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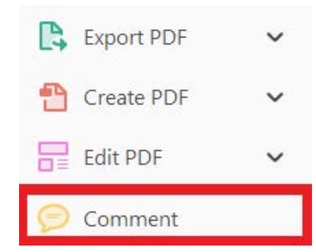

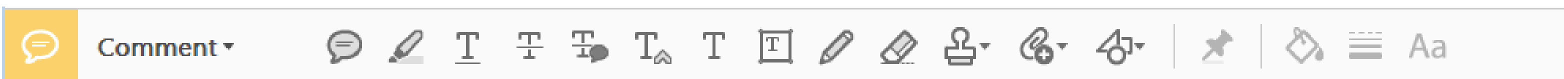

1. Replace (Ins) Tool – for replacing text.

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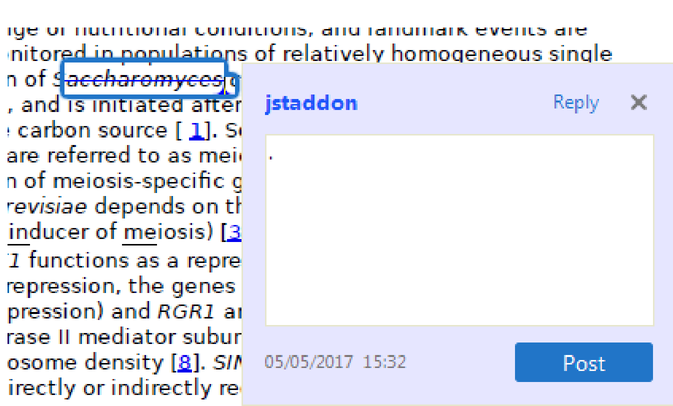

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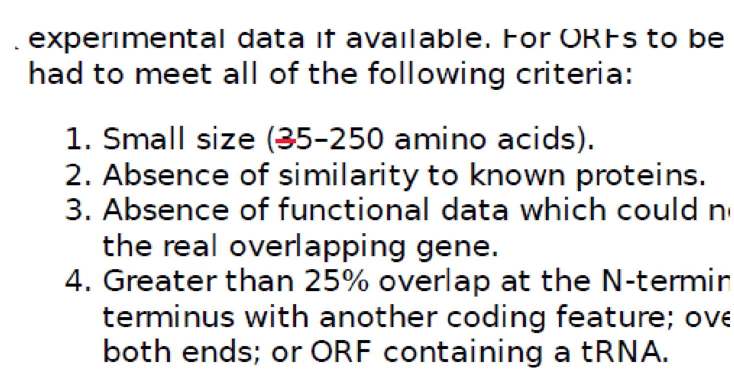

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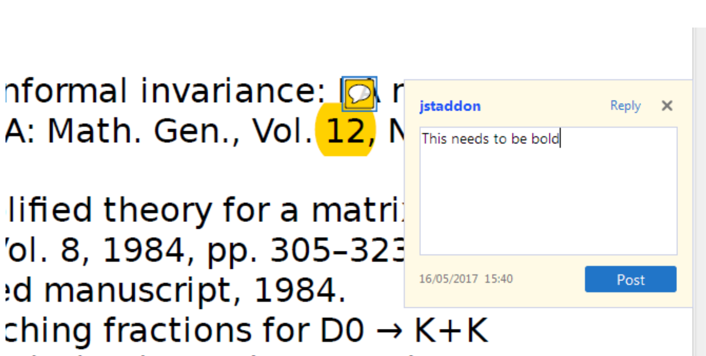

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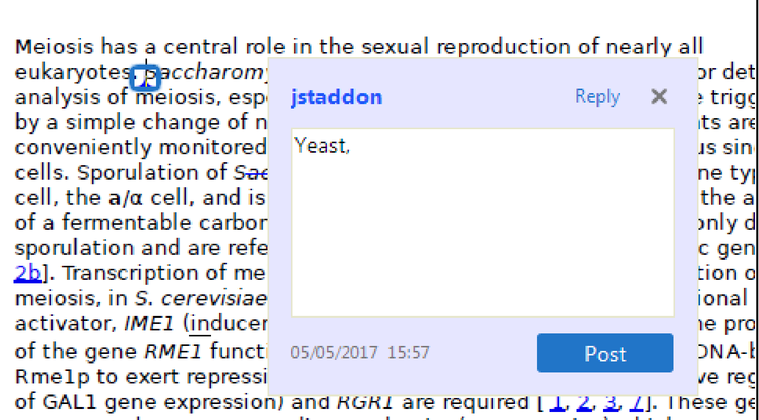

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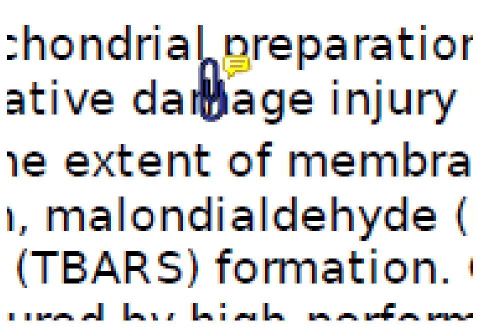

