

Impacts of grassland types and vegetation cover changes on surface air temperature in the regions of temperate grassland of China

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Abstract The sensitivity of surface air temperature response to different grassland types and vegetation cover changes in the regions of temperate grassland of China was analyzed by observation minus reanalysis (OMR) method. The basis of the OMR approach is that reanalysis data are insensitive to local surface properties, so the temperature differences between surface observations and reanalysis can be attributed to land effects. Results showed that growing-season air temperature increased by 0.592 °C/decade in the regions of temperate grassland of China, with about 31 % of observed warming associated with the effects of grassland types and vegetation cover changes. For different grassland types, the growing-season OMR trend was the strongest for temperate desert steppe (0.259 °C/decade) and the weakest for temperate meadow (0.114 °C/decade). Our results suggest that the stronger intraseasonal changes of grassland vegetation are present, the more sensitive the OMR trend responds to the intraseasonal vegetation cover changes. In August and September, the OMR of temperate meadow showed a weak cooling trend. For temperate meadow, about 72.2 and 72.6 % of surface cooling were explained by both grassland type and

increase of vegetation cover for August and September, respectively. For temperate steppe and temperate desert steppe, due to the limited soil moisture and little evaporative cooling feedback, the vegetation changes have no significant effect on the surface air temperature. These results indicate that the impact of grassland types and vegetation cover changes should be considered when projecting further climate change in the temperate grassland region of China.

1 Introduction

Greenhouse gas emission and land use/cover change are regarded as the most important anthropogenic factors that affect climate, and they both tend to increase surface air temperature (Kalnay and Cai 2003; Yang et al. 2009). Land cover change exhibits more local rather than global effects on climate as compared to greenhouse gas emissions. In some cases, the effect of land cover changes in the form of agricultural activity, deforestation, and urbanization may even exceed the effect of greenhouse gases on climate (Roger and Pielke 2005; Dirmeyer et al. 2010). However, due to the lack of reliable methods of separating the local climate change signal from the global climate change, the local response of climate to land cover changes is difficult to assess. Most previous studies adopted numerical simulation methods to investigate the effects of land cover changes (Lean and Warrilow 1989; Henderson-Sellers et al. 1993; Xue 1996; Fu 2003; Snyder et al. 2004; Bala et al. 2007).

Recently, Kalnay and Cai (2003) developed an observation minus reanalysis (OMR) method to estimate the impact of land use/cover change on surface air temperature by taking the difference between surface observations data and NCEP-NCAR (NNR) reanalysis data. The basic theory of the OMR method is that NNR reanalysis surface data estimated from the

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upper-air information combined with model parameterizations do not assimilate surface observations over land and, therefore, are not sensitive to land properties (Lim et al. 2005). Natural climate variability caused by changes in atmospheric circulation and anthropogenic activities is included in both surface observations and reanalysis. Nonetheless, the part of land surface effects, which does not extend higher into the atmosphere (therefore is not included in the reanalysis), is captured only by surface observations. Therefore, the temperature differences between surface observations (which contain all the climate functions) and the NNR reanalysis can be primarily attributed to land effects (Kalnay and Cai 2003).

The OMR method has been widely used to study the impact of land cover change on surface air temperature both globally and regionally (Kalnay and Cai 2003; Frauenfeld et al. 2005; Lim et al. 2005; Zhang et al. 2005; Kalnay et al. 2006; Nuñez et al. 2008; Fall et al. 2010; Hu et al. 2010). Many studies have used the OMR method to assess temperature sensitivity to different vegetation types in terms of surface vegetation index (Yang et al. 2009; Lim et al. 2005, 2008; Wang et al. 2014). Lim et al. (2008) found that there is a greater surface warming trend in the desert areas than other land types at the global scale, whereas the strong evaporative cooling in highly vegetated areas appeared to suppress the surface warming. Similarly, Yang et al. (2009, 2010) found that areas with higher vegetation cover showed smaller warming trend in China, and this finding was further supported by the study in Jiangxi Province of China (Wang et al. 2014). However, these studies just attribute the OMR trends (the difference between observational and reanalysis temperature trends) to land cover changes, ignoring the influence of the differences of physicochemical characteristics and biological processes within the same vegetation type caused by the year-to-year changes of vegetation growth. To a great extent, the status of land cover depends on the condition of surface vegetation cover (Yang et al. 2010), and the influence of the vegetation cover can extend to some extent into the free atmosphere and, thus, may have an impact on the regional climate (Kabat 2004). So far, no study has examined the response of climate change to a specific vegetation type in detail, especially in relation to year-to-year variation in vegetation cover, which may also play an important role in local and regional climates. Furthermore, no effort has been made to assess the response to the second-level vegetation types under some first-level vegetation type. Most studies focused mainly on comparing the responses of climate change to different first-level land vegetation types.

