Deepening Mechanistic Understanding of Land Climate

Michael P. Byrne,[a,b] Gabriele C. Hegerl,[c] Jacob Scheff,[d] William R. Boos,[e,f] Hervé Douville,[g] Suqin Q. Duan,[h] Nora L. S. Fahrenbach,[i] Kirsten Findell,[j] Erich M. Fischer,[i] Moritz Günther,[k] Spencer A. Hill,[l] Cathy Hohenegger,[k] Marysa M. Laguë,[m] F. Hugo Lambert,[n] Justin S. Mankin,[o] Kaighin A. McColl,[p] Quentin Nicolas,[i] Paul A. O'Gorman,[q] Rene Orth,[r] Benjamin D. Stocker,[s,t] Abigail L. S. Swann,[u,v] Lucas R. Vargas Zeppetello,[w] Jakob Zscheischler[x]

[a] *School of Earth and Environmental Sciences, University of St Andrews, St Andrews, UK*

[b] *Centre for Changing Climates, University of St Andrews, St Andrews, UK*

[c] *School of GeoSciences, University of Edinburgh, Edinburgh, UK*

[d] *University of North Carolina, Charlotte, NC*

[e] *Department of Earth and Planetary Science, University of California, Berkeley, CA,*

[f] *Lawrence Berkeley National Laboratory, Berkeley, CA*

[g] *Centre National de Recherches Météorologiques (CNRM), Météo-France, CNRS, Université de Toulouse, Toulouse, France*

[h] *Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, CA*

[i] *Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland*

[j] *Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, NJ*

[k] *Max Planck Institute for Meteorology, Hamburg, Germany,*

[l] *Department of Earth and Atmospheric Sciences, City College of New York, New York, NY*

[m] *Department of Geography, University of British Columbia, Vancouver, BC, Canada*

[n] *Department of Mathematics and Statistics, University of Exeter, UK*

[o] *Department of Geography, Dartmouth College, Hanover, NH*

[p] *Department of Earth and Planetary Sciences and School of Engineering and Applied Sciences, Harvard University, Cambridge, MA*

Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-26-0341.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

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[q] *Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA*

[r] *University of Freiburg, Germany*

[s] *Institute of Geography, University of Bern, Bern, Switzerland*

[t] *Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland*

[u] *Department of Atmospheric and Climate Science, University of Washington, Seattle, WA*

[v] *Department of Biology, University of Washington, Seattle, WA,*

[w] *Department of Environmental Science, Policy, and Management, Berkeley, CA*

[x] *Department of Compound Environmental Risks, Helmholtz Centre for Environmental Research - UFZ, Leipzig, Germany*

Corresponding author: Michael P. Byrne, mpb20@st-andrews.ac.uk

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-26-0341.1.

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ABSTRACT: n/a

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-26-0341.1.

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What, When, Where

Land-Climate Workshop

What: This three-day workshop brought together an international group of researchers focused on advancing mechanistic understanding of land climate. The workshop featured 42 oral and poster presentations, with participants spanning hydrology, ecology, atmospheric science, and climate dynamics.

When: 17-19 June 2026

Where: University of St Andrews, UK

1. Introduction

Understanding the climate of land and its evolution in a warming world is critically important for human health, economies, and ecosystems (Shukla et al. 2019). The 2026 record heatwaves in Europe – which caused tens of thousands of deaths, widespread drought, severe wildfires, and reduced crop yields (Guardian 2026; Joint Research Centre 2026) – underscore the urgent need to comprehensively understand the processes controlling land climate.

Building mechanistic understanding of land climate is a major scientific challenge. Land is an integral component of the climate system that is strongly coupled to the atmosphere and oceans via energy, water, and carbon fluxes. Land is highly heterogeneous in space and time and its climate is influenced by a complex array of processes (e.g., Dickinson 1995). Vegetation (Swann et al. 2016), soil moisture (Seneviratne et al. 2010), land cover and use (Findell et al. 2017), orography (Sandu et al. 2019), radiation (Bollasina et al. 2011), and large-scale atmospheric dynamics (Zhang and Fueglistaler 2020), including advection of heat (McKinnon et al. 2013) and moisture (Byrne and O'Gorman 2016), are all capable of exerting leading-order influences on land climate across regions and timescales. This complexity drives uncertainties in future projections and presents significant challenges to representing land in Earth system models (Simpson et al. 2024; Fisher and Koven 2020).

