Collaborative Research: Greening of the Arctic: Synthesis and models to examine pan-Arctic vegetation change: climate, sea-ice, and terrain linkages

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INTRODUCTION

The GOA-SASS project

Greening of the Arctic (GOA) is one of 228 endorsed projects of the International Polar Year. It addresses the question "*Does the rapid decline of Arctic sea ice affect the tundra and those who depend on it?*" The goals of GOA are to document and analyze the changes to terrestrial vegetation that are occurring across the circumpolar Arctic as a result of climate change. GOA consists of a group of scientists who are part of four funded projects: (1) A North American Arctic Transect, funded by NSF; (2) a Eurasian transect on the Yamal Peninsula, Russia, funded by NASA; (3) the Arctic Geobotanical Atlas, an educational/outreach component funded by NSF; and (4) synthesis and models to examine pan-Arctic vegetation change: climate, sea-ice, and terrain linkages (GOA-SASS), which was funded as part of the NSF Synthesis of Arctic System Science (SASS) initiative. This report contains the major activities and findings from the GOA-SASS component.

Background

The Arctic system has recently been undergoing some dramatic changes in both the structure and function of its components. One of the most apparent changes is the reduction in the extent and thickness of the summer sea ice during the past 30+ years (Stroeve et al. 2008). The extent of the perennial sea ice has declined at the rate of -10.1 percent per decade (Comiso et al. 2008), and the especially rapid retreat of sea-ice in 2005 and 2007 led to increased speculation that the Arctic Ocean may be ice free within this century (Stroeve et al. 2008). Another change is the increased summer greenness of the Arctic as detected using space-based sensors (Jia et al. 2003, Goetz et al. 2005, Bunn et al. 2007). A 17% increase in the greenness index occurred in northern Alaska during 1981-2001 (Jia et al. 2003), and similar changes in tundra greenness were observed for other areas of North America and the whole Arctic (Goetz et al., 2005, Bunn et al. 2007). These changes are attributed to an increase in the extent and abundance of shrubs (Sturm et al. 2001, Tape et al. 2006, Walker et al. 2006), a northward movement of trees from the sub-arctic (Lloyd 2005, Lloyd and Bunn 2007), longer growing seasons and increasing land temperatures (Jia et al., 2003, Goetz et al. 2005).

One, often overlooked, feature of the Arctic tundra is its intimate relationship with the Arctic Ocean and sea ice. Eighty percent of the Arctic tundra (3.2 million km^2) is within 100 km of at least seasonally frozen seawaters that provide the cool summer temperatures necessary for tundra's presence. In other words, the tundra biome is essentially a maritime biome that owes its existence to the summertime cap of cold air centered over the frozen Arctic Ocean. Changes to the boundary of the perennial ice in the Arctic will likely affect a wide variety of other changes to the Arctic System, including northward migration of extra-tropical cyclones, general warming of the land surfaces, increased productivity of the tundra, and a reduction in the extent of the tundra biome.

There is apparently at least a strong correlation (if not causation) between what occurs in the ocean and what happens on land (Lawrence et al. 2008, Bhatt et al. 2008 in prep.-a, b). Lawrence et al. (2008) found, using the Community Climate System Model (CCSM3) (Holland et al. 2006), that rapid sea ice loss triggered accelerations in the rate of terrestrial temperature increases, extending up to 1500 km inland, with peak influences in autumn following the time of minimum Arctic sea ice near mid-September. Important system feedbacks can result from these various changes (Fig. 1). A decreased arctic sea-ice extent leads to a reduction in albedo, greater surface radiation absorption, increased latent heat, and potentially warmer ocean and air temperatures. Warmer ocean and air temperatures could be a positive feedback for continuing ice reduction. On the terrestrial side, earlier snowmelt and taller vegetation also lead to a reduction in albedo, with potentially greater surface and near-surface warming, which again can be a positive feedback for increased rates of snowmelt and vegetation growth. A recent lengthening of the growing season by 2.5 days per decade on the North Slope of Alaska could account for approximately 3.3 Watts m^{-2} $decade^{-1}$ in additional local atmospheric heating, comparable to a doubling of atmospheric CO_2 (Chapin et al. 2005).

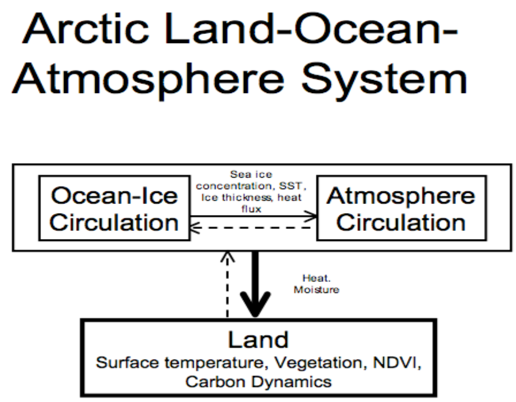

Figure 1. Simple Arctic system diagram emphasizing the effects of the Ocean-Ice and Atmosphere components on the Land component and feedbacks between the components.

If the land surfaces in the Arctic warm as predicted, changes in green biomass can be expected across the entire bioclimate gradient from treeline to the coldest parts of the Arctic. This will affect the permafrost and active layer, carbon reserves, trace-gas fluxes and carbon cycle, hydrological systems, biodiversity, wildlife populations, and the habitability of the Arctic. Changes in the vegetation will also affect the surface albedo with feedbacks to the global climate system. However, before future states of tundra ecosystems can be modeled, it is first necessary to better characterize how the current distribution of pan-Arctic plant communities and tundra production patterns are related to existing climate, sea ice, and terrain variables.

Goals of the project

GOA-SASS has the following overarching goals: (1) analyze the climate/sea-ice/terrain/vegetation linkages by synthesizing a group of recently available long-term circumpolar databases and (2) use this information in combination with models to help predict future response of arctic vegetation.

In this GOA synthesis project we have analyzed a variety of circumpolar maps and remote sensing data to examine the underlying causes of pan-Arctic vegetation change. We have furthermore developed a variety of modeling tools to help predict the consequences of tundra warming at several scales. A synthesis of these circumpolar data sets is especially appropriate now during the International Polar Year. This synthesis is particularly relevant in the U.S. (Alaskan) portion of the Arctic because the sea-ice losses in the Beaufort Sea, north of Alaska, and the changes in land-surface temperatures in the Alaska Arctic are the among the most dramatic in the circumpolar region. Results from this study show that between 1982 and 2007, sea ice in the 50-km coastal strip of the Beaufort Sea declined 29% and land-surface temperatures along the 50-km coastal strip in this region increased 18%. Furthermore, in this same region the maximum Normalized Difference Vegetation Index, an index of vegetation greenness, increased 24% (Bhatt et al. 2008 in prep.).

Organization of this report

Our project is divided into two main research components: Component I: Climate, sea-ice, land-surface temperatures and greening: Spatial and temporal trends and interrelationships (Bhatt, Walker, Raynolds, Comiso, Jia); Component II: Simulation Modeling (Epstein, Kaplan, Lischke, Cook, and Yu).

