 drivers, timing and some impacts of global aridity change

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Abstract
The modeled robustness of the aridity response to climate change has already been well established: global drylands are expanding as increases in potential evapotranspiration outpace precipitation increases. This work considers three questions not previously addressed: (1) in which aridity zones are aridity trends expected to first emerge? (2) To what extent are future populations expected to experience changes in aridity? (3) For which locations and populations is aridity change determined by changes in precipitation versus temperature? Using a multi-model ensemble of general circulation models (GCMs) from the CMIP5 archives, together with population statistics from United Nations databases we find the following: (1) drier regions are projected to dry earlier, more severely and to a greater extent than humid regions. (2) By the end of the century, up to 700 million more people are projected to live in arid regions, with half of humankind living in regions experiencing drying of at least 5% and 3 billion experiencing 25% drying under a high emissions scenario. The largest populations to experience extreme drying are in Africa and Asia. According to GCMs, aridity increases have already begun to emerge in Northern Africa. Populations in sub-Saharan Africa appear to be the most vulnerable considering current water scarcity levels there. And (3) precipitation change is projected to drive the most severe drying in arid regions, contributing to the earliest emerging signals of aridity change and driving the differential drying across aridity zones. A comparison of aridity data derived from observations with model ensemble data suggests that increased aridity is already emerging in the driest regions. In sum, widespread aridity trends across a warming state imply that most of humanity will live in a more arid world.

Significance statement
Understanding how the water cycle will respond to climate change has important implications for human populations. Using climate model projections, it has already been shown that as the climate warms, arid regions are expected to expand in many populated regions. The key conclusions from our work are that most of the world’s population is projected to live in locations that become drier in the 21st century in a business as usual scenario, that arid zones are already drying faster than humid zones, and that precipitation is expected to be the dominant driver of these trends. The largest impacts are expected to occur in Africa, where current water scarcity levels are highest, and where the largest populations coincide with widespread drying.

Introduction
Aridity describes the water deficiency of a given climate and is commonly characterized by the ratio of precipitation (P) to potential evapotranspiration (PET). PET represents the evaporative demand of the atmosphere and is the upper limit of evapotranspiration (ET). Changes in aridity have begun to emerge in response to climate change [1–5]. As the Earth continues to warm, it is expected that terrestrial aridity will increase as increases in PET outpace increases in P over land, altering landscapes, ecosystems, and conditions where people live. Increased aridity contributes to more frequent droughts, severe soil moisture deficits, decreases in carbon uptake, and the expansion of global drylands [6–22]. The response of the global
water cycle to climate change is expected to impact a large portion of the human population [5, 23, 24]. With a 2 °C global temperature increase, for example, increases in aridity are estimated to impact up to 24% of the world’s present population [5], and changes in P or evaporation (E) are estimated to impact half of the world’s population [24], with an expected 40% increase in the number of people living under absolute water scarcity (<500 m³ per capita per year) [23]. The extent to which future populations can be expected to be impacted by aridity change, and drivers of these impacts (e.g. precipitation versus temperature), however, remain open questions and distinguish this work from earlier studies. Finally, while the Held and Soden [25] ‘wet-get-wetter, dry-get-drier’ mechanism has been a useful characterization of global climate change, it has been shown to break down over land [26]. Here, we re-characterize wet and dryland regions using aridity zones and examine rates of aridity increase and the extent to which aridity increases have already emerged in different zones in a different manner than previous publications.

Many climate factors (temperature most prominently) have been identified to have significant impacts on human populations through their associations with conflict, health, crop yields, economies, human migration and access to drinking water (e.g. [27–29]). Populations living in drylands, as classified by the aridity index (P/PET), tend to live in more remote areas, have less access to services, have worse health outcomes, suffer from severe drinking water shortages, and have lower GDP [30]. Further, dryland ecosystems are more sensitive to climate change and land degradation [30]. The potential crises that can arise from the combination of climate and population pressures on water resources is evident in the case of Cape Town, South Africa. At the time of writing this paper, Cape Town is in its third consecutive year of drought and both residential and agricultural water have been severely curtailed in the region [31]. While there are multiple factors that can lead to water shortages in particular places, illuminating the risk of such crises in a warming world is important both for adaptation and mitigation.

