Climate change and drought: the soil moisture perspective

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**Abstract**

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Purpose of review:

We review the extensive and sometimes conflicting recent literature on drought changes under global warming. We focus on soil moisture deficits, which are indicative of associated impacts on ecosystems. Soil moisture is a key state variable of the land surface, reflecting complex interactions between the water, energy and carbon cycles.

Recent findings:

Offline projections relying on soil moisture-proxy metrics indicate dramatic future drought increases, often interpreted as primarily driven by warming-induced increases in evaporative demand. However, such results appear inconsistent with other trends in the land-atmosphere system, including soil moisture, vegetation and evapotranspiration. Recent studies begin to explain these discrepancies, highlighting the importance of soil-vegetation-atmosphere coupling, unaccounted for in offline projections.

Summary:

Future changes in soil moisture droughts should preferably be assessed with prognostic model outputs rather than offline heuristics and be interpreted in the context of the coupled soil-vegetation-atmosphere system.

**Introduction**

Drought is an anomalous lack of water at the land-atmosphere interface. It begins with a reduction of precipitation (known as meteorological drought), and can propagate, as it persists, into soil moisture (agricultural drought) and stream flow, lake levels and groundwater (hydrological drought). Drought can have huge impacts on all aspects of human activities, including water resources, agricultural production, energy generation and industrial output. For example, the recent drought in California caused $2.2B in losses with agricultural losses alone of $810M [1], and led to multiple further effects, such as on water restrictions [2] and land subsidence [3]. Drought also has large impacts on ecosystems, contributing to, for example, tree die-off [4]. In the developing world, where livelihoods are dependent on agriculture, drought can have devastating impacts, leading to famine, migration and potentially conflict [5-7]. As a result, the potential for increasing drought severity, and more generally, a shift in the mean level of aridity, is perhaps one of the more concerning possible consequences of global warming.

We generally have a good understanding of the drivers of meteorological drought variability; that is, a combination of sea surface temperature variability and land-atmosphere feedbacks, in addition to random, and unpredictable, weather fluctuations [8-10]. With climate change, it is expected that this will continue; but as the global climate system changes, drought risk will be altered by the interaction of mean changes with changes in variability and land-atmosphere feedbacks. These potential alterations and related trends have been the focus of numerous articles since the 1990’s and have been increasingly discussed by IPCC reports beginning with the third assessment report [11]. While the last IPCC report [12] indicates that current global trends in droughts are uncertain, it indicates likely increases in regional drought in the future based on climate model projections**.** In addition, in recent years, prominent droughts, such as in the central US in 2012, California from 2012 to 2015 and in east Africa in 2011, have broughtthe topic of drought very much to the forefront of public conversation regarding climate change, with a number of papers arguing that global warming has enhanced the intensity of these recent droughts [13, 14, 15]. It is fair to argue that what has been communicated to the public is the notion that global warming will increase the severity of drought in the future, perhaps dramatically. The scientific literature on the topic is vast and growing since the last IPCC report. At the same time, there remain considerable uncertainties and therefore confusion about current and future trends, and much of this is due to differences in how studies quantify and interpret changes in drought. Thus, a review on the subject is timely.

Much of the uncertainty about changes in drought stems from how drought manifests in “agricultural” drought, better defined as “soil moisture” drought. Soil moisture drought is of key importance because reduced soil water levels are typically associated with soil water stress for vegetation, which constitutes a major constraint on the physiological functioning of natural and cultivated ecosystems and which can thus lead to large impacts on agricultural production. We shall go back to this point throughout the paper. The translation from meteorological drought (i.e., precipitation deficit) to soil moisture drought depends on numerous processes that affect the surface water balance; but, to leading order, soil moisture drought can be viewed as the result of the time-integrated balance between the precipitation deficit and subsequent water losses from the surface in the form of soil evaporation and plant transpiration (i.e., evapotranspiration), runoff to rivers and lakes, and drainage to the subsurface. The complexity of propagation processes leads to uncertainties and misconceptions about how drought is changing and will change in the future, and particularly the role of rising temperatures.

In a first part, we will review how much of the concern about increased soil moisture drought with global warming is based on the notion that increases in evaporative demand with higher air temperatures will lead to increased evaporative losses from the surface and greater soil moisture deficits. In a second part, we will examine issues that have been raised regarding this notion, in particular in terms the consistency with other aspects of model projections of the terrestrial water and carbon cycles. Lastly, we will review recent literature that begins to reconcile these discrepancies. Central to the correct interpretation of projected drought changes in the future is the understanding of projected trends in evaporative demand over land and their link with changes in other variables of the terrestrial water cycle (ET, soil moisture), carbon cycle (CO2 and vegetation) and surface climate in the context of the coupled land-atmosphere system.

