Acta Botanica Sinica
植 物 学 报 2004, **46** (2): 186-193 http://www.chineseplantscience.com

Inter-annual Changes in Eurasian Continent NDVI and Its Sensitivity to the Large-scale Climate Variations in the Last 20 Years

GONG Dao-Yi, SHI Pei-Jun

(*Key Laboratory of Environmental Change and Natural Disaster, Institute of Resources Science, Beijing Normal University*, Beijing 100875, China)

Abstract: The influence of climate change on the terrestrial vegetation health (condition) is one of the most significant problems of global change study. The vegetation activity plays a key role in the global carbon cycle. The authors investigated the relationship of the advanced very high resolution radiometer-normalized difference vegetation index (AVHRR-NDVI) with the large-scale climate variations on the inter-annual time scale during the period 1982-2000 for the growing seasons (April to October). A singular value decomposition analysis was applied to the NDVI and surface air temperature data in the time-domain to detect the most predominant modes coupling them. The first paired-modes explain 60.9%, 39.5% and 24.6% of the squared covariance between NDVI and temperature in spring (April and May), summer (June and August), and autumn (September to October), respectively, which implies that there is the highest NDVI sensitivity to temperature in spring and the lowest in autumn. The spatial centers, as revealed by the maximum or minimum vector values corresponding to the leading singular values, indicate the high sensitive regions. Only considering the mode 1, the sensitive center for spring is located in western Siberia and the neighbor eastern Europe with a sensitivity of about 0.308 0 NDVI/℃. For summer, there are no predominantly sensitive centers, and on average for the relatively high center over 100°-120° E by 45°-60° N, the sensitivity is 0.248 0 NDVI/℃. For autumn, the center is located over the high latitudes of eastern Asia (110°-140° E, 55°-65° N), and the sensitivity is 0.087 5 NDVI/℃. The coherent patters as revealed by the singular decomposition analysis remain the same when coarser resolution NDVI data were used, suggesting a robust and stable climate/vegetation relationship.
Key words: normalized difference vegetation index (NDVI); climate change; sensitivity; large-scale

Climate plays an important role in driving ecosystems to change on both local and global scales. Global climate change and its relationship with the ecological influence and consequences, which involves the carbon (C) cycle are among the most significant problems on the Earth (Houghton *et al.*, 2001; Walther *et al.*, 2002). A numerous researches, based on the ecological classification such as the Holdridge life zone, studied the quantitative relationship between the specific vegetation types and climate parameters such as temperature and precipitation (Li and Shi, 1999; Pan *et al.*, 2003). On the other hand, many works focused on the dynamic relation of vegetation and the climatic driving factors by investigating the long-term variations in both vegetation condition and climate change (Fu and Wen, 1999; Los *et al.*, 2001; Kawabata *et al.*, 2001; Gong and Shi, 2003). The objective of the present study is, by employing the long-term data, to investigate the large-scale response of vegetation over the Eurasian continent to the inter-annual time-scale fluctuations in climate during the last two decades. As a variety of papers indicated that the inter-annual variations in vegetation condition of most northern forest are primarily influenced by temperature (Zuzuki *et al.*, 2000; 2001; Zhu *et al.*, 2001), here we consider only monthly temperature as the climate factor. In the present study, what we are interested in includes whether there are large-scale variations in the Eurasian continent vegetation; if so, whether these variations are linked to the similar spatial scale temperature fluctuation and, how and where the strongest coupling between vegetation and temperature exists, and to what extent they are coupled.

1 Data Preparation

Photosynthetic activity of vegetation can be inferred using such satellite-derived vegetation index as the normalized difference vegetation index (NDVI). In the present study we utilized the widely employed advanced very high resolution radiometer (AVHRR) Land Pathfinder production of monthly maximum value composite. This data sets are available through internet at the web site of http://eosdata.gsfc.nasa.gov/. The original data are, in order to

Received 20 Oct. 2003 Accepted 26 Nov. 2003
Supported by the State Key Basic Research and Development Plan of China (G2000018604) and the Huo Ying Dong Education Foundation (81014).

save space and facilitate transfer, archived in the form of unsigned integer with the physical value range from 0 to 253. Zero means missing data. One denotes water, and two indicates the blank region due to the map projection. Only the values above three would be analyzed. The real geophysical values are obtained by rescaling the data by minus 128 and then multiplying by 0.008. Most of the real geophysical NDVI vary between -0.2 and +0.7 (Agbu and James, 1994).

