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Key Points:

- Warmer climate causes a drier terrestrial-mean environment in terms of P/PET changes for 850-2080
- Drier terrestrial-mean climate in present day than 850-1850 is caused by greenhouse gas increases
- Anthropogenic aerosols have small effect on terrestrial-mean aridity but alter its attributions

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Changes in terrestrial aridity for the period 850–2080 from the Community Earth System Model

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Abstract This study examines changes in terrestrial aridity due to both natural and anthropogenic forcing for the period 850-2080 by analyzing the Community Earth System Model (CESM) Last Millennium Ensemble simulations for 850–2005 and the CESM Large Ensemble simulations for 1920–2080. We compare terrestrial aridity in the Medieval Warm Period (MWP) (950–1250) with that in the Little Ice Age (LIA) (1550–1850), present day (PD) (1950-2005) with the last millennium (LM) (850-1850), and the future (F8.5) (2050-2080) with the LM, to place anthropogenic changes in the context of changes due to natural forcings. The aridity index defined as the ratio of annual precipitation to potential evapotranspiration, averaged over land, becomes smaller (i.e., a drier terrestrial climate) by 0.34% for MWP versus LIA (MWP-LIA), 1.4% for PD versus LM (PD-LM), and 7.8% for F8.5 versus LM (F8.5-LM). The change of terrestrial-mean aridity in PD-LM and F8.5-LM due to anthropogenic forcing is thus 4 and 20 times of that from MWP-LIA due to natural forcing, respectively. It is shown that a drier climate in PD than LM is largely due to a decrease of precipitation while a drier climate in F8.5 than LM, and MWP than LIA, is mainly caused by an increase of temperature. The terrestrial-mean aridity change in PD-LM is, however, largely driven by greenhouse gas increases as in F8.5-LM. This is because anthropogenic aerosols have a small effect on terrestrial-mean aridity but at the same time they totally alter the attributions of aridity changes to meteorological variables by causing large negative anomalies in surface air temperature, available energy, and precipitation. Different from MWP-LIA and F8.5-LM, there are large spatial inhomogeneities in P/PET changes for PD-LM in both magnitudes and signs, caused by anthropogenic aerosols, greenhouse gases, and land surface changes. The changes of terrestrial-mean P and P - E (precipitation minus evaporation) for 850–2080 are also examined. The relative changes in P (P – E) are 0.4% (0.6%) for MWP-LIA, -2.6% (-3.8%) for PD-LM, and 4.7% (11.8%) for F8.5-LM. The signs of changes in P - E and P are the same.

1. Introduction

An aridity index that is defined as the ratio of annual precipitation (*P*) to potential evapotranspiration (PET) is a quantitative indicator of the degree of water deficiency at a given location [*Middleton and Thomas*, 1992]. The PET depends on the surface air temperature, relative humidity, wind speed, and available energy, which can be estimated using the Penman-Monteith algorithm [e.g., *Allen et al.*, 1998]. The United Nations Convention to Combat Desertification, 1994] defines drylands by the scarcity of water with *P*/PET < 0.65. The drylands can be further classified into hyperarid, arid, semiarid, and dry subhumid lands using the aridity index [*Mortimore*, 2009; *Hulme*, 1996; *Middleton and Thomas*, 1992].

By analyzing observations for 1948–2008 and climate model simulations for 1948–2100, *Feng and Fu* [2013] reveal that global drylands have expanded in the last 60 years and will continue to expand in the 21st century. *Feng and Fu* [2013] attributed the past and future drying mainly to the precipitation reduction and PET increase, respectively. For the observationally based aridity analysis, *Feng and Fu* [2013] used observed surface air temperature and precipitation but the radiation energy, humidity, and wind speed from reanalyses. Although different reanalyses led to the consistent results, the long-term change in wind speed and therefore PET remains an open question [*Roderick et al.,* 2007; *McVicar et al.,* 2012; *Scheff and Frierson,* 2014; *Fu and Feng,* 2014].

Using the data compiled by *Feng and Fu* [2013], *Huang et al.* [2015] show that the largest expansion of drylands since the 1960s has occurred in semiarid regions. *Sherwood and Fu* [2014] argue that PET will increase faster than *P* in a warming world, leading to a drier terrestrial climate in the future. *Fu and Feng* [2014] examine the

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change of terrestrial-mean aridity due to the CO₂ increase using CMIP5 transient 2xCO2 simulations, revealing a decrease in *P*/PET (i.e., a drier terrestrial climate) by ~3.4%/°C ocean mean surface temperature increase. Other studies also show a 21st century drying [*Cook et al.*, 2014; *Scheff and Frierson*, 2015] and dryland expansion [*Huang et al.*, 2016]. The predicted changes in near-surface relative humidity and topsoil moisture in the 21st century [*Collins et al.*, 2013] show a general decrease over land regions with a pattern similar to that of the change in *P*/PET [*Sherwood and Fu*, 2014]. These similarities show that changes in near-surface humidity, topsoil moisture, and *P*/PET are tightly coupled. *Lin et al.* [2015a] analyze the terrestrial aridity from the Community Earth System Model (CESM) Large Ensemble (CESM-LE) simulations for 1980–2080 and find that the CESM can reproduce the temporal and spatial variability of aridity derived from observations.

