DETECTING ARCTIC CLIMATE CHANGE USING KÖPPEN CLIMATE CLASSIFICATION

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Abstract. Ecological impacts of the recent warming trend in the Arctic are already noted as changes in tree line and a decrease in tundra area with the replacement of ground cover by shrubs in northern Alaska and several locations in northern Eurasia. The potential impact of vegetation changes to feedbacks on the atmospheric climate system is substantial because of the large land area impacted and the multi-year persistence of the vegetation cover. Satellite NDVI estimates beginning in 1981 and the Köppen climate classification, which relates surface types to monthly mean air temperatures from 1901 onward, track these changes on an Arctic-wide basis. Temperature fields from the NCEP/NCAR reanalysis and CRU analysis serve as proxy for vegetation cover over the century. A downward trend in the coverage of tundra group for the first 40 yr of the twentieth century was followed by two increases during 1940s and early 1960s, and then a rapid decrease in the last 20 yr. The decrease of tundra group in the 1920–40 period was localized, mostly over Scandinavia; whereas the decrease since 1990 is primarily pan-Arctic, but largest in NW Canada, and eastern and coastal Siberia. The decrease in inferred tundra coverage from 1980 to 2000 was 1.4×10^6 km^2, or about a 20% reduction in tundra area based on the CRU analyses. This rate of decrease is confirmed by the NDVI data. These tundra group changes in the last 20 yr are accompanied by increase in the area of both the boreal and temperate groups. During the tundra group decrease in the first half of the century boreal group area also decreased while temperate group area increased. The calculated minimum coverage of tundra group from both the Köppen classification and NDVI indicates that the impact of warming on the spatial coverage of the tundra group in the 1990s is the strongest in the century, and will have multi-decadal consequences for the Arctic.

1. Introduction

Evidence from multiple sources shows that the Arctic climate is changing and changing rapidly. To list several, the annual mean sea level pressure in the polar basin has been decreasing since 1988 (Walsh et al., 1996), the general circulation pattern has changed as represented by the positive phase in the Arctic Oscillation (AO) index since 1989 (Thompson and Wallace, 1998), sea-ice extent has shown a downward trend after 1970 with the minimum in the last 3 yr (Serreze et al., 2003), and there are changes in the land cover, such as a decrease in snow cover, increase in permafrost temperatures in some areas, and decrease in tundra area with replacement by shrubs and changes in tree line (Sturm et al., 2001; Shiyatov, 2003). Summaries of these changes are presented by Serreze et al. (2000), Morison et al. (2001) and Overland et al. (2004a).

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The potential impact of vegetation changes to feedbacks on the atmospheric climate system is substantial because of the large land area impacted and the multi-year persistence of the vegetation cover. These vegetation changes have considerable impacts on the ecosystems in the Arctic and also have global impacts through feedback mechanisms. An important factor of the vegetation change to climate system is that masking of snow cover by increased shrubbiness can accelerate the springtime snow melt and the transition to the summer regime. A transition from lichen to shrubs will also trap snow, providing greater insulation to the surface, and warmer ground temperatures during winter and early spring. One positive feedback is that in the region where tundra has been replaced by shrubs, the growing season albedo would be reduced. This will increase the late winter/early spring energy absorption at the surface and may enhance surface and lower levels of atmospheric warming. This would accelerate more regions of tundra being replaced by shrubs. By comparing photographs taken in northern Alaska during 1948–50 and 1999–2000, Sturm et al. (2001) found distinctive increases in the height and diameter of individual shrubs, and marked increase in the extent and density of the spruce forest. Because his study area was in a location where human disturbances are minimal, he attributed much of the increase in the abundance of shrubs to recent change in climate.

Climate is composed of individual elements, such as, temperature, precipitation, wind, atmospheric pressure, etc. A widely accepted system of climate classification is summarized by Köppen (1931). The Köppen classification uses natural vegetation as an expression of climate, so that many of the climatic boundaries are selected with vegetation limits in mind. Nevertheless, it is based upon annual and monthly means of temperature and precipitation as a surrogate for vegetation. The Köppen classification recognizes five major groups of climate, and lesser subdivisions. This climate-vegetation association provides an empirical and intuitive relation between a multivariate description of climate and an easily visualized natural landscape (Guetter and Kutzbach, 1990).

Since the launch of satellites in the early 1980s, data from the Advanced Very High Resolution Radiometers (AVHRR) have been used to monitor surface changes using the reflectance in the visible and near infrared channels to calculate a parameter termed the Normalized Differences Vegetation Index (NDVI). NDVI is correlated with the fraction of photosynthetically active radiation absorbed by plant canopies and is used as an indicator of vegetation density and photosynthetic capacity, although calibrations may be regionally dependent. Myneni (1997, 1998) has shown that the seasonal mean and amplitude of NDVI in the boreal region between 45°N and 70°N increased from 1981 to 1991. These patterns are consistent with changes in surface air temperature and changes in the seasonal cycle of atmospheric CO_2.

In this study, we quantify the historical changes in vegetation cover in the Arctic region according to Köppen climate classification based on surface air temperatures (SAT), and compare the results with satellite NDVI for the previous two decades. The sections are organized as follows: first, the data sets and methodologies used in the study are described; then the results based on Köppen climate classification are presented. The comparison of Köppen climate classification with satellite NDVI follows and finally conclusions are summarized.

2. Data Sets and Approach

An advantage in using the Köppen climate classification scheme to portray climatic change is its efficiency. A modified version of this classification proposed by Trewartha and Horn (1980) recognizes temperature and precipitation as the two elements of paramount importance. The modified version of the classification has six major groups using letters A to F: A-tropical, C-subtropical, D-temperate, E-boreal, F-polar, and B-dry climate. The first five are based on the thermic zones and the sixth is the dry group, which cuts across first four of the thermic zones. Several sub-groups are based on the precipitation within each climate group.

Because of the meager precipitation in the Arctic, the climate groups in the Arctic region are based on mean monthly SAT (Table I). In the modified Köppen climate classification, tundra group is defined as the monthly mean temperature of the warmest month being less than 10 °C and above freezing. The boreal group has 1 to 3 month of the temperature above 10 °C. When there are four or more months of the mean temperature above 10 °C, the area is classified as the temperate group. These thermic groups have a strong zonal orientation and they correspond closely to zonal patterns in vegetation covers. The polar group, F, is dominated by treeless, tundra vegetation. The boreal group, E, is comprised mainly of coniferous forests and its southern boundary is at about 50°N, but at a slight northern latitude near Eurasian and the northwest of the American continents. The temperate group, D, consists of broadleaf-deciduous forests inland and temperate evergreen forests over maritime regions.

