Climate Change Science Institute
Earth System Modeling

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National Geospatial Intelligence Agency Briefing
Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

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Climate Change Science Institute
Oak Ridge National Laboratory

Oak Ridge National Laboratory

2.2 Earth System Modeling. Improve understanding of the global Earth system, quantify and reduce uncertainties in predictions of Earth system models, and deliver actionable climate change knowledge by developing and applying models and computational tools, integrating models and observational data, and providing usable model results with characterized uncertainties to the impacts community.

1. Improve predictions of climate change and variability by enhancing process representations in Earth system models and conducting model experiments to quantify land-atmosphere feedbacks and biogeochemical, cloud, aerosol, and radiation feedbacks with the climate system.

2. Improve the computational efficiency and numerical accuracy of Earth system models by developing and applying computational performance tools and modern numerical algorithms and libraries to achieve unprecedented performance on Leadership-class computing resources.

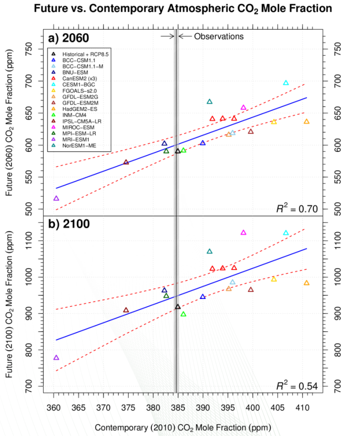
3. Assess multi-model fidelity by confronting models with observational data, applying uncertainty quantification methods, and developing model evaluation tools.

4. Deliver mission-relevant assessments of climate change and the influence of extreme events by analyzing multi-model projections at global, regional, and local scales over decades to centuries.

ESM Theme

Current Science Highlight

- **ACME (2.2.1, 2.2.2, 2.2.3, 2.5.2, 3.6)**. Multi-Lab project initiated Jul 1, 2014. ORNL leading land model (see TECCS Theme), workflow, and performance groups. *Posters 11, 26, 27, 29, 30, 31, 32, 33, 35.*
- **BGC Feedbacks SFA (2.2.3, 2.5.2, 2.5.3, 2.5.4, 3.6)**. Multi-Lab project initiated Oct 2014. ORNL leading overall project and development of next generation model evaluation package (with TECCS Theme). *Posters 11, 21, 22, 23, 24.*
- **NGEE Arctic (2.2.1, 2.2.3, 2.5.1, 2.5.3, 2.5.4, 3.6)**. Multi-Lab project led by ORNL (see TECCS Theme), contributing to landscape characterization and hydrology modeling. *Posters 13, 16.*
- **NGEE Tropics (2.2.1, 2.2.3, 2.5.1, 2.5.3, 2.5.4, 3.6)**. LBNL-led project approved Mar 2015. ORNL leading soil BGC (see TECCS Theme) and site selection, contributing to hydrology modeling, root traits, UQ, model evaluation, etc. *Poster 1.*



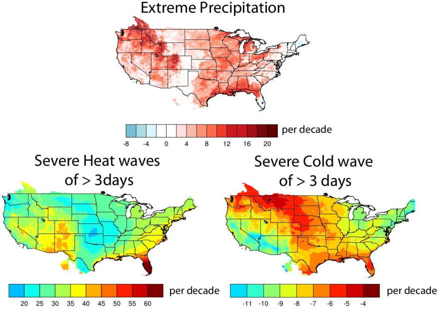
(Hoffman et al., 2014)

ESM Theme

Current Science Highlight

- **Computational efficiency & numerical accuracy (2.2.2)**. Supported by BER/ASCR SciDAC projects & ACME focused on numerical and computer performance bottlenecks & performance on current and future HPC platforms. *Posters 30, 32.*
- **Thermal-Hydrology (2.2.1, 2.2.2, 3.6)**. An improved representation is being developed in TH mode for the PFLOTRAN model for NGEE Arctic. *Poster 13.*
- **LIVV refactoring (2.2.2, 2.5.4)**. The Land Ice Verification and Validation suite was refactored to improve extensibility and performance tracking. *Poster 34.*
- **Downscaled climate projections (2.2.4, 2.5.5, 3.4, 3.6)**. Projections supporting research and energy and water impacts assessments at ORNL, Georgia Tech, Bonneville Power Administration, University of Illinois, Loyola Marymount, Stanford, and South Dakota State. *Poster 36, 52, 53.*

Future Changes (2011-2050 minus 1966-2005) in Climate Extremes



(Ashfaq et al.)