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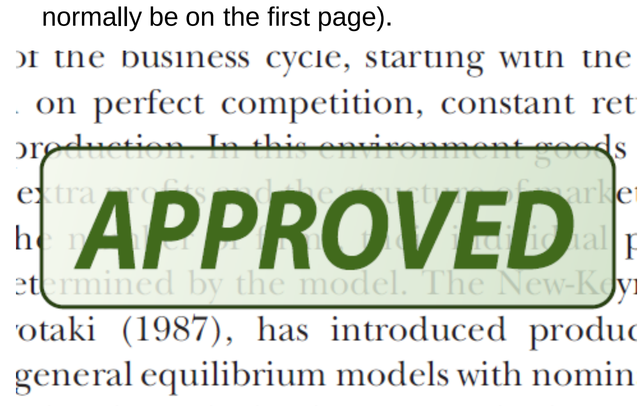
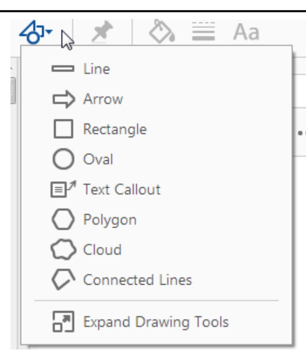


Drawing tools available on comment ribbon



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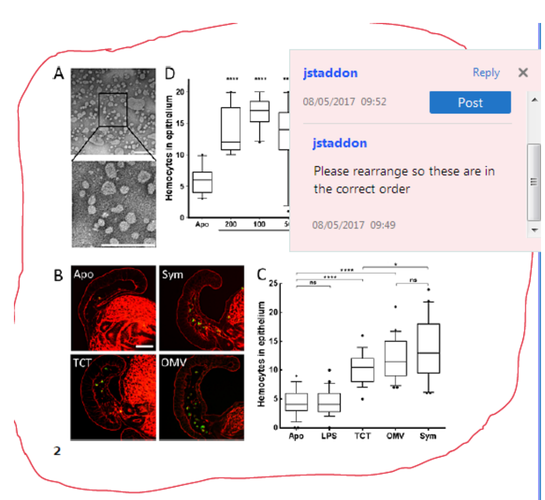

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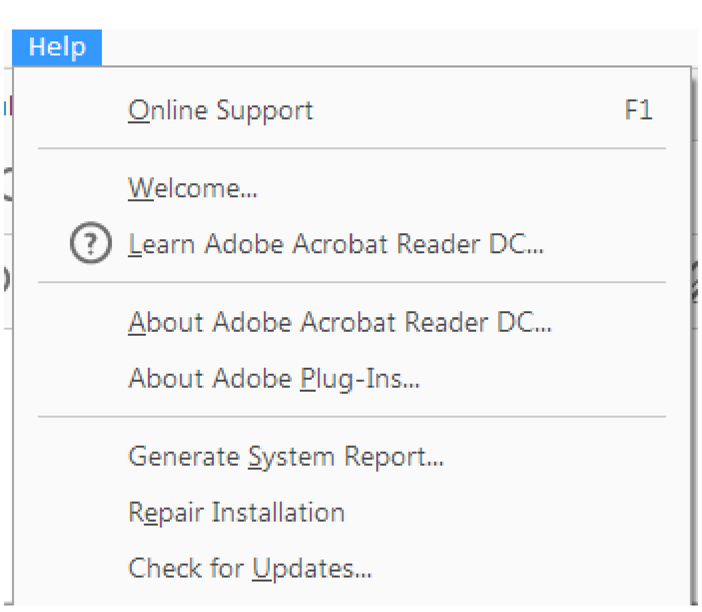

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ARTICLE

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Bridging the divide between human and physical geography: Potential avenues for collaborative research on climate modeling

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Abstract

Despite repeated calls for greater collaboration between physical and human geographers, the unique interdisciplinary potential of geography remains largely underutilized. Yet geographers are well positioned to take a leading role in the interdisciplinary turn in climate-related research. This paper explores the possibilities for physical and human geographers to collaborate within and beyond the discipline, specifically on the topic of climate modeling. We first examine geographical research critically examining the production and circulation of climate knowledge. Drawing on insights from a recent literature called "Critical Physical Geography," we then outline how geographers might engage in collaborative and interdisciplinary work in order to promote more democratic practices of producing climate knowledge, enrich understandings of climate change, and more effectively serve goals of social and environmental justice. We argue that both the discipline of geography and the field of climate research stand to gain enormously from geographers' efforts to talk across the divide between social and natural science within and beyond the boundaries of geography.

KEYWORDS

climate, climatology, Environment & Society, knowledge, modeling, science

1 | INTRODUCTION

Over the years there have been numerous calls for greater collaboration between physical and human geographers, and the question of how to facilitate greater cross-pollination is one that geographers have raised repeatedly (see: Harrison et al., 2004; Johnston, 2003; Lave et al., 2014; Massey, 1999; Tadaki, Salmond, Le Heron, & Brierley, 2012; Thrift, 2002). While select subfields such as political ecology and research on the human dimensions of global change often bring together analyses of the social and natural worlds, the dualism between human and physical geography more generally endures. This is reflected in the fault line running through many departments across Australia, Canada, the United States, and the United Kingdom, the relatively sparse collaboration between human and physical geographers, and their participation in distinct journals and conferences (Johnston, 2003). This has been traced back to the ontological separation of society and nature (Kwan, 2004), as well as the discipline's early, disastrous forays into environmentalism determinism (Randalls, 2017).

