Next-Generation Ecosystem Experiments

NGEE Arctic

Participation in the December 3-7, 2012 American Geophysical Union (AGU) Meeting in San Francisco, CA

Organized Oral Sessions

Poster and Presentation Abstracts

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Sessions Organized by Participants in the NGEE Arctic Project for the 2012 American Geophysical Union (AGU) Meetings

1. The Arctic System: From Critical Process Studies to Global Perspectives

Co-conveners: W. Maslowski (Naval Postgraduate School), K. Dethloff (Alfred Wegener Institute), L.D. Hinzman (University of Alaska Fairbanks), and A. Roberts (Naval Postgraduate School)

Description: The Arctic is a key player of the Earth System, influencing the global surface energy and moisture budget, atmospheric and oceanic circulation and feedbacks. It has experienced major climate changes such as declining cryosphere, warmer climate and ecosystem shifts. Large variability and sensitivity of Arctic climate to global change make their attribution difficult. Yet, such changes may significantly impact global sea level, future climate change, native communities, natural resource exploration, transportation and international diplomacy. We solicit papers that advance a system level understanding of arctic processes and feedbacks and their global links that are contributing to or resulting from Arctic System change.

2. Representing Plot- to Landscape-scale Heterogeneity for Arctic Terrestrial Modeling

Co-conveners: F.M. Hoffman (ORNL) and J.C. Rowland (LANL)

Description: A critical challenge facing efforts to understand coupled earth system responses to climate change is the representation and incorporation landscape attributes and processes in models at all scales and complexity. Financial and logistical constraints limit the spatial and temporal extents of environmental observations in the Arctic, necessitating systematic sampling strategies and quantitative frameworks for scaling measurements and model parameters from plot to landscape scales. This session focuses on biogeophysical observations, analysis, and modeling of Arctic ecosystems from the bedrock to the canopy across all spatial and temporal scales, including characterization of subsurface properties and geomorphological processes, remote sensing of permafrost, and modeling of plant and soil ecosystems in a changing climate. Of particular interest are methods for representing observed heterogeneity at larger scales.

3. Geophysical Characterization of Permafrost Systems

Co-conveners: S. S. Hubbard (LBNL) and B. J. Minsley (USGS)

Description: The complexity of permafrost dynamics and its critical impact on climate feedbacks warrant continued development of advanced characterization and monitoring approaches. Geophysical methods can provide information about subsurface physical, hydrological, thermal and geochemical variations needed to understand these feedbacks in a non-invasive manner and with a spatial coverage and data density that cannot be achieved using point measurements. This session seeks novel examples that use geophysical data to characterize and monitor permafrost systems through integrated inversion of multiple types of data at various scales, and that investigate physical property relationships between geophysical and permafrost-related properties of interest.

4. Permafrost Microbiology

Co-conveners: J.K. Jansson (LBNL) and M.S. Torn (LBNL)

Description: Permafrost represents one of the largest carbon (C) reservoirs on our planet. Permafrost thaw due to global warming would enhance microbial decomposition of organic matter trapped in permafrost, resulting in release of large quantities of carbon dioxide and methane into the atmosphere. Predicting the future of C emissions from thawing permafrost is critical to understand for climate models. However, the microbial identities and their functional roles in permafrost and their response to thaw are largely unknown. Therefore, there is an urgent need to apply advanced, state-of-the-art molecular tools to determine the functional roles of microbes in permafrost. This session aims to present current information obtained using molecular approaches about the role of microbes in processing of organic carbon trapped in permafrost as it thaws and impacts of thaw on biogeochemical processes.

Abstracts Submitted by Participants in the NGEE Arctic Project for the 2012 American Geophysical Union (AGU) Meetings

Simulating Soil Warming on a Permafrost Ecosystem in Fairbanks, Alaska

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In order to understand how increased soil temperatures, due to climate change, will affect arctic ecosystems, it is necessary to have a way to control temperatures within the environment to be studied. A soil warming prototype was developed, installed, and tested, to simulate increased soil temperature scenarios, using an automatically controlled heater array.

The prototype is installed at the U.S. Army, Cold Regions Research and Engineering Laboratory, Permafrost Experiment Station, in Fairbanks, Alaska. A plot area of 30 m-by-30 m was chosen in a spruce, birch, and willow stand. Trees were cleared, with care taken to minimize disturbance to the understory. The soil consists of ice-rich permafrost, generally present to a depth of 60m, with an active layer that varies from 55 to 85 cm. Soils consist of tan and grey silt with permafrost moisture contents ranging from 26 to 41 percent by mass, which is a relatively low moisture content for permafrost.

The warming system consists of a hexagonal array of 127 vertically-installed heating elements arranged in a 25-by-29 m area. Heaters are spaced at a distance of 2.4 m apart, and at a depth of 4 m, with the effective heating depth at the bottom 0.6 m. Three heat zones within the array can be adjusted to a set-point above the current ambient ground temperature. Using integrated feedback loops, the system is able to monitor real time temperature data and automatically adjust the output of 6 separate heater circuits to maintain the desired set-point. Over temperature protection is included to cut power to a zone in the event that the zone temperature overshoots the desired set-point by a specified amount. Temperature monitoring stations are strategically placed throughout the plot area to collect temperature data at different depths. By compiling the temperature data, a three dimensional thermal picture of the area can be created. Power usage data is collected for each heater circuit so that performance can be monitored.

Scenarios of 2, 4, 6, and 8 degree Celsius set-points above ambient soil temperatures have been successfully tested and collected data shows that temperatures can be tightly controlled. Results show that this system provides a promising means to simulate a soil warming scenario, and sets the stage for larger test plots to be installed in the future. The system will be useful in future studies such as comparing computer models, analyzing the effects on organisms within the environment, and ice transitions within the permafrost.

Scaling of Hydrologic Flows Due to Polygonal Ground Features in Arctic Ecosystems

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Arctic and sub-Arctic soils currently contain approximately 1700 billion metric tones of frozen organic carbon, approximately 200 times current annual anthropogenic. This carbon is vulnerable to release to the atmosphere as CO_2 and CH_4 as high-latitude temperatures warm. Polygonal ground, with a characteristic length scale of ~15 m, is a common landscape type that occurs over large parts of Arctic tundra. These ground structures, with high or low centers, dominate the local hydrologic environment, thereby impacting the energy balance, biogeochemical dynamics, vegetation communities, and carbon releases from the subsurface. A recent simulation study by Liljedahl et al. (2012) has shown the importance of low- and high-centered microtropgraphic features on Arctic basin water balance.

In spite of their importance to local hydrologic processes, the impact of these microtopographic features at larger spatial scales is not well understood. In this study, we perform coupled surface-subsurface simulations for synthetic polygonal domains using PFLOTRAN, a parallel, multi-phase, multi-component reactive flow and transport model. Additionally, results from simulations at various model resolutions for the synthetic domains to investigate the effect of spatial scale on simulated infiltration and lateral flow quantities are presented.

Developing a High-latitude Soil Carbon Cycle Model with a Focus on Trait-based Representation of Decomposition

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Global climate change is projected to have a significant impact on high-latitude ecosystems by altering the stability and distribution of annual permafrost and deepening the active layer. High-latitude permafrost soils store large quantities of organic matter, and climate change may lead to increases in organic matter decomposition and the production of carbon dioxide (CO_2). The magnitude of CO_2 flux depends largely on a complex suite of mechanisms primarily regulated by C-cycling microorganisms. In the present study we are developing a mechanistic ecological model by synthesizing multiple microbial traits to reconstruct a representation of the heterotrophic microbial community. The model develops a dynamic energy budget that is scaled against the availability and identity of electron donors and acceptors and represented by an ATP pool. This energy budget contributes to regulating macromolecular synthesis, including exoenzyme production, cell growth, and division. Traits encoded by a hypothetical 'genome' that are specific to individual guilds include growth rate, carbon use efficiency (CUE), and the possession of between 2 and 11 distinct monomer transporters linked to the presence of exoenzymes within the 'genome'. These traits determine the emergence of microbial communities under initial environmental conditions and also community dynamics as conditions change over time. The model prognoses decomposition rates, carbon pool transformations, and CO_2 production. The system ecology was initially studied using a chemostat approach with one or multiple polymeric substrates. Emergence of the heterotrophic community was dependent on the presence of different polymers and trade-offs between physiological traits (e.g., possession of different exoenzymes or growth rate) and the cellular energy budget. Using this approach we examine the dynamics of the heterotrophic community and identify conditions under which copiotrophic and oligotrophic communities dominate. Competition between these groups resulted in differences in decomposition and CO_2 production rates on spatial and temporal scales as CUE changed. We also discuss model predictions under anticipated future climate change scenarios (e.g., increased N-deposition, temperature, and permafrost thaw) to evaluate the role climate driven microbial dynamics might play in future greenhouse gas production.