Though some errors of the Pathfinder production have still been found to exist due to incomplete atmospheric correction resulting from lack of appropriate water vapour and aerosol data, the quality of this data set was significantly improved by correcting for various factors such as intra-sensor degradation (James and Kalluri, 1994). Changes in satellites might induce inhomogeneities. The errors, if exist, should be most manifest in the long-term trends. We compared the trend of Eurasian mean NDVI with the result from other authors based on the different data sets, and found that there are no evident differences. For example, the trend of mean spring (April to May) Pathfinder NDVI over Eurasia is 10.6%/10 a for the period 1982-2000, and this value is almost identical to the results of Zhu *et al*. (2000) (20.87%/18 a for period 1982-1999, i.e. 11.6%/10 a), though they take only vegetated pixel of 8 km resolution into account. Thus we think the Pathfinder data is appropriate to investigate the large-scale inter-annual variations, and do not adjust the possible errors.

Since the precision of the AVHRR visible channels degrades rapidly in twilight areas, most of data in high latitude where the Sun is close to the horizon in winter are missing. The surface snow cover, which exists from the late autumn through the early spring, deteriorates the quality of NDVI data, too. Therefore, in the present research we consider only the growing seasons (from April to October). The average of April to May denotes spring, June to August stands for summer, and September to October means autumn. Due to the satellite non-operation, the data for period September to December in 1994 are not available. To facilitate computation, the gap for September and October of 1994 is filled using the long-term averages at each grid, i.e., the missing data for September 1994 are assigned as the September mean averaged over the 20 months (1981-2001). The missing data for October1994 are assigned as the October mean averaged over 19 months (1982-2000). Then all data are presented in the form of anomalies from the 1982-2000 means for each month and at each grid. This kind of anomaly removes the annual cycle, and retains the inter-annual fluctuations.

A land surface air temperature data set on a 5º longitude × 5º latitude grid was utilized 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; Jones *et al.*, 2001). This data set is used world-widely, and adopted by Intergovernment Panel on Climate Change (IPCC) reports as basic scientific information to assess the global temperature change (Houghton *et al.*, 2001). We used both NDVI and temperature data only for period 1982-2000 and for the domain of 0º-155º E by 20º-75º N.

2 Methods

The high spatial and temporal variability in NDVI arises from a lot of factors, mainly due to local environmental variables. Compared to these local factors, the large-scale climate signals are usually very weak and hard to discern. In order to suppress the high frequency noises, statistical methods such as principal component analysis and spatial-temporal average are often applied to NDVI data (Kogan, 2000). However, the averaging would smooth out the high frequency noise as well as the climate signals simultaneously. The principal component analysis can surely detect the spatial-temporal features embedded in the data set. But the disadvantage is that the detected leading modes may be non-climate induced or even non-vegetation related in some circumstances.

In contrast to principal component analysis, the singular value decomposition (SVD) analysis is concerned with the linear relationships between two different variables. This technique is particularly suited for resolving problems such as the coupling features between NDVI and temperature. This method is often utilized in detecting the degree of coupling between two geophysical variables. In the present study, we applied the SVD technique to the covariance matrix of NDVI and temperature. For more detail about this technique and its application please refer to Wallace *et al.* (1992) and Bretherton *et al*. (1992), and references wherein.

3 Results

We put temperature and NDVI data into two matrices respectively. The two matrices have the same temporal domains (1982-2000, 19 years) but different spatial dimensions (due to the different spatial resolution and data availabilities). After multiplying them we obtained their covariance matrix. We applied SVD analysis to this covariance matrix, and finally got the results, including the singular values, paired singular vectors (paried-modes), and the corresponding expansion coefficients (time series).

As the singular values drop off monotonically with the mode number, the importance of the paired-modes also decreases steadily. Since the sum of the squares of the singular values is equal to the total squared covariance between all the elements of the temperature and NDVI, each singular value indicates the relative importance of the corresponding spatial modes. A higher singular value means the more importance of the associated paired-modes. So, the ratio of each squared singular value to the total squared covariance provides a quantitative measurement to its significance. Usually the first several modes can explain a large portion of the squared covariance. The last modes probably make no sense, just noise or random disturbance. Below we show the SVD analysis results and their meanings for spring, summer and autumn separately.