The CESM Last Millennium Ensemble simulations for the period 850–2005 (CESM-LME) recently become available to the community [*Otto-Bliesner et al.*, 2015]. This ensemble includes simulations forced with the transient evolution of solar intensity, volcanic emissions, greenhouse gases, aerosols, land use conditions, and orbital parameters, both together and individually. The CESM-LME provides a resource for the research community for understanding and attributing the climate variations of the last 1156 years to internal variability and external (both natural and anthropogenic) forcings.

This paper examines the terrestrial aridity by analyzing the CESM-LME simulations as well as those from the CESM-LE to place the anthropogenic changes in the context of changes forced by natural forcing in the past millennium. Section 2 describes the analysis methods and CESM data used in this study. The temporal evolutions of terrestrial-mean aridity and related meteorological variables are presented in section 3, followed by the discussions on the role of individual external forcings in section 4. The spatial patterns of aridity changes are shown in section 5. Section 6 further discusses the underlying methodology using *P*/PET, which was recently criticized by *Roderick et al.* [2015]. *Roderick et al.* [2015] equated lack of precipitation with meteorological aridity and lack of runoff with hydrologic aridity, indicating a wetter future. Their interpretations will also be discussed based on the CESM simulations in section 6. The summary and conclusions are given in section 7.

2. Method and Data

2.1. The PET Algorithm

We obtain PET using the Penman-Monteith algorithm [*Shuttleworth*, 1993; *Allen et al.*, 1998], which is physically based and is superior to empirical formulations [*Donohue et al.*, 2010; *Dai*, 2011; *Sheffield et al.*, 2012]. The Penman-Monteith algorithm is derived to calculate the evapotranspiration by assuming a saturated water vapor at the surface for given atmospheric conditions including available energy ($R_n - G$, where R_n is the net downward radiation and *G* is the heat flux into the ground), surface air temperature (SAT), relative humidity (RH), and the wind speed at 2 m above the surface (*u*2). Following *Allen et al.* [1998], we employ a bulk stomatal resistance (r_s) of 70 s/m under well-watered conditions and a bulk transfer coefficient (C_H) of 4.8×10^{-3} . We use the sum of actual latent heat (LH) and sensible heat (SH) (i.e., LH + SH) to replace $R_n - G$. [*Scheff and Frierson*, 2014]. Though the actual LH and SH are usually different from those with an assumed saturated water vapor at the surface, their sum is conserved for a given $R_n - G$ because LH + SH = $R_n - G$.

2.2. CESM Data and Analysis

We use the CESM-LME simulations for 850–2005 [*Otto-Bliesner et al.*, 2015]. The forcings over this period are associated with volcanic eruptions, solar activity, the orbit of the Earth, land cover, greenhouse gas concentrations, and tropospheric ozone and aerosols. Anthropogenic activities led to major increases in CO_2 , N_2O , and CH_4 during the twentieth century. There have been increases and then decreases in chlorofluorocarbons. There has also been a substantial increase in crop and pasture extent over the past two centuries. Anthropogenic aerosols and anthropogenic-induced ozone changes are considered during 1850–2005. We analyze 30 CESM-LME simulations including 9 with full forcings and 21 with individual forcing. For the latter we have simulations forced with volcanic eruptions (five), solar activity (five), greenhouse gases (three), land surface (three), the Earth's orbit (three), and anthropogenic ozone and aerosols (two), where the number in the parenthesis is the number of ensemble members. The two simulations that considered anthropogenic ozone and aerosols are largely a reflection of aerosol radiative forcing since the latter dominates [*Myhre et al.*, 2013]. The validation of the CESM-LME with all forcings was presented in *Otto-Bliesner et al.* [2015] by

Table 1. Annual Mean Climatology Averaged Over Land and the Globe From CESM-LME During 850–1850 for Surface Air Temperature (SAT), Precipitation (*P*), Potential Evapotranspiration (PET), Aridity Index (*P*/PET), Relative Humidity (RH), Available Energy at Surface ($R_n - G$), Wind Speed at 2 m (u2), Evaporation (*E*), and Runoff

		· = · (·····, a)	771 -	NIT (90)	$R_n - G(W/m)$	uz (m/s)	E (mm/a)	Runon (mm/a)
Land 11.7	872	990	0.88	70.1	79.1	2.0	594	271
Globe 13.1	1093	NA	NA	73.4	104.7	4.5	1093	NA

comparing the simulations with proxy data for surface temperatures, Palmer Drought Severity Index, and El Niño–Southern Oscillation variability.

