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PERSPECTIVE

Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges

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Droughts and heatwaves cause agricultural loss, forest mortality, and drinking water scarcity, especially when they occur simultaneously as combined events. Their predicted increase in recurrence and intensity poses serious threats to future food security. Still today, the knowledge of how droughts and heatwaves start and evolve remains limited, and so does our understanding of how climate change may affect them. Droughts and heatwaves have been suggested to intensify and propagate via land–atmosphere feedbacks. However, a global capacity to observe these processes is still lacking, and climate and forecast models are immature when it comes to representing the influences of land on temperature and rainfall. Key open questions remain in our goal to uncover the real importance of these feedbacks: What is the impact of the extreme meteorological conditions on ecosystem evaporation? How do these anomalies regulate the atmospheric boundary layer state (event *self-intensification*) and contribute to the inflow of heat and moisture to other regions (event *self-propagation*)? Can this knowledge on the role of land feedbacks, when available, be exploited to develop geo-engineering mitigation strategies that prevent these events from aggravating during their early stages? The goal of our perspective is not to present a convincing answer to these questions, but to assess the scientific progress to date, while highlighting new and innovative avenues to keep advancing our understanding in the future.

Keywords: drought; heatwave; land feedback; land–atmospheric interactions

Introduction

While multiple definitions exist, meteorological droughts and heatwaves are commonly regarded as prolonged periods of precipitation shortage and extremely high temperature, respectively. Both can lead to major natural disasters and socio-economic impacts, especially when they occur simultaneously as combined events.[1–3] They cause agricultural loss, plant mortality, air pollution, and water scarcity; they also endanger the sustainability of ecosystems and food production systems, and favor the occurrence of wild fires.[3–7] The progressive intensification and proliferation of these extremes following global warming[8–10] counts among the most critical impacts of climate change on society according to the Intergovernmental Panel on Climate Change.[9,11] Nonetheless, there is a perception that droughts and heatwaves have already become unusually frequent and severe in recent years. This perception has been fueled by unprecedented events of combined water scarcity and extreme heat in Australia (2005–2007), Northeastern China (2009), Europe (2003, 2010, and 2017), or the United States (2013–2015).[3,5,9,12] These extreme events have evidenced our limited understanding of the mechanisms driving their onset and evolution. Operational forecasts still fail to capture the complexity of these driving processes at seasonal scales, thus their accuracy is often insufficient to be used as early warning systems.[13,14] Meanwhile, uncertainties in projected trends from climate models also remain high,[9,10,15] and since terrestrial carbon sinks are heavily affected by these climatic

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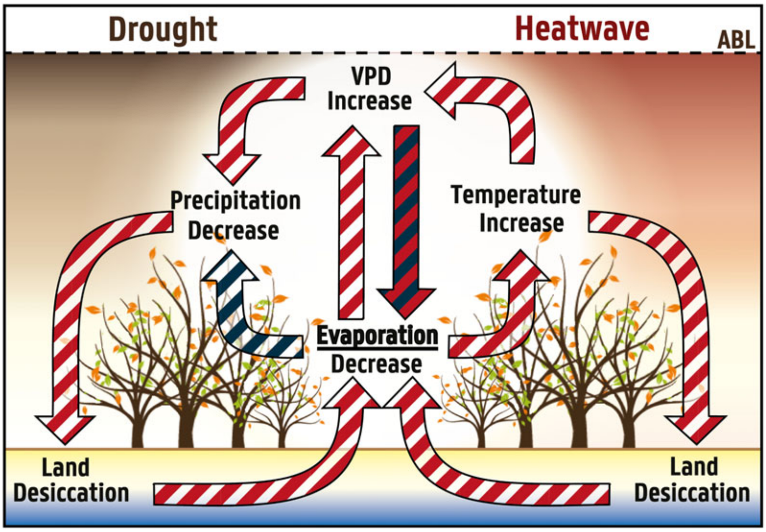

Figure 1. Land feedbacks as local intensifiers of hydro-meteorological extremes. The large-scale response of ecosystems to the high atmospheric demand, heat, and (surface and atmospheric) water stress is thought to be critical to set the magnitude of these events. Here, red color means positive relation (e.g., land desiccation enhances evaporation decrease), while blue color means negative relation. We highlight that the higher vapor pressure deficit (VPD) will typically reduce stomatal conductance and transpiration under conditions of surface water stress. We also note that the selection of relevant processes is boldly simplified in this conceptual diagram.

extremes,[7,13,16–20] these uncertainties propagate to the predictions of global warming.[9,21]

Current understanding of the physics behind meteorological droughts and heatwaves suggests that similar persistent large-scale circulation anomalies are critical for the initiation of both events,[22–25] which partly explains why these extremes often concur. Conversely, similar land–atmospheric feedbacks have been suggested as central in their evolution,[21] even if droughts and heatwaves frequently span different temporal scales, with the latter being typically shorter (days to weeks) than the former (months to years). These feedbacks are intuitive: as soil and vegetation dry out, land evaporation (or *evapotranspiration*[26]) is reduced, hence the air becomes even drier, which may further decrease the likelihood of rainfall and favor the occurrence of meteorological droughts (Fig. 1).[21,27–29] Concurrently, as evaporation progressively declines, a larger fraction of incoming radiation is employed to warm up the environment, which leads to an accumulation of sensible heat in the atmosphere that may develop into a heatwave or exaggerate its magnitude.[4] While multiple studies have revealed that, under certain conditions, rain falls preferentially over soils that are drier than their surroundings, due to the instigation of convection and meso-scale circulation,[30,31] this situation does not necessarily imply more likelihood of rainfall during drought times.[32] Finally, feedbacks that originate from drought-induced changes in surface albedo may also be acknowledged,[33] although recent studies suggest that they are comparatively less important.[34] Therefore, land–atmospheric feedbacks may be central in defining the magnitude of particular extreme events, and also help understand why these two—*a priori* independent—extremes often occur in association. In fact, the imperfect representation of these land–atmospheric feedbacks in models has been suggested as a core reason why seasonal forecasts fail to predict these events,[27,35] but also why trends in climate model projections of these climate extremes remain so uncertain.[9,21]

Land–atmospheric feedback experiments looking at short-scale interactions during droughts and heatwaves have mainly focused on climate modeling activities[36,37] and statistical analysis of meteorological data[38,39] (see below). The advantage of performing coupled model simulations in which land parameters (i.e., vegetation cover and soil moisture) are intervened in one of the experiments is that differences with the control run are unambiguous in terms of causality.[40,41] However, the degree of land–atmospheric coupling varies greatly from model to model, and the results of these experiments are difficult to validate using field measurements,[42] even though recent studies have aimed for such a validation.[43] On the other hand, ground and satellite measurements reflect the actual variability in our coupled system. However, even when accurate observations are available and sophisticated coupling diagnostics are applied, the potential to infer formal causal relationships remains limited.[44–48] This is due to the complex links among the different elements in the land–atmosphere continuum, which reflect in the cross-correlation of multiple variables without the need of implying causality, the various scales of variability and autocorrelation of different elements, the unavoidable confounding effect of hidden variables not being observed, and the complex and bidirectional interactions within the system.[44–46,49] In addition, most observational analyses have focused on local feedbacks, even though most effects can be considered as nonlocal depending on the definition of "locality" (see below).

Due to the difficulties to formally disentangle and quantify the importance of these feedbacks using either observations and/or models, key open questions remain in our goal to uncover their real importance for the occurrence of droughts and heatwaves.[50–52] (1) What is the large-scale response of land evaporation to rainfall deficits and extreme heat in different natural and anthropogenic ecosystems? (2) How does this response regulate the state of the atmospheric boundary layer and thus intensify or buffer the event locally? (3) How do land surface anomalies contribute to the propagation of the events toward other regions? (4) Can our knowledge of these feedbacks be exploited to develop mitigation strategies that go beyond preventing the consequences of these extremes and toward palliating their causes? (5) What is the importance of these feedbacks, not just for the occurrence of particular extreme events, but also for the regional warming and drying trends that our climate models are projecting? The overriding intent and purpose of this perspective paper is to assess the scientific progress in regard to the role of land–atmospheric feedbacks in the occurrence of droughts and heatwaves, identify the main knowledge gaps, and highlight new and innovative avenues to keep advancing our understanding of these processes. In addition, it will discuss some of the modeling and observational tools that have the scope and potential to deliver new and powerful insights to the study of land–atmospheric interactions as an almost separate discipline.

