Wetting and drying trends under climate change

Benjamin F. Zaitchik, Johns Hopkins University
Matthew Rodell, NASA Goddard Space Flight Center
Michela Biasutti, Lamond-Doherty Earth Observatory of Columbia University
Sonia I. Seneviratne, Swiss Federal Institute of Technology in Zurich

Abstract

The geography and timing of changes in water availability under climate change are of considerable societal interest. Characterizing these changes in a robust and meaningful manner, however, has not been easy. In the past decade, studies have engaged two provocative hypotheses to explain and predict large-scale trends in water availability. One hypothesis holds that there will be increased contrasts in available water, as wet places become wetter and dry places become drier. Another hypothesis states that there will be global aridification, as widespread increases in evapotranspiration overwhelm changes in precipitation in most terrestrial regions. There is an extensive and sometimes contentious literature on the evidence for each. In some cases these debates reflect direct disagreement, but the appearance of disagreement is exaggerated by the diversity of methods and terminologies employed in different studies. Herein, we examine the applicability and limits of both hypotheses across different frameworks, scales, and contexts, yielding insights on hydrologic change and the future of water availability.

The terrestrial water balance can be stated in simple form as an equality between precipitation (P) minus evapotranspiration (E) and the sum of runoff (R) and the change in water storage (dS/dt):

$$P - E = R + dS/dt \qquad \text{Eqn 1}$$

The corresponding atmospheric water balance equates the sum of water vapor convergence ($\nabla \cdot Q$) and storage change (dW/dt) with $P - E$. The dW/dt term is small when averaged over months to years, allowing that there is a gradual positive trend associated with atmospheric warming, such that the atmospheric and terrestrial water balances are roughly equated as:

$$\nabla \cdot Q = P - E = R + dS/dt \qquad \text{Eqn 2}$$

In the context of environmental change, this equivalence can be stated in terms of perturbations:

$$\delta(\nabla \cdot Q) = \delta(P - E) = \delta(R + dS/dt) \qquad \text{Eqn 3}$$

This equivalency (applicable over land areas) offers several entry points for predicting changes in the water balance under climate change. First, there is an atmospheric constraint, $\delta(\nabla \cdot Q)$: for any unit of analysis, and for timescales longer than one month, changes in available water at the surface, $\delta(P - E)$, should scale with changes in the convergence or divergence of water vapor. Second, changes in available water at the surface depend on both P and E. Predictions of precipitation change, which are the most commonly delivered form of climate-related hydrological prediction, do not tell the full story of changing water availability, since evapotranspiration is also substantially changing under enhanced greenhouse gas forcing[1,2]. Third, these first two constraints apply to the total change $\delta(R + dS/dt)$. The partitioning between runoff and change in storage, however, is not constrained by the average $\delta(P - E)$ or $\delta(\nabla \cdot Q)$, and yet this partitioning is tremendously relevant to water resources. Not all "available water" in $(P - E)$ is equally manageable, particularly if changes in P variability, for example, lead to greater storm runoff and reduced infiltration to groundwater.

These relationships have been the subject of a surprising amount of debate in recent climate change literature. Two hypothesized trends in response to greenhouse gas warming have drawn considerable attention: that wet areas will become wetter and dry areas will become drier (WWDD)[3–5] or that there will be a general global aridification (GA) of land areas[6–9]. Both hypotheses apply to large scale trends in time-averaged conditions, and they should not be mistaken for water resource predictions at precise locations. Nevertheless, a general tendency towards either WWDD, with its implied redistribution of available water resources to regions that are already water rich, or towards GA, which implies tighter water availability for most land areas, is pertinent to the strategies society develops to cope with climate change impacts. Both the WWDD and GA hypotheses have been hotly contested, and recent studies are sometimes interpreted as discrediting both. Nevertheless, both WWDD and GA persist as frameworks for water availability under climate change, and, in reality, they have not been so much discredited as nuanced and contextualized.

Here we examine the physical bases and limitations basis for each hypothesis and the epistemological and methodological inconsistencies that have led to confusion in its application. In this context, we synthesize how changes in the land water cycle can be summarized from the latest available evidence, including assessments of the 6th assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC)[1,2,10], highlighting three main tendencies: wet events become wetter and dry events become drier (WEWDED), a tendency towards wetter wet seasons and drier dry seasons (WSWDSD), and regional-scale climate regime shifts (CRS) that include shifts from humid to transitional, or transitional to dry climate regimes.

Wet-becomes-Wetter, Dry-becomes-Drier

The first equivalency in Eqn 3, i.e. that the change in atmospheric moisture flux divergence is equal to the change in precipitation minus evaporation, is the foundation for the WWDD framework. On global scale, the Clausius-Clapeyron relationship indicates that as the atmosphere warms it is capable of holding more water vapor, at the rate of 7% per degree of warming[3]. To first order, then, if changes in atmospheric circulations are neglected and relative humidity is constant, this trend in water holding capacity intensifies existing convergence and divergence patterns: $\delta(\nabla \cdot Q)$ scales as $\alpha \delta T (P - E)$, where α is 7%. This suggests a 7% per degree increase in $\delta(P - E)$, such that zones of convergence trend towards larger positive values, and zones of divergence trend towards larger negative values. This $\delta(P - E)$ pattern holds in the zonal average in observations and models and has been diagnosed in numerous regional scale studies[11–17].

