Response of terrestrial aridity to global warming

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Introduction

Potential evapotranspiration (PET): The maximum amount of water capable of being lost from the surface for given atmospheric condition with well supplied surface water (i.e., the evaporative demand of the atmosphere).
**Aridity index (UNEP 1992):**

\[ AI = \frac{P}{PET} \]

E.g., at Tucson, USA

\[ \frac{P}{PET} = 0.12 \]
Drylands are regions with $P/PET < 0.65$, which are further divided into (UNEP 1992; Hulme 1992):

- **Hyper-arid**: $P/PET < 0.05$
- **Arid**: $0.05 < P/PET < 0.20$
- **Semid-arid**: $0.20 < P/PET < 0.50$
- **Dry subhumid**: $0.50 < P/PET < 0.65$
Distribution of World’s Drylands

Dryland Systems
- Hyper-arid
- Arid
- Semi-arid
- Dry subhumid

Source: Millennium Ecosystem Assessment (2005)

Drylands comprise 41.3% of the global terrestrial area.

Drylands were home to 34.7% of the global population in 2000.
How does terrestrial aridity in terms of $P/PET$ respond to anthropogenic climate change?

A view of dryland (with village in the background) in the Sahel, southern Niger
Previous studies focus on change in precipitation, as typical in high-profile reports (e.g., IPCC 2007, 2014), which may not tell the whole story – or perhaps even the main story – of hydrological change.
Most studies of terrestrial dryness focus on droughts (e.g., Dai 2013), rather than on the background aridity changes.

- Drought region versus arid region
  - Anomaly (extreme) versus mean state (background climatology)
Introduction

A drier terrestrial climate
  - Global dryland expansion

Past, present, and future

Conclusions
A drier terrestrial climate

Observational data for 1948-2010
- $T$ and $P$: CPC and UD
- $R$, $RH$ and $u$: GLDAS and the 20$^{th}$ Century Reanalysis

Model data for 1948-2100
- 27 CMIP5 GCMs with historical forcings for 1948-2005 and RCPs 8.5 and 4.5 for 2006-2100
- The simulated data were statistically downscaled to 0.5 degree resolution

CMIP5 transient CO$_2$ 1%/yr increase experiments
- 25 CMIP5 GCMs to doubling CO$_2$
**PET algorithm**

- The PET is based on the Penman-Monteith (PM) algorithm (Maidment 1993; Allen et al. 1998; Sheffield et al. 2012; Scheff & Frierson 2014):

\[
PET = \frac{(R_n - G)\Delta(T_a) + \rho_a c_p e^* (T_a)(1 - RH)C_H}{\Delta(T_a) + \gamma(1 + r_s C_H |u|)} / L_v
\]

where \(R_n - G\) is the surface available energy, \(T_a\) temperature, \(RH\) relative humidity, and \(u\) wind; \(e^*\) is saturated water vapor pressure, \(\Delta = de^*/dT\), \(C_H\) transfer coefficient \((4.8 \times 10^{-3})\), \(r_s\) bulk stomatal resistance under well-water conditions \((70 \text{ s/m})\).
Global dryland distribution for 1961-1990 climatology

Feng & Fu (2013)
Global dryland distributions versus vegetation types from MODIS

Feng & Fu (2013)
Changes in (a) surface air temperature, (b) PET, (c) precipitation, and (d) $P/P_{ET}$ (1961-1990 to 2071-2100) under scenario RCP85

Feng & Fu (2013)
Why do we expect a drier climate under global warming

- As the globe warms global average rainfall increases (e.g., Allen and Ingram, 2002).

![Box plot diagram](image)
The percentage change in $P/PET$ can be written as

$$\Delta \left( \frac{P}{PET} \right) \left/ \left( \frac{P}{PET} \right) \right. \approx \frac{\Delta P}{P} - \frac{\Delta PET}{PET}$$

Noting a similar rate of percentage increase in $P$ over land to that in $E$ over ocean, we have

$$\Delta \left( \frac{P}{PET} \right) \left/ \left( \frac{P}{PET} \right) \right. \approx \left( \frac{\Delta E}{E} \right)_{Ocean} - \frac{\Delta PET}{PET}$$
The Penman-Monteith algorithm can be used to estimate the actual \( E \) over ocean by setting \( r_s = 0 \) and using a \( C_H \) of \( 1.5 \times 10^{-3} \) (Richter and Xie 2008), i.e.,

\[
E = \frac{(R_n - G)\Delta(T_a) + \rho_a c_p e^*(T_a)(1 - RH)C_H |u|}{\Delta(T_a) + \gamma} / L_v
\]
Table. Comparison of annual mean evaporation \((E)\) and its percentage change rate and surface stability \((T_a - T_s)\) change rate over ocean estimated using the PM algorithm and those from the GCMs.

