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NOTES AND CORRESPONDENCE

Changes in Arid Climate over North China Detected by the Köppen Climate Classification

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Abstract

Changes in the arid climate over North China were investigated by applying the Köppen climate classification to Chinese station measurements and global grid data sets compiled over the period of 1951–2000. The use of the Köppen scheme enables us to detect arid climate on a longer time-scale than is attainable through satellite remote sensing. A climatic shift toward a warmer and dryer condition is seen to be robust and substantial enough to cause conspicuous changes in the arid climate in North China from the decades 1951–1970 to the recent decades 1981–2000. The areas of semiarid (BS) and desert (BW) climate exhibit an overall expansion at the periphery of the existing arid zones in the studied period; a significance test shows that the increase in BS area is significant at the 99% confidence level, while that in BW area is relatively marginal. These results are indicative of the meteorological stress due to climatic transformation in North China, which is likely to be an impediment to sustainable re-greening in that region. Therefore, careful consideration of the effects of long-term climate change is required to support on-going and planned vegetation restoration in North China.

1. Introduction

Observational evidences have shown decadal to interdecadal variations of global precipitation in a warming environment over the past half century. As a part of such global fluctuations, East Asian climate has also experienced characteristic changes (Wang and Dong 2002; Qin et al. 2005). For example, North and Northeast China1 have exhibited an increased annual warming and an enhanced summer-to-autumn dryness (Hu et al. 2003; Gemmer et al. 2004; Wang et al. 2004; Endo et al. 2005; Wang et al. 2006a). Concurrently, a warming and wetting trend has been reported in the western part of Northwest China during both summer and winter seasons (Shi et al. 2003; Endo et al. 2005).

Of particular interest is that these regions where the meteorological conditions have changed are largely in major deserts (such as the Taklamakan Desert and the Gobi Desert) and in the semiarid areas that skirt those major deserts. From the point of view of climate classification, desert and surrounding semiarid regions are categorized into "*arid climate*". Therefore, taking into account the geographical coincidence, the long-term transition of the meteorological elements may result in expansion (or retreat) of arid climate.

Normalized difference vegetation index (NDVI) derived from satellite remote sensing, which is usually based on an empirical relationship between the growing season greenness and rainfall measurements, provides a useful technique for the demarcation of arid climate (e.g., Piao et al. 2005). However, because the satellite data are available only since the late 1970s, this approach has difficulty in tracing arid climate changes on an extended time-scale.

In the present study, we will investigate the evolution of arid climate over China between the two epochs prior to and after the 1970s by using a conventional bioclimatic scheme originally proposed by Köppen (1931). The Köppen climate classification utilizes near-surface temperature and precipitation to represent climate regimes, thus detect the climatic shift associated with the primary climate components. We will use various data sets of temperature and precipitation covering the years from 1951 to 2000, a period during which the Köppen scheme can better monitor arid climate than the insufficient record of the NDVI. The Köppen classification also considers arid climate from a continental perspective with spatially continuous boundaries as the satellite remote sensing does.

Our study aims to address the following questions: 1) Are the changes in temperature and precipitation over China substantial enough to alter the extent of arid climate? and 2) If so, are there any systematic variations at the verge of the existing arid climate? Land cover characteristics are known to be sensitive to temperature and precipitation (Barber et al. 2000; Zhou et al. 2001). This study examines whether the long-term variability is favorable to vegetation rehabilitation or if it reflects meteorological stress that would prevent sustainable anti-desertification.

2. Köppen climate classification and data sets

We have adopted the Köppen climate classification summarized in Lutgens and Tarbuck (2006). This recognizes five major climate types; tropical (A), mesothermal (C), microthermal (D), polar (E), and arid (B). The first four types are based on the thermic zones and divided further into subtypes, depending on whether there is a dry spell in summer or winter, no dry season, or a monsoon climate. The arid climate, the target of this study, has two subclasses of semiarid (BS) and desert (BW) climate according to the hydrological balance between rain and potential evaporation. The criteria used in the Köppen classification are mutually exclusive across the primary and secondary types and so is the demarcation of climate regimes. Therefore, the two subtypes in the arid climate are clearly distinguishable from each other and from the rest of the major climate types and their subtypes (Gnanadesikan and Stouffer 2006; Peel et al. 2007).

