

## Higher Northern Latitude NDVI and Growing Season Trends from 1982 to 1999

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**Abstract** Normalized difference vegetation index data from the polar-orbiting National Oceanic and Atmospheric Administration meteorological satellites from 1982 to 1999 show significant variations in photosynthetic activity and growing season length at latitudes  $> 35^{\circ}$  N. Two distinct periods of increasing plant growth were apparent: 1982 to 1991 and 1992 to 1999, separated by a reduction from 1991 to 1992 associated with global cooling resulting from the volcanic eruption of Mt. Pinatubo in June 1991. Average May to September normalized difference vegetation index from  $45^{\circ}$  to  $75^{\circ}$  N increased +9% from 1982 to 1991, decreased -5% from 1991 to 1992, and increased +8% from 1992 to 1999. Variations in normalized difference vegetation index were associated with variations in the start of the growing season of -5.6, +3.9, and -1.7 days, respectively, for the three time periods. Our results support surface temperature increases within the same time period at higher northern latitudes where temperature limits plant growth.

**Keywords** Growing Season · Phenology · Photosynthesis · Climate Change · Time Series · Northern Latitudes

### Introduction

Controversy continues over possible climate change caused by global warming due to the build up of "greenhouse" gases in our planet's atmosphere with major economic consequences for the world economy (Hansen et al. 1998). Satellite data provide one information source that can measure environmental variables to determine if the climate system is stable or changing through time.

Published research on a range of topics strongly suggests recent warming-influenced changes in the northern hemisphere. Atmospheric CO<sub>2</sub> concentration measurements suggest increases in plant growth at higher northern latitudes and an earlier growing season start (Keeling et al. 1996; Randerson et al. 1999). This is consistent with reported increased winter and spring temperatures (Rigor et al. 2000; Hansen et al. 1999; Oechel et al. 2000), reduced snow cover extent in the northern hemisphere (Groisman et al. 1994), reductions in arctic sea ice (Chapman and Walsh 1993; Parkinson et al. 1999), increases of global ocean temperatures (Levitas et al. 2000), phenological measurements from European herbaria (Menzel and Fabian 1999), biological reports of earlier bird breeding and related factors (Brown et al. 1999; Bradley et al. 1999), and satellite studies of increased plant growth and a longer growing season at northern latitudes from 1981 to 1991 (Myneni et al. 1997 and 1998).

We extend our earlier Myneni et al. (1997 and 1998) satellite work from 1981 to 1991 by adding data from 1992 to 1999. We document variations in normalized difference vegetation index, and hence gross photosynthesis, at northern latitudes where surface temperature is a major limiting factor on plant growth.

## **Methods**

We processed the July 1981 to December 1999 daily global satellite record of 4-km data from the advanced very high resolution radiometer instruments carried by the National Oceanic and Atmospheric Administration's (NOAA) polar-orbiting meteorological satellites. Data from channel 1 (0.55-0.68  $\mu\text{m}$ ) and channel 2 (0.73-1.1  $\mu\text{m}$ ) were used to calculate the normalized difference vegetation index (NDVI). Data from NOAA-7 (1981-1985), NOAA-9 (1985-1988), NOAA-11 (1988-1994), NOAA-9 (1994-1995 from the descending node with ~0900 hours local solar overpass time), and NOAA-14 (1995-1999) were used.

Daily AVHRR 4-km data were processed and the normalized difference vegetation index was formed from Channel 1 and channel 2 as  $(2-1)/(2+1)$ . We use the NDVI as a surrogate for photosynthetic capacity, as this spectral measure is highly correlated to the absorbed fraction of photosynthetically-active radiation and thus gross

photosynthesis (Sellers 1985; Asrar et al. 1984; Myneni et al. 1995).

A total of ~40,000 orbits of AVHRR daily data were used from 4 NOAA satellites. The satellite data were mapped into two different Albers equal-area projections: (1) two composite images per month with a grid cell size of 8-km, formed from day 1 to day 15 and from day 16 to the month's end; and (2) a 7-day composite data set with a grid cell size of 11.2-km. The twice-monthly data were used to determine average growing season photosynthetic activity, as cloud contamination is less in ~15-day composite images. The 7-day composite images were used to determine growing season start and end.