We also use the CESM Large Ensemble (CESM-LE) simulations for 1950–2080. The CESM-LE has performed 30 ensemble simulations from 1920 to 2080 [*Kay et al.*, 2015], employing the historical forcing through 2005 and the RCP8.5 scenario forcing for 2006–2080. The CESM-LME used the same forcings as the CESM-LE during the overlapping period with the exception of including orbital changes in insolation not considered in the latter. The CESM-LME and CESM-LE employed the same model except the resolution of atmospheric and land components [*Otto-Bliesner et al.*, 2015]. The CESM-LME uses ~2° horizontal resolution in the atmosphere and land components and ~1° resolution in the ocean and sea ice components, while the CESM-LE uses ~1° resolution in all model components.

This study defines the land as the terrestrial regions between 60°S and 90°N, which cover 26.5% of the globe. It also defines the period of 950–1250 the Medieval Warm Period (MWP), 1550–1850 the Little Ice Age (LIA), 850–1850 the last millennium (LM), 1950–2005 the present day (PD), and 2050–2080 the future (F8.5). The MWP is the same as in *Otto-Bliesner et al.* [2015], but the LIA follows the NASA definition (see http://earthobservatory.nasa.gov/Glossary/?mode=alpha&seg=l&segend=n). The annual mean anomaly is defined with respect to the LM climatology (i.e., the averaged value for 850–1850).

The ensemble mean of the simulations should be interpreted as an estimate of climate response to forcing. In contrast, individual ensemble members contain internal variability of the climate system. Here we use two standard deviation of the ensemble members as a measure of uncertainties associated with internal variability. The CESM simulations may contain biases inherent in the model, which is not addressed in the present study.

Table 1 presents the annual mean climatology of SAT, *P*, PET, *P*/PET, RH, $R_n - G$, *u*2, evaporation (*E*), and runoff, averaged over land and the globe during 850–1850, from the ensemble mean of the CESM-LME with all forcings. The climatology from individual ensemble members shows very little variance because an average over a long time period minimizes the effect of internal variability. The simulated global mean *P* and $R_n - G$ for 850–1850 agree well with observations from 2000 to 2010 within observational uncertainties, and as expected, the simulated SAT is 0.7°C smaller than that for 1961–1990 from the reanalysis (see results from observations and reanalysis in *Fu and Feng* [2014, Table 2]). The simulated RH is slightly smaller than that from the reanalysis, while the simulated global mean surface wind speed is ~20% larger.

3. Temporal Evolution of Terrestrial-Mean Aridity and Related Meteorological Variables

Figure 1 shows time series of annual mean anomalies in SAT, *P*, PET, *P*/PET, RH, $R_n - G$, and *u*2, averaged over land, for 850–2005. A 20 year unweighted smoothing is applied to all the time series in the figures. In response to volcanic eruptions, especially the large ones in terms of total global stratospheric sulfate aerosol injection (e.g., Samalas in 1258, Kuwae in 1452, and Tambora in 1815), we see a decrease in both *P* and PET but a slight increase in *P*/PET (i.e., a wetter climate) along with a decrease in SAT. An increase in RH and a decrease in $R_n - G$ and a slight decrease in *u*2 are also seen. An increase in RH could be a consequence of the increase in *P*/PET but could also be because the land cools more than ocean in response to volcanic aerosols and the RH increases when air moves from ocean to land. During MWP, the annual mean anomalies of SAT, *P*, PET, and $R_n - G$ are largely positive while those in *P*/PET and RH are negative. The anomalies during LIA show opposite signs of those in MWP. A warmer and drier (cooler and wetter) terrestrial climate during MWP (LIA) supports the argument by *Sherwood and Fu* [2014]. The climate anomalies in MWP (LIA) were caused by weaker/less (stronger/more) tropical volcanic eruptions, and more (less) solar activity and both



Figure 1. Temporal evolutions of annual mean anomalies of (a) surface air temperature (SAT), (b) precipitation (*P*), (c) potential evapotranspiration (PET), (d) aridity index (*P*/PET), (e) relative humidity (RH), (f) available energy ($R_n - G$), and (g) wind at 2 m above the surface (*u*2), averaged over land, for 850 to 2005 from CESM-LME. The red lines are the ensemble average of the nine simulations, and the shading denotes two standard deviation of the nine ensembles. The units for *P*, PET, and *P*/PET are in percentage relative to the last millennium (850–1850) climatology. The periods of the Medieval Warm Period (MWP) (950–1250), the Little Ice Age (LIA) (1550–1850), and the present day (PD) (1950–2005) are indicated in Figure 1a.



Figure 2. Same as Figure 1 except for 850–2080 from CESM-LME (850–2005, red) and CESM-LE (1985–2080, blue). The periods of the Medieval Warm Period (MWP) (950–1250), the Little Ice Age (LIA) (1550–1850), present day (PD) (1950–2005), and the future of the RCP8.5 scenario (F8.5) (2050–2080) are indicated in Figure 2a.

MWP and LIA were also partly forced by insolation variations due to the Earth's orbital changes [e.g., *Bradley et al.*, 2003; *Lean*, 2010; *Miller et al.*, 2012; *Berger*, 1978; *Otto-Bliesner et al.*, 2015]. The LIA was also partly caused by land use and land cover changes [*He et al.*, 2014]. The CESM-LME takes into account the temporal variations of these external forcings.

