Next-Generation Ecosystem Experiments – NGEE Arctic

Quarterly Report
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A progress report submitted to

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Modeling soil subsidence associated with permafrost degradation in the Arctic

Sources of greenhouse gas emissions associated with permafrost degradation constitute a large uncertainty in existing climate models. The release of greenhouse gases is mediated by numerous interconnected biogeochemical processes; one facet of these is the interplay between surface deformation and melting of subsurface ice. Scientists at Los Alamos National Laboratory are studying this interplay via numerical modeling of an initially frozen, fluid saturated, porous matrix with a subsequent thaw zone advancing from the surface downward (Figure 2). In this activity, a ice-water-soil model has been implemented within the Finite Element Heat and Mass Transfer (FEHM) model, allowing researchers to simplify stress-strain relationships while still simulating subsidence associated with thawing permafrost.

Simulations indicate that an initially frozen and fluid saturated soil column will collapse upon thawing and fluid drainage if its elastic moduli fall below some minimum allowed thresholds. As an initial condition, post-doctoral associate Kayla Lewis and her advisor George Zyvoloski assumed a saturated and frozen porous soil matrix with a thin outflow region located at depth. This region, hereafter referred to as the drainage face, was held at atmospheric pressure to allow fluid flow out of the system. The drainage face can be envisioned as a flow route that leads to the surface someplace outside of the system. As the soil is thawed from the top, ice within the pore space melts and fluid in the resulting melt layer leaves the system when it reaches the drainage face. The overlying thawed soil is weak enough to collapse upon drainage.

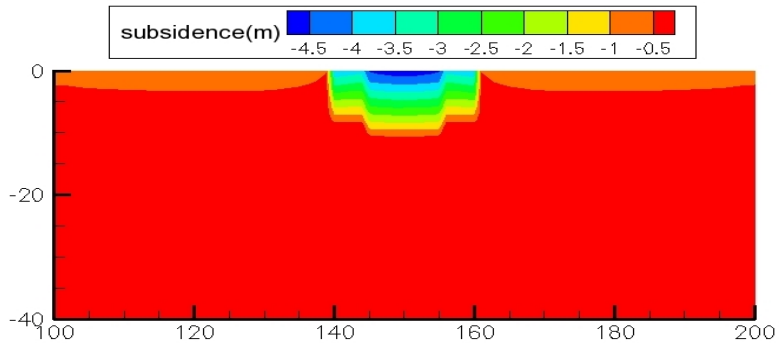


Figure 1. Soil subsidence after 20 years of simulation time.

With the surface temperature fixed at 5°C, a thaw front propagates to ~10 m depth within 20 years and, due primarily to drainage of fluid from the pore space, a zone of soil depressed by ~4.5 meters forms above the initially ice-rich zone. Soil underlying this depressed zone has its permeability reduced by between one and two orders of magnitude.

Future work at LANL will include implementation of the full water-vapor-ice system coupled to the full stress-strain equations to examine coupled thermokarst-hydrology-biogeochemistry process evolution in a warming Arctic. This will be important to the NGEE project as we begin to pull together information on critical properties and processes in Arctic ecosystems and surface and subsurface interactions that drive landscape evolution and change in the Arctic. These will be the foundation of a new land model for inclusion in Earth system models.

Details at a Glance

Activities during the April 1 thru June 30, 2011 quarter include:

- Permafrost freeze-thaw dynamics studied using ORNL high-flux isotope reactor.
- High-resolution model at LANL used to simulate land-atmosphere interactions.
- Ecohydrologists at UAF and ORNL set up new water isotope collaboration.
- Genomic resources for *Salix* spp. lay foundation for genetic studies in Alaska.
- Scientist attends "Climate Change in the Arctic" conference.
- Participants in the NGEE project prepare for multiple activities at upcoming AGU meetings.
- NGEE proposal submitted to Program Managers at BER.
- Plans nearly complete for August site selection trip to Nome and Barrow, Alaska.