ESM Theme

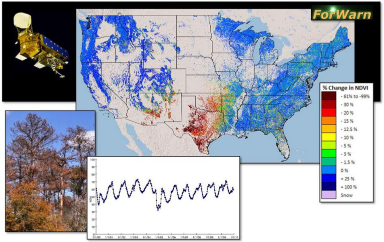
Current Science Highlight

- **ACME model simulations (2.2.1, 3.4, 3.6)**. Coupled simulations are being conducted to establish the v0.1 baseline for the ACME ESM. *Poster 33.*

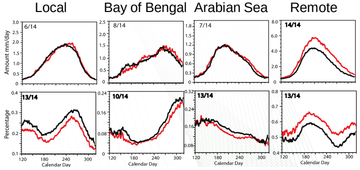
- ***ForWarn* (2.5.3, 3.4, 3.6)**. Continuing development and analyses for vegetation tracking. The *ForWarn* system was included in the U.S. Climate Resilience Toolkit's "Top 25" tools. *Poster 12.*

- **Scalable preconditioner (2.2.2, 3.4)**. A scalable preconditioner was developed in collaboration with partner institutions for the Multiscale SciDAC project.

- **South Asian monsoon (2.2.1)**. Errors in surface energy fluxes during pre-monsoon phase may be a key driver of weaker-than-normal South Asian summer monsoon bias in CMIP5 models.



Absolute and % Contributions to the South Asian Monsoon (Late 20th & 21st Century)



CMIP5 1965-2005 (**black**), CMIP5 RCP8.5 2070-2099 (**red**)
(Mei et al., 2015)

ESM Theme

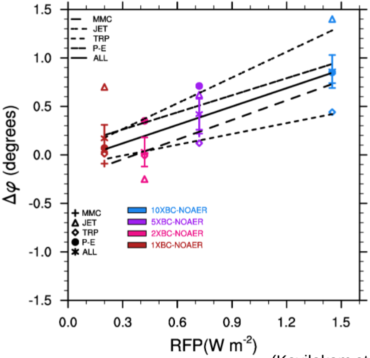
Current Science Highlight

- **Correlation-based regionalization framework (2.5.6)**. Framework being developed to improve sampling of extreme events for evaluating high-resolution simulations of climate extremes. *Poster 26.*

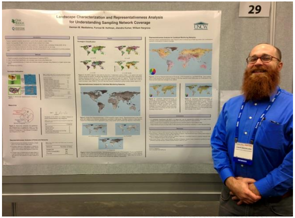
- **Black carbon aerosols (2.2.1)**. Testing the sensitivity of tropical width to BC-induced mid-latitude tropospheric heating. *Poster 25.*

- **AGU & AMS (3.2, 3.3, 3.5)**. Theme members organized or co-organized at least 5 sessions and were presenting-authors for 3 oral (1 invited) and 6 poster (1 invited) presentations and co-authors for 11 oral (6 invited) and 17 poster (1 invited) presentations. For the 95th AMS Annual Meeting, Theme members were presenting-authors for 2 posters and co-authors for 4 posters.

Sensitivity of Tropical Width to Black Carbon-Induced Heating



(Kovilakam et al.)



Postdoc Damian Maddalena at the AGU Fall Meeting

ESM Theme

Current Science Highlight

- **ICCS 2015 (3.2, 3.3, 3.5)**. Co-organizing workshop on "Numerical and Computational Developments to Advance Multi-scale Earth System Models" and "Sixth Workshop on Data Mining in Earth System Science". Two Theme members presenting papers in June.
- **Peer-reviewed literature (2.2.1, 2.2.2, 2.2.3, 2.2.4, 3.5)**. Theme members were authors or co-authors for at least 9 new peer-reviewed papers.
- **Staffing (3.7)**. Three postdocs have departed, one postdoc joined, and two staff members were added (one of which was converted from a CCSI postdoc).
- **ESM and Data Theme meeting (2.5.2, 3.6)**. Joint ESM–Data Theme (including TECCS) on model evaluation and best-available observational data.
- **Hosted Robert Dickinson and Rong Fu (3.1, 3.4)**. Two-day discussions on land-atmosphere interactions and potential collaborative opportunities.
- **March Visit to PNNL (3.4, 3.6)**. Theme discussed collaborations on impacts, adaptation, and vulnerability science and extreme events (includes IAV).

