Theory and the future of land-climate science

Michael P. Byrne[1,2], Gabriele C. Hegerl[3], Jacob Scheff[4], Ori Adam[5], Alexis Berg[6], Michela Biasutti[7], Simona Bordoni[8], Aiguo Dai[9], Ruth Geen[10], Matthew Henry[11], Spencer A. Hill[12,7], Cathy Hohenegger[13], Vincent Humphrey[14], Manoj Joshi[15], Alexandra G. Konings[16], Marysa M. Laguë[17], F. Hugo Lambert[11], Flavio Lehner[18,19,20], Justin S. Mankin[21,7], Kaighin A. McColl[22,23], Karen A. McKinnon[24], Angeline G. Pendergrass[18,19], Marianne Pietschnig[25,26], Luca Schmidt[13], Andrew P. Schurer[3], E. Marian Scott[27], David Sexton[28], Steven C. Sherwood[29], Lucas Vargas Zeppetello[30] and Yi Zhang[31]

[1] *School of Earth & Environmental Sciences, University of St Andrews, UK*

[2] *Department of Physics, University of Oxford, UK*

[3] *School of Geosciences, University of Edinburgh, UK*

[4] *Department of Geography and Earth Sciences, University of North Carolina at Charlotte, USA*

[5] *The Fredy and Nadine Herrmann Institute of Earth Sciences, The Hebrew University, Israel*

[6] *Department of Geography, Université de Montréal, Canada*

[7] *Lamont-Doherty Earth Observatory, Columbia University, USA*

[8] *Department of Civil, Environmental and Mechanical Engineering, University of Trento, Italy*

[9] *Department of Atmospheric and Environmental Sciences, University at Albany, SUNY, USA*

[10] *School of Geography, Earth and Environmental Sciences, University of Birmingham, UK*

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

[12] *Program in Atmospheric and Oceanic Sciences, Princeton University, USA*

[13]*Max Planck Institute for Meteorology, Germany*

[14]*Institute for Atmospheric and Climate Sciences, ETH Zürich, Switzerland*

[15]*Climatic Research Unit, School of Environmental Sciences, University of East Anglia, UK*

[16]*Department of Earth System Science, Stanford University, USA*

[17]*Department of Atmospheric Sciences, University of Utah, USA*

[18]*Cornell University, USA*

[19]*National Center for Atmospheric Research, USA*

[20]*Polar Bears International, USA*

[21]*Department of Geography, Dartmouth College, USA*

[22]*Department of Earth and Planetary Sciences, Harvard University, USA*

[23]*School of Engineering and Applied Sciences, Harvard University, USA*

[24]*Department of Statistics and Data Science, Department of Atmospheric and Oceanic Sciences, and the Institute of the Environment and Sustainability, University of California Los Angeles, USA*

[25]*Department of Geography, University of Exeter, UK*

[26]*Global Systems Institute, University of Exeter, UK*

[27]*School of Mathematics and Statistics, University of Glasgow, UK*

[28]*Met Office, UK*

[29]*Climate Change Research Centre, UNSW Sydney, Australia*

[30]*Department of Environmental Science, Policy, and Management, University of California, Berkeley, USA*

[31]*Courant Institute of Mathematical Sciences, New York University, New York, USA*

Climate over land—where humans live and the vast majority of food is produced—is changing rapidly, driving severe impacts through extreme heat, wildfires, drought, and flooding. Our ability to monitor and model this changing climate is being transformed through new observational systems and increasingly complex Earth System Models (ESMs). But fundamental understanding of the processes governing land climate has not kept pace, weakening our ability to interpret and utilise data from these advanced tools. Here we argue that for land-climate science to accelerate forward, an alternative approach is needed. We advocate for a parallel scientific effort, one emphasising robust theories, that aims to inspire current and future land-climate scientists to better comprehend the processes governing land climate, its variability and extremes, and its sensitivity to global warming. Such an effort, we believe, is essential to better understand the risks people face, where they live, in an era of climate change.

Knowledge of some aspects of continental climate and their responses to global warming are well established. For example, we broadly understand why land warms more rapidly than oceans[1] (Fig. 1), the intensification of extreme precipitation in a warmer atmosphere[2], and how surface runoff is influenced by loss of snowpack[3]. However, knowledge of many other aspects of land climate is underdeveloped. The "wet get wetter, dry get drier" paradigm predicts an amplification of wet/dry contrasts as climate warms[4]. But this paradigm does not generally apply to land regions[5] nor does the poleward expansion of the Hadley cells[6]. Adding to this list is uncertainty over how evapotranspiration (ET) and soil moisture[7,8]—both critical for humans and ecosystems—will be altered by a changing climate. Knowledge of numerous other facets of land climate is similarly unsettled, from basic questions of what governs its mean state, variability, and extremes, to how these facets might change with warming. Why are simulated land temperature changes more uncertain and more diverse, across space and climate models, compared to ocean regions (Fig. 1a,b)? Why are the tropical rainbelts broader and more mobile over land[9]? And how will land humidity evolve as climate warms[10]? Longstanding challenges in simulating land climate—including the diurnal cycle of convection[11]—further highlight shortcomings in our basic understanding.

The challenge of complexity

The climate over land is a complex system shaped by an array of diverse factors, from local surface conditions including soil moisture and plants[12,13] to large-scale atmospheric circulations that connect continents to oceans through the transport of water, heat, and momentum[14,15]. Many of the key processes influencing land climate are spatially heterogeneous, difficult to simulate, and/or poorly observed. For example, land surface models have longstanding problems in simulating turbulent fluxes of heat and water[16,17], for reasons that are not well understood[18]. Sparse and time-limited observational records of important land-climate variables, including root-zone soil moisture[19] and near-surface humidity[20], further impede efforts to advance knowledge of the land-climate system. The role of humanity presents another challenge, with large uncertainties in modelling the influences of land use and management on fluxes of carbon, energy, and water in the past, present, and future[21]. Confronted with such a complex system it can appear a daunting task to develop a deep, mechanistic, conceptual understanding of the kind we would want to read in future textbooks on land climate. But as the field of climate science evolves, we argue that many of the most fascinating and pressing questions relate to land.

