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• Review •

Progress in Semi-arid Climate Change Studies in China

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ABSTRACT

This article reviews recent progress in semi-arid climate change research in China. Results indicate that the areas of semi-arid regions have increased rapidly during recent years in China, with an increase of 33% during 1994–2008 compared to 1948–62. Studies have found that the expansion rate of semi-arid areas over China is nearly 10 times higher than that of arid and sub-humid areas, and is mainly transformed from sub-humid/humid regions. Meanwhile, the greatest warming during the past 100 years has been observed over semi-arid regions in China, and mainly induced by radiatively forced processes. The intensity of the regional temperature response over semi-arid regions has been amplified by land–atmosphere interactions and human activities. The decadal climate variation in semi-arid regions is modulated by oceanic oscillations, which induce land–sea and north–south thermal contrasts and affect the intensities of westerlies, planetary waves and blocking frequencies. In addition, the drier climates in semi-arid regions across China are also associated with the weakened East Asian summer monsoon in recent years. Moreover, dust aerosols in semi-arid regions may have altered precipitation by affecting the local energy and hydrological cycles. Finally, semi-arid regions in China are projected to continuously expand in the 21st century, which will increase the risk of desertification in the near future.

Key words: semi-arid regions, drying, expansion, warming, dynamics

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Article Highlights:

- Semi-arid regions in northern China have experienced significant expansion and the largest warming during the past 100 years.
- Semi-arid climate change is affected by land–atmosphere, ocean–atmosphere and dust–cloud–precipitation interactions as well as human activities.
- The warming and expansion in semi-arid regions increases the challenges in dealing with desertification, food security and water supply.

1. Introduction

With the characteristics of low nutrition content, low vegetation cover, and low water conservation capacity in the soil, semi-arid regions in China are very sensitive to global changes and human activities (e.g., Ma and Fu, 2006, 2007; Fu and Ma, 2008; Huang et al., 2016a). Because of their fragile ecosystems, semi-arid regions are also vulnerable to drought and degradation (e.g., Reed et al., 2012). Semi-arid regions covered ∼15% of the Earth's land surface and supported 14.4% of the global population in 2000 (Safriel and Adeel, 2005; Wang et al., 2012). China has the largest population in the world, and the semi-arid regions in China are one of the major semi-arid regions in East Asia and even the world (Piao et al., 2010). However, the areas of semi-arid regions in China have expanded during the last 60 years, and northeastern China has suffered from drought, while regions of northwestern China have experienced less-severe droughts (Li et al., 2015). Studies have indicated that drying trends may occur most significantly in semi-arid regions in terms of precipitation (P), soil moisture, and drought frequency as a result of global warming, which leads to the intensification of the hydrological cycle (e.g., Chou et al., 2009). Zhang et al. (2003a) found that decreased P and drought that occur over North China are also related to general circulation anomalies. Moreover, the increase in greenhouse gas (GHG) emissions closely associated with human activities and aerosols has contributed to the enhancement of terrestrial aridity and expansion of semi-arid regions across East Asia (Fu and Feng,

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2014; Guan et al., 2015; Zhao et al., 2017). Semi-arid regions dominate the coverage of drylands, and its climate change is a major contributor to the terrestrial climate. Therefore, improving our understanding of climate change in semi-arid regions and its mechanisms, especially in recent years, is a top priority for climate research in China (Huang et al., 2017c).

Recently, semi-arid climate change in China has varied significantly. For instance, Huang et al. (2012) found that the largest warming in China during the past 100 years has occurred over semi-arid regions and has been more significant in winter (Ma and Fu, 2003; Ji et al., 2014). Meanwhile, P over the semi-arid regions in China has shown a "wet-west–dry-east" pattern, but has only experienced a slight increase over western semi-arid regions and has not clearly mitigated the drought stress (Gong et al., 2004; Zhang et al., 2011; Li et al., 2015). Moreover, the climate has become drier in northeastern China (Huang et al., 2016a). The population of semi-arid regions in China mainly relies on rainfed agriculture for their livelihood; therefore, climate fluctuations greatly affect the availability of surface water resources (Liu and Xia, 2004). Moreover, drought in semi-arid regions has been one of the most severe manifestations of climate variability in China over the past six decades (Piao et al., 2010). Ma and Fu (2003) suggested that the drought in semi-arid regions of northern China mainly results from the decrease in P and increase in evaporation. Conversely, semi-arid climate change strongly influences the economy and society and increases the challenges related to food security and water supply in China (Charney, 1975; Huang et al., 2010; Piao et al., 2010; Li et al., 2015). Climate scientists have achieved many outstanding achievements regarding semi-arid climate change in China. To develop appropriate strategies to cope with significant semi-arid climate change and maintain sustainable development in these regions, it is necessary to review and comment on the latest progress in semi-arid climate change and its dynamic mechanisms. Therefore, by focusing on semi-arid climate change against the background of contemporary climate and global change, this article summarizes the characteristics of semi-arid climate change and its dynamic mechanisms in terms of land–atmosphere interactions, ocean–atmosphere interactions, dust–cloud interactions, and human activities. Finally, the projection of aridity in these regions in the future is reviewed and discussed.

2. Distribution and expansion of semi-arid regions

Different from the semi-arid regions adjacent to global oceans, semi-arid regions in China lie inland in northern China between 20°N and 40°N, with less water vapor along a zonal band from middle-west to northeast, which includes some areas of the Tibetan Plateau (TP), where the climate is one of the most unique, dry global midlatitude climates. The formation of a semi-arid climate zone in China with a unique location is mainly caused by TP topography, subsidence of the Hardley circulation, Asian monsoons, westerly belts, urbanization and land-use changes (e.g., Fu, 1994; Qian et al., 2009; Liu et al., 2015; Huang et al., 2017a). The uplift in the TP topography blocks the moisture from oceans and increases the effects of the TP as a heat source in summer and heat sink in winter, which amplifies the seasonal land–ocean contrast and alters the atmospheric circulation (e.g., Liu et al., 2015). Continuous warming has occurred in the TP during the past 30 years and even the hiatus period (Duan and Xiao, 2015; Ma et al., 2017). Meanwhile, descending air induced by stationary waves and dynamic divergent flows due to TP topography compensate for the rising air caused by heating in summer around the TP. Therefore, the uplift of the TP plays an important role in the evolution of the semi-arid climate in China (Chen et al., 2013; An et al., 2014). Furthermore, Asian monsoons can induce Rossby waves and interact with westerlies, resulting in an adiabatic descent that contributes to semi-arid climate. In general, the regional TP climate effects interact with large-scale atmospheric circulations and synoptic-scale and mesoscale systems, which all contribute to the formation of a semi-arid climate. Wu et al. (2009) found that the summertime subtropical desert/monsoon climate is formed in response to the combined effects of continental-scale forcing, local-scale coastal sea-breeze forcing, regional-scale TP forcing, and the positive feedback between diabatic heating and vorticity generation. However, some studies have considered that the retreat and closing of the Tethys Sea and the associated changes in land–ocean distribution patterns contributed to the aridification of Asia (Zhang et al., 2007).