Lessons learned from observations

From soil moisture to evaporation

Although the importance of land surface evaporation for hydrology and agriculture has long been recognized,[53,54] its crucial role in climate has only been highlighted in more recent years.[40,55–57] Overall, natural land evaporation (1) is highly sensitive to changes in radiation and temperature, thus it propagates the radiative effects of anthropogenic emissions throughout the entire water cycle,[58,59] (2) plays a central role in critical climate processes, such as the water vapor and cloud feedbacks, and (3) connects the water and carbon cycles through its coupling to photosynthesis.[60,61] However, as mentioned above, the most direct effect of land evaporation on climate comes from its role in the surface energy partitioning: evaporation directly regulates climate through a series of feedbacks acting on air temperature and precipitation, which may affect climate trends,[62,63] regular meteorological conditions,[30,32,40] and hydro-meteorological extremes[4,39,57] (Fig. 1). As stated above, our focus here is on the latter: the importance of these land feedbacks for the occurrence of droughts and heatwaves. A first and necessary step to understand this importance is to recognize the anomalous response of large-scale evaporation dynamics during the onset and evolution of these events. This response can be viewed as the starting point in the feedback cycles illustrated in Figure 1. The contrasting evaporative response of particular ecosystem types will set their potential to influence the state of the atmosphere (see below) and thus the evolution of the extreme event. Therefore, understanding these ecosystem-specific transpiration responses to extreme atmospheric and environmental conditions is fundamental.[39]

However, to date, modeled fields of land evaporation remain unreliable and our capability to observe evaporation over large scales is still limited.[55,56] Fortunately, the rising interest of the climate community in land evaporation has coincided with an unprecedented availability of global field measurements, particularly due to the efforts of the FLUXNET community.[64] Meanwhile, due to the limitations in coverage of *in situ* measurements, and the difficulties to model evaporation accurately, the scientific community has also turned their eyes to satellite remote sensing.[55,56,65] As such, a wide range of global observational data sets of land evaporation have become available in recent years.[66–68] As evaporation cannot be directly sensed from space, these data sets are still the output of simple models that combine evaporation-related observable variables, either physically or statistically.[66,69–72] This has not hindered the use of these evaporation data in state-of-the-art global water and energy assessments;[73] yet, they are not to be interpreted as direct satellite observations, and rather as model outputs generated based on the satellite forcing data.[74] Nonetheless, an important motivation for relying on remote sensing-based evaporation for the study of droughts and heatwaves is that transpiration—the largest component of terrestrial evaporation globally[75,76]—is extremely difficult to accurately model under conditions of water and heat stress.[77]

During the onset of droughts and heatwaves, the persistent anticyclonic patterns leading to low relative humidity, high air temperature, and reduced cloudiness[78] cause a high atmospheric demand for water that may initially incentivize soil evaporation and plant water consumption through transpiration.[5,78,79] The combination of rainfall deficits (i.e., *meteorological drought*) and increased atmospheric demand may lead to a prolonged and pronounced decline in soil moisture (i.e., *agricultural drought*), and severely impact hydrological systems (i.e., *hydrological drought*).[5] As the meteorological drought or heatwave evolves, the expected evaporative response of an ecosystem becomes more equivocal, and evaporation may start declining as soils dry below a certain threshold (i.e., *critical soil moisture*).[21] The effective impact of soil moisture storage on land evaporation, and in particular on transpiration, has been subject of investigation for many years,[60,80] and despite its pivotal role in land–atmosphere coupling, a thorough understanding of the key controls on this relationship is still lacking.[81–83] This relationship is frequently simplified by considering a wet domain, in which evaporation is mainly controlled by energy (potential evaporation), and a dry domain below critical soil moisture in which evaporation declines with decreasing soil moisture.[21,84] Several observations made during evolving drought conditions confirm the general validity of this conceptual model, despite the potential existence of multiple stress factors other than soil moisture, such as high vapor pressure deficit and extreme temperature.[85] For example, Teuling *et al.* found an increase in evaporation during the onset of droughts in central and western Europe,[79] and an exponential decrease of evaporation as the events persisted, which appears consistent with a linear relation between soil moisture and evaporation below critical soil moisture. However, as one may expect, the relationship between soil moisture and evaporation is bidirectional: in the absence of rainfall, evaporation losses will control the decay of soil moisture, and this decay will in turn regulate stomatal conductance and evaporation;[21,79] this bidirectionality may also make the relationship highly nonlinear.[86] Overall, the timing and extent of the evaporation decline during droughts and heatwaves will depend on the particular ecosystem conditions, such as the soil moisture state during the onset of the event, land cover radiative properties, aerodynamics of the ecosystem, or specific plant hydraulic traits such as root depth or internal processes regulating stomatal conductance.[39,77]

An example of the characteristic response of ecosystem evaporation during the onset and evolution of a meteorological drought is shown in Figure 2. The period highlighted corresponds to the 2012–13 Midwest drought, which led to conditions of "exceptional drought" according to the U.S. Drought Monitor[87] (Fig. 2A). Measurements of evaporation correspond to three eddy covariance sites in Nebraska that are located within few hundred meters from each other and are managed by the University of Nebraska Agricultural Research and Development Center. The first one (US-Ne1) is located in a maize site subject to irrigation, the second (US-Ne2) and third (US-Ne3) are located in maize-soybean rotation plantations; while the latter is rainfed, the former two are often irrigated. The two irrigated sites (US-Ne1 and US-Ne2) show a very characteristic positive anomaly in evaporation during the beginning of the drought event, coinciding with the high vapor pressure deficit, net radiation, and temperature (Fig. 2B). Only US-Ne3 shows a milder increase during the onset, potentially reflecting the lower anomaly in net radiation at this site related to a higher albedo on that year (Fig. 2B). All three sites experienced a pronounced decline

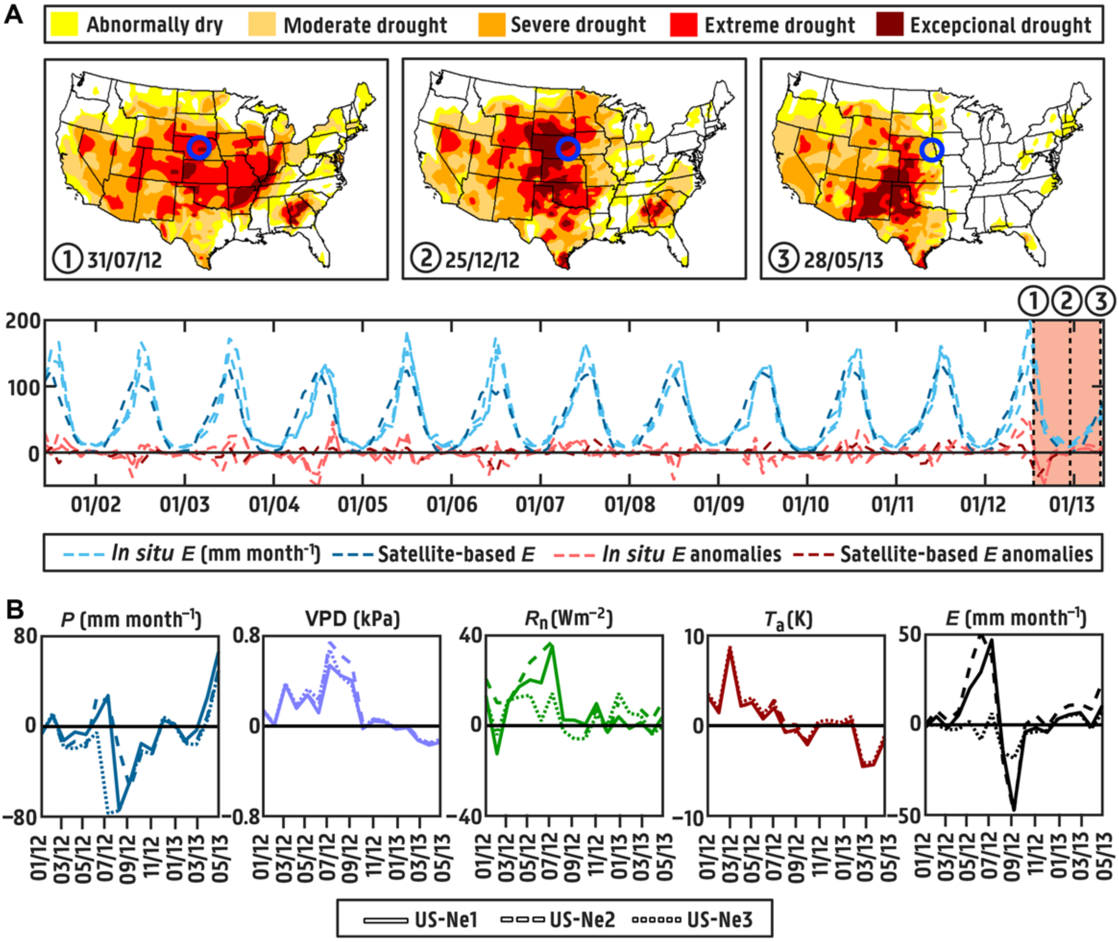

Figure 2. Evaporation during the 2012–13 Midwest drought. (A) Evolution of the event according to the U.S. Drought Monitor[87] (top). Measurements of evaporation (mm month^{-1}) at three eddy covariance cropland sites in Nebraska: US-Ne1, US-Ne2, and US-Ne3 (bottom). The satellite data come from GLEAM v3.2a.[66,88] The blue circles in the maps mark the location of the eddy covariance sites. (B) Anomalies in precipitation (P, mm month^{-1}), vapor pressure deficit (VPD, kPa), net radiation (R_n, W m^{-2}), air temperature (T_a, K), and land evaporation (mm month^{-1}) during the drought.

in evaporation as the event evolved, particularly US-Ne1 and US-Ne2. This decline is qualitatively depicted by the satellite-based data from the Global Land Evaporation Amsterdam Model (GLEAM) v3.2a (Fig. 2A).[66,88] Altogether, this transition from positive to negative anomalies is unprecedented in the 12-year record of *in situ* observations (Fig. 2A). Nonetheless, the spatial response of evaporation is far from being homogeneous: the correlation of evaporation anomalies among the three different sites is lower than the correlation among the sites for any meteorological variable (Fig. 2B). This reiterates the dependency of evaporation on land surface conditions and management, and the consequent spatial heterogeneity of the flux. Here, the contrasting response at each site may arise from differences in soil properties, initial soil moisture, and irrigation, and may reflect as well different crop strategies to cope with water stress,[39,89,90] such as a more isohydric behavior in US-Ne3, a higher stomatal sensitivity to vapor pressure deficit, or a deeper rooting system at that site.