Major Findings

Component I: Climate, sea-ice, land-surface temperatures and greening (Bhatt, Walker, Raynolds, Comiso, and Jia)

This component of the project describes the circumpolar patterns of sea-ice and terrestrial vegetation, as well as their long-term dynamics. Bhatt et al. (2008, in prep., a, b) analyzed the pan-Arctic trends and variations in sea ice concentrations and their correlations with near-coastal ocean and land-surface temperatures, as well as the terrestrial vegetation. Land and ocean surface temperatures were evaluated for all areas within 50 km of the coasts. (The 50-km coastal land region represents approximately 60% of the extent of arctic tundra, and this width is optimal for representing the zone of maximum influence of marine climate on tundra vegetation.) Vegetation productivity was assessed using the remotely sensed Normalized Difference

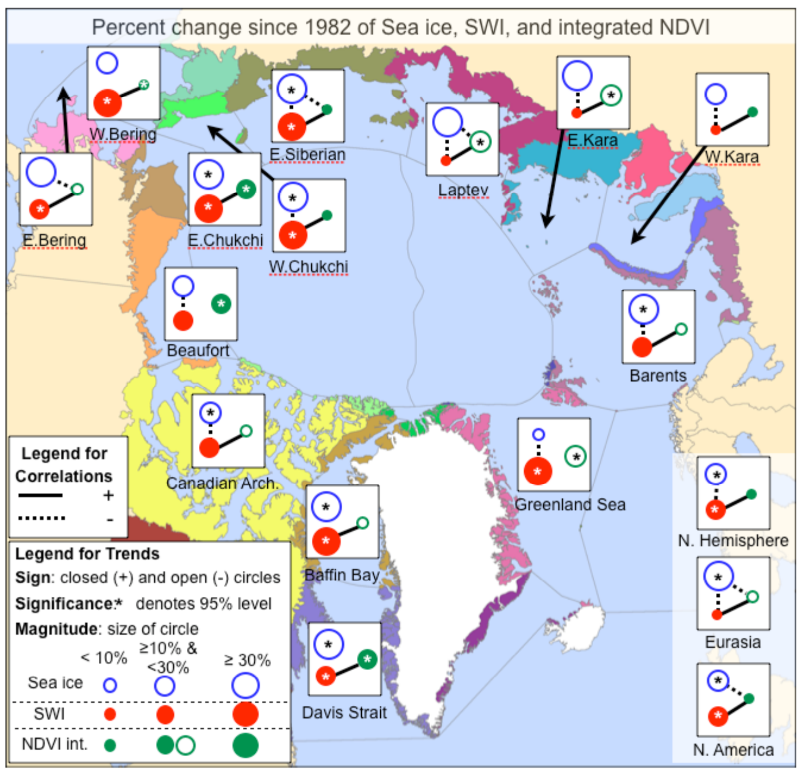

Figure 2. Regional trends of sea ice concentration, SWI, and integrated NDVI shown as percent change since 1982. Regions are delineated according to floristic provinces and Arctic sea boundaries in 50-km zones along the land-ocean interface. SWI and NDVI trends are shown for the May-September period. Sea ice trends are based on a three-week period centered on the week when mean concentrations are 50%, the timing of which varies regionally. Significant positive (negative) correlations are shown with solid (dashed) lines. Sea ice concentration (SWI) has decreased (increased) throughout the Arctic. NDVI trends vary, but in general have been increasing (decreasing) in the North America (Eurasia) (Bhatt et al. 2008 in prep. a).

Vegetation Index (NDVI). The period of analysis spanned from 1982-2007, essentially the duration of the available satellite data. The Arctic was divided into regions based on the Arctic sea delineations in the Russian *Arctic Atlas* (Treshnikov 1985, see Fig. 3). At the pan-Arctic scale, Summer Warmth Index (SWI, sum of mean monthly temperatures > 0°C) and NDVI show statistically significant increases over time, while sea ice shows significant declines.

There are divergent trends in sea-ice and land temperatures in North America and Eurasia (Comiso 2003, Smith et al. 2004) that are also reflected in the NDVI record with a strongly positive NDVI trend in the northern Beringia/ Beaufort Sea region vs. a slightly negative trend in west-central Arctic Eurasia (Bhatt et al. 2008 in prep.-a). Time series from two 50-km coastal regions show that the Beaufort region has had larger sea-ice decreases, SWI increases, and NDVI increases than the W. Kara region (Fig. 3). Both regions exhibit large, yet different, interannual variability.

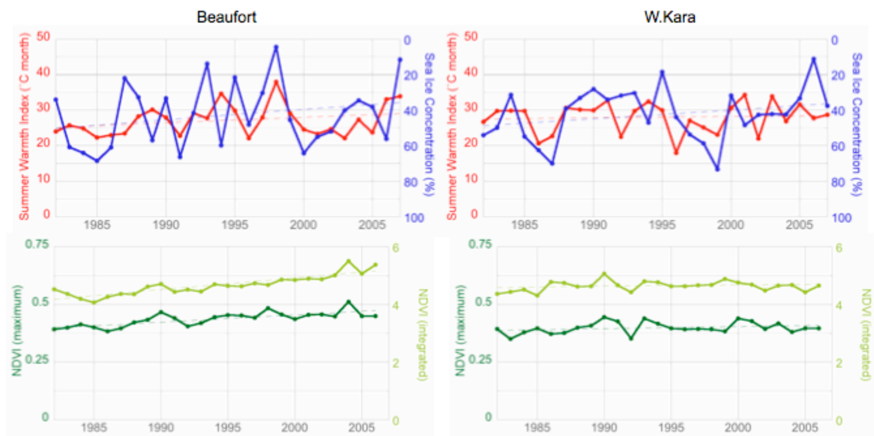

Figure 3. Trends in sea ice, land temperatures and NDVI in the Beaufort region (left) and W. Kara/Yamal region (right) from 1982 to 2007. Sea ice concentration, (% area, blue lines) is averaged from 2-22 July (9-29 July) each year Summer warmth index (SWI, red lines) is the sum of mean monthly temperatures above freezing (˚C mo). Maximum NDVI (dark green) and integrated NDVI (light green) are unit-less greenness indexes derived from AVHRR satellite data. From 1982-2007, sea ice decreased by 29% in the Beaufort and 25% in the W. Kara. SWI increased by 16% in the Beaufort and 4% in the W. Kara. The trends for sea ice and SWI are not significant at p = 0.05 because of high inter-annual variability. From 1982 to 2006 the maximum NDVI increased by 24% in the Beaufort region and 3% in the W. Kara. The NDVI trends in the Beaufort are significant at p = 0.05. From Bhatt et al. 2008, in prep. a.

An important result of our work was to establish a link between sea-ice concentrations and SWI of the coastal tundra. Correlations (Table 1) of linearly detrended time series indicate that sea ice concentration is negatively correlated with SWI and NDVI values. The strength of the correlations between sea ice and integrated NDVI, while always negative, are generally weak. This is consistent with the picture for the pan-Arctic: When sea ice is below average, SWI and NDVI for coastal

Table 1. Correlations between de-trended sea ice, SWI, and integrated NDVI for different Pan-arctic regions. Significance at the 95% (90%) level is indicated in bold (italic) (Bhatt et al. 2008 in prep. a).

