Next-Generation Ecosystem Experiments – NGEE Arctic

Quarterly Report
December 31, 2011

A progress report submitted to

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Program Manager
Department of Energy, Office of Science, Biological and Environmental Research

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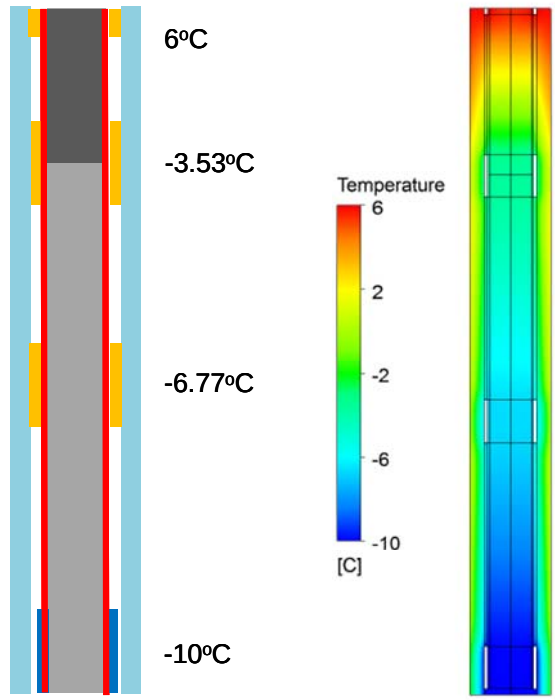
Complex Fluid Dynamics Model Used to Design Permafrost Simulator

The Arctic has long been a C sink, but it could become an important source of C to the atmosphere if a warmer climate leads to the release of vast quantities of stored C in excess of the annual net C uptake by terrestrial Arctic ecosystems. Predicting the fate of permafrost- sequestered carbon has been highlighted as a knowledge gap in recent reports. The nature, magnitude, and rates of these changes in the carbon cycle will depend on climate-driven changes in Arctic biogeochemical, vegetation, and hydrological processes, creating a critical feedback loop. A goal of the NGEE project is to assess the CO_2 and CH_4 flux from thawing permafrost using both field and laboratory approaches. In the laboratory, the approach will be one in which permafrost cores will be subjected to a range of temperatures under strict temperature-controlled conditions. David Graham and Charlotte Barbier, both of ORNL, have been simulating the design and performance of several approches that could be used to impose temperature gradients on permafrost cores. So far, ten designs have been examined, including one that would enclose the permafrost sample in a sleeve of highly conductive copper foil (shown in red) and then cooling coils placed at strategic locations along the length of a 48 inch core. The entire apparatus would then be wrapped in an insulating layer of polyurethane. Simulations reveal that the number and width of the areas cooled by the copper coils and temperature are two important parameters that ultimately affect vertical temperature profiles. It does appear, however, that a system can be designed in which realistic temperature gradients can be imposed and that an approach can be designed whereby a core can be manipulated in order to determine the influence of temperature on CO_2 and CH_4 flux from permafrost soils.



Simulation of temperature profile along permafrost core. Complex fluid dynamics modeling is being used to design and evaluate potential prototype before construction.

Details at a Glance

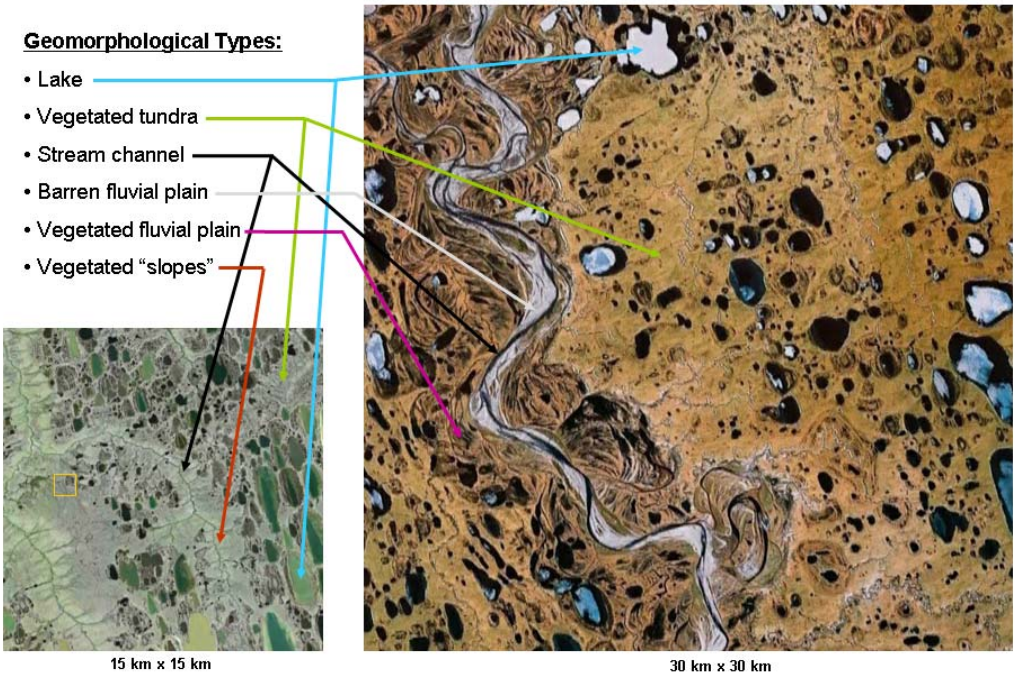
Activities during the October 1 to December 31, 2011 quarter include:

- Scaling white paper delivered to BER
- NGEE poster at AGU focuses on carbon cycle processes in a warmer Arctic
- Provider of logistical support in Barrow changes for the coming year
- NGEE holds first All-Hands meeting
- Sharlene Weatherwax receives briefing on NGEE Arctic project

Progress and Accomplishments

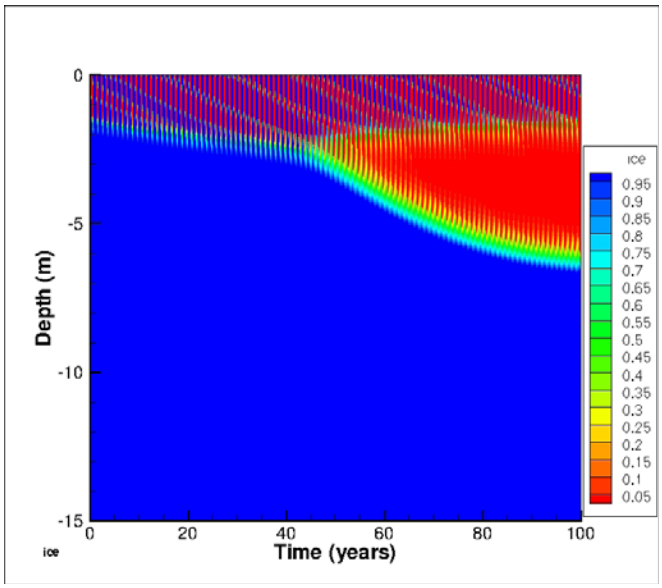
Scaling white paper submitted to BER:

One of the most difficult challenges we face is the NGEE project is how to optimally inform process representations in a global-scale model with knowledge and understanding gained through direct observation and process-resolving simulation at smaller scales – we call this the *up-scaling* problem. Of similar importance and just as daunting is the problem of how to provide appropriate large-scale context to guide strategies for direct observations and fine-scale simulation, allowing interpretation of results which can be meaningful at larger scales – what we refer to as the *down-scaling* problem. These two problems are clearly interrelated: appropriate large-scale context provided to guide measurement and process-resolving simulation is fruitless if no mechanism is in place to migrate new fine-scale knowledge to larger scales, while the up-scaled information itself is likely irrelevant if not conditioned in advance by the large-scale context. It is necessary, then, to solve the up-scaling and down-scaling problems together, referred to in tandem as the scaling problem. To help in this effort, the NGEE team led by Peter Thornton (ORNL) and Bill Riley (LBNL) submitted a white paper to BER describing how we would tackle the scaling problem in support of climate modeling. That white paper addressed a number of topics, but an important one was the identification of geomorphological land units that would guide our modeling and our measurements. This top-down perspective identifies the features on the landscape within which we must take our process measurements. An example for a landscape typical of the North Slope of Alaska is shown below. A second white paper has been requested by BER and will focus on how measurements will be incorporated into this scheme in order to achieve our goal sof 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 (ESM) grid cell (i.e., approximately 30x30 km grid size).



