Current Climate Change Reports (2018) 4:202–209
https://doi.org/10.1007/s40641-018-0094-1



# Drought Indices, Drought Impacts, $CO_2$, and Warming: a Historical and Geologic Perspective

**Jacob Scheff**[1]

Published online: 19 April 2018


**Abstract**

**Purpose of Review** Different types of methods give very conflicting impressions about whether water will become scarcer on land as Earth warms, and in what sense(s). Here, I examine how environmental records from past climate changes can be used to clarify the interpretation of these confusing results.

**Recent Findings** Evidence from the last ice age and the historical era agrees that $CO_2$-driven warming causes a runoff response dominated by regional signals of varying sign, and a vegetation response dominated by greening. This result supports comprehensive Earth system model output, while casting doubt on the interpretation of temperature-driven indices that project widespread "drying" with warming. In contrast, evidence from pre-Quaternary warm climates points to exotic features such as wet subtropics and extremely polar-amplified warming which are not found in model simulations, suggesting unknown forcings and/or feedbacks.

**Summary** The terrestrial eco-hydrologic response to $CO_2$-driven warming in the recent past is consistent with comprehensive models, and not with drought indices. However, in the deeper past, it is consistent with neither.

**Keywords** Climate change · Drought · Paleoclimate · Water cycle · Vegetation · Runoff

## Introduction

Fresh water at Earth's surface is required for all terrestrial life, including human civilization. Terrestrial plants, many of which humans depend upon, need to take up water from the soil in order to replenish the large amount of water they lose to the air (*transpiration*) when they open their leaf stomata to ingest $CO_2$ for photosynthesis. Their additional requirement of water for the photosynthesis reaction itself is usually far smaller. Also, humans directly need river and groundwater flow (*water resources* or *runoff*; equal to precipitation minus evapotranspiration on climate time-scales) for irrigation, industry, and household use and for the maintenance of freshwater ecosystems.

This article is part of the Topical Collection on *Climate Change and Drought*

✉ Jacob Scheff
jscheff@uncc.edu

[1] Department of Geography and Earth Sciences, UNC Charlotte, McEniry 324, 9201 University City Blvd, Charlotte, NC 28223, USA

Because these services are so essential to us, we call it a *drought* when they can no longer be sustained. *Meteorological drought* occurs when regional precipitation falls below normal for a few months or longer. If this results in low soil moisture, constraining plant transpiration (and thus photosynthesis), it is called *agricultural drought*. If it further leads to low streamflow or groundwater recharge, it is termed *hydrological drought* [1, 2].

Yet, agricultural and hydrological drought can also be amplified by high temperatures, sunny conditions, and/or dry air, because these increase the evaporation and transpiration rates for a given surface state (or, equivalently, decrease the stomatal conductance and photosynthesis possible given an evapotranspiration rate.) Thus, while some common drought indices (e.g., standardized precipitation index [SPI]; rainfall deciles) depend on precipitation alone, many others (e.g., Palmer drought severity index [PDSI]; standardized precipitation-evaporation index [SPEI]) also depend on temperature, radiation, and/or humidity, usually through the construct of *potential evapo(transpi)ration* (PE, PET, $E_p$, $ET_p$, $E_0$, $ET_0$, or similar). Likewise, the overall aridity of a climate is often quantified using the ratio of precipitation to PE (the *aridity index* or AI) rather than precipitation alone, because the aridity index is much better related to vegetation and runoff production patterns [e.g., 3–5].

Thus, when these metrics are applied to historical and future climate model output, in which temperature strongly increases but precipitation has little systematic trend, they obtain apparent widespread and large increases in droughts [6, 7] and aridity [5, 8•, 9•, 10], unless a temperature-independent formulation of PE is used [11••, 12]. These dryness-metric responses strongly resemble the models' direct projections of topsoil moisture [e.g., 13••] and surface-layer relative humidity [e.g. 14], suggesting that they have some physical relevance.

Yet, the same models' direct projections of photosynthesis and runoff, which are the main human motivations for defining drought/aridity (and for considering soil moisture) as discussed above, are much less dire-looking [15••,16••]: photosynthesis is projected to increase nearly everywhere [17••,18•], while runoff change broadly resembles precipitation change, with regions of increase and decrease but little systematic trend outside the high latitudes [e.g., 11••, 13••, 18•, 19]. Deeper-layer soil moisture, most relevant for plants, also shows little systematic change [20••]. Thus, drought *indices* do not resemble key drought *impacts* in climate model projections. Figures 1 and A1 of Scheff et al. [17••] summarize these contrasts.

For photosynthesis, the divergence from drought/aridity indices is clearly due to the modeled direct effects of $CO_2$ on the plant water and carbon balance: higher ambient [$CO_2$] permits more $CO_2$ uptake for a given stomatal opening, counteracting the negative effects of warming-forced stomatal closure captured by the indices [21]. Indeed, the large increases in photosynthesis vanish in simulations that turn off $CO_2$ effects [22, 23]. For runoff, the modeled divergence from drought/aridity indices may be caused by a mix of $CO_2$ effects on stomata [e.g., 12, 15••, 16••], strong effects of vapor pressure deficit on stomata [e.g., 24••], more intense rain events that increase the runoff fraction [13••], and/or a possible lack of real temperature dependence of PE [11••].