**1. Projections of increased soil moisture drought with global warming: role of temperature-driven increase in evaporative demand in offline drought metrics**

1.1. Soil moisture drought proxy indices

Variations in soil moisture, including drought events, are difficult to monitor directly on a global or even regional scale: soil moisture is a spatially heterogeneous field, and in situ networks are sparse and unevenly distributed [16,17]. Remote sensing offers the potential to address these issues, but suffers from its own limitations: microwave remote sensing only characterizes surface (top few centimeters) soil moisture, and retrievals are challenging to interpret in highly vegetated regions [16]; gravimetric observations characterize total terrestrial water storage at coarse spatial resolution, which may be ill-suited for monitoring soil moisture specifically; in addition, remote sensing products, especially the most recent ones (e.g., the Soil Moisture Active Passive (SMAP) mission [18]) do not cover enough time to study long-term variations in droughts.

Instead, soil moisture proxies, or metrics, have been used extensively. Conceptually, such metrics consider, in various ways, the balance between moisture supply (precipitation, P) and demand (potential evapotranspiration, PET), with a low supply/demand ratio corresponding to low soil moisture availability and increased drought conditions. The most well-known and used is the Palmer Drought Severity Index (PDSI), which runs monthly precipitation and PET estimates through a simple two-layer water budget model to estimate moisture deficits, at a given time, relative to a long-term climatological average [19]. The PDSI is routinely used to monitor drought conditions over various regions (e.g. the U.S. Drought Monitor; [20]). More recently the Standardized Precipitation Evapotranspiration Index (SPEI; [21]) was proposed, which considers the summed difference between precipitation P and PET. Although it represents background climatological aridity rather than drought events, the Aridity Index (P/PET; [22]) is conceptually similar, in that it characterizes land surface aridity from a moisture supply/demand perspective.

The appeal of this type of approach is that soil moisture changes can then be monitored and analyzed based solely on surface climate observations. This is especially the case when PET is estimated based only on temperature, such as with the Thornthwaite method [23], as was done in the original PDSI formulation [19] and in early studies of long-term drought variability [24] and is still the case in some operational datasets [20]. A more physically-based estimation of evaporative demand is the Penman-Monteith formulation [25], which includes other factors that can drive PET variations such as net radiation, wind speed and humidity [26]. This comes at the cost, however, of increased uncertainty in the different inputs required.

Although the PDSI uses a simple water balance model and suffers from several process-level limitations (e.g., no delayed-runoff from cold-season processes like snow; no direct representation of vegetation), several studies have shown it to be, at least in the present, an acceptable proxy of modeled and observed soil moisture seasonal and inter-annual variability [15, 24, 27-30] as well as of tree ring records over the past 1000 or more years [31].

Given that soil moisture proxies are used to monitor present-day droughts and investigate past changes, it would be natural to apply them as well to climate change projections. This can be done in a straightforward manner by computing the different metrics with climate model projections of near-surface climate. This is appealing as it provides estimates of future changes that can be directly compared with past and present values. In particular, it bypasses the diversity of soil schemes and land hydrology representations in climate models, which leads to large model differences in soil moisture values and their projections, which can be difficult to interpret (32, 33). Instead it derives one consistent metric of drought that can be compared and/or averaged across models. Finally, soil moisture drought metrics can be efficiently computed many times over allowing investigating the impact of different driving variables, input data sets, and methodological schemes [15, 34, 35].

1.2. Projections of increased P and PET over land with global warming

Climate models robustly predict an increase in global-mean precipitation in response to increased radiative forcing [12]. Because precipitation increase is constrained by atmospheric radiative cooling [36, 37], however, it occurs at a much lower rate than the Clausius-Clapeyron rate of increase of atmospheric water vapor with warming: 1 to 2 %/K versus 7%/K. Globally averaged, this increase takes place over land at about the same rate as over oceans, albeit with greater model uncertainty [38]. Precipitation increases over large parts of the land surface, but models simulate robust and significant decreases over subtropical regions, such as Southern Africa, the Mediterranean Basin and Central America. Projections of increased meteorological drought, e.g., based on precipitation indices, are confined to these regions [39].

Penman-Monteith PET, on the other hand, is projected to increase over land at a much greater rate than precipitation – around 5%/K - and much more homogeneously [38, 40, 41]. This reflects the fact that the PET increase is driven primarily by warming-induced increases in vapor pressure deficit and changes in the slope of Clausius–Clapeyron relationship [40]. Noting that i) the fractional change of P over land can be approximated by the fractional change of evaporation over oceans, and that ii) over oceans actual evaporation and PET are equal, the fractional change in P over land can be approximated by that of PET over oceans; the greater fractional increase in PET than in P over land has thus been interpreted as the result of the greater change in PET over land than over oceans [38]. This difference is itself largely caused by the enhanced warming over land relative to ocean as well as by the decrease in relative humidity changes over land, in contrast to slight oceanic increases [42]; both patterns are fundamental, large-scale features of climate change robustly predicted by climate models [43, 44]

1.3 Projections of increased soil moisture drought

When model projections of P and PET are used to calculate “offline” soil moisture drought metrics into the future, this indicates widespread future increases in drought, in general, because PET under global warming increases faster than P.

