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Controls over intra-seasonal dynamics of AVHRR NDVI for the Arctic tundra in northern Alaska

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Abstract. We analysed the Normalized Difference Vegetation Index (NDVI), calculated from biweekly NOAA Advanced Very High Resolution Radiometer (AVHRR) images for northern Alaska at both regional (latitudinal gradients) and site scales. Our objectives were to determine if tundra types and arctic subzones could be differentiated in terms of intra-seasonal patterns of greenness, and to construct the relationships between NDVI and air and soil temperatures. There were common intra-seasonal patterns of NDVI along two latitudinal transects, and a general latitudinal gradient of time of greenness onset and length of growing season was observed. At the site scale, in most cases, wet tundra (WT) had the lowest NDVI values throughout the year, while shrub tundra (ST) had the highest values. The peak NDVI appeared in the period of 22 July to 4 August, with mean values of 0.552 for ST, 0.495 for moist acidic tundra (MAT), 0.434 for sandy tundra (Sandy), 0.426 for moist non-acidic tundra (MNT) and 0.343 for WT. The earliest onset of greenness occurred in ST, followed by MAT, Sandy and MNT, while WT had the latest onset. There were positive linear relationships between bi-weekly NDVI anomalies and air temperature, soil surface temperature, and 20 cm depth soil temperature anomalies in the region. Plant functional type abundances, tundra type, air and soil temperatures all appeared to influence the seasonal dynamics of NDVI.

1. Introduction

One important method of assessing vegetation is to study its phenology; that is, the timing and duration of events such as spring foliation and senescence as they occur for a given plant or plant community. Phenological traits of vegetation have been shown to be closely related to lower atmosphere dynamics (Reed *et al*. 1994), are important in evaluating changes in climate (Potter 1998, Schwartz and Reed 1999), and are used in global change models (Potter 1998).

Traditionally, phenological characteristics of vegetation are acquired by direct

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observation of plants in the field over a variety of temporal intervals. Some temporal characteristics of vegetation, however, can also be obtained by using remote sensing (aerial photographs and satellite sensor data), which produces images that are often more accurate than traditional phenological maps, and potentially with coarser spatial and finer temporal resolution (Vierling *et al*. 1997, Schwartz and Reed 1999).

Several sources of satellite sensor data are available for an objective analysis of intra-seasonal ecological variables. Among them, the Advanced Very High Resolution Radiometer (AVHRR) from the National Oceanic Atmospheric Administration (NOAA) plays a key role in monitoring global and regional processes. Since AVHRR observations are taken daily, there is a high probability of obtaining short-interval time series and cloud-free images (Gutman *et al*. 1994). An important and widely used AVHRR-derived variable for ecological applications is the Normalized Difference Vegetation Index (NDVI). NDVI images are useful for analysing both spatial and temporal vegetation patterns (e.g. Holben 1986, Gutman *et al*. 1994, Zhu and Yang 1996).

There have been numerous remote sensing based studies of arctic vegetation, dealing with estimation of albedo (Eck *et al*. 1997), spectral characteristics (Stow *et al*. 1993, Vieling *et al*. 1997), spatial biomass and vegetation composition (Hope *et al*. 1993, Shippert *et al*. 1995, Walker *et al*. 1995, Jia *et al*. 2002, Walker *et al*. 2002), vegetation mapping (Markon *et al*. 1995, Muller *et al*. 1999, Walker 2000), and inter-annual dynamics of plant growth (Myneni *et al*. 1997). However, minimal work has been done on the spatial heterogeneity of intra-seasonal vegetation dynamics in relation to environmental factors, even though intra-seasonal properties of arctic vegetation are important indicators of climate change (Myneni *et al*. 1997) and may illustrate the sensitivity of arctic vegetation to global warming and the degree to which arctic vegetation provides a sink for atmospheric carbon (Oechel *et al*. 2000).

The objective of this paper is to investigate intra-seasonal dynamics of the tundra vegetation in northern Alaska, using NDVI derived from a 1 km^2 resolution AVHRR dataset. The scientific questions we try to answer here are: (1) What are the intra-seasonal dynamics of NDVI in northern Alaska?; (2) What are the differences in phenology among tundra vegetation types and arctic subzones?; and (3) Are there any relationships between seasonal vegetation patterns and air or soil temperatures?

2. Study sites

The North Slope of Alaska is the northernmost part of the state, and lies above the Arctic Circle. From north to south, there are three arctic subzones: the prostrate dwarf shrub subzone (C), the erect dwarf shrub subzone (D), and the low shrub subzone (E) (Walker 2000), dominated by different types of tundra vegetation, such as moist acidic tundra (MAT), moist non-acidic tundra (MNT), shrub tundra (ST), sandy tundra (Sandy) and wet tundra (WT) (figure 1). Vegetation patterns generally follow a gradient of elevation and temperature, both of which increase with distance from the coast (temperature decreases however at higher elevations in the Brooks Mountain Range). Our study area is part of the North Slope, with a geographic extension of $\sim 100\,000\,km^2$, from 71.4° to 68.0° N latitude. Many studies, including remote sensing analyses, simulation modelling and field experiments, have been and continue to be focused on this region (e.g. Stow *et al.*

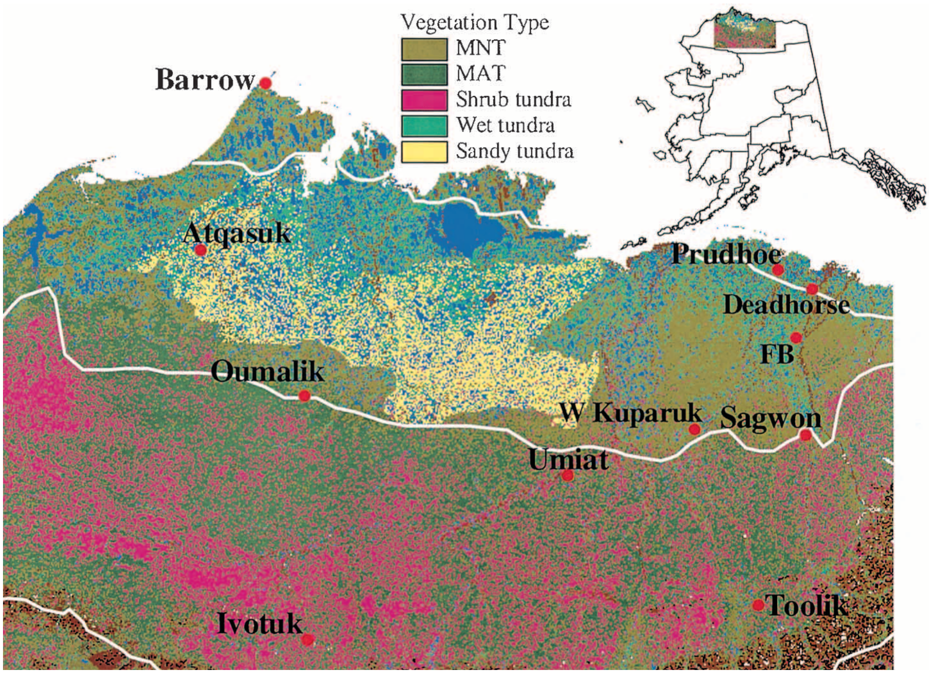

Figure 1. Tundra vegetation classification and location of the sample sites along both transects. The white lines show the boundaries of arctic subzones: the prostrate dwarf shrub subzone (C), the erect dwarf shrub subzone (D), and the low shrub subzone (E). Red points represent meteorological stations, and are also the sample sites for homogeneous tundra patches. FB, Franklin Bluffs.