The mapped data were formed into composite images, visually checked for navigation accuracy, remapped if necessary, and assembled into a time series. Formation of maximum value NDVI composite images minimizes atmospheric effects, scan angle effects, cloud contamination, and solar zenith angle effects without having to resort to an explicit atmospheric correction (Holben 1986). Calibration coefficients were applied after Los (1998). A time- and latitude-varying atmospheric correction was applied for the El Chichon (1982-1984) and Mt. Pinatubo (1991-1993) stratospheric aerosol periods (Tucker et al. 2001). The resulting data were coherent and transitions between satellites were non-existent (figure 1).

NDVI trends over time were determined by averaging the aggregated data within latitude zones by year. Growing season length was determined by a two-step procedure. First, growing season temporal profiles were determined using singular value decomposition over 1° x 1° areas using forty 7-day composite NDVI images for each year. The aggregation to 1° x 1° areas is necessary to smooth the data and minimize variability. The NDVI temporal profiles are parameterized using a technique developed by Badhwar (1982, 1984) for identifying the start, rate of growth, peak, and end of the growing season:

$$\text{Log(NDVI)} = \log(P_1) + P_3(\log(\text{time}) - \log(P_2)) + P_4(P_2^2 - \text{time}^2) \quad (1)$$

where  $P_1$  is displacement of the NDVI vs. time curve,  $P_2$  provides an approximation of the start and end of the growing season,  $P_3$  is related to the magnitude or peak value, and  $P_4$  is the rate of growth or decline of the

growing vegetation (Badhwar 1982 and 1984). To obtain the end of the growing season, each NDVI temporal profile was "cut" in half, and the later half analyzed in a similar fashion to the earlier portion to determine the end of the growing season.

After the  $P_2$  values were determined for the  $1^\circ \times 1^\circ$  grid cells, support vector regression was used to apply the  $P_2$  values to each of the 11.2 km grid cells within the larger  $1^\circ$  square cell. The support vector regression method is an approach for performing classification/regression which represents the combination of two older ideas; the maximum margin method from the empirical analysis domain and the kernel method from the pattern recognition domain (Drucker et al., 1997; Vapnik, 1997). Using support vector regression, it is possible to first transform the original data by a non-linear transformation to a higher dimensional space with a very modest computational cost. The NDVI image time series is then projected into this higher dimension space through the support vectors and an approximate  $P_2$  for each 11.2 km pixel is determined. Growing season length is computed from these  $P_2$  values. A low pass filter was subsequently applied to smooth the resulting  $P_2$  determinations because of residual clouds and other artifacts in the 7-day composites.

## Results

The integrity of the NDVI data was evaluated for calibration errors by comparing time series measurements from desert areas from  $20^\circ$  to  $40^\circ$  N (figure 1). The average slope for the two desert regions was  $<0.00012$  NDVI units year<sup>-1</sup> or  $\sim 0.002$  NDVI units over the 18 years in our study. We feel our third-generation reprocessed data set overcomes the problems identified by Gutman (1999) for the first-generation Global Vegetation Index NDVI data set produced by NOAA for 1985-1998. A recent analysis of solar zenith angle effects by Kaufman et al. (2000) supports our contention that we have minimized this effect in our new data set.

We analyzed May-September average NDVI values north of  $25^\circ$  N from 1982 to 1999. Two periods of increasing NDVI with time were apparent: 1982 to 1991 and 1992 to 1999, separated by a marked decrease in NDVI from 1991 to 1992 (Figure 2 and Table 1). The 1991 to 1992 NDVI decrease was associated with a cooling of the northern hemisphere caused by the eruption

of Mt. Pinatubo in June 1991 (Hansen et al. 1999). The NDVI decrease was apparent from 45° to 75° N.

From 1982 to 1991 for 35° to 75° N, the average May-September NDVI increased +6% to +9%, depending upon latitude zone. The greatest zonal NDVI increase was +11% and occurred in North America in the 55° to 65° N latitude band (table 1). Canada, Europe, and Russia were most affected (figure 3a).

A marked May to September -5% NDVI decrease from 1991 to 1992 occurred from 45° to 75° N (figure 2 and Table 2). This decrease was more pronounced from 55° to 65° N (-6%) and 65° to 75° N (-8%), and most pronounced in North America from 55° to 65° N (-10%). North America was affected to a greater extent than Eurasia in these latitude zones for 1992 when compared to 1991 (figure 3b and Table 1).

