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Northern hemispheric NDVI variations associated with large-scale climate indices in spring

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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 (Advanced Very High Resolution Radiometer Normalized Difference Vegetation Index) data for the period 1982–2000, the authors investigated the relationship of the inter-annual 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, north-west North America (climate-related trend was 18.2% /10 years), south-eastern North America (5.8% /10 years), Europe (6.9% /10 years), high-latitude Asia (12.4% /10 years), and East Asia (8.0% /10 years). 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 0.6°C (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. Myneni *et al*. 2001, Zhou *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)

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(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 analyse 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 (Suzuki *et al.* 2000, Zhou *et al.* 2001). 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 (30° N 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 programme and available via the internet at http://eosdata.gsfc.nasa.gov/. More details of the processing methods used in generating the dataset 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 $1^\circ \times 1^\circ$ datasets 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 $1^\circ \times 1^\circ$ cell. Cells of insufficient data ($n < 18$) or low mean NDVI (< 0.05) were removed from the dataset.

A land surface air temperature dataset on a 5° latitude × 5° 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 dataset (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 2001). Here nine atmospheric circulation indices were considered. Among them, four are based on sea-level pressure (SLP) 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 30°–65° N, 160° E–140° W (Trenberth and Hurrell 1994). The other five indices are based on the middle troposphere (500 hPa) 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 details. 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 shows the definitions for these climate indices.

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: $\text{NDVI} = a + b_1\ \text{AO} + b_2\ \text{NAO} + b_3\ \text{NP} + b_4\ \text{SOI} + b_5\ \text{PNA} + b_6\ \text{EA} + b_7\ \text{WA} + b_8\ \text{WP} + b_9\ \text{EU}$, 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 (von 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 inter-annual 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 continental Eurasia between 40° N and 60° N, south-east USA, 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

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

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

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 USA, north-west North America, and 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 could be attributed to large-scale climate change. We calculated the trends derived from the nine climate indices. Results are shown in figure 1(*b*). 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 increases in these regions as seen in observations. The spatial pattern is fairly consistent with the observations. Five regions show remarkable upward trends since 1982 as well. 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 inter-annual variations there.

To measure quantitatively the changes and compare with the observations we chose five boxes to make regional means. They are (1) north-west North America, 55°–70° N, 165°–120° W, (2) south-eastern North America, 30°–50° N, 90°–60° W, (3) Europe, 40°–60° N, 0°–50° E, (4) high-latitude Asia, 50°–65° N, 70°–110° E, and (5) East Asia, 30°–42° N, 100°–145° E. 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.

Besides the year-to-year variations, many of the secular trends could be attributed to the large-scale climate fluctuations as well. The linear trends in both satellite-sensed and climate-related NDVI in five regions are listed in table 2.

