

### IV.2.2 Intermediate- and Fine-Scale Modeling Requirements

Our intermediate- and fine-scale modeling efforts will benefit from ongoing efforts that have generated flexible and extensible surface and subsurface flow and reactive transport models. As an early NGEE Arctic effort, we will evaluate the capabilities of two such modeling systems (Amanzi and PFLOTRAN), for the purpose of selecting a framework for the further development of NGEE Arctic–specific functionality at intermediate and fine scales. It is clear from the outset that neither of these existing frameworks meets all of the NGEE Arctic scaling framework needs. Our approach is to identify the most appropriate elements from each approach and to move forward with an NGEE Arctic–specific development effort that draws these elements together and introduces new capabilities as needed.

Amanzi (Moulton et al. 2012) is an open-source, modular, object-oriented simulator written in C++ and based on the Trilinos parallel toolkit. Amanzi is under development as part of the DOE Environmental Management-supported ASCEM project. Amanzi accommodates fully unstructured grids, includes computational mesh updating toolkits to allow for dynamic meshes and has a sophisticated multiphysics coordinator to address the coupling among different processes.

PFLOTRAN (Mills et al. 2009) is an open-source (GNU lesser general public licensed) code for simulation of multiscale, multiphase, multicomponent flow and reactive transport phenomena in porous media on computers ranging from laptops to leadership-scale supercomputers. It is a modular, object-oriented code (mostly written in modern Fortran 95/2003) built on top of the Portable, Extensible Toolkit for Scientific Computation (PETSc) parallel framework, which provides access to cutting-edge scalable solvers and infrastructure for “composable” multiphysics simulations. It supports a comprehensive suite of biogeochemical reactions, implicit or operator-split time stepping, finite-volume and mimetic finite-difference discretizations, structured adaptive mesh refinement (experimental), structured and unstructured grids, and parallel input/output.

The following capabilities are required of any computation infrastructure that will address both fine- and intermediate-scale: adequate parallel performance, modularity, extensibility, flexibility in process coupling, flexibility in gridding, and dynamic mesh updating.

**Parallel performance:** Fine-scale simulations resolving scales of individual ice wedge polygons and related vegetation heterogeneities and spanning domains of sizes 100 × 100 × 10 m are estimated, for example, to require approximately 50 million grid cells for subsurface calculations, assuming optimized unstructured grids. This is well within the capability of simple hydrologic codes built on the Trilinos or PETSc parallel frameworks. PFLOTRAN exhibits strong parallel scaling to hundreds of thousands of cores in simulations involving complex reactive chemistry. The Amanzi code exhibits strong parallel scaling to thousands of cores, the limit of its current testing. Based on performance of other Trilinos-based codes, we expect that it will be possible to achieve acceptable scaling in Amanzi to at least tens of thousands of cores. However, performance and required resources for the significantly more complex simulations that include the key couplings required for an Arctic simulator is uncertain for both PFLOTRAN and Amanzi. These uncertainties come from several sources: the possible need for mesh smoothing and associated conservative remapping of the unknown variables, which likely induces a large computational burden (discussed below); uncertainty in the level of detail required in representations of hydrologic and biogeochemical processes; and the novelty of coupled simulations of overland flow, subsurface reactive transport, and freezing and thawing in geologic media.

**Modularity and Extensibility:** Modularity and extensibility are design goals for both PFLOTRAN and Amanzi. Amanzi takes advantage of C++ language features and is fully object oriented and thus highly extensible. PFLOTRAN is largely written in modern Fortran (with some C++ interface code) and, through judicious use of features from Fortran 95/2003, follows an object-oriented paradigm. It is built on top of the highly object-oriented PETSc parallel framework (Balay et al. 2011).

**Flexibility in process couplings:** The fine-scale and intermediate-scale models will couple several different physical, chemical and ecological processes. A range of computational strategies is available for enforcing the couplings, depending on the strength and time scales of interactions. Clearly, fully implicit global coupling among all the processes is not needed. However, significant numerical experimentation will be required to determine optimal coupling strategies, and it is likely that mixed strategies for time stepping (implicit to treat stiff components and explicit to treat non-stiff components) will need to be employed. Thus, flexibility in process coupling is a key requirement for the simulator. In Amanzi, such flexibility is provided through the use of a multiprocess coordinator, which controls the execution of individual process kernels and their interactions. This capability allows coupling between process kernels to be modified with little or no code changes. In PFLOTRAN, this flexibility can be provided using the composable multiphysics infrastructure that has been developed in PETSc over the last few years.

**Flexibility in gridding:** Amanzi is fully unstructured and is based on advanced discretization methods specifically designed for computational cells based on polyhedra of any order. PFLOTRAN originally supported only static, structured grids, but now offers some support for structured adaptive mesh refinement (SAMR) using the SAMR infrastructure framework as well as a newly implemented unstructured grid capability that is currently being tested and is expected to be performing well at scale before September 2012. The unstructured grid capability in PFLOTRAN supports a mixture of distorted low-order polyhedral elements (prisms, tetrahedra, pyramids, hexahedra, and combinations of these types).

**Evolving surface and subsurface geometries:** The capability of the NGEE Arctic landscape simulator to adaptively track an evolving surface topography associated with thermokarst formation is a critical piece of computational infrastructure. This can be done using Lagrangian or Eulerian approaches. In a Lagrangian approach, the computational mesh follows material deformations. For small displacements of the surface elevation caused by thawing, simple Lagrangian mesh motion calculations would be adequate. However, for the relatively large displacements associated with degrading ice wedges, mesh motion will quickly lead to mesh entanglement and invalid meshes. Thus, mesh smoothing—the movement of mesh nodes independently of mechanical displacements to maintain a mesh of sufficient quality—is required. Mesh smoothing must be paired with a remapping of the solution-state variables from the old to the new mesh. Such remappings should conserve water mass and total heat content. Access to multiple mesh toolkits is a primary design requirement for Amanzi and full capability for mesh movement. Smoothing and conservative remapping are anticipated in Amanzi or derivative products by September 2012. Thus far in its development, PFLOTRAN has not targeted problems in which mesh motions are required. However, one avenue for supporting complicated mesh operations in PFLOTRAN is to use the Sieve mesh infrastructure in PETSc, an abstraction that allows complicated mesh operations to be carried out with relative ease. Sieve has been used successfully in the tectonics code PyLith (Aagaard et al. 2011) to represent complicated changes in mesh geometry and topology associated with processes such as fault development.

We note that, precisely because of the difficulties associated with large mesh movements and remeshing, Eulerian approaches—in which the computational grid remains fixed in space while deforming material flows through it—are sometimes preferred for problems involving large deformations, despite reduced accuracy in tracking material interfaces and the computational cost of tracking material movement within the grid. It may be worthwhile to explore such approaches in the NGEE Arctic intermediate- and fine-scale models.

### IV.2.3 Intermediate-Scale Model Development and Tasks

The following key processes are required for the intermediate-scale model: lateral water flow on the surface and in the subsurface, reactive transport of solutes, subsurface heat transport, surface energy balance processes, soil biogeochemistry, and plant dynamics. The intended spatial resolution for the subsurface model is approximately 100 × 100 m in the horizontal direction, with resolutions ranging from 10 × 10 to 100 × 100 m for the atmospheric process model. Processes represented through sub-grid parameterization include polygonal ground and ice wedge dynamics as well as PFT distributions.

The intermediate-scale simulator differs from the fine-scale simulator in three important aspects. First, the effect of microtopography associated with polygonal ground (and vegetation heterogeneity in the case of the near-surface atmospheric calculations) will be a sub-grid parameterization and not represented directly. Second, with topography averaged to the 100 m scale, it is not necessary to represent the full complexity of topographic evolution. Thus, the computationally difficult issue of an adaptive mesh may be avoided at the intermediate scale. Third, it is not necessary to represent the full complexity of the thermal hydrology of freezing/thawing soils or fine-scale turbulence at the intermediate scale. In particular, more approximate and computationally tractable models may be used to represent lateral subsurface thermal flows and effective mixing.

**Task IM1: Development of intermediate-scale model requirements.** Detailed specifications of the mathematical model and algorithmic approaches appropriate at the intermediate scale will be developed. Simple vertical subsidence calculations and associated small-displacement mesh motion may be required to represent thaw subsidence, but the more difficult issues of mesh smoothing and mesh remapping are avoided at the intermediate scale. The requirements document will specify the model processes to be represented as well as algorithm options and required computational infrastructure. Research including prototype development is required to identify appropriate approximations and algorithms for two key processes: representations of subsurface lateral flow and representations of thaw lakes. Variants of a nonlinear Boussinesq equation with a moving lower boundary will be explored as a way of routing water laterally above the seasonally varying frost table. Thaw lakes are not adequately represented by shallow overland flow representations and research is needed to identify an appropriate representation.

**Task IM2: Work plans for Amanzi and PFLOTRAN development.** Work plans describing the effort required to produce the intermediate-scale simulator from Amanzi and PFLOTRAN will be developed. These two work plans will support the decision on foundational architecture for the intermediate scale simulator. Each plan will describe the code modifications required and a plan for testing those modifications. Estimates of level of effort required to complete the work will also be provided. A workshop on the requirements for the intermediate-scale subsurface simulator and work plans for its development will be held by September 2012. Potential users of the community code for intermediate-scale simulation will be invited. In addition, external computational specialists will be asked to participate to provide feedback on the proposed approaches.

**Task IM3: Decision on the intermediate-scale simulator.** A decision on foundational architecture for the intermediate-scale subsurface simulator will be made by October 2012. The decision will be based on an objective evaluation of the existing capabilities of the Amanzi and PFLOTRAN models and their potential for extension, as referenced against the requirements described under Tasks IM1 and IM2. Decisions will be made by consensus of the modeling team. Possible outcomes include adoption of one or the other modeling framework as the foundational architecture for the NGEE intermediate-scale simulator, or the selection of appropriate components from each framework as merged foundational elements for new development.

**Task IM4: Construction of the intermediate-scale simulator.** Work plans from Task IM2 will be executed, following model requirements from Task IM1 as modified by workshop input. Intermediate-scale model development will begin prior to the decision point on foundational architecture (Task IM3), as many model components and algorithms can be developed as modules with well-defined interfaces. Upon completion of Version 1, the code developers will conduct a tutorial workshop addressing code use, the underlying technical basis for each process representation, and preliminary results for test problems.

**Task IM5: Intermediate-scale simulation test cases.** A series of simulation cases will be developed, including simple verification/validation tests that exercise individual process models, synthetic but realistic cases for testing model couplings, and site-specific cases that exercise the full capabilities of the simulator. These cases will be executed concurrently with development of Version 1 of the intermediate-scale simulator.

**Task IM6: Near-surface atmosphere simulations.** We will begin a series of intermediate scale-simulations ranging from 10 × 10 m resolution to 100 × 100 m horizontal resolution, with appropriately scaled vertical resolutions, characterizing the implications of reduced resolution for mixing processes. These simulations will assist in the development of appropriate up-scaling parameterizations for the connection between subsurface and climate-scale atmospheric flows, providing guidance in quantifying up-scaling uncertainties.

**Task IM7: Development and testing of an intermediate-scale biogeochemistry framework.** We will develop a computationally efficient solution for the complex biogeochemistry of Arctic tundra by generalizing relationships between biogeochemical cycles and environmental variables. The modeling will be performed in the intermediate-scale simulator framework emerging from Task IM4. We will begin by integrating the intermediate-scale surface characterization; hydrological and thermal sub-models; and vegetation sub-models with a subsurface biogeochemistry submodel. Simulations will be performed for individual geomorphological units (e.g., low-centered, transitional, and high-centered polygons) found across drained lake basins in the BEO. Model predictions will be compared to measurements of surface trace-gas fluxes, subsurface C and N concentrations, and $NO_{3-}$ concentrations in stream water and lakes.

**Task IM8: Initialization of intermediate-scale model domains.** This task will use the output from landscape characterization and hydro-geomorphology tasks (Tasks LC4, S3, and HG5) associated with characterization and classification of drainage network, hydraulic geometry and connectivity, surface and frost table topography, and storage capacity to define the topographic, thermal and permafrost hydrology components of several intermediate-scale simulation domains over the BEO. This effort includes the explicit characterization of low centered, transitional and high centered polygonal ground found across drained lake basins of different ages as well as interstitial terrain. Results from this task also provide constraints on climate-scale sub-grid parameterization of landunits and soil columns, ensuring consistency in landscape characterization across scales, which is crucial to unbiased up-scaling and down-scaling.

**Task IM9: Intermediate-scale parameter estimation and up-scaling simulations.** We will use results from fine-scale model simulations, generated over subsets of the BEO (Task FM9), as training targets in the parameterization of polygonal ground and ice wedge dynamics in the intermediate-scale model. These processes will be represented explicitly in the fine-scale model, but empirically in the intermediate-scale model. We will employ formal data assimilation methods to determine optimal parameter values, capturing as much of the fine-scale model variability as possible, given constraints imposed by uncertainty in fine-scale model results and observation-based a priori estimates for intermediate-scale parameters. Vegetation dynamics as predicted by the fine-scale model will also be used to parameterize rates of change in PFT distributions as functions of mean thermal, hydrologic, and biogeochemical states. After estimating optimal parameters based on up-scaling, we will perform intermediate-scale simulations over subsets of the BEO. These results serve as input to Task CM6, and will also be subjected to evaluation against integrative observations (Task I1).

**Task IM10: Intermediate-scale boundary constraints and down-scaling simulations.** The intermediate-scale model integration from Task IM9 will be repeated with updated boundary conditions generated under task CM7, and the results will be compared with arbitrary and field-based boundary conditions imposed in earlier simulations. Boundary conditions passed to the intermediate model will include hydrologic outflow, water table depth, soil water saturation state, and soil temperature. Results will be compared with intermediate-scale observations of subsurface state, surface flow, and land-atmosphere flux measurements. This task will also generate new boundary conditions to be passed to the fine-scale model, including surface and subsurface flows as influenced by the dynamic drainage network and thaw lake dynamics of the intermediate-scale model.

### IV.2.4 FINE-SCALE MODEL DEVELOPMENT AND TASKS

The following key processes are required for the fine-scale model: water migration in freezing/thawing soils, overland flow, reactive transport of solutes and colloids, subsurface heat transport, surface energy balance processes, topographic evolution caused by thaw-induced mechanical deformation processes, soil biogeochemical/microbial processes that result in carbon release, and plant dynamics. Support for a multicontinuum reactive transport formulation may also be necessary to represent mobile/immobile regions that coexist within a grid cell. The intended spatial resolution for the subsurface model is fine enough to resolve topography and subsurface heterogeneity within single ice wedge polygons (approximately 0.1 m in the horizontal and 0.02 m to 0.1 m in the vertical). Horizontal domain size will be on the order of 100 × 100 m. Simulating these coupled processes at the spatial resolution and spatial scale required is computationally demanding and software suitable for execution on large parallel computers is required.

The proposed path forward is to develop a set of code requirements for the fine-scale model and then to evaluate PFLOTRAN and Amanzi and derivative products against these requirements to reach a decision on the preferred computational platform. Subsequent development will add any needed additional capabilities, optimize code for computers to be used by NGEE Arctic, undertake a sequence of “confidence building” test simulations, and integrate into the scaling framework.

**Task FM1: Development of fine-scale model requirements.** Detailed specifications of the mathematical model and algorithmic approaches appropriate at the fine scale will be developed. Although the key processes that are required of the fine-scale simulator are understood, detailed specifications of the mathematical models, algorithmic approaches, and computational infrastructure are still needed. For example, computational approaches for topographic evolution may be based on Lagrangian or Eulerian approaches. Computational infrastructure requirements for a Lagrangian approach are relatively well understood. The alternative Eulerian approach based on a fixed grid through which material is propagated has reduced computational infrastructure requirements but also has reduced accuracy due to material mixing at material interfaces. Some prototype development and testing are warranted to refine the Eulerian approach and to evaluate its advantages and limitations in NGEE Arctic context.

**Task FM2: Work plans for Amanzi and PFLOTRAN development.** Work plans describing the effort required to produce the fine-scale simulator from Amanzi and PFLOTRAN will be developed by September 2012. Each plan will describe the code modifications required and a plan for testing those modifications. Estimates of level of effort required to complete the work will also be provided. These two work plans will support the decision on foundational architecture for the fine-scale simulator. A workshop on the requirements for the fine-scale subsurface simulator will be held by September 2012. Potential users of the community code for fine-scale simulation will be invited. In addition, external computational specialists will be asked to participate to provide feedback on the proposed approach. This workshop will be held jointly with the requirements workshop for the intermediate-scale model (Task IM2).

**Task FM3: Decision on the fine-scale subsurface simulator.** A decision on the foundational architecture for the fine-scale subsurface simulator will be made by December 2012. The decision will be based on an objective evaluation of the existing capabilities of the Amanzi and PFLOTRAN models and their potential for extension, as referenced against the requirements described under Tasks FM1 and FM2. Decisions will be made by consensus of the modeling team matrix leads (see Section VI). Possible outcomes include adoption of one or the other modeling framework as the foundational architecture for the NGEE fine-scale simulator, or the selection of appropriate components from each framework as merged foundational elements for new development.

**Task FM4: Construction of the fine-scale simulator.** Work plans from Task FM2 will be executed, following model requirements from Task FM1 as modified by input from the fine-scale workshop. Fine-scale model development will begin prior to the decision-point on foundational architecture (Task FM3), as many model components and algorithms can be developed as modules with well-defined interfaces. Upon completion of Version 1, the code developers will conduct a tutorial workshop addressing code use, underlying technical basis for each process representation, and preliminary results on test problems.

**Task FM5: Fine-scale simulation test cases.** A series of simulation cases will be developed, including simple verification/validation tests that exercise individual process models, synthetic but realistic cases for testing model couplings, and site-specific cases that exercise the full capabilities of the simulator. These cases will be executed concurrently with development of Version 1 of the fine-scale simulator.

**Task FM6: Simulate fluvial landscape evolution.** An important functionality of the fine-scale landscape simulator is to predict changes in topography and drainage patterns as the result of permafrost thaw and thermokarst formation. Existing fluvial landscape evolution modeling approaches will be evaluated for inclusion in the fine-scale simulator. Simulations will explore several idealized cases such as low-slope domains, and flat domains with random initial elevations, and realistic domains based on LiDAR topography from polygonal tundra environments on the BEO. We will also perform exploratory modeling analyses using existing erosion/sedimentation code (Erode, http://csdms.colorado.edu/wiki/Model:Erode) to simulate the process of terrain modifications associated with melting of buried ice wedges and accompanying thermal and mechanical erosion. We will use this exploratory modeling framework to simulate thermokarst propagation and effects on lateral drainage and drying of polygonal networks.

**Task FM7: Subsurface biogeochemical reaction network.** A critical function of the fine-resolution landscape simulator will be to simulate the complex subsurface biogeochemical environment, where multiple functional microbial and fungal groups perform a range of C and N transformations. These biological reactions occur in an environment with various forms of soil organic matter (SOM), mineral surfaces, thermal states, hydrological states, redox states, and competition with plants. The goal of this task will be to develop, test, and apply a biogeochemical reaction network in a 1D reactive transport numerical model that explicitly includes processes relevant to high latitudes. For Phase 1, we will synthesize, from our previous work and from the literature, a reasonable reaction network that includes bacteria and fungal activities, characterization of multiple functional groups and their dependencies on substrates and other environmental variables, freeze and thaw cycles, nitrification, denitrification, plant nutrient uptake, abiotic reactions, and transport. We will use the proposed NGEE chemostat, column, and genomic observations to test the reaction network. Uncertainty and sensitivity analysis of the fine-scale model will be conducted to identify the key parameters and model structures that contribute to model predictions and behavior.

**Task FM8: Initialization of fine-scale model domains.** This task will use the output from landscape characterization, hydro-geomorphology, and biogeochemistry tasks associated with characterization and classification of drainage network, hydraulic geometry and connectivity, surface and frost table topography, soil carbon and ice content, and storage capacity to define the topographic, thermal, and permafrost hydrology components of several fine-scale simulation domains over the BEO. This effort includes the explicit characterization of low-centered, transitional and high-centered polygonal ground and the subsurface distribution of ice wedges that structure the microtopography in these landscapes. Results from this task also provide constraints on intermediate-scale sub-grid parameterization.

**Task FM9: Fine-scale simulations for up-scaling.** We will exercise Version 1 of the fine-scale model over subsets of the BEO, using model parameters; boundary conditions; and initial model thermal, hydrologic, and biogeochemical states from Task FM8. Results from these simulations serve as input to the intermediate-scale model up-scaling parameterization (Task IM9). The fine-scale model includes mechanistic treatment of ice wedge dynamics and dynamic microtopography. We will employ formal data assimilation methods to determine optimal parameter values and initial conditions, capturing as much of the observed fine-scale variability as possible, given constraints imposed by uncertainty in measurements. Simulation results will be evaluated against independent integrative observations (Task I1).

**Task FM10: Fine-scale boundary constraints and down-scaling simulations.** The fine-scale model integration from Task FM9 will be repeated with updated boundary conditions generated under task IM10, and the results will be compared with field-based boundary conditions imposed in earlier simulations. Boundary conditions passed to the fine-scale model will include surface and subsurface flow and the thermal and hydrologic effects of thaw-lake dynamics. Results will be compared with fine-scale observations of subsurface state, surface flow, and land-atmosphere flux measurements (Task I1).

**Task FM11: Near-surface atmosphere simulations.** We will begin a series of fine-scale-simulations ranging from 0.1 × 0.1 m to 10 × 10 m horizontal resolution, with appropriately scaled vertical resolutions, characterizing the implications of reduced resolution for mixing processes. These simulations will assist in the development of appropriate up-scaling parameterizations for the connection between subsurface and climate-scale atmospheric flows, providing guidance in quantifying up-scaling uncertainties.

**Task FM12: Continued development of fine-scale simulator.** Version 1 of the NGEE fine-scale simulator (Task FM4) will represent a significant step forward in the process-resolving representation of Arctic ecosystem processes, but there are important dimensions of the fine-scale simulation problem that we will not be able to incorporate early enough in NGEE Phase 1 to allow a full integration with the up-scaling and down-scaling framework. The purpose of Task FM12 is to continue several lines of development in parallel with the up-scaling and down-exercises, to provide a more capable Version 2 of the fine-scale simulator in time for application in NGEE Phase 2. These efforts will focus on advanced grid representations for landscape deformation and increasingly sophisticated coupling of soil biogeochemical processes with vegetation dynamics.