Many studies report widespread projected decreases over land of the mean value of the PDSI (corresponding to increasing drought conditions) with robust declines over much of North America, the Amazon Basin, southern Africa, the Mediterranean, Europe, southeast China, and parts of Australia [28, 30, 45-47]. Robust PDSI increases (reduced drought) occur mainly in the Northern Hemisphere high latitudes and East Africa. For instance, Zhao and Dai (2015) report that global area under the moderate (severe) drought conditions could increase from 20 % to about 28 % (from 10 % to 16 %) by 2080–2099 based on CMIP5 projections under the RCP4.5 scenario. Large regional drying is projected, such as in the Southwest US and Central Great Plains, where future drought risk likely exceeds even the driest centuries of the Medieval Climate Anomaly (1100–1300 CE), leading to unprecedented (during the last millennium) drought conditions [29].

A key aspect of these analyses is that, although regional drought changes largely mirror the pattern of precipitation change in the models, PDSI decreases extend beyond the regions of reduced precipitation. This reflects the effect of widespread and spatially homogeneous increases in PET, which, superimposed on precipitation changes, not only intensify drying in areas where precipitation decreases in the first place, but also drive areas into drought that would otherwise experience little drying or even wetting from precipitation trends alone, such as the Central Great Plains or Southeast China [28, 30]. In the Southwest US for instance, regional temperature increases alone under the RCP8.5 scenario are found to push “megadrought” risk (defined as multidecadal drought as severe as the worst multiyear droughts of the 20th century) above 70% or 90% by the end of the century, even if precipitation increases moderately or does not change, respectively [35].

Projections with the SPEI are qualitatively similar, if not even more dire, because the calculation of the SPEI is more sensitive to the increase in PET than the PDSI [28]. Consistent with the above, numerous studies using the Aridity Index (P/PET) also reports increasing land aridity in climate projections, stemming from the greater and more homogeneous increase in PET than P over land, with drying patterns resembling those of the studies above [22, 38, 41, 42, 48-52]. Because present-day Aridity Index values broadly correspond to different biomes, this decrease in P/PET is often interpreted in terms of future extension of dryland ecosystems [48].

The above projections are indirect proxies of future soil moisture changes. Confidence in these results is enhanced by the apparent consistency with climate model projections of soil moisture. Although there are differences between climate models in the sophistication of their land surface component and correspondingly large uncertainties in their simulated soil moisture fields, model projections do show robust decreases in surface soil moisture (top 10cm of the soil) around the globe, with, again, similar spatial patterns as mentioned above and regional declines of up to 10% [12, 30, 53]. No regions show robust or statistically significant increases in surface soil moisture, even in regions of increased precipitation. Further, future PDSI changes do appear generally significantly correlated with near-surface and even, in certain regions, root-zone soil moisture changes from the same climate models [29, 30]. The consistency between these different measures of soil moisture drought seemingly seals the case for spatially extensive increased drought conditions in a warmer climate, mainly driven by warming-induced increases in evaporative demand.

**2. Uncertainties in projections of increased drought with global warming: consistency of offline drought metrics with changes in the coupled soil-atmosphere system.**

The extensive and growing literature cited in this first section forms the primary basis for concern regarding the risk of increased soil moisture drought in a warmer climate. However, a number of questions can be raised with respect to the consistency of such projections with other lines of evidence on the evolution of drought in a warmer climate. We discuss some of these next. These involve questions about consistency with data on paleo-environments, with simulated future changes in the terrestrial water cycle taken directly from climate models, and with current estimated trends in drought.

2.1. The Aridity Paradox

The notion that a warmer climate leads to a drier land surface, i.e., increased water stress, driven overwhelming by the effect of warmer temperatures on evaporative demand, appears, however, inconsistent with paleo-evidence and vegetation reconstructions for different colder and warmer past climates.

For instance, the Mid-Pliocene Warm Period, circa 3 Ma ago, is often considered a close enough analogue for current anthropogenic warming, because of similar continental configurations, land elevations and ocean bathymetries as today, and near-modern atmospheric CO2 in the range of 350-450 ppm [54]. Climate model estimates indicate that the global annual mean surface temperature was 2.7–4.0 °C higher at that period than modern (pre-industrial) climate, with little low-latitude warming and strong polar amplification [55]. However, vegetation reconstructions (based on data fusion between dozens of palaeobotanical sites and an ecosystem model) show a general increase in vegetation in this warmer world, including an expansion of tropical savannas and forests at the expense of deserts and a northwards shift of temperate and boreal vegetation zones [56]. A few regions show a shift towards more arid vegetation (e.g., southern Mediterranean), but, to first approximation, there is no evidence of a widespread drying of the land surface and associated expansion of arid ecosystems, in that warmer climate, of the kind suggested by offline soil moisture proxy projections under future warming.

