Reference No: RES 103822, In press, 2003

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Submitted to *International Journal of Remote Sensing*

as

Remote Sensing Letters

Final version

November 28, 2002

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Abstract. Large-scale atmospheric systems, such as the Southern Oscillation, North Atlantic Oscillation, and so on, are important climatic change indicators over the northern hemisphere. These systems play essential roles in regional-to-continental scale climate fluctuation and vegetation activity in response to global change. Using the Pathfinder AVHRR NDVI data for period 1982-2000, the authors investigated the relationship of the interannual variations of spring NDVI to nine large-scale climate indices. On average, 57.2% of the satellite sensed NDVI variance was explained. These climate indices also accounted for a large portion of the trends in NDVI as observed in five regions, namely, the northwest North America (climate-related trend is 18.2%/10yr), southeastern North America (5.8%/10yr), Europe (6.9%/10yr), high-latitude Asia (12.4%/10yr), and East Asia (8.0%/10yr). The results are useful for understanding and predicting the regional-to-continental NDVI variations in response to global climate change.

1 Introduction

Global climate has been experiencing prominent changes during the last two decades or so. The mean temperature averaged over the northern hemisphere has increased by about 0.6ºC (IPCC 2001). Much of the warming occurred in winter and spring and in northern continents. That results in remarkable biological consequences, including promoted vegetation activity, lengthened growing season, and greater biomass productivity (e.g., Zhou *et al.* 2001, Myneni *et al*. 2001). Many studies have reported that NDVI (Normalized Difference Vegetation Index) values over mid- and high- latitude Eurasia and North America have also risen steadily since the early 1980s (e.g., Myneni *et al.* 1998, Kawabata *et al.* 2001, Zhou *et al.,* 2001).

The regional NDVI changes in response to global climate change differ from area to area. The large-scale climate systems play essential roles in connecting global change and regional-to-continental responses of both climate variables and vegetation. For example, a number of studies have addressed the possible connections between regional NDVI and the well-known Southern Oscillation (SO) (e.g., Myneni et al., 1996; Kogan 2000). But, it should be noted that SO usually impacts lower latitude climate and vegetation activity. Over the mid- to high-latitudes some other systems such as North Atlantic Oscillation / Arctic Oscillation (NAO/AO), the Pacific/North American (PNA) pattern, would exert greater influences.

To get a clear understanding of the regional vegetation responses to global climate change, we should understand the roles these atmospheric circulation systems play in affecting the regional climate and NDVI. The objective of the present study was to analyze the extent to which the yearly NDVI variations are induced by the atmospheric circulation fluctuations. Many studies have reported that spring has experienced greater trends than other growing seasons (Zhou *et al.* 2001, Suzuki *et al.* 2000). Spring temperature also shows profound changes during the last two decades (IPCC, 2001). Thus, we focused on the season of spring (April to May). Our target region was limited to the mid- to high-latitude continents (30ºN northward).

2 Data

The Advanced Very High Resolution Radiometer (AVHRR) NDVI data used in the present study were produced by the Earth Observing System Pathfinder AVHRR Land program and available via internet at http://eosdata.gsfc.nasa.gov/. More detail of the processing methods used in generating the data set can be found in James and Kalluri (1994). Because our object was to investigate the large-scale features in climate and NDVI, we used the coarser monthly 1º by 1º data sets to suppress the noise usually existing in the high spatial resolution data. We used NDVI in the present study for the period 1982-2000(n=19). The seasonal mean was averaged for April and May at each 1º×1º cell. Cells of insufficient data (n<18) or low mean NDVI (<0.05) were removed from the data set.

A land surface air temperature data set on a 5º latitude ×5º longitude grid were used in the present study. The observed station temperature data in the form of anomalies from the 1961-1990 base period were collected and interpolated to a regular set of grid boxes, finally resulting in this data set (Jones 1994). We used only the data for the period 1982-2000 as the same time span of NDVI.

