Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 112 (2008) 1884–1894
Remote Sensing of Environment
www.elsevier.com/locate/rse

Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI

Martha K. Raynolds [a,*], Josefino C. Comiso [b,1], Donald A. Walker [a,2], David Verbyla [c,3]

[a] Institute of Arctic Biology, University of Alaska, 311 Irving, P.O. Box 757000, Fairbanks, AK 99775, United States
[b] NASA Goddard Space Flight Center, Oceans and Ice Branch, Code 971, Greenbelt, MD 20771, United States
[c] Department of Natural Resource Management, University of Alaska, Fairbanks, AK 99775, United States

Received 13 April 2007; received in revised form 17 September 2007; accepted 22 September 2007

Abstract

Arctic vegetation distribution is largely controlled by climate, particularly summer temperatures. Summer temperatures have been increasing in the Arctic and this trend is expected to continue. Arctic vegetation has been shown to change in response to increases in summer temperatures, which in turn affects arctic fauna, human communities and industries. An understanding of the relationship of existing plant communities to temperature is important in order to monitor change effectively. In addition, variation along existing climate gradients can help predict where and how vegetation changes may occur as climate warming continues. In this study we described the spatial relationship between satellite-derived land surface temperature (LST), circumpolar arctic vegetation, and normalized difference vegetation index (NDVI). LST, mapped as summer warmth index (SWI), accurately portrayed temperature gradients due to latitude, elevation and distance from the coast. The SWI maps also reflected NDVI patterns, though NDVI patterns were more complex due to the effects of lakes, different substrates and different-aged glacial surfaces. We found that for the whole Arctic, a 5 °C increase in SWI along the climate gradient corresponded to an increase in NDVI of approximately 0.07. This result supports and is of similar magnitude as temporal studies showing increases of arctic NDVI corresponding to increases in growing season temperatures over the length of the satellite record. The strongest positive relationship between NDVI and SWI occurred in partially vegetated and graminoid vegetation types. Recently deglaciated areas, areas with many water bodies, carbonate soil areas, and high mountains had lower NDVI values than predicted by SWI. Plant growth in these areas was limited by substrate factors as well as temperature, and thus is likely to respond less to climate warming than other areas.

Keywords: Normalized difference vegetation index (NDVI); Summer warmth index (SWI); Advanced very high resolution radiometer (AVHRR); Climate change; Circumpolar

1. Introduction

The goal of this research was to use a circumpolar temperature data set to show how long-term temperature-means relate to the existing distribution of arctic vegetation. Climate change is occurring at a faster rate in the Arctic than other biomes, and is resulting in an increase of summer temperatures in almost all areas of the Arctic (Comiso, 2006; Hassol, 2004). Understanding the relationship between existing plant communities and temperature is important in order to effectively monitor changes. In addition, variation along existing climate gradients can help predict where and how vegetation changes may occur as climate warming continues.

We focused on temperature data to investigate the distribution of arctic vegetation, because the existing distribution is largely controlled by climate. Plant community composition is limited to species that are able to tolerate the coldest summer temperatures at any given location (Bliss & Petersen, 1992). Plant physiological activities, such as water and nutrient transport, photosynthesis, and respiration, all occur at minimal

* Corresponding author. Tel.: +1 907 474 6720; fax: +1 907 474 6967.
E-mail address: fnmkr@uaf.edu (M.K. Raynolds).
[1] Josefino.C.Comiso.1@gsfc.nasa.gov.
[2] ffdaw@uaf.edu.
[3] D.Verbyla@uaf.edu.

0034-4257/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2007.09.008

levels in below-freezing temperatures, and increase as plant tissues warm (Lambers et al., 1998). Arctic plants have adapted to cold temperatures by reducing the temperatures at which they achieve a maximum rate of photosynthesis, but these temperatures are still 5 to 10 °C lower than average leaf temperatures in the field (Lambers et al., 1998). As a result, plant energy budgets in the Arctic are limited by summer temperatures, which restrict the amount of plant vegetative growth and reproductive effort possible in any year. Plants that are not well-adapted to photosynthesizing in cold temperatures end up with negative energy balances, and do not survive.

Arctic plants communities have been shown to respond to experimental increases in summer temperature. Meta-analysis of standardized tundra warming experiments determined that deciduous shrub and graminoid vegetation increased and non-vascular vegetation decreased (Walker et al., 2006). These types of vegetation changes interact with snow, soil, and permafrost characteristics (Walker et al., 2006; Sturm et al., 2001) with resulting impacts on arctic animals, human communities, infrastructure and industries that rely on tundra ecosystems.

In addition to temperature, arctic plants can also be limited by dispersal, especially in recently deglaciated areas. However, a study of the Svalbard flora found that the effect of cold summer temperatures on plant establishment was much more limiting to colonization than seed or propagule availability (Alsos et al., 2007). Substrate conditions such as soil moisture or chemistry can also limit plant growth and favor different groups of species (Walker et al., 2001). These substrate limitations are super-imposed on the larger-scale climatic limitations.

To characterize the distribution of arctic vegetation, we used maps and satellite data. The distribution of 15 arctic vegetation types was mapped and described on the Circumpolar Arctic Vegetation Map (CAVM) (CAVM Team, 2003; Walker et al., 2005). The map's unifying circumpolar legend facilitated analysis of the entire Arctic.

The most informative satellite data for studying arctic vegetation are summarized in the normalized difference vegetation index (NDVI), a measure of relative greenness. NDVI is calculated as: $\mathrm{NDVI}=(\mathrm{NIR}-\mathrm{R})/(\mathrm{NIR}+R)$, where NIR is the spectral reflectance in the near-infrared where reflectance from the plant canopy is dominant, and R is the reflectance in the red portion of the spectrum where chlorophyll absorbs maximally. NDVI has a theoretical maximum of 1 and its relationship to vegetation characteristics such as biomass, productivity, percent cover and leaf area index is asymptotically nonlinear as it approaches 1. As a result, NDVI is less sensitive to ground characteristics at higher values, and essentially saturates when leaf area index >1 (van Wijk & Williams, 2005). This is not a severe problem in the Arctic where vegetation is often sparse and patchy: the mean NDVI for the Arctic, excluding ice and water, was 0.32, well below the saturation point (Raynolds et al., 2006).

NDVI has been found to relate well to the biophysical properties of arctic tundra on the ground. NDVI values increase with the amount of vegetation as measured by leaf area index (LAI) and phytomass (Riedel et al., 2005; Shippert et al., 1995). NDVI values correlate well with ground characteristics of arctic vegetation, and can be used to distinguish between vegetation types (Hope et al., 1993; Stow et al., 1993).

Most studies comparing arctic NDVI and temperature have looked at change over time, focusing on the effects of anthropogenic climate change. Myneni et al. (1997), Bogaert et al. (2002), Jia et al. (2003), Zhou et al. (2003) and Goetz et al. (2005) all found increases in arctic NDVI related to increases in temperature over time. There have been questions as to whether these results were an artifact of the satellite record due to orbit degradation and changes in sensors between satellites (Fung, 1997; Kaufmann et al., 2000). Ground studies have been able to document changes in shrub cover in some areas (Tape et al., 2006), but have had difficulty measuring large-scale changes in vegetation cover in the Arctic (Callaghan, 2005). A few studies have looked for effects in the opposite direction: the influence of arctic and boreal vegetation on surface temperatures (Hope et al., 2005) (Kaufman et al., 2003), but in the Arctic the effect is much stronger in the other direction, with summer temperatures determining NDVI values (Kaufman et al., 2003). Changes in arctic NDVI with latitude have been correlated with bioclimate zones (Raynolds et al., 2006) and on the North Slope of Alaska with total summer warmth (Jia et al., 2002).