Table 2. The Changes in Terrestrial-Mean Surface Air Temperature (SAT), Precipitation (*P*), Potential Evapotranspiration (PET), Aridity Index (*P*/PET), Relative Humidity (RH), Available Energy at Surface ($R_n - G$), Wind Speed at 2 m (u2), Evaporation (*E*), and Runoff for the Medieval Warm Period (950–1250) Relative to Little Ice Age (1550–1850) (i.e., MWP-LIA), Present Day (1950–2005) Relative to the Last Millennium (850–1850) (i.e., PD-LM), the Future of RCP8.5 Scenario (2050–2080) Relative to PD (i.e., F8.5-PD), and the F8.5 Relative to LM (i.e., F8.5-LM)^a

	SAT (°C)	<i>P</i> (mm/a)	PET (mm/a)	<i>P</i> /PET (× 10 ⁻²)	RH (%)	$R_n - G (W/m^2)$	$u2 \times 10^{2}$ (m/s)	<i>E</i> (mm/a)	Runoff (mm/a)
MWP-LIA PD-LM F8.5-PD F8.5-LM	0.20 0.20 4.0	3.22 -22.92 64.24 41.32	6.69 	-0.27 -1.17 -5.59 -6.76	-0.11 0.19 -1.93 -1.74	0.25 1.58 5.09 3.51	-0.30 1.36 -0.20 1.16	1.59 12.94 23.74 10.80	1.69 10.34 42.41 32.07

^aMWP-LIA and PD-LM are from the ensemble mean of the CESM-LME, F8.5-PD from the ensemble mean of the CESM-LE, and F8.5-LM = F8.5-PD + PD-LM. All changes are statistically significant at 95% confident level.

During PD, the anomalies are positive in SAT, RH, and u^2 but negative in *P*, PET, *P*/PET, and $R_n - G$. Figure 1 shows a drier terrestrial-mean climate in PD than LM. The PD climate change relative to LM is driven by human activities that led to increases in greenhouse gas concentrations and tropospheric aerosols, and changes in the land surface, in addition to natural forcings [*Myhre et al.*, 2013]. With the 20 year smoothing, the magnitudes of the PD anomalies in SAT, *P*, *P*/PET, $R_n - G$, and u^2 are larger than those caused by Samalas, the largest volcanic eruption in last millennium (in 1258). The global stratospheric aerosol injection in the Samalas eruption has been estimated at about 10 times of that from Mount Pinatubo in 1991 [*Otto-Bliesner et al.*, 2015]. Note that Samalas has a much stronger instantaneous signal than PD-LM but decays quickly in a few years so its 20 year mean signal is weaker than PD-LM. Figure 2 is the same as Figure 1 except from 850 to 2080: 850–2005 from CESM-LME (red) and 2006–2080 from CESM-LE (blue). The magnitudes of all anomalies except u^2 in F8.5 are much larger than any period in 850–2005, with large positive anomalies in SAT, *P*, PET, and $R_n - G$ but negative ones in *P*/PET and RH, largely driven by the increase of greenhouse gas concentrations. A much drier future climate from CESM, which is also shown in *Lin et al.* [2015a], is consistent with the studies by *Feng and Fu* [2013], *Sherwood and Fu* [2014], and *Fu and Feng* [2014].

Table 2 shows the changes in SAT, *P*, PET, *P*/PET, RH, $R_n - G$, *u*2, *E*, and runoff for MWP relative to LIA (MWP-LIA), PD relative to LM (PD-LM), F8.5 relative to PD (F8.5-PD), and F8.5 relative to LM (F8.5-LM), from the ensemble mean of the CESM-LME and CESM-LE simulations. Note that the simulated climatology from the CESM-LE is slightly different from CESM-LME during the overlapping period (not shown). We thus calculate the changes for F8.5-LM as the sum of those from LE_2050–2080 relative to LE_1950–2005 and LME_1950–2005 relative to LME_850–1850. All changes in Table 2 are statistically significant at 95% confident level. We see a decrease in *P*/PET (i.e., a drier climate) along with a SAT increase for MWP-LIA, PD-LM, and F8.5-LM. It is interesting to notice that the sign of changes in *E* and runoff follows that in *P* [*Zhao and Dai*, 2015] and the runoff change is about half of *P* changes for MWP-LIA and PD-LM while it becomes more than 75% for F8.5-LM.

Table 3 shows the percentage changes in terrestrial-mean aridity and the contributions from SAT, RH, $R_n - G$, u_2 , and P for MWP-LIA, PD-LM, F8.5-PD, and F8.5-LM. The terrestrial-mean aridity index becomes smaller (i.e., a drier terrestrial climate) by 0.34% for MWP-LIA, 1.4% for PD-LM, and 7.8% for F8.5-LM. The change in terrestrial-mean aridity in PD-LM and F8.5-LM is therefore about 4 and 20 times of that in MWP-LIA, respectively. In MWP-LIA and F8.5-LM, a drier climate is largely attributed to SAT increases, which is further