There are inherent modes of general atmospheric circulation; those in the lower-to-middle troposphere are of great interest since they exert imperative influence on surface climate. They are widely used for monitoring and investigating regional-to-hemispheric climate changes (e.g., Hurrell, 1996; IPCC, 2002). Here nine atmospheric circulation indices were considered. Among them, four are based on sea level pressure fields, namely, the Southern Oscillation Index (SOI), NAO, AO, and the North Pacific (NP) index. SOI is the standardized sea level pressure difference between Tahiti and Darwin, obtained from the Climate Prediction Center, National Centers for Environmental Prediction (NCEP). NAO is the difference of normalized sea level pressures between Azores and Iceland (Hurrell, 1995). AO is the first expansion coefficient of empirical orthogonal function analysis of sea level pressure over northern hemisphere(20°N northward), obtained from Thompson and Wallace(1998). The NP Index is the area-weighted sea level pressure over the region 30º-65ºN, 160ºE-140ºW (Trenberth and Hurrell, 1994). The other five indices are based on the middle troposphere (500hPa) geopotential height (Z). They are the Eurasian (EU) pattern, the western Pacific (WP) pattern, the western Atlantic (WA) pattern, the Pacific/North American (PNA) pattern, and the eastern Atlantic (EA) pattern. These five patterns are also known as the atmospheric teleconnection patterns. See Wallace and Gutzler (1981) for detail. We recalculated the EU, WP, WA, PNA and EA indices by employing the NCEP/National Center for Atmospheric Research reanalysis 500 hPa height data. Table 1 briefly shows the definitions for these climate indices.

[Insert table 1 about here]

3 Results and discussion

A multivariate regression analysis technique was used to estimate quantitatively the connection between climate indices and NDVI. Given a cell, the relationship is determined by the formula: $NDVI = a + b_1 AO + b_2 NAO + b_3 NP + b_4 SOI + b_5 PNA + b_6 EA + b_7 WA + b_8 WP + b_9 EU$; where b_1- b_9 are the corresponding regression coefficients, and a is the intercept. We utilized the ordinary least-squares technique to estimate these coefficients (van Storch and Zwiers, 1999). Then we applied it to calculate the climate index-associated NDVI at each cell for period from 1982 to 2000.

The variance in large-scale climate-related NDVI was compared with that of the observation cell by cell. This can tell us to what extent the observed NDVI variations arise from the large-scale climate changes. In general, the climate-explained portion of variance is considerably high. Regions, with more than 70% of NDVI variance explained by climate, account for 27% of the cells. Regions with less than 50% of variance explained only consist of 31% of the total cells. On average, 57.2% of the interannual variance in satellite sensed NDVI could be attributed to the large-scale climate fluctuations. In some regions the portion is relatively larger than the others. These large value regions cover the continental Eurasia between 40ºN and 60ºN, the southeast US, and East Asia. In some scattered small regions, such as Alaska and Scandinavia, there is also highly climate-related NDVI variance.

A number of studies stated that there are remarkable positive trends in spring NDVI in Eurasia and North America (e.g. Zhou *et al.* 2001). We also estimated the long-term changes in satellite sensed NDVI. Here the linear trend over time in the whole period 1982-2000 was conducted using ordinary least-square regression, and presented in the term of changes per 10 years (for both NDVI and temperature). As figure 1 shows, large trends appear in most of Europe, the interior Asia, the east coast area of the US, the northwest North America, and the East Asia. Statistical tests show that the trends are significant at the 95% confidence level in most of the cells in these regions. That is generally consistent with previous studies. Our further investigation revealed that a large portion of the trends would be attributed to large-scale climate change. We calculated the trends arisen from the nine climate indices. Results are shown in the middle panel of figure 1. Of great interest, the trends derived from the climate-index-related NDVI (i.e., the trends in NDVI as predicted by climate index based regression) also display notable rising in these regions as seen in observations. The spatial pattern is fairly consistent with the observations. Five regions show remarkable upward trends since 1982 too. These trends are also statistically significant in most of the cells. That means the large-scale climate changes would be responsible for a large portion of the observed NDVI interannual variations there.

