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Expansion of global drylands under a warming climate

S. Feng and Q. Fu

Expansion of global drylands under a warming climate

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Abstract

Global drylands encompassing hyper-arid, arid, semiarid, and dry subhumid areas cover about 41 % of the earth's terrestrial surface and are home to more than a third of the world's population. By analyzing observations for 1948–2008 and climate model simulations for 1948–2100, we show that global drylands have expanded in last sixty years and will continue to expand in the 21st century. By the end of this century, the world's drylands under a high greenhouse gas emission scenario are projected to be $5.8 \times 10^6 \text{ km}^2$ (or 10 %) larger than in the 1961–1990 climatology. The major expansion of arid regions will occur over southwest North America, the northern fringe of Africa, southern Africa, and Australia, while major expansions of semiarid regions will occur over the north side of the Mediterranean, southern Africa, and North and South America. The global dryland expansions will increase the population affected by water scarcity and land degradations.

1 Introduction

Drylands are areas of land with low amounts of water in the soil, which encompass hyper-arid, arid, semiarid, and dry subhumid areas. Drylands occupy about 41 % of the earth's terrestrial surface and are home to more than a third of the world's population (e.g., Mortimore et al., 2009). Knowledge of how anthropogenic climate change will affect the extent of global drylands is essential for water-resource and land-use management in these regions (e.g., Mortimore et al., 2009; Reynolds et al., 2007).

Drylands include desert, grassland and savanna woodland biomes. As one of the world's major ecosystems, the drylands live at the margin of sustainability, where moisture is scarce for all or part of the year (e.g., Mortimore et al., 2009). The ecosystems over drylands are fragile and sensitive to climate change (Reynolds et al., 2007; Solomon et al., 2007; Reed et al., 2012). Both observations and model simulations indicate that ongoing global warming will cause the Earth's drylands to become drier

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(e.g., Solomon et al., 2007; Held and Soden, 2006; Seager et al., 2007; Overpeck and Udall, 2010) but previous studies have focused on climate changes within drylands or specific types of drylands (e.g., semiarid regions) (Held and Soden, 2006; Seager et al., 2007; Overpeck and Udall, 2010; Hulme, 1996; Huang et al., 2012). Here we examine the changes in the areal extent of drylands by analyzing observations for 1948–2008 and simulations from 27 global climate models participating in the phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) for 1948–2100. We show that global drylands have expanded in last sixty years and will continue to expand in the 21st century. By the end of this century, the drylands under a high greenhouse gas emission scenario are projected to be $5.8 \times 10^6 \text{ km}^2$ (or 10 %) larger than the 1961–1990 climatology. Expansion of drylands associated with an increase in aridity as a result of climate change has a direct consequence to the desertification (i.e., land degradation in arid, semi-arid, and dry subhumid areas), and is a central issue for sustainable development, especially in the face of population growth (Reynolds et al., 2007).

This paper is organized as follows. Section 2 describes the methods and data used in this study. The global dryland expansions and changes in aridity are presented in Sect. 3, followed by the summary and conclusions in Sect. 4.

2 Methods and data

Dryland regions are commonly defined (e.g., Mortimore et al., 2009; Hulme, 1996; Middleton and Thomas, 1992) on the basis of the ratio of annual precipitation (P) to annual potential evapotranspiration (PET), the latter represents the evaporative demand of the atmosphere. P/PET is thus a quantitative indicator of the degree of water deficiency at a given location. Drylands are regions with $P/PET < 0.65$, which are further divided into hyper-arid ($P/PET < 0.05$), arid ($0.05 < P/PET < 0.2$), semiarid ($0.2 < P/PET < 0.5$), and dry subhumid (or subhumid for simplicity) ($0.5 < P/PET < 0.65$) regions (Mortimore et al., 2009; Hulme, 1996; Middleton and Thomas, 1992). We calculated PET

using Penman–Monteith algorithm (Maidment, 1993) that includes the effects of surface air temperature, humidity, solar radiation and wind. This algorithm is physically based and is superior to other PET formulations (Donohue et al., 2010; Dai, 2011; Sheffield et al., 2012).

2.1 Instrumental data

Two observed monthly temperature and precipitation datasets were used. The first is the temperature and precipitation dataset from 1948 to present developed by the Climate Prediction Center (CPC) (Fan and van den Dool, 2008; Chen et al., 2002). The second is the temperature and precipitation for 1900–2008 developed at the University of Delaware (UD) (Legates and Willmott, 1990a,b). Both datasets cover the global land areas at $0.5^\circ \times 0.5^\circ$ resolution. Though the UD dataset started in 1900, the historical observations used for gridding are sparse or simply unavailable over many land areas, especially in the Southern Hemisphere during the first half of the 20th Century. Therefore, this study analyzed the period starting from 1948 when both CPC and UD data are available.

Because the two datasets employed a slightly different number of observations with different spatial interpolation methods, the climatology, e.g., for 1961–1990, from the two datasets is slightly different. We adjusted the UD temperature and precipitation so that they have the same monthly climatology as the CPC following Dai (2011). Specifically, the temperature is adjusted according to:

$$[T_{UD,adj}]_{Y,M} = ([T_{UD}]_{Y,M} - [T_{UD,clim}]_M) + [T_{CPC,clim}]_M$$

where $[T_{UD}]_{Y,M}$ and $[T_{UD,adj}]_{Y,M}$ are the original and adjusted UD temperature for year Y and month M , respectively. $[T_{UD,clim}]_M$ and $[T_{CPC,clim}]_M$ are the climatology of the UD and CPC temperature for 1961–1990 on month M . The precipitations of UD are adjusted according to:

$$[P_{UD,adj}]_{Y,M} = [P_{UD}]_{Y,M} / ([P_{UD,clim}]_M + 0.01) \cdot ([P_{CPC,clim}]_M + 0.01)$$

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where $[P_{UD}]_{Y,M}$ and $[P_{UD,adj}]_{Y,M}$ are the original and adjusted UD precipitation for year Y and month M , respectively. $[P_{UD,clim}]_M$ and $[P_{CPC,clim}]_M$ are the climatology of the UD and CPC precipitation for 1961–1990 on month M . We add 0.01 millimeter per month to the denominator to avoid dividing zero. These adjustments ensure that the UD dataset has the same climatology of 1961–1990 as the CPC but do not affect the temporal variations and trends of the UD dataset. We chose to adjust the UD dataset because they are updated irregularly with several years behind while the CPC dataset is regularly updated in near real time. Similar adjustments were used for merging different datasets (Dai et al., 2004) or developing the forcing data for land surface models (Sheffield et al., 2006).