Average May to September NDVI recovered and increased progressively from 1992 to 1999. Average NDVI increased +5% to +10% depending upon latitude zone. A larger area of Eurasia than North America experienced these NDVI increases, although the greatest average latitude zone increase (+15%) occurred from 65° to 75° N in North America; Newfoundland was an area of great increase (figure 3c and Table 1). Adding figures 3a, 3b, and 3c indicated Eurasia was the area most affected from 1982 to 1999 (figure 3d).

## **Discussion**

Our satellite data analysis is consistent with other published reports on variations in growing season length. Analyses of CO<sub>2</sub> flask data from Pt. Barrow, Alaska have suggested increased early season photosynthesis (Keeling et al. 1995, 1996; Randerson et al. 1999). An earlier start of the growing season explained most of the growing season variation in our satellite analysis (Table 2).

From 1982 to 1991 for 45° to 75° N, the growing season started earlier  $6 \pm 1$  days by 1991. The earliest start by 1991 was  $-8 \pm 1$  days from 55° to 65° N within Eurasia. By 1991 the growing season had been extended by  $10 \pm 1$  days for Eurasia in the same latitude zone (table 2).

The growing season started later in 1992 than in 1991, with an average later start from 45° to 75° N of  $4 \pm 1$  days; similar later starts between 1991 and 1992 were found for

all latitude zones  $>45^{\circ}$  in both North America and Eurasia (table 2).

From 1992 to 1999 the  $45^{\circ}$  to  $75^{\circ}$  N growing season started earlier in 1999 by  $2 \pm 1$  days on average;  $65^{\circ}$  to  $75^{\circ}$  N latitude zone in North America had the earliest 1999 start of  $4 \pm 1$  days.

We show increased photosynthetic activity and an earlier start to the growing season at high northern latitudes from 1982 to 1991 and 1992 to 1999. This evidence supports previous reports that increased early season ecosystem photosynthesis explains recent changes in the seasonal cycle of atmospheric  $\text{CO}_2$  at these latitudes (Keeling et al. 1996; Randerson et al. 1999). Zhou et al. (2001) has recently reported high correlations between our higher northern latitude NDVI data and the Hansen et al. (1999) surface temperature data. We show a reduction in NDVI and a later start to the growing season in 1992 from 1991, caused by the temporary global cooling resulting from the Mt. Pinatubo volcanic eruption. The combination of effects from 1982 to 1991, 1991 to 1992, and 1992 to 1999 most greatly affected Eurasia and not North America (figure 3d), largely because of a greater reduction in the 1992 NDVI in North America (figure 3b). This suggests greater gross photosynthesis in Eurasia than North America for the later 1990s than the early 1980s.

## **Conclusions**

Both 1982-1991 and 1992-1999 were two distinct periods of increasing satellite NDVI values, punctuated by a substantial decrease from 1991 to 1992. We conclude higher northern latitude vegetation is responding to warmer temperatures and starting the growing season earlier and continuing the growing season longer. This was interrupted by the eruption of Mt. Pinatubo in 1991, but had recovered by the late 1990s. Our analysis strongly supports a variety of different reports in the literature of an earlier start and later end to the growing season at higher northern latitudes directly linked to increasing surface temperatures.

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## Tables and Figure Captions

Table 1. Average May to September normalized difference vegetation index trends from 1982 to 1991, 1991 to 1992, and 1992 to 1999 in %. The values given for 1982 to 1991 and 1992 to 1999 are the change from the start of the period to the end of the period, using the regression equations in figure 2. The change for 1991 to 1992 is the difference between these years. \* denotes >98% significance and + denotes 95-98% significance; all other values are significant at the 95% level.

Table 2. Start of the growing season and length of growing season determined from 11.2 km grid cell data formed into 7 day composites. Negative numbers denote an earlier start or shorter growing season; positive numbers indicate a longer growing season or later start. We estimate the error of our determinations to be  $\pm 1$  day.

Figure 1. Time series normalized difference vegetation index data from  $45^{\circ}$  to  $75^{\circ}$  N, from the Taklamakan Desert ( $40^{\circ}$  N &  $85^{\circ}$  E), and from the Arabian Desert ( $25^{\circ}$  N &  $40^{\circ}$ E) are plotted from July 1981 through October 1999. The slope of the time plot for the Taklamakan Desert is 0.00001 NDVI units per year while the slope for the Arabian Desert is 0.000006 NDVI units per year.

Figure 2. Plots of zonally-averaged NDVI data from 1982-1999 for Eurasia, North America, and the northern hemisphere for the May-September time period. See table 1 for a summary of the percentage change associated with this figure.

