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Variability of the Seasonally Integrated Normalized Difference Vegetation Index Across the North Slope of Alaska in the 1990s

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Abstract. The interannual variability and trend of above-ground photosynthetic activity of Arctic tundra vegetation in the 1990s is examined for the north slope region of Alaska, based on the seasonally integrated normalized difference vegetation index (SINDVI) derived from local area coverage (LAC) National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data. Smaller SINDVI values occurred during the three years (1992–1994) following the volcanic eruption of Mt Pinatubo. Even after implementing corrections for this stratospheric aerosol effect and adjusting for changes in radiometric calibration coefficients, an apparent increasing trend of SINDVI in the 1990s is evident for the entire north slope. The most pronounced increase was observed for the foothills physiographical province.

1. Introduction

Analyses of normalized difference vegetation index (NDVI) datasets derived from National Atmospheric and Oceanic Administration (NOAA) series Advanced Very High Resolution Radiometer (AVHRR) global area coverage (GAC) data with a spatial resolution of 4–8 km indicate that, for broad latitudinal averages, photosynthetic activity of land surfaces at higher northern latitudes increased from 1981–1999 (Myneni *et al.* 1997, Tucker *et al.* 2001, Zhou *et al.* 2001). One hypothesis for such an increase in satellite sensor derived greenness is that growing season length of boreal forest and Arctic tundra biomes has increased over the past 20–30 years of documented climate warming within polar and sub-polar regions (Sereze *et al.* 2000, Shabanov *et al.* 2002). Other explanations are an increase in primary production resulting from rising atmospheric carbon dioxide (CO_2) concentrations, and/or greater nutrient availability from warming soils and thawing permafrost (Oechel *et al.* 1995).

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While Zhou *et al.* (2001) found that NDVI increased the most within the high northern latitudes over the past two decades, they observed no increase for Arctic and subarctic areas of Alaska, and a small decrease in some of these areas. Conversely, more detailed, site-specific analyses of the north slope of Alaska have shown recent increase in the cover and structure of dwarf shrubs (Sturm *et al.* 2001). Since these shrubs are structurally the tallest plant form within Arctic tundra communities of the north slope and have been shown to have the greatest influence on NDVI, one might expect that greenness has increased for many parts of the north slope in the past few decades.

Based upon field measurements of production and on estimates of biome production, a number of studies confirm that integration or summation of the NDVI over a growing season is correlated with above-ground, net primary production (Goward and Dye 1987). The seasonally integrated normalized difference vegetation index (SINDVI) is defined as the sum of NDVI values for each pixel and all time intervals of maximum value composites (MVCs) (Holben 1986) that the NDVI exceeds a critical value (commonly NDVI >0.1). The greenness rate of change (GRC) is defined as the slope of the least-squares line fitting the interannual variability of SINDVI values over some time period (e.g. decade).

The objective of this letter is to present initial results from a study of a SINDVI time series derived from AVHRR local area coverage (LAC) imagery (nominal 1 km spatial resolution) captured between 1900–1999. The goal is to examine greenness trends across the north slope of Alaska (figure 1), at a finer spatial resolution than has been achieved with previous studies based on AVHRR GAC datasets.