To define the semi-arid regions of drylands and study semi-arid climate change, aridity is the main term used to measure the degree of dryness or water deficiency in a region, as it implies that the permanent water deficiency is closely related to strong insolation, elevated temperature, strong evapotranspiration and low humidity (Mainguet, 1999). Different criteria and climate classification schemes have been proposed for quantifying the degree of aridity at a given location (e.g., Köppen, 1884; Penman, 1948; Thornthwaite, 1948). For example, Palmer (1965) created the original Palmer Drought Severity Index (PDSI) that depends on P, soil moisture, streamflow and potential evapotranspiration (PET), which are mainly used in monitoring and researching drought; however, the PDSI has been criticized for its lack of comparability among diverse climatological regions owing to the empirical parameters used by Palmer in the United States. To make the PDSI usable in China, An and Xing (1986) and Liu et al. (2004) modified the PDSI (denoted by PDSI_CN) with revised weightings and duration factors. Wells et al. (2004) proposed the self-calibrating PDSI (scPDSI) via calibration by using local conditions to calculate the weightings and duration factors, which improved spatial comparability. In addition, the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) have been applied widely to monitor moisture conditions (Vicente-Serrano et al., 2010). Meanwhile, the Surface Wetness Index can be used to define drylands and track meteorological drought (Hulme et al., 1992), but it is restricted by the scarcity of station observations and problematic results derived from remote sensing (Kerr, 2007). In addition, the Aridity Index (AI), which is defined by the ratio of annual P to annual PET, is also considered as a measure of terrestrial aridity and is widely used for defining drylands and studying dryland climate change (e.g., Penman, 1948; Hulme, 1996; Feng and Fu, 2013; Huang et al., 2017a).

By evaluating the regional applicability of these schemes in China, Yang et al. (2017a) found that the scPDSI is more appropriate for China but reduces the value range slightly compared to the PDSI and modified PDSI (PDSI_CN); thus, the classification of aridity should be adjusted accordingly. The SPI and SPEI are more appropriate for humid areas than arid and semi-arid areas because the contributions of temperature change to drought are neglected in the SPI but overestimated in the SPEI when the PET is estimated by the Thornthwaite method instead of the Penman–Monteith algorithm. Meanwhile, Huang et al. (2016a) found that P alone inaccurately defines drylands because it ignores the effect of temperature and PET, while the Köppen–Geiger climate classification underestimates the total drylands. Overall, using the AI to identify drylands and aridity produces the most reasonable and reliable results among these three methods. Currently, more researchers have generally divided the climate classification of drylands using AI criteria and considered that the PET estimated by the common Penman–Monteith equation is closer to the real-world conditions under all climates (An et al., 2014; Qian et al., 2017; Yang et al., 2017a). However, reconciling different measures of terrestrial aridity to address various environmental issues in semi-arid climate change is an important issue that should be addressed in future research (Fu et al., 2016).

Using the AI criteria, drylands are defined as areas with an AI (P/PET) less than 0.65, which can be further classified into hyper-arid (AI $<$ 0.05), arid (0.05 $\leqslant$ AI $<$ 0.2), semi-arid (0.2 $\leqslant$ AI $<$ 0.5) and dry sub-humid (0.5 $\leqslant$ AI $<$ 0.65) regions (e.g., Feng and Fu, 2013). Meanwhile, drylands using a P-based definition can be divided into hyper-arid (annual $P < 50$ mm), arid (50 mm $\leqslant$ annual $P < 200$ mm), semi-arid (200 mm $\leqslant$ annual $P < 400$ mm) and dry sub-humid (400 mm $\leqslant$ annual $P < 600$ mm) regions. Based on the AI and annual P, Li et al. (2015) showed the climatological distribution of semi-arid regions of Chinese drylands for the period 1961–90, as shown in Fig. 1. The areas of semi-arid and dry sub-humid regions defined by the AI (Fig. 1a) are smaller than those defined by P (Fig. 1b), and the semi-arid regions of China are mainly distributed in a zonal band from midwest to northeast, with arid and hyper-arid regions to the northwest and dry sub-humid regions to the southeast. The spatial distribution of semi-arid regions based on the AI (Fig. 1a) also matches well with the grasslands of surface vegetation types in China from Moderate Resolution Imaging Spectroradiometer observations (Fig. 1c). In general, the total area of semi-arid regions is 2.14×10^6 km^2, while the areas of hyper-arid, arid and dry sub-humid regions are 1.06×10^6, 1.42×10^6 and 1.00×10^6 km^2, respectively, suggesting that semi-arid regions dominate the coverage of drylands (Fig. 1a). The semi-arid region of northern China is a transitional zone of instability between the inland arid regions in northwestern China and the humid monsoon areas of southeastern China, which is related to strong climate gradients and biological variables, and vegetation growth in these regions is relatively unstable (e.g., Fu and Wen, 2002; Dai et al., 2004). Moreover, the interactions between the East Asian summer monsoon (Huang et al., 2016a), westerlies and mixed agricultural–pastoral activities make these regions highly vulnerable to natural disasters (Shi et al., 1994), climate change and human activities (Fu and Wen, 2002). For example, both the front and rear edges of Transitional Climate Zone (TCZ) exhibit wide year-to-year shifts historically, and the interannual variability of TCZ is mainly affected by P fluctuation while the long-term trend of TCZ is dominated by potential evaporation (Wang et al., 2017). Meanwhile, the most significant expansion and enhanced warming has occurred over the TCZ of semi-arid regions in the last century (Huang et al., 2012; Ji et al., 2014; Guan et al., 2015). The results from Zhang et al. (2003b) also show that the vegetation-cover change is sensitive to the variation in regional P in the eastern semi-arid regions.

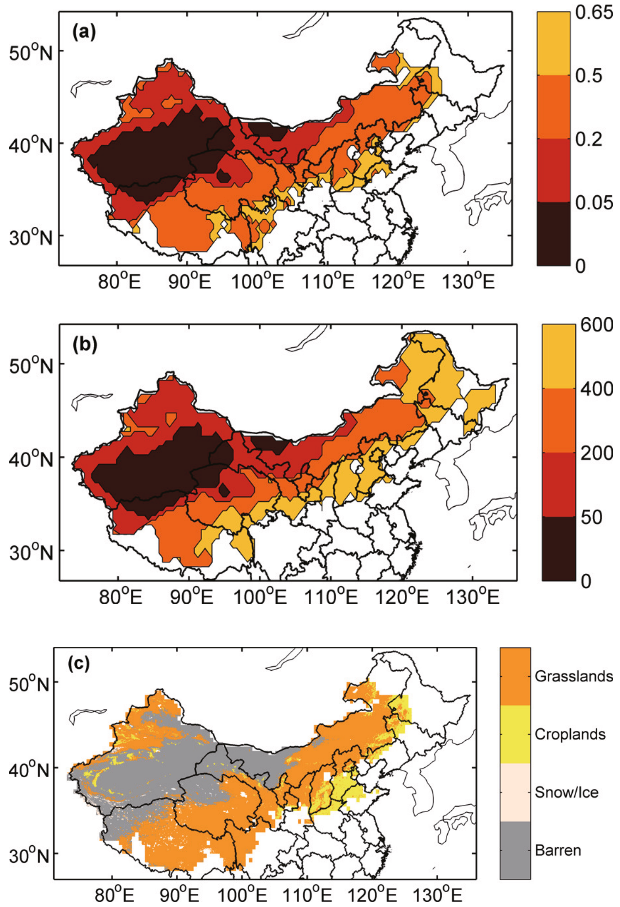

Fig. 1. Climatological distribution of Chinese drylands for the period 1961–90 using the definition of (a) AI [semi-arid regions (0.2 $\leqslant$ AI $<$ 0.5)] and (b) annual P [semi-arid regions (200 $\leqslant P <$ 400)] (units: mm). (c) Corresponding surface vegetation types from MODIS observations. [Reprinted from (Li et al., 2015). With permission of Springer Nature.]

