

## **Collaborative Research: Seasonality of Circumpolar Tundra: Ocean and atmosphere controls and effects on energy and carbon budgets**

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## A. PROJECT SUMMARY

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**Intellectual merit:** Changes in the magnitude and seasonality of Arctic summer vegetation production over the past several decades have been documented. These changes will likely accelerate and have consequences for the entire Arctic terrestrial system, in particular energy and element budgets, and will also feed back to marine and atmospheric systems. The vegetation changes vary spatially across the Arctic and are difficult to interpret without understanding how they are linked to broader changes in the arctic ocean/atmosphere system. The timing of terrestrial vegetation growth may be strongly connected to seasonal patterns of sea-ice concentrations, and ocean and atmospheric temperatures. **Proposed activities:** We will characterize the seasonal linkages between the land surface greenness and a suite of land, atmosphere, and ocean characteristics, focusing on the Beringia/ Beaufort Sea, where there have been strong positive increases in the Normalized Difference Vegetation Index (NDVI) over the past 25 years, and the west-central Arctic Eurasia region, where the NDVI trends have been slightly negative. We will address the following questions: (1) What are the spatial and temporal variabilities in the seasonality of various arctic system components (sea-ice concentration and thickness, ocean and land surface temperatures, ocean heat fluxes, snow cover, and vegetation (NDVI)? Specifically, how do these vary for the major east-west regions (Beringia vs. west-central Arctic Eurasia) and the north-south zonal gradient in the circumpolar Arctic? (2) What role do the atmosphere and ocean circulation patterns play in controlling the seasonality of land temperatures and vegetation production? (3) How do changes in the seasonality of these arctic system components affect vegetation growth and carbon sequestration?

The project is divided into three tasks that address each of these questions. Using both satellite and *in situ* data sets, we will document the seasonal cycles (daily to monthly time scales) of the tundra and marine climate systems at a regional scale throughout the Arctic. We will then employ atmospheric reanalysis datasets to describe local circulation characteristics. We will also use a pan-arctic ice-ocean model to describe ocean circulation patterns relevant for tundra vegetation and apply statistical analyses to investigate mechanisms of ocean-atmosphere-land relationships. A vegetation change model (ArcVeg) will analyze the consequences of land temperature changes for carbon production along climate, disturbance, and soil gradients. The model will be enhanced for seasonality studies, including transition to a daily time step, and will allow us to examine the effects of seasonality changes on the carbon accumulated by different plant functional types and into different plant tissues types. **Transformative research:** Earlier studies have documented major interannual differences in NDVI within the Arctic and between the Arctic and boreal forest regions. Our analyses will focus on how the seasonality (phenology) of the greening patterns in the tundra zone have changed along east-west and north-south gradients within the Arctic, and how these patterns are linked to changes in snow cover, near-shore sea-ice concentrations, sea and land temperatures, ocean heat fluxes, and major climate indices. This will likely lead to a fundamental understanding of arctic system connections, and how we might expect vegetation production to change in the Arctic in response to changes in atmosphere and ocean circulation patterns. **Broader impacts:** Substantive educational components will be developed at the Universities of Virginia, Washington and Alaska, including three graduate students, one post-doc student, inclusion of the results in lectures and demonstrations at the universities, a major new summer undergraduate program at UVA, programs of low-income outreach and the Polar Science Weekend in Seattle, a new class for Alaska K-12 teachers at UAF, and the development of an educational web-site for the project at UAF.



## PROJECT DESCRIPTION

### INTRODUCTION

The **goals** of this project are 1) to characterize the spatial and temporal seasonality of tundra

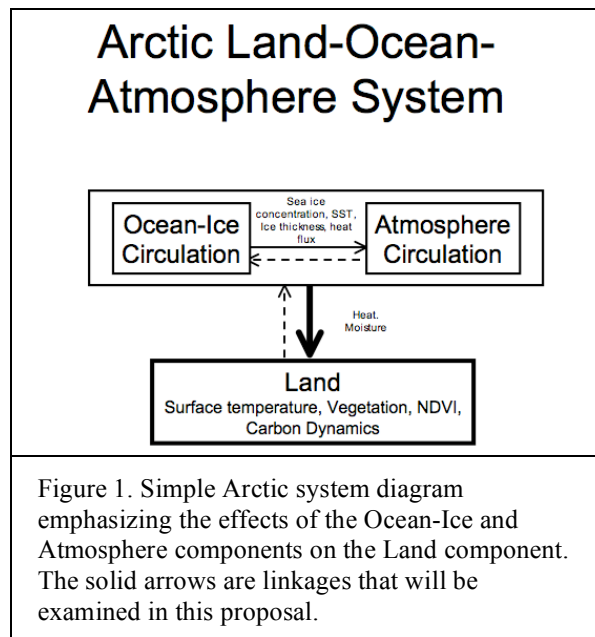


Figure 1. Simple Arctic system diagram emphasizing the effects of the Ocean-Ice and Atmosphere components on the Land component. The solid arrows are linkages that will be examined in this proposal.

vegetation of the circumpolar Arctic in relation to ice-ocean, atmospheric, and land characteristics, 2) to understand the seasonal linkages between the marine environment, the atmosphere, and the terrestrial ecosystems of the Arctic, and 3) to examine the effects of seasonality changes in terrestrial vegetation on Arctic carbon dynamics.

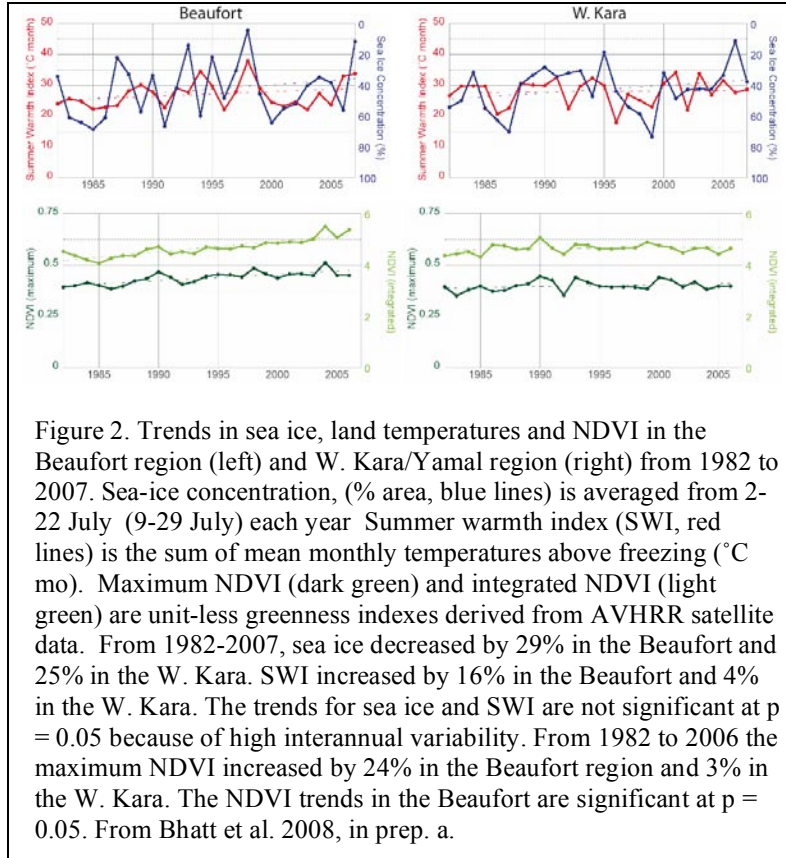
The Arctic system (Fig. 1) has recently been undergoing some dramatic changes in both the structure and function of its components. One of the most apparent changes is the reduction in the extent and thickness of the summer sea ice during the past 30+ years (Stroeve et al. 2008, Comiso 2003, Comiso et al. 2008). The greenness of terrestrial arctic vegetation, as seen from space, has increased over the last 25+ years (Jia et al. 2003, Goetz et al. 2005, Bunn et al. 2007), and