NGEE scientists focus on carbon cycle processes in thawing permafrost at AGU conference:

Cathy Wilson and NGEE colleagues from Los Alamos National Laboratory and Oak Ridge National Laboratory presented a poster at the recent American Geophysical Union meetings in San Francisco that illustrates the value of combining process understanding and modeling. The poster entitled "*Predicting CO_2 and CH_4 Emissions from the Active Layer in Response to Climate Warming*" was co-authored by Bryan Travis, Irena Ossola, Joel Rowland, and Stan Wullschleger. Permafrost resides beneath 25% of the land in the northern hemisphere. An estimated 1600 GT of carbon resides in permafrost. Observations and models suggest that permafrost is warming and thawing, the active layer is thickening, and previously frozen old soil carbon is being converted and released as CH_4 and CO_2. GHG release amounts and rates are poorly constrained, as is the ratio between CH_4 and CO_2. This ratio is important because CH_4 is significantly more powerful as a greenhouse gas than is CO_2. The arctic is projected to experience more precipitation, and more thermokarst pond and lake formation, both of which could result in wetter conditions that favor CH_4 production. At the same time, thermokarst depressions drain the surrounding soil and can lead to thermal erosion and drainage network expansion that promote drier soil conditions that favor CO_2 production. A numerical model named ARCHY was used to explore this question. It can operate in 1-D, 2-D or 3-D, is time-dependent, and includes vertical and lateral water and vapor and gas movement in soils and between soils and atmosphere, snow cover, heat transport, solar irradiation, precipitation, temperature, small scale topography, change of phase between water, ice and vapor, and the spatial distribution of aerobes, anaerobes, and methanotrophs. Simulations for a +6°C warming show a gradual increase in the depth of active layer, with an area of unfrozen soil or talik formed at depth beginning 50 years after the start of the simulations. In addition to these physical changes, significantly more CH_4 evolution occurs in a wet, anoxic column compared to the present day climate, while a drier, oxic column shows more CO_2 evolution but less CH_4. Amounts and rates of emissions can be quantified and related to soil moisture contents and climate temperature increases.



Annual pattern and depth of freeze and thaw of the active layer over 100 years of warming to targets of +6° C above present mean annual temperature.

Options for logistic support in Barrow, Alaska to change in 2012:

A letter was distributed on December 16, 2011 informing researchers of changes in the logistical support in the Barrow, Alaska area. The letter (see Appendix) was from the Ukpeagvik Inupiat Corporation (UIC) and addressed their role in the oversight and management of lands in the Barrow area, including the Barrow Environmental Observatory (BEO). The Barrow Arctic

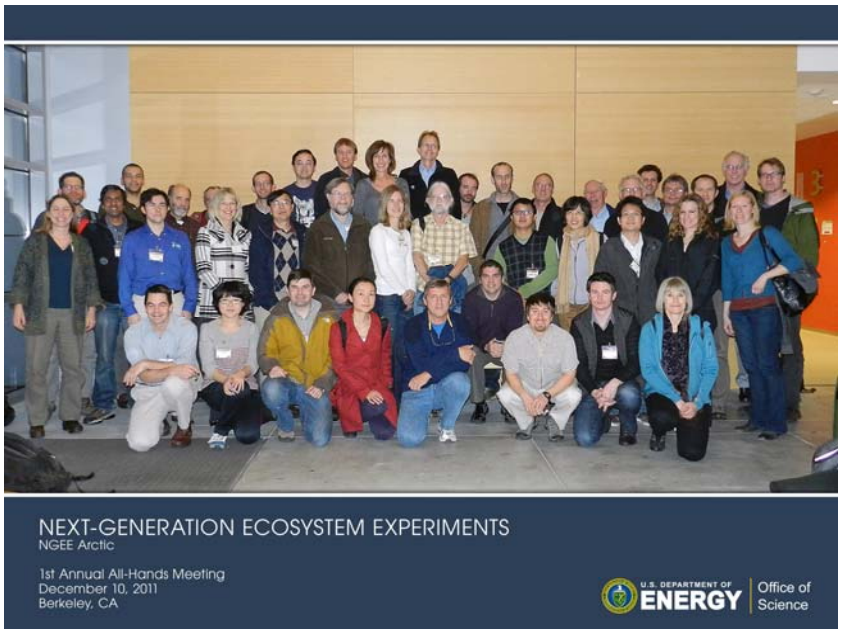
Science Consortium (BASC) will no longer be responsible for managing the UIC-owned BEO or other UIC properties on the former Naval Arctic Research Laboratory (NARL). Instead, logistical support for housing, land permits, etc. will be arranged through UMIAQ, a UIC-owned company and partner with CH2M Hill Poplar Services. Although NGEE has arranged local support through BASC in the past, this change is not expected to impact the project. Stan Wullschleger and Larry Hinzman plan to meet with UMIAQ and CH2M Hill Polar Services representations in mid-January to discuss FY12 activities in Barrow.