The second component of Eqn 3, however, shows that the simple scaling relationship based on $\alpha\delta T$ cannot apply over land. While the ocean offers an unlimited source of water for surface evaporation, it is not physically possible to maintain negative $P - E$ over land for a prolonged period, except in limited areas where lateral surface or groundwater flows provide a water source for E to exceed P[18,19]. This complicates the transport-based WWDD argument over land. In addition, the WWDD assumption of constant relative humidity under warming works best over the ocean. Over land, where E can be water-limited and where surface temperatures, on average, rise faster than over the ocean, relative humidity declines with warming[1]. These limitations to WWDD were noted in its original presentation[3], and subsequent studies have shown that global and zonally averaged WWDD patterns are primarily a product of $P - E$ trends over the ocean in both observations and models[18–20]. From a water resources perspective, WWDD is also limited by the scale of relevance. The simple scaling of $\delta(P - E)$ as $\alpha\delta T(P - E)$ does not apply in a fully distributed, gridded sense[21], and water resource planning is location-specific. Nevertheless, the concept of WWDD gained traction as a short-hand for first-order prediction of water availability changes everywhere.

Given these limitations, why consider WWDD for land at all? For one, understanding the limitations, context, and potential extensions of WWDD can be informative. Doing so helps us to think through the diverse and interacting ways in which the atmospheric impacts of climate change affect water resources. Also, as researchers have interrogated the limitations of WWDD, some resource-relevant dimensions of the framework have proved to apply at regional or seasonal scale.

We begin with the evidence for WWDD over land, as quantified in diagnostic studies of observations and models. We focus on observational studies expressly designed to test WWDD theories, and we give particular emphasis to model diagnostic studies that use Coupled Model Intercomparison Project (CMIP) results, as the CMIPs provide the climate research community with multi-model ensembles that characterize consensus and uncertainties in cutting-edge Global Climate Models (GCMs). In performing these studies, researchers typically recognize that $\delta(P - E)$ is not a physically meaningful indicator for land areas, so they apply wetting/drying indices based on change in the evapotranspiration ratio, runoff ratio, or soil moisture. Use of an aridity index such as the ratio of precipitation to potential evapotranspiration (E_p), P/E_p, for example[18], allows one to define physically meaningful "wet" and "dry" zones over land, and relative changes in P and E can then be studied in those wet and dry zones. Studies adopting this approach have found that WWDD is not consistently valid over land areas. Greve et al.[18] analyzed multiple observational datasets and found that 10.8% of the global land area exhibits WWDD, while 9.5% of the world showed an opposite "WDDW" pattern. Yang et al.[22], using a multiple index approach, found that WWDD applied over 20% of global land area while the opposite pattern was observed in 29% of global land area. For areas where WWDD does apply, they found that WW was more common than DD.

Similarly, Kumar et al.[23] found that in GCMs the WWDD paradigm applied better in land areas that are not water limited, favoring WW. Also working with GCMs, Greve & Seneviratne[19] found that predictions of future change in CMIP5 simulations did not show statistically significant WWDD, except at high latitudes. Focusing on drylands, Li et al.[24] found that decadal variability and trends in P/E_p differed by region, contradicting the general WWDD hypothesis. They attributed this to the influence of changes in sea surface temperature (SST) patterns that lead to regional differences in the impact that greenhouse warming has on precipitation. Feng and Zhang[25] applied satellite-derived soil moisture records to study WWDD. Similar to other studies, they found that WWDD did not apply consistently, but they arrived at different estimates of percent agreement vs. disagreement, and noted that a "wetter-in-wet, dryer-in-dry" pattern does apply: a large percentage of wetting trends were found in wet areas and a large percentage of drying trends were found in dry areas, though this did not apply everywhere. Based on these and other studies, a consensus has emerged that WWDD cannot be assumed over land[1].

A complementary line of research, however, has found that WWDD does apply when one considers seasonality. Chou et al.[26] examined multiple observational datasets and GCM output and found a positive trend in the differences between rainy season and dry season precipitation, due primarily to precipitation increases in wet seasons (WW). This intensification of rainy season relative to dry season precipitation has been found in several other studies[14,27–29], with the greatest increase in wet areas[30], and has been attributed to enhanced water vapor transport into precipitation zones during seasons that already favor convergence. Regional variability and unforced climate variability in the observational record mean that this pattern has not always been confirmed[31–33], but the preponderance of evidence supports the pattern. An overall tendency towards terrestrial drying in the dry season has also been identified in a range of observational records[34].

Combining seasonal and spatial perspectives, one can define “wet” and “dry” areas on the basis of monthly conditions rather than long-term annual mean. Doing so places WWDD in a different context: where a stationary aridity mask addresses the question of how climatologically wet and dry areas will change, a seasonally-varying mask that follows areas of water excess and deficit addresses the question of whether existing rain belts and zones of suppressed precipitation will weaken or strengthen. Studies that take the latter approach consistently find that WWDD is confirmed for global tropical land areas[14,35], and this pattern has been attributed to human influence[36].