Table 3. The Percentage Change (%) in Terrestrial-Mean Aridity (*P*/PET) for the Medieval Warm Period (950–1250) Relative to Little Ice Age (1550–1850) (i.e., MWP-LIA), Present Day (1950–2005) Relative to the Last Millennium (850–1850) (i.e., PD-LM), the Future of RCP8.5 Scenario (2050–2080) Relative to PD (i.e., F8.5-PD), and the F8.5 Relative to LM (i.e., F8.5-LM)^a

	Total	SAT	RH	$R_n - G$	u2	Р
MWP-LIA	-0.34	-0.45	-0.10	-0.15	0.00	0.37
PD-LM	-1.35	-0.35	0.35	1.35	0.02	-2.66
F8.5-PD	-6.45	-8.19	-1.23	-3.03	-0.08	6.08
F8.5-LM	-7.80	-8.54	-0.88	-1.68	-0.06	3.42

^aMWP-LIA and PD-LM are from the ensemble mean of the CESM-LME, F8.5-PD from the ensemble mean of the CESM-LE, and F8.5-PD + PD-LM. Also shown are the percentage contributions from the changes in surface air temperature (SAT), relative humidity (RH), available energy ($R_n - G$), wind speed (u2), and precipitation (P).



Land SAT (°C)

Figure 3. Temporal evolutions of annual mean anomalies in surface air temperature, averaged over land, for 850–2005 from the CESM-LME (a) full-forced and (b–g) single-forcing ensemble simulations. The ensemble spread in the full-forced ensemble is shown by grey shading in all panels, and the ensemble mean of the nine full-forced ensemble members is shown in cyan in Figure 3a.

enhanced by changes in RH and $R_n - G$ but partly compensated by increases in *P*. The relative compensation from *P* is larger in MWP-LIA than F8.5-LM because the precipitation sensitivity (i.e., a percentage increase in *P* normalized by a warming) caused by sulfate aerosols or solar forcing is larger than that caused by greenhouse gases [e.g., *Roeckner et al.*, 1999; *Meehl et al.*, 1996; *Allen and Ingram*, 2002]. Note that from the CESM, the precipitation sensitivity for MWP-LIA is about 2 times of that for F8.5-LM. A drier climate in PD-LM, however, is largely attributed to decreases in *P*, partly compensated by decreases in $R_n - G$ through its impact on PET. *Feng and Fu* [2013] also showed that the drying trend for 1948–2008 was mainly due to a reduction in precipitation from both observational data and CMIP5 simulations. Note that the SAT increase for PD-LM is the same as that for MWP-LIA, about 0.2°C (Table 2). The increases in SAT (RH) slightly enhance (reduce) the PD dryness. The meteorological variable that is responsible for a drier climate in PD is very different from that in F8.5 because of the role of anthropogenic aerosols in PD, which will be discussed further below. Table 3 reveals that the change of surface wind has little effect on the terrestrial-mean aridity,



Figure 4. Same as Figure 3 but for precipitation.

consistent with *Fu and Feng* [2014]. The change of aridity in the 21st century relative to the present climate was discussed in details by *Lin et al.* [2015b].

From Tables 1 and 2, the relative changes in P(P - E) are 0.4% (0.6%) for MWP-LIA, -2.6% (-3.8%) for PD-LM, and 4.7% (11.8%) for F8.5-LM. The signs of changes in P - E and P are the same.

4. The Role of Individual External Forcings

Figure 3 presents the temporal evolutions of annual mean anomalies in surface air temperature, averaged over land, from the CESM-LME full-forced and single-forcing ensemble simulations for 850–2005. For the temporal evolution with forcing from ozone and aerosol only (Figure 3g), the time series before 1850 is from the control runs using forcing at 1850 and after 1850 the forcing due to ozone and aerosol changes. Figures 4–9 are the same as Figure 3 but for *P*, PET, *P*/PET, RH, $R_n - G$, and *u*2, respectively. For SAT, the ensemble with volcanic only (Figure 3f) closely follows the full-forced one for 850–1850, indicating the dominant role of volcanic aerosol forcing during this period. The role of the Maunder (~1645–1715) grand solar minima (Figure 3e) and land use since the late LIA (Figure 3c) can also be seen. In PD, the warming forced by greenhouse gases (Figure 3b) is

Figure 5. Same as Figure 3 but for potential evapotranspiration.

canceled in large part by a cooling due to anthropogenic aerosols (Figure 3g) and in small part by a cooling due to land change (Figure 3c). For precipitation, anthropogenic aerosols and greenhouse gases lead to a decrease (Figure 4g) and increase (Figure 4b), respectively. Because of larger precipitation sensitivity to aerosols than greenhouse gases, there is a net decrease in *P* during PD relative to LM (Figure 4a). The PET with volcanic only also closely follows the full-forced one before 1850 (Figure 5f), while in PD, it is a small difference (negative) between large responses of PET to greenhouse gases and anthropogenic aerosols (Figure 5a, 5b, and 5g).