3.1 Spatial feature for spring (April and May)

Table 1 presents the squared percent covariance explained by the first five paired-modes. Obviously, the proportion of leading paired-modes in spring is the highest among all seasons, 60.9%, almost 2.5 times of the value for autumn. This implies that, in general, there is stronger connection between NDVI and temperature, and also means there is higher vegetation sensitivity to temperature in spring than in summer and autumn. The related centers as shown by the singular vectors are key regions where the two variables display the tightest association or cause-consequence relationship. Therefore, these centers demonstrate the stronger NDVI sensitivity to temperature than other regions. Almost entire mid- to high-latitude Eurasia continent shows the same sign of temperature change, i.e., this temperature mode presents a continental scale variation, and the whole region would be dominated by either positive temperature anomalies or the negative anomalies. The corresponding time series show that there are upward trends, implying that the warming temperature is prevailing there. It should be noted that the temperature change is far from uniform distribution, and the most important region

Table 1 The squared percent covariance of NDVI and temperature explained by the five leading paired-modes for spring (Apr. and May), summer (Jun. to Aug.) and autumn (Sept. and Oct.), respectively

	Spring	Summer	Autumn
Paired-modes 1	60.9%	39.5%	24.6%
Paired-modes 2	13.2%	19.0%	22.2%
Paired-modes 3	10.6%	12.3%	15.6%
Paired-modes 4	5.1%	6.8%	9.3%
Paired-modes 5	2.7%	5.8%	5.9%
Sum	92.5%	83.4%	77.6%

(center) is located in Siberia. Interestingly, for the first paired-modes, NDVI shows a similarly spatial feature, i.e., in association with the positive-prevailing temperature mode, positive NDVI anomalies dominate over most of Eurasian continent. Furthermore, the location of the center in NDVI is identical to that of temperature (Fig.1). The above in-phase relationship clearly reveals that the higher spring temperature gives rise to active vegetation growth, leading to a greener condition, and vice versa. Many studies reported that during the last two decades there experienced the significant warming over the Eurasian continent in winter and spring (Houghton *et al.*, 2001). Thus the first paired-modes might be related to the global temperature warming and the vegetation consequences. However, it should be noted, as IPCC2001 report indicated, that the strongest warming trend in spring occurred in the middle and eastern portion of mid- to high Asian continent during the last two decades, which is not the same region as our first modes demonstrated. This suggests that the area experiencing the strongest temperature variability is not necessarily the same place where NDVI response has the strongest sensitivity. The results also imply that NDVI sensitivity to temperature is selectively significant, and the temperature-NDVI coupling is dependent on the regions.

In addition, the second modes explains 13.2% of the total amount. The spatial features are shown in Fig.2. Compared to modes 1, the second paired-modes are of regional scale. Europe and eastern Asia have the same temperature signs, and the opposite signs appear in Northwest Asia. This kind of pattern shows the similarity with some inherent climate modes, such as the Eurasian pattern (Wallace and Gutzler, 1981). It is interesting to note that the NDVI also demonstrate the similar spatial features again. Thus, the second paired-modes might present the temperature influence of large-scale atmospheric circulation fluctuation and the vegetation responses.

3.2 Spatial feature for summer (June to August)

Figure 3 shows the first paired-modes for summer. The outstanding feature is that there are no evident coupling centers, neither for temperature nor for NDVI. Of course, it is not necessary to mean that there are no variation centers for temperature itself, or for NDVI itself. If we perform the spatial-temporal oriented analysis such as principal component analysis or empirical orthogonal function analysis for summer temperature anomalies over the same region, and the leading mode does show apparently anomalous centers. The results from Fig.3 just mean that there is no region showing the strong coupling between summer temperature and vegetation condition, which implies that there

is no high correlation existing in summer, and that NDVI shows less dependence on and less sensitivity to summer temperature. It is reasonable since summer is the warmest season; heat limitation is not an essential factor. The NDVI in northern forest is usually saturated during summer. If the temperature is higher than normal, it would favor the biological activity to less extent; if the temperature is lower than normal, it would not impact the vegetation too much. This case may be true for most of Eurasia. The second paired-modes for summer is a little similar to the second modes for spring, i.e., something like the Eurasian pattern. However, the magnitude is much weaker than that in spring (the figure is not shown).

3.3 Spatial feature for autumn (September and October)

Figure 4 exhibits the first paired-modes for autumn. Both temperature and NDVI centers are located in eastern Asian continent of north of 50º N. The feature also indicates an in-phase relationship, i.e., higher NDVI being associated with the warmer temperature and lower NDVI with the colder temperature. But the magnitude is much weaker than in spring, even weaker than in summer, which suggests that the NDVI sensitivity to temperature in autumn is the lowest in the whole growing season. It may be partly due to the facts that most annual vegetation conditions are generally determined by the growth in spring and summer. That, if true, implies that the autumn NDVI is primarily connected to the spring-summer NDVI rather than the autumn temperature, and compared to that the climate anomaly is somewhat unimportant. Of course, the strong cold surge, which usually comes forth first in autumn, might cause an early stop of vegetation growth and early beginning of winter conditions. The cold surges often form in the interior Asian continent, particularly in the middle to eastern portion. It is noted that the high relation regions also cover the middle to eastern Asian continent. We might conclude that the paired-modes reveal the influence of the extremely cold airflow. In addition, the strong cold surges can move southward along the East Asia to the South China Sea. Figure 4b also confirms this feature, since the coastal regions in eastern China and southern Japan show the high values of singular value vectors. The spatial pattern in the second paired-mode in autumn is a little similar to the first one, the explained squared covariance is also close to the first paired-modes, thus the second modes might not be independent from the first one.