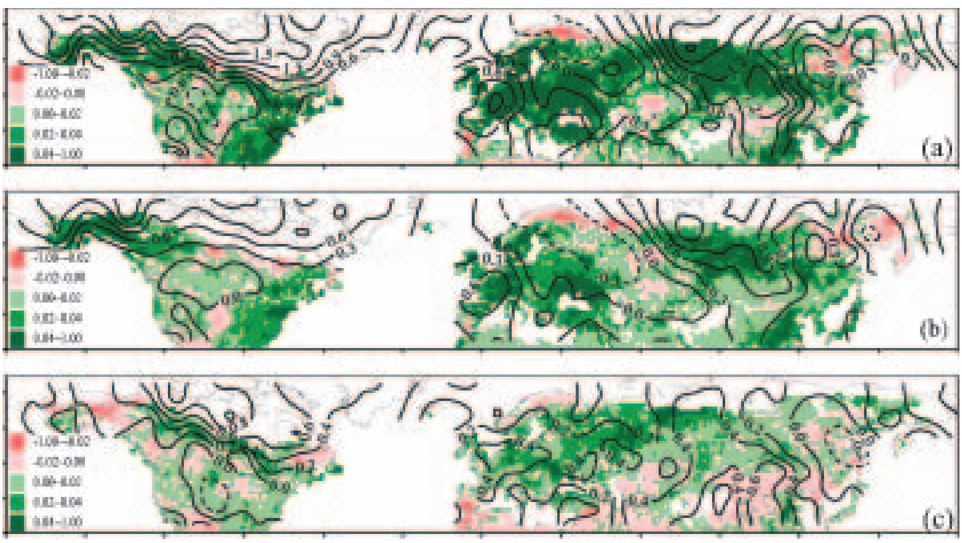

Figure 1. Linear trends in NDVI (in colour) and temperature (contours). (*a*) Observations, (*b*) predicted using climate indices, (*c*) the residuals. Units for NDVI: NDVI/10 years; for temperature: °C/10 years. Regions without sufficient data or low NDVI (<0.05) are blank. The linear trends over time for both NDVI and temperature are estimated by utilizing least-square regression for the period 1982–2000.

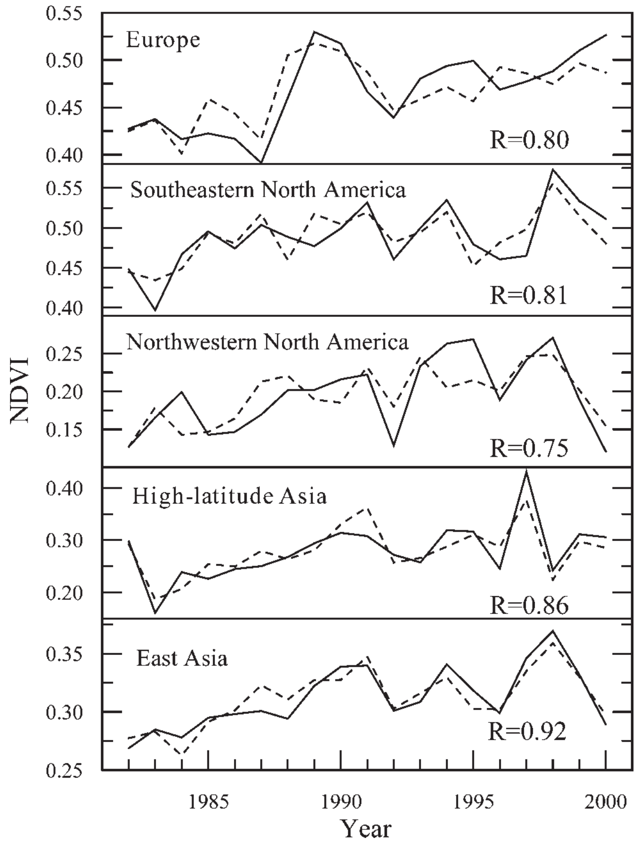

Figure 2. Long-term variations in NDVI for five selected regions. The observations are shown as solid lines and the dashed lines are large-scale climate-related changes.

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

Region	Satellite-sensed trend	Climate index related trend
Europe	0.051 (10.9%)***	0.032 (6.9%)**
South-east North America	0.039 (7.9%)**	0.028 (5.8%)**
North-western 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%.

Clearly, all trends derived from the climate-related NDVI are comparable with the satellite-sensed trends. The greatest two trends occur in the north-western 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 more than 78% of the satellite-sensed trends for the five regions.

In most regions over mid- to high-latitude Eurasia and North America the temperature is the most important factor influencing bioactivity in spring (Suzuki