Given the complexity and importance of land climate, how can the research community accelerate progress? In the atmospheric and ocean sciences, notable advances are being made by increasing the spatial resolution of state-of-the-art ESMs[22]. But unlike in the atmosphere and oceans, where higher resolutions allow for explicit simulation of key processes including deep convection and mesoscale eddies, the case for transitioning to finer resolution models to drive new conceptual breakthroughs in land-climate science is less clear-cut[23]. Land climate is undoubtedly influenced by small-scale processes, so there are potential benefits to incorporating into models more sophisticated representations of, for example, hillslope hydrology[24], groundwater processes[25], and land management[26]. However, complexity does not equate to realism: absent a comprehensive understanding of these processes and how to accurately represent them in models[27], it is possible that such complexity obfuscates more than it clarifies[16]. Persistent and poorly constrained deficiencies in land surface models—highlighted by the PLUMBER project[16–18]—suggest that model development alone, though vital, is unlikely to answer the key questions about land climate highlighted above. Similarly, machine learning tools are increasingly being applied to climate science for developing ESMs[28], parameterising surface fluxes[29], and constructing statistical emulators of land models[30]. Indeed recent successes highlight the potential of machine learning to build physical insight in the atmospheric and ocean sciences[31,32]. But it remains to be seen whether the tools of machine learning are capable of transforming scientific understanding of land climate.

A renewed focus on theory

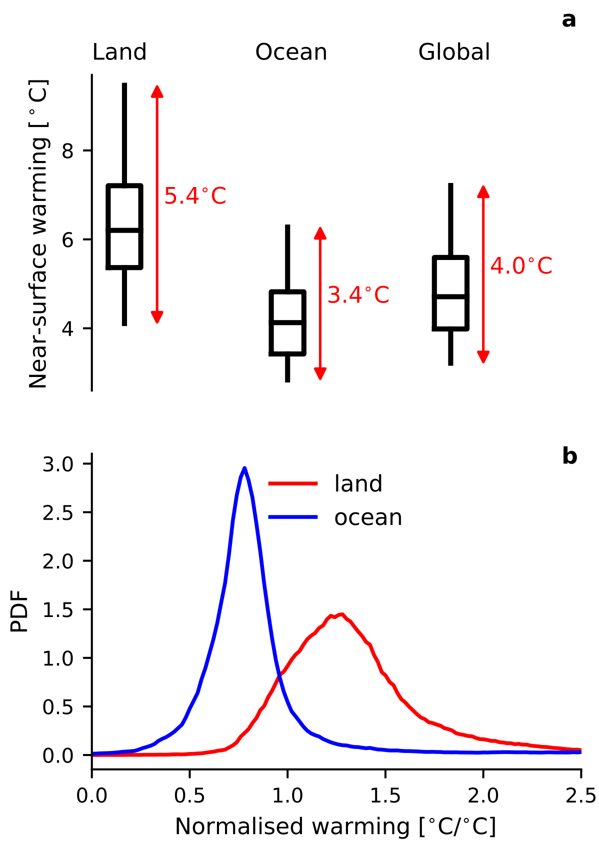

Figure 1: **Simulated climate warming is larger and more uncertain over land.** (a) Boxplots of simulated warming averaged over land (left), ocean (centre), and globally (right) calculated using pre-industrial control and abrupt 4xCO_2 simulations performed by 45 climate models participating in the Coupled Model Intercomparison Project Phase 6[33]. Horizontal lines show the median model values, boxes show the interquartile ranges, and whiskers show the full model ranges. Warming for each model is computed as the time- and area-averaged near-surface temperature change between the final 20 years of the pre-industrial control simulation and years 40-59 of the abrupt 4xCO_2 simulation. Uncertainty across models is indicated by the red arrows and text, with the full model range taken as a simple measure of uncertainty. (b) Multimodel-mean probability density functions (PDFs) of area-weighted near-surface warming over land (red) and ocean (blue), normalised by the global-mean warming in each model. The same models, simulations, and averaging periods are used as in panel (a). The wider land PDF in panel (b) suggests larger differences in near-surface warming, across space and models, relative to oceans.

Here we argue that for land-climate science to move forward, we must step back and reassess our approach. Our philosophy—borne in an era of explosive growth in model complexity and demanding simulation timetables, and shaped by a 2022 workshop at the University of St Andrews—is to redouble efforts to build robust physical understanding of land climate through the development of powerful new theories and refinement of existing conceptual frameworks. Previous work exemplifies this approach, notably the development of theories and simple 'toy' models to understand the land boundary layer[34], land-atmosphere coupling[35], and moist convection over land[36]. To anchor and inspire the next decade of research, we argue that now is the time to position this philosophy at the centre of land-climate science and re-balance our activities such that theory, model development, and observations are prioritised equally.

Development of theory can, and should, proceed in parallel with the imperative to build progressively more sophisticated ESMs. Indeed the gap in climate science between theory and actionable information, particularly at regional scales, is typically filled by state-of-the-art models, which are also invaluable tools for testing and refining the theories advocated for here. But theories that distill conceptual understanding need to be at the core of land-climate science, to enable the research community to compare proposed mechanisms, understand the competing roles of different processes in a coupled system, and make predictions without running complex models. Advances in theory can have practical as well as conceptual benefits, for example making ET easier to estimate[37], increasing confidence in model projections (for example of runoff[38]), and underpinning physically-based emergent constraints to narrow uncertainties in future climate change[39].