Changes in Water Vapor and Atmospheric Circulations

To understand the contrasting failures and successes of the WWDD paradigm, we turn to studies that consider the problem from an atmospheric perspective and linearly split $\delta(\nabla \cdot Q)$ into a thermodynamic term for changes in humidity $\delta Q_t = \mathrm{v} \cdot \delta q$ and a dynamic term for changes in the circulation $\delta Q_d = \delta \mathrm{v} \cdot q$. Conceptually, the degree of success of the WWDD paradigm can be understood by the balance between thermodynamic and dynamic changes under greenhouse gas warming—recognizing that the two are not fully independent. We consider each in turn.

A number of studies adopt a thermodynamic perspective on WWDD, using water vapor changes as an entry point for understanding other fluxes. In this vein, Byrne & O’Gorman[20] probed the question of why $\delta(P-E)$ over land does not scale as $\alpha\delta T(P-E)$ in GCM simulations. They found that much of the inconsistency is due to horizontal gradients in temperature and changes in relative humidity, which they accounted for in an “extended scaling” relationship:

$$\delta(P-E) = \alpha\delta T(P-E) + \left(\frac{\delta H}{H}\right)(P-E) - \mathbf{G}\cdot\boldsymbol{\nabla}(\alpha\delta T) - \mathbf{G}\cdot\boldsymbol{\nabla}\left(\frac{\delta H}{H}\right) \qquad \text{Eqn. 4}$$

Where H is near-surface relative humidity and $\mathbf{G}$ is a modified moisture flux term, such that the second, third, and fourth terms on the right-hand side account for local humidity changes, temperature gradients, and gradients in humidity change, respectively. This extended relationship better explains GCM simulation of wetting and drying trends over land, including the fact that simulated runoff from land surfaces increases less dramatically in CMIP5 GCM simulations than the simple $\alpha\delta T$ convergence scaling would imply, and that $\delta(P-E)$ is smaller than would be expected from convergence scaling at most latitudes.

Accounting for these horizontal gradients in humidity and temperature places $\delta(\nabla \cdot Q)$ in terrestrial context, and in a descriptive sense this reconciles thermodynamic reasoning on water vapor transport with observed and simulated large-scale WWDD patterns. This extended scaling context does not, however, fully explain observed or simulated wetting and drying patterns[20]. This is because even the extended scaling formulation assumes that changes in humidity and temperature dominate changes in atmospheric circulation. In reality, changes in atmospheric circulations related to greenhouse gas warming and, in some cases, to local regional processes, have a major impact on wetting and drying patterns. Indeed, dynamical considerations dominate uncertainty in $\delta(P - E)$ in GCM predictions[37].

The influence of climate change on atmospheric circulations has been a major area of study. A full review of these studies is beyond scope for this paper, and is provided in recent reviews[38] and IPCC AR6 . From the perspective of water resources, a few key topics stand out: the global circulation slowdown, changes in planetary circulations (Hadley and Walker cells), and the emergence of anomalous regional circulations.

Global Circulation Slowdown. First, it is generally understood that greenhouse gas warming induces a globally averaged slowdown in atmospheric circulations, particularly in the tropics and subtropics. To first order: if the concentration of water vapor in the atmosphere increases at 7% per degree warming while global precipitation increases at $\sim 2\%$ per degree[39], then the average speed of the circulation that moves water vapor must decline. The thermodynamic argument is zero dimensional and does not necessarily explain trends in major features of the atmospheric general circulation. Complementary mechanisms have been proposed to explain the observed and predicted slowdown in the atmospheric general circulation. These mechanisms include the influence of reduced atmospheric lapse rate on atmospheric stability and rate of descent in subsidence regions[38,40,41] and the potential for enhanced upper tropospheric warming relative to the surface to reduce temperature gradients between zones of ascent and descent[42–44]. The anticipated reduction in circulation strength under greenhouse gas warming would be expected to counterbalance the thermodynamic tendency towards WWDD: $\delta(\nabla \cdot Q_t)$ and $\delta(\nabla \cdot Q_d)$ would have opposite signs. Given the global increase in precipitation[3,13,45–48], the global scale balance indicates that slowing of the circulation mutes but does not reverse the thermodynamic tendency towards an accelerated hydrological cycle consistent with WWDD, but that global balance does not necessarily apply at regional to local scale.

Large-scale Tropical Circulations. The global slowdown is robust in theory and observation[38], but it is a first order argument that does not consider spatial variability in SST warming or changes in the spatial character of circulations (Figure 1). For example, the intensity and extent of the meridional Hadley cells and zonal Walker cells are critical to $\delta(P - E)$ in tropical and subtropical regions, and intensity changes in the Walker Cells appear to be more robust than those of the Hadley cells[49]. This cannot be explained by global slowdown alone. Similarly, predicted and, to some extent, observed poleward shifts in the descending branch of the Hadley Cell and the location of mid-latitude storm tracks have major implications for regional water resources, as does the observed and predicted narrowing of the tropical rain belt associated with the intertropical convergence zone (ITCZ)[50]. IPCC AR6 indicates medium confidence that the Hadley Cells have intensified in recent decades, and that it is likely that there has been poleward expansion of these cells, and GCM predictions consistently indicate a weakening of the Walker Cells. But the theory and observation of changes to the intensity and structure of these circulations are uncertain and are affected by internal variability[51], leading to a wide range of estimates of how future changes in these circulations will affect regional water resources[52,53].