**Phase 1 Deliverables**

- New version of Community Land Model with explicit sub-grid representations of geomorphological landunits controlling mass and energy fluxes in Arctic ecosystems.
- Operational fine-scale and intermediate-scale process resolving models of Arctic ecosystems, through which climate-scale parameterizations can be quantified.
- Demonstrated ability to integrate new knowledge from process observations and experimentation into a multiscale modeling framework that results in improved predictions across scales.
- A comprehensive set of data-based metrics quantifying model prediction skill and uncertainty for processes related to Arctic ecosystem hydrology, geomorphology, biogeochemistry, and vegetation dynamics.

## IV.3 PROCESS STUDIES AND OBSERVATIONS WITH LINKS TO MODEL DEVELOPMENT AND APPLICATION

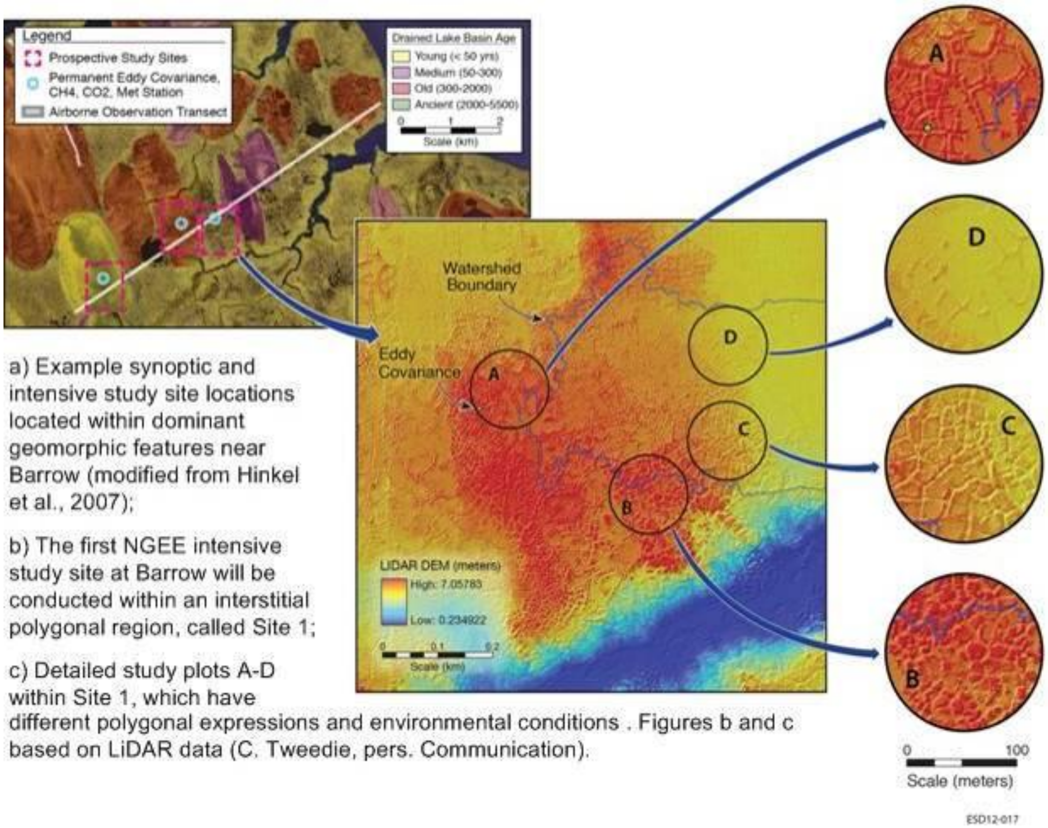
### IV.3.1 SITE CHARACTERIZATION AND DESIGN

Site characterization will be performed to choose optimal locations for NGEE Arctic field studies, to coordinate development of field site infrastructure and installation of key instrumentation, and to facilitate archiving and integration of the foundational datasets collected across the NGEE Arctic project. This activity will benefit from and coordinate with Task LC.1 (Section IV.1.1, "Landscape Characterization and Identification of Geomorphological Features").

**Site Characterization Goal:** Coordinate infrastructure development, ensure safe data acquisition, and archive multiscale, multitype datasets needed for integrated site selection, process understanding, scaling, and model parameterization.

**Task S1: Barrow sampling strategy and first intensive field study site.** Field studies in the first few years of the project will focus on study sites located within the BEO. As described in Sections IV.1.1 and IV.1.2, concurrent efforts will focus on identifying a suitable scaling construct and associated sampling plan for other prospective NGEE Arctic field study regions, which are likely to have geomorphic controls that are different from those of the Arctic coastal plain region.

As described in Section III, the terrestrial landscape of the Barrow Peninsula is a mosaic of thaw lakes, DTLBs, and interstitial polygonal regions (Hinkle et al. 2007, Figure 10a and Figure 4). Given the low topographic relief, low hydraulic gradient, and shallow depth (< 1m) to the top of the permafrost in this




a) Example synoptic and intensive study site locations located within dominant geomorphic features near Barrow (modified from Hinkel et al., 2007);

b) The first NGEE intensive study site at Barrow will be conducted within an interstitial polygonal region, called Site 1;

c) Detailed study plots A-D within Site 1, which have different polygonal expressions and environmental conditions . Figures b and c based on LiDAR data (C. Tweedie, pers. Communication).

**Figure 10. Barrow study sites.**

region, the polygonal landforms greatly influence the microtopography, and in turn, the hydrological stocks and fluxes of the region. Low-centered polygons often have standing water during the growing season (Liljedhal 2012) whereas the middle regions of high-centered polygons are typically well drained. The microtopographically controlled moisture distribution plays a significant role in biogeochemical cycling in this region, as troughs surrounding polygons can serve as pathways for water and nutrients (Woo and Guan 2006) and the depth of the water table below ground surface influences where anaerobic vs aerobic respiration processes dominate (e.g., Zona et al. 2011, Lipson et al. 2012). Indeed, Zuleta et al. (2011) documented that near Barrow, interstitial polygonal regions had a similar $CO_2$ flux signature as did old and ancient DTLBs, together representing ~59% of the regional flux. They further found that medium and young DTLBs had similar signatures and together represented ~35% of the regional flux (the rest stemming from thaw lakes). These studies highlight the potential power of using a geomorphic-based construct to guide Barrow site characterization and the NGEE Arctic hierarchical scaling framework.

Early NGEE Arctic field efforts will include both intensive and synoptic studies conducted within the BEO. Synoptic studies will be performed in the first two years to provide spatially extensive but sparse baseline datasets associated with key geomorphic features in the BEO, including DTLBs of different ages and interstitial polygonal regions. These synoptic campaigns will lay the groundwork for the more intensive subsequent studies. In the first year of the NGEE Arctic project, intensive field studies will also be initiated, where co-located measurements will be conducted to characterize and monitor vegetation dynamics, soil biogeochemistry, energy and hydrothermal processes, and their couplings as are described in detail in Sections IV3.2, 3.3, and 3.4. While in Phase 1, it will not be possible to fully characterize the role of landscape heterogeneity in the evolution of Arctic ecosystems, the sampling approach that we have adopted provides an opportunity to advance process understanding as well as to initialize, parameterize, and validate the NGEE Arctic hierarchical scaling framework.

The first Barrow intensive site ("Site 1") will be developed within an interstitial polygonal region, a prevalent landform in the Arctic tundra. Figure 10b shows the location of the Poly1 study site, which is located to the southwest of the medium-aged DTLB, where many NSF Biocomplexity investigations have been performed (e.g., Zona et al. 2011). Site 1 encompasses an existing eddy covariance tower, and the site soils are classified as aquiturbals. Four study plots have been identified within Site 1 (Figure 10c), each of which has different geomorphic and hydrological conditions (Table 1). Sampling within the plots and along transects that connect these plots will permit exploration of permafrost degradation pathways. Importantly, it will also permit quantification couplings between vegetation dynamics, soil biogeochemistry, hydrology, permafrost dynamics, and energy balance and their influence on greenhouse gas dynamics under different environmental conditions. For example, working between Site 1C and Site 1D will allow us to explore degradation pathways and fluxes associated with low centered polygons under different moisture conditions. Similarly, working between Site 1A and Site 1C will allow exploration of the impact of polygon age on GHG dynamics. As data from synoptic studies conducted within nearby DTLBs become available, additional NGEE Arctic intensive sites will be developed.

**Table 1. Characteristics of representative study plots within Site 1 Intensive Study Site**

| Plot | Polygonal characteristics | Relative elevation | Moisture conditions | Estimated carbon content | Relative estimated age |
|---|---|---|---|---|---|
| A | Transitional low center polygons (with ridges and troughs) | High | Inundated | High | Old |
| B | High center polygons | High | Desiccated | Low | Old-ancient |
| C | Transitional low center polygons (with ridges and troughs) | Moderate | Moderately dry | Moderate | Old |
| D | Low center polygons (no troughs) | Low | Moderately wet | Low-medium | Young |

**Task S2: Field site infrastructure and installation of key instrumentation.** Site infrastructure is needed to enable the acquisition of field measurements in a safe and efficient manner with minimal disturbance to the fragile ecosystem. Examples of site infrastructure include trail mats/boardwalks, instrument site huts, and field power. Access to nearby laboratories and storage containers must also be considered. Many of these components are already established at the Site 1, and infrastructure will be developed for other intensive sites as they are identified through synoptic studies. As is briefly described below, field instrumentation will vary depending on the stage of the site development.

- Synoptic site instrumentation will include acquisition and analysis of remote-sensing data and surface geophysical measurements (electromagnetic and ground-penetrating radar) as well as limited characterization of carbon stock/age, active layer thickness, water levels and aqueous geochemistry, soil texture, and soil gas at select locations along the geophysical transects.
- Intensive study site instrumentation will include eddy covariance system(s) to quantify latent heat flux, sensible heat flux, advection, and $CO_2$ and $CH_4$ fluxes at the scale of tens to hundreds of meters. These sites will also include co-located micrometeorology stations to monitor radiation fluxes, temperatures, and atmospheric conditions. A surface and subsurface monitoring and lysimeter sampling network will be installed for hydrological and aqueous biogeochemical sampling, vegetation will be sampled and characterized, high-resolution geophysical transects will be collected within and between detailed study plots, and soil cores will be collected in and around polygonal features for laboratory analysis and experimentation. Various additional observational measurements and sampling will co-occur within and along transects between plots as part of the hydrogeomorphology, biogeochemistry, vegetation dynamics and energy research described in Sections IV.3.2 through IV.3.

**Task S3: Assemblage of site characterization data.** This task will entail assembling newly collected NGEE Arctic data as well as existing datasets to construct a spatially and temporally explicit database of parameters critical for assessing terrestrial ecosystem processes and feedbacks to climate in and around the NGEE Arctic study sites. Primary existing data inputs will include physiographic data layers at all relevant and available resolutions (including microtopography; geomorphology, soil texture, geochemistry, active layer depth, hydrological and thermal properties, and vegetation); weather and climate data; geophysical transects; and multiscale and multitemporal remote-sensing observations. This repository will evolve as new observations are collected through NGEE Arctic research. The NGEE Arctic data management system, which is expected to serve as a resource for both the NGEE Arctic project team and the community, will take advantage of, connect, and augment existing DOE database tools as described in Section V.

**Phase 1 Deliverables**

- Field environment, safety, and health (ES&H) protocols for NGEE investigators and collaborators (see Section VI).
- Development of field site infrastructure at two intensive sites at the BEO.
- Synoptic characterization within all key/representative geomorphic units at the BEO.
- Intensive characterization of NGEE Site 1.
- Assembly and archiving of existing and new NGEE Arctic datasets that are critical for assessing terrestrial ecosystem processes and feedbacks to climate and are associated with the BEO study sites.

### IV.3.2 HYDROLOGY AND GEOMORPHOLOGY

The Arctic landscape is characterized by standing water at a range of scales, from large thaw lakes and wetlands to smaller thermokarst ponds, standing water in low-centered ice wedge polygons and the troughs between polygons, and puddles between tussocks. These water storage elements control the spatial and temporal distribution of water across the landscape, the timing and magnitude of snowmelt runoff, and the availability of water to plants and soil microbes through the growing season and moderate the land to atmosphere latent and sensible heat fluxes. The degree of connectivity between these storage elements and local to regional drainage paths is highly dynamic. Seasonal frost table deepening enables infiltration and leads to lower connectivity of lateral surface runoff pathways through the complex micro-topography associated with DTLBs, polygonal ground, and other permafrost features. The topographic differences that define the storage capacity and connectivity of these features is often only on the order of a few centimeters (tussocks) or decimeters (polygon ridges, troughs, depth of the frost table) to a few meters (thaw lake depths) of elevation. Due to these limited vertical scales, even small topographic changes due to permafrost and ice wedge degradation have the potential to dramatically alter the hydrologic connectivity and storage capacity of the landscape.

**Hydrology and Geomorphology Goal:** Develop the process knowledge, model algorithms and datasets that will enable the prediction of the evolution of the Arctic tundra thermal, topographic, and hydrologic responses to climate-driven permafrost degradation.

A central theme of the Hydrology and Geomorphology Challenge is to advance process understanding and prediction of climate-driven Arctic landscape evolution and its impact on Arctic hydrology. We will investigate the thermal and hydrologic responses and feedbacks to thermokarst development in ice-rich ground and how these processes control the spatial and temporal availability of water and temperature for biogeochemical, ecological, and physical feedbacks to the climate system. The roles of vegetation and snow (their interaction with topography and their impact on surface and ground temperature and evapotranspiration) is a critical component of this research. Field activities to develop process understanding for model development will be carried out across a gradient of polygonal ground (high-centered to low-centered polygons) nested within a DTLB age gradient (young to old). In the second and third years, we will expand our activities to a second site in contrasting hydro-geomorphic and bioclimatic environments.

**Task HG1: Improve quantification of mechanisms and controls relating to permafrost and ground ice stability and frost table dynamics.** Year 1 efforts will focus on the design and installation of a surface and ground temperature network in Site 1 to improve understanding of the controls on ground temperatures across the range of hydro-geomorphic settings as well as to support hydrology, biogeochemistry, plant dynamics and integrated modeling goals. Year 2 will focus on the development of sub-grid–scale thermal response functions at the same locations for improved prediction of thaw depth dynamics and permafrost stability in intermediate-scale and global models.

**Task HG1.1: Field-based co-located temporally dynamic coupled process measurements** will be undertaken at intensive research sites to quantify the strength of interactions and feedbacks among meteorology, topography, vegetation, snowpack, surface temperature, soil temperature, soil and ground ice properties, soil moisture, surface water levels and temperature, active layer depth, and frost table dynamics.

**Task HG1.2: Improvement of existing thermal-hydrologic models** and with fine and intermediate scale models to develop dynamic sub-grid scale thermal response functions for global models using the data from Task HG1.1 to inform the models.

**Task HG2: Quantify the interactions among thermal, hydrologic, and soil mechanical processes**, and develop process equations and constitutive relationships that describe the initiation and evolution of thaw settlement and thermokarst in a range of hydro-geomorphic conditions. Year 1 activities are focused on the collection of thermal-hydromechanical (THM) cores for troughs, ridges, and low- and high-centered polygons; the building and testing of laboratory freeze-thaw-stress-strain experimental apparatus; and the design, installation, and testing of a range of field-based deformation observation techniques. In Year 2 we will perform column experiments on Site 1 Barrow samples; collect cores from second NGEE Arctic ecoclimate site; implement the most promising field-based deformation measurement techniques; and develop, test, and adopt stress-strain constitutive relationships for the fine-resolution model. In year 3 we will expand our monitoring efforts to additional hydro-geomorphic and bioclimatic sites, and we will complete the development of deformation/geomorphic response functions for models.

**Task HG2.1: Column-scale freeze-thaw and stress-strain experiments** on cores collected from the field will be used to quantify the deformation and failure response of the active layer, ice-rich permafrost, and ice wedges under a range of THM models with stress-strain constitutive relationships.

**TaskHG2.2: Spatially distributed field measurements of ground deformation dynamics** will be co-located with instruments deployed for tasks HG1 and HG3 to understand the role of seasonal freeze thaw cycles and permafrost and ground ice degradation on microtopography and the mechanical, thermal, and hydrologic properties and processes in soil. We will use remote-sensing products in years 2 and 3, which may include sequential LiDAR, ifSAR airborne, and/or surface geophysical surveys to scale point measurements to the geomorphic unit and intermediate model scale. These data, when coupled with thermal and hydrologic data, will be used to develop dynamic sub-landunit deformation/geomorphic response functions for intermediate and global models.

**Task HG3: Quantify the mechanisms and site properties that determine the spatial and temporal distribution** and the lateral and vertical fluxes of surface and subsurface heat and water. Year 1 activities will be focused on identifying important water and biogeochemical flowpaths through the landscape (surface and subsurface flows) so that key fluxes relevant to the three main NGEE Arctic scales of study can be quantified. This task includes measuring water fluxes along the soil/plant/atmosphere continuum to parameterize PFT water use (identifying sources of water and the depth from which water is taken), and evaporation and transpiration partitioning of ecosystem-level water vapor flux. This work explicitly links plant physiological processes with hydrological processes and quantifies the potential effects of vegetation shifts on the partitioning of evaporation vs transpiration. Evaporation-dominated water fluxes link surface soil moisture with the atmosphere but transpiration-dominated fluxes link surface and deeper, stored water with the atmosphere. These activities also support other planned NGEE Arctic work related to biogeochemistry. Year 2 will focus on the implementation of comprehensive surface and subsurface water monitoring network as well as the design and implementation of a flow path tracer experiment. Data from these tasks will be used to inform the development of the process resolving THM + overland flow model and to up-scale thermal-hydrologic processes from the fine to intermediate to global scales.

Up-scaling will be achieved by combining data from HG Tasks 1–3 in fine- and intermediate-scale models to develop dynamic sub-landunit thermal-hydrologic-geomorphic response functions. In Year 3 we will begin implementation of thermal-hydrologic-mechanical field and laboratory studies at a second NGEE Arctic bioclimatic site, and we will expand our response functions to include new hydro-geomorphic settings.

**Task HG3.1: Synoptic sampling of surface waters and groundwaters** for geochemistry and water stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) during the summer period will be undertaken. Surface water from polygonal ground areas, lakes, ponds, and rivers as well as groundwater will be sampled to obtain a cross-scale view of the spatial variability of water chemistry and isotopes. Such data will provide baseline tracer data related to potential flowpath connections between landscape units and may indicate large-scale biogeochemical transformations. The synoptic sampling results will also be used to identify where higher-resolution or targeted measurements of water-stable isotopes may be needed in Year 2 (e.g., for quantifying groundwater/surface water interactions or lake evaporation) and to evaluate the potential utility of nitrogen stable isotopes for understanding large-scale nitrogen cycling.

**Task HG3.2: An integrated surface water/groundwater sampling plan for Year 2 and beyond** will be developed using the synoptic sampling results. The plan will identify the most useful chemical and isotope constituents for analysis and identify locations for continuous and periodic monitoring. The proposed sampling network will support each of the science areas (Hydrology-Geomorphology, Biogeochemistry, and Plant Dynamics) by providing spatially distributed, dynamic geochemical values from surface and subsurface water, which will be used in the development of new process models as well as for model evaluation at all three scales: process resolving, intermediate, and global.

**Task HG3.3: Establish co-located soil water, plant water, and water vapor stable isotope measurements** to identify sources and quantities of water for plant evaporation and transpiration. Vegetation shifts that involve the replacement of mosses with vascular plants have the potential to impact hydrological processes and energy balance because of their impact on the partitioning of evapotranspiration into transpiration and evaporation Evapotranspiration in moss-dominated systems is dominated by evaporation, but in systems dominated by vascular plants, evapotranspiration is dominated by transpiration. Evaporation links surface soil water from recent rain events with the atmosphere and is a physically controlled process. Transpiration links surface (recent) water and deeper (older) water with the atmosphere, and is a physiologically controlled process that can be more challenging to predict /model. Additionally, vegetation shifts (from grasses to shrubs for example) can alter the transpiration dynamics, the sources of water used, and the depth from which the water is taken. Thus, the land-atmosphere connectivity is affected by the proportion of mosses vs vascular plants but also by the type of vascular plants present.

We will explore water use and evapotranspiration partitioning for Arctic PFTs using a newly developed isotope extraction/optical measurement system for small samples of various environmental media. Results will support PFT assessments, their links to stored vs ephemeral water availability, and their links to energy balance. The optically based isotope analyzer will also be tested in Year 1 for long-term continuous measurements of water vapor isotopes to support quantification of terrestrial evaporation fluxes with the goal of making long-term field measurements at eddy covariance tower sites in Year 2. Periodic measurements of plant- and soil-water stable isotopes will also be conducted at an installed field network to quantify how plants are using soil water pools over time. Stable isotope depth profiles in the soil will be monitored using rhizolysimeters.

**Task HG3.4: Application of benign geochemical tracers** at a selected intensive site to gain a quantitative understanding of how the connectivity between flow paths and storage elements evolves seasonally within polygonal ground and to quantify the partitioning of lateral and vertical water and advected heat, carbon, nitrogen, and other constituents of interest.

**Task HG4: Development of Subsurface Water-Sampling Methodologies for Arctic Conditions.** We will compare different sampling methods at a few selected locations to identify the best approaches to support the multiple needs of NGEE Arctic hydrology, plant dynamics, and biogeochemistry objectives in Year 2 and beyond. The dynamics of the active zone make subsurface water sampling a challenge, and it is worthwhile to do some method evaluation and development. Issues of concern related to the saturated zone are that freezing causes frost-jacking of nonanchored wells, changing their depths; the saturated zone is thin and growth is dynamic, making it a challenge to get multiple depth samples in what is expected to be a strongly zoned redox environment. In addition, a thin saturated zone makes it difficult to pump a sample without disturbing the chemistry of deeper or shallower sampling depths. Potential approaches that allow passive collection of samples include the use of diffusion cells and multidepth tube samplers anchored to permafrost. In order to track movement though unsaturated soil (e.g., percolation of snowmelt), other approaches are required to obtain water samples. Therefore, we will test methods such as rhizolysimeters and passive wick methods for sample collection. Both of these methods have been shown to be effective for both chemistry and isotope sampling of unsaturated materials. The wick method has the advantage of providing percolation flux information. A third Year 1 activity will be to test a new sampling apparatus for high-resolution time-series measurements of water stable isotopes in the field. This system will be very useful for targeted isotope studies discussed in the water task for Year 2. The task deliverable will be a journal article on the comparative results from the different sampling approaches as well as the results of the high-resolution isotope apparatus testing. The best techniques will be deployed at NGEE Arctic sites in Years 2 and 3 for comprehensive collection of subsurface water samples in support of biogeochemistry, nitrogen, and hydro-geomorphology tasks. It is anticipated that analysis of process relationships among hydrology, geomorphological units and biogeochemical markers will permit scaling analyses and extrapolation.