Parameterization of an Active Thermal Erosion Site, Caribou Creek, Alaska

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Thermokarst features are thought to be an important mechanism for landscape change in permafrost-dominated cold regions, but few such features have been incorporated into full featured landscape models. The root of this shortcoming is that historic observations are not detailed enough to parameterize a model, and the models typically do not include the relevant processes for thermal erosion. A new, dynamic thermokarst feature has been identified at the Caribou-Poker Creek Research Watershed (CPCRW) in the boreal forest of Interior Alaska. Located adjacent to a traditional use trail, this feature terminates directly in Caribou Creek. Erosion within the feature is driven predominantly by fluvial interflow. CPCRW is a Long-Term Ecological Research site underlain by varying degrees of relatively warm, discontinuous permafrost. This poster will describe the suite of measurements that have been undertaken to parameterize the ERODE model for this site, including thorough surveys, time lapse- and aerial photography, and 3-D structure from motion algorithms.

Ecohydrology of Interior Alaska Boreal Forest Systems

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The ecohydrology of boreal forest ecosystems of Interior Alaska is not well understood largely because of challenges posed by the presence of discontinuous permafrost. Near-surface permafrost results in storage-dominated systems with cold, poorly drained soils, and slow growing, low statured coniferous trees (*Picea mariana*) or CDE's. The transition to permafrost-free areas can occur over a few meters and is accompanied by a vegetation community dominated by large deciduous trees (*Populus* sp. and *Betula* sp.) or DDE's. Typically, areas with permafrost are on north facing slopes and valley bottoms, and areas without permafrost are south facing. In Alaska's boreal forest, the permafrost is very warm and vulnerable to the effects of climate change. Once permafrost begins to thaw, the vegetation community shifts from coniferous to deciduous dominated. Streamflow in watersheds with a larger permafrost distribution tends to be higher and more responsive to precipitation events than in watersheds with low permafrost distribution. In fact, precipitation events in the low permafrost areas do not infiltrate past the rooting zone of the deciduous trees (~5-40 cm). This suggests that the deciduous trees may remove water from the system via uptake and transpiration.

We focus on how vegetation water use affects boreal forest hydrology in areas of discontinuous permafrost. Specifically, we ask: what are the patterns of vegetation water use in areas with and without permafrost? This study focuses on the CDE and DDE systems. Our research sites are established on low and high locations on each aspect (south facing DDE, north facing CDE) to capture the variability associated with the different hillside drainage properties. At each of the four sites during the growing season, we measured various aspects of plant water use dynamics, including water flux, water content, water sources, depth of water uptake in the soil, and water stress. We use a Bayesian framework to analyze the data. We found that, compared to the coniferous trees, the deciduous trees have higher transpiration rates, lower water stress, higher water content, and use rain-derived water during the summer and snowmelt water prior to leaf out. The amount of water taken up and fluxed by deciduous trees is greater at the high site than the low site. The very low water use rates of the coniferous trees suggests that they play a very small role in the boreal water cycle, resulting in more water remaining in the watershed, which eventually moves into the stream. Conversely, the very high water use of the deciduous trees suggests they have a big effect on the boreal water cycle because they remove water from the system and transpire it to the atmosphere. This suggests that if the climate warms as expected, there may be a profound shift in the boreal forest ecohydrology. This transpiration model will be integrated with a storage-based hydrologic model to better understand the relationships between vegetation, permafrost, water and climate in the boreal forest ecosystem.

Imaging Active Layer and Permafrost Variability in the Arctic using Electromagnetic Induction Data

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Characterizing the spatial variability of active layer and permafrost properties is critical for gaining an understanding of Arctic ecosystem functioning and for parameterizing process-rich models that simulate feedbacks to a changing climate. Due to the sensitivity of electrical conductivity measurements to moisture content, salinity and freeze state in the active layer and permafrost and the ease of collecting electromagnetic induction (EMI) data with portable tools over large regions, EMI holds great potential for characterization of permafrost systems. However, inversion of such EMI data to estimate the subsurface electrical conductivity distribution is challenging. The challenges are due to the insufficient amount of information (even when using multiple configurations that vary coil spacing, orientation and elevation and signal frequency) needed to find a unique solution. The non-uniqueness problem is typically approached by invoking prior information, such as inversion constraints and initial models. Unfortunately, such prior information can significantly influence the obtained inversion result.

We describe the development and implementation of a new grid search based method for estimating electrical conductivity from EMI data that evaluates the influence of priors and the information contained in such data. The new method can be applied to investigate two or three layer 1-D models reproducing the recorded data within a specified range of uncertainty at each measurement location over a large surveyed site. Importantly, the method can quickly evaluate multiple priors and data from numerous measurement locations, since the time-consuming simulation of the EMI signals from the multi-dimension search grid needs to be performed only once.

We applied the developed approach to EMI data acquired in Barrow, AK at the Next-Generation Ecosystem Experiments (NGEE Arctic) study site on the Barrow Environmental Observatory. Our specific focus was on a 475-meter linear transect that spanned a range of low- to high-centered polygons. Comparison with collocated point measurements (including deep core), electrical resistivity tomography data, and information from ground penetrating radar data demonstrates that the inverted EMI data permits reliable estimation of electrical conductivity variations in the active layer and permafrost. In particular, we find that electrical conductivity in the active layer correlate to variations in moisture content, whereas deeper imaging responds to the distribution of ice wedges, massive ice and regions of higher salinity. The developed approach represents a significant advance in parameter estimation methods to explore electrical conductivity models that reproduce EMI data and to evaluate the need for and influence of priors.

Mapping Deep Low Velocity Zones in Alaskan Arctic Coastal Permafrost using Seismic Surface Waves

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Permafrost degradation may be an important amplifier of climate change; Thawing of near-surface sediments holds the potential of increasing greenhouse gas emissions due to microbial decomposition of preserved organic carbon. Recently, the characterization of “deep” carbon pools (several meters below the surface) in circumpolar frozen ground has increased the estimated amount of soil carbon to three times higher than what was previously thought. It is therefore potentially important to include the characteristics and processes of deeper permafrost strata (on the orders of a few to tens of meters below surface) in climate models for improving future predictions of accessible carbon and climate feedbacks. This extension is particularly relevant if deeper formations are not completely frozen and may harbor on-going microbial activity despite sub-zero temperatures. Unfortunately, the characterization of deep permafrost systems is non-trivial; logistics and drilling constraints often limit direct characterization to relatively shallow units. Geophysical measurements, either surface or airborne, are often the most effective tools for evaluating these regions. Of the available geophysical techniques, the analysis of seismic surface waves (e.g. MASW) has several unique advantages, mainly the ability to provide field-scale information with good depth resolution as well as penetration (10s to 100s of m with small portable sources). Surface wave methods are also able to resolve low velocity regions, a class of features that is difficult to characterize using traditional P-wave refraction methods.

As part of the Department of Energy (DOE) Next-Generation Ecosystem Experiments (NGEE-Arctic) project, we conducted a three-day seismic field survey (May 12 - 14, 2012) at the Barrow Environmental Observatory, which is located within the Alaskan Arctic Coastal Plain. Even though permafrost at the study site is continuous, ice-rich and thick (>= 350m), our Multichannel Analysis of Surface Waves (MASW) suggests the existence of pronounced low shear wave velocity zones that span the depth range of 2 - 30 meters; this zone has shear velocity values comparable to partially thawed soils. Such features coincide with previous findings of very low electrical resistivity structure (as low as ~10 Ohm*m at some locations) from measurements obtained in the first NGEE-Arctic geophysical field campaign (conducted in the week of September 24 - October 1, 2011). These low shear velocity zones are likely representative of regions with high unfrozen water content and thus have important implications on the rate of microbial activity and the vulnerability of deep permafrost carbon pools.

Analysis of this dataset required development of a novel inversion approach based on waveform inversion. The existence of multiple closely spaced Rayleigh wave modes made traditional inversion based on mode picking virtually impossible; As a result, we selected a direct misfit evaluation based on comparing dispersion images in the phase velocity/frequency domain. The misfit function was optimized using a global search algorithm, in this case Huyer and Neumaier's Multi Coordinate Search algorithm (MCS). This combination of MCS and waveform misfit allowed recovery of the low velocity region despite the existence of closely spaced modes.