This study looked at the whole circumpolar Arctic to determine the relationship between long term means of summer land surface temperatures, and NDVI and vegetation type distribution. We also looked at the spatial change of NDVI with temperature, to verify the correlation reported in the time-series analyses of satellite data.

2. Methods

We compared three data sets: a circumpolar surface temperature data set derived from AVHRR data (advanced very high resolution radiometer) (Comiso, 2006), a circumpolar vegetation map (CAVM Team, 2003), and NDVI data derived from AVHRR data (CAVM Team, 2003; Tucker et al., 2004).

2.1. Temperature data set

Land surface temperatures were calculated from AVHRR data. Geolocation and orbital drift were corrected using standard NOAA procedures (Comiso, 2000). Daily differencing and moving window techniques were used to eliminate cloud-contaminated pixels (Comiso, 2000). A constant emissivity value of 0.94 was used to calculate temperature from the thermal infrared channels 3 (3.5–3.9 μm), 4 (10.3–11.3 μm) and 5 (11.5–12.5 μm). The data were geographically mapped to 12.5-km pixels in a North Pole Stereographic projection, and composited into monthly means from 1982–2003 (Comiso, 2003; Comiso, 2006).

We chose the AVHRR temperature data because of the relatively detailed spatial resolution over the entire polar region, and the long time period spanned by the record. The AVHRR is a horizontally scanning radiometer with a swath width of 2900 km and a field-of-view of 1 mrad, thereby providing data at a spatial resolution of 1.1 km at nadir. Continuous global coverage, however, is available only in a sub-sampled format at about 5- by 3-km resolution. The AVHRR temperature data provide better spatial resolution than modeled data sets, which interpolate between climate stations. Arctic climate stations are few, unevenly distributed around the pole, and located mostly along coasts (Rawlins & Willmot, 2003). The station data have been found to have numerous problems that bring into question the reliability of their time-series data (Pielke et al., in press). The interpolated data sets derived from the station data tend to have high temporal resolution, but relatively coarse spatial resolution (55–100-km pixels, (Rawlins & Willmot, 2003; Rigor et al., 2000), whereas the finer spatial resolution and coarser temporal resolution of the AVHRR temperature data are more appropriate for analyzing vegetation distribution.

The AVHRR data were compiled from 1982 to 2003, providing the longest satellite temperature record available. The length of this record, especially the inclusion of the earliest years, was important in producing a mean that characterized the conditions that created the present distribution of arctic vegetation. Arctic vegetation communities are only beginning to respond to recent climate changes, and our goal was to minimize this effect in the temperature data.

The AVHRR temperature is the surface skin radiant temperature of approximately the first 50 μm of leaf surfaces (Lillesand & Kiefer, 1989). This surface temperature characterizes the environment of low growing tundra plants better than climate station temperature data, which are measured 2 m above the ground in shelters that protect against sun, wind and precipitation. In many situations, especially throughout the winter, there is little difference between ground and surface temperatures (Comiso, 2003). However, when snow melts and albedo of the surface drops, the soil surface warms from the sun's radiation. Differences start to appear for temperatures above 0 °C, and are largest for sunny days and warmest temperatures (Comiso, 2003; Karlsen & Elvebakk, 2003). On a monthly basis, arctic mid-summer land surface temperatures are warmer than air temperatures at 2 m by about 2 °C (AVHRR LST warmer than NOAA data from Umiat Alaska 1982–2000: 2.18 °C in June, 2.08 °C in July; AVHRR LST warmer than Toolik LTER data 1989–2003: 2.92 °C in June, 0.83 °C in July).

Summer warmth index (SWI) was calculated from the AVHRR temperature data (Comiso, 2006). This index characterizes the plant growing season by summing monthly mean temperatures, with a 0 °C threshold required for a month to be included. The months of May–September were evaluated for each year. This index combines the effect of both the length and the warmth of summer temperatures, and is the climate variable found to correlate best with variations in arctic vegetation distribution (Edlund, 1990; Young, 1971).

2.2. CAVM classified attributes

The second data set used in this analysis was the Circumpolar Arctic Vegetation Map (CAVM) (CAVM Team, 2003). The map was created by an international team including scientists from Russia, Norway, Iceland, Greenland, Canada and the United States. The mapped area included all of the arctic tundra, defined as the region north of the climatic limit of trees that is characterized by an arctic climate, arctic flora, and tundra vegetation. Existing data on vegetation distribution and key environmental and biological factors were compiled, using a false-CIR AVHRR image as a base map. The unified circumpolar legend of 15 tundra vegetation types was based on the general outward appearance of the vegetation (physiognomy) (Raynolds & Walker, 2006; Walker et al., 2005).

The CAVM polygon data were used for this analysis. In addition to vegetation type, each polygon also had data on bioclimate subzone, elevation, lake cover, substrate chemistry and landscape type (Walker et al., 2005). Maps of these attributes can be seen on the web site http://www.arcticatlas.org/atlas/cavm/index by clicking on the individual maps at the bottom of the page.

2.3. NDVI data

A 1-km resolution maximum NDVI data set was used for this study. These data were from the U.S. Geological Service EROS AVHRR polar composite of NDVI data for 1993 and 1995 (CAVM Team, 2003; Markon et al., 1995). Daily data were collected by AVHRR sensors onboard NOAA satellites for channel 1, red (0.5 to 0.68 μm) and channel 2, near-infrared (0.725–1.1 μm). These were the same sensors that collected the data for the temperature calculations, though different bands were used. The daily NDVI values were calculated and then composited into one maximum value for 10-day periods. NDVI is affected by a variety of satellite and surface conditions, especially cloud cover and viewing angle, that can be compensated for by compositing data over time (Goward et al., 1991). The maximum values during two relatively cloud-free summers (11 July–31 August in 1993 and 1995) were used to create an almost cloud-free data set of maximum NDVI for the circumpolar Arctic in the early 1990s. Summarizing composited NDVI into maximum NDVI eliminated any seasonal variation in NDVI (Riedel et al., 2005).

The authors tried using the GIMMS AVHRR NDVI data set (Tucker et al., 2004), which covered the same time period as the temperature data, provided a long time period for compositing, and was a commonly used, easily available data set with the latest calibrations and corrections. However, the GIMMS data set did not provide good coverage of the Arctic. Northeastern Greenland, Wrangel Island and a part of the north coast of Chukotka were missing. The data set also had very abrupt swath boundaries in the Taimyr area of Russia, in Chukotka, and in the Canadian Arctic Islands. This swath boundary is due to calibration issues in the GIMMS processing procedure, which used SPOT Vegetation satellite data to mosaic separate swaths. SPOT data were not available north of 70° N (Jia, pers. comm., Tucker pers. comm.), resulting in a distinct boundary line at that latitude.