Region	Week of 50% ice conc.	Correlation, sea ice & SWI	Correlation, SWI & integrated NDVI	Correlation, sea ice & integrated NDVI
N. Hemisphere	23-29 July	**-0.42**	**0.45**	-0.25
N. America	30 July - 5 August	-0.27	**0.41**	**-0.40**
Eurasia	16-22 July	**-0.42**	**0.58**	**-0.46**
Beaufort	7-15 July	**-0.41**	*0.37*	-0.25
W. Kara	16-22 July	**-0.39**	**0.57**	-0.29

zones are generally above average, but there are exceptions. At the continental scale, SWI is increasing everywhere as summer sea-ice concentration decrease. NDVI is strongly increasing in North America and is actually decreasing slightly in the Barents, E. Kara, and Laptev regions (Fig. 2). The largest positive trends of SWI are in North America, while sea ice decreases are greatest in the Laptev and East Siberian Seas (Fig. 2). There is thus substantial heterogeneity in spatial patterns and temporal trends across the regions. There is notable co-variability between the ocean (through sea ice concentrations) and nearby land (through SWI), but the correlations do not prove causality. We also explored links to the large-scale climate drivers (e.g. Arctic Oscillation, Pacific Decadal and North Atlantic Oscillation), which show that large-scale atmospheric circulation during the preceding winter and spring are correlated with SWI. Sea ice is generally negatively correlated with the Arctic Oscillation and positively correlated with the Pacific Decadal Oscillation. SWI and NDVI are generally positively correlated with the AO and negatively correlated with the PDO. These correlations require more thought in terms of mechanisms. Analysis of wind correlations with NDVI and SWI are in progress. Our work also suggests that during the summer growing season, regional atmospheric circulations impact the sea-ice, SWI, and NDVI anomalies in the 50-km coastal region. In addition, there is a negative correlation between spring sea ice cover and summer sea surface temperatures (Steele et al. 2008), so warmer marine air temperatures could supply additional warmth to the land during summer through the ubiquitous onshore sea breeze circulation (Zhang et al. 2008) The role of the atmospheric circulation warrants further attention.

Circumpolar NDVI spatial pattens are confounded by a host of geographical variables (Raynolds et al. 2006a, Raynolds et al. 2006b, Raynolds and Walker 2008, Raynolds et al. 2008b, Raynolds and Walker 2008 in press). Temperature and decreases with increasing latitude, correlating with arctic bioclimate subzones (Fig. 4) and vegetation units. NDVI also decreases

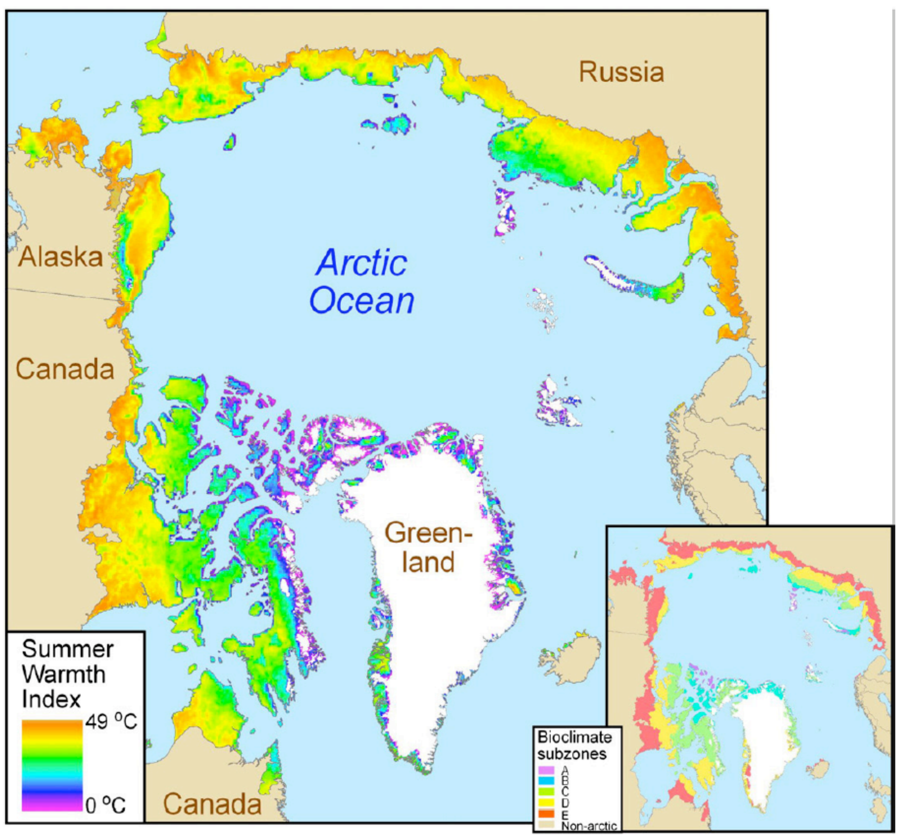

Fig. 4. Map of twenty-two-year mean of summer warmth index (SWI) of arctic tundra, based on AVHRR land surface temperature data 1982–2003 (inset — arctic bioclimate subzones according to the Circumpolar Arctic Vegetation Map). The map derived from AVHRR data shows more detail than the CAVM or temperature maps derived from station data with respect to temperature variations related to mountains, wetlands, and coastal environments, and is more useful for analyzing the NDVI relationships (Raynolds et al. 2008b).

with increasing elevation, greater lake cover, higher permafrost ice-content, thinner soils, and higher substrate pH (Raynolds et al. 2006b, Raynolds and Walker 2008). Most of the Arctic also showed increasing NDVI, with landscape age. We found that for the whole Arctic, a 5 °C increase in SWI along the climate gradient corresponds to approximately 0.07 increase in NDVI, but this trend varies strongly with differences in other factors such as vegetation type, water cover, substrate pH, and glacial history (Raynolds et al. 2008a).

Long-term temporal dynamics of arctic vegetation have been examined in Canada (Jia 2008 submitted). From 1982-2005, the peak annual NDVI increased by 0.49-0.74 % yr^{-1} in the Canadian High Arctic and by 0.46-0.67% yr^{-1} in the Canadian Low Arctic (Fig. 4). The greatest increases in peak NDVI (0.79% yr^{-1}) were found in the mid-latitudes of the Canadian arctic tundra (Bioclimate subzone C). The greatest increases in the temporally-integrated NDVI were found however in the warmest regions of the Canadian Arctic, Subzones D (0.79% yr^{-1}) and E (0.74% yr^{-1}). Clear distinctions in the trends were noted prior to, and following, the eruption of Mt. Pinatubo in 1991.