Progress and Accomplishments

Neutron imaging and tomography of permafrost samples – Preliminary results:

The biogeochemical characteristics of permafrost soils are intimately coupled to water and its distribution in the subsurface. The freezing process sequesters water in ice crystals, while ions are expelled and concentrate in the remaining liquid phase. Thus, even at subzero ambient temperatures liquid water is present within permafrost, existing as a very thin film surrounding soil and ice. This dynamic holds consequences for microbial metabolism and biogeochemical cycles of carbon and nitrogen. As neutrons are particularly sensitive to hydrogen, neutron imaging can reveal the distribution of liquid water and ice in permafrost soil samples. Scientists at ORNL recently used the prototype neutron imaging beamline of the high-flux isotope reactor (HFIR) facility to (1) collect imaging data on permafrost samples to determine neutron absorption characteristics; (2) construct a soil model system and find conditions that enable visualization of the frozen and liquid water boundaries; (3) investigate the dynamics freezing and thawing using neutron contrast variation; and (4) collect a preliminary dataset for neutron tomography and perform a 3D reconstruction of a natural permafrost soil sample.

Alex Johs and Liyuan Liang at ORNL constructed a model system using pure quartz sand saturated with a solution of D_2O Gadolinium as a highly soluble tracer and a variable amount of

sodium chloride to adjust ionic strength. Using a temperature-controlled sample stage capable of manipulating temperature from ambient to -20°C, these scientists were able to record the dynamics of repeated freezing and thawing within timeframes from 1 to 3 hours. As the tracer used in these studies partitions with other dissolved ionic species, the separation of frozen from unfrozen water, which accumulated as salt brine at the solid/liquid interface was observed. The separation effect became more pronounced with slower cooling rates and higher ionic strength.

Future studies will use neutron imaging to investigate the physical structure of permafrost in terms of the spatial distribution of pores and water. Imaging of a permafrost sample through repeated freeze-thaw cycles is expected to reveal the phase transition from ice to liquid water and subsequent migration of water and solutes in the sample. Based on a comparison with the baseline data from the frozen sample, associated changes in porosity, channel formation and thawing-induced settlement of soil particles can be characterized by neutron tomography. A recent proposal awarded to Johs et al. will allow this research to continue into the Fall 2011.

<u>High-resolution simulations of plant-atmosphere interactions in Arctic ecosystems</u>:

Scientists at LANL have enhanced the atmospheric dynamics model HIGRAD and are now using it to simulate complex, three-dimensional plant-atmosphere interactions that depict shrub expansion onto the Arctic tundra at extremely high resolution (Figure 2). The model represents the transport of momentum, heat, moisture, and CO_2 and their exchange between vegetation and surrounding air, and includes a multi-scale treatment of subgrid-scale turbulence that takes into account the generation of turbulence by elements of the vegetation that are not resolved on the grid (i.e., on scales less than 0.1 m).