In the past 60 years, many studies have demonstrated that continuous expansion and significant aridity trends have occurred across semi-arid regions in China (Ma and Fu, 2006; Feng and Fu, 2013; Li et al., 2015; Huang et al., 2016a, 2017a). Figure 2 shows the temporal variations in the areal coverage of semi-arid regions compared with those of hyper-arid, arid, and dry sub-humid regions in China. The rate of expansion for semi-arid regions is the fastest [0.111×10^6 km^2 (10 yr)$^{-1}$] during 1948–2008, while the areas of arid and dry sub-humid regions have increased by 0.013×10^6 km^2 (10 yr)$^{-1}$ and 0.017×10^6 km^2 (10 yr)$^{-1}$, respectively, suggesting that the largest expansion over China during the last 61 years has occurred in the semi-arid regions. Relative to 1948–62, the expansion of semi-arid regions, with relative increases of 33%, is the most severe in drylands, where the areal increase of semi-arid regions is more than 10 times than that in arid and dry sub-humid regions (Table 1). Therefore, the rapid expansion of semi-arid regions has dominated the areal increase in total drylands; in contrast, the area of hyper-arid regions has decreased by 6%, but the reduced amplitude is much less than that of semi-arid expansion. Moreover, Huang et al. (2016a) indicated that the semi-arid expansion over East Asia has been the largest in a single region and accounts for 50% of the global semi-arid expansion. Feng and Fu (2013) suggested that the expansion of semi-arid regions due to climate change is responsible for desertification and has increased the population affected by water scarcity and land degradation. Considering that newly formed semi-arid regions have different features compared with the original type of region, Li et al. (2015) and Huang et al. (2016a) compared the spatial shifts in semi-arid regions towards drier/wetter types for the last 15 years relative to the 1961–90 climatology, as shown in Fig. 3. The newly formed semi-arid regions that transformed from sub-humid/humid regions mainly occurred over Northeast China, stretching from western Heilongjiang and Jilin provinces and eastern Inner Mongolia, across most of Hebei and Shanxi provinces, and then towards southern Gansu Province (Fig. 3a). The newly formed dry sub-humid regions are adjacent to the east of the formed semi-arid regions in northeastern China, but the expansion in dry sub-humid regions is less than that in semi-arid regions. Meanwhile, the transformations of arid and hyper-arid regions from other types of regions were minimal; thus, the formed coverage of semi-arid regions primarily contributed to the shifts towards drier types of regions in drylands across China. Contrary to the shifts towards drier types, the retreat of arid to semi-arid regions was mainly located in small areas of the central TP and along the edge of the Junggar Basin. According to the contributions of different types of transitions to the areal change in semi-arid regions in China (Table 2), the areal change in newly formed semi-arid areas (from

Table 1. Area changes of drylands in China for the total and individual components of hyper-arid, arid, semi-arid and dry sub-humid regions from 1948–62 to 1994–2008, in units of 10^6 km^2. [Reprinted from Li et al. (2015)].

Area	Hyper-arid	Arid	Semi-arid	Sub-humid	Drylands
1948–62	1.12	1.35	1.93	1.02	5.42
1994–2008	1.05	1.41	2.56	1.05	6.07
Difference	−0.07	0.06	0.63	0.03	0.65
Relative difference (%)	−6%	4%	33%	3%	12%

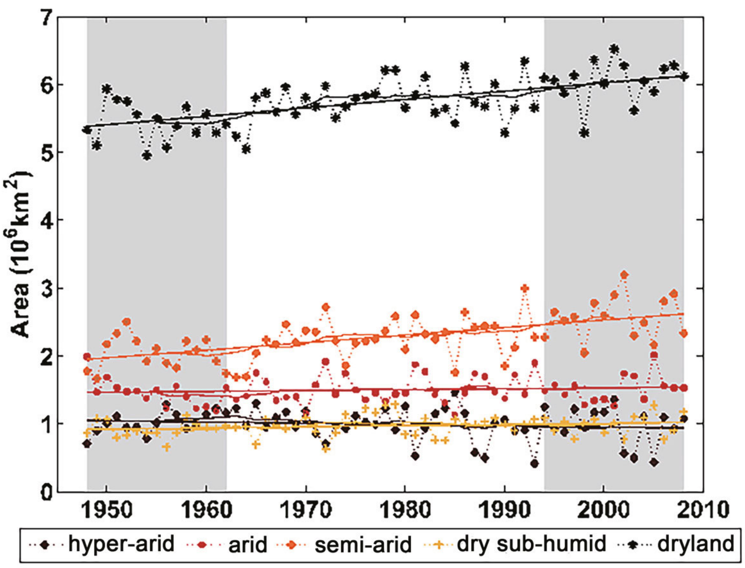

Fig. 2. Temporal variations in areal coverage of drylands in China for the total and individual components, in units of 10^6 km^2. Thick lines are the 15-year smoothing to emphasize the climate change. Solid lines are the fit to the data of the total and individual component of drylands. [Reprinted from (Li et al., 2015). With permission of Springer Nature.]

Table 2. The contributions of different type transitions to the areal change in the last 15 years (1994–2008), relative to 1948–62, in units of 10^6 km^2. [Reprinted from Li et al. (2015)].

Area (10^6 km^2)				
Arid to hyper-arid	Semi-arid to arid	Sub-humid/humid to semi-arid	Humid to sub-humid	Drier land
0.049	0.084	0.638	0.606	1.377
Hyper-arid to arid	Arid to semi-arid	Semi-arid to sub-humid	Sub-humid to humid	Wetter land
0.114	0.092	0.021	0.047	0.274

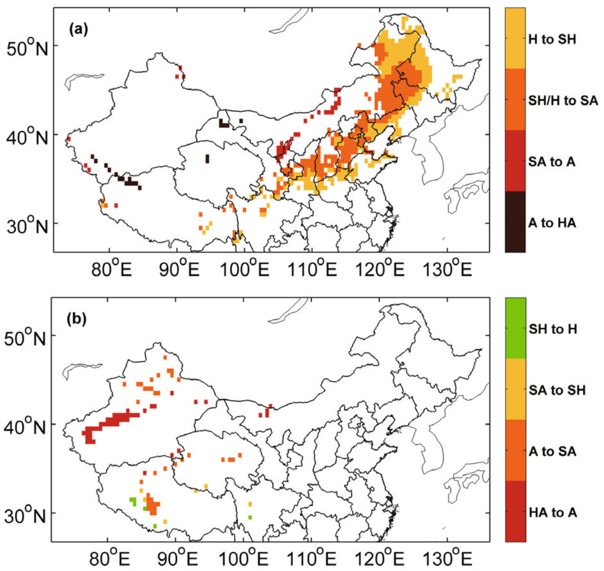

Fig. 3. Changes in coverage to (a) drier types and (b) wetter types for 1994–2008 relative to 1961–90. H, SH, SA, A, HA represent humid, sub-humid, semi-arid, arid, and hyper-arid, respectively. [Reprinted from (Li et al., 2015). With permission of Springer Nature.]

other types to semi-arid regions, 0.73×10^6 km^2) is six times larger than that in semi-arid decreasing areas (from semi-arid regions to other types, 0.105×10^6 km^2). Meanwhile, the areas of semi-arid regions with intensified aridity (drying) are much larger than those with decreased aridity (wetting), indicating that the expansion of semi-arid regions is most severe in northern China, and the newly formed semi-arid regions primarily originated from sub-humid and humid regions; thus, more semi-arid regions become drier, and the aridity has intensified dramatically, especially in the newly formed semi-arid regions. Huang et al. (2016a) also compared the transformation types over East Asia with those of other regions in the world and found that the semi-arid expansion in East Asia is the largest. Many studies have reported that semi-arid expansion associated with an increase in aridity is the result of global warming (Feng and Fu, 2013; Huang et al., 2017b).