A comparison between a subset of the GIMMS and CAVM NDVI data is shown in Fig. 1. Alaska was chosen as a portion of the Arctic that did not have any missing GIMMS data and minimal swath boundary contrast (most of Alaska is south of 70° N). Maximum annual NDVI for 1982–2003 was calculated

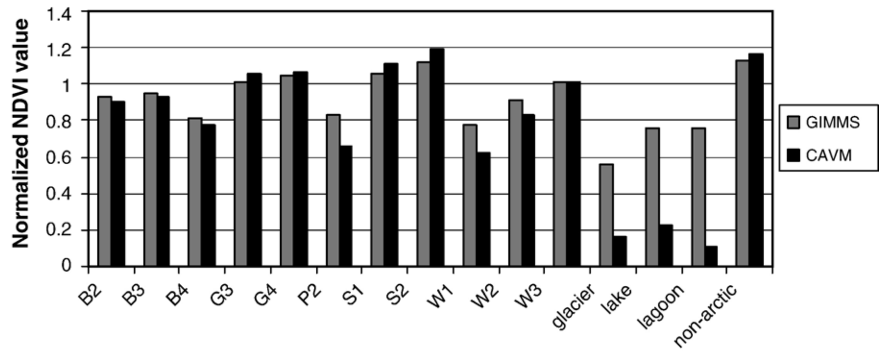

Fig. 1. Comparison of arctic Alaska portion of GIMMS 8-km NDVI data (maximum for 1982–2003) and CAVM 1-km NDVI data (maximum for 1993 and 1995). NDVI mean values of CAVM vegetation types were normalized by the mean of each data set for ease of comparison. See Table 2 for full name of vegetation types.

for the GIMMS data (Tucker et al., 2004). NDVI values for CAVM map polygons of different vegetation types were calculated, and expressed as an index of the mean for easier comparison. The indexed NDVI values for the GIMMS and the CAVM data were similar for all vegetation types except for glaciers, lakes and lagoons. These ice and water cover types had significantly lower NDVI values than surrounding areas (Raynolds et al., 2006), as can be seen in the CAVM values in Fig. 1. They had higher values in the GIMMS data because the larger 8-km pixels of the GIMMS data recorded a mixed signal of land and water or ice. The lower values shown by the 1-km CAVM data more correctly characterize the CAVM polygons. Two vegetation types with smaller differences (P2 and W1) were the least common types in the Alaska map area, and occurred as small polygons that were also not well represented by the GIMMS 8-km pixels.

The CAVM data set provided much higher spatial resolution than the GIMMS data set (1 km vs. 8 km) and the data were complete and uniform for the entire Arctic, so we used the CAVM NDVI data for the circumpolar analysis. The close correspondence of the indexed NDVI values for different common vegetation types in the CAVM and GIMMS data for Alaska demonstrated that the two years included in the CAVM data characterized the vegetation in a similar way as the 22-year GIMMS data set. Interannual variance in AVHRR maximum annual NDVI on two transects across the North Slope of Alaska during the 1990's ranged from 0.03 to 0.05, averaging about 0.04, and was very spatially heterogeneous (Jia et al., 2006). This interannual difference in NDVI is smaller than most of the differences discussed in this study. In addition, this study compared NDVI of large areas, which reduced the spatially heterogeneous interannual variation evident at the 1-km scale (Jia et al., 2006).

2.4. Analysis

The land surface temperature data were used to create a digital map of the 22-year mean of SWI for the Arctic. The CAVM bioclimate subzone and vegetation maps were compared with the raster SWI data. Mixed pixels that included water along coastlines were removed using a 1-pixel (12.5 km) buffer. Mean SWI was calculated for each CAVM vegetation type. For the bioclimate subzone analysis, mountain, water and ice pixels were eliminated, because the CAVM zonation map is a generalized vector map that did not separate out these extra-zonal areas. Mountain zonation was too spatially heterogeneous to map at the CAVM scale of 1:7.5 million. Ice and lakes were eliminated from the analysis because their temperatures do not represent the temperature of zonal vegetated areas. Lake temperatures lag behind land temperatures in the summer due to the higher heat capacity of water, and are thus cooler than land, with lower SWI values. Pixels with elevation >333 m in the Digital Chart of the World (ESRI, 1993), or ones that corresponded to areas mapped as glaciers, nunataks, lakes or lagoons in the CAVM were removed from the SWI grid before the zonal analysis. The remaining pixels were used to calculate mean SWI for each CAVM bioclimate subzone.

Simple linear regression was used to model NDVI as a function of SWI. The 1-km NDVI data set was re-sampled, increasing the pixel size from 1 km to 12.5 km to match the pixel size of the LST data set. Mixed water or ice pixels were avoided by using the coastal-buffered data set described above. Pixels in areas mapped as lakes, lagoons or glaciers in the CAVM were excluded, but all elevations were retained, resulting in 25,690 pixels for the analysis. The regression was carried out with two temperature data sets: the mean SWI for the full 22-year period 1982–2003, and for the two years that matched the NDVI data (1993 and 1995). Using the shorter temperature data set improved the correlation somewhat, but the magnitude of the relationship was almost identical (see Results section below; 22-year data set: $y=0.0137x-0.0204$, $R^2=0.5814$; 2-year data set: $y=0.0134x-0.0351$, $R^2=0.6073$). Interannual variability in NDVI resulted in a slightly better fit better for the 2-year data set, but the circumpolar pattern of vegetation is based on the long-term climate. Since the goal of this paper was to examine spatial variation in arctic vegetation, not temporal variation, the longer-term temperature data set was used in the analysis.

The regression equation was used to create a map of residuals, showing pixels with greater or lower NDVI values than those calculated by the equation. Linear regression was also used to model NDVI as a function of SWI within CAVM categories for vegetation, substrate chemistry, elevation, and percent lake cover. General linear models (GLM) using

