Next-Generation Ecosystem Experiments (NGEE Arctic)

Scaling White Paper – Observations and Process Studies
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Using Process Studies and Observations to Guide, Parameterize, and Evaluate a Hierarchical Scaling Framework for NGEE Arctic

Peter Thornton, Cathy Wilson, Larry Hinzman, Susan Hubbard, David Graham, Liyuan Liang, Richard Norby, Bill Riley, Alistair Rogers, Joel Rowland, Margaret Torn, Stan Wullschleger and the NGEE Arctic Science Team

1. Introduction

We have previously described a scaling approach for NGEE Arctic that uses new process knowledge gained at the point, plot, and landscape scales and concentrates this new knowledge through a nested hierarchy of process representation and subgrid parameterization to arrive at improved predictions of Arctic ecosystem-climate interactions in a global-scale climate system model. The purpose of this companion paper is to provide specific details on how we will use process studies and observations to guide, parameterize, and evaluate the NGEE Arctic hierarchical scaling framework.

We find it useful to distinguish between several different types of process studies and observations, based on their intended application and the ways in which they inform the NGEE Arctic scaling approach. The architecture of the scaling framework is based on a multi-scale characterization of hydrologic basins, surface flow networks, and geomorphologically distinct topographic landscape features. This architecture facilitates the up-scale and down-scale migration of information and knowledge from all of the NGEE Arctic process study challenge areas: hydrology/geomorphology, biogeochemistry, and vegetation dynamics, and energy. Independent observations and process studies are required to evaluate model predictions at multiple scales, and to assess the effectiveness of the scaling architecture in reducing prediction uncertainties at the climate modeling scale.

Our scaling framework is structured by the delineation of drainage basins and surface flow network topology as subgrid components at the climate scale, with further delineation of geomorphologically distinct landscape units within basins as subgrid components of the intermediate scale, and explicitly resolved landscape elements at the finest scale. High-quality datasets of surface elevation and surface spectral characteristics serve as raw inputs to a processing stream that delivers basin and network delineation. Additional datasets of mean climate, climate variability, and vegetation patterns are combined with topographic information to provide quantitative assessments of representativeness, placing each grid cell and subgrid landscape unit in a broader spatial context that extends, with variable levels of fidelity, to the Alaskan Arctic and pan-Arctic domains.

The purpose of this quantitative scaling framework is to provide effective channels for the migration of new knowledge gained through process studies and observations to inform model representations of critical processes at multiple spatial scales, leading ultimately to improved prediction of Arctic ecosystem dynamics and interactions with climate at the global scale. We refer to this information in general as being used to parameterize the NGEE scaling framework. We distinguish between process studies and observations that lead to the development of new model algorithms and parameters within those algorithms, and studies and observations used to specify initial conditions or boundary conditions for simulations at a particular scale. All of the NGEE Arctic challenge areas will be engaged in this core science effort to deliver new knowledge regarding process representation and model initialization. Prioritization of particular process studies and observations will be driven initially by an articulation of cross-scale modeling requirements, tempered by a consideration for the practical constraints imposed by current measurement technologies. Sampling schemes will be optimized to maximize representativeness based on best available information at each spatial scale. Subsequent refinements to sampling strategy, measurement approaches, and model-data integration will be determined through an iterative process of model-data integration, tests of up-scaling and down-scaling approaches, and evaluation against independent observations.

Additional observations and process studies are required to perform independent evaluations of model components, to assess the effectiveness of cross-scale migration of process knowledge, and to test and refine the assumptions behind our metrics of representativeness. Evaluation studies will be carried out in tandem with process studies used to structure the scaling framework and to parameterize its component models. This approach allows us to modify the scaling framework and adopt new parameterizations during the process of model development, parameterization, and cross-scale coupling. Our evaluation approach will follow emerging best practices in uncertainty quantification, with the intent of delivering quantitative estimates of predictive skill which can be used to track modeling progress over time.

The following sections provide specifics related to process studies and observations for each of these main categories (scaling architecture, process representation, model initialization, and evaluation). Details are provided for each modeling scale, and for all core science areas. This document is not intended to be an exhaustive description of every process study and observational component of NGEE Arctic and how each component fits into the scaling framework. Instead, we have tried to include important examples from each area to show how the pieces work together to bring the NGEE Arctic scaling approach to life.

2. Observations and process studies to organize the hierarchical scaling framework

Our scaling approach depends on a conceptualization of subgrid variability in a climate model as structured by a nested hierarchy of drainage basins and landscape elements within these 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 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 must at the same time be 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 which are used to structure and quantify the NGEE Arctic scaling framework at the climate, intermediate, and fine scales.

2.a. Climate scale

Our treatment of the largest spatial scale in the NGEE 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 Phase 1, an operational land model resolution for a system such as the Community Earth System Model (CESM) will likely be on the order of 10 – 30 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 also by insisting that the datasets used to define subgrid variability at this largest scale be available globally.