3. Semi-arid climate change

Climate change associated with changes in *P* and PET lead to semi-arid areal expansion and aridity changes, and many studies have examined climate changes over semi-arid regions in China (e.g., Gong et al., 2004; Zhai et al., 2005; Chen et al., 2011; Wang et al., 2013, 2017; Li et al., 2015; Huang et al., 2016a). For example, in the western semi-arid regions of China, the temperature increased from 1901–2003 (Chen et al., 2009), while *P* generally increased from 1930–2009 (Chen et al., 2011), which was supported by the increase in moisture from the reconstructed PDSI (Li et al., 2006). Figure 4 shows the linear trends of AI, *P*, PET and surface air temperature (SAT) in semi-arid regions over China, which imply that the AI has had a significant drying trend in northeastern China and a wetting trend in the midwestern China. The patterns of the changes in *P* are consistent with those in the AI, with a decrease in the east and an increase in the west over semi-arid regions, but the amplitude of drying in eastern China is much larger than that of wetting in western China, suggesting that the semi-arid climate is obviously dry in the east but slightly wet in the west. The intensified aridity (drying trend) over the past 60 years across semi-arid regions in China is strongly associated with the weakened East Asian summer monsoon (e.g., Qian et al., 2009; Huang et al., 2016a). In addition, the PET pattern is opposite to that of the AI; the SAT warms in all semi-arid regions (except for a small area of the eastern TP), and the increasing trend in the SAT is more obvious in the northeast of the semi-arid regions. The inconsistency in the trends between the PET and SAT in semi-arid regions implies that the SAT is not the only factor controlling the PET (Donohue et al., 2010), and the PET is also affected by factors such as net radiation, wind and humidity. Furthermore, Huang et al. (2016a) compared the newly formed semi-arid regions with old semi-arid regions in China and East Asia because of their different climate characteristics; the study found that the variations in *P*, PET, and AI in the newly formed semi-arid regions were much stronger than those in old semi-arid regions across China, indicating that the decrease in the AI in newly formed semi-arid regions primarily contributes to the drying trend in all semi-arid regions across China. The intensified aridity results from decreasing *P* and increasing temperature in most of the areas in northern China, which leads to semi-arid expansion.

Recently, some studies have shown that global warming is nonuniform, and the warming of semi-arid regions over the last century has been more significant (Huang et al., 2012; Ji et al., 2014; Guan et al., 2015), especially during the cold season (November to March). The contribution of semi-arid regions in Northern Hemisphere (NH) midlatitudes to continental warming reaches approximately 50% (Huang et al., 2012; Ji et al., 2014); in particular, semi-arid warming in Asia

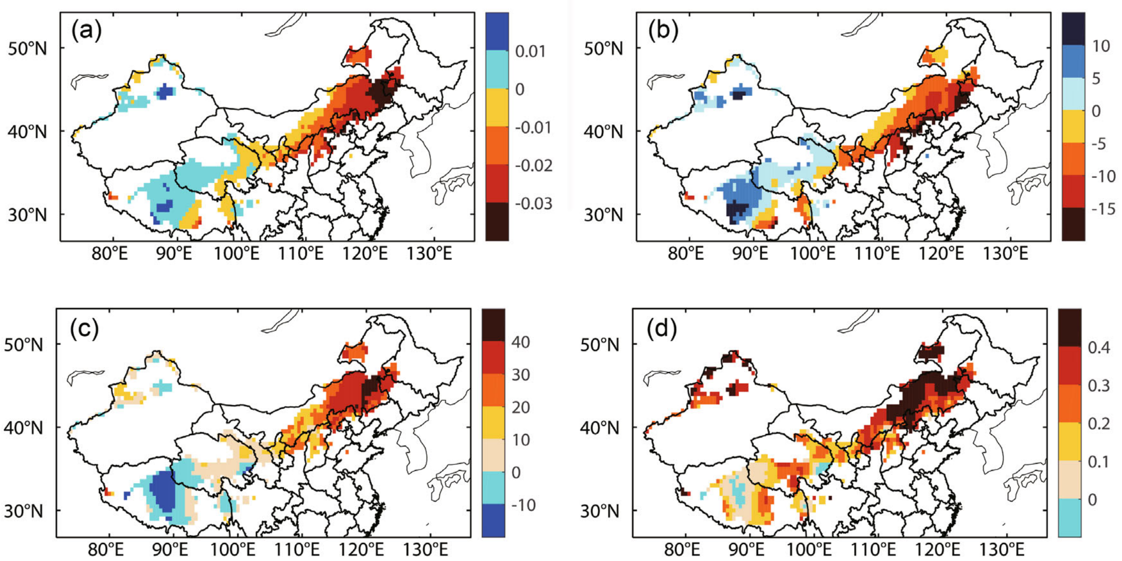

Fig. 4. Spatial distributions of the linear trends in the (a) AI [$(10\text{yr})^{-1}$], (b) P [mm $(10\text{yr})^{-1}$], (c) PET [mm $(10\text{yr})^{-1}$], and (d) SAT [°C $(10\text{yr})^{-1}$] in semi-arid regions in China from 1948 to 2008. [Reprinted from (Huang et al., 2016a). With permission of Springer Nature.]

is most remarkable. Similarly, many studies have found that climate warming in the past 100 years is evident in Northeast, North and Northwest China, which are mainly covered by semi-arid regions (IPCC, 2007; Tang et al., 2010). Li et al. (2015) also showed that warming has enhanced in semi-arid regions in China, especially in northeastern China (Fig. 4b). Guan et al. (2015) investigated the driving factors behind the enhanced semi-arid warming (ESAW) in East Asia by using a recently developed dynamical adjustment method; the results implied that the ESAW over East Asia is induced by regional anthropogenic forcing, which may be closely related to local human activities (Fig. 5). Moreover, Zhou et al. (2016) reproduced the ESAW in historical simulations using anthropogenic and natural forcings, but the ESAW disappeared when only natural forcing was considered, suggesting new potential footprints for anthropogenic warming. On the other hand, some studies consider that the increase in water vapor is the main reason for desert amplification (Zhou, 2016), which further demonstrates that the water vapor in the semi-arid regions is likely controlled by water vapor originated from ocean or sea surface temperature (SST). However, in phase 5 of the Coupled Model Intercomparison Project (CMIP5) simulations, the SAT trend is underestimated in semi-arid areas and overestimated in humid areas, indicating that the CMIP5 simulations have large uncertainties in their response of SAT to global warming (Huang et al., 2016b). In addition, the ESAW may accelerate in the context of a warming climate and, thus, has important societal and economic consequences (Zhou et al., 2016).

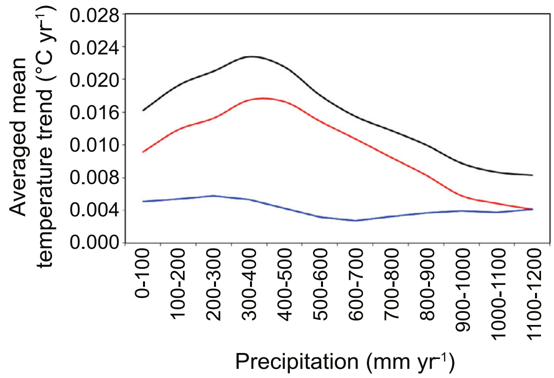

Fig. 5. Regionally averaged cold-season mean-temperature trend as a function of annual P for raw (black), dynamically induced (blue), and radiatively forced (red) temperatures (units: °C yr^{-1}) in the cold season from 1902 to 2011 over East Asia. [Reprinted from (Guan et al., 2015).]