So, what constitutes a successful theory in land-climate science? The answer depends on the problem being considered, but we believe a successful theory should: explain an emergent property of the climate system; be underpinned by robust process understanding; and provide clear mechanistic insights that hold across a hierarchy of numerical model complexity. Theories should also, where possible, be predictive and quantitative (i.e., formulated as an equation or set of equations). Finally, and crucially, a successful theory should be tested against and supported by observational data. Below we highlight three recent advances in land-climate science that showcase the power of theory, before outlining our view on how a renewed focus on theory is needed to accelerate progress in land-climate science:

1. **Land temperature and humidity changes constrained by tropical atmospheric dynamics:** The role of convection and large-scale atmospheric dynamics in shaping tropical land temperature and humidity has been an important conceptual advance over recent decades[1,40,41]. This framework emerged from efforts to understand why, under climate change, warming is stronger over land; the so-called land-ocean warming contrast[40]. Early explanations of this phenomenon were based on the surface energy budget[42]. Radiative forcing at the surface (e.g., due to increases in atmospheric CO_2) are largely balanced in ocean regions by increases in evaporation, resulting in a relatively small increase in surface temperature. In land regions, however, which are often water-limited, radiative forcing is primarily balanced through increases in sensible heat and longwave fluxes, requiring a larger increase in temperature relative to oceans. Though physically intuitive, using this argument to construct a quantitative theory for land temperature change is challenging because surface fluxes de-

pend on multiple factors aside from temperature, including windspeed, soil moisture, and the air-surface temperature disequilibrium.

An alternative framework, inspired by Joshi et al[1], cuts through the complexity of land surfaces to reveal a strong constraint on the response of tropical land to climate change. This framework has transformed understanding of the tropical land-ocean warming contrast and has led to broader insights into large-scale atmospheric controls on near-surface temperature and humidity. In the tropical atmosphere, strong vertical coupling by convection between the boundary layer and free troposphere described by convective quasi-equilibrium[43]—together with horizontal coupling by gravity waves above the boundary layer, resulting in weak free-tropospheric temperature gradients[44]—imply that climatic changes in adiabatically conserved quantities such as moist static energy, a function of temperature and specific humidity near the surface, are tightly coupled between different regions and therefore approximately uniform on large scales[45–47] (Fig. 2). This mechanism, a form of 'downward control' exerted by the overlying atmosphere on near-surface tropical climate, has important implications: Though temperature and specific humidity individually may respond differently to climate change in different regions, for example in tropical savannas versus in rainforests, the combined change (encoded in the moist static energy) is more spatially homogeneous. Local processes, including soil moisture and aridity[46,48], are crucial for controlling how temperature versus humidity changes contribute to the change in moist static energy imposed by the atmosphere. This physical theory underpins advances in understanding the land-ocean warming contrast[1,49], aridity and land relative humidity in a changing climate[41,46,50], and extreme heat[47,51,52], and establishes a simple yet quantitative framework for interpreting models, observations, and the roles of local versus large-scale processes in shaping tropical land climate.

2. **Evapotranspiration predicted by simple theory:** ET is central to regulating the water, energy, and carbon budgets of land regions[53], and affects societies and ecosystems through its influence on hydrology and temperature variability[54]. But ET is directly measured only at a limited number of sites[55], necessitating models of various kinds to estimate ET elsewhere. These models are typically complex, requiring numerous poorly constrained land-surface parameters as inputs, and are imperfect at replicating direct measurements[56]. However, a new theory to predict present-day ET in inland continental regions using minimal input data provides a conceptual advance in understanding and presents an opportunity to greatly expand the database of ET measurements across space and time[37]. The theory is based on the concept of 'surface flux equilibrium' (SFE), which assumes an approximate balance between the surface moistening and heating effects on near-surface relative humidity[57]. This strong coupling between the land surface and overlying atmosphere imprints, in the air properties, information about the land-surface fluxes (i.e., the Bowen ratio) at daily to longer timescales, and appears to dominate alternative atmospheric mechanisms that also contribute to determining the near-surface atmospheric state (e.g., wind-driven moisture and heat convergence). Specifically, the SFE theory permits relatively accurate estimates of ET knowing only the net radiative flux into the surface and the near-surface temperature and specific humidity[37,58], the latter two which reflect the Bowen ratio (Fig. 3). Importantly, these quantities are more

widely available from weather stations than direct ET measurements. The theory reveals an emergent simplicity in ET[37], despite the heterogeneity and complexity of land surfaces.

3. **Leaf physiology incorporated into classical runoff theories:** Runoff from land supplies almost all the water used by humans. In contrast to the time-varying ET estimated by SFE and described above, long-term mean runoff and ET fluxes have long been predicted and understood using the simple theory of Budyko[59], in which the fraction of precipitation that becomes runoff decreases as the ratio of atmospheric evaporative demand to precipitation increases. Budyko quantified evaporative demand using surface net radiation only, but more comprehensive evaporative theories[60] generally also include a well-understood positive temperature dependence[61]. When these more modern methods are used in the Budyko theory, they predict substantial increases in evaporative demand with global warming and systematic decreases in natural runoff[62] (i.e., the component of runoff controlled by natural processes rather than by human activities), which would imply water shortages. Yet such widespread runoff declines are neither observed[63] nor simulated by more comprehensive models[62], leading to the impression of a theoretical deficiency. Yang et al[64] recently resolved this tension by incorporating the ET-reducing closure of leaf stomata by CO_2 into a revised theoretical framework (Fig. 4). The inclusion of this important and well-studied process brought the Budyko-predicted trends in natural runoff much closer to observations and state-of-the-art ESMs, and clarified our understanding of the drivers of runoff in a changing climate. Looking forward, incorporating human activities (e.g., water management) and the effects of wildfire into runoff theories is a priority for future work.