However, it is not immediately clear which of the two projection types to trust: the dryness indices may not account for all of the above processes, but they have been used extensively and successfully for applications. By the same token, the complex land schemes that produce the direct projections do not account for nutrient constraints or for drought-induced plant mortality, both of which inhibit $CO_2$'s photosynthesis benefits [e.g., 25•, 26, 27], and they often have trouble simulating runoff reasonably [e.g., 28, 29].

This presents a major dilemma of interpretation [15••, 17••, 18•, 30]: will future vegetation and runoff changes resemble their direct land-model projections, or will they more resemble the climate-based drought and aridity indices that are successfully used to understand their present variability? The question may be approached theoretically, but one potentially effective strategy is to just examine the responses to $CO_2$-driven global temperature changes *that have already occurred*. Here, we review the evidence for global vegetation, runoff, and hydroclimatic responses to three such changes: the historical anthropogenic warming, the warming from the last glacial maximum (LGM) to the preindustrial Holocene, and finally the deeper-time warming between our present, cold Quaternary period and the warmer Pliocene epoch that preceded it.

## Historical Period Evidence

The world has warmed by about 1 K over the past century (mostly over the more recent decades), and almost all of this warming is due to $CO_2$ and other greenhouse gases, offset to some degree by aerosol-driven cooling [e.g., 31]. Thus, the recent warming is potentially a relevant test case for the above question. However, large regional trends in vegetation, runoff, and hydroclimate over this short of a period can also be caused by unforced, internal precipitation variability [32] and by direct human changes to land cover and land use. So, it is most useful to focus on the planetary-scale character of historical changes.

Dai and Zhao [33••] have globally mapped the trends in PDSI from 1950 to 2012, using precipitation from the US Climate Prediction Center (CPC) and the Global Precipitation Climatology Project (GPCP), and PE computed from Climatic Research Unit (CRU) atmospheric data. Similar to the future simulations, PDSI has significantly declined (i.e., become "drier") over very widespread areas, but has significantly increased only in a few smaller areas. This is especially so over the Old World continents, but is also noticeable over the Americas. As a result, global-mean PDSI has also significantly declined. This is shown to be mostly due to the effect of warming on PE (as in the simulations), and it is especially strong after 1979.

Independently, Huang et al. [9•] mapped the trends in the aridity index from 1948 to 2005, using precipitation from the CPC only, and PE computed by Feng and Fu [2013] from a mix of CPC and Global Land Data Assimilation System (GLDAS) data. The aridity index has also tended toward lower, drier values, though not as ubiquitously as the PDSI (particularly in the Americas). Still, the global-mean aridity index has significantly declined (especially since 1979). Feng and Fu [2013] showed that this global AI decline is mostly due to precipitation (unlike for PDSI) and that it is much stronger than the AI decline simulated by the models over the same period.

Yet, there is no evidence of any global-scale tendency toward *runoff* decline (hydrological drought). Dai and Zhao [33••] have also mapped water-year 1950–2012 runoff trends across almost all of Earth's land, using a large compilation of stream gauge data. The spatial pattern is similar to the PDSI trend spatial pattern (likely since both are driven by the precipitation trend spatial pattern). However, the global balance is much less negative than for PDSI or AI, with large areas of both increasing and decreasing runoff in the Old World and increasing runoff dominating in the Americas. Of the largest 200 rivers in the dataset, 29 have declined significantly, 26 have increased significantly, and 145 have insignificant trends [34•]. Similarly, Milliman et al. [35] found that there was no systematic global runoff trend from 1951 to 2000, except for anthropogenic alterations to certain mid-latitude rivers. All of this qualitatively resembles the model direct runoff simulations, rather than the drought and aridity indices.

For vegetation, the contrast with the drought and aridity indices is even stronger: most global estimates obtain widespread increases, rather than declines. Using three different satellite datasets, Zhu et al. [36••] found that since 1982, leaf area declined significantly over less than 4% of global vegetated land, while it increased significantly over 25–50% of global vegetated land. They infer that only 4% of the increase was due to land-use change; rather most of it was due to $CO_2$ and climate change. The leaf area corresponding to a given annual precipitation amount has also increased, over a wide range of dry climates [21]. The strong increase in seasonality of global $CO_2$ levels since 1974, driven by more productive growing seasons, independently constrains the global photosynthesis trend to be large and positive [37•]. Similarly, the ice-core history of carbonyl sulfide (for which photosynthesis is the main sink) since 1900 can only be explained by a large increase in global photosynthesis [38]. It is often highlighted that there has been no significant change in Canadian boreal forest productivity since 1950 [39], but this still strongly contrasts with what one might have inferred from the extremely negative PDSI trends [33••] and AI trends [9•] occurring in this region. In fact, Zhu et al. [36••] did not find robust leaf area trends in Canada either; rather, their positive global signal comes from other regions.

Thus, for the historical period, evidence strongly suggests that global vegetation and water-resource generation have qualitatively followed their (more optimistic) direct climate-model projections, rather than the (more pessimistic) implications of the drought and aridity indices.

## Glacial-Interglacial Evidence

During the Quaternary period, globally-warm interglacial stages and globally-cool glacial stages have followed each other, ultimately driven by changes in Earth's orbit that affect the viability of large, reflective boreal ice sheets [e.g., 40]. However, much of the global temperature change between each glacial and interglacial was likely accomplished by known changes in $CO_2$ and other greenhouse gases, particularly away from the immediate vicinity of the ice sheets [e.g., 41]. Thus, known glacial-interglacial differences in climate, vegetation, and hydrology could also be used to test the questions in the Introduction. The contrast between the last glacial maximum or LGM (~ 21,000 years ago) and the preindustrial era makes a particularly powerful test case due to the wealth of data, the very large temperature and $CO_2$ signals, and the almost total lack of contamination by precessional hydroclimate forcing or by abrupt climate change [17••, 42]. However, relatively few studies have explicitly examined global vegetation and runoff patterns at the LGM.