2.2 Reanalysis data

To calculate the PET using the Penman–Monteith algorithm (Maidment, 1993; Allen et al., 1998), the surface air temperature, solar radiation, specific humidity and wind speed are needed. Due to scarce observations for specific humidity, solar radiations and wind speed, we chose to use these quantities from the global atmospheric reanalyses following previous studies (Sheffield et al., 2006; Dai, 2011, 2013). This study employed the solar radiation, specific humidity and wind speed data from the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004), which is on half-degree resolution starting from 1948. The solar radiation in GLADS was corrected based on two global radiation products during 1983–2000 (Sheffield et al., 2006). The wind and specific humidity in GLDAS, however, were directly disaggregated from the NCEP-NCAR reanalysis (Kalnay et al., 1996) to a 0.5° resolution. We adjusted the wind and specific humidity in GLDAS to the observationally-based climatology developed by the Climate Research Unit (CRU) of the University of East Anglia (New et al., 1999) following

$$[V_{adj}]_{Y,M} = [V]_{Y,M} / [V_{clim}]_M \cdot [V_{CRU,clim}]_M$$

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where $[V]_{Y,M}$ and $[V_{\text{adj}}]_{Y,M}$ are the original and adjusted climate variables (humidity or wind speed) in GLDAS for year Y and month M , respectively. $[V_{\text{clim}}]_M$ and $[V_{\text{CRU,clim}}]_M$ are the 1961–1990 mean values of GLDAS and CRU, respectively. These adjustments ensure that the humidity and wind speed in GLDAS have the same climatology as the observations.

We also calculated PET using solar radiation, relative humidity and wind speed from the Twentieth Century Reanalysis (20CR) (Compo et al., 2011). The 20CR, extended back to 1871, is the only reanalysis to span the 20th century. Ferguson and Villarini (2012) evaluated the temperature and precipitation data in the 20CR and identified spurious changes in the 1940s. They recommended restricting climate trend analyses to the second half century of the 20CR record. This study used the 20CR data starting from 1948. The radiation, specific humidity and wind speed in 20CR were statistically downscaled to 0.5° resolution (Ramirez-Villegas and Jarvis, 2010). They were also adjusted to have the same climatology of 1961–1990 as the adjusted GLDAS dataset.

To evaluate the observed changes in drylands, we calculated the PET and P/PET using the precipitation and temperature from CPC or UD, and the humidity, solar radiations, and wind speed from GLDAS or 20CR for 1948–2008. Therefore, we have four sets of PET and P/PET from observations (i.e., CPC and GLDAS, CPC and 20CR, UD and GLDAS, UD and 20CR). We use the PET and P/PET derived from CPC and GLDAS in this study but test the sensitivity of our results to other datasets.

2.3 CMIP5 data

We used the output from 27 global climate models (Table 1) with specified historical anthropogenic and natural external forcings for 1948–2005 and with 21st century changes in greenhouse gases and anthropogenic aerosols following the Representative Concentration Pathway 8.5 (RCP8.5) and 4.5 (RCP4.5) for 2006–2100 (Taylor et al., 2012). The first ensemble run was used if a model has multiple ensemble simulations. Because the models have different spatial resolutions ranging from 0.75° to 3.75° (Ta-

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ble 1), the simulated temperature, precipitation, solar radiation, specific humidity and wind speed were statistically downscaled to half-degree resolution (Ramirez-Villegas and Jarvis, 2010) to match that of observational data. The model results were also adjusted so that they have the same climatology of 1961–1990 as the observations. The ensemble mean of the 27 models is analyzed because the multi-model ensemble average is superior to the individual model (Pierce et al., 2009). This ensemble mean can be interpreted as our best estimate of climate responses to given external forcings because individual ensemble runs simulate random internal variations and contain errors associated with individual models. We should keep in mind, however, that natural fluctuations in climate, which cannot be predicted, are expected to occur, and will augment or reduce the magnitude of climate change due to anthropogenic forcing (Deser et al., 2012). Here we use the spread (one standard deviation) and/or consensus (more than 80 %) of the 27 models to measure the uncertainties associated with natural variations and model errors.

In the evaluation of temporal variations of dryland areas, a 15 yr equal weight smoothing is applied to both model and observational data to remove year-to-year fluctuations. It was suggested that a 15 yr smoothing is the optimal averaging windows for climate classifications (Fraedrich et al., 2001).

3 Expansions of global drylands

Figure 1 shows the global distribution of drylands including the individual components for 1961–1990 climatology based on P/PET derived from CPC and GLDAS, which agrees well with previous documentations (e.g., IIASA/FAO, 2003; Mortimore et al., 2009). The derived spatial distribution of hyper-arid, arid, and semiarid regions also matches well with observed surface vegetation types associated with these regions from satellites (Fig. 2). Note that the climatology of global dryland coverage for 1961–1990 from various observational and model data is the same as a result of the ad-

justments (Sect. 2) so that we can focus on the temporal variations and trends of the drylands.