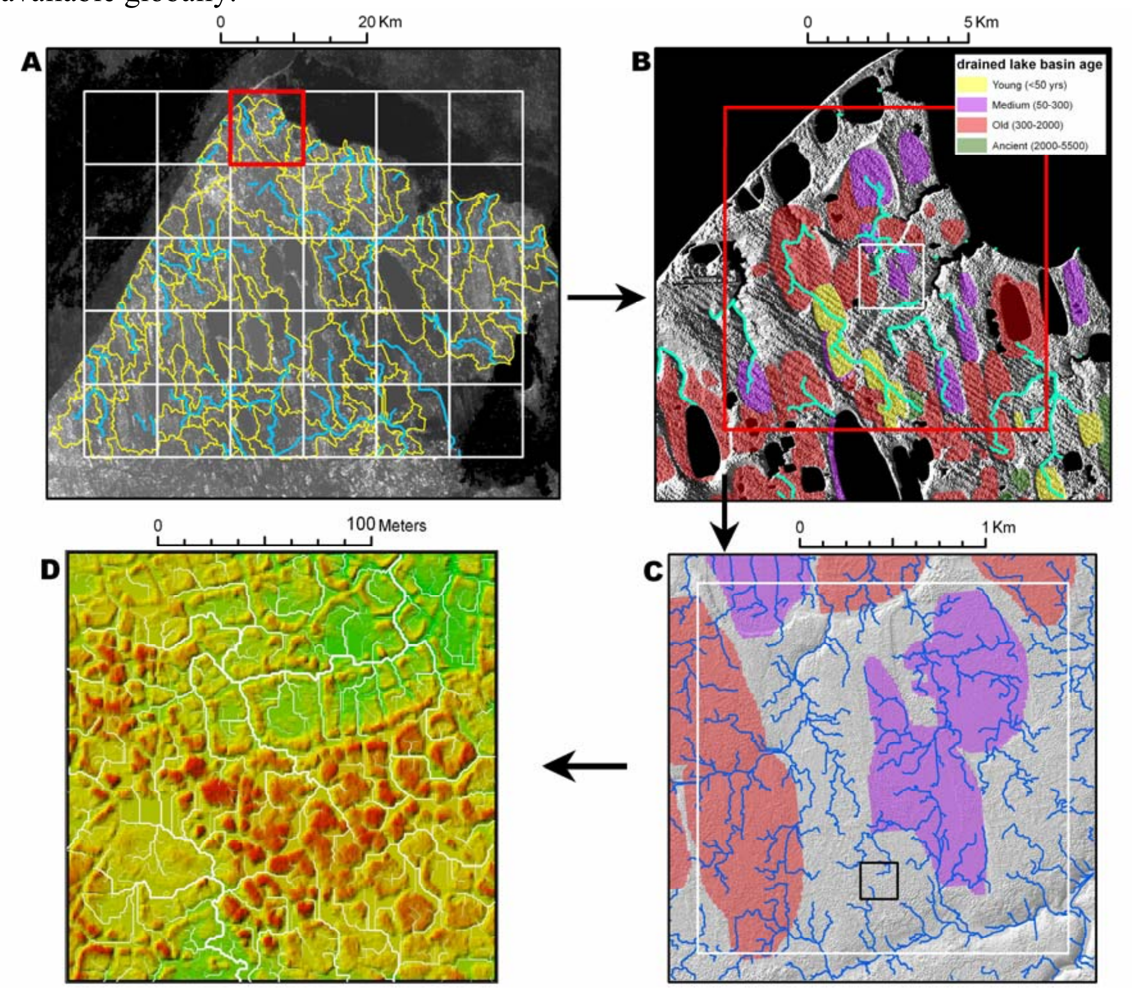

Figure 1. Scaling of hydrologic and geomorphic features as a function of data resolution available at the scale of: A) high-resolution Earth system model (ESM), B) a single ESM grid cell, C) a 2km x 2km domain of high resolution Light Detection and Ranging(LiDAR) topographic data (C. Tweedie) and D) polygonal ground (C. Tweedie, LiDAR). Additional details related to this figure are provided as an Appendix. Source: C. Wilson, G. Altmann, C. Gangodagamage, J. Rowland (LANL); B. Bolton (UAF).

We use the digital elevation model (dataset) derived from NASA's Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER DEM), available globally at 30m 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. For instance, a DEM product with ~10m resolution, generated by TerraSar-X radar satellites, is available by custom order from ASTRIUM (cost ~\$25K/500 km^2). By 2014, ASTRIUM will have a global DEM at this resolution available (presumably at a lower cost since it is not custom ordered). ASTRIUM also currently sells a 30 m DEM generated from SPOT imagery that covers a large fraction of the globe, including what appears to be the entire Arctic outside of ice bodies. 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 10km x 10km high-resolution climate model gridcells near Barrow, AK (Figure 1a).

Our earlier paper describing the NGEE scaling approach provides extensive detail on how these basins and drainage networks are used within the modeling framework to accomplish up-scaling and down-scaling. An important aspect of the approach with relevance to the integration of models, observations, and process studies is the estimation of representativeness, and we include some additional information on that component here. Our efforts over the duration of NGEE Arctic, and particularly during Phase 1, must be guided both by the overarching science goals of improved climate prediction as well as by the practical constraints of selecting sites for intensive process study and observation. What is required are objective measures of the existing and projected future diversity in physical and biological environments at multiple spatial scales, and also metrics to help relate process knowledge gained at a specific location to a broader regional context. A promising method for characterization of representativeness at the climate modeling scale uses multiple environmental input data layers and a clustering algorithm to generate discrete landscape units with uniform variance distributions. The same approach is also able to provide a continuously varying metric describing the representativeness of a particular location in a broader spatial context (Figure 2).