1993, Nelson *et al.* 1998, Epstein *et al.* 2000, Oechel *et al.* 2000, Walker 2000, Walker *et al.* 2002).

For the site scale analysis, we focused on a transitional area (between subzones D and E) south-west of Atqasuk. We defined two 3 pixel $\times$ 3 pixel (9 km^2) patches for each of five tundra types: ST, MAT, MNT, Sandy and WT (figure 1). We employed a Multi-Spectral Scanner (MSS) derived land cover map to select the sample sites and tried to select them as close as possible to avoid any major climatic differences. We used these homogeneous tundra patches to analyse the intra-seasonal NDVI dynamics among tundra types within a similar climatic regime.

Two arctic transects, conceptually developed by the National Science Foundation (NSF)'s Land–Atmosphere–Ice Interactions (LAII), Arctic Transitions in the Land–Atmosphere System (ATLAS) project and other arctic researchers to conduct integrated efforts, are used here to examine the spatial differentiation of phenological features at the regional scale. The western transect starts at Point Barrow, the northernmost part of the state, continues south through Atqasuk and Oumalik, and ends at Ivotuk; the eastern transect, starts at Prudhoe Bay on the coast, continues south through Deadhorse, Franklin Bluffs, Sagwon, and ends south of Toolik Lake (figure 1).

MAT and MNT are the dominant tundra types in northern Alaska. MAT is dominant in much of the subzone E, whereas MNT is dominant over subzone D. Combined they cover about 60% of the land cover in the region (Muller *et al.* 1999). Since the mid-1990s, comparison studies on ecosystem properties between MNT and MAT have been a focus of the Arctic science community (Walker *et al*. 1995, 1998, 2002, Bockheim *et al*. 1998, Ping *et al*. 1998, Muller *et al*. 1999, Walker 2000, Jia *et al*. 2002). Based on MSS/aerial photo image interpretation in 1998 and 1999, we geographically marked a set of homogeneous vegetation patches of MAT and MNT, along with some ST patches that were widely distributed throughout the area and nearby many of the current research sites (figure 1). Most of the patches selected are 3×3 AVHRR pixels, or $9\,km^2$, and are located within homogeneous tundra patches that are large enough to avoid noise due to mixed pixels at 1 km resolution. Tundra type, geographic location, subzone, transitional areas, and most importantly proximity to meteorological stations were all considered during site selection.

3. Methods

As an index of vegetation greenness, the NDVI was calculated as: NDVI = (NIR − R)/(NIR + R); NIR is the spectral reflectance in the near-infrared band (0.725–1.1 μm), where light scattering from the canopy dominates, and R is the reflectance in the red, chlorophyll-absorbing portion of the spectrum (0.58–0.68 μm) (Goward *et al*. 1991). For our analyses, 1995–1999 AVHRR NDVI time series data from the EROS Data Centre of USGS were used as basic datasets. The Alaska AVHRR datasets were based on a 14 day composite period, and the maximum NDVI values were obtained for each period. The purpose of the compositing process however is to avoid the influence of cloud cover, not to obtain maximum NDVI (Holben 1986). The original data were converted into raster GRID format using the Arc/Info Grid pack, for further spatial analysis. A subset of northern Alaska (North Slope) was taken from the state-wide data, so that only the Arctic portion was used in the analysis.

3.1. *Data improvement*

Despite the cloud filtering function of the Maximum Value Composition (MVC) process that was used for the Alaska AVHRR biweekly dataset, cloud contamination still exists in some periods, especially towards the beginning and end of the growing season (Markon 1999, Hope *et al*. 1999). The initial bi-weekly composite series were filtered using the BISE (Best Index Slope Extraction) adaptive filter (Viovy *et al*. 1992). This filter determines NDVI time series data that are contaminated by cloud cover based on some properties of the temporal signal of NDVI. In particular, it assumes that a decrease of NDVI due to surface change cannot be immediately followed by an increase of NDVI, because vegetation cannot regrow that rapidly. The advantage of such a method is that it allows retention of the initial time step (and the rapid increase or decrease of NDVI at the beginning or end of the cycle) and eliminates cloudy events over several months.

Each period throughout the time series was additionally checked for growing season snow or cloud contamination not captured by other methods. Any pixel with lower than 0.09 NDVI during the growing season (between greenness onset and senescence of the pixel) was considered as contaminated (Markon *et al*. 1995, Markon 1999), and was marked and replaced with the inter-annual mean value for that time period.

Correct registration of any space-borne dataset is important in studies concerning multi-temporal comparisons and site-specified investigations. Though Alaska AVHRR datasets have passed through a systematic geographic registration procedure at the USGS Alaska Field Office and have gained a relatively high degree of accuracy (on average, line and sample residuals were less than 1000 m or 1 pixel) (Markon 1999), there were still some periods, especially the early (April–May) and late (later September) growing season, as well as those in 1992 (soon after the Mt Pinatubo volcanic eruption), with relatively high registration error. These errors were mainly caused by large areas of snow cover or cloud contamination and therefore lack distinguishing surface features that can be used in registration. To further improve our dataset, we performed additional geo-referencing for selected periods with high registration errors. An MSS-derived land cover image, USGS Alaska boundary coverage, USGS Alaska river coverage, and a USGS digital elevation model with 1 m vertical resolution were used for this process.

3.2. *Composites of average NDVI, greenness onset date and length of growing season*

Average NDVI is the sum of NDVI values across years for each recording period during the growing season divided by the total number of years observed. In most cases, a 5 year (1995–99) average was used for the calculation, but some proven contaminated periods such as early 1992 (April–May) were excluded from the calculation. Average NDVI (AV-NDVI) composites for each period were calculated based on the pixel-by-pixel grid model:

$$\text{AV-NDVI}_i = \text{Mean}\,(\text{NDVI}_{i1}, \text{NDVI}_{i2}, \ldots \text{NDVI}_{ij}) \tag{1}$$

where $i = 1, 2, \ldots, n$ (period), $j =$ number of years (usually 5).

Date of greenness onset indicates when spring foliage became dense enough to be detected by the sensor over background conditions (such as tree and shrub stems and boles, previous year's dead foliage, barren ground, and snow cover). This is based on greenness values that equal or exceed 0.09 NDVI in the spring. The 0.09 threshold has been shown to indicate when green vegetation is abundant enough to be recorded by the sensor, although different values have been shown more applicable in some situations (Reed *et al.* 1994). Based on the literature, NDVI = 0.09 is set as the threshold for onset of greenness in Arctic tundra in the early growing season (Markon *et al.* 1995). The calculation of onset time was performed for each pixel and each year from 1995 to 1999, with a resolution of 14 days.