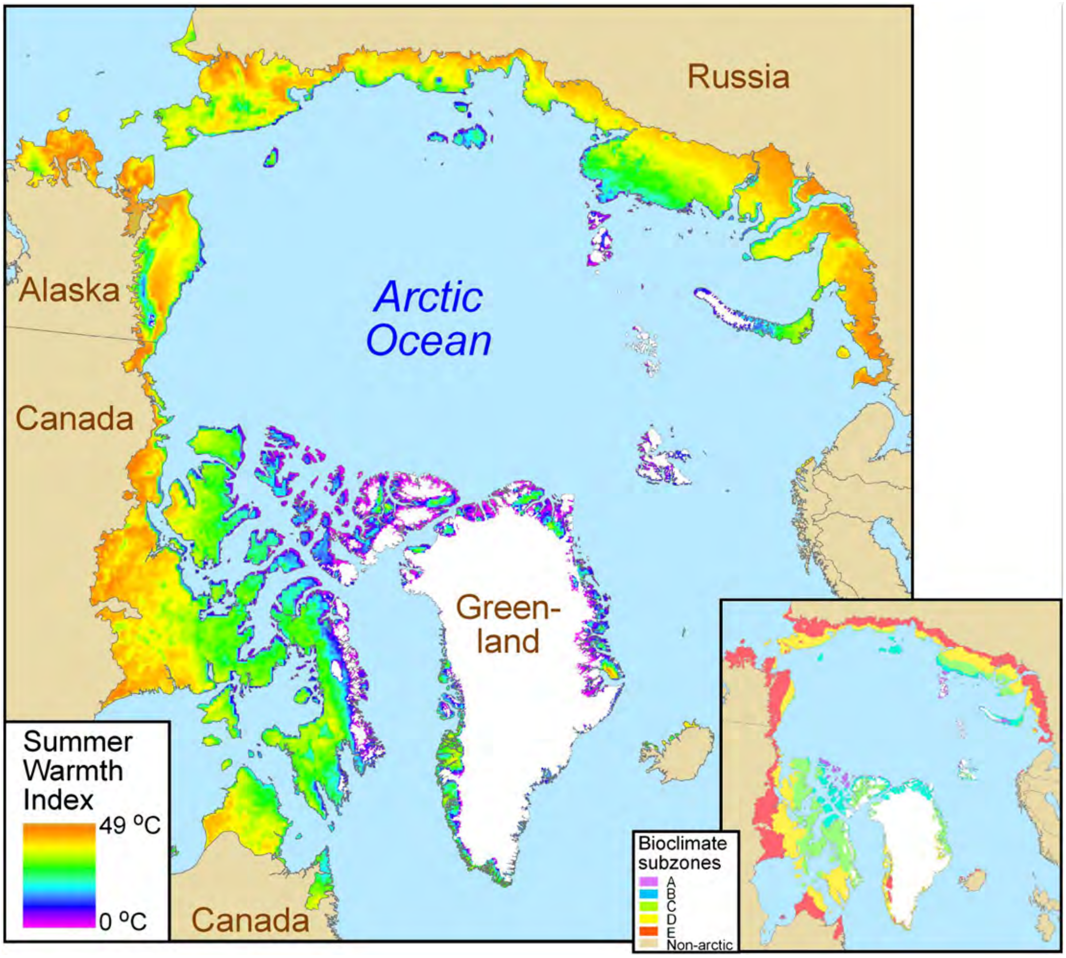

Fig. 2. Map of twenty-two-year mean of summer warmth index (SWI) of arctic tundra, based on AVHRR land surface temperature data 1982–2003 (inset — arctic bioclimate subzones according to the Circumpolar Arctic Vegetation Map).

combinations of factors were run to determine which model accounted for most of the variation in NDVI between CAVM polygons (R Development Core Team, 2006).

3. Results

3.1. SWI

The map of summer warmth index based on a 22-year mean of AVHRR land surface temperatures (Fig. 2) showed a range from 0 to 49.1 °C. The coldest areas were surrounding glaciers and along the coasts of arctic islands, areas that had few months with a mean temperature >0 °C, and means that barely reached above zero during those months. The areas with the warmest summers were the Selawik area in NW Alaska, and the Kanin peninsula area in Western Siberia, which had up to 5 months with means >0 °C, and warm mean monthly temperatures. The temperature gradient from colder northern areas to southern warmer areas was evident on large continental land areas, such as the Taimyr Peninsula and mainland Canada. Steeper coastal temperature gradients occurred, and were especially noticeable on islands. Cooler temperatures not matching the latitudinal gradient were seen at higher elevations in mountain ranges, such as the Brooks Range in northern Alaska, the Kuskokwim Mountains in southwestern Alaska, and the mountains of Chukotka.

The SWI map corresponded well with the map of Tundra Bioclimate Subzones from the CAVM (Fig. 2), with the exception of mountainous areas, which were not delimited on the bioclimate subzone map. The raster SWI map provided

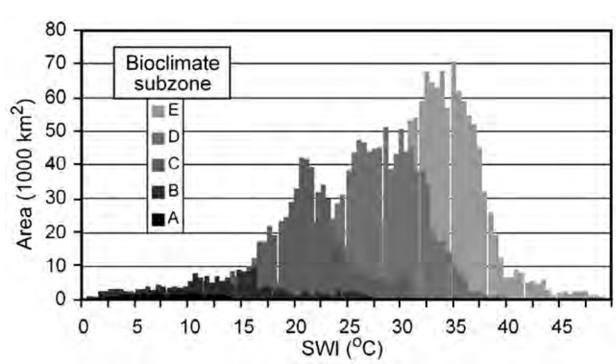

Fig. 3. Summer warmth index (SWI) of CAVM tundra bioclimate subzones A–E, based on mean of AVHRR land surface temperature data 1982–2003, buffered from coasts and excluding non-zonal areas of glaciers, lakes and elevations >333 m.

Table 1
Summer warmth index (SWI) of tundra bioclimate subzones according to CAVM definitions and AVHRR land surface temperature (LST)

Tundra bioclimate subzone	CAVM SWI (°C)	LST SWI±S.D. (°C)
A	<6	8.2±3.4
B	6–9	12.6±5.8
C	9–12	19.8±5.1
D	12–20	27.0±4.9
E	20–35	33.2±4.4

Coastal pixels, water, ice and elevations >333 m were excluded from the SWI data.

more detail than the vector CAVM map, largely because it was based on continuous data rather than interpolation between scattered ground data points (Walker et al., 2005).

Histograms of SWI values for areas mapped as different CAVM bioclimate subzones showed the means and total area increasing from subzone A to subzone E (Fig. 3). The SWI values from Fig. 2 were buffered 1 pixel from coasts, and elevations >333 m and areas mapped as ice or water in the CAVM were not included. The satellite SWI temperatures were warmer than the range described in the CAVM definition of the subzone (Table 1). This was expected since the CAVM definitions were based on station data, while the SWI values were based on radiative land surface temperature (see Methods Section 2.1). The difference was compounded by each additional month included in the SWI, so differences were least for Subzone A and increased for warmer subzones. For Subzone E, the satellite SWI was on the warm end of the defined range, which was much broader than other subzones (20–35 °C). The data showed the expected increase in SWI from Subzone A (the coldest) to Subzone E (the warmest). The warmest parts of Subzone E were the Selawik area in northwestern Alaska, southern Yamal, Gydan and western Siberia. These areas in Russia were also the warmest parts of subzones B, C, and D.

CAVM vegetation types had characteristic SWI values (Table 2). The warmest types, with SWI >25 °C, were all shrub-dominated vegetation types and included Units G3, G4, S1, S2, and W3 (see Table 2 for full vegetation unit names). The coldest types were all partially vegetated areas with cryptogam-dominated vegetation communities, and included Units B1, G1, Nunataks, and Glaciers. Variability (as shown by S.D.) was highest for Mountains (Units B3 and B4) and Lakes, where large variations in SWI occurred on a sub-pixel scale, and lowest for Glaciers and Nunataks where SWI values were consistently low.

Examination of maps of SWI within vegetation types (maps not presented here) showed increases from the northern parts of the range of a vegetation type to the southern parts, and increases in SWI from higher to lower elevations for mountain types. Exceptions to these general trends occurred in south-western Alaska, which included cool parts of the ranges of S1 and S2 in the Kuskokwim Mountains area, and a coastal–inland gradient rather than a north–south gradient for W3 on the Yukon–Kuskokwim Delta. The coldest part of some vegetation types followed elevational gradients rather than latitudinal gradients, such as B2 and P2 in the glaciated mountains of eastern Baffin Island and G4 and S1 in the Brooks Range in northern Alaska. Victoria Island and the Canadian mainland to the south of Victoria I. had the warmest parts of the ranges of B1, B2, G2 and P1. The warmest parts of several vegetation types that bordered treeline were found along river valleys: for

Table 2
Summer warmth index (SWI mean 1982–2003) and normalized difference vegetation index (maximum NDVI 1993 and 1995) of CAVM vegetation types, from AVHRR data