The Köppen climate classification has been widely used to evaluate climate change impacts on climate types (Fraedrich et al. 2001; Peel et al. 2002; Dang et al. 2007; Diaz and Eischeid 2007; Roderfeld et al. 2008) and to diagnose numerical models (Lohmann et al. 1993; Kleidon et al. 2000; Shin et al. 2004; Gnanadesikan and Stouffer 2006). The data used in the previous studies cover not only limited areas but also the entire global land-

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mass with the various spatial resolutions ranging from 4-km pixel to 2°–3° grid box, indicating the applicability of the Köppen scheme to the study of the regional climate changes. The use of the Köppen system generally requires a long-term average of precipitation and surface air temperature. Although many of the previous researches have made use of the climatology derived from the time period longer than 20 years, the Köppen scheme has been often applied to the investigation of decadal variation in climate regimes (e.g., Suckling and Mitchell 2000; Wang and Overland 2004; Miller et al. 2005).

In order to portray the changes in arid climate over China, ensemble (arithmetic) averages at 0.5° × 0.5° resolution for the period of 1951–2000 were established from various global observations (hereafter ENS). These include four monthly precipitation and two monthly near-surface temperature data sets. The data sources are Delaware University (Legates and Willmott 1990), the Climate Prediction Center at the National Center for the Environmental Prediction (Chen et al. 2002), the Global Precipitation Climatology Centre within the project of Variability of Analysis of Surface Climate Observation (Beck et al. 2005), and the Climatic Research Unit (Mitchell and Jones 2005). We also use the Chinese station measurements of monthly temperature and rainfall interpolated on a 0.5° × 0.5° grid system over the same period (STN). These were recorded at 700 meteorological stations across China and archived by the China Meteorological Administration.

3. Changes in precipitation and temperature

Figure 1 shows the epochal differences (1981–2000 minus 1951–1970) in annual precipitation and annual mean temperature derived from the ENS and the STN, which is statistically significant at the 90% confidence level using the *t*-test. Note that interannual variability is smoothed out by applying a 5-year running mean. Interestingly, while the spatial patterns in North and Northeast China bear remarkable resemblance between the ENS and the STN, those in the Northwest China and the Tibetan Plateau differ substantially from each other. The STN delineates increased rainfall in the eastern parts of the Tibetan Plateau and Northwest China, but the ENS does not show any significant trend in the same regions (Figs. 1a and 1b). The temperature in the ENS depicts a warming tendency in eastern Northwest China where the STN displays trivial changes. Even the temperature trends over the Tibetan Plateau have opposite sign between the two data sets (Figs. 1c and 1d).

The global grid data sets used in this study have been extensively utilized in climate change studies. Therefore if epochal differences were consistent across the data sets, it could indicate the robustness of the climatic changes; whereas attention should be paid when they differ from one another. The global data sets for the ENS share the common source of the Global Historical Climatology Network v2, which is a comprehensive, global-surface baseline climate data set. However, each data set has exclusively added its own information to make up for the spatiotemporal scarcity of the station measurements. As such, discrepancies are found over the Tibetan Plateau where the meteorological observations are sparse (Wang and Ding 2006). This, in turn, may cause the contrasting features between the ENS and the STN. Likewise, relatively coarse frequency of observation in Northwest China during the initial periods could also result in the different aspects between the ENS and the STN. Thus, to avoid uncertainties arising from the difference in data sources and interpolation algorithms, analyses will be focused in North and Northeast China east of 105°E.

The annual precipitation shown in Figs. 1a–1b slightly increases in the middle-to-lower reaches of the Yangtze River Valley. The wetting trend in Central China becomes more significant with broader areas when only summertime rainfall is taken into account (figure not shown). These results are in accordance with the previous findings regarding the intensification of summer monsoon precipitation in the Yangtze River basin (Xue 1996; Zheng et al. 1999; Endo et al. 2005; Wang et al. 2006a). In contrast, there is a strong dryness in North China. The long-term decrease of annual rainfall is roughly 4–8 cm in most parts of North China and reaches its maximum greater than 12 cm in the Shandong Peninsula and the Sichuan Basin. Figures 1c and 1d present the epochal changes in annual mean temperature. It is seen that there is a warming trend across North and Northeast China. On the other hand, Central China tends to be cooled with weaker amplitude than the warming tendency over North China. Further examination reveals that the cooling over Central China mainly occurs during warm season due to the enhanced summertime precipitation.