Comparison of the results in Table 1 indicates that much explained squared-covariance in spring is concentrated in the first several paired-modes. For summer and autumn, it is much scattered, suggesting that there might be less factors exerting significant influence on vegetation, and that among these factors the temperature is the most important one. However, for summer and autumn it is not the case. To better understand the NDVI fluctuations in summer and autumn, in addition to temperature, more other factors should be taken into account.

3.4 Sensitivity analysis

The previous sections reveal that there are some key regions where temperature and NDVI are highly correlated. In order to quantitatively estimate the connection between them over there, we analyzed the sensitivity of NDVI in this section. According to Figs.1, 3 and 4, we chose three different centers for spring, summer and autumn, respectively. The mean NDVI and temperature averaged over these regions were carried out, and an ordinary linear regression analysis was applied to the time series. Finally we gained the quantitative relationship between temperature and NDVI for each region. Since the data samples used to calculate the means would affect the variance, only the means based on same spatial grids can be compared with each other. Keeping this point in mind, we picked out NDVI centers with the same pixel numbers for spring, summer and autumn. For spring, the rectangle is 60º-90º E by 55º-65º N. Since there is no outstanding center for summer, we chose a relatively high center of domain of 100º-120º E, 45º-60º N. For autumn the region is 110º-140º E, 55º-65º N. All three regions selected contain the same NDVI pixel number. The results are shown as follows:

Spring: $NDVI = -0.015 + 0.308\ T$, $r = 0.89$, significant level > 99%;

Summer: $NDVI = 0.0068\,9 + 0.248\ T$, $r = 0.52$, significant level > 95%;

Autumn: $NDVI = 0.009\,2 + 0.087\,5\ T$, $r = 0.25$, not significant.

where T is temperature, and r is correlation coefficients. Obviously, among all seasons and all key regions the highest sensitivity of NDVI to temperature occurs in spring, 0.308 NDVI/℃. In summer the sensitivity is lower than spring. Although in autumn there is still positive correlation between NDVI and temperature, the correlation is not significant (Fig.5).

4 Discussion

It should be mentioned that the above analysis concerns only the strong spatial-temporal coupling feature involved in temperature-NDVI variations and would not be expected to explain all of interannual variance in NDVI. For example, Europe is not the center in the first paired-modes for spring, but, some researches reported that there are early-coming growth seasons, enhanced biological activity in spring during the recent years (Black *et al.*, 2000; Zhou *et al.*, 2001), thus leading to strong upward NDVI trends over there. As Fig.6 shows, during the last about 20 years, in addition to Europe, most of the Asian continent also display the tendency to become greener. Some other studies also reported that (Zhou *et al.*, 2001). Mean NDVI averaged over 40º-70º N, 0º-155º E shows a trend in order of 0.021 2 per 10 a for April to October. This value is statistically significant at the 99% confidence level. In all growing seasons, spring shows the strongest trend, too. The trend for the same domain but for April and May is 0.026 3 NDVI per 10 a, also significant above the 99% confidence level, which means that the trend in spring is 24% stronger than the average of the entire growing season. In addition to the linear trends, the year-to-year changes in April and

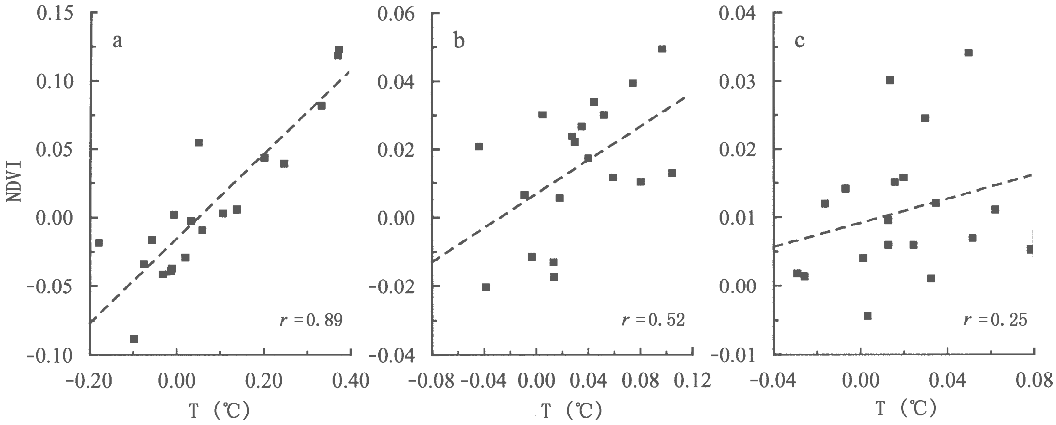

Fig.5. Scatter maps showing the relationships between normalized difference vegetation index (NDVI) and temperature (T) anomalies over the most sensitive regions for spring (**a**), summer (**b**) and autumn (**c**), respectively. Both NDVI and temperature are anomalies.