Modeling Leaf Phenology Variation by Groupings of Species Within and Across Ecosystems in Northern Alaska

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The phenology of arctic ecosystems is driven primarily by abiotic forces, with temperature acting as the main determinant of growing season onset and leaf budburst and in the spring. However, while the plant species in arctic ecosystems require differing amounts of accumulated heat for leaf-out, dynamic vegetation models simulated over a regional to global scale typically assume some average leaf-out for all of the species within an ecosystem. Here, we make use of air temperature records and observational data of spring leaf phenology collected across dominant groupings of species (dwarf birch shrubs, willow shrubs, other deciduous shrubs, grasses, sedges, and forbs) in arctic and ecotonal boreal ecosystems in Alaska. We then parameterize a dynamic vegetation model based on these data for four types of tundra ecosystems (heath tundra, shrub tundra, wet sedge tundra, and tussock tundra), as well as ecotonal boreal white spruce forest. This implementation improves the timing of the onset of carbon uptake in the spring, permitting a more accurate assessment of the contribution of each grouping of species to ecosystem performance. Furthermore, this implementation provides a more nuanced perspective on light competition among species and across ecosystems. For example, in the shrub tundra, the sedges and grasses leaf-out before the shade-inducing willow and dwarf birch, thereby providing the sedges and grasses time to accumulate biomass before shading effects arise. Also in the shrub tundra, the forbs leaf-out last, and are therefore, more prone to shading impacts by the taller willow and dwarf birch shrubs. However, in the wet sedge and heath tundra ecosystems, the forbs leaf-out before the shrubs, and are therefore less prone to shading impacts early in the growing season. These findings indicate the importance of leaf phenology data collection by species and across the various ecosystem types within the highly heterogeneous Arctic landscape. These findings also demonstrate that high-latitude dynamic vegetation models should consider variation in leaf-out by groupings of species within and across ecosystems in order to provide more accurate projections of future plant distributions in Arctic regions.

Topographic Signature of Climate Change: Insights into Climatic Controls on Landscape Evolution Under Permafrost and Non-permafrost Environments

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Climate gradient across the deglaciated North American continental landscape has been a major control on the trajectory of landscape evolution following the Last Glacial Maximum (LGM) (19-25 ka BP). Following deglaciation, landscapes in the Arctic and subarctic regions have been subject to climatic conditions favoring the development and/or preservation of permafrost. In more southerly latitudes, warmer conditions have favored non-permafrost conditions. A comparison of formerly glaciated landscapes in both permafrost and non-permafrost settings offers a unique natural experiment to explore the influence of climate on landscape evolution. Additionally, by comparing formerly glaciated terrains under both permafrost and non-permafrost conditions to landscapes never having undergone glaciation it may be possible to identify unique signatures of glaciation on hill slope morphology and processes. After glaciers retreated, newly exposed landscapes were exposed to both fluvial and hillslope mass wasting processes, the relative balance and influence of these processes on landscape evolution varied depending on Holocene climatic conditions (permafrost versus non-permafrost environments).

Using analysis of high resolution Digital Elevation Model (DEM - 1m) data, we show that the topographic denudation on these landscapes over the past Holocene has imprinted a unique climatic signature. Major differences are observed in landscape regimes and regime transitions. These differences are quantified mainly by introducing a new index, Normalized Directed Distance for Relief (NDDR), that treats the landscape relief differences and successfully identify the climate induced landscape responses. Previously glaciated permafrost landscapes are primarily characterized by narrow divergent hilltops (NDDR <0.3), longer convergent flow paths (500-1000 m) in hillslopes, and abrupt hillslope to fluvial transitions (<100m). Previously glaciated non-permafrost landscapes characterized by relatively large divergent hill slopes (0.3 ≤ NDDR ≤ 0.9), moderately long convergent flowpaths (400-500 m), and hillslope to fluvial transition through longer networks hollows (200-300m). We demonstrate our findings using high resolution lidar dataset obtained for Trail Valley, Mackenzie River, Canada; Brooks Range, North Slope, Alaska; Tenderloot Creek, Montana, and Pleasant, Maine, USA that were previously occupied by North American Laurantide Ice Sheet and Brooks Range glaciers. South Fork Eel River (NDDR > 0.9), California is used a representative temperate non-glaciated basin.

Our results suggest, that in landscapes on the north side of the Laurentide Ice Sheet where permafrost has been present since deglaciation, periglacial landsurface processes such as freeze-thaw driven solifluction process and geomorphic disturbances like active layer detachment etc., limited the development of channel networks and helped to preserve signatures of glaciation on hillslopes. In contrast, in more southerly latitudes, where permafrost is absent fluvial networks have more fully developed but the hill slopes appear to retain some signature of prior glaciation. Finally, now we can test different hypotheses on many possible future trajectories of landscape evolutions under different climate change scenarios.

Characterization and Modeling of Microbial Carbon Metabolism in Thawing Permafrost

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Increased annual temperatures in the Arctic are warming the surface and subsurface, resulting in thawing permafrost. Thawing exposes large pools of buried organic carbon to microbial degradation, increasing greenhouse gas generation and emission. Most global-scale land-surface models lack depth-dependent representations of carbon conversion and GHG transport; therefore they do not adequately describe permafrost thawing or microbial mineralization processes.

The current work was performed to determine how permafrost thawing at moderately elevated temperatures and anoxic conditions would affect CO_2 and CH_4 generation, while parameterizing depth-dependent GHG production processes with respect to temperature and pH in biogeochemical models. These enhancements will improve the accuracy of GHG emission predictions and identify key biochemical and geochemical processes for further refinement.

Three core samples were obtained from discontinuous permafrost terrain in Fairbanks, AK with a mean annual temperature of -3.3°C. Each core was sectioned into surface/near surface (0-0.8 m), active layer (0.8-1.6 m), and permafrost (1.6-2.2 m) horizons, which were homogenized for physico-chemical characterization and microcosm construction. Surface samples had low pH values (6.0), low water content (18% by weight), low organic carbon (0.8%), and high C:N ratio (43). Active layer samples had higher pH values (6.4), higher water content (34%), more organic carbon (1.4%) and a lower C:N ratio (24). Permafrost samples had the highest pH (6.5), highest water content (46%), high organic carbon (2.5%) and the lowest C:N ratio (19). Most organic carbon was quantified as labile or intermediate pool versus stable pool in each sample, and all samples had low amounts of carbonate.

Surface layer microcosms, containing 20 g sediment in septum-sealed vials, were incubated under oxic conditions, while similar active and permafrost layer samples were anoxic. These microcosms were incubated at -2, +3, or +5 °C for 6 months. The pH decreased in all samples (5.5 to 5.9). The proportions of carbon in labile and intermediate turnover pools from permafrost samples decreased during incubation, while microbial biomass carbon increased in all cases. Microcosm samples and original core material were analyzed by 16S rDNA pyrosequencing and showed increased populations of bacteria that ferment simple and complex carbohydrates, as well as acidophilic bacteria. Microbial diversity declined in permafrost samples.

Concentrations of CO_2 and CH_4 were measured monthly by gas chromatography. CO_2 production was highest in the surface/near surface incubations (4-14%) while CH_4 was undetectable. Active layer sediments produced considerably less CO_2 (0.2-0.7%) but CH_4 was detected up to 0.25%. Concentrations of CO_2 found in the deep permafrost incubations were comparable to those in the active layer, while CH_4 was considerably higher ranging from 0.2-0.6%. Overall, the CO_2 generation rate (0.02-0.12 μmol/g/month) was roughly 50 times that of methanogenesis (0.002-0.007 μmol/g/month). GHG levels peaked after 4 months, and the decreasing pH suggested that organic acid accumulation could control GHG biogenesis. Surprisingly, increasing temperature and water content did not necessarily increase GHG emission rates or proportions of CO_2 and CH_4.

A Synthesis of Thermokarst and Thermo-erosion Process Rates

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Permafrost stores substantial amounts of soil organic carbon (SOC) and is increasingly vulnerable to thaw in a warming climate. More than 1000 Pg C were sequestered for millennia in Yedoma, in peat, or in Arctic deltaic deposits below 1 m depth and are thus buffered by permafrost from current biogeochemical cycling. However, projections of future permafrost status indicate a substantial decline in permafrost extent, increase in active layer thickness, and warming of soils across the Northern SOC. These gradual processes can be readily incorporated into models. However, the late Quaternary history of Arctic permafrost regions provides ample evidence that permafrost thaw in phases of rapid warming and wetting is dominated by non-linear processes, rather than gradual top-down thaw. A core factor for this is the presence of spatially inhomogeneously distributed ground ice. Disturbances affecting permafrost with excess ice content can readily result in thermokarst or thermo-erosion through feedbacks between ground ice thawing, subsidence and geomorphic change, surface and subsurface hydrology, and vegetation change.