ESM Theme

Current Science Highlight

- **ICTP visiting scientist (3.2, 3.3)**. Moet Ashfaq served as visiting scientist for developing countries for International Center for Theoretical Physics (ICTP) in Trieste, Italy, and conducted a four week workshop in Islamabad, Pakistan, on the use of Earth system models in climate change impact assessments.

- **C^4MIP SSC for CMIP6 (3.3)**. Forrest Hoffman serving on SSC to define protocol, model outputs, and model evaluation for BGC experiments for CMIP6.

- **Postdoc visit to PNNL (3.4, 3.7)**. Tianyu Jiang was a visiting scientist at PNNL during March 2015, working on analysis of atmospheric dynamics in ESMs.

- **EOA 2016 (3.3)**. Forrest Hoffman serving on Earth Observation Assessment for Climate Societal Benefit Area (SBA) to inform federal agencies and OSTP.

- **Southern Appalachian Science & Engineering Fair (SASEF) (3.2, 3.3)**. Min Xu served as judge for regional science fair in March 2015.

- **ESM modeling workshop (3.2, 3.4, 3.6)**. Theme will conduct a Lab-wide workshop on ESM modeling and analysis to foster collaboration, improve CCSI integration, and provide outreach to other parts of ORNL on June 9, 2015.

ESM Theme

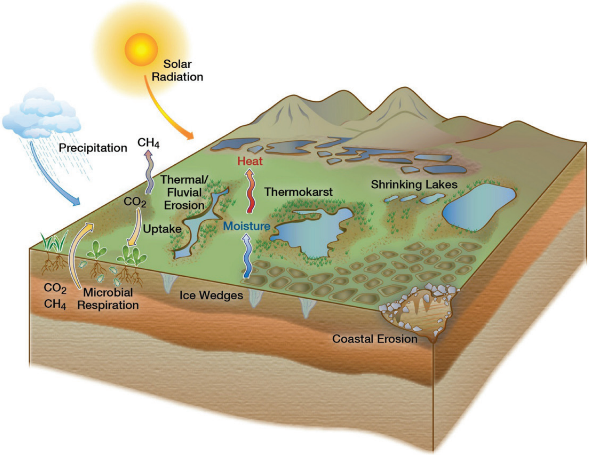
Future Opportunities

- **Mid-term SciDAC proposal (2.2.2, 3.3)**. Theme developing a multi-Lab proposal titled “Launching an Extreme-scale ACME Prototype” for a new project focused on performance portability for the ACME ESM (due May 4).
- **NGEE Arctic Phase 2 proposal (2.2.1, 2.2.3, 3.4, 3.6)**. Multi-Lab project led by TECCS, contributing to site selection and hydrology modeling (due May 15).
- **NASA National Climate Assessment proposal (2.5.3, 3.4, 3.6)**. Collaboration on TECCS-led proposal in collaboration with USDA Forest Service on phenological indicators for climate.
- **NASA ABoVE proposal (2.5.1, 2.5.3, 3.4, 3.6)**. Collaboration on CalTech/JPL-led proposal on site characterization and scaling for Arctic/boreal measurements.
- **Venµs proposal (2.5.1, 3.3, 3.4, 3.6)**. Led proposal (with TECCS) for an international collaboration on tropical ecology to access satellite imagery from a micro-sat being developed by France and Israel.

Site and Network Representativeness

Next-Generation Ecosystem Experiments (NGEE Arctic)

http://ngee.ornl.gov/



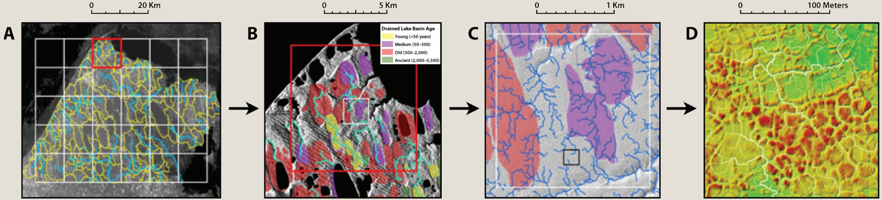
The Next-Generation Ecosystem Experiments (NGEE Arctic) project is supported by the Office of Biological and Environmental Research in the DOE Office of Science.

U.S. DEPARTMENT OF ENERGY · OAK RIDGE National Laboratory · Los Alamos NATIONAL LABORATORY · BERKELEY LAB · BROOKHAVEN NATIONAL LABORATORY · UAF UNIVERSITY OF ALASKA FAIRBANKS

Integrating Across Scales

- NGEE Arctic process studies and observations are strongly linked to model development and application for improving process representation, initialization, calibration, and evaluation.
- A hierarchy of models will be deployed at fine, intermediate, and climate scales to connect observations to models and models to each other in a quantitative up-scaling and down-scaling framework.