While the aridity index, P/PET, is a useful metric in characterizing drylands, the moisture deficit (P–PET), also referred to as the precipitation deficit, is another useful metric since it is highly correlated with both extent of irrigated land and net irrigation water requirements [32, 33]. Using these metrics, it is projected that widespread terrestrial drying will result from global warming due to a combination of factors including widening of the Hadley cell (e.g. [34]), the land-ocean warming contrast (e.g. [11, 35]), and soil moisture feedbacks (e.g. [36]).

In this work we calculate the evolution of the aridity index and the moisture deficit index under greenhouse warming from an ensemble of general circulation models (GCMs). While many of the variables required to calculate the aridity index are not well observed, we include a more limited analysis of observations from the Climate Research Unit (CRU) gridded dataset [37] in order to compare GCM trends with recent observed trends in the aridity index. Our analysis is conducted with three objectives. First, we aim to identify the regions and aridity zones where robust changes in the aridity index and moisture deficit are projected to occur, and the relative timing of these changes. Second, we identify the populations who will be most affected by increased aridity (i.e. decreases in P/PET), by population size, location, and by current levels of water scarcity. And finally, we attribute the relative change in the aridity index to changes in temperature (T) versus P, both globally and regionally. On this final point, the role relative humidity (RH) is also considered, although the relative contributions of RH and other variables (e.g. wind speed and net radiation) to changes in aridity are less significant [38]. To avoid repetitious language in the following text, ‘drying’ or ‘increases in aridity’ are used to describe decreases in both the aridity and moisture deficit indices.

Data and methods

**Aridity indices, robustness, and classifications**

PET is an estimate of the evaporative demand of the atmosphere and changes in PET with a warming atmosphere are largely determined by temperature and RH [38]. PET is the upper limit of ET and the two are equal when soil is fully saturated. There are a number of proposed methods for estimating PET, each with varying degrees of accuracy depending on availability of data, climate type, time scale, and application of interest [17, 39, 40]. For example, for non-water stressed climates and/or months, an energy-only estimate of PET (a modification of the Budyko method) is found to out-perform other PET formulations [41, 42]. For locations where temperature and precipitation are the only well-observed climate variables, a modified version of the Hargreaves formulation does a reasonable job of estimating PET [43]. Following recommendations from the Food and Agriculture Organization (FAO), we implement the Penman–Monteith (PM) formulation for PET [44, 45]. This is a physically based algorithm, including both the surface energy balance and aerodynamic components of PET. As recommended, we apply the PM equation to a reference crop, which provides an estimate of PET for a well-watered crop with an assumed crop height of 0.12 m, a stomatal resistance of 70 s m⁻¹ and an albedo of 0.23. This formulation and parameterization is widely used in the literature [e.g. 5, 8], however a few important limitations should be noted. First, because the PM provides an estimate of PET over a well-watered reference crop, this will introduces biases over non-vegetated land surfaces,
for crops with different parameterizations, or for crops in more arid regions. Second, and importantly, stomatal resistance is assumed to be constant over time, when in fact it is understood to increase with CO₂ concentrations [46]. Therefore, by holding stomatal resistance constant, we risk overestimating PET in a future with higher atmospheric CO₂ concentrations. We explore the potential biases in our estimates of aridity change using the PM formulation of PET, as applied in this paper, to other formulations of PET. In particular, the aridity index using the PM formulation is compared to the Penman equation [47], as well as the PM equation where stomatal resistance is doubled (i.e. takes the value 140 s m⁻¹) by the end of the 21st century. This geographically uniform doubling of stomatal resistance is chosen as an illustrative example of the relative sensitivity of P/PET to stomatal resistance and does not capture a realistic or complete assessment of the potential biases in holding stomatal resistance constant. The results of the sensitivity of aridity change to these choices of metrics are provided in the supplement (figures S2 and S3 are available online at stacks.iop.org/ERL/13/104010/mmedia). The results indicate that the PM equation projects a widespread higher increase in aridity than the Penman equation by a global average of 3% (figure S2). Doubling the stomatal resistance in the PM equation results in a projected percentage change in aridity that is ubiquitously less than that with a constant stomatal resistance, with a global average difference of 23% (figure S3).