[Insert figure 1 about here]

To measure quantitatively the changes and compare with the observations we chose five boxes to make regional means. They are (1) northwest North America, 55º-70ºN, 165º-120ºW, (2) southeastern North America, 30º-50ºN, 90º-60ºW, (3) Europe, 40º-60ºN, 0º-50ºE, (4) high-latitude Asia, 50º-65ºN, 70º-110ºE, and (5) East Asia, 30º-42ºN, 100º-145ºE. Time series of both the climate-related and observed NDVI are shown in figure 2. The correlation between each of the two curves varies in the range from 0.75 to 0.92. On average, 69% of the variance in satellite sensed NDVI is accounted for by the climate indices.

[Insert figure 2 about here]

Besides the year-to-year variations, much of the secular trends would be attributed to the large-scale climate fluctuations too. The linear trends in both satellite sensed and climate related NDVI in five regions are listed in table 2. Clearly, all trends derived from the climate related NDVI are comparable with the satellite-sensed trends. The greatest two trends occur in the northwestern North America and high-latitude Asia. This implies that the two high latitude regions are much more sensitive to global climate change. Generally, climate indices account for above 78% of the satellite sensed trends for the five regions.

[Insert table 2 about here]

In most regions over mid- to high-latitude Eurasia and North America the temperature is the most important factor influencing bioactivity in spring (Zhou *et al.* 2001, Suzuki *et al*. 2000). The relationships between temperature and NDVI for these five regions also support that (see figure 3). Correlation between NDVI and temperature vary from 0.58 to 0.76, all significant at the 99% confidence level (figure 3). Large-scale climate fluctuations influence NDVI by changing the regional temperature. We applied the multiple linear regression to the regional temperature too, and found that the climate indices also explain a large portion of the observed temperature changes. For example, the explained variance for northwest North America is 74%, southeastern North America 48%, Europe 56%, high-latitude Asia 52%, and East Asia 59%. The spatial distribution of trends in NDVI and temperature is also consistent (see middle panel of figure 1). Obviously, the temperature trends associated with the climate indices show large positive values in high-latitude Asia, East Asia, most of Europe south of about 55ºN, and Alaska. The slight positive trends in southeastern US is also comparable to the observations.

[Insert figure 3 about here]

Noteworthily, there remain considerable residual trends in some mid- to high-latitudes, particularly from middle Europe to western Siberia (see the lowest panel of figure 1), despite a large portion of the long-term changes being explained. Some other factors, such as precipitation and local environmental parameters might be responsible for that. This problem needs further research.

It should be mentioned that the multivariate regression was used with only 19 observations; a shorter time span would cause a higher uncertainty in results. More data are clearly needed. Unfortunately, no longer durations are available at present. Nevertheless the well-defined spatial patterns as displayed in figure 1 likely provide additional confidence. The geographical consistency of NDVI changes in association with climate indices seems reasonable (rather than random). In addition, the present study considered only the simultaneous relations between NDVI and climate indices. We tested this issue by taking into account both time-lags (climate indices lead NDVI at most half year) and their significance using a step-wise regression method (retained in the regression equation only those terms that were significant at the 95% confidence level). The results were similar. That might be due to the fact that for a specific region the NDVI responds to a closer atmospheric circulation system much quicker than to a distant one, while a near climate index usually exerts greater influence than the distant ones. For example, NDVI over Siberia shows the largest correlation to EU index with zero time-lag. These problems, as well as some other questions such as the influence of data errors and spatial resolution on the results, were analyzed in detail in a separate manuscript (see Gong and Ho, 2002).

4 Conclusion

Large-scale climate systems can significantly influence the regional temperature and NDVI in spring. Besides the well-known Southern Oscillation, some other large-scale climate systems such as the NAO, AO, PNA, WA, EA, WP, EU, and NP also exert important influences, particularly, in the mid- to high-latitudes in the northern hemisphere. All of the nine important climate indices contribute more than half of the interannual variations and a large portion of the interannual trend. Five regions, namely, the northwest North America, southeastern North America, Europe, high-latitude Asia, and East Asia show much greater connection to the large-scale climate changes than the others.