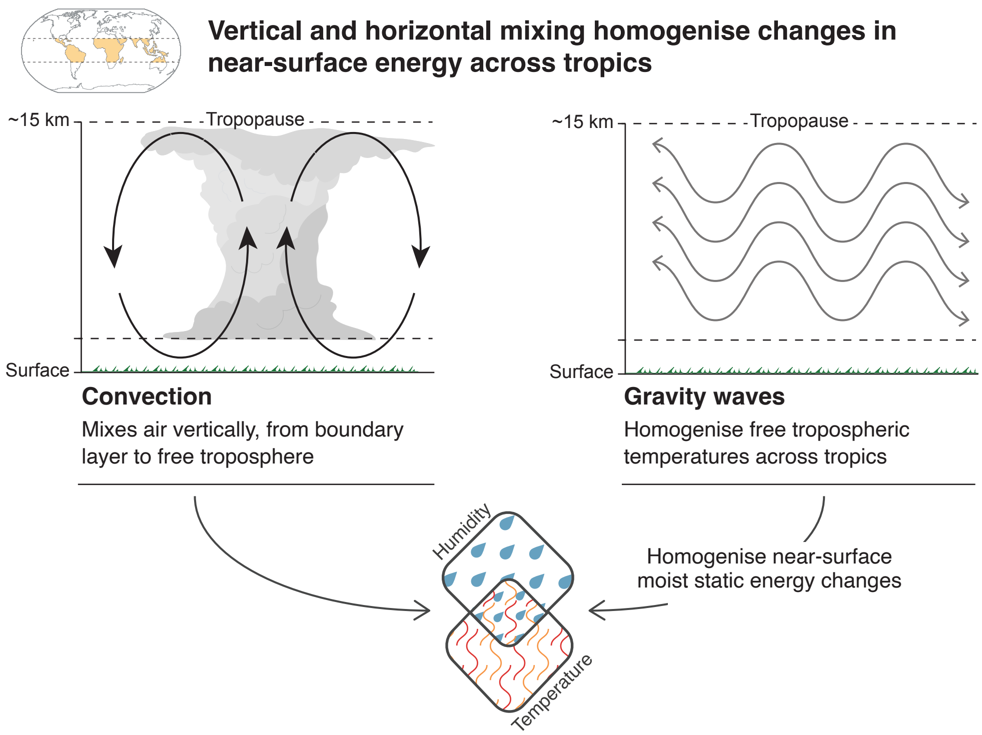

Figure 2: **Atmospheric dynamics constrain changes in tropical land climate.** Schematic illustrating how convection and gravity waves in the tropical atmosphere spatially homogenise climatic changes in near-surface moist static energy. The development of this large-scale atmospheric constraint on tropical land climate has been an important conceptual advance over recent years. Here and in Figures 3 and 4, the title maps highlight where the mechanism is broadly expected to be applicable.

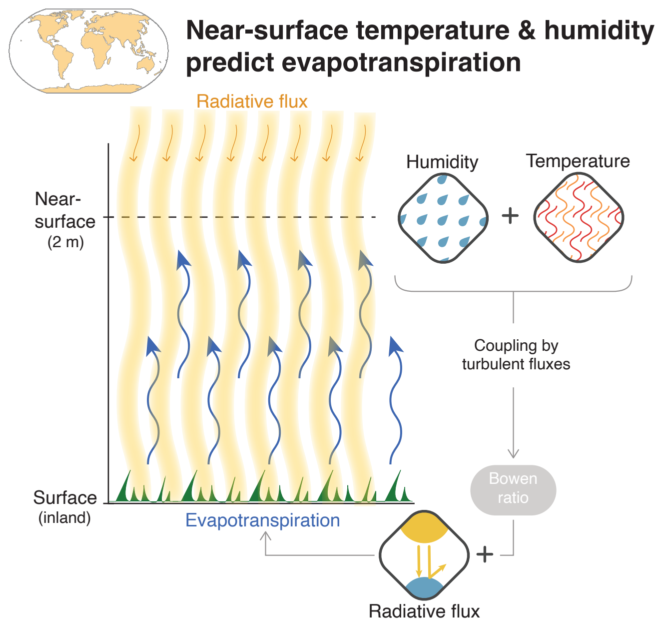

Figure 3: **Evapotranspiration inferred from temperature and humidity measurements.** Schematic highlighting how, following recent theoretical developments, inland ET can be predicted as a simple function of near-surface temperature and humidity along with the net radiative flux into the surface. Note that the grey arrows represent the series of inferences used by the SFE-based theory to make estimates of ET[37], whereas the blue and orange arrows denote, respectively, the turbulent fluxes of heat and water coupling the surface to the near-surface air and the radiative energy fluxes.

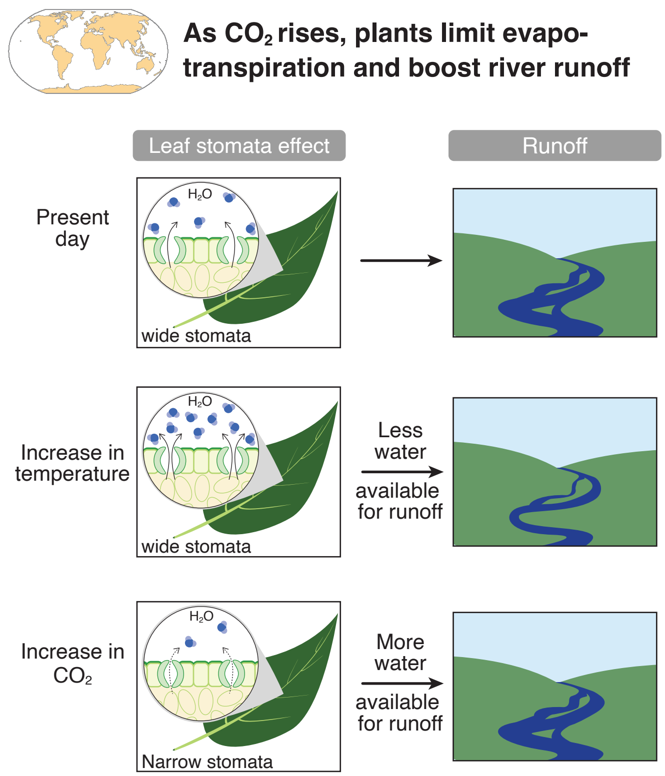

Figure 4: **Stomatal response to increasing CO_2 boosts river runoff.** Schematic depicting the competing effects of temperature versus CO_2 on ET from leaves and on river runoff. The recent incorporation of the CO_2 effect into classical theories has clarified understanding of runoff in a changing climate.

