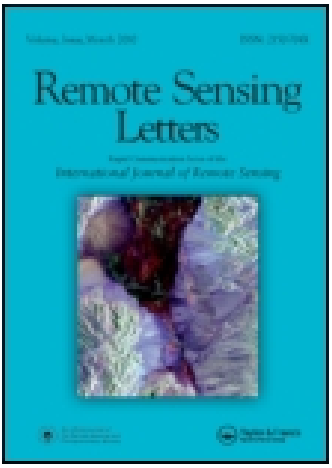

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Non-linear response of vegetation to coherent warming over northern high latitudes

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This study evaluates the large-scale changes in vegetation greenness at northern high latitudes (>60° N) using satellite-measured normalized difference vegetation index (NDVI) and station-merged temperature, precipitation and soil moisture for the period 1982–2008. During this 27-year period, although coherent warming trends were observed at most of the high latitudes, changes in the NDVI showed apparent spatial and temporal heterogeneity. In particular, changes in the hemispheric mean NDVI increased until 1997, but decreased thereafter. Maximum covariance analysis, which is a statistical method to detect large-scale covariability between two variables over time, reveals significant relationships between NDVI and soil moisture (and/or precipitation) in the regions of negative NDVI trends. These results further suggest that local moisture availability also plays a considerable role in the large-scale changes in vegetation as well as coherent warming over the northern high latitudes.

1. Introduction

Changes in vegetation at high latitudes have a strong influence on regional and/or global climate changes (e.g. Bonan 2008, Jeong *et al.* 2011). Many studies have attempted to assess changes in high-latitude vegetation greenness by analysing trends in satellite-measured normalized difference vegetation index (NDVI) (Myneni *et al.* 1997, Tucker *et al.* 2001, Gong and Ho 2003). Although many studies have reported that global warming has resulted in overall greening of the high-latitude regions (Myneni *et al.* 1997, Lucht *et al.* 2002), some have suggested that this interpretation might be too simplistic (Angert *et al*. 2005, Goetz *et al.* 2005, Bunn and Goetz 2006). For example, Angert *et al.* (2005) showed a decrease in NDVI across the northern extra-tropics for the period 1982–2002 and suggested that drier and hotter summers lead to a decrease in the NDVI over the regions. Piao *et al*. (2011) found that the summertime NDVI over Eurasia increased significantly for the period 1982–1997, but decreased thereafter. Wang *et al.* (2011) also showed that the point at which the NDVI changes from positive to negative varies across regions in North America.

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Although the above-mentioned studies provided a general perspective, the hemispheric features of NDVI changes in high latitudes are not yet completely understood. Contradictory results (e.g. greening vs. browning) of previous studies might be a result of the differences in the analysis period and domain. Thus, there is no general consensus on whether the general features of large-scale changes in high-latitude vegetation are related to global or regional warming or both. To deal with these fundamental questions, a better understanding of the relationship between the changes in vegetation greenness and climate changes under persistent warming situations is required. This study is conducted to analyse the covariance between vegetation greenness and climate over high latitudes for the period 1982–2008.

2. Data and method

The NDVI was produced by the National Aeronautics and Space Administration Global Inventory Monitoring and Modeling Systems (GIMMS) group (http://glcf.umiacs.umd.edu/data/gimms/) (Tucker *et al.* 2004) using the data from the Advanced Very High Resolution Radiometer on the National Oceanographic and Atmospheric Administration's polar-orbiting satellites. The data have a spatial resolution of 8 km, global coverage and a 15-day temporal resolution for the period 1982–2008. Several data corrections (e.g. aerosol, cloud, volcanic and sensor degradation) were performed to improve the data consistency (Tucker *et al.* 2005). In this study, the NDVI data were aggregated onto a 0.5° grid to minimize spatial noise and to match the observed surface climate variables described below. Monthly NDVI data are obtained from two consecutive 15-day composites using the maximum value method (Holben 1986). The linear trends for the whole data period are calculated by a simple linear regression model with year as the independent variable and NDVI as the dependent variable.

To evaluate changes in climate, the monthly mean surface air temperature, precipitation and soil moisture for the period 1982–2008 are examined. Data for these three climatic variables, with a $0.5° \times 0.5°$ longitude–latitude resolution and covering the global land area, are all obtained from the National Centers for Environmental Prediction (NCEP) Climate Prediction Center (CPC) (http://www.cpc.ncep.noaa.gov/data/). The accuracy of the CPC data is comparable with that of other existing observation-based data (Xie *et al*. 2007, Fan and van den Dool 2008). These climate data sets also capture most of the common spatiotemporal features in the observed anomaly fields related to climate change and the variability over both regional and global domains (Xie *et al*. 2007, Fan and van den Dool 2008).