As the third largest grassland area in the world (Lee et al. 2002), China's temperate grassland is highly sensitive to climate change (Xiao et al. 1995) and also plays an important role in the regional climate (Piao et al. 2006). The simple structure of grassland vegetation types makes them ideal subjects to study vegetation dynamics by using remote sensing

observations (Piao et al. 2006). Previous studies have found that vegetation activity in China's temperate grassland region increased over the past decades (Fang et al. 2004; Piao et al. 2006), but the possible effect of vegetation increase on climate change has not been reported because most previous studies have focused on the response of grassland vegetation to climate change (Fang et al. 2004; Piao et al. 2006; Chuai et al. 2013). Therefore, studies on the response of climate change to vegetation in the temperate grassland region are of significance to further understand the feedback between grassland vegetation and climate change in China.

In this study, we attempt to examine the impact of grassland types and vegetation cover changes on surface air temperature in the regions of temperate grassland of China. By analyzing OMR trends for different grassland types and incorporating regional vegetation cover changes into regression assessments of surface air temperature, we assess the relationship between OMR trends and grassland vegetation types and vegetation cover changes in terms of normalized difference vegetation index (NDVI). We analyze the OMR trends of different grassland types and the sensitivity of surface air temperature to vegetation cover change for the regions of temperate grassland in China.

2 Materials and methods

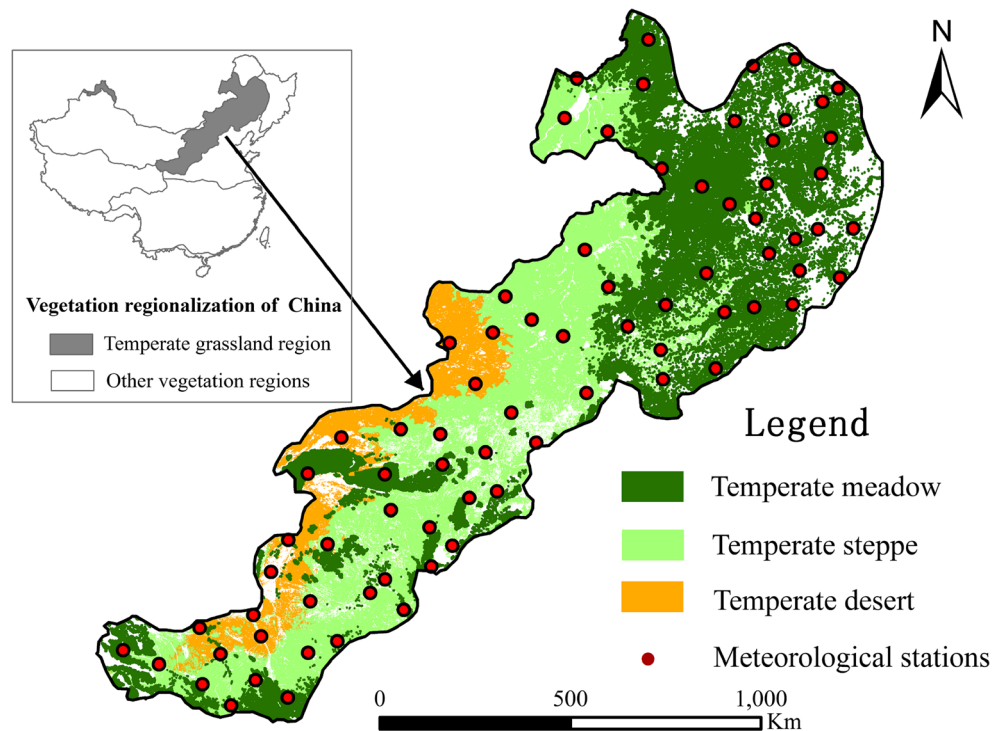
2.1 Study area

According to China's vegetation regionalization, the temperate grassland region of China is mainly distributed in Songliao Plain, Inner Mongolia Plateau, and the Loess Plateau, with a small fraction located in Altay Mountains of Xinjiang (Chinese Academy of Sciences 2001). In this study, we chose the main regions of temperate grassland (excluding the small part in Xinjiang) as our study area (Fig. 1). This temperate grassland region spreads from approximately 104° to 130° E in longitude and 35° to 50° N in latitude. The climate in this region varies from the west arid/semiarid climate to the east wet, half humid monsoon climate. The average annual precipitation ranges from 35 to 530 mm, and the annual mean temperature from -5 to 10 °C (Chuai et al. 2013). Temperate grassland in this region is divided into three major types: temperate meadow, temperate steppe, and temperate desert steppe (Piao et al. 2006). Temperate meadow mainly occurs in the east of the study area, while temperate steppe and temperate desert steppe are mainly distributed in the west arid/semiarid area (Fig. 1).