has been attributed to longer growing seasons and increasing land temperatures (Jia et al., 2003, Goetz et al. 2005), an increase in the extent and abundance of shrubs (Sturm et al. 2001, Tape et al. 2006, Walker et al. 2006), and a northward movement of trees from the sub-arctic (Lloyd 2005, Lloyd and Bunn 2007).

Important system feedbacks can result from these various changes. 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  $3.3 \text{ Watts m}^{-2} \text{ decade}^{-1}$  in additional local atmospheric heating, comparable to a doubling of atmospheric  $\text{CO}_2$  (Chapin et al. 2005). *This demonstrates that relatively small changes in the seasonality of arctic system components (in this case the timing of snowmelt and the onset of vegetation growth) can have relatively large impacts on the system as a whole.*

Spatial patterns of various arctic system components and their long-term (decadal) dynamics have been examined in recent research efforts (with a substantial contribution from this research team), and 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. 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).

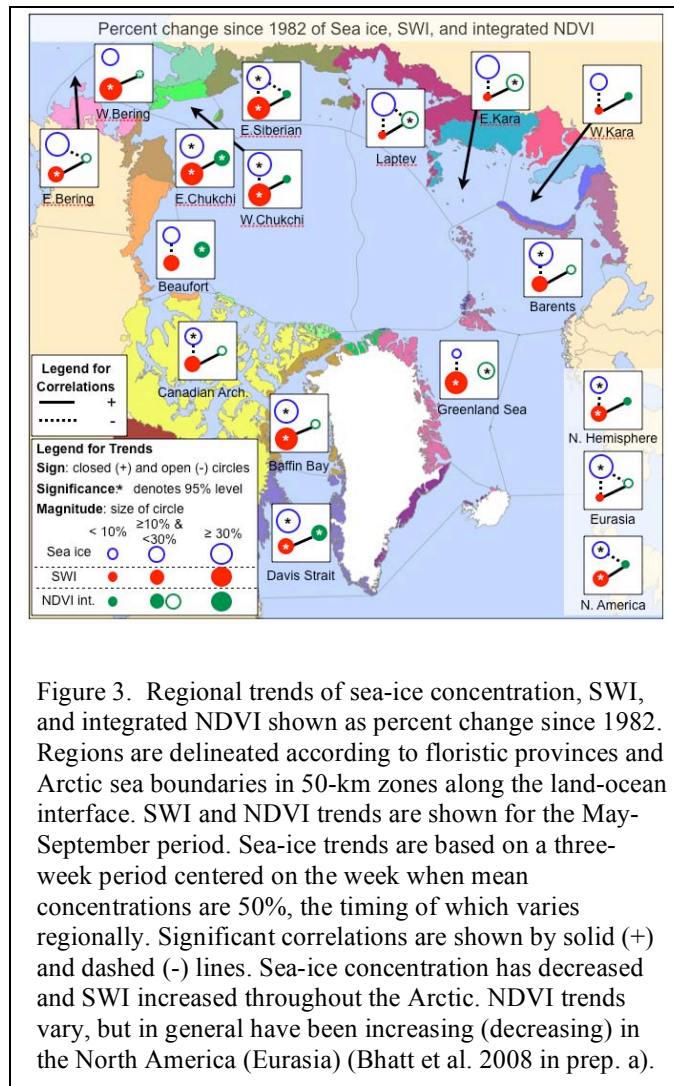


## Background

Results from a recent NSF-funded Synthesis of Arctic System Science project (ARC-0531166 - “Greening of the Arctic”) describe 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 Vegetation Index (NDVI). The period of analysis spanned from 1982-2007, 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  $> 0^{\circ}\text{C}$ ) and NDVI show statistically significant increases over time, while sea ice shows significant declines.

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. 2). Both regions exhibit large, yet different, interannual variability. 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 strengths 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 zones are generally above average, but there are exceptions. At the continental scale, SWI is increasing



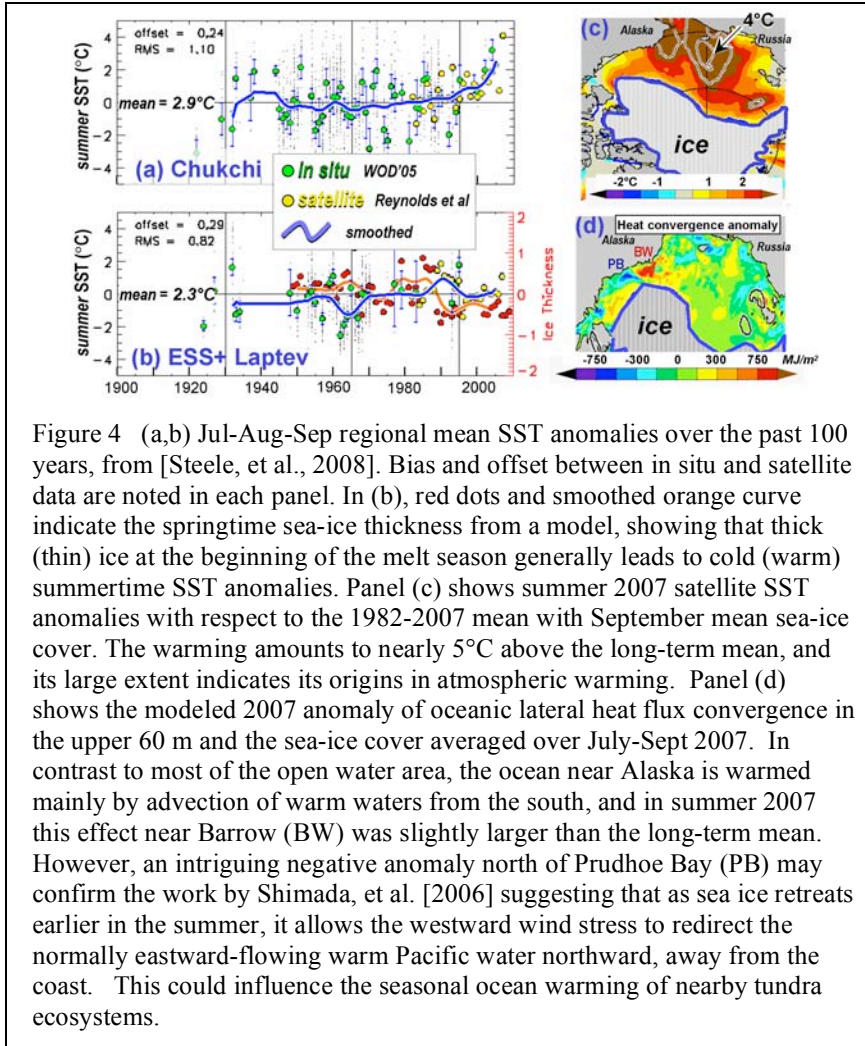
everywhere as summer sea-ice concentration decreases. NDVI is strongly increasing in North America and is actually decreasing slightly in the Barents, E. Kara, and Laptev regions (Fig. 3). The largest positive trends of SWI are in North America, while sea-ice decreases are greatest in the Laptev and East Siberian Seas (Fig. 3). 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 is correlated with SWI. 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. 2008a), so decreased spring sea ice could warm marine air, supplying additional warmth to the land through the ubiquitous