Further expanding on the differences among land use types, pan-European analyses of the impact of summer droughts and heatwaves on flux partitioning at eddy covariance and meteorological sites have shown that forest ecosystems respond fundamentally differently to other ecosystems.[38,39,91] Perhaps surprisingly, over forests, a larger fraction of the positive net radiation anomalies is used to enhance the sensible heat flux during the onset of these events. While for trees, the deeper rooting system may guaranty the access to water during prolonged droughts, the larger stomata regulation may also buffer the initial water loss through transpiration. This reduction in transpiration during the onset of droughts can be accompanied by a substantial increase in water use efficiency,[91] and will be more pronounced for isohydric tree species, in which the high sensitivity of stomata to vapor pressure deficit is larger.[89,92] In fact, recent studies have reported that for forest ecosystems, the high vapor pressure deficit can limit transpiration as much as the dry soils in conditions of stress,[93] with the importance of these drivers being species dependent.[89,90] Nonetheless, disentangling the stress attributed to soil or atmospheric dryness based on observations is far from being an obvious task, given the correlation between soil and atmospheric moisture content.[85] A priori, the increasing stomatal resistance during sudden episodes of extreme hot and dry air advection can occur even if sufficient soil moisture is still available. This implies a positive feedback that is also illustrated in Figure 1, as the subsequent transpiration decline and the increased sensible heat may contribute to the drying and warming of the atmospheric boundary layer (potentially enhanced by entrainment), thus inhibit the generation of clouds and rainfall. A challenge relates to understanding the impact of prolonged drought phenomena, in which plant strategies related to water use during the onset of the event determine the total plant available water in later stages. As such, both the more conservative use of water as well as their deeper rooting system imply an evolutionary advantage for forests compared to nonforest ecosystems, where plant available moisture is lower and used at faster rates during the earlier stages of these events.[39,94] Nonetheless, at multiannual timescales, while perennial ecosystems might recover completely after prolonged droughts, in the case of forests, drought-induced mortality and dieback will increase the ecosystem vulnerability to analogous events in following years.[6,95,96]

From evaporation to atmospheric state

As discussed above, observational studies to date show that ecosystem-specific properties can significantly influence the dynamics of land evaporation during droughts and heatwaves. Since these differences lead in turn to contrasting surface partitioning of radiation, it is safe to argue that land conditions and plant physiology at ecosystem scales have the potential to influence the state and evolution of the atmospheric boundary layer during these extreme events,[97–99] and thus impact the development of extreme meteorological conditions.[100] Along these lines, it is crucial to acknowledge the extent to which Figure 1 simplifies key processes, and to highlight that any change on the atmospheric boundary layer that is triggered by the surface partitioning of radiation, will affect the stability and growth of the boundary layer, and therefore (1) the entrainment of air from the top and (2) the potential influence of air advection from the surrounding. Perhaps due to this complexity, studies merely based on satellite observations and drought indices have yielded limited process understanding, despite raising awareness about the correlation between surface dryness during the event onset and the subsequent event intensity.[42,101]

More mechanistic approaches have focused on the effects of soil moisture and vegetation on the state and evolution of the atmospheric boundary layer, and how these effects affect convection, air temperature, and rainfall.[31,35,49] To do so, a wide range of diagnostics have been developed in recent decades that characterize the effect of land on local convection and rainfall, many of them being embraced within the international Global Energy and Water Exchanges (GEWEX) Local Land–Atmosphere Coupling (LoCo) project, dedicated to examining these interactions to yield new process understanding.[27,30,35,49,102,103] However, only recently, some of these studies have focused specifically on periods of drought.[27–29] As an example, Roundy *et al.* presented a feedback diagnostic that suggested a crucial role of these land–precipitation feedbacks in the local evolution of droughts in the United States, particularly during convective seasons, when the impact of ocean temperatures on continental rainfall is expected to be lower.[27] Using satellite data and balloon sounding profiles combined with a mechanistic model, Miralles *et al.* analyzed the simultaneous occurrence of droughts and heatwaves in Europe to give evidence of the requirement of land–atmospheric feedbacks to develop deep and warm atmospheric boundary layers, where the heat is stored on multiday basis and the temperature progressively escalates to yield a “mega-heatwave.”[4] Once again, even if our purpose here is to discuss land feedbacks in the context of their potential to exaggerate meteorological anomalies, the role of atmospheric circulation in the timing of the onset and offset of these events is critical and should not be overlooked.[104]

Findings from coupled climate models

Multiscale modeling strategies

Given the difficulties to evaluate causal mechanisms across the land–atmosphere interface based on observations,[44–46] idealized model experiments have frequently been used to disentangle the influence of surface conditions on the occurrence of extreme climate.[105] As such, a wide variety of modeling frameworks have been utilized, ranging in complexity and scale of application: from atmospheric boundary layer column models[4] and large eddy simulators,[106] to regional and global climate models.[37,107] Overall, coupled climate models are preferred when evaluating the impact of soil moisture and vegetation on large-scale droughts and heatwaves; regional climate models are often applied to reproduce the effect on land conditions on particular events,[36,37,57,108–111] while global climate models can be used to evaluate the impact of land surface conditions on the statistics of climate extremes.[41,112–114] The latter can be done within a detection-and-attribution framework to jointly assess the influence of anthropogenic emissions.[105] These coupled model experiments are often done in pairs, with one simulation serving as a control run, and a second with prescribed land conditions (i.e., soil moisture, leaf area index, and surface albedo). As such, the comparison of both simulations allows the discrimination of the impact of land conditions on climate.[105] Regional climate simulations—in which the boundary conditions are typically prescribed based on reanalysis data of temperature, humidity, and wind profiles—are frequently used to investigate single events.[37,108–110] The influence of land conditions on the particular extreme event can be isolated as long as the domain of interest is sufficiently large so that humidity and temperature in the region are not fully determined by the reanalysis data on the boundaries.[100]

On the other hand, global climate models cannot yet be used to evaluate the land influence on a particular event because of internal variability. Statistical analyses of global climate model outputs have indicated that the interactions between droughts and heatwaves play an essential role in the context of climate change projections.[57,115] As such, transitional regions between dry and wet climates that are predicted to experience enhanced drying under global warming, like central Europe or central North America, expect an additional increase of hot extremes compared to the mean global temperature—for example, up to 6 °C in central Europe at 2 °C global warming.[116] In addition, there are nonnegligible feedbacks with precipitation in these transitional regions, which are expected to further enhance the drying signal.[40,41] The concomitant increase of drying and warming in these regions also enhances the risk of compound dry and hot extremes.[1,2] Nonetheless, it is not the purpose of this perspective paper to review the progress in what relates to the future projection of global temperature and precipitation extremes, thus the reader is directed to, for example, Sillmann *et al.* and references therein for an overview on that topic.[105] The following section focuses on the regional-scale simulation of specific drought and heatwave events.

Regional climate simulations

A large number of regional model experiments have focused on the 2003 and 2010 heatwave events in Europe as ideal test cases. These events broke temperature records and were accompanied by drought conditions that led to unprecedented socioeconomic and ecological impacts.[117–119] It is imperative to forecast such events well in advance given their dramatic consequences, but their predictability remains poor: the 2003 and 2010 European heatwaves were not simulated accurately by the operational European Centre for Medium-Range Weather Forecasts (ECMWF) system.[120,121] Most coupled regional climate model experiments suggest that while these extreme events were instigated by large-scale atmospheric circulation patterns, soil moisture deficits contributed substantially to their intensity, and potentially to their duration.[25,36,37,108] Some have even suggested that the dry soils constituted a necessary preconditioning to reach extreme temperatures of such a magnitude.[4,25] Modeling studies have indicated that the dry soils during the 2003 event affected the intensity of the heatwave by several degrees: Fischer *et al.* pointed to differences up to 4–5K based on an ensemble of regional climate models with varying degrees of soil moisture.[36,108] This work also demonstrated that the dry-out of the soils can lead to a sharp decrease in geopotential height (by tens of meters), which may further reduce the likelihood of rainfall and exacerbate meteorological drought and heatwave conditions. A more recent modeling study for the 2010 Russian heatwave by Hauser *et al.* identified a 13-fold increase in the probability of exceeding the previous summer heat record in the region due to soil moisture deficit conditions, while the sea surface temperature anomalies in 2010 did not have a strong impact on the occurrence of the event.[113] Even more recently, Rasmijn *et al.* highlighted that the future intensification of heatwaves in Eurasia will be larger than previously expected, with temperature extremes being 8.4 °C higher over western Russia when considering that warmer mean temperatures in the period leading up to the heatwave also imply lower soil moisture at the time of the onset.[114] This study was based on prescribing realistic atmospheric blocking conditions to global climate model projections.

Land–atmospheric feedbacks cannot be studied in isolation without considering the implications for the carbon cycle. State-of-the-art Earth system models represent the terrestrial carbon cycle with different degrees of realism, but they are all expected to capture seasonal anomalies in biomass and photosynthetic activity. Lemordant *et al.* showed that anomalies in vegetation dynamics during spring and summer can substantially modify both the amplitude and duration of heatwaves and droughts.[102] Figure 3 is based on the results of this study. Several simulations with the Weather and Research Forecasting (WRF) model coupled to the Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) land-surface model were performed to isolate the effect of CO_2 on plant physiology and water storage. The results in Figure 3 indicate lower evaporation throughout the growing season when CO_2 is increased, due to decreased stomatal conductance, even though the increase leaf area index counter-balances this effect from mid-March. During the summer, the higher leaf area index increases transpiration, which eventually depletes the water savings from the growing season. As a result, summer temperatures are affected by the changes in water use efficiency and biomass, and how these propagate to changes in soil moisture throughout spring and summer. This conclusively shows that the interactions between land surface and climate extend well beyond the immediate effects of soil moisture on the partitioning on radiation, and can be complex once the temporal evolution of soil moisture and biomass is considered.

