Browning in desert boundaries in Asia in recent decades

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[1] In this study, the changes in desert boundaries in Asia (Gobi, Karakum, Lut, Taklimakan, and Thar deserts) during the growing season (April–October) in the years 1982–2008 were investigated by analyzing the normalized difference vegetation index (NDVI), precipitation, and temperature. In the desert boundary regions, the domain mean NDVI values increased by 7.2% per decade in 1982–1998 but decreased by 6.8% per decade thereafter. Accordingly, the bare soil areas (or nonvegetated areas) of the inside of the desert boundaries contracted by 9.8% per decade in the 1990s and expanded by 8.7% per decade in the 2000s. It is noted that the five deserts experience nearly simultaneous NDVI changes although they cover a very diverse area of Asia. In contrast, changes in temperature and precipitation in the deserts show rather diverse results. In desert boundaries located along 40°N (Gobi, Taklimakan, and Karakum), the decadal changes in vegetation greenness were mainly related to regional climate during the entire analysis period. Precipitation increased in the 1990s, providing favorable conditions for vegetation growth (i.e., greening), but precipitation reduced (19 mm per decade) and warming intensified (0.7°C per decade) in the 2000s, causing less moisture to be available for vegetation growth (i.e., browning). In desert boundaries below 40°N (Lut and Thar), although an increase in precipitation (8 mm per decade) led to greening in the 1990s, local changes in precipitation and temperature did not necessarily cause browning in the 2000s. Observed multidecadal changes in vegetation greenness in the present study suggest that under significant global and/or regional warming, changes in moisture availability for vegetation growth in desert boundaries are an important factor when understanding decadal changes in areas vulnerable to desertification over Asia.

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1. Introduction

[2] A desert is generally defined as an area that receives less than 200 mm of precipitation per year, or as an area where the amount of water lost by evapotranspiration (or evaporation) is larger than that received as precipitation [*United Nations Environment Programme* (*UNEP*), 2009]. These hot and dry regions occupy one quarter, that is, 33.7 million km^2, of Earth's land surface and are widely distributed all over the world. Recently, it has been noted that changes in climate may influence desert boundaries, primarily through changes in precipitation [*Tucker et al.*, 1991; *Piao et al.*, 2005]. These changes in desert boundaries create a range of adverse impacts on climate, biodiversity, and carbon sequestration over the region [*UNEP*, 2009; *Zeng and Yoon*, 2009]. Thus, evaluation of changes in desert areas is a critical issue in order to better understand the influence of climate change.

[3] To identify desert areas, the changes in vegetative biomass in desert boundary regions have been examined in many studies by using the satellite-measured normalized difference vegetation index (NDVI) [*Tucker et al.*, 1991; *Tucker and Nicholson*, 1999; *Anyamba and Tucker*, 2005; *Olsson et al.*, 2005; *Piao et al.*, 2005]. The consensus on the vegetation greenness in desert boundaries is that the increase in precipitation in the last decade of the 20th century has led to greening in desert boundaries, which in turn has led to a decline in the spatial area of deserts. Nevertheless, there are still some uncertainties regarding this conclusion because most previous studies focused on the Sahara or Sahel regions even though the dominant physical processes affecting vegetation growth vary significantly with region and season. Variations in the extent of deserts (e.g., Gobi, Karakum, Lut, Taklimakan, and Thar) in the Asian continent are still not understood well.

[4] The objective of this study is to evaluate changes in desert boundaries by analyzing vegetation greenness, expressed as the NDVI, in boundary regions of the deserts in Asia during the period 1982–2008 (i.e., 27 years). *Piao et al.* [2005]