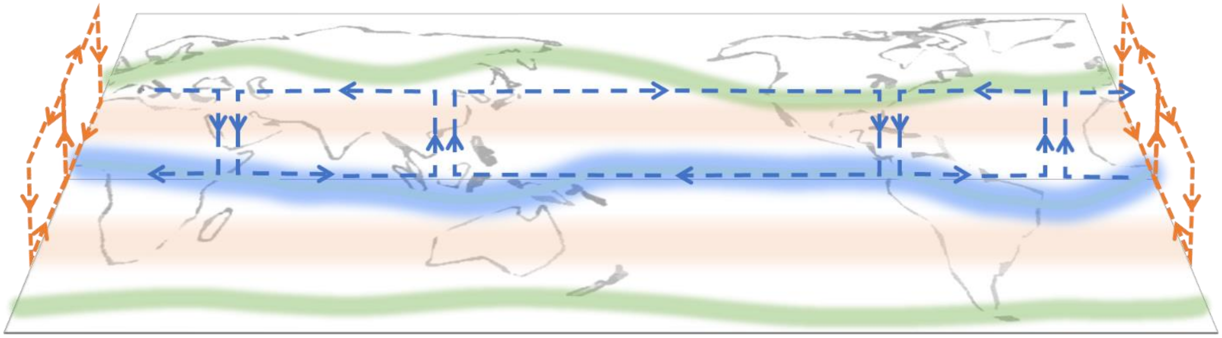

Figure 1: components of the general atmospheric circulation referred to in the text, including the meridional Hadley Cells (orange arrows) and associated generalized subtropical subsidence latitudes (orange shading), the zonal Walker Cells (blue arrows), the Intertropical Convergence Zone (ITCZ; blue shading) and mid-latitude storm tracks (green shading).

Regional Circulation Effects: At regional scale, global thermodynamic and circulation trends are often overwhelmed by other factors. For example, subtropical drying is a robust feature of climate change forecasts, and it has typically been explained in terms of thermodynamics or Hadley Cell expansion. Recent work, however, has demonstrated that simulated subtropical drying over land, where it is present, is a regionally-specific response to a combination of factors, including the perturbed radiative balance, land-ocean SST contrasts, SST warming patterns, and regional atmospheric circulations[54–56]. From a water resources perspective, it is also important to recognize that subtropical precipitation trends show a mix of negative and positive signals at regional scale, rather than uniform drying. In wetting regions, any tendency towards reduced precipitation that might be expected from Hadley Cell expansion or zonally-averaged increases in water vapor divergence is more than offset by regionally-specific factors[54]. This does not mean that these regions are free of water resource concerns, given the potential for increased E, changes in precipitation variability and intensity, and other considerations. But it does mean that the WWDD narrative of subtropical drying due to increased global water vapor transport or expansion of the Hadley Cells does not apply at the scale of resource relevance.

Another consideration is the timescale of atmospheric changes relevant to regional water availability. Changes in atmospheric circulation can emerge as a result of the very rapid response to radiative forcing and land surface warming[54,57,58], relatively fast (timescale of years) response to ice melt and SST warming, and longer term change (decades or more) associated with the establishment of new sea ice and SST patterns[59,60]. This is particularly important when comparing recent observed change to predicted future changes in water availability: the absence of observed short-term trends is not necessarily evidence that a region will not experience longer term trends as SST change sets in. Zappa et al.[61] demonstrate this principle in an idealized study of water limited Mediterranean climates: Mediterranean climates in Chile, California, and around the Mediterranean Sea all experience rapid response drying in GCM simulations with elevated CO_2, driven by radiative forcing and rapid SST change. Over longer timescales, however, California exhibits a reversal to a wetting trend on account of SST adjustments that lead to enhanced inflow of moist air from the Pacific Ocean. Chile and the regions surrounding the Mediterranean Sea, meanwhile, show very little additional long-term change, such that the rapid drying signal persists. All three of these subtropical regions are “dry” by most definitions, and all three exhibit drying in the near-term, consistent with WWDD. But this consistency is lost over longer time horizons.

Changes in monsoon intensity, timing, and variability can have tremendous impacts on water resources in the world’s most populous countries. Such changes are a consequential example of regional climate dynamics superimposed on changes in the global water cycle and global monsoon system. Regional monsoons are linked to the tropical atmospheric overturning circulation through mass flux and the momentum and energy balances[62,63,64]. As such, an understanding of monsoons under climate change requires evaluation of global atmospheric conditions, the general circulation, and regionally-specific dynamics. This complexity is evident in observation: significant decadal scale variability and short-term trends have been diagnosed, but it can be difficult to distribute attribution of these changes between internal climate variability, greenhouse gas warming, aerosols, land cover change, and other factors[65,66].

That said, it is instructive to begin with the first order view of monsoons as moist energetically direct circulations in which a cross-equatorial overturning circulation converges moisture onto tropical and subtropical land. This leads to some simple expectations for monsoon behavior under greenhouse gas warming. Namely, that the wet monsoon zone will receive more water vapor convergence in a warmer climate, due to the greater water holding capacity of the air, and experience positive $\delta(P-E)$, consistent with WWDD. At the same time, warming of the middle to upper troposphere directly by greenhouse gas and indirectly through convection over a warmer ocean might slow the monsoon circulation. In GCM simulations the thermodynamic effect dominates, leading to increases in total precipitation, frequency of extreme precipitation events, rainy season duration, and seasonal range between wet and dry seasons across most of the global monsoon zone[67–69]. This prediction was evident in CMIP5[70] and is larger in CMIP6[69].