To understand the relationships between NDVI and climate (e.g. temperature, precipitation and soil moisture) and to isolate the effects of climate on vegetation, we used the maximum covariance analysis (MCA) method using the seasonal means of variables. In practice, MCA is implemented using singular value decomposition (SVD) (Wallace *et al.* 1992). Simply stated, the elements of the $s \times t$ matrix, $\mathbf{T}$, and the elements of the $s \times t$ matrix, $\mathbf{N}$, are temperature (T) and NDVI (N) at specific values of spatial grid (s) and times (t), respectively. Both T and N at each location are anomalies with respect to the total time period (i.e. 27 years). The covariance matrix $\mathbf{C}$ is obtained from T and N. Thereafter, the SVD on the covariance matrix $\mathbf{C}$ is carried out, yielding the following: a set of singular values and pairs of mutually orthogonal patterns, i.e. the corresponding expansion time coefficients. The results from MCA consist of pairs of spatial modes and corresponding time series, representing co-varying structures.

In this study, for MCA, we regarded climate as the forcing variable and NDVI as the response. Accordingly, the leading pairs of MCA patterns indicate the forcing pattern that has the strongest influence on NDVI; each pair of spatial patterns describes a fraction of the total squared covariance between NDVI and temperature, and the correlation between time series of principal components indicates the strength of coupling between the two variables.

3. Results

Figure 1 displays the spatial distribution of the linear trends of the summer mean (June–August) temperature and NDVI over northern high latitudes (>60° N; NHLs) for the period 1982–2008. In contrast to the generally homogeneous spatial pattern of positive temperature change rates, the spatial distribution of the NDVI trends shows a mixture of positive and negative values. Large positive values are only observed in northeastern Eurasia and the tundra in North America, whereas dominant negative values are randomly distributed over the NHL (figure 1(*b*)). Owing to this apparent spatial heterogeneity in the NDVI change rates, the area-averaged NDVI shows a negligible trend during the whole period (figure 1(*c*)). When we evaluate the differences in mean NDVI values with a 9-year moving window, statistically significant differences, based on Student's *t*-test, are observed for either sides of the two windows in the year 1997.

Accordingly, we compared change in NDVI/year for the period 1982–1997 with the period 1997–2008 (figure 2). During 1982–1997, most of the high-latitude regions showed positive NDVI change rates. The rate of positive changes in Eurasia (0.002/year) was higher than that in North America (0.001/year). Since 1997, most parts of the NHL have shown decreasing NDVI trends. The probability density functions (PDFs) show that the area-averaged NDVI trends over the NHL are −0.0027/year. This large NDVI decrease was twice the rate of the previous rate of greening for the NHL. Particularly, the browning signals in North America show a more rapid change than those in Eurasia.

Figure 3 depicts the covariability distributions and the corresponding expansion time coefficients of the leading MCA modes between NDVI and temperature, precipitation and soil moisture for the period 1982–2008. In MCA between NDVI and temperature, the explained squared covariances are concentrated in the first two leading modes that contribute more than 70% of the total amount. The first mode could be used to explain 58.2% of the total squared covariance between the two variables (figures 3(*a*) and (*b*)). Over northeastern Eurasia and Russia, the centres of positive NDVI are highly consistent with positive temperatures. A strong positive correlation coefficient (e.g. 0.86) between time series of the principal components of NDVI and temperature indicates the dominant strength of the coupling between NDVI and temperature (figure 3(*c*)). Thus, the observed increase in the NDVI over northeastern Eurasia and Russia is associated with the increasing temperature. In contrast, negative NDVI anomalies are observed at various locations at central Eurasia, Canada, Alaska, the Canadian archipelago, northern Europe and the vicinity of east Kara Sea. Overall, spatial distributions of the temperature and NDVI anomalies in the first mode (figures 3(*a*) and (*b*)) are generally consistent with the linear trends of temperature and NDVI, respectively (see figure 1). In contrast to the first mode, the spatial distributions of the second mode, which account for 15.5% of the total covariances, show coherent features over high latitudes (figure not shown).

