Int J Biometeorol (2001) 45:184–190

ORIGINAL ARTICLE

Compton J. Tucker · Daniel A. Slayback
Jorge E. Pinzon · Sietse O. Los · Ranga B. Myneni
Malinda G. Taylor

Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999

Received: 25 October 2000 / Revised: 20 August 2001 / Accepted: 22 August 2001

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 above 35°N. Two distinct periods of increasing plant growth are apparent: 1982–1991 and 1992–1999, separated by a reduction from 1991 to 1992 associated with global cooling resulting from the volcanic eruption of Mt. Pinatubo in June 1991. The average May to September normalized difference vegetation index from 45°N to 75°N increased by 9% from 1982 to 1991, decreased by 5% from 1991 to 1992, and increased by 8% from 1992 to 1999. Variations in the 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 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 whether there is 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 measure of environmental variables to determine if the climate system is stable or changing with time.

Published research on a range of topics strongly suggests recent warming-influenced changes in the Northern Hemisphere. Atmospheric CO_2 concentration measurements suggest increases in plant growth at higher northern latitudes and an earlier start of the growing season (Keeling et al. 1996; Randerson et al. 1999). This is consistent with the reported increased winter and spring temperatures (Rigor et al. 2000; Hansen et al. 1999; Oechel et al. 2000), a reduced extent of snow cover 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, 1998).

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

Materials and 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 μm) and channel 2 (0.73–1.1 μm) 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 approximately 0900 hours local solar overpass time), and NOAA-14 (1995–1999) were used.

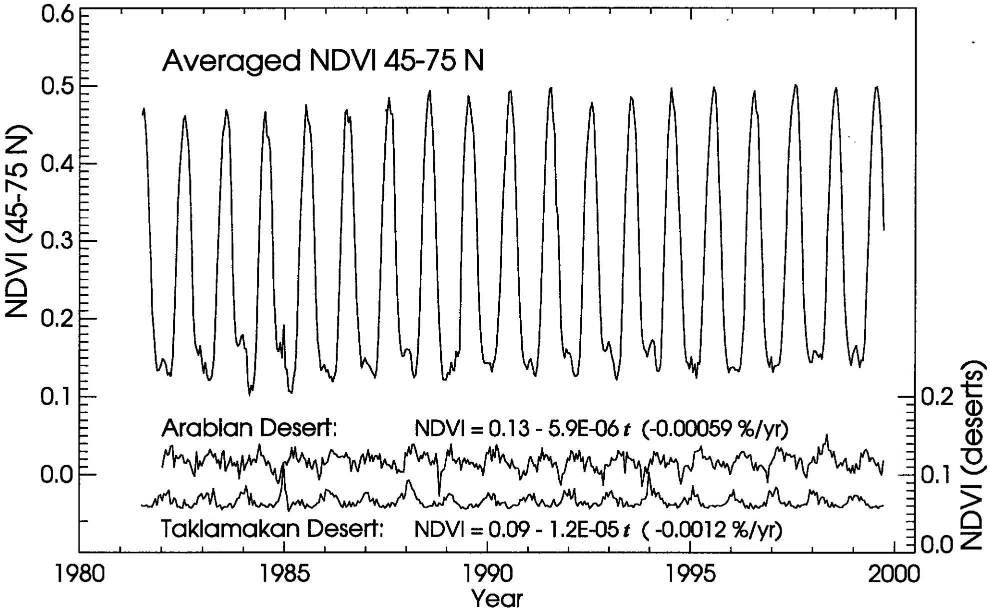
Daily AVHRR 4-km data were processed and the NDVI was formed from channel 1 and channel 2 as (2–1)/(2+1). We use the

Prepared in conjunction with the international conference 'Progress in Phenology: Monitoring, Data Analysis and Global Change Impacts' held in Freising, Germany, October 4–6 2000

C.J. Tucker (✉) · D.A. Slayback · J.E. Pinzon · S.O. Los
M.G. Taylor
Laboratory for Terrestrial Physics, Code 923, NASA/Goddard
Space Flight Center, Greenbelt, Maryland 20771, USA
e-mail: compton@ltpmail.gsfc.nasa.gov
Fax: 301 614 6695

R.B. Myneni
Department of Geography, Boston University,
675 Commonwealth Avenue, Boston, Massachusetts 02215, USA

Fig. 1 Time series of normalized difference vegetation index data from 45°N to 75°N, from the Taklamakan Desert (40°N, 85°E), and from the Arabian Desert (25°N, 40°E) are plotted from July 1981 through October 1999. The slope of the time plot for the Taklamakan Desert is 0.00001 normalized difference vegetation index (*NDVI*) unit/year while the slope for the Arabian Desert is 0.000006 NDVI unit/year



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 around 40,000 orbits of AVHRR daily data were used from four 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 the average growing season photosynthetic activity, as cloud contamination is less in approximately 15-day composite images. The 7-day composite images were used to determine the season start and end of the growing season.