Opportunities for progress

A greater emphasis on developing theories for land climate and its changes is essential for building confidence in future projections, identifying directions for model improvement, validating *in situ* and remote sensing data, and interpreting the dynamics of key processes as new models and observational systems come online. The examples highlighted above demonstrate the potential for theory to further fundamental understanding of land climate. But the next set of advances is now needed. Below we present three areas of land-climate science primed for theory to provide new insights:

1. **Atmospheric circulation and land:** The atmospheric circulation strongly shapes the land climate, from extreme temperatures[65] to the regional water cycle[66]. However, much of our understanding of the atmospheric circulation and its sensitivity to climate change has been developed using aquaplanet models without land surfaces[67,68]. Over recent years, focus has begun to shift towards incorporating land into conceptual frameworks for the atmospheric state and circulation[69–71]. But numerous basic questions persist, including: Why is the tropical rainbelt wider over continents[9]? How can ingredients of the land surface be incorporated into modern theories for monsoons[72]? Why is the poleward expansion of the atmospheric circulation under global warming much weaker over land[6]? How will blocks, often the cause of extreme weather over land, change with warming[73]? And what processes control updraft velocities—and hence influence extreme precipitation—over land [2]? These important questions are ready to be tackled with novel theories.

2. **Water and land:** Beyond a broad tendency for mean relative humidity over land to decrease with warming[41,50,74], basic properties of the land water cycle and its response to climate change remain unexplained. For example, what are the mechanisms determining the spatial and temporal distribution of soil moisture in the current climate[75]? Why do climate models project drier surface soils in most regions[8]? And why do future trajectories for surface and column soil moisture differ[76]? Detailed understanding of near-surface humidity over land is another priority[10], given the strong coupling to trends in extreme temperatures[52,77], extreme precipitation[78], and runoff[79]. The coupling between plants and water has major implications for drought and terrestrial ecosystems, yet its response to climate change is highly uncertain[80]. For example, the effects of plant changes on runoff beyond the simple CO_2-stomatal dependence[64] are likely very large[81] but poorly understood. Finally the phenomenon of 'flash droughts', whose dynamics and predictability are only beginning to be explored[82], is an emerging topic where creative new theories are needed.

3. **Carbon and land:** Carbon uptake and release by terrestrial ecosystems both affects and responds to climate variability and long-term change. The field of carbon-water-climate feedbacks is already rich with examples of simple concepts, theories, and emergent constraints[83–85], providing a way to synthesise or contrast the behaviours emerging from complex ESMs[86]. The carbon-concentration and carbon-climate feedback parameters, for example, encapsulate the overall response of land carbon stocks to changes in atmospheric CO_2 and to global warming, respectively[87]. This global-scale conceptual framework can be used to diagnose and compare complex simulations[88], but is also transferable to climate emulators or models

of reduced complexity[89]. However, similarly simple and adaptable concepts are lacking in other areas of carbon cycle research. There is, for instance, large uncertainty on the extent to which tipping points at regional scales could impact some of the world's largest carbon pools, like permafrost carbon, the Amazon rainforest ecosystem, and global forests[90–93]. To some extent this is because we lack theories, metrics, and frameworks to explain and reconcile the contradicting results obtained from different models and approaches. However, the existing literature on dynamical systems theory is rich with concepts that may be transferable to understand potential tipping points in the carbon cycle if they can be adequately constrained by observations, similar to what has been done to study transitions between stable system states or attractors in ecology and population dynamics[94,95].

Outlook

To discover, test, and refine the powerful theories for land climate advocated for in this perspective, and to maximise benefits for the wider climate community, technical tools and scientific talent are needed. On the tools side, we have at our disposal a range of models spanning idealised[96] to state-of-the-art ESMs[33], alongside the emerging generation of 'global storm resolving' models[22] and flexible, process-based hydrologic models[97]. This model hierarchy is well positioned for building new understanding of land climate. However, a lack of observations presents a major challenge[98]: Despite recent progress, for example in remote sensing of surface soil moisture[99], we simply do not have long-term datasets with wide spatial coverage for many important land-climate quantities, including root-zone soil moisture and ET. Thus, to parallel the development of models and efforts to construct theories for land climate, new instrumental observations of essential land surface fluxes and reservoirs are required. Opportunities to further leverage existing observational datasets, with the goal of improving models and testing theories, should also be exploited. Beyond observational uncertainty, whenever we ground new theory in observations we also have to contend with the complicating influence of internal climate variability. Separating the forced response from internal variability at regional scales is still challenging and can harbour surprises that can influence our theories[100]. Empirical-statistical methods to isolate the forced response, and new theory on internal variability itself, will thus need to accompany our endeavour to refine understanding of land climate and its changes with warming.

On the talent side, to tackle the important questions in land-climate science we need to continually inspire, recruit, and resource diverse cohorts of researchers from a range of primary disciplines spanning atmospheric science, hydrology, ecology, physics, mathematics, computer science, and beyond. Engaging scientists from the broader climate community—those working primarily on atmospheric dynamics, for example—also has the potential to bring new ideas and drive progress in land-climate science. Through this perspective, alongside a series of workshops and summer schools we aim to coordinate over coming years, our goal is to engage these current and future generations of researchers—as well as major funding bodies and established land-focused research initiatives—in our vision to place theory at the core of land-climate science.

State-of-the-art models, observational systems, and machine learning are transforming our ability to simulate, monitor, and emulate many aspects of land climate. But our scientific understanding has not kept pace, and we now lack robust theories to comprehend the rich complexity being revealed by these advanced tools. Now is the time to change course and underpin models, observations, and machine-learning techniques with new theories so that we maintain and advance the deep, mechanistic understanding of land climate needed to meet the challenges of an uncertain future.

1. Joshi, M. M., Gregory, J. M., Webb, M. J., Sexton, D. M. H. & Johns, T. C. Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. *Climate Dynamics* **30**, 455–465 (2008).

2. Pfahl, S., O'Gorman, P. A. & Fischer, E. M. Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Climate Change* **7**, 423–427 (2017).

3. Milly, P. C. & Dunne, K. A. Colorado river flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science* **367**, 1252–1255 (2020).

4. Held, I. M. & Soden, B. J. Robust responses of the hydrological cycle to global warming. *Journal of Climate* **19**, 5686–5699 (2006).