3.1 Dryland expansions

Climate change associated with changes in precipitation and PET would lead to changes in aridity (i.e., P/PET) and thus the areal extent of drylands. Figure 3 shows the time series of dryland areas including the total and its individual components from both observations and models. The global drylands from observations have been expanding during the past 60 yr (Fig. 3a). The area of global drylands in recent 15 yr (1991–2005) is $\sim 2.4 \times 10^6 \text{ km}^2$ (or 4%) larger than that during the 1950s. The areas of individual dryland components except hyper-arid regions show increases. The observed maximum (minimum) area of semiarid (arid) regions during 1970s is a result of large positive precipitation anomalies in Southern Hemisphere over Australia, Southern Africa, and Patagonia (Hulme, 1996), which led to a transition of arid to semiarid regions. Figure 4 indicates that the temporal variations of T , P , PET, and dryland areas are very similar based on various observational datasets.

An expansion of global drylands is also a robust feature in the simulations of 27 global climate models, though the rate is smaller than observations in last 60 yr (Fig. 3). Because the observationally derived PET for 1948–2008 is well simulated by the models (Fig. 4c), the weaker expansion seen in the models is very likely caused by the differences in precipitation. Figure 4b shows that the ensemble mean of the 27 models is able to capture the downward trends of the observed precipitation from late 1940s to early 1980s. However, the models simulated an increased precipitation after early 1980s while the observations show little noticeable trend.

Evidence from both observations and models shows that over the past few decades the tropics have widened (e.g., Fu et al., 2006; Lu et al., 2007; Seidel et al., 2008; Johanson and Fu, 2009; Zhou et al., 2011), which results in shifts in precipitation patterns (Seidel et al., 2008), especially a reduction of precipitation in the latitudes between subtropical dry zone and mid-latitude precipitation belts (Zhou et al., 2011; Scheff and

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Frierson, 2012). Model-predicted expansion rates of the tropics, however, are significantly less than observations (Lu et al., 2007; Johanson and Fu, 2009), which could be a result of large natural variability, model deficiencies, and/or uncertainties in external forcings in models (Allen et al., 2012). Smaller modeled expansions of global drylands (Fig. 3) than observations would at least partly be caused by the underestimation of modeled tropical expansion. Precipitation over land is also strongly influenced by natural variability of sea surface temperature patterns (Schubert et al., 2009; Feng et al., 2011), which could largely contribute to the differences between models and observations (Dai, 2013).

Despite the differences between model and observations, the models are able to simulate the robust expansion of drylands (Fig. 3). The models also suggest a stronger trend in the first half of this century from both RCP8.5 and RCP4.5 than in the second half of the last century, followed by a continuing expansion in RCP8.5, but with little change in RCP4.5 after the 2050s. The global drylands in RCP8.5 (RCP4.5) are projected for 2071–2100 to increase in units of 10^6 km^2 by 5.8 ± 2.6 (2.7 ± 1.3) for the total, 1.3 ± 1.2 (0.6 ± 0.6) for dry subhumid, 2.1 ± 1.5 (1.0 ± 0.7) for semiarid, 1.8 ± 1.3 (1.0 ± 0.8) for arid, and 0.5 ± 1.5 (0.1 ± 0.8) for hyper-arid regions, relative to 1961–1990. These increases correspond to relative increases of 10 % (4 %), 15 % (7 %), 10 % (4 %), 10 % (5 %), and 5 % (1 %), respectively. There is a broad consensus among climate models that global drylands will expand in the 21st Century: of the 27 models for RCP8.5 (RCP4.5), expansions are seen in 26 (27) models for the total, 27 (24) for semiarid, 26 (22) for arid, and 22 (24) for dry subhumid regions, which are all more than 80 % (i.e., 22 to 27) of the models. The exception is for hyper-arid regions: only 14 (15) of 27 models show an expansion. If slower rates in the last 60 yr from models than observations (Fig. 3) were partly caused by model deficiencies, the model projections may underestimate the expansion of global drylands.

The projected expansions of drylands are not homogeneous over the globe, and some occur in politically unstable regions. Figure 5 shows projected changes in drylands to drier (a) and wetter (b) types for 2071–2100 in RCP8.5 relative to 1961–1990.

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Major expansions of arid lands are projected over southwest North America, the northern fringe of Africa, southern Africa, and Australia. Expansions of arid regions are also seen in Afghanistan, Iran, Iraq, and Argentina. Major expansions of semiarid regions are projected over the north side of Mediterranean, southern Africa, and North and South America. Major expansions of hyper-arid areas will occur over northern Africa, parts of Saudi Arabia and Iraq, and southern Africa.

In southwest North America during 1961–1990 (Fig. 1), the arid lands occupied the Nevada, Arizona, southern California, southern Utah, and southwest New Mexico. By the end of this century, the arid regions are projected to expand to occupy most of the New Mexico, western Texas and most northern Mexico. The semiarid lands will also expand eastward by 2–3° of longitude in the Great Plains (Fig. 5a). In the Mediterranean region the semiarid climate is projected to expand to cover the edge of Black Sea, Greece, southern Italy and northern Spain. Over the northern fringe of Africa (northern coastal regions of Morocco, Algeria and Tunisia), the arid and hyper-arid climate is projected to expand into regions where the climate is currently semiarid. In southern Africa, the semiarid region is projected to expand northward and eastward while the arid climate is projected to cover most of the Namibia and majority of the Botswana.

Figure 6 is the same as Fig. 5a but for projected changes for which more than 80% of the models agree. By comparing these two figures, we see less confidence in projected dryland expansions over east Australia, China, Mongolia, and Kazakhstan. More than 80% of the models, however, agree on major projected expansions of drylands shown in Fig. 5a.

Besides expanding, the drylands in tropical Africa and India and part of northwest China are projected to shrink, suggesting reducing aridity in those regions (Fig. 5b). The retreat of hyper-arid (arid) to arid (semiarid) in the southern Sahara countries along with the expansions of hyper-arid and arid regions in the northern fringe of Africa indicates a poleward shift of northern African drylands. The areas with reducing aridity (Fig. 5b), however, are much smaller than areas with intensified aridity (Fig. 5a). Furthermore there is little consensus among the models (not shown) on the projected

shrinking areas of drylands as a result of simulated internal variability and model uncertainty.

