Simulating the Effects of Anthropogenic Aerosols on Terrestrial Aridity Using an Aerosol–Climate Coupled Model

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ABSTRACT

The comprehensive effects of anthropogenic aerosols (sulfate, black carbon, and organic carbon) on terrestrial aridity were simulated using an aerosol–climate coupled model system. The results showed that the increase in total anthropogenic aerosols in the atmosphere from 1850 to 2010 had caused global land annual mean precipitation to decrease by about 0.19 (0.18, 0.21) mm day\(^{-1}\), where the uncertainty range of the change (minimum, maximum) is given in parentheses following the mean change, and reference evapotranspiration ET\(_0\) (representing evapotranspiration ability) to decrease by about 0.33 (0.31, 0.35) mm day\(^{-1}\). The increase in anthropogenic aerosols in the atmosphere from 1850 to 2010 had caused land annual mean terrestrial aridity to decrease by about 3.0% (2.7%, 3.6%). The areal extent of global total arid and semiarid areas had reduced due to the increase in total anthropogenic aerosols in the atmosphere from preindustrial times. However, it was found that the increase in anthropogenic aerosols in the atmosphere had enhanced the terrestrial aridity and thus resulted in an expansion of arid and semiarid areas over East and South Asia. The projected decrease in anthropogenic aerosols in the atmosphere from 2010 to 2100 will increase global land annual mean precipitation by about 0.15 (0.13, 0.16) mm day\(^{-1}\) and ET\(_0\) by about 0.26 (0.25, 0.28) mm day\(^{-1}\), thereby producing a net increase in terrestrial aridity of about 2.8% (2.1%, 3.6%) and an expansion of global total arid and semiarid areas.

1. Introduction

The land surface of the earth can be classified into several categories, based on terrestrial aridity. For example, the aridity index (AI) recommended by the United Nations Environment Programme (UNEP 1992) divided the land surface into six categories: hyper-arid (AI \(< 0.05\)), arid (0.05 \(< AI \(< 0.2\)), semiarid (0.2 \(< AI \(< 0.5\)), dry subhumid (0.5 \(< AI \(< 0.65\)), subhumid (0.65 \(< AI \(< 1\)), and humid (AI \(> 1\)) (Feng and Fu 2013; Zhao et al. 2015). It is evident that arid (including hyper-arid) and semiarid areas are more sensitive to global climate change (Emanuel et al. 1985; Huang et al. 2012, 2013).

The earth is facing increased levels of desertification, which can be caused by both human activities and climate variations (Reynolds et al. 2007). Many studies have found that the area of dry land had expanded under past global warming, and it is expected that the expansion of dry lands will continue over the next 100 years due to the increase in the atmospheric levels of greenhouse gases (IPCC 2007; Feng and Fu 2013). Many simulation studies have revealed that the increased emission of greenhouse gases has led to an aggregation of terrestrial aridity and/or an expansion of arid areas (Emanuel et al. 1985; Gao and Giorgi 2008; Fu and Feng 2014; Fraedrich and Sielmann 2011; Cook et al. 2014). For example, Fu and Feng (2014) analyzed the Coupled Model Intercomparison Project phase 5 (CMIP5) transient
CO$_2$ to 2 × CO$_2$ simulation and found that the increase in CO$_2$ would generally cause a drier climate. Using a regional climate model, the International Centre for Theoretical Physics Regional Climate Model (ICTP RegCM), Gao and Giorgi (2008) found that the increase in greenhouse gases under the Intergovernmental Panel on Climate Change (IPCC) A2 and B2 scenarios could cause a northward expansion of dry lands in the Mediterranean region by the end of the twenty-first century.

In addition to greenhouse gases, aerosols are also important drivers of climate change that are significantly influenced by human activities. The overall radiative forcing of anthropogenic aerosols is negative and can offset a large portion of the global warming caused by greenhouse gases. The effects of anthropogenic aerosols on regional climate, especially over monsoon regions, have been investigated in many studies. For example, it was found that anthropogenic aerosols could weaken the East Asian summer monsoon (Zhang et al. 2012) and the South Asian summer monsoon (Bollasina et al. 2011). However, the effects of anthropogenic aerosols on terrestrial aridity have rarely been studied and are poorly understood. Zhao et al. (2015) found that dust aerosol did not cause an expansion of arid and semi-arid areas using the aerosol–climate coupled model BCC_AGCM2.0.1_CUACE/Aero (Zhang et al. 2012; Wang et al. 2013). Lin et al. (2016) found that black carbon (BC) aerosol led to a global increase in terrestrial aridity with the Community Earth System Model version 1 (Myhre et al. 2013; Lin et al. 2016).