Modeling the SOC feedbacks of thermokarst and thermo-erosion dynamics has been confined to local scales thus far, but modelers strive to make progress and start incorporating thermokarst as a disturbance process into land surface schemes or ecosystem models. For successful implementation, the natural variability in the magnitude, extent, rate, and frequency of thermokarst and thermo-erosion, and their connection to various environmental settings and variables, requires refined characterization.

To understand and quantify this variability, we synthesized rates of thermokarst and thermo-erosion processes associated with a variety of permafrost degradation features, including thermokarst lakes, taliks, retrogressive thaw slumps, and peat plateaus. In addition to >180 references we analyzed, we bolstered the number and spatial distribution of thermokarst lake expansion rate measurements using own field and remotely sensed observations. Our database indicates that average shore erosion rates for thermokarst lakes range from 0.1 to 2 m/yr, while some maximum rates reach >12 m/yr. Measured and modeled talik growth under lakes or following disturbances indicates very rapid rates in the initial phase of talik formation (vertical thaw up to 1 m/yr) and a substantial reduction with increasing talik thickness. Headwall retreat rates in retrogressive thaw slumps were found to range from 1-10 m/yr, while maximum rates may reach 10-20 m/yr and exceed 40m/yr in some extreme cases.

Overall, we found that it is challenging to compare data reported in the literature due to widely different observation methods and periods as well as the lack of existing reporting standards for key parameters. However, despite these challenges, a general picture of thermokarst and thermo-erosion process rates begins to emerge that may be useful to better constrain boundary conditions for such processes in models and eventually allow better assessments of carbon mobilization from permafrost thaw.

Effects of Spatially Variable Snow Cover on Thermal Regime and Hydrology of an Arctic Ice Wedge Polygon Landscape Identified using Ground Penetrating Radar and LIDAR Datasets

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Ice wedge polygons are common in Arctic terrains underlain by permafrost. Permafrost degradation could transform low- into high centered polygons, causing profound changes in the hydrologic regime of Arctic lands, which in turn, could affect the energy balance and subsurface biodegradation of organic carbon responsible for greenhouse gas production. Understanding the linkages between microtopography, snow cover, thermal properties, and thaw depth is critical for developing a predictive understanding of terrestrial ecosystems and their feedbacks to climate. In this study, we use high frequency (500-1000 MHz) ground penetrating radar (GPR) data acquired in spring 2012 within the Next-Generation Ecosystem Experiment (NGEE) study site in Barrow, AK to characterize the spatial variability of snow distribution. We compare it's distribution to microtopography, estimated using LIDAR data, and thaw depth, also estimated using ground penetrating radar collected at different times during the year and simulated over time using mechanistic thermal-hydrologic modeling. The high spatial resolution offered by LIDAR and ground penetrating radar permit detailed investigations of the control of microtopography on snow and thaw layer depth.

Results suggest that microtopographical variations are responsible for substantial differences in snow accumulation. In low centered polygons, snow depth can be up to four times greater in the troughs than on the rims. Both modeling and observations suggest that the microtopography-governed snow thickness affects the thermal properties of the subsurface and thus the thaw layer thickness; regions with thicker snowpack generally correspond to regions of greater thaw depth. We conclude that a transition from low- to high centered polygons will not only impact watershed runoff but, since snow accumulation is sensitive to the microtopography, it will also impact snow distribution. In turn, snow distribution affects thaw depth thickness, and the propensity for microbial degradation of organic carbon and production of greenhouse gasses.

Association Between Permafrost Degradation and Soil Greenhouse Gas Fluxes in the Alaskan Arctic

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The Arctic is projected to warm at nearly twice the rate of the global average in the coming century. Climate change can generate both negative and positive feedbacks with Arctic ecosystems: As atmospheric carbon dioxide increases, plants grow more quickly, thus absorbing more carbon. As temperatures rise however, Arctic permafrost thaw could make more soil carbon susceptible to microbial degradation, leading to the release of more greenhouse gases (positive feedback) or more nitrogen for plant growth (negative feedback). Therefore, to accurately predict the effects of climate change, we must understand how the amount of greenhouse gas flux from the soil surface changes with soil temperature, soil moisture, depth to frozen ground, microtopography and permafrost degradation.

We conducted fieldwork in the Alaskan Arctic, at the Barrow Environmental Observatory as part of the U.S. DOE Next-Generation Ecosystem Experiment (NGEE-Arctic). We sampled from areas that are representative of three levels of permafrost degradation: low-centered, transitional, and high-centered. Each sampling area may be further decomposed into three microtopographic components: troughs, edges, and centers. We measured the soil greenhouse gas fluxes and flux variability of each treatment over the growing season (using static chambers), soil moisture, soil temperature, and depth to frozen ground. As permafrost thaws during the growing season, we observe how greenhouse gas fluxes change as depth to permafrost increases. This may allow us to extrapolate how greenhouse gas fluxes would change due to a climate-change-induced temperature increase.

The Impacts of Permafrost Thaw on Land-Atmosphere Greenhouse Gas Exchange in Recent Decades over the Northern High Latitudes

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Coupled climate-carbon models project that the northern high latitudes will serve as a substantial land carbon sink during the 21st century because both climate warming and elevated global [CO_2] favor increased productivity and carbon uptake in the region. However, these models lack many of the key processes governing high-latitude ecosystem processes, and none have accounted for soil organic matter (SOM) decomposition associated with permafrost thaw. In contrast, results based on incorporating all of the major factors controlling the high-latitude C budget in process model simulations suggest that the land-based sink of arctic and boreal ecosystems is currently weakening in part due to temperature-driven increases in SOM decomposition.

We hypothesize that climate-driven warming will lead to increasing active layer thickness (ALT) and the thawing of previously frozen SOM, thus accelerating C and N cycling throughout the system. Competing mechanisms analyzed here include the positive feedback to warming through the decomposition and release of previously frozen SOM as CO_2 and CH_4, and the negative feedback associated with the uptake of atmospheric CO_2 through net primary production (NPP) stimulated by increased vegetation N uptake. To parse out these mechanisms, we compared results from experimental simulations using the Terrestrial Ecosystem Model (TEM), which include explicit simulations of climate-driven ALT dynamics, with a ‘control’ simulation where ALT was held constant through the transient period.

Across the Pan-Arctic domain over the 1990 to 2006 time period, model results show a wide-spread increase in the depth to permafrost, with a stronger trend over the discontinuous permafrost zone (3.9 mm/yr) than that over the continuous zone (2.5 mm/yr). Simulated ALT shows good agreement with observational data from the Circumpolar Active Layer Monitoring (CALM) network in terms of annual means, the range of spatial variability, and temporal patterns. Analysis of the simulation experiments provides anestimate of 280 TgC/yr thawed from previously frozen SOM. Despite the greater rate of thaw over the discontinuous permafrost zone, the majority (60%) of the thawed SOM (170 TgC/yr) was found in the continuous zone, reflecting the larger area and higher density of SOM of this zone. Of this thawed SOM, the TEM estimates that 615 $MtCO_2eq/yr$ was released to the atmosphere, with 71% (436 $MtCO_2eq/yr$) from the continuous zone and 8.6% (52.9 $MtCO_2eq/yr$) of the total forcing as CH_4. While the impact of ALT dynamics on SOM decomposition resulted in a consistently strong increase in CO_2 and CH_4 emissions, the magnitude and even sign of the impact on NPP was more variable across sub-region and year. Compared to the control, TEM estimates an increase of 80 $MtCO_2eq/yr$ in NPP, which represents a 13% negative feedback relative to CO_2 and CH_4 emissions. With all components combined, our simulation experiment estimates a net greenhouse gas forcing of 535 $MtCO_2eq/yr$ directly tied to ALT dynamics modeled over the Pan-Arctic domain between 1990 and 2006. This represents a significant factor in the overall land-based greenhouse gas source of 640 $MtCO_2eq/yr$, and an additional 6.8% contribution on top of the combined 7792 $MtCO_2eq/yr$ fossil fuel emissions from the eight Arctic nations over this time period.

Quantifying Interdependence among Processes and Characterizing Dynamic Controls across Spatial Scales by Linking Climate, Hydrology and Ecosystem Models

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The sub-arctic environment can be characterized as being in the zone of discontinuous permafrost. As such, most of the current and expected changes in climate and the associated hydrologic response (increases in precipitation, temperature, and active layer depth; decreased permafrost extent; and tree-line expansion and vegetation composition) will be experienced first in this region. One of the major challenges posed to the research community is to establish the link between permafrost and changes of the boreal forest to a warming climate and a changing freshwater system. This is a major challenge due to the high degree of fine-scale spatial and temporal heterogeneity in boreal hydrologic, thermal and ecologic processes, which are currently inadequately represented in both fine- and meso-scale hydrologic models.