Similarly, the Last Glacial Maximum (20kyr ago), which was around 5C cooler globally than modern climate, featured less forests and much wider distribution of dry vegetation biotopes, including deserts, grasslands, savanna, and dry steppe [57], suggesting greater hydrological constraint, on average, on ecosystems. While very low levels of atmospheric CO2 (190 ppm) at that time also likely limited vegetation productivity [58] and contributed to these biogeographic differences [59], overall such differences do not appear consistent with the notion that warmer (colder) climates are associated with substantially greater (lower) soil moisture stress on vegetation.

The apparent inconsistency between paleo-evidence and drought projections has been called the “Aridity Paradox”, with some authors arguing that it implies some level of misinterpretation of future drought/aridity projections from climate models [60].

2.2. Consistency between projections from offline drought metrics and climate model outputs

As mentioned above, using simple, offline metrics is an appealing and efficient approach to analyze future change in soil moisture drought. However, beyond simulated surface climate, model simulations of the terrestrial water cycle can also be analyzed directly. For some variables, they do not appear entirely consistent with projections from offline drought metrics.

First, we should note that over the global land surface, terrestrial water fluxes (precipitation P, evapotranspiration ET and runoff Q) are all projected to increase on average over the 21st century [12, 30]. Patterns of multimodel mean annual changes in P, ET and Q look broadly similar, with robust regional decreases in Central America, the Mediterranean, and Southern Africa, and no significant changes or robust increases elsewhere. This suggests, to leading order, a primary role of precipitation change, rather than temperature, in driving future changes in terrestrial hydrology and is consistent with interpretations of drivers of historic runoff changes [61]. Models also project widespread, nearly-homogeneous increases in vegetation (except to some extent in the above mentioned regions) [59, 62]. As noted above, models do project reduced surface soil moisture over large parts of the globe, with around 70% of land areas exhibiting reductions in the multi-model mean projection under the RCP8.5 scenario [12, 33, 53]. However, total-column soil moisture changes are more uncertain [33, 63], and only slightly negative in the global mean [64, 65]. Further investigation, such as considering the multi-model median instead of the mean in order to avoid results being skewed by large permafrost disappearance at high latitude in a few models, as well as integrating soil moisture down to a common 3-meter depth across models in order to better characterize soil moisture availability for vegetation, indicates that future projections exhibit roughly 50% of land area with either positive or negative changes [33]. Thus, multi-model projections in P, ET, Q, soil moisture and vegetation appear, at face value, qualitatively inconsistent with the notion of widespread, temperature-driven drying of the land surface under global warming.

Mean soil moisture change does not necessarily reflect changes in drought events, however, as changes in variability can also affect the occurrence of extreme events. Comparatively fewer studies have analyzed future drought projections based directly on climate modeled soil moisture, and these do show increases in drought area, duration and frequency, but with large model uncertainties and significant changes being restricted to regions of decreased mean precipitation [39, 64].

As indicated above, studies based on offline drought metrics generally verify that their projections correlate with soil moisture projections [29, 30]. However, there are some caveats to such comparisons. First, they may be limited to specific regions [30], which tend to be where precipitation decreases, and so do not address the claimed drying effect of temperature increase even in the case of no precipitation change. Metrics based on precipitation, soil moisture and the PDSI have indeed been shown to be similarly sensitive to precipitation changes, but to show metric-dependent responses to changes in temperature [66]. Secondly, the use of surface soil moisture in such comparisons is problematic [30], because, as mentioned above, projected soil moisture changes exhibit a vertical gradient, with more negative changes near the surface, in particular in northern hemisphere mid-latitudes [33]. Thus, top surface soil moisture may not represent well total changes in soil water availability to vegetation. Finally, regional comparisons between PDSI and soil moisture projections are not always convincing for models taken individually [29], highlighting the complexity of the relationship between changes in surface climate, off-line metrics and actual soil moisture across models. Several studies have shown discrepancies between drought projections based on PDSI and soil moisture anomalies, when PDSI is calculated with the more temperature-sensitive Thornwaite PET [68], but also when it is calculated with the more physically realistic Penman-Monteith PET [66, 68, 69].

So, overall, analysis of column-integrated soil moisture from climate models indicates slight global decrease in mean levels, and corresponding increases in drought conditions, but mostly in regions of decreased precipitation. Soil moisture changes appear consistent with projections from drought metrics in such regions, however, they do not suggest increased drought conditions outside of those, in contrast to what is projected by drought metrics as a result of temperature effects.