4. The dynamics of semi-arid climate change

Land–atmosphere feedbacks respond to climate changes and substantially amplify the aridity response (Berg et al., 2016), and these interactions control the energy balance, water cycle and carbon cycle through turbulent flux at the atmospheric boundary layer, which plays an important role in semi-arid climate change (e.g., Wu et al., 2009; Huang et al., 2017a). Global climate variations affect the characteristics of the land surface in semi-arid regions, such as the distribution of soil moisture, albedo, vegetation, and watershed hydrology. In turn, changes in land surface parameters alter atmospheric variations via the fluxes of energy, water, carbon and momentum, creating feedback that further affects the semi-arid climate (Maestre et al., 2013; Cheng et al., 2015; Berg et al., 2016; Xiao and Duan, 2016; Duan et al., 2017; Huang et al., 2017a). Liu et al. (2006) found a positive feedback of vegetation greenness with SAT and P from observations, indicating the important interactions among soil moisture, vegetation, surface albedo, and climate in semi-arid regions. From the perspective of energy, the available energy is theoretically balanced by the sensible heat flux (SH) and latent heat flux (LH), and the SH comprises a higher proportion of the available energy due to the LH being limited by the soil water supply over semi-arid regions. Soil moisture, as a factor in land–atmosphere feedbacks, controls the near-surface temperature and evapotranspiration, and a low soil moisture content and *P* over semi-arid regions limits the evaporation and transpiration of vegetation cover, which leads to a low mean LH over semi-arid regions (Huang et al., 2017b). Heating from solar and infrared radiation is primarily released through SH over semi-arid regions, while extra heating can be used for evapotranspiration over humid regions; thus, surface temperatures over semi-arid regions rise sharply to create a large land–air temperature gradient (Fig. 6). Therefore, a lack of evapotranspiration due to limited soil moisture and vegetation cover leads to the high sensitivity of surface temperatures to extra energy from increased GHGs over semi-arid regions (e.g., Yin et al., 2014; Cheng et al., 2015; Cheng and Huang, 2016; Huang et al., 2017b).

In terms of the water cycle, semi-arid regions have become drier in northeastern China during recent years, accompanied by soil drying caused by decreasing *P* and enhanced warming. At the same time, soil suction has increased with drying soil, and the remaining soil moisture has become less absorbable for plant roots; thus, evapotranspiration and *P* may be reduced, leading to an increase in SH and temperature. Moreover, the increased temperature can further decrease the soil moisture and *P*, which could enhance the drying trends and make the regions even drier. The soil water loss, decreased evapotranspiration, and increased temperature form a positive feedback loop, which can continue until the soil is completely dry, resulting in desertification (Seneviratne et al., 2010). Furthermore, soil moisture–carbon–temperature feedbacks also play an important role in local land–atmosphere interactions and the carbon cycle. Excluding the recipients of climate changes induced by increasing carbon dioxide (CO_2) (Huang et al., 2016b), semi-arid regions are the largest contributors to the trends and interannual variabilities in the terrestrial carbon sink (Poulter et al., 2014). Semi-arid expansion against the background of global warming reduces the capacity of soil organic carbon storage; thus, soils store less carbon and emit more CO_2 into the atmosphere, which aggravates warming and causes a positive feedback cycle, where drying and warming both intensify (Huang et al., 2017a, b). However, these feedbacks are difficult to constrain in a defined area due to their impacts on each other and are still less documented in semi-arid regions in China. To improve our understanding of the role of land–atmosphere interactions over semi-arid regions in China, the temporal- and spatial-scale effects, as well as multiple feedback processes, need to be considered.

Wu et al. (2009) indicated that ocean–atmosphere forcing contributes to the formation of climate systems, including deserts and monsoons, in the summertime subtropics. Many studies have shown that oceanic oscillations, as factors in ocean–atmosphere feedbacks, modulate the decadal climate variations in semi-arid regions across China (e.g., Ma and Fu, 2006; Wang et al., 2008; Qian and Zhou, 2014). For example, Yang et al. (2017b) suggested that the Pacific SST pattern plays a dominant role in the anomalies of annual *P* and associated atmospheric circulation over eastern China, whereas the Atlantic SSTs contribute to a lesser degree. During the warm phase of the Pacific SST pattern, the semi-arid regions in northeastern China are prone to drought by inducing northwesterly wind anomalies and pushing the monsoons to the south (Ma and Shao, 2006; Ma and Fu, 2007), which explains the robust drying trend in northeastern China (Ma and Fu, 2003; Ma and Dan, 2005). Yang et al. (2017c) indicated that the Pacific Decadal Oscillation (PDO) affects East China *P* patterns by modulating the large-scale circulation pattern on both the interannual and intraseasonal scales. Lin et al. (2017) found that the negative phase of the PDO is associated with strong southerly summer monsoons, which are favorable for increasing the occurrence of local extreme rainfall over North China. Furthermore, the interdecadal variability in the PDO can exert a modulating effect on El Niño–Southern Oscillation (ENSO) teleconnections over East Asia (Wang et al., 2014; Dong and Dai, 2015). In semi-arid regions over China,

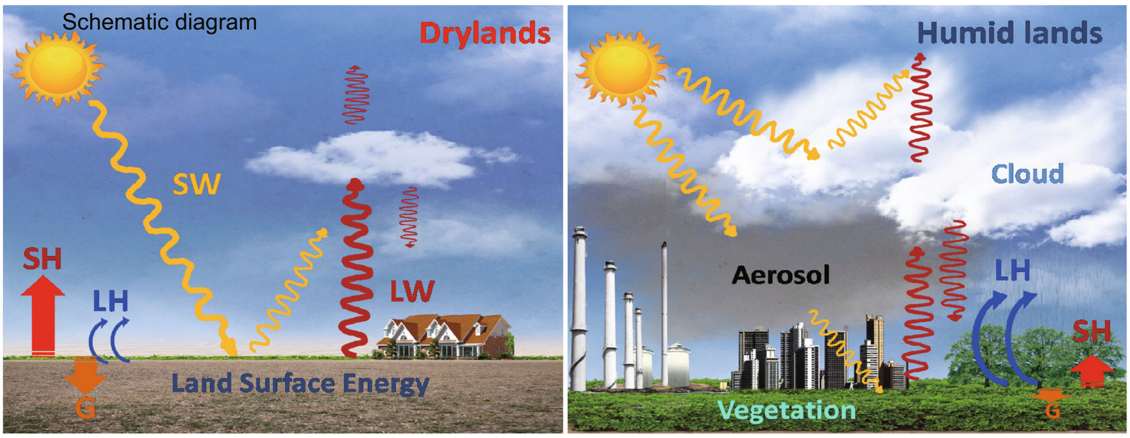

Fig. 6. Schematic diagram of local thermodynamic processes in drylands and humid lands. [Reprinted from (Huang et al., 2017b).]

ENSO-induced drying trends are magnified when ENSO is in phase with the PDO, while the dry variations weaken or even disappear when ENSO is out of phase with the PDO (Wang et al., 2014). Moreover, the response of the Hadley cell expansion to ocean–atmosphere feedbacks during recent decades has been responsible for enhanced aridity and water shortage changes in semi-arid regions of the NH (Seager et al., 2007).