3.2 Changes in global aridity

Changes in global aridity are caused by changes in temperature through its impact on PET, and precipitation, which leads to the expansion of drylands. At the end of the 21st century, the large increase of surface temperature (Fig. 7a) is largely responsible for a much enhanced PET throughout the global land (Fig. 7b) with large increases in Northern Hemisphere mid- and high latitudes and North and South America, but less in Africa, Australia and India. Consistent with previous studies (Solomon et al., 2007), the projected precipitation (Fig. 7c) increases over most of Eurasia, tropical Africa and the middle and high-latitude North America but decreases in the subtropical regions including areas near Mediterranean Sea, southwestern North America, southern Africa and most of Australia and South America. The response of precipitation to global warming can be interpreted as a result of poleward expansion of the Hadley cell (Scheff and Frierson, 2012) and the “dry-get-drier” thermodynamic mechanism (Held and Soden, 2006). The projected changes in precipitation and increases in PET collectively lead to the projected changes in P/PET (Fig. 7d), showing decreases in most of the global land between $60^\circ N$ and $60^\circ S$ except India, northern China, Eastern equatorial Africa and the southern Saharan regions, consistent with shrinking drylands in those regions but expansion in others (Fig. 5).

It is important to quantify the role of precipitation and PET in the P/PET changes. We estimate the roles of the P and PET in the P/PET changes using:

$$\Delta \left(\frac{P}{PET} \right) = \frac{1}{PET} \Delta P - \frac{P}{PET^2} \Delta PET + \frac{P}{PET^3} (\Delta PET)^2,$$

where $\Delta \left(\frac{P}{PET} \right)$ is the changes in P/PET , $\frac{1}{PET} \Delta P$ is the contribution of P changes to P/PET change, and the second and the third terms on the right hand side are the

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contribution of PET changes to P/PET changes. Figure 8 shows the changes in P/PET (Fig. 8c or Fig. 7d) due to changes in precipitation (Fig. 8a) and PET (Fig. 8b). An increasing in PET (Fig. 7b) leads to an increase in aridity (i.e., a decrease in P/PET) (Fig. 8b) everywhere. The mixture of increase and decrease of P (Fig. 7c) leads to mosaic changes in P/PET (Fig. 8a). All together, the changes in PET and P lead to an increase in aridity over majority of the global land between 60° N and 60° S (Fig. 8c).

We also quantify the role of P and PET in the P/PET changes that lead to changes of drylands types. Figure 9 shows the changes in P/PET and the contributions from P and PET, averaged over changed areas along with the projected area changes for RCP8.5. For areas projected to change to drier types, the increase in PET plays a dominant role in those from humid (dry subhumid) to dry subhumid (semiarid) while the precipitation decrease becomes more important for other changes to drier regions. The regions with reducing aridity are all controlled by increasing precipitation (see green bars in Fig. 9). Figure 10 is the same as Fig. 9 except for results from the historical runs (a) and observations (b) for changes of 1991–2005 relative to 1948–1962. The important difference from the future projection is that the decrease of precipitation dominates the decrease in P/PET that led to the expansion of drylands. This is because greenhouse gas induced warming during the past sixty years is much smaller than what is projected to occur at the end of the 21st century, while anthropogenic forcings considered in historical simulations such as black carbon aerosols, increases in tropospheric ozone, and stratospheric ozone depletion favor the expansion of the subtropical dry zone (Johanson and Fu, 2009; Allen et al., 2012). The role of precipitation from observations (Fig. 10b) is similar to that from historical simulations. It is noted that the dryland expansion in the last sixty years (i.e., 1991–2005 versus 1948–1962) from models is only $0.35 \times 10^6 \text{ km}^2$, which is much smaller than $2.4 \times 10^6 \text{ km}^2$ from observations. This difference could be due to large natural SST variations in last 60 yr which were not captured by the models (Schubert et al., 2009; Feng et al., 2011; Dai, 2013) as well as the underestimation of the Hadley cell expansion. The models also do not simulate the enhanced wintertime warming over the mid- and high-latitude Northern

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Hemisphere continents during the later 20th century (e.g., Huang et al., 2012), which is largely caused by natural variability (Wallace et al., 2012). This may also be partly responsible for the differences.

The increase of PET and change in precipitation patterns under a warming climate are leading to an increase in global aridity (Fig. 7d) and expansion of global drylands (Figs. 3 and 5), and thus an increase in the population affected by water scarcity (Milesi et al., 2010). Extensive land use and other human activities may further amplify these changes (Reynolds et al., 2007). Another important consequence of these changes is the desertification, i.e., the land degradation in arid, semi-arid, and dry subumid areas resulting from various factors, including climatic variations and human activities (UNCCD, 1994). Some form of severe land degradation is already present on 10 to 30 % of drylands (Reynolds et al., 2007), which likely to expand substantially in the face of climate change and population growth. Such changes could result in fundamental shifts in ecosystems and human settlements. Paleoclimate records indicate that climate change and increased aridity had played a key role in the collapse of Maya culture in Central America (Haug et al., 2003) and Tiwanaku civilization in the Andes (Binford et al., 1997). The recent persistent drought and increasing aridity in the southwestern US have witnessed higher mortality of trees, more bark-beetle outbreaks, more wildfires, and a reduction of forest productivity in the region (Williams et al., 2012). The rising temperature, increasing aridity, and expanding drylands along with extensive land uses could herald major social challenges and risks that would exacerbate regional tensions (Jones, 2011), which accentuates the urgent to develop proactive planning and adaptation strategies for global drylands.