The mapped data were formed into composite images, visually checked for navigation accuracy, remapped if necessary, and assembled into a time series. The formation of maximum value NDVI composite images minimizes atmospheric effects, scan-angle effects, cloud contamination, and solar-zenith-angle effects without an explicit atmospheric correction being required (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. The resulting data were coherent and transitions between satellites were non-existent (Fig. 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 by singular-value decomposition over 1°×1° areas using 40 7-day composite NDVI images for each year. The aggregation to 1°×1° areas is necessary to smooth the data and minimize variability. The NDVI temporal profiles are parameterized by a technique developed by Badhwar (1982) and Badhwar et al. (1984) for identifying the start, rate of growth, peak, and end of the growing season:

$$\mathrm{Log}\,(\mathrm{NDVI}) = \log P_1 + P_3\,(\log t - \log P_2) + P_4\,(P_2^2 - t^2)$$

where P_1 is the displacement of the NDVI versus time (t) 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; Badhwar et al. 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 had been determined for the 1°×1° 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°×1° cell. The support vector regression method is an approach for performing classification/regression that 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 first to 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-dimensional 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°N to 40°N (Fig. 1). The average slope for the two desert regions was less than 0.00001 NDVI unit year^{-1} or around 0.0002 NDVI unit 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 35°N from 1982 to 1999. Two periods when NDVI increased with time were apparent: 1982–1991 and 1992–1999, separated by a marked decrease in NDVI from 1991 to 1992 (Fig. 2 and Table 1).