Current challenges

Nowadays, the scientific community agrees on a potentially key role of land surface conditions in the development of dry and hot extreme events.[21] Given the catastrophic impacts these events brought in recent years, and the projections that indicate that present-day extremes will become the norm in the future, the climate community is faced with the responsibility to predict these events accurately and in advance. Only if the drivers of droughts and heatwaves are well understood, we may be able to predict these events with the accuracy required to successfully mitigate their socio-economic and ecological consequences. However, to further understand the role of land surface conditions as a driver of these extremes, important research challenges remain. Some of them are merely technical, while others require true discoveries to foster progress. The following discussion explores a few of these challenges without aiming to be exclusive.

On the realistic model representation of evaporation

Given the important role of cloud feedbacks in the climate system, it is easy to justify the need for high-resolution land–atmospheric coupled models to explicitly solve for convection. While this topic has received much interest in recent years,[122–124] the adequate model representation of the terrestrial segment of the land–atmospheric coupling has arguably received less attention.[125] In particular, the representation of evaporation in land surface schemes remains a bottleneck in land–atmospheric feedback studies.[43,44] Above, we highlighted the strong dependency of land evaporation on soil properties and vegetation traits—such as stomatal/xylem conductance or rooting depth—which are largely unconstrained in climate and ecosystem models.[77,126] As discussed above, the impact of extreme climate on vegetation is species-dependent, yet current land surface model representations are still based on prescribed parameterizations per plant functional type. The effects of water and heat stress

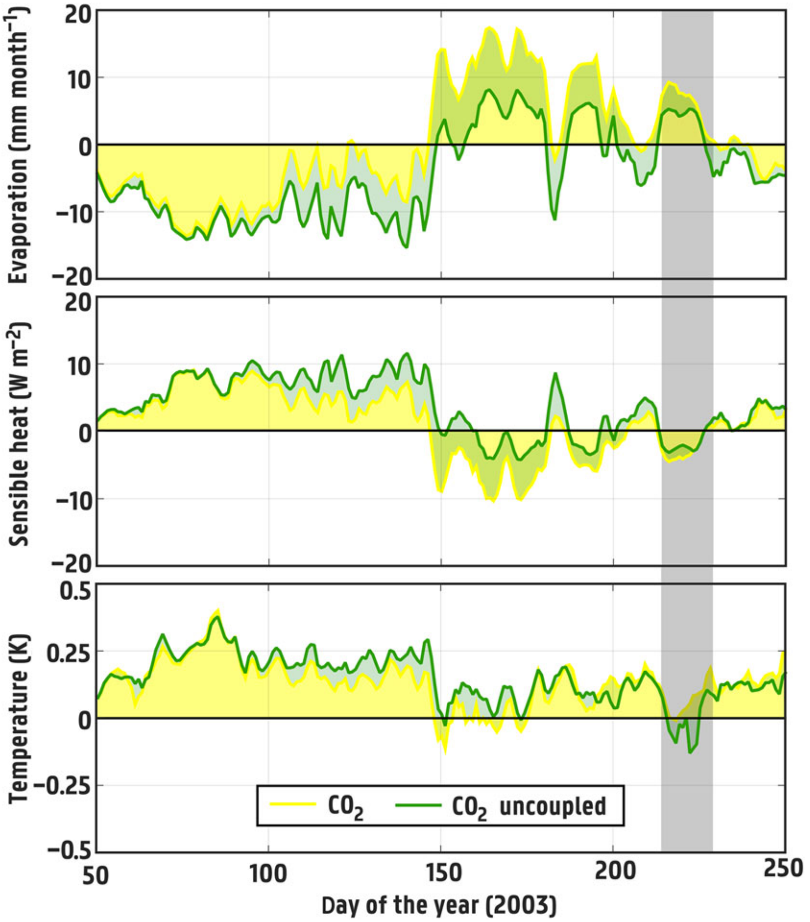

Figure 3. CO$_2$ effect on plant physiology and impact on the 2003 heatwave. Differences in evaporation (top), sensible heat flux (middle), and maximum daily air temperature (bottom) between considering the effects of CO$_2$ on stomatal conductance and water use efficiency versus ignoring these effects (yellow lines and areas). The fraction of that effect that is purely physiological and does not relate to the cumulative impact of soil moisture savings due to the higher water use efficiency is depicted in green (lines and areas). For full details, see Lemordant *et al.*[100]

on transpiration and photosynthesis are rather rudimentarily treated by prescribing a certain response to extreme air temperature, humidity, and soil moisture deficit,[55] and often assuming the same drought sensitivity for all plant species.[77] In addition, as rising CO$_2$ concentrations increase ecosystem water use efficiency, transpiration dynamics are expected to be modified in most ecosystems,[127–129] potentially affecting these feedbacks.[100]

As such, it is still unlikely that state-of-the-art climate models accurately represent the potential of droughts and heatwaves to self-intensify via land feedbacks. However, there is significant progress in model representation of the transpiration response to stress conditions in land surface schemes; a more evolved coupling of transpiration to photosynthesis involving the explicit characterization of plant hydraulics is slowly becoming a reality.[130,131] Since these processes affect the temporal and spatial response of land evaporation during droughts and heatwaves, their improved representation in land surface schemes is expected to have an impact on the projected duration and intensity of the events. Of course, being able to observe the large-scale impact of drought and heatwaves on transpiration would also represent a major advance. While current satellite-based evaporation models are still not able to fully reflect these impacts,[68] their future as observational benchmark data for current climate models looks promising, thanks to the recent and programmed launch of several satellite missions providing multispectral, infrared, and microwave data.[132,133]

Teleconnected feedbacks and event self-propagation

A second, more conceptual, challenge relates to disentangling the role of land feedbacks in the spatiotemporal propagation of drought and heatwave events. In previous sections, we have extensively discussed that land–atmospheric feedbacks may lead to a local intensification of these events (Fig. 1). What may be more controversial to acknowledge is that, under a Langrangian perspective, these feedbacks may prolong the life expectancy of the event by aiding it to travel to other locations, or even trigger new events in remote regions (Fig. 4). In the case of meteorological droughts, these links in space are expected, since land evaporation in upwind (source) areas contributes moisture for precipitation to downwind (sink) regions.[134–136] In a recent example, Keys *et al.*[137] pointed to the importance of forest evaporation for downwind rainfed agriculture, and Miralles *et al.*[138] highlighted the role of land evaporation for the supply of rainfall in water-limited regions. This within-continent water vapor transport enables the existence of "*teleconnected* land–atmospheric feedbacks." These feedbacks may help droughts propagate, that is, expand to neighboring regions or concatenate as a sequence of events. As the upwind source desiccates, the reduction in evaporation results in less moisture being transported into downwind locations, which may in turn experience rainfall deficits as well (Fig. 4); this situation is more likely to occur in regions that rely heavily on rainfall of terrestrial origin, such as large parts of North America, Eurasia, and West Africa.[134,135,139,140] Furthermore, the accompanied impact of land desiccation on long-range heat and water vapor circulation may favor (or disfavor) the occurrence of new extreme events in other locations.[24,105,108] However, efforts so far have concentrated either on land feedbacks on rainfall *in situ*[29,30,32,35,40,102,103] (Fig. 1), or on moisture transport within continents, but not focusing explicitly on land–precipitation feedbacks or drought.[134,135,139,141,142]

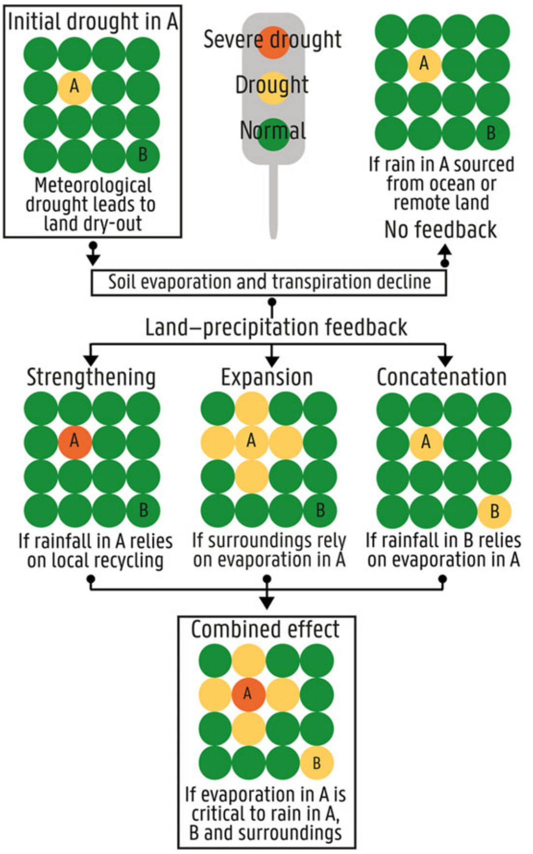

Figure 4. Self-intensification and self-propagation of droughts. Local and teleconnected land feedbacks may aid the intensification and propagation (expansion and concatenation) of meteorological droughts.