4 Summary and conclusions

In this study, we analyze the change of global aridity and dryland expansions in terms of P/PET using various observational datasets for 1948–2008 along with 27 climate model simulations from the CMIP5 for 1948–2100. We show that global drylands have

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expanded in last sixty years with observed rates much faster than simulations, and will continue to expand in the 21st century. By the end of this century, the world's drylands under a high greenhouse gas emission scenario (RCP8.5) are projected to be $5.8 \times 10^6 \text{ km}^2$ (or 10%) larger than in the 1961–1990 climatology. The major expansion of arid regions will occur over southwest North America, the northern fringe of Africa, southern Africa, and Australia, while major expansions of semiarid regions will occur over the north side of the Mediterranean, southern Africa, and North and South America. It is also shown that most of the global land between 60° N and 60° S except India, northern China, Eastern equatorial Africa and the southern Saharan regions will become significantly drier. Expansion of global drylands associated with an increase in aridity will increase the population affected by water scarcity and land degradations.

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Table 1. A list of CMIP5 GCMs used in this study with a brief description. The historical run (1850–2005) and two future scenario (RCP4.5 and RCP8.5) runs (2006–2100) from each model are used. The first ensemble run is used if a model has multiple ensemble runs.

	Model name	Resolution (lon by lat)	Origin
1	BCC-CSM1.1	2.815 × 2.815	Beijing Climate Center, China
2	CanESM2	2.815 × 2.815	Canadian Centre for Climate, Canada
3	CCSM4	1.25 × 0.9	National Center for Atmospheric Research, USA
4	CESM1-BGC	1.25 × 0.9	National Center for Atmospheric Research, USA
5	CESM1-CAM5	1.25 × 0.9	National Center for Atmospheric Research, USA
6	CMCC-CM	0.75 × 0.75	Centro Euro-Mediterraneo per i Cambiamenti, Italy
7	CMCC-CMS	1.875 × 1.875	Centro Euro-Mediterraneo per i Cambiamenti, Italy
8	CNRM-CM5	1.40 × 1.40	Centre National de Recherches Meteorologiques, France
9	CSIRO-Mk3.6	1.875 × 1.875	Commonwealth Scientific and Industrial Research, Australia
10	FGOALS-g2	2.815 × 3.0	Institute of Atmospheric Physics, CAS, China
11	GFDL-CM3	2.5 × 2.0	Geophysical Fluid Dynamics Laboratory, USA
12	GFDL-ESM2G	2.5 × 2.0	Geophysical Fluid Dynamics Laboratory, USA
13	GFDL-ESM2M	2.5 × 2.0	Geophysical Fluid Dynamics Laboratory, USA
14	GISS-E2-H	2.5 × 2.0	NASA Goddard Institute for Space Studies, USA
15	GISS-E2-R	2.5 × 2.0	NASA Goddard Institute for Space Studies, USA
16	HadGEM2-CC	1.875 × 1.25	Met Office Hadley Centre, UK
17	HadGEM2-ES	1.875 × 1.25	Met Office Hadley Centre, UK
18	INM-CM4	2.0 × 1.5	Institute for Numerical Mathematics, Russia
19	IPSL-CM5A-LR	3.75 × 1.875	Institut Pierre-Simon Laplace, France
20	IPSL-CM5A-MR	2.5 × 1.25	Institut Pierre-Simon Laplace, France
21	IPSL-CM5B-LR	3.75 × 1.875	Institut Pierre-Simon Laplace, France
22	MIROC5	1.40 × 1.40	Atmosphere and Ocean Research Institute, Japan
23	MIROC-ESM	2.815 × 2.815	Japan Agency for Marine-Earth Science and Technology, Japan
24	MIROC-ESM-CHEM	2.815 × 2.815	Japan Agency for Marine-Earth Science and Technology, Japan
25	MPI-ESM-LR	1.875 × 1.875	Max Planck Institute for Meteorology, Germany
26	MRI-CGCM3	1.125 × 1.125	Meteorological Research Institute, Japan
27	NorESM1-M	2.5 × 1.875	Norwegian Climate Centre, Norway

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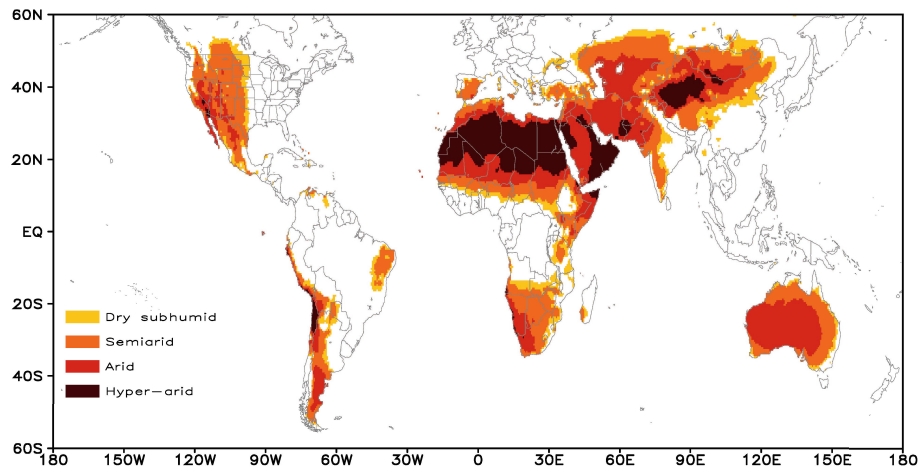


Fig. 1. Global distribution of drylands for 1961–1990 climatology derived from P/PET ratio based on observations.