2.2 Data

Data used in this study are as follows: (1) monthly surface air temperature data from surface observation and NNR

Fig. 1 The locations of meteorological stations and distribution of unchanged grasslands in the temperate grassland region of China from the 1980s to 2006



reanalysis during 1982 to 2006. The observation data were obtained from 77 meteorological stations distributed in the temperate grassland region of China, provided by the National Meteorological Information Center, available at China Meteorological Data Sharing Service System (CMDSSS) (<http://cdc.cma.gov.cn/index.jsp>). The initial quality control of the observation data was performed by the National Meteorological Information Center of the China Meteorological Administration (Xu et al. 2013). We adopted the method used by Wang and Gaffen (2001) to further assure the quality and consistency of the data as described in detail in our previous study (Shen et al. 2014). With the vigorous data assurance policy, the quality and consistency of the observation data were guaranteed. The NNR temperature data were provided by the Physical Sciences Division of NOAA/Earth System Research Laboratory (www.esrl.noaa.gov/psd). The NNR data was available on the gaussian grid (Kalnay et al. 1996; Kalnay and Cai 2003), with 42 NNR grid points falling into the study area. (2) NDVI data from 1982 to 2006 was obtained from the Global Land Cover Facility, Global Inventory Modeling and Mapping Studies (GIMMS), with a spatial resolution of $8\text{ km} \times 8\text{ km}$ and 15-day composite (maximum value) temporal resolution (Tucker et al. 2005). This data set had been processed with atmospheric, radiometric, and geometric corrections. (3) Two periods of land use/cover data of China in the 1980s and 2005–2006 were obtained from raster land cover products of China with $100\text{ m} \times 100\text{ m}$ pixels (Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences), provided by the

National Earth System Science Data Sharing Platform (ESSDSP) (<http://www.geodata.cn>). The land use maps were classified into 6 first levels (woodland, grassland, farmland, construction land, water and wetland, and unused land) and 25 second levels of land use categories.

2.3 Methods

This study aims to examine the OMR (difference between observation and reanalysis) trends of different grassland types and the sensitivity of surface air temperature to vegetation cover change. In order to reduce the influence of land use/cover change on temperature, we extracted unchanged patches of the grasslands from the 1980s to 2006 in the study area (Fig. 1) by comparing the two-period land use maps. In brief, we first reedited two raster land cover maps by giving a single value to each land use category (such as 1, 2, 3, 4); then, we made raster calculation (image subtraction) and finally extracted the unchanged patches from the resulting raster by setting others (the value of which is not equal to 0) invalid. The processing steps of temperature data are as follows:

1. Linearly interpolating the NNR gridded temperatures to individual meteorological stations and computing temperature anomalies with respect to the 25-year mean annual cycle for both interpolated reanalysis and observations (Kalnay and Cai 2003).
2. Calculating the OMR, OMR trend, observation trend, and NNR trend for each station from surface temperature

anomalies of the observation and NNR reanalysis (Fall et al. 2010). Using anomalies rather than absolute values can reduce the effect of altitude on temperature results (Simmons et al. 2004). In this study, the trends were estimated by the Mann-Kendall (MK) test and simple linear regression (Mann 1945; Kendall 1975).

3. Interpolating the average temperatures (including observation, NNR, and OMR temperatures, respectively) and temperature trends (using the simple kriging method in ArcGIS) in the study area and resampling the resulting raster data to the same spatial resolution as NDVI data.

The maximum value compositing (MVC) method (Pettorelli et al. 2005) was used to reconstruct the NDVI data into the monthly maximum NDVI data set. According to the land use map, we extracted monthly NDVI, temperature values for the grassland vegetation during the growing season (April–October) from 1982 to 2006. To obtain the grid point values, we first converted the raster data of NDVI indices to points (using the “raster to point” tool in ArcGIS) and then extracted temperature values by these points (using the “extract values to points” tool in ArcGIS). The average values of temperature and NDVI for a particular grassland type were obtained from the averages of all grid points belonging to the same grassland type (Chuai et al. 2013).

3 Results and discussion

3.1 Time series of growing-season surface air temperature

We compared the time series of growing-season surface temperature anomalies from the observation and NNR reanalysis in the regions of temperate grassland of China (Fig. 2a). Results showed a good agreement between observations and NNR in terms of the interannual variability and the long-term trends, as indicated by the correlation coefficient ($r=0.972$). This agreement confirms the results from previous studies which showed that NNR captured the observed interannual fluctuations very well (Kalnay and Cai 2003; Frauenfeld

et al. 2005; Kalnay et al. 2006; Lim et al. 2008; Fall et al. 2010).

Similar to the previous studies (Kalnay and Cai 2003; Lim et al. 2005), both the observations and reanalysis surface temperature showed a warming trend, and the warming trend of observations ($0.592\text{ }^{\circ}\text{C/decade}$) was larger than that of reanalysis ($0.412\text{ }^{\circ}\text{C/decade}$) (Fig. 2a). This is partially attributable to the poor reproduction of surface air temperature change signal associated with the effects of land surface properties in the reanalysis data (Lim et al. 2008). The OMR (difference between observation and reanalysis) time series showed a positive trend of $0.181\text{ }^{\circ}\text{C/decade}$ for temperate grasslands in China (Fig. 2b). To summarize, the average warming amplitude of the observations and OMR was 0.592 and $0.181\text{ }^{\circ}\text{C/decade}$, respectively. Therefore, the OMR trend accounted for about 31 % of the observation warming. This proportion could be associated with the effect of land use/cover types and other surface property changes. Similar results were found by Wang et al. (2014) for Jiangxi Province of China.