Physiognomic vegetation type	CAVM unit	SWI (mean±S.D.)	NDVI (mean±S.D.)
Cryptogam, cushion-forb barren	B1	11.0±5.3	0.09±0.05
Cryptogam barren (bedrock)	B2	21.2±6.6	0.18±0.09
Non-carbonate mountain complex	B3	19.4±9.7	0.26±0.16
Carbonate mountain complex	B4	18.5±11.2	0.26±0.20
Rush/grass, cryptogam tundra	G1	9.6±5.3	0.16±0.12
Graminoid, prostrate dwarf-shrub, forb tundra	G2	23.1±7.4	0.30±0.13
Non-tussock sedge, dwarf-shrub, moss tundra	G3	28.3±5.6	0.39±0.12
Tussock sedge, dwarf-shrub, moss tundra	G4	31.4±5.1	0.48±0.11
Prostrate dwarf-shrub, herb tundra	P1	20.9±7.2	0.21±0.12
Prostrate/hemiprostrate dwarf-shrub tundra	P2	17.7±6.3	0.18±0.08
Erect dwarf-shrub tundra	S1	30.5±5.2	0.40±0.11
Low-shrub tundra	S2	32.8±4.0	0.47±0.10
Sedge/grass, moss wetland	W1	20.9±6.7	0.29±0.13
Sedge, moss dwarf-shrub wetland	W2	27.0± 4.7	0.39±0.10
Sedge, moss, low-shrub wetland	W3	36.7	0.48±0.10
Nunatak		4.5	NA
Glacier		2.8	NA
Lake		23.4	NA
Lagoon		24.2	NA

Coastal pixels were excluded.

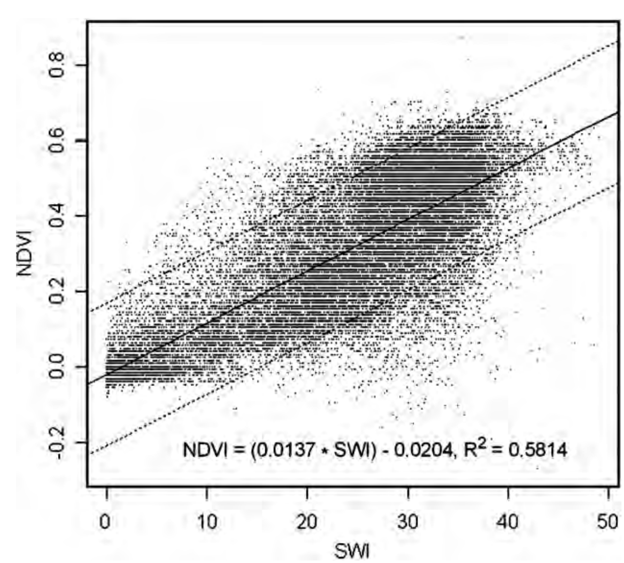

Fig. 4. Regression analysis of normalized difference vegetation index (NDVI) as a function of summer warmth index (SWI, °C), regression line (solid)±1 S.D. (dotted lines). The NDVI values are maximum NDVI from AVHRR data from 1993 and 1995. The SWI values are mean AVHRR land surface temperatures 1982–2003, buffered from coasts and excluding lakes and ice.

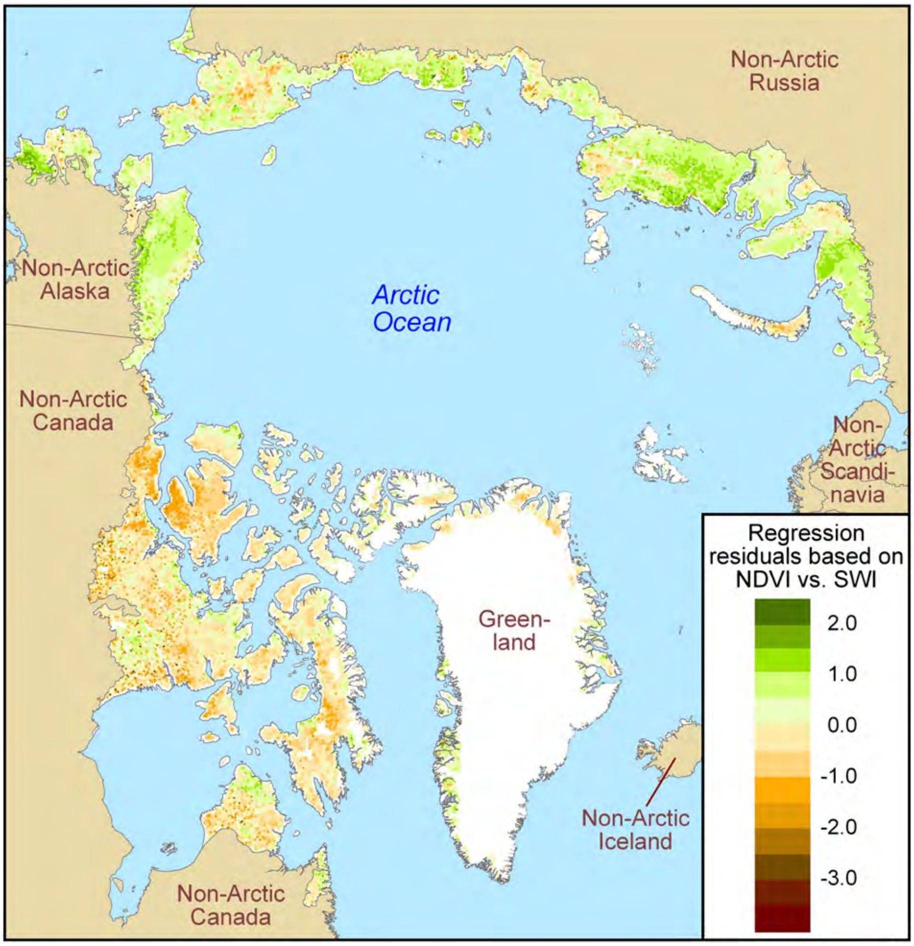

Fig. 5. Map of regression residuals from analysis of maximum NDVI (1993–1995) as a function of SWI (mean 1982–2003) (units are standard deviations of NDVI). Pixels with greater NDVI values than predicted based on their SWI have positive residuals, those with lower NDVI values have negative residuals. Pixels within 1 pixel of the coast and those mapped by the CAVM as water or ice were excluded from the analysis.