Figure 3. Northern hemisphere plots of NDVI change 1982 to 1999 showing the areas of greatest NDVI increase. (a) 1982-1991; (b) the 1991-1992 cooling; (c) 1992-1999; and (d) the summation of figures 3a + 3b + 3c. Refer also to figure 2 and table 1.

Table 1.

## May-September NDVI trends

### Percent Change

Region	Period	Latitude North				
		35-45	45-55	55-65	65-75	45-75
Global	1982-1991	5.7*	8.7*	9.4*	7.4*	8.7*
	1991-1992	0.3	-2.8	-6.3	-7.8	-5
	1992-1999	4.9*	5.5*	9.4*	9.7*	7.6*
Eurasia	1982-1991	7.8*	9.0*	9.0*	7.8*	8.8*
	1991-1992	0	-1.2	-5.1	-7.7	-3.9
	1992-1999	5.1*	3.9+	9.0*	7.9*	6.5*
North America	1982-1991	2.9+	8.0*	10.5*	6.5+	8.6*
	1991-1992	0.9	-6.3	-9.9	-7.8	-7.8
	1992-1999	4.6+	8.7*	10.4*	14.9*	10.1*

### Slope

Region	Period	Latitude North				
		35-45	45-55	55-65	65-75	45-75
Global	1982-1991	0.2	0.38	0.41	0.24	0.36
	1991-1992	0.001	-0.012	-0.027	-0.025	-0.02
	1992-1999	0.22	0.32	0.54	0.42	0.42
Eurasia	1982-1991	0.22	0.38	0.41	0.28	0.37
	1991-1992	0	-0.005	-0.023	-0.027	-0.016
	1992-1999	0.2	0.23	0.55	0.38	0.37
North America	1982-1991	0.14	0.38	0.4	0.18	0.34
	1991-1992	0.004	-0.029	-0.037	-0.02	-0.03
	1992-1999	0.29	0.53	0.51	0.5	0.52

Table 2.

A. Variation in Length of growing season (days), from start of time period to end (I.e., 1982 to 1991, etc.)

Land Area	Latitude Zone (degrees)				
	35-45	45-55	55-65	65-75	45-75
Northern Hemisphere					
1982-1991	-1.0	1.2	6.9	3.1	3.9
1991-1992	0.5	-0.8	-5.0	1.5	-2.0
1992-1999	-3.5	-0.9	2.4	-0.8	0.4
Eurasia					
1982-1991	0.9	1.0	10.2	2.8	5.0
1991-1992	-3.0	0.0	-8.0	1.0	-3.0
1992-1999	-0.7	-1.3	4.3	-1.5	0.9
North America					
1982-1991	-2.7	2.3	4.0	3.8	3.3
1991-1992	4.0	-1.5	-2.0	2.0	-1.0
1992-1999	-6.2	-0.5	0.5	0.0	0.0

A. Variation in start of growing season (days), from start of time period to end (I.e., 1982 to 1991, etc.)

Land Area	Latitude Zone (degrees)				
	35-45	45-55	55-65	65-75	45-75
Northern Hemisphere					
1982-1991	-5.5	-5.8	-6.9	-2.2	-5.6
1991-1992	1.0	2.3	6.3	2.5	3.9
1992-1999	-0.1	-0.9	-2.0	-2.4	-1.7
Eurasia					
1982-1991	-3.2	-4.7	-8.2	-0.7	-5.3
1991-1992	4.0	2.0	5.5	3.0	3.6
1992-1999	-1.0	-3.3	-2.7	-1.1	-2.6
North America					
1982-1991	-7.8	-7.8	-5.5	-3.2	-5.9
1991-1992	-2.0	2.5	7.0	2.0	4.2
1992-1999	0.9	1.4	-1.3	-3.8	-0.7