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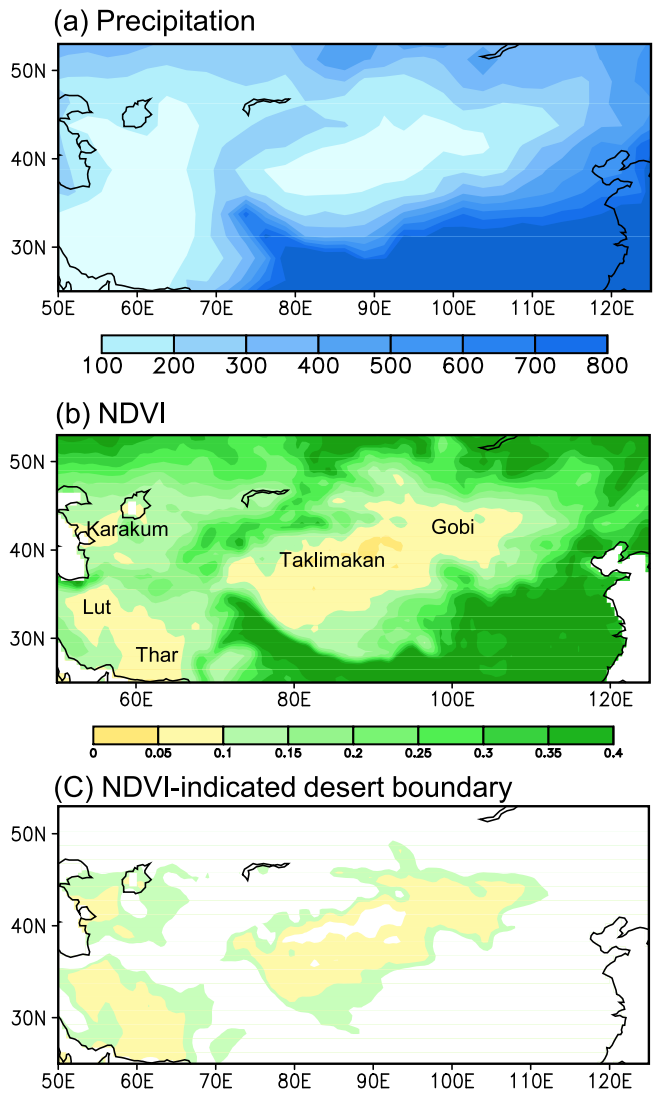

Figure 1. Spatial distributions of climatology of growing season mean (a) precipitation, (b) NDVI, and (c) desert boundaries as indicated by NDVI in the Asian desert region during the period 1982–2008. The color coding used in Figure 1c is as in Figure 1b.

reported a decline in the extent of the desert area in China for 1982–1999; this decline is mainly associated with an increase in precipitation and global warming during this period. After 1999, however, precipitation in the northern part of China declined, which limited the greening trend over the same target region [*Park and Sohn*, 2010]. Here, we evaluate the changes in vegetation greenness in desert boundaries in Asia for the entire 27 year period (1982–2008). To our knowledge, this is the first study that focuses on understanding the changes in midlatitude deserts, as indicated by NDVI, on multidecadal and continental scales.

2. Data

[5] The NDVI is a quantitative measure of photosynthetically active vegetation, and is calculated from the amount of light reflected by land surface at visible (R_{VIS}) and near-infrared (R_{NIR}) wavelengths, such that $N_{DVI} = (R_{NIR} - R_{VIS})/(R_{NIR} + R_{VIS})$. Healthy vegetation absorbs most visible light and reflects a large portion of NIR light, thus having a higher NDVI value; conversely, sparsely vegetated or bare surfaces reflect more visible and less near-infrared light, thus having a lower NDVI value. In this study, NDVI data were obtained from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar-orbiting satellites. These datasets were produced by the NASA Global Inventory Monitoring and Modeling Systems (GIMMS) group at a spatial resolution of 8 × 8 km and a 15 day temporal resolution over the period 1982–2008. Several data corrections (e.g., aerosol, cloud, volcanic, and sensor degradation) were performed to improve the accuracy of the data. Details of the data methodology are reported by *Tucker et al.* [2005]. GIMMS NDVI data have been used in previous studies to analyze desertification, vegetation greenness, growing seasons, and phenology [*Tucker and Nicholson*, 1999; *Brown and de Buers*, 2008; *Jeong et al.*, 2009]. Here, the NDVI data were aggregated onto a 0.5° grid to minimize possible errors. Monthly NDVI data were obtained from two 15 day composites using the maximum value method [*Holben*, 1986].

[6] To evaluate the environmental changes, the monthly mean precipitation, surface air temperature, and Palmer Drought Severity Index (PDSI) were examined. The monthly mean precipitation data were obtained from the Global Precipitation Climatology Project (GPCP) version 2 combined precipitation data set [*Adler et al.*, 2003]. The GPCP has a 2.5° grid spatial resolution which was merged in the analysis using precipitation estimates from station rain gauge observations and satellite infrared data. Interannual and climatological features of GPCP precipitation data over Asia produce a relatively higher quality when compared to other global reanalysis data [*Adler et al.*, 2003].