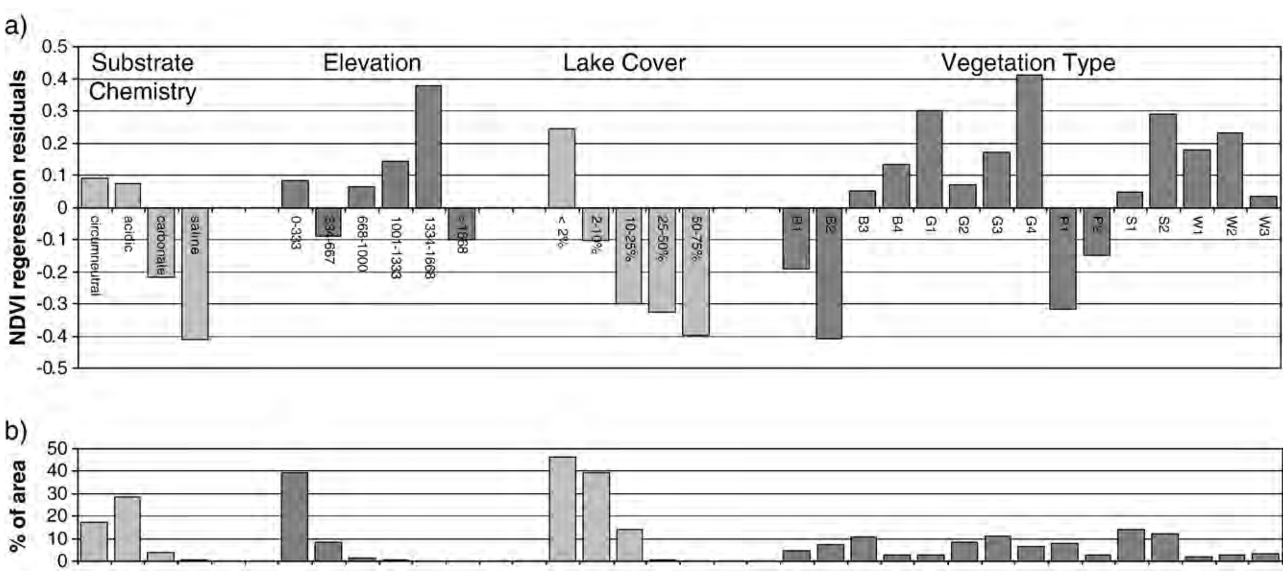

Fig. 6. a) Regression residuals from analysis of NDVI (maximum1993 and 1995) as a function of SWI (mean 1982–2003) for CAVM mapped categories: (see Table 2 for full name of vegetation types). Units are standard deviations of NDVI. Pixels within 1 pixel of the coast and those mapped by the CAVM as water or ice were excluded from the analysis. b) Percent of analyzed area (land area of Arctic) in each category.

G2 the Lena and Indigirka Rivers, for G3 the Mackenzie River, for S2 the Mackenzie, Pechora and Ob Rivers, and for G4 the Kobuk and Noatak Rivers.

3.2. NDVI as a function of SWI

The regression of NDVI as a function of SWI showed a highly significant positive relationship, with least variation around the regression line in the coldest and warmest parts of the Arctic (Fig. 4), and a slope of 0.0137 NDVI/°C SWI. A map of the regression residuals, showing pixels with more or less NDVI than the regression equation was created (Fig. 5). Negative numbers showed areas where there was less NDVI than would be expected given the temperatures. The pixels with the lowest negative residuals were mostly water. Other areas with negative residuals were places where limitations besides temperature occurred: glaciated areas on Baffin Island and the Canadian Shield, carbonate soil areas in the western Canadian Arctic Island and adjacent mainland, steep mountains in Chukotka, Taimyr Peninsula and Novaya Zemlya. Positive numbers (green areas in the map) showed areas with higher NDVI values than would be expected given the temperatures. These included the Kuskokwim Mountains in Alaska, areas of the Taimyr Peninsula, and the Yugorsky Peninsula in Western Siberia.

Analysis of the regression residuals by CAVM categories showed the effect of several different attributes (Fig. 6). Substrate chemistry played a large role: areas with carbonate and saline soils had strongly negative regression residuals. Analysis by elevation showed that most areas above 666 m elevation had positive regression residuals, especially areas between 1333 and 1666 m, while areas above 1666 m had negative residuals. Regression residuals were negative for all areas with >2% lake cover, and the effect increased with percent lake cover. Residuals were negative for two barren vegetation types (B1-Cryptogam, cushion-forb barren, B2-Cryptogam barren (bedrock)) and two prostrate shrub types (P1-Prostrate dwarf-shrub, herb tundra, P2-Prostrate/hemiprostrate dwarf-shrub tundra). Regression residuals were especially high for one graminoid type (G4-Tussock sedge, dwarf-shrub, moss tundra).

Linear regression of NDVI as a function of SWI within different vegetation types were all highly significant due to large sample sizes ($p<0.0001$) (Table 3). Much of the variability in NDVI was not explained by SWI: R^2 values were <0.5 for all but the mountain complexes (B3 and B4), and were <0.1 for two southern vegetation types, G4 and S2. B3, B4, G1, W1 and G2 had the highest slope values (>0.01 NDVI/°C SWI), meaning that the NDVI values of these types increased the most with increasing SWI. B1 and G4 had the lowest slope values (<0.004 NDVI/°C SWI). B1 is mostly barren, with a consistently low mean NDVI value (mean = 0.09). G4, tussock tundra, had a much higher mean NDVI (0.48), but it was fairly constant and did not change much with SWI.

Table 3
Results of linear regression of maximum NDVI (1993 and 1995) as a function of SWI (mean 1982–2003) for CAVM vegetation types ($p<0.0001$ for all regressions)

CAVM vegetation unit [a]	Slope (NDVI/SWI)	Intercept	R^2	n (# 12.5-km pixels)	Area (1000 km^2)
B1	0.0033	0.0512	0.1045	779	224.9
B2	0.0064	0.0472	0.2400	2186	371.8
B3	0.0128	0.0124	0.5902	2590	538.9
B4	0.0153	−0.0141	0.7502	636	131.8
G1	0.0145	0.0194	0.4130	326	140.8
G2	0.0102	0.0626	0.3366	1814	428.7
G3	0.0098	0.1104	0.2056	2973	568.9
G4	0.0045	0.3363	0.0411	1995	335.7
P1	0.0062	0.0791	0.1438	1792	399.4
P2	0.0073	0.0531	0.3323	597	139.6
S1	0.0093	0.1180	0.1866	3852	689.3
S2	0.0076	0.2262	0.0907	3338	612.9
W1	0.0117	0.0496	0.3473	223	101.1
W2	0.0091	0.1467	0.1626	501	136.0
W3	0.0083	0.1775	0.1215	780	159.1
ALL [b]	0.0137	−0.0204	0.5814	25690	4978.9

Coastal pixels, water and ice were excluded.
[a] See Table 2 for full name of vegetation types.
[b] See Fig. 4 for graph of regression.

3.3. General linear model of NDVI

Comparing general linear models of the data, a model that included SWI, lake cover, substrate chemistry, landscape type and vegetation physiognomy accounted for 73.6% of the variation in NDVI. All of the factors were significant, but SWI accounted for most of the variation (68.5%), lake cover for 3.6%, and the other factors together accounted for 1.5% of NDVI variation.

4. Discussion

4.1. Warmest parts of the Arctic

Treeline expansion and loss of tundra area can be expected to occur first in the warmest parts of the Arctic, though treeline advance may also be limited by the presence of permafrost, excessive soil moisture, fire and insects (Callaghan, 2005; Lloyd, 2005). The map of summer warmth index clearly showed the areas of the Arctic where plants experienced the warmest growing conditions between 1982 and 2003. The areas with the highest SWI were the Selawik area in northwestern Alaska, the southern Yamal and Gydan Peninsulas, and the Kanin Peninsula area in Western Siberia. Other parts of the southern Arctic had monthly means >15 °C in mid-summer but had fewer warm months, summing to lower total SWI. Many arctic river valleys had the warmest portions of several vegetation types. These areas along the Mackenzie River in Canada, the Yukon, Kobuk and Noatak Rivers in Alaska, and the Lena, Indigirka, Ob and Pechora Rivers in Russia are areas where vegetation types are likely to change with climate warming.