Figure 1: Averaged NDVI time series

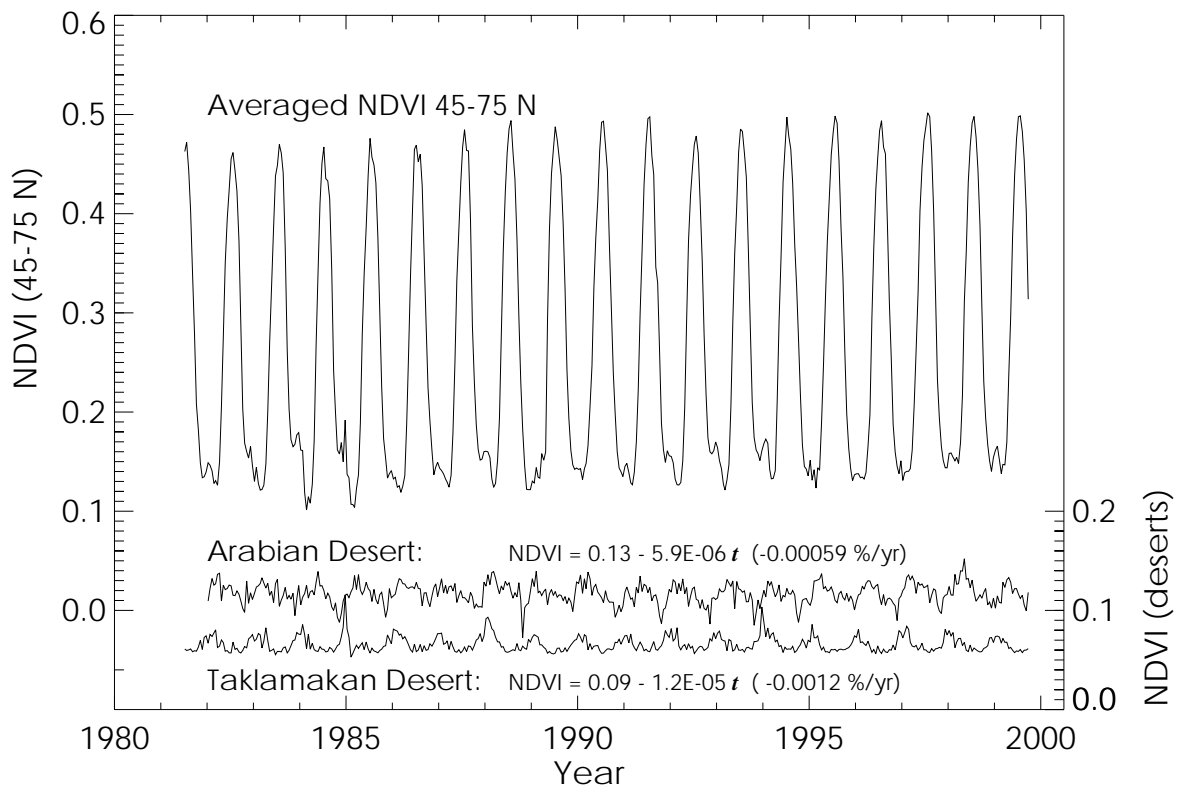
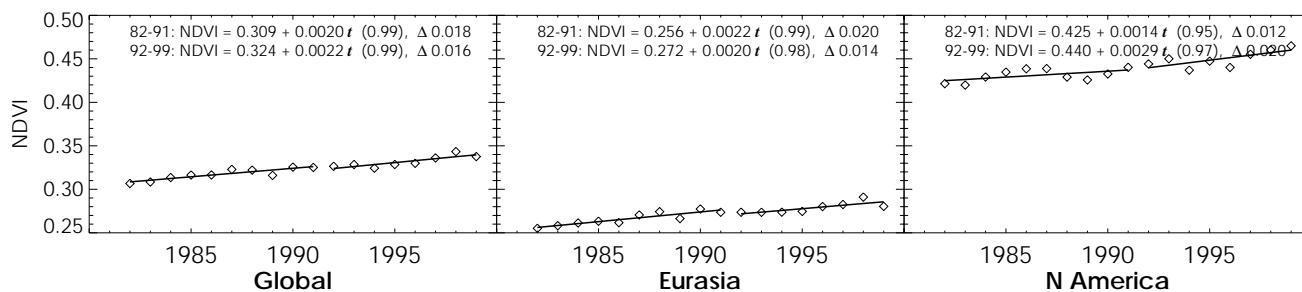
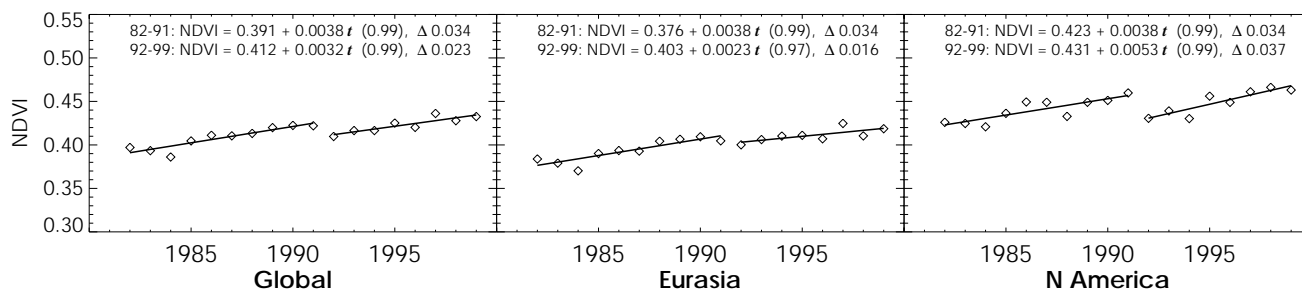