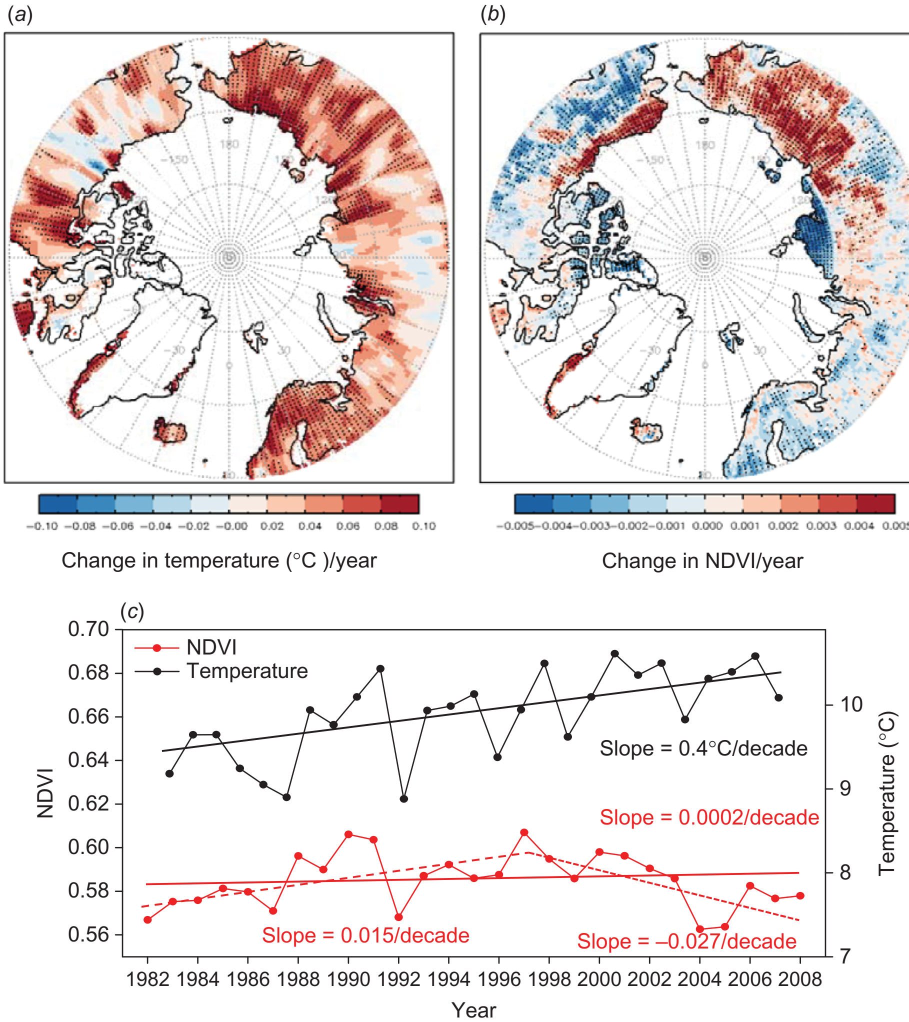

Figure 1. (*a*) Spatial distribution of the linear trends in summer temperature. (*b*) Same as (*a*) but for the normalized difference vegetation index (NDVI). Black dots in figure indicate the statistical significance at the 95% confidence level. (*c*) Time series of the area-averaged NDVI and temperature at high latitudes for the period 1982–2008. Solid lines show linear trends in the temperature (black line) and NDVI (red line) across the entire period. The dashed red line indicates linear trends in NDVI from 1982 to 1997, and the dotted red line from 1997 to 2008.

In the MCA between precipitation and NDVI, about 70% of the total variance is explained by the three leading modes. The first mode explains 32.7% of the total squared covariance with a 0.84 correlation coefficient between them. Except for the northeastern parts of the Eurasian continent, most of the Arctic region shows negative NDVI anomalies (figure 3(*d*)). However, coherent negative precipitation anomalies are only observed in the central part of North America and northern Europe (figure 3(*e*)). In that region, in-phase NDVI–precipitation relationships suggest that either an increase in precipitation resulted in favourable vegetation growth in that region or vice versa (figure 3(*f*)). The second mode accounts for 29.1% of the total