[7] The monthly mean temperature was obtained from the Japanese 25 year Reanalysis Project (JRA-25) conducted by the Japan Meteorological Agency (JMA) [*Onogi*, 2007]. The latest JMA numerical assimilation and forecast systems and the collected observational data sets (i.e., conventional surface and upper air observations, various satellite observations, and snow data) have been used to generate consistent and high-quality reanalysis data sets for climate research. The JRA-25 has a 1.25° grid resolution and shows good agreement with in situ observations [*Onogi*, 2007]. The monthly mean PDSI is a standardized measure of surface moisture conditions that integrate moisture supply (precipitation) and demand (which depends on temperature) and was calculated from these observed parameters by *Dai et al.* [2004] (available at http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html). The PDSI data has a 2.5° grid spatial resolution. While the published PDSI data are limited until the year 2003, it is the only data set available to evaluate the moisture conditions in the analysis region.

3. Climatology of Precipitation and NDVI

[8] Figure 1 shows the spatial distribution of averaged growing season precipitation and NDVI over Asia. The study area lies between 47°E and 125°E and between 25°N and 55°N. This area includes a sizeable part of the Gobi, Karakum, Lut, Taklimakan, and Thar deserts as well as their boundary regions. During the growing season (April–

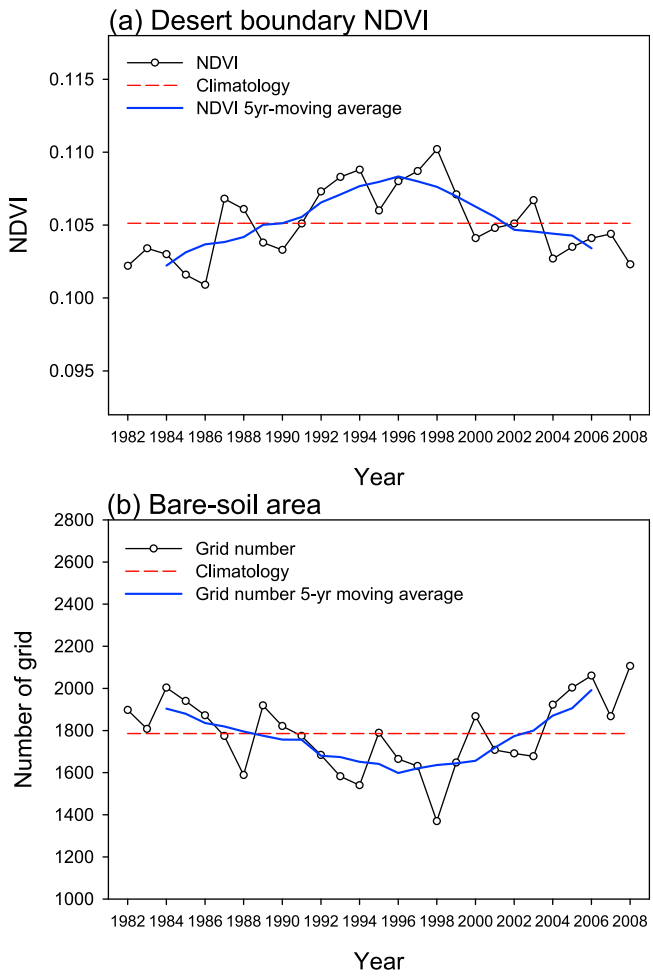

Figure 2. Interannual variations of (a) growing season mean desert boundaries as indicated by the NDVI and (b) the number of grid points in the bare soil areas as defined by NDVI < 0.1, during the period 1982–2008.

October), precipitation in the analysis region ranges from 50 to 800 mm. The largest area of precipitation is located near the Asian monsoon region, covering the southern to eastern parts of Asia. From the southeastern part to the northwestern part of the region, the precipitation amounts slightly diminish. Corresponding NDVI values are smallest (<0.1) inside of the 200 mm precipitation line. Given that a mean NDVI below 0.1 indicates bare soil [*Zhou et al.*, 2001], the distributions of NDVI denote the arid areas in the target region well. Overall, areas with small values of NDVI correspond to areas with small amounts of precipitation.