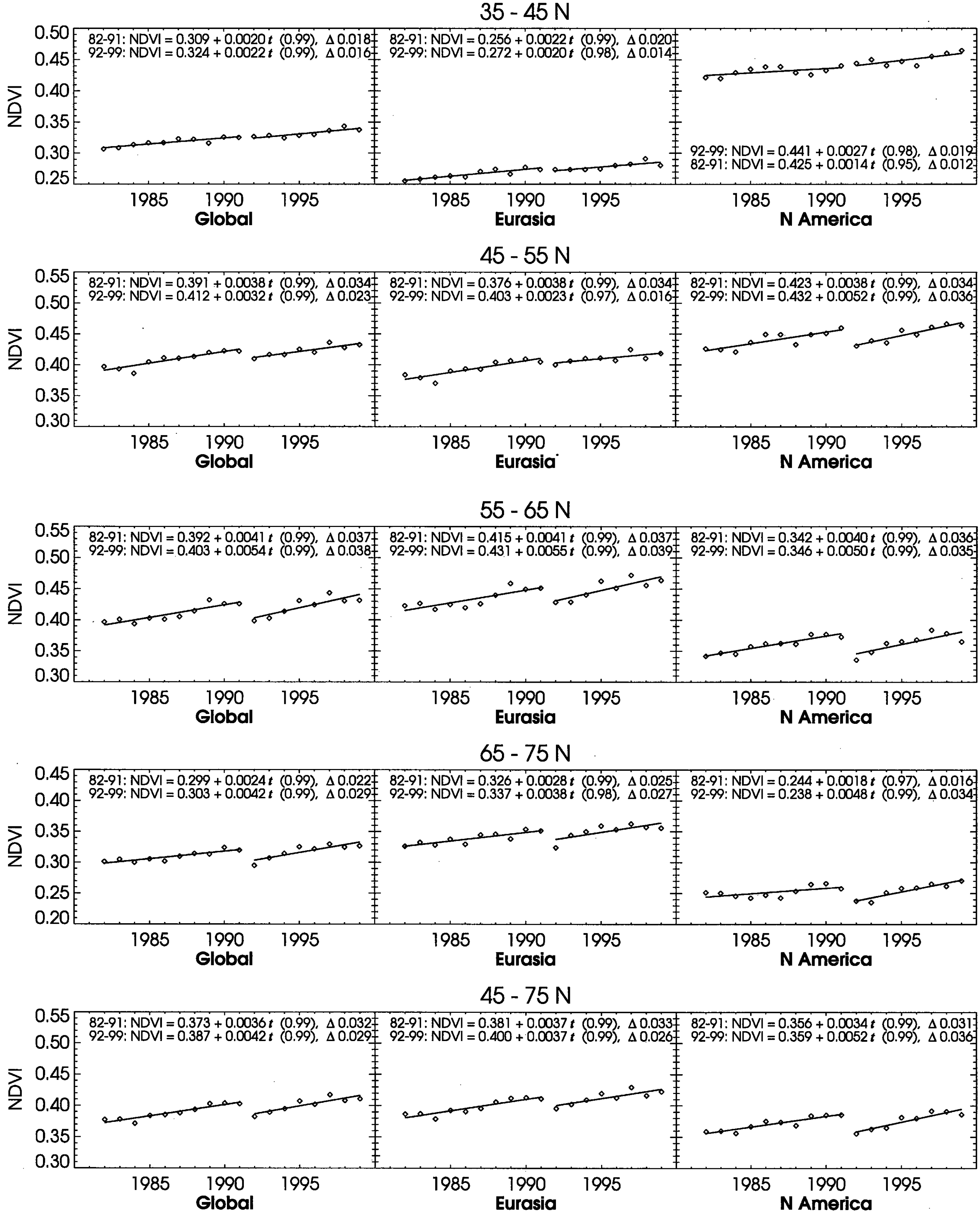


Fig. 2 Plots of zonally averaged NDVI data from 1982 to 1999 for Eurasia, North America, and the Northern Hemisphere for the May–September period. See Table 1 for a summary of the percentage change associated with this figure. In all regression equations, ‘t’ equals the year –1982 (e.g., for 1983, t=1, etc.)

Table 1 Average May to September normalized difference vegetation index trends from 1982 to 1991, 1991 to 1992, and 1992 to 1999. 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 Fig. 2. The change for 1991 to 1992 is the difference between these years

Parameter	Region	Period	35–45°N	45–55°N	55–65°N	65–75°N	45–75°N
Change (%)	**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	–10.1	–8.0	–7.8
		1992–1999	4.6**	8.7*	10.4*	14.9*	10.1*
Slope	**Global**	**1982–1991**	0.002*	0.004*	0.004*	0.002*	0.004*
		1991–1992	0.001	–0.012	–0.027	–0.025	–0.020
		1992–1999	0.002*	0.003*	0.005*	0.004*	0.004*
	Eurasia	**1982–1991**	0.002*	0.004*	0.004*	0.003*	0.004*
		1991–1992	0	–0.005	–0.023	–0.027	–0.016
		1992–1999	0.002*	0.002**	0.006*	0.004*	0.004*
	North America	**1982–1991**	0.001**	0.004*	0.004*	0.002*	0.003*
		1991–1992	0.004	–0.029	–0.037	–0.021	–0.031
		1992–1999	0.003**	0.005*	0.005	0.005*	0.005*

* Above 98% significance
** 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 ±1 day

Area and period	Variation (days)				
	35–45	45–55	55–65	65–75	45–75
Variation in length of growing season					
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
Variation in start of growing season					
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