Complexity also presents challenges to building the theories and conceptual models needed to (Byrne et al. 2024): (i) advance fundamental understanding of land climate; (ii) inform the development of Earth system models; and (iii) guide policies for mitigating and adapting to climate change. Overcoming these challenges in land-climate science requires expertise spanning a diverse

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FIG. 1. Participants at the Land-Climate Workshop. Photo taken in St Mary's Quad, at the University of St Andrew, on June 17th 2026.

set of traditional disciplines, including hydrology, ecology, atmospheric science, climate dynamics, scientific computing, and remote sensing.

At the University of St Andrews in June 2026 – just poleward of the extreme heatwaves occurring further south in Europe (WMO 2026) – we convened the Land-Climate Workshop (Fig. 1). This was the latest in a series of loosely-connected workshops, beginning at St Andrews in 2022 with subsequent events at Harvard University from 2023-25, designed to share progress on key questions in land-climate science. An emergent thread across the workshops – and again prominent through this year's presentations – is the emphasis on advancing mechanistic understanding of climate-relevant land processes through the use of a hierarchy of tools including pencil-and-paper theory, idealized numerical simulations, global km-scale Earth system models and, increasingly, machine learning. The workshop had 42 participants who delivered 30 oral and 12 poster presentations examining a wide range of topics across spatial scales (Fig. 2).

2. Scientific themes

Participants were free to present on any aspect of land-climate science, with sessions designed following the submission of abstracts. Themes that emerged were: Land Vegetation; Atmospheric Dynamics and Land; Land Water; Land Temperatures; and Land Extremes. Below we summarize

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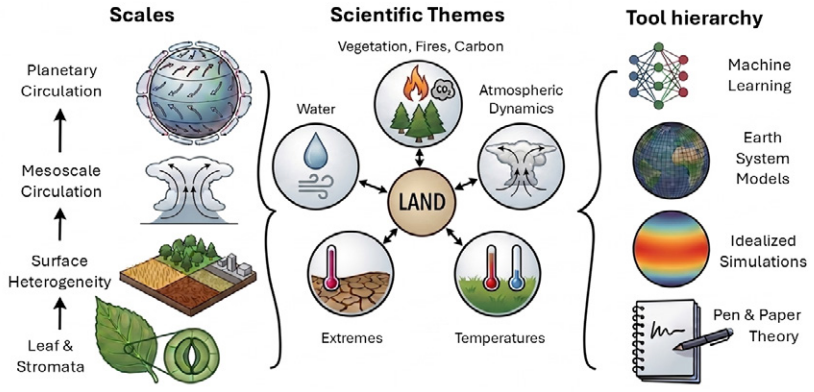

FIG. 2. Schematic summarizing the scientific themes, spatial scales, and range of research tools featured in presentations at the Land-Climate Workshop. The schematic was created with Powerpoint and Gemini.

the oral presentations under these themes, highlight emerging areas of focus, and conclude with an outlook.

a. Land Vegetation

Two-way interactions between climate and vegetation are relevant to understanding, for example, the sensitivity of the Earth system to radiative forcings (Cao et al. 2010) and the evolution of the terrestrial carbon sink (Fung et al. 2005). Several presentations focused on climate-vegetation interactions, including two talks on the atmospheric and surface conditions controlling wildfires and their trends. The opening talk examined the empirical, quasi-linear relationship between the logarithm of burned area and metrics of fuel aridity (e.g., Abatzoglou and Williams 2016). Combining assumptions on the geometry of wildfires and their number density, a simple theory was derived which suggests that burned area scales as aridity cubed, refining understanding of the empirical relationship. The theory captures the time series of historical burned area and predicts, among other effects, that increasing aridity will expand large fires more than small fires. The next talk addressed future changes in wildfires by considering what indicator of fuel aridity is most appropriate for projections. Vapor pressure deficit (VPD), a commonly-used measure of evaporative demand, increases sharply with warming, suggesting vast increases in burned area. It was argued in the talk, however, that VPD is a poor measure of evaporative demand, resulting in

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projections that greatly overstate future drying (Tang and McColl 2025). The presentation proposed an alternative approach for wildfire projections based on soil moisture, a more direct proxy for fuel aridity. Soil moisture generally decreases with warming but at a slower rate than increasing VPD, with the implication that the sensitivity of wildfires to climate warming is overstated by VPD-based metrics (Cheng et al. 2026).