5. Greve, P. *et al.* Global assessment of trends in wetting and drying over land. *Nature Geoscience* **7**, 716–721 (2014).

6. Schmidt, D. F. & Grise, K. M. The response of local precipitation and sea level pressure to Hadley cell expansion. *Geophysical Research Letters* **44**, 10,573–10,582 (2017).

7. Berg, A. & Sheffield, J. Evapotranspiration partitioning in CMIP5 models: uncertainties and future projections. *Journal of Climate* **32**, 2653–2671 (2019).

8. Cook, B. I. *et al.* Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future* **8** (2020). E2019EF001461.

9. Hohenegger, C. & Stevens, B. Tropical continents rainier than expected from geometrical constraints. *AGU Advances* **3** (2022). E2021AV000636.

10. Simpson, I. R. *et al.* Observed humidity trends in dry regions contradict climate models. *Proceedings of the National Academy of Sciences* **121**, e2302480120 (2024).

11. Lee, Y.-C. & Wang, Y.-C. Evaluating diurnal rainfall signal performance from CMIP5 to CMIP6. *Journal of Climate* **34**, 7607–7623 (2021).

12. Seneviratne, S. I. *et al.* Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment. *Geophysical Research Letters* **40**, 5212–5217 (2013).

13. Swann, A. L. S. Plants and drought in a changing climate. *Current Climate Change Reports* **4**, 192–201 (2018).

14. Lambert, F. H. & Chiang, J. C. H. Control of land-ocean temperature contrast by ocean heat uptake. *Geophysical Research Letters* **34** (2007). L13704.

15. Teng, H., Leung, R., Branstator, G., Lu, J. & Ding, Q. Warming pattern over the northern hemisphere midlatitudes in boreal summer 1979–2020. *Journal of Climate* **35**, 3479–3494 (2022).

16. Best, M. J. *et al.* The plumbing of land surface models: benchmarking model performance. *Journal of Hydrometeorology* **16**, 1425–1442 (2015).

17. Haughton, N. *et al.* The plumbing of land surface models: Is poor performance a result of methodology or data quality? *Journal of Hydrometeorology* **17**, 1705–1723 (2016).

18. Haughton, N., Abramowitz, G. & Pitman, A. J. On the predictability of land surface fluxes from meteorological variables. *Geoscientific Model Development* **11**, 195–212 (2018).

19. Li, Z.-L. *et al.* Soil moisture retrieval from remote sensing measurements: Current knowledge and directions for the future. *Earth-Science Reviews* **218**, 103673 (2021).

20. Willett, K. *et al.* HadISDH land surface multi-variable humidity and temperature record for climate monitoring. *Climate of the Past* **10**, 1983–2006 (2014).

21. Pongratz, J. *et al.* Land use effects on climate: current state, recent progress, and emerging topics. *Current Climate Change Reports* **7**, 99–120 (2021).

22. Hohenegger, C. *et al.* ICON-Sapphire: simulating the components of the Earth system and their interactions at kilometer and subkilometer scales. *Geoscientific Model Development* **16**, 779–811 (2023).

23. Beven, K. J. & Cloke, H. L. Comment on: "Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water" by Eric F. Wood et al. *Water Resources Research* **48** (2012). W01801.

24. Fan, Y. *et al.* Hillslope hydrology in global change research and Earth system modeling. *Water Resources Research* **55**, 1737–1772 (2019).

25. Barlage, M., Chen, F., Rasmussen, R., Zhang, Z. & Miguez-Macho, G. The importance of scale-dependent groundwater processes in land-atmosphere interactions over the central United States. *Geophysical Research Letters* **48** (2021). E2020GL092171.

26. Pongratz, J. *et al.* Models meet data: Challenges and opportunities in implementing land management in Earth system models. *Global Change Biology* **24**, 1470–1487 (2018).

27. Clark, M. P. *et al.* The evolution of process-based hydrologic models: historical challenges and the collective quest for physical realism. *Hydrology and Earth System Sciences* **21**, 3427–3440 (2017).

28. Schneider, T., Lan, S., Stuart, A. & Teixeira, J. Earth system modeling 2.0: A blueprint for models that learn from observations and targeted high-resolution simulations. *Geophysical Research Letters* **44**, 12–396 (2017).

29. Wulfmeyer, V. *et al.* Estimation of the surface fluxes for heat and momentum in unstable conditions with machine learning and similarity approaches for the LAFE data set. *Boundary-Layer Meteorology* **186**, 337–371 (2023).

30. Dagon, K., Sanderson, B. M., Fisher, R. A. & Lawrence, D. M. A machine learning approach to emulation and biophysical parameter estimation with the Community Land Model, version 5. *Advances in Statistical Climatology, Meteorology and Oceanography* **6**, 223–244 (2020).

31. Yuval, J. & O'Gorman, P. A. Stable machine-learning parameterization of subgrid processes for climate modeling at a range of resolutions. *Nature Communications* **11** (2020).

32. Zanna, L. & Bolton, T. Data-driven equation discovery of ocean mesoscale closures. *Geophysical Research Letters* **47** (2020). E2020GL088376.

33. Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* **9**, 1937–1958 (2016).

34. Betts, A. K. Idealized model for equilibrium boundary layer over land. *Journal of Hydrometeorology* **1**, 507–523 (2000).

35. Brubaker, K. L. & Entekhabi, D. An analytic approach to modeling land-atmosphere interaction: 1. Construct and equilibrium behavior. *Water Resources Research* **31**, 619–632 (1995).

36. Findell, K. L. & Eltahir, E. A. Atmospheric controls on soil moisture–boundary layer interactions. Part I: Framework development. *Journal of Hydrometeorology* **4**, 552–569 (2003).

37. McColl, K. A. & Rigden, A. J. Emergent simplicity of continental evapotranspiration. *Geophysical Research Letters* **47** (2020). E2020GL087101.

38. Scheff, J., Coats, S. & Laguë, M. M. Why do the global warming responses of land-surface models and climatic dryness metrics disagree? *Earth's Future* **10** (2022). E2022EF002814.