For vegetation, Prentice et al. [43] (building on extensive previous work) used a global LGM pollen and plant macrofossil database to show that global natural forest cover is much more extensive today than it was during the LGM, despite the warmer temperatures—and that LGM vegetation was much more open, sparse, and unproductive. Critically, they found that a standard plant model which successfully reproduces preindustrial vegetation can only reproduce this LGM sparseness (given LGM climate estimates) if the direct effects of low $CO_2$ (180 ppm at the LGM) on the plants' carbon and water balance are included. Without direct $CO_2$ effects, the predicted LGM vegetation is much too green, forested, and productive compared to data. Thus, global plant fossil data confirm a $CO_2$-driven greening under glacial-to-interglacial greenhouse warming, rather than an aridity-driven loss of production.

Scheff et al. [17••] added to this analysis by explicitly mapping the present-to-LGM vegetation-greenness contrast for each site in the above fossil database, enabling direct comparison between the actual present-to-LGM changes in vegetation and the model-projected present-to-LGM contrasts in variables such as photosynthesis, PDSI, and AI. They found that the model projections strongly resemble those for the future, with much higher photosynthesis simulated in the preindustrial than the LGM (see also [18•]), but generally lower (drier) PDSI and AI in the preindustrial than the LGM, especially outside of the high latitudes. The plant fossil data again confirm a widespread greening, resembling the photosynthesis projections but not at all resembling the PDSI or AI projections. Very large regions have projections of PDSI and AI drying from LGM to preindustrial, but data showing vegetation greening.

For LGM-present runoff contrasts, the most comprehensive dataset is the global closed-basin lake area compilation of Harrison and Bartlein [44], Fig. 14.8e. Steady-state lake water balance requires that the area of an endorheic or closed-basin lake is proportional to the total runoff input to the lake from the surrounding basin. In this dataset, declines in runoff (from LGM to preindustrial) are stronger and more widespread than increases, perhaps suggesting that the AI and PDSI drying result is actually relevant for runoff change in this case. However, past lake highstands are by nature much more geologically visible than past lake lowstands, biasing any such compilation towards a forward drying trend [S. Harrison, pers. comm, 2015.] Indeed, almost all of the individual sites in this compilation seem consistent with the local direct climate model projections of LGM-present runoff contrast, qualitatively validating the land models' ability to project runoff [17••]. The more focused compilation of Putnam and Broecker [45] similarly emphasized the regional nature of the large LGM lakes (and assumed a drier LGM tropical belt to balance), rather than suggesting a global tendency towards more or less water resource availability. Again, this is consistent with the LGM direct runoff simulations.

## Neogene (Deeper-Time) Evidence

Even Quaternary interglacials, such as our current Holocene, are quite cold and icy compared to most of Earth's recent history [46]. In fact, most of the Cretaceous, Paleogene, and Neogene periods (145 to 2.6 million years ago) were much warmer than today, with high-latitude forests reaching further poleward and much-reduced (or absent) polar ice [47]. The reasons for this warmth are not completely clear, but geologic proxies suggest that $CO_2$ was higher—at times much higher—than preindustrial [42]. In the Pliocene (~ 5–3 million years ago) epoch of the Neogene, for which there is a particular wealth of data, $CO_2$ was likely about 400 ppm [48], and the planet was several degrees warmer than preindustrial, particularly in the subtropics and extratropics [49, 50].

Yet, the evidence for Pliocene terrestrial ecology and hydrology does not at all resemble future model projections, whether direct or drought-index-based: the subtropics and dry parts of the midlatitudes of both hemispheres were apparently much wetter than today, on the basis of both vegetation and runoff proxies [51–54, 55••]. $CO_2$ of 400 ppm hardly seems large enough to cause such a greening by direct effects on vegetation alone [55••], and the runoff increases are recorded in the very regions where climate models project future runoff to decline. Much of the Mediterranean basin even supported laurel-leaved forests during this time [56], which are specifically adapted to high, year-round rainfall.

Two immediate causes have been invoked to explain this surprising pattern. It was recognized early on [52, 54] that the "permanent El Niño" tropical Pacific state reconstructed for the Pliocene [57] would contract and extend the subtropical jets and storm tracks, wetting parts of the subtropics by the same mechanism that a transient El Niño event does today. More recently, Burls and Fedorov [49, 55••] showed that coupled climate models can reproduce neither the Pliocene's wet subtropics nor its strongly polar-amplified, tropically-damped warming structure. However, when this observed warming structure is *imposed* as a lower boundary condition, models succeed in simulating strong subtropical wetting, as the Hadley cells dramatically weaken.