Perhaps more than any other topic of geographical inquiry, anthropogenic climate change collapses the dualism between nature and society, forcing us to confront their very entanglements (Chakrabarty, 2009). The "Anthropocene" (Crutzen, 2006; Zalasiewicz, Williams, Steffen, & Crutzen, 2010), the proposed epoch during which humans are understood to be a dominant environmental force, has placed humankind in the foreground as agents shaping geological processes over an unprecedented planetary scale, demanding geoscientists provide more thorough analyses of the human dimensions of climate change. At the same time, climate change exposes the inextricable links between the human and more-than-human worlds, requiring the attention of social scientists to the biophysical dimensions of climate change. Lave and Lutz (2014) argue that considering the "physical and social implications together rather than separately" (p. 740) provides a means to produce more "robust and policy-relevant research" (p. 751). As a socio-environmental process, by its very nature climate change necessitates interdisciplinary research (Lave et al., 2014). It therefore offers especially fertile grounds for utilizing the interdisciplinary potential of geography.

In this paper, we make the case for a more pluralistic and interdisciplinary approach to climate research, particularly climate modeling. We believe geographers are especially well positioned to make a valuable contribution to this effort. As Lahsen (2010) argues: "work emerging from geographers suggests the potential of the field to help lead the development of new, more integrated approaches to the study of climate change" (p. 163). This paper examines the possibilities for approaches from geography to inform more interdisciplinary approaches to climate modeling, with the aim of engaging in more democratic practices of knowledge, enriching understandings of climate change, and more effectively serving goals of social and environmental justice. We first examine geographical research critically examining the production and circulation of climate knowledge, including work wherein geographers have effectively collaborated within and beyond the discipline. We then turn to outline how geographers might lead more interdisciplinary approaches to climate modeling, drawing on insights from a recent literature called "Critical Physical Geography" (Lave, 2014; Lave, 2015a; Lave et al., 2014).

2 | GEOGRAPHERS' CONTRIBUTIONS TO CLIMATE KNOWLEDGE

2.1 | Geographers as producers of climate knowledge

Anthropogenic climate change is accelerating the rate at which processes in nature reshape the surface of the Earth, and the climate system is said to be entering a "new normal" (e.g., Flato, Hiler, & Mayer, 2017). But what is meant by "normal" (Hulme, Dessai, Lorenzoni, & Nelson, 2009), and for how long has human activity affected it; for hundreds of years or for many thousands (Ruddiman, 2003)? As a discipline, geography is ideally placed to interrogate these questions, and geographers have played a key role as producers of climate knowledge even if, as Castree (2014) observes that, "research we might otherwise associate with Geography as a discipline is now occurring outside the subject" (p. 445).

The climate dynamics of the Holocene epoch, roughly since the end of the last "Ice Age," coincides with the unprecedented growth of human population size and sociocultural complexity; the appearance of urban environments, techno-culture, and industrialization; and the capacity of the human species to affect environmental changes on a global scale, vis-a-vis, the Anthropocene. Through the coarse lens of paleoclimate proxies, the Holocene climate was once seen as a relatively warm, less drought-stricken, and stable period of the planet's climate history. Over the past few decades, however, due in large part to rising interdisciplinary focus on the Holocene environment, evidence of several global-scale rapid climate change events over the Holocene has nuanced that view (Alley et al., 2003; Mayewski et al., 2004). (The notion that climatic variability, in particular, affected the stability of agro-ecological systems has a long history, in which geographers were deeply involved [e.g. Butzer, 1980; Büntgen et al., 2011].)

Geographers have long been privileged witnesses to environmental change due to their traditional role as field-based documentarians of the planet's reciprocal processes of physical evolution, dynamic equilibria of weathering, erosion, and the climate. As the record of standardized instrumental measurements grew, the complexity of the earth climate system, a term that includes the terrestrial, ocean, and atmospheric feedbacks that produce the climate, was gradually expressed; and the most remote of places proved to be some of the most sensitive to changes in the processes that shaped them. Yet many of the most scientifically influential paleoclimate records, based upon proxies which were once solidly within the domain of geography departments (e.g., tree-rings), have been produced by nongeographers (Mann et al., 2008; Mann, Bradley, & Hughes, 1998; Moberg, Sonechkin, Holmgren, Datsenko, & Karlén, 2005). Geographers certainly produce critical climate science, but particularly from within interdisciplinary collaborations, such as the Intergovernmental Panel on Climate Change (IPCC) research reports, or working as hydrologists and other earth system scientists (e.g., Rodysill et al., 2017). Although geography departments remain active in the critical role of collecting raw data, the necessary analytics and theory of climate change is driven by specialized groups (often containing or affiliated with academic geographers) within atmospheric and earth systems science departments, further demonstrating the need for greater interdisciplinary efforts in climate change research.