The influence of each index on regional vegetation and climate differ from region to region. For example, the EU is correlated significantly with the high-latitude Asian NDVI (r=0.73) and temperature (r=0.47), while the PNA with northwestern North American temperature (r=0.68) and NDVI (r=0.48), regional NDVI features associated with each of these climate indices should also be considered in detail. The information from that would be helpful for understanding the regional-to-continental vegetation activity, and their relationship with temperature and precipitation in response to global climate change.

Here we considered only temperature, this was reasonable for most temperate and boreal ecosystems, but not for all of them. In future studies, the precipitation changes in association with the large-scale climate indices and its relationship with NDVI should be examined. In addition, further studies for other seasons, taking into account both temperature and precipitation, are also needed.

Acknowledgments

This research is supported by projects of NKBRSF- G2000018604, Huo Ying-Dong Education Foundation-81014 and NSFC-40105007. NDVI data used by the authors in this study include data produced through funding from the Earth Observing System Pathfinder Program of NASA's Mission to Planet Earth in cooperation with NOAA. The data were provided by the Earth Observing System Data and Information System, Distributed Active Archive Center at Goddard Space Flight Center which archives, manages, and distributes this data. Thanks are due to the three anonymous reviewers for helpful comments and suggestions.

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Captions

Table 1. Important large-scale climate indices based on the atmospheric circulation. "Z" means the 500hPa geopotential height, "*" denotes the normalization.

Table 2. Trends of NDVI in five regions. Trends are shown in NDVI /10yr and %/10yr (in parentheses).

Figure 1. Linear trends in NDVI (in color) and temperature (in contour). Uppermost panel: observations. Middle panel: predicted using climate indices. Lowest panel: the residuals. Units for NDVI: NDVI/10yr, for temperature ºC/10yr. Regions without sufficient data or low NDVI (<0.05) are blank. The linear trends over time for both NDVI and temperature are estimated by utilizing least-square regression for the period 1982-2000.

Figure 2. Long-term variations in NDVI for five selected regions. Shown in solid lines are the observations, dashed lines are large-scale climate related changes.

Figure 3. Scatter plots of regional temperature against NDVI in observations. Temperature is in anomaly with respect to 1961-1990.

Tables and Figures

Table 1. Important large-scale climate indices based on the atmospheric circulation. "Z" means the 500hPa geopotential height, "*" denotes the normalization.

Index	Definition	Source
AO	Time coefficient of the EOF analysis of SLP for extratropical northern hemisphere (20ºN northward)	Thompson and Wallace 1998
NAO	Difference of normalized SLP between Azores and Iceland	Hurrell 1995
NP	Area-weighted SLP over the region 30º-65ºN, 160º-140ºW	Trenberth and Hurrell 1994
SOI	Standardized SLP difference between Tahiti and Darwin	Climate Prediction Center
WA	$[Z^*_{(55°N,\ 55°W)} - Z^*_{(30°N,\ 55°W)}]/2$	Wallace and Gutzler 1981
PNA	$[Z^*_{(20°N,\ 160°W)} - Z^*_{(45°N,\ 165°W)} + Z^*_{(55°N,\ 115°W)} - Z^*_{(30°N,\ 85°W)}]/4$,	Wallace and Gutzler 1981
EA	$Z^*_{(55°N,\ 20°W)}/2 - Z^*_{(25°N,\ 25°W)}/4 - Z^*_{(50°N,\ 40°E)}/4$	Wallace and Gutzler 1981
WP	$[Z^*_{(60°N,\ 155°E)} - Z^*_{(30°N,\ 155°E)}]/2$	Wallace and Gutzler (1981)
EU	$Z^*_{(55°N,\ 75°E)}/2 - Z^*_{(55°N,\ 20°E)}/4 - Z^*_{(40°N,\ 145°E)}/4$	Wallace and Gutzler (1981)

Table 2. Trends of NDVI in five regions. Trends are shown in NDVI /10yr and %/10yr (in parentheses).