[9] To investigate the changes in desert boundaries by considering the climatological distributions of NDVI and precipitation, we used the general definition of "desert" on the basis of precipitation [*Tucker et al.*, 1991; *UNEP*, 2009]. *Tucker et al.* [1991] proposed a threshold value of NDVI matching a growing season rainfall to be 200 mm. Accordingly, we have defined a desert boundary as an area that receives climatologically 200 mm yr^{-1} of precipitation. The related values of average growing season NDVI in such desert boundaries range from 0.05 to 0.15. These boundaries' NDVI ranges are consistent with the values used in an earlier study in China [*Piao et al.*, 2005]. To understand the area vulnerable to desertification, we defined a desert boundary as an area with climatological values $0.05 \leq \text{NDVI} \leq 0.15$. This delineation of desert boundaries is displayed in Figure 1c. We further formed a hypothesis that an increase in NDVI in the region denotes a decrease in bare soil area in the climatologically fixed desert area, whereas a decrease in NDVI in the region indicates an increase in bare soil area. Furthermore, we investigated the annual NDVI 0.1 contour line (i.e., bare soil line); these bare soil lines are located in the climatologically fixed desert boundary. However, changes in the annual line are very complicated to understand. Thus, instead of using the contour line, we analyzed overall changes in NDVI spatial patterns in the fixed desert boundary (e.g., greening or browning).

4. Changes in the Desert Boundary

[10] To evaluate changes in vegetation greenness in desert boundaries in Asia as a whole, interannual variations of the domain-averaged NDVI value for the growing season and the bare soil grid number in the focused desert boundaries are displayed from 1982 to 2008 (Figure 2). As seen in Figure 2, the NDVI shows strong interannual (and/or multidecadal) variations; most of the highly positive anomalies were observed in the 1990s whereas most negative anomalies were observed in the 1980s and 2000s (Figure 2a). When the NDVI is assessed with a 5 year moving average, the multidecadal variation becomes substantial. In the period 1982–1998, the NDVI increased at a rate of 0.004 per decade, whereas in the period 1998–2008, the NDVI decreased at a rate of 0.003 per decade. These opposite changing rates in the two periods were found to be significant at the 99% confidence level. Regarding the changes in NDVI in the fixed desert boundaries, changes in the number of bare soil grids are shown in Figure 2b. Because regions of NDVI below 0.1 are recognized as bare soil or nonvegetated areas [*Zhou et al.*, 2001], the number of grids with NDVI below 0.1 was defined as the number of bare soil grids in the climatologically fixed boundary area. Based on the lowest latitude in the analysis domain, the number of grids is calculated with latitudinal weighting (e.g., cosine factor). We note that variations of the bare soil grid numbers were highly correlated with variations in the mean NDVI (correlation coefficient −0.82). This significant negative correlation confirms our hypothesis that an increase in NDVI denotes a decrease in bare soil area in the climatologically fixed area and vice versa. Between 1982 and 1998, the total area of bare soil in Asia decreased by 9.8% per decade; however, thereafter the total area of bare soil increased by 8.7% per decade. Both changes are found to be significant at the 99% confidence level. Thus, considering changes in NDVI and the number of bare soil grids, the bare soil area in the desert boundaries contracted in the 1990s and expanded in the 2000s. Although the analysis region is slightly different, the present results are consistent with those of *Piao et al.* [2005]. They reported that NDVI-indicated desertification over the Gobi was reduced from 1982 to 1999. It is interesting to note that desertification after 1999 has not yet been reported because of data period limitations in previous studies.