While high-resolution records of recent climate change have yielded strong evidence of global warming, they cannot, in isolation, be the evidentiary "smoking gun" for anthropogenic climate change. Rather, paleoclimatic records to establish baseline ecological equilibria allow for statistical testing of instrumental measurements (and model projections) of, for instance, drought, with preinstrumental records; and thus observed (and projected) climate events may be attributed to anthropogenic climate change in terms of likelihood (e.g., Ault et al., 2018). They provide a baseline of normative behavior for the preindustrial earth climate system, in contrast to the rapid and unprecedented northward movement of the boreal tree line (see Overpeck et al., 1997). Attributing climate change to human activity remains a challenge due to the irreducibility of coupled, complex natural systems, differences in methods and instrumentation among disciplines (i.e., getting different measurements to agree), and even simple lack of interdisciplinary consensus on the semantic and rigorous meaning of "attribution" (Hulme, 2014). Meta-analyses of patterns of change across ecosystems are well suited to settling questions of attribution. For example, plant biology is well understood and, in some cases, centuries of records of plant phenology exist (e.g., Chuine et al., 2004). Systematic transformations of community assemblages, earlier spring emergence and later winter dormancy, and the gradual spread of tree lines northwards and to higher mountain elevations, taken in aggregate, is a clear manifestation of rising mean annual temperature (see Parmesan & Yohe, 2003). These amount to a concerted effort to abstract and understand the earth's climate system or a recursive pipeline of climate data acquisition (from proxies, field-based instruments, and satellites) and incremental improvement of climate models (Mearns et al., 2009).

Since geographers, as field researchers, are typically well located to observe the change of their sites, they are ideally situated to communicate their research in experiential terms. Striking drone images of geographers' fieldwork studying Greenland moulins exposed the scale and pace of change to the ice sheet to the public (Davenport, Haner, Buchanan, & Watkins, 2015; Prisco, 2016). The warming Arctic invites collaboration between physical and human geographers researching coupled natural–human systems, such as the likely consequences of reduced summer sea ice for circumpolar ecosystems, commerce, and power relations. For example, Stephenson, Smith, and Agnew (2011) combine “climate model projections of air temperature, snow depth, and sea ice with static datasets on land cover, topography, hydrography, built infrastructure, and human settlements” (p. 1) to model the implications of climate change for Arctic transportation systems. They argue that “modelling the societal implications of climate change requires new integrative approaches that bridge highly different methodologies between disciplines” (p. 4). Several interdisciplinary research teams have also contributed studies of climate change impacts and adaptation in mountainous regions, integrating biophysical and social factors in their analyses of hydrological changes (Carey et al., 2014; Mark et al., 2017) and incorporating western scientific and experiential or local ecological knowledge (Gurgiser et al., 2016).

For scientists, the degree of change in mountain glaciers is well established (see Figure 4.8 in Vaughan et al., 2013, p. 337), but high-resolution drone image feeds are somehow more visceral and accessible. Moreover, physical geographers presently hold a uniquely dualistic, and enviable, role as participants in the construction of dominant climate science and international climate policy discourses. As individuals, they are producers of climate system knowledge, but often invisibly as geographers within interdisciplinary settings, such as through their participation in IPCC reporting groups; and as identified geographers seated within “hard-to-define” departments, they have the institutional freedom to adapt to new lines of research. Human geographers also, particularly those who research adaptation (e.g., Adger, 2003, 2006), have been actively involved in the IPCC Working Groups II and III (Castree et al., 2014), contributing to reports examining human dimensions of climate change such as adaptation, risk, and vulnerability.

2.2 | Examining the construction and application of climate science

Beyond being themselves producers of climate science, geographers have also critically examined the production and application of climate science while foregrounding questions of justice (Randalls, 2017). Numerous scholars drawing on feminist and postcolonial traditions have critiqued the narrow, Western-based, and normative understanding of what constitutes climate knowledge. Israel and Sachs (2013) mobilize Donna Haraway's notion of the “god trick” Q4 to describe how mainstream climate science often makes claims to providing an objective (and therefore authoritative) view, “seeing everything from nowhere” (Haraway, 1988, p. 581). As a major actor in the production of climate knowledge, influential in shaping both policy and public discourse, the IPCC has been critiqued for its “techno-scientific approach” (Israel & Sachs, 2013, p. 37) that privileges an “economic and econometric approach” (Roscoe, 2016, p. 655) while marginalizing social science perspectives (Victor, 2015) and other understandings of climate. Bridging the natural/social science divide, political ecologists emphasize the importance of incorporating local knowledge of climate.

Drawing on scholarship from science and technology studies (STS) and feminist science studies, geographers have paid close and critical attention to the scientific practices central to the production of climate knowledge and analyzed the parameters, baselines, and definitions used by climate scientists, their limitations, and embedded assumptions (Hulme, 2010). Bridging human and physical geography, Demeritt (2001) draws on his experiences of Q5 working alongside climate scientists and policy makers at the Atmospheric Environmental Science of Environment Canada in order to closely examine and document the assumptions made by scientists as they produce general circulation models (GCMs). Through this close analysis, he illustrates the “analytical abstractions” these models necessarily make, and the resulting “blindness” of these global scale models to the differentiated and unequal processes of climate change and adaptation (p. 313). Informed by Donna Haraway's view of knowledge as both situated and incomplete, his point is not that GSMs are in some way false; rather, he argues that they are necessarily “partial” (p. 313). While Demeritt impressively illustrates the social and political practices that shape science production, his contribution is largely a critique, coupled with a call for more reflexive climate science and investments in building public understanding and trust of science. How we are to achieve these goals remains less clear.