Region	Satellite sensed trend	Climate index related trend
Europe	0.051 (10.9%)#	0.032 (6.9%)**
Southeast North America	0.039 (7.9%)**	0.028 (5.8%)**
Northwestern North America	0.035 (18.1%)*	0.036 (18.2%)**
High-latitude Asia	0.050 (17.8%)**	0.035 (12.4%)*
East Asia	0.029 (9.3%)#	0.025 (8.0%)#

* significant at 90% confidence level, ** at 95%, # at 99%

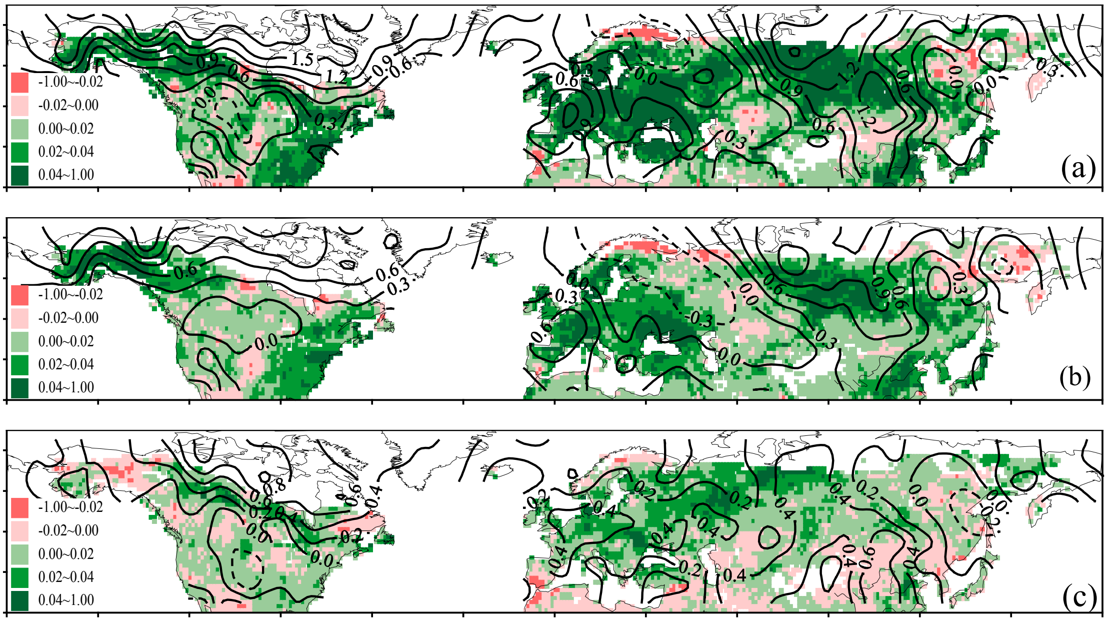

Figure 1. Linear trends in NDVI (in color) and temperature (in contour). Uppermost panel: observations. Middle panel: predicted using climate indices. Lowest panel: the residuals. Units for NDVI: NDVI/10yr, for temperature ºC/10yr. Regions without sufficient data or low NDVI (<0.05) are blank. The linear trends over time for both NDVI and temperature are estimated by utilizing least-square regression for the period 1982-2000.