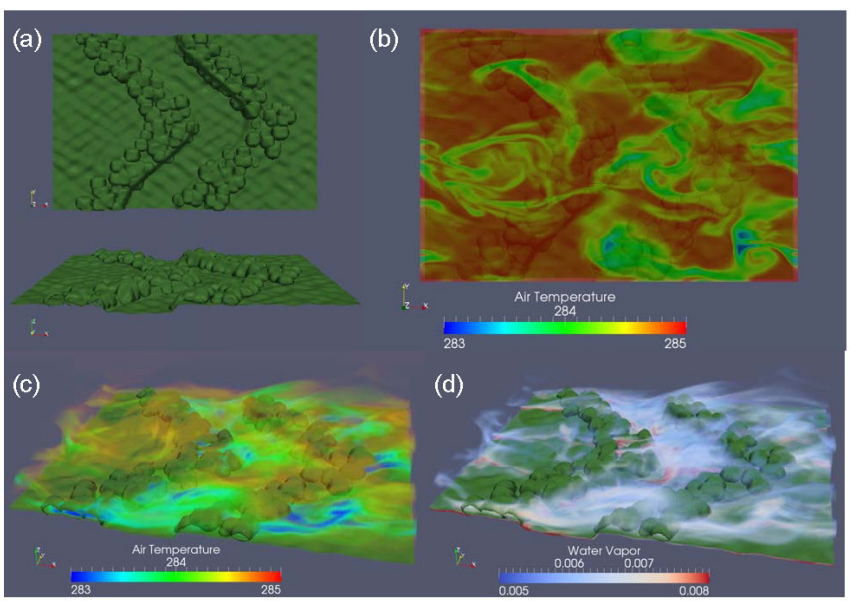


Figure 2. (a) Plan and elevation views of the landscape and the vegetation. The domain is 30 m in the *x*-direction, 20 m in the *y*-direction, and 20 m in the vertical (i.e., *z*-) direction. A shallow depression that is 1 m deep and 5 m wide – such as might arise due to permafrost degradation – transects the domain, and is surrounded on each side by a 5 m wide region of shrub-like vegetation that is ~1 m in height on average; this vegetation is taken to have properties characteristic of low-shrub tundra. Elsewhere, the ground is

covered by uniform grass of ~0.15 m height. The terrain has small-scale undulations with horizontal and vertical scales of ~0.8 m and ~0.3 m, respectively. (b) Air temperature (in K) in an *x*-*y* plane at $z = 2$ m. (c) Volume rendered three-dimensional depiction of air temperature (in K). (d) Volume rendered three-dimensional depiction of water vapor mixing ratio (in kg kg^{-1}).

Preliminary tests of the coupled model by Phil Cunningham and Rod Linn were conducted in the context of an idealized scenario representative of an Arctic ecosystem, shown in Figure 2a. The initial atmospheric state for the simulation shown here is representative of daytime conditions in the Arctic summer, and assumes neutral stability with a surface temperature (both air and plant) of 285 K, and winds blowing in the positive *x*-direction (~6 m s^{-1} at 10 m above the ground). The initial atmospheric water vapor mixing ratio is uniform and equal to 5 g kg^{-1}. The model is periodic in both horizontal directions, and the simulation is run for a long enough period of time for a fully turbulent boundary layer to develop and for the heat transfer balances between solar and terrestrial radiation, convective heating, and evaporation and transpiration to equilibrate.

Figure 2b shows the air temperature on a horizontal plane slightly above the top of the shrubs, and illustrates the highly turbulent nature of the dynamics in this example that represents a complex nonlinear interplay between radiative and convective heat transfer, moisture exchange between the plants and the air that includes heat exchange due to evaporation/transpiration, and both resolved and subgrid-scale turbulence arising from the impacts on the airflow of drag due to the heterogeneous vegetation. Three-dimensional views of air temperature (Figure 2c) and water vapor mixing ratio (Figure 2d) highlight further the complex and turbulent nature of the coupled plant-atmosphere dynamics, although it is important to note that a consistent feature of this particular simulation is the enhanced concentrations of water vapor and associated cooler air temperatures immediately downstream of both shrub-covered regions. The model and the results shown here represent a unique tool to explore a variety of questions concerning coupled plant-atmosphere dynamics. Moreover, as model development evolves, the potential for its use within the context of NGEE will expand to include both the investigation of hypothesis-based physical process studies as well as the interpretation of measurements collected in field experiments.

Jessie Cable from University of Alaska visits ORNL:

Jessie Cable, a post-doctoral research associate from the International Arctic Research Center (IARC) at the University of Alaska, Fairbanks recently visited ORNL to assist with development of a new isotopic water extraction system. The system allows for the rapid and complete extraction of liquid water from plant or soil samples for subsequent analysis of ^{1}H, ^{2}H, ^{16}O and ^{18}O using a Picarro Isotopic Water Analyzer. The technique reduces sample processing time by eight-fold, allowing for greater sample throughput. Plant physiologist Jeff Warren collaborated on this venture and will use this instrument for NGEE activities. Jessie also presented a well-

attended seminar on ecohydrology in Alaska, where the focus of her talk was on stable isotopes and hierarchical Bayesian data analysis to assess impacts of climate change on vegetation shifts and terrestrial water cycle processes in Arctic and Subarctic systems. Jessie met with participants in the NGEE project for related discussions.