This study explores the comprehensive effects of three anthropogenic aerosols [sulfate (SF), BC, and organic carbon (OC)] on terrestrial aridity. Section 2 describes the model and analytical methods that are used in this study. The comprehensive effects of anthropogenic aerosols on terrestrial aridity are presented in section 3, followed by a summary and conclusions in section 4.

2. Model, simulations, and analytical methods

a. Model and simulations

The aerosol–climate coupled system China Meteorological Administration (CMA) Unified Atmospheric Chemistry Environment for aerosols (BCC_AGCM2.0.1_CUACE/Aero; Zhou et al. 2012) of the Beijing Climate Center (BCC) was used in this study.

BCC_AGCM2.0.1 was developed by the National Climate Center of the China Meteorological Administration (NCC/CMA), and is based on the Community Atmospheric Model version 3.0 of the National Center for Atmospheric Research (NCAR) (Collins et al. 2004; Wu et al. 2010). BCC_AGCM2.0.1 is coupled with the NCAR Community Land Model version 3.0 (Oleson et al. 2004). The horizontal resolution is set at T42 (about 2.8° × 2.8°), with 26 vertical layers. Wu et al. (2010) has given a detailed description of BCC_AGCM2.0.1 and found that it reproduced the present-day climate fairly well. Zhang et al. (2014) and Jing and Zhang (2013) improved the cloud-radiation physical process in BCC_AGCM2.0.1 by incorporating the cloud overlapping scheme of the Monte Carlo independent column approximation (MiICA; Pincus et al. 2003), with the Beijing Climate Center Radiation Transfer Model (BCC_RAD; Zhang et al. 2003, 2006a,b).

The aerosol module CUACE/Aero was developed by the Institute of Atmospheric Composition of the Chinese Academy of Meteorological Sciences, and is based on the Canadian Aerosol Model (CAM; Gong et al. 2002, 2003; Zhou et al. 2012). Five kinds of aerosols are considered in CUACE/Aero: SF, BC, OC, dust, and sea salt, of which the first three are emitted mainly by human activities, while the last two are emitted primarily through natural processes. CUACE/Aero is a size-segregated aerosol module, with the radii of each type of aerosol divided into 12 bins (0.005–0.01, 0.01–0.02, 0.02–0.04, 0.04–0.08, 0.08–0.16, 0.16–0.32, 0.32–0.64, 0.64–1.28, 1.28–2.56, 2.56–5.12, 5.12–10.24, and 10.24–20.48 μm). All aerosols are externally mixed with each other. SF, OC, and sea salt are assumed to be soluble and the other two kinds of aerosols are assumed to be insoluble.

In BCC_AGCM2.0.1_CUACE/Aero, the transport, chemical transformation, cloud interaction, and removal of aerosols were computed online. The method used to calculate the optical properties of aerosols and the effects of water vapor on the optical properties of hygroscopic aerosols were introduced in Zhao et al. (2015). Studies have shown that BCC_AGCM2.0.1_CUACE/Aero simulated the properties of aerosols very well (Zhang et al. 2012; Wang et al. 2013, 2016; Zhao et al. 2015; Kristiansen et al. 2016). A two-moment bulk microphysical scheme (Morrison and Gettelman 2008; Gettelman et al. 2008) has been implemented into BCC_AGCM2.0.1_CUACE/Aero, which enables both the mass and number concentrations of cloud droplets and ice crystals to be predicted (Wang et al. 2014). Thus, the direct and semidirect effects of aerosols, and the interaction between aerosols and stratospheric clouds, can be considered in the model.

Three sets of experiments were conducted using the emissions of aerosols and their precursors for the years of 1850, 2010, and 2100, referred to as EXP_PRE, EXP_CUR, and EXP_FUL, respectively. All model parameters in the three sets of experiments were identical, apart from the aerosol emissions. In each set of experiments, five ensemble members were included by changing...
The model’s initial conditions. To get different initial conditions, an experiment (INIT) was run for 6 yr before the three sets of experiments, with prescribed climatological sea surface temperature and sea ice and the emissions of aerosols and their precursors for the year of 2010. Three types of files were output in INIT: initial, restart, and history files, among which the initial files (output yearly) were used as the different initial conditions for the three sets of experiments. The emissions of aerosols and their precursors were obtained from the IPCC (http://www.iiasa.ac.at/web-apps/tnt/RcpDb).

