IOP Publishing — Environmental Research Letters
Environ. Res. Lett. 4 (2009) 045006 (6pp) doi:10.1088/1748-9326/4/4/045006

Climate change in Inner Mongolia from 1955 to 2005—trends at regional, biome and local scales

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Received 9 March 2009
Accepted for publication 13 July 2009
Published 15 October 2009
Online at stacks.iop.org/ERL/4/045006

Abstract
This study investigated the climate change in Inner Mongolia based on 51 meteorological stations from 1955 to 2005. The climate data was analyzed at the regional, biome (i.e. forest, grassland and desert) and station scales, with the biome scale as our primary focus. The climate records showed trends of warmer and drier conditions in the region. The annual daily mean, maximum and minimum temperature increased whereas the diurnal temperature range (DTR) decreased. The decreasing trend of annual precipitation was not significant. However, the vapor pressure deficit (VPD) increased significantly. On the decadal scale, the warming and drying trends were more significant in the last 30 years than the preceding 20 years. The climate change varied among biomes, with more pronounced changes in the grassland and the desert biomes than in the forest biome. DTR and VPD showed the clearest inter-biome gradient from the lowest rate of change in the forest biome to the highest rate of change in the desert biome. The rates of change also showed large variations among the individual stations. Our findings correspond with the IPCC predictions that the future climate will vary significantly by location and through time, suggesting that adaptation strategies also need to be spatially viable.

Keywords: climate change, biome, Inner Mongolia, scale

1. Introduction

The global climate has changed rapidly with the global mean temperature increasing by 0.7 °C within the last century (IPCC 2007). However, the rates of climate change are significantly different among regions (IPCC 2007). This is primarily due to the varied types of land surfaces with different surface albedo, evapotranspiration and carbon cycle affecting and responding to the climate in different ways (Meissner *et al* 2003, Snyder *et al* 2004, Dang *et al* 2007). Most efforts in climate change studies have focused on the global scale, although regional-scale analysis is important for mitigating its negative effects and the development of adaptation plans.

The Inner Mongolia autonomous region (IM) is the third largest province of China (1.18 million km^2) and lies in the southeast section of the area studied by the Northern Eurasian Earth Science Partnership Initiative (NEESPI, http://neespi.org, Groisman *et al* 2009). IM encompasses a core region of semi-arid climate but also includes areas with arid and semi-humid climates in the southwest and north, respectively. Biogeographically, IM divides into contributions from three biomes: forest, grassland and desert (Olson *et al* 2001). The semi-arid to arid areas in IM are expected to be most vulnerable to climate change (Ojima *et al* 1998).