Length of growing season represents the number of days from initial vegetation green-up in the spring to senescence in the fall; it is based on date of green-up and date of senescence. Again, we used NDVI = 0.09 as the threshold for both onset and senescence in Arctic tundra. For each pixel, the periods with a NDVI exceeding 0.09 were summed to determine length of growing season. The calculation of length of growing season was performed for each pixel and each year from 1995 to 1999. Given the 14 day composite period the error in this variable can be up to 28 days for a single pixel.

3.3. *Seasonal NDVI curves by vegetation types and along regional transects*

Based on the sample sites we defined using the MSS land cover map, we sampled and compared average NDVI values among five arctic tundra vegetation types, within a relatively homogeneous climatic regime, for each bi-weekly period throughout the growing season.

We also analysed the bi-weekly NDVI during the growing season for MAT along the western Arctic transect and MNT along the eastern Arctic transect. We analysed different tundra types for each transect due to the scarcity of ground measurements and large homogeneous tundra patches across the entire length of the transects. We analysed MAT along the western transect, because there is a complete gradient of MAT available in the west; we analysed MNT in the east for the same reason. We used 3 pixel $\times$ 3 pixel sample sites along the transects in the analysis.

3.4. *Correlations between bi-weekly NDVI and air/soil temperature*

Correlations between bi-weekly series of NDVI anomalies versus mean air temperature, soil surface temperature and 15–20 cm depth soil temperature anomalies were analysed for seven sites along the transects, separately for MAT and MNT. The soil temperature data used here are provided by Kane and Hinzman via the NSF Arctic System Sciences (ARCSS) website (http://arcss.colorado.edu). Linear regressions were performed for Barrow, Prudhoe Bay, Franklin Bluffs, Sagwon and Toolik Lake, Umiat and West Kuparuk (see figure 1). In order to eliminate solar radiation as a factor that is strongly correlated with both NDVI and temperature, we regressed the anomalies (or differences) from the mean against each other. Bi-weekly time series for both NDVI and temperatures were used for the analysis. The analysis is expressed as the equation:

$$(\mathrm{NDVI}_{\mathrm{period,\ year}} - \mathrm{Mean\text{-}NDVI}_{\mathrm{period}}) \text{ versus } (T_{\mathrm{period,\ year}} - \mathrm{Mean\text{-}}T_{\mathrm{period}}) \qquad (2)$$

4. Results

4.1. *Phenology: onset of greenness and length of growing season*

The onset of greenness occurred first in late April to early May in the south-west of the study area and around the Toolik Lake area, where shrub tundra dominates, then extended northward to the mid-slope in early June (figure 2). By late June, most of the North Slope has entered the growing season. The areas along the coastline and the areas with a high percentage of water bodies were the latest to reach the onset of greenness threshold. Again, comparing with a land cover map, we found that the areas with earliest onset (13–26 May) were positively related to the percentage of shrub tundra. The boundary of late May to early June onset (yellow) was quite close to the boundary between subzones D and E, as well as the MNT/MAT boundary, which reflects the importance of vegetation type and plant community composition on 1 km scale greenness. Most of subzone D reached onset in early to mid-June, while subzone C turned green even later (late June to early July). Subzone C is dominated by WT and is also associated with large water bodies. With high amounts of frozen water in winter time in this area, it takes time to get soil to thaw before any vegetation growth can occur. Based on meteorological records, snow cover retreats in early to mid June in subzone C, much later than in the south.

The longest growing season (over 113 days) appeared to the south-west of Oumalik and around the Toolik Lake area; growing season length declined northward to about 99–112 days at the mid-slope and dropped to less than 100 days on the coast, similar to the pattern of onset. There is a significant positive relationship between onset of greenness and length of growing season, and a similar spatial pattern of these variables can be observed from the images. It appeared that the spatial differentiation is mainly controlled by onset time, rather than the time

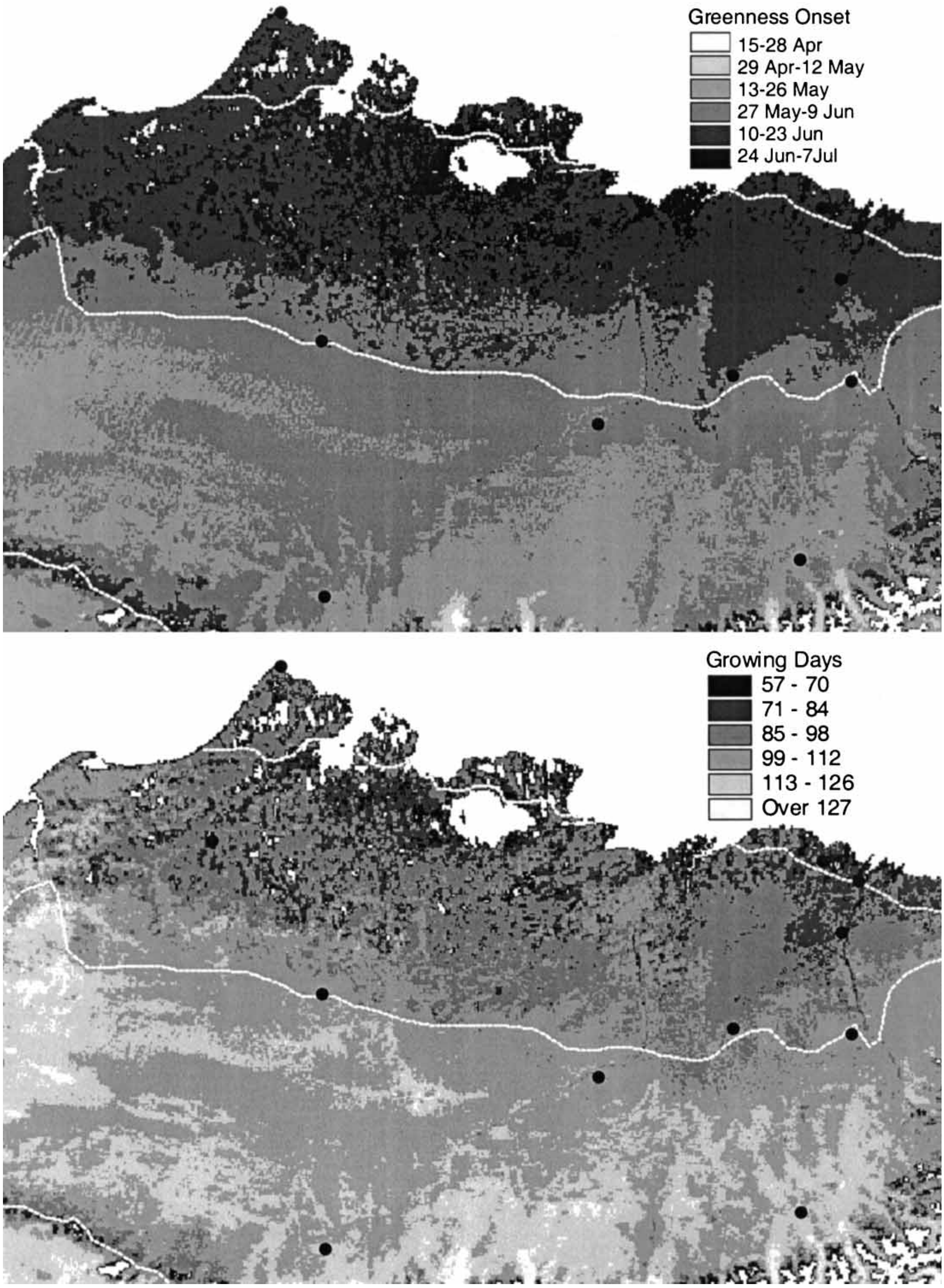

Figure 2. Phenological indices derived from 1995 to 1999 bi-weekly NDVI data: (*a*) time of onset of greenness; (*b*) length of growing season (greenness period). In both cases, a threshold of 0.09 was used for the calculation. Due to the bi-weekly temporal resolution, both results are in 14 day intervals. The white lines and black points represent the subzones and meteorological stations, respectively, the same as in figure 1.

of senescence. From the intra-seasonal curves (see figures 4 and 5) we can detect a major separation in NDVI along transects in early June, yet the whole region essentially senesced during the same period (early October).