2.3. Uncertainties in current, observed trends in droughts

If drought metric projections are to be believed, this raises the question of whether a drying signal is detectable in current, observed trends in drought over the last few decades. Here, we show that uncertainties in future drought projections between soil moisture and offline drought metrics are also reflected in assessments of current trends.

First, while some studies report an increase in soil moisture drought across the globe based on the evolution of the PDSI [24, 34, 45], there are significant uncertainties even in the calculation of the PDSI over recent decades. These revolve around: i) the formulation used to compute PET, e.g., the choice between a simple temperature-based parameterization like Thornthwaite and the more realistic Penman-Montheith [70]; the choice of the calibration time period for the computation of the PDSI itself [71, 72]; iii) the choice of climate forcing dataset, in particular for precipitation [72]. While some combinations of these options leads to the conclusion that drought has been increasing [34], others can lead to estimates of little change in drought conditions, with no clear indication as to which individual methodology is best [70].

As indicated in the first section, soil moisture is challenging to monitor from space. However, efforts have been conducted to merge the different available global passive and active microwave remote sensing products going back to the late 1970’s into one dataset, offering the possibility to analyze the evolution of surface soil moisture over time [73]. Global-scale trends over 1991-2016 show little trace of overall decrease [74]. Spatial patterns include a few more regions (60% of the land area) with negative trends [17, 75]. Caution is advised, however, when interpreting these results because of the short-term record that is dominated by individual ENSO events, and the inability of this product to characterize soil moisture beneath dense vegetation, in mountain areas and in frozen soils.

Another option to investigate the evolution of soil moisture drought over the past few decades is to use comprehensive land models forced by estimates of historical climate, or to rely of renanalysis estimates of soil moisture. For instance, when the VIC hydrological model is forced by a hybrid reanalysis–observation forcing dataset over 1950-2008, an overall small wetting trend in global soil moisture is found, with predominantly decreasing trends in drought duration, intensity, and severity, although a switch towards increasing drought conditions around 1970 is noted [64]. Similarly, a multi-variate index based on precipitation and soil moisture data from land model simulations and remote sensing observations suggests no positive global trend in drought extent over 1982-2012 [76]. While their significance is limited on a global scale, it is also worth noting that over Eastern Europe, some of the few long-term in-situ measurements available (in a region where PDSI projections suggest strong future drying) show no decrease over 1958-2002, but rather a positive soil moisture trend for the entire period of observation, with the trend leveling off in the last two decades [77].

These uncertainties were reflected in the IPCC decreasing its level of confidence in the assessment of historical trends in drought from its fourth to its fifth report. It is also worth noting that over the last four decades, “global greening”, i.e. a widespread increase in leaf area index (LAI) measured by satellite, has been observed [78], including in semi-arid areas [79]. Such an increase is qualitatively consistent with the large growth in gross primary productivity estimated over the twentieth century [80], and would appear inconsistent with a concurrent increase in soil moisture deficits and vegetation water stress.

**3. Re-interpreting projections of increased soil moisture deficits in a warmer world**

In this last section, we review some recent studies that begin to reconcile the above inconsistencies, and suggest ways forward. Central to the correct interpretation of current and projected drought changes is the understanding of trends in evaporative demand over land in the context of the coupled land-atmosphere system: PET changes are a function of global warming but land-atmosphere feedbacks also modulate surface warming.

3.1 Evaporative regimes and land atmosphere coupling

Essential but implicit in the PET-driven view of increased soil moisture drought is that ET follows the warming-induced PET increase, thus depleting soil moisture: “*In most GCM projections, the drying signal over land is dominated by [temperature]-induced increases in PET acting to amplify evaporative water losses from the soil and surface*” [81]. However, ET projections are never analyzed concomitantly in such studies. We see several issues with that line of argument.

First, the concept of increasing ET as a feature of increasing soil moisture drought, i.e. of increasingly water-stressed vegetation, may be considered, in and of itself, somewhat paradoxical: in the long-term, one would expect increased drought to be associated with *lower* mean ET, because ecosystems become increasingly water-limited and transpiration decreases. Perhaps this argument should really be understood as that of an initial increase in ET driven by increased evaporative demand depleting soil moisture enough that, once soil moisture deficits become large enough, vegetation becomes more water-limited and mean ET is reduced. This mechanism would be necessary in particular to explain diagnoses of increased drought in regions of no precipitation change. However, ET increases rather monotonically on a global scale in CMIP5 projections [30], and a cursory evaluation of model projections in regions without any decline in P reveals no systematic concave, non-monotonic ET trajectory over time (i.e., initial increase followed by a decrease).