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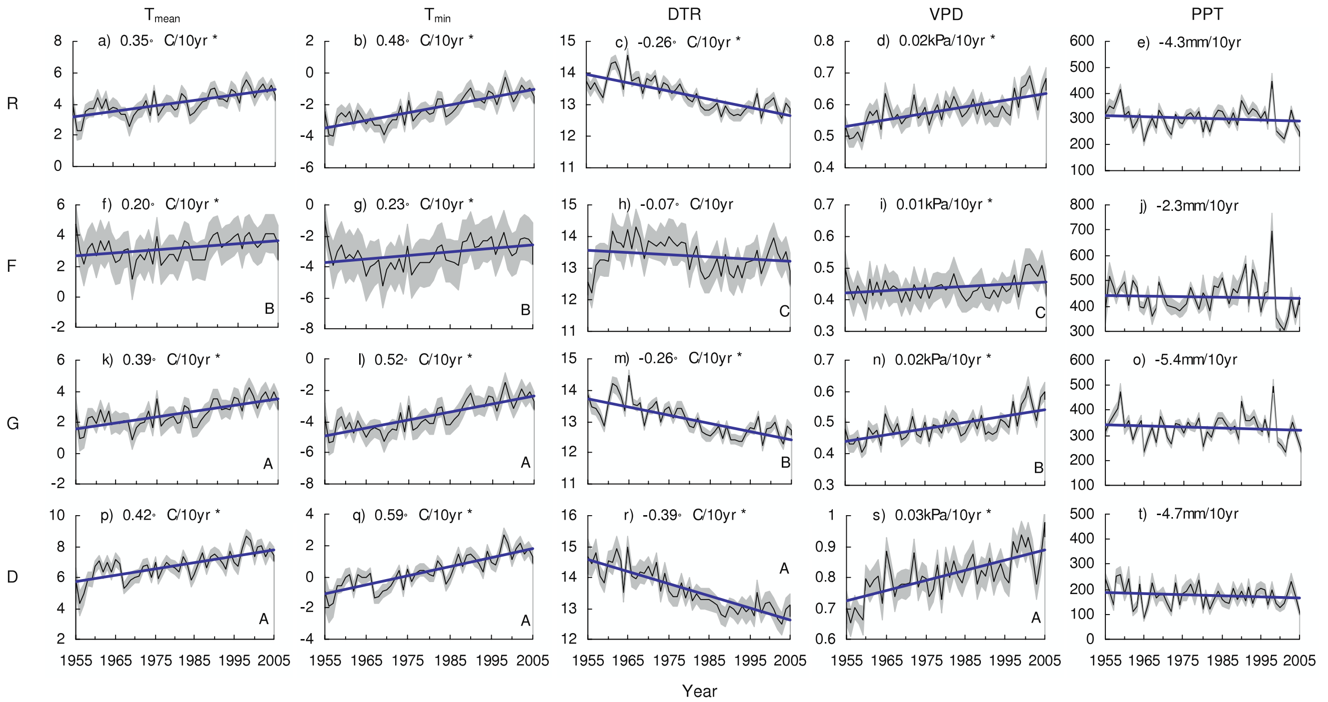

Figure 1. Fifty-year trends of annual mean T_{mean}, T_{min}, DTR (°C), VPD (kPa) and annually accumulated precipitation (mm) in the region (R) and three biomes (F—forest, G—grassland, D—desert). In each subplot, the annual means with plus/minus standard error were shown by the black curve and shaded area; the bold solid line represented the linear fit; and the number was the regression slope (stars meant slopes were significant). Capital letters A, B and C referred to the slope differences among biomes (at the significance level of 0.05).

In the last 50 years, in particular, the core region of IM was undergoing a relatively rapid socioeconomic development with significant increases in population, urbanization and intensified land use practices. It is becoming the consensus that climate change is likely to affect not only the ecological and physiological features of the natural system but also of the human system (IPCC 2001, 2007) and it is critical for both scientists and policymakers to understand the historical changes of the climate in IM. Our primary objective in this study is to highlight the changes in the regional climate over the past 50 years, with particular focuses on the differences among the biomes.

2. Methods

The climate data used in this study was from 51 meteorological stations in IM, provided by the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). The analyzed climate variables included daily mean, maximum and minimum temperature, daily temperature range (T_{mean}, T_{max}, T_{min}, DTR, °C), vapor pressure deficit (VPD, kPa; calculated from T_{mean} and relative humidity) and daily precipitation (PPT, mm). The stations were evenly distributed across IM, with 10, 23 and 18 stations in the forest, grassland and desert biomes, respectively. Although the data recordings from some individual stations started earlier, we used the data from 25 stations that started in 1955 to represent the entire region. The number of stations increased to 49 in 1960 and 51 in 1971.

We calculated the annual series (means of T_{mean}, T_{max}, T_{min}, DTR and accumulated PPT) for the region and each biome. The long-term trends of the climatic parameters were examined for the region, each biome and each station using the least squares linear regression analysis—an approach frequently used in climate change studies (e.g. Qian and Lin 2004, Bartholy and Pongrácz 2007). T-tests were used to examine the differences in the trends (i.e. the slopes of linear regression) among the biomes and the means of the climate variables between two continuous decades (with *repeated measures*). All statistical tests were performed using SAS (version 9.1, SAS Institute Inc., Cary, NC, USA).