Examining regional systems within the global monsoon, however, makes it clear that this generalized reasoning does not explain all predicted changes in the monsoon, and that changes in regional circulation need to be considered as well[71,72]. First, the predicted increases in monsoon duration and precipitation are almost entirely a product of changes in the Northern Hemisphere[72,73]. Predicted precipitation change in the Southern Hemisphere is small and uncertain, including uncertainty in the South American and Australian monsoon systems. This asymmetry can be understood as a product of asymmetric warming, as the northern hemisphere is expected to warm more quickly than the southern hemisphere, leading to a shift in the Hadley Cells and increased precipitation in the Northern Hemisphere monsoons[73,74]. Intensification and lengthening of the Asian monsoons come at the expense of the Australian monsoon. Interestingly, GCMs forecast that the North American Monsoon will weaken over the 21st century, with precipitation particularly reduced over Central America[75]. This runs counter to general Northern Hemisphere monsoon strengthening and to simple moisture convergence reasoning, possibly because of the unique role of jet dynamics in the North American monsoon[76]. Notably, the intensity of precipitation extremes within the North American Monsoon region is predicted to increase, as a result of thermodynamic conditions[77]. There is greater confidence in this prediction than there is in the prediction of changes in precipitation totals[78–80].

As the examples of the monsoons, Mediterranean climates, and subtropical drying demonstrate, regional changes in circulation can determine the spatial pattern of wetting and drying trends. The paradigm of a growing gap between wet and dry conditions due to differences in scaling between water vapor and precipitation that underlies WWDD is, however, quite powerful when considering variability. To first order, wet seasons tend to become wetter and dry seasons tend to become dryer under greenhouse gas warming. This pattern applies over land and is relevant when considering climate change impacts on water resources.

Global Aridification

In contrast to the WWDD emphasis on increasing disparities in available water, Global Aridification (GA) focuses on the potential for general drying under climate change in most regions[7,81–84]. Viewed through the lens of precipitation alone, the GA hypothesis is surprising. There is consensus that, averaged over both land and ocean, P increases under greenhouse gas warming, and observations indicate that P has increased over land areas in the global average[10]. The fact that researchers have found evidence for GA in both observations and model output despite globally averaged trends in P emphasizes the importance of the full water balance for wetting and drying trends.

In approaching the literature on GA, one must distinguish between meteorological aridity, hydrological aridity, and agroecological aridity (Figure 2). Meteorological aridity is a function of atmospheric water supply and demand. Supply is typically quantified as precipitation, while atmospheric evaporative demand is quantified with variables like Potential Evapotranspiration (E_P), relative humidity, or vapor pressure deficit. The aridity index (P/E_P) is frequently presented as an indicator of meteorological aridity, though there can be problems in its application, as described below. Hydrological aridity relates to changes in land water storage or flows, and is quantified in reductions in $P - E$, soil moisture, groundwater, snowpack, or runoff. Agroecological aridity is concerned with reductions in net ecosystem productivity, and can be tracked using vegetation indices, carbon fluxes, and other ecological measures.

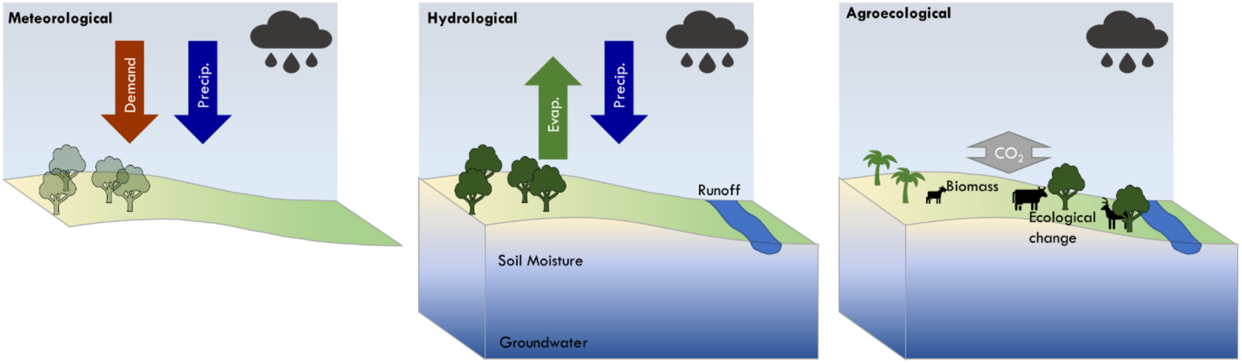

Figure 2: Processes involved in meteorological, hydrological, and agroecological aridification. Meteorological focuses on atmospheric supply and demand, with some methods accounting for vegetation influence on E_P. *Hydrological involves the water balance and can be estimated in terms of actual fluxes (*$P - E$*, runoff) or water storage. Agroecological examines trends in carbon fluxes, productivity, and ecological indicators of aridity.*

Trends in each form of aridity are sensitive to different combinations of processes, and they might not correlate with each other. This is evident when considering how intensity and timing of precipitation may influence different types of aridity. If the same annual total volume of precipitation is concentrated in more intense events, for example, or comes as rain rather than snow, then runoff might increase even as P/E_P decreases. Changes in timing can also produce contrasting trends for different aridification metrics[85]. WWDD on seasonal timescales, for example, in which precipitation is concentrated in wet seasons, might lead to an increase in total annual runoff but reductions in average annual soil moisture. The diagnosis of feedback processes also depends on how aridification is defined: GCM experiments indicate that reduced soil moisture under global warming amplifies (meteorological) aridification via a positive feedback on E_P[86], while a GCM investigation of drylands shows that reduced soil moisture mitigates (hydrological) aridification via a negative feedback on actual evapotranspiration (E) that buffers soil moisture loss[87].