**Task HG5: Develop quantitative relationships between readily classified remote-sensing features and surface and subsurface properties and process domains for model initialization**. This task is strongly linked to the landscape classification activities. It is focused on synthesis of existing observations and on the collection and analysis of in situ measurements and ground-based geophysical surveys. These data will be used to develop and apply automated classification and data assimilation techniques that will enable us to initialize high-resolution, intermediate-scale, and global models in three dimensions with data at appropriate scales and representative variance. In the first year we will focus on the collection of ground-based geophysical (complex electrical, radar, seismic, and electromagnetic) data where we have high-resolution LiDAR topography and spectral datasets and intensive in situ measurements of surface and ground temperature, meteorology, hydrology, vegetation, and biogeochemistry observations. We will test our data assimilation products and techniques in existing high-resolution and intermediate-scale models. In Year 2 we will couple knowledge gained at the fine resolution with fractional area classification of DTLBs, thaw lakes, and other hydro-geomorphic features to develop global model sub-grid–scale land properties and process domain initialization datasets. Year 3 efforts will focus on expanding in situ and geophysical ground truth datasets to additional NGEE Arctic sites and the application of multiscale data assimilation techniques to more diverse hydro-geomorphic settings.

**Task HG5.1: Surveys of the variation in temperature, soil moisture, active layer depth, and soil properties** coupled with ground-based geophysical surveys. Surface and subsurface properties will be characterized on a high-resolution grid at intensive study sites to assess fine-scale variance in properties and covariance of surface and subsurface properties. Data will be used to develop data assimilation techniques and to initialize models. In particular, we will investigate the covariance of ground temperature, soil moisture, ground ice, thaw depth, and soil properties (texture, carbon characteristics) as a function of topography, surface hydrology, and vegetation.

**Task HG5.2: Synthesis and analysis of available observations** from the BEO and other sites in Alaska will be performed to develop synthetic and site (best representation of actual site with appropriate variance) models for the development and testing of the high-resolution THM models under a range of climate and landscape conditions. These models aim to represent critical process-relevant properties of a range of hydro-geomorphic settings, including high- and low-centered polygons in young to old DTLB environments, and later catena properties in upland environments. A wealth of in situ meteorological, thermal, and hydrologic data exists within the BEO, the LTERs, and other Alaska sites that can be used to develop the test models. In Year 2 we will focus on quantifying variance in subsurface properties for the Barrow Peninsula and on the development of intermediate-scale subsurface model initialization data for a 30 × 30 km grid cell. Year 3 work will extend the synthesis and assimilation of data from existing research sites across Alaska with data from additional NGEE Arctic sites in other arctic landscapes.

**Task HG6: In situ, geophysical, and remote-sensing hydro-geomorphic measurements will be used to calibrate models and evaluate model performance**. We will apply these analyses to validate scaling relationships. In Year 1 we will focus on using the thaw depth, snow cover, soil moisture, soil temperature, and inundation seasonal dynamics observations described above to evaluate fine-scale model predictions of these same quantities. For evaluation of the intermediate-scale model, we use existing surface runoff weirs and perform runoff measurements in a hydrographic survey mode to design a nested surface runoff measurement network to be implemented in Years 2 and 3. In Year 3 we will also expand our runoff measurement network to an additional NGEE Arctic site for initial testing. The surface runoff network will be integrated with the subsurface monitoring network described in task HG3. The network will include surface runoff gages in low- and high-centered polygonal ground around intensive sites and at one or two additional 0.5–5 $km^2$ watershed scales and will provide data to evaluate predictions of hydrologic flow and connectivity. For both fine- and intermediate-scale models we will evaluate the predicted partitioning of lateral and vertical water fluxes using eddy covariance data. Predicted seasonal hydrology dynamics will be evaluated in part through measured early and late summer fractional inundation area for 10 × 10 km regions using remote-sensing products and field ground truth along transects. For global-scale hydrology, we will evaluate predicted hydrologic flow against observed river flow from large instrumented basins with long historical records. Based on large-scale remote-sensing inputs and intermediate-scale ground truth observations, we will estimate fractional inundated area changes between early and late summer and will compare to model representations of this process.

**Phase 1 Deliverables**

- Thermal response function for permafrost and ground ice stability, based on hydrological and geomorphological interactions.
- THM model of initiation and evolution of thaw settlement and thermokarst formation.
- Process-resolving model of subsurface, surface, and plant water distribution and flow developed.
- Development and implementation of quantitative approaches to characterize and relate land-surface and subsurface variability using remote-sensing and surface geophysical datasets.
- Calibration and evaluation of hydrologic models using runoff measurements.

## IV.3.3 BIOGEOCHEMISTRY

The carbon fixation, sequestration, and emission processes in permafrost regions present a great uncertainty in global C cycle and climate models (BERAC 2010, Roberts et al. 2010. The Arctic has been a C sink for millennia, but it could become an important source of $CO_2$ and $CH_4$ to the atmosphere if a warmer climate leads to the release of vast quantities of stored C in excess of the annual net carbon uptake. The nature, magnitude, and rates of these changes in the C cycle will depend on climate-driven changes in Arctic biogeochemical, vegetation, and hydrological processes, creating a critical feedback loop (Grosse et al. 2011).

**Biogeochemistry Goal:** Develop a quantitative model of organic matter decomposition rates in high-latitude soils with underlying permafrost, as needed to improve predictions of $CO_2$, $CH_4$, and $N_2O$ GHG feedbacks on changing Arctic ecosystems.

Close interactions between modeling, field observation, and laboratory measurement teams will build a framework for the initialization, parameterization, testing, and improvement of biogeochemical process representations in multiple modeling scales. Observations and experimental results will reduce uncertainty in models' GHG response functions attributable to impacts on C turnover times associated with (1) temperature, moisture, and aqueous chemistry (e.g., pH and redox potential); (2) SOM structure, C cascades, and intrinsic turnover times; (3) sorption and physical protection by soil minerals; and (4) freeze-thaw cycles and microbial adaptation. The investigations of fundamental biogeochemical processes will be represented in greatest detail at the fine scale of models, which most closely addresses the spatial scale of core sampling and subsequent experimentation. However, the integrated knowledge from many of these studies will be directly applicable to process representations and parameterizations in the intermediate- and climate-scale models.

**Task BGC1: Soil and Groundwater Sampling.** During the first year, observations and measurements will focus intensively on a single geomorphic unit, a low-centered polygon in BEO Site 1. This wet meadow tundra contains Typic Aquiturbel or Histoturbel soil, with an active layer ~20–55 cm deep (Hubbard et al. 2012). Replicate frozen core samples (approximately 7.7 cm diameter by 1 m depth) will be removed from the center, ridge, and trough regions of this low-centered polygon using a SIPRE auger (redesigned with DOE support) and hydraulic drill (Hughes and Terasmae 1963, Bockheim and Hinkel 2007). Core samples will be shipped frozen to laboratories for the analyses and experiments described below. In addition to intensive sampling at this site, representative core samples will be removed from nearby high-centered and transitional polygonal tundra on the BEO.

A basic suite of analyses will be performed on these samples. To initialize models, organic carbon and nitrogen composition, bulk density, pH, texture, microbial community profiling, and soil water content will be measured in soil and permafrost horizons to a depth of approximately 1 m (Burtt 2011, Johnson et al. 2011). These results will be used to initialize models at all scales.

In collaboration with the hydrology and geomorphology group (Task HG4), groundwater wells or piezometers will be installed to sample water from the surface to the permafrost table. These water samples will be compared with analyses of soil water from core samples. Geochemical measurements performed will include pH; ionic composition and concentration; oxidation-reduction potential; dissolved $O_2$, $CO_2$, $CH_4$, and $H_2$ concentrations; dissolved organic matter (DOM) and particulate organic matter (POM) concentrations; and chemical characteristics (Rinnan and Rinnan 2007); and fluid electrical conductivity measurements. Concentrations of redox-sensitive species such as nitrate-nitrite-ammonium, sulfate-sulfide, Fe(II/III) and Mn(II/IV) will be analyzed in the field or in the laboratory. Interpretation of the biogeochemical wellbore-based measurements will be performed in the context of the microtopography and spatially variable subsurface environmental variables (e.g., soil moisture, temperature) that will be characterized as described in Section IV.3.2, "Hydrology and Geomorphology."

In subsequent years, sampling will focus on additional geomorphologically distinct features and interstitial tundra identified from fine-scale elevation and remote-sensing data. The controlling factors for biogeochemical processes will be compared across DTLBs of various ages to parameterize fine- and intermediate-scale models.

**Task BGC2: SOM Turnover Times and GHG Fluxes in Thawing Soils.** In all soils, some organic matter degrades more rapidly than others; therefore, models such as CLM conceptualize belowground C as residing in several interconnected pools with varying intrinsic decomposition rates (turnover times) (Jenkinson and Coleman 2008, Parton et al. 2010). Predicted C storage and fluxes in these models depend critically on how (1) these turnover times and their dependencies on local conditions are formulated, (2) the C cascade is designed, and (3) the belowground N cycle is formulated (Thornton and Rosenbloom 2005).

The physical and chemical differences among these pools are poorly defined (Trumbore 2009, Kleber et al. 2011) because SOM consists of heterogeneous C sources with varying chemical compositions, structural characteristics, degrees of polymerization, water solubility, and mobility (Ping et al. 1997). Most Alaskan permafrost soils are high in organic C but have a low degree of humification compared with temperate soils (Tarnocai et al. 2009). Therefore, a large proportion of SOM can be mineralized in Alaskan soils, including both extractable and nonextractable fractions (Dai et al. 2000). Recent studies have indicated that the $CO_2$ and $CH_4$ released into the atmosphere from these permafrost soils have $\Delta^{14}C$ values that are characteristic of older, buried C (Schuur et al. 2009, Wahlen et al. 1989). Therefore, accurately modeling the turnover times of SOM pools will be key to predicting GHG emissions from thawing permafrost. The following measurements will improve the representation of C cycling in Arctic tundra by identifying SOM structural and adsorption properties that control the bioavailability of C pools.

Soils from each horizon will be fractionated for mineralogical analysis and spectroscopic analysis of SOM structure. We will use advanced spectroscopic techniques, such as 2D excitation- emission (EEM) fluorescence and Fourier-transform infrared (FTIR) spectroscopy, to interrogate chemical and structural changes of soil carbon and its degradation rates in response to soil warming and microbial degradation. A proposal for the Pacific Northwest National Laboratory Environmental Molecular Sciences Laboratory (EMSL) high-resolution mass spectrometry and $^{1}H$- and $^{13}C$-nuclear magnetic resonance user facilities will be developed to extend structural characterization of SOM. The $\delta^{13}C$ and $\Delta^{14}C$ values of significant SOM pools will be measured in collaboration with the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory (LLNL) (Guilderson and McFarlane 2009). The $\Delta^{14}C$ values of carbon in litter, roots, and organic matter will be used to estimate long-term ecosystem residence times of organic C with depth (Torn et al. 2002, Trumbore 2009).

Dissolved ionic species, such as $Fe^{2+}$ and $Ca^{2+}$, facilitate aggregation of organic matter in water. Depending on pH and mineralogy, DOM also interacts with the surface of sediment grains (Gu et al. 1994, Sollins et al. 2009), which could alter its susceptibility to microbial attack and thus its preservation and translocation in the permafrost soil. To test this hypothesis, the interactions between organic matter and sediment minerals will be analyzed. First, intact soil grains will be examined using micro-Raman and FTIR spectroscopies to probe the bonding mechanisms between organic C and mineral phases. Second, in batch experiments, dissolved organic compounds will be extracted and subsequently added to different mineral fractions of permafrost and active layer soils. The extent of sorption and stabilization will be determined. Geochemical conditions such as $E_h$ (aerobic or anaerobic redox potential), pH, and dissolved ionic species are expected to influence C-surface reaction processes and will be considered in the design of these experiments. The bioavailability of both the desorbed and adsorbed compounds, and of the original SOM, will be determined using long-term incubation experiments. By separating carbon into bioavailable desorbed compounds and protected adsorbed compounds in each POM and mineral-associated organic matter fraction, these experiments will distinguish measureable C pools, enabling predictive modeling of the dynamics of SOM degradation and transformation from one C pool to another.

The response functions for $CO_2$ and $CH_4$ production in current land models require additional parameterization of temperature and oxygen controls on SOM decomposition rates in Arctic soils. Microcosms containing homogenized soils from major active layer and permafrost horizons will be incubated at temperatures measured during the thawing shoulder season and summer, as reported by thermistor arrays and archived data from the CALM project (Hinkel and Nelson 2003). $CO_2$ and $CH_4$ production rates will be calculated using biweekly gas chromatography measurements, and changes in the concentration of chemical redox species [Fe(II)/Fe(III), and Mn(II)/Mn(IV)] will be determined at the end of the 6–8 week incubation period. Changes in microbial community composition will be monitored using high-throughput molecular phylotyping in collaboration with the Joint Genome Institute. The isotopic composition of $CO_2$ and $CH_4$ released into the headspace will be analyzed at CAMS to estimate the ecosystem age of carbon decomposed in the active layer vs that from recently thawed permafrost material.

In addition to microcosm incubations, mesocosms will be established using intact cores. A two-stage cooling apparatus will be constructed to gradually thaw soil cores to an equilibrium approximating the vertical thermal gradient during mid-summer. Access ports will permit sampling, and instrumentation arrays will monitor changes in temperature, water content, and chemistry along the vertical profile. Periodic sampling of the headspace, soil, and pore water along the length of the column will be used to measure changes in concentrations of gases and solutes, quality of SOM, and the microbial community during the controlled thaw. These time-series data will be used to parameterize and test 1D models of the soil column.

Methanotrophic bacteria oxidize $CH_4$ to $CO_2$. Methane biogeochemistry models recognize a high level of uncertainty surrounding this important process (Riley et al. 2011). Methane oxidation will be measured in microcosms prepared using soil samples taken from different depths and proximity to the rhizosphere to assess root-stimulated methanotrophic microbial communities (Wagner et al. 2005). Microcosm incubations will also be used to determine response functions to changes in temperature, $CH_4$ and $O_2$ pressure, pH and water saturation. Molecular markers of methanotrophy will be measured using quantitative, real-time polymerase chain reaction (RT-PCR) with degenerate primers specific for methane monooxygenase genes and stable isotope probing, using $^{13}CH_4$ or $^{13}CH_3OH$ (Kelly and Wood 2010). Measurements of methane oxidation rates will be coupled to metagenomic and metaproteomic analyses to identify changes in methanotroph populations and activity that will parameterize fine-scale models (Graham et al. 2011).

During the summer field seasons, integrated $CO_2$ and $CH_4$ fluxes will be measured from the surface of the intensively studied polygonal tundra. These GHG emissions will be measured using chambers and laser-based infrared gas analysis (Natali et al. 2011). The isotopic composition of collected $CO_2$ will be measured at CAMS to compare the age of mineralized C with the age of SOM C from soil horizons and fractionated pools.

Eddy covariance systems will be used to measure 30-minute average net fluxes of $CO_2$, $CH_4$, latent heat, and sensible heat with a footprint on the order of 100 × 50 m. These measurements will be performed according to standard methods for AmeriFlux type systems (Sachs et al. 2008, Vourlitis and Oechel 1997, Wille et al. 2008, Fan et al. 1992), and the results will be used to derive landscape-scale functions of the entire ecosystem response to light, water, and temperature. These functions will be used, through an up-scaling approach, to derive scale-dependent parameters in the intermediate and climate-scale models.

Some information relevant to our understanding of biogeochemistry dynamics will also be available at the climate modeling scale. Starting in 2012, the NASA Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) will fly over the North Slope of Alaska with an airborne remote-sensing payload that includes an L-band radiometer/radar and a nadir-viewing spectrometer to measure surface parameters that control gas emissions (i.e., soil moisture, freeze/thaw state, surface temperature) and total atmospheric columns of $CO_2$, $CH_4$, and CO. NGEE Arctic scientists are in discussion with the CARVE PI (C. Miller) to share data, since the NGEE Arctic surface eddy flux data will be very useful for CARVE and the CARVE transects will provide a statistical sampling for testing NGEE Arctic models at the climate scale.

**Task BGC3: Soil Freeze-Thaw Effects on Decomposition and SOM Distribution.** Water and ice are heterogeneously distributed in the subsurface. This spatiotemporal variability of soil wetness and ice volume impacts soil pore water flow, chemistry (including redox potential), tension, and soil temperature. During freezing and the binding of water in ice crystals, ions are expelled and concentrate in the remaining liquid phase (Price 2007). Even at subzero ambient temperatures, liquid water exists within permafrost as a very thin film surrounding sediment and ice. This unfrozen water can facilitate mass transport and retard the thermal response of the active layer or permafrost (Romanovsky and Osterkamp 2000). These extreme conditions support nutrient transport and even microbial activity (Ponder et al. 2008). Therefore, at temperatures near 0°C the soil water freezing point is believed to control the temperature response to microbial activity (Nicolsky et al. 2007, Koven et al. 2011, Matzner and Borken 2008). Models are beginning to represent the temperature and moisture controls on decomposition rates near the soil freezing point, but these response functions require parameterization (Lawrence et al. 2009).

Large, temperature-controlled column experiments will be designed (aligned with Task HG2) to examine the effects of freeze-thaw processes on SOM degradation mechanisms and rates, N dynamics, and associated GHG production under different soil characteristics (texture, porosity), liquid water and ice contents, and freeze-thaw cycle characteristics. The ~1 m long columns, which will consist of continuous core of active layer sediments underlain by permafrost, will be subject to several freeze-thaw cycles to mimic in situ environmental conditions. Sampling ports will be installed along the length of the column and at the effluent to nondestructively assess the key hydrogeological, biogeochemical, and geophysical properties and their transformations over space and time, including water content, temperature, pressure, pH, DOM, gas flux, $NO_{3-}$ and $NH_{4+}$, $^{14}C$ isotopic signatures, and geophysical attributes (dielectric constant and complex resistivity). Parallel columns will be set up to obtain complementary measurements using destructive sampling and computerized tomography (CT) scanning (see Appendix XIV.2), including: ice content, $\delta^{13}C$ and H/D ratio of methanogen precursors and products.

The freeze-thaw column experiments are expected to be especially useful for (1) quantifying the mechanisms and rates of SOM decomposition as a function of local environment (e.g., moisture, water phase, solutes, pH, temperature, texture); (2) identifying the vertical location within the column where $CO_2$, $CH_4$, and dissolved organic carbon (DOC) are being produced; (3) characterizing the interacting C and N dynamics and impacts of moisture and temperature on microbial activity at the freeze-thaw boundary; (4) quantifying microbial activity and functional speciation associated with SOM degradation, competition for resources, and local conditions; (5) assessing how vertical variability in rates and mechanisms compares with integrated measures, such as effluent fluxes; and (6) quantifying the geophysical signatures of environmental characteristics that control organic carbon degradation (i.e., water content, water phase, soil textures) and the distribution of organic carbon degradation products (i.e., gas bubble volume, dissolution/ precipitation), which is a necessary step prior to the use of these methods at the field scale for nondestructive biogeochemical-hydrological monitoring. The response functions for these freeze-thaw experiments will be incorporated directly into model decomposition algorithms for models at all spatial scales.

**Task BGC4: Carbon-Nitrogen Interactions.** Nitrogen availability is predicted to be a strong control on plant photosynthesis, growth, and respiration in the Arctic. Thawing permafrost could release nitrogen into the active layer, stimulating plant growth and microbial activity (Keuper et al. 2012). Parameterizing and improving models' response functions to nitrogen speciation in the active layer and thawed permafrost is a priority for representing couplings of the carbon and nitrogen cycles (Xu et al. 2011, Thornton et al. 2007). Reports of $N_2O$ greenhouse emissions suggest that microbial nitrification and denitrification can be significant mineralization processes in some environments (Elberling et al. 2010). In cooperation with the vegetation dynamics group (Task V3), the biogeochemistry group will identify key components of the Arctic nitrogen cycle that respond to thawing permafrost. In addition to the measurements of organic and inorganic nitrogen species in soil horizons and permafrost, microcosms and soil columns (described above) will be used to investigate nitrogen mineralization and mobilization. Microcosms of active layer soil amended with $^{15}N$-labeled tracer substrates like $NH_{4+}$, $NO_{3-}$, $N_2$, nucleosides or amino acids will be established. Mass spectrometry will be used to measure $^{15}N$ incorporation into microbial biomass. Metagenomic and metaproteomic analyses will be used to identify microbial populations that rapidly assimilate these labeled nitrogen sources (Mackelprang et al. 2011, Banerjee and Siciliano 2012). If significant amounts of $N_2O$ are detected from samples, then nitrification and denitrification processes will be interrogated.

### Phase 1 Deliverables

- Geochemical and microbial characterization of permafrost core samples obtained from study sites for model parameterization.
- Temperature response function for GHG production in soil columns and microcosms developed and compared with field measurements.
- Characterization of SOM pools and turnover times to develop a predictive model of SOM decomposition and availability.

- Response function for soil freeze-thaw effects on SOM transport, decomposition, and GHG production developed using soil columns.
- Measurements of key nitrogen species in core samples and microcosms to parameterize models and prioritize N cycle studies.

### IV.3.4 VEGETATION DYNAMICS

A reorganization of the Arctic plant community may be a significant result of climate change that drives important feedbacks to the atmosphere and to permafrost stability (Epstein et al. 2004, Walker et al. 2006, Sturm 2010). Increasing predominance of shrubs over smaller-statured tundra vegetation may create substantial feedbacks to the ecosystem and the climate system through changes in albedo, energy exchanges (water and heat), snow depth, timing and extent of permafrost thaw, water and nutrient availability, microbial activity, and relative $CO_2$ uptake and release (McGuire et al. 2006). Changes in the presence of mosses in an ecosystem would have subsequent consequences for soil temperature and permafrost stability because of their important role in insulating the soil (Walker et al. 1994). Furthermore, some mosses support methanotrophs, which oxidize methane (Kip et al. 2010), whereas sedges provide a conduit for methane transport from soil to atmosphere (King et al. 1998). Changes in plant community composition, such as a shift to shrub-dominated systems and a reduction in moss cover, will alter evapotranspiration dynamics from evaporation (physically controlled fluxes) to transpiration (physiologically controlled fluxes), which would be critical information for predicting evapotranspiration dynamics with climate and permafrost change. Additionally, shrub-dominated systems will increase carbon gain and landscape-level water-use efficiency. Hence, the structure and function of the plant community and their responses to a changing environment are central to our analyses of biogeochemical cycling, hydrology, and feedbacks between the tundra and the atmospheric and climate systems.