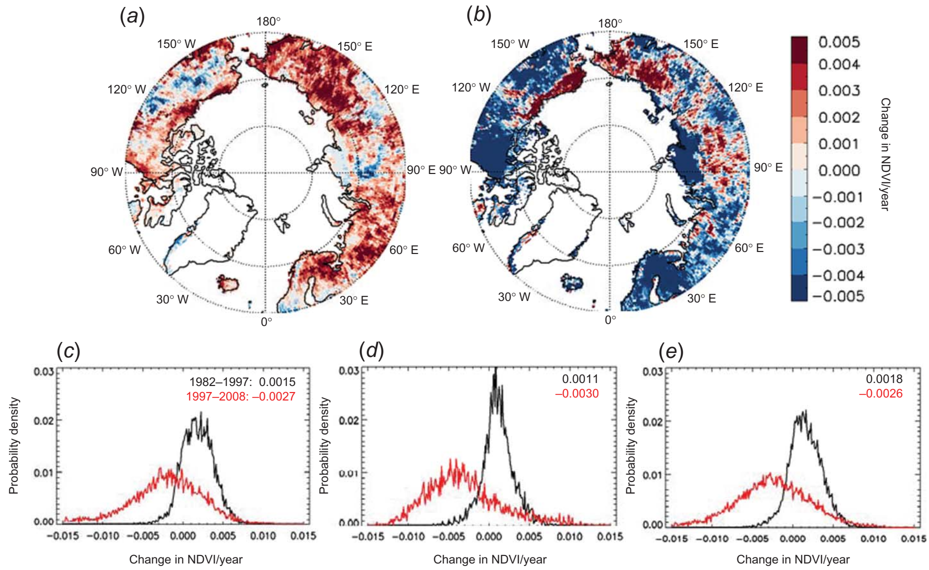

Figure 2. Spatial patterns of linear trends in NDVI for (*a*) 1982–1997 and (*b*) 1997–2008 (*c*) Probability density functions (PDFs) of linear trends of NDVI over NHL for the periods 1982–1997 (black line) and 1997–2008 (red line), respectively. (*d*) Same as (*c*) but for North America. (*e*) Same as (*c*) but for Eurasia. The black (red) number indicates mean values of each PDF for the period 1982–1997 (1997–2008).

squared covariance with a positive correlation coefficient (0.91) between NDVI and precipitation. Dominant NDVI–precipitation connections are observed in Alaska, the central part of North America and central Eurasia (figures 3(*g*) and (*h*)). Temporal variations in that region suggest that decreases in precipitation led to a decrease in vegetation greenness in that region (figure 3(*i*)). This is qualitatively consistent with the current model results showing that vegetation productivity can be influenced by water availability (Zhang *et al*. 2008).

In the MCA between NDVI and soil moisture, the first mode accounts for 65% of the total squared covariance with a strong positive correlation coefficient (e.g. 0.93). The dominant in-phase relationships between soil moisture and NDVI are observed in Alaska and northern Europe (figures 3(*j*) and (*k*)). Here, it is interesting to note that the statistically significant inflection is also observed in the year 1997, as shown in the time series of the first leading mode in soil moisture and NDVI (figure 3(*l*)). The same temporal trends of NDVI with soil moisture suggest that a decrease in soil moisture led to a decrease in NDVI after 1997. In particular, the inflection point in the time series of the first leading mode of NDVI and soil moisture is consistent with the inflection point in original NDVI trends (i.e. 1997). Because soil moisture is calculated from the balance between moisture supply (i.e. precipitation) and demand (i.e. temperature), the consistent inflection point in the first leading soil moisture mode strongly suggests that the importance of moisture has gradually increased with continuous warming.

4. Conclusion

In this study, we evaluated changes in large-scale NDVI and climate variables at northern high latitudes (>60° N) from 1982 to 2008. Although temperature trends showed