To implement the PM formulation of PET we use GCM output of monthly air surface temperature, precipitation, relative humidity, sensible heat flux, and latent heat flux, and daily values of wind speed, which are averaged to the monthly time scale. All GCM output are interpolated to a uniform grid with a 2° latitude by 2° longitude resolution. The algorithm and list of GCMs used in this analysis are provided in the SI.

We use a 19-member multi-model GCM ensemble run under the ‘business as usual’ (Representative Concentration Pathway (RCP) 8.5) scenario. For each GCM, we calculate historical annual P/PET aridity values at each grid cell using the 1976–2000 time period. Note that while we consider annual values, P/PET will depend on the time unit of aggregation. We consider changes in aridity to be robust if at least 70% of models agree on the direction of change in aridity at any one grid cell and if the multi-model mean (MMM) aridity change exceeds 5% relative to historical values. If the MMM change in aridity is less than 5%, we consider there to be an insignificant change in aridity. For the moisture deficit index we consider absolute changes in P-PET to be significant if they exceed 84 mm yr⁻¹. This value was chosen to qualitatively match the mapped 5% changes in P/PET.

For observations, we use the CRU dataset [37] version TS4.00, which provides gridded monthly data over land spanning the 1901–2015 time period. This dataset provides precipitation, based on observations, as well as PET, estimated using the P-M equation. Trends in aridity using CRU data are calculated over the 1976–2015 time period using ordinary least squares regression.

For aridity zones, we adhere to the classification of the United Nations Convention to Combat Desertification [48], which uses P/PET values to subdivide drylands into aridity zones of hyper-arid (<0.05), arid (0.05–0.2), semi-arid (0.2–0.5), and dry sub-humid (0.5–0.65). We consider any P/PET values above 0.65 to be humid for the purposes of this analysis. Hyper-arid zones are excluded from our analysis because they occupy very little land area and have very few inhabitants.

**Population data**

For population density we use the Gridded Population of the World version 4 dataset [49], which provides population density estimates at a 30 arc second resolution for 2015. This dataset is compiled from the 2010 round of Population and Housing Census, which collected housing data from 2005–2014 and extrapolated for the year 2015. We average population density to a 2° latitude by 2° longitude grid resolution to match the GCM data.

For population projections we use country level UN population estimates (1950–2015) and population growth estimates (2016–2100) from the United Nations, Department of Economic and Social Affairs, Population Division [50]. These population growth estimates assume a medium fertility variant which assumes that global fertility rates decline from 2.5 children per woman in 2010–2015 to 2.0 children per woman by the end of the 21st century. Under this scenario, global population reaches 11 billion by 2100. While the most developed countries are projected to have smaller populations by mid-century than they do today, the least developed countries’ populations are projected to continue to grow, though the rate of growth slows during the century. We assume that country level growth rates can be applied evenly to all population density grid cells found within the country boundaries.

Country level water consumption data come from Aquastat, a dataset from the United Nations Food and Agriculture Organization [51]. Total per capita water consumption is used in the analysis, which is an aggregate of municipal, agricultural, and industrial water consumption.

**Results and discussion**

**Aridity change in the 21st century CMIP5 multi-model ensemble**

We begin by illustrating the emergence of drying trends in the CMIP5 RCP 8.5 MMM in figure 1. For reference, calculated historical aridity distributions are
presented in figure S1.) The panels on the left illustrate the percentage change in the aridity index whereas the panels on the right illustrate the absolute change in the moisture deficit. For both metrics, we see an emerging drying trend in Northern and Southern Africa, parts of Latin America, Southern Europe and Australia early in the 21st century. By mid-century, models project these regions, together with the southern portion of North America, to experience robust drying with aridity increases exceeding 10% and the moisture deficit exceeding 200 mm yr^{-1}. Upon inspection, figure 1 suggests that drier regions (as shown in S1) experience both an earlier emergence and a greater degree of drying. This is explored further in figure 2.