Geographers have also critically analyzed the conditions under which climate knowledge is produced, illustrating how practices central to climate science are deeply embedded within social and cultural contexts. Hulme and Dessai (2008) call for recognition that climate scenarios are social objects, "designed through negotiation, not discovered through research" (p. 68) involving scientists, policy makers, communities, and other stakeholders. Lave (2012) argues that politico-economic forces shape the production of contemporary environmental knowledge, including climate change research. Borrowing the term "science regimes" from historian of science Dominic Pestre, she argues that there has been a significant shift towards a "neoliberal science regime" (p. 21), marked by the privatization and enclosure of environmental knowledge, with implications for how knowledge is produced and for whom. Larner (2011) meanwhile draws our attention to the emergence of a "wide range of globalizing 'intermediaries … consultants, communicators, public engagement experts, think tanks, journalists, social entrepreneurs and political activists" who "all play explicit roles in producing and circulating [climate change knowledge]" (p. 330), rendering it global yet simultaneously heterogeneous and unstable.

Building on geographical research examining the application of environmental expertise (typically to serve particular colonial, imperialist, or neoliberal agendas), geographers have examined the science–policy interface to interrogate how climate science is adopted by policymakers, often resulting in problematic governance goals (Boykoff, Frame, & Randalls, 2010; Pielke, 2005). Studies have sought to understand the apparent disjuncture between the nuanced conclusions drawn by climate scientists and their uptake in climate policy. Randalls (2010) traces the historical emergence of temperature targets in climate research and their adoption into climate policies, documenting how the 2°C temperature target became "a political anchor for mitigation policy" (p. 602) despite being contested within the scientific community. Further, Sanderson, O'Neill, and Tebaldi (2016) demonstrate that meeting such a target will require aggressive greenhouse gas (GHG) emission controls that are hard to square with political realities. The failure of sufficient GHG controls-based mitigation, it is argued, necessitates that either we adapt to climate change at an unprecedented pace and magnitude, or as Crutzen (2002) suggests, consider "large-scale geo-engineering projects, for instance to 'optimize' climate" (p. 23). Geo-engineering raises significant questions regarding the "geo" to be engineered, for whom, and by whom (Hulme, 2012). Conscientious geo-engineers will rely on climate and complex earth-system models to estimate the climatic consequences of their intentional modifications (also see Bellamy, Chilvers, Vaughan, & Lenton, 2012). (Recall that all models are abstractions of nature, emphasizing certain variables and physical processes). Gannon and Hulme (2018) explore the contested meanings of an ocean fertilization project to restore the estuary of a culturally and economically significant salmon fishery in British Columbia among Indigenous and non-Indigenous stakeholders. Designing models to reflect questions of local importance (such as differing conceptualizations of human–nature relations articulated by communities) is crucial if climate governance is to be at all equitable. Climate scientists and policy makers find themselves in similar debates which may provide useful insights for guiding collaboration between human and physical geographers. While the precision of climate models and overall quality of ~~the~~ climate science has improved over the past several decades, a persistent problem is reconciling fundamentally different philosophies: that of climate science (grounded in terms of hypothesis tests, substantive evidence, and statistical confidence intervals) and that of policy which requires performative certainty and encourages binary choices for decision-makers (though this latter point is contested; see Stirling, 2010).

2.3 | Pluralizing and situating climate knowledge

Geographers are well placed to examine the role of space, place, and scale (Liverman, 1999) in shaping climate knowledge, therefore countering representations of climate science as providing "a view from nowhere." Building on the discipline's contributions to understanding the geographies of science (Livingstone, 2002, 2003), geographers have drawn attention to the distinct geographies and situatedness of climate science. Mahony and Hulme (2016) use the term "epistemic geographies" to "denote the spatialities of the techno-scientific knowledges which underpin understandings of human-induced climate change" (p. 2). They demonstrate how climate knowledge, while operating as a form of "authoritative and global knowledge" (p. 8), is anchored in and shaped by particular places (such as our chosen field sites). Examining the broad literature critically examining the IPCC, Hulme and Mahony (2010) call for greater attention to "the local and situated characteristics of climate change knowledge" (p. 714), a task which they envision physical and human geographers undertaking together.

Geographers (among others) have called for the pluralization of climate knowledge and an appreciation of the alternative ways of knowing climate that are routinely marginalized in dominant climate discourse. More specifically, geographers have highlighted the value of climate research and policy that "embraces a cultural approach to climate as well as a scientific one" (Randalls, 2017, p. 11; Adger, Barnett, Brown, Marshall, & O'brien, 2013; Mahony & Hulme, 2016). In a similar effort, Thornes and McGregor (2003) call for a cultural turn in climatology: "The study of the processes of, and the interactions and feedbacks between, the physical and human components of the climate system at a variety of temporal and spatial scales" (p. 178), the possibilities of which have been recently explored by Tadaki et al. (2012) but have yet to be operationalized. Drawing our attention to practice as well as knowledge, Goldman, Daly, and Lovell (2016) use ethnographic data to illustrate how Maasai, NGO, and scientific communities "enact" droughts in multiple ways that sometimes overlap but also contradict one another. Such an approach, they argue, "dislodges the assumed superiority of scientific knowledge" (p. 32).