Meanwhile, disturbances in monsoons and westerly winds are also important factors in semi-arid climate change in China (Qian et al., 2009), as they are closely associated with the land–sea thermal contrast. As suggested by Wallace et al. (1995) and He et al. (2014), the land–sea thermal contrast can induce feedbacks between ocean and atmospheric circulations. Both the zonal and meridional land–sea thermal contrast contribute to inducing an abrupt shift in thermally forced atmospheric circulations, such as asymmetric zonal and meridional thermal forcing (ZTF and MTF, respectively), which affects the intensity of westerlies, planetary waves, monsoons, and blocking frequencies and further affects the climate changes over NH continents, including the semi-arid climate change in China (He et al., 2014; Huang et al., 2017a, c). Semi-arid regions are largely influenced by blocking, especially in winter. He et al. (2014) found that the ESAW is accompanied by a decrease in blocking frequencies. As shown in Fig. 7, when surface thermal forcing in the NH follows the cold-ocean–warm-land pattern due to the CO_2 greenhouse effect, the ZTF decreases and reduces the blocking frequencies by modulating planetary waves. In contrast, the westerly wind is weakened, and topographic forcing is enhanced when surface forcing follows the warm-ocean–cold-land pattern, which is favorable for the persistence of blocking and cooling. Huang et al. (2017c) indicated that the internal climate variability associated with oceanic oscillations and Arctic amplifications, by altering the ZTF and MTF, can enable a decadal modulated oscillation (DMO), which influences the terrestrial temperature in semi-arid regions on decadal to multidecadal time scales. The upward DMO contributes to accelerated warming, similar to that during the last 20 years of the 20th century, while the downward DMO suppresses the long-term warming trend, which resulted in a

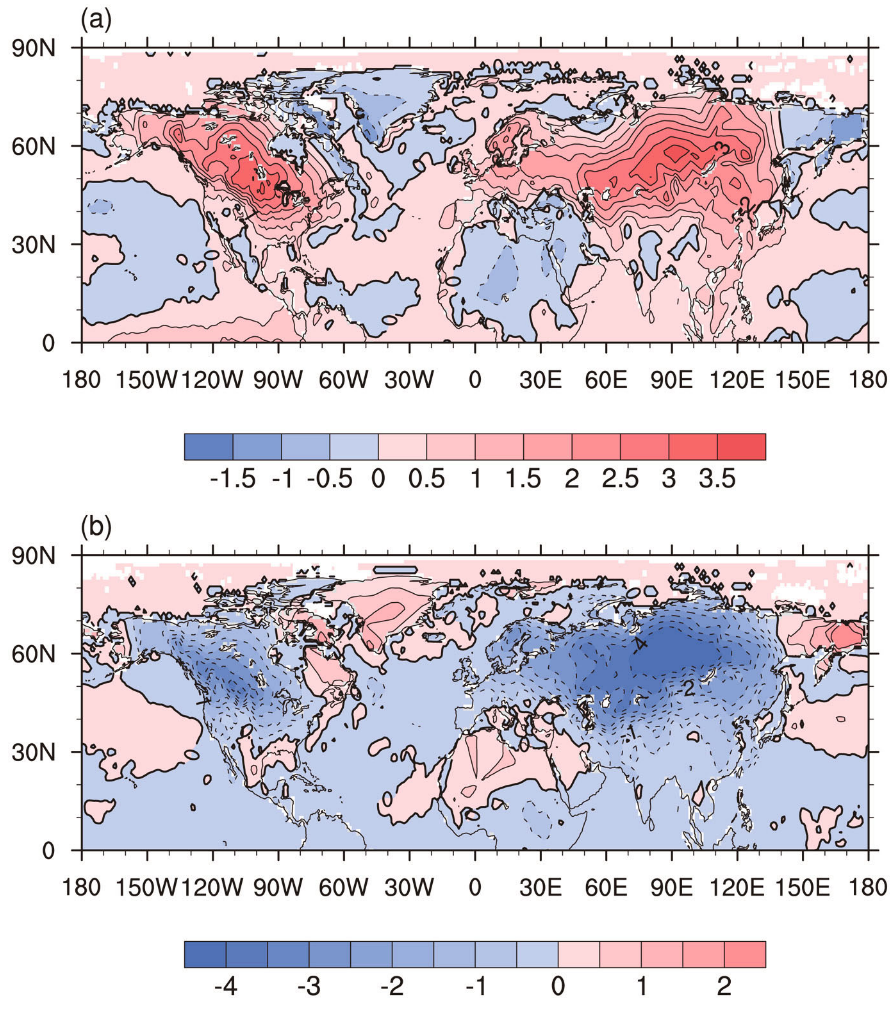

Fig. 7. Composite SAT anomaly fields (units: °C) in winter (December–February) for (a) positive and (b) negative phases of land–sea thermal contrast. Contour intervals: 0.5 °C. [Reprinted from (He et al., 2014).]

cooling trend over Eurasia during the recent warming hiatus period.

Based on satellite observations, ground-based measurements, and model simulations (Huang et al., 2007; Wang et al., 2010a; Bi et al., 2011; Chen et al., 2013), the large amounts of dust particles in East Asia emitted from arid and semi-arid regions are also considered significant factors affecting semi-arid climate change over China, through their direct effects on solar and thermal radiation (e.g. Li, 2004; Huang et al., 2014) and indirect/semi-direct effects on clouds and *P* (e.g., Twomey, 1977; Albrecht, 1989; Huang et al., 2006a, b, c, 2009). East Asia is one of the major sources of dust aerosols in the NH, and dust from deserts in China increased most obviously from 1970 to 2000 but has generally decreased since 2000, with oscillations in recent years (e.g., Xia et al., 2016). Huang et al. (2008) indicated that dust in China often originates from the Taklimakan and Gobi deserts, with more frequent dust storms occurring in the Taklimakan Desert than the Gobi Desert, which can be transported long distances by prevailing westerlies (Fig. 8). Meanwhile, because of the unique TP topography, with dynamical and thermal forcing, dust aerosols from the Taklimakan Desert compared to African dust emissions could be transported to the TP and even eastern China via upper tropospheric westerly jets (Huang et al., 2007, 2008; Ge et al., 2014), which could alter atmospheric stability and circulation (Huang et al., 2007; Zhao et al., 2015; Li et al., 2016b). Moreover, dust outbreaks are sensitive to changes in land-surface conditions, such as moisture and vegetation growth, over East Asia (Kurosaki et al., 2011).

In addition, dust aerosols in East Asia have an important impact on the microphysical properties and formation of clouds, by acting as cloud condensation nuclei and ice nuclei (first/second indirect effect and invigoration effect) and altering the relative humidity and stability of the atmosphere (semidirect effect) (Li et al., 2010, 2011). Moreover, the effects of dust also interact with cloud properties to alter the atmospheric dynamics, surface energy budget, and hydrological cycle, which further influences semi-arid climate change. Huang et al. (2006a, b, 2010) compared cloud properties under dusty and dust-free conditions over semi-arid regions in Asia and found that dust aerosols decreased the ice-cloud effective particle size and optical depth of cirrus clouds (Kawamoto et al., 2004; Su et al., 2008; Wang et al., 2010b). Dust aerosols over Asian semi-arid regions have a near warming effect at the top of the atmosphere but a cooling effect at the surface, while a warming effect occurs within the atmosphere (Huang et al., 2014). Furthermore, dust–cloud interactions can enhance or suppress semi-arid *P* due to the spatial distributions of dust aerosols, TP topography, cloud types, local humidity, and atmospheric circulation. Han et al. (2013) indicated using a climate–chemistry–aerosol model that dust radiative forcing decreased the *P* over the Yangtze River region and large areas of northeastern China. There is a positive feedback loop in the dust aerosol–cloud–*P* interactions over semi-arid regions (Huang et al., 2014, 2017a); for instance, a decrease in rainfall and subsequent deficit in soil moisture contribute to increasing dust storms, which further reduces the low-cloud cover and water vapor and increases the high-cloud cover, resulting in suppressed *P* and increased dust storms. Therefore, more dust storms occur in arid and semi-arid regions under feedback conditions, which further contributes to the desertification observed in recent decades and accelerated aridity over semi-arid regions in Asia (Huang