The aerosol emissions for the years of 2010 and 2100 were based on representative concentration pathway 4.5 (RCP4.5). To find a compromise between fully considering aerosol–climate interactions and saving computation time, a slab ocean model (Hansen et al. 1984) was coupled with the main model in all experiments. Danabasoglu and Gent (2009) found that it was accurate enough to study the equilibrium climate sensitivity using the Community Climate System Model, version 3 (CCSM3) and a slab ocean model. All experiments were run for 60 yr, with the first 30 yr as spinup time (Fig. 1), and the results of the last 30 yr were used for analysis.

b. Analytical methods

The comprehensive climatic effects of anthropogenic aerosols in the atmosphere, at present and in the future (e.g., the effects of anthropogenic aerosols on global surface temperature, atmospheric circulation, and precipitation) have been discussed in Zhang et al. (2016). However, Zhang et al. (2016) did not discuss the effects of anthropogenic aerosols on terrestrial aridity, which was the focus of this study. Therefore, the changes in AI and relevant variables (e.g., precipitation, reference evapotranspiration, and relative humidity) due to changes in anthropogenic aerosols in the atmosphere were analyzed in this study.

The AI used to define terrestrial aridity in this work had also been used by the United Nations Convention to Combat Desertification (UNCCD) to define arid, semiarid, and dry subhumid areas. It represents the ratio of annual mean precipitation \( P \) to annual mean reference evapotranspiration \( ET_0 \). For AI purposes, the earth’s land surface can be divided into six climate types (Fig. 2): hyper-arid (AI < 0.05), arid (0.05 < AI < 0.2), semiarid (0.2 < AI < 0.5), dry subhumid (0.5 < AI < 0.65), subhumid (0.65 < AI < 1), and humid (AI > 1). The \( ET_0 \) is the evaporation and transpiration over a hypothetical reference surface, with an assumed crop height of 0.12 m, a surface resistance of 70 s m\(^{-1}\), and an albedo of 0.23. The \( ET_0 \) represents the potential water requirement of a specific area (Allen et al. 1998):

\[
ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273}u_2e_\text{ea}(1 - RH)}{\Delta + \gamma(1 + 0.34\text{g}_\text{a})}. \tag{1}
\]

In Eq. (1), \( R_n \) is the net radiation flux density on the surface (MJ m\(^{-2}\) day\(^{-1}\)); \( G \) is soil heat flux density (MJ m\(^{-2}\) day\(^{-1}\)); \( T \) is air temperature at 2-m height (°C); \( u_2 \) is wind speed at 2-m height (m s\(^{-1}\)); \( e_s \) and \( e_a \) are saturation and actual water vapor pressure (kPa), respectively; and \( \Delta \) and \( \gamma \) are the slope vapor pressure curve and psychrometric constant (kPa °C\(^{-1}\)), respectively. Equation (1) can be derived from the bulk formulas for sensible heat (SH) and latent heat (LH) flux, and the surface energy balance equation in Fu and Feng (2014). In the surface energy balance equation, \( R_n - G \) is equal to, and can be replaced by, \( SH + LH \), and was referred to as the surface available energy (AE) in Fu and Feng (2014).

The ensemble means of the simulated variables relevant to AI in EXP_CUR were compared with observational/reanalysis data over land (Fig. 3). The observational/reanalysis data included 2-m air temperature and water vapor pressure from the Climatic Research Unit of the University of East Anglia (CRU; www.cru.uea.ac.uk), precipitation from the Global Precipitation Climate Center (GPCC; http://gpcc.dwd.de), and AE (SH + LH) and surface wind speed from the U.S. National Centers for Environmental Prediction (NCEP) and NCAR (http://www.esrl.noaa.gov/psd/data/reanalysis/). From Fig. 3, it could be seen that the simulated variables in EXP_CUR generally agreed...
well with observational/reanalysis data in terms of geographical distribution. However, the simulated AE and surface temperature in EXP_CUR were generally smaller than that of observational/reanalysis data (Figs. 3a3 and 3d3), which consequently resulted in negative biases in the simulated precipitation and water vapor pressure (Figs. 3b3 and 3e3). The cooler shift shown in Fig. 1 was also found in a simulation of the NCAR Community Climate Model version 3 (NCAR CCM3) when it was coupled with a slab ocean model (Kristjánsson et al. 2005). To study the effects of anthropogenic aerosols in the atmosphere on terrestrial aridity under current climate settings, the simulated monthly mean variables (2-m air temperature, precipitation, surface wind speed, AE, and water vapor pressure) in all experiments were treated with the following method (Dai 2011):

$$X' = X - \overline{X}_{\text{EXP_CUR}} + \overline{X}_{\text{obs}},$$

(2)

where $X$ and $X'$ represent specific variables before and after treatment, respectively; $X_{\text{EXP_CUR}}$ and $X_{\text{obs}}$ represent the corresponding variables from EXP_CUR and observational/reanalysis data, respectively; and the overbar indicates the long-term mean.