New LDRD project in land surface modeling initiated at ORNL:

A new project entitled "Coupled Simulation of Surface-Subsurface Hydrologic Processes and Terrestrial Ecosystem and Climate Feedbacks: From Arctic Landscapes to the Continental United States" was recently funded through the ORNL Laboratory Directed Research and Development (LDRD) program. This two-year modeling activity is led by Richard Tran Mills and his colleagues Forrest Hoffman, Gautam Bisht, Jitendra Kumar, Liyuan Liang, Melanie Mayes, Peter Thornton, and Stan Wullschleger. Richard and his team argued that representation of hydrologic processes in current land surface models suffer from an over-simplification or complete omission of physical processes. For example, most land surface models have a one-dimensional representation of subsurface flow and heat transport, a unidirectional flow from surface to subsurface, and no freeze-thaw dynamics. To enable to facilitate future data-model interactions, several important aspects of climate change impacts on hydrology and associated feedbacks, this project seeks to integrate detailed surface-subsurface thermal, hydrologic, and biogeochemical reaction models with comprehensive models of geophysical and land surface processes, using leadership-class supercomputers. Richard and others will develop models of rigorously coupled surface-subsurface hydrologic interactions and subsurface freeze-thaw dynamics, and integrate these into the massively parallel subsurface flow and reactive transport model PFLOTRAN. This extended PFLOTRAN model will be coupled with the Community Land Model (CLM), the land component of the Community Earth System Model (CESM), to enable novel studies, at field to regional scales, of the interactions between surface-subsurface hydrologic and biogeochemical processes and the terrestrial ecosystem and associated climate feedbacks, especially those related to hydrologically induced surface and subsurface carbon cycling. A particular motivation for this project comes from the desire to study permafrost degradation and the poorly-understood yet potentially large carbon-climate feedbacks that are believed by many to be taking place in the Arctic.

NGEE holds first All-Hands meeting at LBNL:

The NGEE project held its first annual All-Hands meeting December 10, 2011 at the Molecular Foundry, Lawrence Berkeley National Laboratory. One one-day event brought together 46 participants in the project. Discussions focused on an overview of activities in 2011, highlights from each of the 5 science themes, and then break-out sessions that allowed researchers plenty of time to discuss field and laboratory activities coming up in Year 1 of the project.



<u>NGEE scientists engage in several outreach activities at AGU</u>:

The AGU meeting was a busy time for NGEE scientists. Team members participated in three separate activities during the December 5-9 time period. A summary includes:

- **DOE's Terrestrial Ecosystem Sciences Town Hall: A Next Generation of Ecosystem Experiments.**

This town hall meeting on December 8, 2011 highlighted the goals and objectives of the Terrestrial Ecosystem Science (TES) program within the U.S. DOE, Office of Biological and Environmental Research. Mike Kuperberg presented the program's vision and funding strategy while emphasizing the Next-Generation Ecosystem Experiment (NGEE) project, a major 10-year effort in the Arctic. NGEE seeks to understand, characterize, and model the response of permafrost-dominated ecosystems to climate change. Larry Hinzman (UAF) presented his thoughts on Arctic science needs; followed by Peter Thornton (ORNL) who outlined the needs of the climate modeling community in high-latitude ecosystems. Stan Wullschleger (ORNL) then presented a short introduction to the NGEE project and closed with an invitation to a "Learn More" session where the community could learn how they could become more engaged in the project.

- **NGEE "Learn More" session.**

A special afternoon session was organized for December 9, 2011 at the San Francisco Marriott Marquis hotel where people interested in the NGEE project could come and hear more about specific research. Larry Hinzman presented an overview of the project and then Stan

Wullschleger lead participates in a discussion of research goals and objectives. Approximately 40 people attended and discussion was lively and supportive.

- **Briefing of BER Sharlene Weatherwax on NGEE.**

A session on Friday, December 9, 2011 was scheduled at the request of Mike Kuperberg to brief Associate Director of Science for Biological and Environmental Research Sharlene Weatherwax on the NGEE project. Sharlene was aware of the project and wanted to hear FY11 progress and plans for the coming year. Eleven members of the NGEE leadership team spent about 3 hours with Mike and Sharlene talking about the project.

Santa Fe Conference highlights ecosystem-climate feedbacks in the terrestrial Arctic:

Cathy Wilson, Larry Hinzman and Stan Wullschleger co-organized a special session at this year's Third Santa Fe Conference on Global and Regional Climate Change. The conference was held in Santa Fe, October 31 to November 4, 2011. The session was entitled "Understanding and predicting climate impacts and feedbacks in the terrestrial Arctic" and featured presentations by Ted Schuur (Carbon cycle process; University of Florida), Howard Epstein (shrub expansion, University of Virginia), Eugenie Euskirchen (carbon flux from tundra ecosystems, University of Alaska, Fairbanks), and David Lawrence (climate modeling, National Center for Atmospheric Research). The goal of the session was to highlight the synergy that exists between process understanding and global climate models for improved prediction.