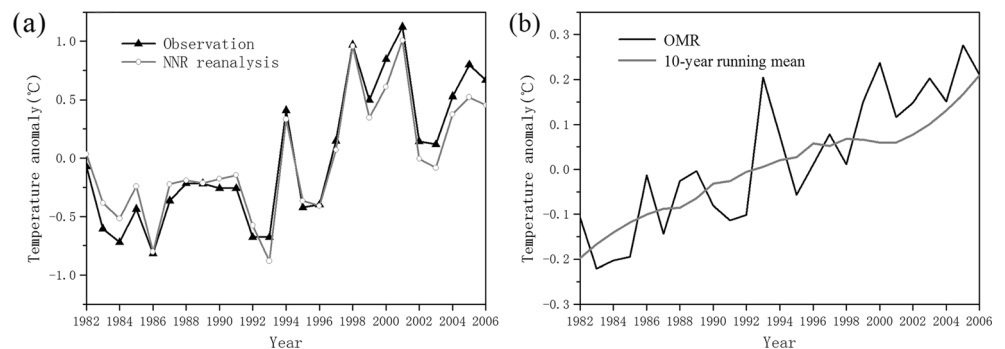
3.2 The OMR trends associated with surface vegetation

3.2.1 Relationship between surface air temperature and the vegetation index

In order to examine the surface air temperature with respect to surface vegetation change for temperate grasslands in China, we related the surface temperature changes estimated by observation, NNR, and OMR to different surface vegetation indexes. The decadal trends in growing-season surface temperature of observation, NNR, and OMR at each grid point were scatter-plotted with mean growing-season NDVI (Fig. 3).

The results showed no significant relationship between the decadal observation trends and the NDVI ($r=0.007$, $P=0.581$), presumably because the observation data reflect all climate change signals. However, as reported by Lim et al. (2008), the decadal trends of NNR reanalysis were significantly correlated with NDVI ($r=0.415$, $P<0.001$), indicating that the relationship demonstrated in modeling experiments of previous studies (Xue and Jagadish 1993; Dai et al. 2004; Hales

Fig. 2 Time series of surface air temperature anomalies derived from **a** observation and NNR and **b** the OMR. Anomaly values are obtained by removing the 25-year mean from 1982 to 2006



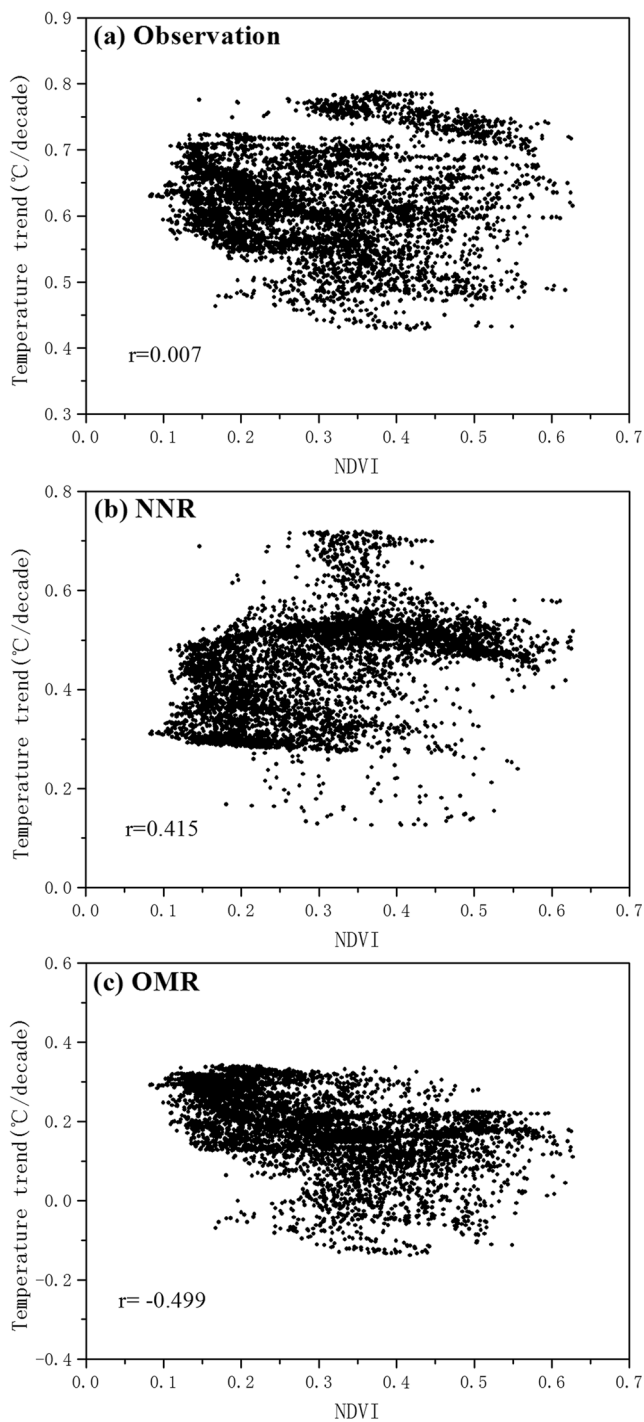


Fig. 3 Scatter diagram between the growing-season NDVI and the decadal trends in growing-season surface temperatures of **a** observation, **b** NNR, and **c** OMR. Here r is the correlation coefficient of all the data points