The effects of anthropogenic aerosols on terrestrial aridity and relevant variables were discussed by comparing different sets of experiments (e.g., EXP_CUR vs. EXP_PRE). As had been introduced in section 2a, there were five ensemble members in each set of experiments.

The uncertainty range of the change of a specific variable is given in parentheses by the maximum and minimum changes following the mean change, caused by the variation of anthropogenic aerosols in the atmosphere. And the significance of the results shown in figures (e.g., Fig. 4) was reflected by the consistency of the changing signs of a specific variable in five pairs of experiments (e.g., EXP_CUR – EXP_PRE).

### 3. The effects of anthropogenic aerosols in the atmosphere on terrestrial aridity

#### a. 1850–2010

According to RCP4.5, the global emissions of SO$_2$, BC, and OC have increased by about 110.16, 5.07, and 14.60 Tg yr$^{-1}$ from 1850 to 2010, respectively. The column burdens of anthropogenic aerosols in the atmosphere increased mostly in industrial regions (not shown), which were located mainly in the Northern Hemisphere (NH). The overall increase in anthropogenic aerosols in the atmosphere had generally led to a surface cooling effect, with a global annual mean change in surface temperature of about $-2.53$ K (Zhang et al. 2016). The surface cooling caused by the increase in anthropogenic aerosols in the atmosphere depressed evaporation and consequently led to a decrease in global annual mean precipitation.

From 1850 to 2010, the increase in anthropogenic aerosols in the atmosphere led to a decrease in land...
annual mean precipitation of about 0.19 (0.18, 0.21) mm day$^{-1}$ (Fig. 4a). It should be noted that “land” here and hereafter did not include the South Pole and small islands in the ocean. Precipitation increased over eastern South America, southwestern Africa, and most parts of Australia (all these areas are to the south of the equator), and decreased over northwestern South America, mid-Africa, South Asia, and most parts of Southeast Asia (these areas are mainly to the north of the equator). These contrasting changes in precipitation
on the two sides of the equator could be attributed to the enhanced Hadley cell in the NH caused by the increase in anthropogenic aerosols in the atmosphere from 1850 to 2010. The surface cooling caused by anthropogenic aerosols was more significant over the NH middle and high latitudes than elsewhere on the globe, leading to an enhancement of the north branch of the Hadley cell and a consequent southward shift of the intertropical convergence zone (ITCZ) rain center (Zhang et al. 2016). The enhanced Hadley cell in the NH could also explain why precipitation increased over the Mediterranean region, enhanced near-surface relative humidity, and wind speed $W_{2m}$ [Eq. (1)]. McVicar et al. (2012) found that surface wind speed had displayed a decreasing trend over recent decades. However, this decreasing trend might not be attributed to anthropogenic aerosols in the atmosphere, because the increase in total anthropogenic aerosols in the atmosphere reduced the radiative energy arriving at the surface and caused a surface cooling, thereby lowering near-surface saturation water vapor pressure and increasing near-surface relative humidity.

The third column of Table 1 shows the contributions of the changes in $T_{2m}$, $AE$, $RH_{2m}$, and $W_{2m}$ to the change in land annual mean $\Delta ET_0$. The calculation method was as follows: 1) one specific variable was taken from EXP_CUR (e.g., took $T_{2m}$ from EXP_CUR and kept the other three variables from EXP_PRE); 2) the land annual mean $ET_0$ ($ET_0'$) was calculated using the $T_{2m}$ from EXP_CUR and the $AE$, $RH_{2m}$, and $W_{2m}$ from EXP_PRE; and 3) the difference between $ET_0'$ and the $ET_0$ calculated with all variables from EXP_PRE was considered to be the contribution of the change in $T_{2m}$ to $\Delta ET_0$. It can be seen from the third column of Table 1 that the increase in total anthropogenic aerosols in the atmosphere from 1850 to 2010 caused a little increase in $\Delta ET_0$. The small increase in $W_{2m}$ could be attributed to the enhanced Hadley cell in the NH, which was caused by the increase in total anthropogenic aerosols in the atmosphere (Zhang et al. 2016).