4.2. *Intra-seasonal patterns of NDVI among tundra vegetation types at the site scale*

Several differences in NDVI patterns were observed among five vegetation types dominating the region (figure 3): (1) Wet tundra had the lowest NDVI values for each period, while shrub tundra had the highest values; (2) The peak NDVI appeared in period 9 (22 July to 4 August) for all five vegetation types, with the values of 0.552 for ST, 0.495 for MAT, 0.434 for Sandy, 0.426 for MNT, and 0.343 for WT; (3) The earliest onset of greenness occurs in ST, followed by MAT, MNT, Sandy and WT; and (4) The spatial standard deviation for WT and Sandy were greater than other types, which may be indicative of water bodies within WT, and soil parent material and lichen patches varying within sandy tundra.

The spectral–temporal profiles of NDVI values also reflected the difference of phenological patterns among tundra types. As graminoid or moss-dominated plant communities, MNT and WT had relatively smooth and flat intraseasonal NDVI curves, though the latter had lower values throughout the growing season. By contrast, the shrub-dominated ST and MAT had much steeper increases during the early growing season, especially in late May, while ST tended to reach a peak earlier than MAT. Sandy tundra also had a sharp increase in NDVI in the early growing season, but this occurred one period later, during early June. The sharp increases are likely due to different deciduous shrub cover in ST, MAT and Sandy. The differentiation of NDVI curves may be used for further vegetation categorization with 1 km resolution.

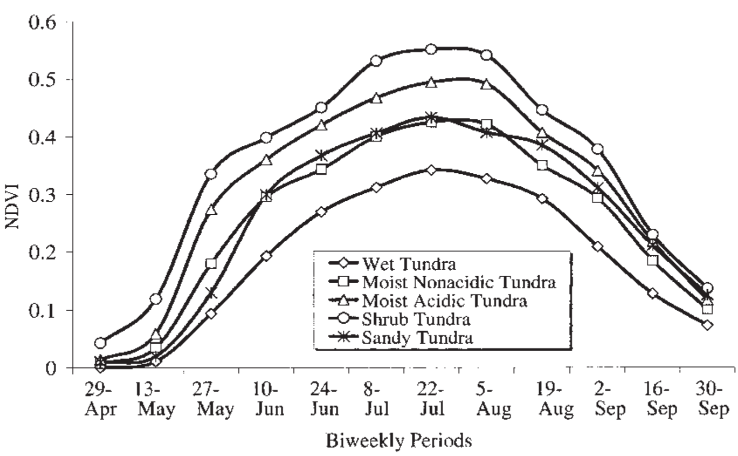

Figure 3. Intra-seasonal patterns of NDVI among tundra vegetation types. The values are based on 1995–1999 averages, and at the homogeneous tundra sample sites located south-west of Atqasuk. Note that periods that occur prior to 29 April are not presented on this graph.

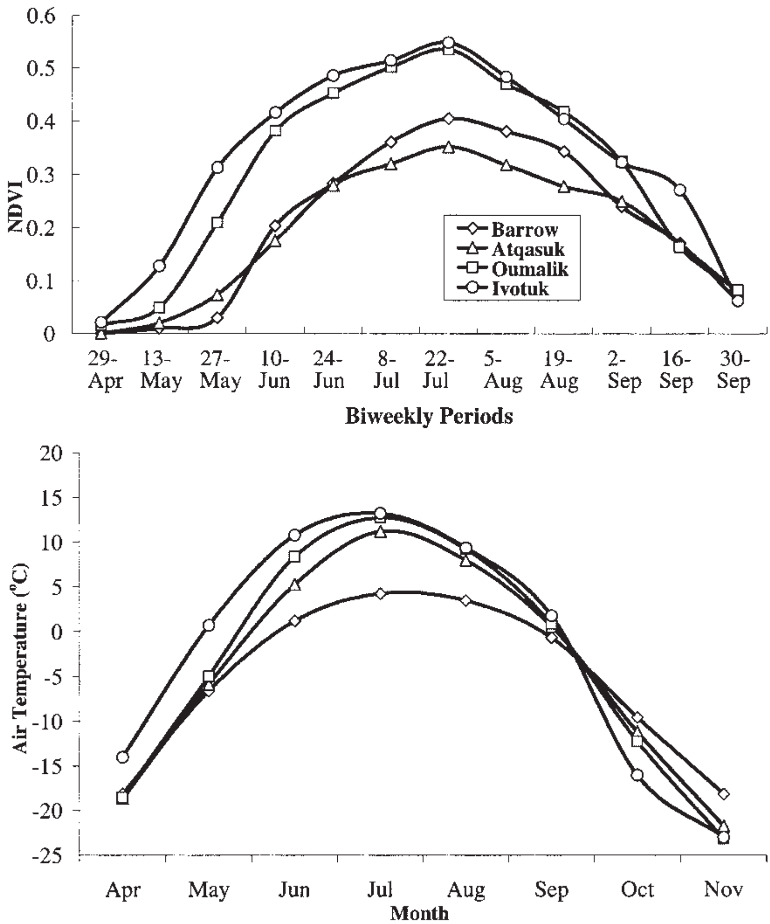

Figure 4. Intra-seasonal patterns of NDVI and air temperature along the western transect. (*a*) Average NDVI, 1995–1999; (*b*) mean air temperature.