Acknowledging that: "What counts as 'evidence' and what passes for 'relevant knowledge' are necessarily relative to the diverse and debatable values and goals that different societies hold dear" (Castree, 2017, p. 65), research has emphasized that climate change has multiple meanings for different communities and places (Castree, 2017; Hulme, 2008; Rice, Burke, & Heynen, 2015). Drawing on Haraway's ideas of "feminine objectivity" (an understanding of knowledge as limited and situated), Israel and Sachs (2013) call for revaluation of the local environmental knowledge possessed by women, people of color, and people of the global South. Carey, Jackson, Antonello, and Rushing (2016) argue that attending to "folk glaciology" (p. 781)—alternative "ways of knowing" glaciers and cryoscapes, including local, Indigenous, and non-western knowledge—would disrupt the overt focus on Western science, producing more equitable research and, by extension, more just futures. In doing so, they make a "larger intervention into global environmental change (especially climate change) research and policy" (p. 787) that geographers might learn from.

A call to decenter western modes of climate science should not be conflated with an attempt to discredit it. Hulme (2010) observing that global scale of much climate science renders it "brittle" (p. 562) and unable to withstand scrutiny at different scales, argues that a more cosmopolitan approach to knowledge production would produce more robust climate science. Operationalizing such an approach, Rice et al. (2015) deploy ethnographic methods to examine the experiential knowledge of Southern Appalachian communities. Bringing scientists and members of the public together, the Coweeta Listening Project (CLP) is an action–research collective that seeks to "integrate social and ecological science through the coproduction and democratization of knowledge, and build useful and meaningful connections between scientists and the public" (p. 256). The project brings to light the experiential and place-based forms of knowledge that have been excluded by the North Carolina legislature and mainstream climate discourses. Similarly, Geoghegan and Leyshon's (2012) ethnography of farming practices in Cornwall, England illustrates how lay narratives of climate change discourse are drawn from embodied and experiential forms of knowledge, such as farming practices and memories of weather. Bringing these alternatives ways of knowing to light is important since: "Valuing people's everyday experiences of climate change and diverse ways of knowing climate (even when they might be scientifically imprecise) *provides the possibility for people and communities to act on climate change* through the knowledge and experience they already have" (Rice et al., 2015, p. 254, emphasis added). Given the growing concern over the lack of nonscientific institutional progress along a path illuminated by evidence (Ripple et al., 2017; Shabecoff, 1988; Union of Concerned Scientists, 1997, 2005), and demands for actionable research (Castree et al., 2014; Dilling & Lemos, 2011; McNie, 2007), geographers might operationalize these insights through collaborative research efforts.

3 | A CRITICAL PHYSICAL GEOGRAPHY APPROACH TO CLIMATE MODELING

We now turn in the final section of this paper to explicate one potential avenue for collaborative research that might better equip geographers to produce climate research that serves public interests and goals of social and environmental justice: a “Critical Physical Geography” (Lave et al., 2014) of climate modeling. As a subfield, the basis of Critical Physical Geography (CPG) is an understanding that “socio-biophysical landscapes are as much the product of unequal power relations, histories of colonialism, and racial and gender disparities as they are of hydrology, ecology, and climate change” (Lave et al., 2014, p. 3). The field aims to combine critical social theory and attention to power relations with a deep understanding of biophysical processes and natural science. For example, Blue and Brierley (2016) bring together geomorphology and philosophy to challenge conceptualizations of measuring as a way of “knowing”; identifying river morphologies, for example, may be based on “normative expectations as to how the river ‘should be’” (p. 193) with implications for the kind of features, land use practices, and people that are assumed to (not) belong. In the practices and methodologies of climate scientists who manipulate global climate model products, we see the potential for power relations shaped by colonial legacies and unequal politico-economic structures (Lave, 2015b) to be enhanced or reproduced by products meant for use by the broader scientific community, policy makers, and stakeholders.

Both human and physical geographers have expressed a keen awareness of the power dynamics and related issues of access, participation, and inclusion in climate governance and thus are well positioned to think critically about these pervade climate science and policy. Scholarship in ~~development geography,~~ political geography, and human dimensions of climate change research has illustrated how particular power relations are encoded in and reproduced by climate science. Geographers have documented how states seek to influence or intervene in the production and circulation of climate knowledge, for example by pressuring IPCC scientists to omit “damaging information” (Fogel, 2005, p. 206), or by pulling GHG emission data (O'Lear, 2016). Geographers have also explored how particular forms of knowledge are granted greater authority over others. For example, collaborations between government agencies and scientific institutions have resulted in the privileging of high-resolution digital elevation models over other ways of knowing the Arctic (King & Tadaki, 2018, p. 77). Further, while climate models have come to constitute a dominant form of climate knowledge, “relatively few countries and institutions can afford them” (Lahsen, 2005, p. 898), raising pertinent questions of accessibility.