The change in ET0 ($\Delta ET_0$) depends on the simultaneous changes in 2-m air temperature $T_{2m}$, surface AE, 2-m relative humidity $RH_{2m}$, and wind speed $W_{2m}$ [Eq. (1)]. The increase in total anthropogenic aerosols in the atmosphere from preindustrial times led to changes in land annual mean $T_{2m}$, $AE$, $RH_{2m}$, and $W_{2m}$ of about $-3.4$°C ($-3.5$°C, $-3.3$°C), $-6.2$ ($-6.4$, $-6.0$) W m$^{-2}$, $2.7$% (2.5%, 2.9%), and 0.016 (0.014, 0.018) m s$^{-1}$, respectively (Table 1). The decreases in $AE$ and $T_{2m}$ and the increase in $RH_{2m}$ all facilitated a decrease in land annual mean $ET_0$. The increase in total anthropogenic aerosols in the atmosphere from 1850 to 2010 led to a decrease in land annual mean $ET_0$. The calculation method was as follows: 1) one specific variable was taken from EXP_CUR (e.g., took $T_{2m}$ from EXP_CUR and kept the other three variables from EXP_PRE); 2) the land annual mean $ET_0$ ($ET_0'$) was calculated using the $T_{2m}$ from EXP_CUR and the $AE$, $RH_{2m}$, and $W_{2m}$ from EXP_PRE; and 3) the difference between $ET_0'$ and the $ET_0$ calculated with all variables from EXP_PRE was considered to be the contribution of the change in $T_{2m}$ to $\Delta ET_0$. It can be seen from the third column of Table 1 that the increase in total anthropogenic aerosols in the atmosphere from 1850 to 2010 depressed $ET_0$ mostly by decreasing $T_{2m}$, and then by increasing $AE$, and then by increasing $ET_0$. The increase in anthropogenic aerosols in the atmosphere had little effect on $ET_0$ by changing $W_{2m}$. 

### Table 1. Land annual mean changes in $T_{2m}$ (K), $AE$ (W m$^{-2}$), $RH_{2m}$ (%), and $W_{2m}$ (m s$^{-1}$) caused by the increase in total anthropogenic aerosols in the atmosphere from 1850 to 2010, and their contributions to $\Delta ET_0$ (mm day$^{-1}$); uncertainty ranges (from minimums to maximums) are given in parentheses, and the relative contributions of different variables to $\Delta ET_0$ are in the rightmost parentheses in the third column.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Changes in variable</th>
<th>Contribution to $\Delta ET_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{2m}$</td>
<td>$-3.4$ ($-3.5$, $-3.3$)</td>
<td>$-0.18$ ($-0.18$, $-0.17$) (48.6%)</td>
</tr>
<tr>
<td>$AE$</td>
<td>$-6.2$ ($-6.4$, $-6.0$)</td>
<td>$-0.14$ ($-0.15$, $-0.13$) (37.8%)</td>
</tr>
<tr>
<td>$RH_{2m}$</td>
<td>$2.7$ ($2.5$, $2.9$)</td>
<td>$-0.062$ ($-0.079$, $-0.055$) (16.8%)</td>
</tr>
<tr>
<td>$W_{2m}$</td>
<td>$0.016$ ($0.014$, $0.018$)</td>
<td>$0.012$ ($0.010$, $0.014$) (3.2%)</td>
</tr>
</tbody>
</table>

The changes in annual mean (a) precipitation and (b) $ET_0$ (mm day$^{-1}$) over land caused by the increase in anthropogenic aerosols in the atmosphere from 1850 to 2010, with the black dots indicating that the differences of the 5 pairs of experiments (EXP_CUR − EXP_PRE) have the same sign.
total contributions of the changes in \( T_{2m}, \ AE, \ RH_{2m}, \) and \( W_{2m} \) to \( \Delta ET_0 \) were about \(-0.37 \text{ mm day}^{-1}\), which was slightly larger than the real change in \( ET_0 \) \((-0.33 \text{ mm day}^{-1})\) in absolute value.

The equation \( AI = \frac{P}{ET_0} \) can be written in a differential form [Eq. (3)]. It was reported previously that the land annual mean changes in \( P \) and \( ET_0 \) caused by the increase in anthropogenic aerosols in the atmosphere from 1850 to 2010 were \(-0.19 \ (-0.21, -0.18) \) and \(-0.33 \ (-0.35, -0.31) \text{ mm day}^{-1}\), and their relative changes were about \(-8.1\% \ (-9.0\%, -7.7\%) \) and \(-10.8\% \ (-11.4\%, -10.4\%) \), respectively, leading to a net increase in the land annual mean \( AI \) of about 3.0\% (2.7\%, 3.6\%). This meant that by depressing reference evapotranspiration more than precipitation, the increase in total anthropogenic aerosols in the atmosphere since preindustrial times reduced the land annual mean terrestrial aridity. It could be seen from Fig. 5b that terrestrial aridity decreased over most areas in the Southern Hemisphere and midlatitudes of the NH. However, terrestrial aridity increased over some dry lands in the southwestern United States, Central America, northwestern China, Mongolia, and some areas in the NH high latitudes (e.g., Alaska, Greenland, east Siberia) and near the equator (e.g., South Asia and Southeast Asia), because of the increase in anthropogenic aerosols in the atmosphere from 1850 to 2010:

\[
\frac{\Delta AI}{AI} = \frac{\left( \frac{\Delta P}{P} - \frac{\Delta ET_0}{ET_0} \right)}{\left( 1 + \frac{\Delta ET_0}{ET_0} \right)}. \tag{3}
\]