Variability across the ensemble in *P*/PET (Figure 6) is larger than most other variables and driven by variations in *P* (Figure 4). Figure 6 shows that in PD, a decrease in *P*/PET is caused by greenhouse gases (Figure 6b), which is slightly compensated by small positive anomalies due to both land change (Figure 6c) and anthropogenic aerosols (Figure 6g). The small effect of aerosols on terrestrial-mean aridity is consistent with the studies by *Zhao et al.* [2014] and *Lin et al.* [2015b, 2016]. A small increase of RH in PD is caused by positive anomalies due to anthropogenic aerosols (Figure 7g) and land use (Figure 7c), which is largely canceled by a negative anomaly due to greenhouse gas increases (Figure 7b). Figure 8 shows that anthropogenic aerosols

Land P/PET (%)

Figure 6. Same as Figure 3 but for aridity index.

(land use) cause a large (small) negative anomaly in $R_n - G$ in PD, while greenhouse gases cause a moderate positive one. By summation, the PD has a significant negative anomaly in $R_n - G$, and its effect on *P*/PET partly compensates that due to a decrease of *P* (Table 3). It should be noted that despite their small effect on terrestrial-mean aridity in PD (Figure 6g), anthropogenic aerosols totally alter the attributions of aridity change to meteorological variables (Table 3), by causing a large negative anomalies in *P* (Figure 4g), $R_n - G$ (Figure 8g), and SAT (Figure 3g). Different from F8.5 in which the SAT increase is the main factor leading to a drier climate, a decrease of *P* in PD is the main factor (Table 3). The latter may make the detection and attribution of the PD climate change in terms of aridity difficult because of much larger internal variability in *P* (Figure 4) than in PET (Figure 5). The change in PET forced by greenhouse gas increases is largely related to the temperature changes [*Scheff and Frierson*, 2014]. An increase of *u*2 in PD is caused by the land use (Figure 9c), while there are small decreases due to both greenhouse gases and anthropogenic aerosols (Figures 9b and 9g).

It should also be noted that a scaling of the change in aridity index by an increase of global (or ocean) mean temperature is a useful approach to examine and compare its responses to individual forcings [e.g., *Fu and Feng*, 2014]. But it is less useful for the change forced by more than one forcing agent at the same time,

Figure 7. Same as Figure 3 but for relative humidity.

e.g., by both aerosols and greenhouse gases. The scaled change in aridity index for the latter could become infinite when the mean temperature change becomes zero.

5. Spatial Distribution of Terrestrial Aridity Changes

Figure 10 shows global distributions of percentage changes in *P*, —PET, and *P*/PET between MWP and LIA. Note that the sum of percentage changes in *P* and —PET is approximately equal to the percentage change in *P*/PET [*Fu and Feng*, 2014]. We see a wetter climate over north side of Africa, India, and west China but a drier climate in parts of USA, Brazil, southern Africa, Eurasia, and east China (Figure 10c). The former is largely because of the *P* increases (Figure 10a), while the latter is because of the PET increases (Figure 10b). It is noticed that the spatial pattern of aridity change for MWP-LIA (Figure 10c) is similar to that for the 21st century [see *Feng and Fu*, 2013, Figure 7d].

Figure 11 is the same as Figure 10 except for PD-LM. There are large inhomogeneities in spatial patterns of changes in *P*, PET, and *P*/PET in both magnitudes and signs. The inhomogeneity in the *P*/PET change pattern (Figure 11c) is largely due to *P* (Figure 11a) and to less extent PET (Figure 11b). The spatial inhomogeneities in

Figure 8. Same as Figure 3 but for surface available energy.

P are caused by anthropogenic aerosols, greenhouse gases, and land surface change (not shown). Figure 11 shows that the CESM climate is drier in PD than in previous (LM) period over southwest and southeast of North America, large part of Canada, north and south of South America, west of northern Africa, southern Africa, Mediterranean region, southern Asia including south India, and Siberia, while the remainder of land is largely becoming wetter. The aridity change is largely driven by the anthropogenic forcings.

6. Further Discussions of the Underlying Methodology Using P/PET

Roderick et al. [2015] questioned that "warmer is more arid" by *Sherwood and Fu* [2014] and *Fu and Feng* [2014] who used *P*/PET. They argued that the problem is the use of a fixed r_s in the PET calculations in these studies. Note that the concept of PET is not used in a climate model run. Following the Penman-Monteith algorithm, the PET is determined by SAT, RH, $R_n - G$, u_2 , and r_s , which are all functions of space and time. The present study, as in *Feng and Fu* [2013] and *Fu and Feng* [2014], indeed employed a fixed r_s of 70 s/m in deriving PET and treated SAT, RH, $R_n - G$, and u_2 as changing variables but not r_s . Before we address the issue of using a constant r_{si} it is important to point out that by using the SAT, RH, $R_n - G$, and u_2 from a climate

Figure 9. Same as Figure 3 but for wind speed at 2 m above the surface.

model with dynamic vegetation, the impact of spatial distribution of vegetation and its change on the simulated SAT, RH, $R_n - G$, and u^2 have been effectively considered.