Therefore, these remote interactions, which are ultimately regulated by land conditions, remain largely unstudied,[24,41,105,108] and their role in the propagation of droughts and heatwaves remains unknown. The conceptual diagram in Figure 4 expands upon the processes involved in the (local) self-intensification illustrated in Figure 1 to embrace this hypothetical (remote) self-propagation of a drought event. If we consider a region *A* under a prolonged deficit in rainfall, the drying of soil and vegetation and subsequent decline in evaporation may further reduce the local likelihood of rainfall (Fig. 1)—especially if *A* strongly depends on moisture recycling (i.e., rainfall in *A* comes from evaporation in *A*)—leading to the drought intensification. If rainfall in the surroundings of *A*, or even in a remote region *B*, largely originates from evaporation in *A*, these land feedbacks may reduce the likelihood of rainfall in those regions. Consequently, following this reasoning, the original dry-out in *A* expands geographically, and may generate new drought events in remote locations. We note that these processes do not rely on a hypothetical influence of land conditions on synoptic or meso-scale wind circulation; this impact on circulation patterns has also been investigated in recent years and merits specific attention.[31,143,144]

The same framework summarized in Figure 4 can be applied to heatwave events. While this remains speculative, the heat accumulated during a heatwave as the high temperatures desiccate the soils is also transported downwind; as such, the self-propagation of the heatwave is also expected. Figure 5 shows, for the 2010 Russian heatwave, the synoptic conditions (near-surface air temperature and mean sea-level pressure) according to the ECMWF reanalysis ERA5,[145] and the land surface state (root-zone soil moisture and sensible heat flux) from GLEAM v3.2a.[66,88] The epicenter of the heatwave is marked by the black contours, and is here defined as the area experiencing afternoon temperatures exceeding three standard deviations with respect to the seasonal expectation.[146] Following the isobars, the persistent anticyclone located northwest brought a continuous flow of warm air from the southeast. But the southeast region was already experiencing a drought and extreme temperatures during the period prior to the 2010 heatwave (July 1–10). The advection of the air that had been warmed up by the dry soils in this upwind region was certainly critical for the escalation of temperatures in the 2010 mega-heatwave: according to the results by Miralles *et al.*, 40% of the heat stored in the atmospheric boundary layer during the event came from advection.[4] Bearing this in mind, local and remote land conditions influenced the peak in temperature; their effects were regulated by feedbacks on the growth and state of the atmospheric boundary layer, and were still conditioned on synoptic circulation. Needless to say, while the impact of these feedbacks on meso-scale or even synoptic-scale wind circulation is also possible, evidence of these effects is even more elusive given the difficulties to disentangle these impacts with either regional or global climate models.[24,108,144] If these teleconnected land–atmospheric feedbacks are deemed crucial for the occurrence of extreme events, the skill of state-of-the-art meteorological forecast and global climate models to represent these processes should also be evaluated.

Geo-engineering strategies to mitigate extreme events

The identification of hot-spot regions, like *A* in Figure 4, which are sensitive to droughts and heatwaves and supply moisture to other vulnerable land areas (such as *B*), may allow the design of land geo-engineering strategies to dampen the intensification and propagation of these events. This brings us to the third and final challenge here discussed, which is that of the potential of geo-engineering solutions to mitigate the impact of droughts and heatwaves. Recent studies have suggested that, due to the strong effect of regional land feedbacks for the projected changes in hot and dry extremes, human-induced modifications of these feedbacks could potentially mitigate such extreme climate. This has been shown as particularly relevant for low-emission scenarios.[147,148] Relevant modifications include, for instance, changes in irrigation,[148,149] or land surface albedo.[150,151] The climate effects of such modifications could potentially be integrated among other ecosystem services.[152]

In addition, the benefits of afforestation, deforestation, or reforestation along these lines still need to be explored. While the phenological response and sensitivity of forests to drought conditions,[126,153] the impact of drought events on the terrestrial carbon cycle,[6,7,18,19,154] and the influence of forests on general climatic conditions through feedbacks (via, e.g., albedo, roughness, evaporation, and carbon exchange)[155,156] have been a subject of intense investigation in recent years, the effects of forests on meteorological drought occurrence remain less explored.[157–160] As mentioned above, Teuling *et al.* showed that vegetation functional traits, such as root depth and stomatal conductance, were central to the contrasting influence of forests and grasslands on heatwave temperatures.[39] Analogous land-cover dependencies are expected during meteorological droughts, given the known influence of forests on rainfall.[155,156] In fact, Bagley *et al.* recently studied the evolution of the 2005 and 2010 Amazonian droughts, and suggested that deforestation, due to its negative impact on transpiration, could have further reduced precipitation during these events.[158] To date, most land geo-engineering solutions for mitigating the effects of long-term climate change

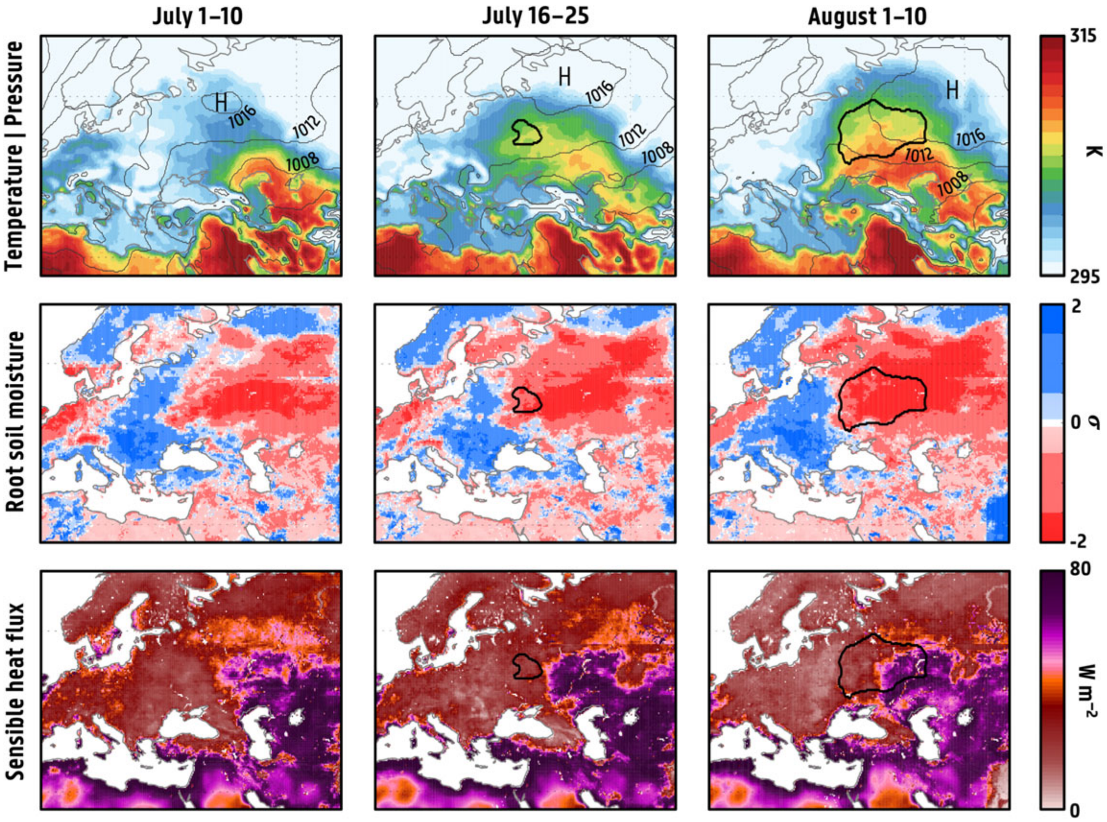

Figure 5. Synoptic conditions and land surface state during the 2010 Russian heatwave. For a 10-day period prior to the heatwave (July 1–10), the onset (July 16–25), and the peak of the event (August 1–10): (top) average afternoon near-surface air temperature (K) and mean sea-level pressure (hPa) from ERA5,[145] (middle) average anomalies in root-zone soil moisture expressed in the number of standard deviations (σ) from GLEAM v3.2a,[66,88] (bottom) average surface sensible heat flux (W m^{-2}) from GLEAM v3.2a.[66,88] Black contours mark the region affected by the heatwave, defined by the seasonal anomalies in average afternoon near-surface air temperature exceeding a threshold of three standard deviations.[146]

have targeted the increase of surface albedo or the enhancement of carbon sequestration.[155,161,162] In the context of droughts, since forests help sustain evaporation for longer,[39,77] afforestation and reforestation measures may (a priori) be beneficial to prevent the propagation of more extreme drought events. However, these predictions are speculative, as the impact of land-cover change and land management on meteorological drought occurrence remains largely unstudied.

Conclusion

As droughts and heatwaves are expected to increase in magnitude and frequency, climate models point at land–atmosphere coupling as a key reason for this exacerbation.[114] Findings from experimental studies over the last decade confirm the results from earlier work on the role of soil moisture and vegetation state in the evolution of hydrometeorological extremes.[33,163–165] However, the difficulties to disentangle the importance of these feedbacks, either through statistical or process-based approaches, still leave plenty of open questions. As such, progress is needed to (1) quantify the large-scale response of land evaporation to soil and atmospheric moisture deficits and extreme heat, and understand ecosystem-specific responses, (2) unveil the extent to which the changes in surface energy partitioning induced by these hydrometeorological extremes regulate the evolution of the atmospheric boundary layer, which will ultimately determine the capability of the events to locally (self-)intensify, (3) track the fate of individual events and the extent to which land feedbacks fuel their self-propagation to other regions, (4) further explore the role of land conditions in the development of event-favorable synoptic and meso-scale circulation patterns, and (5) and exploit our knowledge of these feedbacks to develop mitigation strategies based on geo-engineering. Finally, quantifying the impact of land-use change and land management on atmospheric moisture transport and heat advection during droughts and heatwaves remains an important cornerstone that connects all these challenges, and would allow exploration of geo-engineering solutions to mitigate the expansion and concatenation of extreme events. As such, the role of land conditions in the evolution of droughts and heatwaves remains an important topic of ongoing research. Progress in future years may enhance our capabilities to anticipate these events, and thus mitigate the devastating socio-economic and ecological impacts they engender.

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Competing interests

The authors declare no competing interests.

