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

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A. PROJECT SUMMARY

Changes to the vegetation of the Arctic are intimately linked to changes to the sea-ice cover, land-surface temperatures, and a host of terrain variables. *The overarching goals of our proposed research are to (1) explore the sea-ice/terrain/vegetation linkages by synthesizing a group of recently available long-term circumpolar databases, (2) examine how the vegetation of the circumpolar Arctic is responding to global climate change, and (3) use this information in combination with models to help predict future response of arctic vegetation.* ***Intellectual merit of the project:*** The project will directly address the question of how the terrestrial vegetation of the Arctic has responded to climate change to date and how it will respond in the future as portions of the Arctic Ocean become seasonally ice free as indicated by current trends in sea ice. An average17% increase in greenness, as measured by the normalized difference vegetation index (NDVI), occurred in northern Alaska from 1981 to 2001, concomitant with strong ice retreat in the Beaufort Sea and rising land-surface temperatures. The trend in NDVI is consistent with observations regarding shrub cover, modeling, and experimental evidence linking temperature increases to biomass increases. We will synthesize 23+ years of data from Earth-orbiting satellites in combination with detailed circumpolar maps of climate, vegetation, terrain, and substrate variables to determine how the ocean and land have interacted during the years of record, and then use this information to improve existing models of Arctic vegetation change. We will primarily use a time series of surface temperature, sea-ice, and NDVI data from the Advanced Very High Resolution Radiometers (AVHRR) aboard the NOAA satellites. A host of other remote sensing data will compliment these to extend the length of the record and to look at finer scale changes. The primary region of study is the circumpolar Arctic as defined by the presence of tundra vegetation and an Arctic climate. A larger area defined by the arctic watershed will be studied in less detail. We will create a circumpolar integrated geographic information system for this region. The NDVI patterns will be analyzed spatially and temporally with respect to mapped variables including land-surface temperatures (LSTs), sea-ice patterns, the age of the terrain, substrate, topography, elevation, and regional floras. We will use vegetation change models to determine if the greening detected thus far can be used to project future patterns of vegetation change in the Arctic. A spatial analysis using BIOME4, a global model of vegetation change, will predict changes in the patterns of arctic and boreal plant communities, and ArcVeg, a model of arctic vegetation dynamics, will link the changes detected using remote sensing to ground-based measurements of plant-species composition and structure to examine the rates at which changes can be expected. ***Broader impacts resulting from the project.*** Our study addresses a major component of the complex suite of interrelated atmospheric, oceanic, and terrestrial changes that is the subject of the Study of Environmental Arctic Change (SEARCH). Understanding the spatial and temporal patterns of arctic vegetation change is a key to understanding changes to many other component of the Arctic system, including permafrost, hydrological cycles, wildlife, feedbacks to the global climate, and human utilization. The project will be hosted on the Arctic Geobotany Center's web site and will be highlighted as an interactive component of the Arctic Geobotanical Atlas using state of the art visualization tools. Our project will be strongly coordinated with other ARCSS projects that are examining vegetation and other components of the Arctic System. The Greening of the Arctic initiative has been submitted for endorsement by the International Polar Year Joint Committee. If funded, the project will also be integrated into a package of projects as the US contribution to IPY. Other parts of the Greening of the Arctic initiative that will be proposed separately include a plan to monitor plant biomass across the full arctic bioclimate gradient, and an outreach/ educational component that will involve local communities in the research and train a group of young investigators so that standardized measurements can be continued in the future.

B. TABLE OF CONTENTS

...The tundra seems immense and durable. Standing on hill a near Sagwon on Alaska's North Slope in March the white landscape stretches to the horizon in all directions. The tundra, now hidden by a rough layer of snow, seems as eternal and unchangeable as the sturdy muskoxen partially obscured by blowing snow on a nearby ridge. It is hard to imagine that this scene could change rapidly, but both the tundra and the muskoxen are threatened by changes happening 100 km away in the ice-covered Beaufort Sea.

C. PROJECT DESCRIPTION

INTRODUCTION

One of the major questions facing Arctic terrestrial ecologists at the moment is what will happen to the tundra regions if the Arctic Ocean becomes seasonally ice free as indicated by current trends in sea ice (ARCSS 2004). Changes to the vegetation will have major implications for the permafrost, snow, hydrology, soils, wildlife, and people who live in the Arctic (Sturm et al. 2003). They also have global implications because of albedo and trace-gas feedbacks to the climate system (Beringer et al. 2001; Chapin III et al. 2000). Several new circumpolar databases 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 (Fig. 1 and 2). 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 (Fig. 2). 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 extratropical cyclones, general warming of the land surfaces, and reduction in the extent of the tundra biome (Serreze et al. 2000; Hinzman et al. 2005 in press; Wang and Overland 2004; Kaplan 2005). 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. New circumpolar maps and remote sensing data provide tools to examine the underlying causes of pan-Arctic vegetation change. A synthesis of these circumpolar data sets is especially appropriate now leading up to the International Polar Year planned for 2007-2008.

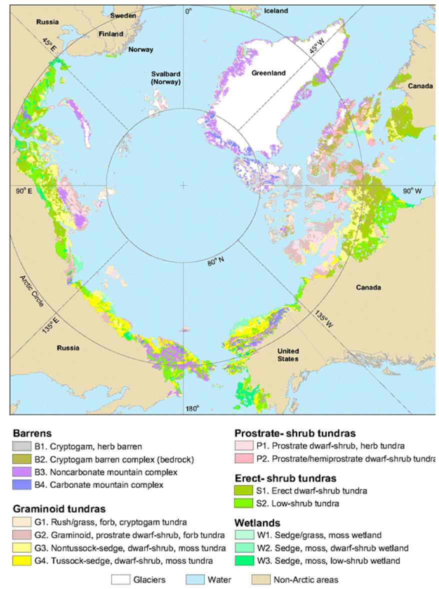

Fig. 1. The Arctic biome. The southern boundary of the mapped area is tree line. Note the close proximity of all parts of the biome to perennially or seasonally frozen seawaters. Modified from the Circumpolar Arctic Vegetation Map (CAVM Team 2003).

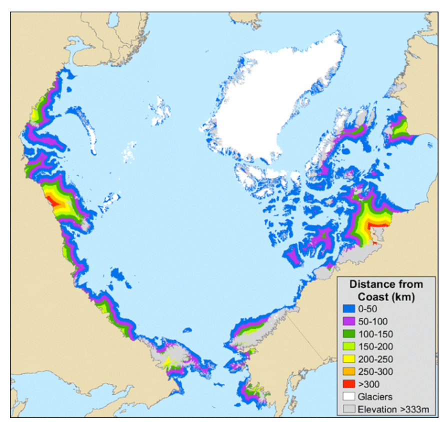

Fig. 2. Proximity of lowland tundra areas to sea ice in 50-km increments. 61% of the tundra is within 50 km of sea ice (blue buffer), 80% is within 100 km (gray and blue buffers), and 100% is within 350 km. Upland areas above 333 m (gray areas) were excluded from the analysis because these area experience sufficient adiabatic cooling to shift to colder elevation belts.

ORGANIZATION OF THIS PROPOSAL

We first review four areas of research that stimulated development of this proposal, including trends of decreased sea ice and increased land-surface temperatures, increased greening in Alaska, development of several pan-Arctic databases, and models of arctic vegetation change. Along with these reviews we present several questions that are driving our research. We then describe the system that we will examine and four components of the research with specific tasks to address the questions. A fifth component addresses the topic of project management and outreach.

STIMULUS FOR THIS RESEARCH AND MAJOR QUESTIONS

Trends of decreased sea ice and increased land surface temperatures. General circulation models (GCMs) predict that the Arctic will warm on an area average of between 3.2 and 6.6 ˚C when CO_2 in the atmosphere is double that of preindustrial levels (Holland & Bitz 2003), which is predicted to occur within the next 26 to 60 years (New 2005). Records from 1980 to 2003 indicate that the perennial ice in the Arctic Ocean declined at a rate of 9.2% per decade. Concurrently, the Arctic surface temperatures rose steadily over much of the Arctic landmasses except in some parts of northern Russia and the Greenland ice cap (Fig. 3) (Comiso 2005). Land-surface temperatures (LST) over North America show a 1.06 ± 0.22 ˚C decade^{-1} warming (Comiso 2003), the largest temperature increases on the globe. The large positive trends in surface temperatures are in part caused by more open water surfaces due to the retreat of the perennial ice cover as suggested by models showing an amplification of warming over the Arctic Ocean (Holland & Bitz 2003). Interdecadal cyclical patterns of sea-ice extent (Proshutinsky & Johnson 1997; Thompson & Wallace 1998) are other possible contributing factors. Surface temperatures are most highly correlated with sea-ice concentration in the seasonal sea-ice regions, the portion of the ice pack that melts annually. The ice in the Beaufort Sea north of Alaska has retreated most dramatically, and this region has warmed particularly strongly.

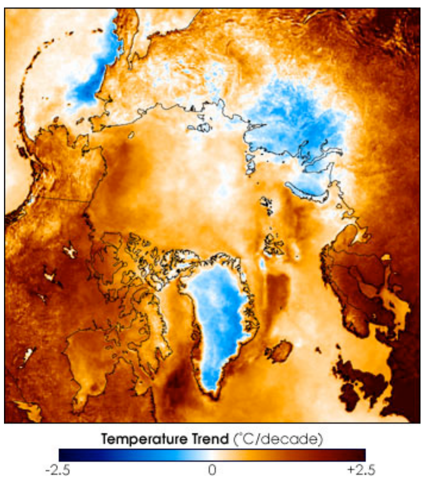

Fig. 3. Annual temperature anomalies in the Arctic from 1981 to 2003, based on AVHRR thermal infrared data. Blue areas show areas of cooling and red areas are warmed. Note the strong warming in the Beaufort Sea north of Alaska, and the warming over the terrestrial areas of North America, and cooling in the western Bering Sea, Greenland ice cap, the Taimyr Peninsula and arctic islands in Russia. Adapted from Josefino Comiso, http://earthobservatory.nasa.gov/Study/ArcticIce/.

These changes have been linked to a wide variety of phenomena in the Arctic, including altered permafrost temperatures (Romanovsky et al. 2002), snow melt (Groisman et al. 1994), treelines (Shiyatov 2003) and shrubs (Sturm et al. 2001). Summaries of system-wide changes are reported in several references (Hinzman et al. 2005 in press; Morison et al. 2001; Overland et al. 2004; Serreze et al. 2000). We will address the following specific question relating climate and sea ice to vegetation patterns: *How are the climate dynamics in the Arctic linked to sea-ice distribution patterns, land-surface temperatures, and terrestrial NDVI?*

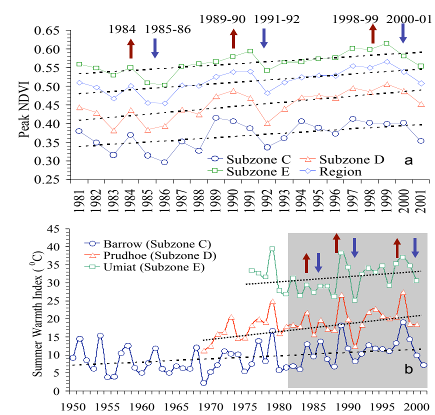

Fig. 4 (a) Time series of peak NDVI derived from 8-km resolution AVHRR data from 1981 to 2001 among the bioclimate subzones and for the whole Arctic Slope. (b) Summer warmth index (SWI) over the past 22-50 years at meteorological stations in each bioclimate subzone. Dashed lines are linear regressions. The shaded area in (b) highlights the period of SWI covered by the NDVI data in (a). The arrows show years of corresponding increases (red) and decreases (blue) in NDVI and SWI. From Jia et al. (2003).

Greening of northern Alaska. The length of the satellite-based record is now sufficient to show meaningful trends of increased production associated with the warming trends. Over the length of the AVHRR satellite observations (1981-2001), the greenness of northern Alaska as measured by the normalized difference vegetation index (NDVI), increased by 13% to 19% and averaged 17% across the whole Arctic Slope (Fig. 4a) (Jia et al. 2003). The increase in NDVI occurred during a period when the summer warmth index (SWI) measured at ground stations across northern Alaska increased by 0.16-0.34˚C yr^{-1} (Fig. 4b). (The SWI is equivalent to thawing degree months or the sum of the mean monthly temperatures greater than 0˚C.) NDVI apparently responds very quickly in warm years; years with greater NDVI generally correspond to years of higher temperatures (red and blue arrows in Figs. 4a, b). The trend is consistent with greening patterns observed elsewhere in the north (Lucht et al. 2002; Myneni et al. 1997; Zhou et al. 2001). An increase in biomass is expected with warming, as suggested by many other lines of evidence, including results from warming experiments (Shaver et al. 2000), modeling studies (Gilmanov 1997; Williams et al. 2000); patterns of biomass and NDVI along natural arctic temperature gradients (Jia et al. 2002; Lucht et al. 2002), and observations of recent shrub increases in northern Alaska (Sturm et al. 2001).

Jia et al. (2003) also showed that the time series of NDVI varies considerably with vegetation type, and substrate (Fig. 5). Other studies have shown that landscape age (Walker et al. 1995) and substrate pH strongly affect patterns of NDVI and a host of ecosystem properties including trace-gas fluxes and energy budgets (Walker et al. 1998). The magnitude of the NDVI change in northern Alaska is, however, surprising and suggests that rapid vegetation change is especially strong in this part of the Arctic.

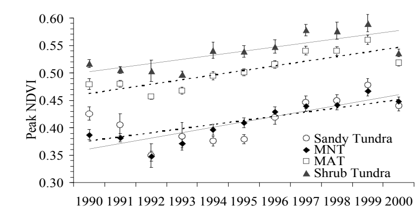

Fig. 5. Time series of Peak NDVI based on 1-km resolution AVHRR data among sandy tundra, moist nonacidic tundra (MNT), moist acidic tundra (MAT, and shrub tundra. From Jia et al. (2003).

The trend in NDVI can be linked to recently documented changes in shrub cover in Alaska (Silapaswan et al. 2001; Sturm et al. 2001; Tape et al. 2004). Correlations of modern NDVI with biomass along the climate gradient in northern Alaska indicate that the observed average 17% increase in NDVI corresponds to about a 150 g m^{-2} increase in biomass, and most of this is likely due to increases in shrub biomass (Jia et al. 2003). At pan-Arctic scales, the most important factor controlling the distribution and abundance of vegetation is the amount of summer warmth available for plant production (Alexandrova 1971; Matveyeva 1998; Yurtsev 1994). Shrub height, growth rings, and biomass are all strongly correlated with total summer warmth (Walker 1987; Walker et al. 2003). Shrub growth along streams inland from the Arctic coast show an exponential response to temperature compared to a much more subdued linear response of open-tundra willows (Walker 1987), probably because of warmer soils and increased nutrient flux in streamside areas, suggesting that biomass will probably respond most strongly to warming in areas with greater nutrients and/or microsites with warmer soils (Shaver et al. 2000). There are no time series of vegetation biomass measurements that can be linked directly to the NDVI record; however, oblique aerial photographs taken in the 1940s and 1950s of many areas in northern Alaska indicate that shrub cover has increased dramatically over much of northern Alaska in the past 50 years (Tape et al. 2004).

The Jia et al. (2003) study was the primary impetus behind this proposal. Major questions raised by it include: *(1) Is the detected trend in NDVI due entirely to a trend in greening of the vegetation or are other factors involved, such as instrument calibration and atmospheric effects? (2) Has a similar pattern of greening also occurred elsewhere in the Arctic? (3) Does greening and production elsewhere in the Arctic correspond to sea-ice fluctuations and land-surface-temperature trends? (4) How do other factors such as bioclimate subzones, precipitation, regional floras, landscape age, substrate type, and topography influence the trends in NDVI? (5) Has the greening occurred evenly across broad landscapes, or has it been confined to local areas of greater warmth, moisture, or nutrient flux, such as south-facing slopes, water tracks, and streams?*

Circumpolar vegetation and NDVI maps. Arctic vegetation will not respond uniformly to climate change because the vegetation is controlled by many factors in addition to climate (Walker 2000). Most recent global modeling experiments and analyses of projected vegetation change treat Arctic ecosystems too simplistically, often lumping arctic vegetation into one to five categories despite large variations in the species composition, structure, and biogeochemical characteristics (Bohn et al. 2000; Gribova & Tichomirov 1985). The recent Circumpolar Arctic Vegetation Map (CAVM) and its geographic information system (GIS) will be major tools in our analysis (Fig. 1) (CAVM Team 2003; Raynolds et al. 2005b (submitted); Raynolds et al. 2005 (in press); Walker et al. 2002; Walker et al. 2003; Walker et al.