Two sources are used for specification of surface air temperature. The first is the NCEP/NCAR reanalysis monthly air temperature at the sigma level of 0.995 (Kalnay et al., 1996). A comparison of the reanalysis's 2-m air temperature and air temperature at sigma level 0.995 with selected stations over the Arctic region shows that the latter agrees better with the station observations than the former. The second source is the monthly global land surface air temperature created by Climate

TABLE I
The modified Köppen climate classification

Climate group	Subgroup	Letter	Criteria
Temperate		D	$\bar{T} >= 10\,^{\circ}\mathrm{C}$ for 4 or more months
Boreal		E	$\bar{T} >= 10\,^{\circ}\mathrm{C}$ for 1–3 months
Polar	Tundra	Ft	$0^{\circ}\mathrm{C} <= \bar{T} < 10\,^{\circ}\mathrm{C}$ in summer
	Perpetual frost	Fi	$\bar{T} < 0\,^{\circ}\mathrm{C}$ in summer

Research Unit of University of East Anglia, United Kingdom (CRU TS2.0) (New et al., 1999, 2000). The CRU data is supplied on a 0.5 degree grid, covering the global land surface for the period of 1901–2000. This data set was generated by computing anomalies of the station data for 1901–2000 relative to 1961–90 climatology. These station anomalies were then interpolated to a 0.5 degree grid. The grids of anomalies were then combined with the global climatology for 1961–90 at 0.5 degrees to obtain grids of absolute temperature.

The satellite NDVI is calculated from visible (VIS) and near-infrared (NIR) light reflected by vegetation. The first AVHRR channel (0.58–0.68 μm) is in a part of the spectrum where chlorophyll causes considerable absorption of incoming radiation, and the second channel (0.73–1.10 μm) is in a spectral region where spongy mesophyll leaf structure leads to considerable reflectance. The contrast between responses of the two bands forms a ratio, which defines the NDVI,

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{VIS}}{\mathrm{NIR} + \mathrm{VIS}}. \tag{1}$$

The NDVI, a nonlinear function between -1 and $+1$, provides an areal average measure of the amount and photosynthetic activity of vegetation. Values for vegetated land generally range from 0.1 to 0.7, with values greater than 0.5 indicating dense vegetation. For snow, inland water bodies, desert, and exposed soils the value ranges between -0.2 to 0.1. NDVI is highly correlated with vegetation parameters such as green-leaf biomass and green-leaf area and is of considerable value for vegetation discrimination (Justice et al., 1985).

Two NDVI data sets are used in the present study. One is from NASA, a product as part of the NOAA/NASA Pathfinder AVHRR Land program (PAL). The other is from Boston University [ftp://crsa.bu.edu/pub/rmyneni/myneniproducts/AVHRR_DATASETS, improved NDVI data sets (version 3), courtesy of Prof. Myneni]. The NASA NDVI data set (hereafter termed NASA) is derived from the AVHRR on the “afternoon” NOAA operational meteorological satellites (NOAA-7, 9, 11, and 14), covers the period July 1981 to September 2001, and is on a global 1-degree resolution grid. The data set is derived from 8 km, 10-day composites which are formed from daily data of visible and near-infrared channel reflectances. The data processing included improved navigation, cloud masking, calibration and Rayleigh atmospheric correction. The Boston University Version 3 (PAL) data set (BU3 will be used in the text hereafter) is based on the PAL data set, but has 10 days to 1 month temporal compositing, and 8 to 16 km spatial compositing, and corrections for orbital loss. A special correction was applied to BU3 for the period of June 1991 to January 1995 to compensate for the contaminations due to the Mount Pinatubo eruption using monthly near-surface air temperature and precipitation (Song, et al., 2003). The BU3 data are on 0.5-degree horizontal resolution, and are interpolated to a 1-degree resolution for comparisons with the NASA data set.

3. Historical Changes in the Coverage of the Tundra Group

3.1. ARCTIC-WIDE CHANGE

Using monthly mean SAT from NCEP and CRU, each grid point is classified based on the modified Köppen classification. Within the polar climate group two subdivisions are recognized: Fi, the icecap, or the perpetual frost group, where the maximum summer temperature of all months is below 0 °C; and Ft, the tundra group, where the warmest month is less than 10 °C and above freezing (Table I). Guetter and Kutzbach (1990) used 11 °C instead of 10 °C for determining the boundary separating boreal (E) from polar (F) climate group in their model simulation results. They found an improved correspondence with the tundra/forest boundary in the Hudson Bay area and in eastern Siberia when compared with the climate and vegetation maps of Walter (1984). We carried out computations using 11 °C as the criterion, and found insignificant differences in decadal variations compared to the 10 °C criterion. We present results based on the 10 °C criterion for tundra group (Ft) and for boreal and temperate groups.

The spatial distributions of Köppen climate classifications for two selected years are shown in Figure 1. The left panels of Figure 1 are for 1978, the year with high tundra group coverage based on NCEP. Agreement between CRU (top) and NCEP (bottom) is seen in the spatial distribution of each climate group. During this particular year when high coverage of tundra group is depicted, the tundra group was classified along most of the Arctic coast regions and occupies most of the Nunavut, the region northwest of Hudson Bay in Northern Canada. A significant portion of east Siberia is also identified as tundra group (more in CRU than NCEP). The year 1998 has the lowest tundra group coverage as indicated by both analyses (middle panels of Figure 1). During this year, most of the Canadian archipelago and northeast Alaska (CRU only) are still covered by the tundra group, as well as along the west coastline of Greenland and on the Arctic coasts of Eurasian continents. Based on the Köppen criteria significant portions in the coverage of tundra group have been replaced by boreal group in the past 20 yr, as indicated by green colors in the right panels of Figure 1. The replacement of the tundra group by the boreal group is quite consistent between the two analyses. The lost tundra group areas are on the northern slope of coastal Alaska, in Nunavut province, along the Arctic coasts of central Eurasia, and inland Siberia. In northwest Canada, there is also a region of lost coverage in tundra group indicated by the NCEP analysis (bottom, right panel), but it is smaller in the CRU analysis (top, right panel). The coverage of tundra group being replaced by boreal group are further supported by NDVI data, as discussed in the next section. Along the periphery of Greenland, except the northern part, some of the tundra group is replaced by perpetual frost, which indicates that the summer season climate became cooler in that region during the last 20 yr.