Secondly, if the PET-driven view of increased soil moisture drought was correct, a corollary would be that models with greater warming, and thus greater increase in PET, would show greater increase in ET and greater soil moisture depletion. This is not the case: investigation of CMIP5 models reveals, that, over much of the land surface, changes in ET and PET are anti-correlated across models, in particular in the vegetative season (summer; Fig. 1a). This reflects the complementary relationship that exists between PET and ET [82]: in moisture-limited regimes, which in summer cover a large portion of the land surface [83], lower ET modulates the surface energy budget in a way that leads to higher near-surface temperature, and thus higher PET. Because ET changes are positively correlated (across models) with soil moisture changes (Fig. 1b), it does appear that greater changes in PET are associated with more negative soil moisture changes, as would be expected based on PET-based assessments, but the causality with respect to ET changes is opposite. This result, across models, is consistent with studies showing that, in the context of one given model, warming over land is largely modulated by changes in moisture availability [65, 83, 84]. Therefore, over large parts of the land surface that are soil moisture-limited, (including the Northern Hemisphere mid-latitudes in summer), a better understanding of changes in near-surface hydroclimate may arguably be achieved by considering changes in moisture supply first (Fig. 1).

A similar argument can be made regarding studies relying on analysis of offline metrics to show that ongoing warming has intensified recent drought events, such as the 2012-2015 drought in California [14, 15]. Since warming enhances PET values, it inevitably leads to a decrease in PDSI values, i.e. a diagnosis of increased drought. However, no attempt is made in such studies to explicitly analyze land surface hydrology and land-atmosphere exchanges, nor to separate the share of warming that is caused by the drought itself [85]. When land-atmosphere model experiments are used to simulate the impact of increased radiative forcing over the last century, diagnoses based on bivariate indicators of precipitation and root-zone soil moisture indicate decreased probability of drought occurrence in California [86]. Over the Central Great Plains, soil moisture variability, as simulated by an offline, physically-comprehensive land model over the last 60 years, is largely dominated by precipitation variability over temperature, including during recent drought events such as the 2012 drought [87].

If changes in near-surface temperature and PET are caused in part by changes in water availability, it raises the question whether using changes in near-surface temperature and PET to infer changes in water availability (as is done, essentially, in offline drought studies) leads to a “double-counting” of land-atmosphere feedbacks. Note that this would true of any offline land surface modeling approach based on atmospheric outputs from coupled land-atmosphere models. This could be investigated more systematically by comparing offline and online hydrological outputs.

3.2 Physiological impact of atmospheric CO2 on vegetation

Because trends in PET are modulated by changes in ET, processes that affect ET changes will also have an impact on PET trends. Of particular relevance is the impact of increasing atmospheric CO2 levels on plant physiology.

Rising atmospheric CO2 levels stimulate carbon assimilation in plants but also reduce leaf-level stomatal conductance, allowing plants to reduce water losses per unit of carbon gain [88]. These effects are included in most (though not all) climate model projections. For end-of-century projections, the net effect is generally that even though CO2 fertilization leads to increased vegetation and leaf area, the effect of decreased leaf-level conductance dominates, and bulk (total) stomatal conductance decreases [89]. As a result, transpiration increase is limited (compared to a counterfactual case where higher CO2 levels would not affect plant physiology), and this physiologically induced constraint on ET changes leads to additional warming and drying of the near-surface atmosphere [65, 90-92]. For instance, the decrease in near-surface relative humidity caused by the physiological effect of CO2 is of the same magnitude as that caused by the radiative effect of CO2 [65, 92]. This warming and drying results in an enhanced increase in PET, which, crucially, will be interpreted by PET-driven offline metrics as reflecting additional soil water stress [65, 66, 92]. Since this increase in PET is caused by plants in the first place, however, this interpretation is clearly erroneous; in fact, reduced stomatal conductance actually conserves soil water in climate models [65, 92]. In other words, changes in atmospheric aridity are partially decoupled from vegetation water stress under higher CO2 levels.

The CO2 effect partly explains the discrepancy between drought projections based on offline PET-based metrics and model projections of soil moisture. Another manifestation of the same issue is that, while bulk stomatal conductance is included into the Penman-Moneith formulation of PET [40], all studies relying on PET-based metrics assume that it remains constant in the future. Because PET is a diagnostic quantity that is not used in climate models, PET projections cannot directly be compared to a true, internally-consistent model value of PET. However, changes in non-water-stressed ET computed in the climate models themselves can be considered a proxy of the real simulated change in evaporative demand: analysis of such changes show that Penman-Monteith PET projections severely overpredict true changes in evaporative demand, in large part because they do not account for changes in stomatal conductance [89]. In other words, PET increases in studies based on offline drought metrics are overestimated. The assumption of constant stomatal conductance may be common partly because model outputs of stomatal conductance are generally not available to use, but in theory, these could be factored into PET calculations. Whether the resulting reduction in future projected PET would correspond exactly to the share of total PET increase from stomatal closure and land-atmosphere feedbacks in an open question [65, 92]. In any case, the best predictor (again, based on the comparison with changes in non-water-stressed ET) has been shown to be simply net radiation [89], which leads to much more nuanced projected changes in aridity than if using Penman-Monteith PET [93, 94].