39. Klein, S. A. & Hall, A. Emergent constraints for cloud feedbacks. *Current Climate Change Reports* **1**, 276–287 (2015).

40. Byrne, M. P. & O'Gorman, P. A. Land–ocean warming contrast over a wide range of climates: Convective quasi-equilibrium theory and idealized simulations. *Journal of Climate* **26**, 4000–4016 (2013).

41. Sherwood, S. & Fu, Q. A drier future? *Science* **343**, 737–739 (2014).

42. Manabe, S., Stouffer, R. J., Spelman, M. J. & Bryan, K. Transient responses of a coupled ocean–atmosphere model to gradual changes of atmospheric CO_2. Part I. Annual mean response. *Journal of Climate* **4**, 785–818 (1991).

43. Arakawa, A. & Schubert, W. H. Interaction of a cumulus cloud ensemble with the large-scale environment, Part I. *Journal of the Atmospheric Sciences* **31**, 674–701 (1974).

44. Sobel, A. H. & Bretherton, C. S. Modeling tropical precipitation in a single column. *Journal of Climate* **13**, 4378–4392 (2000).

45. Byrne, M. P. & O'Gorman, P. A. Link between land-ocean warming contrast and surface relative humidities in simulations with coupled climate models. *Geophysical Research Letters* **40**, 5223–5227 (2013).

46. Berg, A. *et al.* Land–atmosphere feedbacks amplify aridity increase over land under global warming. *Nature Climate Change* **6**, 869–874 (2016).

47. Zhang, Y., Held, I. & Fueglistaler, S. Projections of tropical heat stress constrained by atmospheric dynamics. *Nature Geoscience* **14**, 133–137 (2021).

48. Duan, S. Q., Findell, K. L. & Fueglistaler, S. A. Coherent mechanistic patterns of tropical land hydroclimate changes. *Geophysical Research Letters* **50**, e2022GL102285 (2023).

49. Byrne, M. P. & O'Gorman, P. A. Trends in continental temperature and humidity directly linked to ocean warming. *Proceedings of the National Academy of Sciences* **115**, 4863–4868 (2018).

50. Byrne, M. P. & O'Gorman, P. A. Understanding decreases in land relative humidity with global warming: Conceptual model and gcm simulations. *Journal of Climate* **29**, 9045–9061 (2016).

51. Buzan, J. R. & Huber, M. Moist heat stress on a hotter Earth. *Annual Review of Earth and Planetary Sciences* **48**, 623–655 (2020).

52. Byrne, M. P. Amplified warming of extreme temperatures over tropical land. *Nature Geoscience* **14**, 837–841 (2021).

53. Teuling, A. *et al.* A regional perspective on trends in continental evaporation. *Geophysical Research Letters* **36** (2009). L02404.

54. Seneviratne, S. I., Lüthi, D., Litschi, M. & Schär, C. Land–atmosphere coupling and climate change in Europe. *Nature* **443**, 205–209 (2006).

55. Pastorello, G. *et al.* The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data. *Scientific Data* **7**, 1–27 (2020).

56. Mueller, B. & Seneviratne, S. I. Systematic land climate and evapotranspiration biases in cmip5 simulations. *Geophysical Research Letters* **41**, 128–134 (2014).

57. McColl, K. A., Salvucci, G. D. & Gentine, P. Surface flux equilibrium theory explains an empirical estimate of water-limited daily evapotranspiration. *Journal of Advances in Modeling Earth Systems* **11**, 2036–2049 (2019).

58. Chen, S., McColl, K. A., Berg, A. & Huang, Y. Surface flux equilibrium estimates of evapotranspiration at large spatial scales. *Journal of Hydrometeorology* **22**, 765–779 (2021).

59. Budyko, M. I. *Climate and Life* (Academic Press, 1974).

60. Monteith, J. L. Evaporation and surface temperature. *Quarterly Journal of the Royal Meteorological Society* **107**, 1–27 (1981).

61. Scheff, J. & Frierson, D. M. W. Scaling potential evapotranspiration with greenhouse warming. *Journal of Climate* **27**, 1539–1558 (2014).

62. Milly, P. C. D. & Dunne, K. A. Potential evapotranspiration and continental drying. *Nature Climate Change* **6**, 946–949 (2016).

63. Dai, A. Historical and future changes in streamflow and continental runoff: A review. In Tang, Q. & Oki, T. (eds.) *Terrestrial Water Cycle and Climate Change: Natural and Human-Induced Impacts*, vol. 221 of *Geophysical Monograph Series*, 17–37 (2016).

64. Yang, Y., Roderick, M. L., Zhang, S., McVicar, T. R. & Donohue, R. J. Hydrologic implications of vegetation response to elevated CO_2 in climate projections. *Nature Climate Change* **9**, 44–48 (2019).

65. Wehrli, K., Guillod, B. P., Hauser, M., Leclair, M. & Seneviratne, S. I. Identifying key driving processes of major recent heat waves. *Journal of Geophysical Research: Atmospheres* **124**, 11746–11765 (2019).

66. Seager, R. *et al.* Dynamical and thermodynamical causes of large-scale changes in the hydrological cycle over North America in response to global warming. *Journal of Climate* **27**, 7921–7948 (2014).

67. Kang, S. M., Held, I. M., Frierson, D. M. & Zhao, M. The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM. *Journal of Climate* **21**, 3521–3532 (2008).

68. Bordoni, S. & Schneider, T. Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. *Nature Geoscience* **1**, 515–519 (2008).

69. Hohenegger, C. & Stevens, B. The role of the permanent wilting point in controlling the spatial distribution of precipitation. *Proceedings of the National Academy of Sciences* **115**, 5692–5697 (2018).

70. Zhou, W. & Xie, S.-P. A hierarchy of idealized monsoons in an intermediate GCM. *Journal of Climate* **31**, 9021–9036 (2018).

71. Biasutti, M., Russotto, R. D., Voigt, A. & Blackmon-Luca, C. C. The effect of an equatorial continent on the tropical rain belt. Part I: Annual mean changes in the ITCZ. *Journal of Climate* **34**, 5813–5828 (2021).