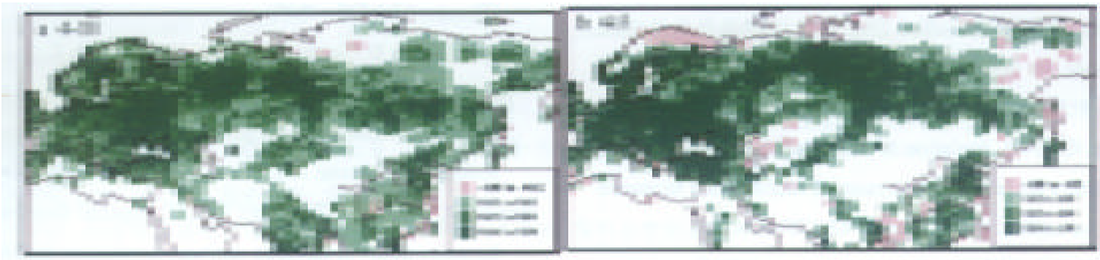

Fig.6. Linear trends of normalized difference vegetation index (NDVI). **a.** Whole growing seasons (April **to** October). **b**. spring (April and May) in period 1981-2000. Only strong trends with values ≥ 0.02 and ≤ -0.02 NDVI per decade are shown.

May also show the high correlation with the average condition for April to October as a whole. They correlate at a value of 0.9 for the period 1982-2000, implying that about 80% of the interannual NDVI variation in growing seasons is associated with the vegetation condition in spring. Therefore, we should pay more attention to spring when considering the response of ecosystem to climate changes.

Our analyses do not show any temperature-NDVI coupling center in the leading SVD modes over China for all seasons. This may be due to, compared to the other Eurasian continent regions, the lower NDVI sensitivity to temperature over there. However, in both spring and whole growing season there is a significant positive trend over the eastern China, particularly in the northern plains. Temperature in eastern China is increasing during the last 20 years, indicating there is general in-phase relationship between temperature and NDVI. However, for such monsoon driving ecosystems as in East Asia the monsoon precipitation plays an essential role in the vegetation condition and its anomaly (Fu and Wen, 1999). In northern China, where arid, semi-arid and semi-humid environments occupy most of portion of areas, there is a positive correlation between NDVI and rainfall. But observations show both annual and growing season precipitation had not increased in the last 20 years, and contrary to this, it decreased indeed. The inconsistency between the decreasing precipitation, warming temperature and greening vegetation may partly arise from the advancement of agriculture activity in China. These regions showing strong NDVI trend in eastern China (mostly in northern plains) are part of the main advanced agricultural regions. Vegetation here would benefit from the modern irrigation systems, which could evidently reduce the impacts of natural rainfall deficit on plants, and also benefit from a warming temperature.

In the present study, we do not use all of the $1^\circ \times 1^\circ$ NDVI data sets in the SVD analysis since, if so, the covariance matrix is too large to perform the SVD on the personal computer due to the limitation of computer memory. Instead, we use the re-sampled $2^\circ \times 2^\circ$ resolution NDVI. In order to check whether the changes in NDVI resolutions would change the results or not, we perform the same process using the remained $2^\circ \times 2^\circ$ data and an even coarser resolution data set re-sampled at $3^\circ \times 3^\circ$ grids. We find that all these have the similar results. For example, using the other $2^\circ \times 2^\circ$ resolution data for spring the first three modes explain 60.6%, 13.3% and 10.8% of the total squared covariance; for $3^\circ \times 3^\circ$ resolution the explained proportion is 61.0%, 12.7% and 10.8%, almost the same. In addition to the explained covariance, the spatial patterns are alike, too, which implies that the NDVI-temperature relationship revealed by SVD is not dependent on the data resolution, and that the features of strong large-scale temperature signals and the NDVI responses presented in the present study are robust and stable.

References:

Agbu P A, James M E. 1994. The NOAA/NASA Pathfinder AVHRR Land Data Set user's manual. Goddard Distributed Active Archive Center, NASA, Goddard Space Flight Center. Technical Report. 1 - 105.