4.3. *Intra-seasonal patterns of NDVI along latitudinal transects*

On the western transect, all the intra-seasonal NDVI curves of MAT followed a similar trend: NDVI values increased gradually from late May or early June until early August, when peak NDVI occurred. Greenness dropped steadily until the end of the growing season (early October). Throughout all the periods, there was lower NDVI in the north and higher in the south, except for Atqasuk, which had lower peak NDVI values than the Barrow site, even though Barrow had much colder summer temperatures. NDVI in the first three periods showed the sequence of onset of greenness. In the process of onset the sites were well separated, but in the process of senescence these sites were less differentiated, which could be due to lack of differentiation in late season air temperatures (figure 4). Highest spatial variation of NDVI values occurred at the Atqasuk site, which indicates the strong influence of the existence of water bodies. Sub-pixel analysis overlaid with MSS data showed a high percentage of water within 1 km pixels around Atqasuk (D. Walker, personal communication). In addition, although the tundra around Atqasuk was categorized as MAT, it is more likely azonal vegetation (i.e. the vegetation distributed under a certain climate is not correspondent directly to the climate, instead

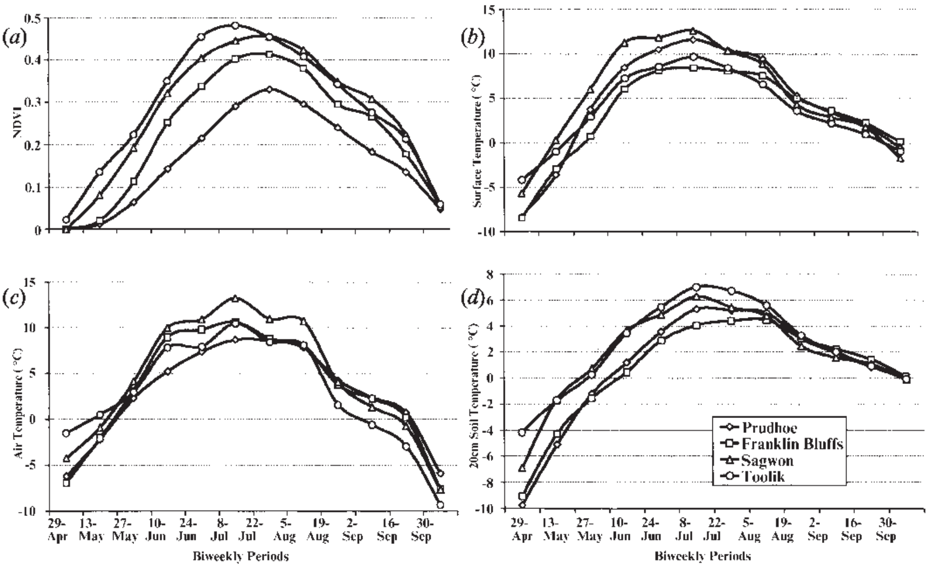

Figure 5. Intra-seasonal patterns of NDVI and warmth variables along the eastern transect. (*a*) Average NDVI, 1995–1999, (*b*) mean air temperature, (*c*) surface temperature, (*d*) 20 cm depth soil temperature.

it is more controlled by substrate) considering the sandy soil and low percentage of shrub cover, low nutrients, and high lichen cover (Walker *et al.* 2002).

Along the eastern transect, the intra-seasonal curves of MNT also followed similar trends: NDVI values increased gradually from late April or early May until peak NDVI in early August. The greenness dropped steadily until the end of the growing season (early October). Throughout all the periods used here, there was lower NDVI in the north and higher in the south; the peak NDVI at Prudhoe Bay was only about 60% of that at Toolik Lake. The MNT sites were better separated throughout the growing season compared with MAT. NDVI in the first three periods showed the sequence of onset of greenness. The entire transect senesced at almost the same period (early October), again possibly due to a regionally consistent drop in air temperatures. There was a dramatic increase in NDVI from Deadhorse to Franklin Bluffs, which is only 20 km to the south. There is however no apparent steep difference in summer air temperature and elevation; a possible explanation is greater moss cover and less cryoturbation at Franklin Bluffs (Ping *et al.* 1998, Bockheim *et al.* 1998, Walker *et al.* 2002).

Another interesting find is a major difference of NDVI across the MAT/MNT boundary, with lower values on the MNT side and much higher values on the MAT side. This dichotomy was also observed in terms of phytomass, primary productivity, species diversity and pH by Walker *et al.* (1998). This contrast existed in most of the periods throughout the growing season. At the peak, NDVI for MAT was approximately 20–30% higher than MNT, as observed around Oumalik and Sagwon Hill.

4.4. *Correlation between bi-weekly NDVI and air/soil temperature*

Biweekly air temperature, soil surface temperature and soil temperature followed similar patterns: the temperatures increased gradually from late April or early May until peak values in early July. The temperatures then dropped steadily until the end of the growing season (early October). A gradient along the transects was also observed in terms of temperatures, i.e. lower in the north and higher in the south.

There are positive relationships between NDVI and air temperature, soil surface temperature, and 20 cm depth soil temperature anomalies for all sites, indicating the importance of near surface warmth to plant growth and biomass accumulation (table 1, figures 4 and 5). Significant linear regressions ($p<0.05$) were found between biweekly NDVI and air temperature, surface temperature and 20 cm depth soil temperature at Toolik Lake, Franklin Bluffs and West Kuparuk. Generally, NDVI versus air temperature was the best relationship, and MNT had a higher correlation with warmth factors than MAT at Sagwon Hill, whereas MAT had the stronger correlations at Franklin Bluffs and Toolik Lake. In general MAT had higher intra-seasonal variabilities than MNT.

As mentioned before, both NDVI and temperatures were more spatially separated during early periods of the growing season than the later ones. So as a *post hoc* analysis we excluded the periods after peak, and used only periods from May to early August to perform the regressions. Higher correlations were reached for most of the cases, while Barrow and Sagwon Hill improved significantly (table 1). This result indicates that intra-seasonal variability in NDVI is positively

Table 1. Summary of the regression analysis of bi-weekly series of NDVI anomalies versus mean air temperature, surface temperature and 15–20 cm depth soil temperature anomalies, with only periods from May to early August used. Regressions were performed separately for MNT and MAT. Regressions that are significant at the 0.05 level (two-tailed) are highlighted as bold text.

Site	Type	NDVI vs air temp.	NDVI vs surface temp.	NDVI vs 20 cm temp.
Barrow	MNT	$\mathbf{y=0.0152x+0.0035}$ $\mathbf{R^2=0.387}$	NA	NA
	MAT	$\mathbf{y=0.0196x+0.0046}$ $\mathbf{R^2=0.5202}$	NA	NA
Umiat	MAT	$y=0.0031x+0.0012$ $R^2=0.0932$	NA	NA
Prudhoe	MNT	$\mathbf{y=0.0078x+0.0015}$ $\mathbf{R^2=0.3994}$	NA	NA
W Kuparuk	MNT	$y=0.0093x+0.003$ $R^2=0.2976$	$y=0.005x-0.009$ $R^2=0.1076$	$y=0.0086x-0.0066$ $R^2=0.2567$
Franklin Bluffs	MNT	$y=0.0045x-0.0028$ $R^2=0.1268$	$\mathbf{y=0.0166x-0.0035}$ $\mathbf{R^2=0.3478}$	$y=0.0192x-0.0042$ $R^2=0.1981$
	MAT	$y=0.0053x+0.0021$ $R^2=0.2489$	$y=0.0121x+0.0018$ $R^2=0.2541$	$y=0.0152x+0.0013$ $R^2=0.17$
Sagwon Hill	MNT	$y=0.0066x+4E–06$ $R^2=0.1791$	$y=0.0034x-0.0072$ $R^2=0.0431$	$y=0.0018x-0.0082$ $R^2=0.004$
	MAT	$\mathbf{y=0.0063x+0.0022}$ $\mathbf{R^2=0.1721}$	$y=0.0039x-0.0069$ $R^2=0.0748$	$y=0.0053x-0.007$ $R^2=0.0475$
Toolik Lake	MNT	$\mathbf{y=0.0077x+0.0007}$ $\mathbf{R^2=0.3532}$	$y=0.0122x+0.0023$ $R^2=0.2871$	$\mathbf{y=0.0193x+0.0022}$ $\mathbf{R^2=0.417}$
	MAT	$\mathbf{y=0.0084x+0.0033}$ $\mathbf{R^2=0.3541}$	$\mathbf{y=0.014x+0.005}$ $\mathbf{R^2=0.3229}$	$y=0.0183x+0.005$ $R^2=0.3148$

related to the variability of air temperature and soil temperature, and the temperatures in early periods of the growing season had a greater contribution to NDVI variability. It also demonstrated that effects of air temperature are strongly buffered at the soil surface and at 15–20 cm depth.