One obvious difference between changes in the aridity index versus the moisture deficit index in figure 1 concerns the regions of uncertainty, as shown in white. For example, figures 1(a)–(c) suggests that models are uncertain about the direction of change in aridity over the Saharan desert, whereas figures 1(d)–(f) show a robust drying trend. This is a result of the historical aridity signal being nearly equal to zero in this region due to very small annual precipitation values. Small differences in precipitation between future and historical projections in any one GCM can have a large influence on the percentage change of the MMM, even if most GCM’s aridity values stay very close to zero.

We investigate further the rate and degree of increases in aridity by aridity zone. Figures 2(a) and (d) illustrates the proportion of land area, by aridity zone, where there is a robust drying signal across models in this scenario. Figure 2(a) shows that 50% of land area in all aridity zones is projected to be at least 5% more arid by 2075. There is remarkable agreement across all aridity zones in terms of the proportion of land area that is projected to become more arid. In contrast, figure 2(d) indicates that the moisture deficit is increasing earlier and across more land area in all dry-land classified zones as compared to the humid zone. For example, by 2035, ~60% of arid land area will have
a robust drying signal, while ~45% of dry sub-humid land area and just over 20% of humid land area will have a robust drying signal. Figures 2(b) and (c) illustrate how the robustness of the aridity response changes as the threshold of drying increases. Figures 2(b) and (c) show that more severe drying emerges earlier in arid zones than in humid zones, and a greater fraction of the land area exhibits robust drying for arid regions. A similar trend is shown for the moisture deficit (see figures 2(e) and (f)). Figures 6 and S7 indicate that this difference in drying across aridity zones is driven mainly by precipitation change differentials across aridity zones.

Figures 3(a) and (b) show the trends from an ordinary least squares regression over 1976–2015 of the decadal percentage change in aridity relative to 1976–2000 for the CMIP5 multi-model median and CRU observations, respectively. The spatial pattern in trends shows remarkable similarity between the multi-model median and observations. A wetting signal is shown in the Sahel, Greenland, and Northwestern Australia, and a drying signal is shown throughout most of Sub-Saharan Africa, Europe, Saudi Arabia, the Southwestern United States and Brazil. The observed trends show a larger magnitude signal than the multi-model median, though this is not surprising given that variability would be smoothed out in the ensemble median. Analogous maps to figure 3(b) for individual single runs of different GCM simulations (shown in figure S4) show similar magnitudes of trends, though sometimes in different locations.

Figure S5 shows the proportion of land mass by aridity zone where CRU observations show a decrease in P/PET of 5% or greater relative to 1976–2000. The analogous plot for individual GCM simulations is shown in figure S6. Observations indicate that arid zones have already experienced a greater extent of drying than more humid zones. The same is projected to be true for many of the individual GCM simulations.

**Populations and aridity change over the 21st century**

Figure 4 illustrates population density (number of people km$^{-2}$) in locations projected to experience robust minimum aridity changes of various magnitudes relative to 1976–2000. These maps include projections of population growth. Figures 4(a) and (b) show that according GCMs, a robust drying trend of 5% or greater emerges in some regions in the 2001–2015 time period, coinciding with populations in parts of Northern Africa, the Middle East, and South America. Figure 4(c) is analogous to figure 4(b) but for CRU observations, which indicate that populations adjacent to the Mediterranean Sea have already
Figure 3. (a) Trend in the CMIP5 multi-model median decadal percentage change in P/PET from 1976–2015 relative to the 1976–2000 annual mean P/PET value. Colors are plotted for trend values that are significant at the 90% confidence level. (b) As in (a) but for the CRU observational dataset.