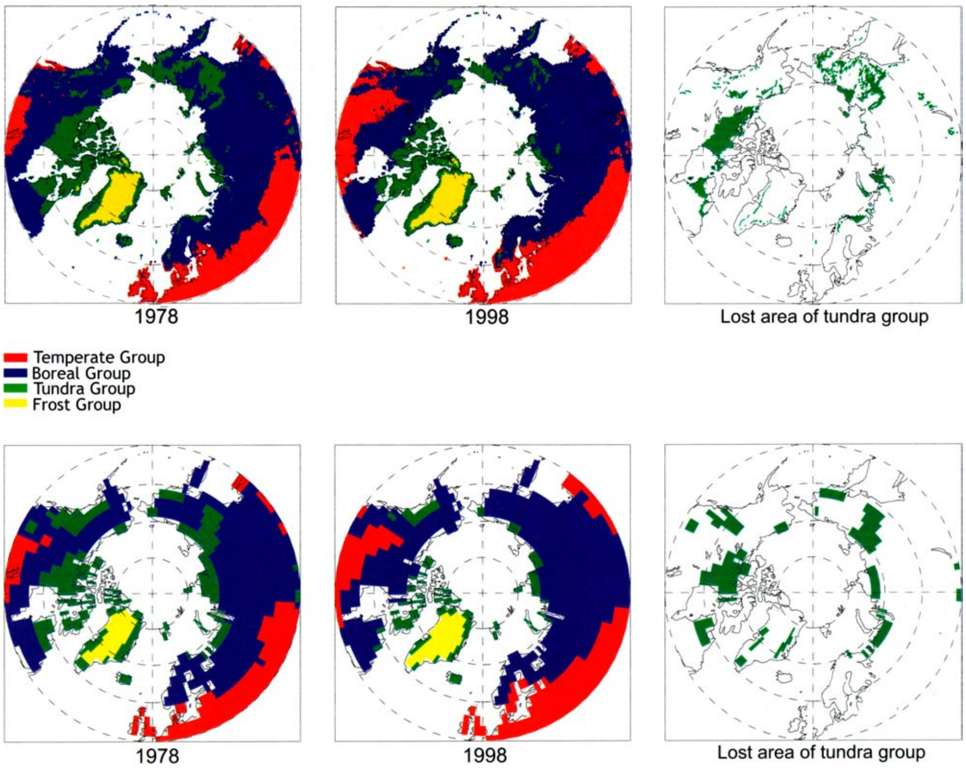

Figure 1. Spatial distribution of climate classifications for selected years. Green color indicates the tundra group, blue for boreal group, red for temperate group and yellow for perpetual frost group. The top panels are based on CRU and bottom ones are based on NCEP analyses. The left panels show the year of 1978, the middle ones are for the year 1998 and the right panels show the changes in area of tundra group between the two years.

By comparing both middle panels with those on the left in Figure 1, we also see that a significant portion of the boreal group (blue area) has been replaced by the temperate group (red area) between 50 to 60°N over both the North American continent and Eurasia continent. For the 2 yr selected, there is a fairly good agreement in the spatial patterns of the climate classifications between the two analyses.

Figure 2 shows the time series of the area coverage for each climate group in the Arctic region (50–90°N) based on the a one-sided two analyses with a one-sided 3-yr running mean applied. The use of 3-yr mean acknowledges that plant growth is not an instantaneous process. There is a weak trend toward reduced coverage of tundra group (Figure 2a, thick solid line) from the beginning of the century to 1940. From the early 1940s to the late 1970s, the area of tundra group varied with little overall trend. Both analyses indicate low coverage of tundra group in the middle of 1950s. Since the late 1970s large decreases are seen in the coverage of tundra group in both analyses. When a linear regression model is applied to the time series, linear trends of -7.6×10^4 km^2/yr (CRU) and -6.8×10^4 km^2/yr (NCEP) are found for

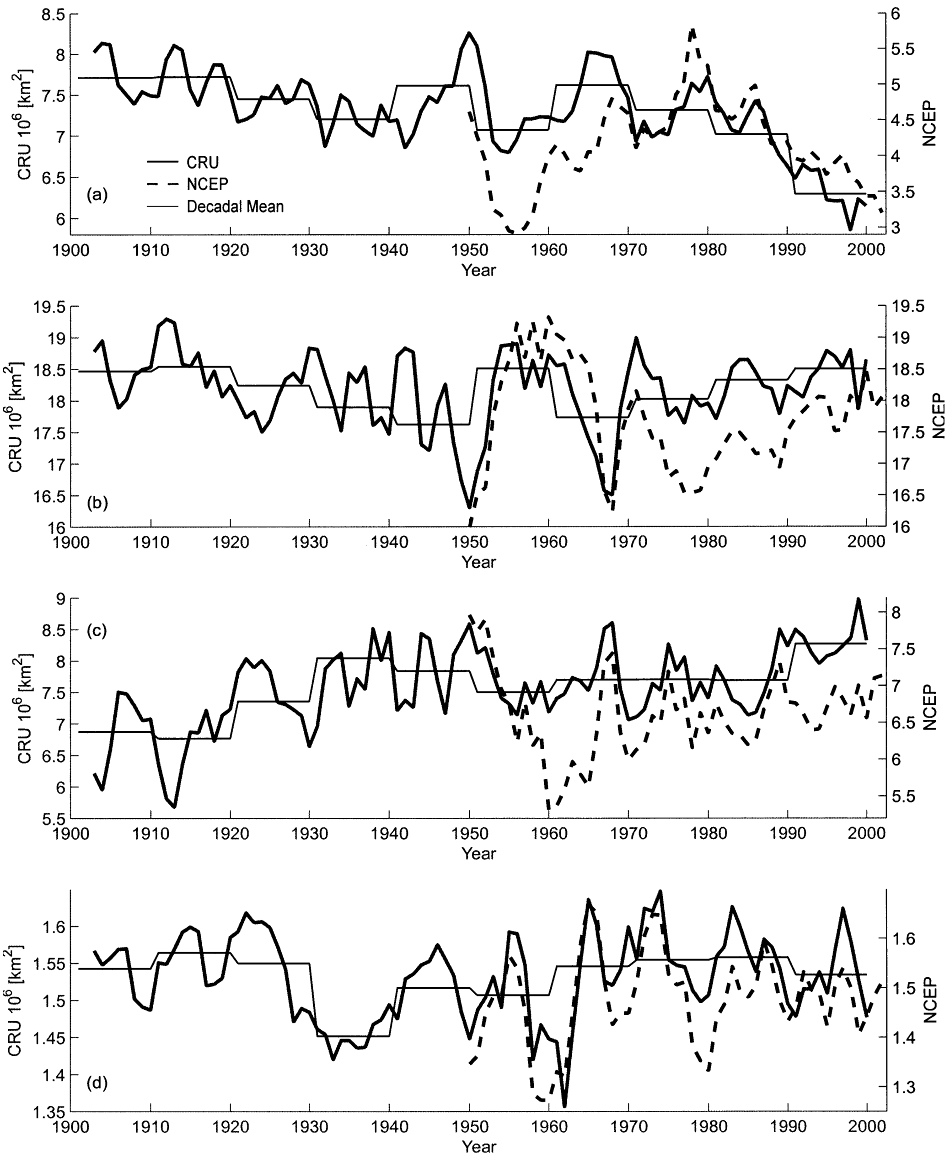

Figure 2. Time series of the area occupied by each climate group based on Köppen classification. The solid line is based on CRU analysis and the dashed one is based on NCEP/NCAR reanalysis. From top down, they are for (a) tundra group, (b) boreal group, (c) temperate group, and (d) frost group. The step-like thin solid lines indicate the decadal means for each group. The units are in 10^6 Km^2.