For all climate types except hyper-arid, the increase in anthropogenic aerosols in the atmosphere caused a reduction of the mean precipitation (Fig. 5a). For hyper-arid climate, the uncertainty of the mean \( \Delta P/P \) was much larger than that for other climate types, resulting in a larger uncertainty of the mean \( \Delta AI/AI \). For arid climate, the mean precipitation did not decrease as much as that for other more humid climate types in percentage, because precipitation increased over some arid regions, such as central and western Australia, southwestern Africa, and the Mediterranean region (Fig. 4a). Overall, anthropogenic aerosols in the atmosphere depressed the mean \( ET_0 \) for all climate types. It can be seen from Fig. 5a that, for all climate types, the mean \( ET_0 \) decreased more severely than precipitation, leading to positive changes in the mean \( AI \) or decreases in mean terrestrial aridity. The positive changes in the mean \( RH_{2m} \) for all climate types suggested that the decreases in terrestrial aridity were robust, because the ground and surface air were closely coupled with each other. By depressing the water demand of evapotranspiration more than precipitation, the overall increase in the levels of anthropogenic aerosols in the atmosphere decreased the mean terrestrial aridity for all climate types. It should be noted that the changes in \( RH_{2m} \) in Fig. 5a were relative changes, which differed from those in Table 1.

The increase in total anthropogenic aerosols in the atmosphere from preindustrial times could also cause conversion between adjacent climate types (Fig. 6). For example, some arid (including hyper-arid) and semiarid areas over the Mediterranean region and central Asia were converted to wetter climate types, whereas some dry subhumid and subhumid areas in the southwestern United States, eastern Africa, the Arabian Peninsula, South Asia, northern China, and southern Mongolia were converted to drier climate types (Fig. 6a). In the Southern Hemisphere, the increase in anthropogenic aerosols in the atmosphere from 1850 to 2010 mainly
caused arid and semiarid areas to convert to wetter climate types (Fig. 6a).

Semiarid areas are the margins of total arid (including hyper-arid) and semiarid areas, and the mutual conversion between semiarid and dry subhumid areas reflects the expansion or reduction of total arid (including hyper-arid) and semiarid areas. From a global perspective, 30 grids were converted from semiarid to dry subhumid areas by the increase in anthropogenic aerosols, and 16 grids were converted in the opposite direction (Fig. 6a), indicating that the increase in anthropogenic aerosols from preindustrial times led to some reduction of total arid and semiarid areas. This result, together with the increase in AI (Fig. 5), suggested that the increase in total anthropogenic aerosols from 1850 to 2010 generally caused a decrease in terrestrial aridity on a global scale. However, it should be noted that the terrestrial aridity was aggravated and the arid and semiarid areas...
areas were expanded over North America, South Asia, and especially over East Asia due to the increase in anthropogenic aerosols in the atmosphere from the preindustrial era (Fig. 6a).

Apart from the UNEP (United Nations Environment Programme) method, there are many climate classification methods, including the Köppen–Geiger method (Köppen 1900; Köppen 1900; Kottek et al. 2006), the Budyko method (Budyko 1974; Fraedrich and Sielmann 2011), and the Thornthwaite method (Thornthwaite 1948). Although the calculation used in these classification methods varies, they have a similar technique for determining if an area is arid or not by comparing its water demand and supply. Normally, the water supply of a specific area is given by precipitation, but the water demand has diverse representations. For example, water demand is represented by reference evapotranspiration in the UNEP method, and by a precipitation threshold in the Köppen–Geiger method and an energy-equivalent water flux in the Budyko method.

The Köppen–Geiger and Budyko classification methods were used to test the robustness of the results shown in Fig. 6a. With the Budyko method, land surface was classified into tundra, forest, savanna and steppe, semidesert, and desert, and the mutual conversion between savanna and steppe and semidesert was used to reflect the expansion or reduction of the total arid and semiarid areas (Fig. 6b). With the Köppen–Geiger method [definitions of up to 30 climate types are given in Kottek et al. (2006)], the mutual conversion between steppe and desert was used to reflect the expansion or reduction of total arid areas (Fig. 6c). It can be seen from Fig. 6b that 25 grids were converted from semidesert to savanna and steppe, and 30 grids were converted in the opposite direction, reflecting very little expansion of desert and semidesert areas. From Fig. 6c, it could be seen that 35 grids were converted from desert to steppe, and only 6 grids were converted in the opposite direction.