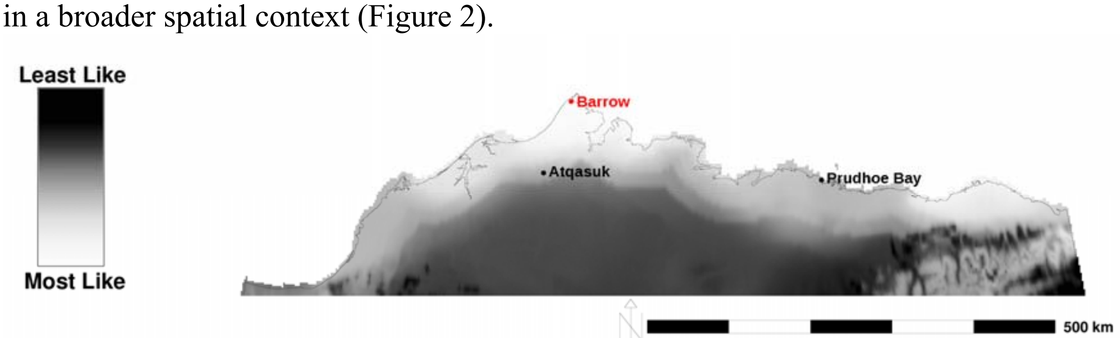

Figure 2. Expression of Barrow representativeness over the North slope of Alaska. Source: Forrest Hoffman, Jitendra Kumar, Richard Tran Mills; ORNL.

Because it engages the same environmental constraints imposed on the NGEE models, this approach provides direct, objective, and quantitative guidance to the process study and observational campaigns. It also provides a framework within which the scaled linkages between observations and models can be evaluated (see details in Section 5).

2.b. Intermediate scale

As mentioned in our first NGEE scaling paper, current understanding has guided us to implement an intermediate scale of simulation, with a domain size on the order of one to several climate-scale gridcells, 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. 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 thermoerosion along a lake margin, ice wedge erosion, the headward expansion of a drainage feature, bank overflow or coastal erosion. Drained thaw lake basins (DTLBs) are clearly recognizable features of the Arctic lowlands (Figure 1b). Once drained, the basins are subject to revegetation, organic matter accumulation, and ice wedge growth associated with permafrost aggradation in the unfrozen lake substrate. Polygonal ground develops over the time frame of decades to hundreds of years, and ponding in the resulting troughs may begin 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 1b). We also intend to use DTLBs of different ages as primary 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 subgrid 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 semi-automated 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.

It is important to note that while 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 drainage patterns. In order to derive accurate drainage 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 1c). 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 a minimum of 1m resolution for all intermediate-scale modeling domains. As NGEE 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.

2.c. Fine-scale

As stratified by DTLBs and interstitial tundra, we will select representative subsets for fine-scale process studies, observation, and modeling. The same LiDAR elevation datasets which 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 1d). 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 which we think structure landscape processes at these scales, such as polygon rims, troughs, high centers, and low centers.

3. Process studies and observations to improve model algorithms and to constrain algorithm parameterizations

While hydrologic basins and network topology at multiple scales provide the organizing framework for the NGEE Arctic scaling approach, we require well-orchestrated process studies and observations of hydrology, geomorphology, biogeochemistry, vegetation patterns, and energy exchange to populate this scaling architecture and achieve the broader goal of optimally informing process representations in a global-scale model with knowledge and understanding gained through direct observation and process resolving simulation at finer scales.

Here we provide details on the key process studies and observations within each of the NGEE Arctic challenge areas just mentioned, describing how these observations are organized at fine, intermediate, and climate-modeling scales, and how they interact with each other and with the scaling architecture to improve representation of Arctic tundra ecosystems and climate prediction in a process-rich model. To help make the discussion specific and clear, we focus this description on multi-scale research efforts in and around the Barrow Environmental Observatory (BEO), as representative of a broader Alaskan North slope region (Figure 2). The full NGEE Arctic proposal describes the process of site selection and staging of research effort over multiple years. This section provides details on observations and process studies used to develop or improve model algorithms and to constrain model algorithm parameterizations. Sections 4 and 5 describe observations used to initialize models, and to evaluate models and the scaling approach, respectively.

3.a. Hydrology and Geomorphology

The key goal of the Hydrology-Geomorphology challenge is to develop the process knowledge, model algorithms and data sets that will enable the prediction of Arctic tundra hydrological responses to climate driven permafrost degradation. 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 polygons and the troughs between polygons, and puddles between tussocks. These water storage elements control the spatial and temporal distribution of water on the landscape, the timing and magnitude of snowmelt runoff, the availability of water to plants and soil microbes through the growing season, and the latent and sensible heat fluxes from the land to the atmosphere. 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 in response to thermokarst have the potential to dramatically alter hydrologic storage and connectivity of the landscape. A central focus of this challenge is to advance process understanding and prediction of the hydrologic and thermal responses and feedbacks to thermokarst development in ice rich ground and how these climate driven changes will control the spatial and temporal availability of water for biogeochemical, ecologic and physical feedbacks to the climate system. 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 drained thaw lake basin age gradient (young to old) (Figure 3).