Identification and quantification of the key processes linking plant community structure and function to soil moisture and nutrient availability are essential for refining mechanistic-based models of arctic ecosystems and for linking biogeochemical cycling models to vegetation dynamics models in an integrated, coupled land-climate model framework for both regional and global scales. The composition of the plant community can be measured directly at local scales, and changes in community composition in response to climate warming and permafrost degradation can be inferred from manipulative experiments and observations across gradients of permafrost degradation; however, representation of plant community function and dynamics is more challenging at the grid-cell scale. Scaling plant function to the grid-cell scale should be based on observable relationships between plant community composition and geomorphic units. Furthermore, a process-based framework is needed for predicting changes in the plant community and associated function as the climate changes and permafrost degrades.

**Vegetation Dynamics Goal:** Describe and quantify the mechanisms that drive structural and functional responses of the tundra plant community to changing resource availability, in support of a predictive framework for evaluating GHG and energy feedbacks to climate through vegetation dynamics.

Our approach will rely on the use of PFTs, which group plant species according to common morphological or physiological traits (e.g., broadleaf woody plants, sedges, mosses, and lichens). CLM calculates gross primary productivity (GPP), or gross ecosystem C uptake, using functional relationships describing plant photosynthesis in relation to prevailing temperature, light, and foliar nitrogen concentration. The relationship is parameterized for different PFTs, and the fraction of land area populated by different PFTs is used to generate GPP estimates for a grid cell. New fine-scale measurements and process understanding are needed to parameterize CLM for the tundra and provide appropriate boundary conditions for up-scaling beyond the domain of direct measurement. Additional measurements are needed to provide independent model evaluation. Three specific needs are (1) observations to estimate current PFT distribution across the landscape, (2) data to inform functional relationships describing GPP of arctic PFTs, and (3) process understanding to project how PFT distribution will change with permafrost degradation.

**Task V1: Characterize plant community composition.** Documentation of the characteristics of the plant community in relation to polygon features will provide the fundamental framework for estimating plant community composition and function at the grid-cell scale and for refining PFTs for predictive relationships.

**Task V1.1: Vegetation survey plots** (1 × 1 m) will be established at the center, edge, and trough of three to five replicated polygons in each of three polygon types (low-centered, high-centered, and intermediate). Species composition of these plots will be determined by visual estimation of fractional coverage (Fletcher et al. 2012).

**Task V1.2: Leaf Area Index** (LAI) of plant communities across the polygon gradients will be measured using an LAI-2200 Plant Canopy Analyzer.

**Task V1.3**: At the end of the growing season, plants in 0.2 × 0.2 m subplots will be harvested and aboveground biomass and leaf area will be measured by species.

**Task V2: Improve PFT definitions.** CLM currently uses only two PFTs (one grass and one shrub type) to represent arctic vegetation, greatly limiting its capability to represent arctic plant functions and feedbacks or to simulate arctic response to a warming climate. The 10 arctic PFTs in the Terrestrial Ecosystem Model (TEM) (Euskirchen et al. 2009) allow a superior basis for hypothesis testing of the relevant vegetation parameters, and we will use TEM as guidance for improving the PFTs in CLM. We will augment the PFT definitions with plant parameters that are needed to improve GPP and albedo calculations in CLM. In particular, we will measure the spectral properties and parameters of photosynthetic biochemistry and leaf physiology that are key CLM inputs and that facilitate up-scaling to the landscape level (e.g., leaf mass per unit area, leaf area index, $v_{c,max}$, and tissue N concentration; Thornton and Zimmermann 2007, Xu et al. 2012) for a range of tundra plant species across different PFTs, measured under arctic summer conditions across the gradients created by high-centered and low-centered polygons and other thermokarst features.

**Task V2.1:** Focusing on key plant species representing different PFTs, use a LI-COR 6400XT gas exchange system to measure $CO_2$ assimilation in relation to internal leaf $CO_2$ concentration, from which $v_{c,max}$ can be calculated. Measurements will be made three times during the growing season.

**Task V2.2:** Measure N concentration, leaf mass per unit leaf area, and derive the fraction of leaf N invested in Rubisco ($fN_{Rubisco}$) in the leaves used in the gas exchange measurements.

**Task V2.3:** Measure spectral characteristics, including albedo, of individual leaves and mixed-species plant communities using handheld and track-based scanning spectroradiometers throughout the snow-free season. Foliar N concentration of the scanned leaves will then be determined.

**Task V3: Make PFTs dynamic.** The primary data needed for estimation of PFT distribution across the landscape are assessments of plant community composition (fractional cover) across the thermokarst gradients in different geomorphic units, as described above. We also need data and process understanding to enable predictions of changes in plant community composition as permafrost degrades in a warming climate. We have developed a working hypothesis that permafrost degradation causes a change in water and N availability and distribution that will drive changes in PFT distribution across the landscape. The data needed to test this hypothesis and to develop the functional relationships for modeling include seasonal variation in active-layer N availability, plant-soil feedbacks that alter C-N cycling and N availability, plant use of available N (including seasonal dynamics, root distribution, and N fixation), and root distribution of plants in relation to available water. Our objective will be to establish a new set of PFTs based on N acquisition and allocation rather than plant morphology. The research will be guided by a plant physiological model of C-N interactions (Xu et al. 2012).

**Task V3.1:** At peak standing crop at the end of the growing season, soil cores associated with each aboveground community measurement will be used to assess community-level root biomass and rooting depth distribution. These samples will also determine the N concentration and content of belowground biomass throughout the active layer. We will also carefully excavate root systems of the most important species in order to determine species-specific root distribution and N concentration of roots with depth in the active layer. Species-specific rooting characteristics will help us to better understand and project the causes and consequences of changes in belowground biomass and N content in response to permafrost degradation. Root distribution of different species will be analyzed in relation to soil water availability.

**Task V3.2:** Seasonal variation in plant-available nutrient concentrations in the active layer will be measured using ion-exchange resins (Giblin et al. 1994, Natali et al. 2011) at locations adjacent to vegetation survey plots. The resins, which provide a time-integrated measure of plant-available N, P, and other elements, will be deployed from mid-June to August, August to October, and October to June in order to capture seasonal dynamics.

**Task V3.3:** Forms of nitrogen available in the active layer will be assessed as extractable concentrations of organic N, $NH_4^+$, and $NO_3^-$ in a subsample of soil taken from the cores used to determine rooting biomass and depth distribution. These data will also be analyzed in relation to landscape and plant community characteristics and will be used to inform nutrient cycling rates in models.

**Task V3.4:** Plant influence on C and N metabolism in the active layer will be measured in soil sampled from plant communities occurring across the sequence of permafrost degradation. Soil cores will be used to sample active layer soils from two different depth intervals, and root-free, homogenized soil will be incubated under standard laboratory conditions (e.g., Iversen et al. 2012). Incubations will be conducted both aerobically and anaerobically to assess the potential influence of saturated soil conditions, as well as across a field-relevant range (i.e., from –2°C to 10°C) of temperatures in order to provide a temperature response surface for model parameterization. $CO_2$ and $CH_4$ emission will be measured by gas chromatography, and net $NH_4^+$ and $NO_3^-$ mineralization rates will be assessed using an autoanalyzer to determine the difference in KCl-extractable $NH_4^+$ or $NO_3^-$ over time as compared with initial samples. Changes in total N over time will also be assessed in order to determine the relative importance of organic compared with inorganic N at a given time. Plant detritus (leaf litter, roots) of different PFTs (shrubs, sedges, moss) will be added to some samples to determine whether increased biomass and litter production of different PFTs will affect soil nitrogen cycling.

**Task V3.5:** Nitrogen fixation activity in root systems, soil, and bryophytes will be assayed using the acetylene reduction approach (Hardy et al. 1968). Samples will be incubated in a 10% acetylene atmosphere, and ethylene production will be measured by gas chromatography.

**Task V3.6:** Plant C and N metabolism will be measured in foliage and, if possible, fine roots to improve understanding of N acquisition and use. Measurement of key parameters associated with plant N metabolism [i.e., plant N pools ($NO_3^-$, free amino acids and protein), C pools (starch and sucrose)] and with the activity of key enzymes associated with C and N metabolism will provide physiological data on N metabolism and relocation within the plant and will improve characterization of N use by different functional types.

**Task V3.7:** P concentration in foliage will be measured using a Lachat autoanalyzer and will be evaluated in relation to N concentration as a potential limiting growth factor.

**Task V4: Parameterize nitrogen allocation model.** Data collected for Tasks V2 and V3 will be used to parameterize a plant nitrogen allocation model (Xu et al. 2012) that will provide guidance for defining N-based PFTs and input to CLM on vegetation feedbacks to climate-related changes in soil N availability. The model derives the proportion of carboxylation nitrogen based on temperature, $CO_2$, and radiation conditions, which is then fed into the Farquhar photosynthesis model. Model output will be compared to calculated values (Task V2.1) based on direct measurement of $v_{c,max}$ and leaf N concentration. Plant acclimation to climate is simulated by dynamically adjusting nitrogen allocation for light absorption, electron transport, carboxylation, respiration, and storage. The acclimation capability can be different for different species. Nitrogen allocation coefficients are then provided in a look-up table to the Ecosystem Demography model (Fisher et al. 2010), which will be used to track the functional nitrogen availability through simulation time. Optimal nitrogen content per unit leaf area will be estimated in the model by maximizing the nitrogen-use efficiency at the individual leaf level. The estimated optimal area-based leaf nitrogen content will be compared with observed values to assess the capability of plants to adjust their leaf mass per unit area (LMA). Model sensitivity will depend on the plant nitrogen allocation strategies and leaf area-nitrogen dependence. Sensitivity analysis for parameters (e.g., nitrogen storage duration) of different species will be used to define how to group species into PFTs that are responsive to changing N availability.

**Task V5: Initialize PFT representation.** The relationships we establish that relate plant community composition to geomorphic units, coupled with larger-scale information of the distribution of geomorphic units within a grid cell, will provide a basis for model initialization of fractional PFT representation. This estimate will not depend on an assumption of linear scaling from point estimates of PFT composition and hence will be a more accurate representation of the complexity of the arctic landscape. Landscape-scale GPP estimates will then emerge from the coupling of fractional PFT distribution with the PFT-specific physiological parameters describing photosynthesis (e.g., $v_{c,max}$). By incorporating new functional relationships between PFTs and N dynamics, and N dynamics within geomorphic units, a dynamic vegetation component [e.g., the Ecosystem Demography model (Fisher et al. 2010), being developed as the next-generation vegetation model for CLM] can be introduced to CLM that permits changes in the fractional PFT distribution (and resulting GPP) from the initial condition as permafrost degradation is simulated. Similarly, the model of the plant component of albedo will be initialized by combining the parameter set of albedo of individual PFTs with the fractional representation of PFTs within the grid cell.

**Task V6: Measure carbon flux across scales.** The model structure for GPP calculation will be evaluated against observations at both plot and landscape scales. Plot-scale (several square meters) measurements of C flux can be made periodically across the thermokarst gradients to compare short-term model estimates of net C exchange (GPP minus ecosystem respiration) for the given mix of PFTs with the measured flux. These small-scale, instantaneous chamber-based measurements will also enable tests of the model to resolve differences in $CO_2$ and $CH_4$ fluxes from different geomorphologic units. The framework for predicting dynamic vegetation in response to permafrost degradation can be tested against measured differences in plant community composition across existing thermokarst features.

Data-based landscape-scale estimates of GPP cannot be generated by up-scaling plot-scale measurements because of the highly heterogeneous nature of plant distribution and productivity (Street et al. 2007). A preferred approach will be to exploit emergent properties of the landscape that are seen through the relationship between leaf area index and total canopy N content (Williams and Rastetter 1999, van Wijk et al. 2005), which together are strong predictors of photosynthetic capacity and gross primary production (Williams et al. 2001, Ollinger et al. 2008).

**Task V6.1:** Plot-scale chambers. Portable gas exchange chambers (~ 1 $m^3$) constructed from flexible greenhouse material (Huxman et al. 2004) with a tripod equipped with an open path infrared gas analyzer (LI-COR 7500), air temperature and photosynthetically active radiation sensors, and mixing fans will be used to measure plot-level net $CO_2$ and $H_2O$ exchange. This approach integrates the fluxes of all the PFTs on each plot. These data will be used to verify the ability of the model to predict C dynamics from information about PFTs.

**Task V6.2:** Landscape-Scale GPP. Predictive relationships will be established between plant spectral data and the N content and photosynthetic capacity of different PFTs (Objective V2) and combined with observations of plant community composition. Canopy-scale N concentrations will be estimated from canopy N obtained through aircraft imaging spectroscopy, in combination with LAI from remote imagery of NDVI. These estimates will then be used to derive fine-scale estimates of gross primary production through direct comparison with plot and tower-based measurements and to landscape-scale estimates of GPP for model evaluation.

**Task V7: Measure plant contribution to albedo across scales.** The composition of the plant community will affect albedo during the snow-free part of the year because different plants (or PFTs) absorb and reflect radiation differently, and emergence of shrubs above the snow cover will affect albedo during the winter (Sturm et al. 2005). The vegetation component of albedo will be estimated from leaf-level spectral data combined with PFT distribution. Unlike most of the other feedbacks between land and atmosphere, albedo can be measured directly at the scale of a grid cell as well as at plot scales and on individual plant leaves, creating strong opportunities for testing our scaling approach. Albedo at the landscape scale will be measured via remote sensing and will be compared with modeled values after the vegetation component is integrated in the model with the albedo from lakes and snow.

**Phase 1 Deliverables**

- Plant community composition descriptions from study sites for the development of Arctic PFTs.
- Physiological characterization of plant species, including photosynthetic parameters, spectral signatures, and N metabolism, for N allocation model and predictions of albedo and GPP.
- Measurements of plant-available N to develop a predictive model of plant community composition and dynamic N-based PFTs.

## IV.4 INDEPENDENT OBSERVATIONS FOR INTEGRATED MODEL EVALUATION

As part of the NGEE Arctic goal to improve model representations of Arctic ecosystem processes and thereby enhance the fidelity of climate predictions, an important objective is to quantify model bias and uncertainty and document improvement in climate prediction. Accomplishing this objective will require a diverse array of independent observations that have not been used to parameterize or initialize models. These observations may be used to evaluate not only model predictions of multiple states and processes at multiple scales, but also the effectiveness of the scaling approach itself.

This section specifies the primary independent data streams that we will generate and the evaluation methods that we will employ to assess model performance at fine, intermediate, and climate modeling scales. We will focus on predictions of climate forcing by the ecosystem, namely the ecosystem-atmosphere exchange of energy, greenhouse gases, and water. These fluxes are controlled by (or emerge from) the interaction among vegetation, hydrologic, and biogeochemical processes and thus integrate over model simulations of the three process areas of NGEE Arctic.

**Integrated Model-Data Evaluation Goal:** Quantify the integrated climate forcing from ecosystem greenhouse gas, energy, and water fluxes across a range of permafrost conditions and spatial scales and document improvement in model predictive skill of this forcing.

Although a number of excellent studies have been carried out in recent years that examine climate feedbacks related to either energy-albedo (e.g., Sturm et al. 2001b) or biogeochemistry (e.g., Schuur et al. 2008), few have included observations of both biogeochemistry and energy feedbacks. Thus, there have not been adequate datasets for testing simulations of the full suite of climate feedbacks—particularly across the range of scales targeted by NGEE Arctic. We will generate observations needed to construct the full surface energy budget and GHG budget of the ecosystem. We will evaluate the ability of the models to represent the integrated system response and the validity of using these models to evaluate future changes in energy, water, and biogeochemical influences on climate.

The influence of Arctic ecosystems on climate, and in particular on fluxes of GHGs, energy, and mass, will be evaluated at scales corresponding to our three modeling scales. It will not be possible to make direct observations of all quantities at all scales, but we have identified important, observable quantities at each scale. We will also make a suite of isotopic measurements that are diagnostic of model performance in simulating these integrated fluxes.

**Task I.1.1: Independent Observations of Land-Atmosphere Exchange.** We will collect observations that integrate land-atmosphere exchange processes at scales useful for testing the multiscale models. A few of these observations were described in the process research sections above. We propose to do intensive testing of scaling from fine to intermediate scale (10 cm to footprint of eddy flux tower), and evaluation with remote-sensing products at the climate scale. In each case, we aim to compare models with the native scale of observations for each quantity of concern. The tasks for this section are to measure net fluxes of GHGs ($CO_2$, $CH_4$, $N_2O$), sensible and latent fluxes, spectrally binned reflectances, surface temperature, and ground heat flux. To achieve fine-scale reflectance observations during the shoulder season, we will evaluate the need for tram-mounted instruments and will deploy a tram system as appropriate. Hydrologic output will be measured as part of the Hydrology tasks. These observational tasks (denoted Task I.1.1–Task I.1.8), approaches, and scales are outlined in Table 2.

**Table 2. Observations for Integrated Data-Model Tasks: Approaches to observing ecosystem-atmosphere exchanges at fine-to-climate scales for model evaluation**

(IRGA = portable infrared gas analyzer. GC = gas chromatograph. Chamber diam. 30 cm)

| Task | Observations Approach | Fine | Scale Intermediate | Climate |
|---|---|---|---|---|
| Task I.1.1 | Net $CO_2$ flux | Chamber with Li-6400 IRGA or GC with thermal conductivity detector | Eddy covariance. Chamber transects | NASA CARVE |
| Task I.1.2 | Net $CH_4$ flux | Chamber—GC with flame ionization detector | Eddy covariance Chamber transects | NASA CARVE |
| Task I.1.3 | Net $N_2O$ flux | Chamber—GC with electron capture detector | Chamber transects | — |
| Task I.1.4 | Latent heat flux (ET) | Chambers. Fine-scale modeling | Eddy covariance | Derived products from satellite and aircraft transects. |
| Task I.1.5 | Sensible heat flux | Fine-scale modeling | Eddy covariance | |
| Task I.1.6 | short wave (albedo) and long wave energy fluxes | Hand-held sensors and tram-mounted sensors | Remote sensing, airborne and satellite | Remote sensing, airborne and satellite |
| Task I.1.7 | Surface temperature | Hand-held sensor and tram-mounted sensors | Remote sensing, airborne and satellite | Remote sensing, airborne and satellite |
| Task I.1.8 | Net ground heat flux | Geophysical observations and fine-scale models | — | — |

**Task I.1.2: Isotopic Observations for Land-Atmosphere Exchange.** We will analyze the isotopic composition of key stocks and flows that will be useful in testing or constraining integrated predictions. For example, the $^{14}CO_2$ composition of soil respiration is predicted by CLM4.5, and an independent measurement of this value can indicate how well the model simulates the age of carbon being respired as thaw deepens. Some of the observed isotopic values are not yet predicted by the models, but they will be used to develop other validation variables. For example, the hydrology models will not predict the isotopic composition of water, but water isotopes can be used to partition the water flows into constituent flows that are predicted by the model (e.g., sources of subsurface lateral flows or evaporation vs transpiration). The isotope observation tasks (denoted Task I.2.1–Task I.2.5), approaches, and applications are shown in Table 3. These tasks are (1) Carbon isotopic composition of $CO_2$ in soil respiration and soil gas ($^{14}CO_2$ and $^{13}CO_2$); (2) isotopic composition ($^{13}C$-$CH_4$, H/D-$CH_4$, $^{14}C$) of $CH_4$ in soil respiration and soil gas; and (3) Isotopic composition of water in outflow, inundated areas, and plant tissue. An important sub-task will be design, construction, and installation of gas sampling wells in the

**Table 3. Observations of isotope signatures of carbon and water fluxes: Integrating across processes and scales**

All of these observations will be applied to fine scale models except water isotopes from outflow waters will be applied at the intermediate scale. The samples for carbon isotope species will be sampled in net soil fluxes and soil gas.

| Task | Observations | Sampling Approach | Application |
|---|---|---|---|
| Task I.2.1 | $^{14}CO_2$ | Manual chambers and small gas sampling wells, plumbed to molecular sieve. Sample extraction and preparation in lab. | Age of soil carbon being respired. |
| Task I.2.2 | $^{13}CO_2$ | Co-sampled with $^{14}CO_2$. Additional samples taken with syringe and placed in flasks or vials for analysis in lab. | Methane (oxidation) contribution to $CO_2$ flux |
| Task I.2.3 | $^{13}C$-$CH_4$ and H/D-$CH_4$ | Manual chambers plumbed to flasks. Sample extraction and preparation in lab. | Pathway of $CH_4$ production and fraction of production that has been oxidized before release. |
| Task I.2.4 | $^{14}CH_4$ | Manual chambers plumbed to flasks. Sample extraction and preparation in lab. | Age of soil carbon bring respired as $CH_4$ |
| Task I.2.5 | Water isotopes (H/D and $^{18}O$) in soil water, snow, streams, ponded water, leaves, and outflow | Survey sampling. Samples of water or tissue stored in flasks or vials and analyzed in the lab. | Exploratory in Year 1 to see if there is enough variation to use isotopes for: ET flux source partitioning, plant water source, and source of (sub-) surface water flow. |

different landscape functional units. Vacuum line capabilities for efficient extraction of small-volume samples will be implemented at Lawrence Berkeley National Laboratory (LBNL). The $^{14}C$ of roots and SOM are useful diagnostics for modeling of more specific processes and are included in the vegetation and biogeochemistry sections above.

**Task I.1.3: Evaluate model performance and assess improvement in prediction skill.** We will estimate prediction errors by comparing output with observations, with a focus on comparisons at the native scale of observations as much as possible. In terms of error estimation, initially we will focus on simple comparisons, expressing differences as root mean square error and evaluating the correlations between modeled and observed quantities. Critically, we will compute these error estimations after completing each phase of model development—for example as observations are applied for parameter inversion or process understanding leads to changes to the model structure—to provide an objective test of model improvement and to quantify improvement in prediction skill.

For time series data, we will conduct evaluations over different averaging periods, such as daily, monthly, and seasonally, to test representation of diurnal and seasonal dynamics. For spatially distributed data, we will conduct evaluations at different spatial scales, testing the up-scaling and down-scaling components of our scaling approach. We will use the observations listed in Table 1 as well as other metrics for model performance that we derive from these datasets, such as light use efficiency and the short-term temperature response of ecosystem respiration. Metrics appropriate for the range of processes integrated in the model (e.g., biogeochemistry, hydrology), spatial scales (fine to climate scale), and temporal scales (hourly to centuries) will be designed to facilitate these comparisons.