Thus, whatever unknown factor(s) explain the Pliocene warming's extreme latitudinal dependence, and its El Niño-like pattern in the tropical Pacific, also dynamically explain the large divergence of Pliocene hydrology from projected future hydrology. Speculatively, these factors may include missing warm-pool negative longwave feedbacks from convective organization [58], much weaker high-latitude negative cloud phase feedbacks than modeled [59], vegetation-dust-cloud feedbacks [60•], or possibly chemistry-climate feedbacks [61]. However, they also may simply reflect totally unknown forcings or boundary conditions that were active in the Pliocene but are not a factor in future warming. Thus, it is hard to say whether future warming will produce Pliocene-like hydrologic and temperature responses. Indeed, the historical evidence reviewed above, and the more uniform observed structure of warming so far, would argue against it. However, the Pliocene greenhouse reminds us that dynamical hydroclimate surprises could still await us in the future, defying both the dryness-index-based projections and the land-scheme-based projections of drought and aridity impacts.

## Synthesis and Caveats

Thus, despite the strong global trend toward droughts and aridity projected under future $CO_2$-linked warming using climate-based *indices*, past $CO_2$-linked warming has not caused any major global increase in the main drought and aridity *impacts* (i.e., vegetation and runoff decline). Instead, it has tended to cause changes in the opposite, positive sense (Table 1), particularly for vegetation.

For the historical warming and the glacial-interglacial warming, this is because the direct climate-model projections of vegetation and runoff impacts are actually much more positive (or less negative) than the drought/aridity index changes, and the actual vegetation and runoff changes were far more like the direct projections than like the indices. For the interglacial-to-Pliocene warming, however, the actual vegetation and (especially) runoff changes did not resemble either type of projection, instead featuring strong dynamically driven subtropical wetting and greening with just a modest $CO_2$ increase. Thus, we understand the drought-impact changes due to $CO_2$ and warming in the more recent past, but key feedbacks or forcings must still be missing from our understanding of the changes that accompanied deeper-time warming. In any case, all of this evidence suggests that future projections of index-based trends toward drought and aridity are unlikely to be relevant to future changes in runoff and vegetation production, which are the primary drought impacts.

**Table 1** Observed and modeled global dryness-index and drought-impact changes for three past instances of warming with $CO_2$ increase

| Warming/$CO_2$ episode | Historical | Glacial-Preindustrial | Preindustrial-Pliocene |
|---|---|---|---|
| Modeled dryness indices | Drying [5, 6] | Drying [17••] | |
| Observed dryness indices | Drying [9•, 33••] | | |
| Modeled photosynthesis impacts | Greening [15••, 22, 23] | Greening [17••, 18•, 43] | |
| Observed vegetation impacts | Greening [36••, 37•, 38] | Greening [17••, 43] | Large greening, especially subtropics [51, 53, 54, 55••] |
| Modeled runoff impacts | Neutral [31] | Neutral to drying [17••, 18•] | Neutral unless warming pattern imposed [55••] |
| Observed runoff impacts | Neutral [33••, 34•, 35] | Drying or neutral [44, 45]; matches modeled well [17••] | Large subtropical/midlatitude wetting [51, 52, 54, 55••] |

One might ask whether the index-based drought projections are still important for other impacts. Indeed, one major drought impact that does not stem from either runoff declines or photosynthetic declines is *fire*. Drought instead encourages fire via its negative effects on vegetation liquid water content or fuel moisture, which normally inhibits fire by evaporatively cooling the vegetation when it is heated by flames or lightning. To the extent that fuel moisture responds to climate change in a similar manner to topsoil moisture (which in turn responds much like the drought indices, as discussed in the Introduction), the index-based global drying projections may in fact be relevant for global fire and flammability trends.

Speculatively, this seems particularly likely for dead fuels, whose insides are more exposed to the air. Live fuels may not dry out in this way because they are hydraulically connected to the deeper soil, which is not projected to systematically dry [20••], and because they have working stomata that can conserve water in response to increasing $CO_2$ and vapor pressure deficit. However, if live fuels' moisture content is still affected by atmospheric conditions to some extent, the drought index trends may be relevant for live fuels as well. In any case, there is clearly a need for physical, explicit modeling of fuel moisture under greenhouse climate change, rather than the empirical approaches that currently prevail [62].

In addition to all of this, $CO_2$-driven increases in vegetation productivity would presumably increase the total amount of fuel to burn, even as that fuel becomes drier. Thus, $CO_2$ greenhouse warming could actually be an ideal forcing for more frequent and intense fires, even as it does not systematically affect runoff. Indeed, Harrison and Bartlein [44] also compiled the global LGM charcoal flux records (their Fig. 14.8d) and found that the warm preindustrial had significantly higher charcoal deposition than the cold LGM at a large majority of their sites (though this contrast could also be due to the large increase in agricultural and ecological burning by humans from the LGM to the preindustrial, rather than climate or $CO_2$.)

Another important drought impact that does not simply follow from runoff or photosynthesis is the increase in surface sensible heat flux at the expense of latent heat flux [i.e., the decline in evaporative fraction, or increase in Bowen ratio], which causes warming and an increase in temperature variability [63] with societal impacts. However, the climate models project little systematic trend in evaporative fraction or Bowen ratio, even as they project strong index-based drying [8•]. Thus, this also may be a drought impact for which the drought indices are not relevant under $CO_2$-driven climate change. Reasons could include the above-mentioned coupling of transpiring plants to the non-drying deeper soil rather than to the drying topsoil, as well as the direct positive temperature effect on the evaporative fraction from basic thermodynamics [64]. Even more fundamentally, the evaporative fraction is determined by the actual evaporation flux and by the radiative energy supply to the surface, neither of which is projected to systematically change much [15••, 19].