Black T A, Chen W J, Barr A G, Arain M A, Chen Z, Nesic Z, Hogg E H, Neumann H H. 2000. Increased carbon sequestration by a boreal deciduous forest in years with a warm spring. *Geophys Res Lett*, **27**:1271 - 1274.

Bretherton C S, Smith C, Wallace J M. 1992. An intercomparison of methods for finding coupled patterns in climate data. *J Climate*, **5**:541 - 560.

Fu C B, Wen G. 1999. Variation of ecosystems over East Asia in association with seasonal, interannual and decadal monsoon climate variability. *Clim Change*, **43**:477 - 494.

Gong D Y, Shi P J. 2003. Northern hemispheric NDVI variations associated with the large-scale climate indices in spring. *Int J Remote Sens*, **24**:2559 - 2566

Houghton J T, Ding Y H, Griggs D J, Noguer M, van der Linden P J, Dai X, Maskell K, Johson C A. 2001. Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. 881.

James M E, Kalluri S N V. 1994. The Pathfinder AVHRR land data set: an improved coarse-resolution data set for terrestrial monitoring. *Int J Remote Sens*, **15**:3347 - 3364.

Jones P D, Osborn T J, Briffa K R, Folland C K, Horton E B, Alexander L V, Parker D E, Rayner N A. 2001. Adjusting for sampling density in grid box land and ocean surface temperature time series. *J Geophy Res*, **106**:3371 - 3380.

Jones P D. 1994. Hemispheric surface air temperature variations: a reanalysis and an update to 1993. *J Climate*, **7**:1794 - 1802.

Kawabata A, Ichii K, Yamaguchi Y. 2001. Global monitoring of interannnual changes in vegetation activities using NDVI and its relationships to temperature and precipitation. *Int J Remote Sen*, **22**:1377 - 1382.

Kogan F N. 2000. Satellite-observed sensitivity of world land ecosystems to El Nino/La Nina. *Rem Sen Environ*, **74**:445 - 462.

Li X-B, Shi P-J. 1999. Research on regulation of NDVI change of Chinese primary vegetation type based on NOAA/AVHRR data. *Acta Bot Sin*, **41**:314 - 324. (in Chinese)

Los S O, Collatze G J, Bounoua L, Sellers P J, Tucker C J. 2001. Global interannual variations in sea surface temperature and land surface vegetation, air temperature, and precipitation. *J Climate*, **14**:1535 - 1549.

Pan Y Z, Li X B, Gong P, He C Y, Shi P J, Pu R L. 2003. An integrative classification of vegetation in China based on NOAA/AVHRR and vegetation-climate indices of the Holdridge life zone. *Int J Remote Sens*, **24**:1009 - 1027.

Suzuki R, Nomaki T, Yasunari T. 2001. Spatial distribution and its seasonality of satellite-derived vegetation index (NDVI) and climate over Siberia. *Int J Climato*, **21**:1321 - 1335.

Suzuki R, Tanka S, Yasunari T. 2000. Relationships between meridional profiles of satellite-derived vegetation index (NDVI) and climate over Siberia. *Int J Climato*, **20**:955 - 967.

Wallace J M, Gutzler D S. 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon Wea Rev*, **109**:784 - 812.

Wallace J M, Smith C, Bretherton C S. 1992. Singular value decomposition of wintertime sea surface temperature and 500-mb height anomalies. *J Climate*, **5**:561 - 576.

Walther G R, Post E, Convey P, Menzil A, Parmesan C, Beebee T, Fromentin J M, Hoegh-Guldberg O, Bairlein F. 2002. Ecological responses to recent climate change. *Nature*, **416**:389 - 395.

Zhou L M, Tucker C J, Kaufmann R K, Slayback D, Shabanov N V, Myneni R. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *J Geophy Res*, **106**:20069 - 20083.

(Managing editor: HAN Ya-Qin)

Clear Figures

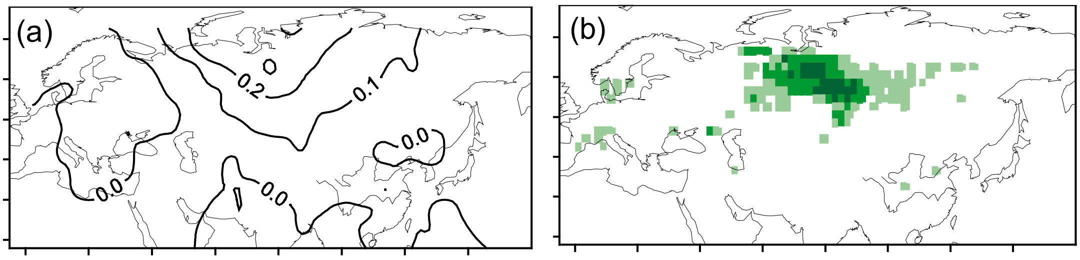

Fig.1. First paired-modes of temperature (**a**) and NDVI (**b**) for April-May. NDVI scalar interval is 0.02, only values of 0.04~0.06，0.06~0.08，and >0.08 are shown.   There is no value less than ñ0.04. Weak signals between ñ0.04 and +0.04 are not shown for simplicity. Temperature anomalies are shown as contours with interval of 0.1. Both units are arbitrary.