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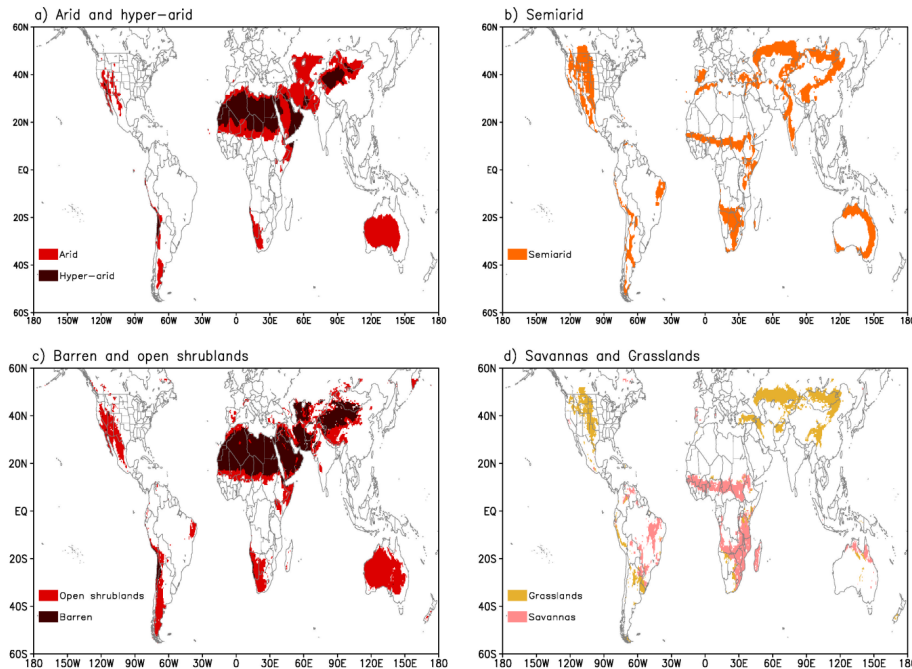


Fig. 2. Global distribution of **(a)** arid and hyper-arid and **(b)** semi-arid regions derived from P/PET ratio based on observations versus corresponding surface vegetation types in **(c)** and **(d)**, respectively, from satellite Moderate-resolution Imaging Spectroradiometer (MODIS) observations [ISLSCP II MODIS (Collection 4, 2010) IGBP Land Cover, available on-line <http://daac.ornl.gov/>]. On the lower left panel, the barren soil and open shrublands, respectively, are shown as dark red and red. On the lower right panel, the Savannas and Grasslands, respectively, are shown as pink and light yellow.

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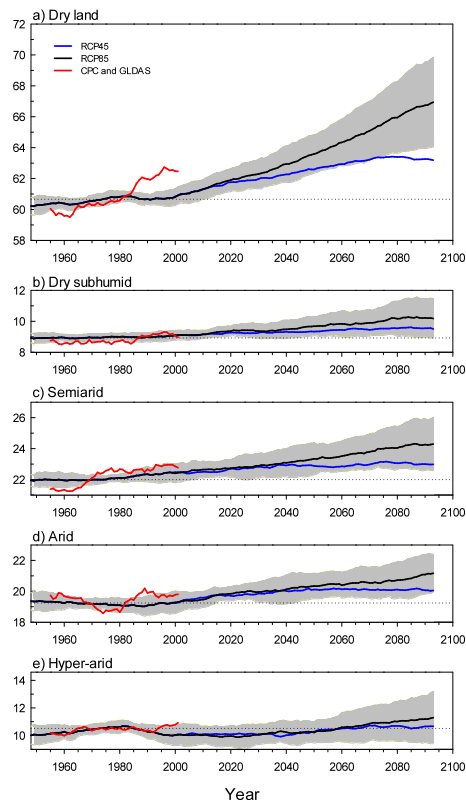


Fig. 3. Temporal variations in areal coverage of global drylands for **(a)** the total and individual components of **(b)** dry subhumid, **(c)** semiarid, **(d)** arid, and **(e)** hyper-arid regions. Thick black (blue) lines are the ensemble average of the 27 models from historical/RCP8.5 (RCP4.5) simulations. Dotted line shows the climatology of 1961–1990. The grey shading denotes one standard deviation of the 27 models from historical/RCP8.5 simulations. Red lines are for dry-land areas based on observational data. A 15 yr running smoothing was applied to emphasize the climate change.

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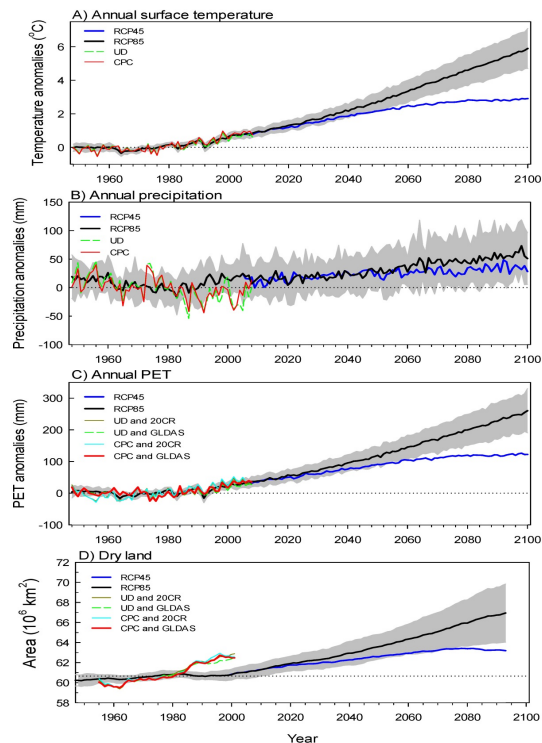


Fig. 4. Temporal variations of annual mean **(a)** surface air temperature, **(b)** precipitation, and **(c)** PET, averaged over land between 60° N and 60° S, and **(d)** total area of global drylands. Thick black (blue) lines are the ensemble average of the 27 models from historical/RCP8.5 (RCP4.5) simulations. Dotted line shows the climatology of 1961–1990. The grey shading denotes one standard deviation of the 27 models from historical/RCP8.5 simulations. In **(a)** and **(b)**, the observations from CPC (UD) data are shown as red (green dashed) lines. In **(c)** and **(d)**, the observational results from combinations of UD or CPC, with 20CR or GLDAS indicate that the temperature and precipitation are from UD or CPC, and the solar radiation, humid and wind speed are from the 20th century reanalysis or GLDAS.