Hydrologic and Geomorphic Features at Multiple Scales. *At the scale of (A) a high-resolution ESM, (B) a single ESM grid cell, (C) a 2 × 2 km domain of high-resolution Light Detection and Ranging (LiDAR) topographic data, and (D) polygonal ground. Yellow outlines in panel A show geomorphologically stable hydrologic basins, connected by stream channels (blue). Colored regions in panels B and C show multiple drained thaw lake basins within a single 10 × 10 km grid cell (B) or a 2 × 2 km domain (C), with progressively more detailed representation of stream channels (blue). Colors in panel D represent higher (red) to lower (green) surface elevations for a fine-scale subregion, with very fine drainage features (white). [Los Alamos National Laboratory, University of Alaska Fairbanks, and University of Texas at El Paso]*



Quantitative Sampling Network Design

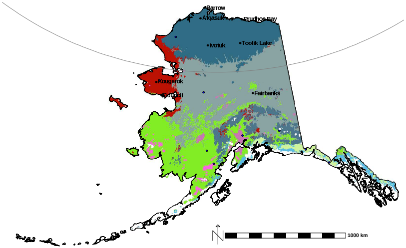
- Resource and logistical constraints limit the frequency and extent of observations, necessitating the development of a systematic sampling strategy that objectively represents environmental variability at the desired spatial scale.
- Required is a methodology that provides a quantitative framework for informing site selection and determining the representativeness of measurements.
- Multivariate spatiotemporal clustering (MSTC) was applied at the landscape scale (4 km^2) for the State of Alaska to demonstrate its utility for representativeness and scaling.
- An extension of the method applied by Hargrove and Hoffman for design of National Science Foundation's (NSF's) National Ecological Observatory Network (NEON) domains.

Data Layers

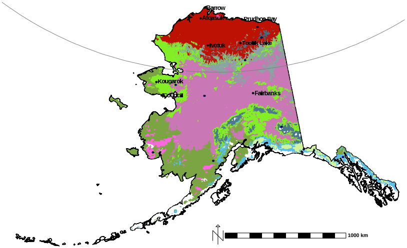
Table: 37 characteristics averaged for the present (2000–2009) and the future (2090–2099).

Description	Number/Name	Units	Source
Monthly mean air temperature	12	$^\circ$C	GCM
Monthly mean precipitation	12	mm	GCM
Day of freeze	mean	day of year	GCM
	standard deviation	days	
Day of thaw	mean	day of year	GCM
	standard deviation	days	
Length of growing season	mean	days	GCM
	standard deviation	days	
Maximum active layer thickness	1	m	GIPL
Warming effect of snow	1	$^\circ$C	GIPL
Mean annual ground temperature at bottom of active layer	1	$^\circ$C	GIPL
Mean annual ground surface temperature	1	$^\circ$C	GIPL
Thermal offset	1	$^\circ$C	GIPL
Limnicity	1	%	NHD
Elevation	1	m	SRTM

10 Alaska Ecoregions, Present and Future



2000–2009

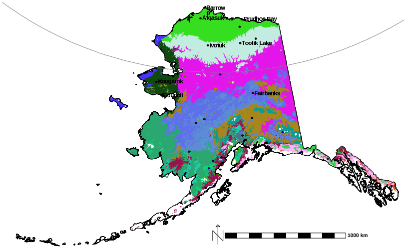


2090–2099

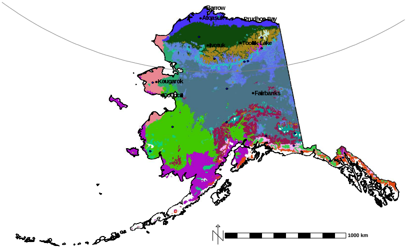
(Hoffman et al., 2013)

Since the random colors are the same in both maps, a change in color represents an environmental change between the present and the future. At this level of division, the conditions in the large boreal forest become compressed onto the Brooks Range and the conditions on the Seward Peninsula "migrate" to the North Slope.