Given the prediction for increased average P over global land under greenhouse gas warming, the meteorological GA hypothesis is best understood in terms of evaporative demand[21,88]. The demand term can be defined using a number of atmospheric variables. We focus on E_P because it is widely used and because its applications are debated. As a starting point, it is understood that E_P increases for both land and ocean under greenhouse gas warming, primarily due to the elevated air temperature. This understanding is grounded in theory and modeling results[9,89,90], which indicate that E_P over land should increase at ~5% per degree and that the rate of increase per degree should be fairly spatially uniform[8,9,91]. The rate of E_P increase over land is larger than over the ocean because warming over land is greater[20,92], leading to reduced relative humidity and increased vapor pressure deficit[83]. This increase in E_P underlies predictions of continental drying. True to this understanding, a number of studies that have employed E_P as a standalone term or as a component in an aridity index have found that greenhouse gas warming causes a widespread drying over land, with much larger areas showing declines in water availability than might be expected from precipitation trends alone[7,8,81,82,84,91,93–95]. This predicted drying is accompanied by substantial increases in drought[6,96–100], though the question of GA is distinct from the question of whether droughts increase under climate change: where GA is concerned with trends in prevailing aridity, the frequency, duration, and intensity of droughts are sensitive to changes in climate variability and land cover conditions[101].

There are, however, several complications for GA reasoning. One identified problem is the "pan evaporation paradox," which received considerable attention in the literature but has mostly been resolved conceptually and observationally. Conceptually, a trend towards reduced pan evaporation in the later 20th century led to the question of whether the hydrological cycle was slowing[102], in contradiction to GA. As researchers quickly recognized, however, reduced pan evaporation could be associated with a complementary increase in E[103–105] and could also be a product of differences between E_P from a vegetated surface and an open water pan evaporation measurement[103]. This conceptual resolution to the problem still left open the possibility that evaporative demand was declining, suggesting a decrease in meteorological aridity. Recent studies of pan evaporation from several regions, however, indicate that the declining trend has plateaued or reversed in recent decades[106–108], as the influence of increased vapor pressure deficit has overwhelmed other meteorological factors[109]. This brings the pan evaporation trend into agreement with energy balance models[110], GCM predictions, and general theory.

Other complications with E_P-driven GA include apparent inconsistencies with studies of paleoclimate, which indicate that cooler periods are drier, while warmer periods are characterized by vegetation expansion and, seemingly, a reduction in moisture limitation[88,111–114]. This suggests that from an agroecological perspective, "warmer is wetter" over land. From a hydrological perspective, coupled GCM simulations of future climate tend not to show dramatic declines in streamflow, and trends in soil moisture differ by method and metric[86,101,115–117], indicating that the coupled models do not predict hydrological GA in the coming century. These paleoclimate and GCM results would appear to be a contradiction to GA, but there is not necessarily a contradiction between meteorological drying and agroecological or hydrological wetting—the processes governing each are distinct.

But while opposing trends in different types of aridity can be explained, problems arise when trends relevant to meteorological aridification are misapplied or misinterpreted when studying hydrological or agroecological aridification. Milly and Dunne[118] emphasize these problems. They point out that E_P is a diagnostic field in GCMs that is sensitive to meteorology and land-vegetation-atmosphere processes. This diagnostic E_P field is not always included in public GCM data portals, so studies of hydrological aridity GCM trends often rely on offline E_P calculations. This is often done by applying a fixed parameter Penman-Monteith formulation[119,120], or similar. This offline E_P estimate is then applied to calculate simplified aridity or drought indices, or to drive offline simulations with a hydrological model. Note that the Penman-Monteith formulation is, formally, a reference evapotranspiration for a well-watered crop rather than an E_P[121].

The problem with the offline approach, then, is that the diagnostic E_P calculation does not take reduced stomatal conductance under elevated CO_2 into account. While that process is included in the land model in modern GCMs, it is not part of simplified drought index calculations, and it is not always considered in offline hydrological models. This can lead to a spurious overestimate of future E, resulting in exaggerated drying trends in soil moisture and runoff[101,118]. Other reasons that these offline, E_P-based indices might overestimate drying include the fact that the indices are typically calculated on monthly timescales or longer; that resistances to E require multilayer vegetation and land surface parameterizations to be captured effectively; and that offline indices ignore land-atmosphere feedbacks, including those mediated by vegetation physiology, type, and structure[86,101,122]. For these reasons, use of E_p diagnosed from GCM output is problematic when applied to predictions of agricultural or hydrological aridification, including via the application of simplified metrics like the aridity index.