Vegetation and climate form a coupled system whereby vegetation affects climate from the "bottom up" and climate affects vegetation from the "top down". The bottom-up control of vegetation on climate was featured in a presentation comparing global reforestation potentials. It was demonstrated that the location of reforestation is at least as critical as total reforested area for global cooling (Fahrenbach et al. 2026). By accounting for biogeophysical feedbacks – including albedo-driven warming and evapotranspiration-driven cooling – strategic reforestation was shown to achieve the same net global cooling using half the land area vs. less targeted scenarios. The top-down control of climate on vegetation was the focus of a presentation on gross primary productivity (GPP), which demonstrated that forests experience reduced GPP due to the legacy effects of drought (Yu et al. 2025).

Carbon is one means through which vegetation couples to climate (Sellers et al. 1996; Friedlingstein et al. 2006). The question of whether storms affect terrestrial carbon storage was investigated using standalone land simulations forced by meteorology from a km-scale model, in which the dynamics of convective storms are explicitly simulated, and a coarse-resolution model with parameterized convection. GPP increased in the km-scale simulations relative to the coarse simulations due to shorter-duration precipitation events for the same precipitation amount (Lee and Hohenegger 2026). The cutting edge of Earth system modeling was also showcased, with new results presented from a 1-year global simulation at a resolution of 10 km with fully-interactive water, energy, and carbon cycles. These results highlight the emerging potential of high-resolution models for understanding climate-vegetation interactions at the global scale.

b. Atmospheric Dynamics and Land

The question of how land shapes overlying atmospheric circulations was explored through several presentations. On regional scales in the tropics, soil moisture gradients were shown to control the development of mesoscale convective systems through their influence on wind shear (Barton et al.

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2025; Taylor et al. 2026). Convection was also the focus of a presentation which asked: What makes convection stronger – and lightning more frequent – over land compared to oceans? Hypotheses to explain this long-observed phenomenon include the influence of aerosols on cloud microphysics (Sherwood et al. 2006) and stronger updrafts over land due to wider clouds and reduced entrainment (Williams and Stanfill 2002). The presentation proposed an alternative hypothesis based on the heterogeneity of land surfaces (Robinson et al. 2025), for example due to orography or soil moisture patterns. In very high-resolution simulations this heterogeneity is capable of driving strong updrafts over land, an effect that is absent in coarse-resolution simulations. The presentation highlighted that to understand intense convection over land and its response to a warming climate, resolving fine-scaled surface features is likely to be essential.

Staying in the tropics but on the planetary scale, the longstanding question of what drives the Walker circulation was re-examined with new simulations. A striking result was that when zonal gradients in ocean heat uptake – the driver of the Walker circulation, in conventional thinking – are removed, the circulation strength is largely unchanged. This suggests a central yet under-appreciated role for land in driving planetary-scale atmospheric circulations (Günther and Kang 2026).

c. Land Water

Several workshop presentations addressed questions related to water – on land, above land, and moving between the land and atmosphere.

In contrast to oceanic regions, where specific humidity increases with temperature at approximately the Clausius-Clapeyron rate (Held and Soden 2000; Schneider et al. 2010), there is incomplete understanding of how humidity over land evolves in a changing climate (Simpson et al. 2024). Two presentations probed this question using Earth system models, with the first examining changes in relative humidity between the pre-industrial period and Last Glacial Maximum (LGM). Land relative humidity generally decreases in a warming climate (Simmons et al. 2010; Byrne and O'Gorman 2018), suggesting it should increase as climate cools. However, counter to this expectation, models show decreases in land relative humidity in many regions under LGM conditions (Scheff et al. 2017). Extending the established ocean-influence theory for land humidity – which suggests a leading role for moisture advection from ocean regions (Byrne and O'Gorman 2016;

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Chadwick et al. 2016) – it was found that the drop in sea level at the LGM is a key influence on land humidity changes and the asymmetric responses to warming vs. cooling.

The second presentation discussed water-tagging simulations in which the contributions of ocean evaporation vs. terrestrial evapotranspiration to land humidity were directly diagnosed. Across simulations with different prescribed SSTs, water vapor evaporated from the oceans and advected over continents is the dominant influence on changes in land specific humidity at all latitudes. But for land relative humidity changes, terrestrial evapotranspiration is more influential as its contribution to specific humidity scales with warming at a smaller rate compared to saturation specific humidity (Byrne et al. 2026). The radiative effects of land-sourced water vapor were the focus of another presentation using water-tagging simulations, which found that land-derived water vapor is the main source of downwelling longwave radiation at the surface in some regions (e.g., eastern Eurasia; Laguë et al. 2025). A subsequent presentation derived an approximation to the spectrum of this downwelling radiation using a simple power-law theory for Planck emission and water vapor's optical depth based on statistical physics (Zhang 2026).