2005 in press). The CAVM uses a ‘zonal’ concept as a central organizing principle (Fig. 6). Zonal vegetation and soils occur on relatively flat, mesic areas with fine grained-soils, not influenced by extremes of soil chemistry, snow or disturbance. The Arctic Zone is subdivided into five subzones, The subzones are defined mostly on the basis of mean July temperature (MJT). Subzone A is the coldest, with MJTs less than 2 ˚C, and Subzone E the warmest with MJTs between 10 and 12 ˚C. Each subzone has a characteristic suite of plant growth forms, from cushion forbs in the coldest subzone to low shrubs up to 2 m tall in the warmest subzone. The vegetation map legends note dominant plant functional types within each of the map units, which are necessary for dynamic regional vegetation change models (DGVMs) (Kittel et al. 2000). The zonal map indicates the vulnerability of some areas of the Arctic to global change (Walker et al. 2005 in press). For example, Bioclimate Subzone A is the coldest part of the Arctic with mean July temperatures less than 2 ˚C and occupies only about 2% of the Arctic. It is located primarily on islands at the cold end of the climate gradient and has unique vegetation adapted to the very coldest environments. If the climate warms, the current vegetation distribution could change, limiting Subzone A to new land exposed by melting glaciers or possibly eliminating it altogether. The bioclimate subzones on the CAVM have very general contours, based on data from widely scattered climate stations. Finer-scale regional variations caused by continentality and elevation differences are missing in the current portrayal. One major objective of our proposed work is to improve the portrayal of bioclimate by using mean land-surface-temperature values derived from satellite data (Comiso 2003).

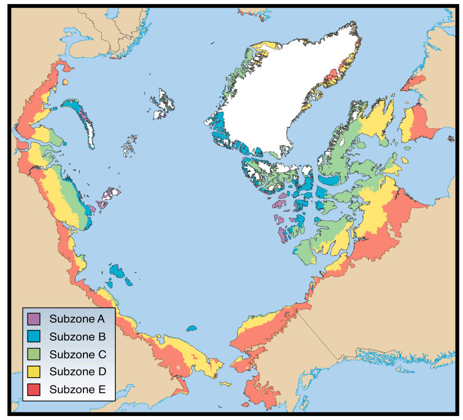

Figure 6. Arctic bioclimate subzones

The zonal approach works well for much of the Arctic, however large areas do not have zonal vegetation because of factors such as rugged topography, large wetlands, recent glaciation, large-scale alluvial or aeolian deposition, or cold saturated soils due to permafrost (Razzhivin 1999). Any attempt to spatially model the effects of climate change on the vegetation patterns and production in the Arctic will need to consider the complexities of the terrain. Some large azonal areas such as extensive wetlands and mountainous areas were mapped as separate units on the CAVM. The CAVM also includes information on substrate (parent material) chemistry, surficial geology, which is fairly detailed in Canada based on (Fulton 1985) and was also mapped for Russia, but using a different system. Critical information that is currently missing includes soil texture and glacial history of the landscapes. Recent soil and glacial geology maps will be used to improve portrayal of the substrates.

Another important component of the CAVM GIS is a Peak-NDVI map (Fig. 7) of the Arctic (Walker et al. 2003). This image is a composite of AVHRR data that shows the Arctic at maximum greenness during 1993 and 1995, two relatively warm years in the Arctic, when there was minimum snow and ice cover on the terrestrial areas (Walker et al. 2003). The patterns of NDVI on this map are quite complex, but there are clear transitions associated with terrain features (mountains, wetlands, shield areas) and precipitation regimes. Moisture is generally less of a controlling factor than temperature for arctic tundra vegetation because low temperatures and permafrost limit evaporation and percolation that control soil moisture. However, snow cover insulates the ground surface during winter, raising soil temperatures for much of the year (Walker et al. 2001; Sturm et al. 2001). Deep snow can promote the growth of dense

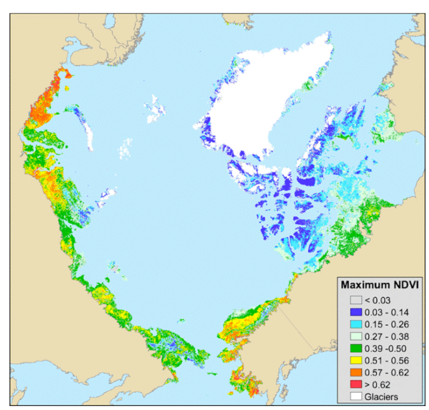

Fig. 7. Maximum NDVI of the Arctic. From Walker et al. (2003).

shrubs and protect woody plants from desiccation and abrasion in the winter, as is the case with the *stlanik* (*Pinus pumila*) vegetation of northeastern Siberia (Yurtsev 2004). Also there are feedbacks between snow depth and increasing shrub heights (Sturm et al. 2001). Examination of the NDVI map of the Arctic (Fig. 7) indicates that anomalously high NDVI may be occurring in areas with deeper snow cover such as the European Russian Arctic and areas near tree line with dense alder vegetation, and some areas on the Seward Peninsula, Yukon-Kuskokwim Delta, and the Arctic Slope in Alaska. Most likely there are strong interactions between warm winter temperatures, deep snow, warm soils, and discontinous permafrost permitting luxuriant shrub growth in these areas. Snow depth is difficult to map using remote sensing techniques, but continental scale maps have been synthesized in recent years using combinations of ground and remote-sensing information.

The CAVM maps have generated many questions regarding the distribution of the mapping units and NDVI patterns with respect to such things as climate and terrain boundaries. As a start, our questions include: *(1) How does the present-day combination of climate, topography, terrain age, and substrate influence the patterns of vegetation and biomass across the circumpolar Arctic? (2) How will climate change affect the composition, patterns, and production of future Arctic biomes. (3) How is the greening occurring within regional landscapes; is it occurring broadly, or is it more patchy, occurring in local warm microclimates or in areas that may have greater amounts of nutrients and water, such as along streams or on south-facing slopes?*

Modeling vegetation patterns. A good start toward answering these questions has been achieved with vegetation change models. Numerous modeling approaches have been used to help predict the consequences of climate change to arctic vegetation at regional and circumpolar scales (Kittel et al. 2000; Rastetter et al. 2003). One recent approach used the Köppen climate classification system to determine how vegetation boundaries have shifted based on changes in climate over the past 100 years (Wang & Overland 2004). The authors determined that climate has already changed sufficiently to potentially eliminate about 20% of the present distribution of tundra and that the changes have been strongest during the 1990s. The most sophisticated model that addresses both changes in the composition and spatial patterns of global vegetation is BIOME4, a recent iteration of the BIOME model (Kaplan 2005; Prentice et al. 1992). The BIOME series of global vegetation models are coupled carbon and water-flux models that predict steady-state vegetation distribution, structure, and biogeochemistry. They have been applied to a wide variety of studies of biogeography, biogeochemistry, and climate dynamics. The BIOME4 model has recently been used to simulate paleo-Arctic environments, present day ecosystems, and future changes in these systems (Bigelow et al. 2003; Kaplan 2005; Kaplan et al. 2003).

In a simulation to recreate present-day vegetation with climate and substrate as the drivers, BIOME4 recreated the general distribution of five broad tundra physiognomic types that are displayed on the CAVM (Fig. 1 and 7), but there was considerably less correspondence between the simulated tundra map and the observed map than there was in forested portions of the simulations (Kaplan 2005). Kaplan attributed the relatively low correspondence in the Arctic to the following factors: (1) The simulated map did not take into account large areas of exposed bedrock, particularly in the Canadian Shield. (2) There is a lack of good temperature data in the High Arctic, particularly in the coldest parts of the Arctic (Subzone A). (3) Hyper-maritime area such as southwestern Alaska and Chukotka are not properly represented because of the influence of water-logged soils, and cool summer temperatures. Other very important factors are the age of landscapes, the distribution of ice-rich permafrost, and soils with special properties

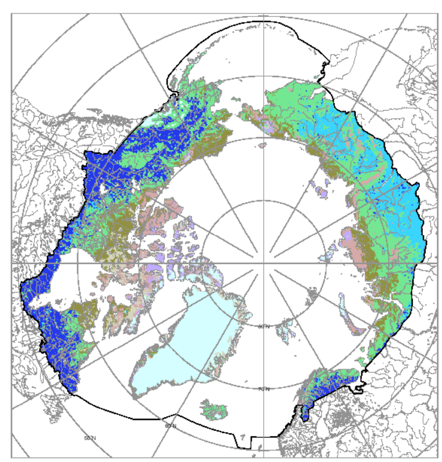

Fig. 7. Simulated present-day vegetation from the BIOME4 model. The southern boundary of the map combines the Arctic as defined by the Arctic Monitoring and Assessment Program (AMAP) and the Conservation of Arctic Flora and Fauna (CAFF). The legend is not included to save space. The general zonal patterns in the Arctic are comparable to those on the CAVM (Fig. 1). From Kaplan (2005).

such as very sandy or very gravelly soils. *One of the goals of the proposed synthesis will be for the mappers to work closely with the BIOME4 modelers to incorporate glacial boundaries, soil, improved climate, and permafrost information into the GIS to improve parameterization of the drivers in the model. We will also work to derive a model that links predictions of NPP for each tundra type with NDVI.*

Models linking biogeochemical cycling and vegetation change. Another major challenge in vegetation change studies is to determine the rates of change as governed by biogeochemical processes that strongly limit vegetation production in arctic tundra ecosystems (Shaver et al. 2001; Shaver et al. 2000). Patterns of change as inferred from output of the BIOME4 model provide a picture of the region once it has stabilized under a climate change scenario, but it does not provide information on the transient dynamics of vegetation nor the intermediate states, which are likely to exist over many decades until the vegetation approaches an equilibrium with a new climate. The ArcVeg model was developed explicitly for examining the soil nutrient effects on inter-annual changes in tundra vegetation structure and function, and will be used to directly link the processes of biogeochemical cycling with species and vegetation change (Epstein et al. 2000, 2001, 2004b). ArcVeg simulates tundra vegetation changes from year-to-year at the structural level of plant functional types (PFTs) or species; currently twenty arctic tundra and boreal forest plant types are parameterized within the model. While simulating vegetation change is the ultimate product of the model, the general framework is one of nutrient mass balance, with nitrogen being the key nutrient limiting the vegetation of arctic tundra. Climate change scenarios within the model alter the available nitrogen for plants in addition to the length of the growing season, driving dynamics of vegetation. Dynamics of the zonal vegetation at the functional type level can be extrapolated to the extent of bioclimate subzones. Key results of recent studies using the ArcVeg model include (1) Transient dynamics of arctic tundra vegetation in response to warming produce compositions of plant functional types that differ from any typical zonal vegetation community (Epstein et al. 2000); (2) Tundra vegetation can undergo several stages of transient change starting with a response by the current dominant PFTs and followed by a period of competition between more responsive sub-dominants and the current dominant types (Epstein et al. 2000); (3) Models that operate at the level of plant functional types or species provide a potentially better picture of regional scale vegetation dynamics and nutrient cycling than more lumped vegetation models (Epstein et al. 2001); (4) Climate warming simulations in ArcVeg for Low-Arctic, moist acidic tundra, project increases in shrub biomass and a decline in mosses (Epstein et al. 2004b), consistent with field warming experiments at Toolik Lake and with the International Tundra Experiment (ITEX) (Chapin et al. 1995, Hobbie and Chapin 1998, Walker et al. submitted); (5) Vegetation changes occur not just as changes in the mean values of PFT biomass, but also as changes in the spatial variance of PFT biomass (Epstein et al. 2004b).

THE CLIMATE–SEA-ICE–TERRAIN–VEGETATION SYSTEM

We will examine how the vegetation of the circumpolar Arctic is responding to recent changes in climate and sea ice, and how these changes are modified by terrain variables, such as soils, topography, and bedrock, and use this information to help predict future response of arctic vegetation (Fig. 8). Traditionally, the Arctic system has been studied by separate groups of scientists studying the ocean, atmosphere, land, and ice components of the system. Our team consists of experts in geobotany, sea ice, climatology, soils, permafrost, remote sensing, and vegetation modeling who will address the central question of how pan-Arctic vegetation has responded to climate change and how it will change in the future. The project also has strong linkages to projects studying other components of the total Arctic System including the

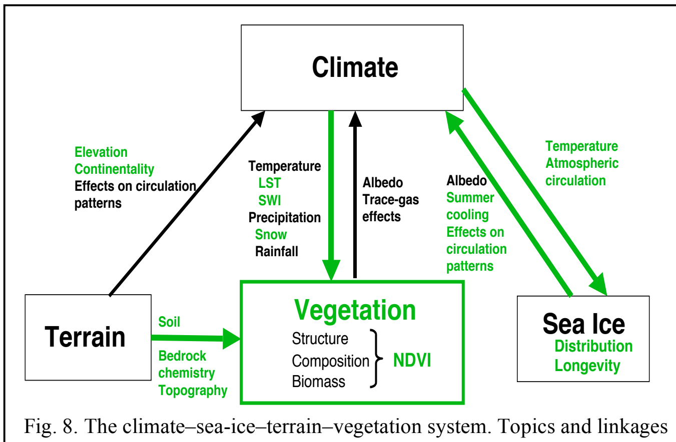

Fig. 8. The climate–sea-ice–terrain–vegetation system. Topics and linkages highlighted in green are the main foci of this proposal.

geophysical environment, carbon budgets, wildlife, and humans. Our project is divided into four main research components and a management component.

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

Justification. Over the last 40 years the largest decreases of arctic ice extent, which are evident at nearly all longitudes around the arctic basin, have occurred during the summer at a rate of 4-6% per decade (Deser et al. 2000). Particularly large decreases of summer sea ice have been observed during the 1990's in the East Siberian and Laptev Seas (Deser et al. 2000; Parkinson et al. 1999; Rigor et al. 2002) and more recently in the Beaufort Sea (Serreze et al. 2003). Recent changes in the arctic are not homogenous but display a complex spatial pattern, which is likely to have implications for vegetation trends. A movie of minimum sea ice extent over the 1979-2004 period data set constructed by Comiso (svs.gsfc.nasa.gov/vis/a000000/a003000/a003065/index.html) clearly shows that there is considerable year to year variability of sea ice edge and that during the most recent 10 years the ice edge has been far from the shore in the Siberian and Alaskan arctic whereas the ice has been close to shore in the Taimyr Peninsula region. This is consistent with the observed cooling trend of surface temperatures over the Taimyr Peninsula (Comiso 2003). This spatial complexity can be attributed in part to the atmospheric circulation that forces the sea ice variability. Circulation originating from the North Atlantic Sector has a strong influence on the Barents, and Kara Seas (Polyakov et al. 2003), while atmospheric conditions over Eurasia and the North Pacific play a more important role over the Laptev, East Siberian, Chukchi, and Beaufort Seas. Changes in other climate parameters have been detected in the arctic in recent decades, which are consistent with reduced sea ice. The most significant arctic maritime air temperature increases have been during spring based on the IABP/POLES data over the 1979-96 period (Rigor et al. 2000; Serreze et al. 2000). Ice thickness in the shallow marginal seas is more strongly influenced by air temperature history than ocean heat fluxes (Wadams 1994), leading to the notion that warmer air temperatures during spring can either accelerate the melting of the ice or be a consequence of increased ocean to air heat flux due to more open water. In any case, the causality is complex but the early spring warming is consistent with a longer growing season in the arctic. We propose to examine the climate dynamics associated with the recent changes in sea-ice, land-surface temperatures and pan-arctic vegetation. Overall, surface temperatures have warmed over most of the arctic but fall and winter display cooling trends in the Taimyr Peninsula over the 1981-2001 satellite record (Comiso 2003), making an investigation of pan-arctic trends of vegetation changes of especially interesting.

Questions, approaches. (1) How are seasonal sea ice conditions and snow cover related to the integrated seasonal NDVI and maximum NDVI throughout the arctic? It is hypothesized that land surface temperatures tend towards cooler (warmer) conditions when sea ice is present (absent) along the coastal margins. Therefore, in a warmer climate, when large decreases in summer sea ice may be more common, the air-sea exchanges of heat and moisture are likely to influence the large-scale climate and prolong the growing season over the arctic. (2) How important are climatic conditions (air temperature, atmospheric winds, ice conditions, climate indices, snow cover) the preceding spring, winter, and fall on the sea ice area during summer and consequently for vegetation? It is hypothesized that the summer warming and sea ice reductions are likely associated with the previous cold season circulation changes (Wallace et al. 1996). This is supported by recent studies that show that extreme summer anomalies in Barents-Kara-Laptev (Deser et al. 2000) and the Beaufort-Chukchi (Maslanik et al. 1999) are correlated with the atmospheric circulation from the preceding spring. We propose to examine the role of previous seasonal anomalies on the vegetation in a systematic manner for the entire arctic.