5. Discussion

5.1. *Dataset quality*

The production of the 1995–1999 Alaska AVHRR datasets was based on a maximum NDVI value compositing process (Markon 1999). Subsequently, the data content in each of the different data layers was based on the outcome of the NDVI value used for the composite period. The NDVI value and compositing process are largely affected by the date on which the data were acquired, the greenness of the pixel value, and satellite viewing and solar zenith angle (Goward *et al*. 1991, Zhu and Yang 1996).

In Alaska, data acquired during April, and perhaps the first week in May, may have little effect on the temporal qualities of measured greenness because much of the land surface is still covered with snow, or in a state of pre-leaf emergence. However, it is important to begin with these early periods to assess possible changes in growing season length that are due to early or late green-up among years, or for comparison with future datasets. Although georeferencing has been performed with high accuracy, and further correction has also been made to reduce geographical errors, spatial shifting still exists. Therefore, it was not appropriate to use any single pixel as a sample site; instead, 3 pixels $\times$ 3 pixels centred within homogeneous vegetation patches were necessary to reduce geographical errors. As an Arctic region, snowfall during the growing season, even mid-summer on the North Slope is not uncommon (Sturm *et al*. 2001). Due to its strong reflectance of both red and infrared bands, the snow cover limits the spectral signature of green plants beneath it and reduces NDVI to near zero. We removed summer snow contamination because of our interest in vegetation patterns; however, this is obviously a natural process in the Arctic.

5.2. *Transitional features*

Based on the homogeneous vegetation samples as shown in figure 1, we summarized peak NDVI, Time-integrated NDVI (TI-NDVI, the sum of NDVI values >0.09 within a year), onset time, length of growing season and elevation (table 2). There are five transition areas that can be distinguished:

- MNT West: Barrow–Atqasuk–Oumalik
- MAT-ST West: Barrow–Atqasuk–Oumalik–Ivotuk
- MNT East: Deadhorse–Franklin Bluffs–Sagwon–Toolik
- MAT-ST East: Franklin Bluffs–Sagwon–Toolik
- MNT-MAT boundary: Oumalik and Sagwon.

Several interesting patterns can be observed from the summary. First, although the Atqasuk sandy sites showed lower peak NDVI than the Barrow MAT site, they had greater TI-NDVI, earlier onset and a longer growing season, which reflected the influence of temperature along the latitudinal gradient. Second, if we replace the Atqasuk sandy site with the south-west Atqasuk MAT site, all five indices fall between those of Barrow and Oumalik, which may reflect the actual zonal gradient along the western transect. It should be noted that this alternative site is about

Table 2. Summary of NDVI along various transitions in northern Alaska.

Site	Peak NDVI		TI-NDVI*		Onset date†		Green time (d)		Elevation (m)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*n*
MNT, Western Arctic transect											
Barrow 1	0.396	0.020	2.461	0.096	170	1.68	88	2.49	6	0.66	9
SW Atqasuk 1	0.426	0.033	3.002	0.158	165	2.23	107	2.88	38	2.37	18
Oumalik 1	0.444	0.025	3.017	0.199	159	0.64	103	1.20	60	1.86	18
MAT/ST, Western Arctic transect											
Barrow 2	0.437	0.012	2.394	0.099	170	0.94	88	2.47	11	0.85	9
Atqasuk 4	0.412	0.024	2.772	0.208	168	1.73	97	1.75	30	0.79	9
SW Atqasuk 2	0.495	0.012	3.599	0.094	159	0.70	109	1.99	48	3.52	18
Oumalik 2	0.546	0.010	3.774	0.076	159	0.70	105	1.87	100	3.74	27
Ivotuk 2	0.509	0.011	3.801	0.088	150	2.35	112	2.08	489	4.86	9
Ivotuk 3	0.563	0.006	3.941	0.056	152	1.43	110	1.73	609	5.05	9
MNT, Eastern Arctic transect											
Deadhorse 1	0.321	0.021	1.994	0.147	170	1.26	87	2.16	15	0.79	9
FB 1	0.445	0.011	2.948	0.085	169	1.22	90	1.51	94	4.34	27
Sagwon 1	0.457	0.013	3.268	0.116	159	1.33	101	1.91	182	3.12	27
Toolik 1	0.449	0.009	3.187	0.069	148	0.97	114	1.75	651	5.48	9
MAT/ST, Eastern Arctic transect											
FB 2	0.488	0.005	3.372	0.092	165	1.57	97	1.39	224	5.08	18
Sagwon 2	0.527	0.006	3.957	0.099	155	1.96	105	2.26	313	7.08	27
Toolik 2	0.511	0.009	3.964	0.031	148	1.12	116	0.91	588	2.76	9
Toolik 3	0.564	0.012	4.038	0.037	156	1.94	106	1.62	772	6.49	9
MNT–MAT boundary											
Oumalik 1	0.444	0.025	3.017	0.199	159	0.64	103	1.20	60	1.86	18
Oumalik 2	0.546	0.010	3.774	0.076	159	0.70	105	1.87	100	3.74	27
Sagwon 1	0.457	0.013	3.268	0.116	159	1.33	101	1.91	182	3.12	27
Sagwon 2	0.527	0.006	3.957	0.099	155	1.96	105	2.26	313	7.08	27

1: MNT, 2: MAT, 3: ST, 4: Sandy, FB: Franklin Bluffs.

*TI-NDVI: time-integrated NDVI, accumulated NDVI values >0.09 during the growing season.

†Julian date.

20 km south-west of the Atqasuk meteorological station and is outside of our defined transect boundary. This is a zonal MAT site instead of a sandy one. Third, the MNT/MAT boundary at Oumalik and Sagwon can be clearly distinguished in terms of peak NDVI and TI-NDVI, with approximately 20–30% difference in NDVI values between the two sides of the transition. We also noticed that there is a dramatic change of elevation at this boundary, and two subzones also meet here. So, at present there may be several confounding factors that control the boundary. Finally, from Deadhorse to Franklin Bluffs, there was a sharp change in NDVI, which may reflect less moss cover and strong cryoturbation around Deadhorse (Ping *et al.* 1998, Walker *et al.* 2002).