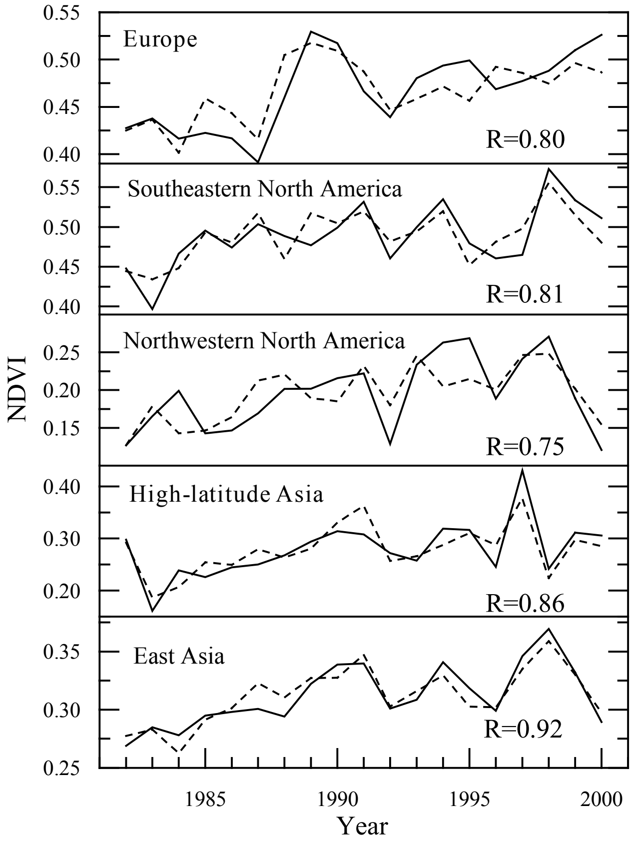

Figure 2. Long-term variations in NDVI for five selected regions. Shown in solid lines are the observations, dashed lines are large-scale climate related changes.

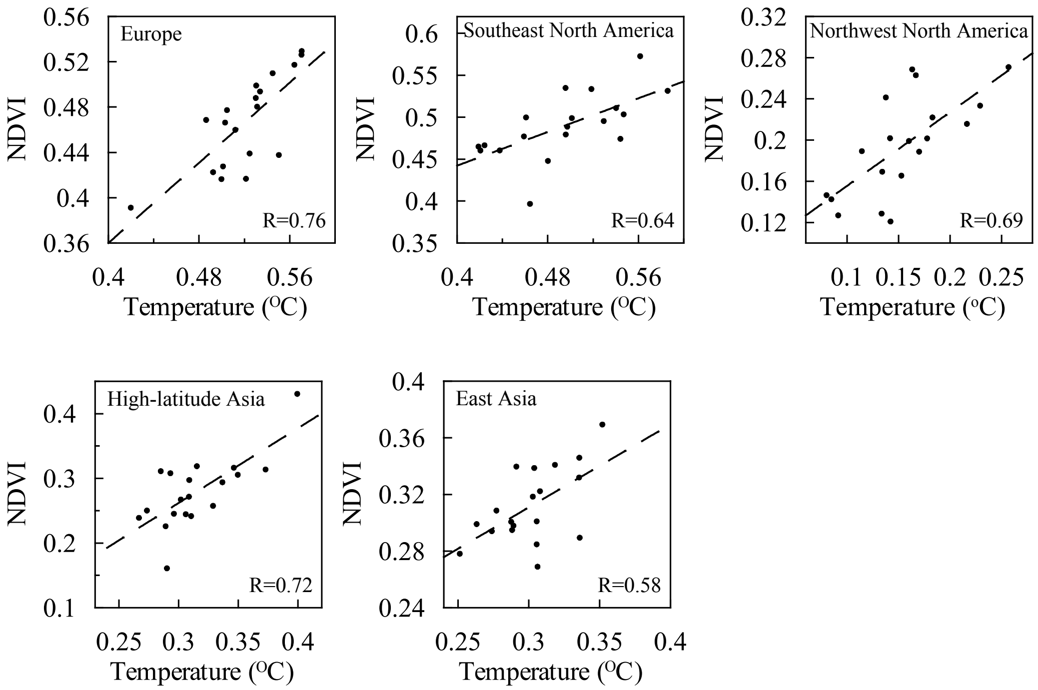

Figure 3. Scatter plots of regional temperature against NDVI in observations. Temperature is in anomaly with respect to 1961-1990.