Yet the impacts of structures of power (such as capitalism, colonialism, and patriarchy) currently feature less heavily, if at all, in physical geographers' analyses of climate change impacts (Carey et al., 2016). A CPG approach to modeling would not stop short of critically analyzing the social contexts in which climate models are produced; it would also seek to inform modelers how to incorporate these insights into the development of the models and analyses of their results. For example, integrating CPG perspectives may prove to be a valuable contribution to the general utility of modeled products, like downscaled climate models. Downscaling climate models demands choices and expertise during phases of production and interpretation, respectively, which remain specialized. Also embedded in the practice of downscaling are the choices that researchers make, based on commitments of time and resources like computing power, as well as fundamental decisions like what region and over what period to simulate, which privilege some users over others. When faced with an arbitrary choice on geographic scaling or grid-cell positioning, a CPG-informed modeler may expand a boundary, or center a pixel, to improve the CPG-informed representation of an informationally underserved location or community. To this end, a CPG of modeling should start with the practical goals of improving modelers' senses of local scale and accessibility, and progress towards a distribution of expertise and shared capacity building.

Here, “local scale” means adjusting the products of academic analysis to be appropriate for lay consumption. This is just as much about spatially downscaling climate model projections as explaining the limitations of downscaling, and climate models in general, but it is also about generating information of relevance to stakeholders, on terms declared by the stakeholders themselves. This process would necessarily involve drawing on the insights of political ecology and development geography to incorporate critical understandings of who constitutes a “stakeholder” and to more meaningfully involve individuals and communities in the process of designing models. For instance, soil is just as important to crops as water and light, and precise information on root-zone soil profiles is impossible from remote platforms; pedologic data (e.g., soil composition and horizons, organic carbon content, salinity, and water-table depth) as well as local knowledge (e.g., pests, best microbial environments, land tenure, parochial rights, and practices) can only come from the ground.[1] We intend scale to include bilateral academic–community engagement: using local informants to contribute to the recursive generation of “locally scaled” products; improving geospatial and cultural coverage of locally scaled products from state-of-the-art climate models. Ideally, a CPG of modeling should take alternative, nonstandard patterns of system organization seriously. This means prioritizing models that are shareable across different platforms, open-sourced, and mutable by design. Although practically difficult for global climate models, whose architecture is constrained by performance considerations, other modelers see value in this approach (Cai, Judd, & Lontzek, 2012; Moore et al., 2018; Phillips, Deser, & Fasullo, 2014).

We use “accessibility” to refer to ready access to state-of-the-art model outputs, analytics, and data, and adjusting the products of academic analysis to be appropriate for lay consumption; that is, to be of practical use by those stakeholders whose environments the models abstract. As an illustration of what we mean by accessibility, we use flood risks. Global flood risks are increasing due to climate change and the relatively high rates of population growth in at-risk flood zones (Jongman, Ward, & Aerts, 2012). To keep pace with the rate of vulnerability, Willner, Levermann, Zhao, and Frieler (2018) found that the American Midwest and Northern Europe will need to adapt rapidly, but even speedier adaptation must occur throughout sub-Saharan Africa and the Indian Subcontinent, from Rajasthan across the piedmont of the Himalaya to the Bengal coast, and the islands of Southeast Asia. In spite of anticipated growth of population and wealth, bearing the costs of adaptation will be complicated in Asia and Africa. This is because their urban centers, engines of growth in both cases, are located in the highest risk flood zones. Economic exposure will be greatest in Asia, 370% increase by 2050 over 2010 levels, and then in Sub-Saharan and North Africa (Jongman et al., 2012, p. 832).

Analyses such as these are valuable to large aid agencies and makers of public policy in governments, but how can they be made more practically useful for those who will experience floodin[illegible] the house-builders, the field-sowers, the city-planners whose decisions will set the parameters of future adaptation choices? Part of the solution is technological, something hydrologists have been working on for some time (Famiglietti, Murdoch, Lakshmi, & Hooper, 2010). High-resolution flood hazard maps are increasingly becoming available, driven by a nexus of improved computation, applied expertise, and data from remote sensor platforms (Dottori et al., 2016; Wood et al., 2011). The Global Flood Awareness System (GloFAS) is a web-based platform which makes freely available state-of-the-art hydrological and flood hazard mapping at high-resolution, offering global flood alerts with up to 45 days of lead-time (Alfieri et al., 2013). In short, privileged access to state-of-the-art modeled products advantages the privileged party. It is easy to see how the immediate market value of land may underrepresent the future value, informed by modeled projections, and how access to higher quality projections mitigates risk, increases negotiating power, and adds a perspective of future conditions to one party, while that of the other is rooted in past conditions. As a framework for circumventing this, GloFAS is a reasonable target but not an end in itself: accessibility also means translating the specialist language of modelers to that of lay users.

Finally, we imagine that CPG-informed climate models could offer superior predictors of the totality of the consequences of policy choices and therefore more reliable sources of information for policy makers. For instance, over time, the policy options guiding emissions scenarios narrow. In order to have any chance of meeting the 2°C Paris target, drastic cuts to emissions are likely insufficient, and strategies to remove carbon from the atmosphere, or negative emissions technologies (NETs), are required.[2] One approach, termed afforestation and reforestation (AR), is to convert large tracts of cropland to forest, or conserve established forest in place, thereby “locking up” atmospheric carbon in woody biomass and untilled soils. In practice, this will require significant increases in cropland productivity and land use efficiency in combination with vastly improved forest management. But as Smith et al. (2016) point out, no proposed NET is a panacea: for AR to work as a NET, for example, vast tracts of productive agricultural land will likely need to be converted to forest, in spite of population growth and new demand for food crops, including meat. The likely future market value of a preserved tract of old-growth forest is a tractable problem for a modeler (though not an easy one); the cultural injury of its eternal loss, like the once extensive cedar forests of Lebanon, is not. These considerations are especially pertinent at present, particularly in the United States where the (now former) Environmental Protection Agency (EPA) director, Scott Pruitt, publicly speculates that global warming may bring about the "ideal surface temperature" for humans (Ramahlo, 2018). (Consider, for instance, that model projections were ideally suited to the task of predicting an engineered global climate whose management would be aimed at optimizing growing seasons over the US corn-belt). We expect CPG to inform the perspective of analysts engaged in such an evaluation, as well as deepen the bench of internationally influential experts (e.g., for an analysis of social networks of IPCC mitigation experts, see Corbera, Calvet-Mir, Hughes, & Paterson, 2016).