Using the Caribou-Poker Creeks Research Watershed (located near Fairbanks, Alaska) as a test study site, we present a framework to improve meso-scale hydrologic simulations in the Alaskan boreal forest through improved parameterization derived from fine-scale ecohydrologic simulations. The fine-scale, storage-based, ecohydrologic model will integrate vegetation water use with permafrost dynamics along with the other major hydrologic processes within a Bayesian framework. Baseline simulations from both the fine-scale ecohydrologic model and a meso-scale hydrologic model (Variable Infiltration Capacity, VIC) will be made and compared. Meso-scale parameterizations, derived from the fine-scale simulations, will be implemented into the VIC model. Results will be evaluated by comparing the newly parameterized simulations with the baseline simulations as well as observations.

Horizontal and Vertical Profiling of Microbial Communities Across Landscape Features at NGEE Site, Barrow, AK

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Low-and high-centered polygons in permafrost-dominated ecosystems have distinct geochemical and hydrological characteristics that are expected to alter microbial processes that govern carbon cycle dynamics in Arctic landscapes. Key questions that must be answered if we are to represent these dynamics and their underlying controls into Earth System Models include: 1) Through which pathways is carbon processed in different areas of these polygons? 2) What regulates the release of C as CO_2, or methane, and 3) Which microorganisms are responsible? As part of the Next-Generation Ecosystem Experiments (NGEE Arctic) project, we collected samples across a transect of polygon features near Barrow, Alaska. The transect included samples from centers, edges and troughs of high-centered and low-centered polygons, including organic and deeper mineral soil layers. In addition, we took a 1.6 m deep core from our field site and sectioned it vertically to determine the microbial composition at different depths from active layer through upper layers of permafrost. Prior to sectioning, the core was CT-scanned to determine the physical heterogeneity throughout the core. Total DNA was extracted from sub-samples and the microbial community composition in the samples was determined by sequencing of 16S rRNA genes. The resulting microbial profiles were related to corresponding environmental variables. We found that microbial community composition varied according to location across the polygons. Differences in elevation and moisture content were identified as the primary drivers of the observed changes in microbial composition. Methanogenic archaea were more abundant in the centers of low-centered and wetter polygons than high-centered polygons. These data suggest a potential for increased methane production towards the centers of polygons. By contrast, polygon edges had a greater relative abundance of typically aerobic soil microbes that suggests C loss as CO_2 would predominate in these environments. A majority of the sequences found could not be reliably classified. Therefore, a current goal is to isolate novel representative organisms from these communities. In addition, we are sequencing the total metagenomic DNA to obtain information about the functional gene composition across the polygon transects. This information will be valuable for prediction of microbial responses to changes in environmental conditions including temperature, moisture, and resource stoichiometry. The long-term goal is to use this information to parameterize or constrain trait-based models of soil biogeochemistry to improve predictions of C flux in thawing permafrost.

Active Layer and Permafrost Thermal Regimes in Ice Wedge Polygon Dominated Regions of Alaska

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Large areas of Alaskan Arctic tundra are covered by the patterned ground features created by repeated freezing and thawing of soil underlain by aerially continuous permafrost. Polygonal ground structures play an important role in controlling the surface-subsurface hydrology and thermal regimes of this dynamic landscape. Micro-topographic variations in these polygonal feature-dominated areas drive the surface-subsurface hydrologic flows which, in turn, have a strong influence on the subsurface thermal hydrology. Advective heat transport by surface flows and lateral movement of groundwater in the subsurface leads to complex heterogeneous subsurface thermal regimes. Differential heat transport mediated by lateral flows in the subsurface often leads to connectivity among the otherwise isolated polygons, thus changing the local scale hydrology in these systems. We investigate the soil thermal regimes and their control on local scale hydrology in areas of patterned ground using conceptual models and for sites near Barrow, Alaska, through simulations at sub-meter scale resolution for low-centered, high-centered and transition polygons. We also study the thermal and hydrologic characteristics of low- and high-centered polygons and develop schemes for representation, parameterization and scaling in the control of these localized processes for the larger landscape. We achieve this through characterization of the patterned ground using high resolution LiDAR and high fidelity simulations at various scales and resolutions combined with the coupled multiscale-multiphase-multicomponent surface-subsurface reactive flow and transport model PFLOTRAN.

The Hydrology of Arctic Landscapes with Differing Ice Wedge Polygon Type Through Field Measurements and Modeling

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Ice wedge polygons are common in landscapes underlain by permafrost. Still, their role on watershed-scale hydrology is constrained. We combined field measurements with thermal- and hydrologic modeling to assess the effect of ice wedge polygon type on landscape-scale hydrologic fluxes and stores. The physically-based model WaSiM was applied to airborne LiDAR and schematic DEMs, and forced by climate data from the Biocomplexity Experiment, Barrow, Alaska. Simulations and field measurements were concentrated to four sites, i.e. landscape types: high-centered, low-centered, and two transition polygon sites (the latter having both low-centers and troughs). Model simulations suggest that low-centered polygons, through elevated rims, reduce runoff while increasing evapotranspiration and water storage. The high-centered polygon landscape favors runoff, while storage and evapotranspiration drastically decrease. Continuous field measurements in neighboring, individual ice wedge polygons presents drastically different seasonal variability in water tables between study sites, despite the same landscape-scale end-of-winter snowpack water storage. It is evident from the field and modeling analyses that microtopography plays an important role on low-gradient Arctic wetland watershed-scale hydrology. Further, the fine microtopographical variability results in hydrologic characteristics that can present important geomorphological feedbacks. A shift in ice wedge polygon type could potentially dominate the initial effects of altered climate on Arctic wetland hydrology.

Progress Towards Coupled Simulation of Surface/Subsurface Hydrologic Processes and Terrestrial Ecosystem Dynamics Using the Community Models PFLOTRAN and CLM

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Accurately simulating regional water cycle dynamics is challenging because of strong soil moisture-rainfall feedbacks and large uncertainties associated with vegetation and energy interactions. Earth system models of today cannot accurately capture such interactions, because current-generation land surface models (LSMs) 1) do not explicitly represent the fine-scale spatial variability of topography, soils, and vegetation that play a significant role in determining the response of hydrologic states (soil moisture) and fluxes (interception, infiltration, runoff, evapotranspiration) and 2) over-simplify or completely omit some key physical processes, such as lateral flow of water and heat, surface-subsurface interactions, realistic groundwater-vadose zone interactions, and freeze-thaw dynamics. Capturing such processes is critically important for predicting regional precipitation, vegetation productivity, and the disposition of carbon stored in potentially vulnerable permafrost under scenarios of climate change. Towards this end, we have added coupled surface water-groundwater interactions to the the open-source, massively parallel flow and reactive transport model PFLOTRAN, and have been developing a framework for coupling PFLOTRAN with the Community Land Model (CLM).

PFLOTRAN is an open-source (LGPL-licensed) code -- with a growing community of users -- developed for simulation of multiscale, multiphase, multicomponent subsurface flow and reactive transport problems on machines ranging from laptops to leadership-class supercomputers. It has been applied in studies of contaminant fate and transport, geologic CO_2 sequestration, and geothermal energy production, among others, and has been run using up to 262,144 processor cores on Jaguar, the Cray XK6 supercomputer at Oak Ridge National Laboratory. We have recently added a surface flow component in PFLOTRAN that is integrated with the subsurface. The underlying solver framework employed allows significant flexibility in how the governing equations are solved, and we will compare different surface flow formulations as well as coupling strategies between the surface and subsurface domains. Additionally, for studies of hydrology in Arctic regions, we have added a three-phase ice model. We will present some demonstrations of this capability and discuss solver strategies for handling the strong nonlinearities that arise.

To provide a unified treatment of the unsaturated and saturated zones and to enable lateral redistribution of soil moisture (and eventually surface water, heat, and nutrients) in regional climate models, we have developed an approach for coupling PFLOTRAN with CLM. CLM is the global land model component used within the Community Earth System Model (CESM) to simulate an extensive set of biogeophysical and biogeochemical processes occurring at or near the terrestrial surface. We will describe our approach for replacing the existing CLM hydrology using PFLOTRAN and present some preliminary simulations undertaken with the CLM-PFLOTRAN coupled model.