A preliminary analysis of the seasonality of sea-ice, its variability, and trends (Fig. 5) reveals distinct patterns of the summer open-water season in the W. Kara compared to the Beaufort sea coasts, which are in nearly the same bioclimate regions. The Kara has an extended open-water period in the fall, and sea-ice concentrations are less variable than in the Beaufort. The coastal Beaufort region has a more pronounced negative trend of sea ice than the Kara, particularly in the fall season, that is related to the recent strong retreat of the perennial sea ice in the Beaufort. We have produced similar graphs for all the land-sea regions in the Arctic (see Fig. 3). The patterns in the northern Beringia region (E. Siberian Sea eastward to the Beaufort Sea) contrast sharply with the situation in the central-west Arctic Eurasia. The different NDVI and sea-ice patterns

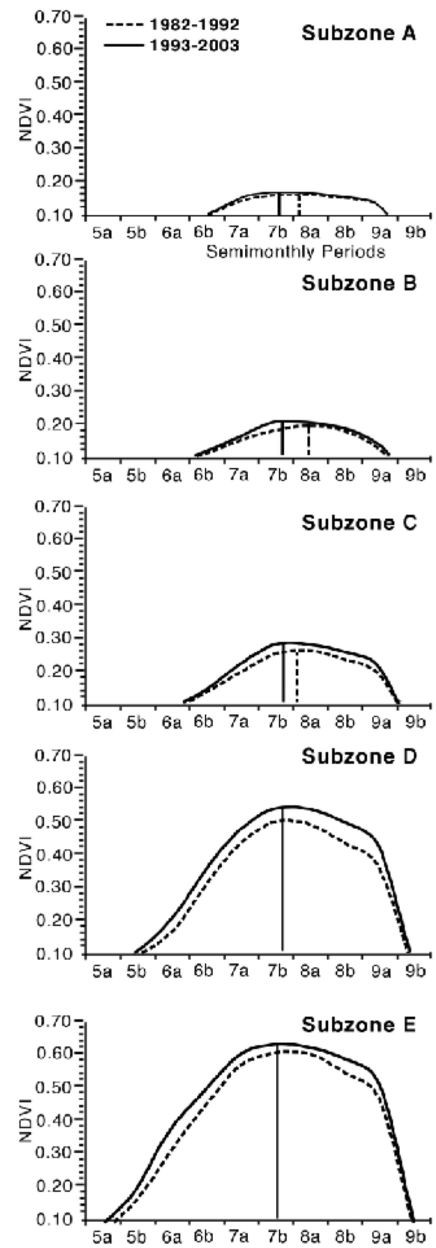

Figure 5. Integrated NDVI curves for 1982-1992 (dashed lines) and 1993-2003 (solid lines) within the five bioclimate subzone in the tundra zone of Arctic Canada. The x-axes show semi-monthly time periods, from which the maximum NDVI values were extracted. There has been an increase in maximum NDVI within all five subzones. Vertical lines show the shift toward an earlier maximum NDVI within the High Arctic subzones (A, B, and C). An earlier onset of greening of greening has occurred only in the Low Arctic (subzones D and E). Modified from Jia et al. 2008 in review.

are likely caused by differences in the ocean and atmospheric circulation patterns in each region, which will be a major focus of our proposed work.

We are also interested in how coastal sea-ice concentrations have varied temporally along north-south gradients in the Arctic and how these may affect the shifts in seasonal NDVI patterns within bioclimate subzones (Fig. 6). As expected, there is considerably less coastal open water in the cold Canadian Archipelago (bioclimate subzones A, B, and C), than in either the middle Arctic areas, represented by the Beaufort and W. Kara seas in Figure 6 (mainly bioclimate subzones C and D), or the southern Arctic area, represented by the W. Bering Sea in Figure 6 (mainly bioclimate subzone E). The sea ice concentration is most variable in the middle Arctic areas and there is a pronounced long-term trend of more open water in the spring and fall seasons in the middle Arctic areas.

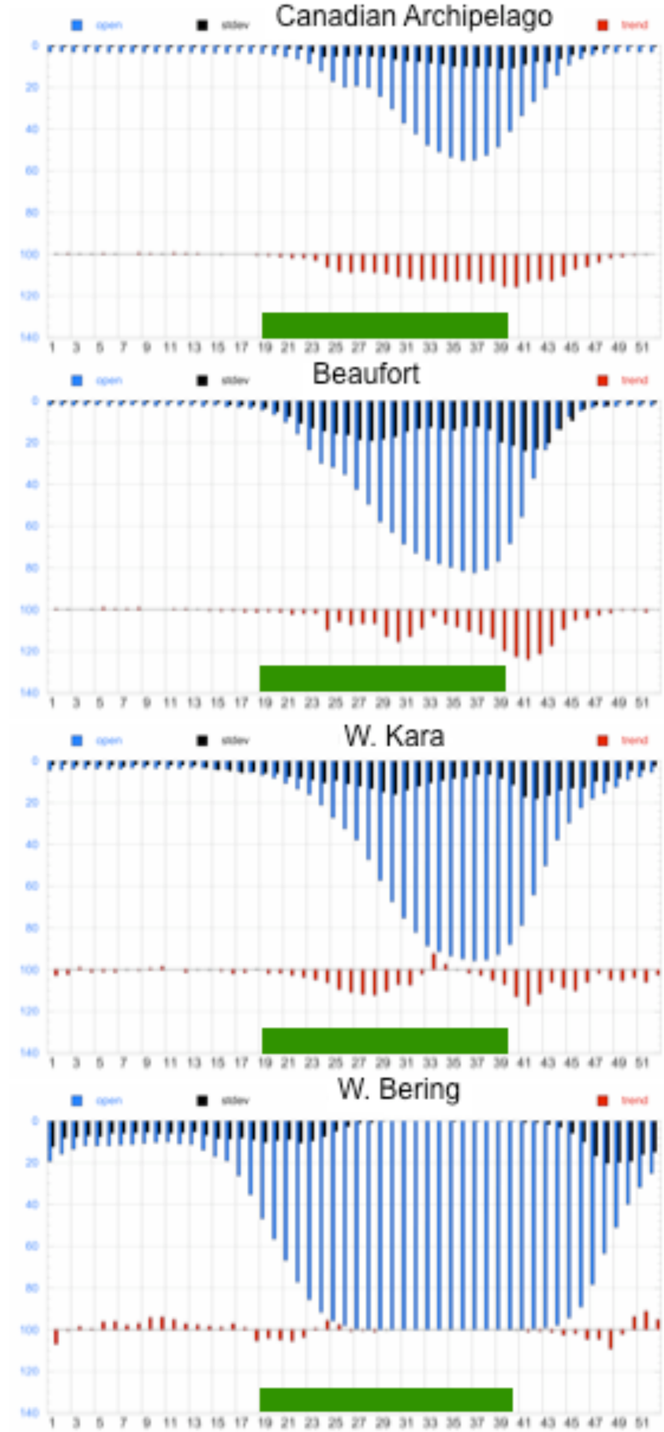

Figure 6. Weekly climatological open water fraction (blue), standard deviation (black) and sea ice concentration trend (red) in % area, starting with the topmost panel, for the Canadian Archipelago, Beaufort, W. Kara, and W. Bering. The green box indicates the average period of plant activity as identified by NDVI > 0 (Bhatt et al. 2008 in prep.-a).