72. Geen, R., Bordoni, S., Battisti, D. S. & Hui, K. Monsoons, ITCZs, and the concept of the global monsoon. *Reviews of Geophysics* **58**, e2020RG000700 (2020).

73. Woollings, T. *et al.* Blocking and its response to climate change. *Current Climate Change Reports* **4**, 287–300 (2018).

74. Simmons, A. J., Willett, K. M., Jones, P. D., Thorne, P. W. & Dee, D. P. Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets. *Journal of Geophysical Research: Atmospheres* **115** (2010).

75. Vargas Zeppetello, L. R., Trevino, A. M. & Huybers, P. Disentangling contributions to past and future trends in US surface soil moisture. *Nature Water* 1–12 (2024).

76. Berg, A., Sheffield, J. & Milly, P. C. Divergent surface and total soil moisture projections under global warming. *Geophysical Research Letters* **44**, 236–244 (2017).

77. Zhang, Y. & Boos, W. R. An upper bound for extreme temperatures over midlatitude land. *Proceedings of the National Academy of Sciences* **120** (2023). E2215278120.

78. Williams, A. I. & O'Gorman, P. A. Summer-winter contrast in the response of precipitation extremes to climate change over northern hemisphere land. *Geophysical Research Letters* **49** (2022). E2021GL096531.

79. Byrne, M. P. & O'Gorman, P. A. The response of precipitation minus evapotranspiration to climate warming: Why the "wet-get-wetter, dry-get-drier" scaling does not hold over land. *Journal of Climate* **28**, 8078–8092 (2015).

80. Dai, A., Zhao, T. & Chen, J. Climate change and drought: a precipitation and evaporation perspective. *Current Climate Change Reports* **4**, 301–312 (2018).

81. Mankin, J. S., Seager, R., Smerdon, J. E., Cook, B. I. & Williams, A. P. Mid-latitude freshwater availability reduced by projected vegetation responses to climate change. *Nature Geoscience* **12**, 983–988 (2019).

82. Pendergrass, A. G. *et al.* Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nature Climate Change* **10**, 191–199 (2020).

83. Prentice, I. C., Dong, N., Gleason, S. M., Maire, V. & Wright, I. J. Balancing the costs of carbon gain and water transport: testing a new theoretical framework for plant functional ecology. *Ecology Letters* **17**, 82–91 (2014).

84. Anderegg, W. R. *et al.* Woody plants optimise stomatal behaviour relative to hydraulic risk. *Ecology Letters* **21**, 968–977 (2018).

85. Wenzel, S., Cox, P. M., Eyring, V. & Friedlingstein, P. Emergent constraints on climate-carbon cycle feedbacks in the cmip5 earth system models. *Journal of Geophysical Research: Biogeosciences* **119**, 794–807 (2014).

86. Gregory, J. M., Jones, C. D., Cadule, P. & Friedlingstein, P. Quantifying carbon cycle feedbacks. *Journal of Climate* **22**, 5232–5250 (2009).

87. Friedlingstein, P. *et al.* Climate–carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *Journal of Climate* **19**, 3337–3353 (2006).

88. Arora, V. K. *et al.* Carbon–concentration and carbon–climate feedbacks in CMIP5 Earth system models. *Journal of Climate* **26**, 5289–5314 (2013).

89. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmospheric Chemistry and Physics* **11**, 1417–1456 (2011).

90. Anderegg, W. R. *et al.* A climate risk analysis of Earth's forests in the 21st century. *Science* **377**, 1099–1103 (2022).

91. Lenton, T. M. *et al.* Climate tipping points — too risky to bet against. *Nature* **575**, 592–595 (2019).

92. K Braghiere, R. *et al.* Tipping point in North American Arctic-Boreal carbon sink persists in new generation earth system models despite reduced uncertainty. *Environmental Research Letters* **18** (2023). 025008.

93. Malhi, Y. *et al.* Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences* **106**, 20610–20615 (2009).

94. Pisarchik, A. N. & Feudel, U. Control of multistability. *Physics Reports* **540**, 167–218 (2014).

95. van Nes, E. H., Hirota, M., Holmgren, M. & Scheffer, M. Tipping points in tropical tree cover: linking theory to data. *Global Change Biology* **20**, 1016–1021 (2014).

96. Vallis, G. K. *et al.* Isca, v1. 0: A framework for the global modelling of the atmospheres of Earth and other planets at varying levels of complexity. *Geoscientific Model Development* **11**, 843–859 (2018).

97. Clark, M. P. *et al.* A unified approach for process-based hydrologic modeling: 2. Model implementation and case studies. *Water resources research* **51**, 2515–2542 (2015).

98. Santanello Jr, J. A. *et al.* Land–atmosphere interactions: The LoCo perspective. *Bulletin of the American Meteorological Society* **99**, 1253–1272 (2018).

99. Entekhabi, D. *et al.* The soil moisture active passive (SMAP) mission. *Proceedings of the IEEE* **98**, 704–716 (2010).

100. Lehner, F. & Deser, C. Origin, importance, and predictive limits of internal climate variability. *Environmental Research: Climate* **2** (2023). 023001.

Acknowledgements We thank the Carnegie Trust for the Universities of Scotland for generously funding a workshop on land-climate science at the University of St Andrews (June 6-8th, 2022) which inspired this perspective. We also thank Melissa Gomis for graphical assistance with Figures 2-4. MPB was supported by the UKRI Frontier Research Guarantee scheme [grant number EP/Y027868/1] and SAH was funded by NSF award #2123327.

Competing Interests The authors declare no competing interests.

Corresponding Author Correspondence should be addressed to the lead author (email: mpb20@st-andrews.ac.uk).

Author Contributions MPB, GCH, and JS wrote the initial draft; all authors contributed to editing and revising the manuscript.

Data Availability The model data used to produce Figure 1 are provided by the World Climate Research Programme's Working Group on Coupled Modelling and can be accessed at https://esgf-node.llnl.gov/search/cmip6/.

Code Availability The code used to produce Figure 1 is available from the corresponding author on request.