Land relative humidity generally decreases as climate warms. But India is a notable exception, where relative humidity has been increasing steadily since the 1970s. Why is this region evolving differently? Several factors are likely to be important, according to another workshop presentation, including moisture transport from neighboring oceans as well as regional influences from aerosols and large-scale irrigation.

A range of presentations addressed atmosphere-land water fluxes and the impacts on surface water. Temporal consolidation of precipitation was shown to decrease terrestrial water storage by causing water to pond on the surface and thereby more easily evaporate (Lesk and Mankin 2026). With extremes expected to increase faster with warming relative to mean precipitation, this work has important implications for water management over coming decades. The connection between extreme precipitation and flooding was also addressed, specifically how to reconcile increases in extreme precipitation with limited changes in flooding (Sharma et al. 2018). Using a storyline approach applied to high-impact events, it was found that although precipitation intensified with warming as expected, flooding did not intensify due to decreases in runoff prior to the floods.

How precipitation minus evapotranspiration ($P - ET$) responds to climate change is a longstanding problem (Lambert et al. 2025). A rule-of-thumb for mean $P - ET$ changes – wet-get-wetter,

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dry-get-drier (Chou and Neelin 2004; Held and Soden 2006) – does not apply over land at daily timescales, motivating the need for an alternative. Transforming to a phase space defined by climatological aridity and daily soil moisture, two presentations discussed how $P - ET$ changes under warming align with soil moisture regimes rather than geographical space, establishing a new conceptual framework for understanding changes in the terrestrial water cycle (Duan et al. 2023, 2024).

Land processes modulate the flux of water out of the surface through evapotranspiration. The response of plants to a changing climate, including hotter temperatures and increased atmospheric CO_2, creates substantial uncertainty in future evapotranspiration (Swann et al. 2016; Mankin et al. 2019). The relative importance of specific plant processes for evapotranspiration, including leaf area growth, stomatal closure, photosynthetic down-regulation, and surface roughness, were discussed at the workshop (Zarakas et al. 2024). Even in the present climate, simulated evapotranspiration in Earth system models is biased relative to observations during periods of water stress (Ukkola et al. 2016; Zhao et al. 2022; Giardina et al. 2025). Together, these presentations highlighted the complex and persistent challenges in accurately simulating evapotranspiration.

The timing of seasonal precipitation is crucially important for farmers across the world, including in India where the monsoon dominates the water cycle. Accurate, interpretable forecasts of monsoon onset are essential for making informed decisions on when to plant crops. Blending ensembles of AI-generated weather forecasts with statistical models, a skillful new forecasting system for monsoon onset was presented (Aitken et al. 2026). The system delivers weekly forecasts to 38 million Indian farmers and demonstrates the potential of emerging AI models to positively impact agriculture and livelihoods in highly-populated tropical regions.

The presentations under this theme highlighted major knowledge gaps in the field, including incomplete understanding of how land humidity, $P - ET$, and plants respond to climate change. But the presentations also documented significant progress on these problems, achieved through a spectrum of approaches from AI to perturbed parameter ensembles to simple theories. A renewed ambition, emerging from the workshop, is to build on this progress and move the field forward towards solving these longstanding problems related to land and water.

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d. Land Temperatures

Several presentations addressed the temperatures of land, from the leaf scale to the planetary scale and from seasonal evolution to long-term trends.

What sets leaf temperature? Traditionally, this was thought to reflect water stress and energy partitioning. But new, ongoing research suggests that surface roughness is more influential than moisture for leaf temperature, with implications for understanding photosynthesis during hot and dry compound events.

Discrepancies between climate models and observations in temperature trends over the historical period, including in the tropics and western Europe, were discussed in two presentations. At a time when vast areas are recording unprecedented temperatures and wildfires exacerbated by dry conditions, better understanding the respective influences of natural variability vs. anthropogenic emissions (greenhouse gases, aerosols) on trends in European climate is a challenging and urgent task (Douville et al. 2025; Douville 2026).

Finally, the question of why spring is longer than fall (in terms of the seasonal cycle of daily-mean temperature) over extratropical land was investigated. A hypothesis was presented whereby this asymmetry in land temperature is linked to asymmetry in the SST seasonal cycle driven by the ocean mixed layer, which is then advected over land. Work to test this elegant idea is ongoing.