<table>
<thead>
<tr>
<th></th>
<th>(E) (mm)</th>
<th>Percentage change rate in (E) (%/°C)</th>
<th>Change rate in (T_a - T_s) (°C/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penman-Monteith</td>
<td>1267 (90)</td>
<td>1.92 (0.39)</td>
<td>0.07 (0.03)</td>
</tr>
<tr>
<td>Directly from GCMs</td>
<td>1300 (62)</td>
<td>1.71 (0.40)</td>
<td>0.06 (0.02)</td>
</tr>
</tbody>
</table>

Fu & Feng (2014)
Since the PM algorithm can be applied to both PET over land and E over ocean, we can examine the change in $P/\text{PET}$ in the framework of the PET by comparing its changes over land and ocean.

Both PET over land and E over ocean are a function of surface air temperature ($T_a$), relative humidity ($RH$), wind speed ($u$), and available energy ($R_n - G$).
- Ingredient one: Land surface warms on average, about 50% more than oceans (e.g., Manabe et al. 1992; Joshi et al. 2008)

Fu & Feng (2014)
Ingredient two: Reduced relative humidity near the surface over land but increased RH over ocean (e.g., Simmons et al. 2010; O’Gorman and Muller 2010; Sherwood and Fu 2014)

Fu & Feng (2014)
The surface winds change little over both land and ocean.

Fu & Feng (2014)
Ingredient three: Part of increased net downward radiation is transported to deep ocean (e.g., Hansen et al. 2005; Johnson et al. 2011; Loeb et al. 2012)

Fu & Feng (2014)
Change of net radiative energy budget at the surface

Fu & Feng (2014)
Change of net radiative energy budget at the surface

Fu & Feng (2014)
Ingredients that contribute to a drier terrestrial climate in a warming world

Fu and Feng (2014)
Our scale analysis shows an averaged decrease of \( P/PET \) by \( \sim 3.4\%/K \) over land.
Changes in (a) $P/P_{ET}$ and (b) RH (1980-1999 to 2080-2099) under scenario RCP85

Sherwood & Fu (2014)
Temporal variations of global dryland areas for (a) the total and individual components of (b) dry subhumid, (c) semiarid, (d) arid, and (e) hyper-arid regions.

Feng and Fu (2013)
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.

Feng and Fu (2013)
Changes in dryland coverage to drier types (1961-1990 to 2071-2100) under scenario RCP8.5

Feng and Fu (2013)
The climate over land will become drier in a warming world.

The change in the evaporation over ocean is slower than the change in potential evapotranspiration over land, which leads to a drier terrestrial climate in the future.

By the end of this century, the world’s drylands can be 5.8x10^6 km^2 (or 10 \%) larger than in the 1961–1990 climatology.
Past, present, future

- CESM-LME simulations for 850-2005 (Otto-Bliesner et al. 2015) and CESM-LE for 1920-2080 (Kay et al. 2014)

- Simulations forced with the transient evolution of solar intensity, volcanic emissions, greenhouse gases, aerosols, land use conditions, and orbital parameters, both together and individually.

- to place anthropogenic changes in the context of changes due to natural forcings during last millennium
Conclusions (II)

- The aridity index averaged over land, becomes smaller (i.e., a drier terrestrial climate) by 0.34% for MWP versus LIA, 1.4% for PD versus LM, and 7.4% for F8.5 versus LM.

- The terrestrial aridity change in PD-LM is largely driven by greenhouse gas increases. Despite small effects on terrestrial-mean aridity, anthropogenic aerosols totally alter the attributions of aridity changes to meteorological variables by causing large negative anomalies in surface air temperature, available energy, and precipitation.

- This study indicates that geoengineering through solar radiation management could not address the problem of a drier climate caused by greenhouse gas increases.
The PM algorithm was derived from the standard bulk formula for the sensible heat \( (SH) \) and latent heat \( (LH) \) fluxes along with the surface energy budget equation

\[
SH = \rho_a c_p C_H (T_s - T_a) |u|
\]

\[
LH = \rho_a L_v C_H (q^* (T_s) - q^* (T_a) RH) |u| / (1 + r_s C_H |u|)
\]

\[
R_n - G = SH + LH
\]

where \( T_s \) is the temperature at the surface interface, \( LH = PET*L_v \), and \( q^* \) is the saturated water vapor mixing ratio.