et al. 2004) is absent in NNR reanalysis. In those modeling experiments, the surface warming was stronger in low vegetation areas. This moderate relationship between the decadal trends of NNR reanalysis and NDVI presents the lack of reproduction of the surface temperature change signal associated with the impact of vegetation (Lim et al. 2008). The

decadal OMR trends were negatively correlated with the NDVI ($r = -0.499$, $P < 0.001$), which is consistent with previous studies where OMR trends decrease with the increase of NDVI (Lim et al. 2008; Yang et al. 2010; Wang et al. 2014). The results suggest that there are a weak warming response to land greenness and a strong surface warming response to land barrenness.

3.2.2 Comparison of the OMR trends with different vegetation types

To examine the surface temperatures with respect to surface vegetation types, we associated the OMR trends with different temperate grassland types in China. Figure 4 shows the decadal growing-season OMR trends for three different grassland types that did not change during the study period. The OMR trend of temperate desert steppe (0.259 °C/decade) was obviously larger than the other two types. By contrast, temperate steppe showed a moderate decadal warming (0.171 °C/decade), while temperate meadow showed the smallest warming trend (0.114 °C/decade). The OMR trends for different temperate grassland types in our study were comparable to a previous study (≥ 0.110 °C/decade) with different grasslands over the whole China (Yang et al. 2009).

Contrary to the OMR pattern, we found that the mean growing-season NDVI was the largest for temperate meadow (0.430) and the smallest for temperate desert steppe (0.166) (Fig. 4). This means that the higher the vegetation cover, the smaller the OMR trends, which is consistent with the findings from studies such as Lim et al. (2008), Yang et al. (2009), and Wang et al. (2014) who found that the OMR trend decreased with the increase of surface vegetation greenness. This phenomenon can be accounted for by the fact that the evaporation feedback decreases the surface warming. For temperate meadow which is characterized by abundant precipitation, the high soil moisture and strong evaporation feedback damp surface warming, resulting in a smaller warming trend than the other two grassland types. Because temperate steppe vegetation is

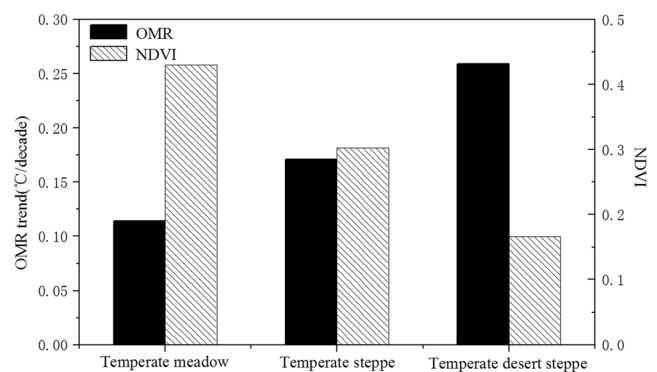


Fig. 4 Decadal growing-season OMR trends and mean growing-season NDVI of three grassland types that did not change during 1982–2006

less green than temperate meadow, the cooling feedbacks from the leaves are weaker than those in temperate meadow areas. This contributes to the moderate surface warming over these areas. For temperate desert steppe which is characterized by dry climate, the evaporation feedback is weak due to limited soil moisture over arid areas (Lim et al. 2005, 2008). Therefore, a larger proportion of the available energy at the surface is transmitted in the form of sensible heat, exerting a warming effect on the near-surface air temperature.

3.3 Variation of the OMR trend with the intraseasonal vegetation change

Considering NDVI has intraseasonal changes, we expect that the OMR trend may also present an intraseasonal variation in response to changes in vegetation. To understand the variation in OMR trends associated with intraseasonal changes of vegetation, we estimated the monthly variation of the OMR trends for three grassland types (Fig. 5).

As shown in Fig. 5, temperate meadow has the largest monthly changes of vegetation cover, while temperate steppe and temperate desert steppe have relatively little variance. Accordingly, the OMR trend of temperate meadow showed a strong inverse monthly fluctuation with the NDVI. And it even showed a cooling trend in August (-0.090 °C/decade) and September (-0.030 °C/decade) (Fig. 5). For temperate steppe, with the moderate monthly changes of vegetation cover, the OMR trend also showed an intraseasonal cycle but was less obvious than temperate meadow. For temperate desert steppe, with NDVI under 0.21 in the whole growing season, it did not show a significant monthly variance. Our results suggest that the stronger intraseasonal changes of grassland vegetation are present, the more sensitive the OMR trend responds to intraseasonal changes in vegetation. During the growing season especially in summer, the cooling effect of leaves reduces the response of surface temperature to CO₂ radiative forcing (Bonan 2008; Jackson et al. 2008), resulting in a weak surface warming trend. However, for temperate desert steppe which has small vegetation cover, due to the limited soil moisture and the weak cooling effect of evaporation feedback, the OMR warming trend remains high with little intraseasonal change throughout the growing season.