Although the results deduced from the UNEP, Budyko, and Köppen–Geiger methods differed from each other in details (Fig. 6), two main conclusions could be reached. First, all the results did not suggest that the increase in anthropogenic aerosols in the atmosphere from 1850 to 2010 led to an obvious expansion of arid and semiarid areas on a global scale. Second, all the results indicated that arid and semiarid areas expanded in varying degrees over North America, South Asia, and East Asia because of the increase in anthropogenic aerosols in the atmosphere. Over East Asia and South Asia, the expansion of arid and semiarid areas caused by the increase of anthropogenic aerosols was significant with all the three classification methods.

According to RCP4.5, the emissions of SO₂, BC, and OC decreased by about 93.72, 4.36, and 23.21 Tg yr⁻¹ from 2010 to 2100, respectively. The emission level of OC in 2100 was even lower than that in 1850. The regions where anthropogenic aerosols in the atmosphere increased from 1850 to 2010 were also the regions where anthropogenic aerosols in the atmosphere were projected to decrease in the future. It was suggested by Zhang et al. (2016) that the decrease in anthropogenic aerosols in the atmosphere from 2010 to 2100 would bring about a generally warmer climate and more precipitation from a global perspective.

The decrease in anthropogenic aerosols in the atmosphere from 2010 to 2100 led to an increase in land annual mean precipitation of about 0.15 (0.13, 0.16) mm day⁻¹. It can be seen from Fig. 7a that precipitation increased over northern South America, southwestern North Africa, mid-Africa, South Asia, and most parts of Southeast Asia (these areas are mainly to the north of the equator). In contrast, over eastern South America, southwestern Africa, and most parts of Australia, which
are to the south of the equator, precipitation decreased. Zhang et al. (2016) suggested that this changing pattern of precipitation near the equator was mainly due to the northward shift of the ITCZ rain center. Over the NH middle and high latitudes, annual mean precipitation mainly increased, except for the Mediterranean region and parts of central Asia.

The decrease in anthropogenic aerosols in the atmosphere from 2010 to 2100 led to an increase in land annual mean ET₀ of about 0.26 (0.25, 0.28) mm day⁻¹, nearly twice that of land annual mean precipitation. It can be seen in Fig. 7b that except for parts of Greenland, ET₀ increased over almost all land areas.

In percentage, the decrease in total anthropogenic aerosols in the atmosphere from 2010 to 2100 led to an increase in land annual mean precipitation of about 6.7% (5.9%, 7.2%), and in land annual mean ET₀ of about 9.7% (9.1%, 10.6%), resulting in a decrease in the AI of about 2.8% (2.1%, 3.6%). For all climate types except hyper-arid, the annual mean precipitation and ET₀ were both increased by the decrease in total anthropogenic aerosols in the atmosphere, and the increases of ET₀ were larger than that of P, resulting in negative changes in the AI (Fig. 8a). The decreases in the annual mean RH₂m for all climate types were in accordance with the changes in the AI (Fig. 8a). The decreases of RH₂m could be attributed to the warming caused by the decrease in anthropogenic aerosols in the atmosphere and the resulting increase in saturation water vapor pressure.

The decrease in total anthropogenic aerosols in the atmosphere generally led to a decrease in the terrestrial aridity on the north side of the equator (e.g., northern South America, the north coast of the Gulf of Guinea, the east coast of mid-Africa), whereas it exacerbated the terrestrial aridity over most areas between 30°S and the equator (Fig. 8b). The decrease in total anthropogenic aerosols in the atmosphere also exacerbated the terrestrial aridity over most areas of the NH middle and high latitudes, except the southwestern United States, Alaska, central and western Greenland, northwestern China, Mongolia, and eastern Siberia. The pattern of the change in AI caused by the decrease in anthropogenic aerosols in the atmosphere from 2010 to 2100 was generally the reverse of that caused by the increase in anthropogenic aerosols in the atmosphere from 1850 to 2010 (Fig. 5b).

The decrease in anthropogenic aerosols caused many dry lands in the Southern Hemisphere, the Mediterranean region, and central Asia to convert to much drier climate types, whereas it caused some arid and semiarid areas over western North America, East Asia, and South Asia to convert to wetter climate types (Fig. 8c). From a global perspective, 14 grids were converted from semiarid to dry subhumid climate, and 22 grids were converted in the opposite direction, reflecting an expansion of total arid (including hyper-arid) and semiarid areas. However, it can be seen from Fig. 8c that arid and semiarid areas were reduced in East Asia and South Asia because of the reduction of total anthropogenic aerosols in the atmosphere.