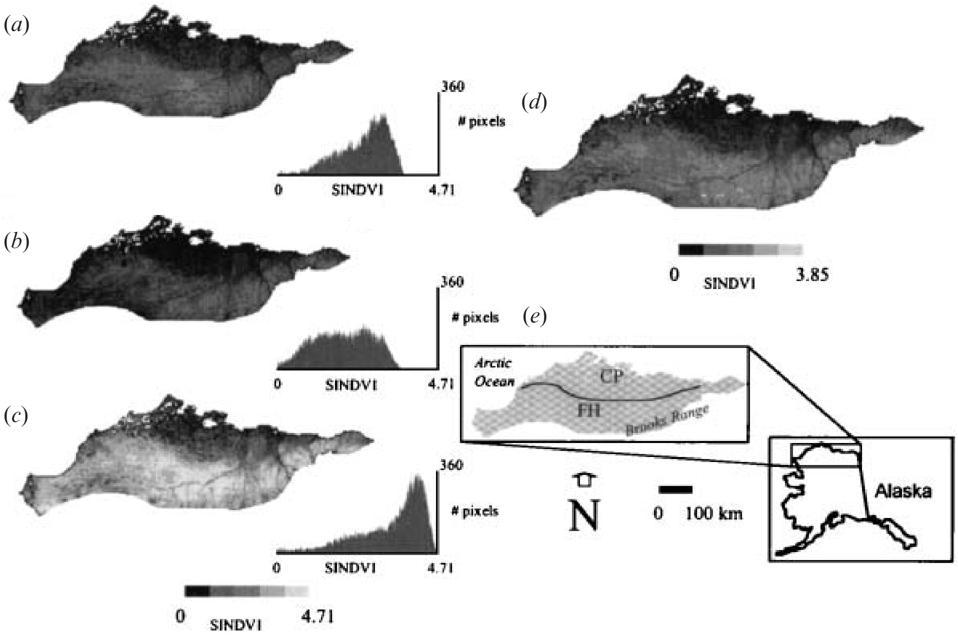

Figure 1. (*a*)–(*c*) Maps and associated histograms of SINDVI for the north slope in 1990, 1994 and 1998, representing the baseline, overall minimum and overall maximum years for the decade, respectively; (*d*) map of decadal mean SINDVI; and (*e*) study area map of the north slope delineating the coastal plain (CP) and foothills (F) physiographical provinces.

2. Methods

An NDVI time series of the north slope region for growing seasons in the 1990s was produced by assembling NOAA AVHRR LAC (1 km) images from several sources. This was accomplished by incorporating AVHRR MVCs of the state of Alaska for the period July 1990–October 1995 and April–October 1997, produced by the US Geological Survey (USGS) Earth Resources Operation Survey (EROS) Data Center (EDC). Our team recalibrated EDC 1991 and 1992 datasets using updated radiometric calibration coefficients for NOAA-11 (Eidenshink 1992) and augmented the EDC datasets by producing MVCs for April–June 1990 and the growing seasons of 1996, 1998 and 1999. Only data from afternoon (NOAA-11 and -14) and near-nadir overpasses were incorporated. Calibration coefficients for NOAA-14 were initially based on Vermote and Kaufman (1995) which assume no change in the digital number to radiance relationship after 1996. Spatial registration of MVC images was refined by interactive selection of control points and application of first-order warping functions. A twice-monthly (15 or 16 days) compositing interval was used for 1990–1994 and a 14-day interval for 1995–1999.

Hope *et al.* (in press) found that optical depth at 0.55 μm associated with stratospheric aerosols from the eruption of Mt Pinatubo was the environmental variable that most explained variations in the SINDVI from 1989–1996 for the Kuparuk River watershed of the north slope region. In an attempt to minimize stratospheric aerosol effects from the Mt Pinatubo eruption, Stow *et al.* (2001) explored scene-based radiometric normalization approaches. None of these approaches was successful in normalizing NDVI values during this period, primarily because of a lack of large ($>1\,km^2$) stable dark objects or other invariant features within the scene encompassing the north slope region (Stow *et al.* 2001).

An alternative approach was implemented that exploited a procedure for correcting the stratospheric aerosol effect on NDVI from AVHRR–GAC data developed by the Global Inventory Monitoring and Modeling Systems (GIMMS) group at National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) (Vermote and El Saleous 1994). This procedure is based on the assumptions that optical depth of stratospheric aerosols is longitudinally constant and dark ocean pixels are suitable as calibration points. LAC NDVI values were cross-calibrated to the GIMMS NDVI datasets for 1991–1993 using an empirical line approach that was based on systematically spaced, co-registered samples (8 km in extent), as described in Stow *et al.* (2001).

LAC pixels were spatially aggregated by averaging 3×3 blocks of pixels to minimize misregistration effects. The 3 km NDVI MVC raster data were integrated (i.e. per-pixel summation) over each growing season to derive maps of SINDVI for each year of the 1990s. The integration period was defined as the series of MVC pixels for which NDVI exceeded the value of 0.1 within the potential growing season from April–October.

3. Results

SINDVI maps and associated histograms for the north slope in 1990, 1994 and 1998 (figure 1(*a*)–(*c*)) represent the baseline, minimum and maximum years for the decade, respectively. Spatial patterns of SINDVI are persistent in maps for all years of the 1990s except 1994, where the south-western portion of the north slope was frequently cloud covered. The map of decadal mean SINDVI in figure 1(*d*) shows that higher values are found in the foothill province and lower values in the coastal plain, with the lowest SINDVI values in the low-lying areas covered by thaw lakes and wet sudge tundra vegetation. The map portrays the dichotomous productivity levels of the foothills and coastal plain physiographical provinces.

Gradually increasing and statistically significant trends of SINDVI (i.e. moderately increasing GRC) for the north slope are apparent in figure 2. Figure 2 illustrates the trend for SINDVI values without and with the GIMMS-based correction of the stratospheric aerosol effect from Pinatubo (for 1991–1993), respectively. Differences in SINDVI after correction are −0.23, +0.44 and +0.35 for 1991, 1992 and 1993, respectively. In 1995 and subsequent years, SINDVI values rise substantially and exceed pre-Pinatubo levels. The GRC trends for both datasets are positive and are significantly greater than zero (table 1). The GRC of the north slope for the original dataset is +0.15 per year, or a 6% average annual increase from the 1990 baseline year, and is +0.12 per year for the GIMMS-based corrected dataset.