the last two decades. This is a reduction in tundra group coverage of close to 1.4×10^6 km^2 from 1980 to 2000 based on both data sets. Note the different scales on the left and right axes of Figure 2. The coarse resolution in NCEP analysis results has less total tundra group areal coverage than CRU analysis. This is in part because the total land area in NCEP analysis for 50–90°N is 86% of that in CRU analysis. Most of the missed land areas are along the Arctic coast, and in the Canadian archipelago, where the areas are classified as tundra group based on CRU analysis. This can be seen from the left and middle panels in Figure 1. Thus the percentage loss of the tundra group between 1980 and 2000 is substantial but different between the two analyses: 20% (CRU) and 28% (NCEP) from the 1970s decadal mean baseline.

A further analysis (figure is not shown) reveals that the discrepancy in the coverage of tundra group between CRU (thick solid line of Figure 2a) and NCEP (dashed line) during 1950 is due to the differences over east Siberia region. For about two decades, the CRU analysis depicts constant coverage of tundra group in East Siberia region, whereas NCEP analysis describes this region as the boreal group.

The boreal group (Figure 2b) covers more than 50% of the land area north of 50°N. The downward trend in the last 20 yrs shown in the tundra group (Figure 2a) is accompanied by an upward trend in the boreal group as seen in both data analyses (Figure 2b), although the slope is greater in NCEP (5.1×10^4 km^2/yr) than in CRU (1.0×10^4 km^2/yr) analysis. In the early 1900s, however, at the same period when the coverage of tundra group decreased, the coverage of boreal group also showed a decline (solid line in Figure 2b). The low coverage of the tundra group in the 1950s was accompanied by a sustained high value in boreal group in both analyses. A recent study by Overland et al. (2004b) based on station observations showed that the warm anomalies in SAT during 1920–50s are regional and happened predominately in winter and spring season. Our increase in the coverage of tundra group from 1940s to 1950s indicates that for vegetation, it is the threshold (10 °C in summer month in this case) rather than the magnitude of temperature anomalies which matter to the tundra group shifts.

The temperate group occupies about 22% of the land area north of 50°N (Figure 2c). Both analyses show upward trends in the area of the temperate group since 1970, but the slope for the last 20 yr is larger in CRU analysis (solid line in Figure 2c)—6.9×10^4 km^2/yr in CRU and 2.0×10^4 km^2/yr in NCEP analyses. Both analyses show similar variations during 1950 to 1970: a sharp decrease in the coverage of the temperate group, with minimum in the 1960s and then an increase in the coverage for about another 10 yr, with a peak value in 1969. The decrease in the temperate group during 1950s from both analyses coincides with a decrease in the tundra group and increase in the boreal group. On the other hand, an increase in the temperate group coverage occurred from 1900 to the 1940s, at the same period a decrease occurred in the tundra and boreal groups. These behaviors indicate that the climate system reacted differently during these two warming periods, and the reasons need to be further investigated.

The area of the perpetual frost group is less than 5% of the land cover in the polar region. Both CRU and NCEP analyses show a modest decrease with a trend of -3.0×10^3 km^2/yr from 1980 to 2000 (Figure 2d). However, the averaged area in the last 20 yr is only slightly less than that in the early 1900s.

In the last four decades, the decrease in the coverage of tundra group is accompanied by two types of changes in the other climate groups: from 1961 to 1990 it was accompanied by an increase in boreal area only, and from 1991 to 2000 it was accompanied by increases in the coverage of both the boreal and temperate group. This is clearly shown by the thin step-like solid lines in Figure 2, which are the decadal means (from CRU) for each climate group. This change is different from the early period of the century, when the decrease in the tundra group was accompanied by a decrease in the boreal group but an increase in the temperate group. The variations in the relationship between the coverage of tundra, boreal and temperate groups in the past 100 yr suggest that the warming regimes in 1990s are different compared with their earlier counterparts. The decadal means of tundra group in the 1940s and 1960s are close to its historical maximum in the 1910s (7.6×10^6 km^2 vs 7.7×10^6 km^2), a recovery from its minimum. However, the trend since the 1970s has the largest magnitude and greatest duration of the century.

3.2. REGIONAL CHANGES

Przybylak (2003) divided the Arctic into six climate regions plus the central Arctic. Overland et al. (2004b) analyzed an instrumental data set of 59 weather stations north of 64°N based on the Global Historical Climatology Network (GHCN) datasets and noted considerable differences in interdecadal temperature variability based on season and region, but major covariability within regions. Here we divide the Arctic into five sub-regions that generally overlap Przybylak's regions over land area:

1. Scandinavia/Eurasia, with longitude of 10°W–120°E,
2. Siberia, 120°E–170°W,
3. Northwest America covering 50–90°N, 170°W–80°W and 75–90°N and 80–70°W,
4. Northeast America of 50–70°N, 80–70°W, and 50–90°N, 70–40°W, and
5. Greenland/North Atlantic, 50–90°N, 40–10°W.

Figure 3 shows the anomalies of the area occupied by each climate group, based on a 100 yr mean for each sub-region. The frost type is not shown as it covers only a small land area, mostly in Greenland. For the same reason, the fifth sub-region (Greenland) is not shown, as only a small portion is tundra group, and its change in the past 100 yr is small.

In Scandinavia/Eurasia (Figure 3a) and NW America (Figure 3c) the variations of boreal and temperate groups dominate the past 100 yr. The two classified groups are negatively correlated (dashed and dotted lines, respectively), with a correlation of −0.94 over Scandinavia/Eurasia, and −0.70 over NW America. In Siberia (Figure 3b) the change between tundra (solid line) and boreal (dashed) groups dominates; the correlation of these groups is −0.95. Over NE America region (Figure 3d) the variations are similar to Siberia, but the amplitudes are small.