[11] To understand multidecadal changes in the vegetation greenness in the desert boundaries, we examined changes in

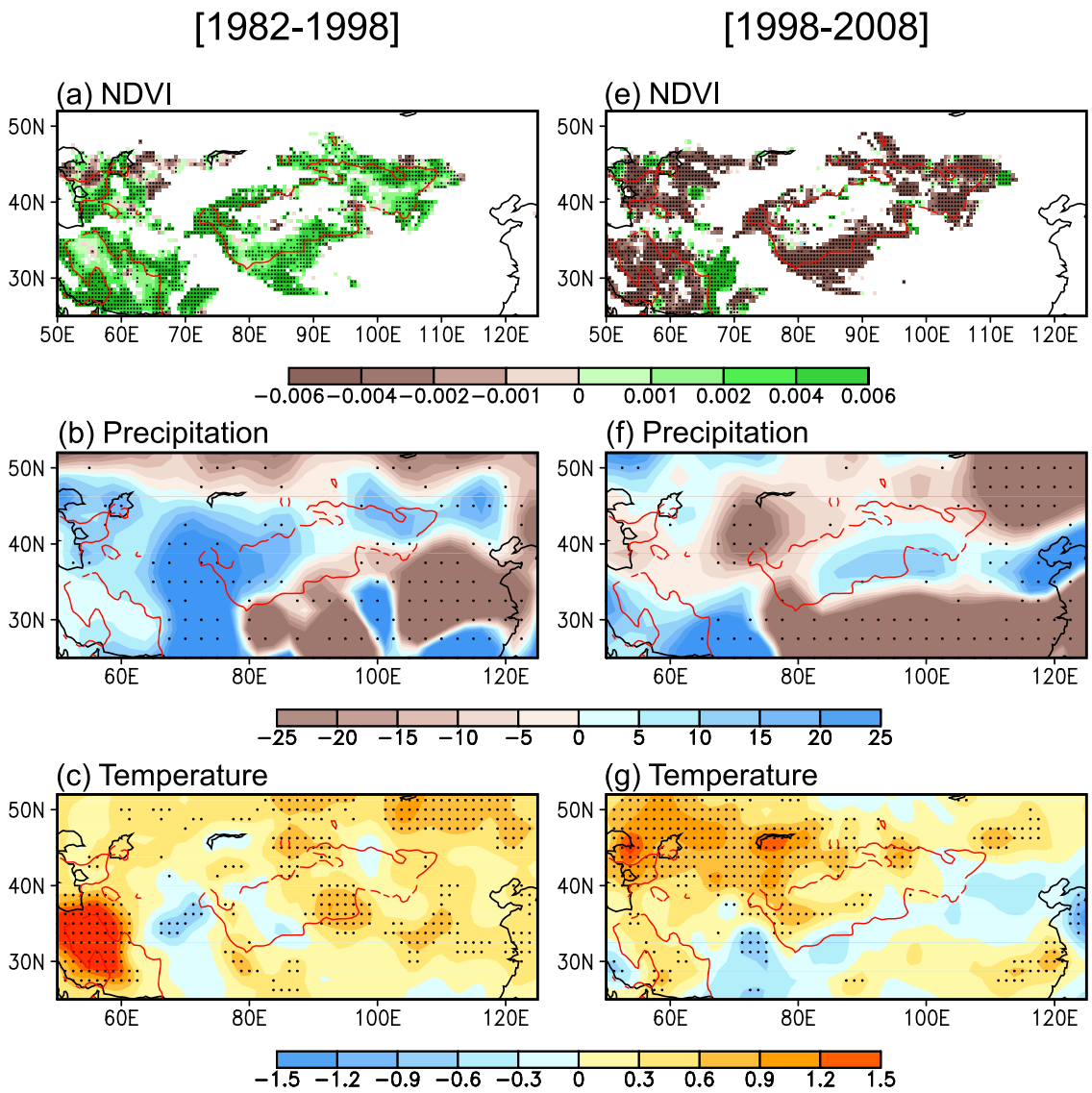

Figure 3. Spatial distributions of the average growing-season (April–October) NDVI, precipitation, and temperature linear trends for the periods (a–c) 1982–1998 and (e–g) 1998–2008. The dots indicate areas with NDVI changes that are statistically significant at the 95% confidence level. The red contour indicates the climatological NDVI 0.1 line during the analysis period.