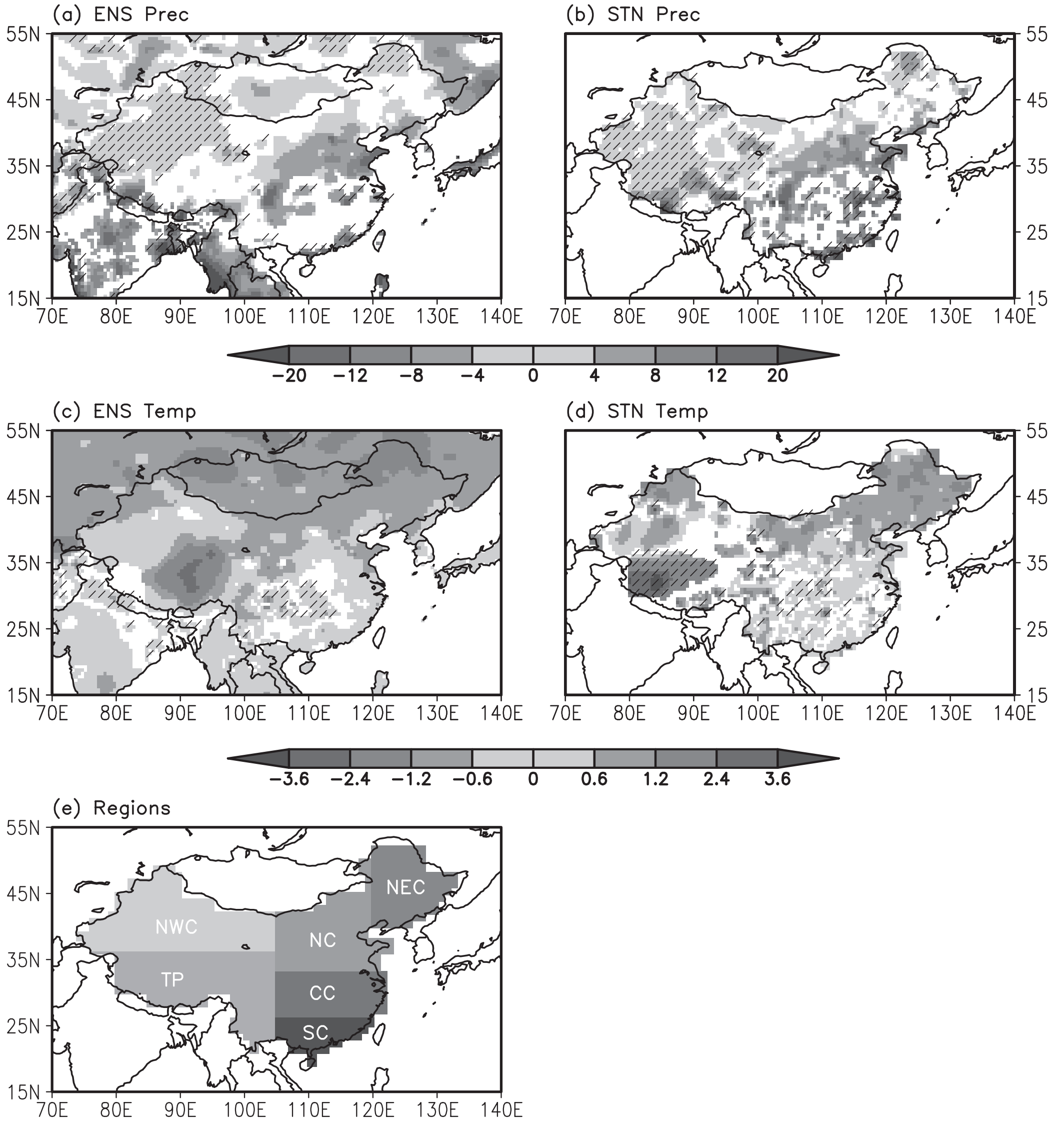

Fig. 1. Epochal changes (1981–2000 minus 1951–1970) in (a, b) annual precipitation (positive values are hatched) and (c, d) annual mean temperature (negative values are hatched) obtained from the ensemble average of global grid data sets (left) and the Chinese station measurements (right) after applying a 5-year running mean. Units are [cm] for precipitation and [°C] for temperature. The differences significant at the 90% confidence level using the *t*-test are plotted. Figure 1e shows the geographical divisions defined in this study (NWC: Northwest China, NC: North China, NEC: Northeast China, TP: Tibetan Plateau, CC: Central China, and SC: South China).