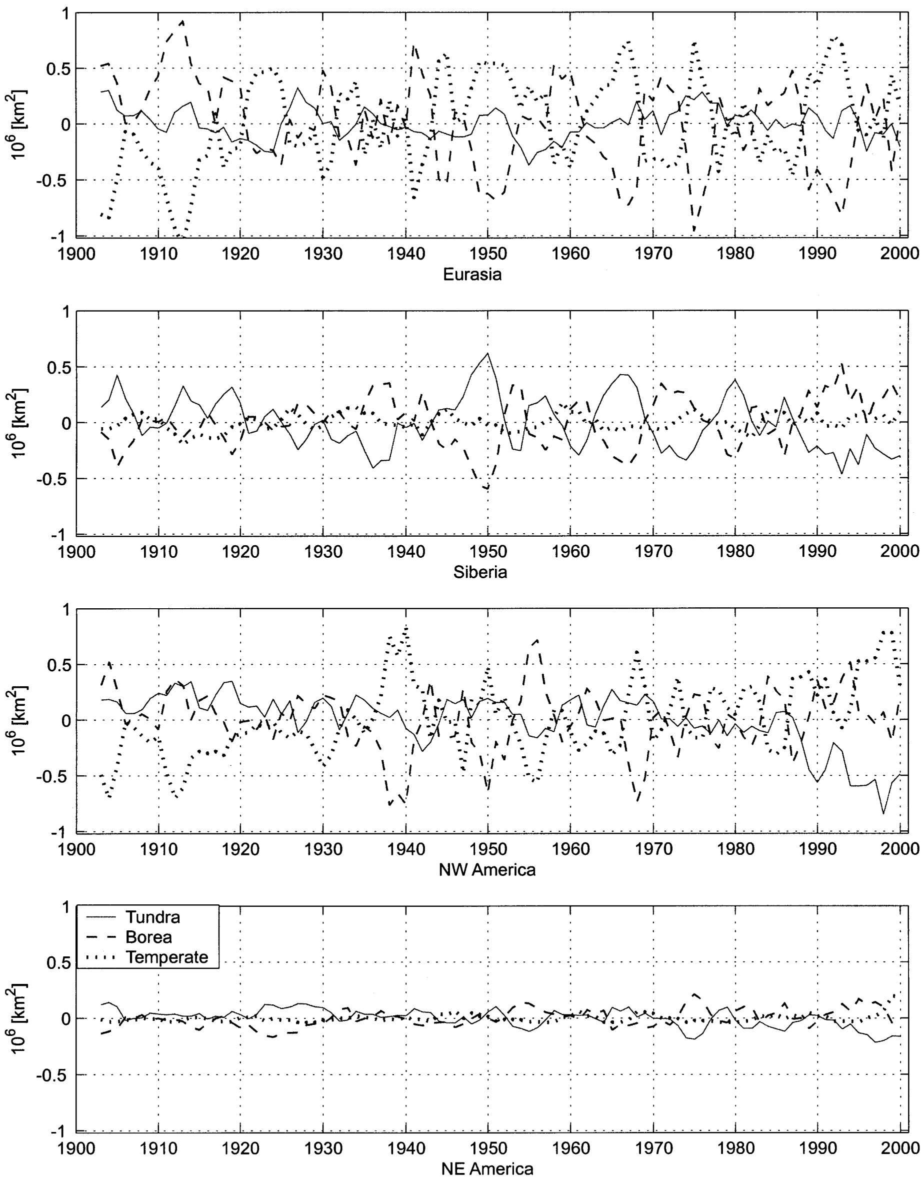

Figure 3. The anomaly of the area occupied by each climate group from its 100 yr mean for each sub-region. From top down, it is for (a) Scandinavia/Eurasia, (b) Siberia, (c) NW America and (d) NE America. The solid line indicates the tundra group, dashed line indicates the boreal group, and the dotted line indicates the temperate group. Units are 10^6 km^2.

Among all the four sub-regions, the tundra group has the largest variability over Siberia.

The decrease in the coverage of the tundra group in the first third of the 20th century was localized, primarily in Scandinavia/Eurasia. The North American sub-regions had little systematic changes. On the other hand, the decrease in the coverage of the tundra group in the last 30 yrs is pan-Arctic. Siberia and both regions of North America (Figures 3b to 3d) show a substantial decrease. The Scandinavia/Eurasia region shows only a modest decrease in the last 10 yrs (Figure 3a) as the total tundra group area is small in the second half of the 20th century.

The decrease in the areal extent of tundra group over the last three decades is consistent with recently published photographs regarding vegetation change in the Arctic. Shiyatov (2003) shows that significant spatio-temporal changes took place in the upper treeline ecotone in the Polar Ural Mountains (66–67°N, 65–66°E). By presenting several pairs of aerial pictures, Sturm et al. (2001) show that small bushes in the Alaska tundra have increased in size and number in recent decades. These photographs are intriguing evidence that changes have occurred in vegetation cover.

3.3. DISCUSSION

Figure 4 shows spring (April to June) and summer (July and August) time temperature anomalies averaged over the period of 1981 to 2000 based on CRU analysis. Comparing the warm anomalies from both seasons with the top right panel of Figure 1, we see that the maximum warm anomalies in the last 20 yr are located in Alaska, NW and northern part of Canada, over central Eurasia and lower part of east Siberia, and are generally not in the same location as the major regions with a decrease in the coverage of the tundra group.

To further contrast regions of the Arctic that experienced warming with change in tundra group coverage, we consider the fractional area that experienced significant warmth. Figure 5 shows the percentage of grid cells in the polar region (of total 25982 valid land points) where the temperature anomalies in both spring and summer are greater than one standard deviation. In the first three decades, there

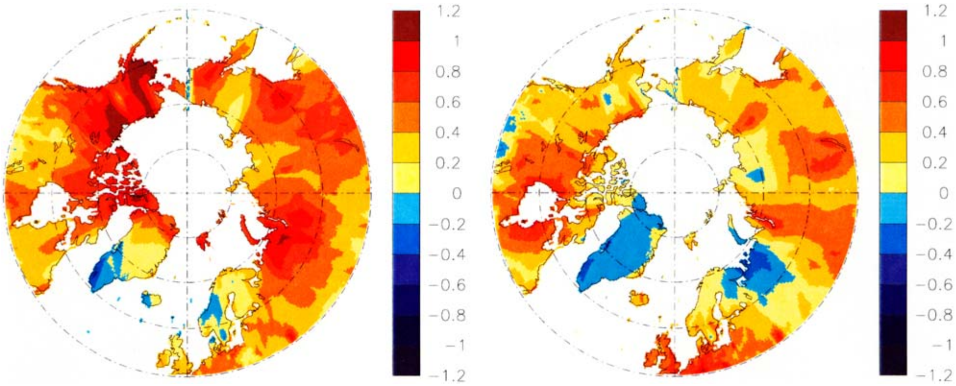

Figure 4. Temperature anomalies for the period of 1981–2000 based on CRU analysis averaged for spring (left panel) and summer (right panel) season.