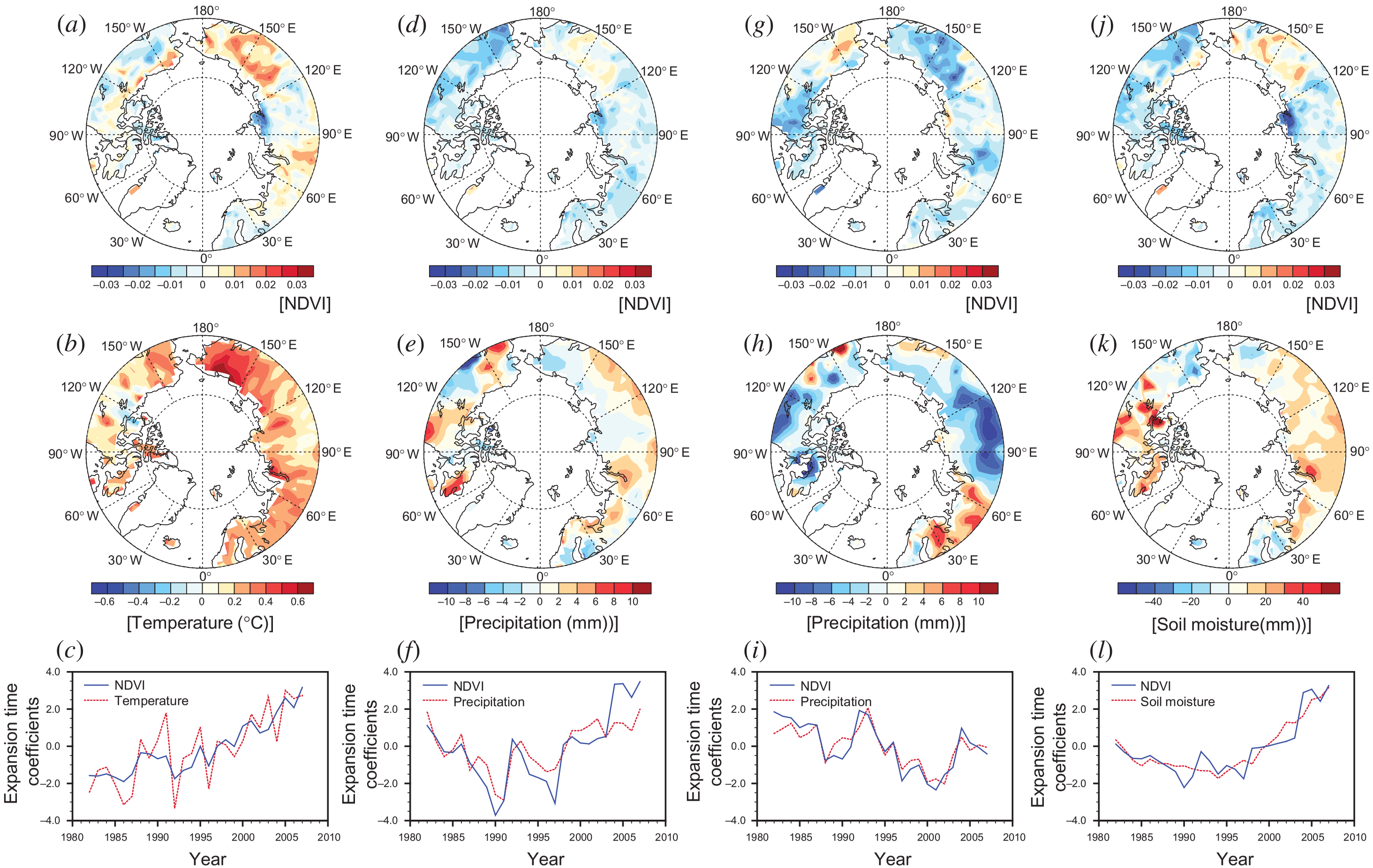

Figure 3. Spatial patterns of expansion coefficients of (*a*) NDVI and (*b*) temperature for the first leading modes of SVD between NDVI and temperature, respectively. (*c*) Time series of expansion coefficients for the first leading modes of SVD between NDVI and temperature. Spatial patterns of expansion coefficients of (*d*) NDVI and (*e*) precipitation for the first leading modes of SVD between NDVI and precipitation, respectively. (*f*) Time series of expansion coefficients for the first leading modes of SVD between NDVI and precipitation. Spatial patterns of expansion coefficients of (*g*) NDVI and (*h*) precipitation for the second leading modes of SVD between NDVI and precipitation, respectively. (*i*) Time series of expansion coefficients for the second leading modes of SVD between NDVI and precipitation. Spatial patterns of expansion coefficients of (*j*) NDVI and (*k*) soil moisture for the first leading modes of SVD between NDVI and temperature, respectively. (*l*) Time series of expansion coefficients for the first leading modes of SVD between NDVI and soil moisture.

coherent positive changes over the analysis domain, the trends in the NDVI showed apparent spatial heterogeneity. These results indicate that the spatial patterns of NDVI changes do not respond linearly to hemispheric warming. Considering the spatial patterns of NDVI trends, although some parts of negligible NDVI trends are explained by long-term changes in temperature, considerable portions of negative NDVI trends are attributed to the moisture depletions as well as warming in that region. Our results also suggest that observed non-linear response of vegetation to warming is shown to be valuable for the evaluation of the performance of climate models coupled with dynamic vegetation. Here, one thing to note is that this study is only focused on the large-scale changes in vegetation greenness related to climate. Thus, our results do not imply that variations in detailed specific regions are necessarily explained by non-climatic factors. For example, significant positive changes in NDVI in northern Alaska can be related to sea–ice variations (Bhatt *et al.* 2010). In addition, other factors, such as fire damage (Goetz *et al.* 2005) and insect damage (Soja *et al.* 2006), can also lead to changes in local vegetation at high latitudes.

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