onshore sea breeze circulation (Zhang et al. 2008a). The role of the atmospheric circulation warrants further attention.

Circumpolar NDVI spatial patterns are strongly related to a host of geographical and climate variables (Raynolds et al. 2006a, Raynolds et al. 2006b, Raynolds and Walker 2008, Raynolds et al. 2008b, Raynolds and Walker 2008 in press). NDVI decreases with increasing latitude, correlating with arctic bioclimate subzones and vegetation units. NDVI also decreases with increasing elevation, greater lake cover, higher permafrost ice-content, thinner soils, and higher substrate pH (Raynolds et al. 2006b, Raynolds

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	<b>-0.42</b>	<b>0.45</b>	<b>-0.25</b>
N. America	30 July - 5 August	<b>-0.27</b>	<b>0.41</b>	<b>-0.40</b>
Eurasia	16-22 July	<b>-0.42</b>	<b>0.58</b>	<b>-0.46</b>
Beaufort	7-15 July	<b>-0.41</b>	<b>0.37</b>	<b>-0.25</b>
W. Kara	16-22 July	<b>-0.39</b>	<b>0.57</b>	<b>-0.29</b>



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<sup>-1</sup>) and E (0.74% yr<sup>-1</sup>). Clear distinctions in the trends were noted prior to, and following, the eruption of Mt. Pinatubo in 1991.

The land trends are consistent with patterns in the ocean. Most areas of the upper Arctic Ocean are now warming, i.e., summer Sea Surface Temperatures (SSTs) are increasing from year to year (Steele et al. 2008a) (Fig. 4). The exception is the perennially ice-covered central Arctic Ocean, although this domain is shrinking. Summer (mean July-August-September) 2007 SSTs were up to 5 °C above the 1982-2006 mean over the Chukchi Borderland region, where sea-ice retreat was most dramatic. Most peripheral seas of the Arctic Ocean show warming SSTs over the last 7-12 years, whereas earlier times showed some warming, others cooling. The tentative conclusion is that the entire area is experiencing warming in response to the general climate warming and sea-ice melting of the arctic seas. Model simulations indicate that northward ocean transport of relatively warm Pacific water via the Bering Strait was greater in summer 2007 than in previous years (2000-2006) (Zhang et al. 2008b, Zhang et al. 2008 submitted). This

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<sup>-1</sup> in the Canadian High Arctic and by 0.46-0.67% yr<sup>-1</sup> in the Canadian Low Arctic. The greatest increases in peak NDVI (0.79% yr<sup>-1</sup>) were found in

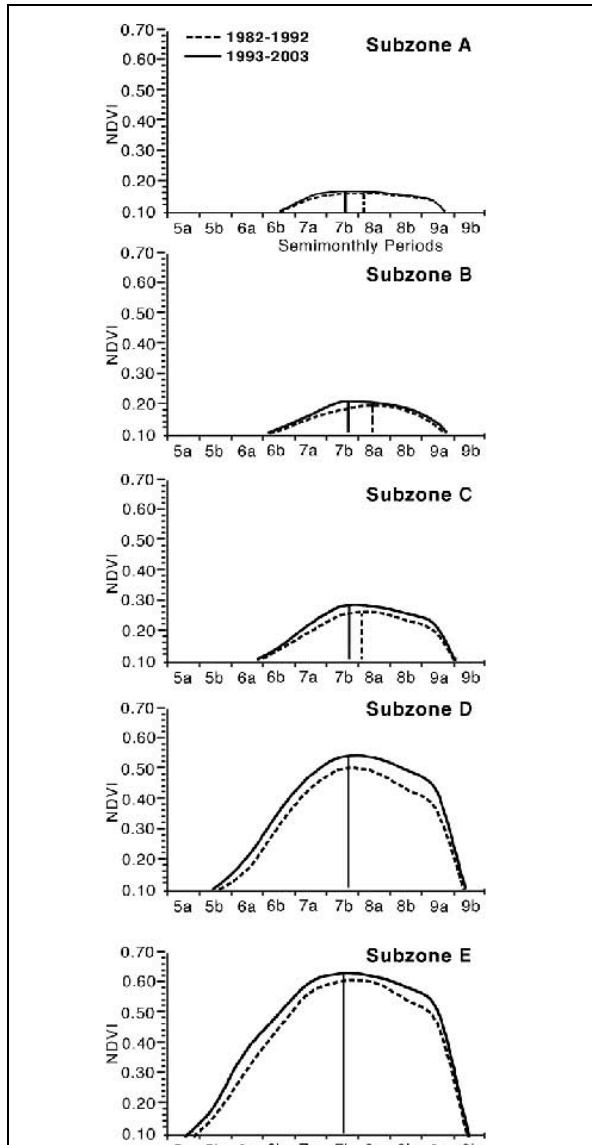


Figure 5. Integrated NDVI curves for 1982-1992 (dashed lines) and 1993-2003 (solid lines) within the five bioclimate subzone in the tundra zone of Arctic Canada. The x-axes show semi-monthly time periods, from which the maximum NDVI values were extracted. There has been an increase in maximum NDVI within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

contributed to ocean warming to a greater degree than usual, but the effect was mostly confined to the Alaskan arctic coast.