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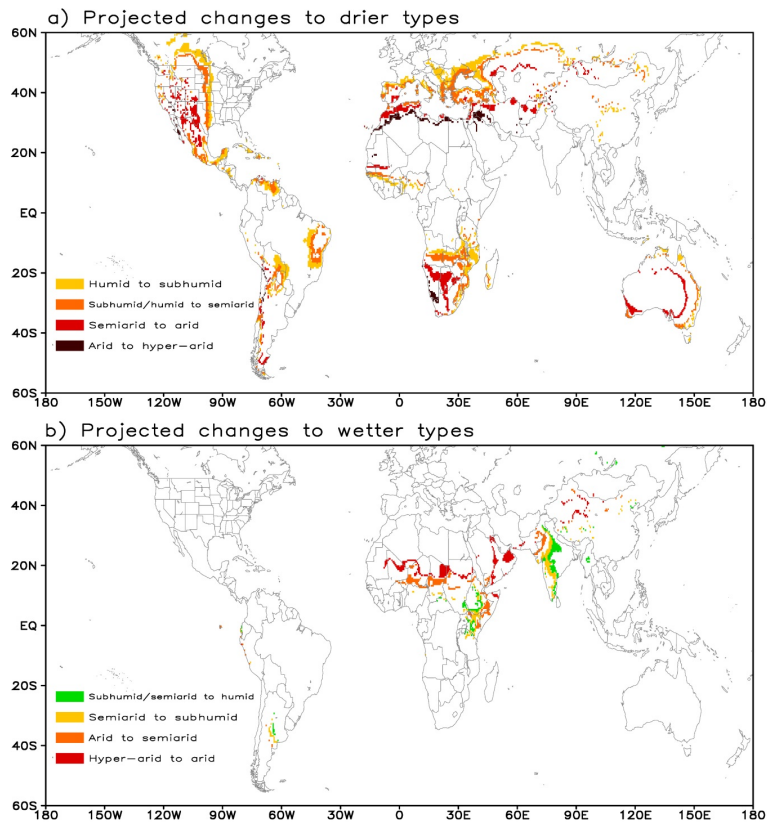


Fig. 5. (a) projected changes in coverage to drier types for 2071–2100 under scenario RCP8.5 relative to 1961–1990, and (b) same as (a) but to wetter types, based on the ensemble average of the 27 models.

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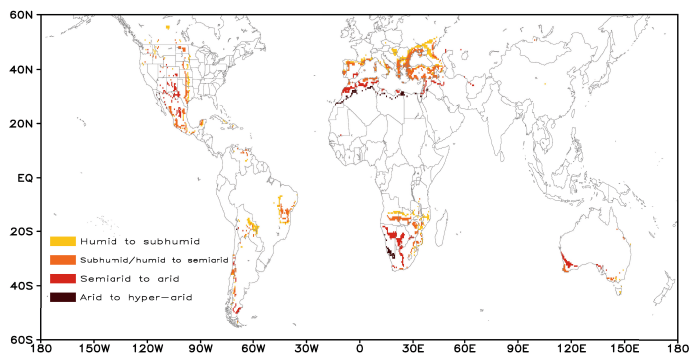


Fig. 6. Same as Fig. 5a but for projected area changes to drier types where more than 80 % of the 27 models agree on the sign.

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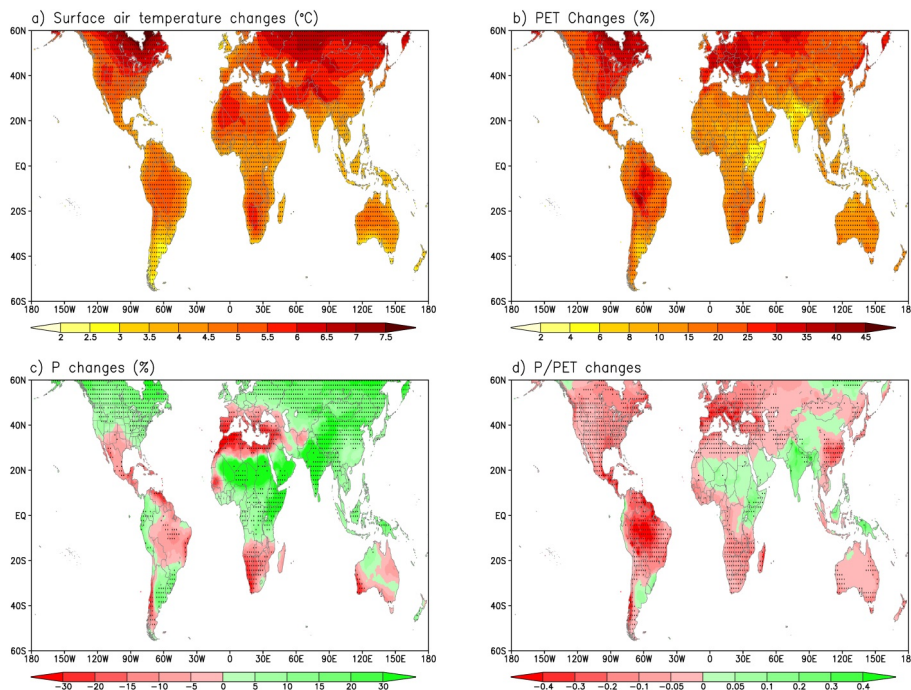


Fig. 7. Projected changes in **(a)** surface air temperature ($^{\circ}\text{C}$), **(b)** PET (%), **(c)** precipitation (%), and **(d)** P/PET for 2071–2100 relative to 1961–1990 under scenario RCP85 from 27 climate models. Grid points are stippled where more than 80 % of these models agree on the sign.