At the fine scale, model predictions of biogeochemical dynamics will be evaluated against chamber-based fluxes and observed vertical distributions of carbon and nitrogen compounds in soil organic matter (see BGC tasks). Energy and temperature predictions will be compared using observations from hand-held instruments. A subset of plant community composition observations will be reserved for evaluation of dynamic vegetation model predictions in response to permafrost degradation and resource redistribution (see vegetation tasks).

At the intermediate scale, predicted seasonal hydrology dynamics will be evaluated against observations of surface runoff and fractional inundation area (see Hydrology tasks). Eddy covariance measurements of energy and greenhouse gas fluxes will be used to evaluate landscape-scale predictions, based on dynamic estimates of the measurement footprints. Predictions of landscape-scale LAI and canopy N content will be evaluated against ground and airborne spectroscopy and leaf level measurements (see Vegetation tasks). Emergent relationships between LAI and canopy N content might also provide an independent evaluation of model predictions of landscape-scale GPP.

There are fewer opportunities for evaluation at the climate modeling scale because of challenges in making robust observations at large spatial scales. Albedo and other spectral reflectance measurements present a good opportunity for climate-scale model evaluation, since remote-sensing observations under clear-sky conditions can provide excellent climate-relevant estimates of landscape-scale albedos, including estimates of reflectances in visible and near infrared wavebands.

**I.1.4: Data-model integration to examine changes in energy budget and greenhouse gas forcing associated with permafrost degradation.** We will generate model-independent estimates of the integrated climate forcing to compare with model prediction. For example, total GHG radiative forcing will be estimated as the sum of all GHG fluxes (on instantaneous molecular-forcing or global-warming-potential basis). We will use these integrated climate forcing estimates to compare with model predictions at different spatial scales. The models will be used to generate hypotheses about the ecosystem processes that will determine future magnitude and rates of feedback. These hypotheses will be explored with Phase 1 data but will also be used to help prioritize efforts in Phase 2. In other words, Phase 2 will be informed by the uncertainty analysis conducted by comparing model output to observations and also by model experiments (e.g., sensitivity analyses).

To generate the independent estimate of forcing, we will construct site-level energy and GHG budgets directly from the observations. We will, for example, apply the simple radiative forcing approach employed by Randerson et al. (2006) in his comparison of energy and GHG effects from a sub-Arctic forest wildfire. Briefly, the forcing from each variable will be expressed as W $m^{-2}$ integrated over the time frame in which it operates. We will combine plot measurements with remote sensing to evaluate climate forcing associated with permafrost degradation at Barrow and potentially other sites as well.

As an initial model experiment to generate hypotheses and priorities for Phase 2, we will explore the hypothesis that that Arctic landscapes contain critical thresholds across which small perturbations can qualitatively alter the state of the system. We will begin to investigate whether small amounts of permafrost degradation are amplified by changes in soil structure, hydrology, and insulation, leading to degradation that is practically irreversible. For example, shrub expansion causes changes in albedo and surface energy fluxes that reinforce warming and shrub establishment, and put the system into a new energy-balance state (with climate consequences). This task will be carried into Phase 2 as a primary objective of NGEE Arctic: assessing the potential for arctic ecosystems to undergo irreversible change and/or contribute to abrupt climate change. There are many different components of Arctic ecosystems that could have large, local-to-global climate impacts, such as permafrost degradation and thermokarst, shrub emergence or encroachment and associated effect on albedo, and $CO_2$ and $CH_4$ release. In Phase 1, this activity will be initiated with observations and modeling at fine-scale to eddy-flux scale.

**Phase 1 Deliverables**

- Integrated measurements of land-atmosphere exchange processes for model evaluation: GHG fluxes, heat fluxes and surface reflectance.
- Estimations of SOM turnover in field samples from isotopic composition measurements of soil gases.
- Evaluation of predictive model performance using independent estimates of radiative forcing.

## IV.5. PHASE 2 VISION

Our objectives for NGEE Arctic are novel and highly ambitious, and we expect that achieving those objectives will require focused effort from our large and capable team extending over a decade or longer. By establishing clear goals and laying a solid foundation in NGEE Arctic Phase 1, we are intentionally positioning our team for the long-term effort that will lead to success in Phase 2.

Our ultimate objective is delivery of a *new class of ecosystem model,* distinguished by its multiscale mechanistic representation of Arctic subsurface, surface, and vegetation canopy (i.e., bedrock to canopy) processes and by its implementation within a global Earth System prediction framework. Our Phase 1 plan is devoted to establishing a comprehensive architecture for this new modeling approach, and to the construction, parameterization, and application of a full-scale prototype—the NGEE Arctic scaling framework. This effort involves the carefully coordinated efforts of Arctic process scientists making measurements and conducting field and laboratory experiments, and modeling experts carrying out the design and development of the multiscale landscape simulator. During Phase 1, we will develop an iterative cycle of model-motivated experimentation and observation, model parameterization, and field-scale evaluation. This powerful cycle will become foundational to Phase 2 activities using model sensitivity and uncertainty analysis and new process knowledge to direct computational, experimental, and observational efforts towards outstanding problems in Arctic ecosystem and climate predictions.

We expect that our experience during Phase 1 with integration of new process knowledge into the scaling framework, and with design and implementation of new multiscale modeling capabilities will form the basis of a Phase 2 research effort. That Phase 2 effort will strengthen the process representations introduced in Phase 1, expand upon the scaling framework architecture in areas where new process knowledge unveils previously unanticipated mechanistic controls, and push forward on the scientific frontier of quantifying improved prediction skill at the climate-scale through model-observation-experiment integration at process-resolving scales. In addition to advances in process understanding, we expect that new approaches for up-scaling and down-scaling will emerge through our Phase 1 efforts. We will engage the broad scientific community in this effort and together evaluate scaling applied to other regions of Alaska and the Arctic. The spatial scale of our activities in Phase 2 will be defined by a commitment to achieve improved climate predictions through process-rich representation at Pan-Arctic to global scales. We expect that the longer time horizon for Phase 2 will afford the flexibility to explore the most promising of these alternative scaling approaches in parallel with refinement of our prototype framework.

# V. DATA MANAGEMENT PLAN

The open sharing of data among researchers, the broader scientific community, and the public is critical to advancing the scientific goals and objectives of the NGEE Arctic project. The project is expected to generate diverse datasets from observations, experiments, and models across field plot, watershed, regional, and global scales. These data will include automated data collected from weather stations and trace-gas systems, observations from remote-sensing platforms, manual data collection efforts during large campaign-based field work, and discrete datasets generated from chemical, biochemical, and molecular characterizations of soil, water, microbial, and plant samples. Large output files from a suite of fine- to climate-scale models will also be generated within the NGEE Arctic project. Finally, the project will draw on a wealth of existing data products collected and generated by other national and international monitoring networks and research organizations across the Arctic.

Developing the data management infrastructure required for this activity will be a significant challenge. Nonetheless, the NGEE Arctic project is committed to upholding a rigorous and high-quality data management strategy and the implementation of that strategy in an innovative, cost-effective data collection, management, distribution, and archival framework. The goal of this effort will be to implement guidelines and procedures for collecting, tracking, storing, and providing data both within the project and with the larger scientific community.

The scope of NGEE Arctic data management and of the flow of data and information before, during, and after data acquisition, generation, analysis, and modeling activities can be effectively represented in a lifecycle framework (see Figure 11). NGEE Arctic will implement a data management program and infrastructure to support the complete data lifecycle of planning, collection, quality assurance, documentation, preservation and security, sharing and archiving, analysis and modeling, and finally as input to the next NGEE Arctic task plan.

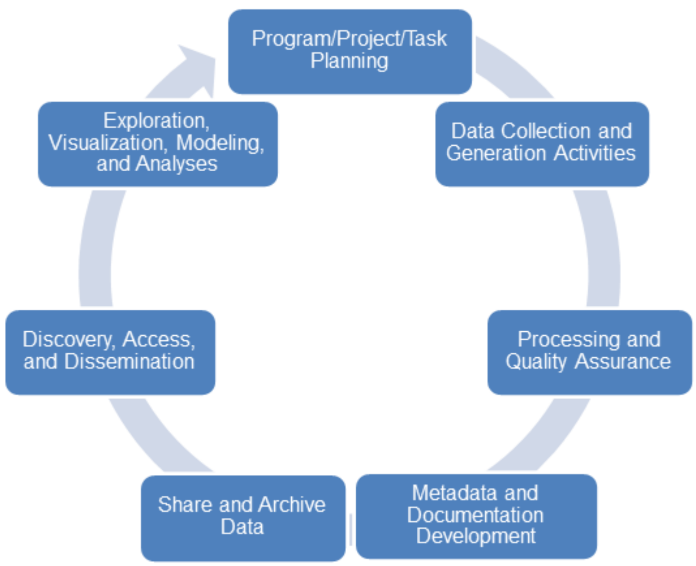



**Figure 11. Data lifecycle framework for the NGEE Arctic.** Metadata capture and development is integral to virtually all steps in the lifecycle (e.g., during data collection) even though it is represented as a single box in the figure.

It is important the NGEE Arctic data management plan and system be designed to help satisfy the stated scientific objectives of the project and the needs of the intended modeling communities. The design should also deliver necessary metrics and information needed by the sponsors. One can never predict or envision all potential uses of measurements and model results stemming from the NGEE Arctic project, so the data management plan and system design must attempt to capture and store all relevant data and generate metadata necessary to enable use well beyond the lifetime of the NGEE Arctic project.

NGEE Arctic data management plans are consistent with the data policies of the sponsoring DOE Office of Biological and Environmental Research (BER) Program for Terrestrial Ecosystem Science. The NGEE guidelines and procedures for collecting, preserving, sharing, and archiving data will be clearly described and the roles and responsibilities of NGEE participants will be clearly defined. Final model products will be shared and archived consistent with BER data policies.

## V.1 DATA MANAGEMENT APPROACH AND FRAMEWORK

The NGEE Arctic data management plan and system must be comprehensive, addressing all aspects of the data lifecycle—collection, quality assessment, documentation, distribution, and archiving. The system must be robust and sustainable in the long term. As the NGEE Arctic project transitions from understanding the current state of the Arctic tundra ecosystem to a climate change response experiment, the data system must be portable and expandable to handle the transition. Use of data and metadata standards are essential to satisfying the diverse needs of the modeling communities and the anticipated expanded use of NGEE measurements and results worldwide. Standards promote interoperability across data systems, projects, and disciplines. There is no single, off-the-shelf data system suitable to handle the breadth and diversity of NGEE Arctic data, model results, and metadata. Value-added and derived products will be generated within the NGEE Arctic data framework, and these products must have known quality characteristics and be tailored to satisfy model requirements.

The proposed NGEE data management framework recognizes the need to have different types of data management for different broad groupings of NGEE data types (see Figure 12). The NGEE Arctic data team proposes to leverage ORNL's existing data center capabilities [e.g., the Atmospheric Research Measurement (ARM) Archive] and relevant project-level data activities to handle these diverse and potentially high-volume observational and model data as illustrated in Figure 12. By leveraging existing data center capabilities and use of common services (e.g., assigning digital object identifiers (DOIs) to NGEE Arctic datasets, creating and distributing standards-based metadata), NGEE will ensure long-term archiving and use of the NGEE Arctic data collection. The proposed NGEE Arctic data system will reside at ORNL as a distributed data archive drawing on a multitude of ORNL, and to a lesser degree other national laboratory, data expertise to manage the NGEE Arctic data and model output collection and to offer them through a single point of access (i.e., a data portal) located at ORNL.

The following sections describe the five major components of the proposed NGEE Arctic data management framework.

### V.1.1 FIELD AND LABORATORY DATA MANAGEMENT INFRASTRUCTURE

The proposed NGEE data management effort will customize and deploy the Sample Information Management System (SIMS) currently used in the Plant-Microbes Interface (PMI) project and BioEnergy Science Center (BESC) to track and manage NGEE Arctic samples and data derived from those samples and from field and laboratory measurements. The SIMS deployment will facilitate tracking of experimental processes based on NGEE's data flow and procedures. The NGEE Arctic SIMS will consist of the following key components tailored specifically for NGEE Arctic field biology and laboratory experimental data:

1. Project management system
2. Standards-based metadata entry tool
3. Tracking tool for the collected field samples
4. Data-processing tool for the field and lab data
5. Visualization and data access services
6. Open-source relational database for storing the field and lab data

### V.1.2 IN SITU OBSERVATIONAL DATA MANAGEMENT INFRASTRUCTURE

As described in Task S2 and shown in Figure 12, NGEE Intensive Study Sites may deploy a broad range of instruments and measurement systems. Although DOE-based efforts have defined protocol for archiving data associated with land surface and global models, the scientific community is still struggling with how to effectively manage subsurface datasets, which often include hydrological, geological, geochemical, microbiological, and geophysical measurements collected over a wide range of different

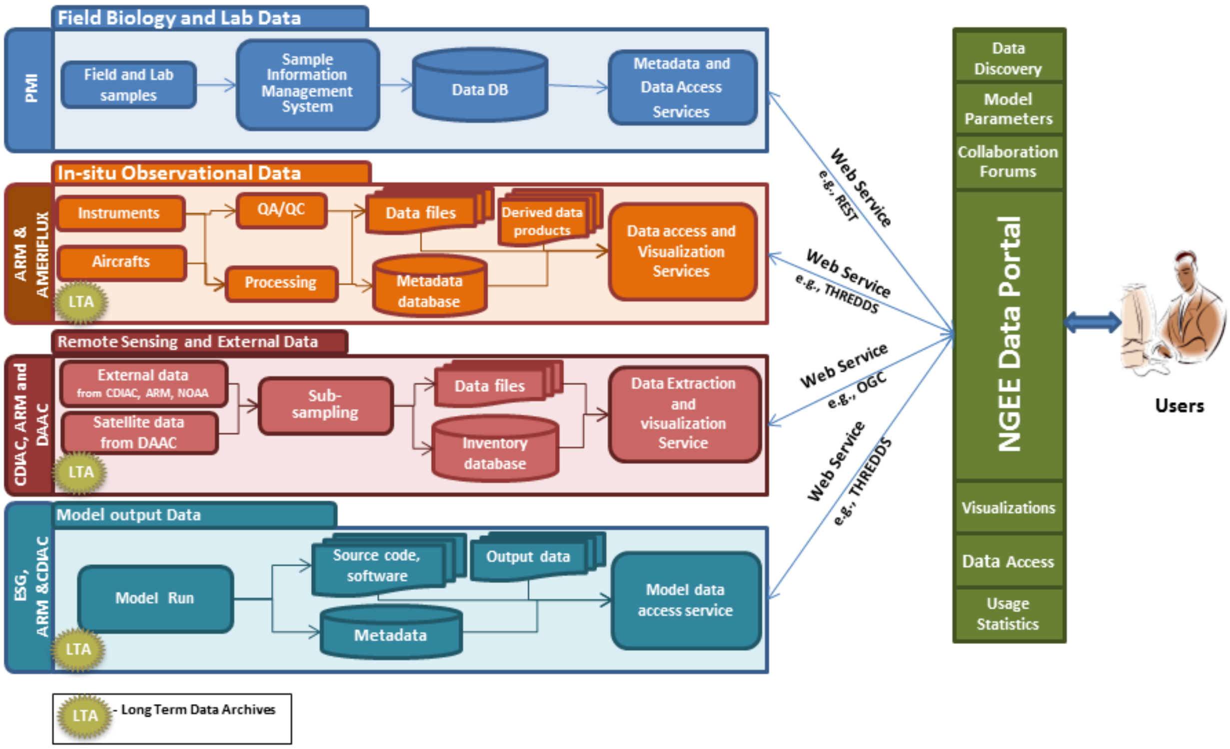



**Figure 12. Proposed NGEE data management framework.**

The proposed framework leverages existing data management expertise and infrastructure from ORNL data centers and projects and builds a next-generation data portal residing at ORNL using various data access services.

spatial and temporal sampling schemes. The NGEE data management team proposes an infrastructure to manage both continuous and periodic datasets with the following features:

- Project management system.
- Site access tracking tools to document field instrument calibrations and to monitor the operating status of site instruments.
- Data assembly and processing tools to gather data from instrument data loggers and transfer to the data archive.
- Data quality infrastructure to monitor and assess the quality of the data and provide data quality reports.
- Processing and reprocessing workflow to generate data files. Processing will also include generation of quality flags and will incorporate gap-filling strategies. The reprocessing will include generation of derived or value-added products. Output data will be prepared in a common data format such as Network Common Data form (NetCDF) and will follow community standards such as the Climate Forecasting (CF) convention.
- Metadata infrastructure will contain metadata creation tools, a metadata database, and web services to query the metadata.
- Data archival system will archive raw and processed data files incorporating effective versioning, file naming, and backup strategies.
- Data access infrastructure including data sub-setting and visualization services. These services will be accessed from the NGEE data portal using community protocols such as Thematic Realtime Environmental Distributed Data Services (THREDDS), Open-source Project for a Network Data Access Protocol (OpenDAP), and Representational State Transfer (REST) web services.

The NGEE data team will collaborate with the ARM and the Carbon Dioxide Information Analysis Center (CDIAC) AmeriFlux programs and leverage their expertise and infrastructure to perform many of the above tasks.

### V.1.3 REMOTE-SENSING AND EXTERNAL DATA MANAGEMENT INFRASTRUCTURE

The NGEE science team will use a variety of airborne and satellite products, including airborne remote-sensing data from NASA's CARVE to understand biogeochemistry dynamics, NDVI gross primary production (GPP) estimates for comparison with field- based estimates, and LiDAR data to study hydrologic patterns. The NGEE data team will effectively use the existing ORNL Distributed Active Archive Center (DAAC) data management infrastructure to retrieve these data from external sources and make them available via various web services, which will be accessed from the NGEE data portal. The ORNL DAAC's spatial access tool, sub-setting tools, data inventory database, and standards-based web services will be effectively used to archive and distribute these remote-sensing and satellite data.

To handle other field-based data from external sources, the data team will use the existing data management capabilities available in CDIAC and the ARM Archive. The data team will also enable access to some of the CDIAC, ARM and National Oceanic and Atmospheric Administration (NOAA) datasets relevant to the NGEE model intercomparison studies. This includes ARM eddy covariance data, CDIAC/AmeriFlux eddy covariance data, CDIAC meteorological data for Barrow, and NOAA high-precision $CO_2$ flask and in situ measurements from Barrow.

In collaboration with CDIAC, ARM, and the ORNL DAAC, the NGEE data team will deploy the following key cyber-infrastructure components to manage and facilitate external data useful to the NGEE Arctic project.

1. Data-harvesting system to gather external data by consuming various web services such as the Open Geospatial Consortium (OGC), REST, and THREDDS services
2. Metadata management system to describe these data using various community standards [e.g., the Federal Geographic Data Committee (FGDC), Data Interchange Format (DIF), International Organization for Standardization (ISO) 19115]
3. Data sub-sampling tools
4. File-based data archival system
5. Data access, sub-setting and visualization services to retrieve and use these data through the NGEE data portal

### V.1.4 MODEL OUTPUT DATA MANAGEMENT INFRASTRUCTURE

The NGEE science team will use a variety of models including the CESM, intermediate and fine-scale Arctic process simulators, and other models described in Section III.2.1. The NGEE Arctic model outputs and codes will need to be archived and available. The NGEE data management team proposes to collaborate with ORNL's ESG Gateway to manage and archive the model output and with ORNL's MAST-DC to manage and archive NGEE codes and input data. The ESG currently has a flexible workflow and tools to manage large scale climate model outputs. In coordination with the ESG, the NGEE data team will deploy the following key components to archive and distribute NGEE-relevant model data:

1. Metadata creation tool to describe the model data and capture data provenance
2. Data conversion tools to generate NetCDF CF-compliant data files from the model outputs
3. Archival system for model output, codes, and input data
4. Data distribution services using THREDDS and OpenDAP protocols which will be called from the NGEE data portal
5. Data publication system to publish the model output in the ORNL ESG Gateway

### V.1.5 NGEE ARCTIC DATA INTEROPERABILITY

The NGEE data team will adopt community standards, data services, and protocols to ensure data integration vital to seamlessly delivering data to users from distributed NGEE data archives. The framework will use Open Archive Initiate–Protocol for Metadata Harvesting (OAI-PMH), THREDDS, OpenDAP, OGC and other REST-based web services to allow the data interoperability component to fetch the data necessary to satisfy user queries from the NGEE distributed data sources. Semantic services will be used to map model parameters with observational measurements. In addition, a monitoring tool will also be deployed in each data source to constantly check the status of these data sources and their services. Data integration will be accomplished using the data packing component (discussed in the Section V.1.6, "NGEE Data Portal").

### V.1.6 NGEE ARCTIC DATA PORTAL

The NGEE data team will build a data portal that will allow the NGEE science team to manage, archive, and distribute diverse datasets using a single web portal as described in Figure 12. The NGEE data portal will act as a gateway to access distributed, archived data from data sources such as SIMS, ARM, CDIAC, and the ESG. The team will evaluate the currently available data portal systems (e.g., Drupal, PMI, GeoPortal) and select one best suited for NGEE. The NGEE data portal will include the following key components and features:

1. Data inventory harvesting component: This will enable the NGEE data portal to harvest data inventory and science metadata from the distributed NGEE data sources (from SIMS, ARM, CDIAC, and the ESG).
2. Data Search and Discovery Tool: The team will enable the next-generation data search capabilities using the Mercury metadata search tool. Mercury is a distributed metadata harvesting, indexing, and searching tool developed by ORNL using various open source technologies. Mercury is currently used by numerous data centers and projects, including CDIAC, the CDIAC Ocean Carbon Data Management Project, Wind Energy Informatics, and the ORNL DAAC. Mercury can parse metadata from a variety of formats, including FGDC, ISO19115, Dublin Core, DIF, and NetCDF. Mercury allows users to easily find data using full text, keywords, geospatial, temporal, and facet-based searches. A prototype Mercury instance for NGEE is already implemented with existing metadata from CDIAC, ARM, and FLUXNET projects (http://mercury.ornl.gov/ngee)
3. Model Parameter Mapping component: This will map various model parameters from relevant observational measurements. This will allow the users to find related observational measurements for model-data intercomparisons (example: OBS4MIP variables for the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project Phase 5 (CMIP5) model intercomparison activity).
4. Content Management and Collaboration System: This content management system will handle document-level data across the entire NGEE project. It will provide a single unified repository to manage any content type (e.g., documents, publications, citations, images, data sheets). The content management system will have an intelligent reference engine that will enable real-time content tagging with project entities like goals, project-wide events, and project participants, thus enabling intelligent tracking of the document lifecycle. These contents will be indexed in the NGEE Mercury search index, which will provide powerful and flexible browsing and searching capabilities. An NGEE collaboration platform will be designed as a structureless social utility that connects and facilitates a group of like-minded co-workers to share information and to collaborate on and discuss a given scientific task. The platform will enable efficient team collaboration and data sharing among NGEE researchers. It will use modern collaboration and social networking features to provide an environment to collect and share their resources through unified privacy attributes set forth project-wide.
5. Standards-based data retrieval and packaging component: This will allow the NGEE data portal to retrieve the data from the distributed NGEE data sources. Initially, the data portal will provide basic

data packaging options to the users, but in Year three of this project, the data team will develop data conversion capabilities enabling the data portal to convert the retrieved data into a common format before providing the data to the users.