Geochemical Characterization of Lateral Distribution of Water and Carbon in Arctic Landscapes

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Complex Arctic drainage networks can potentially lead to significant redistribution of significant amounts of dissolved and particulate carbon. The current generation of global climate models represent hydrology as primarily a vertical water balance. Excess water is assigned as stream flow and routed as highly simplified river networks from one grid cell to the next. Topographic features of lowland arctic landscapes, especially polygonal ground, thaw ponds, and lakes, comprise a complex and tortuous drainage network that impounds and routes a significant portion of snowmelt and precipitation. Climate driven warming and degradation of permafrost may lead to changes in the low relief features that control hydrology and lateral carbon transport in low gradient regions like the North Slope of Alaska.

Sampling techniques are being deployed in a synoptic survey mode to quantify the connectivity of surface water features and the lateral redistribution of water and carbon throughout the landscape. We are deploying a combination of anchored piezometers, floating drive points, and diffusion cells at multiple depths in the saturated zone within the Barrow Environmental Observatory (BEO) as part of the Next Generation Ecosystem Experiment – Arctic project. Fiberglass wicks and macrorhizons are being employed to sample the unsaturated zone. Parameters to be analyzed include metals, anions, DOC, TOC, DON, dissolved methane, and isotopes of water, DIC and DOC. These results will allow us to better delineate hydrologic flow paths, redox transformations, biogeochemistry and lateral carbon fluxes.

The thawed portion of the active layer during August 2012 ranged from 30-50 centimeters with a thin (~10 cm) organic horizon overlying clay soils. Lateral hydrologic fluxes appear to be predominately surface flows and subsurface flows in the thin organic layer. Findings on optimal sampling techniques will be presented along with surface and subsurface aqueous and isotopic geochemical results from a gradient of polygonal terrain ranging from high-centered to low-centered polygons. Results from drainages, ponds and lakes in the BEO will also be presented. Preliminary oxygen and deuterium isotope measurements from samples collected in September 2011 and June 2012 (the latter during snowmelt) show significant isotopic variation ranging from ~-7 to -22 per mille and -75 to -165 per mille, respectively. Most samples fall along a local meteoric water line as calculated from GNIP data, though September pond and low-centered polygon samples are suggestive of a small evaporative effect.

We will use these data to test improved representations of surface runoff and subsurface flow in high resolution physically based global models.

Testing Hypotheses of Soil Organic Matter Dynamics in a Mechanistic Reactive Transport Model

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The range of processes hypothesized to be important for long-term soil organic matter dynamics far exceeds the capabilities of current land models integrated in regional- to global-scale climate models. Yet SOM stability and CO_2 fluxes from soils to the atmosphere are critical for future projections of climate. Recent syntheses of processes that may influence the trajectory of future soil C storage emphasize mineral interactions, enzyme dynamics, microbial population dynamics, transport, and interactions with plants and nutrient cycles. We contend that evaluating the relative importance of these processes requires a numerical modelling structure that allows for consistent comparison with observations, uncertainty characterization, and as mechanistic as possible a representation of the processes. We will describe a detailed spatially-resolved 3-dimensional reactive transport solver (TOUGHREACT) that represents abiotic and biotic SOM transformations and multi-phase flows. The modeling framework allows for explicit representation of (1) SOM interactions with minerals and their temperature, pH, and redox dependencies; (2) multiple microbial groups with different survival strategies and environmental sensitivities; (3) aqueous, gaseous, and sorbed phases; and (4) disaggregation of litter inputs, depolymerisation productions, and microbial bodies into an arbitrary number of SOM functional groups. The model accurately represented vertically-resolved bulk SOM in grassland and forest ecosystems using a baseline set of parameters. After testing, we used the model to investigate the relative impact of various mechanisms affecting SOM storage. Model predictions highlight the importance of sorption, aqueous transport, and microbial dynamics for the slow turnover of SOM that is observed below the rooting zone. We will also describe (1) model structural and parametric uncertainty; (2) methods to extract low-order model representations from the detailed reactive transport solutions for application in climate models; and (3) experimental and observational results needed to improve the believability of these types of next-generation SOM models.

Photosynthetic Characterization of Plant Functional Types from Coastal Tundra to Improve Representation of the Arctic in Earth System Models

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The primary goal of Earth System Models (ESMs) is to improve understanding and projection of future global change. In order to do this they must accurately represent the carbon fluxes associated with the terrestrial carbon cycle. Photosynthetic CO_2 uptake is well described by the Farquhar, von Caemmerer and Berry model of photosynthesis, and most ESMs use a derivation of this model. One of the key parameters required by the Farquhar, von Caemmerer and Berry model is an estimate of the maximum rate of carboxylation by the enzyme Rubisco ($V_{c,max}$). In ESMs the parameter $V_{c,max}$ is usually fixed for a given plant functional type (PFT) and often estimated from the empirical relationship between leaf N content and $V_{c,max}$. However, uncertainty in the estimation of $V_{c,max}$ has been shown to account for significant variation in model estimation of gross primary production, particularly in the Arctic. As part of a new multidisciplinary project to improve the representation of the Arctic in ESMs (Next Generation Ecosystem Experiments - Arctic) we have begun to characterize photosynthetic parameters and N acquisition in the key Arctic PFTs. We measured the response of photosynthesis (A) to internal CO_2 concentration (ci) in situ in two sedges (*Carex aquatilis, Eriophorum angustifolium*), a grass (*Dupontia fisheri*) and a forb (*Petasites frigidus*) growing on the Barrow Environmental Observatory, Barrow, AK. The values of $V_{c,max}$ (normalized to 25°C) currently used to represent Arctic PFTs in ESMs are approximately half of the values we measured in these species in July, 2012, on the coastal tundra in Barrow. We hypothesize that these plants have a greater fraction of leaf N invested in Rubisco (F_{LNR}) than is assumed by the models. The parameter $V_{c,max}$ is used directly as a driver for respiration in some ESMs, and in other ESMs $V_{c,max}$ is linked to leaf N content and N acquisition through F_{LNR}. Therefore, these results have implications for ESMs beyond photosynthesis, and suggest that physiological characterization of a more extensive list of PFTs would be a useful resource for ESMs.

Measuring and Modeling Changes in Permafrost Temperature at the UAF Permafrost Observatory in Barrow, Alaska

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In 2001, a Permafrost Observatory was established within the Barrow Environmental Observatory in Barrow, Alaska under the auspices of the International Arctic Research Center of the University of Alaska Fairbanks. The observatory was established at the locations where permafrost temperatures were measured during the 1950s and early 1960s by M. Brewer of the U.S. Geological Survey to compare present permafrost temperatures with those obtained by M. Brewer. Those measurements were of very high quality, with a precision of generally 0.01°C. Comparison of permafrost temperature profiles obtained at the same location by Brewer on October 9, 1950 and by the UAF research group on October 9, 2001 shows that at the 15-meter depth (which is slightly above the depth of annual temperature variations) the permafrost temperature was warmer by 1.2°C in 2001 than in 1950. Since 2001, permafrost temperature at this depth increased additionally by 0.5°C. Most of this latest increase happened after 2005. Similar permafrost temperature dynamics during the last ten years was observed at the UAF Permafrost Observatories in the Prudhoe Bay region and could be explained both by an increase in air temperatures and in the snow depth at these locations.

A site-specific numerical model for the Barrow permafrost temperature regime was developed in the GI Permafrost Lab. The model was calibrated using data from shallow (down to one meter) soil temperatures obtained by K. Hinkel at a Barrow site with surface conditions similar to the Brewer site. No data from the Brewer sites were used for the calibration. Comparison of the modeling results and the Brewer’s measured data shows an excellent agreement. The daily air temperatures and snow cover thickness during the entire period of measurements (1924-2011) at the Barrow meteorological station were used as input data for this calibrated model. As a result, a time series of daily ground temperatures for the depths between 0 and 200 meters were obtained. Analysis of this time series will be used in this presentation to reveal the effect of changes in air temperature and in snow depth on permafrost temperature and on the active layer thickness. Possible changes in these parameters as a result of the predicted changes in climate during the 21st century will be also presented.