Model results also indicate that sea-ice decline in 2007 arose from wind forcing sea ice northward in the Canada Basin and southward out Fram Strait, in combination with “usual” atmospheric heating, acting on a relentlessly thinning and increasingly vulnerable sea-ice pack (Lindsey et al. 2008, Schweiger et al. 2008, Zhang et al. 2008a, Zhang et al. 2008b, Zhang et al. 2008c, Lindsey et al. 2008 in press). Further, prediction of September mean sea-ice extent using statistical relationships between modeled parameters in earlier months and September ice extent did not provide a particularly accurate forecast for September 2007. This was probably because of the highly unusual conditions in 2007, which historical models could not predict. Although sea-ice *extent* was unusually low in 2007, sea-ice *thickness* in summer 2007 generally followed a linear trend line from previous years.

### ***Preliminary results of the seasonality of sea ice, temperatures, and vegetation throughout the Arctic***

While the spatial patterns and some of the long-term (years-decades) dynamics of arctic system components have received substantial attention recently, this call for proposals was initiated as the result of a paucity of information regarding changes in the seasonal timing of events and their effects within the arctic system. Our preliminary analyses show that changes in the seasonality of vegetation for the Canadian Arctic vary across different bioclimatic subzones (Jia 2008 submitted) (Fig. 5). Two commonalities across all tundra subzones were that the peak vegetation greenness, as indicated by the NDVI, increased from the period 1982-1992 to 1993-2003, and the end of the growing season did not change for any subzone (Fig. 5).

However there were some key differences in seasonality changes. In the Low Arctic subzones (Subzones D and E), there was clearly an earlier start to the growing season by approximately 6-



7 days, yet the date of Peak NDVI did not change. Thus, there was a longer growth period to a greater maximum in green vegetation. In the High Arctic subzones (Subzones C-A), there was no shift in the spring onset of vegetation growth, yet growth proceeded more rapidly to an earlier and greater Maximum NDVI. The temporally-integrated NDVI (TI-NDVI), (the area under the NDVI curve = sum of the semimonthly values) increased in all subzones. There also exists a contrast in the seasonal cycle of NDVI between the W. Kara and the Beaufort regions. The vegetation greens up more rapidly in the spring in the Beaufort than the W. Kara, and the Kara has slightly higher NDVI in the fall (Fig. 6). This may be the result of a somewhat later sea-ice melting and an extended fall ice-free season in the Kara compared to the Beaufort (Figure 7). A comparison of the five-year averages of maximum biweekly NDVI from 1982-1986 and 2002-2006 also indicated that this contrast has increased over the data record (not shown). Namely, green-up is earlier in the Beaufort while fall comes later in W. Kara. The space-based observations of greening and senescence patterns in each region are consistent with field observations of Walker and Epstein, who noted the extraordinarily long green season on the Yamal Peninsula in 2007 and 2008 compared to that in northern Alaska.

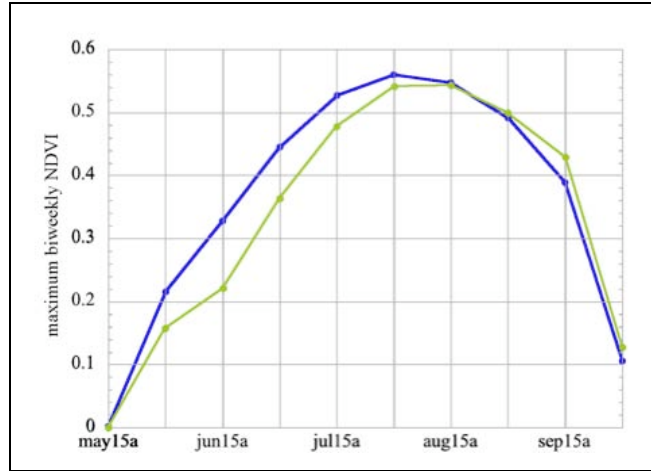


Figure 6 Climatological seasonal cycle (1982-2006) of semimonthly maximum NDVI in the Beaufort (blue) and W. Kara (green) regions.

A preliminary analysis of the seasonality of sea ice, its variability, and trends (Fig. 7) 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, 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 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 (see Figure 5). 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 7 (mainly bioclimate subzones C and D), or the southern Arctic area, represented by the W. Bering Sea in Figure 7 (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.

## PROPOSED ACTIVITIES

### *Research questions*

The project is divided into the three broad components as shown in Table 2.

### **Component 1: Circumpolar seasonality characterization (Bhatt, Walker, Steele, Reynolds, Comiso, Epstein, Jiong)**

Our earlier work examined interannual trends of vegetation greenness, land-surface temperatures, and sea-ice concentrations. In the proposed work, we will focus on the *seasonal* variability of these same factors plus several other land and sea variables along east-west and north-south gradients within the Arctic.

We will first construct plots of the seasonal trends of each variable that portray the magnitude, variability and trend of the variable for discrete time intervals (daily to semi-monthly) for the whole year. (See Fig. 7 for an example related to sea-ice concentration). We will document the circumpolar spatial and temporal seasonal trends and variability of sea-ice concentration, snow, NDVI, LST, ocean heat content, SST, and sea-ice thickness from 1982 (the beginning of the AVHRR satellite record for NDVI) to the present and closely examine how atmosphere and ocean circulation affect the spatial and temporal seasonality of the terrestrial system.