Figure 2: May - September average NDVI by year

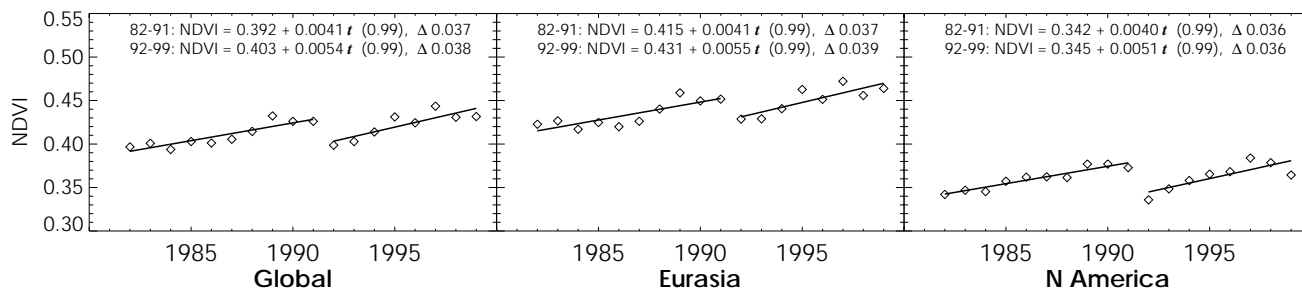
35 - 45 N



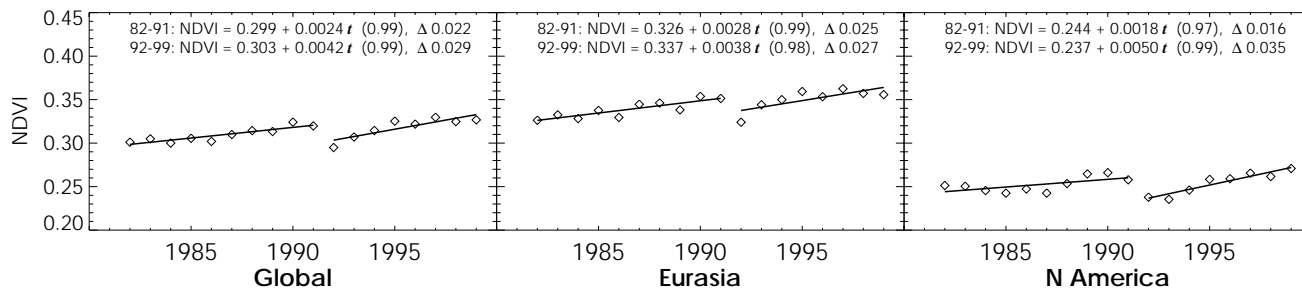
45 - 55 N



55 - 65 N



65 - 75 N



45 - 75 N

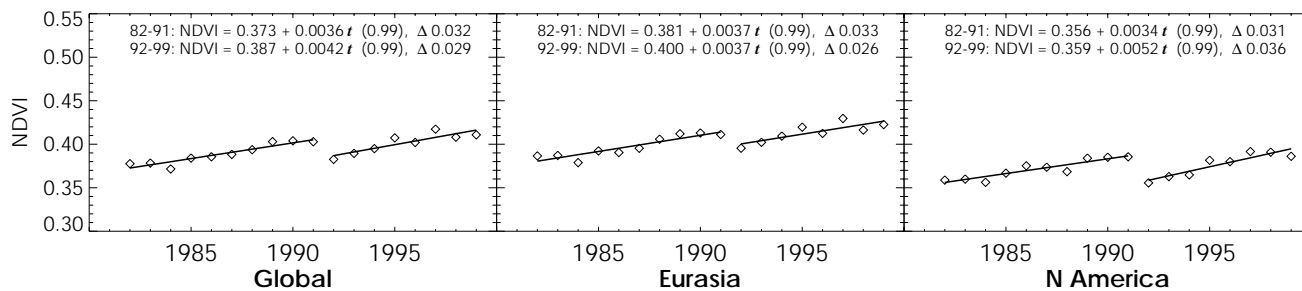