4.2. NDVI as a function of SWI

Summer temperatures are the most important factor controlling the distribution of arctic vegetation, as demonstrated by the general linear model. In the linear regression analysis, 58% of the variation in circumpolar maximum NDVI was explained by SWI, which is the same proportion found by Jia et al. (2006) in their analysis of AVHRR NDVI data from two transects across the North Slope of Alaska during the 1990's. The magnitude of the relationship is also similar to previous work analyzing changes in NDVI over time. In the twenty years between 1981 and 2001, SWI based on northern Alaska climate station data increased 3.2–6.8 °C, while the annual maximum NDVI (AVHRR data) increased 0.078±0.026 during the same time period (Jia et al., 2003). According to the regression equation calculated by this study, a 5 °C increase in SWI (the mid-point of Jia et al.'s range) correlated to an increase of 0.069 in NDVI, so the increase in NDVI seen in the AVHRR data for northern Alaska over time is similar in scale to what was seen in the circumpolar SWI–NDVI spatial relationship.

4.3. Residuals of NDVI as a function of SWI regression

The residual map showed areas where factors other than temperature limited vegetation growth, and conversely, where conditions were optimal for vegetation growth. The effect of glaciation on arctic vegetation could be clearly seen in the negative residuals throughout the Canadian Shield and other glaciated areas. Similarly limitations due to carbonate soils were evident in some parts of the Canadian Arctic. Areas with both carbonate soils and relatively recent deglaciation, like southern Victoria Island, had especially low residuals. On the other hand, areas with high residuals showed where vegetation responded to warmer temperatures with increased vegetative growth. Since NDVI correlates well with biomass in the Arctic (Shippert et al., 1995; Walker et al., 2003), these areas can be interpreted as especially productive areas, where conditions were optimal for vegetation growth. They included areas unglaciated during the last glacial maximum 20,000 years ago (northern Alaska, southern and western Taimyr Peninsula,Yakutia) (Ehlers & Gibbard, 2004) and areas with high precipitation (Western Siberia, Kuskokwim Mountains) (Treshnikov, 1985).

4.4. Effects of environmental characteristics on NDVI

The CAVM attributes were useful in exploring environmental characteristics controlling arctic vegetation. Plant growth in areas with large negative residuals was limited by factors other than SWI, and thus is likely to respond less to climate warming than other areas. The effect of lake cover on NDVI was evident: increased lake cover resulted in higher negative residuals, and lake cover was the second most important variable (after SWI) in the general linear model for NDVI. Substrate chemistry played a strong role in carbonate and saline soil areas, which had large negative residuals, but these areas only account for 4.0% of the Arctic. The positive regression residuals for elevations >666 m, and increasing residuals up to 1666 m elevation, indicated a positive effect of elevation on NDVI. This was likely due to increased slope and precipitation associated with increased elevation. Lower elevations tend to have flatter slopes, which have wetter soils and shallower active layers (Jorgenson, 2001), limiting the amount of soil nutrients available to plants. Better drained conditions are more favorable for shrubs, which form communities with higher NDVI than graminoid-dominated vegetation types (Riedel et al., 2005).

4.5. NDVI as a function of SWI for different arctic vegetation types

The regression of NDVI as a function SWI for different vegetation types showed the highest slopes for partially vegetated High Arctic vegetation types and graminoid vegetation types. These are the types where increases in temperature are likely to result in the largest increases in NDVI. This matches results from tundra warming experiments, where increases in biomass were greatest in colder locations (Jonasson et al., 1999). Increases in NDVI are also likely to occur where vegetation physiognomy changes to include larger plant lifeforms, such as the boundaries between graminoid and shrubs types, and between shrub and forest types (Epstein et al., 2004; Tape et al., 2006).

Regression R^2 values of SWI vs. NDVI were low for individual vegetation types partly because each occurred in only a portion of the total arctic SWI range and had a limited characteristic range of NDVI values. The two mountain complex types (B3 and B4) had the greatest slopes and R^2 values, and as complexes of different vegetation types that occurred throughout the Arctic, included the full range of SWI and NDVI values. Tussock tundra (G4) and low shrub (S2) had particularly low slopes and R^2 values. These types grow only in the warmest areas of the Arctic, and had relatively small ranges of SWI values, but wide ranges of NDVI values. In the southern Arctic, there is more variation in vegetation cover than occurs in the northern Arctic, ranging from partially barren areas with prostrate vegetation along rivers and ridges to tall shrub thickets along drainages. This variation can exist as inclusions within areas mapped as predominantly G4 or S2. Slope, aspect, and variations in soil chemistry and moisture all have larger effects on vegetation physiognomy (and thus NDVI) in the warmer than in colder parts of the Arctic.

5. Conclusions

The results of this study confirmed the validity of the satellite-derived land surface temperature data set, demonstrating expected temperature gradients with latitude, elevation and distance from coast. The map of SWI based on satellite data gives the best picture available of the spatial patterning of the climate variable that is most important to arctic plants. The map is more spatially detailed than maps interpolated from climate stations, or bioclimate maps based on known plant distribution. The relatively small scale (12.5-km pixels) and continuous coverage of the temperature data make this data set a valuable tool for understanding the distribution of arctic vegetation, characterizing existing vegetation types, and understanding which areas may be most vulnerable to changes in vegetation due to climate change.

One of the most important results of this study is the confirmation of satellite studies showing changes in arctic

NDVI, countering the possibility that the results were an artifact of the satellite record. This study found similar-scale changes in NDVI with changes in SWI over a spatial dimension as those reported from time-series analyses. This result provides important support for the trends seen in satellite NDVI data during recent decades, even though scientists have not yet been able to confirm them through vegetation sampling on the ground.

Acknowledgements

We thank Vladimir E. Romanovsky and Stein-Rune Karlsen for discussions of the relationship between air and ground temperatures in the Arctic. Detailed comments from three anonymous reviewers were very helpful in making this paper clearer and more informative. This project was funded by the "Greening of the Arctic" National Science Foundation ARC grant # 0531180 and a University of Alaska Graduate Fellowship.

References

Alsos, I. G., Eidesen, P. B., Ehrich, D., Skrede, I., Westergaard, K., Jacobsen, G. H., et al. (2007). Frequent long-distance plant colonization in the changing Arctic. *Science*, *316*, 1606−1609.

Bliss, L. C., & Petersen, K. M. (1992). Plant succession, competition and the physiological constraints of species in the high arctic. In F. S. I. Chapin, R. L. Jefferies, J. F. Reynolds, G. R. Shaver, & J. Svoboda (Eds.), *Arctic ecosystems in a changing climate: an ecophysiological perspective* (pp. 111−136). San Diego CA: Academic Press, Inc.

Bogaert, J., Zhou, L., Tucker, C. J., Myneni, R. B., & Ceulemans, R. (2002). Evidence for a persistent and extensive greening trend in Eurasia inferred from satellite vegetation index data. *Journal of Geophysical Research*, *107*, 1−14.

Callaghan, T. V. (2005). Chapter 7, arctic tundra and polar desert ecosystems. *Arctic Climate Impact Assessment* (pp. 243−352). Cambridge, UK: Cambridge University Press.

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

Comiso, J. C. (2000). Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements. *Journal of Climate*, *13*, 1674−1696.

Comiso, J. C. (2003). Warming trends in the Arctic from clear sky satellite observations. *Journal of Climate*, *16*, 3498−3510.

Comiso, J. C. (2006). Arctic warming signals from satellite observations. *Weather*, *61*, 70−76.