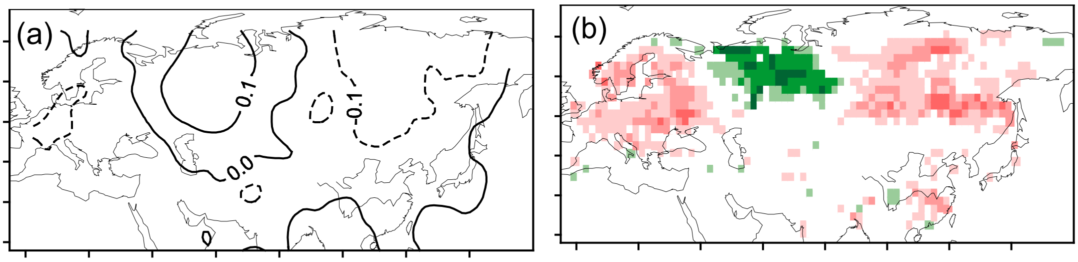

Fig.2. Second paired-modes of temperature (**a**) and NDVI (**b**) for April-May. NDVI scalar interval is 0.02, from dark green to bright red indicate values of >0.08, 0.08~0.06, 0.06~0.04，ñ0.04~ñ0.06, ñ0.06~ñ0.08, and <ñ0.08 consequently.   Weak signals between ñ0.04 and +0.04 are not shown for simplicity. Temperature anomalies are shown as contours with interval of 0.1. Both units are arbitrary.

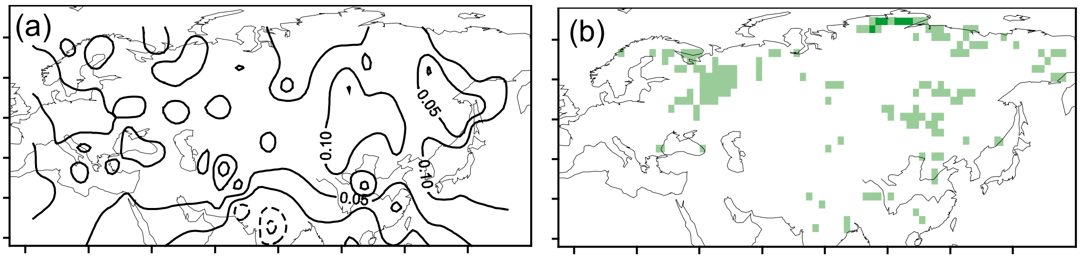

Fig.3. First paired-modes of temperature (**a**) and NDVI (**b**) for June-August. NDVI scalar is as same in Fig.1. Temperature anomalies are shown as contours with interval of 0.05. Both units are arbitrary.

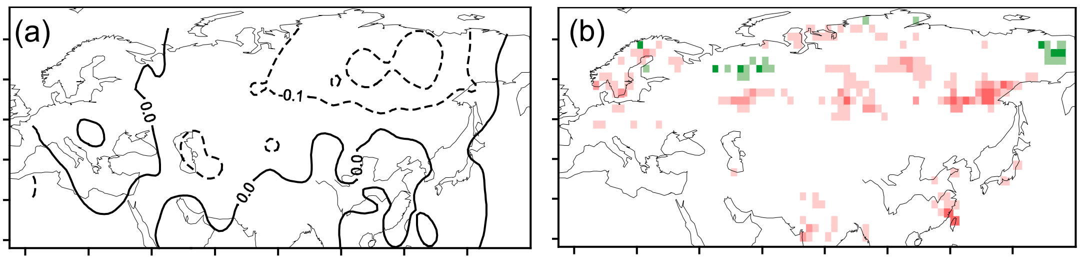

Fig.4. First paired-modes of temperature (**a**) and NDVI (**b**) for September-October. See Fig.2 for NDVI scales. Temperature anomalies are shown as contours with interval of 0.1. Both units are arbitrary.