Finally, beyond explaining discrepancies between the responses of different drought metrics, the CO2 fertilization effect, by increasing plant water use efficiency, is also the likely reason why simulated vegetation is able to increase across the globe in climate model projections despite reduced mean soil moisture and higher vapor pressure deficit [62]. Interestingly, however, CO2 fertilization itself can directly lead in some cases to soil moisture decrease. Indeed, while CO2 fertilization generally decreases ET (because leaf-level transpiration decreases more than LAI increases), in some regions and models the increase in vegetation dominates, and CO2 fertilization leads to increased ET and reduced soil moisture, although reduced soil moisture levels remain sufficient to avoid water stress [95]. This model behavior suggests the coexistence of both a “greener” and “drier” future across some regions.

**Conclusion**

The notion that global warming will lead to dramatically increased drought conditions over land is a salient element of the public discussion on climate change and its impact. A review of the literature on drought projections reveals that such expectations are based on assessments relying on simple, offline drought metrics, or heuristics, applied to recent observations or climate model projections of surface climate. Used as a proxy for soil moisture, these offline tools report increases in soil moisture droughts, and more generally mean aridity levels, driven mainly by warming-induced increases in PET.

However, these projections are essentially ‘black-box’ type assessments that remain largely blind with respect to actual changes in land surface hydrology and land-atmosphere exchanges. Particularly problematic is their reliance on PET, a diagnostic quantity that can be calculated but plays no direct role in the surface energy and water budget, and whose interpretation, in particular in water-limited environments, is rendered complex by the strong coupling between land surface hydrology, vegetation and surface climate. Perhaps as a result, it can be argued that the physical interpretation of these projections is often simplistic, as it holds an essentially demand-driven view of evaporation changes and neglects the role of land-atmosphere coupling. Even more importantly, such projections do not account for changes in stomatal conductance driven by rising atmospheric CO2 concentrations, which have been shown to bias these metrics negatively.

The use of offline, “atmosphere-centric” [92] metrics may be justified for present-day monitoring of droughts, where the focus is on the large-scale spatial pattern. A metric like the PDSI was indeed initially designed (in the sixties) to that aim, in the absence of extensive hydrological measurements and at a time when more comprehensive physically-based, large-scale hydrological modeling was not available. However, there is limited justification today, beyond simplicity of use, to apply them to climate model outputs to investigate future drought trends. Instead, prognostic model outputs of land surface hydrology can be investigated directly. Doing so leads to more nuanced assessments of future soil moisture drought and land aridity, as well as runoff [89, 96]. Moreover, by focusing on model outputs, we can better understand projected coupled changes in the carbon and water cycles at the land surface, such as the impact of CO2-driven changes in plant physiology on surface hydrology and extremes. This comprehensive approach is essential because, as is shown in this review, different parts of the soil-vegetation-atmosphere system may exhibit different and even opposite-sign changes. The use of offline metrics is often justified by the uncertainties of land surface modeling in climate models. However, these structural and physical model uncertainties partly reflect real uncertainties in our current understanding of soil-vegetation-atmosphere processes: it may be argued that reflecting such uncertainties, at this point, is a necessity in our assessment of future changes. While offline metrics are simpler to use and interpret, this approach comes at the expense of ignoring the complexity of the natural system by using a single and greatly simplified model. This is analogous to the uncertainty in cloud changes with global warming, which in climate models is the result of many imperfectly constrained model parameterizations, and which is the main source of uncertainty in model projections. In the face of these uncertainties, the answer is not to use a simple idealized model of cloud changes, but rather to characterize and understand these uncertainties and continue efforts in model evaluation and development [97]. Similarly, we argue that simple, offline drought metrics should be abandoned as a climate change impact tool, in favor of assessment based on comprehensive coupled land-atmosphere model output that takes into account model uncertainties. At the same time, efforts must continue to further develop, calibrate and evaluate land surface models, particularly the representation of vegetation and its response to soil moisture stress.