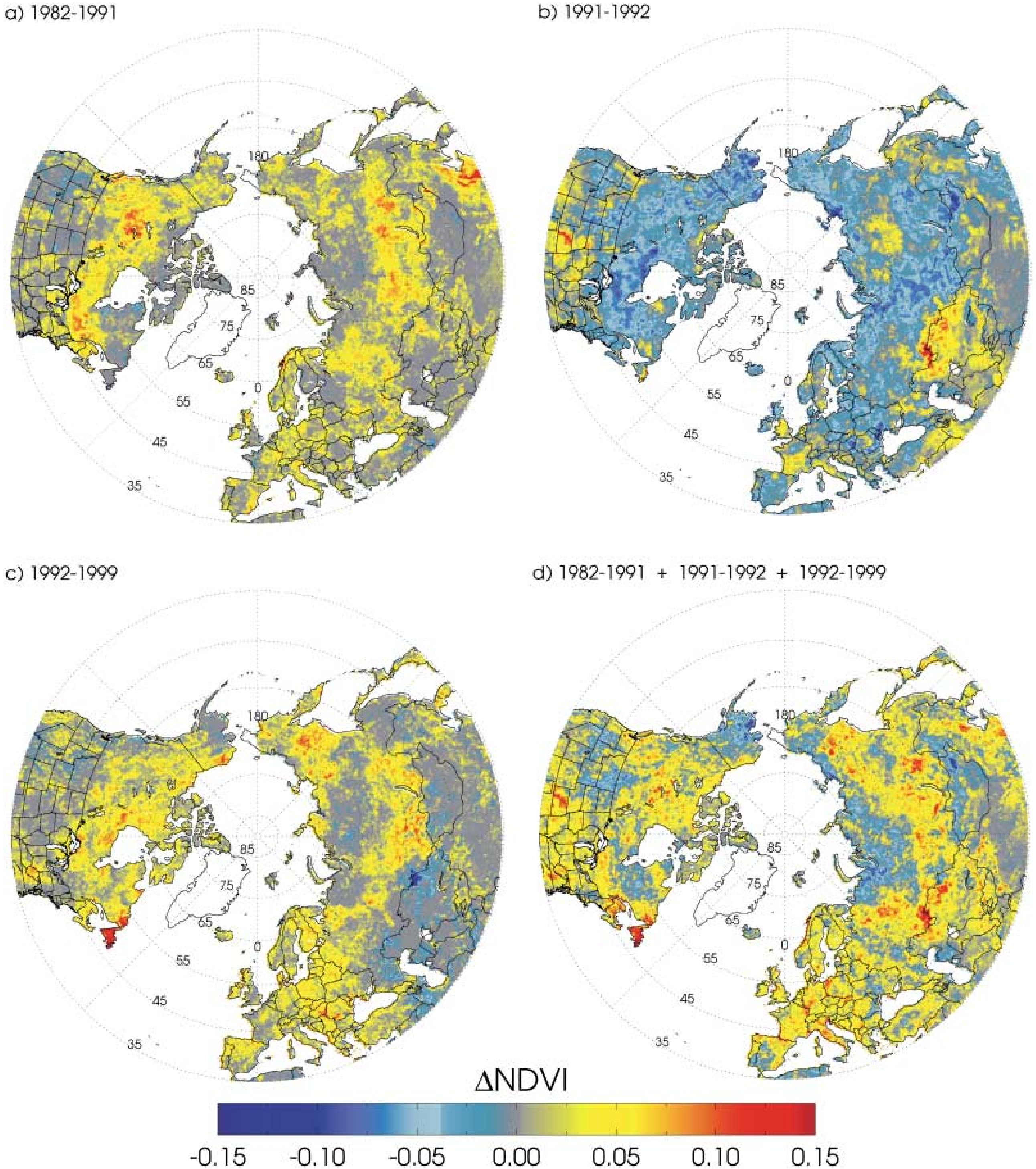


Fig. 3 a–d Northern Hemisphere plots of NDVI changes from 1982 to 1999 showing the areas of greatest NDVI increase. **a** 1982–1991; **b** the 1991–1992 cooling; **c** 1992–1999; **d** the summation **a**+**b**+**c**. Refer also to Fig. 2 and Table 1

The 1991–1992 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°N to 75°N.

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

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

The average May to September NDVI recovered and increased progressively from 1992 to 1999. The average NDVI increased by 5%–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°N to 75°N in North America; Newfoundland was an area of great increase (Fig. 3c). Together Fig. 3a, 3b, and 3c indicates that Eurasia was the area most affected from 1982 to 1999 (Fig. 3d).

Discussion

Our satellite data analysis is consistent with other published reports on variations in growing season length. Analyses of CO_2 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°N to 75°N, the growing season was starting earlier, occurring 6±1 days earlier by 1991. By 1991 the season was starting 8±1 days earlier from 55°N to 65°N within Eurasia. By 1991 the growing season had been extended by 10±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°N to 75°N of 4±1 days; similar later starts between 1991 and 1992 were found for all latitude zones further than 45°N in both North America and Eurasia (Table 2).

From 1992 to 1999 the 45°N to 75°N growing season was starting earlier, occurring 2±1 days earlier on average in 1999; the 65°N to 75°N latitude zone in North America had the earliest 1999 start: 4±1 days in advance.

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 CO_2 at these latitudes (Keeling et al. 1996; Randerson et al. 1999). Zhou et al. (2001) have 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 than in 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 (Fig. 3d), largely because of a greater reduction in the 1992 NDVI in North America (Fig. 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 distinct periods of increasing satellite NDVI values, punctuated by a substantial decrease from 1991 to 1992. We conclude that vegetation in higher northern latitudes is responding to warmer temperatures, starting the growing season earlier and continuing for longer. This trend 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.