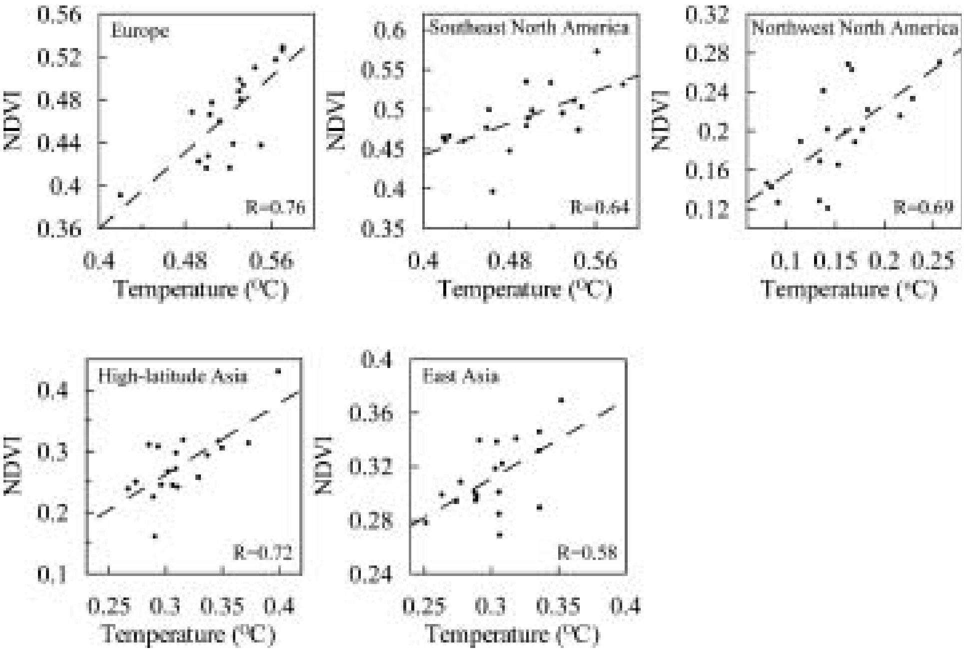

Figure 3. Scatter plots of regional temperature against NDVI in observations. Temperature is in anomaly with respect to 1961–1990.

et al. 2000, Zhou *et al.* 2001). The relationships between temperature and NDVI for these five regions also support that (see figure 3). The correlation between NDVI and temperature varies 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 north-west North America is 74%, south-eastern 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 figure 1(*b*)). 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 55° N, and Alaska. The slight positive trends in south-eastern USA is also comparable to the observations.

It is noteworthy that there remain considerable residual trends in some mid- to high latitudes, particularly from middle Europe to western Siberia (see figure 1(*c*)), 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 by most half year) and their significance using a step-wise regression method (we 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, the NDVI over Siberia shows the largest correlation to the 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 analysed 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 inter-annual variations and a large portion of the inter-annual trend. Five regions, namely, north-west North America, south-eastern 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 is correlated significantly with north-western 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 its 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.

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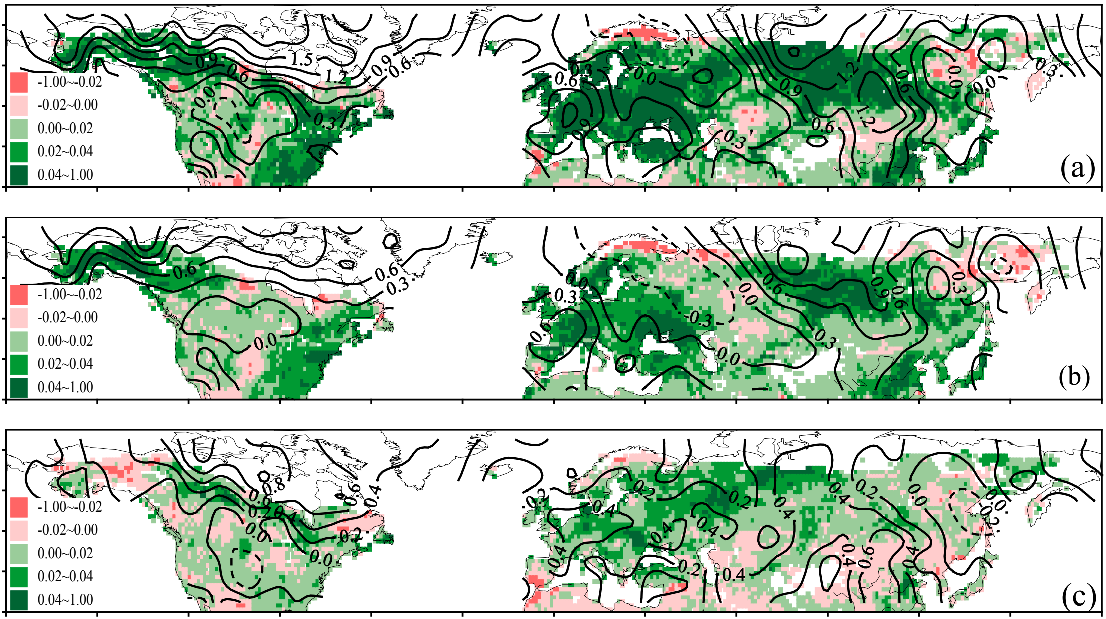