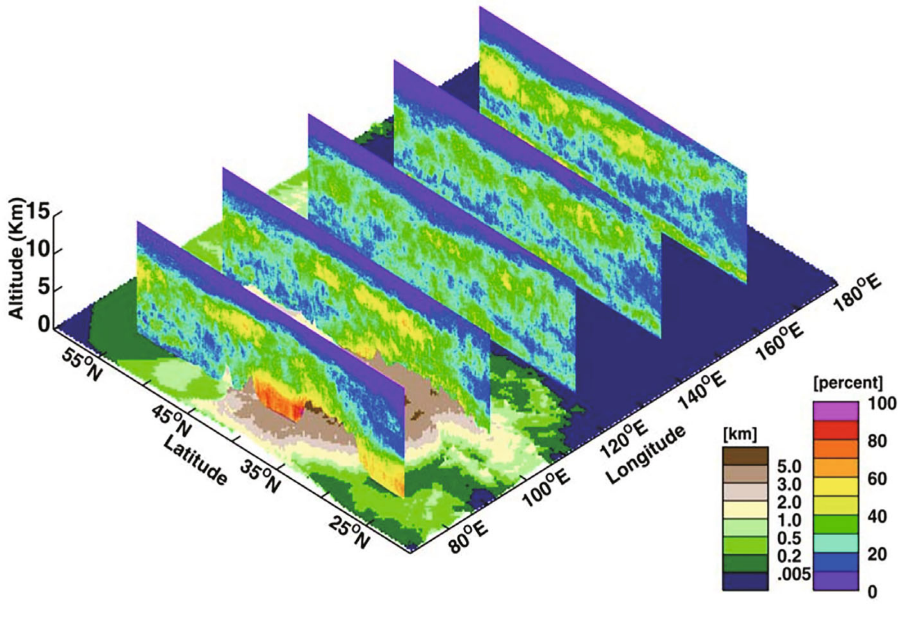

Fig. 8. Dust event vertical structure from CALIPSO observations over the Taklamakan Desert (80°E), Gobi Desert (102°E), eastern China (124°E), Yellow Sea (146°E), and the Pacific Ocean (168°E) superimposed on a regional map. Coloring on the right represents the dust event frequency of occurrence in percent. [Reprinted from (Huang et al., 2008).]

et al., 2014).

With rapid economic development, more GHGs and pollutants, such as aerosols, have been emitted, which are key forcing agents associated with human activities (Huang et al., 2017a). Desertification, which is the loss of biodiversity and other forms of environmental deterioration, is partially the result of human activities (Huang et al., 2016a, b). Many studies have indicated that human activities, such as increased CO_2 emissions, anthropogenic aerosols, land use and urbanization, play an important role in semi-arid climate change over China (e.g., Dai, 2013; Guan et al., 2015; Lin et al., 2015; Fu et al., 2016; Huang et al., 2017a; Xu and Yang, 2017; Zhang et al., 2017). For instance, under high CO_2 emissions, projected drying trends exist over semi-arid regions during the 21st century (Feng and Fu, 2013; Huang et al., 2016b). Zhao et al. (2017) found that the increase in anthropogenic aerosols in the atmosphere enhanced the terrestrial aridity and resulted in semi-arid expansion over East Asia. Lin et al. (2015, 2016) examined the changes in AI forced by CO_2 and aerosols over China using Community Earth System Model simulations and found that GHGs and aerosols can significantly affect regional AI, and the AI response to CO_2 decreased (drying) in almost all semi-arid regions in China, while the AI response to aerosols (black carbon and sulfate) increased (wetting) to the west and northeast but decreased (drying) in central areas across semi-arid regions of China (Fig. 9). Li et al. (2016a) investigated the effects of anthropogenic aerosols on temperature variability in semi-arid regions over China using CMIP5 models and found that anthropogenic aerosols reduced the temperature in the region. Moreover, Zhao et al. (2015) found that dust aerosols can cause surface cooling and reduced P over semi-arid regions in the NH, based on aerosol–climate coupled simulations. Guan et al. (2016) found that population density/change was correlated with anthropogenic dust aerosols in the semi-arid regions of East China, which further aggravated drought, indicating that human activities affect semi-arid climate change (Huang et al., 2014, 2015).

In addition, natural and human activities have modified land-use and cover change (LUCC), which interacts with the environment, has significant effects on the ecosystems of semi-arid regions and, consequently, directly or indirectly exerts significant influence on climate change (Deng et al., 2013). Negative LUCC may dry the local climate, leading to degradation, especially in semi-arid regions (Fu and Wei, 1993; Fu et al., 2016). The land cover degradation in northern China has accelerated in the last five decades, and the remaining grassland area in Inner Mongolia has significantly degraded (Wang et al., 2004), which could lead to a decrease in P and an increase in surface temperature in semi-arid regions by altering various physical characteristics of the land surface, such as albedo, surface roughness, soil water and thermal variables (Zhang and Zhang, 2005; Zhang et al., 2009; Yu and Xie, 2013). Using a regional climate model, Chen et al. (2017) indicated that net radiation and evaporation reduced within degraded areas after simulating vegetation degradation over the semi-arid regions of China. Li et al. (2017) indicated that the observed warming trend over semi-arid regions in northern China during 1946–2005 could be largely attributable to anthropogenic forcings, while the internal variability is still larger than the forced variation in semi-arid P. To better understand and quantify the contributions of human activities to semi-arid climate change, additional studies are needed.