atmospheric environments averaged for the growing seasons during two separate periods, 1982–1998 and 1998–2008. Figure 3 depicts spatial distributions of time mean NDVI and precipitation for the growing season and linear trends of temperature for the periods 1982–1998 (Figures 3a–3c) and 1998–2008 (Figures 3e–3g). Linear trends in each variable (e.g., NDVI, temperature, and precipitation) were determined using standard least squares fitting methods. The dots in Figure 3 outline areas with significant changes at the 95% confidence level. In the period 1982–1998, changes in NDVI values in the desert boundaries exhibited generally increasing (i.e., greening) trends over most of the region (Figure 3a). Interestingly, although the five deserts cover a very wide region in Asia, NDVI changes occurred simultaneously everywhere. However, intensive greening features are dramatically changed to decreasing NDVI changes for 1998–2008, except in the right-hand portion of the Thar desert's boundary (Figure 3e). In contrast to the changes in NDVI, spatial patterns of precipitation and temperature show rather diverse changes during both periods (Figures 3b and 3c and Figures 3f and 3g, respectively). To examine local changes in the three variables, we divided the total desert boundary area into eight regions (northern Gobi, southern Gobi, northern Taklimakan, southern Taklimakan, Karakum, Lut, left Thar, and right Thar) on the basis of distinct features of multidecadal variations in NDVI (Figures 3a and 3e).

[12] Magnitudes of linear trends in the three variables in each region are summarized in Table 1. Among the eight regions, the desert boundaries located along 40°N have similar characteristics of change in all variables. Positive changes (0.004 to 0.008 per decade) in NDVI during 1982–

Table 1. Magnitudes of Linear Trends in NDVI, Precipitation (*P*), and Temperature (*T*) in Eight Regions[a]

Boundary Region	1982–1998			1998–2008		
	NDVI	*T* (°C)	*P* (mm)	NDVI	*T* (°C)	*P* (mm)
Northern Gobi	+0.008	+0.5	+19	−0.005	+0.9	−10
Southern Gobi	+0.007	+0.6	−21	−0.005	−0.2	+12
Northern Taklimakan	+0.008	+0.1	+31	−0.006	+1.2	−22
Southern Taklimakan	+0.006	+0.4	−21	−0.007	−0.5	−24
Karakhum	+0.004	+0.5	+29	−0.005	+1.3	+12
Lut	+0.005	+1.2	+4	−0.004	+1.0	+11
Left Thar	+0.009	+1.0	+8	−0.004	+0.0	+13
Right Thar	+0.005	+0.1	+22	+0.006	−0.7	+28

[a]Plus sign indicates positive change in variable, and minus sign indicates negative change in variable.

1998 change to negative values (e.g., −0.005 to −0.007 per decade) thereafter. Comparing the changes in precipitation and temperature between the periods 1982–1998 and 1998–2008, precipitation changes are reversed from positive (19 to 31 mm per decade) to negative (−10 to −24 mm per decade), but the temperature maintains positive changes with magnitudes (0.5°C to 1.3°C per decade) throughout the entire period. Furthermore, changes in NDVI are strongly correlated with those of precipitation (e.g., 0.65). In desert boundaries located along 40°N, decrease in NDVI, reduced precipitation, and enhanced warming in the recent decades indicate that under continuous warming, the moisture supply related to precipitation may modulate the vegetation growth in that region.

[13] The influence of moisture availability for vegetation growth is also seen in the PDSI change in desert boundaries located along 40°N (Figure 4). For example, during 1982–1998, the positive NDVI areas also show positive PDSI signs, suggesting that an increase in precipitation is sufficient to provide moisture for vegetation growth; this precipitation compensates for the moisture loss caused by warming-induced evapotranspiration. However, during 1982–1998, moisture deficit as a result of reduced precipitation led to a decrease in NDVI in that region. Recently, *Park and Sohn* [2010] reported that precipitation in the northern part of China has slightly diminished from the year 2000, and has contributed to the decrease in NDVI over the region. Furthermore, climate simulations with an interactive vegetation model revealed that most of an increase in vegetation greenness over the arid region in midlatitudes from 1982 to 1999 is generally explained with an increase in local precipitation [*Piao et al.*, 2006]. These previous studies confirm the importance of moisture supply for multidecadal changes in vegetation greenness in the present study.