Data sources. The key source of historical surface temperature data is the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration satellites (Comiso 2003). These sensors have monitored the Arctic daily for 23+ years, and provide a superb geospatially and temporally registered record of changes to the sea-ice, land-surface temperatures, and vegetation (Comiso & Parkinson 2004). Sea-ice concentration is available from the earlier part of the record (1978-) from the SMMR instrument and since 1987 from the SSMI instrument. Ice conditions from these two sensors have been combined into one data set by and will be used in conjunction with remote sensing information about the age of the ice (Comiso 2002). Each summer, most first year ice tends to melt away completely, leaving the perennial ice at the end of the summer. Gridded monthly temperature data based on in situ measurements complied by the Climate Research Unit (CRU) at the University of East Anglia will complement the higher spatial and temporal resolution remote sensing data. The NCEP daily reanalysis (Kalnay et al. 1996) will provide information about the large-scale atmospheric circulation (e.g. hemispheric sea level pressure) on monthly, weekly, and daily time scales. Key northern hemispheric climate indices (e.g. North Atlantic Oscillation, Arctic Oscillation, and Pacific Decadal Oscillation), will serve to relate high latitude climate anomalies to larger scale climate patterns.

Task 1. Climate indices and vegetation. The relationship between climatic indices and vegetation will be investigated over the growing season. The arctic will be divided into climatically consistent regions delineated by the primary seas (Greenland, Barents, Kara, Laptev, E. Siberian, Chukchi, and Beaufort) (Treshnikov & al. 1985). Indices of sea ice concentration, sea ice temperature, ice age, snow cover, and atmospheric conditions in these climate divisions will be compared using standard climate analysis tools (e.g. correlations, composites) with the spatial and area averaged seasonal and maximum NDVI. In this task we aim to elucidate the relationship between climate variables, particularly sea ice variations, and seasonal NDVI. Intra-seasonal climate variations will also be examined, wherever higher temporal resolution remote sensing data is available.

Task 2. Seasonal-ice linkages. The broader climatic issues of persistence from winter to summer and that from late-summer to winter will be investigated. Is freeze up delayed when ice is severely reduced during the summer throughout the arctic? The availability of high temporal resolution (weekly) data will enable a detailed analysis of this persistence. The mechanisms behind such persistence are critical for understanding longer terms climate conditions, which influence vegetation and in order to develop any predictive skill.

Anticipated products. (1) A spatial map that identifies regions of the Arctic Ocean that play a key role in the greening of vegetation. The map would identify the minimum ice retreat in a given geographical region needed for certain thresholds of greening. This is an attempt to quantify the extent of the greening associated with a particular amount of sea ice reduction. (2) Identification of key climate variables, both concurrent and from previous seasons, which play a role in determining the amount of summer sea ice and therefore the vegetation conditions. (3) NDVI predictive capability. Based on the climate-vegetation relationships we identify in the proposed study, we can develop a framework that could be used to estimate future NDVI based on sea ice conditions from climate change scenario simulations.

Component II: Spatial patterns of circumpolar vegetation and NDVI (Jia, Raynolds, Walker)

Justification. Vegetation and NDVI maps of the Arctic reveal complex patterns that are clearly related to regional variations in terrain and climate. As reviewed in the introduction, current vegetation-change models have problems replicating the pattern of vegetation in the Arctic because of sparse climate data and lack of mapped information on such things as soil texture, ground-ice, bedrock exposures, and maritime influences (Kaplan 2005). In order to understand how the Arctic has responded to ongoing climate change and to predict future changes, it is first necessary to understand how the present-day patterns of plant communities and biomass are related to regional climate patterns and variations in such major factors as landscape age, parent material and land-surface temperatures. This component will synthesize recent mapped information regarding these variables and analyze the effects on the distribution of vegetation types and NDVI. The results of these analyses will then be used to improve vegetation change models for the Arctic.

Questions, approach. The primary question addressed by Component II is: (1) How does the combination of land-surface temperatures, landscape age, and parent material influence vegetation patterns and NDVI across the pan-Arctic? The approach to answering this questions will be to: (1) synthesize the information from a suite of recently available circumpolar maps and data sets, (2) use these data to analyze relationships between climate, terrain, and vegetation in different parts of the Arctic, and

(3) integrate the results of this analysis with the input and output of global climate and vegetation change models.

Data sources. Satellite imagery and Geographical Information Systems (GIS) have facilitated the study of the Arctic as a whole. A number of circumpolar maps and data sets have been assembled by international teams, including the Circumpolar Arctic Vegetation Map (CAVM Team 2003), Quaternary glaciation maps (Ehlers & Gibbard 2004), circumpolar paleo-vegetation maps (Kaplan et al. 2003), the Northern Circumpolar Soils Map (Tarnocai et al. 2003), the Circum-Arctic Map of Permafrost and Ground-ice Conditions (Brown, 2000), and circumpolar land-surface- temperature maps (Comiso 2003; Comiso 2005). Snow depth data will come from data for North America (Brown et al. 2003) and Russia (Armstrong 2001). Because many important processes do not stop at tree line, it will also be necessary to study change across the forest boundary. A logical boundary for this larger region is the Arctic Basin, which includes the watersheds of all rivers emptying into the Arctic Ocean (Rekacewicz 1998). A long-term goal that cannot be accomplished within the three years of this proposal will be to develop an integrated database for this much larger region. As an interim solution we will use data from the Global Land Cover Map (JRC 2003) for areas south of tree line.

Task 1. Define and assemble climate data. We will use NASA compilations of land surface temperature derived from AVHRR satellite imagery, which include monthly summaries of the Arctic from August 1981 to July 2001 (Comiso 2003). These data, with approximately 1- km pixels, are at a good scale to improve the resolution of the CAVM bioclimate subzones. We will determine the most relevant measure of Arctic summer temperatures: mean July temperature, thawing degree months (sum of monthly mean temperatures > 0^{o}C), or possibly some other proxy for temperature such as growing season length. In some areas precipitation will help explain vegetation anomalies. Average snow depth data will come from the best available data for North America (Brown et al. 2003) and Russia (Armstrong 2001).

Task 2. Assemble and synthesize substrate data. Soil texture is needed to derive information on soil moisture and nutrient holding capacity. We will use the Northern Circumpolar Soils Map (Tarnocai et al. 2003) as a base, and include data from the FAO digital Soil Map of the World (FAO/UNESCO 1990) and other sources to develop a unified legend that characterizes the available data into units that are important to vegetation. The combination of these data, along with the Circum-Arctic Map of Permafrost and Ground-ice Conditions (Brown et al. 1997) will provide good information on soil moisture holding capacity. Quaternary geologic history has had a strong effect on Arctic soils. Recent glaciations limit the amount of time the surface has been available for soil development, plant colonization, and the evolution of plant communities. For data on glaciations (including deglaciation dates, proglacial lakes and sea level changes) we will use maps developed by the International Quaternary Association (Ehlers & Gibbard 2004).

Task 3. Analysis. The climate and substrate data will be assembled into the CAVM GIS and their spatial distribution will be analyzed in relation to the distribution of vegetation as shown by the CAVM. Patterns between regions, between vegetation types, and within vegetation types will be analyzed using area summaries and overlayed maps. We will analyze trends in environmental factors in relation to NDVI values, using regression and descriptive statistics. We will use a suite of multivariate analyses to determine which of the variables account for most of the variance in arctic vegetation distribution.

Task 4. Interfacing with models. Data from Tasks 1-3 will be made available for use as input to modeling efforts (see Component IV) by archiving them with the CAVM data on the Alaska Geobotany Center web site (www.geobotany.uaf.edu), and including them as part of the NSF-funded Arctic Geobotanical Atlas. The final step in this project will be to compare the factors controlling vegetation distribution with output from vegetation change models including BIOME4 (Kaplan et al. 2003; Prentice et al. 1992) and the ArcVeg model (Epstein et al. 2000). These models predict where and how vegetation will change in response to climate changes. We will evaluate where climate is the major controlling factor, and where Arctic vegetation is likely to respond the fastest to predicted climate changes. We will combine this information with results from experimental studies, such as the ITEX studies (Henry &

Molau 1997), that describe the types of changes that can be expected in different plant functional types due to climate change . We will also use the results to help other investigators evaluate how circumpolar vegetation change will affect different ecosystem functions, such as the effects on active-layer thickness (Nelson et al. 1998; Walker et al. 2003), cryoturbation (Walker et al. 2004), snow distribution (Sturm et al. 2001), fluxes of energy and albedo (Chapin III et al. 2004), hydrological processes (Vorosmarty et al. 2001), and wildlife (Griffith et al. 2002).

Anticipated products. (1) An integrated vegetation, climate, soil, and terrain database that will be useful to a wide variety of other studies in the Arctic. (2) A synthesis of how and where arctic vegetation and NDVI can be expected to change in response to climate change. (3) An analysis of NDVI patterns that will improve our knowledge of the interactions between climate, terrain, and vegetation that can be detected from space. (4) A wide variety of applications for conservation purposes – for example, predicting which vegetation types will become more or less common, and which are likely to become rare – and for management purposes because wildlife distribution and human activities in the Arctic will change along with vegetation patterns.

Component III: Temporal patterns of circumpolar NDVI (Jia, Bhatt, Comiso, Markon, Epstein)

Justification. The Arctic system is expected to be highly sensitive to climate change and to play a significant role in biospheric feedbacks to global climate (Overpeck et al., 1997; Serreze et al., 2000). A warming of the Arctic along with continuing declining sea ice has been documented over the past three decades (Comiso 2005) are likely to affect various tundra ecosystem properties and to be reflected in the NDVI. The AVHRR-NDVI record is long enough now to detect meaningful trends with respect to the vegetation greenness and phenology records (NCEROS, 2005; Tucker et al., 2004; Stow, 2004). Jia et al. (2003) noted a strong decadal trend of increase of vegetation greenness in northern Alaska that corresponds with less sea ice in the Beaufort Sea and warming of adjacent land surfaces. This has stimulated this investigation to examine how NDVI is changing across various bioclimate subzones over the entire Pan-Arctic region and how this might vary with sea-ice distribution, surface temperatures, vegetation type, and terrain variables.

Questions, approach. The major questions that will be addressed are: (1) Is the trend in NDVI detected in northern Alaska due entirely to changes of the vegetation or are other factors related to instrument calibration and atmospheric effects involved? (2) Has a similar pattern of greening also occurred elsewhere in the Arctic? (3) How do surface temperatures, precipitation, regional floras, landscape age, substrate type, and topography influence the trends in NDVI? (4) Has the greening occurred evenly across broad landscapes, or has it been confined to local areas of greater warmth, moisture, or nutrient flux? The approach to answering these questions will be to first of all examine NDVI data from other sensors and in other parts of the Arctic to verify the magnitude of the trend in northern Alaska. Are similar trends apparent in other areas that are warming strongly (e.g. northern Canada)? And have areas that have cooled (e.g. the Taimyr Peninsula) shown negative trends in NDVI? The circumpolar NDVI data will be stratified by sea-ice regions, floristic provinces, long-term land-surface temperature regimes and a host of vegetation and terrain variables to see how these factors affect the NDVI trends.

Satellite	Spatial resolution	Spectral Bands	Temporal Frequency	Availability	Capacity
AVHRR GAC	8km	6	30 days	1981-	Large scale monitoring of vegetation greenness and growing season
AVHRR LAC	1km	6	7 days	1990-	Greenness, moisture, and spatial transitions
MODIS	250/500/ 1000m	36	10 days	1999-	Greenness, moisture, and spatial transitions
Landsat	15/30m	7	5 yr	1972-	Vegetation types, transitional zones
DEM	10m, 1km	1	NA	2003-2004	Measurements of elevation, slope, aspect, and 3-D view
QuickBird	0.6/2.8m	5	6 days	2002-	Canopy cover, vegetation type, frost scars, polygon patterns
IKONOS	1/4m	5	6 days	2001-	Canopy cover, vegetation type, frost scars, polygon patterns

AVHRR: Advance Very-High Resolution Radiometer
MODIS: Moderate Resolution Imaging Spectroradiometer
QuickBird: high resolution satellite data by DigitalGlobe Inc.
DEM: Digital Elevation Model

Data sources. This project will use the Circumpolar 23+ yr record of monthly AVHRR GAC (8-km) data assembled by the NASA Goddard Space Center (Tucker et al, 2004; 2005), the Alaska 15+ yr record of weekly AVHRR LAC (1-km) dataset provided by the USGS EROS data center (Markon, 2001;

NCEROS, 2005), and the North America 5+ yr record of 10-day Moderate Resolution Imaging Spectroradiometer (MODIS) (500-m) dataset processed and provided by the NASA MODIS Vegetation Team (Carroll et al., 2005). The AVHRR GAC data is the longest complete remote sensing time series (1981-present) available to cover the entire research region, with 8-km pixel resolution and 30-day spatial resolution. The AVHRR LAC data provides us the opportunity to monitor ecosystem changes in the lower portion of the Arctic with finer spatial (1-km) and temporal (7-day) resolution since the early 1990s. With 250/500/1000m spatial resolution and 36 bands ranging from visible to short wave infrared (SWIR), MODIS enables us to examine more detailed patterns of NDVI within each AVHRR pixel with a particular focus on transitional zones. Its SWIR bands have the capacity to estimate soil moisture, snow cover and sea ice, while its thermal bands can be used to derived land surface temperature. Major parameters of the remote sensing datasets used in this proposed study are listed in the table.

Task 1: Confirmation of magnitude of greening in northern Alaska. At present, it is not known with certainty that the magnitude of the trend detected in the Jia et al. (2003) study is due entirely to changes in the vegetation or if it is partially due to sensor calibration error or trends in the transparency of the atmosphere (Stow et al. 2003, Hope et al. 1995). We will reanalyze the new dataset of both GAC and LAC with higher temporal resolution and longer time coverage to obtain a more confident magnitude of greening and more accurate estimates of possible earlier onset and lengthening of growing season. We will also check the results from the NOAA Advanced Very High Resolution Radiometer (AVHRR) NDVI values against other sensors such as MODIS, the Landsat Thematic Mapper (TM), and SPOT. The trend observed in Alaska occurred in a region with pronounced warming over the period of the NDVI record, so we will also check the NDVI trends in other parts of the Arctic where long-term temperature trends have been either neutral or negative.

Task 2: Circumpolar NDVI trends. We will analyze the 23+ yr circumpolar AVHRR GAC (8-km) dataset for across the five bioclimate subzones over the entire pan-Arctic region for inter-annual fluctuations and trends of NDVI using the methods of Jia et al. (2003). We will use image differencing among several representative time periods and time series auto-regression to calculate absolute values and rates of changes. Then, using the field data of biomass, leaf-area index (LAI), NDVI, thaw depth, soil moisture, and other variables measured in different subzones and vegetation types, we will be able to establish regression models between AVHRR-NDVI and those variables. If significant relationships are found, we will use the equation to interpret NDVI in terms of the biophysical variables, creating new map data layers.

Task 3: NDVI trends with respect climate and terrain. We will stratify the data into bioclimate subzones and vegetation types, by masking with the maps of CAVM subzones, vegetation, sea-ice, and geobotanical variables. Processing will consist of spectral analysis and supervised classification along with hand-editing to accurately map land cover classes that in our experience cannot be detected accurately by automated means. These maps will provide the basic information for the extension of the vegetation and patterned ground dynamics measurements in the field to the pan-Arctic region.