Component II: Simulation Modeling (Epstein, Cook, Kaplan, Lischke and Yu)

The modeling component of the project had four separate, yet related, components, that all differ in their representation of arctic and sub-arctic vegetation. At the coarsest resolution, University of Virginia graduate student, Ben Cook, examined the interactions between the land surface (specifically snow and vegetation) and climate for the circumpolar Arctic and sub-arctic. He used the general circulation-based Community Atmosphere Model (CAM) and Community Land Model (CLM), along with the CLM-DGVM (Dynamic Global Vegetation Model), all developed at NCAR, to simulate changes in vegetation, snow, soils, and climate of northern systems in response to dynamics of different forcing variables. Cook et al. (2007) found that when the vegetation was simulated dynamically (i.e. with the DGVM), climate was highly

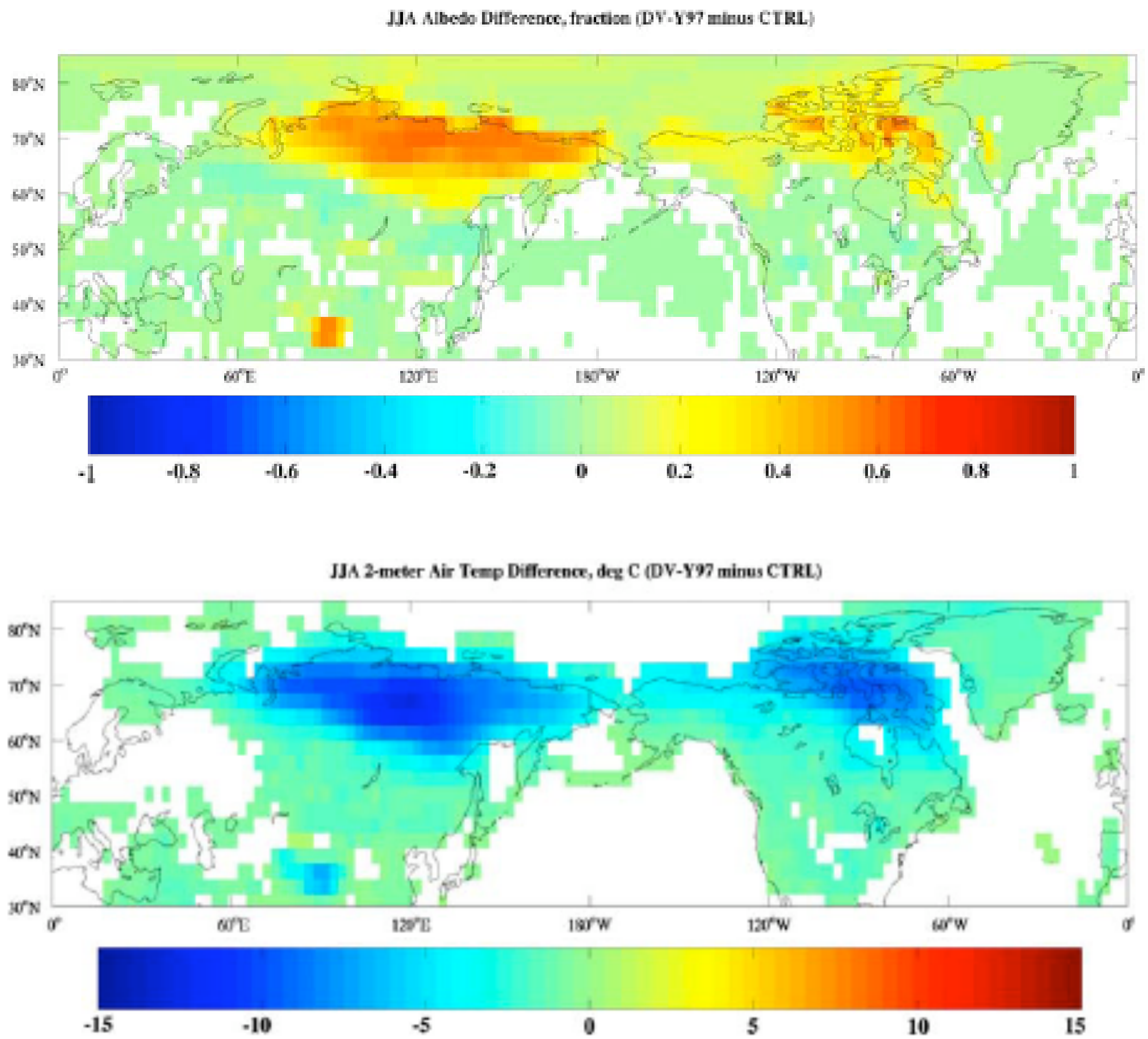

Figure 7 – Changes in albedo and air temperatures in the NCAR CAM/CLM/DGVM with increasing snow cover

sensitive to the snow cover parameterization in the land model. Increased snow cover led to increased albedo atmospheric cooling, and a southerly retreat of boreal forest; this yielded a positive feedback on increasing albedo, and a strong cooling effect (Figure 7). Cook et al. (2008) examined the effects of snow thermal conductivity on soil and atmospheric temperatures. They found that high conductivity (low insulation) snow led to increased heat exchange with dramatic soil cooling and ice formation in the winter, persisting slightly into the summer season. From an atmospheric perspective, high conductivity snow led to winter warming and moderate summer cooling. Cook is also working with Kaplan and Epstein on a third paper (Cook et al. in prep.) to examine Arctic Oscillation impacts on climate and terrestrial ecosystems of the high latitudes.

At the vegetation type level (e.g. low shrub tundra, dwarf-shrub tundra, graminoid-forb tundra), but also with a circumpolar extent, Jed Kaplan used the BIOME4 model to simulate changes in the distribution of tundra types throughout the circumpolar Arctic in response to GCM climate change projections. In order to quantify the effects of climate change on arctic soils and vegetation cover with changing climate, he worked on creating a state of the art land surface model with complete representation of both permafrost and tundra vegetation dynamics that may be applied at circum-Arctic scales. Kaplan and collaborators took process representations from two modern land models, the LPJ Dynamic Global Vegetation Model (LPJ-DVGM) and the Community Land Model (CLM 2.5) and adapted them specifically for arctic conditions. The resulting coupled land surface physics and vegetation model is called the ARVE-DGVM. The ARVE-DGVM is currently in an intense testing phase, using data on vegetation and soil properties collected by the North American Arctic Transect and Yamal field components of this project, along with other datasets.

The ARVE-DGVM represents the soil in 17 layers of exponentially increasing thickness, which extend to 115m below the soil surface. Such a representation of deep soils is necessary for correctly simulating permafrost dynamics, particularly on century timescales. Initial testing indicates that the permafrost scheme works well, but may be too sensitive to the wintertime insulating effects of snow cover. Model uncertainties are currently being investigated, and model deficiencies in light of the observational data are being addressed. In 2009, an extensive application of the ARVE-DGVM will begin to simulate climate-induced changes in arctic vegetation and soils at high spatial resolution (<12.5km), using baseline temperature data acquired through remote sensing from our partners in this project.

Two models were used at the plant functional type / species level, one for tundra vegetation and the other for sub-arctic forests. Heike Lischke used the TreeMig model to simulate the dynamics of northward advancing sub-arctic forests in response to climate warming along a Siberian latitudinal transect. She found that in simulations of TreeMig, where seedling dispersal was explicitly modeled, the projected treeline migration was 177 m/yr in a 2°C warming scenario.