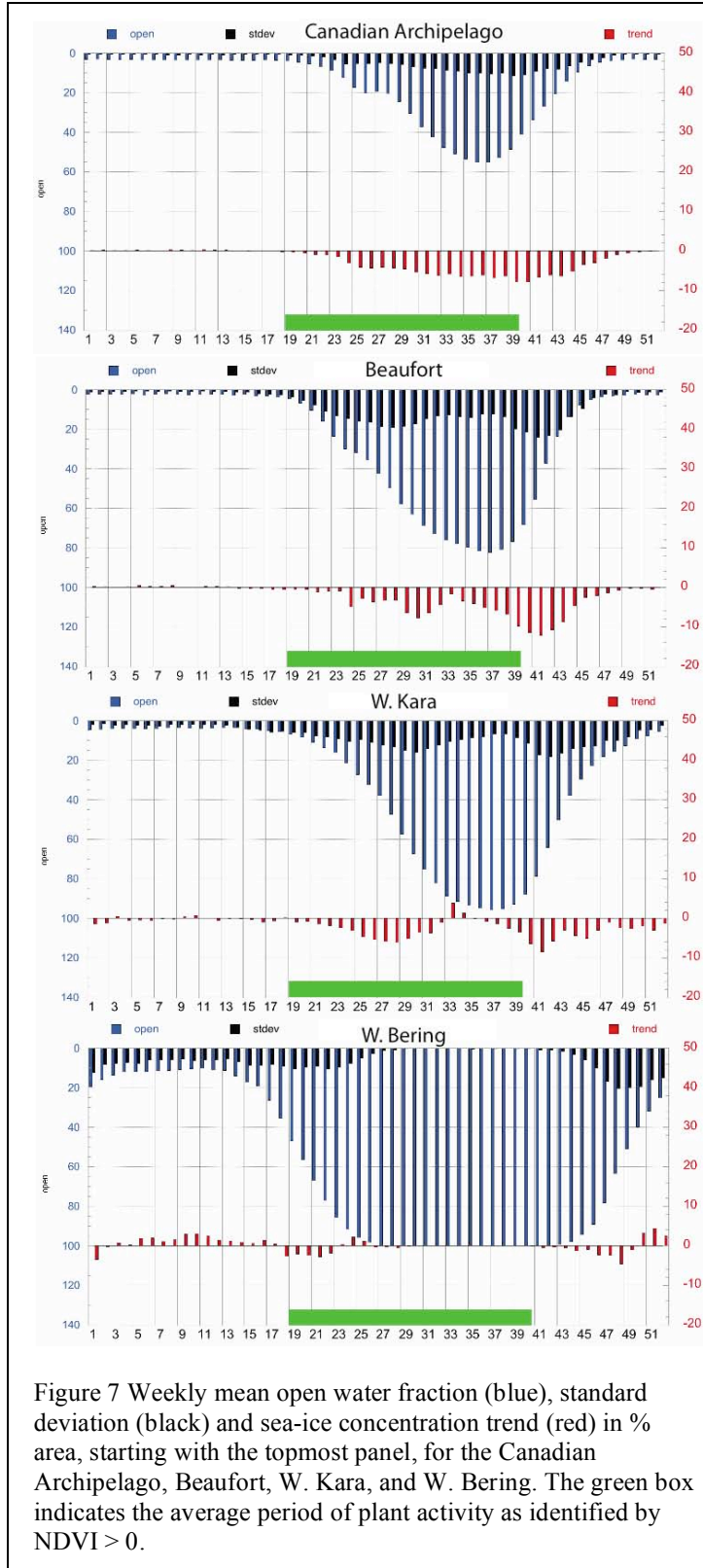


Figure 7 Weekly mean open water fraction (blue), standard deviation (black) and sea-ice concentration trend (red) in % area, starting with the topmost panel, for the Canadian Archipelago, Beaufort, W. Kara, and W. Bering. The green box indicates the average period of plant activity as identified by NDVI > 0.

**Table 2.** Major components of the project, questions and research approaches.

<b>Component</b>	<b>Questions</b>	<b>Approach</b>
1. Circumpolar seasonality characterization	<p>(a) What are the spatial and temporal variabilities in the seasonality of various arctic system components (sea-ice, ocean and land surface temperatures, ocean heat fluxes, snow cover, and vegetation (NDVI)?</p> <p>(b) How do these vary for the major east-west regions (Beringia vs. west-central Arctic Eurasia)?</p> <p>(c) How do these vary along the north-south zonal gradient in the circumpolar Arctic?</p>	<p>(a) Construct time series for each system variable within the 50-km coastal area with each ocean/land region and apply statistical analyses to develop understanding of relationships.</p> <p>(b) Identify key process that explain the contrasts between the east and the west.</p> <p>(c) Examine the variability of the land variables (NDVI, Land Surface Temperature=LST, Snow) within each subzone of each ocean/land region.</p>
2. Atmosphere and ocean controls of terrestrial seasonality	<p>(d) What is the role of large-scale climate patterns in controlling the seasonality of the sea ice and land variables?</p> <p>(e) What is the role of local atmospheric circulation in the seasonality of the marine and terrestrial environment?</p> <p>(f) How do ocean circulation patterns control the timing terrestrial seasonality?</p>	<p>(d) Use time series from Component 1 to investigate relationships with hemispheric circulation patterns and storm track measures.</p> <p>(e) Employ atmospheric reanalysis datasets (NCEP/NCAR, NARR) to describe local circulation characteristics (e.g. winds, moisture, temperature advection).</p> <p>(f) Use PIOMAS pan-arctic ice-ocean model to describe ocean circulation patterns relevant for tundra vegetation and apply statistical analyses to develop understanding of relationships.</p>
3. Land energy and carbon linkages	<p>(g) How do changes in the seasonality of the arctic system components (e.g. earlier start to growing season, increased total summer warmth) affect vegetation growth and carbon sequestration?</p>	<p>(g) Use phenomenological models to relate seasonal NDVI to carbon gains; modify ArcVeg vegetation change model to be a daily time step model and run a suite of simulations to examine effects of climate change on plant-functional-type production.</p>

The next step is to examine the details of the trends, relationships to each other, and atmosphere / ocean linkages. It is evident that the trends in sea ice are generally larger during the transitions seasons (See red bars in Fig. 7), particularly in the Beaufort and W. Kara regions. A circumpolar geographic information system will be used to examine the inter-relationships between NDVI seasonality vegetation type, soil type, glacial history, and regional lake abundance using methods developed in earlier work (Raynolds et al. 2006b, Raynolds and Walker 2008).

To characterize the nature of the ocean connections, the analysis will employ the 25 km resolution Special Sensor Microwave Imager (SSM/I) estimates of *sea-ice concentration*, based on a bootstrap algorithm (Comiso et al. 2008), and AVHRR radiometric *surface temperature* (Comiso 2003, 2006), both covering the period from January 1982 to present. The surface temperature data have recently been enhanced by applying more effective cloud masking techniques and an improved consistency in calibration through the utilization of in situ surface temperature data. We will also use daily *sea-ice thickness* model output available to us via a numerical sea ice-ocean model (Zhang 2005) which assimilates observed ice concentration following Lindsay and Zhang (2006) and is forced by NCEP/NCAR reanalysis data. Where available, satellite, aircraft-based, and drifting buoy data on ice thickness will be used to supplement the model ice thickness output. Also, the satellite sea surface temperature data will be supplemented by vertically integrated upper *ocean heat content* (over the upper 50 m) available from the model and from drifting buoys, which provide an understanding of subsurface heat that might be available to the surface under strong mixing conditions such as during coastally-trapped storms (Serreze et al. 2001). We will use the NASA GIMMS maximum *NDVI* to represent tundra greenness but expect to switch to a new NDVI data set, which will be calibrated using Greenland and use a polar projection when it becomes available (J. Comiso, personal communication). We will also analyze *snow cover*, using the NSIDC Northern Hemisphere EASE-Grid Weekly Snow Cover because the green up of plants begins when the snow melts. Our preliminary analysis with this data set suggests no discernible snow trend in the Beaufort region. This could be attributed to the weekly resolution of the data set but an analysis of daily in situ snow measurements from Kuparuk also do not suggest an earlier snow melt (Cherry et al. 2008 submitted).