5.3. *Plant functional types, biomass and NDVI*

There are major differences among these tundra types in terms of dominant life forms and surface properties, which partly contribute to the NDVI differentiations

(Chapin *et al.* 1996, Walker 2000). ST is a group of plant communities dominated by low shrubs such as *Salix alaxensis*, *Betula nana*, *Alnus crispa*, etc. (Muller *et al.* 1999). In MAT, the dominant life forms are dwarf (<40 cm) and low (40–200 cm) shrubs, which form a canopy over tussock graminoids (Walker *et al.* 1995). In MNT, the dominant life forms are graminoids and prostrate dwarf shrubs, while moss is also important as a major contributor to biomass and coverage. Shrubs form scattered patches among graminoid cover in MNT (Walker *et al.* 1995, 2002). WT is usually dominated by rhizomatous sedges and/or mosses and includes more than 10 cm of peat. WT soils are often covered with 1–10 cm of standing water, and surrounded by water bodies. The existence of standing water also contributes to the lower NDVI values. Sandy tundra is dominated by tussock graminoids and dwarf shrubs, with light-colour sandy soil parent material and lichen patches. This could have partly contributed to higher reflectance and therefore lower NDVI.

Aboveground green biomass, particularly deciduous shrub foliage, is a major contributor to NDVI patterns (Hope *et al.* 1993). Walker *et al.* (2000) found that biomass at the northern end of the latitudinal gradient is about the same for MAT and MNT (about $400\,g\,m^{-2}$), however at the southern end MAT biomass is about 50% greater (about 900 vs $600\,g\,m^{-2}$). It is suspected that MAT and MNT have similar flat or gently sloping biomass increases from the coast inland, and then MAT increases markedly at the boundary between subzones D and E. Our satellite sensor data clearly show such a trend in NDVI. Once the shrubs reach a certain stature (>40 cm tall) in MAT, they are above the graminoids and are able to dominate the plant canopy, which can have a strong effect on NDVI.

Shrub biomass showed only a small increase in MNT from north to south (75 to about $125\,g\,m^{-2}$), but MAT shrub biomass increased about 12-fold (25 to over $325\,g\,m^{-2}$) (Walker *et al.* 2002). Walker *et al.* (2002) also found that moss biomass shows a strong spatial response to temperature in MNT (less than $100\,g\,m^{-2}$ at the northern end of the transects to over $350\,g\,m^{-2}$ at the southern end). MAT moss biomass shows less of a response. Much of the openness of the MNT canopy is due to frost boils, and it may be that the mosses toward the southern end of the gradient are able to colonize more of the open spaces, as the frost boils become less active. We assumed that abundance of shrubs is the major contributor to NDVI within MAT, while moss coverage or graminoids appear to be key factors that influence the NDVI signature of MNT along latitudinal gradients (Walker *et al.* 2002).

Shippert *et al.* (1995) indicated that shrub tundra had Leaf Area Index (LAI) values greater than 3, tussock tundra (MAT and MNT) had LAI values between 1 and 2, while wet tundra was much lower (less than 1). A recent comparison of MNT and MAT also indicated important differences in LAI ($0.84\,m^2\,m^{-2}$ in MAT compared with 0.50 in MNT) and bare soil coverage (0.8% in MAT compared with 7.5% in MNT) (Walker *et al.* 1998). It is suggested that the difference of NDVI among these tundra types reflects their difference in ecosystem structure and function. NDVI values derived from nadir PS-II measurements and SPOT images for different tundra types also show the significant differences among them. The peak NDVI for WT, non-woody tussock tundra (i.e. MNT) and woody tussock tundra (i.e. MAT) were 0.31, 0.51 and 0.56 (Vierling *et al.* 1997), and those tundra types were well separated on late July SPOT NDVI images (Stow *et al.* 1993), supporting our observations.

5.4. *Soil, snow and NDVI*

An International Tundra Experiment (ITEX) study suggested that tussock tundra ecosystems are sensitive to extended growing season length and soil warming, and that rising soil temperatures lead to earlier and increased leaf area development (Oberbauer *et al.* 1998), the latter being a major contributor to NDVI (Eck *et al.* 1997). It was also argued that deeper snow cover in the Arctic may produce feedbacks on climate and biota particularly through effects on warmer soil temperatures and associated nutrient mineralization, higher run-off and soil moisture, and protection of overwintering buds (Walker *et al.* 1998). This pattern may be the result of shrub–snow–soil interactions (Walker *et al.* 1994, Ping *et al.* 1998, Sturm *et al.* 2001). A canopy of erect shrubs facilitates accumulation of snow at the site. Snow cover keeps a warmer soil surface and thus higher unfrozen water content in the active layer throughout winter, which provides favourable conditions for an earlier development of shrubs as soon as the snow retreats in mid-May. Data from Ivotuk show that soil moisture in the active layer at 15–20 cm depth for a shrub site is almost 3 times that for a moss-dominated site (20.5% vs 7.5% by volume) in winter months.

To get a better understanding of the effect of soil temperature and moisture on NDVI, especially that of onset, peak and senescence, we compared some different soil profiles at the same meteorological–ecological stations. The hypothesis behind this analysis is that soil features drive different vegetation properties among sites. Based on the data availability, we selected Betty Pingo (very close to Prudhoe) and Ivotuk to represent subzones D and E, respectively. The first site is dominated by WT, with small patches of MNT, whereas the second site is located on a mosaic of ST, MAT and MNT.

At the Betty Pingo station, we examined the crossing dates of 0° C for both early and late growing season in 1994–1998. For surface temperature, the MNT site is 6.8 days earlier in spring and 1.2 days later in fall to reach this point compared to WT; for 15 cm depth soil temperature, the values are 4.1 and 11.5 days, respectively. There are no major differences in terms of biweekly mean values between the two sites, and the MNT site had slightly higher maximum values and lower minimum values than the WT site. This may partly explain the earlier onset and longer growing season for MNT compared to WT as observed from AVHRR NDVI.

At the Ivotuk station, we examined both soil temperature and moisture from 1998 to 2000. For 20 cm soil temperature, the ST site was 9.5 days earlier in spring and 1.5 days later in fall to reach the 0° C crossing point compared with the MAT site; considering the biweekly average 20 cm soil temperatures, the maxima are almost the same but the minimum is 2.6° C warmer at the ST site. For 20 cm soil moisture, the ST site is greater in both summer (74% vs 63%) and winter (20.5% vs 7.5%) than the MAT site. A sharp increase in 20 cm soil moisture in the early growing season was observed at both sites. This increase occurred on 19 May in 1999 and 30 May in 2000 at the ST site, compared with 28 May and 16 June for the MAT site.

It was also indicated by other investigators (Nelson *et al.* 1998, Ping *et al.* 1998, Romanovsky and Osterkamp 1999) that winter soil temperature and soil water availability differ significantly among tundra types, and that they play an important role in determining early spring phenology of tundra. They found that at the same meteorological station and under the same air temperatures, that ground surface temperatures vary significantly among sites with different vegetation cover, especially during winter. For example, at Ivotuk, February surface temperature was the coldest at the MNT site (−14.25° C), slightly warmer at the MAT site (−13.28° C) and much warmer at the ST site (−10.28° C). The largest amount of liquid water in the frozen active layer was measured at the ST and the MAT sites, less unfrozen water was at the MNT sites, and almost no unfrozen water was measured at the WT site during winter. These results support our observations, and together help explain the major differences in NDVI among tundra types, such as earlier onset and longer growing season for ST compared with MAT and MNT as observed from AVHRR NDVI. It is also necessary to point out that the soil temperature in MAT is warmer than MNT during the winter but much colder during the summer. The time of thaw for most of the root zone could be one of the key points for explaining the difference in onset time and onset NDVI values between MAT and MNT.