Interactions with other Agencies, Universities, and National Laboratories

Eric Kasischke, University of Maryland visited ORNL on November 2, 2011. Eric presented a seminar on his research interests (see Appendix) and then engaged NGEE researchers in a series of discussions to explore interactions between NGEE and the NASA-sponsored Arctic-Boreal Vulnerability Experiment (ABoVE). The ABoVE project is a long-term international research initiative led by NASA. ABoVE is designed to produce new knowledge needed to understand how climate change impacts ecosystems in the High Northern Latitude region, and how these changes produce feedbacks to climate and are influencing ecosystem services. Through research that integrates and synthesizes geospatial information products generated from airborne and space borne remote sensors with data from field studies and ground-based monitoring, ABoVE will focus on addressing three key questions:

- *What patterns of changes in ecosystem dynamics and land surface characteristics have occurred over the past 25-50 years and are likely to occur in the near future (5 to 25 years) and over the longer term (25 to > 100 years)?*
- *What processes, interactions, and feedbacks control the vulnerability of Arctic and Boreal ecosystems and landscapes to structural and functional change in a changing climate?*
- *How will potential future changes to the land surface in Arctic and Boreal regions contribute to positive and negative feedbacks to local, regional and global climates?*

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 press).

Presentations:

Hubbard et al. 2011. Next-generation ecosystem experiments (NGEE Arctic). American Geophysical Union, December 5-9, 2011. San Francisco, CA.

Workshops Attended:

Critical Zone Observatories (CZO) workshop, November 8-10, 2011. University of Delaware, Newark, DE.

Research Coordination Network, Permafrost Vulnerability workshop, December 4, 2011, San Francisco, CA.

American Geophysical Union, December 5-9, 2011. San Francisco, CA.

Posters:

Wilson et al. 2011. Predicting CO_2 and CH_4 emissions from the active layer in response to climate warming. American Geophysical Union, December 5-9, 2011. San Francisco, CA.

Upcoming Meetings:

Joint Genome Institute (JGI), Genomics of Energy & Environment, 7th Annual DOE JGI User Meeting, March 20 - 22, 2012, Walnut Creek, California.
Web site: http://www.jgi.doe.gov/meetings/usermeeting/

European Geophysics Union, General Assembly, April 22-27, 2012, Vienna, Austria.
Web site: http://meetings.copernicus.org/egu2012/

Tenth International Conference on Permafrost, June 25-29, 2012, Salekhard, Russia.
Web site: http://www.ticop2012.org/

Press Releases and News Clips

LBNL News Center
A Trip to Alaska in Search of Future Climate Change:
http://newscenter.lbl.gov/feature-stories/2011/09/14/alaska-climate-change/

ORNL Today
Collaborative Effort Leads to Improved Climate Models of Changing Tundra
http://www.ornl.gov/info/features/get_feature.cfm?FeatureNumber=f20111123-00

NY Times
As Permafrost Thaws, Scientists Study the Risks
http://www.nytimes.com/2011/12/17/science/earth/warming-arctic-permafrost-fuels-climate-change-worries.html?_r=1&hp

Nature
Permafrost Science Heats up in the United States
http://www.nature.com/news/permafrost-science-heats-up-in-the-united-states-1.9681

Scientific American
Research to Examine Effect of Arctic Warming on Frozen Soils
http://www.scientificamerican.com/article.cfm?id=permafrost-science-heats-up

Appendix

December 16, 2011

UKPEAĠVIK INUPIAT CORPORATION

RE: UIC's Continued Commitment to Scientific Research in Barrow

Dear UIC stakeholder,

As President of Ukpeaġvik Inupiat Corporation (UIC), I would like to take this opportunity to communicate recent changes with regards to the support of scientific research activities in Barrow, Alaska. It is important to me that you and your organization hear directly from UIC regarding this matter, and that you understand UIC's continued commitment to the scientific research that is conducted in Barrow.

As you may be aware, UIC recently terminated the authority of the Barrow Arctic Science Consortium (BASC) to manage the UIC-owned Barrow Environmental Observatory (BEO) and other UIC properties, and has also terminated BASC's leases of UIC-owned buildings, including a number of buildings at the former Naval Arctic Research Laboratory (NARL). Although UIC has decided to part ways with BASC, UIC's decisions are not intended to prevent BASC from continuing to provide support services to the scientific community. These recent changes reflect UIC's desire to encourage and support research activities in our region in a manner that not only promotes an understanding of environmental changes and creates economic sustainability for our community, but is also consist with the mission and vision of UIC as set forth by our Board of Directors, including active oversight and management of our lands.