[14] In addition to changes in desert boundaries located along 40°N, possible relationships between changes in NDVI and changes in temperature and precipitation also show diverse features (Table 1). In southern Taklimakan, although there is a decrease in precipitation (−21 mm per decade), NDVI in this region displays a positive change (0.006 per decade). Contrary to other desert boundaries in Asia, southern parts of Taklimakan are mainly located in high-altitude regions. Generally, vegetation growth in cold climate areas such as high-altitude and Arctic areas is mainly controlled by temperature [*Liu et al.*, 2006]. Thus, an increase in temperature in such a region may lead to an increase in NDVI regardless of precipitation changes. Furthermore, while an increase in NDVI over the desert boundaries located below 40°N (e.g., Lut, southern Gobi, and left Thar) is related to an increase in both precipitation and temperature during 1982–1998, a decrease in NDVI during the more recent decades was independent of precipitation and temperature changes. Although a decrease in PDSI during 1998–2008 (e.g., dry condition) supports the changes in NDVI in the above three regions (Figure 4b), it is not sufficient to fully explain NDVI decreases. Here, it is also notable that changes in vegetation growth in the last three areas (e.g., Lut, southern Gobi, and left Thar) might be influenced by nonclimatic factors (e.g., deforestation, excessive irrigation, overgrazing, cultivation, and urbanization) [*UNEP*, 2009]. Because a desert boundary is extremely vulnerable to external forces, influence of human activity can strongly affect the changes in vegetation growth in desert boundaries. For example, the increase in cultivation and urbanization can cause excessive groundwater use, which will remove water needed for vegetation growth [*UNEP*, 2009]. Moisture deficit caused by human activity and associated vegetation browning may further increase the aridity in a desert boundary. Thus, the influence of nonclimate factors may be more significant to changes in NDVI

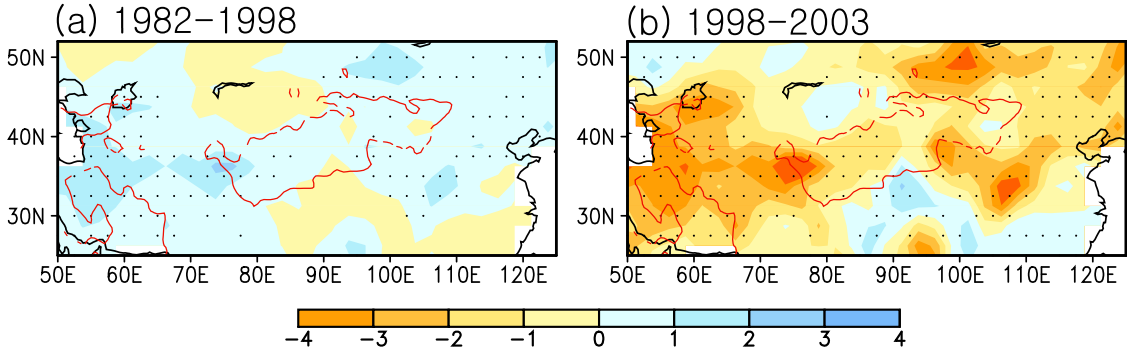

Figure 4. Spatial distributions of the average growing season (April–October) PDSI anomaly for the periods (a) 1982–1998 and (b) 1998–2003. The dots indicate areas with PDSI changes that are statistically significant at the 95% confidence level.

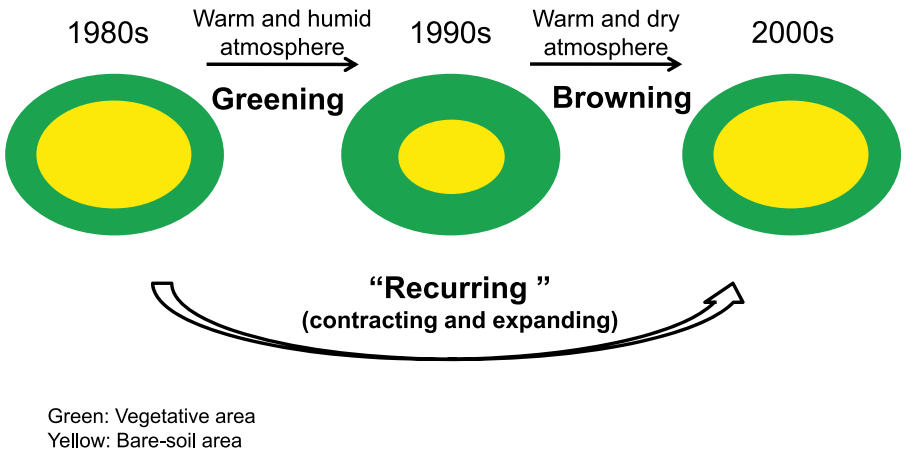

Figure 5. Idealized schematics of recurring features of desert areas in Asia.

in the desert boundaries located below 40°N. Hence, the influence of nonclimate factors should be evaluated.