References

1. Zscheischler, J. *et al.* 2018. Future climate risk from compound events. *Nat. Clim. Change* **8:** 469–477.
2. Zscheischler, J. & S.I. Seneviratne. 2017. Dependence of drivers affects risks associated with compound events. *Sci. Adv.* **3:** e1700263.
3. Mazdiyasni, O. & A. AghaKouchak. 2015. Substantial increase in concurrent droughts and heatwaves in the United States. *Proc. Natl. Acad. Sci. USA* **112:** 11484–11489.
4. Miralles, D.G., A.J. Teuling, C.C. van Heerwaarden & J. Vilà-Guerau de Arellano. 2014. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nat. Geosci.* **7:** 345–349.
5. Liu, Y. *et al.* 2015. Agriculture intensifies soil moisture decline in Northern China. *Sci. Rep.* **5:** 11261.
6. Doughty, C.E. *et al.* 2015. Drought impact on forest carbon dynamics and fluxes in Amazonia. *Nature* **519:** 78–82.
7. Anderegg, W.R.L., C. Schwalm, F. Biondi & J.J. Camarero. 2015. Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science* **349:** 528–532.
8. Dai, A. 2013. Increasing drought under global warming in observations and models. *Nat. Clim. Change* **3:** 52–58.
9. Seneviratne, S.I. *et al.* 2012. Changes in Climate Extremes and their Impacts on the Natural Physical Environment. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* C.B. Field *et al.*, Eds.: 109–230. Cambridge University Press.
10. Prudhomme, C. *et al.* 2014. Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proc. Natl. Acad. Sci. USA* **111:** 3262–3267.
11. Flato, G. *et al.* 2013. Evaluation of climate models in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T. F., et al., Eds.: 741–866. Cambridge University Press.
12. van Dijk, A.I.J.M., L.J. Renzullo, Y. Wada & P. Tregoning 2014. A global water cycle reanalysis (2003–2012) merging satellite gravimetry and altimetry observations with a hydrological multi-model ensemble. *Hydrol. Earth Syst. Sci.* **18:** 2955–2973.
13. Sheffield, J. *et al.* 2014. A drought monitoring and forecasting system for Sub-Sahara African water resources and food security. *Bull. Am. Meteorol. Soc.* **95:** 861–882.
14. Weisheimer, A. & T.N. Palmer. 2014. On the reliability of seasonal climate forecasts. *J. R. Soc. Interface* **11:** 20131162.
15. Burke, E.J. & S.J. Brown. 2008. Evaluating uncertainties in the projection of future drought. *J. Hydrometeorol.* **9:** 292–299.
16. Poulter, B. *et al.* 2014. Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. *Nature* **509:** 600–603.
17. Zscheischler, J. *et al.* 2014. Impact of large-scale climate extremes on biospheric carbon fluxes: an intercomparison based on MsTMIP data. *Global Biogeochem. Cycles* **28:** 585–600.
18. Reichstein, M. *et al.* 2013. Climate extremes and the carbon cycle. *Nature* **500:** 287–295.
19. van der Molen, M.K. *et al.* 2011. Drought and ecosystem carbon cycling. *Agric. For. Meteorol.* **151:** 765–773.
20. Mystakidis, S., S.I. Seneviratne, N. Gruber & E.L. Davin. 2017. Hydrological and biogeochemical constraints on terrestrial carbon cycle feedbacks. *Environ. Res. Lett.* **12:** 014009–014012.
21. Seneviratne, S.I. *et al.* 2010. Investigating soil moisture–climate interactions in a changing climate: a review. *Earth Sci. Rev.* **99:** 125–161.
22. Rowell, D.P. 2009. Projected midlatitude continental summer drying: North America versus Europe. *J. Clim.* **22:** 2813–2833.

23. Seager, R. & M. Hoerling. 2014. Atmosphere and ocean origins of North American droughts. *J. Clim.* **27:** 4581–4606.
24. Vautard, R. *et al.* 2007. Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. *Geophys. Res. Lett.* **34:** L07711.
25. Quesada, B., R. Vautard, P. Yiou, *et al.* 2012. Asymmetric European summer heat predictability from wet and dry southern winters and springs. *Nat. Clim. Change* **2:** 736–741.
26. Savenije, H.H.G. 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrol. Process.* **18:** 1507–1511.
27. Roundy, J.K., C.R. Ferguson & E.F. Wood. 2013. Impact of land–atmospheric coupling in CFSv2 on drought prediction. *Clim. Dyn.* **43:** 421–434.
28. Santanello, J.J.A. & C.D. Peters-Lidard. 2013. Diagnosing the nature of land–atmosphere coupling: a case study of dry/wet extremes in the US Southern Great plains. *J. Hydrometeorol.* **14:** 3–24.
29. Zaitchik, B.F., J.A. Santanello, S.V. Kumar & C.D. Peters-Lidard. 2013. Representation of soil moisture feedbacks during drought in NASA Unified WRF (NU-WRF). *J. Hydrometeorol.* **14:** 360–367.
30. Taylor, C.M., R.A. de Jeu, F. Guichard, *et al.* 2012. Afternoon rain more likely over drier soils. *Nature* **489:** 423–426.
31. Taylor, C.M. *et al.* 2011. Frequency of Sahelian storm initiation enhanced over mesoscale soil–moisture patterns. *Nat. Geosci.* **4:** 430–433.
32. Guillod, B.P., B. Orlowsky, D.G. Miralles, *et al.* 2015. Reconciling spatial and temporal soil moisture effects on afternoon rainfall. *Nat. Commun.* **6:** 6443.
33. Eltahir, E.A.B. 1998. A soil moisture rainfall feedback mechanism 1. Theory and observations. *Water Resour. Res.* **34:** 765–776.
34. Teuling, A.J. & S.I. Seneviratne. 2008. Contrasting spectral changes limit albedo impact on land–atmosphere coupling during the 2003 European heat wave. *Geophys. Res. Lett.* **35:** L03401.
35. Santanello, J.A., J. Roundy & P.A. Dirmeyer. 2015. Quantifying the land–atmosphere coupling behavior in modern reanalysis products over the U.S. southern Great Plains. *J. Clim.* **28:** 5813–5829.
36. Fischer, E.M., S.I. Seneviratne, D. Luthi & C. Schar. 2007. Contribution of land–atmosphere coupling to recent European summer heat waves. *Geophys. Res. Lett.* **34**. https://doi.org/10.1029/2006gl029068.
37. Stegehuis, A.I. *et al.* 2015. An observation-constrained multi-physics WRF ensemble for simulating European mega heat waves. *Geosci. Model Dev.* **8:** 2285–2298.
38. Hirschi, M. *et al.* 2010. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nat. Geosci.* **3:** 1–5.
39. Teuling, A.J. *et al.* 2010. Contrasting response of European forest and grassland energy exchange to heatwaves. *Nat. Geosci.* **3:** 722–727.
40. Koster, R.D. *et al.* 2004. Regions of strong coupling between soil moisture and precipitation. *Science* **305:** 1138–1140.
41. Seneviratne, S.I. *et al.* 2013. Impact of soil moisture–climate feedbacks on CMIP5 projections: first results from the GLACE-CMIP5 experiment. *Geophys. Res. Lett.* **40:** 5212–5217.
42. Miralles, D.G., M.J. van den Berg, A.J. Teuling & R.A.M. de Jeu. 2012. Soil moisture–temperature coupling: a multiscale observational analysis. *Geophys. Res. Lett.* **39**. https://doi.org/10.1029/2012gl053703.
43. Gevaert, A.I., D.G. Miralles, R.A.M. de Jeu, *et al.* 2018. Soil moisture–temperature coupling in a set of land surface models. *J. Geophys. Res. Atmos.* **123:** 1481–1498.
44. Green, J.K. *et al.* 2017. Regionally strong feedbacks between the atmosphere and terrestrial biosphere. *Nat. Geosci.* **10:** 410–417.
45. Orlowsky, B. & S.I. Seneviratne. 2010. Statistical analyses of land–atmosphere feedbacks and their possible pitfalls. *J. Clim.* **23:** 3918–3932.
46. Papagiannopoulou, C. *et al.* 2017. A non-linear Granger-causality framework to investigate climate—vegetation dynamics. *Geosci. Model Dev.* **10:** 1945–1960.
47. Dirmeyer, P.A. *et al.* 2016. Confronting weather and climate models with observational data from soil moisture networks over the United States. *J. Hydrometeorol.* **17:** 1049–1067.
48. Dirmeyer, P.A. *et al.* 2018. Verification of land–atmosphere coupling in forecast models, reanalyses and land surface models using flux site observations. *J. Hydrometeorol.* **19:** 375–392.
49. Santanello, J.A. *et al.* 2017. Land–atmosphere interactions: the LoCo perspective. *Bull. Am. Meteorol. Soc.* https://doi.org/10.1175/bams-d-17-0001.1.
50. Ford, T.W. & J.T. Schoof. 2016. Oppressive heat events in Illinois related to antecedent wet soils. *J. Hydrometeorol.* **17:** 2713–2726.
51. Meng, X.H., J.P. Evans & M.F. McCabe. 2014. The impact of observed vegetation changes on land–atmosphere feedbacks during drought. *J. Hydrometeorol.* **15:** 759–776.
52. Sun, Y. *et al.* 2015. Drought onset mechanisms revealed by satellite solar-induced chlorophyll fluorescence: insights from two contrasting extreme events. *J. Geophys. Res. Biogeosci.* **120:** 2427–2440.
53. Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. Lond. Ser. A* **193:** 120–145.
54. Horton, R.E. 1919. Rainfall interception. *Mon. Weather Rev.* **47:** 603–623.
55. Dolman, A.J., D.G. Miralles & R.A.M. de Jeu. 2014. Fifty years since Monteith's 1965 seminal paper: the emergence of global ecohydrology. *Ecohydrology* **7:** 897–902.
56. Wang, K. & R.E. Dickinson. 2012. A review of global terrestrial evapotranspiration: observation, modeling, climatology, and climatic variability. *Rev. Geophys.* **50**. https://doi.org/10.1029/2011rg000373.
57. Seneviratne, S.I., D. Luthi, M. Litschi & C. Schar. 2006. Land–atmosphere coupling and climate change in Europe. *Nature* **443:** 205–209.
58. Wild, M. & B. Liepert. 2010. The Earth radiation balance as driver of the global hydrological cycle. *Environ. Res. Lett.* **5:** 025203.