6. Visualization Tools: The NGEE data portal will provide a variety of visualization platforms to display diverse datasets. This includes model data visualization using Ultrascale Visualization-Climate Data Analysis Tools (UV-CDAT), geospatial visualization using Google Earth and ORNL WebGIS tools, advanced time-series visualizations using ARM NetCDF visualization tools, and biological and lab data visualization using Google visualization widgets.
7. Data Publication Service: This functionality will allow NGEE scientists to publish any derived or value-added products back to the NGEE data portal. These data will be archived in the CDIACNGEE data archive.
8. User Statistics Tool: The NGEE data portal will capture and present usage statistics.

## V.2 NGEE ARCTIC DATA MANAGEMENT CHALLENGES

Despite the many attractive features of the proposed NGEE data management infrastructure, several challenges and data science research issues remain. Enabling meaningful and credible integration of data types across varying spatial and temporal domains within the NGEE data system will be a significant challenge for both the project team and the entire community. Integrating data from multiple sources for users in a transparent fashion, both within the NGEE project and outside, through the NGEE data portal while maintaining proper source attribution and provenance will need to be addressed. The NGEE Arctic organizational structure must include data management representation in order for the system to meet the scientific needs of the NGEE Arctic research community and broader scientific community and ensure the long-term availability of NGEE measurements and model results for future experiments, models, and synthesis efforts. (See Section VI, “Management and Communication Strategy.”)

# VI. MANAGEMENT AND COMMUNICATION STRATEGY

## VI.1 PROJECT ORGANIZATION—ROLES AND RESPONSIBILITIES

The NGEE Arctic project involves multidisciplinary scientists, collaborating across multiple national laboratories and universities in the United States. The project resides within the Energy and Environmental Sciences Directorate (EESD) of Oak Ridge National Laboratory (ORNL) and is composed of a laboratory research director (LRD), a chief scientist, and science teams, each of which has a science team lead (STL) and contributing research staff and collaborators. Institutional leads (ILs) have been designated to assist the LRD in planning and tracking budgets and deliverables across the science topic areas.

S. Wullschleger, who reports to G. Jacobs (director of the Environmental Sciences Division, within EESD at ORNL), is the LRD of the NGEE Arctic project. He has overall responsibility for the NGEE Arctic project and serves as the single point of contact (POC) for direct communications with program managers at DOE BER (Figure 13). As LRD he provides scientific leadership and ensures the integration and success of the project by soliciting advice from the external scientific advisory board (SAB) and by seeking feedback from STLs, ILs, and staff. He has full authority to manage all aspects of the NGEE Arctic project with DOE approval and works closely with the chief scientist and the STLs for updates of milestones/deliverables and financial reports. He oversees capability and facilities development, including leadership and succession planning, national and international collaboration, and outreach.

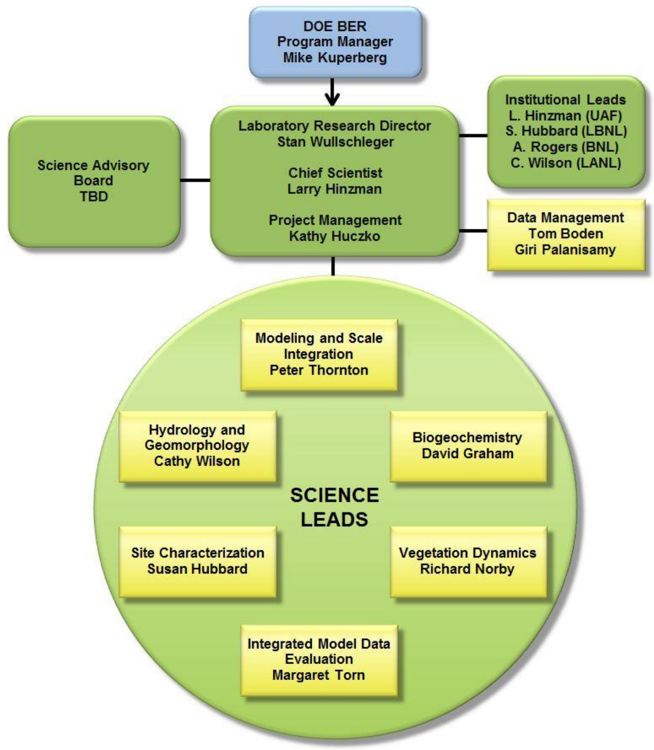



**Figure 13. Organizational structure of the NGEE Arctic project.**

The LRD is assisted by a chief scientist, L. Hinzman, at the University of Alaska Fairbanks (UAF). The chief scientist shares day-to-day responsibilities for the scientific and technical direction of the project. STLs have been designated for each of the identified teams. Together, the LRD, chief scientist, STLs, and ILs form the core team for the NGEE project. Data management will be provided to the project and lead by a data management lead. Infrastructure and support will be provided through the participating institutions and subcontracted services where prudent. The SAB, consisting of experts not affiliated with the project from academic, government, and nongovernmental organization (NGO) sectors will be created. The SAB, director, chief scientist, science team leads, and other personnel working on the project will have clearly defined roles and responsibilities (see Table 4).

The NGEE Arctic project utilizes the most relevant expertise at ORNL, including staff from the Environmental Sciences and Biosciences Divisions. External collaborators at other DOE national laboratories and at universities actively participate in the project. Figure 14 shows the organizational chart and staffing for the NGEE Arctic project. The STLs, including D. Graham, R. Norby, P. Thornton, C. Wilson, S. Hubbard, and M. Torn are responsible for integrating activities within and across the science teams, gathering project data, generating regular reports, meeting safety requirements, and

**Table 4. NGEE Arctic project personnel's roles, responsibilities, and authorities**

| Role | Responsibilities | Authorities |
|---|---|---|
| Science advisory board | • Advise on the scientific thrusts of the project<br>• Review project plans<br>• Review progress toward project goals | • Assess performance of the project R&D team<br>• Assess scientific quality and discuss progress with project director and chief scientist |
| Director | • Provide overall leadership for the NGEE Arctic project<br>• Single contact point for DOE<br>• Ensure project integration<br>• Seek inputs from the core team; data, operations and finance managers<br>• Capability development | • Exercise full authority to manage all aspects of the project with DOE approval; approve yearly program plan and release budget; make requests to STL's, project manager for regular milestone/deliverable and finance manager for financial report documentation; data manager for input/ reports |
| Chief scientist | • Contribute to scientific direction of the project<br>• Establish connections to national and international scientific community | • Represent NGEE Arctic project goals and objectives to larger Arctic science community<br>• Seek out collaborations on behalf of the project |
| Institutional leads | • Advise LRD<br>• Track institutional budgets against deliverables<br>• Assist with planning and reviews<br>• Anticipate staffing issues and resolution of performance concerns | • Coordinate development of institutional task plan and budgets<br>• Monitor institutional deliverables across science areas<br>• Plan adjustments to project plan and budget allocations as appropriate |
| Science leads | • Integrate activities within and across the project elements<br>• Monitor deliverables and productivity<br>• Track budgets against deliverables<br>• Provide inputs for periodic reports<br>• Mentor staff and facilitate collaboration | • Develop yearly task plan and budgets<br>• Set objectives and deliverables for task staff<br>• Monitor progress and meet financial performance targets<br>• Assess subcontractor performance |
| Project staff | • Execute scope of research consistent with proposal plan<br>• Responsible for data collection, record keeping, analysis, interpretation, and submission of annual reports and publications | • Modify scope of work as appropriate in consultation with science leaders<br>• Alert appropriate science leader or project director when problems arise |
| Project manager | • Gather dashboard data and share with project participants<br>• Generate regular reports<br>• Monitor deliverables<br>• Subcontractor management<br>• Provide financial management and reporting to project director, chief scientist, and science leaders<br>• Responsible for ESH&Q | • Manage planning documents including project time lines and work breakdown structure (WBS)<br>• Request project information as requested by the Core Team and report to project director<br>• Request input from subcontractors for LRD and Science Leaders<br>• Assess research safety and quality plans |
| Data manager | • Communicate data sharing expectations across team<br>• Seeking input from QA manager for initial QA/quality control for data collected<br>• Post data to web site following data-sharing and archival policy | • Request data inputs from project teams with approved data reporting and archival procedures<br>• Raise issues to project director and task leader if and when a data quality problem arises |

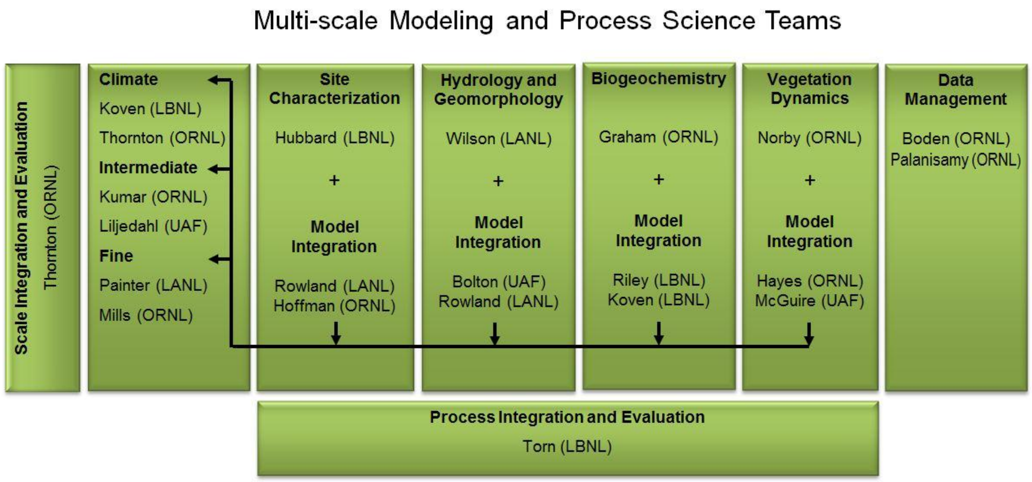



**Figure 14. Multi-Scale Modeling and Process Science Teams.**

monitoring requirements, and monitoring deliverables and scientific performance. The STLs are responsible to the LRD, and together with the chief scientist, they prepare annual science plans and budgets for each team, monitor progress, and ensure performance. With the LRDs approval, STLs adjust plans and budget allocations for the scientific efforts. Staff team members are responsible for conducting the planned studies and for meeting science team deliverables; assessing, presenting, and publishing results; and mentoring postdoctoral associates, students, and guests.

**Staff effort:** Key personnel involved in each of the NGEE Arctic science teams and their general roles and responsibilities are described in the following sections. The time allocation of staff involved in the project is shown in Section X, “Budget and Budget Justification.” ORNL has partnered with other national laboratories and several universities to build a truly multidisciplinary team that together will deliver the ambitious goals and objectives of the NGEE Arctic project.

**Multiscale Modeling Team:** P. Thornton (ORNL) will lead this team, with primary responsibility for coordinating modeling efforts across scales and across process domains, as well as overall coordination between modeling team and process science teams. Two deputy modeling leads have also been designated for each of the three scales and for each of the three process domains. W. Bolton (UAF), an expert in spatially distributed hydrologic modeling in Arctic landscapes, and J. Rowland (LANL), an expert in Arctic geomorphology and hydrology, will serve as deputy leads for hydrology/ geomorphology process modeling across scales. W. Riley (LBNL), a biogeochemist who studies and simulates carbon and nitrogen cycles, coupled land-surface and atmospheric exchange, and climate change, and C. Koven (LBNL), a land surface modeler with expertise on Arctic methane biogeochemistry, will serve as deputy leads for biogeochemistry process modeling across scales. D. Hayes (ORNL) and A. D. McGuire (UAF), experts on Arctic vegetation and carbon cycling, will serve as deputy leads for vegetation dynamics modeling across scales. C. Koven and P. Thornton will serve as deputy leads for climate-scale modeling across process domains. S. Painter (LANL), an expert in subsurface flow and transport modeling, and A. Liljedahl (UAF), an expert in Arctic watershed hydrology, will serve as deputy leads for intermediate-scale modeling across process domains. R. Mills (ORNL), an expert in parallel computation numerical methods and subsurface hydrology, and V. Romanovsky (UAF), an expert in permafrost geophysics will serve as deputy leads for fine-scale modeling across process domains. The modeling team lead and deputy leads will steer the efforts of the larger NGEE Arctic modeling group, including multiple laboratory science staff, university researchers, and postdoctoral researchers. Deputy leads for modeling in the process domains will maintain close coordination with measurement leads in each process domain. Modeling leads will also coordinate closely with the leads for integrated model evaluation, site characterization, and data management to ensure rapid and effective exchange of knowledge and information across the broader team.

**Site Characterization Team:** S. Hubbard (LBNL), who has extensive experience in field experimentation and shallow subsurface characterization using remote datasets, will lead this team and will lead and will participate in several associated tasks. Her team will include J. Rowland (LANL), who has extensive expertise in land surface dynamics and hydrology; he will lead the NGEE landscape characterization tasks and participate in several hydrology/Geomorphology tasks. F. Hoffman (ORNL), who is a computational scientist with extensive experience working with global datasets relevant to climate, will lead the representative and scaling tasks. K. Williams (LBNL) and J. Ajo-Franklin (LBNL) will work with the NGEE team and with Hubbard on Tasks S1-S3.

**Hydrology/Geomorphology Team**: C. Wilson (LANL) will lead this science focus. Key staff on this team will include J. Rowland, B. Newman, J. Heikoop from LANL; L. Hinzman, A. Liljedahl, W. Bolton, J. Cable, V. Romanovsky, A. Kholokov, J. Cherry, G. Grosse from UAF; and S. Hubbard, J. Ajo-Franklin, T. Kneafsey, and B. Freifeld from LBNL. In addition to these staff, several postdoctoral researchers and students will also have key roles within the team. The primary skill set and project responsibilities of this team are outlined below. Although thee members are listed by institution, this team is working together closely on all aspects of the hydrology and geomorphology science focus area.

Researchers from LANL will primarily focus on the application of tracers and stable isotopes to quantify lateral hydrologic connectivity, the partitioning of precipitation between runoff, perennial ponding, and evapotranspiration as well as the development of model evaluation datasets. Wilson is a hydrologist and geomorphologist who will focus on the synthesis and analysis of hydrologic, thermal, and geomorphological data to inform modeling tasks, including the development of landunit-based thermal-hydrologic response functions for the intermediate and global scale models. Rowland is a geomorphologist who will lead the landscape classification science focus as well as process studies to understand controls on topographic evolution and the scaling of coupled deformational and geomorphic processes to the larger landscape. Newman is a hydrologist with expertise in the application of isotopes to quantify hydrologic pathways and constituent fluxes through landscapes. Heikoop is a geochemist with expertise in the application of trace element, major element, and isotope geochemistry to environmental systems. They will develop and analyze observational datasets to quantify lateral connectivity of surface water from the polygon to global grid cell scale, the interaction between surface and subsurface flow. and the partitioning of water between lateral (runoff) and vertical (evapotranspiration) fluxes.

Researchers from UAF will focus on the design, deployment, and analysis of meteorologic, hydrologic, and thermal process observations and their representations in process models and the development of model evaluation datasets. Hinzman is an Arctic hydrologist who will provide oversight of the UAF team and will work with Wilson on the synthesis of process studies for model development. Cable is an Arctic terrestrial ecologist who will characterize the evapotranspiration process of arctic PFTs for NGEE models using stable isotopes. Liljedahl and Bolton, permafrost hydrologists, will focus on measuring and modeling the hydrologic regime from the ice wedge polygon to the watershed scale in the Arctic Coastal Plain and on the Seward Peninsula, respectively. Romanovsky and Kolokov are permafrost scientists who will characterize thermal properties and processes for inclusion in local- to global-scale thermal permafrost models. Grosse will contribute to the development an understanding of geomorphological dynamics associated with the processes of degrading permafrost and landscape evolution. J. Cherry is an Arctic hydroclimatologist with expertise in meteorological instrumentation and airborne remote sensing. She will maintain meteorological instrumentation on the Seward Peninsula, manage the data obtained from the instrumentation, and coordinate airborne remote sensing with the UAF Integrated Sensor System.

Researchers from LBNL will focus on the geophysical and experimental characterization of subsurface material properties and the assimilation of these data into model initialization datasets and the development of THM constitutive relationships. Hubbard will provide overall leadership of the LBNL activities as well as specific tasks focused on characterizing the subsurface using geophysical approaches and relating land surface, active layer, and ground ice variability to each other. Ajo-Franklin, a geophysicist, has expertise in the development and use of seismic methods to quantify porous media structure and deformation from the pore to plot scales. For NGEE, he will deploy and test in situ deformation observation techniques and will assist with ground ice characterization. T. Kneafsey, who is a geologist and a mechanical engineer with expertise in coupled geomechanical-hydrological processes, will lead the freeze-thaw column experiments to provide constitutive relationships for models. Barry Freifeld is a mechanical engineer who has extensive experience in thermal fiber-optic monitoring. He will participate in hydrothermal characterization focused in implementation of fiber-optic techniques at the NGEE sites.

**Biogeochemistry Team**: D. Graham is an expert in microbial biochemistry, methanogenesis, and microbial evolution; he will lead this team. L. Liang (ORNL) is an expert in environmental subsurface chemistry and aqueous geochemistry; she will lead tasks measuring rates and mechanisms of subsurface transport processes and carbon interactions with sediment minerals. B. Gu (ORNL) is an expert in SOM and its interactions; he will lead tasks to measure rates and mechanisms of soil carbon transformation and carbon-mineral interactions. D. Elias and T. J. Phelps (ORNL) are experts in microbial biogeochemistry and anaerobic subsurface microbiology; they will lead tasks establishing microbial microcosms and mesocosms to measure rates and modes of microbial transformations. R. Hettich (ORNL) is an expert in mass spectrometry and proteomics; he will lead tasks using metaproteomics to compare microbial activities. E. Brodie and J. Jannson (LBNL) are experts in molecular microbial ecology; they will lead tasks using metagenomics and microbial community analysis. S. Hubbard, Y. Wu, T. Kneafsey, and S. Nakagawa (LBNL) are experts in geophysical and hydrological processes; they will lead tasks studying the impact of freeze-thaw processes on SOM dynamics. M. Torn (LBNL) is an expert in GHG flux measurements and isotopic analysis; she will lead field tasks for integrative measurements of GHG production and $^{14}C$ analysis. W. Riley and C. Koven (LBNL) will coordinate closely with the team on biogeochemical process modeling. Postdoctoral research associates and technical support staff at ORNL and LBNL will assist with each of these tasks.

**Vegetation Dynamics Team**: R. Norby (ORNL) will lead this team effort. Norby is a plant physiological ecologist with interest in nitrogen cycling, plant-soil interactions, and ecosystem responses to climate change. C. Iversen (ORNL) will be responsible for measurements of N cycling in the active layer. V. Sloan, a postdoctoral researcher, will work with Norby and Iversen to characterize plant community composition, root distribution, and plant nitrogen contents. J. Childs will provide field and laboratory technical assistance at ORNL. A. Rogers (BNL) is responsible for plant physiological measurements, including leaf gas exchange and biochemistry. N. McDowell (LANL) and J. Cable (UAF) will make measurements of water isotopes in plants and whole-system gas exchange. C. Xu (LANL) will be responsible for integrating plant and soil measurements into a model of C-N interactions. D. McGuire (UAF), E. Euskirchen (UAF), and D. Hayes (ORNL) will use the data from this task to improve the representation of plant functional types in models.

**Integrated Task and Evaluation Team:** M. Torn (LBNL), who is a principal investigator (PI) of the ARM Carbon project that includes three eddy covariance systems, will lead this team and many of the tasks. She will be assisted by D. Billesbach (University of Nebraska, Lincoln), who is a biometeorologist and is the instrument mentor for two eddy covariance systems for the ARM Carbon project in the Southern Great Plains and who has long experience with laser-based instrumentation for methane concentrations.

**Data Management Team**: The NGEE Arctic data management team will be co-led by T. Boden and G. Palanisamy. Tom will be responsible for managing the data team, interacting with the NGEE science team, and gathering input and feedback from end users. Giri will oversee the design and development of the data system architecture including data interoperability and systems operations. Additional members of the team include L. Hook, R. Devarakonda, G. Kora, and others. They will be responsible for the metadata management, NGEE data portal, field and laboratory data management, and web services components of the plan, respectively. Additional members from ORNL and our partner institutions will be identified to support specific elements (e.g., data quality) and data types (e.g., hydrology and geophysics).

**Scientific Advisory Board**: The SAB will provide input to the NGEE Arctic project LRD through review of plans, progress, and participation in periodic team conference calls and meetings. Members will be selected from the national and international community. We seek members from across a wide range of disciplines, including researchers in the carbon cycle and subsurface sciences, ecosystem and climate modelers, representatives from other state and federal agencies, data management specialists, and members who possess traditional knowledge of local tribal entities. Our initial plan is to stagger the appointments of SAB members and ask them to serve 2 to 3 years. We will rotate off any members who as a result of their association with the project become collaborators on the NGEE Arctic project. The tenure and other details of the SAB will be outlined in a charter to be prepared in 2012.

## VI.2 PROJECT COMMUNICATION

Key to successful management of a project of this size and complexity is frequent, clear, and effective communication among research partners. Therefore, the NGEE Arctic project will implement a strategy for communication within the project, with external collaborators, with the larger scientific community, and with program managers and other external stakeholders.