Figure 4. (a) Population density experiencing a decrease in P/PET of 5% in 2001–2015 relative to 1976–2000 for scenario RCP 8.5. (b) As in (a) except close up on the Mediterranean sea and adjacent land area. (c) And is (b) except that changes in P/PET are calculated using CRU observations from 2001–2015 relative to 1976–2000. (d)–(f) Population density experiencing a decrease in P/PET of 5%, 10% and 20%, respectively, in 2041–2060 relative to 1976–2000. (g)–(i) As in (d)–(f) except aridity changes are projected for the time period 2081–2100 relative to 1976–2000. Colors indicate the projected population density (# people km$^{-2}$) living in locations where robust drying is projected to occur. Grey indicates that the majority of models do not exceed the drying threshold.
experienced a drying of 5% or greater. By mid-century (figures 4(d)–(f)), the extent and degree of drying has increased such that aridity changes are expected to be 20% or greater in regions highlighted in figures 4(b) and (c). By mid-century, Southern Africa, most of Europe, and Central America are projected to experience a robust decrease in P/PET by 10% or greater, and China, most of the United States and parts of Canada are projected to experience a robust decrease in P/PET of 5% or greater. These projected drying patterns continue to spread in extent and become more severe by the end of the 21st century (see figures 4(g)–(i)).

We could reframe this question by asking ‘how many more people will live in arid zones by the end of the century’. Assuming population distributions remain unchanged, this analysis indicates that approximately 200 million more people are projected to live in arid and hyper-arid regions (P/PET < 0.2) by the end of the century if global emissions follow a business as usual trajectory (see figure S8 showing population distribution by the CMIP5 MMM aridity index (P/PET) under historical climate and at the end of 21st century). If population growth estimates are accounted for then the number of people living in arid zones is projected to double. This is equivalent to approximately 700 million more inhabitants in arid zones by the end of this century. This suggests both that dry zones are projected to dry further and that dry zones are regions where we expect to see high population growth. The largest population increase in arid regions is projected to occur in Africa and the Middle East (see figures S9 and S10 for the locations of these populations).

One of the central aims of this paper is to probe the impacts of aridity change on global populations. To do this, we ask the question ‘to what extent will the aridity index change in countries where per capita water consumption is presently very low’. To answer this question we consider aridity changes in countries where inhabitants are living under absolute water scarcity (shown in figure 5). Absolute water scarcity is defined by per capita water withdrawals at or below 500 m$^3$/person/year [51, 52]. As a reference point, the United States’ per capita water withdrawal is just over 1500 m$^3$/yr$^{-1}$, whereas most countries in Africa have a
per capita water withdrawal of less than 100 m$^3$ yr$^{-1}$.

In Figure 5, the most vulnerable regions are shown to be in Southern Africa, large parts of Europe and Brazil, where inhabitants presently live under absolute water scarcity, and drying is projected to emerge early in the 21st century. Note that some developed countries with low water consumption appear in parts of Europe (for example, France and Germany). This is in part due to low industrial and agricultural water consumption in these regions.

### Drivers of aridity change and population impacts

In this final section, we investigate the drivers of aridity change and the relative contributions of temperature and precipitation to aridity change and impacts. Figure 6(a) shows projected changes in aridity by mid-century where temperature is held constant at historical values. This pattern holds for other time periods. Here we see a robust drying in southern Africa, the southern United States and Mexico, Europe, China, parts of Australia and throughout most of Latin America. We also see a robust wetting in Northern Canada, the horn of Africa, India, throughout the Tibetan plateau and the eastern portion of Russia. The individual contributions of precipitation, temperature, and RH to total aridity change are shown in S11. Here we see that temperature contributes to ubiquitous drying, with increased drying in northern latitudes. The contributions from RH are small in comparison to both temperature and precipitation although it should be noted that such an offline calculation is unable to account for the inherent coupling between relative humidity, temperature, and precipitation. By considering these relative changes, we see that precipitation is driving the most variability in aridity change, whereas temperature change is leading to increased PET globally.