The coherent features across the data sets suggest robust long-term meteorological variability in North China. In addition, the spatial patterns of the climatic variability display a climatic shift toward a warmer and dryer condition, signifying possible expansion of arid climate in North China.

4. Interdecadal variability of arid climate

The criteria for the Köppen classification are based on annual and monthly precipitation as well as annual and monthly mean temperature (Table 1). Seasonality of precipitation is also important to determine the aridity threshold (P_{cri} in Table 1). In

Table 1. Definition of arid climate in the Köppen climate classification (Lutgens and Tarbuck 2006). Here, T_{ave} and P_{ann} indicate annual mean temperature (°C) and annual precipitation (cm), respectively, and P_{cri} is an aridity threshold.

Type	Criteria
BW	$(T_{ave} + P_{cri}) > P_{ann}$ $P_{cri} = 0$: rainfall in the coldest 6 months $\geq 70\%$ of P_{ann} $= 7$: rainfall in the coldest and warmest 6 months $< 70\%$ of P_{ann} $= 14$: rainfall in the warmest 6 months $\geq 70\%$ of P_{ann}
BS	$2(T_{ave} + P_{cri}) > P_{ann} > (T_{ave} + P_{cri})$

North China wet season is summer and the rainfall amount in summer (i.e., in the warmest 6 months) is unexceptionally greater than 70% of annual precipitation; thus the aridity threshold has the value of 14 for the whole period of interest. Suppose that annual rainfall in North China is decreased substantially. This must be caused mostly by a reduction in summer precipitation because of the dominant contribution of summer rainfall to the annual precipitation. However, the ratio of summer rainfall amount to the annual precipitation would change little, thereby the P_{cri} most likely has the same value of 14. While the P_{cri} remains invariable, annual precipitation (P_{ann}) is significantly decreased, which, in conjunction with the significant increase in annual mean temperature (T_{ave}), could result in the expansion of arid climate.

Figures 2a–2d and 2f–2i show the interdecadal variations of BS type (i.e., semiarid climate) for two adjacent decades derived from the ENS and the STN, respectively. For instance, Fig. 2a (2f) is plotted for the mean state of 1951–1960 and 1961–1970 using the ENS (the STN). The grid boxes shaded with dark (medium) grey denote the BS type recognized solely by a succeeding (previous) decade, indicating expansion (retreat) of BS regime; whereas light grey denotes the regions of BS type analyzed by both preceding and subsequent decades. Overall, the outer boundary of BS type tends to spread outwards from the previous decade to the next decade, although minor withdrawal also appears at certain portions of the BS periphery. The long-term eastward expansion of BS regime is more obvious in Fig. 2e (2j), which depicts the evolution of BS type between the two epochs of 1951–1970 and 1981–2000 obtained from the ENS (the STN); the BS regions over North China in the first epoch are surrounded by the extended BS areas in the last epoch.

The interdecadal changes in BW type (i.e., desert climate) are presented in Fig. 3 in the same format as in Fig. 2. Again, the boundary of desert climate stretches outward on the whole, with the result that the BW type in 1951–1970 is also bounded by that in 1981–2000 (Figs. 3e and 3j). It is worth to note that the variations of BW type in Figs. 3e and 3j are exactly opposite to the changes in BS type that occurred at the inner edge of the BS regime (see Figs. 2e and 2j), indicating that the decline of the semiarid regime is occupied by the expansion of the desert climate. The spatiotemporal patterns of arid climate obtained from the two data sets agree well with each other, manifesting the fidelity of the detected changes in arid climate in North China.

Figure 4 represents the decadal anomalies of arid climate area evaluated against the reference climatology of 1951–2000. Here, the areas of BS and BW types were calculated in North China using the ENS, the STN, and the combination of ENS (STN) temperature and STN (ENS) precipitation. Note that the sub-domains of 111–125°E, 30–40°N and 117–125°E, 30–45°N were excluded so as to assess the changes in areal extent occurring mainly at the boundaries of the major arid zones. The spreading among the four data sets is modest, and their temporal variations are consistent. The areas of both BS and BW regimes are above normal over the recent 20 years and lower than climatology during the first two decades. The mean differences between pre- and post-1970s averaged among the four data sets are about 108×10^3 km^2 for BS type and 39×10^3 km^2 for BW type, respectively.