Resequencing of *Salix arctica* to enable population genetic studies in the NGEE project:

Scientists at ORNL have submitted a Community Sequencing Program (CSP) proposal to the DOE Joint Genome Institute. This activity, one that supports the goals and objectives of the NGEE project, seeks to resequence multiple *Salix arctica* genotypes, a pioneer shrub throughout the Alaska. The species is among several that are implicated in the recent expansion of shrubs northward into the Arctic tundra with consequences for regional energy budgets and net carbon exchange rates of permafrost-dominated ecosystems. The CSP research will develop the necessary genomic resources to characterize the structure of *S. arctica* communities in two contrasting Arctic environments (Council and Barrow, Alaska) and then mine single nucleotide polymorphisms or SNPs from the genomic sequence to use in population genetics and trait association studies along a latitudinal and bioclimatic gradient from the Seward Peninsula to the North Slope. Wellington Muchero and David Weston are leading this effort and have already successfully established genotypes of *S. arctica* in the greenhouse (see picture).

Dan Hayes travels to Arctic science meeting in Copenhagen:

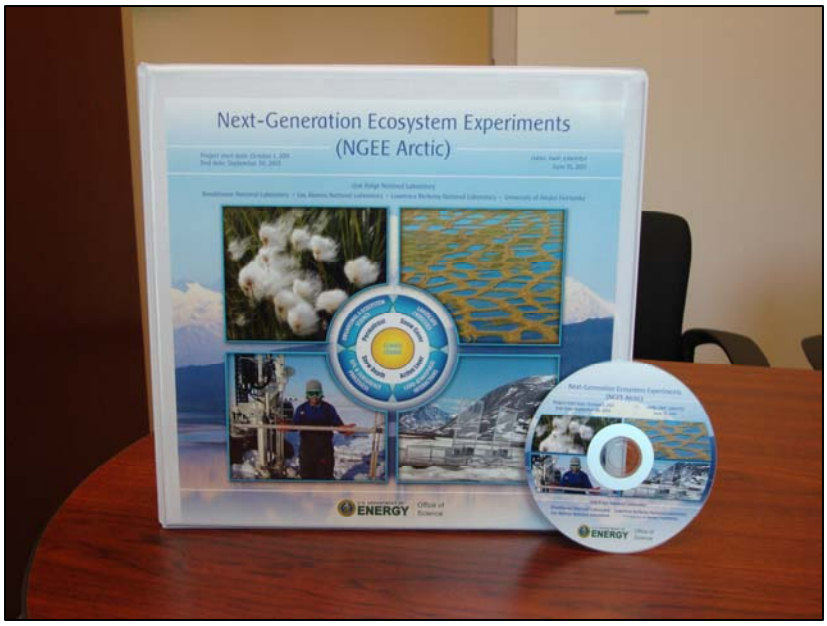
The Arctic Monitoring and Assessment program (AMAP), along with Aarhus University and the University of Copenhagen, sponsored a conference on "The Arctic as a Messenger for Global Processes: Climate Change and Pollution" from 3 to 6 May, 2011, in Copenhagen, Denmark. The conference included talks by invited keynote speakers, oral presentations selected on the basis of submitted abstracts, poster presentations and short oral presentations of selected posters. Dan Hayes from ORNL gave an oral presentation entitled “Is the northern high latitude land-based CO_2 sink weakening?” in the parallel session on climate (see Appendix for abstract). The presentation included an analysis of recent modeling studies that highlight key driving forces altering the terrestrial carbon cycle of arctic tundra and boreal forest ecosystems across the circumpolar region. In addition, the conference provided a venue to highlight the final report on "Snow, Water, Ice, and Permafrost in the Arctic". A panel discussion associated with the release of this report developed messages to be communicated to the Arctic Council Ministerial meeting that took place in Greenland one week after the conference.