### **Component 2: Atmosphere and ocean controls of terrestrial seasonality (Bhatt, Steele, Walker, Reynolds, Atmospheric science student, Comiso)**

Our research will focus on analyzing the seasonal NDVI patterns in relation to characteristics of the near-shore ocean and sea-ice environment, atmospheric circulation, regional winds, and land characteristics. We will devote particular attention to the climate mechanisms behind the striking contrast between the vegetation response to declining sea ice in Berengia and west-central Eurasia by examining the seasonality of the atmosphere and marine systems in the 50-km coastal zone in these regions (Fig. 4).

The large-scale climate and local atmospheric circulations both play a role in the state of the 50-km coastal domain sea ice (Bhatt et al. 2008 in prep.-a) and land surface temperatures at interannual time scales. Arctic sea-ice decline in the 1990's is associated with the positive phase of the North Atlantic Oscillation (NAO) (Deser et al. 2000), which is characterized by enhanced storminess and warm moist air penetration into the Arctic. The NAO has approached more neutral values since 2000 yet the ice melt has accelerated, suggesting several mechanisms are in play. Maslanik et al. (2007) demonstrate that the net local atmospheric circulation in the Arctic is consistent with continued ice reduction. This analysis will build on these past studies that examine the general Arctic ice decline but will focus on the changes in the 50-km ocean-land coastal domain that are important for tundra vegetation. This will require an analysis of both the large-scale and regional-scale circulation patterns.

Atmospheric circulation will be analyzed using the NCEP/NCAR Reanalysis and North American Regional Reanalysis (NARR) data sets. The climatology, variability, and trends of summer atmospheric circulations in the circumpolar Arctic regions will be documented. This analysis will help to develop better estimates of the large-scale versus local forcing of coastal tundra NDVI and LST anomalies. In addition, Zhang et al. (2008a) have performed a suite of regional model (WRF) simulations for the Northern Alaska-Beaufort regions, which documents the strong influence of summer sea breezes on coastal land surface temperatures. Their simulations as well as other dynamically downscaled model results over Alaska are available to us for this project to study mechanisms. The atmospheric reanalysis data sets will be analyzed regionally to evaluate local atmospheric circulation and relate it to land and ocean surface temperature trends and variability. For example, we expect that coastal tundra ecosystems may be highly sensitive to an early summer sea-ice retreat (possibly in response to anomalous winds such as in the East Siberian Sea in June 2007) that comes at the height of the growth season, relative to a late summer ice retreat (forced perhaps by thermodynamic ice-albedo feedback) that arrives as terrestrial ecosystems are moving into senescence. We will also compare LST with SST and ocean heat content data to understand better the changing seasonal relationships between how heat is absorbed and transferred between marine and terrestrial regimes. For example, we expect that LST may last longer into the fall near marine areas with high sea-ice melt-back and resulting ocean warming. However, this may not be the case in certain areas where warm ocean currents have been re-directed by changing surface stresses over the summer as sea ice retreats (Figure 4d).

### **Component 3: Land energy and carbon linkages (Epstein, Jia, Environmental Sciences Student)**

One method for assessing the effects of changing vegetation seasonality on carbon budgets is to use phenomenological relationships that exist between remotely-sensed indices of vegetation and field observations of aboveground biomass. Published relationships exist between the normalized difference vegetation index (NDVI) and the biomass of aboveground vegetation (or some components of aboveground vegetation) for arctic tundra ecosystems (Hope et al. 1993, Boelman et al 2003, 2005, Reidel et al. 2005). Epstein additionally has an extensive dataset of NDVI and aboveground vegetation biomass (manuscript in prep.) collected from sites throughout the Arctic of both North America (Epstein et al. 2008) and Russia, including data from all five of the arctic bioclimate subzones (Subzones A-E; sensu Walker et al. 2005). *Growing season curves of the NDVI* generated from satellite data (Component I) could thus be translated into growing season aboveground biomass curves, and the accumulation of carbon in aboveground tissue could be estimated. For an additional whole-season approach, the temporally-integrated (within a growing season) NDVI (TI-NDVI) has been related to the peak season aboveground biomass (Jia et al. 2006), and these relationships could be used to assess interannual changes in the stocks of aboveground carbon.

Using phenomenological relationships is a strictly empirical approach to estimating vegetation carbon. For a somewhat more mechanistic approach, and to identify other carbon pools in addition to those in aboveground vegetation, simulation modeling will be used. ArcVeg is an arctic tundra vegetation dynamics model that was developed to examine the controls of climate and grazing on the temporal aspects of tundra plant communities (Epstein et al. 2000, Epstein et al. 2001, Epstein et al. 2004, Epstein et al. 2007). The model presently runs on an annual time

step, although the growing season is partitioned into a maximum of five growth periods dependent on climate and interannual stochastic weather. The driving factors in ArcVeg are the climate regime, the grazing regime, and the soil organic matter, which exerts a control on the nitrogen available for plant growth. In the most recent version of ArcVeg, twelve plant functional types are simulated, ranging from non-vascular vegetation (mosses and lichens) to various types of herbaceous plants (e.g. forbs, graminoids) and various types of shrubs (e.g. deciduous, evergreen, erect, prostrate). Plant functional types compete for available soil nitrogen and grow depending on nitrogen uptake and retranslocation, and their efficiencies for converting nitrogen to biomass. The use of ArcVeg will therefore allow us to examine the effects of seasonality changes on the carbon accumulated by different plant functional types (and in different plant tissues, i.e. foliage, wood, roots), not just the vegetation biomass as a whole.

Our approach will be to modify ArcVeg to be a daily time step model. Since the growing season in ArcVeg is already partitioned, albeit not daily, the structure for this change is already in place in the code. The new model will be driven by the *seasonality of land surface temperatures* generated in Component I. The ArcVeg model could therefore project changes in plant community composition, plant functional type biomass, and carbon accumulation for the different tundra regions based on observed changes in temperature seasonality. In addition to these projections, the ArcVeg model would be used “experimentally” to gain insight into the following questions: 1) What are the effects of an earlier start to the growing season (without an increase in total summer warmth) on arctic tundra plant communities and carbon accumulation? 2) What are the effects of increased summer warmth (without an increase in the length of the growing season) on arctic tundra plant communities and carbon accumulation? 3) How do the two effects of increased growing season length and increased total summer warmth combine to influence plant community composition and carbon accumulation in arctic tundra ecosystems? The modeling analyses will be conducted for each arctic bioclimate subzone (Subzones A-E) along both a North American and a Russian (Yamal Peninsula) transect, where field data exist for model parameterization (Epstein et al. 2008, Walker et al. 2008a, Walker et al. 2008 submitted.).