Biweekly meetings will be held (1) between the LRD and the core team (e.g., STLs, ILs, and chief scientist) to review and resolve any issues with respect to integration and progress and (2) among the NGEE Arctic project team to discuss technical advances in each task. These meetings will be staggered so that, in essence, the NGEE Arctic team is communicating weekly. In addition, STLs will meet with their science team and external collaborators regularly to ensure that research tasks are performed appropriately. Quarterly and annual reports will be prepared and transmitted to BER so program managers can review project milestones and research progress. Progress against outcomes will be assessed by STLs quarterly. The NGEE Arctic web site, and eventually the NGEE Arctic Data Portal, will be used to exchange documents, datasets, and information related to the project. In addition, a variety of tools will be utilized to keep team members informed and engaged: conference calls, virtual meetings via WebEx or ReadyTalk, face-to-face meetings, mini-workshops, and annual retreats will be held to promote discussion, collaboration, and integration within the project. Emerging virtual communication platforms such as that of wiki or social-networking sites will be utilized to support communication with other scientific efforts, the general public, and associated stakeholders. A web site is already on line and available for use by NGEE Arctic participants (see Figure 15). The project team maintains and regularly updates the web site, which is accessible to the public. It describes ongoing research efforts and provides summaries and abstracts of published results, posters, presentations, and pictures (http://ngee.ornl.gov). Participants in the project post daily updates to the NGEE Arctic blog when in the field conducting research of interest to the public and stakeholders (http://ngee-arctic.blogspot.com/). This has been a valuable tool for outreach and education.

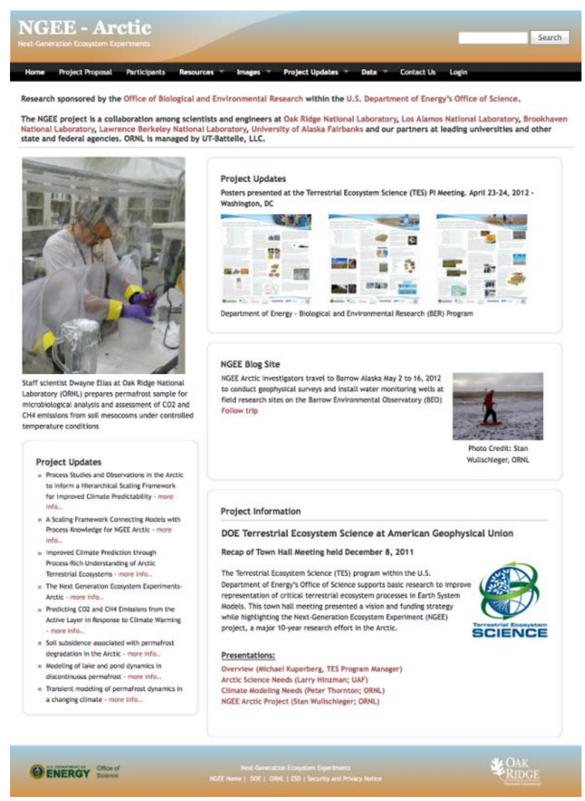



**Figure 15. Project web site (http://ngee.ornl.gov).**

## VI.3 MEASURES OF PERFORMANCE

The NGEE Arctic team is committed to tracking and documenting performance related to all aspects of our integrated model-experiment project. As such, we have identified a number of areas for which we will develop quantifiable measures of performance.

**Milestones, deliverables, and outcomes:** Each task has associated with it a series of milestones, deliverables, and expected outcomes. They are stated in the form of high-level products as outlined in the proposal text and are described in more detail in the Appendix XIV.1. We will take this information and, with the help of our project manager, translate it into a work breakdown structure (WBS). In project management, WBS is a formal process whereby a project is decomposed into smaller components. It defines and groups discrete work elements in a way that helps organize and define the total work scope of the project. We will share this WBS with BER program managers and will illustrate how it is being used to track deliverables, costs, and achievements of the project. Our goal will be the timely delivery of tasks and accomplishments within budget.

**Scientific productivity:** A research project is often defined by publications, abstracts, posters, presentations, and conferences attended. We will track and report these statistics in these categories. However, the NGEE Arctic project is committed to delivering publications and other outcomes that (1) emphasize cross-disciplinary results and conclusions; (2) involve co-authors from multiple institutions; (3) highlight integrated nature of highly coupled Arctic ecosystems; and (4) showcase strategies and approaches for integration of experiments, observations, and models. It will be these four categories of publications that we will devote considerable effort throughout this project.

**Site establishment and availability:** The NGEE Arctic project is envisioned to be seen (and used) by the community as a scientific resource. While not a user facility per se, sites will be used by the larger scientific community with our encouragement and facilitation. Metrics of interactions with national and international collaborations will be tracked and reported. Emphasis will be placed on two important areas: collaborations and providing air, water, soil, and plant samples upon request. A user's guide will be developed in Phase 1 to facilitate this process.

**Modeling framework:** One of the primary goals of our Phase 1 efforts is the development of a scaling framework that enables process understanding to be translated from plot to landscape to regional and global scales. As explained in Sect. III, "Approach," this scaling framework will involve both process studies and observations conducted across geomorphological landunits on the Arctic Coastal Plain and then multiscale modeling to allow representation of critical processes in climate models. A key measure of performance will be Phase 1 progress in this area and delivery of a framework that has been tested and evaluated in preparation for Phase 2 activities elsewhere in Alaska.

**Model improvement:** The NGEE Arctic project seeks to develop a process-rich model of tundra ecosystems, one that can be used to represent processes at the scale of a high-resolution grid cell. This capability should allow improved simulations of landscape change or evolution and the consequences thereof to climate prediction. It is explicit that we will be able to quantify improvements in climate prediction. We will develop metrics (e.g., uncertainty quantification) and report them as we begin to incorporate improved process-level representation into Earth System models.

**Data management infrastructure:** It is critical that as we develop scientific understanding of Arctic ecosystems, both through process studies and models, we make that knowledge available to the larger scientific community. The NGEE Arctic project will do that through a data portal, where information generated through our analyses will be accessible in a user-friendly environment.

**Leadership:** While we will be careful to focus on the tasks at hand, we will also provide where appropriate scientific leadership through involvement in state and federal agency activities that will benefit from input from our multidisciplinary team of investigators. We will explore international collaborations and/or involvement in activities that will strengthen our ultimate goal of understanding carbon cycle processes across the Pan-Arctic.

**Safety:** Given the remote setting of the NGEE Arctic project, an important measure of performance will be scientific accomplishments in the field and the laboratory supported by a sound safety plan and strong safety record. We will develop a safety plan for NGEE partners and collaborators in Year 1 of the project and will then hold people accountable for attention to safety procedures.

## VI.4 PERSONNEL RECRUITMENT AND SUCCESSION PLANNING

ORNL management, the NGEE Arctic LRD, ILs, and the STLs are committed to successfully staffing this project and ensuring a continuity of effort. During annual project planning, the core team will assess personnel requirements and will actively manage attrition through (1) strategic hiring of staff, postdoctoral research associates, or graduate students at the national laboratory and university partners; (2) developing internal talent to assume increased responsibility; and (3) establishing external collaborations with researchers who can provide technical expertise. Anticipated personnel changes and planned resolution of staffing gaps will be included in the yearly updates to the program plan and will be discussed with DOE. Two high-priority issues are to augment expertise in CLM/CESM modeling and to develop succession plans for all key NGEE Arctic science leadership staff.

Developing internal talent will be essential to preparing the next generation of leaders for terrestrial ecosystem research supporting DOE’s mission. The core team has recruited staff from the partner organizations to develop and implement this project based on their expertise and productivity in modeling and process fields that are critical to the attainment of NGEE Arctic goals. While some staff are used to operating in large, multidisciplinary projects, meeting project goals will require a unique coordination of modeling and observation/experimentation. The team is developing this interactive culture through joint planning meetings, literature discussions, coordinated conference presentations (e.g., sessions, symposia, workshops, and “town Hall” meetings); collaborative Laboratory Directed Research and Development (LDRD) projects; invited speakers; and joint publications. University partners with expertise in Arctic research are also actively engaged in discussions with staff to share field work experiences, references to key datasets, foundational literature, safety information, cultural knowledge, and introductions to other Arctic research projects. The partner organizations will also identify professional development opportunities for young staff, including management training seminars, high-profile presentations, publication and peer review opportunities, and training in project management and financial planning.

The core team members, particularly STLs, are leading recruitment of new postdoctoral researchers and strategic staff hires for this project. Postdoctoral researcher associates have been recently hired to execute tasks in the Vegetation Dynamics, Biogeochemistry, and Integrated Model-Data Evaluation areas. International searches are ongoing for postdoctoral researchers in Hydrology/Geomorphology and Multiscale Modeling areas.

## VI.5 FACILITATING PROJECT INTEGRATION

The NGEE Arctic project, as described earlier in the proposal, has a matrixed organizational structure that was designed specifically to facilitate integration: integration across partner institutions, integration across disciplines, and integration of models and experiments. This organization is strengthened by the fact that many of our measurement tasks contribute directly to models by providing a dataset for model parameterization, process representation, initialization, or evaluation. In turn, many of the modeling tasks depend on experiments and observations to provide input. This integration is reflected in the scientific task descriptions outlined in the Appendix XIV.1. In addition, while individual teams are encouraged to discuss specifics within a given task, our biweekly conference calls and annual all-hands meeting will foster continual interaction between our process science and multiscale modeling teams.

## VI.6 PERIODIC REPRIORITIZATION OF RESEARCH TASKS

The LRD and STLs will evaluate scientific progress and accomplishments on a routine basis. It is fully expected that, with time, tasks will come to a conclusion. As a result, opportunities will arise periodically for adding new studies, techniques, and collaborators. The NGEE Arctic project will implement a change control policy for handling such decisions (see Appendix XIV.3). The Core Team will continually assess and implement changes needed for the success of NGEE Arctic goals.

## VI.7 QUALITY ASSURANCE AND RISK MANAGEMENT

The NGEE Arctic project has been planned to include methods for ensuring quality in research and for implementing standard procedures for regulatory requirements. Leadership of the project has been established (see Section VI.1) that provides communication among the teams via the project core team. The core team of this project is committed to the delivery to our sponsor of a process-rich ecosystem model based on the studies and observations of the evolution of Arctic ecosystems in a changing climate.

The project will leverage numerous existing systems and will be executed with the collaborative efforts of highly qualified researchers. The provision of adequate infrastructure and work environment has been planned in the field and at the participating institutions. Responsibility and budget authority are planned as noted in Section VI.1, "Project Organization—Roles and Responsibilities," and in the Task Tables in Appendix XIV.1. The collection of data and samples has been planned to ensure the long term viability where appropriate.

A framework for identifying, monitoring, and managing the risk associated with uncertainties will be established to provide tools to science leaders and the project director to ensure that risk that threatens the success of the project are mitigated in a timely and efficient manner.

## VI.8 EDUCATION AND COMMUNITY OUTREACH

Education and community outreach (E/CO) will be an important priority that will pervade through all levels of the NGEE Arctic project. It will be clearly communicated that it is the responsibility of scientists to not only share research results with other scientists in their field, but to also communicate their ideas and findings to the general public. The NGEE Arctic project aims to develop and apply the state of the art in science to study the impacts and predict the future response of ecosystems to climate change—an issue of critical global concern.

It is in the public interest that we make every attempt throughout the project to educate and engage the larger community as to what we are doing and why we are doing it. To relate NGEE Arctic science to this wider, global community, an objective of the project will be to include the publication of popular articles of more general interest in addition to typically targeted scientific journal articles. At a finer scale, we will communicate NGEE Arctic activities by engaging media outlets and civic organizations that serve the state of Alaska and its communities.

Beyond our broad obligation of science in general, the study locations in Alaskan communities for the NGEE Arctic project offer both special responsibilities and unique opportunities to engage in E/CO. The on-the-ground activities and experimental setups proposed in NGEE Arctic will take place in and around Alaskan native communities with deep connection to their land and resources. There exists a rich history of these local communities interacting with, participating in, and even driving international scientific efforts. Lessons learned through this history demonstrate that fostering an open and transparent communication between scientists and local people is paramount to a successful research campaign. As a key component of NGEE Arctic, we will engage the communities at each study location through "town hall" style meetings in which we will inform local stakeholders on the objectives and activities of the project as well as provide a forum for two-way discussion. Important benefits to NGEE Arctic from engaging the local communities include a collaborative environment from which to glean key knowledge of the local environment and of the logistics involved in working in these areas.

A goal of the E/CO activities is to educate and engage the public in the observation, measurement, and basic science associated with the NGEE Arctic project goals as they relate to the study of the Arctic system in a changing world. Secondary education is an ideal level at which to achieve this goal with the added opportunity to develop the next generation of scientists, decision makers and educators. Our E/CO will provide teachers with the foundation upon which to build a lasting program for continued development of students' knowledge and interest in the scientific disciplines.

Implementation of the E/CO component will leverage the Global Learning and Observations to Benefit the Environment (GLOBE) program as the existing, systemic, and sustainable educational framework best suited to both address the goal of this component and take advantage of the subject matter most relevant to NGEE Arctic. There is an active program through the International Arctic Research Center at UAF with a history of extending GLOBE activities to schools throughout Alaska. There are more than 200 GLOBE-participating schools in Alaska, a state where opportunities abound for promoting the participation of underrepresented groups in Earth science within communities that have been disproportionately affected by the impacts of global climate change (see Karl et al. 2009). By directly engaging students and educators through hands-on, interactive educational activities, we aim to increase science and technology literacy and awareness of DOE's mission among students, educators, and, by extension, their families and the community as a whole. This component will contribute to inspiring community involvement and building the strategic partnerships necessary for carrying out a successful project with wide-ranging benefits.

## VI.9 PARTNERSHIPS WITH LOCAL NATIVE ENTITIES

This research will be conducted in accordance with the Principles for the Conduct of Research in the Arctic (Arctic Social Sciences 1999). As such, we will work closely with local people to identify research sites that are acceptable for these studies but that will not infringe upon places of sensitive cultural heritage. We will meet with local community members to explain the purpose of our research and the approaches to be used, and we will adapt where possible our implementation of field activities to minimize impacts to local residents. We will take every opportunity to explain our activities and demonstrate our results. Research results will be explained in nontechnical terms and, where feasible, will be communicated as displays that can be shown in local community centers or museums. Research reports, data descriptions, and other relevant materials will be provided to the local community. Special efforts will be made to communicate results that are responsive to local concerns. We will incorporate local knowledge and understanding of natural processes in our science where possible. Local cultural traditions, languages, and values will be respected. Our researchers will strive to make use of local and traditional knowledge and experience. When possible, we will provide meaningful experience and training for young people. We will present a positive impact to the community by buying our commodities locally, by participating in community events when appropriate, and by encouraging people from the local community and across the nation, to better understand Arctic climate dynamics.

## VI.10 RELATIONSHIP TO OTHER PROJECTS

The **Atmospheric Radiation Measurement (ARM)** program is one a principal contribution of the DOE to the U.S. Global Change Research Program. ARM focuses on the radiative energy balance of the Earth, the primary determinant of global climate, and especially on the influence of clouds on that balance. The North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) Cloud and Radiation Testbed (CART) is located in Barrow, less than a kilometer from the proposed NGEE Arctic site. Long-term measurements of radiation and energy balance for the site would be useful to NGEE Arctic investigators as they place plot-based estimates of net energy balance into a larger landscape to regional scale. In turn, NGEE Arctic could provide a mechanistic underpinning for long-term trends observed by the ARM program. Additionally, the ARM program has developed infrastructure in the Barrow area that could facilitate a rapid start to the NGEE Arctic project in Phase 1. To the extent possible we could take advantage of those facilities and lessons learned by ARM scientists involved in data collection, data communication, and data management. (See letter of support from M. Ivey in the letters at the end of this section.)

The **Regional Arctic System Model (RASM)** is a DOE-funded project to develop and apply a regional Arctic system model to address improved decadal Arctic climate projections. It builds on the earlier research that resulted in the development of the fully coupled Regional Arctic Climate Model (RACM), consisting of atmosphere, land-hydrology, ocean and sea ice components. RASM will soon launch a new series of model improvements, including inclusion of ice sheets, ice caps, mountain glaciers, and dynamic vegetation to allow investigation of coupled physical processes responsible for decadal-scale climate change and variability in the Arctic. Members of the NGEE Arctic team have spoken to investigators involved in the RASM activity, and there is general agreement that insights derived from several of our Challenge areas (e.g., Nitrogen and Energy), thus supporting the enhanced description of processes in the RASM model. (See letter of support from W. Maslowski.)

The **Global Change Research Group (GCRG) at San Diego State University (SDSU),** led by Walter Oechel, has maintained eddy covariance flux towers at three sites in Arctic Alaska: Barrow, Atqasuk, and Ivotuk. The three sites form a 300 km north–south transect on the North Slope of Alaska, each site representing distinct vegetation communities common to the Arctic. The importance of these tower measurements cannot be understated as they provide a long-term record of one of the largest, most volatile carbon stocks on the planet. The long-term records of net ecosystem exchange (NEE) will be valuable as NGEE Arctic looks to interpret $CO_2$ and $CH_4$ flux and net energy balance at sites that span a range of permafrost conditions. (See letter of support from W. Oechel.)

The **Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)** is sponsored by NASA. It will collect detailed measurements of important GHGs on local to regional scales in the Alaskan Arctic and demonstrate new remote-sensing and improved modeling capabilities to quantify Arctic carbon fluxes and carbon cycle-climate processes. CARVE will provide an integrated set of data that will provide a useful comparison to the plot and landscape observations of carbon dynamics obtained in Phase 1 by the NGEE Arctic team. CARVE would like to have ground-truth sites along its flight path, and NGEE Arctic would be able to provide that ground-based observation. (See letter of support from C. Miller.)

The **Circumpolar Active Layer Monitoring (CALM)** program is sponsored by the NSF. It has as a goal to observe the response of the active layer and near-surface permafrost to climate over multidecadal time scales. The CALM observational network was established in 1991 and worldwide has more than 125 sites in 15 countries. There are currently two CALM sites in Barrow (one is Atqasuk near Barrow on the North Slope) and at sites in Council and Kougarok on the Seward Peninsula. Long-term records at these sites will be important time series to place our Phase 1 and ultimately Phase 2 observations into a longer time frame. In turn, we will provide to the CALM team information on geophysical characterization, surface hydrology, and other process-level knowledge that will help describe contributions of various factors to changes in permafrost temperature and active layer thickness over time. (See letter of support from N. Shiklomanov.)

The **Spatial and Temporal Influences of Thermokarst Failures on Surface Processes in Arctic Landscapes** is an NSF-sponsored project. This is a collaborative, interdisciplinary effort to study the responses of Arctic landscapes to permafrost degradation and thermokarst caused by structural failure following the melting of ground ice. The research seeks to quantify linkages among climatology, hillslope hydrology, geomorphology, geocryology, community ecology, soil nutrient dynamics, microbial ecology, trace gas dynamics, and aquatic ecology. The sites of interest to this team are those in the foothills of the North Slope. As such our efforts in Barrow and the Seward Peninsula represent a great comparison that together encompass much of the Alaska tundra. We have agreed to share information from the NSF-sponsored project and NGEE Arctic Phase 1 activities in hopes of achieving a common understanding of the causes and consequences of permafrost degradation and thermokarst formation throughout Alaska. (See the letters of support from W. Bowden and M. Gooseff.)

The **Arctic Landscape Conservation Cooperative (LCC)** is a public-private partnership among the federal, state, and local government agencies, Tribes, nongovernmental organizations, academic institutions, and other entities operating within Arctic Alaska and northern Canada. It is convened by the Department of Interior and seeks to provide the resource manager with scientific information and management tools needed to anticipate the effects of climate-driven habitat change and to incorporate that understanding into conservation planning. NGEE Arctic welcomes the opportunity to contribute to the goals of the Arctic LCC as part of its community outreach objectives. (See the letter of support from D. Vincent-Lang.)

The **Arctic Network Inventory and Monitoring Program (ARCN)** is administered by the National Park Service with a goal to collect, compile, and synthesize scientific information about the Arctic network of parks in order to facilitate their preservation, unimpaired, for future generations. This is a major component of the National Park Service's strategy to improve park management through greater reliance on scientific information. The network includes five park units in northern Alaska that cover 19.3 million acres of land. The intent of the National Park Service's monitoring program is to track a subset of physical, chemical, and biological elements and processes of park ecosystems. These data will be of great value to NGEE Arctic for extrapolating results over larger areas. (See letter of support from park superintendents G. Dudgeon, Superintendent, Gates of the Arctic National Park and Preserve; F. Hays, Superintendent, Western Arctic Parklands; and J. Pomrenke, Superintendent, Bering Land Bridge National Preserve.)

The NSF-sponsored **Critical Zone Observatories (CZOs)** are environmental laboratories established at six locations in the United States to study the chemical, physical, and biological processes that shape the Earth's surface. The goals, objectives, and approaches used in the NGEE Arctic project and especially our focus on how fundamental geophysical and ecological processes potentially shape the Arctic landscape are consistent with those of the CZO. The CZO currently does not have a field location in Alaska; NGEE Arctic sites could contribute to this gap in understanding the complexity of cold regions. Moreover, leaders of the CZO network of sites have invested considerable time and energy in developing a framework for data management. The NGEE Arctic project intends to learn from and leverage this particular aspect of the CZO. (See the letter of support from M. Williams.)

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25 May 2011

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Dear Larry,

I was glad to hear that you and others working on a proposal for the Next Generation Ecosystem Experiment selected Barrow as a candidate site for field studies. I want to briefly summarize several recent conversations in which I have been included about the potential for collaboration between NGEE and ARM programs.

First, measurements that we are currently taking routinely at the Barrow ARM site or measurements that we will be adding in the near future will be useful to NGEE researchers. Atmospheric radiative flux, meteorological measurements up to 40 m above the surface, cloud, aerosol, and precipitation properties in the Barrow area are just a few that come to mind. We are adding methane flux and Eddy covariance measurement stations in Barrow with Recovery Act funding. We have user support mechanisms that can guide NGEE researchers to instrument or data experts if questions arise about data access and visualization, measurement methods, and data quality. It seems very likely that measurements made as part of NGEE field studies in Barrow could be useful to the broader research community, and ARM management can discuss ways in which ARM and NGEE data might be cross-linked and referenced for access by researchers.

Second, the ARM Program currently has logistical resources in Barrow that we can make available to NGEE staff provided there is no resulting interference with ARM-funded projects. The "ARM Duplex" with accommodations for visitors and also office space in the BARC building are leading examples of resources that could be useful to folks visiting Barrow for the NGEE program. As the NGEE field site in Barrow develops, we can gauge how best to share logistic support in the Barrow area.

Third, I think it may be to our mutual benefit in the future to share a few specific technical support resources. I can envision sharing costs for a year-round technician in Barrow, for example, or a technician based at UAF that could deploy quickly to Barrow.