Edlund, S. A. (1990). Bioclimatic zones in the Canadian Arctic Archipelago. In C. R. Harrington (Ed.), *Canada's missing dimension — science and history in the Canadian Arctic Islands* (pp. 421−441). Ottawa: Canadian Museum of Nature.

Ehlers, J., & Gibbard, P. L. (2004). Quaternary glaciations — Extent and chronology. *Developments in quaternary science.* Amsterdam: Elsevier.

Epstein, H. E., Beringer, J., Gould, W. A., Lloyd, A. H., Thompson, C. C., & Chapin III, F. S. (2004). The nature of spatial transitions in the Arctic. *Journal of Biogeography*, *31*, 1917−1933.

ESRI. (1993). Digital Chart of the World, Sept. 1993. Environmental Systems Research Institute, Inc., Redlands, CA.

Fung, I. (1997). A greener north? *Nature*, *386*, 659−660.

Goetz, S. J., Bunn, A. G., Fiske, G. J., & Houghton, R. A. (2005). Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences*, *102*, 13521−13525.

Goward, S. N., Markham, B., Dye, D. G., Dulaney, W., & Yang, J. (1991). Normalized difference vegetation index measurements from the advanced very high resolution radiometer. *Remote Sensing of Environment*, *35*, 257−277.

Hassol, S. J. (2004). *Impacts of a warming arctic, arctic climate impact assessment* (pp. 146). Cambridge, UK: Cambridge University Press.

Hope, A., Engstrom, D. R., & Stow, D. A. (2005). Relationship between AVHRR surface temperature and NDVI in arctic tundra ecosystems. *International Journal of Remote Sensing*, *26*, 1771−1776.

Hope, A. S., Kimball, J. S., & Stow, D. A. (1993). The relationship between tussock tundra spectral reflectance properties, and biomass and vegetation composition. *International Journal of Remote Sensing*, *14*, 1861−1874.

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.

Jia, G. J., Epstein, H. E., & Walker, D. A. (2006). Spatial heterogeneity of tundra vegetation response to recent temperature changes. *Global Change Biology*, *12*, 42−55.

Jonasson, S., Michelsen, A., Schmidt, I. K., & Nielsen, E. V. (1999). Responses in microbes and plants to changed temperature, nutrient and light regimes in the Arctic. *Ecology*, *80*, 1828−1843.

Jorgenson, M. T. (2001). *Ecological subsections of the Bering Land Bridge National Preserve (I. ABR)* (pp. 76). Anchorage, AK: National Park Service.

Karlsen, S. R., & Elvebakk, A. (2003). A method using indicator plants to map local climatic variation in the Kagerlussuaq/Scoresby Sund area, East Greenland. *Journal of Biogeography*, *30*, 1469−1491.

Kaufman, R. K., Zhou, L., Myneni, R. B., Tucker, C. J., Slayback, D., & Shabanov, N. V. (2003). The effect of vegetation on surface temperature: a statistical analysis of NDVI and climate data. *Geophysical Research Letters*, *30*, 2147.

Kaufmann, R. K., Zhou, L. M., Knyazikhin, Y., Shabanov, N. V., Myneni, R. B., & Tucker, C. J. (2000). Effect of orbital drift and sensor changes on the time series of AVHRR vegetation index data. *IEEE Transactions on Geoscience and Remote Sensing*, *38*, 2584−2597.

Lambers, H. F., Chapin, F. S. I., & Pons, T. L. (1998). Physiological plant ecology. New York: Springer-Verlag.

Lillesand, T. M., & Kiefer, R. W. (1989). Remote sensing and image interpretation. New York: John Wiley & Sons.

Lloyd, A. H. (2005). Ecological histories from Alaskan tree lines provide insight into future change. *Ecology*, *86*, 1687−1695.

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

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

Pielke, R. A., Davey, C. A., Niyogi, D., Steinweg-Woods, J., Hubbard, K., Lin, X. (in press). Unresolved issues with the assessment of multi-decadal global land surface temperature trends. *Journal of Geophysical Research.*

R Development Core Team. (2006). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rawlins, M. A., & Willmot, C. J. (2003). Winter air temperature change over the terrestrial arctic, 1961–1990. *Arctic, Antarctic and Alpine Research*, *35*, 530−537.

Raynolds, M. K., & Walker, D. A. (2006). Satellite land surface temperatures and tundra vegetation. *2006 Arctic Science Conference* (pp. 55). Fairbanks AK: AAAS.

Raynolds, M. K., Walker, D. A., & Maier, H. A. (2006). NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment*, *102*, 271−281.

Riedel, S. M., Epstein, H. E., Walker, D. A., Richardson, D. L., Calef, M. P., & Edwards, E. (2005). Spatial and temporal heterogeneity of vegetation properties among four tundra plant communities at Ivotuk, Alaska, U.S.A. *Arctic, Antarctic and Alpine Research*, *37*, 25−33.

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.

Shippert, M. M., Walker, D. A., Auerbach, N. A., & Lewis, B. E. (1995). Biomass and leaf-area index maps derived from SPOT images for Toolik Lake and Imnavait Creek areas, Alaska. *Polar Record*, *31*, 147−154.

Stow, D. A., Hope, A. S., & George, T. H. (1993). Reflectance characteristics of arctic tundra vegetation from airborne radiometry. *International Journal of Remote Sensing*, *14*, 1239−1244.

Sturm, M., McFadden, J. P., Liston, G. E., Chapin, F. S. I., Racine, C. H., & Holmgren, J. (2001). Snow-shrub interactions in arctic tundra: A hypothesis with climatic implications. *Journal of Climate*, *14*, 336−344.

Tape, K., Sturm, M., & Racine, C. H. (2006). The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. *Global Change Biology*, *12*, 686−702.

Treshnikov, A. F. (1985). Arctic Atlas, pp. 204. Head Administration of Geodesy and Cartography of the Soviet Ministry, Moscow.

Tucker, C. J., Pinzon, J. E., & Brown, M. E. (2004). Global Inventory Modeling and Mapping Studies (GIMMS) Satellite Drift Corrected and NOAA-16 incorporated normalized difference vegetation index (NDVI), Monthly 1981–2003. Global Land Cover Facility, University of Maryland.

van Wijk, M. T., & Williams, M. (2005). Optical instruments for measuring leaf area index in low vegetation: Application in arctic ecosystems. *Ecological Applications*, *15*, 1462−1470.

Walker, D. A., Bockheim, J. G., Chapin, F. S., 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., Jia, J. G., Balser, A., Copass, C., & Edwards, E. J. (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. (2005). The Circumpolar Arctic Vegetation Map. *Journal of Vegetation Science*, *16*, 267−282.

Walker, M. D., Wahren, C. H., Hollister, R. D., Henry, G. H. R., Ahlquist, L. E., & Alatalo, J. M. (2006). Plant community responses to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences*, *103*, 1342−1346.

Young, S. B. (1971). The vascular flora of St. Lawrence Island with special reference to floristic zonation in the Arctic Regions. *Contributions from the Gray Herbarium*, *201*, 11−115.

Zhou, L., Kaufmann, R. K., Tian, Y., Myneni, R. B., & Tucker, C. J. (2003). Relation between interannual variations in satellite measures of northern forest greenness and climate between 1982 and 1999. *Journal of Geophysical Research*, *108*, 4004.