### ***Links with land- and sea-based observation programs***

It is critical that these studies be linked to ground-based measurements wherever possible. While this proposal does not include a component for field observations, such data will be used in this project. The proposed work is an interaction of several International Polar Year (IPY) initiatives. The Greening of the Arctic (GOA) initiative is investigating changes to plant biomass, NDVI, and other site variables in the circumpolar Arctic and has conducted ground-based observations at a variety of sites, primarily along transects in North America and Eurasia. Where relevant we will use the data from these earlier and ongoing studies to help in calibration of the data obtained from space-based sensors. The North American Arctic Transect (NAAT) traverses all five Arctic bioclimate subzones in Alaska and Canada (Walker et al. 2008a), and the Yamal Transect traverses five bioclimate subzones in Russia (Walker et al. 2008 submitted.). A major focus of both transects is to monitor vegetation (biomass, species composition, NDVI, LAI), soils, active layer, and permafrost temperatures on zonal sites at representative locations along the complete bioclimate gradient. Both projects are working collaboratively with other IPY initiatives to develop a suite of key circumpolar measurements, including the Circumpolar Biodiversity Monitoring Programme (CBMP), International Tundra Experiment (ITEX), the circumpolar

Active Layer Monitoring (CALM) project, the Thermal State of Permafrost (TSP), and fungal genomic dynamics at extreme cold temperatures. A proposal has just been submitted to NASA to continue ground observations along the Yamal Peninsula in Russia, and an Arctic Observatory Network (AON) proposal has just been submitted to NSF to evaluate the feasibility of establishing permanent terrestrial ecosystem observation capabilities in the extreme High Arctic of Canada at Isachsen, Mould Bay, and Green Cabin (all of which are part of the NAAT).

In situ marine data collected as part of AON will also be used in this project, for example from summer hydrographic surveys in the Beaufort Gyre (A. Proshutinsky, PI) and the central/western Russian arctic seas (I. Polyakov, PI). Also, drifting buoys will provide ice thickness (D. Perovich, PI), SST, and ocean heat content (I. Rigor and J. Toole, PIs). Further, a new proposal to AON has just been submitted by co-PI Steele to deploy specialized ocean thermistor string buoys to better determine the upper ocean warming of the seasonally ice-free margins of the Arctic Ocean.

## **PROJECT MANAGEMENT**

This is a collaborative effort of three Principal Investigators from three institutions: Uma Bhatt from the Department of Atmospheric Sciences and Geophysical Institute at the University of Alaska Fairbanks; Howard Epstein in the Department of Environmental Sciences at the University of Virginia; and Mike Steele from Polar Science Center, University of Washington.

Dr. Bhatt will lead the effort on analyzing the changing seasonality of circumpolar sea-ice. A graduate student, supervised by Bhatt in Atmospheric Sciences will analyze the atmospheric circulation associated with the tundra zone. Analyzing the circumpolar dynamics of vegetation and snow seasonality will be a collaborative effort among Drs. Bhatt and Epstein, assisted by Co-PI Dr. Skip Walker, collaborator Martha Reynolds (University of Alaska Fairbanks), and data consultants Dr. Jiong Jia from the Chinese Academy of Sciences and Dr. Joey Comiso from NASA Goddard. Dr. Steele will analyze the heat budget implications of changing seasonality in the arctic marine and (with other PIs) the terrestrial regimes. Dr. Epstein will lead the modeling effort to examine the effects of changes in land surface temperatures and vegetation seasonality on tundra plant community dynamics and carbon accumulation by the vegetation.

## **BROADER IMPACTS**

A major goal of this proposal is to provide significant research opportunities for undergraduate students at the participating universities. Two undergraduate students will conduct summer research under the guidance of PI Howard Epstein and his graduate students. The undergraduates will be carefully selected among rising third- and fourth-year students at the University of Virginia (UVA), with one student from the PI's department, Environmental Sciences. In order to broaden participation to students in other fields, providing the kind of experience not otherwise available, a second student will come from another department or college (e.g., chemistry, engineering). The Center for Undergraduate Excellence at UVA will publicize this opportunity. Undergraduates will benefit from the opportunity to participate in a vibrant research program, potentially meeting researchers from throughout the world, with attendance at an international meeting. As important members of the research team, these students will be intimately involved in data processing and analysis. They will develop the remote sensing and simulation modeling skills that are being practiced by the PIs and their graduate students. In addition to providing

research assistance, each student will take on an independent research project that could form the basis for a distinguished major's thesis or a proposal for further independent work.

All of the students participating in this project will be contributing to meaningful research on global change, in a very dynamic region. They will also be a part of a growing community of undergraduate researchers at the University of Virginia. Evidence of the strength of U.Va.'s undergraduate research in the sciences is provided by the fact that two U.Va. students received the Barry M. Goldwater Scholarship in 2008, and three students did so in 2007. Students created the Undergraduate Research Network as a way of spreading the excitement of research throughout the undergraduate population. This student group, sponsored by the Center for Undergraduate Excellence, holds two research symposia each year; convenes numerous workshops on such topics as “How to Get Involved in Research” and “How to Give an Effective Research Presentation”; and publishes a journal of undergraduate research, *The Oculus*. The Center for Undergraduate Excellence will advise the students funded by this grant about additional opportunities to conduct research, such as through the Harrison Undergraduate Research Award program; opportunities to present their research nationally or internationally (e.g., at the Atlantic Coast Conference's Meeting of the Minds or the Universitas 21 undergraduate research conference); and how to apply for nationally competitive scholarships such as the Fulbright or Rhodes scholarships, for which this research experience will be an asset.

The University of Washington has a strong program of community outreach at the Polar Science Center. M. Steele lectures and gives demonstrations about the arctic, climate change, and oceanography to pre-K through high school students, to a quarterly General Environmental Science class at the Art Institute of Seattle, to minority and low-income outreach organizations such as GEAR-UP = Gaining Early Awareness and Readiness for Undergraduate Programs and REACH = Resource for Enhancing Academic and Community Help, and as part of the annual science fair at the Jewish Day School of Seattle. These outreach efforts will continue in the coming years, and will incorporate the results of the present project. M. Steele also actively participates in the annual 4-day Polar Science Weekend (**PSW**), which has drawn 5000, 10,000, and 7600 attendees in 2006, 2007, and 2008. For PSW, Steele has developed an interactive activity called the “*Salinity Taste Test*” in which visitors learn about ocean salinity by tasting 3-6 samples of water with varying salinity, thereby also learning how sensitive a “salinometer” their tongues are. The exhibit is staffed in part by grade school kids who have been recruited by visits to their classrooms in the previous few months, where the concepts of salinity and the hydrologic cycle are introduced. Steele has also developed a show for PSW called “*Extreme Cold*” in which he uses a variety of materials, including liquid nitrogen, to discuss the arctic, climate change, and the difference between fresh and salty ice. Attendance at the 5-7 shows given over the weekend is typically over 1000. PSW 2009 is scheduled for February 26 – March 1. For more information, visit [http:// psc.apl.washington.edu/ psw/](http://psc.apl.washington.edu/psw/) or attend the fall AGU talk “PSW: A university / science center collaboration” in session ED03.