Given the bimodal nature of SINDVI frequency distribution for the foothills and coastal plain physiographical provinces, the north slope region was stratified based upon provincial boundaries and computed mean values of each province for each year. The foothills and coastal plains subregions exhibited a significantly increasing

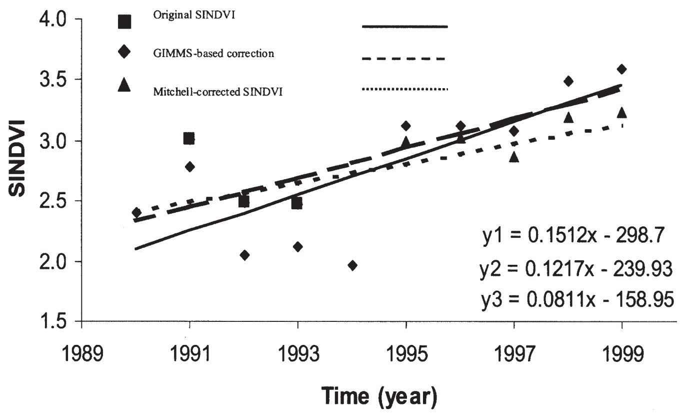

Figure 2. Interannual variability of SINDVI for the north slope 1990–1999 with least-squares fit lines. y1 = original SINDVI; y2 = GIMMS corrected SINDVI; y3 = Mitchell corrected SINDVI.

Table 1. Seasonally integrated normalized difference vegetation index (SINDVI)—baseline (1990) values and greeness rate of change (GRC) for three versions of AVHRR time series. GRC is estimated as slope of least-squares line of time series trend in units of $\Delta\text{SINDVI}\cdot\text{yr}^{-1}$.

Extent	1990 (baseline) SINDVI	GRC		
		Original	GIMMS-based corrected	GIMSS and Mitchell calibration
North slope region	2.4	±0.15 (p=0.01)	+0.12 (p=0.02)	+0.08 (p=0.07)
Foothills province	2.7	+0.17 (p=0.01)	+0.14 (p=0.02)	+0.10 (p=0.07)
Coastal plain province	2.0	+0.12 (p=0.02)	+0.10 (p=0.03)	+0.06 (not significant)

GRC trend of approximately +0.17 and +0.12 per year, respectively for the conventional dataset, and +0.14 and +0.10 per year, respectively for the GIMMS-based corrected dataset (table 1).

4. Discussion and conclusions

While a trend of increasing SINDVI values over the decade is apparent, it may be accentuated by several factors including: (1) depressed levels following the eruption of Mt Pinatubo, (2) changes in the radiometric calibration relationship for NOAA-14 AVHRR over time, and (3) drift and differences in the time of acquisition and therefore solar zenith angle (SZA), for NOAA-11 and -14 satellites. The first factor is relevant, even though NDVI LAC data were cross-calibrated with the corrected GIMMS dataset. The correction of stratospheric aerosol effects may be incomplete for 1992 and 1993 and was not implemented for 1994, since the GIMMS dataset had not been corrected for this year. SINDVI values appear to be depressed in the 1992–1994 period because of reduced primary production and/or growing season length in the period of high stratospheric aerosol concentrations from the Mt Pinatubo eruption (Zhou *et al.* 2001). Conversely, the correction for 1991 appears to be excessive. Estimates of stratospheric aerosol optical depths (NASA GISS 2001) suggest that the Pinatubo effect may not have been evident at Arctic latitudes until late in the 1991 growing season.

Published estimates of updated calibration coefficients for NOAA-14 vary substantially (Mitchell 1999, Rao and Chen 1999, Tahnk and Coakley 2001), but most suggest a reduction in radiance coefficients relative to the flat line assumption after 1996 of Vermote and Kaufman (1995), the basis for the original NDVI time-series. NDVI was recalibrated and recomputed SINDVI values for 1997–1999 using the commonly cited, updated NOAA-14 calibration coefficients of Mitchell (1999). The north slope trend for the dataset derived with post-1996 Mitchell (1999) recalibration is statistically significant with a GRC of +0.8 per year, or 3% increase per year from the 1990 baseline. Based on the recalibrated data, GRC values for the foothills subregion is significant at 0.10 and for the coastal plain is not significantly different from zero.

Another possible cause for different trends for the 1990–1994 and 1995–1999 periods is that NDVI values were based on data from the AVHRR instrument on NOAA-11 in the earlier period and a different sensor on NOAA-14 in the latter period. The mean SZA for the MVC associated with peak greenness between 1994–1995 of the north slope decreased by 6%. However, Vierling *et al.* (1997) determined that NDVI of Arctic tundra vegetation on the north slope stays generally constant or increases slightly with increasing SZA, which is the opposite of the relationship between apparent SINDVI trends and SZA variations for NOAA-11 and -14.