Task 4: Heterogeneity of greening. We will analyze the 15+ yr AVHRR LAC (1-km) datasets in the regions where data are available with a similar approach to that described for the GAC data, and then compare the results with AVHRR GAC-derived maps. In this finer resolution approach, we will examine changes of vegetation greenness among vegetation types and floristic zones, and find out how the differences in vegetation composition are reflected in NDVI dynamics. By examining the NDVI time series with fine temporal resolution (7-day), we expect to have more accurate and better understanding on heterogeneous changes of two important vegetation phenological characteristics, onset of greenness and length of growing season, and to be able to detect possible earlier onset and lengthening of growing season across bioclimate gradients. We will also examine sub-pixel heterogeneity of the GAC data against LAC data. To examine the details of greening, we will produce a series of NDVI maps from Landsat data for the periods 1972, 1977, 1983, 1988, 1993, 1998 and 2003 from 4-5 calibrated scenes covering areas surrounding our field sample sites (Walker et al. 2003; Walker et al. 2004 in press) across the different bioclimate subzones. We already have in hand 24 MSS, TM, and ETM+ images from 1972-

2002 for the Kuparuk River area covering some sample sites in Subzones D and E in northern Alaska. We plan to select an area of the Subzone D-E transition zone in northern Alaska as a test area to examine 30-m scale landscape dynamics over 30+ years, with an approximate 5-year repeat Landsat images over the same area. We are interested in seeing possible shifting of the transition zone, particularly with respect to changes in shrub abundance. We will also compare a series of MODIS images that cover the region of the upper Kuparuk River where we have a detailed GIS at 1:25,000 scale that is registered that will allow us to examine where on the landscapes NDVI is increasing most rapidly. In this way, we could examine sub-pixel heterogeneity of AVHRR data against MODIS data. We will then use data fusion techniques among AVHRR GAC, LAC and MODIS to see if we can take advantage of both the long time series of AVHRR and the high spatial resolution of MODIS. It has been shown the enhanced vegetation index (EVI) derived from MODIS dataset is more capable of contrasting vegetation greenness than NDVI. We will examine EVI time series and compare the results against NDVI.

Anticipated products. (1) Empirical and remote-sensing-based estimates of the trends and rates of vegetation greenness/biomass changes at various temporal/spatial scales among pan-Arctic regions over the past 23+ years; (2) spatial distribution and greenness/biomass patterns of tundra vegetation in the transitional regions in both Alaska and the Canadian Arctic; (3) maps of vegetation biomass/LAI change rates over past 23+ years.

Component IV: Simulation Modeling (Epstein, Kaplan, Jia)

Justification. A combination of remotely-sensed observations (Jia et al. 2003; Silapaswan et al. 2001; Sturm et al. 2001), warming experiments (Chapin et al. 1995; Hobbie & Chapin 1998) and field-scale observations (Chapin et al. 1995) have indicated relatively rapid changes in arctic tundra vegetation over the past several decades, likely in response to climate changes. While remote sensing is being used in this project to provide the spatial coverage that is not possible with field experiments and observations alone, *simulation modeling will be used to generate the temporal projections* that are not possible with any of the other methodologies.

Questions, approach, and tasks. This project component has two main questions: 1) How will climate change affect the patterns of vegetation types, composition and production of future Arctic biomes, and 2) Can the patterns of greening that have occurred thus far be used to project future patterns of vegetation change within the Arctic? The approach to answering these questions will be to conduct two separate but complementary simulation modeling efforts. The first will use BIOME4, a steady-state model that projects responses of vegetation types to climate change, using coupled carbon and water flux modules and a plant functional type approach (Kaplan et al. 2003). The second effort will use a transient dynamics vegetation model, ArcVeg, to simulate plant community composition and biomass changes, as nutrient cycles (carbon and nitrogen) respond to climate alterations (Epstein et al. 2004).

Data Sources. In addition to the two simulation models, BIOME4 and ArcVeg, this project component will utilize circumpolar datasets described in Components II and III in addition to general circulation model climate change output for the Arctic. We will also utilize existing relationships between aboveground plant biomass, LAI, and NDVI (Jia et al. 2003; Riedel et al. 2005 in press), developed by the PIs on other NSF-funded projects.

Task 1 - BIOME4 Simulations. Our main objective for BIOME4 is to simulate the changes in the distribution of arctic tundra vegetation and boreal forest types based on general circulation model projections of climate change. BIOME4 represents four extant tundra vegetation types and two boreal forest types within its current structure; it is generally used at continental and global scales with resolutions on the order of 10-km square grid cells. In the validation of BIOME4 against the present-day vegetation distribution, the prediction of tundra types ranged from 26% to 60% (Kaplan 2005), which could be improved upon. The lack of a strong correspondence between simulated and observed tundra vegetation are due in part to the presence of large, unvegetated areas in northern Canada and the paucity of reliable temperature data in the High Arctic. In addition, regions with a strong oceanic influence are poorly simulated. Newly developed circumpolar datasets should dramatically improve the utility of the

BIOME4 model and generate more accurate projections of vegetation change. Surface temperatures since the 1970s, derived from AVHRR infrared data (Comiso 2003), will be used as a new temperature dataset. In addition, circumpolar maps, either recently developed or in progress, of glaciations, permafrost distribution and soil characteristics will provide additional information and constraints for the BIOME4 simulations.

Task 2 - ArcVeg Simulations. The conceptual framework for the ArcVeg model is based on the premise that the arctic tundra is in general a nitrogen-limited ecosystem, whereby plant productivity is constrained by the availability of forms of nitrogen for plant uptake (i.e. ammonium, nitrate, dissolved amino acids). Air and soil temperature increases would increase decomposer activity, making more nitrogen available for plant growth. Warming would additionally increase the length of the growing season, which would make conditions more suitable for the growth and sustainability of plant types with a greater component of woody tissue, such as deciduous and evergreen shrubs. These are the general conditions under which the ArcVeg model simulates the dynamics of vegetation in response to climate change. Our plan is to simulate the dynamics of plant biomass and functional type composition for the zonal vegetation in each of the arctic Subzones (A-E). The warming scenario used will be a 3°C increase ramped linearly over a 50-year period, which is consistent with GCM scenarios for the region (New 2005). A 3°C increase essentially represents a climate shift from a given arctic Subzone to the adjacent southern Subzone. However, because of the transient nature of the ArcVeg model, the Subzones will not just shift northward. The addition of the circumpolar glaciation dataset will improve the simulation of soil organic matter development within ArcVeg, and provide a much more accurate picture of the effects of soil organic matter on vegetation dynamics.

Task 3 – Compare model output with observed NDVI changes. Existing relationships between plant biomass and NDVI developed on the Arctic Slope of Alaska (Jia et al. 2003, Riedel et al. 2005) will be used to transpose the ArcVeg simulations of biomass over time for each Subzone into time-series of NDVI. These simulated NDVI time-series will be compared to the observed NDVI time-series from the AVHRR dataset; we will use ~25 year NDVI record (since 1981) at an 8 x 8 km resolution and ~15 year record at the 1 x 1 km resolution. The ArcVeg model was initially parameterized and validated with data largely collected before 1990 (Epstein et al. 2000); therefore it is a rather good representation of the baseline conditions. The biomass-NDVI relationships are being improved upon for the Low Arctic and developed for the High Arctic as part of a currently-funded NSF Biocomplexity Project (Kelley et al. 2004; Walker et al. 2003). These relationships will facilitate the simulation of NDVI dynamics for all five arctic Subzones for comparison with satellite data

Task 4 – Model enhancements and future projections using data on vegetation changes that have already occurred. Differences in the comparisons between simulated vegetation patterns and observed vegetation patterns for both the BIOME4 model and the ArcVeg model should reveal key pieces of information regarding the applicability of our conceptual model of tundra vegetation. Do the models reasonably project vegetation patterns? Which of the two models has the best correspondence with the observed data? Do we over- or underestimate the presence of tundra vegetation types circumpolarly? Do we over- or underestimate the degree of NDVI changes in response to warming across the five arctic Subzones? The answers to these questions will inform us as to what potential aspects of our models need further refinement. Enhancement of the models based on these findings will allow for more accurate projections of future vegetation dynamics. In addition, the circumpolar heterogeneity of greening over the past several decades will dictate which particular areas have experienced the greatest changes (increases or decreases) in vegetation. One hypothesis is that spatial transition zones between tundra vegetation types are likely to experience the greatest responses to climate change. The greatest changes will be observed at the transition between dwarf-shrub tundra and low-shrub tundra (Epstein et al. 2004 in press.). The spatial patterns of NDVI time-series will allow us to test these specific hypotheses. Are vegetation changes in the Arctic occurring largely due to changes in plant functional type composition, or are they more due to increases in biomass of all existing plant functional types? Last, the observed changes in vegetation will provide new baseline data for additional modeling simulations and projections of future vegetation dynamics

Anticipated products. (1) Improved input to arctic vegetation changes models. (2) Circumpolar maps of predicted tundra vegetation changes in response to climate dynamics over the next several decades. (3) Enhanced understanding and models of arctic vegetation change dynamics.

Component V: Project management (Walker, Raynolds, Maier)

Project personnel and organization. Dr. D.A. Walker will manage the project. Each component of the project has a co-PI who has primary responsibility for that component (first name in headers for the components). See the budget justification for explanation of roles of each participant.

Coordination. This project involves close coordination between three universities, two government agencies, and several international collaborators. This project will be closely coordinated with other ARCSS synthesis projects. Vegetation change is closely tied to several other components of the Arctic system, and the results and products of our synthesis efforts will be made quickly available to other scientists. The Greening of the Arctic project has been submitted to the International Polar Year (IPY) Joint Committee for endorsement as an IPY initiative. The work proposed here is the first of three parts of the initiative. The second part will establish a baseline of biomass harvests across the full Arctic bioclimate gradient in coordination with other Arctic vegetation monitoring projects. The third piece is an outreach/ educational project that will involve local communities in the research and train a group of young investigators so that standardized measurements can be continued in the future. The project will also be coordinated with other ongoing circumpolar mapping and modeling studies such as the BIOME4 modeling project (Kaplan 2005) and the GLOBIO project (Nelleman et al. 2001).

Data management and outreach. Data will be centrally managed at the Alaska Geobotanical Center (AGC), University of Alaska Fairbanks. Martha Raynolds will facilitate day-to-day activities and be the data manager of the project. Metadata will be written for each data set following national protocols and made available to the wider science community through the Joint Office for Science Support (JOSS) as soon as it becomes available and is quality checked. Final archiving will be done through the Arctic Data Coordination Center and Geographic Information Network of Alaska (GINA) at UAF and the Arctic Data Coordination Center (ADCC). All data management and archiving will follow protocols established by the ARCSS Data Management Committee.

A web page will be developed and highlighted as part of the Arctic Geobotanical Atlas, which is a web-based hierarchic geographic information system currently under development at AGC. The site will include a state-of-the-art visualization tool called TerraExplorer, which is a “full-motion flight” simulator. This is being developed by Matt Nolan at UAF as part of another grant. The software will permit the user to “fly’ through a hierarchy of spatial and temporal arctic landscapes to view historic and projected sea-ice retreat, along with warming and greening of the land and changes in the land cover. This project will also be highlighted as part of a new Geoinformatics course at UAF (GEOS F378).

Workshops. One project workshop will occur each year. It will be organized in conjunction with a national international meeting where members will present the results of their research or at an annual ARCSS meeting. The tentative site for these workshops the University of Virginia, NASA-Goddard and Jena, Germany, where the BIOME model is being developed, but other venues may arise and be more appropriate. The project is budgeting travel to one workshop/conference per year for each member of the team.

Schedule. Most of the data assembly will occur in the first year. Analyses will be spread across all three years and coordination with the modeling and project synthesis will occur mainly in year 3.

D. RESULTS OF PRIOR NSF SUPPORT

1. Arctic Climate Change, Substrate, and Vegetation, OPP-9908829, $1,828,990, 7/1/99 – 9/31/04, D.A. Walker, PI, W.A. Gould and H. Epstein, Co-PIs

This project is part of the Land-Atmosphere-Ice Interactions (LAII) Arctic Transitions in the Land-Atmosphere System (ATLAS) study. The primary goal of the overall project was characterization of the fluxes of energy, water, and trace gases in the Arctic. One component of our studies involved mapping the vegetation of northern Alaska, Canada, and the circumpolar Arctic (CAVM Team 2003; Gould et al. 2003; Gould et al. 2003; Muller et al. 1999; Muller et al. 1998; Raynolds et al. 2005a (in press); Walker 2000; Walker et al. 2002; Walker et al. 2005 in press). The importance of the vegetation maps to the proposed work were reviewed in the main body of the proposal. The project also characterized the vegetation, soil, and spectral reflectance patterns in relationship to zonal vegetation boundaries in the Arctic (Copass et al. 2000; Epstein et al. 2004.; Riedel et al. 2005 in press; Riedel et al. 2005 in press; Walker 2000; Walker et al. 1998). Numerous other remote sensing publications resulted from this study (Jia et al. 2002; Jia et al. 2004; Jia et al. 2004 submitted; Riedel et al. 2005 in press; Riedel et al. 2005 in press; Walker et al. 2002; Walker et al. 2003). *This work was highly relevant to the proposed synthesis because the most significant finding was the major change in greenness that has occurred across the northern Alaska during the past 20 years (Jia et al. 2003) as discussed in the main body of this proposal.* Another important finding was large differences in many key ecosystem processes that occurred on different substrates (Walker et al. 1998). Soils in moist nonacidic areas have about half the carbon storage and twice the depth of thaw of moist acidic areas (Ping et al. 1998). We and other investigators have found the differences in substrate cause major differences in soil heat flux (Nelson et al. 1998), evapotranspiration, respiration, gross primary production and trace gas fluxes (Chapin III et al. 2000; Fahnestock et al. 1998; Jones et al. 1998; Reeburgh et al. 1998; Walker et al. 1998), spectral properties (Jia et al. 2004 submitted) cryoturbation (Bockheim et al. 1998), snow cover (Walker et al. 2001), wildlife habitat (Walker et al. 2001), and the effects of disturbance (Auerbach et al. 1997).

2. Biocomplexity associated with biogeochemical cycles in frost boil ecosystems. OPP-0120736, $2,750,421, 10/1/01-9/30/06, D.A. Walker, PI, H.E. Epstein, W.A. Gould, W.B. Krantz, R. Peterson, C.L. Ping, V.E. Romanovsky, Co-PIs

This ongoing project is examining patterned-ground ecosystems at 10 sites along an 1800-km transect across all five Arctic bioclimate subzones in North America. Frost-heave features play an important role in Arctic ecosystems functions, including the flux of trace gases to the atmosphere, flux of water and nutrients to streams, and the recycling of important nutrients to wildlife populations. The response of these systems to climate change is different in each bioclimate subzone. . The study consists of an interdisciplinary team of vegetation and ecosystems scientists, climate and permafrost specialists, soil scientists, and modelers who are examining the climate, permafrost, geomorphology, soils, vegetation, and invertebrate insects associated with frost boils. *This study is relevant to the proposed work because it is the only detailed transect that has used consistent sampling protocols to measure vegetation biomass, LAI, species composition, and NDVI across the full Arctic climate gradient. The biomass, NDVI, and LAI information from this study will be a key data set in the proposed synthesis.* The project also has a strong educational component. 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 potion of the gradient (Walker et al. 2003; Walker et al. 2004 in press), descriptions of the differential frost heave model, a physically based model of self-organization of frost boils and earth mounds (Peterson & Krantz 2003; Peterson et al. 2003), description of a numerical model of frost-boil dynamics (Nikolsky et al. 2004), characterization of the vegetation (Kade et al. 2005 in press), descriptions of the soil processes in frost boils (Michaelson et al. 2002; Ping et al. 2003; Ping et al. 2002), the active layer (Kelley et al. 2004), and the educational component (Gould et al. 2003).

3. Towards an arctic geographic information network: a web-based plant-to-planet-scale geobotanical atlas centered on the Toolik Lake Field Station, Alaska. ARC-0425517, $819,460, 12/15/04-11/30/07. D.A. Walker, PI.

This recently funded project will create a web-based multi-scale Arctic Geobotanical Atlas (AGA) for the Toolik Lake Field Station, the North Slope of Alaska, and circumpolar region using internet-map server (IMS) technology. *This project is relevant to the proposed work because many datasets in the AGA* *will be used for the synthesis, and information and maps derived from the Greening of the Arctic project will be incorporated into the AGC and made available via the web to a wide-variety of users.*

E. REFERENCES

Starred (*) references are products of prior NSF support listed above.

Alexandrova, V.D. 1971. Principles of the zonal division of the vegetation of the Arctic. *Bot. Zh* 56: 3-21.

ARCSS. 2004. Arctic System Science (ARCSS(Program Synthesis Retreat 2004, Lake Tahoe, California, 8-14 2004, URL http://www.arcus.org/ARCSS/2004_Retreat/index.html.

Armstrong, R. 2001. Historical Soviet Daily Snow Depth, Version 2 (HSDSD). National Snow and Ice Data CenterCD-ROM, Boulder, CO.

Auerbach, N.A., Walker, M.D. & Walker, D.A. 1997. Effects of roadside disturbance on substrate and vegetation properties in arctic tundra. *Ecological Applications* 7: 218-235.