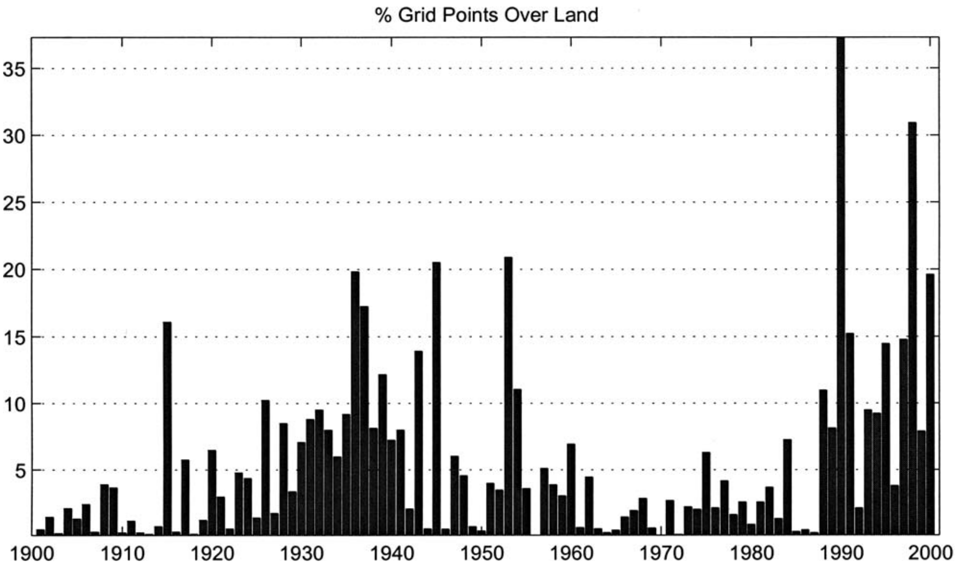

Figure 5. The ratio in percentage of land coverage with continuous strong spring and summer warm anomalies based on CRU data north of 50°N.

was only 1 yr that the fraction exceeded 15% and most of the years with values below 5%. The decadal averaged fractions are comparable in 1930s (10.6%) and 1990s (12.8%). These percentages support the hypothesis that it is the continuous warming during spring and summer in the 1990s and possibly the 1930s that results in the land cover changes. However, the largest values (greater than 30%) are in the 1990s: 1990 and 1997. It is possible that these 2 yr contribute to establishing the persistence of vegetation cover change over large areas of the Arctic.

To confirm our visual inspection of trends, we applied an objective method, the Haar wavelet analysis, to investigate the low frequency signature of the time series. The Haar wavelet analysis separates a time series into an orthonormal system of functions over different frequency bands and has the advantage of excellent time localization. When the Haar wavelet analysis is applied to the time series of the four classified vegetation groups for the last century, all wavelet variance estimates decay at a rate consistent with white noise, with exception of the tundra group series. Figure 6 shows the components of a maximal overlap discrete transform (MODWT) for the tundra group time series based upon Haar wavelet analysis with the original time series shown at the bottom. A residual $\tilde{V}_4$ series (top curve, Figure 6) nicely shows the overall downward trend and the increasing descending trend in the previous 20 yr. There is no apparent time variation in the higher frequency curves (W1 and W2). The tundra group series does have considerable variance at low frequencies however (W3 and W4), an indicator of a stochastic process with a long memory characteristics. Fitting a fractionally differenced model indicates that tundra group series has considerable autocorrelation at long temporal lags and

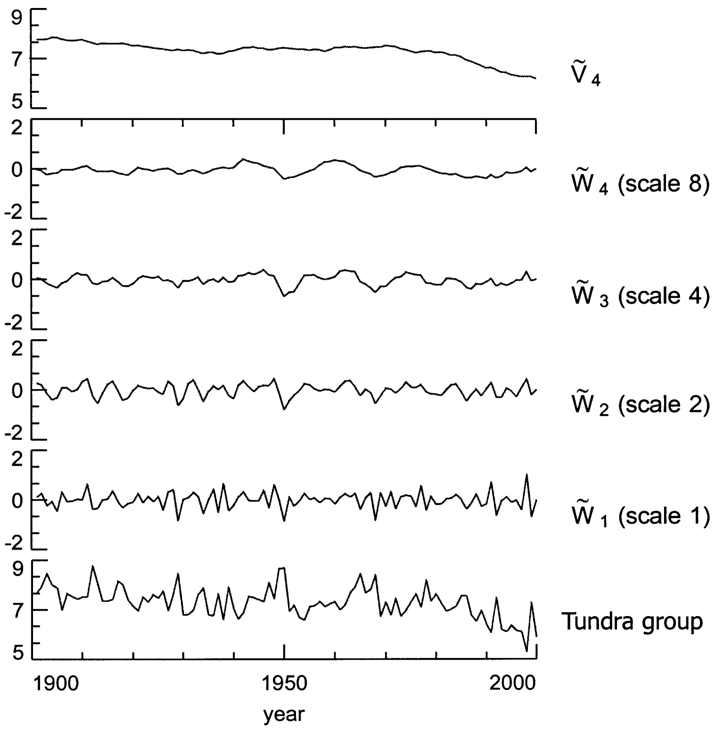

Figure 6. Haar wavelet analysis of the time series of the tundra group. The bottom curve shows the time series of the tundra group, the middle four curves show the decompositions for each frequency band, and the top curve is the residual.

a parameter value of $\delta = 0.3$ is found (Percival et al., 2002). The allowable range of δ is $0 < \delta < 0.5$ with 0.0 being white noise; therefore the value of $\delta = 0.3$ suggests moderate long memory, i.e., low frequency structure in the tundra group time series. Thus, even though we use temperature as an indicator for vegetation area, our tundra proxy has considerable multi-year to decadal structure.

4. Comparison with NDVI Data

More direct measures of the vegetation coverage, in particular the “greenness of the earth” is provided by the satellite-based NDVI. This time series begins in the early 1980s. By construction, NDVI is highly correlated with vegetation parameters (Justice et al., 1985). Zhou et al. (2001) analyzed the NDVI data over North America and Eurasia between 40–70°N produced by the Global Inventory Monitoring and Modeling Studies (GIMMS) group. They found that about 61% of the total vegetated areas between 40–70°N in Eurasia show a persistent increase in growing season NDVI over a broad contiguous swath of land from central Europe through Siberia to the Aldan plateau (N.E Siberia) during the period from July 1981 to December 1999.