The change of PET by neglecting the higher-order terms can be written in the form

$$\Delta \text{PET} \approx \frac{\partial \text{PET}}{\partial \text{SAT}} \Delta \text{SAT} + \frac{\partial \text{PET}}{\partial \text{RH}} \Delta \text{RH} + \frac{\partial \text{PET}}{\partial (Rn - G)} \Delta (Rn - G) + \frac{\partial \text{PET}}{\partial u^2} \Delta u^2 + \frac{\partial \text{PET}}{\partial r_s} \Delta r_s$$
(1)

where the climatology value of r_s should be used for the coefficients of the five changing terms on the right. The use of a constant r_s would lead to two questions: How would it affect the response of PET to changing SAT, RH, $R_n - G$, and u_2 (i.e., the first four terms on the right side of equation (1)) and how would PET change with r_s for given SAT, RH, $R_n - G$, and u_2 (i.e., the last term in equation (1))? On the first question, *Scheff and Frierson* [2014] showed that widely different choices of vegetation parameters including r_s do not affect the big picture of PET changes at the end of the 21st century. *Fu and Feng* [2014] showed that the changes in *P*/PET due to 2xCO₂ differ by only about 15% using $r_s = 0$ versus 70 s/m. Note that r_s is always positive over land and from the Penman-Monteith algorithm, a larger r_s leads to a larger response of PET to a temperature

Figure 10. Global distributions of percentage changes (%) in (a) *P*, (b) – PET, and (c) *P*/PET, taken as the difference between the Medieval Warm Period (MWP) (950–1250) and Little Ice Age (LIA) (1550–1850) using the ensemble mean of the CESM-LME full forcing simulations. Grid points with statistical significance at the 95% level using the student *t* test are stippled.

increase (i.e., more drying for a given warming). Therefore, using a constant r_s of 70 s/m does not alter our conclusion that warmer is more arid based on *P*/PET changes in response to those in *P*, SAT, RH, $R_n - G$, and u2.

By considering r_s as a variable, the relative change of PET with r_s alone following the Penman-Monteith can be written in the form

$$\frac{1}{2\text{ET}} \frac{\partial \text{PET}}{\partial r_s} = -\frac{\gamma C_H |u2|}{[\Delta(\text{SAT}) + \gamma(1 + r_s C_H |u2|)]},$$
(2)

where Δ is the slope of the saturated water vapor pressure curve and $\gamma =$ $(c_p p_s)/(0.622L_v)$ where p_s is the surface pressure, c_p the specific heat of air, and L_v the latent heat of vaporization for water. Equation (2) shows that PET decreases with the r_s increase, and the relative change is a function of SAT, u2, p_s , C_H , and r_s . The magnitude of the change is largest when $r_s = 0$ by given other parameters. We obtain $\partial \text{PET}/\partial r_s/\text{PET} = -0.4\%/\text{ms}^{-1}$ for а $SAT = 12^{\circ}C$, u2 = 2.0 m/s, $p_s = 100 \text{ kPa}$, $C_H = 4.8 \times 10^{-3}$, and $r_s = 0$. Our studies do not consider the response of PET to changing r_s in the Penman-Monteith framework (i.e., the last term in equation (1)) because very little is known about the bulk vegetation changes due to the CO₂ concentration increase and the climate change induced [Scheff and

Frierson, 2014] and thus Δr_s . This of course does not necessarily mean that such a response is not important. But it is important to note again that the impact of plant physiological changes on PET through meteorological variables (i.e., the first four terms on the right side of equation (1)) has been effectively considered in our studies.

Both PET and pan evaporation measured at weather stations are accepted as a measure of atmospheric evaporative demand. Pan evaporation measures the response of atmospheric evaporative demand to meteorological variables but not to r_s . This is similar to PET with fixed r_s . Despite a fast surface temperature increase in the second half of the twentieth century, a decrease in pan evaporation was observed, which was called the pan evaporation paradox. *Roderick and Farquhar* [2002] showed that the decrease in pan evaporation is due to decreases in solar radiation reaching at the surface. Our model results, also showing a decrease (increase) in PET (SAT) in the second half of the twentieth century (see Figure 1 and Table 2), generally agree with the observation. Table 3 shows that a decrease in PET in PD-LM can be almost all attributed to a decrease in $R_n - G$, which supports the argument by *Roderick and Farquhar* [2002]. An important point here is that as the global temperature increases, the PET does not have to increase, as in the PD-LM when the effect of anthropogenic aerosols on PET outweighs the effect of GHG increases.

Figure 1c shows that PET decreases for 1950–1975 and then increases for 1975–2005. The latter increase does not agree with many observations that show decreases in pan evaporation from the 1970s to

Figure 11. Same as Figure 10 but between the present day (PD) (1950–2005) and the last millennium (LM) (850–1850).