To test the statistical significance of the detected area changes, the *t*-test was used after filtering short-term disturbances through a 5-year running mean (Table 2). The results indicate that the area of BS type in the first and last epochs is significantly different at the 99% confidence level throughout all the data sets examined. Meanwhile, two data sets out of four data sets do not pass the 90% confidence level, suggesting that the expansion of BW regime is marginally significant.

5. Discussion and concluding remarks

A widely accepted notion for desertification is land degradation in arid and semiarid zones driven

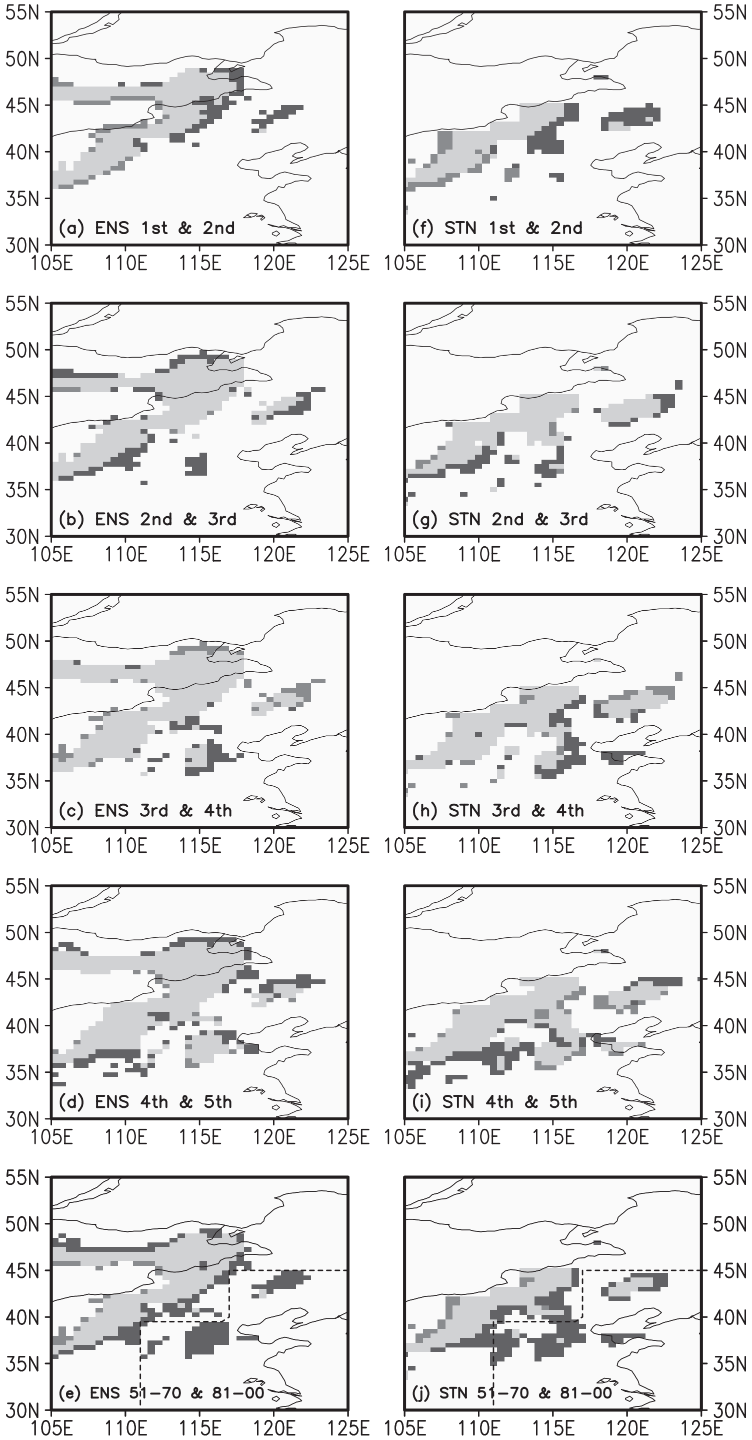

