

Greening of arctic Alaska, 1981–2001

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[1] Here we analyzed a time series of 21-yr satellite data for three bioclimate subzones in northern Alaska and confirmed a long-term trend of increase in vegetation greenness for the Alaskan tundra that has been detected globally for the northern latitudes. There was a 16.9% ($\pm 5.6\%$) increase in peak vegetation greenness across the region that corresponded to simultaneous increases in temperatures. We also examined the changes for four specific vegetation types using an 11-yr finer resolution (1-km) satellite data and found that the temporal changes in peak and time-integrated greenness were greatest in areas of moist nonacidic tundra. These changes in greenness between 1981 and 2001 correspond approximately to a 171 g/m^2 ($\pm 81 \text{ g/m}^2$) increases in aboveground plant biomass for Alaskan tundra. This remotely sensed interpretation is conducted in the absence of long-term biomass records in the region. **INDEX TERMS:** 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 9315 Information Related to Geographic Region: Arctic region; 1640 Global Change: Remote sensing. **Citation:** Jia, G. J., H. E. Epstein, and D. A. Walker, Greening of arctic Alaska, 1981–2001, *Geophys. Res. Lett.*, 30(20), 2067, doi:10.1029/2003GL018268, 2003.

1. Introduction

[2] Terrestrial ecosystems of high latitudes are expected to be highly sensitive to climate change and to play a significant role in biospheric feedbacks to global climate [Bonan *et al.*, 1995]. A warming of the Arctic of Alaska has been documented over the past three decades [Serreze *et al.*, 2000; Oechel *et al.*, 2000], and these changes are likely to affect various tundra ecosystem properties [Epstein *et al.*, 2000; Chapin *et al.*, 1995]. Global scale studies have shown a general trend of increase in vegetation greenness in northern latitudes since the early 1980s. An 8% increase in the seasonal amplitude of the normalized difference vegetation index (NDVI) was detected from 1982–1990 at 65°N and higher latitudes [Myneni *et al.*, 1997], and a northern latitude greening trend and a longer growing season was simulated over 1982–1998 using a biogeochemical model forced with climate data [Lucht *et al.*, 2002]. However, there have been few finer-scale examinations of the differentiation of

changes within regions and among vegetation types. In this study, we focus on the biome of Arctic tundra in northern Alaska. We first use a global 8-km resolution Advanced Very High Resolution Radiometer (AVHRR) NDVI dataset to see if similar trends in NDVI occurred in the Arctic Slope of Alaska as documented for global northern latitudes as a whole. We analyzed the inter-annual patterns of peak NDVI in relationship to long-term climate records for three Arctic bioclimate subzones. We then used a local 1-km resolution AVHRR-NDVI dataset to examine greenness changes in homogeneous vegetations with climate and biomass in order to identify the most sensitive vegetation types. Finally, we evaluated whether air temperature is correlated with changes in vegetation greenness.

2. Data and Method

[3] The Arctic Slope of Alaska lies north of the crest of the Brooks Range. From north to south, there are three bioclimate subzones [Walker, 2000], Subzone C (prostrate dwarf shrub), D (erect dwarf shrub), and E (low shrub), which correspond approximately to areas with mean July air temperatures in the ranges of $5\text{--}7^\circ\text{C}$, $7\text{--}9^\circ\text{C}$ and $9\text{--}12^\circ\text{C}$ respectively. Moderately drained surfaces have four main types of tundra vegetation, moist sandy tundra (MST), moist non-acidic tundra (MNT), moist acidic (or tussock) tundra (MAT), and shrub tundra (ST) [Muller *et al.*, 1999]. We used two methods for sampling and summarizing satellite data. For a bioclimatic summary, we used a modified bioclimate map (see Figure 1), masking a 16-km wide belt near the coast to avoid errors of pixel mixture. For a vegetation type summary, we selected 41 sample sites of homogenous vegetation based on an interpretation of satellite imagery and aerial-photos. The sites were 9 km^2 each and were located within homogenous tundra patches that are large enough to avoid noise due to mixed pixels at 1-km resolution.

[4] The NDVI is an index of vegetation greenness: $\text{NDVI} = (\text{NIR} - \text{R})/(\text{NIR} + \text{R})$, where NIR is the spectral reflectance in the near-infrared band ($0.725\text{--}1.1 \mu\text{m}$), and R is the reflectance in the red chlorophyll-absorbing portion of the spectrum ($0.58\text{--}0.68 \mu\text{m}$). Two NOAA-AVHRR datasets were analyzed: (1) The 1990–2000 biweekly data set at 1-km resolution from the EROS Data Center of the USGS; (2) the 1981–2001 monthly data set at 8-km resolution from NASA Goddard Space Flight Center. We performed georeferencing correction for selected periods with high registration errors, using digital elevation model and map layers of coastline and rivers.