Finally, a reminder is needed that the large model-projected increases in photosynthesis may fail to verify in some locations in the near term, due to processes like nutrient limitation [25•, 26] and mortality [27, 65]. Paleo-increases in atmospheric $CO_2$ were much slower than future increases, giving ecosystems more time to take advantage of them, and recent historical increases were more modest than anticipated future increases, decreasing the potential role of nutrient constraints. The above caveat is particularly relevant for crops, which are usually highly nutrient- (or even light-) limited, grown as monocultures, and very negatively sensitive to warming itself, independent of any water or $CO_2$ effects [66, 67•]. However, the higher $CO_2$ should still usually enable plants to lose less *water* to transpiration for the same amount of photosynthesis [68•], counteracting the opposite tendency from warming that is reflected in the drought/aridity indices. Thus, the index-based *drying* should still be treated with skepticism for crops, even as the model projections of large productivity increases should also be treated with skepticism. Also, to the extent that the models overestimate greening for any region (crop or non-crop), they must also underestimate the runoff increase for that region under the same local climate projection, since greening increases transpiration and thus decreases runoff for a given precipitation amount [15••, 17••, 69•]. This would cause the runoff responses to match the dryness indices even more poorly than they already do.

## Conclusion

Several commonly used temperature-sensitive drought and aridity *indices*, when applied to future climate model output, warn us of widespread global drying trends to come. However, drought and aridity affect society mainly through negative *impacts* on photosynthesis and on runoff production—and the same climate models project photosynthesis to broadly increase, and runoff to not systematically change outside of the high latitudes. This leads to a quandary of interpretation: should we believe the index projections, or the impact projections?

Here, I address this question by reviewing the evidence from three past cases in which global warming and $CO_2$ increase were accompanied by well-known global vegetation and runoff changes: the historical warming over the last decades to century, the warming from the last glacial maximum to the pre-industrial, and the warming between the pre-industrial and the greenhouse Pliocene (5–3 million years ago.)

In each case, the observational literature implies that vegetation indeed became broadly greener, and runoff did not systematically decline. In the historical and glacial-interglacial cases, these responses were in general agreement with direct climate-model projections, but did not usually resemble the concurrent, drying-dominated changes in the drought and aridity indices. In the Pliocene case, the responses did not resemble either type of projection: rather, the subtropics became much wetter with warming in every sense, likely due to the dynamical effects of the very extreme (and unpredicted) spatial pattern of the warming. In short, past $CO_2$-linked warming has not been accompanied by the drought *impacts* one might expect given the familiar drought and aridity *index* projections.

Therefore, we should be skeptical of the tacit assumption that future trends toward index-based drought and aridity will actually be accompanied by systematic negative impacts to vegetation and water resources. However, other negative impacts of dryness, especially to fuel moisture and fire, may still loom large—and positive impacts to vegetation may also fail to materialize in some settings (in crops, especially). More physically based modeling and long-term observation are clearly needed to better understand all of these potential responses.

**Acknowledgements** The author thanks Qiang Fu and Brian Soden for the invitation, and also thanks David Battisti, Alexis Berg, Natalie Burls, Ben Cook, Ed Cook, Aiguo Dai, Alexey Fedorov, Qiang Fu, Sandy Harrison, Tim Herbert, Justin Mankin, Chris Milly, Michael Roderick, Jeremy Caves Rugenstein, Christopher Scotese, Richard Seager, Sonia Seneviratne, Abby Swann, and Park Williams for conversations that contributed to the framing and focus of this review.

## Compliance with Ethical Standards

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

## References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Wilhite DA, Glantz MH. Understanding the drought phenomenon: the role of definitions. Water Int. 1985;10:111–20. https://doi.org/10.1080/02508068508686328.
2. AMS Council: Drought: an information statement of the American Meteorological Society. https://www.ametsoc.org/ams/index.cfm/about-ams/ams-statements/statements-of-the-ams-in-force/drought/ (2013). Accessed 27 Jan 2018.
3. Budyko M. Climate and Life. New York: Academic Press; 1974.
4. Middleton N, Thomas DSG. World atlas of desertification. 2nd ed. London: Arnold; 1997.
5. Feng S, Fu Q. Expansion of global drylands under a warming climate. Atmos Chem Phys. 2013;13:10081–94. https://doi.org/10.5194/acp-13-10081-2013.
6. Zhao T, Dai A. Uncertainties in historical changes and future projections of drought. Part II: model-simulated historical and future drought changes. Clim Chang. 2016;144:535–48. https://doi.org/10.1007/s10584-016-1742-x.
7. Cook BI, Smerdon JE, Seager R, Coats S. Global warming and 21st century drying. Climate Dyn. 2014;43:2607–27. https://doi.org/10.1007/s00382-014-2075-y.
8.• Scheff J, Frierson DMW. Terrestrial aridity and its response to greenhouse warming across CMIP5 climate models. J Climate. 2015;28:5583–600. https://doi.org/10.1175/JCLI-D-14-00480.1. **Mapped the CMIP5 future projections of evaporative fraction.**
9.• Huang JP, Yu HP, Guan XD, Wang GY, Guo RX. Accelerated dryland expansion under climate change. Nat Clim Change. 2016;6:166–71. https://doi.org/10.1038/nclimate2837. **Made the only known global map of observed historical change in the aridity index.**
10. Park CE, Jeong SJ, Joshi M, Osborn TJ, Ho CH, Piao S, et al. Keeping global warming within 1.5°C constrains emergence of aridification. Nat Clim Chang. 2018;8:70–4. https://doi.org/10.1038/s41558-017-0034-4.
11.•• Milly PCD, Dunne KA. Potential evapotranspiration and continental drying. Nat Clim Change. 2016;6:946–9. https://doi.org/10.1038/nclimate3046. **Showed clearly that the Penman-Monteith PE scaling is not relevant to the response of actual evapotranspiration and runoff in climate models, and proposed interesting possible reasons for this.**
12. Milly PCD, Dunne KA. A hydrologic drying bias in water-resource impact analyses of anthropogenic climate change. J Amer Water Resour Assoc. 2017;53:822–38. https://doi.org/10.1111/1752-1688.12538.
13.•• Zhao T, Dai A. The magnitude and causes of global drought changes in the twenty-first century under a low-moderate emissions