Fig. 2. Changes in BS climate between two adjacent decades: (a, f) 1951–1960 and 1961–1970, (b, g) 1961–1970 and 1971–1980, (c, h) 1971–1980 and 1981–1990, (d, i) 1981–1990 and 1991–2000. (e, j) Changes in BS climate between the two epochs of 1951–1970 and 1981–2000. The results are obtained from the ensemble average of the global grid data sets (ENS, left) and the Chinese station measurements (STN, right). Light grey indicates the BS type common in both decades, and medium (dark) grey denotes the one identified only by the preceding (subsequent) decade. Dashed lines in (e, j) indicate the regions excluded from the evaluation for Fig. 4 and Table 2 (see Section 4 for details).

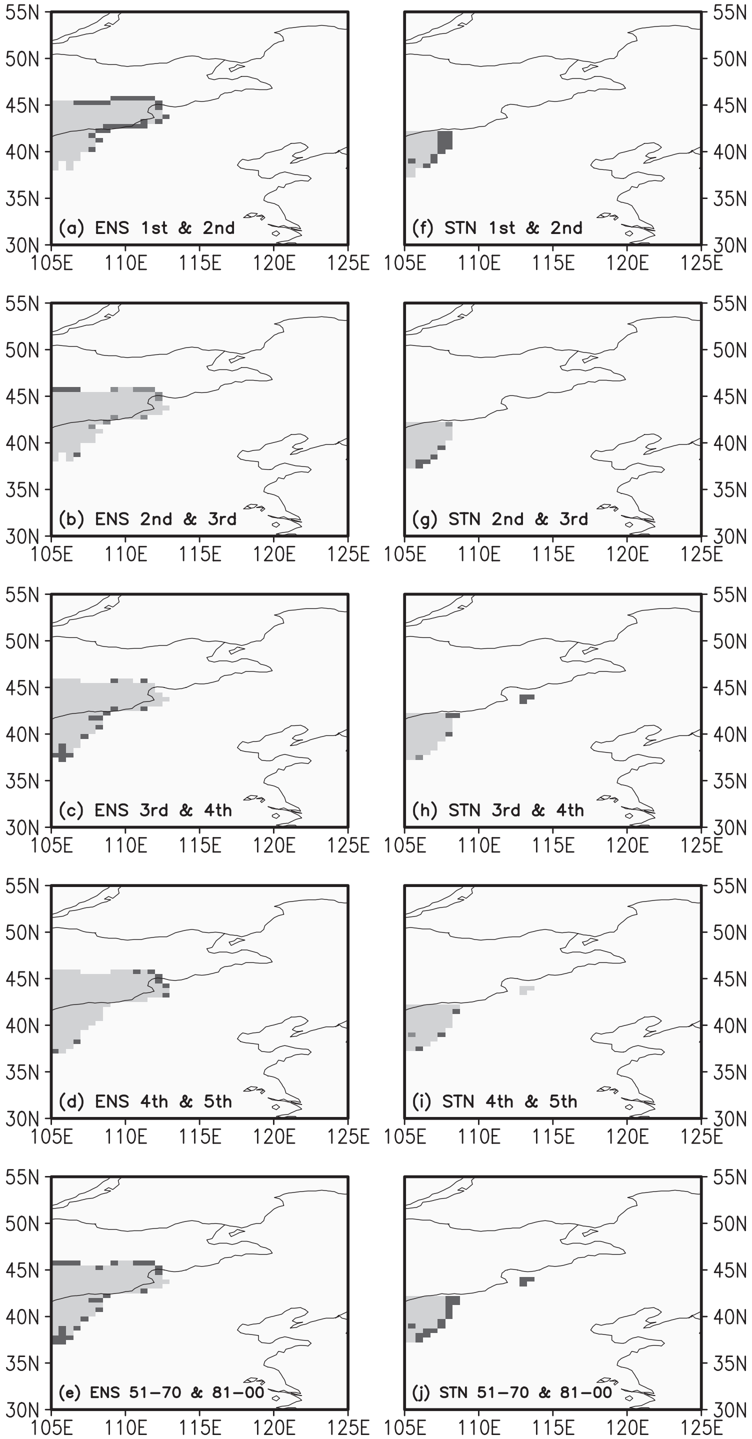

Fig. 3. Same as Fig. 2 except for BW climate.