Interestingly, the most extreme drying due to precipitation change occurs in the subtropics and coincides with the most arid regions of the world. This point is illustrated in S7, which shows the relative contributions of T and P to aridity change, by aridity zone, and by intensity of aridity change. We notice that temperature increases tend to dominate the drying response in all types of arid zone for mild drying ($\Delta P$/$\text{PET} = -5\%$). However, for more extreme drying, precipitation plays an increasingly important role, more so for drier regions.

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**Figure 6.** (a) Percentage change in P/PET in 2040–2060 relative to 1976–2000 under RCP 8.5 where temperature is held constant at 1976–2000 values. (b) Shows the fraction of aridity zone over time, by area, where at least 70% of GCMs agree precipitation (P) will decrease by at least 5%. Same as (b) except for an increase in P of at least 5%.
In figures 6(b) and (c), we explore this question further by considering the robustness of the proportional changes in P across aridity zones. Figure 6(b) illustrates that robust decreases in P are projected to occur early in the 21st century over arid regions extending over approximately 30% of land area. Humid regions see very little decreases in precipitation by comparison. In contrast, figure 6(c) shows that humid regions are projected to see a robust increase in P over more than 50% of humid land area by 2075. This is a far greater increase in P than is exhibited by drylands. This robust trend in P across aridity zones suggests that precipitation may be the driving mechanism leading the differential trend in the aridity index across aridity zones. RH was also considered and results are shown in S12; arid zones are projected to see the largest extent of both RH increases and RH decreases, suggesting that RH is not driving the trend in aridity change across aridity zones.

While the Held and Soden [25] ‘wet-get-wetter, dry-get-drier’ mechanism was shown to break down over land [26], we have shown here that a moisture mechanism that appears to hold over land may be better described as ‘most-land-gets-more-arid, humid land-gets-more-rain’. Note, however, that a number of the humid regions receiving more rain are sparsely populated, and we address this point further below.

Figure 7(a) shows the total number of people who live in regions projected to see an increase in aridity of 25% or greater (i.e. P/PET decreases by 25% or more), assuming that the population distribution remains unchanged. Here, the solid line represents the MMM value as a function of global mean temperature change and the shaded region indicates $+/−1$ standard deviation. The green line provides the projected values under RCP 8.5, the purple assumes temperature is held constant at historical values, and the red line assumes that precipitation is held constant at historical values. With a 5°C increase in global mean temperature, the MMM projects that 2 billion people will be subjected to aridity increases of 25% or more. If global temperatures remain at 2°C, this value is instead roughly half a billion people. If, instead we calculate these values assuming the medium variant population growth (see figure 7(c)), then the MMM projects that 3 billion people will be living in a region that is 25% more arid than historical values, as shown in figure 7(b).

Considering the relative impacts of the purple and red lines, we see that for both figures 7(a) and (b), precipitation seems to more important than temperature in driving the population level aridity change, especially for global mean temperature values $<3$°C. Their relative contributions converge for higher global mean temperature values. Figure S13 shows that more than half of the world’s population is projected to experience drying of 5% or more.

Figure S14 shows analogous plots to figure 7 but disaggregated by continent. According to GCMs, Africa is projected to experience the largest population impacts with more than a billion inhabitants expected to experience a drying of 25% or more. The second largest population projected to see increases in aridity is in Asia, where ~750 million people are projected to be impacted by aridity increases of 25% or greater. Surprisingly, even in Europe, where populations are decreasing over time, models still project that nearly half a billion people will live in places undergoing severe drying of 25% or greater under a global mean warming of 5°C. S14 shows that for Europe and North America, aridity change is largely driven by warmer air surface temperatures (note the proximity of the red line to the green line in these figures). In Africa and Latin America, aridity change is driven by decreases in precipitation.

The analogous plot to S14, but weighted by land area instead of population size is shown in S15.

Conclusions

In this paper we set out to identify the regions where robust aridity changes are projected to occur and the relative timing and extent of these changes. We find that robust changes in both the aridity index (P/PET) and the water deficit (P-PET) are emerging first and more severely in dry zones (figures 1 and 2) whereas humid regions are seeing a slower, less extensive, and less extreme increase in aridity.