For purposes of assuring that full support and continuity are provided to any and all parties that may currently be conducting or supporting scientific research in Barrow, I would like to make you aware of the following resources that are available to your organization through UIC. For the convenience of the scientific community, each available resource includes a single point of contact.

1. ARCTIC LOGISTICS SUPPORT FOR RESEARCH ACTIVITIES FUNDED THROUGH THE NATIONAL SCIENCE FOUNDATION (NSF) AND OTHER AGENCIES. UIC will continue to support and encourage research activities with the NSF and other entities. UMIAQ, a UIC-owned company and partner of CH2M Hill Polar Services, was recently awarded a long-term contract with the

Corporate Headquarters | PO Box 890 | Barrow, AK 99723 | P 907.852.4460 | F 907.852.4459
Anchorage Office | 3201 C Street, Ste 801 | Anchorage, AK 99503 | P 907.677.5201| F 907.677.5280

NSF to provide logistical support services for Arctic research projects. UMIAQ provides a one-stop solution for researchers by providing not only logistical support, but local labor, equipment and lodging resources. UMIAQ supports a wide variety of research projects with their logistical needs, to include Arctic orientation, field support, bear guard/hazing, ice guides, permitting, and local communication. The single point of contact for coordinating logistics support for research activities is:

Dominique Fox, Project Coordinator, UMIAQ
Phone: (907) 273-1841 Email: dominique.fox@uicumiaq.com.

2. LAND USE PERMITS FOR SCIENTIFIC RESEARCH ON THE BEO AND OTHER UIC LANDS. The UIC Board of Directors is deeply committed to continuing the dedicated use of the BEO as a *"scientific research district … to conserve areas that have scientific value or have been used for scientific research."* Consistent with this direction, UIC will honor all existing land use permits for scientific research that were previously issued until such permits expire. In addition, UIC will continue to issue land use permits for scientific research to interested parties, but will do so exclusively through its subsidiary UMIAQ which will administer all such permits on behalf of the UIC Lands Department. Land use permits for scientific research meeting all applicable requirements will be recommended by UMIAQ for approval by the UIC Lands Department. The single point of contact for the processing of scientific land use permits is:

   Dominique Fox, Project Coordinator, UMIAQ
   Phone: (907) 273-1841 Email: dominique.fox@uicumiaq.com.

3. USE OF UIC-OWNED BUILDINGS AND PROPERTY, INCLUDING BUILDINGS AT THE FORMER NARL SITE. Although UIC has terminated all of BASC's leases of UIC-owned property, including a number of buildings at the former NARL site, UIC has a strong desire to ensure stability and continuity to all existing users of these buildings and property, as well as other members of the scientific community. All persons or entities that would like to utilize UIC-owned property at NARL or other locations are **strongly encouraged** to contact UIC Real Estate at their earliest possible convenience to make arrangements. UIC shall give the highest priority to all such requests and will do its best to ensure that all parties that have previously made use of UIC-owned property through BASC are provided every opportunity to enter into a direct leasing relationship with UIC Real Estate. The single point of contact for making arrangements for

use of UIC-owned buildings and property that were previously leased to BASC is:

Arnold Brower, Manager, UIC Real Estate
Phone: (907) 852-7464 Email: arnold.brower@ukpik.com.

In summary, I appreciate the opportunity to communicate these developments to you and look forward to continuing to support and partner with you in future endeavors. As we work through this transition, please know that I am available for questions or meetings as requested and can be reached at (703) 919-5548.

Quyanaq,

Anthony E. Edwardsen, President/CEO

SEMINAR ANNOUNCEMENT

""Feedbacks between climate, fire severity, and permafrost degradation in Alaskan black spruce forests"