Beringer, J., Chapin III, F.S., McHugh, I., Tapper, N.J., Lynch, A.H., Serreze, M.C. & Slater, A.G. 2001. Impact of arctic treeline on synoptic climate. *Geophysical Research Letters* 28: 4247-4250.

Bigelow, N.H., Brubaker, L.B., Edwards, M.E., Harrison, S.E., Prentice, I.C., Anderson, P.M., Andreev, A.A., Bartlein, P.J., Christensen, T.R., Cramer, W., Kaplan, J.O., Lozhkin, A.V., Matveyeva, N.V., Murray, D.F., McGuire, A.D., Razzhivin, Y.Y., Ritchie, J.C., Smith, B., Walker, D.A., Igarashi, A.D., Kremenetskii, K.V., Paur, A., Pisaric, M.F.J. & Volkova, V.S. 2003. Climate change and Arctic ecosystems I: Vegetation changes north of 55˚N between the last glacial maximum, mid-Holocene and present. *Journal of Geophysical Research* 108. D19 8170, doi:1029/2002JD00258.

*Bockheim, J.G., Walker, D.A., Everett, L.R., Nelson, F.E. & Shiklomanov, N.I. 1998. Soils and cryoturbation in moist nonacidic and acidic tundra in the Kuparuk river basin, arctic Alaska, U.S.A. *Arctic and Alpine Research* 30: 166-174.

Bohn, U., Gollub, G. & Hettwer, C. 2000. Map of the Natural Vegetation of Europe, Scale 1:2 500 000. Federal Agency for Nature Conservation, Bonn.

Brown, J., Ferrians, O.J., Heginbottom, J.A. & Melnikov, E.S. 1997. Circum-arctic map of permafrost and ground-ice conditions, Map CP-45. U.S. Geological Survey.

Brown, R.D., Brasnett, B. & Robinson, D. 2003. Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. *Atmosphere-Ocean* 41: 1-14.

Carroll, M.L., DiMiceli, C.M., Sohlberg, R.A., Townshend, J.R.G., 2005. 250m MODIS Normalized Difference Vegetation Index. College Park, Maryland: The Global Land Cover Facility.

*CAVM Team. 2003. Circumpolar Arctic Vegetation Map (Scale 1:7,500,000). Conservation of Arctic Flora and Fauna (CAFF) Map No. 1, U.S. Fish and Wildlife Service, Anchorage, AK.

Chapin III, F.S., McGuire, A.D., Randerson, J., Pielke, R., Baldocchi, D., Hobbie, S.E., Roulet, N., Eugster, W., Kasischke, E., Rastetter, E.B., Zimov, S.A. & Running, S.W. 2000. Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* 6 (s. 1): 211-223.

Chapin III FS, Shaver GR, Giblin AE, Nadelhoffer KJ, Laundre JA. 1995, Responses of Arctic tundra to experimental and observed changes in climate. *Ecology* 76:694-711.

Chapin III, F.S., Sturm, M., McFadden, J.P., Key, A.H., Lloyd, A.H., McGuire, A.D., Rupp, T.S., Beringer, J., Epstein, H.E., Hinzman, L.D., Jia, G.J., Lynch, A.H., Ping, C.L., Schimel, J.P., Serreze, M., Tape, K.D., Thompson, C.D.C. & Walker, D.A. Amplification of arctic summer warming by land-surface changes. Submitted to *Nature*.

Chapin, F.S., III, Shaver, G.R., Giblin, A.E., Nadelhoffer, K.J. & Laundre, J.A. 1995. Responses of arctic tundra to experimental and observed changes in climate. *Ecology* 76: 694-711.

Comiso, J.C. 2002. A rapidly declining perennial sea ice cover in the Arctic. *Geophysical Research Letters* 29, no. 20 1956, doi 1029/2002/GL015650.

Comiso, J.C. 2003. Warming trends in the Arctic from clear sky satellite observations. *Journal of Climate* 16: 3498-3510.
Comiso, J.C. 2005. Impact studies of a 2˚C global warming on the arctic sea ice cover. In: L. Rosentrater (Ed.), *Eivdence and implications of dangerous climate change in the Arctic*. World Wildlife Federation International Arctic Programme, pp. 43-55.
Comiso, J.C. & Parkinson, C.L. 2004. Satellite-observed changes in the Arctic. *Physics Today*: 38-44.
*Copass, C.D., Beringer, J., McGuire, D., Chapin, F.S. & Walker, D.A. 2000. Characterization of vegetation biomass and structure along a gradient from tundra to forest at treeline in Council, Alaska. *Eos, Transactions, American Geophysical Union, 2000 Fall Meeting* 81: F228.
Deser, C., Walsh, J.E. & Timlin, M. 2000. Arctic sea ice variability in the context of resent atmospheric circulation trends. *Journal of Climate* 13: 617-633.
Ehlers, J. & Gibbard, P.L. 2004. Quaternary Glaciations – Extent and Chronology, Part I Europe; Part II North America: Part III South America, Asia, Africa, Australia, Antarctica. In: J. Rose (Ed.), *Developments in Quaternary Science*. Elsevier, Amsterdam, pp. 475.
Epstein, H.E., Walker, M.D., Chapin III, F.S. & Starfield, A.M. 2000. A transient, nutrient-based model of arctic plant community response to climate warming. *Ecological Applications* 10: 824-841.
Epstein, H.E., F.S. Chapin III, M.D. Walker and A.M Starfield. 2001. Analyzing the functional type concept in arctic plants using a dynamic vegetation model. *Oikos* 95:239-252.
*Epstein, H.E., Beringer, J., Gould, W.A., Lloyd, A.H., Thompson, C.D., Chapin , F.S., III, Michaelson, G.J., Ping, C.L., Rupp, T.S. & Walker, D.A. 2004a. The nature of spatial transitions in the Arctic. *Journal of Biogeography* 31:1917-1933.
Epstein, H.E., M.P. Calef, M.D. Walker, F.S. Chapin III, A.M. Starfield. 2004b. Detecting changes in arctic plant communities in response to warming over decadal time scales. *Global Change Biology* 10:1325-1334.
*Fahnestock, J.T., Jones, M.H., Brooks, P.D., Walker, D.A. & Welker, J.M. 1998. Winter and early spring CO2 efflux from tundra communities of northern Alaska. *Journal of Geophysical Research* 103: 29023-29027.
FAO/UNESCO. 1990. Soil Map of the World. FAO/UNESCO, Rome, Italy.
Fulton, R.J. 1985. Surfical Materials of Canada. Geological Survey of Canada.
Gilmanov, T.G. 1997. Phenomenological models of the primary productivity of zonal arctic ecosystems. In: W. C. Oechel, T. Callaghan, T. Gilmanov, J. I. Holten, B. Maxwell, U. Molau and B. Sveinbjörnsson (Eds.), *Global Change and Arctic Terrestrial Ecosystems*. Springer, New York, pp. 402-436.
*Gould, W.A., Raynolds, M.A. & Walker, D.A. 2003. Vegetation, plant biomass, and net primary productivity patterns in the Canadian Arctic. *Journal of Geophysical Research* 108: ALT 8-1 to 8-14.
*Gould, W.A., Walker, D.A. & Biesboer, D. 2003. Combining research and education: bioclimatic zonation along a Canadian Arctic Transect. *Arctic* 56: 45-54.
*Gould, W.A., Gonzalez, G. & Walker, D.A. 2003. Biocomplexity of frost-boil ecosytems: integrating science and education (poster), *Biocomplexity of the Environment Awardees Meeting*, Arlington, VA, 15-17 Sep 2003.
Gribova, C.A. & Tichomirov, B.A. 1985. Vegetation, 1:10,000,000-scale map, *Arctic Atlas*. Chief Administrator of Geodesy and Cartography of the Soviet Ministry, Moscow, pp. 120-121.
Griffith, B., Douglas, D.C., Walsh, N.E., Young, D.D., McCabe, T.R., Russel, D.E., White, R.G., Cameron, R.D. & Whitten, K.R. 2002. The Porcupine caribou herd. In: D. C. Douglas, P. E. Reynolds and E. B. Rhode (Eds.), *Arctic Refuge coastal plain terrestrail wildlife research summaries, Biological Scince Report USGS/BRD/BSR-2002-0001*. U.S. Geological Survey, Biological Resources Division, Reston, VA.
Groisman, P.Y., Karl, T.R. & Knight, R.W. 1994. Observed impact of snow cover on the heat balance and thr rise of continental spring temperatures. *Science* 263: 198-200.

Gutman, G. Garik, 1991, Vegetation indices from AVHRR: An update and future prospects. Remote Sensing of Environment, 35(2-3):121-136.
Hall, Dorothy K.; Riggs, George A.; Salomonson, Vincent V., DiGirolamo, Nicolo E., and Bayr, Klaus J. 2002, MODIS snow-cover products. Remote Sensing of Environment, 83(1-2):181-194.
Henry, G.H.R. & Molau, U. 1997. Tundra plants and climate change: the International Tundra Experiment (ITEX). *Global Change Biology* 3 (Suppl. 1): 1-9.
Hinzman, L., Bettez, N., Bolton, W.R., Chapin , F.S., III, Dyurgerov, M., Fastie, C., Griffith, B., Hollister, R.D., Hope, A., Huntington, H.P., Jensen, A., Jia, G.J., Jorgenson, T., Kane, D.L., Klein, D.R., Kofinas, G., Lynch, A.H., Lloyd, A.H., McGuire, A.D., Nelson, F., Oechel, W.C., Osterkamp, T.E., Racine, C., Romanovsky, V.E., Stone, R., Stow, D., Sturm, M., Tweedie, C.E., Vourlitis, G., Walker, M.D., Walker, D.A., Webber, P.J., Welker, J.E., Winker, K. & Yoshikawa, K. 2005 in press. Evidence and implications of recent climate change in northern Alaska and other Arctic regions. *Climatic Change*.
Hobbie SE, Chapin III FS. 1998. The response of tundra plant biomass, aboveground production, nitrogen, and CO_2 flux to experimental warming. *Ecology* 79**:**1526-1544.
Holland, M.M. & Bitz, C.M. 2003. Polar amplification of climate change in the Coupled Model Intercomparison Project. *Climate Dynamics* 21: 221-232.
*Jia, G.J., Epstein, H.E. & Walker, D.A. 2002. Spatial characteristics of AVHRR-NDVI along latitudinal transects in northern Alaska. *Journal of Vegetation Science* 13: 315-326.
*Jia, G.J., Epstein, H.E. & Walker, D.A. 2003. Greening of arctic Alaska, 1981-2001. *Geophysical Research Letters* 30, 2067, doi: 10.1029/2003GL1018268.
*Jia, G.J., Epstein, H.E. & Walker, D.A. 2004. Controls over intra-seasonal dynamics of AVHRR NDVI for the Arctic tundra in northern Alaska. *International Journal of Remote Sensing* 25: 1547-1564.
* Jia, G.J., Epstein, H.E. & Walker, D.A. Spatial heterogeniety of tundra vegetation response to recent temperature changes. Submitted to *Global Change Biology*.
*Jones, M.H., Fahnestock, J.T., Walker, D.A., Walker, M.D. & Welker, J.M. 1998. Carbon dioxide fluxes in moist and dry arctic tundra during the snow-free season: responses to increases in summer temperature and winter snow accumulation. *Arctic and Alpine Research* 30: 373-380.
JRC. 2003. *GLC2000: Global Land Cover Map for the Year 2000*. European Commission Joint Research Centre, Ispra, Italy.
*Kade, A., Walker, D.A. & Raynolds, M.K. 2005 in press. Plant communities and soils in cryoturbated tundra along a bioclimate gradient in the Low Arctic, Alaska. *Phytocoenologia*.
Kalnay, E., MKanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Wollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Jenne, R. & Joseph, D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the Ameriican Meteorological Society* 77: 437-471.
Kaplan, J.O. 2005. Climate change and arctic vegetation. In: L. Rosentrater (Ed.), *Evidence and Implications of Dangerous Climate Change in the Arctic*. World Wildlife Foundation International Arctic Programme, pp. 25-41.
Kaplan, J.O., Bigelow, N.H., Prentice, I.C., Harrison, S.P., Bartlein, P.J., Christensen, T.R., Cramer, W., Matveyeva, N.V., McGuire, A.D., Murray, D.F., Razzhivin, Y.Y., Smith, B., Walker, D.A., Anderson, P.M., Andreev, A.A., Brubaker, L.B., Edwards, M.E. & Lozhkin, L.V. 2003. Climate change and Arctic ecosystems II: Modeling, paleodata-model comparisons, and future projections. *Journal of Geophysical Research* 108. D19 8170, doi:1029/2002JD002559.
*Kelley, A.M., Epstein, H. & Walker, D.A. 2004. Role of vegetation and climate in permafrost active layer depth in Arctic Alaska and Canada. *Journal of Glaciology and Climatology* 26: 269-273.
Kittel, T.G.F., Steffen, W.L. & Chapin III, F.S. 2000. Global and regional modelling of Arctic-boreal vegetation distribution and its sensitivity to altered forcing. *Global Change Biology* 6: 1-18.
Kruse, J., B. White, H. Epstein, B. Archie, M. Berman, S. Braund, F. Chapin III, J. Charlie Sr., J. Eamer, N. Flanders, B. Griffith, S. Haley, L. Huskey, D. Klein, G. Kofinas, S. Martin, S. Murphy, W.

Nebesky, C. Nicolson, K. Peter, D. Russell, A. Starfield, J. Tetlichi, A. Tussing, M. Walker, O. Young. 2004. Sustainability of arctic communities: an interdisciplinary collaboration of researchers and local knowledge holders. Ecosystems 8:815-828.

Lucht, W., Prentice, I.C., Myneni, R.B., Sitch, S., Friedlingstein, P., Cramer, W., Bousquet, P., Buermann, W. & Smith, B. 2002. Climate control of the the high-latitude vegetatin greening and Pinatubo effect. *Science* 296: 1687-1689.

Markon, C.J., 1999, Characteristics of the Alaskan 1 km advanced very high resolution radiometer data sets used for analysis of vegetation biophysical properties, U.S. Geological Survey, Open-File Report 99-401, Reston, Virginia, 90 p.

Markon, C.J., 2001, Seven-year phenological record of Alaskan ecoregions derived from Advanced Very High Resolution Radiometer Normalized Difference Vegetation Index data, U.S. Geological Survey, Open-File Report 01-11, Reston, Virginia,, 58 p.

Maslanik, J.A., Serreze, M.C. & Agnew, T. 1999. On the record reduction in 1998 western Arctic sea-ice cover. *Journal of Geophysical Research* 26: 1905-1908.

Matveyeva, N.V. 1998. *Zonation in Plant Cover of the Arctic*. Russian Academy of Sciences, Proceedings of the Komarov Botanical Institute, St. Petersburg, 219 pp.

*Michaelson, G.J., Ping, C.L. & Walker, D.A. 2002. Cryptogamic crusts on frost boils, *Eos Transactions. AGU Fall Meeting Supplement*, pp. F260.

Morison, J., Alexander, V., Codispoti, L., Delworth, T., Dickson, B., Eicken, H., Grebmeier, J., Kruse, J., Overland, J.E., P., S., Serreze, M. & Walsh, J. 2001. *SEARCH: Study of Environmental Arctic Change*. Polar Science Center, Applied Physics Laboratory, Seattle, WA.

*Muller, S.V., Racoviteanu, A.E. & Walker, D.A. 1999. Landsat MSS-derived land-cover map of northern Alaska: extrapolation methods and a comparison with photo-interpreted and AVHRR-derived maps. *International Journal of Remote Sensing* 20: 2921-2946.

*Muller, S.V., Walker, D.A., Nelson, F., Auerbach, N., Bockheim, J., Guyer, S. & Sherba, D. 1998. Accuracy assessment of a land-cover map of the Kuparuk River basin, Alaska: considerations for remote regions. *Photogrammetric Engineering & Remote Sensing* 64: 619-628.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G. & Menani, R.R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386: 698-702.

NCEROS, 2005, Alaska 7 and 14 Day AVHRR NDVI time series, 1990-2004, USGS, National Center for Earth Resources Observation Satellites, Sioux Falls, S.D., USA

Nelleman, C., Kullerud , L., Vistnes, I., Forbes, B.C., Husby, E., Kattenborn, B.P., Rouaud, J., Magomedova, M., Bobiwash, R., Lambrechts, C., Schel, P.J., Tveitdal, S., Gran, O. & Larsen, T.S. 2001. *Global method for mapping human impacts on the biosphere: The Arctic 2050 scenario and global application.* United Nations Environment Programme, UNEP/DEWA/TR-01-3.