Epstein and Yu used the ArcVeg tundra dynamics model to simulate the dynamics of tundra plant communities for the five arctic subzones, in response to climate change projections. In a recent effort of theirs (Yu and Epstein in prep), the ArcVeg model is being used to examine the interactions among climate, soil organic matter, and grazing in structuring the tundra vegetation. In essence, this is a simulation analysis comparing the two regions for which this research group has the most recent field experience: the North American Arctic Transect and the Yamal Transect in Siberia. The North American tundra systems have finer-textured soils with higher organic matter content, and they are grazed by wild caribou. The Yamal tundra systems have coarser-texture soils with less organic matter, and are grazed more intensely by managed reindeer herds.

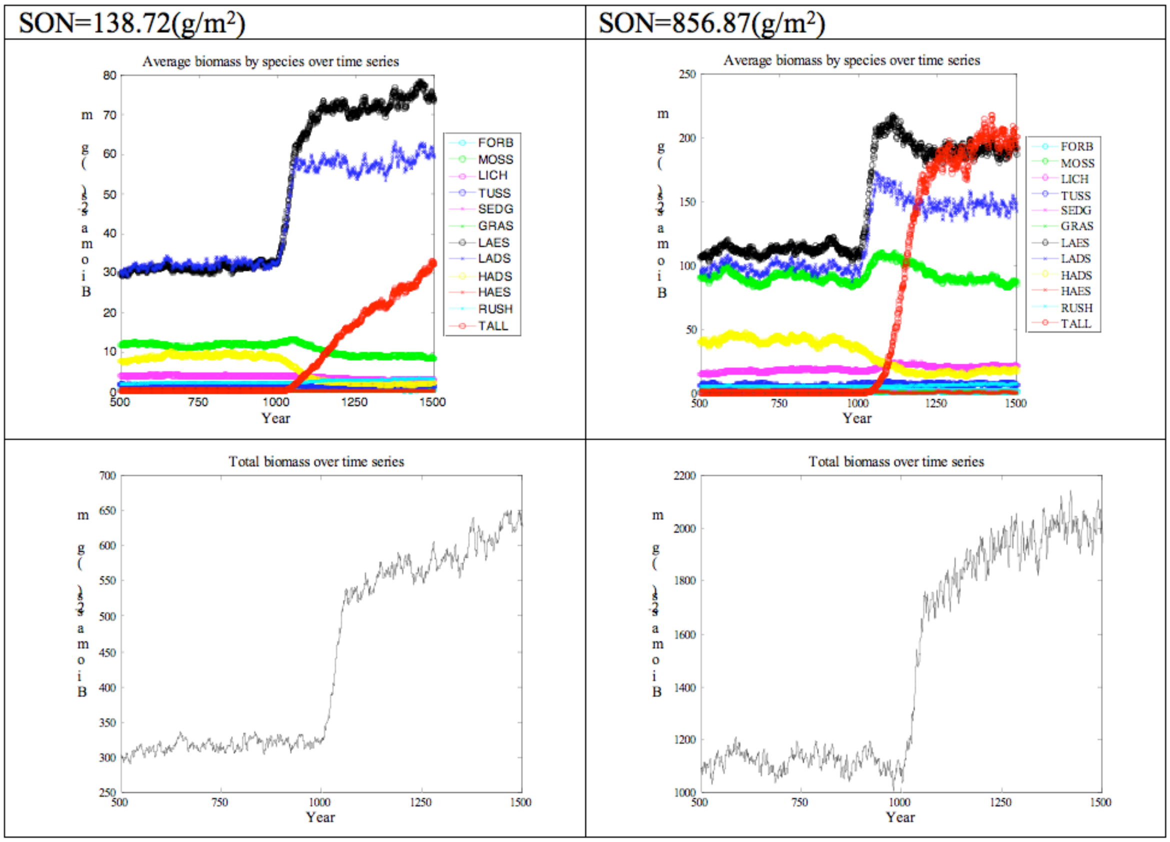

Figure 8 - Comparison of tundra PFT biomass and total biomass in sandy and clay sites, i.e. two soil organic nitrogen levels.

Some key results indicate that a six-fold difference in soil organic nitrogen from Yamal soils to NAAT soils in Low Arctic tundra yields approximately a three-fold increase in total biomass under present and warmed (2°C ramped over 50 years) climates (Figure 8). The greater soil organic nitrogen also led to greater moss biomass (both absolute and relative amounts) and to a more rapid increase in low shrubs with climate warming.

A synthesis of results from three of these models (BIOME4, ArcVeg, TreeMig) and the first two years of this project was conducted and published in a special IPY series in the journal Computing in Science and Engineering (Epstein et al. 2007).

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Zhang, J., M. Steele, R. Lindsay, A. Schweiger, and J. Morison. 2008. Ensemble 1-year predictions of arctic sea ice for the spring and summer of 2008. Geophysical Research Letters 35:L08502.

ACTIVITIES:

Meetings attended with one or more presentations regarding the Greening of the Arctic initiative (oral talk or poster):

1. ICARP II meeting, Copenhagen, Denmark, 10-12 Nov 2005
2. NOAA State of the Arctic Workshop, Woods Hole, MA, 24-26 Oct 2005
3. ARCSS SASS Investigators Meeting, Seattle, WA, 26-27 Mar 2006
4. Northern Eurasia Earth Science Partnership Initiative (NEESPI) Cold Lands & Arctic Coast (CLAC) meeting, Fairbanks, AK, 6-8 Apr 2006
5. Bi-Annual Circumpolar Remote Sensing Symposium, Seward, AK, 16-19 May 2006
6. The Arctic Forum, Washington DC, 25-26 May 2006
7. Arctic AAAS Meeting, Fairbanks, AK, 2-4 Oct 2006,
8. NASA Land-Cover Land-Use Change (LCLUC) Meeting, University of Maryland, 10-12 Oct 2006
9. 7th International Conference on Global Change, Fairbanks, AK, 19-20 Feb 2007
10. NASA LCLUC Meeting, University of Maryland, 4-6 Apr 2007
11. Canadian Meteorological and Oceanographic Society, Canadian Geophysical Union, American Meteorological Society, St. Johns, Newfoundland, 28 May-1 Jun 2007
12. AGU Fall Meeting, San Francisco, 10-14 Dec 2007
13. Yamal LCLUC meeting, Moscow, Russia, 28-31 Jan 2008
14. Circumpolar Biodiversity Monitoring Project (CBMP) Partnership Workshop, Washington, DC, 6-7 Mar, 2008
15. NEESPI Focus Research Center for Biogeochemical Cycles, Jena, Germany, Mar 17-19 2008
16. Arctic Observations Integration Workshop, Palisades, NY, 17-20 Mar 2008
17. NASA LCLUC Meeting, University of Maryland, 4-6 Apr 2008
18. European Geophysical Union (EGU) Meeting, Vienna, Austria, 13-18 April 2008
19. NASA Carbon Cycle and Ecosystems Joint Science Workshop, Adelphi, MD, 28 Apr-2 May 2008
20. The 2008 Little Alaska Weather Symposium (LAWS '08), 12-13 May 2008, University of Alaska Fairbanks, Fairbanks Alaska.
21. 9th International Conference on Permafrost, Fairbanks, AK, 29 Jun-3 Jul 2008

22. Arctic AAAS Meeting, Fairbanks, AK, 15-17 Oct 2008
23. Arctic Forum, 18 Oct 2008
24. AGU Meeting, 15-19 Dec 2008

Project meetings

1. AGU Fall Meeting, San Francisco, CA, Dec 2005
2. AGU Fall Meeting, San Francisco, CA, Dec 2006
3. NASA LCLUC Meeting, University of Maryland, 13 Oct 2006
4. GOA meeting, Copenhagen, Denmark, 8-11 Feb 2007