Dr. Eric Kasischke
Professor of Biogeography
University of Maryland

Wednesday, November 2, 10:00 am
Building 2040 Room 278

Dr. Kasischke's research interests focus on two areas: **(1)** understanding how fire and the climate interact to influence ecosystem processes and carbon cycling in the world's boreal forests and peatlands; and **(2)** developing approaches to use spaceborne imaging synthetic aperture radar (SAR) to monitor spatial and temporal characteristics of the earth's land surface. In carrying out this research, he conducts inter-disciplinary research with ecologists, atmospheric scientists, carbon cycle modelers and scientists interested in using remote sensing to observe the effects of fire throughout the boreal region. His current research is focused in several areas: first, carrying out field-based research on patterns of fire severity and post-fire succession in Interior Alaska; second, carrying out analyses of how to use satellite imagery to assess fire severity and post-fire vegetation regeneration; third, assessing the degree to which SAR imagery can be used to monitor variations in soil moisture and inundation in boreal forests and peatlands; and fourth, developing approaches to integrate field and satellite observations to assess changes in terrestrial carbon cycling in the boreal region. Dr. Kasischke is also leading a synthesis effort on the impacts of disturbance on the terrestrial carbon budget for the North American Carbon Program (NACP). Finally, he is leading an effort to define a large-scale, multi-year field campaign for NASA's Terrestrial Ecology Program.

Host: Daniel Hayes 574-7322

E. A. SCHUUR

Abrupt thaw, as seen here in Alaska's Noatak National Preserve, causes the land to collapse, accelerating permafrost degradation and carbon release.

High risk of permafrost thaw

Northern soils will release huge amounts of carbon in a warmer world, say **Edward A. G. Schuur, Benjamin Abbott** and the Permafrost Carbon Network.

Arctic temperatures are rising fast, and permafrost is thawing. Carbon released into the atmosphere from permafrost soils will accelerate climate change, but the magnitude of this effect remains highly uncertain. Our collective estimate is that carbon will be released more quickly than models suggest, and at levels that are cause for serious concern.

We calculate that permafrost thaw will release the same order of magnitude of carbon as deforestation if current rates of deforestation continue. But because these emissions include significant quantities of methane, the overall effect on climate could be 2.5 times larger.

Recent years have brought reports from the far north of tundra fires[1], the release of ancient carbon[2], CH_4 bubbling out of lakes[3] and gigantic stores of frozen soil carbon[4]. The latest estimate is that some 18.8 million square kilometres of northern soils hold about 1,700 billion tonnes of organic carbon[4] — the remains of plants and animals that have been accumulating in the soil over thousands of years. That is about four times more than all the carbon emitted by human activity in modern times and twice as much as is present in the atmosphere now.

This soil carbon amount is more than three times higher than previous estimates, largely because of the realization that organic carbon is stored much deeper in frozen soils than was thought. Inventories typically measure carbon in the top metre of soil. But the physical mixing during freeze–thaw cycles, in combination with sediment deposition over hundreds and thousands of years, has buried permafrost carbon many metres deep.

The answers to three key questions will determine the extent to which the emission of this carbon will affect climate change: How much is vulnerable to release into the atmosphere? In what form it will be released? And how fast will it be released? These questions are easily framed, but challenging to answer.

KNOWN UNKNOWNS

As soils defrost, microbes decompose the ancient carbon and release CH_4 and carbon dioxide. Not all carbon is equally vulnerable to release: some soil carbon is easily metabolized and transformed to gas, but more complex molecules are harder to break down. The bulk of permafrost carbon will be released slowly over decades after thaw, but a smaller fraction could remain within the soil for centuries or longer. The type of gas released also affects the heat-trapping potential of the emissions. Waterlogged, low-oxygen environments are likely to contain microbes that produce CH_4 — a potent greenhouse gas with about 25 times more warming potential than CO_2 over a 100-year period. However, waterlogged environments also tend to retain more carbon within the soil. It is not yet understood how these factors will act together to affect future climate.

The ability to project how much carbon will be released is hampered both by the fact that models do not account for some important processes, and by a lack of data to inform the models. For example, most large-scale models project that permafrost warming depends on how much the air is warming above them. This warming then boosts microbial activity and carbon release. But this is a simplification. Abrupt thaw processes can cause ice wedges to melt and the ground surface to collapse, accelerating the thaw of frozen ground[5]. Evidence of rapid thaw is widespread: you can see it in the 'drunken' trees that tip dangerously as a result of ground subsidence, and in collapsed hill slopes marked by scars from landslides. These are just some of the complex processes that models don't include.

At the same time, few data are available to support these models because of the difficulties of gathering data in extreme environments. Only a handful of remote field stations around the world are collecting data to support this research, even though the permafrost zone covers about almost one-quarter

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of the Northern Hemisphere's land area. The field studies that do exist confirm that permafrost thaw is tightly linked to ground subsidence and soil moisture as well as temperature. So modelling carbon emissions from permafrost thaw is much more complex than a simple response to temperature alone.

Models have flaws, but experts intimately familiar with these landscapes and processes have accumulated knowledge about what they expect to happen, based on quantitative data and qualitative understanding of these systems. We have attempted to quantify this expertise through a survey developed over several years.