When considering trends in E, as opposed to E_P, one needs to engage the role of vegetation in connecting subsurface water to the atmosphere. As noted above, increases in CO_2 enhance plant water use efficiency[123–126]. This could have the effect of reducing the anticipated E across climate zones, possibly leading to increases in runoff, groundwater recharge, and/or soil moisture[122,127–131]. Another important mechanism for reduced water use is the fact that plants can limit transpiration under dry conditions to avoid desiccation[132]. This implies a partial decoupling of increases in atmospheric evaporative demand and evapotranspiration under soil moisture stress. Models indicate that both the CO_2 and soil moisture effects can result in substantial reductions in atmospheric humidity[86].

These water efficiency effects, however, are counteracted by enhanced plant growth under elevated CO_2, longer growing seasons in cold-limited climates, and increased soil moisture in regions experiencing wetting[127,128,133–137]. In recent decades there has been an observed contribution of increased vegetation growth to a positive trend in terrestrial E, while evidence of increased stomatal resistance is mixed across ecosystems and climate conditions[1,138–142].

On net, it is not clear to what extent the combined effects of CO_2-induced plant water use efficiency and plant reduction of evapotranspiration under soil drying will lead to global reductions in hydrological aridity—that is, a tendency towards a globally-averaged “warmer is wetter” trend. Studies of GCM output indicate that global runoff increases with greenhouse gas warming. This trend, in part, can be understood as a function of regional increases in precipitation, a shift from frozen to liquid precipitation in some regions, and a concentration of precipitation in more extreme events[1]. Many of these studies, however, depend on models that do not include the potential for structural vegetation or ecological change. This means that they do not fully account for the potential for E to increase with greening in an elevated greenhouse gas world[88] and may be systematically biased by accounting for physiological water use efficiency effects while ignoring increased water use due to plant growth[136].

Cui et al.[143] examined these vegetation influences in GCM experiments. They found that in wet areas simulated plant structural response to CO_2 saturates: after a certain point, nutrient, temperature, and light limitations prevent continued increase in vegetation growth. This allows the water use efficiency effect to dominate. In drylands, meanwhile, increases in vapor pressure deficit driven by water vapor divergence and land-sea warming contrasts are reinforced by CO_2-induced increases in stomatal resistance and reductions in E[86,144,145]. But in these ecosystems the plant structural response is far from saturated, and water use efficiencies gained from elevated CO_2 can offset water limitations on photosynthesis[146–148]. This can lead to significant greening even as atmospheric aridity increases[149]. The implication is that the combined physiological and ecological impacts of elevated CO_2 support a hydrological WWDD rather than GA, as wetter areas retain more water due to plant physiological effects while dry areas experience offsetting physiological and structural influence on E. This feature is confirmed in other studies[133,134], but with variability in geography and aridity thresholds.

A CMIP5 GCM study by Lemordant et al.[144] yielded geographic patterns similar to Cui et al.[143] at large scale, reflecting the relative magnitudes of physiological and structural effects. Lemordant et al.[144] particularly emphasized the magnitude of influence that plant physiological and structural responses have on hydrology and the coupled carbon cycle. E, $P - E$, and evaporative fraction all exhibited greater sensitivity to physiological change than they did to changes in P or in direct radiative effects of elevated greenhouse gases. This strong influence of vegetation was found despite the fact that GCMs tend to underestimate vegetation-mediated land-atmosphere feedbacks[150]. These feedbacks can be particularly strong in regions that are transitional between water limited and energy limited regimes[132,150–153] and during ecologically significant extreme events[154–157].

The results of these studies are consistent with paleoclimate evidence of “warmer is greener,” as plant leaf area index and vegetation cover increase in dry, warm areas. From the perspective of available water—that is, hydrological aridity—patterns are geographically mixed and, if anything, appear to be more consistent with a vegetation tendency to reinforce WWDD than to drive the system towards either systematic GA, as one might infer from an analysis of atmospheric demand, or systematic wetting, as one might infer from physiological effects alone.

It is worth noting that most studies of GA (and of WWDD) focus on natural vegetation responses and feedbacks related to greenhouse gas warming. But other anthropogenic influences, including aerosol loading—which on the balance appears to mitigate GA[158]—and land cover change can also matter[159,160]. Interactions between aridity trends and water management may also have significant implications for water resources in some regions (**Box 1**).

Box 1: Irrigation and aridification

Irrigation distributes water across the surface, resulting in increased evapotranspiration. This can affect aridity at regional scale. In some cases it is a buffering effect: increased humidity can reduce evaporative demand, and under some conditions can enhance precipitation locally or downwind. Irrigation also alters surface energy fluxes through changes in albedo and turbulent fluxes, with potential impacts on mesoscale circulations and planetary boundary layer conditions relevant to both atmospheric demand and precipitation[161,162].

Another aridity-irrigation interaction relevant to water management is "climate-induced pumping," in which water withdrawals increase during dry periods. In the context of aridification, this means that water resources will be depleted faster than anticipated. The influences of rainfall deficit and evaporative demand on climate-induced pumping are geographically specific[163] and depend on management strategy and regulations. The ultimate impact of aridification on the sustainability of agricultural production in irrigation-dependent regions depends, in part, on these dynamics. In a modeling study, Nie et al.[163] found that climate-induced pumping in the United States was greatest in transitional climate zones rather than semi-arid to arid regions. This suggests that increased irrigation demand under climate change could amplify water stress in regions that are not currently the focus of efforts to reduce unsustainable groundwater use.