While impacts on ecosystems and nature are likely to be important even in unpopulated areas, here we considered various thresholds of robust increases in aridity under a business as usual emissions scenario and human populations. GCM projections show that densely populated regions adjacent to the Mediterranean Sea (North Africa and parts of the Middle East) have already begun to exhibit a robust drying trend (figure 4(a)). This is consistent with observed drying trends (figure 3(b)). By mid-century these regions are projected to be at least 20% drier under the RCP 8.5 emissions scenario, while densely populated regions throughout most of Europe, China, and Southern Africa and coastal cities in United States are projected to dry by at least 5%.

If current projections are valid, populations living in arid regions will grow by between 200 and 700 million people by the end of the 21st century (figure S8). While it is known that global drylands are expanding [8], here we have shown both how this expansion is projected to coincide with human populations (as mapped in S9 and consistent with [5]) and that many arid regions are expected to see high population growth. Reduced global emissions of greenhouse gases could reduce these impacts on human populations compared to the business as usual scenario [5], and populations may migrate if aridity changes become intolerable, but here we have examined how business as usual emissions together with current estimates of
future population distributions would collide in the absence of such actions.

While we identified regions where aridity change is projected to coincide with large populations, it is important to recognize that this does not describe the full extent of aridity impacts on human populations. Sparsely populated yet agriculturally intensive areas, for instance, will no doubt have important economic outcomes [24].

We also examined the extent to which precipitation and temperature changes affect aridity change. Figure 6(a) shows that even without temperature increases, a drying signal is robust across GCMs throughout Southern Africa, most of Europe, Australia, most of Latin America and China. Increases in temperature serve to exacerbate drying in these locations. These regions coincide with regions where we expect drying to emerge first (e.g. figures 1(a) and (d)) and where we expect relative drying to be the most extreme (e.g. figures 1(c) and (f)). There are locations, (e.g. most of Asia), where drying is projected despite increases in precipitation.

We identify precipitation change to be the driver of differential drying across aridity zones. According to GCMs, ~30% of drylands experience a robust decline in precipitation and almost no humid regions

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Figure 7. (a) Number of people who live in regions subjected to >25% decrease in P/PET as a function of change in mean global temperature. This is based on population distributions for 2015, where global population was 7.4 billion people. The solid lines represent the MMM and the shaded region represents +/- 1 std. The green line is for the RCP 8.5 scenario. The red line is the same as the green line except precipitation is held constant. The purple line is the same as the green line except precipitation is held constant. (b) As in (a) except populations increase following the UN Medium Variant population projections as shown in (c).
(≈5%) exhibit declines in precipitation with global warming. Further, larger portions of humid regions (>50% of land area) see a robust increase in precipitation. Humidity was not found to drive the differential drying across arid zones (shown in S1I and S12).

We examine how extreme aridity increases (i.e. a decrease in P/PET of 25% or more) are projected to coincide with human populations. With a global temperature increase of 2 °C, approximately half a billion people are projected to live in locations experiencing extreme drying. Whereas, with a 5 °C increase (a possibility by the end of the century under the RCP 8.5 emissions scenario), 2–3 billion are projected to live in locations undergoing extreme drying, with most of those people living in Africa and Asia (figure S14). In Africa, the drying is largely driven by precipitation declines, whereas in Asia temperature and precipitation contribute more evenly.

While the ‘wet-get wetter, dry-get drier’ paradigm has been a useful way to characterize global climate change, some recent studies have probed its applicability over land, and here we have further probed its application for human populations. Our key conclusion is that most of the world’s population is projected to live in locations that become drier in the 21st century. Further, we have shown that arid zones are drying faster than humid zones, and that precipitation is driving this trend. The largest population impacts occur in Africa, which again, are most influenced by changes in precipitation. Most of sub-Saharan Africa is also living under absolute water scarcity (see figure 5), making these populations most vulnerable to increases in aridity. As populations plan to adapt to or mitigate climate change, this work suggests that a drier global future for human society is a paramount challenge.

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