Ongoing research focuses on spatial pattern analyses of GRC magnitudes to determine if greenness of particular tundra vegetation types appears to be increasing more rapidly than other types. Such analyses better exploit the finer spatial resolution characteristics of the LAC-derived SINDVI dataset, compared with datasets derived from GIMMS or other GAC-derived datasets. The relationship between dwarf shrub cover and areas of higher GRC using very high resolution (0.5 m) digital images from an airborne multispectral system is also being analysed. The LAC dataset is being expanded spatially, by including Arctic tundra lands of the Seward Peninsula of Alaska and Chukotka Peninsula of the Russian Far East. It will also be expanded temporally by generating MVCs for 2000 and 2001. By searching NOAA archives of AVHRR LAC data, it is possible and may be worthwhile to extend the record length to as early as 1985.

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References

Eidenshink, J. C., 1992, The 1990 conterminous U.S. AVHRR data set. *Photogrammetric Engineering and Remote Sensing*, **58**, 809–813.

Goward, S., and Dye, D., 1987, Evaluating North America net primary productivity with satellite observations. *Advances in Space Research*, **7**, 165–174.

Holben, B., 1986, Characteristics of maximum value composite images for temporal AVHRR. *International Journal of Remote Sensing*, **7**, 1417–1437.

Hope, A., Boynton, W., Stow, D., and Douglas, D., submitted, Interannual growth dynamics of vegetation in the Kuparuk River watershed based on the normalized difference vegetation index. *International Journal of Remote Sensing*, **00**, 000–000.

Mitchell, R., 1999, CSIRO Atmospheric Research, http://www.dar.sciro.au/rs/CalWatch/calwatch.html.

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

NASA GISS, 2001, National Aeronautics and Space Administration Goddard Space Institute, stratospheric aerosol data, http://www.gis.nasa.gov/data/strataer/.

Oechel, W., Vourlitis, G., Hastings, S., and Bochkarev, S., 1995, Change in arctic CO_2 flux over two decades: effects of climate change at Barrow, Alaska. *Ecological Applications*, **5**, 846–855.

Rao, C., and Chen, J., 1999, Revised post-launch calibration of the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAA-14 spacecraft. *International Journal of Remote Sensing*, **20**, 3485–3491.

Sereze, M., Walsh, J., Chapin, F., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W., Morison, J., Zhang, T., and Barry, R., 2000, Observational evidence of recent change in the northern high-latitude environment. *Climatic Change*, **46**, 159–207.

Shabanov, N., Zhou, L., Knyazikhin, Y., Myneni, R., and Tucker, C., 2002, Analysis of interannual changes in northern vegetation activity observed in AVHRR data during 1981 to 1994. *IEEE Transactions on Geoscience and Remote Sensing*, **40**, 115–130.

Stow, D., Daeschner, S., Hope, A., Douglas, D., Myneni, R., and Zhou, L., 2001, Spatial-temporal trend of seasonally-integrated normalized difference vegetation index as an indicator of changes in arctic tundra vegetation in the early 1990s. *Proceedings of the International Geoscience and Remote Sensing Symposium, Sydney, Australia, July 2001*. Piscataway, New Jersey: IEEE, vol. 1, 181–183.

Sturm, M., Racine, C., and Tape, K., 2001, Increasing shrub abundance in the Arctic. *Nature*, **411**, 1251–1256.

Tahnk, W., and Coakley, J., 2001, Improved calibration coefficients for NOAA-14 AVHRR visible and near-infrared channels. *International Journal of Remote Sensing*, **22**, 1269–1284.

Tucker, C., Slayback, D., Pinzon, J., Los, S., Myneni, R., and Taylor, M., 2001, Higher northern latitude NDVI and growing season trends from 1982 to 1999. *International Journal of Biometeorology*, **45**, 184–190.

Vermote, E., and El Saleous, N., 1994, Stratospheric aerosol perturbing effect on the remote sensing of vegetation: operational method for the correction of AVHRR composite NDVI. *SPIE Atmospheric Sensing and Modeling*, **2311**, 19–29.

Vermote, E., and Kaufman, Y., 1995, Absolute calibration of AVHRR visible and near-infrared channels using ocean and cloud views. *International Journal of Remote Sensing*, **16**, 2317–2340.

Vierling, L., Deering, D., and Eck, T., 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.

Zhou, L., Tucker, C., Kaufman, R., Slayback, D., Shabanov, N., Fung, I., and Myneni, R., 2001, Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research*, **106**, 20 069–20 083.