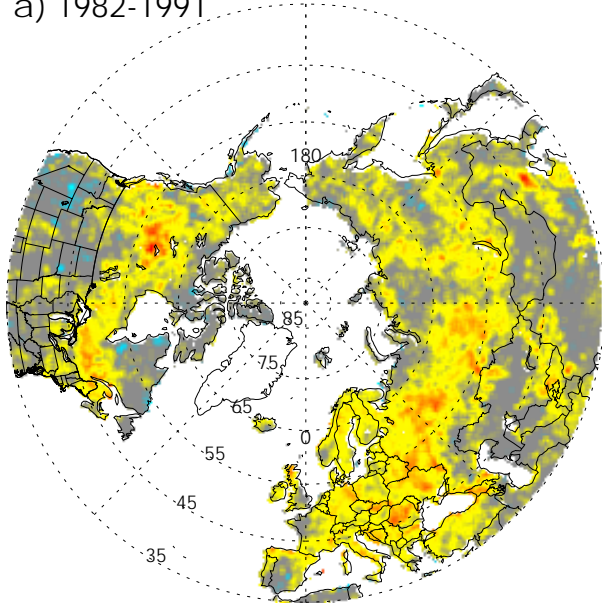
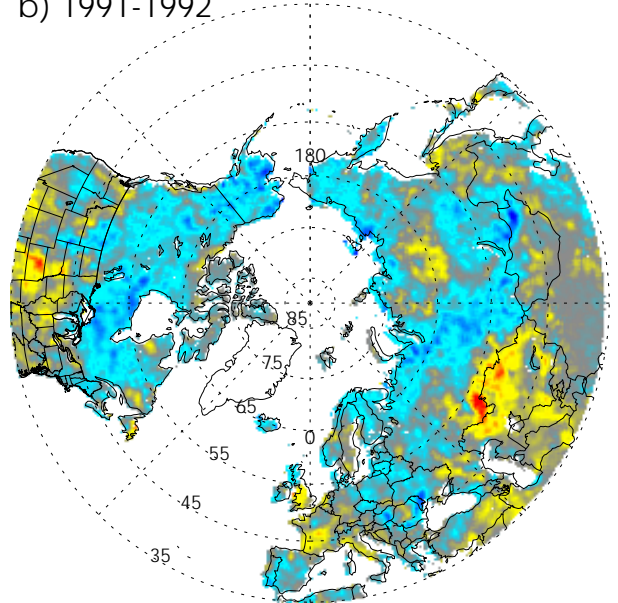


Figure 3: May-September NDVI trends

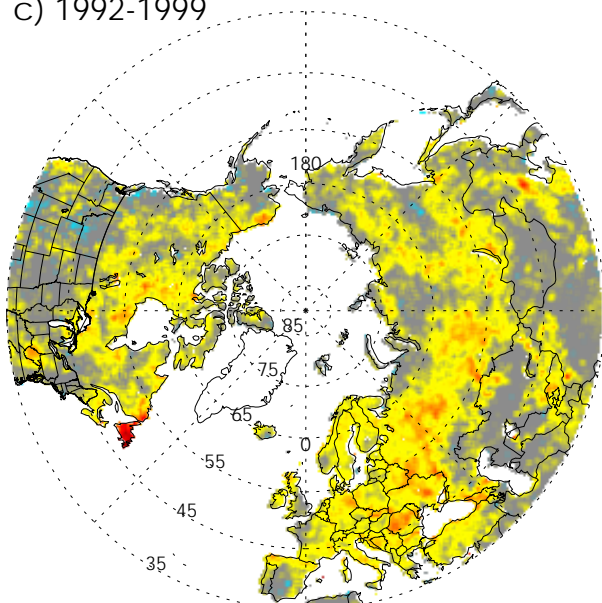
a) 1982-1991



b) 1991-1992



c) 1992-1999



d) 1982-1999