*Nelson, F.E., Hinkel, K.M., Shiklomanov, N.I., Mueller, G.R., Miller, L.L. & Walker, D.A. 1998. Annual and interannual active layer thaw patterns on the North Slope of Alaska. *Journal of Geophysical Research (Atmospheres)* 103: 28963-28974.

New, M. 2005. Arctic climate change with a 2˚C global warming. In: L. Rosentrater (Ed.), *Evidence and Implications of Dangerous Climate Change in the Arctic*. World Wildlife Foundation International Arctic Programme, pp. 7-23.

Nikolsky, D.J., Romanovsky, V.E., Tipenko, G.S. & Walker, D.A. 2004. A coupled thermo-mechanical model of differential frost heave. *Eos Transactins, AGU* Fall Supplement, 85: F431.

Overland, J.E., Spillane, M.C. & Soreide, N.N. 2004. Integrated analysis of physical and bilogical pan-arctic change. *Climatic Change* 63: 291-322.

Overpeck, J., *et al*. Arctic environmental changes over the last four centuries. *Science* **278**, 1251-1256 (1997).

Parkinson, C.L., Cavalieri, D.J., Gloersen, P., Zwally, H.J. & Comiso, J.C. 1999. Arctic sea ice extents, areas, and trends,1978-1996. *Journal of Geophysical Research-Oceans* 104: 20837-20856.

Peterson, R.A. & Krantz, W.B. 2003. A mechanism for differential frost heave and its implications for patterned ground formation. *Journal of Glaciology* 49: 69-80.

*Peterson, R.A., Walker, D.A., Romanovsky, V.E., Knudson, J.A., Raynolds, M.K. & Krantz, W.B. 2003. A differential frost heave model: cryoturbation-vegetation interactions. In: M. Phillips, S. M. Springman and L. U. Arenson (Eds.), *Permafrost: Proceedings of the Eighth International Conference on Permafrost*. A.A. Balkema Publishers, Zurich, Switzerland, pp. 885-890.

Pavelsky, Tamlin Muir and Smith, Laurence C., 2004, Spatial and temporal patterns in Arctic river ice breakup observed with MODIS and AVHRR time series, Remote Sensing of Environment, 93(3): 328-338.

Ping, C.L., Michaelson, G.J., Overduin, P.P. & Stiles, C.A. 2003. Morphogenesis of frost boils in the Galbraith Lakearea, arctic Alaska. In: M. Phillips, S. M. Springman and L. U. Arenson (Eds.), *Permafrost: Proceedings of the Eighth International Conference on Permafrost*. A.A. Balkema Publishers, Zurich, Switzerland, pp. 897-900.

*Ping, C.L., Bockheim, J.G., Kimble, J.M., Michaelson, G.J. & Walker, D.A. 1998. Characteristics of cryogenic soils along a latitudinal transect in Arctic Alaska. *Journal of Geophysical Research* 103: 28917-28928.

*Ping, C.L., Michaelson, G.J., Kimble, J., Shur, Y.L. & Walker, D.A. 2002. Morphogenesis of soils associated with frost boils. *Eos, Transactions, American Geophysical Union* 83: F259.

Polyakov, I., Bekryaev, R., Alekseev, G., Bhatt, U.S., Colony, R., Johnson, M. & Makshtas, A. 2003. Variability and trends of air temperature and pressure in the maritime Arctic, 1875-2000. *Journal of Climate* 16: 2067-2077.

Prentice, I.C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A. & Solomon, A.M. 1992. a global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography* 19: 117-134.

Proshutinsky, A. & Johnson, M. 1997. Two circulation regimes of the wind driven Arctic Ocean. *Journal of Geophysical Research* 102: 12,493 - 12,514.

Rastetter, E.B., Aber, J.D., Peters, D.P.C., Ojima, D.S. & Burke, I.C. 2003. Usiing mechanistic models to scale ecological processes across space and time. *BioScience* 53: 68-76.

*Raynolds, M.A., Walker, D.A. & Maier, H.A. 2005b (submitted). NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment*.

*Raynolds, M.K., Walker, D.A. & Maier, H.A. 2005a (in press). Plant community-level mapping of Arctic Alaska based on the Circumpolar Arctic Vegetation Map. *Phytocoenologia*.

Razzhivin, V.Y. 1999. Zonation of vegetation in the Russian Arctic. In: I. Nordal and V. Y. Razzhivin (Eds.), *The Species Concept in the High North - A Panarctic Flora Initiative*. The Norwegian Academy of Science and Letters, Oslo, pp. 113-130.

*Reeburgh, W.S., King, J.Y., Regli, S.K., Kling, G.W., Auerbach, N.A. & Walker, D.A. 1998. A CH4 emission estimate for the Kuparuk River basin, Alaska. *Journal of Geophysical Research* 103: 29005-29014.

Rekacewicz, P. 1998. Arctic watersheds, *AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo Norway, BCS 100: The Circumpolar World. Module 7: Environment, Climate Change, and Pollution*. UNEP-GRID, Arendal Norway, Oslo, Norway.

Riedel, S.M., Epstein, H.E. & Walker, D.A. 2005a in press. Biotic controls over spectral indices of arctic tundra vegetation. *International Journal of Remote Sensing*.

Riedel, S.M., Epstein, H.E., Walker, D.A., Richardson, D.L., Calef, M.P., Edwards, E.J. & Moody, A. 2005b in press. Spatial and temporal heterogeneity of LAI, NDVI, and aboveground net primary production for four tundra types in northern Alaska. *Arctic, Antarctic and Alpine Research*.

Rigor, I.G., Colony, R.l. & Martin, S. 2000. Variations in surface air temperature observations in the Arctic, 1979-1997. *Journal of Climate* 13: 896-914.

Rigor, I.G., Wallace, J.M. & Colony, R.L. 2002. Response of sea ice to the Arctic Oscillation. *Journal of Climate* 15: 2648-2663.

Romanovsky, V.E., Burgess, M., Smith, S., Yoshikawa, K. & Brown, J. 2002. Permafrost temperature records: indicators of climate change. *EOS,Transactions* 83: 589,593, 594.
Salomonson, V. V. and Appel, I., 2004, Estimating fractional snow cover from MODIS using the normalized difference snow index. Remote Sensing of Environment, 89(3):351-360.
Serreze, M.C., Walsh, J.E., Chapin, F.S., III, Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T. & Barry, R.G. 2000. Observational evidence of recent change in the northern high-latitude environment. *Climatic Change* 46: 159-207.
Serreze, M.C., Maslanik, J.A., Scambos, T.A., Fetterer, F., Stroeve, J., Knowles, K., Fowler, C., Drobot, S., Barry, R.G. & Haran, T.M. 2003. A record minimum arctic sea ice extent and area in 2002. *Geophysical Research Letters* 30: 1110, doe:10.1029/2002Glo16406.
Shaver , G.R., Bret-Harte, M.S., Jones, M.H., Johnstone, J., Gough, L., Laundre, J. & Chapin , F.S., III. 2001. Species composition interacts with fertilizer to control long-term change in tundra productivity. *Ecology* 82: 3163-3181.
Shaver, G.R., Canadell, J., Chapin III, F.S., Gurevitch, J., Harte, J., Henry, G., Ineson, P., Jonasson, S., Mellilo, J., Pitelka, L. & Rustad, L. 2000. Global wraming and terrestrial ecosystms: A conceptual framework for analysis. *BioScience* 50: 871-882.
Shaver GR, Chapin III FS. 1991. Production:biomass relationships and element cycling in contrasting Arctic vegetation types. *Ecological Monographs* 61:1-31.
Shiyatov, S.G. 2003. Rates of change in the upper treeline ecotone in the polar Ural mopuntains. *Past Global Changes (PAGES) News* 11.
Silapaswan, C.S., Verbyla, D. & McGuire, A.D. 2001. Land cover change on teh Seward Peninsular: The use of remote sensing to evaluate potential influences of climate change on hisotrical vegettain dynamics. *Canadian Journal of Remote Sensing* 5: 542-554.
Sturm, M., Racine, C. & Tape, K. 2001. Increasing shrub abundance in Arctic. *Nature* 411: 547-548.
Sturm, M., McFadden, J.P., Liston, G.E., Chapin III, F.S., Racine, C.H. & Holmgren, J. 2001. Snow-shrub interactions in arctic tundra: a hypothesis with climatic implications. *Journal of Climate* 14: 336-344.
Sturm, M., Chapin, F.S., Edwards, M.E., Griffith, D.B., Huntington, H.P., Kofinas, G.P., Lloyd, A.H., Lynch, A.H., Peterson, B.J., Pielke, R.A., Schimel, J.P., Serreze, M.C. & Shaver, G.R. 2003. *PACTS (Pan-Arctic Cycles, Transitions, and Sustainability): A Science Plan*. Land-Atmosphere-Ice Interactions Science Management Office, University of Alaska, Fairbanks, 53 pp.
Tape, K.D., Sturm, M. & Racine, C. 2004. Changing vegetatin and fluvial morphology in northern Alaska detected using aerial photographs. *Eos Transactins, AGU* 85: F475, abstract #C421-02.
Tarnocai, C., Kimble, J., Waltman, S., Swanson, D., Goryachkin, S., Naumov, Y.M., Stolbovoi, V., Jakobsen, B., Broll, G., Montanarella, L., Arnoldussen, O., Arnalds, O. & Yli-Halla, M. 2003. Northern Circumpolar Soils, 1:10,000,000-scale map. Research Branch, agriculture and Agri-Food Canada, Ottawa, Canada.
Thompson, D.W.J. & Wallace, J.M. 1998. The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters* 28: 1297-1300.
Treshnikov, A.F. & al., e. 1985. Arctic Atlas. Head Office of Geodesy and Cartography of the Soviet Ministry of USSR, Moscow, pp. 204.
Tucker, Compton J., Pinzon, Jorge E., Brown, Molly E., 2004, Global Inventory Modeling and Mapping Studies (GIMMS) Satellite Drift Corrected and NOAA-16 incorporated Normalized Difference Vegetation Index (NDVI), Monthly 1981-2003.
Tucker, C. J., J. E. Pinzon, M. E. Brown, D. Slayback, E. W. Pak, R. Mahoney, E. Vermote and N. El Saleous. 2005. An Extended AVHRR 8-km NDVI Data Set Compatible with MODIS and SPOT Vegetation NDVI Data. International Journal of Remote Sensing (in press).
Vorosmarty, C.J., Hinzman, L.D., Peterson, B.J., Bromwich, D.H., Hamilton, L.C., Morison, J., Romanovsky, V.E., Sturm, M. & Webb, R.S. 2001. *The Hydrologic Cycle and its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study*. Arctic Research Consortium of the United States, Fairbanks, 84 pp.

Wadams, P. 1994. Sea ice thickness changes and their relation to climate. In: O. M. Johannessen, R. Muench and J. E. Overland (Eds.), *American Geophysical Union, Geophysical Monography The Nansen Centennial 85*, pp. 337-362.

Walker, D.A. 1987. Height and growth-ring response of Salix lanata ssp. richardsonii along the coastal temperature gradient of northern Alaska. *Canadian Journal of Botany* 65: 988-993.

*Walker, D.A. 2000. Hierarchical subdivision of arctic tundra based on vegetation response to climate, parent material, and topography. *Global Change Biology* 6: 19-34.

Walker, D.A., Auerbach, N.A. & Shippert, M.M. 1995. NDVI, biomass, and landscape evolution of glaciated terrain in northern Alaska. *Polar Record* 31: 169-178.

*Walker, D.A., Billings, W.D. & Molenaar, J.G.d. 2001. Snow-vegetation interactions in tundra environments. In: H. G. Jones, R. W. Hoham, J. W. Pomeroy and D. A. Walker (Eds.), *Snow Ecology*. Cambridge University Press, Cambridge.

*Walker, D.A., Gould, W.A., Maier, H.A. & Raynolds, M.K. 2002. The Circumpolar Arctic Vegetation Map: AVHRR-derived base maps, environmental controls, and integrated mapping procedures. *Int. J. Remote Sensing* 23: 25521-2571.

*Walker, D.A., Bockheim, J.G., Chapin, F.S.I., Eugster, W., Nelson, F.E. & Ping, C.L. 2001. Calcium-rich tundra, wildlife, and the "Mammoth Steppe". *Quaternary Science Reviews* 20: 149-163.

*Walker, D.A., Epstein, H.E., Kuss, P., Michaelson, G.J., Ping, C.L., Raynolds, M.K., Romanovsky, V.E. & Tarnocai, C.T. 2004. Interactions of multiple factors in creating small patterned-ground features across the Arctic bioclimate gradient. *Eos Transactins, AGU* 85, fall supplement: F424.

*Walker, D.A., Epstein, H.E., Jia, J.G., Copass, C., Edwards, E.J., Gould, W.A., Hollingsworth, J., Knudson, J., Maier, H., Moody, A. & Raynolds, M.A. 2003. Phytomass, LAI, and NDVI in northern Alaska: relationships to summer warmth, soil pH, plant functional types and extrapolation to the circumpolar Arctic. *Journal of Geophysical Research - Atmospheres* 108: 8169, doi:10.1029/2001d00986.

*Walker, D.A., Kade, A.N., Michaelson, G.J., Ping, C.L., Raynolds, M.K., Romanovsky, V.E., Epstein, H.E., Kelley, A.M., Gould, W.A., Gonzalez, G., Krantz, W.B. & Tarnocai, C.T. 2003. Biocomplexity of frost-boil ecosystems: models for analyzing self-organizaiton across the Arctic bioclimate gradient, *Biocomplexity in the Environment Awardees Meeting*, Arlington, VA, 15-17 Sep 2003.

* Walker, D.A., Epstein, H.E., Gould, W.A., Kelley, A.M., Kade, A.N., Knudson, J.A., Krantz, W.B., Michaleson, G., Peterson, R.A., Ping, C.L., Raynolds, M.A., Romanovsky, V.E. & Shur, Y. 2004. Frost-boil ecosystems: complex interactions between landforms, soils, vegetation, and climate. *Permafrost and Periglacial Processes* 15:171-188.

*Walker, D.A., Jia, G.J., Epstein, H.E., Raynolds, M.A., Chapin , F.S., III, Copass, C.D., Hinzman, L., Knudson, J.A., Maier, H., Michaelson, G.J., Nelson, F., Ping, C.L., Romanovsky, V.E. & Shiklomanov, N. 2003. Vegetation-soil-thaw-depth relationships along a low-arctic bioclimate gradient, Alaska: Synthesis of Information from the ATLAS Studies. *Permafrost and Periglacial Processes* 14: 103 - 123.

*Walker, D.A., Raynolds, M.K., Daniels, F.J.A., Einarsson, E., Elvebakk, A., Gould, W.A., Katenin, A.E., Kholod, S.S., Markon, C.J., Melnikov, E.S., Moskalenko, N.G., Talbot, S.S., Yurtsev, B.A. & CAVM Team. 2005 in press. The Circumpolar Arctic Vegetation Map. *Journal of Vegetation Science*.

*Walker, D.A., Auerbach, N.A., Bockheim, J.G., Chapin, F.S.I., Eugster, W., King, J.Y., McFadden, J.P., Michaelson, G.J., Nelson, F.E., Oechel, W.C., Ping, C.L., Reeburg, W.S., Regli, S., Shiklomanov, N.I. & Vourlitis, G.L. 1998. Energy and trace-gas fluxes across a soil pH boundary in the Arctic. *Nature* 394: 469-472.

Wang, M. & Overland, J.E. 2004. Detecting Arctic climate change using Koppen climate classification. *Climatic Change* 67: 43-62.

Williams, M., Eugster, W., Rastetter, E.B., McFadden, J.P. & Chapin, F.S. 2000. The controls on net ecosystem productivity along an arctic transect: A model comparison with flux measurements. *Global change Biology* 6(S1): 116-126.

Yurtsev, B.A. 1994. Latitudinal (zonal) and longitudinal (sectoral) phytogeographic division of the circumpolar arctic in relatin to the strucure of the vegetation map legend. In: D. A. Walker and C. J. Markon (Eds.), *Circumpolar Arctic Vegetation Mapping Workshop, Komarov Botanical Institute, St. Petersburg, Russia, March 21-25, 1994*, pp. 77-83.

Yurtsev, B.A. 2004. Some problems in the botanical-geographic division of the north-eastern Asia. *Botanchiski Zhurnal* 89: 908-923.

Zhou, L., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N.V. & Myneni, R.B. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to1999. *Journal of Geophysical Research - Atmospheres* 106: 20,069-20,083.