SURVEY SAYS

Our survey asks what percentage of the surface permafrost is likely to thaw, how much carbon will be released, and how much of that carbon will be CH_4, for three time periods and under four warming scenarios that will be part of the Intergovernmental Panel on Climate Change Fifth Assessment Report. The lowest warming scenario projects 1.5 °C Arctic warming over the 1985–2004 average by the year 2040, ramping up to 2 °C by 2100; the highest warming scenario considers 2.5 °C by 2040, and 7.5 °C by 2100. In all cases, we posited that the temperature would remain steady from 2100 to 2300 so that we could assess opinions about the time lag in the response of permafrost carbon to temperature change.

The survey was filled out this year by 41 international scientists, listed as authors here, who publish on various aspects of permafrost. The results are striking. Collectively, we hypothesize that the high warming scenario will degrade 9–15% of the top 3 metres of permafrost by 2040, increasing to 47–61% by 2100 and 67–79% by 2300 (these ranges are the 95% confidence intervals around the group's mean estimate). The estimated carbon release from this degradation is 30 billion to 63 billion tonnes of carbon by 2040, reaching 232 billion to 380 billion tonnes by 2100 and 549 billion to 865 billion tonnes by 2300. These values, expressed in CO_2 equivalents, combine the effect of carbon released as both CO_2 and as CH_4.

Our estimate for the amount of carbon released by 2100 is 1.7–5.2 times larger than those reported in several recent modelling studies[6–8], all of which used a similar warming scenario. This reflects, in part, our perceived importance of the abrupt thaw processes, as well as our heightened awareness of deep carbon pools. Active research is aimed at incorporating these main issues, along with others, into models.

Are our projected rapid changes to the permafrost soil carbon pool plausible? The survey predicts a 7–11% drop in the size of the permafrost carbon pool by 2100 under the high-warming scenario. That scale of carbon loss has happened before: a 7–14% decrease has been measured in soil carbon inventories across thousands of sites in the temperate-zone United Kingdom as a result of climate change[9]. Also, data scaled up from a single permafrost field site point to a potential 5% loss over a century as a result of widespread permafrost thaw[2]. These field results generally agree with the collective carbon-loss projection made by this survey, so it should indeed be plausible.

Across all the warming scenarios, we project that most of the released carbon will be in the form of CO_2, with only about 2.7% in the form of CH_4. However, because CH_4 has a higher global-warming potential, almost half the effect of future permafrost-zone carbon emissions on climate forcing is likely to be from CH_4. That is roughly consistent with the tens of billions of tonnes of CH_4 thought to have come from oxygen-limited environments in northern ecosystems after the end of the last glacial period[10].

All this points towards significant carbon releases from permafrost-zone soils over policy-relevant timescales. It also highlights important lags whereby permafrost degradation and carbon emissions are expected to continue for decades or centuries after global temperatures stabilize at new, higher levels. Of course, temperatures might not reach such high levels. Our group's estimate for carbon release under the lowest warming scenario, although still quite sizeable, is about one-third of that predicted under the strongest warming scenario.

Knowing how much carbon will be released from the permafrost zone in this century and beyond is crucial for determining the appropriate response. But despite the massive amount of carbon in permafrost soils, emissions from these soils are unlikely to overshadow those from the burning of fossil fuels, which will continue to be the main source of climate forcing. Permafrost carbon release will still be an important amplifier of climate change, however, and is in some ways more problematic: it occurs in remote places, far from human influence, and is dispersed across the landscape. Trapping carbon emissions at the source — as one might do at power plants — is not an option. And once the soils thaw, emissions are likely to continue for decades, or even centuries.

The scientific community needs to collect more data and develop more-sophisticated models to test the hypotheses presented by this survey. Fortunately, awareness of the problem is increasing and these are starting to happen. The US Department of Energy, for example, has initiated a project called Next-Generation Ecosystem Experiments — Arctic, which aims to improve the representation of these processes in large-scale models. NASA is pursuing an Arctic–Boreal Vulnerability Experiment, which aims to improve satellite observations of this region. The Vulnerability of Permafrost Carbon Research Coordination Network funded by the US National Science Foundation, of which we are part, is bringing together people and observations to synthesize results and validate models. These are just some of the many international initiatives aimed at filling these research gaps.

In the meantime, our survey outlines the additional risk to society caused by thawing of the frozen north, and underscores the urgent need to reduce atmospheric emissions from fossil-fuel use and deforestation. This will help to keep permafrost carbon frozen in the ground. ■

'Drunken' trees reveal areas of subsidence.

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