3.4 Effects of vegetation change on surface air temperature trend

3.4.1 Trends in monthly NDVI for different grassland types

To examine the changes in monthly NDVI, we calculated the annual trends of monthly NDVI by vegetation type (Table 1). The average monthly NDVI showed an increasing trend in all 7 months for all the three grassland types. Among these grassland types, temperate steppe had the largest increase rate of

NDVI over the whole growing season, except in October. Increasing trends were noticeable in the average NDVI for all 7 months, implying that all these months contributed to the increase of NDVI during the growing season (Piao et al. 2006). Among these months, August had the fastest increasing rate of average NDVI for temperate grasslands in China, which is consistent with previous studies (Piao et al. 2006; Guo et al. 2014). The rates of NDVI generally increased from April to August and then decreased, with the smallest value in October for temperate meadow and temperate steppe, but in April for temperate desert steppe (Table 1). The mechanisms for this intraseasonal evolution of the rate of NDVI change for temperate grasslands in China still need to be further explored.

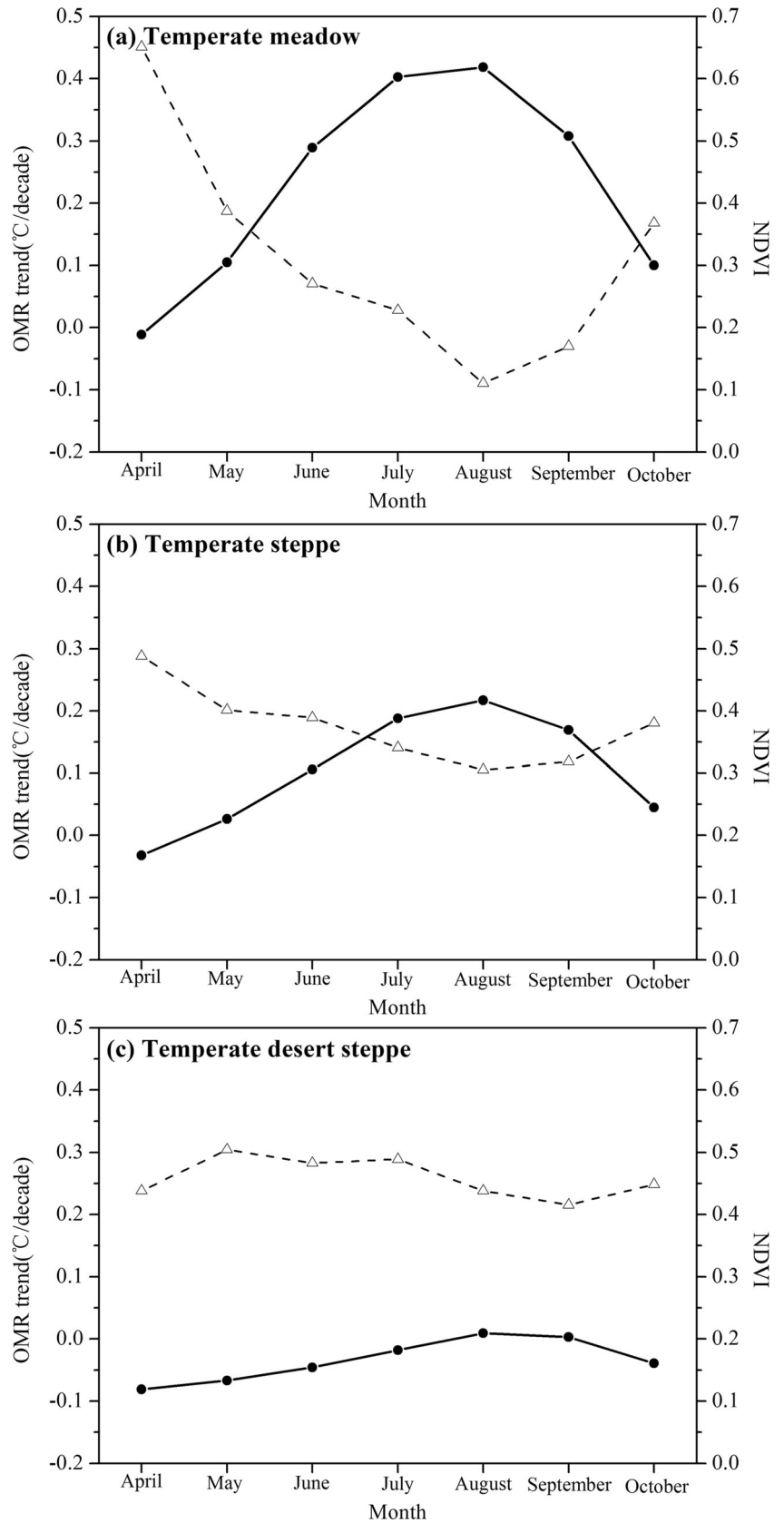
3.4.2 Monthly variation of correlation between OMR trend and NDVI

Due to a potential relationship between OMR and vegetation cover, the increase of growing-season NDVI for temperate grasslands may have some effects on surface air temperature. However, the year-to-year variations of vegetation cover (represented by NDVI trends) are accompanied by the spatial variation of different vegetation types/properties (represented by average NDVI), which adds some complexity to study the effects of vegetation changes on surface temperature. Therefore, both the grassland types and year-to-year variations in vegetation cover should be considered when investigating the effects of vegetation changes on surface air temperature.