scenario. J Climate. 2015;28:4490–512. https://doi.org/10.1175/JCLI-D-14-00363.1. **Showed clearly that topsoil moisture projections resemble drought-index projections, but runoff projections do not.**

14. Sherwood S, Fu Q. A drier future? Science. 2014;343:737–9. https://doi.org/10.1126/science.1247620.
15.•• Roderick ML, Greve P, Farquhar GD. On the assessment of aridity with changes in atmospheric CO2. Water Resour Res. 2015;51:5450–63. https://doi.org/10.1002/2015WR017031. **Largely inspired this review, by pointing out that the most important drought impacts are to photosynthesis and to runoff, and that neither is projected to follow the drought indices under future warming.**
16.•• Swann ALS, Hoffman FM, Koven CD, Randerson JT. Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. Proc Natl Acad Sci USA. 2016;113:10019–24. https://doi.org/10.1073/pnas.1604581113. **Showed clearly that runoff-production projections do not resemble drought-index projections, and that the direct effects of CO2 account for a large portion of this divergence.**
17.•• Scheff J, Seager R, Liu H, Coats S. Are glacials dry? Consequences for paleoclimatology and for greenhouse warming. J Climate. 2017;30:6593–609. https://doi.org/10.1175/JCLI-D-16-0854.1. **Showed that the warming from the Last Glacial Maximum to the preindustrial was characterized both by greening and by index-based "drying," calling into question the relevance of the latter for the former under increasing CO2.**
18.• Greve P, Roderick ML, Seneviratne SI. Simulated changes in aridity from the last glacial maximum to 4xCO2. Environ Res Lett. 2017;12:114021. https://doi.org/10.1088/1748-9326/aa89a3. **Usefully summarized the direct model projections for a wide range of different aridity impacts, both for future warming and for glacial-interglacial warming.**
19. Collins M, Knutti R, Arblaster J, Dufresne JL, Fichefet T, Friedlingstein P, et al. Long-term climate change: projections, commitments and irreversibility. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, et al., editors. Climate change 2013: the physical science basis. Cambridge: Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change; 2013. p. 1029–136.
20.•• Berg A, Sheffield J, Milly PCD. Divergent surface and total soil moisture projections under global warming. Geophys Res Lett. 2017;44:236–44. https://doi.org/10.1002/2016GL071921. **Quantified deeper-layer soil moisture projections across CMIP models, for the first time.**
21. Donohue RJ, Roderick ML, McVicar TR, Farquhar GD. Impact of CO2 fertilization on maximum foliage cover across the globe's warm, arid environments. Geophys Res Lett. 2013;40:3031–5. https://doi.org/10.1002/grl.50563.
22. Arora VK, Boer GJ, Friedlingstein P, Eby M, Jones CD, Christian JR, et al. Carbon-concentration and carbon-climate feedbacks in CMIP5 earth system models. J Clim. 2013;26:5289–314. https://doi.org/10.1175/JCLI-D-12-00494.1.
23. Shao P, Zeng XB, Sakaguchi K, Monson RK, Zeng XD. Terrestrial carbon cycle: climate relations in eight CMIP5 earth system models. J Clim. 2013;26:8744–64. https://doi.org/10.1175/JCLI-D-12-00831.1.
24.•• Novick KA, Ficklin DL, Stoy PC, Williams CA, Bohrer G, Oishi AC, et al. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. Nat Clim Change. 2016;6:1023–7. https://doi.org/10.1038/nclimate3114. **Highlighted strong evidence for the closure of stomata under high vapor-pressure deficit, which offsets the effects of warming on evapotranspiration assumed by the Penman-Monteith scaling.**
25.• Wieder WR, Cleveland CC, Smith WK, Todd-Brown K. Future productivity and carbon storage limited by terrestrial nutrient availability. Nat Geosci. 2015;8:441–5. https://doi.org/10.1038/ngeo2413. **Reviewed the substantial evidence for nutrient constraints on near-term CO2-driven photosynthetic increases.**
26. De Kauwe MG, Medlyn BE, Zaehle S, Walker AP, Dietze MC, Hickler T, et al. Forest water use and water use efficiency at elevated CO2: a model-data intercomparison at two contrasting temperate forest FACE sites. Glob Chang Biol. 2013;19:1759–79. https://doi.org/10.1111/gcb.12164.
27. Williams AP, Allen CD, Macalady AK, Griffin D, Woodhouse CA, Meko DM, et al. Temperature as a potent driver of regional forest drought stress and tree mortality. Nat Clim Chang. 2012;3:292–7. https://doi.org/10.1038/nclimate1693.
28. Koster R. Efficiency space – a framework for evaluating joint evaporation and runoff behavior. Bull Amer Meteor Soc. 2015;96:393–6. https://doi.org/10.1175/BAMS-D-14-00056.2.
29. Sheffield J, Barrett AP, Colle B, Fernando DN, Fu R, Geil KL, et al. North American climate in CMIP5 experiments. Part I: evaluation of historical simulations of continental and regional climatology. J Clim. 2013;26:9209–45. https://doi.org/10.1175/JCLI-D-12-00592.1.
30. Fu Q, Lin L, Huang J, Feng S, Gettelman A. Changes in terrestrial aridity for the period 850-2080 from the Community Earth System Model. J Geophys Res Atmos. 2016;121:2857–73. https://doi.org/10.1002/2015JD024075 .
31. Flato G, Marotzke J, Abiodun B, Braconnot P, Chou SC, Collins W. Evaluation of climate models. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, et al., editors. Climate change 2013: the physical science basis. Cambridge: Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; 2013. p. 741–866.
32. Deser C, Knutti R, Solomon S, Phillips AS. Communication of the role of natural variability in future North American climate. Nat Clim Chang. 2012;2:775–9. https://doi.org/10.1038/nclimate1562 .
33.•• Dai A, Zhao T. Uncertainties in historical changes and future projections of drought. Part I: estimates of historical drought changes. Clim Change. 2016;144:519–33. https://doi.org/10.1007/s10584-016-1705-2. **Contains the only known up-to-date global map of observed historical change in Palmer drought severity index, and one of the few global maps of observed historical change in runoff production.**
34.• Dai A. Historical and future changes in streamflow and continental runoff: a review. In: Tang Q, Oki T, editors. Terrestrial water cycle and climate change: natural and human-induced impacts, Geophysical Monograph 221. 1st ed. Wiley; 2016. p. 17–37. **One of the only global-scale reviews of historical change in river runoff.**
35. Milliman JD, Farnsworth KL, Jones PD, Xu KH, Smith LC. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951-2000. Glob Planet Chang. 2008;62:187–94. https://doi.org/10.1016/j.gloplacha.2008.03.001.
36.•• Zhu Z, Piao S, Myneni RB, Huang M, Zeng Z, Canadell JG, et al. Greening of the Earth and its drivers. Nat Clim Change. 2016;6:791–5. https://doi.org/10.1038/nclimate3004. **Showed that multiple independent satellite datasets agree that leaf area increases have been much more prevalent globally than leaf area decreases.**
37.• Wenzel S, Cox PM, Eyring V, Friedlingstein P. Projected land photosynthesis constrained by changes in the seasonal cycle of atmospheric CO2. Nature. 2016;538:499–501. https://doi.org/10.1038/nature19772. **Strongly argued that the upward trend in seasonality of CO2 levels implies that gross photosynthesis is also substantially increasing, and will continue to.**
38. Campbell JE, Berry JA, Seibt U, Smith SJ, Montzka SA, Launois T, et al. Large historical growth in global terrestrial gross primary production. Nature. 2017;544:84–7. https://doi.org/10.1038/nature22030.