At the fine scale we focus on the interactions between thermal, hydrologic and soil mechanical processes and the development and improvement of process algorithms and constitutive relationships for process resolving models. 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 environmental conditions. Field-based co-located coupled process measurements (including isotopes and environmental tracers) will be undertaken at intensive research sites (Figure 3) to quantify mechanistic relationships and interactions between climate, snow pack, surface temperature, soil temperature, depth of thaw, soil moisture, water levels, inundation area, ice wedge dynamics, soil deformation and water flux. We will also apply benign geochemical tracers at a selected intensive site to gain a quantitative understanding of how flow path and storage element connectivity evolves seasonally within polygonal ground and to quantify the partitioning of lateral and vertical water and advected heat, carbon and nitrogen.

At the intermediate scale we aim to develop quantitative relationships between readily classified remote sensing features and physical, chemical and biological surface and subsurface properties and processes across the landscape. This entails coupled ground-based geophysical surveys, remote sensing campaigns and in-situ ground truth measurements along transects across DTLBs and polygonal ground gradients. A synoptic survey of surface and subsurface water chemistry and isotopic composition in lakes, ponds, polygons, troughs, streams and rivers will be undertaken to assess sources of water and the relative contribution of those sources to storage and lateral fluxes in the spring and late summer. These data, when coupled with plant surveys will also provide information on water use for different plant functional types. Both the geophysical and water chemistry survey efforts will enable quantification of heterogeneity and variance in the landscape and the extrapolation of process understanding gained at the fine scale to the grid cell scale.