In order to assess temperature sensitivity to different vegetation types and vegetation cover changes in terms of surface vegetation index, we calculated the spatial correlations between the OMR trend and the NDVI (average NDVI and NDVI trend) for each month (Table 2). Results showed that the OMR trends of all three grassland types were negatively correlated with NDVI for all 7 months, with the exception of April for temperate desert steppe. The observed negative correlations between the OMR trend and the NDVI indicate that there is an increasing OMR trend with decreasing vegetation greenness and vice versa, which is consistent with previous studies (Lim et al. 2008; Yang et al. 2010; Wang et al. 2014).

In different seasons, the correlation between monthly OMR trends and monthly NDVI (both average and trends) generally increases from April to August and then decreases, especially for temperate meadow and temperate steppe. This intraseasonal evolution of the correlation is similar to that of NDVI trend (Table 1), indicating that vegetation changes may have more obvious impacts on surface air temperature when the changes of vegetation are much larger (Yang et al. 2009). The correlation between OMR trends and average NDVI is more obvious from July to September, when the vegetation cover of temperate meadow and temperate steppe is the largest during the growing season (Fig. 5). This relationship suggests that the effect of vegetation on surface air temperature is more

Fig. 5 a–c Monthly variation of the OMR trend (°C/decade) in response to the monthly vegetation change of temperate grasslands in China. *Dash lines with open triangle* denote the monthly variation of OMR trend, and *solid lines with closed circle* denote monthly NDVI change



noticeable when the vegetation cover is dense, and the effect becomes limited when the vegetation cover is relatively low.

For temperate meadow, the correlations between the OMR trend and average NDVI reached the significant level

Table 1 Monthly NDVI trends per decade for different grassland types during 1982 to 2006

Vegetation types	April	May	June	July	August	September	October
Temperate meadow	0.006	0.010	0.008	0.010	0.020	0.020	0.003
Temperate steppe	0.006	0.011	0.010	0.012	0.023	0.021	0.003
Temperate desert steppe	0.001	0.003	0.002	0.003	0.011	0.003	0.002

($P < 0.05$) from July to October. By contrast, the correlations between the OMR trend and NDVI trend were only significant in August and September, when the increases of NDVI were the largest in all 7 months (Table 1). Similar to temperate meadow, the OMR trend of temperate steppe was negatively correlated with NDVI in all months, but only significant in August. For temperate desert steppe, however, the OMR trend did not show a significant correlation with NDVI in any month (Table 2).

The difference in correlation coefficients between OMR trend and NDVI showed that the OMR trend was more negatively correlated with NDVI for temperate meadow (high vegetation greenness) than other two grassland types (low vegetation greenness). This finding contradicts several previous studies (Lim et al. 2008; Wang et al. 2014), which found that the dependence of OMR trend on vegetation greenness got worse as vegetation greenness increased. This difference is mainly due to the different vegetation types selected in the research. In our study, we only studied grassland and compared 3 second-level vegetation types under this first-level vegetation type, whereas these previous studies compared all the first-level vegetation types. In the temperate grassland region of China, due to the arid/semiarid climate for temperate steppe and temperate desert steppe, temperate meadow with relatively high vegetation cover shows more noticeable intraseasonal change than the other two grassland types (Fig. 5). However, with respect to all the vegetation types, high vegetation cover areas such as evergreen forest areas always exhibit relatively weak intraseasonal change than low vegetation cover areas (Wang et al. 2014). Therefore, the

OMR trend is more sensitively responsive to high vegetation cover for grassland vegetation, but less responsive to low vegetation cover for all the vegetation types.

3.4.3 Surface air temperature change as a function of different surface vegetation types and NDVI changes

To further investigate the effect of vegetation changes on surface temperature, the OMR trends were regressed on average NDVI and NDVI trend by using the multiple stepwise regression method. The regression results are indicated in Table 3. They are statistically significant at the 95 % level.

For temperate meadow, the OMR trends showed a dependence on average NDVI for all months except April. However, the significant effect of NDVI trend on OMR trend was only found in August and September, when the increase rate of NDVI reached about 0.002 per year. This indicates that the changes of vegetation do not have a significant impact on surface temperature until vegetation changes reach some intensity (Yang et al. 2009). In August and September when the OMR showed a cooling trend (-0.09 and -0.03 °C/decade), the dependence of the OMR trends on the average NDVI integrating the NDVI trend performed better than that removing the NDVI trend. About 72.2 and 72.6 % of surface cooling were explained by this surface vegetation type (average NDVI) and increase of surface vegetation cover (NDVI trend) in August and September, respectively. Excluding the effect of increasing vegetation cover, the average NDVI just explained 53.1 and 57.5 % of surface cooling in August and September, respectively.