39. Girardin MP, Bouriaud O, Hogg EH, Kurz W, Zimmermann NE, Metsaranta JM, et al. No growth stimulation of Canada's boreal forest under half-century of combined warming and CO2 fertilization. Proc Natl Acad Sci U S A. 2016;113:E8406–14. https://doi.org/10.1073/pnas.1610156113.
40. Huybers P. Glacial variability over the last two million years: an extended depth-derived agemodel, continuous obliquity pacing, and the Pleistocene progression. Quaternary Sci Rev. 2007;26:37–55. https://doi.org/10.1016/j.quascirev.2006.07.013.
41. Broccoli AJ, Manabe S. The influence of continental ice, atmospheric CO2, and land albedo on the climate of the last glacial maximum. Climate Dyn. 1987;1:87–99. https://doi.org/10.1007/BF01054478.
42. Masson-Delmotte V, Schulz M, Abe-Ouchi A, Beer J, Ganopolski A, González Rouco JF, et al. Information from paleoclimate archives. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, et al., editors. Climate change 2013: the physical science basis. Cambridge: Contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; 2013. p. 383–464.
43. Prentice IC, Harrison SP, Bartlein PJ. Global vegetation and terrestrial carbon cycle changes after the last ice age. New Phytol. 2011;189:988–98. https://doi.org/10.1111/j.1469-8137.2010.03620.x.
44. Harrison SP, Bartlein PJ. Records from the past, lessons for the future: what the palaeorecord implies about mechanisms of global change. In: Henderson-Sellers A, McGuffie K, editors. The future of the world's climate. Elsevier; 2012. p. 403–406.
45. Putnam AE, Broecker WS. Human-induced changes in the distribution of rainfall. Sci Adv. 2017;3:e1600871. https://doi.org/10.1126/sciadv.1600871.
46. Zachos JC, Dickens GR, Zeebe RE. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature. 2008;451:279–83. https://doi.org/10.1038/nature06588.
47. Boucot AJ, Xu C, Scotese CR, Morley RJ. Phanerozoic paleoclimate: an atlas of lithologic indicators of climate. SEPM Concepts in Sedimentology and Paleontology. 2013;11.
48. Bartoli G, Hönisch B, Zeebe RE. Atmospheric CO2 decline during the Pliocene intensification of northern hemisphere glaciations. Paleoceanography. 2011;26:PA4213. https://doi.org/10.1029/2010PA002055.
49. Burls NJ, Fedorov AV. Simulating Pliocene warmth and a permanent El Niño-like state: the role of cloud albedo. Paleoceanography. 2014;29:893–910. https://doi.org/10.1002/2014PA002644.
50. Fedorov AV, Brierley CM, Lawrence KT, Liu Z, Dekens PS, Ravelo AC. Patterns and mechanisms of early Pliocene warmth. Nature. 2013;496:43–9. https://doi.org/10.1038/nature12003.
51. Dowsett H, Thompson R, Barron J, Cronin T, Fleming F, Ishman S, et al. Joint investigations of the middle Pliocene climate I: PRISM paleoenvironmental reconstructions. Glob Planet Chang. 1994;9:169–95. https://doi.org/10.1016/0921-8181(94)90015-9.
52. Molnar P, Cane MA. Early Pliocene (pre-ice age) El Niño-like global climate: which El Niño? Geosphere. 2007;3:337–65. https://doi.org/10.1130/GES00103.1.
53. Salzmann U, Haywood AM, Lunt DJ, Valdes PJ, Hill DJ. A new global biome reconstruction and data-model comparison for the middle Pliocene. Glob Ecol Biogeogr. 2008;17:432–47. https://doi.org/10.1111/j.1466-8238.2008.00381.x.
54. Goldner A, Huber M, Diffenbaugh N, Caballero R. Implications of the permanent El Niño teleconnection "blueprint" for past global and north American hydroclimatology. Clim Past. 2011;7:723–43. https://doi.org/10.5194/cp-7-723-2011.