20 Alaska Ecoregions, Present and Future



2000–2009

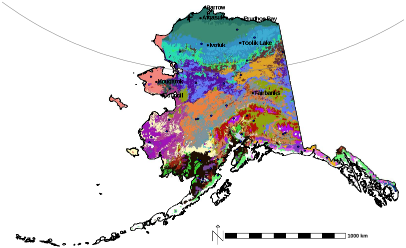


2090–2099

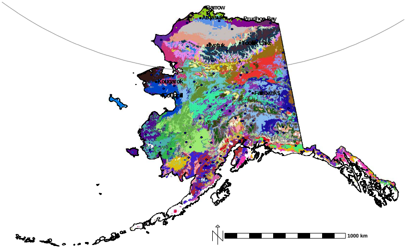
(Hoffman et al., 2013)

Since the random colors are the same in both maps, a change in color represents an environmental change between the present and the future. At this level of division, the two primary regions of the Seward Peninsula and that of the northern boreal forest replace the two regions on the North Slope almost entirely.

50 and 100 Alaska Ecoregions, Present



$k = 50$, 2000–2009



$k = 100$, 2000–2009

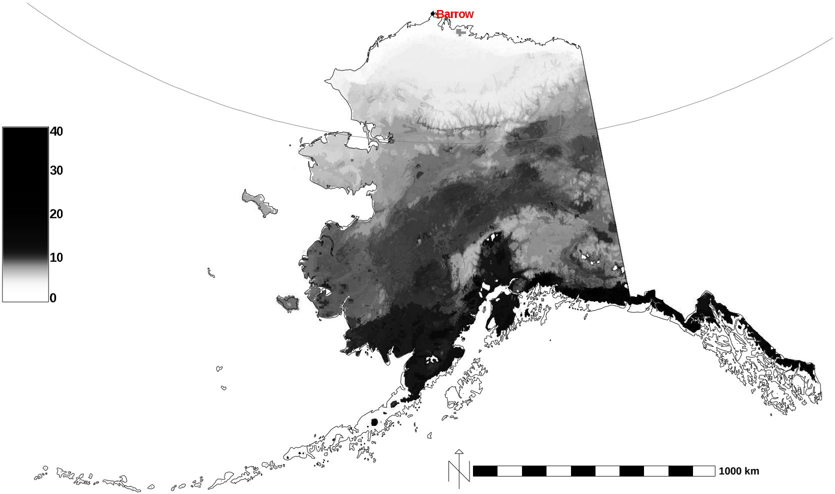
(Hoffman et al., 2013)

Since the random colors are the same in both maps, a change in color represents an environmental change between the present and the future. At high levels of division, some regions vanish between the present and future while other region representing new combinations of environmental conditions come into existence.

NGEE Arctic Site Representativeness

- This representativeness analysis uses the standardized *n*-dimensional data space formed from all input data layers.
- In this data space, the Euclidean distance between a sampling location (like Barrow) and every other point is calculated.
- These data space distances are then used to generate grayscale maps showing the similarity, or lack thereof, of every location to the sampling location.
- In the subsequent maps, white areas are well represented by the sampling location or network, while dark and black areas as poorly represented by the sampling location or network.
- This analysis assumes that the climate surrogates maintain their predictive power and that no significant biological adaptation occurs in the future.

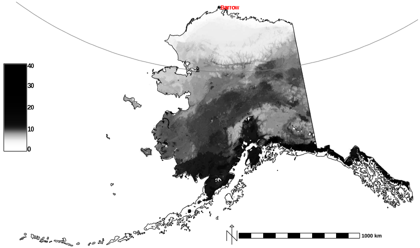
Present Representativeness of Barrow or “Barrow-ness”



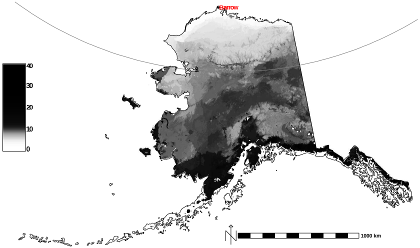
(Hoffman et al., 2013)

Light-colored regions are well represented and dark-colored regions are poorly represented by the sampling location listed in **red**.