Table 2 Correlation coefficients between OMR trend and NDVI

Month	Temperate meadow		Temperate steppe		Temperate desert steppe	
	Average NDVI	NDVI trend	Average NDVI	NDVI trend	Average NDVI	NDVI trend
April	-0.145	-0.009	-0.039	-0.007	0.084	0.096
May	-0.216	-0.012	-0.076	-0.060	-0.132	-0.095
June	-0.245	-0.074	-0.265	-0.184	-0.102	-0.074
July	-0.452*	-0.333	-0.383	-0.294	-0.021	-0.135
August	-0.728**	-0.627**	-0.505*	-0.354**	-0.193	-0.258
September	-0.822**	-0.439**	-0.291	-0.311	-0.112	-0.032
October	-0.418*	-0.234	-0.271	-0.314	-0.206	-0.086

* $P < 0.05$; ** $P < 0.01$

Table 3 Summary for regression models of different surface vegetation types

Month	Model	Temperate meadow		Temperate steppe	
		AR ²	Sig.	AR ²	Sig.
April	–	–	–	–	–
May	M1	0.139	0.036	–	–
June	M1	0.158	0.009	–	–
July	M1	0.204	0.021	0.098	0.044
August	M1	0.531	0.000	0.326	0.026
	M2	0.722	0.000	–	–
September	M1	0.575	0.000	0.107	0.034
	M2	0.726	0.000	–	–
October	M1	0.175	0.034	–	–

Predictors of M1: (constant), average NDVI. Predictors of M2: (constant), average NDVI, and NDVI trend. Here “–” denotes that no parameter was introduced into regression equation

AR² adjusted determination coefficient, Sig. statistical significance

For temperate steppe, average NDVI had a significant effect on OMR trend in July, August, and September. Although with larger increasing trend of NDVI than temperate meadow (Table 1), the increase of temperate steppe cover did not have a significant effect on OMR trend in all 7 months, indicating that the cooling feedback from increasing vegetation is not significant for temperate steppe. This may be explained by the relatively limited soil moisture in temperate steppe areas than in temperate meadow areas.

For temperate desert steppe, consistent with the results of correlation analysis, there was no significant response of the OMR trends to the surface properties and vegetation changes (data not shown). It is suggested that the vegetation changes of temperate desert steppe do not have a significant effect on the surface temperature.

4 Summary

By using surface temperature data from observation and NNR reanalysis, the OMR (observation minus reanalysis) approach suggested by Kalnay and Cai (2003) was used to investigate the sensitivity of surface air temperature response to grassland types and vegetation cover changes in the regions of temperate grassland of China. Our results showed a good agreement between observed and reanalyzed temperature trends in the regions of temperate grassland of China, confirming the ability of reanalysis to capture the observed interannual variability. As reanalysis data is insensitive to local surface properties, the OMR method is a robust tool to estimate the temperature trends driven by the impact of land cover types and surface changes.

For temperate grasslands in China, growing-season surface air temperature increased by 0.592 °C/decade, and the growing-season OMR trend was 0.181 °C/decade. Therefore, about 31 % of observation warming could be associated with the effect of grassland vegetation types and vegetation changes. The growing-season OMR trends for three grassland types presented obvious differences, with the largest surface warming trend (0.259 °C/decade) for temperate desert steppe and the smallest trend (0.114 °C/decade) for temperate meadow. The negative correlation between NDVI and OMR trends indicates that there are a weak warming response to land greenness and a strong surface warming response to land barrenness.

The OMR trend patterns were dependent on intraseasonal vegetation fluctuation for temperate meadow, which had a strong intraseasonal vegetation variation. In August and September, the OMR of temperate meadow even showed a weak cooling trend (–0.090 and –0.030 °C/decade, respectively). In contrast, temperate desert steppe did not show a strong intraseasonal OMR trend variance due to the relatively limited soil moisture and weak cooling effect of evaporation feedback. Our results suggest that the stronger intraseasonal changes of grassland vegetation are present, the more sensitive the OMR trend responds to the intraseasonal vegetation changes.

The OMR trends showed a dependence on vegetation type for temperate meadow almost throughout the growing season, and temperate steppe from July to September. For temperate meadow, about 72.2 and 72.6 % of surface cooling were explained by both surface vegetation type and increase of surface vegetation cover for August and September, respectively. For temperate steppe and temperate desert steppe, due to the limited soil moisture and little evaporative cooling feedback, the increase of vegetation cover did not significantly affect the surface air temperature during 1982–2006.

The results in this study revealed that temperate desert steppe gets more warming than the other two grassland types in the temperate grassland region of China. For temperate meadow, however, the increase of vegetation may suppress the surface warming when vegetation changes reach certain intensity. Thus, the impact of grassland types and vegetation cover change should be considered when projecting further climate change in the temperate grassland region of China.

It should also be noted that there still exist some limitations in this study. Although we attributed the OMR differences primarily to the land effects, the OMR differences may also be caused by some other factors, including inaccuracies due to the interpolation methods used in the study, inaccuracy related to satellite and radiosonde data (which are part of the reanalysis), and to potential biases in the surface station records. In addition, future research should also investigate the potential effects of land use changes on air temperatures in the temperate grassland region of China.

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