Together the presentations under this theme made clear how understanding of perhaps the most fundamental property of land climate – its temperatures – is still evolving, highlighting the complexity of land-surface processes and their interactions.

e. Land Extremes

The final workshop theme focused on land extremes, with AI weather forecasts of record-breaking events highlighted in the opening presentation. Though AI models have demonstrated remarkable predictive skill for many weather and climate phenomena, physics-based models were found to outperform the AI models in simulating record-breaking extremes, suggesting caution in using AI for rare events (Zhang et al. 2026). Other aspects of heat extremes were also addressed, including a case study of the Pacific Northwest heatwave using simulations initialized with differing land-surface conditions and the circulation nudged to observations. By examining the evolution of

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land–atmosphere coupling through the heatwave, this study demonstrated that soil moisture exerted an important, state-dependent influence on the event (Duan et al. 2025).

Soil moisture and heat extremes also featured prominently in a presentation on the drivers of compound drought-heatwave events, with particular emphasis on the need for daily and sub-daily data to accurately capture the physical processes at play (Yin et al. 2023; Findell et al. 2024). During drought-heatwave events, soil moisture and daily maximum temperatures are strongly anti-correlated, but the correlation of evapotranspiration with these variables varies markedly by event. In land-surface-driven events, evapotranspiration deficits follow and strongly correlate with soil moisture deficits. In contrast, atmosphere-driven events feature elevated near-surface temperatures that drive increased evapotranspiration (Yoon et al. 2026). Current efforts to understand and attribute causal factors driving evapotranspiration changes in observationally-based datasets and Earth system models were also discussed.

Drought-heatwave events are an example of the broader and highly diverse class of compound events (Zscheischler et al. 2020), which featured prominently in a talk on risk assessment and climate-change attribution. The future likelihood of drought-heatwave events is largely determined by local precipitation trends (Bevacqua et al. 2022), yet uncertainties are substantial due to the rarity of such high-dimensional events (Bevacqua et al. 2023). Climate-model uncertainties for specific changes affecting globally relevant sectors can be large even at fixed warming levels. For example worst-case outcomes for drought changes in breadbasket regions, for forest fire risk, or for heavy precipitation in urban areas can be much more extreme at 2°C of warming than the model average at 3° or 4°C would suggest (Bevacqua et al. 2026).

The question of what sets the upper limit on extreme temperatures was also explored through the lens of convective coupling (Nicolas and Hotz 2026). An upper bound based on a dry adiabat connecting the boundary layer to the free troposphere was proposed, but observational and reanalysis data showed that this theoretical bound is often exceeded in arid regions due to the development of super-adiabatic layers close to the surface. Other aspects of extreme events discussed at the workshop included the 2022 drought and maize crop failure in Europe, for which more than 30% of the drought intensity and spatial extent was attributed to climate change (Bevacqua et al. 2024), and the impact of El Niño-Southern Oscillation on extreme rainfall in India via the dynamics of low-pressure systems (Hill et al. 2025). A final strand explored the connections

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between tipping points and extreme events. In the current warming climate, irreversible and abrupt changes can be triggered by extreme events (Romanou et al. 2025). A community assessment concluded that the risk of such tipping points is increasing yet difficult to quantify due to limitations in our understanding of, for example, land-atmosphere coupling in forested regions (Hansen et al. 2026).

Across many of the presentations, a common thread was the uncertainties that are inherent when studying rare land extremes with limited sample sizes (e.g., compound events, tipping points). It was shown that AI is not a "silver bullet" for overcoming these uncertainties because extreme events by definition sit at, or beyond, the edges of reliable training datasets. Instead, the presentations demonstrated the lasting utility and value of physics-based models, analyses, and theories for understanding land extremes in a changing climate.

3. Outlook

The emphasis of the Land-Climate Workshop on deepening mechanistic understanding, often through the development of theory and conceptual frameworks supported by a hierarchy of numerical models and observational systems, gave the event a unique 'flavor' that participants valued. The diversity of phenomena discussed across the five themes – from leaf-scale thermodynamics, to monsoon forecasts for farmers, to the role of land in driving planetary-scale circulations, to the carbon cycle at km-scale, and more – also felt distinctive and demonstrated the richness of land-climate science. Many presentations could readily have been labeled under multiple themes, highlighting the strong mechanistic links connecting different aspects of land-climate science (e.g., soil moisture emerged across themes as a key determinant of fuel aridity, atmospheric humidity, and convective-scale circulations). A priority, building on the success of the workshop, is to further develop this nascent community to help meet the increasingly urgent need for interdisciplinary research on critical questions in land-climate science.

Acknowledgments. The organizers thank the Leverhulme Trust for financial support (grant PLP-2024-046) and Stuart Allison for the group photo in Fig. 1. Valuable feedback from Donghui Li on an earlier draft of this meeting summary is also gratefully acknowledged.

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