3. Results and discussion

3.1. Regional change

The three temperature measures of annual T_{mean}, T_{max} and T_{min} increased from 1955 to 2005. The rate of change was higher in T_{mean} (0.35 °C/10 yr, figure 1(a)) and T_{min} (0.48 °C/10 yr, figure 1(b)) than in T_{max} (0.23 °C/10 yr). The higher rate of change in T_{min} and lower rate of change in T_{max} resulted in a decreasing trend of DTR (−0.26 °C/10 yr, figure 1(c)). These results are consistent with previous studies showing that the warming rate was more pronounced in minimum than in maximum temperature in northeastern and northern China (Zhai *et al* 1999, Hu *et al* 2003, Zhai and Pan 2003). Indeed, DTR decreased throughout most of China during the past half-century, with one of the most significant regional decreases (1.00–1.25 °C) occurring in northeast China (Qian and Lin 2004).

PPT showed a regional decrease of 21.5 mm (7% of the annual average) within the period 1955–2005 (figure 1(e)).

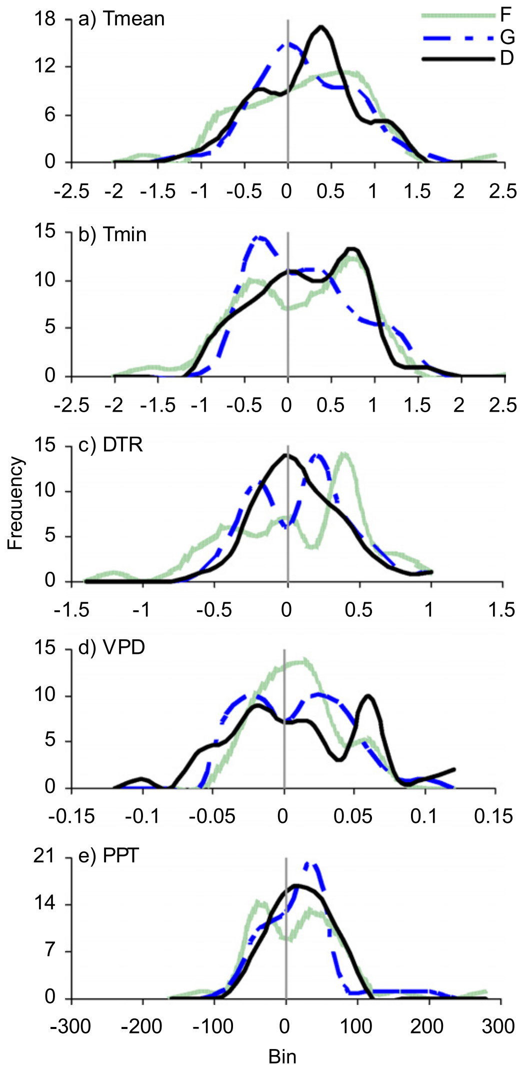

Figure 2. Comparison of the frequency distribution of residues in T_{mean} (°C), T_{min} (°C), DTR (°C), VPD (kPa) and PPT (mm) among three biomes (F—forest, G—grassland, D—desert). The residue was the difference between the mean and 50 year trend of linear regression (1955–2005) for each biome and variable.

Although the trend in PPT was not significant ($p > 0.05$), it does not disagree with the results showing a slightly decreasing trend in PPT in the semi-arid region of northern China (Gong *et al* 2004). Nevertheless, VPD increased significantly at the rate of 0.02 kPa/10 yr (figure 1(d)). This is consistent with a recent IPCC assessment projecting the evaporative demand to increase almost everywhere because the water-holding capacity of the atmosphere increases with higher temperatures (Bates *et al* 2008). Predictably, higher VPD at constant PPT will deplete soil moisture and result in a generally drier environment.