5. Summary and Discussion

[15] In this study, we analyzed the long-term changes in the NDVI of desert boundaries in Asia during growing seasons in the period 1982–2008. Figure 5 shows a summary of changes in vegetation greenness and associated changes in a bare soil area in the climatologically fixed desert boundaries in Asia as a whole. From 1982 to late 1999, the NDVI in the climatologically fixed desert boundaries increased significantly at a rate of 0.004 per decade. After 1998, however, the NDVI inversely changed at a rate of −0.003 per decade. In association with NDVI changes in the desert boundary, bare soil areas first contracted by 9.8% and then expanded by 8.7%. Therefore, changes in the desert areas in Asia clearly showed contraction and expansion on a multidecadal scale. Although the five deserts cover a vast region in Asia, multidecadal-scale NDVI changes occurred simultaneously. However, regional climate changes show more diverse features. Specifically, over the desert boundaries located along 40°N (e.g., Gobi, Taklimakan, and Karakum), the continuous greening and browning features of desert boundaries were mainly caused by an increase in precipitation in the 1990s and a decrease in precipitation in the 2000s; under continuous warming from 1982 to 2008. It is suggested that the increase in precipitation and global and/or regional warming resulted in atmospheric conditions that are suitable for vegetation growth in the desert boundaries during the 1990s; however, reduced precipitation and intensified warming interrupted vegetation growth during the mid-2000s. However, in the desert boundaries located in the Lut and Thar areas, changes in regional climatic conditions are insufficient to explain recent browning. Thus, nonclimatic factors (e.g., cultivation, deforestation, overgrazing, and urbanization) may lead to changes in desert boundaries in that region.

[16] In association with vegetative changes in desert areas, variations in the NDVI of desert boundaries are important for evaluating changes in frequency, occurrence, and amplitude of dust events. Some recent studies reported that by the end of the 1990s, dust activity over the northern part of the Gobi has decreased slightly along with vegetation greening [*Lee and Sohn*, 2009]. Owing to the relationship between vegetation greenness and dust, the recurring features of vegetation greenness in the mid-2000s should be taken into account for a precise understanding of dust activity over Asia. Furthermore, previous studies reported the possible influence of vegetation feedback on climate [*Jeong et al.*, 2009, 2010]. Vegetation greenness is thought to be a major factor that alters surface atmospheric conditions by directly affecting surface albedo, emissivity, and soil moisture content, aas well as altering latent and sensible heat fluxes [*Xue*, 1997]. For example, an increase in vegetation greenness reduces albedo and thus can lead to a warm and dry atmosphere; conversely, it also increases evapotranspiration and thus can lead to a cool and humid atmosphere. Hence, the feedback influence of the *net* effect of these two factors related to vegetation in desert boundary regions can result in the expansion or contraction of the desert areas [*Zeng and Yoon*, 2009].

[17] Although the present study identified contraction and expansion of desert areas in Asia, extensive analysis is needed to confirm the broader scope of changes in deserts in the region. In this study, we focused on changes in NDVI in association with precipitation and temperature. However, anthropogenic activities (e.g., deforestation, excessive irrigation, and overgrazing) and changes in land management also cause large-scale vegetative changes. Furthermore, on the interannual scale, moisture inflow related to large-scale climate variations (e.g., Arctic Oscillation, El Niño, La Niña, Pacific Decadal Oscillation, and changes in monsoon circulation) may also contribute to NDVI changes in desert boundaries. *Mariotti* [2007] reported that humidity in central Asia, where both Lut and Thar deserts are located, is strongly influenced by a southwesterly moisture flux from the Arabian Sea and tropical Africa during spring and autumn. Thus, transported moisture may be a greater factor when explaining the change in NDVI in central Asia than that explained by the change in local temperature and precipitation. These concerns will be the subject of follow-up studies.

[18] **Acknowledgments.** This research was funded by the Korea Meteorological Administration Research and Development Program under grant CATER 2006-4204.

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