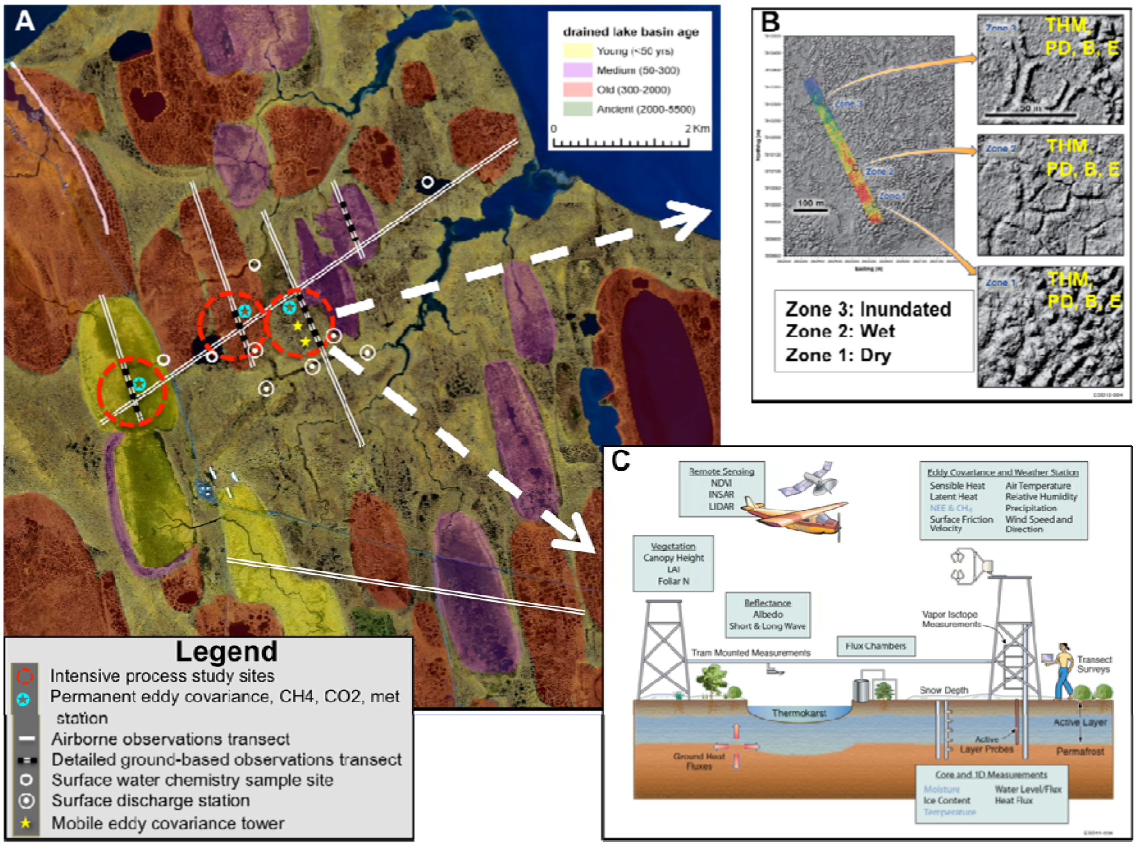

Figure 3. Hypothetical observational framework. A) WorldView-2 image showing possible locations of intensive process study sites for fine scale observations (red dashed circles) and transects across and within DTLBs of different ages at the BEO. B) Close-up of polygonal ground and a ground based geophysics survey along a high resolution transect (black dashed line in panel 3A) within an intensive process study site. Each intensive site is comprised of the range of permafrost features (eg. low, moderately low and high centered polygons) that control local hydrology. C) Coupled observations of temperature, hydrology, soil mechanics (THM), Plant Dynamics (PD), Biogeochemistry (B) and Energy (E) would be made across the range of permafrost features at the intensive sites. These measurements would coincide with positions on airborne survey transects, backed up by additional ground truth along those transects. Source: C. Wilson, G. Altmann, T. Rahn, J. Rowland (LANL); S Hubbard, M. Torn (LBNL).

At the climate-modeling scale we focus on developing analysis tools to extract and interpret information in remote sensing products that quantify relationships between Pan Arctic available topography (ASTER), hydrology (GRACE), land feature (LANDSAT) and snow cover (MODIS).

3.b. Biogeochemistry

An important objective under the biogeochemistry challenge area is to develop process representations and parameterizations which are applicable at multiple modeling scales. The biogeochemical dynamics of Arctic tundra ecosystems control climate system feedbacks through greenhouse gas emissions from buried organic matter. These processes are hypothesized to be sensitive to freeze-thaw dynamics and associated hydrologic variability in the landscape. Our approach is therefore to understand how microbial processes in tundra soils respond to thermal, hydrological, and chemical factors, with the assumption that these physical and chemical factors are represented appropriately at each modeling scale. This approach recognizes and facilitates potentially important interactions between microbial dynamics and physical setting, for example the influence of soil saturation state and pH on decomposition of various plant and microbially-derived substrates. The investigations of fundamental biogeochemical processes will be represented in greatest detail at the fine scale, 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 at the intermediate and climate scales.

Column-scale freeze-thaw experiments will produce a response function for soil organic matter (SOM) decomposition with respect to temperature, pH, and moisture near the critical soil freezing point. This response function will be incorporated directly into model decomposition algorithms for models at all spatial scales. Sampling will follow the subgrid structure of the scaling framework. Cores will be collected from DTLBs of various ages and from interstitial tundra areas. Sampling within these areas will focus on geomorphologically distinct features identified from fine-scale elevation and remote sensing data, organized around the previously described features of polygonal ground. Incubations of core samples (microcosms that provide point measurements) and soil/permafrost columns (mesocosms) will be performed to determine the SOM decomposition rates, affected by temperature, pH, electron acceptors, SOM structural properties, and in situ microbial enzymatic activities. Greenhouse gas flux measurements from microcosms, column mesocosms, and soil gas chambers at DTLB plots will be related to temperature, pH, and oxygen controls on respiration, methanogenesis, and methanotrophy to derive CO_2/CH_4 emission functions.

Our working hypothesis is the response functions derived from experimental investigations are consistent across multiple environments, providing appropriate constraints on organic matter input, and site-specific hydrologic, thermal, and chemical states of the subsurface. If so, we will use this consistent set of biogeochemistry response functions in the fine, intermediate, and climate-scale models. We will also represent these forcings to the biogeochemistry system in each of the physical settings represented, either explicitly or in subgrid statistical form, at each modeling scale.

At the intermediate spatial scale, 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 order of 100 m x 50 m. These measurements will be used to derive landscape-scale functions of the entire ecosystem response to light, water, and temperature. These functions will be used, through the up-scaling approach described in our initial whitepaper, to derive scale-dependent parameters in the intermediate and climate-scale models. This approach avoids the errors associated with linear scaling assumptions currently employed in state-of-the-art climate prediction models. With appropriate care to maintain independence between parameterization and evaluation datasets, these observations are also useful for testing model predictions, as described below.

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 scientists are in discussion with the CARVE PI (C. Miller) to share data since the NGEE surface eddy flux data will be very useful for CARVE and the CARVE transects will provide a statistical sampling for testing NGEE models at the climate scale. CARVE has expressed willingness to consider adding flights cover the NGEE transect from Barrow to Council in future years if NGEE builds out the transect.

3.c. Vegetation Dynamics

In common with our research efforts under the biogeochemistry challenge area, process studies and observations on vegetation dynamics will mostly be focused on fine scales, with sampling structured to represent variance associated with the hydrologic basin, DTLB, and polygonal ground components of the scaling architecture. Our working hypothesis is that vegetation dynamics can be represented primarily as functions of hydrologic and thermal setting, with important secondary contributions from the long-term interactions of vegetation and heterotrophic communities resulting in varying degrees of soil organic matter accumulation and nutrient availability over time. We expect this secondary variability to be structured in part by the time since last long-term inundation, as captured by DTLB age classes in our scaling architecture.