Arctic process session organized for upcoming AGU meetings**:**

Participants in the NGEE project proposed, and had approved, a Union Session that will address coupled processes in the Arctic, focusing on how impacts in high-latitudes are likely to impact climate in mid-latitude systems. Through what is believed to be a series of multiple feedbacks

and amplification processes, some surprising and not well understood changes are occurring in the Arctic. Poorly quantified interactions are occurring between components of complex systems including atmosphere, permafrost, vegetation, hydrology, geomorphology, biogeochemistry, snow, clouds, sea and glacial ice, and the oceans over a range of space and time scales. While an obvious focus of this session will be on processes impacted in high-latitude systems, the organizers of this workshop seek input on how these changes are also beginning to impact oceans, land, and atmospheric circulation patterns beyond the Arctic. Observational, theoretical, and numerical studies that focus on emergent, nonlinear, and threshold-dominated amplification processes and teleconnections are encouraged to submit abstracts and presentations to this session. Conveners include James Overland (NOAA), James White (Univ. Colorado), Cathy Wilson (LANL), and Stan Wullschleger (ORNL).

NGEE proposal submitted:



A multi-laboratory team of scientists joined by strategic university partners submitted the final version of the NGEE proposal to Program Managers at BER on June 15, 2011. The proposal describes how the Arctic is undergoing a system-wide reorganization in response to an altered climate. The mechanisms responsible for this change have been unpredictable and difficult to isolate due to a large number of interactions among individual components of the system. The NGEE project will quantify the complex physical, chemical, and biological behavior of terrestrial ecosystems in Alaska. The project will focus on interactions that drive ecosystem-climate feedbacks through greenhouse gas fluxes and changes in surface energy balance associated with thawing permafrost and threshold-dominated permafrost degradation and thermokarst formation, and the many processes that arise as a result of these landscape dynamics. Research sites will be located along a bio-climatic gradient that spans tundra and shrub-tundra transition zones on the North Slope and Seward Peninsula. The ultimate deliverable of the NGEE project is a high-resolution terrestrial system model that is able to simulate coupled thermal, hydrological, geomorphic, biogeochemical, and vegetation processes as needed to predict the evolution of a warming Arctic landscape and its feedback to the global climate system. This vision includes field observations; laboratory experiments; modeling of critical and interrelated water, nitrogen, carbon, energy dynamics; and important interactions from the molecular to the landscape scale that drive feedbacks to the climate system. Review of the proposal is scheduled for August 4, 2011.

Site selection trip planned for Council and Barrow:

The NGEE Team has arranged visits to potential field sites in Council and Barrow, Alaska for this coming August (see Appendix for tentative itinerary). The goal of the visit is to familiarize participates with tundra ecosystems found throughout Alaska and specifically to assess research sites along a bioclimatic gradient where NGEE Phase 1 activities are to take place. Nine scientists and engineers from across the NGEE team will travel to Alaska, as will a photographer. Participants will gather in Anchorage, then onto Nome where two days will be spent visiting potential field research sites in nearby Council. A charter flight will transport the team northward to Barrow (Figure 3). Intermediate stops along the way will familiarize researchers with the remote villages and ecosystems that surround the communities of Kougarok, Ivotuk, and Atqasuk. Team members will meet with local village councils in both Council and Barrow. Participants in the trip include Stan Wullschleger, Larry Hinzman, Susan Hubbard, Cathy Wilson, Rich Norby, Margaret Torn, David Graham, Alistair Rogers, and Keith Lewin.

Figure 3. Bowhead whale bones and Inupiaq boat frames welcome visitors to Barrow, Alaska.

Interactions with other Agencies, Universities, and National Laboratories

Preparation of the NGEE proposal provided a good opportunity to share our goals and objectives with others and identify areas of potential collaboration. Substantive discussions were held with the following projects and associated PIs.

- Regional Arctic System Model (RASM); PI Wieslaw Maslowski.
- Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE); PI Charles “Chip” Miller.
- Circumpolar Active Layer Monitoring (CALM); PI Nikolay Shiklomanov.
- Spatial and Temporal Influences of Thermokarst Failures on Surface Processes in Arctic Landscapes; co-PIs William Bowden and Michael Gooseff.