At the decadal scale, the regional T_{mean} increased steadily throughout the study period, with the inter-decadal increases only significant in the last two decades (table 1). Meanwhile, the regional T_{min} and DTR changed significantly during the periods 1976–1985 and 1986–1995. From the first to the last decade, decadal T_{mean} and T_{min} increased by 1.2 °C and 1.7 °C, respectively, while DTR decreased by 0.9 °C. The period of 1986–1995 showed the largest increase in temperature, with T_{mean} and T_{min} increasing by 0.7 °C and 1.0 °C, respectively, and DTR decreasing by 0.4 °C as compared to the previous decade. Similar observations of the highest increase in temperature at the end of the 20th century were also reported for other regions (Kumar *et al* 2005, Bartholy and Pongrácz 2007). Regional VPD showed insignificant increases in the first four decades but it increased significantly in the last decade. The decadal VPD increased by 0.09 kPa from the first to the last decade. Regional PPT showed an insignificant trend, with both increases and decreases over the five decades.

3.2. Variations among the biomes

The rates of change varied among the biomes. They were generally high in the desert biome, intermediate in the grassland biome and low in the forest biome (figures 1(f)–(t)). The lower rates of change in the forest biome may be related to the moderating influence of forests on climate (Bonan *et al* 1992). Notably, the higher rates of change in the grassland and desert biomes coincided with the dramatic land use changes and more intense human activities in these areas (Chuluun and Ojima 2002, John *et al* 2009). The difference in the trends between the grassland and desert biomes seemed consistent with the results showing a warming and drying trend by simulating the removal of grasslands in the central USA (Snyder *et al* 2004). Dang *et al* (2007) examined the temperature changes by dividing the globe into seven vegetation/surface classes. They found a higher increase in the temperate forest (0.23 °C/10 yr) than that in the bare ground (0.19 °C/10 yr) from 1950 to 2004. This seemingly contradictory finding to our results suggested that the studies at the global or continental scales did not resolve the regional details. Nevertheless, it is clear that global climate change has produced ecosystem- or region-dependent consequences.

The biome-specific rates of change in climate variables concurred with larger-scale periodicities beyond the inter-annual variability. For example, T_{mean} in the forest biome was mainly higher, lower, and again higher than the long-term trend in 1955–1965, 1966–1990 and 1991–2005, respectively (figure 1(f)). This larger-scale periodicity was similar but the dispersion of the annual means around the general trend increased from the forest to the grassland and further to the desert biome. The clustering of years with individual variables above and below the 50 year trend affected the frequency distribution of positive and negative residuals (figures 2(a)–(e)). Both residuals of T_{mean} and T_{min} showed left skews in the grassland biome and right skews in the desert biome, suggesting that both variables tended to cluster at the lower range of values in the grassland as compared to the desert (figures 2(a) and (b)). The different skewed distributions in the data of the desert and grassland biomes further suggested that the differences in the rates of change would increase if the variables continue to increase with the same periodicity as during the previous 50 years.

DTR appeared more randomly distributed in the desert whereas it clustered below and above the long-term trend in the grassland biome (figure 2(c)). This pattern was in agreement