Land surface albedo is a critical determinant of ecosystem-climate interactions. The details of vegetation type and fractional cover are especially important to estimates of land surface albedo in regions with relatively low vegetation cover, with significant contributions to albedo from plants and bare ground. Albedo in regions impacted by snow cover is also especially sensitive to the distribution, stature, and reflectance properties of vegetation. A process-based understanding of vegetation dynamics in Arctic tundra is therefore crucial to accurate predictions of land surface albedo at any spatial scale. Additional interactions of vegetation distribution with hydrologic, thermal, and chemical setting leads to a complex expression of land surface albedo at various spatial scales. To characterize these relationships and provide model parameterizations suitable at multiple scales, observations will be conducted across DTLB and polygonal ground gradients to determine the contributions of individual plant functional types (PFTs) to plot-scale albedo, using handheld and track-based scanning radiometers.

In addition to the controls on land surface albedo, understanding of vegetation dynamics is also critical to estimation of net primary production and the associated production of plant material that enters the broader biogeochemical cycling as litter inputs. Observations will be made to determine the parameters of photosynthetic biochemistry and leaf physiology that are key model inputs and that facilitate up-scaling to the landscape level. Examples include specific leaf mass, leaf area index, maximum carboxylation rate, tissue nitrogen concentration, and the fraction of leaf N invested in Rubisco for a range of tundra plant species across different PFTs. Measurements will be made under Arctic summer conditions across the gradients created by high-centered and low-centered polygons and other thermokarst features.

Process studies will be conducted to develop response functions relating plant community composition (fractional cover) and phenology to resource gradients created by high-centered and low-centered polygons and other thermokarst features. Additional process studies will be used to parameterize a plant physiological model of C-N interactions, including measurements of active-layer N availability, litter feedbacks to soil C-N cycling, and plant use of available N (seasonal dynamics of N uptake, root distribution, N fixation). The goal here is to develop a new set of PFTs based on N acquisition and allocation, rather than or in addition to the current approach based on plant morphology or leaf habit, which will enable multi-scale predictions of changes in plant community composition as permafrost degrades in a warming climate.

Vegetation-snow dynamics will play an important role in model predictions at fine, intermediate, and climate-modeling scales. Experimental manipulations to quantify the interactions of plant communities with snow depth and duration, and the associated influence on land surface albedo, are important to inform our understanding of multi-scale ecosystem climate feedbacks, but we do not foresee undertaking new manipulations of this sort in NGEE Arctic, at least during Phase 1. We intend to perform a literature survey and synthesis of previous work on this topic, and to develop model parameterizations on that basis. Similarly, we will compile and synthesize previous work relating the response of plant community composition to large-scale mean climate and climate variability.

3.d. Surface Energy Balance

Observations to close the surface energy budget are an important component of our efforts to improve process representation and model parameterization at multiple spatial scales. We will measure upwelling and downwelling short-wave and long-wave radiation with tram-mounted and handheld sensors across the gradients of DTLB age, and over variation in polygonal ground types. These observations will be made to supplement process studies of the effect of fractional inundated area and vegetation community composition on albedo and surface energy balance. Observations of photosynthetically active radiation (PAR) will be used in studies of plant CO_2 exchange. Net ground heat flux is difficult to measure, because heat flux plates do not perform very well, so NGEE will use temperature gradients and other geophysical measurements combined with fine-scale, tuned models of the site.

Eddy covariance systems will be used to measure sensible and latent heat flux, as well as CO_2 and CH_4 flux during the growing season. As described in the biogeochemistry section, these observations contribute to studies of plant water use efficiency and evaluating the linearity of processes. The energy components of these measurements will be used to improve model parameterizations related to fractional inundated area expressed at intermediate and climate-modeling scales.

4. Process studies and observations to initialize models

A critical point of connection between observations and the model-centric NGEE scaling approach is the use of innovative field methods to define the boundary conditions for model realizations at all three spatial scales. We refer here to state and flux variables imposed on the spatial boundaries of the modeling domain at each modeling scale, as well as initial states imposed within the modeling domain at the simulation start time. Surface geopotential height (elevation) is a critical state which is considered here as an initial condition to generate the scaling architecture, and has already been described in detail (Section 2). Other states of interest here include vertical distributions of temperature, concentrations of water and ice, and soil organic matter. Essential boundary fluxes include hydrologic inflow from regions outside the modeling domain, associated dissolved content, and water, energy, momentum, and trace gas exchanges between the land surface and the near-surface atmosphere. Model requirements and available data sources for boundary condition and initialization vary by spatial scale, as summarized below, and in Figure 4.

At the fine scale, we will use ground-based geophysical surveys to quantify thaw depth, snow cover, ice content, soil moisture, and soil properties across nested polygonal ground gradients within young to old drained lake basins. Measurement of soil and ice properties from cores extracted along geophysical transects will be used to interpret these geophysical observations. Vertical distribution of carbon and nitrogen compounds in soil organic mater will be derived from analysis of soil and permafrost cores at intensively characterized field sites. Plant community composition, including fractional cover of important species and PFTs, will be measured at the plot scale in relation to geomorphic units.