Application of Unsupervised Clustering using Sparse Representations on Learned Dictionaries to develop Land Cover Classifications in Arctic Landscapes

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Techniques for automated feature extraction, including neuroscience-inspired machine vision, are of great interest for landscape characterization and change detection in support of global climate change science and modeling. Successful application of novel unsupervised feature extraction and clustering algorithms for use in Land Cover Classification requires the ability to determine what landscape attributes are represented by automated clustering. A closely related challenge is learning how to precondition the input data streams to the unsupervised classification algorithms in order to obtain clusters that represent Land Cover category of relevance to landsurface change and modeling applications. We present results from an ongoing effort to apply novel clustering methodologies developed primarily for neuroscience machine vision applications to the environmental sciences. We use a Hebbian learning rule to build spectral-textural dictionaries that are adapted to the data. We learn our dictionaries from millions of overlapping image patches and then use a pursuit search to generate sparse classification features. These sparse representations of pixel patches are used to perform unsupervised kmeans clustering. In our application, we use 8band multispectral Worldview-2 data from three arctic study areas: Barrow, Alaska; the Selawik River, Alaska; and a watershed near the Mackenzie River delta in northwest Canada. Our goal is to develop a robust classification methodology that will allow for the automated discretization of the landscape into distinct units based on attributes such as vegetation, surface hydrological properties (e.g. soil moisture and inundation), and topographic/geomorphic characteristics. The challenge of developing a meaningful land cover classification includes both learning how optimize the clustering algorithm and successfully interpreting the results. In applying the unsupervised clustering, we have the flexibility of selecting both the window size over which spectraltextural dictionaries are defined and the number of clusters to be output. We find that adjusting both these factors has significant influence on how the algorithm segments the landscape into clusters. To interpret and assign land cover categories to the clusters we both evaluate the spectral properties of the clusters and compare the clusters to both field- and remote sensing-derived classifications of landscape attributes. Field data sets include observations, photographs, and maps of vegetation cover. Remotely sensed data streams include NDVI and LiDARderived analysis of landsurface attributes. Additionally, we are exploring using subsets and normalized indices of the full 8band images to both focus clustering on specific landsurface attributes such as soil moisture and vegetation and to better understand the spectral and spatial controls on the clustering results.

Five Years of Variability in Snow Depth and Active Layer Hydrologic and Thermal Regime Across an Ice Wedge Polygon in Barrow, Alaska

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Ice wedge polygons, common to the low-gradient Arctic tundra, give rise to several microtopographical units and a diverse range of ecosystem microcosm over short distances (meters). The rims of low-centered polygons, mounds of high-centered polygons, basins (centers) of low-centered polygons and polygon troughs result in a somewhat systematic mosaic of surface and subsurface characteristics due to the organized network of ice wedges. In order to assess the importance of specific ice wedge features on larger-scale (> km2) fluxes of energy, water and carbon, including their geomorphological stability, it is necessary to quantify the sub-meter scale variations in ice wedge polygon snow depth and active layer hydrologic and thermal regime.

An ice wedge polygon having both troughs, a low center and a wide rim was instrumented in fall 2007 within the Barrow Environmental Observatory, Barrow, Alaska. Hourly measurements included soil temperature at three depths and near-surface soil moisture at 29 sites. Snow and active layer depth was measured manually in April/May and September, respectively. The results present large variability in snow depth, active layer depth, time of freeze-up, and near-surface soil temperature that are correlated to feature type (trough, low center and rim). For example, end-of-winter snow depth Is about twice as deep in the troughs as on the rims, resulting in an >10 °C soil temperature difference during cold spells. Further, a complete freeze up, defined as the rapid soil cooling that follows the end of phase change, occurs about a month later in the troughs than the exposed and dry rims. The identified fine-scale spatial variability in active layer and surface characteristics of ice wedge polygon landscapes may impose important controls large-scale energy, water and carbon exchange.

Linking Vegetation Composition to Geomorphic Units in a Polygonal Tundra Landscape: a Framework for Improving Estimates of Plant Functional Type Coverage in Ecosystem Models

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Fractional coverage of plant functional types within a grid-cell is a key parameter in broad-scale carbon and nutrient cycle models, but the heterogeneity of Arctic landscapes, where plant communities dominated by differing plant functional types vary at scales of tens of meters, makes this challenging to estimate. Here, we quantify plant community composition in relation to geomorphic units (centers, ridges and troughs) associated with a gradient from low-center to high-center polygons in the coastal tundra at Barrow, Alaska. We surveyed plant communities in 1 x 1m plots across four polygon types, and also undertook destructive harvests to characterize leaf area index, above and below-ground biomass and plant carbon and nitrogen stocks. We hypothesized that the functional type composition of plant communities is readily predictable from elevation throughout the gradient, with higher productivity, sedge–dominated communities at wet, low elevation positions and low-productivity lichen-dominated communities at drier, higher elevation positions. Our results support this hypothesis with respect to center and trough communities, but suggest that further classification of polygon type is required to accurately predict ridge community composition. Overall, improving understanding of the links between plant community composition and recognizable geomorphic units in these complex tundra landscapes provides a framework from which to upscale ecosystem functional measurements, and also to predict the effects of a changing climate.

Characterizing the Measurements Necessary to Constrain Soil Biogeochemistry Structural Uncertainty in CLM4: a Measurement-Oriented Modeling Approach

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Incomplete understanding of soil biogeochemical processes leads to a variety of biogeochemistry model structures. When these models are calibrated and evaluated with a limited number of measurements, structural equifinality may occur such that none of the models is superior to the others. This structural equifinality becomes a significant uncertainty source when those models are applied to simulations of regional and global terrestrial ecosystem processes. Here, we used the CLM4-BeTR model, a biogeochemical transport and reaction module integrated in CLM4, to explore what measurements are needed to constrain structural uncertainty in the representation of soil biogeochemistry. We considered two vertically resolved soil biogeochemistry formulations: CLM4-CN and CLM4-CENTURY. Through forward simulations, we investigated the multi-temporal-scale characteristics of the model's structural uncertainty in soil organic matter (SOM) dynamics, and found that (1) the time series of soil-surface CO_2 efflux is only useful to constrain the turnover time of the fast SOM pool, (2) belowground root structure and vertical SOM distribution is better constrained by the profiles of soil CO_2 concentrations, and (3) the slow SOM pool dynamics can only be constrained using simulated and observed soil 14C profiles. We will also discuss how to make best use of the measurement-oriented modeling approach to differentiate soil respiration components and to establish a list of recommended measurements to constrain the two belowground biogeochemistry submodels in CLM4.

High Resolution Characterization of Heterogeneous Arctic Tundra Subsurface Properties using a Multiscale Bayesian Fusion Approach with Geophysical Datasets

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Recent findings suggest that climate change has a significant impact on the arctic landscape, which could in turn cause feedback to the climate system due to the large amount of carbon stored in permafrost. A new Department of Energy, Office of Science project–called the Next-Generation Ecosystem Experiment (NGEE Arctic)–will develop a process-rich predictive model for understanding how permafrost thaw and degradation changes landscape, hydrology, biogeochemical processes and vegetation, and predicting how these changes affect the feedbacks to the climate system. The subsurface properties–such as active layer thickness (ALT), soil moisture, snow depth and geochemical parameters–are key parameters for such modeling; especially for simulation of the hydrological and geochemical processes that control microbial carbon decomposition. Although models require a large-scale domain to represent a system, these subsurface properties are known to be highly heterogeneous over small spatial scales due to the influence of factors such as microtopography and drainage network distribution.

This work presents a data fusion method based on a hierarchical Bayesian model for integrating multiscale, multitype datasets and prior knowledge to provide estimates of heterogeneous subsurface properties and their associated uncertainty. The surface geophysical data are noninvasive and spatially extensive, which increases the spatial coverage in subsurface and reveals the finescale variability. Remote sensing data can further increase the spatial coverage through the subsurfacesurface property correlation. The model consists of two submodels: data model and process model. First, the process model describes the heterogeneous field of each subsurface property mathematically; it can be a mechanistic model (e.g., land evolution model, hydrological model) or datadriven model. The datadriven process model – developed based on the prior knowledge and exploratory data analysis – is particularly powerful to constrain the estimation of heterogeneous fields in the arctic tundra system, where the mechanistic process models are highly complex. Second, the data model connects the heterogeneous field to multiscale datasets. Once we establish the data and process models, we estimate the heterogeneous fields using the Markov Chain MonteCarlo method.

We demonstrate our approach using co-located datasets collected at the Barrow Environmental Observatory, Alaska, including thaw depth, soil temperature, snow depth, aqueous geochemistry, ground penetrating radar data, electrical resistivity tomography, and airborne LIDAR. We obtain high-resolution estimates of ALT, soil water content, snow depth and other subsurface properties over a several hundred meter-scale domain, which allows us to closely examine the controls of, for example, microtopography on snow accumulation and resulting thaw depth and thermal profiles. We discuss the value and utility of the method and each dataset for parameterizing NGEE Arctic process-resolving reactive transport simulators and understanding linkages between land surface and subsurface variability.