1990s [McVicar et al., 2012; Wang et al., 2012]. The observed decrease in pan evaporation was attributed to observed decreases in wind speed and incident surface solar radiation. Although the model does simulate a slight decrease in wind since the 1970s (Figure 1g), it is too small to have any global effect on PET. It is not clear what is responsible for observed stilling in wind speed, and the possible causes include human activities, natural variability, and/or data artifact [Roderick et al., 2007; Pryor et al., 2009; Vautard et al., 2010; Bichet et al., 2012; McVicar et al., 2012; Chen et al., 2012; Wever, 2012; Yang et al., 2013; Hou et al., 2013; Kim and Paik, 2015]. While reconciling the model results and observations is beyond the scope of this study, it is worth noting that collocating the model results with observations both spatially and temporally is necessary for the comparison between model and observations since the latter does not have a global coverage. It should also be noted that the model-used temporal variation of anthropogenic aerosol radiative forcing that affects the variation of PET may have large uncertainty both locally and globally [Boucher et al., 2013].

This study uses *P*/PET as a measure of terrestrial aridity, showing that warmer is more arid [*Sherwood and Fu*, 2014; *Fu and Feng*, 2014]. *Roderick et al.* [2015] equated lack of precipitation with meteorological aridity and lack of runoff with hydrologic aridity. Using their measures, warmer becomes wetter in MWP-LIA and F8.5-LM while the warmer is more arid for PD-LM, from CESM simulations (see Table 2). For F8.5-LM, for example, the relative changes in *P*/PET, *P*, and *P* – *E* from Tables 1 and 2 are –7.7%, 4.7%, and 11.8%, respectively, indicating a drier future based on *P*/PET but wetter one based on *P* or *P* – *E* following *Roderick et al.* [2015].

Roderick et al. [2015] argued that the warmer being more arid in *Sherwood and Fu* [2014] is based on the assumption that *E* follows PET and therefore increases faster than *P* leading to a reduction in runoff. We want to clarify here that we *did not* make such assumption in *Sherwood and Fu* [2014] and *Fu and Feng* (2014). Table 2 shows that the change in P - E follows the sign of change in *P* instead of *P*/PET. In addition, the changes in *P* and runoff do not address the 21st century declining of near-surface relative humidity and topsoil moisture [*Collins et al.*, 2013] but *P*/PET does [*Feng and Fu*, 2013; *Sherwood and Fu*, 2014]. It is an important future research topic to reconcile different measures of terrestrial aridity to address various environmental issues in rapidly changing climate. It should also be noted that while an increase of CO₂ would increase the water use efficiency of vegetation, how vegetation responds to a warming due to an increase of CO₂ is still an open question [e.g., *Van der Sleen et al.*, 2015; *Reich et al.*, 2014; *Claesson and Nycander*, 2013]. We believe that a change in atmospheric evaporative demand is among many important factors that need to be considered.

7. Summary and Conclusions

The CESM-LME [*Otto-Bliesner et al.*, 2015] provides a resource for understanding and attributing the climate variations of the last 1156 years (850–2005) to natural and anthropogenic forcings. This paper focuses on terrestrial aridity by analyzing the CESM-LME and CESM-LE simulations to place the anthropogenic changes in present day (PD) (1950–2005) and the future (F8.5) (2050–2080) in the context of changes caused by natural forcing in the last millennium (LM) (850–1850).

We show that terrestrial-mean aridity index, measured by *P*/PET, becomes smaller (i.e., a drier climate) by 0.34% for the Medieval Warm Period (MWP) (950–1250) versus the Little Ice Age (LIA) (1550–1850), 1.4% for PD versus LM, and 7.8% for F8.5 versus LM. The change of terrestrial-mean aridity in PD-LM and F8.5-LM is thus four and twenty times of that from MWP-LIA, respectively. A small aridity change in MWP-LIA is partly because the precipitation sensitivity (i.e., a percentage increase in *P* normalized by the warming) caused by sulfate aerosols/solar activities is larger than that caused by greenhouse gases. It is shown that a drier (i.e., a smaller aridity index) climate in PD than LM is largely due to a decrease of precipitation while a drier climate in F8.5-LM and MWP-LIA is mainly due to an increase of temperature. The terrestrial-mean aridity change in PD-LM is, however, largely driven by greenhouse gas increases as in F8.5-LM. This is because anthropogenic aerosols have small net effect on terrestrial-mean aridity but at the same time they totally alter the attributions of aridity changes to meteorological variables by causing large negative anomalies in surface air temperature, available energy, and precipitation. That a precipitation decrease becomes the main factor leading to a drier PD climate would make the detection and attribution of the PD climate change in aridity more difficult because of much larger internal variability in precipitation than temperature.

We examine the spatial pattern of changes in terrestrial aridity for MWP-LIA and PD-LM. We notice that the spatial pattern of aridity change for MWP-LIA is similar to that for the 21st century. But there are large inhomogeneities in spatial patterns of *P*/PET changes for PD-LM in both magnitudes and signs, which are driven by the anthropogenic forcings including anthropogenic aerosols, greenhouse gases, and land surface changes.

We also show the changes of terrestrial-mean *P* and *P* – *E* (precipitation minus evaporation) for 850–2080. The relative changes in *P* (*P* – *E*) are 0.4% (0.6%) for MWP-LIA, -2.6% (-3.8%) for PD-LM, and 4.7% (11.8%) for F8.5-LM. The signs of changes in *P* – *E* and *P* are the same.

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