With the decrease in total anthropogenic aerosols in the atmosphere, land annual mean T₂ₚ increased by about 2.8°C (2.7°C, 2.9°C), AE increased by about 4.9 (4.7, 5.1) W m⁻², and RH₂m decreased by about 2.2% (2.0%, 2.4%) (Table 2), all of which facilitated an increase in ET₀. It can be seen from Table 2 that the
decrease in total anthropogenic aerosols in the atmosphere caused an increase in ET₀, mostly by increasing T₂m, to a lesser extent through increasing surface AE, and then through decreasing RH₂m. Tables 1 and 2 both suggest that anthropogenic aerosols in the atmosphere influenced ET₀ mainly by changing the surface temperature and then by altering the surface available energy and relative humidity, but very slightly by changing the surface wind speed.

It was found that regardless of whether the total anthropogenic aerosols in the atmosphere increased from 1850 to 2010 or decreased from 2010 to 2100, the land annual mean P and ET₀ always changed in the same direction, although this differed from some individual aerosols. For example, Lin et al. (2016) found that BC could decrease the land annual mean precipitation and increase land annual mean potential evapotranspiration. It can also be seen from Figs. 5a and 8a that the change in land annual mean ET₀ was always larger than that in P, resulting in the domination of ΔET₀/ET₀ in ΔAI/ΔI. It was reported that the change in land precipitation depended mostly on the variation of ocean evaporation (Fu and Feng 2014). The simulated relative changes of annual mean evaporation over the ocean in this work were −7.1% (−8.0%, −6.8%) and 6.3% (5.7%, 7.3%) because of the increase (from 1850 to 2010) and decrease (from 2010 to 2100) in anthropogenic aerosols in the atmosphere, respectively. The relative changes of annual mean precipitation over land and evaporation over the ocean were close to each other and both smaller than that of annual mean ET₀ over land in magnitude. As the actual evaporation is equal to the ET₀ on the ocean (Fu and Feng 2014), the comparison between land P and ET₀ is actually the comparison between ocean and land ET₀ (Fu and Feng 2014). It is known that when climate changes, the ocean is better at self-adjusting than land, resulting in a larger change in ET₀ over land than that over the ocean, which explains why the land annual mean change in ET₀ is always larger than that in P, regardless of the increase or decrease in total anthropogenic aerosols in the atmosphere.

4. Conclusions and discussion

Using an AI recommended by UNEP, the comprehensive effects of anthropogenic aerosols in the atmosphere on terrestrial aridity and the areal extent of arid and semi-arid areas were explored using an aerosol–climate coupled model.

The increase in anthropogenic aerosols in the atmosphere from 1850 to 2010 depressed land annual mean ET₀ [by about 0.33 (0.31, 0.35) mm day⁻¹] more than precipitation [by about 0.19 (0.18, 0.21) mm day⁻¹] by reducing surface temperature and AE, and increasing surface relative humidity. As a result of this severe reduction in water demand, the land annual mean terrestrial aridity decreased by about 3.0% (2.7%, 3.6%). The increase in land annual mean surface relative humidity by about 2.7% (2.5%, 2.9%) was in accordance with the relief of terrestrial aridity. For all climate types, the mean terrestrial aridity was decreased. From a global perspective, the areal extent of arid (including hyper-arid) and semi-arid areas was reduced because of the increase in anthropogenic aerosols in the atmosphere. However, it should be noted that arid and semi-arid areas expanded over East Asia and South Asia.

The decrease in anthropogenic aerosols in the atmosphere from 2010 to 2100 led to an increase in land annual mean precipitation by about 0.15 (0.13, 0.16) mm day⁻¹, which was not enough to offset the increase in land annual mean ET₀ [by about 0.26 (0.25, 0.28) mm day⁻¹], resulting in a net increase in terrestrial aridity and the areal expansion of total arid and semi-arid areas. However, the terrestrial aridity over East Asia and South Asia decreased because of the reduction in levels of anthropogenic aerosols in the atmosphere.

In this study, the interaction between aerosols and convective clouds was not considered. As has been discussed in IPCC (2013), the indirect effects of aerosols might be overestimated when the interaction between aerosols and convective clouds is not considered. More studies of the effects of aerosols on terrestrial aridity, including full aerosol–cloud interactions, are therefore needed in the future. Some studies have suggested that different aerosols influence terrestrial aridity in different ways. Therefore, more studies on how each type of atmospheric particle affects terrestrial aridity are required. Anthropogenic aerosols in the atmosphere reduce terrestrial aridity by depressing water demand more severely than precipitation, but it is not clear if this reduction of terrestrial aridity will be of benefit to life on
Earth. This is an interesting topic for future research, but was beyond the scope of this study.

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