*Exceptional Service in the National Interest*

- 2

As you know well from many years of field work in Alaska and the Arctic, the impressions that visiting researchers make on the local communities can have profound implications with consequences, both positive and negative, that may persist in those communities for years. I am very pleased that you are taking a lead role on the science part of NGEE. I believe it will be in our mutual best interest to actively promote science in Barrow, maintain a positive image of DOE and specifically BER in the community through outreach and education, and stay in close communication with each other when issues arise that might have negative impacts on either NGEE or ARM. Your experience in native Alaskan communities will be of great value to all involved.

You and our other colleagues at UAF have been and continue to be highly-valued collaborators in our work in Barrow for ARM. I look forward to the proposed expansion of the long-standing excellent relationship among UAF, the International Arctic Research Center, the ARM Program, and soon, NGEE.

Regards,

Mark D. Ivey

NAVAL POSTGRADUATE SCHOOL

DEPARTMENT OF OCEANOGRAPHY

May 31, 2011

Stan D. Wullschleger, PhD
Environmental Sciences Division
Oak Ridge National Laboratory
Building 2040, Room E212, MS 6301
Oak Ridge, TN 37831-6301

Dear Dr. Wullschleger:

We are pleased to hear that the Department of Energy is initiating the Next Generation Ecosystem Experiment (NGEE), which is intended to develop better understanding and model representation of the physical aspects of a warming climate in the Arctic. The focus of this project on the land surface processes and variables, such as sensitive to climate warming permafrost, and on their representation in the land surface schemes within climate models, will directly support the development of next generation terrestrial ecosystem and hydrology models and will provide observations for their critical evaluation. Your specific objectives of developing a high resolution terrestrial system model able to simulate coupled thermal, hydrological, geomorphic, biogeochemical and vegetation processes mesh well with the goals of our DOE-funded Regional Arctic System Model (RASM) project and presents many opportunities for collaboration amongst our team members. RASM has a strong commitment to high resolution modeling of land surface processes through continued development and application of the Variable Infiltration Capacity Model (VIC) and its extension to include representations of dynamic vegetation and biogeochemical processes. The proposed NGEE field observations should provide needed information for development and testing of advanced next generation land model schemes. We expect that through shared data, collaborative discussions on translating measurements into model code, and model testing and inter-comparisons both our teams can make better and more efficient progress, which in the end will benefit all arctic science.

Sincerely,

On behalf of the Regional Arctic System Model (RASM) Project

Wieslaw Maslowski
RASM Project PI
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May 31, 2011

Dr. Stan D. Wullschleger, PhD
Environmental Sciences Division
Oak Ridge National Laboratory
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Oak Ridge, TN 37831-6301

Dear Dr. Wullschleger:

I am pleased to offer my collaboration to the participants of the Arctic Next Generation Ecosystem Experiment. As you know, for many years, my research team has operated chamber based measurements, eddy covariance tower flux measurements, aircraft based flux measurements, complex, multi-factorial manipulations, and experiments, and at many locations in northern Alaska, including several sites identified for intensive observation in NGEE. We are currently operating 5 eddy covariance measurement stations in or near the Barrow Experimental Observatory. We will be pleased to share our insight and expertise in operating these complex technical systems in such a harsh environment. We are also striving to develop better models of ecosystem response to a warming climate, which we understand is one goal of the NGEE program. We would also be happy to collaborate with your researchers on building better models of the response of the Arctic ecosystem to a warming climate.

Sincerely yours,

Walter C. Oechel

Dr. Walter C. Oechel
Distinguished Professor of Biology,
Coordinator, SDSU Joint Doctoral Program in Ecology
Director, Global Change Research Group

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June 6, 2011

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Dear Larry:

I acknowledge that I am identified by name as a Collaborator to the investigation entitled *NEXT-GENERATION ECOSYSTEM EXPERIMENTS (NGEE-ARCTIC)* to be submitted by you and Stan Wullschleger (ORNL) to the Biological and Environmental Research program, Office of Science, US Department of Energy (DOE). I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. I offer my collaboration as Principal Investigator of the *CARBON IN ARCTIC RESERVOIRS VULNERABILITY EXPERIMENT (CARVE),* a NASA-funded Earth Ventures (EV-1) mission and my contributions are not a NASA commitment to or endorsement of the DOE program.

As you know, CARVE's goal is to collect detailed measurements of atmospheric $CO_2$ and $CH_4$ concentrations on local to regional scales in the Alaskan Arctic, and demonstrate new remote sensing and improved modeling capabilities to quantify Arctic carbon fluxes and carbon cycle-climate processes. Additionally, our payload includes the Passive-Active L-band System (PALS), a microwave radar/radiometer that delivers freeze-thaw state, inundation state, soil moisture, and surface temperature data, enabling CARVE to study the critical linkages between the carbon and hydrologic cycles. More details on the CARVE mission may be found at http://science.nasa.gov/missions/carve/.

CARVE aircraft campaigns will be based out of Fairbanks, AK and occur throughout the spring, summer and fall seasons of 2012-2014. CARVE's baseline flight paths include

- A track from Fairbanks to Barrow that overflies the flux towers in Ivotuk, Atqasuk and Barrow
- A track along the Yukon River Valley to sample areas with persistent ground water throughout the growing season
- A track from Fairbanks to Deadhorse that overflies many permafrost boreholes, the Toolik Lake LTER site, and the Anaktuvuk River Fire burn area

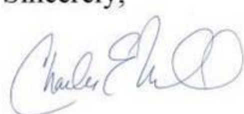
- A circuit of interior Alaska, sampling burn recovery chronosequences and the Bonanza Creek LTER ground sites in Bonanza Creek and Poker Flat

The scientific objectives of NGEE-Arctic - to provide data, theory, and models to improve representations of high-latitude terrestrial processes in Earth system models, particularly the processes by which warming may drive increased plant productivity and atmospheric carbon uptake and storage in biomass and soils, as well as those processes that may drive an increase in the release of $CH_4$ and $CO_2$ through microbial decomposition of soil carbon stored in thawing permafrost – are well aligned with CARVE's objectives.

Your plans to initiate field studies in the summer of 2012 at Council and near Barrow overlap well in time and space with the CARVE science flights. The extensive surface energy balance, subsurface temperature and moisture measurements you plan to collect will enable us to extend our aircraft transect from Barrow to the Seward Peninsula. Overflights of your ground measurement sites will provide valuable ground truth for the CARVE aircraft measurements, and CARVE's continuous aircraft measurements and modeling will enable more accurate extrapolation of the NGEE-Arctic ground site data across the Alaskan domain. Ultimately, the combined data sets will enable rigorous validation of ecosystem evolution modeling, feedback processes, and carbon emissions. In return for an open exchange of data and collaboration on scientific analysis and papers, the CARVE team will coordinate flight plans with your team during periods of overlapping deployment.

I look forward to this collaboration and the benefits it will yield for both projects.

Sincerely,



Charles Miller, CARVE Principal Investigator

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THE GEORGE WASHINGTON UNIVERSITY
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THE DEPARTMENT OF GEOGRAPHY

Larry D. Hinzman,
Director
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May 31, 2011

Dear Larry,

On behalf of the entire Circumpolar Active Layer Monitoring (CALM) team, I would like to express our enthusiastic support for your proposed Next Generation Ecosystem Experiment.

Several of your proposed field sites in Alaska are located in proximity to existing CALM sites. In the past, this approach has allowed us to avoid redundancies in instrumentation and data collection and to share logistical and intellectual recourses (including data). I see great potential for continuation and expansion of such collaborations under your prospective project. I am particularly enthusiastic about your focus on collecting extensive observations related to the surface energy balance and subsurface temperature and moisture. This work is directly in line with the CALM observational program and will greatly complement our ongoing long-term active-layer and near-surface permafrost measurements in Alaska. Implementation of simultaneous observations on climate, landscape, active-layer, permafrost, and hydrologic parameters at regional level will allow more detailed analysis of the processes involved in climate-permafrost-hydrology interactions and more accurate assessment of spatial and temporal changes in broad range of permafrost landscapes. It will also provide a basis for scaling observations to the regional level.

I wish you good luck with your proposal and hope for productive collaborations between CALM and your current and future projects.

Nikolay I. Shiklomanov
Assistant Professor
PI of the NSF-funded CALM project
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OF ENVIRONMENT AND NATURAL RESOURCES

21 May 2011

Dr. Larry D. Hinzman, Director
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Fairbanks, AK 99775-7340

Dear Larry,

I read with great interest about the Next Generation Ecosystem Experiment that you are planning with collaborators from the Oak Ridge National Laboratory, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Brookhaven National Laboratory and the University of Alaska. I understand that you plan to submit this proposal to the Department of Energy shortly. This is an exciting new initiative that addresses an important need. I think that the work that we are currently doing in several National Science Foundation funded projects, including the ARCSS/Thermokarst Project, the Changing Seasonality in Arctic Stream Networks project, the Anaktuvuk Burn project, and several parts of the Arctic Long-Term Ecological Research project could contribute to the new initiative that you are planning.

Best of luck with this proposal. I am confident in saying that should your project be funded, my colleagues and I will share data with you and would be happy to collaborate on the development of the models you propose to produce.

Sincerely,

William B. Bowden
Patrick Professor of Watershed Science and Planning
Lead PI, ARCSS/Thermokarst project
Lead PI, Changing Seasonality in Arctic Stream Networks project
Co-PI, Anaktuvuk Burn Project
Science Coordinator, Streams Component, Arctic LTER project

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23 May 2011

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Dear Larry,

I am very happy to learn about the Next Generation Ecosystem Experiment (NGEE) that you are planning with collaborators from Department of Energy Laboratories (Oak Ridge National Laboratory, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Brookhaven National Laboratory) and the University of Alaska. The proposed work is greatly needed as the scientific community, land managers, and society at large seeks to understand the responses of Arctic ecosystems to changing permafrost and climate conditions in the north. Findings from our current projects *Spatial and Temporal Influences of Thermokarst Failures on Surface Processes in Arctic Landscapes*, and *How does changing seasonality affect the capacity of arctic stream networks to influence nutrient fluxes from the landscape to the ocean?*, both funded by the National Science Foundation, will provide excellent opportunities to compare, contrast, and link findings from our sites in the North Slope foothills to your proposed sites on the Seward Peninsula and near Barrow. We are looking forward to cooperating with your research group to leverage findings from all of these efforts to enhance our understanding of these systems.

Sincerely,

Michael N. Gooseff
Associate Professor
Co-PI on ARCSS-TK project (http://thermokarst.psu.edu)
Co-PI on CSASN project (http://water.engr.psu.edu/csasn)

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Dear Dr. Hinzman:

This letter states the intention of the Arctic Landscape Conservation Cooperative (LCC) to collaborate with the Department of Energy's Arctic Next Generation Ecosystem Experiment (NGEE). The Arctic Landscape Conservation Cooperative is part of a network of public-private partnerships, convened by Department of the Interior, and intended to provide a collaborative approach to resource management on a landscape scale. The goals of the Arctic LCC are: to provide information and forecasts of climate-associated ecosystem change and other landscape stressors; determine how climate driven changes affect subsistence users; and provide improved data and information access to managers.

Along with the Western Alaska LCC, and the newly formed Alaska Climate Science Center, we are supporting a multi-year project at the University of Alaska which is aimed at coupling permafrost, fire/disturbance, terrestrial ecosystem, and hydrologic models in order to forecast changes in habitat that are important to resource managers. Better understanding of the feedbacks among these processes, gained through the NGEE, will be vital to improving and validating these models; the investment of the LCCs in this model framework will be useful to the NGEE and provide a vehicle for transferring this knowledge to resource managers. Current Arctic LCC work also includes modeling the susceptibility of lakes in northern Alaska to sudden drainage, hydrometerologic data rescue, and design of better observation networks to monitor trends in physical and ecosystem change across the region. These activities are expected to continue into the foreseeable future, and will contribute to the NGEE's knowledge base and potential to extrapolate NGEE experimental results to the ecoregional scale.

Sincerely,

Douglas Vincent-Lang
Chair, Arctic LCC

# United States Department of the Interior

NATIONAL PARK SERVICE
Arctic Network Inventory & Monitoring Program
4175 Geist Road
Fairbanks, Alaska 99709

2 June 2011

Larry Hinzman
Director
International Arctic Research Center
PO Box 757340
930 Koyukuk Drive, 423 Akasofu Building
Fairbanks, AK 99775-7340

Stan D. Wullschleger
Environmental Sciences Division
Oak Ridge national Laboratory
Oak Ridge, Tenn

Dear Dr. Hinzman and Dr. Wullschleger,

The Superintendents of the National Park Service Arctic Inventory and Monitoring Network (ARCN) are excited about the potential to collaborate with the proposed Next-Generation Ecosystem Experiments (NGEE-Arctic) project. This is a perfect opportunity to utilize the information gathered in both the NPS effort and the NGEE-Arctic effort to advance our knowledge of high latitude ecosystems and improve our understandings of how these areas will be impacted by climate change. The NGEE-Arctic goal of improved prediction and reduced uncertainly in climate models has direct relevance to park management as the NPS formulates plans to maintain these lands in the future

The National Park Service Arctic Inventory and Monitoring Network (ARCN) includes five park units in northern Alaska that cover 19.3 million acres of land (http://science.nature.nps.gov/im/units/arcn/). The intent of the NPS monitoring program is to track a subset of physical and, chemical, and biological elements and processes of park ecosystems. Elements and processes that ARCN is tracking that may be of particular interest in regards to NGEE-Arctic include weather/climate, permafrost, fire extent and severity, lake communities, snowpack, terrestrial landscape patterns and dynamics (remotely sensed information), and terrestrial vegetation and soils (field based work). Data from these efforts would be of great value to the NGEE-Arctic effort. Conversely, data collected in association with NGEE-Arctic would greatly bolster ARCN data sets and enhance our ability to make inferences across NPS landscapes. Through our collaborative efforts we can strengthen NGGE-Arctic modeling efforts to better quantify the responses of high latitude ecosystems to atmospheric and climate change.

The NPS sees a number of opportunities for collaboration. NPS contributions to this collaborative effort could include data sharing, coordinated field efforts, assistance with the NPS permitting and compliance process, and in some cases, access to facilities for basing field work.

Partnerships are key to effective monitoring and we look forward to this collaboration. The staff of the Arctic Network of parks would welcome the opportunity to forward the success of this work. We are looking forward to discussing the options for getting this imporant research completed.

Sincerely,
Superintendents, Arctic Inventory and Monitoring Network

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Dr. Stan D. Wullschleger
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6422

Dear Stan,

As scientific participant and lead of the NSF sponsored Critical Zone Observatory (CZO, http://criticalzone.org/index.html) data management effort, it is my pleasure to support the the Next Generation Ecosystem Experiment (NGEE) proposal that you are leading. I was very interested to learn about the NGEE project during our recent meeting in Washington DC and to share with your some of our CZO experiences.

As you know, the CZO consists of a suite of instrumented watershed study sites ('observatories') that are distributed in different physiographic and hydrological environments, including California, New Mexico, Arizona, Colorado, Pennsylvania, Delaware, and Puerto Rico. Individually and collectively, CZO research focuses on exploring how the critical zone operates and evolves, including predictions of its response to future climate and land-use. Using a common infrastructure to measure hydrogeochemistry as well as soil and canopy properties, CZO multi-disciplinary teams strive to quantify mass and energy balances. The infrastructure and scientific research is intended to enable better predictions of how the critical zone will respond to climate and land-use changes as well as help address scientific questions, such as the missing continental carbon sink. Importantly, there are no CZOs located in high-latitude sites, such as those proposed by NGEE to address terrestrial ecosystem processes and feedbacks to climate.

There are many facets of possible collaboration between the NSF-sponsored CZOs and the DOE-sponsored NGEE. As the lead of the CZO data management effort, I can attest to the importance of establishing an integrated data management framework to enable publication, sharing and advanced data analysis and modeling. I have already shared with you my opinion about priorities for establishing the NGEE data management system, as well as the templates, protocols, and standards that we have adopted for the CZOs. I commit to continuing to work with your team as it establishes and implements the NGEE data management framework.

I also see a fantastic opportunity for scientific collaboration between the NGEE and the CZOs. As our initial meeting was organized by our respective NSF and DOE program managers, I am hopeful that there will be a programattic effort to facilitate such collaboration, rendering the NGEE a 'sister CZO'. To that end, a common data management architecture would facilitate cross-site synthesis. I also suspect that collaborations between individual CZO and NGEE investigators will arise where there is mutual interest and benefits; the recent conversation with NGEE co-PI Susan Hubbard and CZO PI Roger Bales is one example of spontaneous collaborations that are to be expected.

In summary, I am very supportive of your proposed research.

This is a neat idea, and I look forward to being able to collaborate with you on this project. Good luck with the proposal!

Mark W. Williams

Mark Williams
Principal Investigator, Niwot Ridge LTER program

# VII. SAFETY PLAN

Safety at Arctic field sites will be an integral component of the team's research planning and execution. While each partner organization (DOE national laboratories, universities, and subcontractors) must establish safety requirements for its staff, the NGEE Arctic leadership team will promote discussions of hazards and best practices for fieldwork and will recommend personal protective equipment that mitigates hazards. As the lead institution for this project, ORNL will establish guidelines for fieldwork that all project participants must review and acknowledge. We expect that specific activities and equipment will require additional training and that such training will be provided on-site by subcontractors or qualified staff. This training will be documented, and any training materials will be made available for review. Both printed, on-site documentation and electronic resources will be provided to project participants.

Risk assessment will be a continuous process, closely tied to risk management, training, and management oversight. Because field activities will be performed in isolated areas of northern Alaska, including local knowledge is integral to safety. Our conversations with logistics providers and native people have apprised us of many local hazards and safeguards, and we expect those discussions will grow. The NGEE Arctic team has also solicited safety information from the DOE ARM facility on the North Slope of Alaska (Ivey 2012), NSF investigators and the logistics provider (UMIAQ) (Polar Field Services 2012), U.S. military staff (Roberts and Hamlet 2001), and petroleum exploration companies that operate in the region (BP Exploration 2010). University collaborators bring great experience operating in the Arctic, and ORNL staff members have coordinated team safety in large DOE-supported FACE, SPRUCE and Integrated Field Research Challenge (IFRC) projects.

From these resources, the NGEE Arctic team has already identified a series of hazards pertaining to fieldwork on the North Slope:

- Mechanical hazards: drilling equipment, vehicles, snow machines, all-terrain vehicles, ergonomic, slips/falls, and cuts/abrasions.
- Geographic and weather-related hazards: cold-related injuries (including hypothermia and frostbite), dehydration, storms, wind, flooding, seasonal depression, communication disruptions, disorientation, and bear encounters.
- Exposure hazards: electrical shock, hazardous materials, and noise.

Each identified hazard will be addressed prior to the commencement of field activities through work controls, training plans, checklists, safeguards and personal protective equipment provisions. However, it is essential that participants have a mechanism to stop unsafe situations in the field. Both the national laboratories and Ukpeaġvik Iñupiat Corporation (UIC), the parent corporation of logistics provider UMIAQ, are committed to a "stop work authority" policy. Through this mechanism, all workers are empowered to stop activities that may be unsafe to human health or the environment without negative consequences or retaliation. A stop work action triggers immediate review by knowledgeable personnel until issues are resolved. Although this authority is rarely exercised, it is an essential component of safety plans that enlist individuals and teams to share responsibility for safety. The team will also recognize an individual's decision not to pursue approved activities based on different levels of experience and physical condition.

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# VIII. FACILITIES COMPONENT

The NGEE Arctic project will develop over the course of its Phase 1 and Phase 2 activities a series of instrumented field sites and associated research infrastructure in Alaska. The coordinated measurements of hydrology, geomorphology, biogeochemistry, and vegetation dynamics at these sites will create an attractive resource for the external scientific community to conduct complementary analyses. Therefore the NGEE Arctic project will develop procedures whereby external investigators can request air, plant, soil, and water samples or assistance accessing field research sites in order to conduct original, peer-reviewed research. Measurements and datasets will be made available at the project web site according to the Data Management Plan. *A Researcher's Guide to Collaboration in the NGEE Arctic Project* explains the process of obtaining samples and conducting fieldwork (Figure 16). Models for this guide will include the ORNL Field Research Center's user guide, the Rifle IFRC web site, and the Institute of Arctic Biology Toolik Field Station web site as well as the user proposal planning documents of DOE BER user facilities such as EMSL, JGI and ARM. The guide will describe the goals and objectives of the NGEE Arctic project; field sites; infrastructure; ancillary environmental data; on-going research activities; and types of soil, plant, and water samples collected and archived. It will include contact information to encourage preliminary discussions, a Sample Request Form, and a Collaboration Request Form. These forms will identify initial responsibilities of the NGEE Arctic project and those of the requesting investigator. Forms will be available in an editable PDF format and will have instructions for web-based submission. It is expected that form submission will begin a dialog that facilitates a full understanding of an investigator's scientific goals and resource requirements. Once research goals and objectives have been identified and deemed to be uniquely within the scope of existing field or laboratory activities, a full work plan would be required and will be evaluated by a coordinating panel that may include the NGEE Arctic Leadership Team, relevant task leads, members of the scientific advisory panel and DOE program managers, depending on the scope of the request. If approved, the collaborator will be informed of any and all regulatory requirements, safety and site-access training, and communication expectations (e.g., quarterly reporting) as their research is integrated into the work flow of the NGEE Arctic project. It is hoped that by providing assistance, samples, and by implementing a mechanism whereby others can participate in NGEE Arctic research that we will create a value-added scientific resource not only for the project, but for our sponsor at the DOE BER and the larger scientific community.

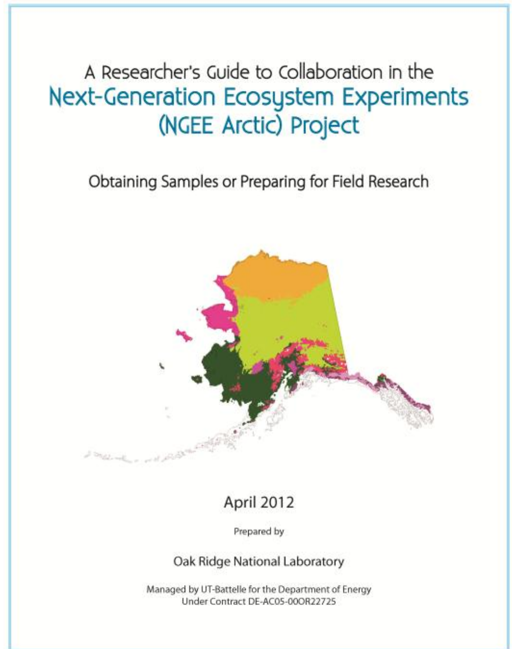


**Figure 16. NGEE Collaboration Handbook.**

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