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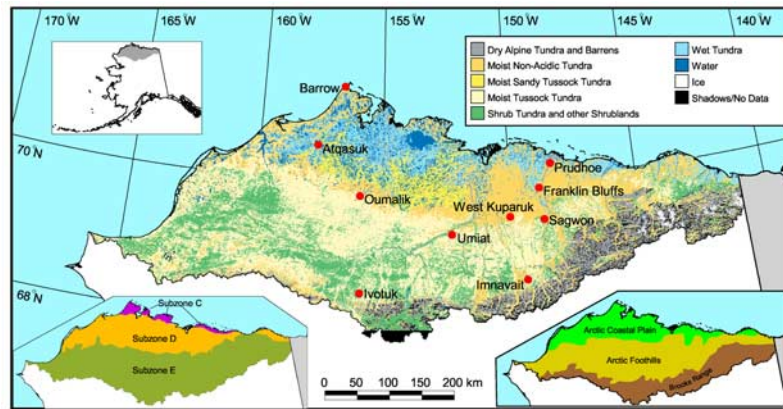


Figure 1. Tundra classification and zonation in northern Alaska. The lower left inset shows the bioclimate subzones. The lower right inset is a map of ecoregions based on physiography. Red points are meteorological stations and also sample sites.

[5] Annual peak NDVI (Peak-NDVI), the peak of greenness during the growing season, was calculated as the maximum measurable NDVI recorded during each year from 1981–2001 for 8-km data and from 1990–2000 for 1-km data. Time-integrated NDVI (TI-NDVI) was calculated as the cumulative value of NDVI recorded during each growing season for biweekly values greater than 0.09 [Reed *et al.*, 1994; Jia *et al.*, 2002] from 1991–2000 for 1-km data. We excluded 1990 in 1-km TI-NDVI calculations, because there were no data available for April and May. Both were calculated on a pixel-by-pixel basis for each year. Based on the modified bioclimate map, we summarized 8-km peak NDVI by the three subzones for each year from 1981–2001. We also summarized 1-km resolution data for each year from 1990–2000 for the homogenous vegetation samples. ArcGIS spatial analysis module was used for all above analyses. We performed autoregression for the time series of NDVI with subzones and vegetation types, and then generated linear relationships to determine if there were significant differences in NDVI trends among them.

[6] We used meteorological data from 10 stations for spatial-temporal analysis. Among them, three stations (Barrow, Umiat and Prudhoe) with long-term records were used to construct long-term summer warmth index (SWI) datasets for three subzones. SWI, the sum of monthly mean air temperatures greater than 0°C, was calculated annually for each of the stations and compared to the NDVI inter-annual series. We analyzed the correlations between SWI and TI-NDVI or Peak-NDVI, separately for the three bioclimatic subzones and four vegetation types.

[7] To establish relations between NDVI and vegetation biomass at different spatial scales, we measured above-ground plant biomass at various sample sites (Figure 1). For each site 6–10 random 20 × 50-cm clip-harvest plots were selected from 121 points within a 100 × 100-m grid; the biomass samples were then dried to constant weight [Walker *et al.*, 2003]; Surface NDVI was also measured using an Analytical Spectral Devices FieldSpec spectrometer at Igotuk, AK, with the sensor held 1-m above the canopy and for MNT, MAT and ST plots; plots were then harvested and the biomass data analyzed as above. With these field-scale data, we were able to perform regressions

between NDVI (AVHRR and surface) and plant biomass (Figure 4).

3. Results and Discussion

[8] There was a general increasing trend in peak NDVI from 1981 to 2001 in each bioclimate subzone, with short-term declines in 1985–86, 1992, and 2000–01 (Figure 2a). The increase of 0.078 (± 0.026) or 16.9% ($\pm 5.6\%$) in Peak