Present vs. Future Barrow-ness



2000–2009

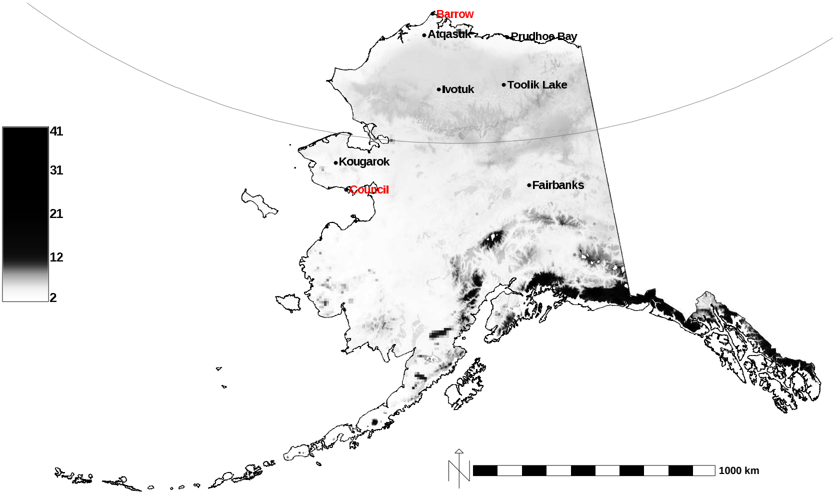


2090–2099

(Hoffman et al., 2013)

As environmental conditions change, due primarily to increasing temperatures, climate gradients shift and the representativeness of Barrow will be reduced in the future.

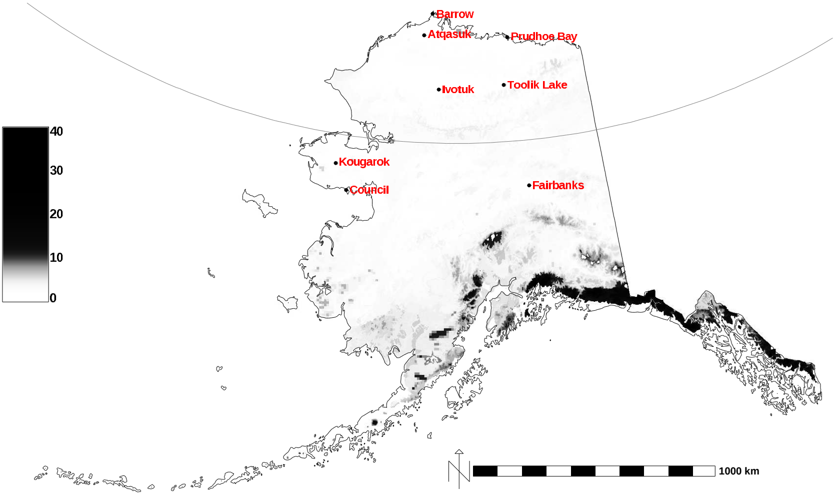
Network Representativeness: Barrow + Council



(Hoffman et al., 2013)

Light-colored regions are well represented and dark-colored regions are poorly represented by the sampling location listed in **red**.

Network Representativeness: All 8 Sites



(Hoffman et al., 2013)

Light-colored regions are well represented and dark-colored regions are poorly represented by the sampling location listed in **red**.

State Space Dissimilarities: 8 Sites, Present (2000–2009)

Table: Site state space dissimilarities for the present (2000–2009).

Sites	Council	Atqasuk	Ivotuk	Toolik Lake	Kougarok	Prudhoe Bay	Fairbanks
Barrow	9.13	4.53	5.90	5.87	7.98	3.57	12.16
Council		8.69	6.37	7.00	2.28	8.15	5.05
Atqasuk			5.18	5.23	7.79	1.74	10.66
Ivotuk				1.81	5.83	4.48	7.90
Toolik Lake					6.47	4.65	8.70
Kougarok						7.25	5.57
Prudhoe Bay							10.38

(Hoffman et al., 2013)

State Space Dissimilarities: 8 Sites, Present and Future

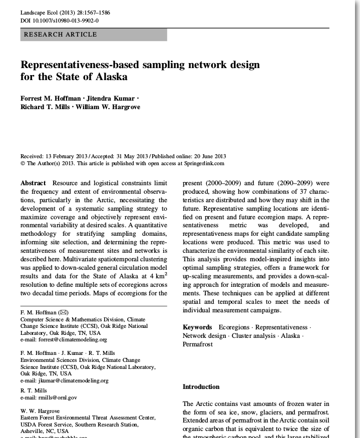
Table: Site state space dissimilarities between the present (2000–2009) and the future (2090–2099).