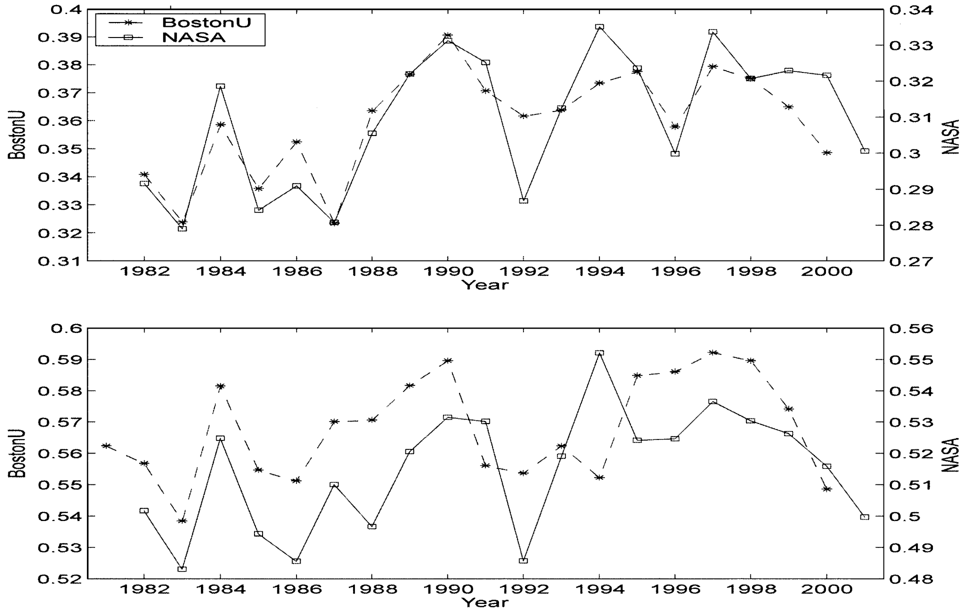

Figure 7. The spatially averaged NDVI value based on NASA (solid line) and BU3 (dashed line) data for the Arctic region (50–90°N). The top panel is for spring (April to June) and the bottom panel is for summer (July and August).

Figure 7 shows the spatially averaged NDVI based on NASA (solid line) and BU3 (dashed line) data for the Arctic region (50–90°N). NDVI is valid only during the growing season, from April to October. Here we show two seasonal means, which are relevant to our study: the spring (April to June) and the summer (July and August). The two NDVIs show similar interannual variability, for both seasons. However, the BU3 data tend to have larger values for both seasons and have smoother curves than the NASA data. The corrections to the 1991 Mount Pinatubo eruption in the BU3 data smoothed the time series by increasing the low value in the year 1992 in both spring and summer seasons. There was another volcanic eruption, El Chichon (Mexico) that occurred in the summer of 1982, but no smoothing technique was applied in either analysis. This may explain the low NDVI values in the following year, 1983, in both NASA data and BU3 data. For the previous 20 yr, the averaged spring NDVI is 0.36 (BU3) and 0.31 (NASA) north of 50°N. The averaged summer NDVI value is 0.57 for BU3, and 0.52 for NASA. Part of the reason for the higher values in the BU3 data is that most of the data north of 75°N are masked out during the correction procedure, whereas small NDVI values are found in the NASA data set. Myneni et al. (1997) point out that the GIMMS data were independently calibrated, and this different calibrating scheme affects derived trends in AVHRR data. The differences in the interannual variability and the decadal means suggest that NDVI values are quite sensitive to the procedures and processing methods of the original satellite data.

TABLE II
The correlations of NDVI and climate classification groups

	Boreal + Temperate		
	CRU/NASA	CRU/BU3	NCEP/NASA
Arctic region (50–90°N)	0.71[a]	0.47[b]	0.58[a]
North America (170°W–60°W, 50–75°N)	0.61[a]	0.61[a]	0.49[b]
Eurasia (10°W–170°W, 50–75°N)	0.45[b]	0.16	0.20

[a] The letter a next to the number indicates that it passed statistical test with 99% confidence.
[b] Indicates that is passed the test at 90% confidence level.

Table II lists the correlation coefficients between the domain averaged NASA/BU3 NDVI values and the combined boreal and temperate groups from climate classification based on CRU and NCEP analyses for the Arctic region, the North America and Eurasia continents, respectively. Four of nine numbers in Table II passed a statistical significant test with 99% confidence and another three passed with 90% confidence. The area of boreal and temperate groups are positively correlated with NDVI values. This is true not only over the Arctic region, but also on individual continents. Due to the coarse spatial resolution in NCEP analyses, the classified vegetation groups correlate with the domain averaged NASA NDVI values at lower confidence level compared with CRU analyses, as seen in Table II (column 4). The correlations between BU3 and the classified groups from NCEP analyses are weak and only the correlations for North America passed the 90% confidence level test (numbers are not shown). This may in part due to smoothing of the data. Zhou et al. (2001) found a photosynthetically vigorous Eurasia in comparison to North America between 1982 and 1998. We found that the correlation between the classified groups and the NDVI over North America is higher than that over Eurasia continent from both analyses. Since the calibration of reflectance in AVHRR channels is regionally dependent, this may in part contribute to the different correlations seen in Table II. The variation in the correlation of regional domain averaged NDVI with the Köppen classification suggests a need for additional research on the vegetation changes in the Arctic. This is especially important due to the lack of data on vegetation type and distribution in the historical record.

For visual comparison of Köppen classification with NDVI, the left panel in Figure 8 displays the decadal averaged vegetation distribution (1991–2000) based on CRU data using the Köppen classification, and the middle panel is the climatology of the NASA summer (July and August) NDVI for the last 20 yr (1981–2000). Comparison of the panels supports the concept that areas of the tundra group are generally indicated by NDVI values of 0.1–0.4 (blue color) in Figure 8b, in agreement with the Köppen classification in Figure 8a (green color), especially along the Arctic coasts in both continents, in the Canadian archipelago and along the

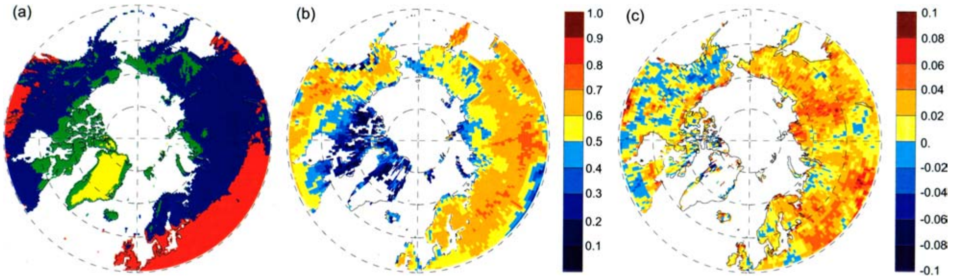

Figure 8. (a) The spatial distribution of Köppen climate classification based on CRU data averaged for the last decade (1991–2000). The color code is the same as in Figure 1. (b) The summer month (July and August) climatology (1981–2000) of the NASA NDVI (c). The change of NDVI based on 10 yr means for 1990s minus 1980s.