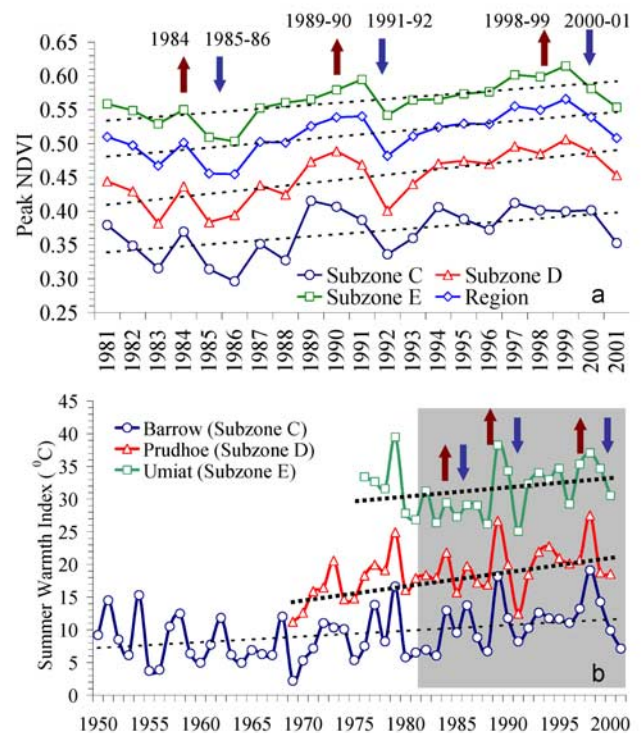


Figure 2. Time series of peak NDVI derived from 8-km resolution AVHRR data from 1981 to 2001 (a) and SWI over the past 22–50 years (b) among bioclimate subzones. Dashed lines are linear regressions. The shaded area highlights the period of SWI covered by NDVI data.

NDVI on the Arctic Slope for this period is greater than that reported for the northern latitudes as a whole [Zhou *et al.*, 2001; Lucht *et al.*, 2002]. Zhou *et al.* [2001] has indicated heterogeneous changes in NDVI in North America from 1981–1999, and even slight decreases in parts of Alaska and boreal Canada. However, our results show clearly a trend of increase in NDVI in the region. The highest peak NDVI increases occurred for Subzone D (0.082 ± 0.028 , 18.7%), followed by Subzone E (0.069 ± 0.022 , 12.6%) and Subzone C (0.056 ± 0.032 , 15.1%). The increases in NDVI correspond to a general pattern of increasing temperature within all subzones (Figure 2b). The warming trend on the Arctic Slope is expressed by a summer warmth index (SWI) increase of $0.09\text{--}0.19^\circ\text{C/yr}$ over the past 22–50 years and $0.16\text{--}0.34^\circ\text{C/yr}$ over the time of the NDVI record, with the greatest increase occurring in Subzone D. Generally, years with greater NDVI values coincide with warm temperatures, and drops in NDVI correspond with cold summers, as shown by arrows in Figure 2.

[9] The 1-km data showed similar general temporal patterns as the 8-km data. Both Peak NDVI and Time-integrated NDVI (TI-NDVI) have the lowest decadal mean values for moist sandy tundra and the highest values for shrub tundra. Peak NDVI from 1990–2000 and TI-NDVI from 1991–2000 increased for all vegetation types, with an interruption in 1992 due to the eruption of Mt. Pinatubo in late 1991. The data also showed differences in trends among the vegetation types. Peak NDVI generally increased by 0.061 (or 13.6%) for the 11-year period. The greatest increase in Peak-NDVI occurred for MNT (0.073), followed by MAT (0.059), shrub tundra (0.052) and sandy tundra (0.043). TI-NDVI increased by 0.526 (or 17.7%) for the 10-year period (Figure 3). Both MNT and MAT had high increases in TI-NDVI, whereas sandy tundra had a relatively low increase (0.23). Nearly all of our results suggest that the greatest changes in NDVI have occurred

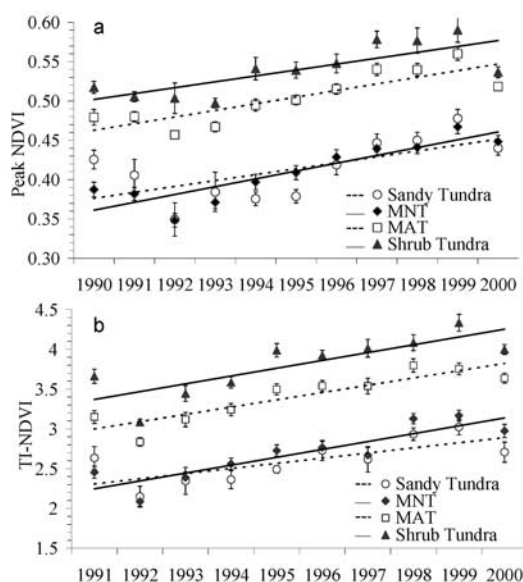


Figure 3. Time series of peak NDVI (a) and TI-NDVI (b) based on 1-km resolution AVHRR data among tundra vegetation types. Error bars represent plus/minus standard error.