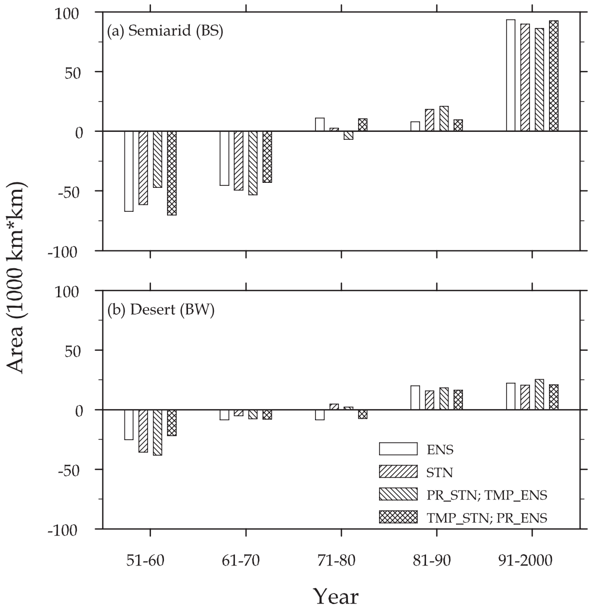

Fig. 4. Decadal anomaly in the area of (a) semiarid and (b) desert climate calculated in North China. Note that the subregions of 111–125°E, 30–40°N and 117–125°E, 30–45°N are excluded from this calculation (see Fig. 2 for the excluded regions). The reference climate is 1951–2000.

Table 2. Changes in areal extent of arid climate over North China between 1951–1970 and 1981–2000 and their statistical significance after applying a 5-year running mean. Units are 10^3 km^2 for area and % for confidence level, respectively. See Fig. 2 for the regions excluded from the statistical test.

	Semiarid (BS)			Desert (BW)		
	51–70	81–00	*t*-test	51–70	81–00	*t*-test
ENS	320	425	99	136	147	
STN	354	432	99	134	157	90
PR_STN; TMP_ENS	334	418	99	131	153	90
TMP_STN; PR_ENS	339	443	99	138	148	

by climate variations and human activities (Agnew and Warren 1996). However, due to the complexity in separating the contributions from the different external forcings, it remains unclear whether the degradation in arid landscape is attributable primarily to anthropogenic pressures or to natural variability (Wang et al. 2006b). This study does not purport to be one of such cause-and-effect studies. Instead, we have analyzed long-term variations of arid climate inferred from the major climate constituents (i.e., temperature and precipitation) by applying the Köppen climate classification. Unlike the NDVI technique, the use of Köppen scheme allows one to probe climatic transformation over an extended time period.

The desertification over inland China has been a topic of debate. A number of recent studies have shown that the arid and semiarid areas in northern China have diminished during the last 20 years due largely to land management and afforestation (e.g., Piao et al. 2005; Xue et al. 2005), which, however, is in contrast to the strengthened anthropogenic activities (such as enhanced grazing and increased population) during the same period (Wang et al. 2006b). Furthermore, since the rehabilitated areas are small compared to the existing areas of semiarid regions and sandy lands, it deems to be dubious whether the local to regional changes in the atmospheric circulation and rainfall distribution due to the vegetation restoration could be favorable for the maintenance of the rehabilitated areas (Zheng et al. 2002; Sen et al. 2004). Sen et al. (2004) demonstrated in an idealized numerical simulation that even relatively large re-greening in northern China might be vulnerable without abundant water resources or intensive irrigation because vegetation reclamation would produce more intense precipitation rather than more frequent rainfall that is more appropriate to maintaining the rehabilitated areas.

Meteorological variables measured in North China over the past 50 years have exhibited notable changes. We have demonstrated that the changes in the primary climate components are strong enough to cause climatic transformation that favors enlargement of arid climate in North China. In particular, the long-term expansion of steppe climate at the verge of the existing semiarid zones is seen to be robust and statistically significant across the various data sets employed, although that of the desert climate is inconclusive.

Observed climate conditions and analyzed climate trends over North China imply insufficient rain to balance potential evaporation. Though, whether this deficiency is deducible chiefly from the interdecadal rainfall variability or from the background warming is unanswered, it can be suggested that the resultant climate variability likely hinders on-going and planed efforts on vegetation restoration. Therefore, careful consideration on the unexpected burden is required for effective anti-desertification in North China.

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