		Future (2090–2099)							
	Sites	Barrow	Council	Atqasuk	Ivotuk	Toolik Lake	Kougarok	Prudhoe Bay	Fairbanks
Present (2000–2009)	Barrow	3.31	9.67	4.63	6.05	5.75	9.02	3.69	11.67
	Council	8.38	1.65	8.10	5.91	6.87	3.10	7.45	5.38
	Atqasuk	6.01	9.33	2.42	5.46	5.26	8.97	2.63	10.13
	Ivotuk	7.06	7.17	5.83	1.53	2.05	7.25	4.87	7.40
	Toolik Lake	7.19	7.67	6.07	2.48	1.25	7.70	5.23	8.16
	Kougarok	7.29	3.05	6.92	5.57	6.31	2.51	6.54	5.75
	Prudhoe Bay	5.29	8.80	3.07	4.75	4.69	8.48	1.94	9.81
	Fairbanks	12.02	5.49	10.36	7.83	8.74	6.24	10.10	1.96

(Hoffman et al., 2013)

Representativeness: A Quantitative Approach for Scaling

- MSTC provides a quantitative framework for stratifying sampling domains, informing site selection, and determining representativeness of measurements.
- Representativeness analysis provides a systematic approach for up-scaling point measurements to larger domains.



Landscape Ecol (2013) 28:1567–1586
DOI 10.1007/s10980-013-9902-0

RESEARCH ARTICLE

Representativeness-based sampling network design for the State of Alaska

Forrest M. Hoffman · Jitendra Kumar · Richard T. Mills · William W. Hargrove

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Abstract Resource and logistical constraints limit the frequency and extent of environmental observations, particularly in the Arctic, necessitating the development of a systematic sampling strategy to maximize coverage and objectively represent environmental variability at desired scales. A quantitative methodology for stratifying sampling domains, informing site selection, and determining the representativeness of measurement sites and networks is described here. Multivariate spatiotemporal clustering was applied to down-scaled general circulation model results and data for the State of Alaska at 4 km^2 resolution to define multiple sets of ecoregions across two decadal time periods. Maps of ecoregions for the present (2000–2009) and future (2090–2099) were produced, showing how combinations of 37 characteristics are distributed and how they may shift in the future. Representative sampling locations are identified on present and future ecoregion maps. A representativeness metric was developed, and representativeness maps for eight candidate sampling locations were produced. This metric was used to characterize the environmental similarity of each site. This analysis provides model-inspired insights into optimal sampling strategies, offers a framework for up-scaling measurements, and provides a down-scaling approach for integration of models and measurements. These techniques can be applied at different spatial and temporal scales to meet the needs of individual measurement campaigns.

Keywords Ecoregions · Representativeness · Network design · Cluster analysis · Alaska · Permafrost

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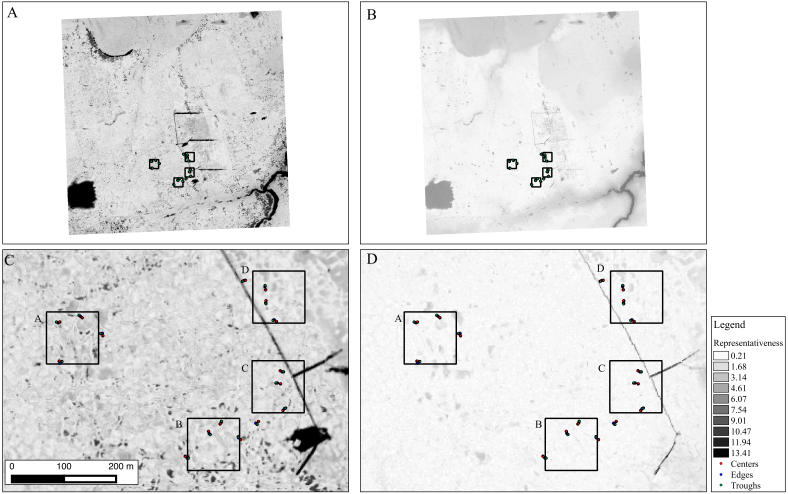
Introduction

The Arctic contains vast amounts of frozen water in the form of sea ice, snow, glaciers, and permafrost. Extended areas of permafrost in the Arctic contain soil organic carbon that is equivalent to twice the size of

- Methodology is independent of resolution, thus can be applied from site/plot scale to landscape/climate scale.
- It can be extended to include finer spatiotemporal scales, more geophysical characteristics, and remote sensing data.

Hoffman, F. M., J. Kumar, R. T. Mills, and W. W. Hargrove (2013), Representativeness-based sampling network design for the State of Alaska, *Landscape Ecol.*, 28(8):1567–1586, doi:10.1007/s10980-013-9902-0.