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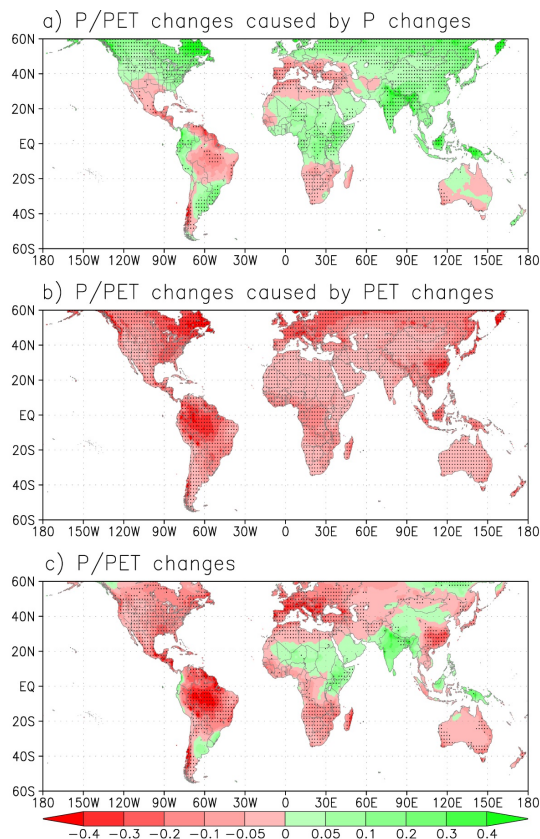


Fig. 8. Contributions of (a) precipitation and (b) PET to (c) projected changes in P/PET for 2071–2100 relative to 1961–1990 under scenario RCP85 from 27 climate models. Grid points are stippled where more than 80 % of these models agree on the sign.

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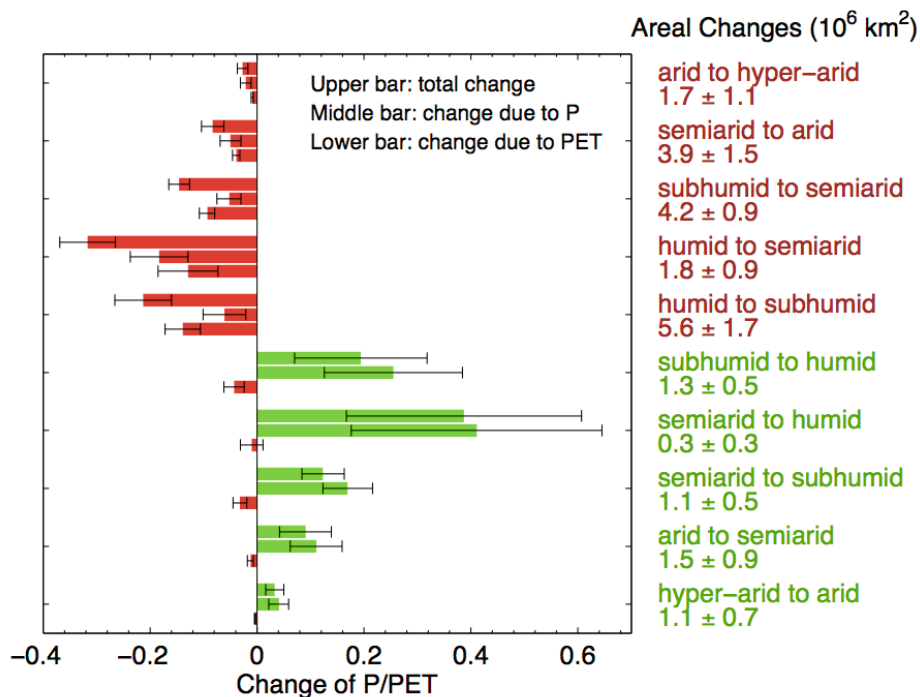


Fig. 9. Changes in P/PET (upper bar) and contributions of precipitation (middle bar) and PET (lower bar) to P/PET changes from 1961–1990 to 2071–2100 for RCP8.5, averaged over changed areas of drylands from 27 models. Error bars give the one standard deviation of the 27 models. The numbers on the right show the projected area changes.

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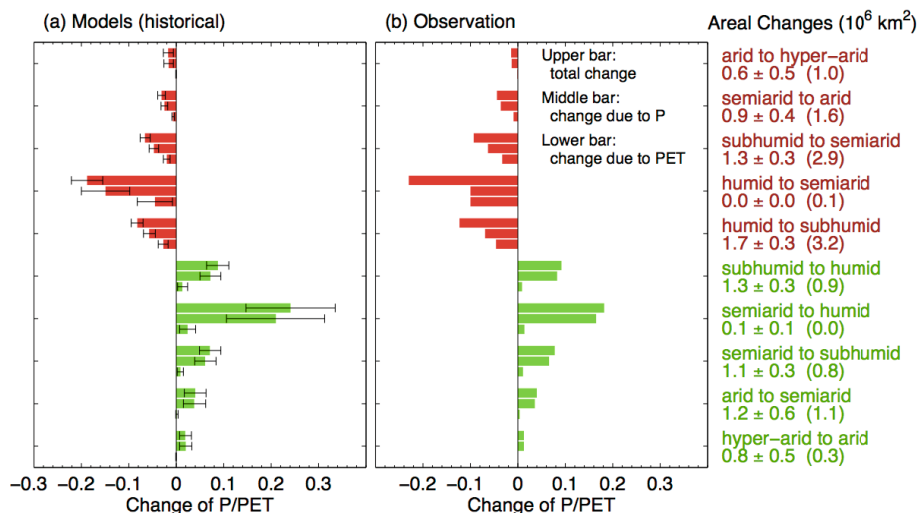


Fig. 10. Changes in P/PET (upper bar) and contributions of precipitation (middle bar) and PET (lower bar) to P/PET changes from 1948–1962 to 1991–2005, averaged over changed areas of drylands from **(a)** historical simulations and **(b)** observations. Error bars give the one standard deviation of the 27 models. The numbers on the right and those in parentheses show area changes from models and observations, respectively.

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