- Arctic Landscape Conservation Cooperative (LCC); Director Douglas Vincent-Lang.
- Arctic Network Inventory and Monitoring Program (ARCN); Greg Dudgeon, Superintendent, Gates of the Arctic National Park and Preserve; Frank Hays, Superintendent, Western Arctic Parklands; and Jeanette Pomrenke, Superintendent, Bering Land Bridge National Preserve.
- Critical Zone Observatories (CZO); co-PI Mark Williams.

Publications, Presentations, and Posters

Publications:

Graham D.E., M.D. Wallenstein, T.A. Vishnivetskaya, M.P. Waldrop, T.J. Phelps, S.M. Pfiffner, T.C. Onstott, L.G. Whyte, D. Gilichinsky, D.A. Elias, R. Mackelprang, N.C. VerBerkmoes, R.L. Hettich, D. Wagner, S.D. Wullschleger and J.K. Jansson (2011) Microbes in thawing permafrost: The unknown variable in the climate change equation. The ISME Journal: Multidisciplinary Journal of Microbial Ecology (in review).

Presentations:

April 3-5, 2011: Omics in the Arctic; JGI Strategic Planning Retreat, Asilomar, CA.

April 26-28, 2011. Next-Generation Ecosystem Experiments (NGEE Arctic); Subsurface Biogeochemistry Research (SBR) PI Meeting Washington DC.

Workshops Attended:

Subsurface Biogeochemistry Research (SBR) Data Management workshop, April 28-29, 2011. Washington DC.

The Arctic as a Messenger for Global Processes: Climate Change conference, May 3-6, 2011. Copenhagen, Denmark.

Vulnerability of Permafrost Carbon: Research Coordination Network, June 1-3, 2011. Seattle, WA.

Posters: None at this time.

Upcoming Meetings:

Third Santa Fe Conference on Global and Regional Climate Change, October 31 to November 3, 2011. Santa Fe, New Mexico. This conference will focus on climate change and variability from observational and modeling perspectives, climate forcings, and feedbacks at global and regional scales.

Press Releases and News Clips

None at this time.

Appendix

Is the northern high latitude land-based CO_2 sink weakening?

Daniel .J. Hayes, A. David McGuire, David W. Kicklighter, Kevin R. Gurney, and J.M. Melillo

Oak Ridge National Laboratory, Oak Ridge, TN
U.S. Geological Survey, Alaska Cooperative Fish and Wildlife Research Unit, University of Alaska Fairbanks, AK
The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA
Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN

Abstract:

Studies compiled by the Arctic Monitoring and Assessment Programme supported Arctic Carbon Cycle Assessment (McGuire et al., 2009) indicate that, historically, terrestrial ecosystems of the northern high latitude region may have been responsible for up to 60% of the global net land-based sink for atmospheric CO_2. However, these regions have recently experienced remarkable modification of the major driving forces of the carbon cycle, including surface air temperature warming that is significantly greater than the global average and associated increases in the frequency and severity of disturbances. Whether arctic tundra and boreal forest ecosystems will continue to sequester atmospheric CO_2 in the face of these dramatic changes is unknown. Here we show the results of model simulations that estimate a 41 Tg C yr^{-1} sink in the boreal land regions from 1997 to 2006, which represents a 73% reduction in the strength of the sink estimated for previous decades in the late 20th Century. Our results, along with those from a subset of atmospheric inversion models, suggest that CO_2 uptake by the region in previous decades may not be as strong as previously estimated. Our simulation experiments attribute the recent decline in sink strength as the combined result of 1) weakening sinks due to warming-induced increases in soil organic matter decomposition and 2) strengthening sources from pyrogenic CO_2 emissions as a result of the substantial area of boreal forest burned in wildfires across the region in recent years. Such changes create positive feedbacks to the climate system that accelerate global warming, putting further pressure on emission reductions to achieve atmospheric stabilization targets.