Aridification and Drought

Studies of GA generally focus on trends in time-mean conditions. In this context, "aridification" refers to the average state, and not necessarily to the frequency of dry (or wet) extremes. As already noted, however, the processes that contribute to a trend in average aridity play out over a range of timescales. Globally, the intensity of precipitation extremes increases with warming at a greater rate than total precipitation[164–166]. In regions affected by increased extremes, we expect a larger percentage of rainfall will occur under conditions of soil saturation or overwhelmed infiltration capacity, increasing the average runoff fraction and leading to high streamflow at the expense of local water recharge. At seasonal scale, wetting of wet seasons and drying of dry seasons[27,30,33] also favors runoff over recharge. These intensity and seasonality trends help to explain why GCMs can predict widespread reduction in soil moisture even when the spatial extent of precipitation and runoff reductions is more limited[85], though the extent of this divergence depends on method of analysis[101]. Changes in intraseasonal variability[167] and snow accumulation and melt[168] also have substantial implications for hydrology and agroecology. Forecasts of future regional[169–172] or general global aridification, then, involve a combination of processes across timescales.

The relevance of shorter timescales to GA brings us to the question of global trends in drought[2,85,101]. In contrast to aridification, drought is a transient phenomenon defined relative to prevailing conditions. As with GA, discussion of drought trends can be complicated by definitions. *Meteorological drought*, defined in terms of precipitation deficit, *agricultural or ecological drought*, most commonly defined in terms of soil moisture anomaly, and *hydrological drought*, defined in terms of surface or groundwater supply, develop on different timescales and are sensitive to different atmospheric and surface processes. Studies of drought can also differ in baseline, input data, thresholds, and focus on intensity, duration, or frequency of events.

Drought trends have been addressed in recent reviews[101,173] and IPCC AR6[2]. These reviews have noted a global tendency towards increased evaporative demand over land—meteorological aridification—that exerts a positive forcing on drought. Overall, however, trends in all classes of drought are regionally-specific rather than global, on account of regional hydrological processes and precipitation trends. Drought increases, like aridification, are most widespread when defined in terms of soil moisture deficits, on account of soil moisture sensitivity to increased evaporative demand and, in some regions, runoff partitioning. The geographic pattern of observed and predicted drought trends generally looks similar to patterns found in studies of aridification. This is not inherently obvious, since drought trends are sensitive to climate variability as well as overall trends, though this might be a product of the uncertainty in predicted changes in climate variability[53]: there simply isn't confidence in model predictions of the processes that might decouple drought risk from long-term water balance trends.

Outlook

So, are WWDD and GA useful frameworks? Both fail when applied as all-encompassing statements on climate trends, but each is valid in specific contexts. WWDD applies best for studies of seasonal trends (or trends in seasonally migrating wet and dry zones) rather than for regions defined as "wet" or "dry" based on long-term average conditions. GA may hold for meteorological aridification or, in some analyses, for hydrological aridification defined in terms of soil moisture, but appears not to hold for runoff or for agroecological aridity.

From a research perspective, the idealizations that underlie the appropriately contextualized versions of WWDD and GA can offer an entry point for studying process, including in cases where the frameworks fail. At regional scale, for example, one can consider how changes in atmospheric humidity, atmospheric stability and circulations, land-atmosphere interactions, or vegetation change may influence a trend that is consistent or inconsistent with WWDD, and how those processes might relate to a more nuanced framework such as wet seasons becoming wetter and dry seasons drier (WSWDSD) or wet events to becoming wetter while dry events become drier (WEWDED)[174]. Considering the meteorological processes proposed to drive GA, meanwhile, can be useful when studying climate regime shifts (CRS), in particular as humid regions become transitional and transitional regions enter dry climate regimes. These shifts to drier climate regimes are critically important and offer a more specific and targeted framing of aridification trends.

This utility when formulating and testing hypotheses, however, is counterbalanced by the risk that catchy phrases like WWDD or GA may continue to be adopted as short-hand and misapplied in other fields and in public communication of climate science. Recognizing this risk, we conclude that it would be more useful for climate scientists to refer directly to the processes and variables that underlie these frameworks rather than resorting to WWDD or GA shorthand. Discussion of positive trends in evaporative demand over land or of thermodynamic influence on water vapor transport are more both more specific and less likely to be miscommunicated, even if (and perhaps because) they don't roll of the tongue quite so easily.

Moving forward, the focus on disentangling processes rather than assuming generalized outcomes, as well as on carefully assessing regional specificities, will continue to be of high relevance for predictions of water availability and to water resource management under climate change. In pursuing this predictive capability, it is important to distinguish between descriptive explanation, including results presented in many of the diagnostic studies reviewed here, and predictive explanation, in which theory has been embodied in models with predictive skill. Finally, the interference of human activities on the water cycle does not only manifest through increases in greenhouse gases and associated global warming and climate change, but also through direct perturbations of the water cycle from irrigation and land use and land cover change. A comprehensive assessment of expected water cycle changes in the coming decades thus needs to integrate the different dimensions of human impacts on the global and regional water exchanges.

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