59. Chou, C. *et al.* 2013. Increase in the range between wet and dry season precipitation. *Nat. Geosci.* **6:** 263–267.
60. Jarvis, P. 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **273:** 593–610.
61. Monteith, J.L. 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* **19:** 205–234.
62. Douville, H., A. Ribes, B. Decharme, *et al.* 2012. Anthropogenic influence on multidecadal changes in reconstructed global evapotranspiration. *Nat. Clim. Change* **2:** 1–4.
63. Sheffield, J., E.F. Wood & M.L. Roderick. 2012. Little change in global drought over the past 60 years. *Nature* **491:** 435–438.
64. Baldocchi, D. *et al.* 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bull. Am. Meteorol. Soc.* **82:** 2415–2434.
65. Kalma, J.D., T.R. McVicar & M.F. McCabe. 2008. Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data. *Surv. Geophys.* **29:** 421–469.
66. Miralles, D.G. *et al.* 2011. Global land-surface evaporation estimated from satellite-based observations. *Hydrol. Earth Syst. Sci.* **15:** 453–469.
67. Mueller, B. *et al.* 2013. Benchmark products for land evapotranspiration: LandFlux-EVAL multi-data set synthesis. *Hydrol. Earth Syst. Sci.* **17:** 3707–3720.
68. Miralles, D. *et al.* 2016. The WACMOS-ET project—part 2: evaluation of global land evaporation data sets. *Hydrol. Earth Syst. Sci.* **20:** 823–842.
69. Mu, Q., M. Zhao & S.W. Running. 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sens. Environ.* **115:** 1781–1800.
70. Fisher, J.B., K.P. Tu & D.D. Baldocchi. 2008. Global estimates of the land–atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites. *Remote Sens. Environ.* **112:** 901–919.
71. Su, Z. 2002. The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. *Hydrol. Earth Syst. Sci.* **6:** 85–99.
72. Jung, M. *et al.* 2010. Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature* **467:** 951–954.
73. Wild, M. *et al.* 2014. The energy balance over land and oceans: an assessment based on direct observations and CMIP5 climate models. *Clim. Dyn.* **44:** 3393–3429.
74. McCabe, M.F. *et al.* 2016. The GEWEX LandFlux project: evaluation of model evaporation using tower-based and globally gridded forcing data. *Geosci. Model Dev.* **9:** 283–305.
75. Schlesinger, W.H. & S. Jasechko. 2014. Transpiration in the global water cycle. *Agric. For. Meteorol.* **189–190:** 115–117.
76. Jasechko, S. *et al.* 2013. Terrestrial water fluxes dominated by transpiration. *Nature* **496:** 347–350.
77. De Kauwe, M.G. *et al.* 2015. Do land surface models need to include differential plant species responses to drought? Examining model predictions across a latitudinal gradient in Europe. *Biogeosciences* **12:** 7503–7518.
78. Karl, T.R., *et al.* 2012. US temperature and drought: recent anomalies and trends. *EOS* **93:** 473–474.
79. Teuling, A.J. *et al.* 2013. Evapotranspiration amplifies European summer drought. *Geophys. Res. Lett.* **40:** 2071–2075.
80. Ball, J.T., I.E. Woodrow & J.A. Berry. 1987. A Model Predicting Stomatal Conductance and its Contribution to the Control of Photosynthesis under Different Environmental Conditions in *Progress in Photosynthesis Research.* I. Biggins, Ed.: 221–224. Martinus Nijhoff.
81. Powell, T.L. *et al.* 2013. Confronting model predictions of carbon fluxes with measurements of Amazon forests subjected to experimental drought. *New Phytol.* **200:** 350–365.
82. Verhoef, A. & G. Egea. 2014. Modeling plant transpiration under limited soil water: comparison of different plant and soil hydraulic parameterizations and preliminary implications for their use in land surface models. *Agric. For. Meteorol.* **191:** 22–32.
83. Combe, M., J.V.G. de Arellano, H.G. Ouwersloot & W. Peters. 2016. Plant water-stress parameterization determines the strength of land–atmosphere coupling. *Agric. For. Meteorol.* **217:** 61–73.
84. Budyko, M.I. 1974. *Climate and Life.* Academic Press.
85. Novick, K.A. *et al.* 2016. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nat. Clim. Change* **6:** 1023–1027.
86. Baker, I.T. *et al.* 2017. Closing the scale gap between land surface parameterizations and GCMs with a new scheme, SiB3-Bins. *J. Adv. Model. Earth Syst.* **9:** 691–711.
87. Svoboda, M. *et al.* 2002. The drought monitor. *Bull. Am. Meteorol. Soc.* **83:** 1181–1190.
88. Martens, B. *et al.* 2017. GLEAM v3: satellite-based land evaporation and root-zone soil moisture. *Geosci. Model Dev.* **10:** 1903–1925.
89. Konings, A.G., A.P. Williams & P. Gentine. 2017. Sensitivity of grassland productivity to aridity controlled by stomatal and xylem regulation. *Nat. Geosci.* **10:** 284–288.
90. West, A.G., K.R. Hultine, J.S. Sperry, *et al.* 2008. Transpiration and hydraulic strategies in a pinon–juniper woodland. *Ecol. Appl.* **18:** 911–927.
91. Wolf, S. *et al.* 2013. Contrasting response of grassland versus forest carbon and water fluxes to spring drought in Switzerland. *Environ. Res. Lett.* **8:** 035007–035014.
92. van Heerwaarden, C.C. & A.J. Teuling. 2014. Disentangling the response of forest and grassland energy exchange to heatwaves under idealized land–atmosphere coupling. *Biogeosciences* **11:** 6159–6171.
93. Sulman, B.N. *et al.* 2016. High atmospheric demand for water can limit forest carbon uptake and transpiration as severely as dry soil. *Geophys. Res. Lett.* **43:** 9686–9695.
94. Zaitchik, B.F., A.K. Macalady, L.R. Bonneau & R.B. Smith. 2006. Europe's 2003 heat wave: a satellite view of impacts and land–atmosphere feedbacks. *Int. J. Clim.* **26:** 743–769.
95. Anderegg, W.R.L., J.M. Kane & L.D.L. Anderegg. 2012. Consequences of widespread tree mortality triggered by

drought and temperature stress. *Nat. Clim. Change* **3:** 30–36.