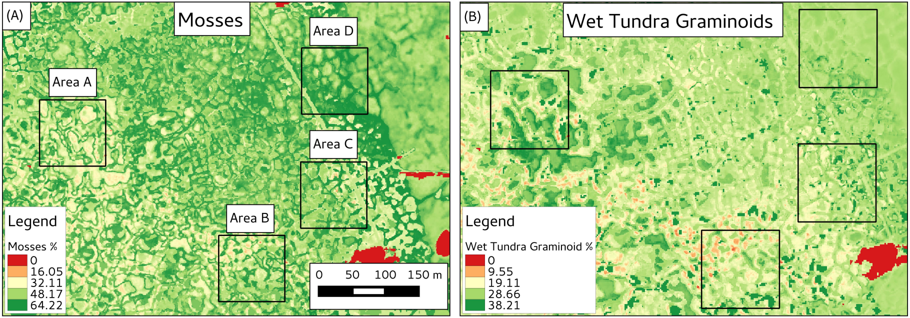
Barrow Environmental Observatory (BEO)



(Langford et al., in prep)

Representativeness map for vegetation sampling points in A, B, C, and D sampling area including phenology (left) and for a single date (right), based on WorldView2 satellite images for the year 2010 and LiDAR data.

Barrow Environmental Observatory (BEO)

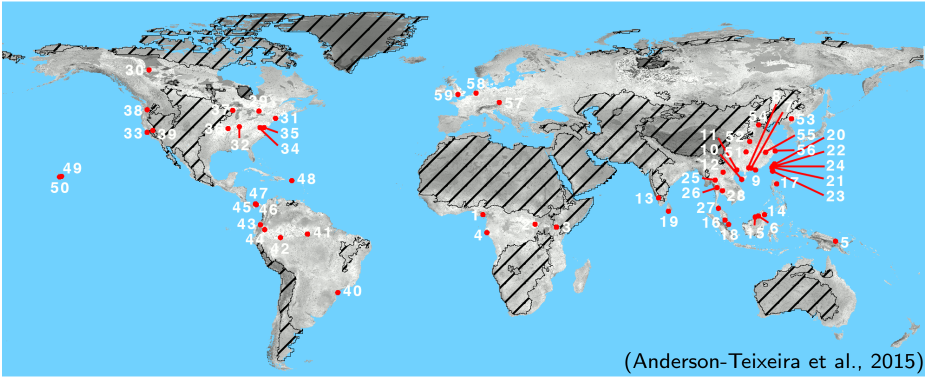


(Langford et al., in prep)

Mosses and wet tundra graminoids PFT % for Areas A, B, C, D.

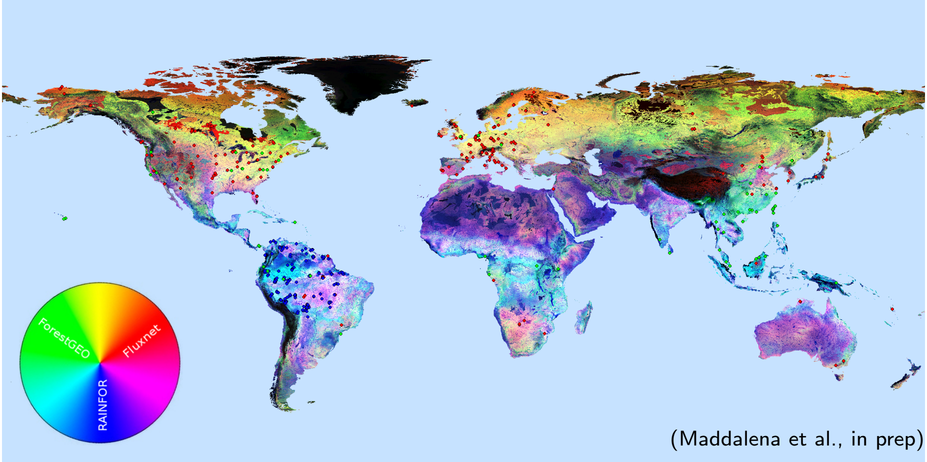
Example plant functional type (PFT) distributions scaled up from vegetation sampling locations.

ForestGEO Network Global Representativeness



Map illustrating ForestGEO network representation of 17 bioclimatic, edaphic, and topographic conditions globally. Light-colored regions are well represented and dark-colored regions are poorly represented by the ForestGEO sampling network. Stippling covers non-forest areas.

Triple-Network Global Representativeness



Map indicates which sampling network offers the most representative coverage at any location. Every location is made up of a combination of three primary colors from Fluxnet (red), ForestGEO (green), and RAINFOR (blue).

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