Scaling Process Studies and Observations in the Arctic for Improved Climate Predictability

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A fundamental goal of the Next-Generation Ecosystem Experiments (NGEE-Arctic) project is to improve climate prediction through process understanding and representation of that knowledge in Earth System models. Geomorphological units, including thaw lakes, drained thaw lake basins, and ice-rich polygonal ground provide the organizing framework for our model scaling approach for the coastal plains of the North Slope of Alaska. A comprehensive suite of process studies and observations of hydrology, geomorphology, biogeochemistry, vegetation patterns, and energy exchange and their couplings will be undertaken across nested scales to populate the NGEE 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 the evolution of permafrost degradation and its impact on topography and thermal conditions and how these changes control the spatial and temporal availability of water for biogeochemical, ecological, and physical feedbacks to the climate system. Field activities to inform model development is being carried out across a gradient of polygonal ground nested within a drained thaw lake basin age gradient near Barrow, Alaska. Co-analysis of in-situ observations with ground based geophysical and airborne and satellite based remote sensing products from the single polygon to multiple drained lake basin scale is revealing surface-subsurface variability and interactions that influence or control local hydrology, greenhouse gas production, vegetation and the energy balance. We are using a range of data assimilation and fusion techniques to combine spatially extensive data sets developed from multi-scale field data with intensive data being collected from both controlled laboratory experiments using field cores and in-situ thermal, hydrologic, biogeochemical and ecologic observations to improve process understanding and parameterize, calibrate and evaluate models. Process studies that have the greatest potential for reducing prediction uncertainty were 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 permafrost landscape features. A metric of effectiveness for our scaling approach will be the degree to which prediction at each successive scale is improved as the result of integration of observations and models.

Monitoring Freeze Thaw Transitions in Arctic Soils using Complex Resistivity Method

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The Arctic region, which is a sensitive system that has emerged as a focal point for climate change studies, is characterized by a large amount of stored carbon and a rapidly changing landscape. Seasonal freeze-thaw transitions in the Arctic alter subsurface biogeochemical processes that control greenhouse gas fluxes from the subsurface. Our ability to monitor freeze thaw cycles and associated biogeochemical transformations is critical to the development of process rich ecosystem models, which are in turn important for gaining a predictive understanding of Arctic terrestrial system evolution and feedbacks with climate.

In this study, we conducted both laboratory and field investigations to explore the use of the complex resistivity method to monitor freeze thaw transitions of arctic soil in Barrow, AK. In the lab studies, freeze thaw transitions were induced on soil samples having different average carbon content through exposing the arctic soil to temperature controlled environments at +4 ^{o}C and -20 ^{o}C. Complex resistivity and temperature measurements were collected using electrical and temperature sensors installed along the soil columns. During the laboratory experiments, resistivity gradually changed over two orders of magnitude as the temperature was increased or decreased between -20 ^{o}C and 0 ^{o}C. Electrical phase responses at 1 Hz showed a dramatic and immediate response to the onset of freeze and thaw. Unlike the resistivity response, the phase response was found to be exclusively related to unfrozen water in the soil matrix, suggesting that this geophysical attribute can be used as a proxy for the monitoring of the onset and progression of the freeze-thaw transitions. Spectral electrical responses contained additional information about the controls of soil grain size distribution on the freeze thaw dynamics. Based on the demonstrated sensitivity of complex resistivity signals to the freeze thaw transitions, field complex resistivity data were collected over time at the DOE Next-Generation Ecosystem Experiment study site in Barrow, AK. This presentation will discuss the use of the laboratory and field experiments to gain a better understanding of the spatial and temporal dynamics of freeze-thaw processes that critically control subsurface biogeochemical functioning in Artic systems.

Improved Climate Prediction through a System Level Understanding of Arctic Terrestrial Ecosystems

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The Arctic region, which is a sensitive system that has emerged as a focal point for climate 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. These are sensitive systems, 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 focuses on the highly dynamic landscapes of the North Slope where thaw lakes, drained thaw lake basins, and ice-rich polygonal ground offer distinct land units for investigation and modeling. Activities in the early stage of the project are focused on the Barrow Environmental Observatory (BEO), where a multi-disciplinary team of scientists will study interactions that drive critical climate feedbacks within these environments through greenhouse gas fluxes and changes in surface energy balance associated with permafrost degradation, and the many processes that arise as a result of these landscape dynamics. Our scaling approach builds 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-grid units, we expect to be able to characterize permafrost dynamics at multiple spatial scales in Arctic tundra landscapes. Our approach, one that embraces a model-data integration paradigm, 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., 30x30 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.

Next-Generation Carbon-Nitrogen Dynamics Model

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Nitrogen is a key regulator of vegetation dynamics, soil carbon release, and terrestrial carbon cycles. Thus, to assess energy impacts on the global carbon cycle and future climates, it is critical that we have a mechanism-based and data-calibrated nitrogen model that simulates nitrogen limitation upon both above and belowground carbon dynamics. In this study, we developed a next generation nitrogen-carbon dynamic model within the NCAR Community Earth System Model (CESM). This next generation nitrogen-carbon dynamic model utilized 1) a mechanistic model of nitrogen limitation on photosynthesis with nitrogen trade-offs among light absorption, electron transport, carboxylation, respiration and storage; 2) an optimal leaf nitrogen model that links soil nitrogen availability and leaf nitrogen content; and 3) an ecosystem demography (ED) model that simulates the growth and light competition of tree cohorts and is currently coupled to CLM. Our three test cases with changes in CO_2 concentration, growing temperature and radiation demonstrate the model's ability to predict the impact of altered environmental conditions on nitrogen allocations. Currently, we are testing the model against different datasets including soil fertilization and Free Air CO_2 enrichment (FACE) experiments across different forest types. We expect that our calibrated model will considerably improve our understanding and predictability of vegetation-climate interactions.

Simulating CO_2 and CH_4 Production and Consumption from Incubated Permafrost Soils: How Important are the Microbial Mechanisms

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An incubation experiment was conducted to examine the production and consumption of the greenhouse gases CO_2 and CH_4 in soils of the top layer, active layer, and permafrost layer under various moisture and temperature conditions using soil cores extracted from the Alaskan permafrost region. The incubation results confirmed the production of hydrogen gas and acetic acid resulting in a decreased soil pH. Three key mechanisms for production and consumption of CH_4 are suspected; CH_4 production from acetic acid and H_2 and CO_2, and aerobic CH_4 oxidation. We translated these mechanisms into a subroutine program which was then combined with decomposition subroutines in the community land model (CLM4) to evaluate the performance of these mechanisms in simulating CO_2 and CH_4 production and consumption from the incubated permafrost soils. Two guilds of microorganisms for methanogenesis and one group for methanotrophy were simulated. The simulation results confirmed that microbial mechanisms are critically important in reconstructing the observed changes in temporal CO¬$_2$ and CH_4 concentrations. There are large variations in CO_2 and CH_4 production and consumption among the different soil layers. Acetic acid production caused the observed drop in soil pH, which in turn exerted a substantial effect on CO_2 and CH_4 dynamics. The moisture and temperature had significant effects on microbial mechanisms and further on CO_2 and CH_4 production and consumption. Further efforts will be incorporating microbial dynamics and these mechanisms into the Community Earth System Model for a global scale investigation.

Community Land Model (CLM) Assessment on Simulating and Analyzing Water, Carbon and Nitrogen Cycles in Arctic Coastal Tundra at Barrow, Alaska

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Recent climate warming has been widely hypothesized to be one of primary contributors to shifting both biophysical and biological conditions of Arctic tundra ecosystem and thus water, carbon and nitrogen cycles. Both constrains on integrating multiple-scale observations scattered in various sources and comprehensive process-based model assessments on those may hinder our further and/or deepen understanding of climate impacts on Arctic tundra and their feedbacks. This preliminary study is to assess and improve, as needed, the Community Land Model (CLM-CN mode) on simulating soil water, temperature, nitrogen nutrient and other factors and their effects on soil-plant C stocks and/or fluxes in Arctic tundra at Barrow, Alaska. The model assessment is carried out by exploring and using data compiled from various researches, e.g., AmeriFlux, US/IBP, ITEX and others during past few decades in the area. We add a simple N emission subroutine in the current released CLM4 (in CESM1.0.4) and modify soil water drainage boundary conditions so that model can partially capture the landscape position effects of hydrological process on thermal and biogeochemical processes. We initially parameterize and initialize the model for Arctic tundra at Barrow, AK with 4 new plant functional types (PFTs): mosses, forbs, graminoids, and shrubs, based on literature study. It shows strong inter-annual variance of C fluxes, which tightly coupled with water, temperature and N nutrient dynamics. We then conduct a factory model experiments with drainage classes and varying PFT compositions in order to understand possible water, C and N cycle variations if vegetation changes over landscape. This preliminary analysis is of importance to apply for CLM model in this highly heterogeneous coastal Arctic tundra region under historical and projected climate changes.