96. Williams, A.P. *et al.* 2010. Forest responses to increasing aridity and warmth in the southwestern United States. *Proc. Natl. Acad. Sci. USA* **107:** 21289–21294.
97. Ek, M.B. & A.A.M. Holtslag. 2004. Influence of soil moisture on boundary layer cloud development. *J. Hydrometeorol.* **5:** 86–99.
98. Holtslag, A.A.M. & M. Ek. 1996. Simulation of surface fluxes and boundary layer development over the pine forest in HAPEX-MOBILHY. *J. Appl. Meteorol.* **35:** 202–213.
99. Betts, A.K., J.H. Ball, A. Beljaars., *et al.* 1996. The land surface–atmosphere interaction: a review based on observational and global modeling perspectives. *J. Geophys. Res.* **101:** 7209–7225.
100. Lemordant, L., P. Gentine, M. Stéfanon, *et al.* 2016. Modification of land–atmosphere interactions by CO_2 effects: implications for summer dryness and heat wave amplitude. *Geophys. Res. Lett.* **43:** 10240–10248.
101. Herold, N., J. Kala & L.V. Alexander. 2016. The influence of soil moisture deficits on Australian heatwaves. *Environ. Res. Lett.* **11:** 1–8.
102. Tawfik, A.B., P.A. Dirmeyer & J.A. Santanello. 2015. The heated condensation framework. Part I: description and southern Great Plains case study. *J. Hydrometeorol.* **16:** 1929–1945.
103. Findell, K.L., P. Gentine, B.R. Lintner & C. Kerr. 2011. Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation. *Nat. Geosci.* **4:** 434–439.
104. Meehl, G.A. & C. Tebaldi. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* **305:** 994–997.
105. Sillmann, J. *et al.* 2017. Understanding, modeling and predicting weather and climate extremes: challenges and opportunities. *Weather Clim. Extrem.* **18:** 65–74.
106. Cioni, G. & C. Hohenegger. 2017. Effect of soil moisture on diurnal convection and precipitation in large-eddy simulations. *J. Hydrometeorol.* **18:** 1885–1903.
107. Vautard, R. *et al.* 2013. The simulation of European heat waves from an ensemble of regional climate models within the EURO-CORDEX project. *Clim. Dyn.* **41:** 2555–2575.
108. Fischer, E.M., S.I. Seneviratne, P.L. Vidale, *et al.* 2007. Soil moisture–atmosphere interactions during the 2003 European summer heat wave. *J. Clim.* **20:** 5081–5099.
109. Keune, J. *et al.* 2016. Studying the influence of groundwater representations on land surface–atmosphere feedbacks during the European heat wave in 2003. *J. Geophys. Res. Atmos.* **121:** 13301–13325.
110. Stéfanon, M., P. Drobinski, F. D'Andrea, *et al.* 2013. Soil moisture–temperature feedbacks at meso-scale during summer heat waves over Western Europe. *Clim. Dyn.* **42:** 1309–1324.
111. Stéfanon, M., P. Drobinski, F. D'Andrea & N. de Noblet-Ducoudré. 2012. Effects of interactive vegetation phenology on the 2003 summer heat waves. *J. Geophys. Res. Atmos.* **117**. https://doi.org/10.1029/2012jd018187.
112. Kala, J. *et al.* 2016. Impact of the representation of stomatal conductance on model projections of heatwave intensity. *Sci. Rep.* **6:** 23418.
113. Hauser, M., R. Orth & S.I. Seneviratne. 2016. Role of soil moisture versus recent climate change for the 2010 heat wave in western Russia. *Geophys. Res. Lett.* **43:** 2819–2826.
114. Rasmijn, L.M. *et al.* 2018. Future equivalent of 2010 Russian heatwave intensified by weakening soil moisture constraints. *Nat. Clim. Change* **8:** 381–385.
115. Vogel, M.M. *et al.* 2017. Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture–temperature feedbacks. *Geophys. Res. Lett.* **44:** 1511–1519.
116. Seneviratne, S.I., M.G. Donat, A.J. Pitman, *et al.* 2016. Allowable CO_2 emissions based on regional and impact-related climate targets. *Nature* **529:** 477–483.
117. Schar, C. *et al.* 2004. The role of increasing temperature variability in European summer heatwaves. *Nature* **427:** 332–336.
118. Barriopedro, D., E.M. Fischer, J. Luterbacher, *et al.* 2011. The hot summer of 2010: redrawing the temperature record map of Europe. *Science* **332:** 220–224.
119. García-Herrera, R., J. Díaz, R.M. Trigo, *et al.* 2010. A review of the European summer heat wave of 2003. *Crit. Rev. Environ. Sci. Technol.* **40:** 267–306.
120. Weisheimer, A., F.J. Doblas-Reyes, T. Jung & T.N. Palmer. 2011. On the predictability of the extreme summer 2003 over Europe. *Geophys. Res. Lett.* **38:** L05704.
121. Dole, R. *et al.* 2011. Was there a basis for anticipating the 2010 Russian heat wave? *Geophys. Res. Lett.* **38:** L06702.
122. Anber, U., P. Gentine, S. Wang & A.H. Sobel. 2015. Fog and rain in the Amazon. *Proc. Natl. Acad. Sci. USA* **112:** 11473–11477.
123. Hohenegger, C., P. Brockhaus, C.S. Bretherton & C. Schär. 2009. The soil moisture–precipitation feedback in simulations with explicit and parameterized convection. *J. Clim.* **22:** 5003–5020.
124. Zhang, K. *et al.* 2017. Influence of superparameterization and a higher-order turbulence closure on rainfall bias over Amazonia in Community Atmosphere Model version 5. *J. Geophys. Res. Atmos.* **122:** 9879–9902.
125. Dirmeyer, P.A. 2011. The terrestrial segment of soil moisture–climate coupling. *Geophys. Res. Lett.* **38**. https://doi.org/10.1029/2011gl048268.
126. Anderegg, W.R.L. *et al.* 2015. Tree mortality predicted from drought-induced vascular damage. *Nat. Geosci.* **8:** 367–371.
127. Keenan, T.F. *et al.* 2013. Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature* **499:** 324–327.
128. Cheng, L. *et al.* 2017. Recent increases in terrestrial carbon uptake at little cost to the water cycle. *Nat. Commun.* **8:** 110.
129. Paschalis, A., G.G. Katul, S. Fatichi, *et al.* 2017. On the variability of the ecosystem response to elevated atmospheric CO_2 across spatial and temporal scales at the Duke Forest FACE experiment. *Agric. For. Meteorol.* **232:** 367–383.

130. Anderegg, W.R.L. *et al.* 2017. Plant water potential improves prediction of empirical stomatal models. *PLoS One* **12:** e0185481.
131. Xu, X., D. Medvigy, J.S. Powers, *et al.* 2016. Diversity in plant hydraulic traits explains seasonal and inter-annual variations of vegetation dynamics in seasonally dry tropical forests. *New Phytol.* **212:** 80–95.
132. Fisher, J.B. *et al.* 2017. The future of evapotranspiration: global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources. *Water Resour. Res.* **53:** 2618–2626.
133. McCabe, M.F. *et al.* 2017. The future of Earth observation in hydrology. *Hydrol. Earth Syst. Sci.* **21:** 3879–3914.
134. Gimeno, L., A. Drumond, R. Nieto, *et al.* 2010. On the origin of continental precipitation. *Geophys. Res. Lett.* **37**. https://doi.org/10.1029/2010GL043712.
135. van der Ent, R.J., H.H.G. Savenije, B. Schaefli & S.C. Steele-Dunne 2010. Origin and fate of atmospheric moisture over continents. *Water Resour. Res.* **46**. https://doi.org/10.1029/2010wr009127.
136. Herrera-Estrada, J.E., Y. Satoh & J. Sheffield. 2017. Spatiotemporal dynamics of global drought. *Geophys. Res. Lett.* **44:** 2254–2263.
137. Keys, P.W. *et al.* 2012. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences* **9:** 733–746.
138. Miralles, D.G. *et al.* 2016. Contribution of water-limited ecoregions to their own supply of rainfall. *Environ. Res. Lett.* **11:** 1–12.
139. Gimeno, L. 2014. Oceanic sources of continental precipitation. *Water Resour. Res.* **50:** 3647–3649.
140. Dirmeyer, P.A., J.F. Wei, M.G. Bosilovich & D.M. Mocko. 2014. Comparing evaporative sources of terrestrial precipitation and their extremes in MERRA using relative entropy. *J. Hydrometeorol.* **15:** 102–116.
141. Dirmeyer, P.A., K.L. Brubaker & T. DelSole. 2009. Import and export of atmospheric water vapor between nations. *J. Hydrol.* **365:** 11–22.
142. Trenberth, K.E., J.T. Fasullo & J. Mackaro. 2011. Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *J. Clim.* **24:** 4907–4924.
143. Koster, R.D. *et al.* 2017. Hydroclimatic variability and predictability: a survey of recent research. *Hydrol. Earth Syst. Sci.* **21:** 3777–3798.
144. Koster, R.D., Y. Chang & S.D. Schubert. 2014. A mechanism for land–atmosphere feedback involving planetary wave structures. *J. Clim.* **27:** 9290–9301.
145. Hersbach, H. & D. Dee. 2016. ERA5 reanalysis is in production. ECMWF Newsletter. 147. June 15, 2018. https://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production.
146. Dee, D.P. *et al.* 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quart. J. Roy. Meteorol. Soc.* **137:** 553–597.
147. Seneviratne, S. *et al.* 2018. Climate extremes, land–climate feedbacks, and land-use forcing at 1.5°C. *Philos. Trans. A Math. Phys. Eng. Sci.* **376**. https://doi.org/10.1098/rsta.2016.0450
148. Hirsch, A.L., M. Wilhelm, E.L. Davin, *et al.* 2017. Can climate-effective land management reduce regional warming? *J. Geophys. Res. Atmos.* **122:** 2269–2288.
149. Thiery, W. *et al.* 2017. Present-day irrigation mitigates heat extremes. *J. Geophys. Res. Atmos.* **122:** 1403–1422.
150. Ridgwell, A., J.S. Singarayer, A.M. Hetherington & P.J. Valdes. 2009. Tackling regional climate change by leaf albedo bio-geoengineering. *Curr. Biol.* **19:** 146–150.
151. Davin, E.L., S.I. Seneviratne, P. Ciais, *et al.* 2014. Preferential cooling of hot extremes from cropland albedo management. *Proc. Natl. Acad. Sci. USA* **111:** 9757–9761.
152. Seneviratne, S.I. *et al.* 2018. Land radiative management as contributor to regional-scale climate adaptation and mitigation. *Nat. Geosci.* **11:** 88–96.
153. Bréda, N., R. Huc, A. Granier & E. Dreyer 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. *Ann. For. Sci.* **63:** 625–644.
154. Gatti, L.V. *et al.* 2014. Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. *Nature* **506:** 76–80.
155. Bonan, G.B. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* **320:** 1444–1449.
156. McPherson, R.A. 2016. A review of vegetation–atmosphere interactions and their influences on mesoscale phenomena. *Prog. Phys. Geogr.* **31:** 261–285.
157. Lee, J.-E., B.R. Lintner, C.K. Boyce & P.J. Lawrence. 2011. Land use change exacerbates tropical South American drought by sea surface temperature variability. *Geophys. Res. Lett.* **38**. https://doi.org/10.1029/2011gl049066.
158. Bagley, J.E., A.R. Desai, K.J. Harding, *et al.* 2014. Drought and deforestation: has land cover change influenced recent precipitation extremes in the Amazon? *J. Clim.* **27:** 345–361.
159. Xue, Y. & J. Shukla. 1996. The influence of land surface properties on Sahel climate. Part II. Afforestation. *J. Clim.* **9:** 3260–3275.
160. Xue, Y. & J. Shukla. 1993. The influence of land surface properties on Sahel climate. Part 1: desertification. *J. Am. Meteorol. Soc.* **6:** 2232–2245.
161. Koch, K. & H.J. Ensikat 2008. The hydrophobic coatings of plant surfaces: epicuticular wax crystals and their morphologies, crystallinity and molecular self-assembly. *Micron* **39:** 759–772.
162. Smith, P. 2012. Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20 years? *Global Change Biol.* **18:** 35–43.
163. Brubaker, K.L. & D. Entekhabi. 1996. Analysis of feedback mechanisms in land–atmosphere interaction. *Water Resour. Res.* **32:** 1343–1357.
164. Entekhabi, D., I. Rodriguez-Iturbe & R.L. Bras. 1992. Variability in large-scale water-balance with land surface atmosphere interaction. *J. Clim.* **5:** 798–813.
165. Taylor, S.A. 1952. Use of mean soil moisture tension to evaluate the effect of soil on crop yields. *Soil Sci.* **74:** 217–226.