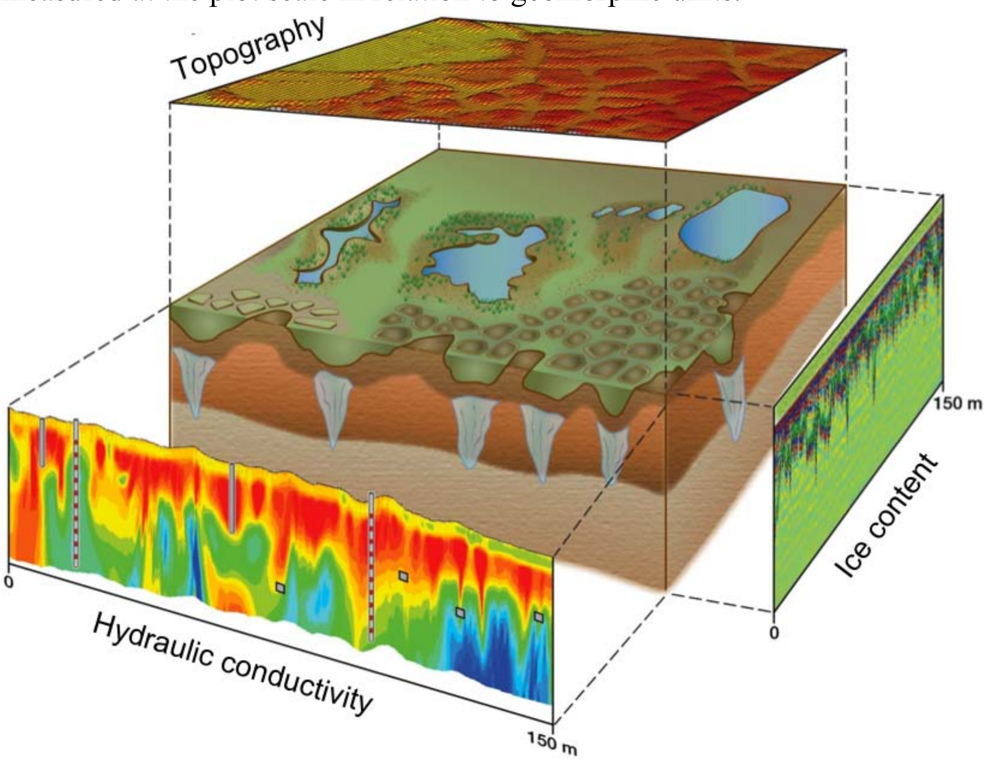

Figure 4. Conceptual diagram showing use of point measurements, ground surveys and airborne topographic data to initialize process resolving models. Source: S. Hubbard (LBNL).

At the intermediate scale, we will use remote sensing information to specify the locations of lakes and ponds, and their associated albedos. Vegetation community sampling performed at the fine scale will be used as ground reference to derive vegetation cover maps from remote sensing information at the intermediate scale. A wealth of *in situ* meteorological, thermal, and hydrologic data exists across the BEO, and we will perform a synthesis of the available observations. These will be supplemented as needed with NGEE-specific observations of hydrologic flow, thermal state, and near-surface weather forcing.

At the climate-modeling scale, additional remote sensing observations will be used to estimate fractional area of lakes and ponds, and associated albedos. Fractional area of PFTs will also be derived from remote sensing inputs, scaled as for the intermediate case from plot-scale measurements and association with geomorphological units. We expect to achieve an improved representation of vegetation type distributions at the climate scale by adopting Arctic PFT definitions proposed by Arctic research community since this typology presents a strong association with geomorphological variation, unlike the current PFT structure of the Community Land Model. During NGEE Phase 1 we will perform a synthesis of existing geomorphologic and hydrologic data for Alaska, and identify high-priority areas or variables for further observations.

5. Process studies and observations to evaluate model predictions and generate uncertainty estimates

A fundamental objective for NGEE Arctic is to demonstrate improvement in Arctic ecosystem process representation and associated improvements in climate prediction. Accomplishing that objective requires a diverse array of independent observations, not used to parameterize or initialize models, which may be used to evaluate model predictions of multiple states and processes at multiple scales, and which can also be used to evaluate the effectiveness of the scaling approach itself. Here we provide some representative examples of the independent data streams and the evaluation methods and metrics that will be employed to assess prediction skill of individual processes at individual scales. We also provide a detailed discussion of how independent observations and process studies will be used to evaluate the up-scaling and down-scaling components of the scaling approach.

At the fine scale, we will make *in situ* measurements of thaw depth, snow cover, soil moisture, soil temperature and inundation seasonal dynamics at intensive process study sites and along transects, for use in evaluating fine-scale model predictions of these same quantities. We will make periodic measurements of carbon flux (CO_2 and CH_4) at the plot scale (several square meters) in temporary gas-exchange chambers deployed across the thermokarst gradients, to evaluate short-term model predictions of net carbon exchange for a given mix of PFTs. Model predictions of vertically-resolved biogeochemical dynamics will be evaluated against observed vertical distributions of carbon and nitrogen compounds in soil organic matter, from analysis of soil and permafrost cores at intensively characterized field sites. 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. These evaluations of model time series predictions will be made against independent gradient measurements, assuming a space-for-time equivalence.