The results of the project will also be incorporated into graduate atmospheric science classes taught at UAF by Bhatt such as *Climate and Climate Change*. Bhatt has organized a one-credit seminar class *Climate Journal Club*, which has met weekly for the past 5 years to discuss climate related topics with an emphasis on interdisciplinary scientific exchanges. This endeavor has been a success with typically 6-12 faculty, postdocs, and students participating each week. The



attendees are specialists in climate sciences, oceanography, geology, biology, statistics, hydrology, political science, natural resources management and other fields. In addition, the results will be made available to K-12 teachers throughout Alaska through the UAF Science Educational Outreach Center. This new center provides a comprehensive list of programs and activities that facilitates access to cutting-edge science research results for educators. All of these educational activities aim to provide students with a skill set, preparing them to apply their knowledge to unsolved problems, and to entrain currently underrepresented groups in the physical sciences. The project will also have a web site at the Alaska Geobotany Center with a virtual tour of the NAAT transect and patterns of greening that are occurring across the Arctic.

## CONCLUSION

The seasonal progression of arctic terrestrial biomass, and the timing and magnitude of peak biomass are changing. This change is not consistent across all tundra ecosystems, for reasons that are still unclear. Preliminary research indicates a potential link with the seasonality of nearby marine surface conditions, i.e., sea ice and upper ocean properties. We propose to perform both statistical and model-based analyses to better understand these important linkages. We follow this with a modeling analysis of the effects of changing vegetation seasonality on plant functional type composition and arctic terrestrial carbon accumulation (or loss). The results will be a synthetic view of changing seasonality across the land/ocean boundary of the Arctic Ocean.

## RESULTS OF PRIOR NSF SUPPORT

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**1. Biocomplexity associated with biogeochemical cycles in frost boil ecosystems.** OPP-0120736, \$2,750,421, 10/1/01-9/30/07, D.A. Walker, PI, H.E. Epstein, W.A. Gould, W.B. Krantz, R. Peterson, C.L. Ping, V.E. Romanovsky, Co-PIs. *This study is relevant to the proposed work because it established the North American Arctic Transect where ground information for climate, soil, vegetation, and geomorphological information were collected along the complete arctic bioclimate gradient.* Publications to date have included an overview of the project and a conceptual model of how vegetation affects the morphology of patterned ground forms with results from the Low Arctic portion of the gradient (Walker et al. 2003, Walker et al. 2004) descriptions of the differential frost heave model, a physically based model of self-organization of frost boils and earth mounds (Peterson and Krantz 2003, Peterson et al. 2003), characterization of the vegetation and its effect on the thermal properties of the soil (Kade et al. 2005, Kade 2006, Kade et al. 2006, Kade and Walker 2008), descriptions of the soil processes in frost boils (Michaelson et al. 2002, Ping et al. 2005), the active layer (Kelley et al. 2004), the hydrological system (Daanen et al. 2007), and the educational component of the project (Gould et al. 2003). A synthesis of the project has been published in a special section of *Journal of Geophysical Research*; nine papers describe the vegetation, soils, biomass, spectral properties, and the models used along the North American Arctic Transect (Daanen et al. 2008b, Epstein et al. 2008, Michaelson et al. 2008, Nicolsky et al. 2008a, Peterson and Krantz 2008, Ping et al. 2008, Reynolds et al. 2008c, Walker et al. 2008a, Walker et al. 2008b). Additional papers published elsewhere or in preparation further describe the models (Daanen et al. 2008a, Nicolsky et al. 2008b, Peterson 2008), measurements of frost heave (Daanen et al. 2007, Romanovsky et al. 2008); the special characteristics of bioclimate subzone A (Walker et al. 2008c), vegetation in the High Arctic (Vonlanthen et al. 2008 (in press)), carbon sequestration (Ping et al. 2008 in press), and a synthesis of the zonal vegetation along the transect (Kuss et al. 2008 in prep.).

Several hard-copy data reports are also available on line at [http://www.geobotany.uaf.edu/library/reports/#bc\\_reports](http://www.geobotany.uaf.edu/library/reports/#bc_reports) (Raynolds and Walker 2003, Munger et al. 2004, Raynolds et al. 2004, Raynolds 2005, Barreda et al. 2006, Vonlanthen et al. 2006).

**2. Greening of the Arctic: Synthesis and models to examine the effects of climate, sea-ice, and terrain on circumpolar vegetation change.** NSF ARC-0531180, \$481,765 to UAF and \$406,603 to University of Virginia, 2005-2007. 1/1/06-12/31/08. D.A. Walker and H.E. Epstein, Co-PIs. The Greening of the Arctic initiative examines the sea-ice, climate and vegetation interrelationships and the relevance to people living in the Arctic. *This project is very relevant to the work proposed here because of its focus on the inter-relationships between sea-ice, land-surface temperatures, and vegetation greenness.* The results of this project offer a fresh perspective to view and study changes to the vegetation of the whole Arctic. 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<sup>2</sup>) is within 100 km of at least seasonally frozen seawaters that provide the cool summer temperatures necessary for tundra's presence. Publications to date have focused on a summary of the modeling results (Epstein et al. 2007) (Epstein et al. 2007), summaries of the NDVI relationships in Canada (Jia 2008 submitted) relationships of circumpolar NDVI to patterns of biomass (Raynolds et al. 2006b), land surface temperatures (Raynolds et al. 2008a), glacial geology (Raynolds and Walker 2008 in press), and permafrost (Raynolds and Walker 2008); and the influence of sea ice on land-surface temperatures, and NDVI (Bhatt et al. 2007, Bhatt et al. 2008, Bhatt et al. 2008 in prep.-a).

**3. A Heat Budget Analysis of the Arctic Climate System.** NSF ARC-0531103, \$204,799, 10/05-9/09, M. Steele. In this project we have provided a first-ever coordinated view of the arctic climate system's energy budget (Serreze et al. 2007). A key finding was that over the entire Arctic Ocean, atmospheric warming is more important to ocean warming than lateral heat flux convergence in ocean currents. We are recently looking again at this partition for the energy budget over open water areas during recent summers (Steele et al. 2008b), and finding a similar result, although northward advection of Pacific-origin waters does play a strong regional role (Zhang et al., 2008a). These latest studies were motivated by our research into the incredible warming of the upper Arctic Ocean in summer 2007, set in an historical context using archived data from the past 100 years (Steele et al., 2008a). The relative roles of ocean, atmosphere, and pre-conditioning in the amazing sea-ice retreat of 2007 and attempts to predict future conditions have been the subject of several studies partly funded by this project (Lindsay et al. 2008a, Lindsay et al. 2008b, Schweiger et al. 2008b, Zhang et al. 2008b, Zhang et al. 2008c).

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