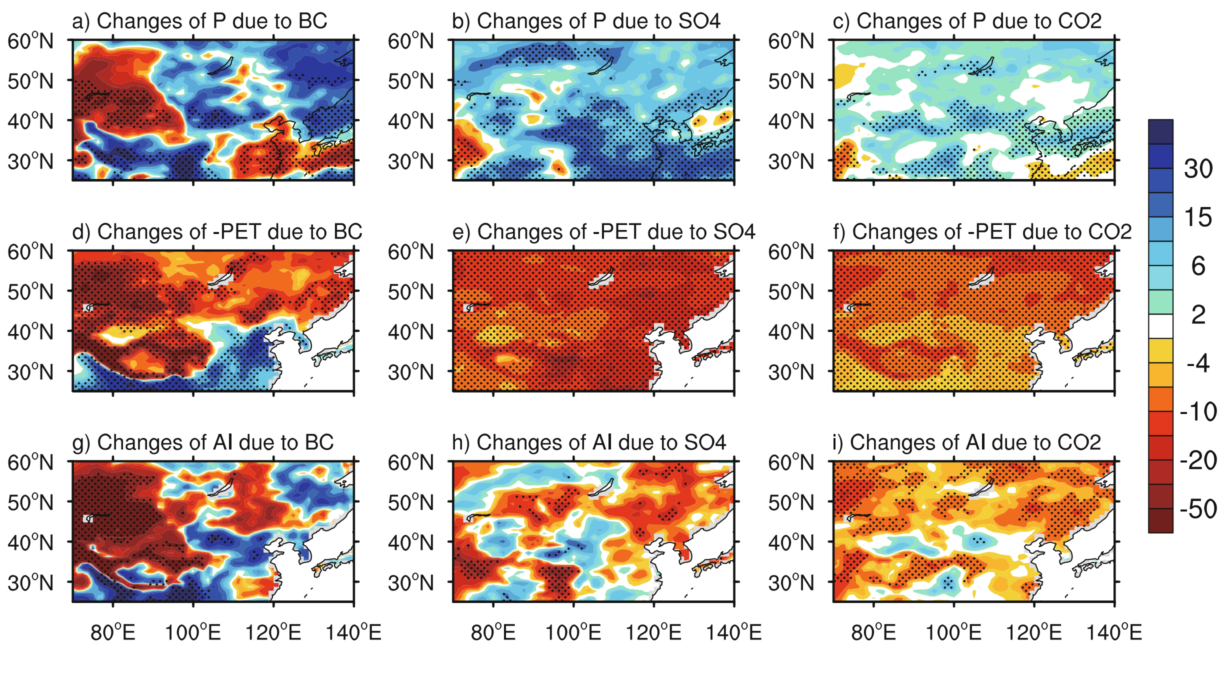

Fig. 9. Changes (units: % °C^{-1}) in P, PET and AI due to black carbon (BC) and sulfate (SO_4) aerosols (left-hand and middle panels) and CO_2 (right-hand panels), scaled by global-mean SAT changes. Gray regions do not have statistically significant changes based on a 95% confidence interval from a two-sided t-test. [Reprinted from (Lin et al., 2016).]

5. Projection of semi-arid climate

Semi-arid expansion over China that has mainly transformed from the sub-humid/humid regions is most remarkable during the past 60 years, and intensified aridity has primarily occurred in northeastern semi-arid regions (Li et al., 2015; Guan et al., 2016; Huang et al., 2016a). Based on the observations of semi-arid expansion in the past, many studies have forecast future semi-arid expansion in China and other regions, but there are substantial uncertainties in estimating recent drought changes both in terms of historical changes and future projections (Dai and Zhao, 2017). Using climate model simulations from CMIP5, Feng and Fu (2013) found that semi-arid regions over China at the end of the 21st century (2071–2100), under Representative Concentration Pathway 8.5 (RCP8.5), are projected to be larger than those in the historical period (1961–90), and mainly occur in the regions of central and southern China. However, many studies have indicated that the CMIP5 simulations do not perform well in capturing semi-arid expansion and climate change in the historical period (1948–2005), with semi-arid regions in China underestimated on the basis of observations (Ji et al., 2015; Huang et al., 2016b; Zhao and Dai., 2015, 2017). For example, Ji et al. (2015) found that the simulated global expansion of semi-arid regions during 1991–2005 was far less than the observed expansion, and the semi-arid expansion in China was underestimated due to overestimated P and underestimated SAT. Therefore, Huang et al. (2016b) used observational data to correct the CMIP5 projections and investigated coverage changes in semi-arid and other subtype regions of drylands under RCP8.5 emission scenarios. The results showed that, in the future, the semi-arid areas of China will continue to expand, and increased semi-arid regions will mainly be distributed in northeastern China (Fig. 10). Continuous expansion in semi-arid regions may have consequences regarding desertification, food security and water supply; therefore, the semi-arid regions in northeastern China are the highest priority for strengthening policy measures to adapt to climate change and reduce risks related to water resources (Xia et al., 2017).

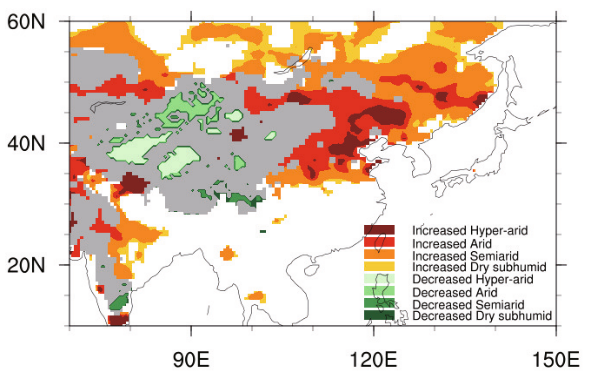

Fig. 10. Area changes in semi-arid and other subtype regions of drylands in East Asia from the corrected CMIP5 and RCP8.5 relative to the baseline (1961–90) for the future period of 2096–2100. The gray shading denotes the baseline drylands present in 1961–90. Changes include any transition from adjacent and nonadjacent subtypes. [Reprinted from (Huang et al., 2016b)]

6. Summary and discussion

In this article, based on recent research progress, we systematically summarize the temporal and spatial characteristics of semi-arid regions and review semi-arid climate change in China over the last 60 years. Moreover, we discuss the major dynamic processes affecting semi-arid climate change in terms of land–atmosphere interactions, ocean–atmosphere interactions, dust–cloud–P interactions, and human activities. Studies have found that semi-arid regions dominate the coverage of drylands in northern China; however, semi-arid areas have continuously expanded during the last 60 years and are considered as the largest expansion for drylands in China. The expanded semi-arid regions have mainly been transformed from sub-humid/humid regions, where the climate has become drier and warmer, particularly in the newly formed semi-arid areas. Studies indicate that the drying trend in semi-arid regions over China during the last 60 years is strongly associated with the weakened East Asian summer monsoon. Meanwhile, semi-arid regions have undergone the largest degree of warming compared to other regions across China during the past 100 years, mainly because of radiatively forced processes.

During the process of climate change, land–atmosphere interactions and human activities can influence the intensity of the regional temperature response in semi-arid regions, in which the effect of anthropogenic forcing is greater than that of natural forcing. Ocean–atmosphere interactions may modulate decadal climate change in semi-arid regions by altering the intensities of westerlies, monsoons, planetary waves, and blocking frequencies. Moreover, dust–cloud–P interactions have a significant impact on P by affecting the local energy and hydrological cycles in semi-arid regions across China. However, current findings indicate that CMIP5 simulations do not perform well in simulating semi-arid climate change. After correcting the CMIP5 simulations based on historical data, semi-arid regions in China are projected to continuously expand in the near future under a high emissions scenario, which will increase the risk of land degradation and water scarcity.

Although significant progress has been made in recent studies on semi-arid climate change and its dynamics over China, many unsolved issues remain to be further investigated in future studies. For instance:

(1) There is still a lack of high-quality datasets for studying and forecasting semi-arid climate change over China. Future studies should combine various datasets based on ground-based measurements, satellite observations, and climate reconstructions to study semi-arid climate change on multiple time scales and further compare the regional characteristics and correlations within different semi-arid regions across China and other regions of the world.

(2) Previous studies have mainly focused on the regional means of climatic factors in semi-arid regions across China, but few studies have focused on typical underlying surfaces in different semi-arid regions to examine climate change and dynamics in these regions. Meanwhile, the semi-arid regions across China are some of the major semi-arid regions in East Asia, and further studies need to analyze typical semi-arid climate change in China.

(3) The mechanisms of semi-arid climate change are still not well understood, and there is still a lack of robust research on the mechanisms and numerical simulations of semi-arid climate change in the context of global change. Moreover, the attributions of human-induced perturbations and natural forcings to semi-arid climate change should be further quantified and evaluated.

(4) Climate models have not performed well in the simulation and prediction of semi-arid climate change across China; thus, the ability to simulate aridity and climate change in semi-arid regions should be further improved in future climate models.

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