At the intermediate scale we will implement a nested surface runoff monitoring network to evaluate predictions of hydrologic flow and connectivity. This 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. Predicted seasonal hydrology dynamics will be evaluated in part through measured early and late summer fractional inundation area for 10 km x 10 km regions using remote sensing products and field ground truth along transects. 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. We will use airborne imaging spectroscopy coupled to predictive relationships between leaf and canopy optical properties and the N concentration and photosynthetic capacity of different PFTs and plant communities, established through ground-based spectroscopy, to determine landscape-scale leaf area index and canopy N concentration. These observation-based estimates will be used to evaluate model predictions of the same quantities. Emergent relationships between leaf area index and canopy N concentration might also provide an independent evaluation of model predictions of landscape-scale GPP.

Evaluation opportunities at the climate modeling scale are fewer and suffer from the practical challenges of making robust observations at large spatial scales. 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 compare to model representations of this process. Albedo measurements present a particularly 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, and variation in percent reflectance with zenith angle.

As described in our first whitepaper, the NGEE scaling approach uses an iterative process of up-scaling and down-scaling to arrive at optimal estimates of model parameterizations and boundary conditions at multiple scales. An underlying assumption is that process studies and observations carried out at a particular scale provide the most direct benefit, in terms of improved prediction skill, at that scale, while some benefit from a particular set of observations is also obtained at coarser scales, through up-scaling, and at finer scales, through down-scaling. We will evaluate this underlying assumption through two separate approaches. First, we will use independent short-term intensive measurement campaigns to evaluate the metrics of representativeness which form an important part of the NGEE scaling framework. Second, we will use independent observations at multiple scales, where such exist, to perform explicit tests of the scaling approach as it impacts specific model-predicted states and fluxes.

In the first case, we will evaluate our representativeness metrics by identifying sites outside of our primary intermediate and fine scale study regions which show strong similarity to primary sites as measured, for example, by Barrow-ness (Figure 2), DTLB age (Figure 1b), and fine-scale geomorphic characterization (Figure 1d). Preliminary analysis suggests that such sites are readily accessible by short helicopter flight or snow machine trip departing, for example, from Barrow. We would deploy to these sites with a subset of our measurement capabilities, and make short-term (one to several days) intensive measurements of model-predicted processes and states. Examples include ground-based geophysical surveys of thaw depth, thermal gradients, and water and ice content, as well as core samples to characterize carbon and nitrogen compounds in soil organic matter with depth in the active layer. We would also make rapid surveys of plant community composition and sample for leaf-level chemistry and physiology. We envision deploying mobile eddy flux measurement systems as part of these remote evaluations of representativeness. All these measurements would be compared against expected values based on stratified sampling in the primary study regions. By comparing these short-term observations with model predictions from these secondary sites, we would begin to form a quantitative basis for estimation of the component of prediction uncertainty which results from inadequate model initialization, and also from errors inherent in the representativeness metrics.

To perform a more direct evaluation of the integrated effectiveness of our scaling approach, we will obtain independent observations of a few key process variables at each spatial scale in the nested scaling hierarchy, and compare these observations first with initial model predictions at each scale, prior to model scaling, and later with the optimized predictions at each scale emerging from the iterative up-scaling and down-scaling approach. A metric of effectiveness for our scaling approach will be the degree to which prediction skill at each scale is improved as the result of iterative scaling. One application of this evaluation method will focus on multi-scale albedo, since direct observations of albedo are available at all three spatial scales: from hand-held and track-mounted radiometers, and from high resolution and moderate resolution remote sensing products. We will also make use of the nested nature of watersheds and hydrologic outflow monitoring in our study regions to evaluate scaling effectiveness in improving predicted runoff generation.

Appendix

Additional detail related to Figure 1:
Panel A shows a 60km by 50km domain overlain by a 10km by 10km high resolution ESM grid. Sub-grid scale hydrologic watersheds (yellow lines) and streams/rivers (blue lines) were generated from the global ASTER topographic data set (grey-scale layer under derived hydrologic information) supplemented with IFSAR data in ARC Map using a drainage area threshold value of $10km^2$. The red grid cell covers the Barrow Peninsula and the Barrow Environmental Observatory (BEO) highlighted in panel B. Panel B shows a drainage network (green) derived from 5m resolution IFSAR topographic data using a drainage area threshold of $1km^2$. The hydrologic data is overlain on a grey hillshade of the IFSAR derived topography. Also shown is Hinkel's (pers. comm.) DTLB age classification map. The white square in panel B maps to panel C. The use of 0.25m resolution LiDAR topographic data in panels C and D enables the generation of very high resolution drainage networks and basins. In Panel C we used a drainage area threshold of $0.1km^2$ to generate the drainage network shown in blue, which is overlain on a hillshade of the LiDAR topography. At this scale we see the emergence of the relationship between DTLBs and a complex drainage network that is both constrained within the topography of the DTLB old shorelines and cuts across to drain the basins in multiple places. Panel D shows how polygonal ground further defines the fine scale structure of surface drainage paths as well as the degree of connectivity between low centered polygons, troughs and the rest of the drainage network. The white hydrologic drainage network shown in panel D was generated using Rivertools software and is underlain by a color hillshade of local elevation (red values area ~ 1-2m higher than green values).