For example, analysts might work with local communities in order to incorporate alternative understandings of "value" into analyses, thereby broadening the definition of "value" as it has been defined by environmental policy emerging from the global North, which has systematically underrepresented Indigenous and non-Western voices. To achieve this, a CPG of modeling might learn from existing examples of radical participatory modes of research deployed in the production of environmental knowledge. For example, Lane et al. (2011) deploy a radical participatory framework to research flood risk management wherein local community members contributed not only to identifying research questions and aims, but also to conceptualizing models. In doing so, they also problematized the dichotomy between universal, expert knowledge and local, lay knowledge. Also instructive is Whitman, Pain, and Milledge's (2015) use of participatory action research to examine farm slurry pollution in collaboration with a UK Rivers Trust. Reflecting on the process of coproducing not only knowledge, but also the research design itself, they argue "if the scientific method is removed from its traditional hierarchy of expertise and scientists work with others in collaboration, research may become more democratic and innovative, but by no means unscientific" (Whitman et al., 2015, p. 635). Such an approach is radical because it requires that we face the deeply political nature of climate change head on and resist claims that politics and science exist in separation.

Geographers might draw on the insights of these radical participatory approaches, creating research collaborations between geographers and communities with the highest stake in the research, which value and incorporate each of their distinct ways of knowing climate into the process of designing and applying models. As Ford, Vanderbilt, and Berrang-Ford (2012) argue with respect to Indigenous communities, those most at risk from climate change need to be allocated a place in climate research that is "commensurate with their stake in the climate change issue" (p. 211). Yeh (2016) echoes this sentiment, arguing that to deny the validity of local knowledge is to "perpetuate the ultimately colonial practice of allowing unacknowledged (Western) epistemologies to masquerade as universal ones" (p. 3). More closely engaging with such communities—as coresearchers and producers of knowledge rather than simply as "stakeholders"—thus holds the potential to democratize climate science by making space for "more democratic debate and argument based in a wider discussion of values, norms, and experiences" (Rice et al., 2015, p. 254) relating to climate and by incorporating plural ways of valuing and knowing the environment. As Castree et al. (2014) write: "different conceptions of needs may frame plural notions about 'appropriate solutions' and 'relevant evidence'" (p. 763). Following this, a CPG approach to climate modeling would be sensitive to the full range of "values, means and ends that together might inform deliberations and decisions about future societal trajectories" (p. 763). In this way, geographers might generate more socially relevant climate research that better serves the interests of communities "at the sharp end" (Whitman et al., 2015, p. 623) of climate change. Furthermore, integrating local ecological knowledge and western climate science holds the potential to advance our understandings of climate change since "neither alone is a panacea for understanding and adapting to climate change" (Klein et al., 2014, p. 142). This is illustrated by Klein et al. (2014) who find that the personal observations of Tibetan herders offer important insights into climate and ecological change in an area where western scientific data is sparse.

4 | CONCLUSION

If climate-related research is to better serves goals of social and environmental justice, social and natural scientists must do more to meaningfully engage with one another. Geographers are well positioned to play a leading role in guiding this interdisciplinary turn. To date, human and physical geographers have made important contributions to the study of climate change: participating in the production of climate science; providing critical insights into the production and construction of climate science; and making a convincing case for engaging with differently situated ways of knowing climate. While STS and feminist perspectives on climate science have brought to light important issues regarding objectivity, power relations, and justice, these approaches have often fallen short of providing practical alternatives to actually doing climate science. By comparison, scholarship in CPG aims to operationalize critical perspectives in geography, bringing them to bear on research praxis. Drawing on recent scholarship on CPG to discuss climate modeling, we have outlined just one of many potential avenues through which to undertake such work. Collaboration is not an easy undertaking; it demands negotiating different academic languages, training cultures, models of knowledge production, and bureaucratic barriers (Harrison et al., 2004; Iveson & Neave, 2010; Lave, Biermann, & Lane, 2018; Whitman et al., 2015). Collaborating also requires that we remain open to experiencing the failures of our efforts. Nonetheless, we believe that geography and climate research stand to gain enormously from our efforts to talk across the divide.

ENDNOTES

[1] See Lansing and Kremer (1993) for a discussion of the emergence of traditional practices in Bali, Indonesia, which emerged from local plant phenologies and pathologies and prevented large-scale outbreaks of pests.

[2] For detail of NETs beyond afforestation and reforestation, mentioned in this article, see the review by Smith et al. (2016) in *Nature Climate Change*.

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