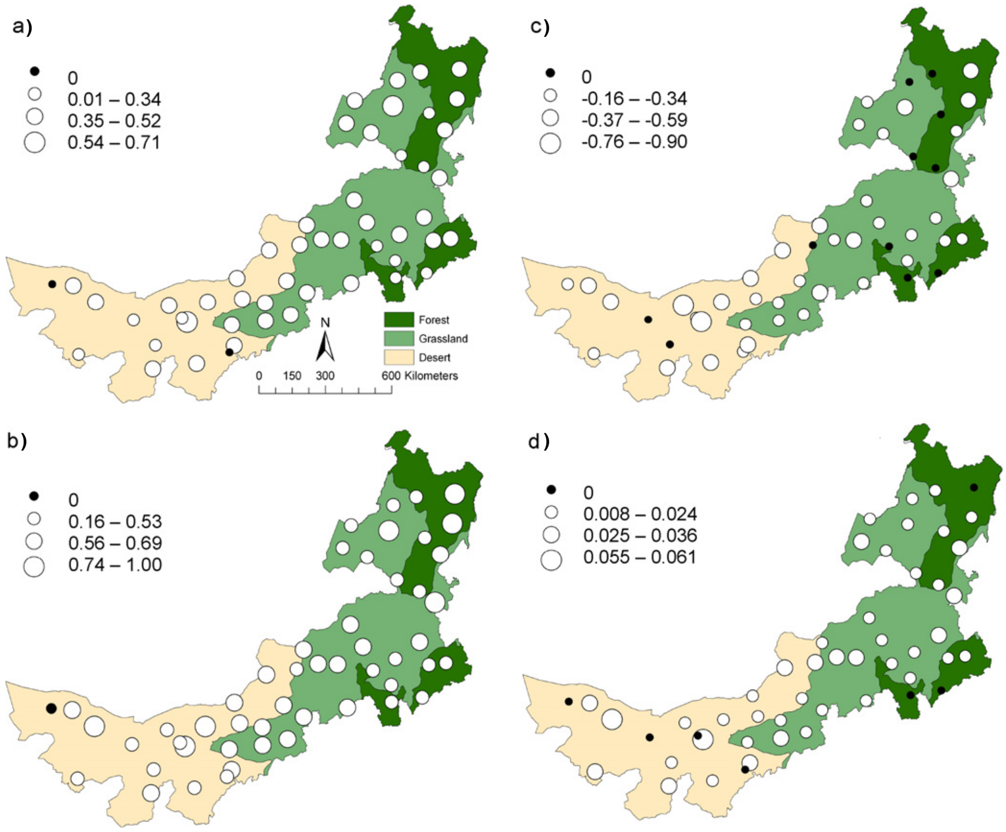

Figure 3. Spatial variations of trends in the climate variables based on the 51 meteorological stations in IM. The inside polygons represented the boundaries of the three biomes. Solid circles meant the trends were not significant (at the confidence level of 0.05) during the period 1955–2005. There were 2, 1, 11 and 7 stations for T_{mean}, T_{min}, DTR and VPD showing insignificant changes, respectively; hollow circles of different sizes meant the differences in the rate of changes. (a) Rate of change in T_{mean}(°C)/10 yr. (b) Rate of change in T_{min}(°C)/10 yr. (c) Rate of change in DTR (°C)/10 yr. (d) Rate of change in VPD (kPa)/10 yr.

Table 1. Comparison of the decadal means in the climate variables in IM from 1955 to 2005. Values in parentheses represented *p* levels testing the significance of the difference between a decade and its preceding one. Arrows represented significant increasing or decreasing trends (at the level of 0.05).

Decade	T_{mean}	T_{min}	DTR	VPD	PPT
1955–1965	3.6	−3.0	13.9	0.55	318
1966–1975	3.5 (0.95)	−3.0 (0.89)	13.7 (0.10)	0.57 (0.25)	286 (0.24)
1976–1985	3.8 (0.38)	−2.5 (0.05)↑	13.2 (0.00)↓	0.58 (0.45)	303 (0.21)
1986–1995	4.5 (0.00)↑	−1.5 (0.00)↑	12.8 (0.00)↓	0.59 (0.27)	319 (0.51)
1996–2005	4.8 (0.04)↑	−1.3 (0.11)	13.0 (0.17)	0.64 (0.00)↑	290 (0.24)
1955–2005	4.0	−2.3	13.3	0.58	303

with a stronger large-scale periodicity in the temperature variables in the grassland than in the desert biome. The clustered deviations from the trend of DTR in the grassland were further projected onto the frequency distribution of VPD residuals. In contrast, the forest biome appeared to have a stark damping effect on the variability of VPD and consequently produced a near-normal frequency distribution despite a significantly clustered variability in PPT (figures 2(d) and (e)).