Publications (acknowledgement to ARC 0531180 included in the paper)*

1. *Alcaraz, D., E. Chuvieco, and H. Epstein. Temporal trends in post-fire regeneration patterns of boreal forests using 1km AVHRR NDVI (in prep.).
2. *Bhatt, U.S., D. A. Walker, M. K. Raynolds, J. C. Comiso 'Influence of Regional Sea Ice Variability on Arctic Tundra' in Seventh International Conference on Global Change: Connection to the Arctic (GCCA-7), 19-20 February, 2007, Fairbanks, Alaska, pages 76-78.
3. *Bhatt, U.S., D.A. Walker, M.K. Raynolds, J.C. Comiso. 2007. Influence of Regional Sea Ice Variability on Arctic Tundra. CMOS/CGU/AMS 2007 Congress Meeting, St John's, Newfoundland Canada, 31 May 2007 (poster date). Canadian Meteorological and Oceanographic Society, Canadian Geophysical Union, American Meteorological Society.
4. *Bhatt, U. S., D. A. Walker, M. K. Raynolds, J. Comiso, and H. E. Epstein. 2008 in prep.-a. Panarctic trend and variability in the land-ocean margins of sea-ice concentrations, land-surface temperatures, and tundra vegetation greenness. Earth Interactions.
5. *Bhatt, U. S., D. A. Walker, M. K. Raynolds, J. Comiso, and H. E. Epstein. 2008 in prep.-b. Role of atmospheric processes in trends and variability of sea-ice, land-surface temperatures, and tundra vegetation greenness in Alaska. Atmospheric Research.
6. *Bhatt, U.S., D.A. Walker, M. Raynolds, J. Comiso. 2007. The relationship between sea ice variability and arctic tundra on the pan-Arctic, regional and site scales. *Eos Trans. AGU 88 (52),* Fall Meeting Supplement, Abstract U41C-0612.
7. *Bhatt, U., D. Walker, M. Raynolds, and J. Comiso. 2008. Examining relationships between sea ice and Arctic vegetation on the Pan-Arctic, regional and site scales. European Geosciences Union, Geophysical Research Abstracts 10:EGU2008-A-11271, http://www.cosis.net/abstracts/EGU12008/11271/EGU12008-A-11271.pdf.
8. Comiso, J. C. and F. Nishio. (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res. 113,* C02S07, doi:10.1029/2007JC004257.
9. Comiso, J.C., C.L. Parkinson, R. Gersten, and L. Stock (2008), Accelerated decline in the Arctic sea ice cover, *Geophy. Res. Lett.* 35, L01703, doi:10.1029/2007GL031972.
10. *Cook, B.I., G.B. Bonan, S. Levis, and H.E. Epstein. 2008. The thermal insulative effect of snow in the climate system. Climate Dynamics 31:107-124.
11. *Cook, B.I., G.B. Bonan, S. Levis, and H.E. Epstein. 2007. Rapid vegetation responses and feedbacks amplify climate model response to snow cover changes. Climate Dynamics 30:391-406.
12. *Cook, B.I., H.E. Epstein, T.M. Smith, and J.O. Kaplan. Artic Oscillation and El Niño Southern Oscillation induced climate impacts and terrestrial ecosystem responses. (in prep.)
13. *Epstein, H.E., J.O. Kaplan, H. Lischke, and Q. Yu. 2007. Simulating future changes in arctic and sub-arctic vegetation. *Climate Dynamics* Jul/Aug 2001:12-23.
14. Epstein, H. E., D. A. Walker, P. Kuss, E. Karlejaärvi, and G. Matyshak. 2008. Tundra vegetation

properties along a latitudinal gradient of the Yamal Region of Russia European Geosciences Union, Geophysical Research Abstracts 10:EGU2008-A-04406, http://www.cosis.net/abstracts/EGU02008/04406/EGU02008-A-04406.pdf.

15. Epstein, H. E., D. A. Walker, M. K. Raynolds, G. J. Jia, and A. M. Kelley (2008), Phytomass patterns across a temperature gradient of the North American arctic tundra, *J. Geophys. Res*., 113, G03S02, doi:10.1029/2007JG000555.

16. *Goetz, S.J., H.E. Epstein, F. Achard, D. Alcaraz, U. Bhatt, A. Bunn, J. Comiso, M. Hansen, G.J. Jia, J.O. Kaplan, H. Lischke, A. Lloyd, D.A. Walker, and Q. Yu. (Submitted) Vegetation productivity and disturbance changes across arctic northern Eurasia: Satellite observations and simulation modeling. In: Gutman, G. and P. Groisman, and Reissell. (ed.) Eurasian Arctic Land Cover and Land Use in a Changing Climate.

17. *Jia, G.J., H.E. Epstein and D.A. Walker. 2008. Vegetation greening in the Canadian Arctic related to warming. *Journal of Geophysical Research - Biogeosciences* in press.

18. *Jia, G.J., H.E. Epstein, and D.A. Walker. 2007. Trends in vegetation greenness in the Arctic from1982-2005. *Eos Trans. AGU 88 (52),* Fall Meeting Supplement, Abstract B21-0041.

19. Kade, A. and D.A. Walker. 2008. Experimental alteration of vegetation on nonsorted circles: effects on cryogenic activity and implications for climate change in the *Arctic. Arctic, Antarctic and Alpine Research*, 40: 96-103.

20. Leibman, M.O., H.E. Epstein, A.V. Khomutov, N.G. Moskalenko, D.A. Walker. 2008. Relation of active layer to depth to vegetation on the central Yamal Peninsula, Russia. 177-178 in: Kane, D.L. and K.M. Hinkle. *Ninth International Conference on Permafrost, Institute of Northern Engineering*, University of Alaska Fairbanks. Extended Abstracts.

21. Ping, C.-L., G. J. Michaelson, M. T. Jorgenson, J. M. Kimble, H. Epstein, V. E. Romanovsky, and D. A. Walker. 2008. High stocks of soil organic carbon in North American Arctic region. *Nature Geoscience* 1:615-619.

22. Raynolds, M.K., D. A. Walker and H. A. Maier. 2006. NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment* 102:271-28.

23. *Raynolds, M. K., J. C. Comiso, D. A. Walker, and D. Verbyla. 2008. Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI. *Remote Sensing of the Environment* 112:1884-1894.

24. *Raynolds, M.K and D.A. Walker. 2008. Circumpolar relationships between permafrost characteristics, NDVI and arctic vegetation types. 1469-1474 *in:* Kane, D.L. and K.M. Hinkle. *Ninth International Conference on Permafrost*, Institute of Northern Engineering, University of Alaska, Fairbanks.

25. *Raynolds, M. K. and Walker, D. A. 2008 (accepted, in revision): The effects of deglaciation on circumpolar distribution of arctic vegetation. *Canadian Journal of Remote Sensing*.

26. *Raynolds, M. K., D. A. Walker, C. A. Munger, C. M. Vonlanthen, and A. N. Kade (2008), A map analysis of patterned-ground along a North American Arctic Transect, *J. Geophys. Res*., 113, G03S03, doi:10.1029/2007JG000512.