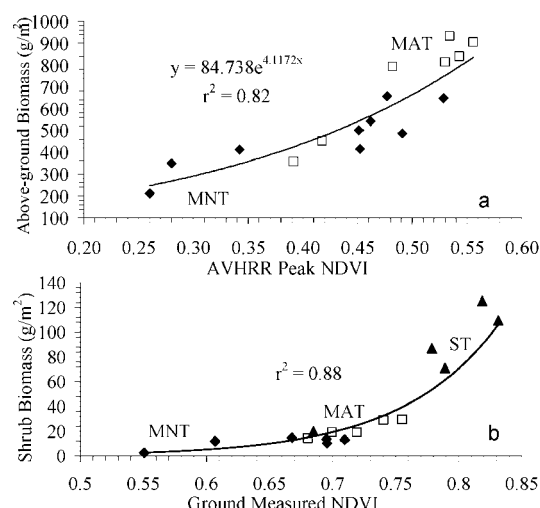


Figure 4. Correlations between NDVI and aboveground plant biomass. (a) AVHRR Peak-NDVI vs. total biomass on the North Slope; (b) ground measured NDVI vs. shrub biomass in Ivotuk.

in moist nonacidic, graminoid-dominated tundra, which currently has relatively low shrub cover. Slight changes in shrub cover within this type may cause relatively large changes in NDVI compared to the other types (Figure 4). The relatively lower increase rates for shrub-dominated tundra may also be a result of saturating values of NDVI. These hypotheses are supported by spatial NDVI and biomass analyses at both local and regional scales. Slight increases in shrub biomass for MNT can lead to a strong NDVI increase, while similar increases in shrub biomass for shrub tundra only yield slight NDVI increases. For the whole area, TI-NDVI and Peak NDVI are highly correlated ($r^2 = 0.82$), showing that much of variation in TI-NDVI is related to the change of Peak NDVI.

[10] There is evidence from the International Tundra Experiment (ITEX) and other studies showing the increase of shrub growth on the Arctic Slope and other areas [Arft *et al.*, 1999; Sturm *et al.*, 2001; Hobbie and Chapin, 1998]. A substantial increase in shrub abundance has been reported in the Alaskan Arctic over the past 50 years [Sturm *et al.*, 2001], which is believed to have contributed to increased productivity in some areas. Others have studied the effects of aerosols on NDVI [Lucht *et al.*, 2002; Hope *et al.*, 2003] and vegetation productivity [Gu *et al.*, 2002] following the Mt. Pinatubo eruption in 1991, but these effects appear to be transitory, and NDVI continued to increase after aerosol concentrations returned to pre-Pinatubo levels.

[11] The temporal-spatial series of both Peak-NDVI and TI-NDVI showed positive relations with SWI. TI-NDVI had a stronger relation with SWI than Peak-NDVI ($r^2 = 0.69$ vs. $r^2 = 0.51$, $p < 0.01$). After separating the sites into subzones and vegetation types, the relationship between SWI and NDVI became less strong. However, the correlations between TI-NDVI and SWI were still greater ($r^2 = 0.40\text{--}0.54$) than those between Peak-NDVI and SWI ($r^2 = 0.15\text{--}0.38$). The NDVI increase in Subzone D and MNT were significantly greater than other subzones and vegetation types (t-tests, $p < 0.05$), and the greatest correlations

occurred for Subzone D and MNT, again indicating their potentially high sensitivity to climate change. There is also significant difference between shrub tundra and MAT in TI-NDVI, but no significant difference in peak NDVI between them. Increases in both TI-NDVI and Peak NDVI for sandy tundra are significantly lower than other vegetation types, which may reflect less response of azonal vegetation to climate change. These results suggest that temporal changes of vegetation greenness are largely controlled by SWI, though it is also affected by other ecological factors [Jia *et al.*, 2002].

[12] At both regional and local scales, NDVI is likely a meaningful indicator of aboveground plant biomass on the Arctic Slope. With 16 biomass sample sites throughout the region, we found that NDVI explained over 82% of total biomass ($y = 84.738 e^{4.1172x}$, Figure 4a). With 17 biomass samples at Iivotuk, 88% of the variance in deciduous shrub foliar biomass was explained with ground-measured NDVI ($y = 0.0022e^{12.973x}$, Figure 4b). Among a latitudinal gradient from north to south Peak-NDVI values of 0.26–0.53 for MNT correspond to 223–647 g/m² of biomass, and values of 0.39–0.56 correspond to 452–932 g/m² for MAT. Utilizing this spatial relationship to interpret temporal dynamics [Rastetter *et al.*, 1992], the increases of 0.078 ± 0.026 in Peak-NDVI between 1981 and 2001 correspond approximately to a 171 g/m² (± 81 g/m²), or 28.1% ($\pm 13.3\%$) increases in aboveground plant biomass for Alaskan tundra. This remarkable change could be accounted for by increases in the deciduous shrub biomass that have been shown to be very responsive to changes in the summer air temperatures [Chapin *et al.*, 1995; Oechel *et al.*, 2000]. Changes in shrub cover are likely to have a multitude of effects on other ecosystem properties and processes. They likely have a major influence on regional energy and carbon budgets [McFadden *et al.*, 1998; Oechel *et al.*, 2000] and therefore potential feedbacks to climate.

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