west coasts of Greenland. Tundra area calculated from Figures 8a and 8b are also in agreement with Circumpolar Arctic Vegetation Map (CAVM Team 2003). The areas of boreal and temperate group have distinct boundaries based on Köppen classification (Figure 8a), but grid cells of boreal and temperate groups are intermixed in the NDVI values (Figure 8b). A second issue is that in the midlatitudinal zone (45–55°N), the use of only thermal criterion in the Köppen classification may not be sufficient; precipitation should be included in the climate classification to distinguish different tree types, or the sub-groups within the major climate groups and to account for temporal differences in their photosynthetic activity. However, since the magnitude of NDVI is related to the level of photosynthetic activity, it may be more difficult to distinguish between the boreal and temperate zones during the summer from satellite data.

Over much of Eurasia (Figure 8c) the NDVI values have increased in the 1990s (1991–2000) compared with the 1980s (1981–90), while over North America, there are quite large areas with decreased NDVI values. Similarly, Zhou et al. (2001) found that NDVI decreased in parts of Alaska, boreal Canada, and northeastern Asia from the 80s to the 90s. They attribute this decrease to temperature-induced drought in these regions. The orange to light red color in Figure 8c indicates an increase of 0.02–0.06 in NDVI values. Comparing Figure 8c with Figure 8b, we see that a significant portion of this increase in NDVI is located in the tundra areas of Northern Alaska, the Canadian archipelago, Northeast Siberia, and along the Arctic coastlines of the central Eurasian continent.

Figure 9 shows the time series of the tundra areas based on NASA NDVI values of 0.1–0.4 (solid line with X) together with the CRU (solid line with diamond) and the NCEP (dashed line with square) tundra group time series with 3-yr running mean applied for the last 20 yr. Similar downward trends are seen from all three analyses. A linear trend of -5.8×10^4 km^2/yr is found for the NDVI tundra area coverage. The NDVI depicted tundra series correlates with the other two tundra curves at 0.69 (CRU) and 0.73 (NCEP), respectively, with

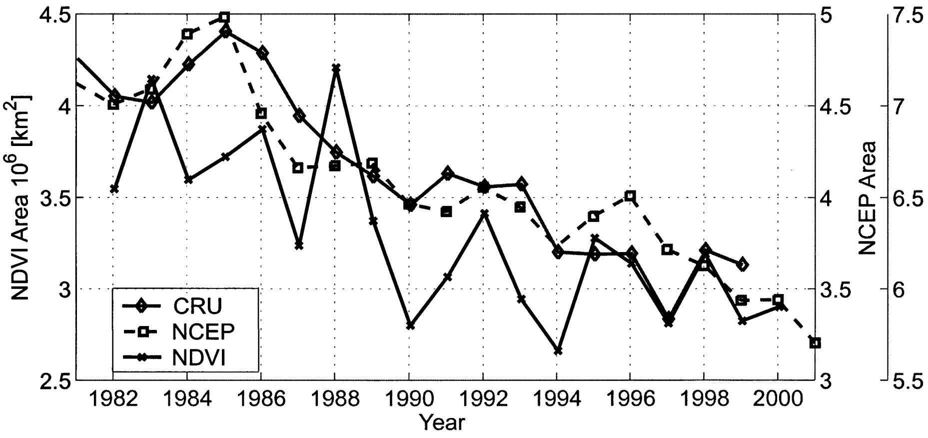

Figure 9. The coverage of the tundra group for the last 20 yrs based on NDVI (solid line with X) values 0.1–0.4 and Köppen classification of CRU (solid with diamond) and NCEP (dashed with square) analyses. Units are 10^6 km^2. The time series based on CRU and NCEP have 3-yr running mean applied.

99% confidence level for the period 1982–2000. The 2001 NDVI value is not included in the calculation as the AVHRR pathfinder NDVI values after 2000 are unreliable, because orbital shifting and other factors might be serious (Myneni, personal communication). Similarly, the areas of combined boreal and temperate groups based on Köppen classification correlate with those of NDVI values of 0.4 to 0.9 at 0.54 (CRU) and 0.47 (NCEP) with 99% confidence level. A slightly lower correlation is found if the unsmoothed Köppen classification time series is used.

5. Concluding Remarks

The potential impact of vegetation changes in the Arctic region to feedbacks on the atmospheric climate system is substantial because of the large surface area impacted and the multi-year persistence of the vegetation cover. Using Köppen climate classification based on SAT and satellite NDVI, a significant decrease (on the order of 20% based on CRU) in the coverage of tundra group has occurred since 1980. This agrees with anecdotical observations in the Arctic region of expansions of shrub tundra into regions that used to be occupied by sedge tundra, and of boreal forest into regions that used to be occupied by tundra (Sturm, et al., 2001, Shiyatov, 2003). The consequences of the vegetation change traps snow, providing greater insulation to the surface and warmer ground temperature during winter and early spring, reduces the growing season albedo, increases spring and summer energy absorption, and enhances atmospheric warming. Masking of snow cover by increased shrubbiness accelerates springtime snow melt and the transition to the summer regime.

We make use of monthly temperature of the warmest months as a proxy for vegetation cover. Comparison with the NDVI shows that this assumption is reasonable. It is expected that vegetation has memory on longer time scales than temperature, although NDVI shows considerable interannual variability. The multi-year character of our tundra proxy is evident from the wavelet analysis. An important feature of our analyses is that the regions identified as changing area of the tundra group based on the $<10\,^{\circ}$C monthly temperature requirement are different from the regions of maximum temperature trends. Thus, our vegetation proxy is not simply an alternate for general Arctic warming. For vegetation change it is this temperature threshold, rather than the magnitude of the anomalies, which matters.

In the Arctic region, the area of the tundra group shows significant change in the last 100 yr based on CRU data. The areas of tundra group have decreased several times, and then recovered from its low values in the past century. However, since the late 1970s, there is only a downward trend. For the last 20 yr, the reduction carries a linear trend of -7.6×10^4 km^2/yr (-6.8×10^4 km^2/yr from NCEP and -5.8×10^4 km^2/yr from NASA NDVI), which represents about a 20% (CRU) or 1.4×10^6 km^2 decrease from 1980 to 2000 in the coverage of the tundra group. The other major difference is that decreases earlier in the century are more regional in character, while the recent changes are pan-Arctic. Given the persistence of the recent changes, this study supports the potential for multi-decadal consequences to ecosystems and human activities in the Arctic.

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