6. Conclusions

To summarize our findings, vegetation type and soil substrate have important controls over intra-seasonal NDVI patterns regardless of climate, and separation of NDVI among vegetation types is greater early in the growing season than late. Major differences in NDVI occur throughout the growing season among five tundra types, with shrub tundra having the greatest and wet tundra the lowest NDVI values.

As expected, temperature gradients in the region also have a strong control over intra-seasonal NDVI. The bi-weekly variability in air and soil temperatures, however, can explain up to 50% of the bi-weekly NDVI. MAT generally has a stronger correlation with seasonal temperatures compared with MNT. Overall, interactions among vegetation, regional climate, soil substrate, and microclimate all contribute to the NDVI signature.

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References

Bockheim, J. G., Walker, D. A., Everett, L. R., Nelson, F. E., and 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.

Chapin, F. S. III, Bret-Harte, M. S., Hobbie, S., and Zhong, H., 1996, Plant functional types as predictors of transient responses of arctic vegetation to global change. *Journal of Vegetation Science*, **7**, 347–358.

Eck, T. F., Deering, D. W., and Vierling, L. A., 1997, Arctic tundra albedo and its estimation from spectral hemispheric reflectance. *International Journal of Remote Sensing*, **18**, 3535–3549.

Epstein, H. E., Walker, M. D., Chapin, F. S. III., and Starfield, A. M., 2000, A transient, nutrient-based model of arctic plant community response to climatic warming. *Ecological Applications*, **10**, 824–841.

Goward, S. N., Markham, B., and Dye, D. G., 1991, Normalized Difference Vegetation Index measurements from the Advanced Very High Resolution Radiometer. *Remote Sensing of Environment*, **35**, 257–277.

Gutman, G., Ignatov, A., and Olson, S., 1994, Towards better quality of AVHRR composite images over land: reduction of cloud contamination. *Remote Sensing of Environment*, **50**, 134–148.

Holben, B. N., 1986, Characteristics of maximum-value composite images from temporal AVHRR data. *International Journal of Remote Sensing*, **7**, 1417–1434.

Hope, A. S., Kimball, J. S., and Stow, D. A., 1993, Relationship between tussock tundra spectral reflectance properties and biomass and vegetation composition. *International Journal of Remote Sensing*, **14**, 1861–1874.

Hope, A. S., Pence, K. R., and Stow, D. A., 1999, Response of the normalized difference vegetation index to varying cloud conditions in Arctic tundra environments. *International Journal of Remote Sensing*, **20**, 207–212.

Jia, G. J., Epstein, H. E., and Walker, D. A., 2002, Spatial characteristics of AVHRR-NDVI along latitudinal transects in Northern Alaska. *Journal of Vegetation Science*, **13**, 315–326.

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**, 179–190.

Markon, C. J., 1999, Characteristics of the Alaskan 1 km Advanced Very High Resolution Radiometer data sets used for analysis of vegetation biophysical properties. USGS Open File Report, 99-088.

Muller, S. V., Racoviteanu, A. E., and 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.

Myneni, R., Keeling, C., Tucker, C., Asrar, G., and Nemani, R., 1997, Increased plant growth in the northern latitudes from 1981 to 1991. *Nature*, **386**, 698–702.

Nelson, F. E., Hinkel, K. M., Shiklomanov, N. I., Mueller, G. R., Miller, L. L., and Walker, D. A., 1998, Annual and interannual active layer thaw patterns on the North Slope of Alaska. *Journal of Geophysical Research*, **103**, 28 963–28 973.

Oberbauer, S. F., Starr, G., and Pop, E. W., 1998, Effects of extended growing season and soil warming on carbon dioxide and methane exchange of tussock tundra in Alaska. *Journal of Geophysical Research*, **103**, 29 075–29 082.

Oechel, W. C., Vourlitis, G. L., Hastings, S. J., Zulueta, R. C., Hinzman, L., and Kane, D., 2000, Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature*, **406**, 978–981.

Ping, C. L., Bockheim, J. G., Kimble, J. M., Michaelson, G. J., and Walker, D. A., 1998, Characteristics of cryogenic soils along a latitudinal transect in Arctic Alaska. *Journal of Geophysical Research*, **103**, 28 917–28 928.

Potter, C. S., 1998, Global analysis of empirical relations between annual climate and seasonality of NDVI. *International Journal of Remote Sensing*, **19**, 2921–2948.

Reed, B. C., Brown, J. F., VanderZee, D., Loveland, T. R., Merchant, J. W., and Ohlen, D. O., 1994, Measuring phenological variability from satellite imagery. *Journal of Vegetation Science*, **5**, 703–714.

Romanovsky, V. E., and Osterkamp, T. E., 1999, Unfrozen water in the active layer and permafrost and its effects on physical and biological processes. *EOS Transactions*, **80**, F33.

Schwartz, M. D., and Reed, B. C., 1999, Surface phenology and satellite sensor-derived onset of greenness: an initial comparison. *International Journal of Remote Sensing*, **20**, 3451–3457.

Shippert, M. M., Walker, D. A., Auerbach, N. A., and 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., Burns, B. H., and Hope, A. S., 1993, Spectral, spatial and temporal characteristics of Arctic tundra reflectance. *International Journal of Remote Sensing*, **14**, 2445–2462.

Sturm, M., McFadden, J. P., Liston, G. E., Chapin III, F. S., Racine, C. H., and Holmgren, J., 2001, Snow–shrub interactions in Arctic tundra: a hypothesis with climatic implications. *Journal of Climate*, **14**, 336–344.

Vierling, L. A., Deering, D. W., and Eck, T. E., 1997, Differences in arctic tundra vegetation type and phenology as seen using bidirectional radiometry in the early growing season. *Remote Sensing of Environment*, **60**, 71–82.

VIOVY, N., ARINO, O., and BELWARD, A., 1992, The Best Index Slope Extraction (BISE): a method for reducing noise in NDVI time series. *International Journal of Remote Sensing*, **13**, 1585–1590.

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., and SHIPPERT, M. M., 1995, NDVI, biomass and landscape evolution of glaciated terrain in northern Alaska. *Polar Record*, **31**, 169–178.

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., and VOURLITIS, G. L., 1998, Energy and trace-gas fluxes across a soil pH boundary in the Arctic. *Nature*, **394**, 469–472.

WALKER, D. A., EPSTEIN, H. E., JIA, G. J., BALSAR, A., COPASS, C., EDWARDS, E. J., GOULD, W. A., HOLLINGSWORTH, J., KNUDSON, J., MEIER, H., MOODY, A., and RAYNOLDS, M. K., 2002, 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* (in press).

WALKER, M. D., WALKER, D. A., and AUERBACH, N. A., 1994, Plant communities of a tussock tundra landscape in the Brooks Range Foothills, Alaska. *Journal of Vegetation Science*, **5**, 843–866.

ZHU, Z. L., and YANG, L., 1996, Characteristics of the 1-km AVHRR data sets for North America. *International Journal of Remote Sensing*, **17**, 1915–1924.