Tentative Itinerary

NGEE Field Recognizance Trip
Council and Barrow, Alaska

Participants: David Graham, Larry Hinzman, Susan Hubbard, Roy Kaltschmidt, Keith Lewin, Richard Norby, Alistair Rogers, Margaret Torn, Cathy Wilson, Stan Wullschleger

August 14 (Sunday): Anchorage, Alaska

August 15 (Monday): Nome, Alaska; meetings with local community members/CPS

August 16 (Tuesday): Visit field site in Council, Alaska; rental cars?

August 17 (Wednesday): Aerial flyover of Council and on to Barrow; Charter flight with Hageland Aviation Services (http://www.hageland.com/).

August 18 and 19 (Thursday and Friday): Visit potential field sites in Barrow, Alaska; discussions with BASC; meetings with local community.

August 19 (Friday): Depart; flight leaves Barrow around 8:00 pm, or

August 20 (Saturday): Depart; flight leaves Barrow around 11:00 am

Lodging:

Anchorage, Alaska
Holiday Inn Express Anchorage
4411 Spenard Road, Anchorage, AK 99517
Tel: 907-248-8848

Nome, Alaska
Aurora Inn & Suites
302 East Front Street
Tel: 907-443-3838

Barrow Arctic Science Consortium (BASC): Housing is already arranged.

Seminar

Modeling forest ecosystem C, N and water processes and interactions under climate warming and other environmental changes

Fengming Yuan
Institute of Arctic Biology, University of Alaska Fairbanks

Abstract:

Global climate warming and other environmental changes has impacted forest ecosystem in Northern America in terms of its biophysical and biogeochemical processes and interactions in a very complexity way. Modeling evolution, together with field investigations and experiments, would be an effective pathway to understand and/or disentangle various responses and feedbacks to those changes. For an example, by incorporating a N-modulated photosynthesis algorithm into Canadian Land Surface Scheme (CLASS), improvement in simulating forest GEP, NEP and indirectly transpiration at daily, monthly or yearly time-steps were detected for Canadian boreal and temperate forests. However, its incorporation into a climate model framework would need further proof. In a California mixed forest ecosystem, which receives almost the highest atmospheric N deposition in the nation, DAYCENT's capacity in modeling soil-plant C and N cycling might be different by coupling a finite element transient soil water flow module, HYDRUS. Compared to semi-dynamical water module (original DAYCENT module), transient water module driven DAYCENT produced higher NOx and methane emission and larger N leaching losses, although total water balance was not affected significantly. For high-latitude boreal forests, thickness-variable organic soil horizons would be a challenge to simulate its soil temperature and moisture dynamics under climate warming and fire regime change. A dynamic organic module specifically for this was developed and tested at basin-scale. It demonstrated its advantage to model boreal forest C stocks responding to climate warming and fire history. The implications and lessons from these researches to ecological and/or biogeochemical model development are discussed.

Host: Peter Thornton

Seminar

Rising methane emission from natural wetlands in northern permafrost region in the 2000s: Is the permafrost methane-climate feedback triggered?

Xiaofeng Xu
Auburn University

Abstract:

The northern mid-high latitudes are very important in global carbon cycle and climate warming due to the permafrost carbon-climate feedback which might trigger rapid climate warming if more carbon was released to the atmosphere as temperature rises. Given that the methane is more than twenty-five times stronger than carbon dioxide in terms of global warming potential, the feedback would be much stronger if the carbon releases as methane. Using a combination of an ecosystem model, site-level observations, and satellite data, the rising emission of methane from natural wetlands in the northern permafrost region was examined. The major factors were studied and identified. Among the multiple global change factors, the temperature is the major driving factor for rising methane emissions. The growing season dominated increases in methane emission indicates that the enhanced vegetation activity also contributes to the rising methane emission. The site-level large pulse of methane emission in spring thawing period was observed and extrapolated to the northern permafrost region; the methane emission during spring thawing period largely explains the recent increase in atmospheric methane concentration. Vegetation activity and spring thawing are two critical mechanisms in the permafrost methane-climate feedback yet needs more investigation in the near future. Incorporation of the permafrost methane-climate feedback into the regional climate model would be important and urgent.

Host: Peter Thornton