27. *Raynolds, M.K. 2009 in prep. Synthesis of circumpolar controls on NDVI.

28. Richter-Menge, J., J. Overland, M. Svoboda, J. Box, M. J. J. E. Loonen, A. Proshutinsky, V. Romanovsky, D. Russell, C. D. Sawatzk, M. Simpkins, I. R. Armstrong, Ashik, L.-S. Bai, D. Bromwich, J. Cappelen, E. Carmack, J. Comiso, B. Ebbinge, I. Frolov, J. C. Gascard, M. Itoh, G. J. Jia, R. Krishfield, F. McLaughlin, W. Meier, N. Mikkelsen, J. Morison, T. Mote, S. Nghiem, D. Perovich, I. Polyakov, J. D. Reist, B. Rudels, U. Schauer, A. Shiklomanov, K. Shimada, V. Sokolov, M. Steele, M.-L. Timmermans, J. Toole, B. Veenhuis, D. Walker, J. Walsh, M. Wang, A. Weidick, and C. Zöckler. 2008. *Arctic Report Card 2008.* http://www.arctic.noaa.gov/reportcard.

29. *Walker, D.A., U.S. Bhatt, M.K. Raynolds, V.E. Romanovsky, G.P. Kofinas, J.P. Kuss, B.C. Forbes, F. Stammler, T. Kumpula, E. Kaarlejärvi, M.O. Leibman, N.G. Moskalenko, A.A. Gubarkov, A.V. Khomutov, D.S. Drozdov, H.E. Epstein, Q. Yu, G.J. Jia, J.O. Kaplan, J.C. Comiso. 2008a (submitted). Cumulative effects of rapid land-cover and land-use changes on the Yamal Peninsula, Russia. *In:* Gutman, G. and P. Groisman, and Reissell. (ed.) *Eurasian Arctic Land Cover and Land Use in a Changing Climate.*
30. *Walker, D. A., H. E. Epstein, and J. M. Welker (2008b), Introduction to special section on Biocomplexity of Arctic Tundra Ecosystems, *J. Geophys. Res*., 113, G03S00, doi:10.1029/2008JG000740.
31. *Walker, D. A., H. E. Epstein, V. E. Romanovsky, C. L. Ping, G. J. Michaelson, R. P. Daanen, Y. Shur, R. A. Peterson, W. B. Krantz, M. K. Raynolds, W. A. Gould, G. Gonzalez, D. J. Nicolsky, C. M. Vonlanthen, A. N. Kade, P. Kuss, A. M. Kelley, C. A. Munger, C. T. Tarnocai, N. V. Matveyeva, and F. J. A. Daniëls (2008c), Arctic patterned-ground ecosystems: A synthesis of field studies and models along a North American Arctic Transect, *J. Geophys. Res*., 113, G03S01, doi:10.1029/2007JG000504.
32. *Walker, D. A., and Greening of the Arctic Team. 2008d. Application of space-based technologies and models to address land-cover/land-use change problems on the Yamal Peninsula, Russia. European Geosciences Union, Geophysical Research Abstracts 10:EGU2008-A-05697, http://www.cosis.net/abstracts/EGU02008/05697/EGU02008-A-05697.pdf.
33. *Walker, D.A., T.D. Hamilton, C.L. Ping, R.P. Daanen, W.W. Streever. 2008e. *Dalton Highway Field Trip Guide for the Ninth International Conference on Permafrost.* Guidebook 9. State of Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys, 110 pp.
34. Walker, D. A., H.A. Maier, E.M. Barbour. 2008f. A web-based arctic geobotanical atlas and a new hierarchy of maps of the Toolik Lake Region, Alaska, 1893-1898 *in:* Kane, D.L. and K.M. Hinkle. *Ninth International Conference on Permafrost*, Institute of Northern Engineering, University of Alaska Fairbanks.
35. *Walker, D. A., M. K. Raynolds, and W. A. Gould. 2008g. Fred Daniëls, Subzone A, and the North American Arctic Transect. *Abhandlungen aus dem Westfälischen Museum für Naturkunde* 70:387-400.
36. Vonlanthen, C. M., D. A. Walker, M. K. Raynolds, A. Kade, H. P. Kuss, F. J. A. Daniëls, and N. V. Matveyeva. 2008 Patterned-ground plant communities along a bioclimate gradient in the High Arctic, Canada. *Phytocoenologia* 28:23-63.
37. *Yu, Q. and H. Epstein. 2008. Evaluating Arctic Tundra System Resilience to Grazing Disturbances: A Modeling Approach. Geophysical Research Abstracts, 10: EGU2008-A-12154. http://www.cosis.net/abstracts/EGU2008/12154/EGU2008-A-12154-1.pdf.

TRAINING AND DEVELOPMENT

1. The project has five students involved in graduate studies: Qin Yu (Ph.D.), Ben Cook (Ph.D., graduated), Gerald Frost (M.S.), Corinne Munger (M.S., graduated), Martha Raynolds (Ph.D., will graduate June 2009). Three post doctoral students, Domingo Alcaraz, Patrick Kuss, and Corinne Vonlanthen were also partially funded by the project.

2. Uma Bhatt was the instructor for Climate Journal Club the spring semester (Jan-May 2007) each every Friday from 3:30-4:30. This is an informal forum for discussing current research results and research results from this project were discussed during the semester.

3. D.A. Walker presented a seminar to the Institute of Arctic Biology on 21 Nov 2008, entitled “Greening of the Arctic and IPY initiative: Does the loss of sea ice affect the tundra and those who depend on it?”

4. Epstein will teach a seminar-style course for second-year students at the University of Virginia in the Spring of 2009 entitled “Arctic Ecosystems in a Changing Environment.”

OUTREACH ACTIVITIES

1. Uma Bhatt co-edited the special IPY series of six articles for the journal *Computing in Science and Engineering* continues. In addition to editorial duties, this project entails preparing sidebars for each of the special IPY articles, which Bhatt has done with co-guest editor D. Newman.

2. Skip Walker developed the Dalton Highway Field Trip for the Ninth International Conference on Permafrost (Walker et al. 2008e). This is a major conference and field trip that introduced 45 participants to the climate gradient in northern Alaska and the greening that is occurring. The guidebook should have a long life and be used for several other field trips along the Dalton Highway.

3. Martha Raynolds presented a talk for local community science forum, “Science Café”, titled 'Searching for the Effects of Climate Change on Arctic Vegetation'. She also presented a talk to 45 GLOBE teachers, 23 March, Fairbanks titled “Arctic vegetation: its distribution and characteristics”.

4. A major synthesis of projects along the North American Arctic Transect was completed and published as a special issue of the *Journal of Geophysical Research — Biogeosciences* (Walker et al. 2008b.).

5. Epstein presented a talk entitled “New Estimates of Carbon Stores in Arctic Tundra and Permafrost Soils for the American Meteorological Society Environmental Science Seminar Series, Washington, D.C., September 26, 2008.

6. Walker, Epstein and Forbes will present the Greening of the Arctic as one of four IPY projects highlighted an IPY press conference at the upcoming AGU meeting in San Francisco on Dec 16.