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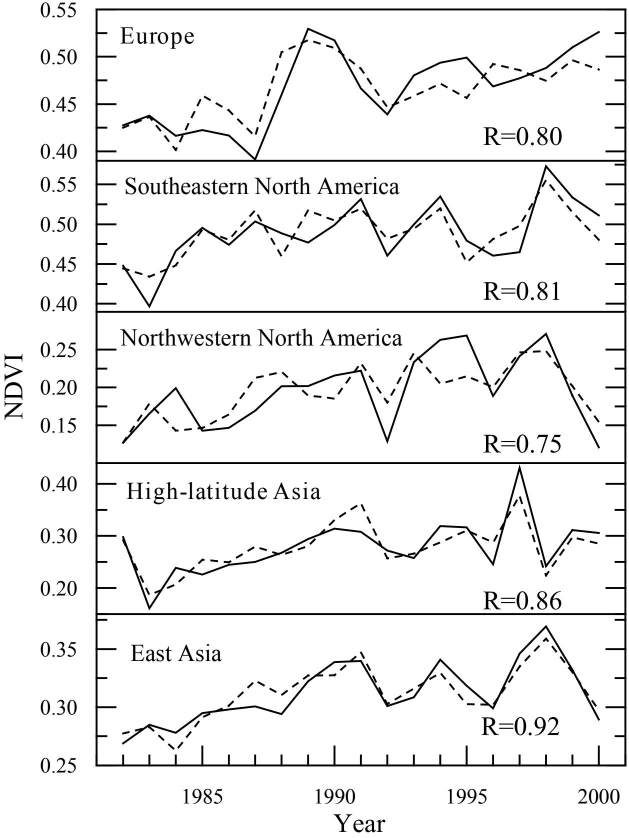

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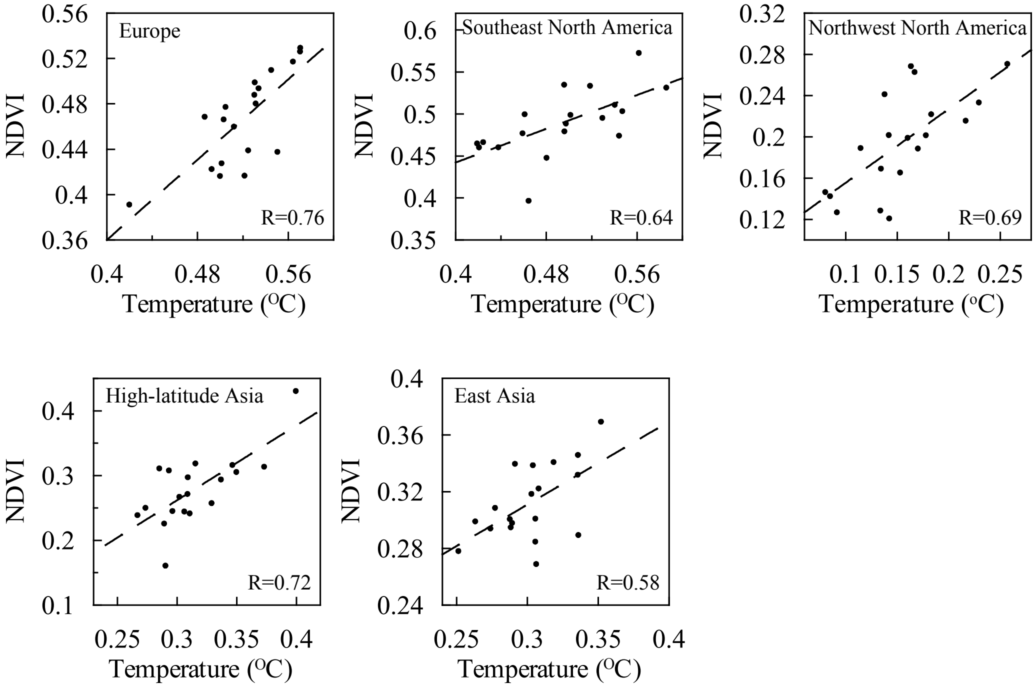

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