55.•• Burls NJ, Fedorov AV. Wetter subtropics in a warmer world: contrasting past and future hydrological cycles. Proc Natl Acad Sci USA. 2017;114:12888–93. https://doi.org/10.1073/pnas.1703421114. **Showed for the first time that the Pliocene's wet subtropics were a direct consequence of its highly latitude-dependent warming structure, which forced an atmospheric circulation very different from today's.**
56. Marino P, Castiglia G, Bazan G, Domina G, Guarino R. Tertiary relict laurophyll vegetation in the Madonie mountains (Sicily). Acta Botanica Gallica. 2014;161:47–61. https://doi.org/10.1080/12538078.2013.870047.
57. Philander SG, Fedorov AV. Role of tropics in changing the response to Milankovich forcing some three million years ago. Paleoceanography. 2003;18:1045. https://doi.org/10.1029/2002PA000837.
58. Emanuel K, Wing AA, Vincent EM. Radiative-convective instability. J Adv Model Earth Syst. 2014;6:75–90. https://doi.org/10.1002/2013MS000270.
59. Tan I, Storelvmo T, Zelinka MD. Observational constraints on mixed-phase clouds imply higher climate sensitivity. Science. 2016;352:224–7. https://doi.org/10.1126/science.aad5300.
60.• Sagoo N, Storelvmo T. Testing the sensitivity of past climates to the indirect effects of dust. Geophys Res Lett. 2017;44:5807–17. https://doi.org/10.1002/2017GL072584. **Showed that dust effects on mixed-phase clouds, which are large but not included in climate models today, can explain a significant part of the extreme polar amplified warming of the Pliocene.**
61. Unger N, Yue X. Strong chemistry-climate feedbacks in the Pliocene. Geophys Res Lett. 2014;41:527–33. https://doi.org/10.1002/2013GL058773.
62. Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. Proc Natl Acad Sci U S A. 2016;113:11770–5. https://doi.org/10.1073/pnas.1607171113.
63. Koster RD, Schubert SD, Suarez MJ. Analyzing the concurrence of meteorological droughts and warm periods, with implications for the determination of evaporative regime. J Clim. 2009;22:3331–41. https://doi.org/10.1175/2008JCLI2718.1.
64. Hartmann D. Global physical climatology. 2nd ed. Elsevier; 2016.
65. Anderegg WRL, Flint A, Huang CY, Flint L, Berry JA, Davis FW, et al. Tree mortality predicted from drought-induced vascular damage. Nat Geosci. 2015;8:367–71. https://doi.org/10.1038/ngeo2400.
66. Battisti DS, Naylor RL. Historical warnings of future food insecurity with unprecedented seasonal heat. Science. 2009;323:240–4. https://doi.org/10.1126/science.1164363.
67.• Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, et al. Temperature increase reduces global yields of major crops in four independent estimates. Proc Natl Acad Sci USA. 2017;114:9326–31. https://doi.org/10.1073/pnas.1701762114. **Comprehensively reviewed the large, direct negative effects of warming on crop production.**
68.• Deryng D, Elliott J, Folberth C, Müller C, Pugh TAM, Boote KJ, et al. Regional disparities in the beneficial effects of rising CO2 concentrations on crop water productivity, Nat Clim Change. 2016;6:786–90. https://doi.org/10.1038/nclimate2995. **Examined in detail how the rise in $CO_2$? can improve crops' water balance, counteracting some of the warming effects.**
69.• Mankin JS, Smerdon JE, Cook BI, Williams AP, Seager R. The curious case of projected twenty-first-century drying but greening in the American west. J Climate. 2017;30:8689–710. https://doi.org/10.1175/JCLI-D-17-0213.1. **Highlighted the trade-off between positive $CO_2$? effects on vegetation and runoff, and the potential for underestimation of the latter given overestimation of the former.**