F. BIOGRAPHICAL SKETCHES

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Professional Preparation:

1964-1967U.S. Air Force Academy - Mechanical Engineering, Astronautics

1972	B.A.	Environmental Biology, University of Colorado, Boulder
1977	M.A.	Environmental Biology, University of Colorado, Boulder
1981	Ph.D.	Environmental Biology, University of Colorado, Boulder

Appointments:

Professor, Department of Biology and Wildlife, University of Alaska Fairbanks 1999-present

Director, Alaska Geobotany Center, 1999-present

Fellow, Institute of Arctic and Alpine Research, University of Colorado 1986-1999

Co-Director, Tundra Ecosystem Analysis and Mapping Laboratory 1986-1999

Assistant Professor (1986-1994), Associate Professor (1994-1998), and Professor (1998-1999) Attendant-Rank, Department of Environmental Population and Organismic Biology, University of Colorad

Publications, five most relevant:

Jia, G.J., Epstein, H.E. & Walker, D.A. 2003. Greening of arctic Alaska, 1981-2001. *Geophysical Research Letters* 30, 2067, doi: 10.1029/2003GL1018268.

Walker, D.A. 2000. Hierarchical subdivision of arctic tundra based on vegetation response to climate, parent material, and topography. *Global Change Biology* 6: 19-34.

Walker, D.A., Gould, W.A., Maier, H.A. & Raynolds, M.K. 2002. The Circumpolar Arctic Vegetation Map: AVHRR-derived base maps, environmental controls, and integrated mapping procedures. *Int. J. Remote Sensing* 23: 25521-2571.

Walker, D.A., Epstein, H.E., Jia, J.G., Copass, C., Edwards, E.J., Gould, W.A., Hollingsworth, J., Knudson, J., Maier, H., Moody, A. & Raynolds, M.A. 2003. Phytomass, LAI, and NDVI in northern Alaska: relationships to summer warmth, soil pH, plant functional types and extrapolation to the circumpolar Arctic. *Journal of Geophysical Research - Atmospheres* 108: 8169, doi:10.1029/2001d00986.

Walker, D.A., Raynolds, M.K., Daniels, F.J.A., Einarsson, E., Elvebakk, A., Gould, W.A., Katenin, A.E., Kholod, S.S., Markon, C.J., Melnikov, E.S., Moskalenko, N.G., Talbot, S.S., Yurtsev, B.A. & CAVM Team. 2005 in press. The Circumpolar Arctic Vegetation Map. *Journal of Vegetation Science*.

Five other significant publications:

Walker, D.A., Auerbach, N.A., Bockheim, J.G., Chapin, F.S.I., Eugster, W., King, J.Y., McFadden, J.P., Michaelson, G.J., Nelson, F.E., Oechel, W.C., Ping, C.L., Reeburg, W.S., Regli, S., Shiklomanov, N.I. & Vourlitis, G.L. 1998. Energy and trace-gas fluxes across a soil pH boundary in the Arctic. *Nature* 394: 469-472.

Walker, D.A., Auerbach, N.A. & Shippert, M.M. 1995. NDVI, biomass, and landscape evolution of glaciated terrain in northern Alaska. *Polar Record* 31: 169-178.

Walker, D.A., Billings, W.D. & Molenaar, J.G.d. 2001. Snow-vegetation interactions in tundra environments. In: H. G. Jones, R. W. Hoham, J. W. Pomeroy and D. A. Walker (Eds.), *Snow Ecology*. Cambridge University Press, Cambridge.

Walker, D.A., Bockheim, J.G., Chapin, F.S.I., Eugster, W., Nelson, F.E. & Ping, C.L. 2001. Calcium-rich tundra, wildlife, and the "Mammoth Steppe". *Quaternary Science Reviews* 20: 149-163.

Walker, D.A., Jia, G.J., Epstein, H.E., Raynolds, M.A., Chapin , F.S., III, Copass, C.D., Hinzman, L., Knudson, J.A., Maier, H., Michaelson, G.J., Nelson, F., Ping, C.L., Romanovsky, V.E. & Shiklomanov, N. 2003. Vegetation-soil-thaw-depth relationships along a low-arctic bioclimate gradient, Alaska: Synthesis of Information from the ATLAS Studies. *Permafrost and Periglacial Processes* 14: 103-123.

Synergistic activities:

Currently PI on a grant to create a web-based hierarchical Arctic Geobotanical Atlas.

Major synthesis of information in chapters and articles on snow ecology (Walker et al. 2001), Arctic vegetation (Walker et al. 2005 in press), and active layer-vegetation interactions (Walker et al. 2003).

Service on the National Research Council Committee on Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities (2000-2003) and resulting book: NRC, N.R.C. 2003. *Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope*. National Academies Press, Washington, D.C., 288 pp.

Co-editor of book Jones, H.G., Pomeroy, J.W., Walker, D.A. & Hoham, R.W. 2001. *Snow Ecology*. Cambridge University Press, Cambridge, 378 pp.

Directed the creation and publication of the Circumpolar Arctic Vegetation Map (CAVM Team 2003), an 11-year effort involving 35 vegetation scientists from all Arctic countries.

Collaborators and other affiliations:

Pat Anderson, *University of Washington; Andrei Andreev, Alfred Wegner Insittute for Polar and Marine Research, Potsdam, Germany;* Pat Bartlein, *University of Oregon;* Nancy Bigelow, *UAF;* Jim Bockheim, *University of Wisconsin; Linda Brubaker, University of Washington;* Terry Chapin, *UAF, Berkeley;* Torben Christiansen*, Lund University, Sweden;* Wolfgang Cramer*, Potsdam Institute for Climate Impact Research, Potsdam, Germany;* Scott Daeschner*, San Diego State University;* Fred Daniels, *Institute of Plant Ecology, Muenster Wilhelms University;* David Douglas*, USGS, Juneau, AK;* Mary Edwards*, University of Washington;* Arve Elvebakk, *University of Tromso, Norway;* Eythor Einarsson, *Icelandic Institute of Natural History, Reykjavik, Iceland;* Howard E. Epstein, *University of Virginia;* John Gamon, *California State University;* William A. Gould, *International Institute of Tropical Forestry USDA, San Juan, PR;* Brad Griffith, *UAF;* Sandy Harrison, *Max Plank Institute for Biogeochemisty, Jena, Germany*; Larry Hinzman*, UAF;* Allan Hope*, San Diego State University;* Fred Huemmrich*, University of Maryland;* Stan Houston*, California State University;* Jiong Jia, *Colorado State University;* Jed Kaplan*, Max Plank Institute for Biogeochemisty, Jena, Germany;* Adik Katenin*, Komarov Botanical Institute, St. Petersburg Russia;* Alexia M. Kelley*, Ph.D. student, University of Virginia;* Sergei Kholod*, Komarov Botanical Institute, St. Petersburg Russia;* Julie Knudson, *Colorado State University;* William B. Krantz*,* *University of Cincinnati;* Andrea Lloyd*, Middlebury College;* Anatoly Loshkin*, Northeast Interdisciplinary Scientific Research Institute, Magadan Russia;* Amanda Lynch*, University of Colorado;* Carl Markon*, USGS, Anchorage, AK;* Nadya Matveyeva, *Komarov Botanical Institute, St. Petersburg, Russia;* Joe McFadden*, University of Minnesota;* Evgeny Melnikov*, Earth Cryosphere Institute, Moscow, Russia;* Dave McGuire*, UAF;* Gary Michaelson*, Palmer Research Center, UAF;* Natalia Moskalenko*, Earth Cryosphere Institute, Moscow, Russia;* Dave Murray*, UAF;* Ranga Myneni*, Boston University;* Fritz Nelson*, New York University, Albany;* Aaron Petersen*, San Diego State University;* Rorik Peterson*, UAF,* Chien-Lu Ping*, Palmer Research Center, UAF;* Colin Prentice*, Max Plank Institute for Biogeochemisty, Jena, Germany;* Martha Raynolds*, UAF;* Valodya Razzhivin, *Komarov Botanical Institute, St. Petersburg, Russia;* James Ritchie, *Pebbledash Cottage, Corfe, Taunton, UK;* Vladimir Romanovsky*, UAF;* Scott Rupp*, UAF;* Mark Serreze*, University of Colorado;* Buck Sharpton*, UAF;* Cherie Silapaswan*, UAF;* Yuri Shur*, UAF;* Benjamin Smith, *Max Plank Institute for Biogeochemisty, Jena, Germany;* Matthew Sturm*, US Army CRREL, Fairbanks;* Doug Stow*, San Diego State University;* Stephen Talbot*, USFWS, Anchorage, AK;* Ken Tape, *UAF;* David Verbyla*, UAF;* Jeff Welker*, UAA; Kenji Yoshikawa, UAF; Craig Tweedie, Michigan State University;* Brian Noyle*, Space Imaging Solutions;* Liming Zhou*, Georgia Institute of Technology.*

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Graduate students and post docs:

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Professional Preparation:

University of Pittsburgh, PA.	B.S.E Mechanical Engineering, B.A., Russian 1983
University of Wisconsin, Madison, WI.	Atmospheric Sciences, M.S. 1989
University of Wisconsin, Madison, WI.	Atmospheric Sciences, Ph.D. 1996
COLA, Calverton, MD	Atmospheric Sciences, Postdoc. 1997-8

Appointments:

2004- Associate Professor, Geophysical Institute & Atmospheric Science Program, UAF

2003-2004 Research Associate Professor, IARC/Frontier, U. of Alaska Fairbanks
1998-2003 Research Assistant Professor, IARC/Frontier, U. of Alaska Fairbanks

1997-1998 Postdoc Researcher, Center for Ocean Land Atmosphere Studies, Calverton, MD

1996-1997 Research Scientist, Ross Computational Resources, Madison, WI

1989-1995 Research Assistant, University of Wisconsin, Madison

1986-1989 Graduate Fellowship, University of Wisconsin, Madison

1983-1985 Secondary school teacher in Kenya as US Peace Corps Volunteer

Five most relevant publications:

2005 Bhatt, U. S., D. E. Newman, B. A. Carreras , and I. Dobson, Understanding the Effect of Risk Aversion on Risk, Thirty-eighth Hawaii International Conference on System Sciences, Hawaii, January 2005.

2004 Polyakov, I. , G. V. Alekseev, L. Timokhov, U. S. Bhatt, R. L. Colony, H. L. Simmons, D. Walsh, J. Walsh, Variability of the intermediate Atlantic Water of the Arctic Ocean over the last 100 years, J. Climate,17(23), 4485-4497.

2004 Hu, Z.-Z., E. K. Schneider, U. S. Bhatt, and B. P. Kirtman, Potential mechanism for response of El Niño–Southern Oscillation variability to change in land surface energy budget, J. Geophys. Res., 109, D21113, doi:10.1029/2004JD004771.

2004 Alexander, M. A., U. S. Bhatt, J. Walsh, M. Timlin, and J. Miller, The Atmospheric Response to Realistic Arctic Sea Ice Anomalies in an AGCM during Winter., J. Climate 17, 890-905.

2003 Bhatt, U. S., E. Schneider, and D. Dewitt, Influence of North American land processes on North Atlantic SST variability, *Global and Planetary Change*, 37, 33-56. doi:10.1016/S0921-8181(02)00190-X. (COLA Tech Report 112).

Other Publications:

2004 Zhang, X., J.E. Walsh, J. Zhang, U. S. Bhatt, and M. Ikeda, Climatology and Interannual Variability of Arctic Cyclone Activity, 1948 – 2002, J. Climate, 2300-2317.

2003 Polyakov, I., R. Bekryaev, G. Alekseev, U. S. Bhatt, R. Colony, M. Johnson, and A. Makshtas, Variability and trends of air temperature and pressure in the maritime Arctic, 1875-2000, *J. Climate*, 16, 2067-2077.

2003 Polyakov, I., G. Alekseev, R. Bekryaev, U. S. Bhatt, R. Colony, M. Johnson, V. Karklin, D. Walsh, and A. Yulin, Long-term variability of ice in the arctic marginal seas, *J. Climate* 16, 2078-2085.

2003 Tilley, J.S., J.E. Walsh, U.S. Bhatt, N. Mölders, and S. Vavrus, Arctic atmospheric and system modeling: A survey of IARC-related activities, *Tohoku Geophys. Journal*, 36, 397-409.

2002 Polyakov, I., G. Alekseev, R. Bekryaev, U. S. Bhatt, R. Colony, M. Johnson, V. Karklin, A. Makshtas, D. Walsh, and A. Yulin, "Observationally-based assessment of polar amplification of global warming", *Geophysical Research Letters*, 1878, doi:10.1029/2001GL011111.

Synergistic Activities:

Chair of American Meteorological Society committee on Polar Meteorology and Oceanography, term 2003-2006.

Reviewer of papers and proposals for AGU, AMS, NOAA, and NSF.

Scientific Outreach Activities: State Fair, Science Fair Judge, & K-12 classroom presentations. Mentoring REU students (4 since 1999).

Graduate Teaching: Introduction To Atmos. Sci. (Fall 2000), Scientific Presentations (Fall 2002), Climate Seminar (Fall 2004), Atmospheric Dynamics I (Spring 2005).

Interdisciplinary Collaboration: Co-PI on NASA funded project titled 'Glaciers, climate, the ocean and solid earth deformation in southern Alaska: an interdisciplinary study'.

Recent Collaborators:

M. A. Alexander (NOAA/CDC), R. Bekryaev (AARI), R. Colony (IARC/Frontier), Z. Z. Hu (COLA), B. Kirtman (COLA), J. Miller (INE/UAF), I. Polyakov (IARC/Frontier), J. Scott (NOAA/CDC), E. K. Schneider (COLA), M. Timlin (U of Illinios), J. Tilley (U. of N. Dakota), J. Walsh (UAF), J. Zhang (GI/UAF), X. Zhang (IARC/Frontier).

Graduate and Postdoctoral Advisors:

Postdoctoral Advisor: E. K. Schneider (COLA),

Ph.D.: D. Battisti (U. Washington) and D. Houghton (U. Wisconsin),

M.S.: S. Hastenrath (U. Wisconsin).

M.S. and Ph.D. Thesis Advisees:

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JOSEFINO C. COMISO (MAJOR COLLABORATOR, EXCEPTIONAL QUALIFICATIONS THAT MERIT CONSIDERATION IN THE EVALUATION OF THIS PROPOSAL))

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Professional preparation:

1962 B.S. Physics, University of the Philippines, Quezon City, RP

1966 M.S. Physics, Florida State University, Tallahassee, FL

1972 Ph.D. Physics, University of California at Los Angeles (UCLA)

Appointments:

1977-79 Senior Member of the Technical Staff, CSC

1973-77 Research Associate, Univ. of Virginia

1972-73 Assistant Research Physicist, UCLA

1963-64 Instructor, University of the Philippines

1962-63 Scientist, Philippine Atomic Research Center, Quezon City

Five most relevant publications:

Comiso, J. C. and Parkinson, C.L. 2004. Satellite observed changes in the Arctic, *Phys. Today 57*(8), 38-44, 2004.

Comiso, J.C., Yang, J., Honjo, S., and Krishfield, R.A. 2003. The detection of change in the Arctic using satellite and buoy Data, *J. Geophys. Res. 108*(C12), 3384, doi:1029-2002jc001247, 2003.

Comiso, J. C., 2003. Warming Trends in the Arctic, *J. Climate* , *16*(21): 3498-3510.

Ackley, S.F., P. Wadhams, J.C. Comiso, and Worby, A. 2003. Decadal decrease of Antarctic sea ice extent from whaling records revisited on the basis of historical and modern sea ice records, *Polar Research*, *22*(1): 10-25.

Comiso, J. C., Cavalieri, D.J., and Markus, T. 2003. Sea ice concentration, ice temperature, and snow depth, using AMSR-E data, *IEEE TGRS, 41(2),* 243-252, 2003.

Five other publications:

Comiso, J.C. 2002. Correlation and trend studies of the sea ice cover and surface temperatures in the Arctic, *Annals of Glaciology*, *34*, 420-428, 2002.

Comiso, J. C. and Cota, G.F. (in review, 2005). Spatial and interannual variations in pigment concentrations in the Arctic and peripheral seas and their correlations with surface temperature, clouds, and wind, *J. Geophys. Res*.

Comiso, J.C., 2005. Impact Studies of a 2^o C global warming on the Arctic sea ice cover, in *2^o is too much! Evidence and implications of Dangerous Climate Change in the Arctic*, ed. Lynn Rosentrater, WWF International Arctic Programme, Oslo, Norway, pp 44-56, 2005.