References

Asrar GE, Fuchs M, Kanemasu ET, Hatfield JL (1984) Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agron J 76:300–306

Badhwar GD (1984) Use of Landsat-derived profile features for spring small-grains classification. Int J Remote Sens 5:783–797

Badhwar GD, Austin WW, Carnes JG (1982) A semi-automatic technique for multitemporal classification of a given crop within a Landsat scene. Pattern Recognition 15:217–230

Bradley NL, Leopard AC, Ross J, Huffaker W (1999) Phenological changes reflect climate change in Wisconsin. Proc Natl Acad Sci USA 96:9701–9704

Brown JL, Li SH, Bhagabati N (1999) Long-term trend toward earlier breeding in an American bird: A response to global warming? Proc Natl Acad Sci USA 96:5565–5569

Chapman WL, Walsh JE (1993) Recent variations of sea ice and air temperatures in high latitudes. Bull Am Meteorol Soc 74:33–47

Drucker H, Burges C, Kaufman I, Smola A, Vapnik V (1997) Support vector regression machines. In: *Advances in neural information processing systems*, vol 9, Wiley Inter-Science, New York

Groisman PY, Karl TR, Knight TW (1994) Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. Science 263:198–200

Gutman GG (1999) On the use of long-term global data of land refectances and vegetation indices derived from the advanced very high resolution radiometer. J Geophys Res 104:6241–6255

Hansen JE, Sato M, Lacis A, Ruedy R, Tegen I, Matthews E (1998) Climate forcings in the industrial era. Proc Natl Acad Sci USA 95:12753–12758

Hansen J, Ruedy R, Glascoe J, Sato M (1999) GISS analysis of surface temperature change. J Geophys Res 104:30997–31022

Holben BN (1986) Characteristics of maximum-value composite images from temporal AVHRR data. Int J Remote Sens 7:1417–1434

Kaufmann RK, Zhou LM, Knyazikhin Y, Shabanov NV, Myneni RB, Tucker CJ (2000) Effect of orbital drift and sensor changes on the time series of AVHRR vegetation index data. IEEE Trans Geosci Remote Sens 38:2584–2597

Keeling CD, Whorf TP, Wahlen M, Pilcht J van der (1995) Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. Nature 375:666–670

Keeling CD, Chin JFS, Whorf TP (1996) Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. Nature 382:146–149

Levitus S, Antonov JI, Boyer TP, Stephens C (2000) Warming of the world ocean. Science 287:225–229

Los S (1998) Estimation of the ratio of sensor degradation between NOAA AVHRR channels 1 and 2 from monthly NDVI composites. IEEE Trans Geosci Remote Sens 36:206–213

Menzel A, Fabian P (1999) Growing season: extended in Europe. Nature 397:659

Myneni RB, Hall FB, Sellers PJ, Marshak AL (1995) The interpretation of spectral vegetation indices. IEEE Trans Geosci Remote Sens 33:481–486

Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. Nature 386:698–702

Myneni RB, Tucker CJ, Keeling CD, Asrar G (1998) Interannual variation in satellite-sensed vegetation index data from 1981 to 1991. J Geophys Res 103:6145–6160

Oechel WG, Vourlitis GL, Hastings SJ, Zulueta RC, Hinzman L, Kane D (2000) Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. Nature 406:979–981

Parkinson CL, Cavalieri DJ, Gloersen P, Zwally HJ, Comiso, JC (1999) Arctic sea ice extents, areas, and trends, 1978–1996. J Geophys Res 104:20837–20856

Randerson JT, Field CB, Fung IY, Tans PP (1999) Increases in early season ecosystem uptake explain recent changes in the seasonal cycle of atmospheric CO_2 at high northern latitudes. Geophys Res Lett 26:2765–2768

Rigor IG, Colony RL, Martin S (2000) Variations in surface air temperature observations in the arctic, 1979–1997. J Climate 13:896–914

Sellers PJ (1985) Canopy reflectance, photosynthesis, and transpiration. Int J Remote Sens 6:1335–1372

Vapnik VN (1997) Statistical learning theory. In: Advances in neural information processing systems, vol 9. Wiley Inter-Science, New York

Zhou L, Tucker CJ, Kaufmann RK, Slayback D, Shabanov NV, Myneni RB (2001) Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. J Geophys Res 106:20069–20083