Indeed, we would like to emphasize again that concerns about future soil moisture drought essentially reflect concerns about associated impacts on ecosystems: there is little value in soil moisture levels in and of themselves. However, future model projections paint the picture of a slightly drier (from a soil moisture perspective) but also greener world. This primarily reflects the role of CO2 fertilization (as well as increased temperature, and precipitation in some regions). If the concern is about ecosystem health, perhaps we should focus less on future soil moisture levels or anomalies, but directly on soil water stress. While those two quantities are certainly linked, a changing environment, in particular higher CO2 levels, may affect this relationship. In other words, how much is vegetation currently water-limited globally, and how much will it be in the future? Taken at face value, the “greener” future depicted by models seems to suggest that global vegetation will face little increase in soil moisture stress. However, many reasons exist to remain skeptical about current model projections of future vegetation: over-simplicity of parameterization of plant hydraulic stress, lack of representation of nutrient constraints, of drought-related mortality and succession dynamics, of biotic stress (which may increase in a warmer world), etc. Efforts are underway to improve or include such processes in models; perhaps future vegetation will not be as healthy as current models suggest. While global increases in vegetation have been observed over the last decades, recent observations suggest a shift from a period dominated by the positive effects of fertilization to a period characterized the rise of negative impacts of climate change [98]. Further work is thus critically needed, both in terms of model improvement and interpretation of model projections, and in better monitoring and understanding ongoing global-scale changes in different aspects of the soil-vegetation-atmosphere system.

**Conflict of interest**

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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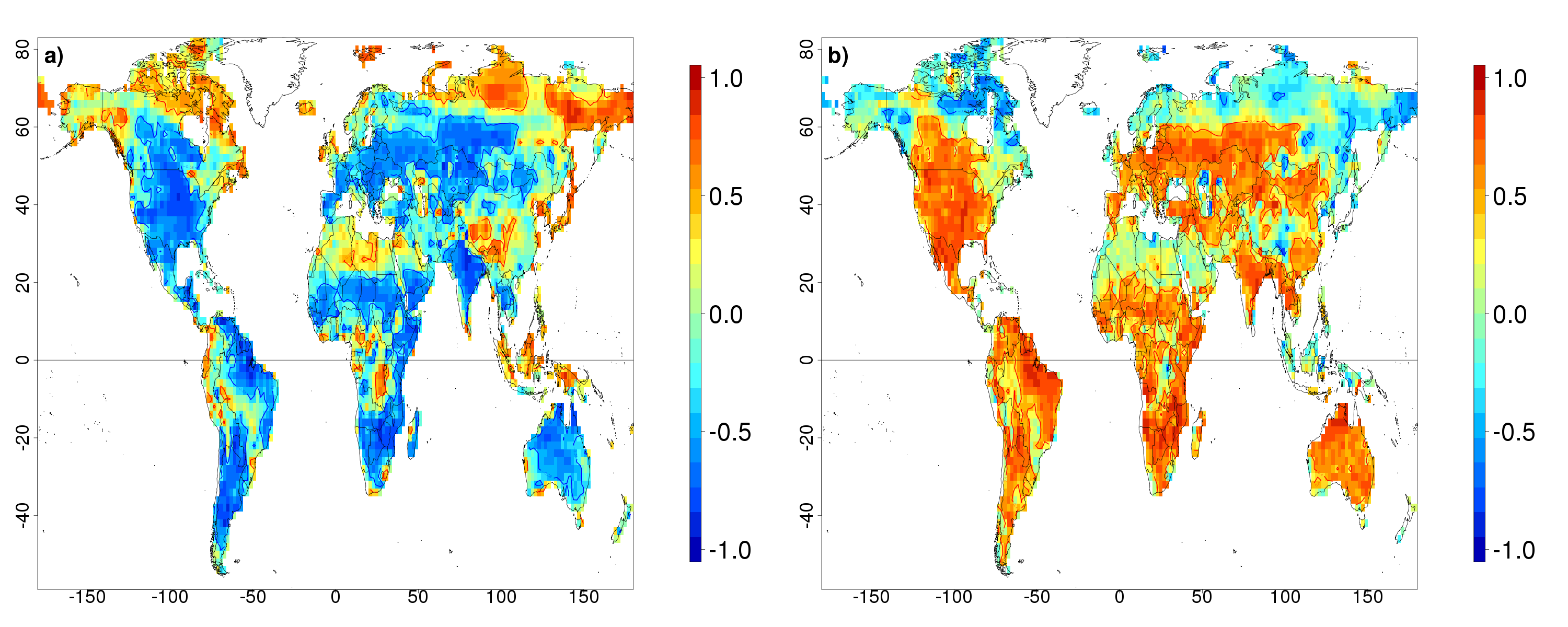


Figure 1: (a): Correlation across 27 models between projected changes in PET and ET between 1950-2005 and 2071-2100 under the RCP8.5 scenario, in June-July-August in the northern hemisphere and December-January-February in the southern hemisphere; (b) same as (a), but with surface soil moisture and ET changes, for 24 models. Red and blue contour lines indicate correlations significant at the 5% level (positive and negative, respectively).