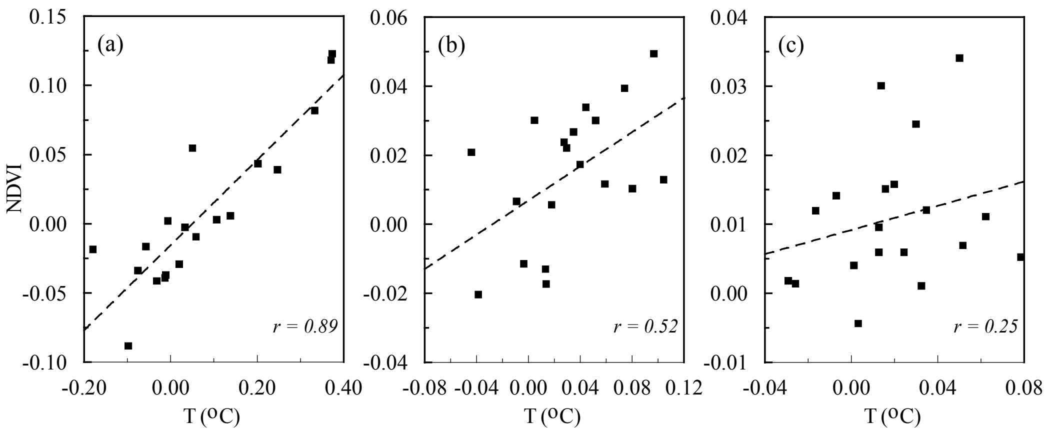

Fig.5 Scatter maps showing the relationships between NDVI and temperature anomalies over the most sensitive regions for spring (**a**), summer (**b**) and autumn (**c**), respectively. Both NDVI and temperature are anomalies.

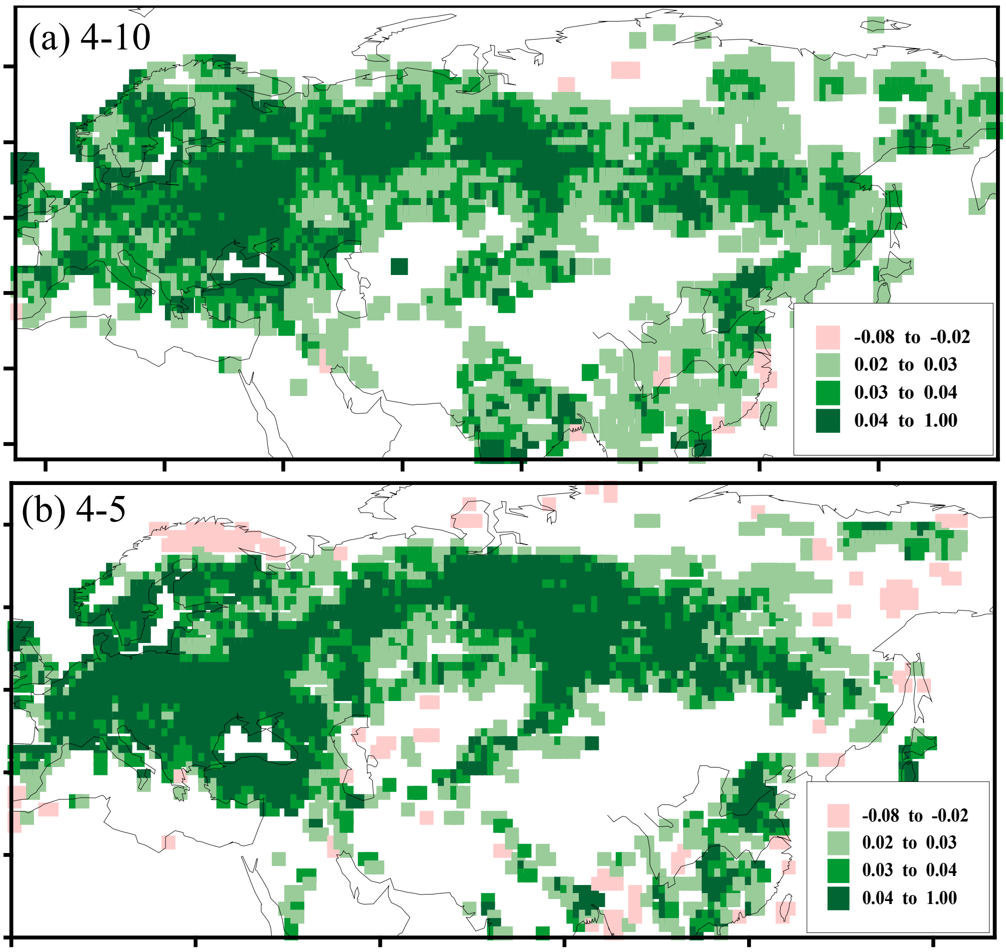

Fig.6 Linear trends of NDVI for (**a**) whole growing seasons (April-October) and (**b**) spring (April-May) in period 1981-2000. Only strong trends with values ⩾0.02 and ⩽-0.02 NDVI per decade are shown.