Yang, J., Comiso, J.C., Walsh, D., Krishfield, R.A., and Honjo, S. 2004. Storm-driven mixing in the upper
Arctic Ocean and its relation to the Arctic Oscillation, *J. Geophys. Res.*, *109*, C04008, doi:10.1029/2001JC001248.

Comiso, J.C. 2001. Satellite observed variability and trend in sea ice extent, surface temperature, albedo, and clouds in the Arctic, *Ann. Glaciol. 33*, 457-473, 2001.

Synergistic activities:

Honors and awards: 1982, 2003 - NASA Group Achievement Award; 1987, 1991, 1994, 1996, 2000, 2004 - Special Service or Performance Awards, NASA/GSFC; 1988 - Peer Award for Best Paper, Laboratory for Oceans, NASA/GSF; 1990 - Electromagnetics Academy, Who's Who in the World, in North America, in Frontiers of Science & Technology, and in Electromagnetics. ***Special experiences:*** Chief Scientist: NASA Aircraft/Nuclear Submarine Arctic Sea Ice Project, 1987; Chief Scientist: NASA Aircraft Okhotsk Sea and Antarctic Campaigns, 2003 and 2004; ***Principal Investigator (PI) of the sea ice components of the following field projects:*** 1986 Winter Weddell Microwave Experiment; 1988 AMERIEZ Passive Microwave Experiment; 1989, 1992 Winter Weddell Gyre Microwave Experiments; PI/Team member of the AMSR-E facility instrument for EOS-Aqua and ADEOS-2; PI for JERS1 SAR and ERS1 (and ERS2) SAR Polar Projects. ***Member:*** The WCRP/CliC Observational Products Panel (OPP), 1999-present; Science Advisory Group of the MIMR instrument (ESA&NASA), 1992-1996; The AMS Committee on Polar Meteorology and Oceanography (1990-93); STX Evaluation Board (1992-present); Multicultural Diversity Committee (1995-96); Editorial Staff of the Phil. Journal of Science, Annals of Glaciology, and an AGU Monograph; President (1987-1988) and Chairman of the Board of Directors (2001-2003) of PAASE; Visiting Scientist at the University of the Philippines (1995), University of Tasmania, Austrialia (1996, 1997), Woods Hole Oceanographic Institution (1998, 2000).

CARL MARKON (MAJOR COLLABORATOR, EXCEPTIONAL QUALIFICATIONS THAT MERIT CONSIDERATION IN THE EVALUATION OF THIS PROPOSAL)

Address: Alaska Geographic Science Office, 4230 University Dr, Suite 230, Anchorage, AK 99508-4664, markon@usgs.gov

Professional Preparation:

M.S. Degree, Biology, 2001, University of Alaska, Anchorage, AK.

A.A. Degree, Wildlife Biology, 1981, Anchorage Community College, Anchorage, AK

B.S. Degree, Forestry, 1976, University of Minnesota, St. Paul, MN

Appointments:

U.S. Geological Survey, Alaska Geographic Science Office, Physical Scientist 2002-present

Raytheon Corporation, Contractor to the U.S. Geological Survey, Anchorage, AK, supervisory senior scientist, 1992-present

TGS technology, Inc., Anchorage, Alaska, Senior Scientist, 1984-1992

US Fish and Wildlife Service, Anchorage, AK, Natural Resources Specialist, 1982-1984

US Fish and Wildlife Service, Anchorage, AK, Biological Technician, 1977-1982

Publications (Five most relevant):

Markon, C.J., 2003, A Temporal Study of Urban Development for the Municipality of Anchorage, Alaska, GeoCarto International, 18(3): 21-33.

Markon, C.J., and Peterson, K.M., 2002, The utility of estimating net primary productivity over Alaska using baseline AVHRR data, International Journal of Remote Sensing, 23(21):4571-4596

Markon C.J., 1995. The history and use of remote sensing for conservation and management of federal lands in Alaska. Natural Areas Journal 15:329-338.

Markon, C.J., Fleming, M.D., and Binnian, E.F., 1995. Characteristics of vegetation phenology over the Alaskan landscape using AVHRR time-series data. Polar Record 31(177):179-190.

Markon, C.J., and Derksen, D.V., 1994. Identification of tundra land cover near Teshekpuk Lake, Alaska using SPOT satellite data. Arctic 47(3): 222-231.

Publications (five others):

Markon, C.J., 1992. Land cover mapping of the Upper Kuskokwim Resource Management area, Alaska, using Landsat and digital data base approach. Canadian Journal of Remote Sensing 18(2):62-71.

Talbot, S.S., and Markon, C.J., 1988. Intermediate-scale vegetation mapping of Innoko National Wildlife Refuge, Alaska using Landsat MSS digital data. Photogrammetric Engineering and Remote Sensing 54(3):377-383.

Talbot, S.S., and Markon, C.J., 1986. Vegetation mapping of Nowitna National Wildlife Refuge Alaska using Landsat MSS digital data. Photogrammetric Engineering and Remote Sensing 52(6):791-799.

Raynolds, M.K., and Markon, C.J., eds, 2002. Fourth International Circumpolar Arctic Vegetation Mapping Workshop, Open-File Report 02-181, 132 p.

Markon, C.J., and Talbot, S.S., 2002, A hierarchical approach to mapping southwest arctic Alaska, in Raynolds, M.K, and Markon, C.J., eds, Fourth International Circumpolar Arctic Vegetation Mapping Workshop, Open-File Report 02-181, p. 92.

Synergistic activities

Over 20 years of professional remote sensing experience as research scientist, primarily in the areas of aerial photo interpretation and digital analysis of satellite data and associated ancillary data for land cover/land use mapping, wildlife habitat mapping, phenological studies, and global change studies. Developed time series of AVHRR data for Alaska, and will provide data support for the proposed work.

MARTHA K. RAYNOLDS (PH.D. STUDENT, EXCEPTIONAL QUALIFICATIONS THAT MERIT CONSIDERATION IN THE EVALUATION OF THIS PROPOSAL)

Professional Preparation

Dartmouth College, Geography-Environmental Studies, B.A. 1978

Virginia Polytechnic Institute and State University, M.S. Botany, 1980

University of Alaska Fairbanks, Vegetation mapping, current Ph.D. student

Appointments

Research Associate, University of Alaska Fairbanks, 2001-present

Research Assistant, University of Alaska Fairbanks, 1999-2001

Consulting Ecologist, ABR, Inc., Fairbanks, 1995-1999

Botanist, Arctic National Wildlife Refuge, USF&WS, 1987-1992

Publications (Five most closely related):

Raynolds, M.K., D. A. Walker and H. A. Maier. Submitted 2004. NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment*.

Walker, D.A., M.K. Raynolds, F.J.A. Daniels, E. Einarsson, A. Elvebakk, W.A. Gould, A.E. Katenin, S.S. Kholod, C.J. Markon, E.S. Melnikov, N.G. Moskalenko. S.S. Talbot, B.A. Yurtsev, and the CAVM Team. In press 2005. The Circumpolar Arctic Vegetation Map. *Journal of Vegetation Science*.

Raynolds, M.K., D. A. Walker and H. A. Maier. (in press 2005). Plant community-level mapping of arctic Alaska based on the Circumpolar Arctic Vegetation Map. *Phytocoenologia*.

CAVM Team (D.A. Walker (project director), W.A. Gould, L.C. Blliss, S.A. Edlund, M.K. Raynolds, S.C. Zoltai, F.J.A. Daniëls, C. Bay, M. Wilhelm, E. Einarsson, G. Gundjonsson, A. Elvebakk, B.E. Johansen, F.V. Ananjeva, D.S. Drozedov, A.E. Katenin, S.S. Kholod, L.A. Konchenko, Y.V. Korostelev, E.S. Melnikov, N.G. Moskalenko, A.N. Polezhaev, O.E. Ponomareva, E.B. Pospelova, I.N. Safronova, R.P. Shelkunova, B.A. Yurtsev, M.D. Fleming, C.J. Markon, D.F. Murray, and S.S. Talbot). 2003.. *Circumpolar Arctic Vegetation Map*. Scale 1:7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Walker, D. A., H. E. Epstein, G. J. Jia, A. Balsar, C. Copass, E. J. Edwards, W. A. Gould, J. Hollingsworth, J. Knudson, H. Maier, A. Moody, and M. K. Raynolds, 2003. Phytomass, LAI, and NDVI in northern Alaska: relationships to summer warmth, soil pH, plant functional types and extrapolation to the circumpolar Arctic. *Journal of Geophysical Research* Vol. 108, No. D2, 8169, doi:10.1029/2001JD000986.

Five other relevant papers:

Walker DA, H.E. Epstein, W.A. Gould, A.M. Kelley, A.N. Kade, J.A. Knudson, W. B. Krantz, G. Michaelson, R.A. Peterson, C.L. Ping, M.K. Raynolds, V.E. Romanovsky, Y.Shur. 2004. Frost-boil ecosystems: complex interactions between landforms, soils, vegetation, and climate. Permafrost and Periglacial Processes 15: 171-188.

Gould, W.A., M. K. Raynolds and D.A. Walker. 2003. Vegetation, plant biomass, and net primary productivity patterns in the Canadian Arctic. *Journal of Geophysical Research*, 108 (D2):8167, doi:10.1029/2001JD000948.

Gould, W.A., M.K. Raynolds, D.A. Walker, H.A. Maier, S. Edlund, and S. Zoltai. 2002. Canadian arctic vegetation mapping. *International Journal of Remote Sensing* 23:4597-4609.

Walker, D.A., W.A. Gould, M.K. Raynolds, H.A. Maier. 2002. The Circumpolar Arctic Vegetation Map: Environmental controls, AVHRR-derived base maps, and integrated mapping procedures. *International Journal of Remote Sensing*, 23: 2551-2570.

Raynolds, M.K. and N.A. Felix. 1989. Airphoto analysis of winter seismic trails in northeastern Alaska. *Arctic* 42(4):362-367.

G. SUMMARY PROPOSAL BUDGET

H. BUDGET JUSTIFICATION

Salaries and benefits. This is a collaborative proposal with the University of Virginia. The University of Alaska Fairbanks is the lead university. The project PI will be Dr. D.A. Walker, who will lead the project and participate in Component II. He is on a 50% FTE and is requesting 1 mo salary support in year 2 and 2 months in year 3. Uma Bhatt, who is a research associate in the Geophysical Institute, will be a co-PI and lead Component I of the project. She is requesting 1 mo salary per year. We are requesting 6 mo salary per year for Martha Raynolds, who is a geobotanist who will perform the spatial analysis of the NDVI and CAVM data. She did much of the mapping for the Circumpolar Arctic Vegetation Map, will design a Ph.D. project around Component II.

The UVa part of the collaboration includes the salaries for Gensuo Jia and Howard Epstein. Epstein is lead PI on the UVa portion of the collaboration and will lead Component IV. Gensou Jia will lead Component III and participate in components I, II, and IV. A Ph.D. student will work on the modeling component with Howie Epstein and Jed Kaplan.

Other collaborators in the project include Jerry Brown and Evgeny Melnikov, who will help with integration of the circumpolar permafrost data, and Charles Tarnocai and Chien-Lu Ping, who will help with integration of the circumpolar soils data (see letters of collaboration). The international collaborators include Charles Tarnocai in Canada, Jed Kaplan, who has worked extensively with the European Joint Research Council, and Natalya Moskalenko and Evgeny Melnikov at the Earth Cryosphere Institute in Moscow, who have developed an integrated GIS of vegetation, landscapes, and permafrost variables for Russia. The project will have two Ph.D. students.

Other technical staff at UAF include Hilmar Maier (salary covered by other funding) who will be in charge GIS data management and development of the web page.

Permanent equipment. No permanent equipment is requested in this grant.

Travel. Travel funds are requested to attend one workshop per year for the 7 people involved in the UAF portion of the grant (Walker, Bhatt, Raynolds, Comiso, Markon, Tarnocai, Moskalenko). Two meetings are planned at either UVa or NASA Goddard in Maryland, and one meeting is planned for Jena, Germany, where the BIOME model is being developed. $2000 is budgeted for each domestic trip, and $2500 is budgeted for each international trip.

Participant support costs. There are no participant support costs in the budget.

Other direct costs.

Materials and supplies. $2000 per year is budgeted for remote sensing imagery and maps for Components I and II,

Computer. $2000 per year is budgeted to cover anticipated GIS and remote sensing support, including plotter and copier supplies. Salary support for the Hilmar Maier, our GIS Manager is covered by other projects.

Publication and communication. $2000 per year is budgeted for page charges for at least 2 publications per year, and for communication costs involved in the project.

Services. $20,000 per year is budgeted for SGT Inc., which is a contractor to NASA Goddard for creating the remote-sensing and visualization products required for the participation of Josefino Comiso. Dr. Comiso has over 35 years experience with remote-sensing analysis of sea-ice and surface temperature data in the Arctic and Antarctic.

Other. In-state-tuition fees are requested for the Ph.D. of Martha Raynolds.

Indirect costs. An agreed **modified total direct cost (F&A)** rate is set at 47.5% by the University of Alaska Fairbanks. All professional and technician salaries are increased 3% annually. All materials and service costs are estimates based on current information available at the time of the writing.

I. CURRENT AND PENDING SUPPORT

J. FACILITIES, EQUIPMENT, AND OTHER RESOURCES

ALASKA GEOBOTANY LAB, UNIVERSITY OF ALASKA FAIRBANKS

The mission of AGC is to explore and understand global tundra ecosystems and to foster responsible land use and conservation of these systems. The Center is dedicated to excellence in field research, teaching and making our teaching and research relevant to societal issues and concerns. Interdisciplinary geobotanical research involves the cooperation among vegetation scientists, soil scientists, hydorolgists, geologists, geographers, permafrost specialists, and other involved in Earth system research. Our primary areas of interest are climate change, paleoecology, vegetation classification and analysis, geobotanical mapping, snow ecology, and disturbance ecology in northern regions. AGC is located in the Institute of Arctic Biology (IAB) at the University of Alaska Fairbanks. The facilities of the Institute include a well-staffed administrative office, and a library specializing in northern topics.

AGC's lab facilities include equipment to support vegetation and soil field research and computer equipment to support GIS and remote-sensing work. AGC's current computing resources include a total of 14 GIS workstations, personal workstations, portable notebook computers, file servers and web servers. The AGC maintains a full complement of high-end software and peripheral devices to support our GIS and remote-sensing environment, allowing us to perform advanced GIS analysis, image processing and graphic layout on the Unix, Macintosh and Intel platforms. The major software packages currently used at

AGC include ARC/Info Workstation, ArcView and ArcGIS (Environmental Research Systems, Inc.) for geographic information system analysis and cartographic design, ENVI (Research Systems, Inc.) and Land Analysis System (USGS) for manipulation and analysis of multi-spectral remote sensing data, Photoshop (Adobe Systems, Inc.) for editing graphic images and Studio MX (Macromedia, Inc.) for website development and graphic production. We will also utilize TerraExplorer, a 3-D “full motion flight” simulator developed by Skyline Software, which is being developed as a user interface for the web site for the Arctic Atlas.

K. LETTERS OF COMMITMENT

NASA Goddard Space Flight Center
Laboratory for Hydrospheric and Biospheric Processes, Code 614.1
Greenbelt, MD 20771

28 February 2005

Dr. Donald A. Walker
Institute of Arctic Biology and Department of Biology and Wildlife
University of Alaska, Fairbanks, Fairbanks, AL 99775

Dear Dr. Walker:

This letter is meant to reiterate my desire to work with you as a collaborator in a project entitled "Greening of the Arctic: systhesis of circumpolar databases to examine vegetation change," that is being proposed in response to an announcement of opportunity by the National Science Foundation. This project is in line with what I have been working on in the past few years and is actually an area that I believe deserves more attention in light of the recently observed warming and changes in the Arctic region.

As indicated in our previous telephone and email communications, I will provide relevant information about the seasonal and interannual variations in surface temperature and sea ice cover data during the period that we have historical satellite observations. Enclosed is a budget for contractor support (through SGT, Inc.), that I will need to enable me to fulfill my obligations. The budget will include the development and/or refinement of surface temperature algorithms in sub-polar regions.

I am looking forward to an opportunity to work with you and help meet the objectives of the proposed project.

Sincerely,

Josefino C. Comiso

Senior Research Scientist

Budget for Dr. Josefino C. Comiso

Contractor Support provided by SGT, Inc. ------------------------------ $20,000.00/year
The amount includes salary and benefits of a programmer/analyst for
a period of one and a half month.