3.3. Spatial variability below the biome scale

The increasing trends in T_{mean} and T_{min} were found across the region (figures 3(a) and (b)). However, large differences existed in the rates of change among the individual stations. Except for those that showed no significant changes (figures 3(a)–(d)), the rate of change in T_{mean}, T_{min}, DTR and VPD ranged from 0.01–0.71 °C/10 yr, 0.16–1.00 °C/10 yr, −0.16 to −0.90 °C/10 yr and 0.008–0.061 kPa/10 yr, respectively. The most significant trends of T_{mean} (0.54–0.71 °C/10 yr) and/or T_{min} (0.74–1.00 °C/10 yr) occurred in the desert and the northern parts of the grassland and forest biomes. The highest rate of decrease in DTR occurred in the desert biome (−0.76 to −0.90 °C/10 yr, figure 3(c)). Conversely, five out of ten stations in the forest biome showed no change in DTR.

The highest spatial variability in the change of VPD occurred in the desert biome, which included locations with the most significant increase in VPD but also the highest number of locations where VPD did not change. Similar to the findings at the regional and biome scales, most of the individual stations showed no significant change in PPT. Only one station north of the Lang Shan Mountain in the desert biome showed a significant increase in PPT (16.7 mm/10 yr). Conversely, one station at the desert–grassland transition and one station in the southern part of the forest biome showed significant decreases in PPT (−11.3 mm/10 yr and −17.7 mm/10 yr, respectively).

Along with the differences among the biomes, the correlation analysis further showed the degree of influence of latitude and longitude gradients on the climate trends. The geographic location seemed to exert influence only on the changes in T_{max} and VPD in this region. With longitude increasing, the rate of change in VPD decreased ($R^2 = 0.21$, $p = 0.002$); with latitude increasing, the rate of change in T_{max} increased ($R^2 = 0.26$, $p < 0.001$).

Future in-depth studies are needed to consider the effects of regional-scale land use and land cover (LULC) change on climate and its feedback processes. Even sub-regional LULC may either suppress or enhance trends in climate change. For example, Zhang *et al* (2003) reported that increasing bareness from grassland led to the decrease in soil moisture, which added to the acceleration of grassland degradation (i.e. a positive feedback to climate change).

The warming and drying climate may affect human systems in various aspects in IM, such as reducing vegetation production and crop yield (Hou *et al* 2008), reducing biodiversity (John *et al* 2008) and aggravating desertification (Gao *et al* 2003). The findings of differences among biomes also suggested that biome-specific and/or sub-regional adaptation strategies are needed to cope with the changing climate and its potential feedbacks with LULC change. Conservation for forests would be favorable to alleviate the warming trend. For both the grassland and desert biomes, the increased water stress primarily calls for a careful management of water resources.

4. Summary

The changes in temperature, PPT and other related climate variables indicated that IM, as a region, has changed to a warmer and drier environment over the past 50 years, with the rates of change being most significant during the last 30 years. The deviations of some climate variables from the long-term trend showed obvious periodic rhythms, especially in temperature. Notably, stronger changes in temperature and VPD were found in the grassland and desert biomes than in the forest biome. Both scientific predictions of ecosystem dynamics and development of adaptation plans need to consider these differences in time and space. The IPCC stated that the future climate would vary significantly by location and through time across the globe. We conclude a similar statement for the IM region.

Acknowledgments

This study was conducted as part of the Northern Eurasia Earth Science Program Initiative (NEESPI) and supported by the National Aeronautics and Space Administration (NASA) grant (NEWS 2004 NRA: NN-H-04-Z-YS-005-N) of the Land Cover and Land Use Change Program (LCLUC) and the US–China Carbon Consortium (USCCC), which promotes collaborative research among interested institutions in the US and China. We also thank the partial support of the German Research Foundation (DFG) and the National Natural Science Foundation of China (NSFC).

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