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JOHN T. ABATZOGLOU* AND LAUREN E. PARKER**

ABSTRACT

Global climate change is a topic that has garnered much attention in recent decades from both scientific and policy arenas. This article provides a synopsis of the current state of the science, and reviews the challenges of climate change in scientific, policy, and public arenas. Secondly, we provide a review of observed changes in global climate with a more detailed view of climatic changes and their subsequent impacts on terrestrial systems across the American West. We specifically highlight studies published since 2014 that provide current insights to the collection of science on climate change; its impacts on the American West; and complement national and international assessment reports.

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I. INTRODUCTION: THE NATURE OF CLIMATE SCIENCE IN THE ANTHOPOCENE

During an era of mounting evidence for a warming planet, scientific interest in global climate change has grown alongside skepticism in the topic—and science more broadly—among the public in the United States.[1] Political interest and resultant polarization of climate change in the US has multiple origins. Among those most prevalent are the perceived economic impacts of enacting policies and regulation on energy use and development to mitigate climate change.[2] Science needs to be decoupled from politics to effectively and objectively function. This occurs in the

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1. *See, e.g.*, Stuart Capstick et al., *International Trends in Public Perceptions of Climate Change Over the Past Quarter Century*, 6 WIREs : CLIMATE CHANGE, 35, 35 (2015); Jason T. Carmichael et al., *The Great Divide: Understanding the Role of Media and Other Drivers of the Partisan Divide in Public Concern Over Climate Change in the USA, 2001–2014*, 2017 CLIMATIC CHANGE, 599, 599.

2. P. Sol Hart et al., *Public Attention to Science and Political News and Support for Climate Change Mitigation*, 5 NATURE CLIMATE CHANGE 541, 544 (2015).

scientific domain via the scientific method. By contrast, dialogs on the topic of climate change in the public domain invariably intertwine science, politics, and perceptions. We provide a basis for divergent trajectories of scientific knowledge and public perceptions of climate change by first discussing the nature of climate science and then comparing barriers for progress on climate change in the scientific, policy, and public spheres.

Climate science is similar to other sciences in that it relies on observations, theory, and experiments. Climate science differs from traditional sciences like biology and chemistry in two important ways. First, climate science is inherently interdisciplinary as the study of the climate system draws on the fields of physics, chemistry, and biology, as well as how humans interact with this system. Secondly, as the study object is Earth, performing scientific experiments necessitates employing models. Climate science uses a rich collection of observational data compiled from ocean buoys, weather balloons, and satellites, as well as data from climate system models. These models, called global climate models, are governed by the laws of physics and are numerical representations of the interactions between the atmosphere, ocean, biosphere, and other aspects of the Earth system. While models are imperfect, they provide a reputable means to test scientific theory and provide information to help guide decision-making.

The concept that global warming is a response to increased levels of atmospheric carbon has existed for well over a century.[3] Physicist Svante Arrhenius was the first to calculate the amount of warming induced by increasing atmospheric carbon dioxide concentrations (CO_2) in the late nineteenth century.[4] In the 1970s Manabe and Wetherald (1975) developed the first numerical climate models to estimate how the planet would warm if CO_2 doubled.[5] The state of the science suggests that there is irrefutable evidence that the planet has warmed over the past century and that human activity is the preeminent cause of the warming.[6]

Although science is intended to help inform policy and countless studies suggest substantial impacts to humanity and natural resources from climate change,[7] national and international policies have been slow to progress. Climate change policies have lagged the best available science in both adaptation and mitigation approaches. Climate adaptation approaches are intended to minimize detrimental impacts and capitalize on potential opportunities due to local-to-regional climate change, as well as to develop more climate-ready and climate-resilient landscape and communities.[8] By contrast, climate mitigation approaches are primarily aimed

3. Spencer Weart, *The Discovery of Global Warming [Excerpt]*, SCIENTIFIC AM. (Aug. 17, 2012), https://www.scientificamerican.com/article/discovery-of-global-warming/.

4. Henning Rodhe et al., *Svante Arrhenius and the Greenhouse Effect*, 26 AMBIO 2, 2 (1997).

5. Syukuro Manabe & Richard T. Wetherald, *The Effects of Doubling the CO2 Concentration on the Climate of a General Circulation Model*, 32 J. ATMOSPHERIC SCI., 3, 3 (1975).

6. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS 11 (2013).

7. *See, e.g.*, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2014: IMPACTS, ADAPTATION, AND VULNERABILITY 4 (2014) [hereinafter CLIMATE CHANGE 2014] ; *See also* U.S. GLOBAL CHANGE RES. PROGRAM, CLIMATE CHANGE IMPACTS IN THE UNITED STATES 7–18 (2014) [hereinafter U.S. GLOBAL CHANGE RES. PROGRAM].

8. *See* CLIMATE CHANGE 2014, *supra* note 7.

at reducing the amount of human-caused greenhouse gas emissions.[9] The scale and scope of adaptation and mitigation clearly differ. Adaptation is done locally to alleviate climate impacts including, but not exclusive to, those expected with climate change.[10] Whereas mitigation efforts are a collective effort aimed at reducing the magnitude of global human-caused climate change.[11]

The initial efforts towards an international agreement on climate change mitigation began in 1990 with the United Nations Framework Convention on Climate Change on the heels of the largely successful Montreal Protocol.[12] The Montreal Protocol was an international policy to eliminate the use of chlorofluorocarbons as science had implicated this entirely man-made gas as the culprit behind the decline in stratospheric ozone concentrations.[13] Unlike the ozone hole problem, which required the elimination of a gas used by a handful of industries, solutions to human-caused climate change are complicated by the fact that a majority of the world's economy over the latter part of the twentieth century and early twenty-first century has been dependent on carbon-based energy.[14] The 1997 Kyoto Protocol attempted to establish rules for reducing carbon emissions on a country-by-country basis, imposing larger reductions on some developed countries while allowing developing countries to increase their emissions in an effort to not limit economic growth.[15] The Kyoto Protocol largely failed as countries like the US chose not to ratify the agreement. Further, other countries failed to meet their goals—or met their goals but outsourced their carbon emissions—thereby contributing to the rapid increase in emissions seen in developing countries like China over the past twenty years.[16]

Individual countries and states (e.g., California) have implemented largely successful policies to curtail carbon-based energy sources and proactively invest in sectors of the economy that can capitalize on developing non-carbon based energy sources.[17] In late 2015, the Paris Agreement tasked countries to set their own trajectories—defined as nationally determined contributions (NDC)—to limit the amount of warming globally to no more than 2°C above pre-industrial conditions; and to support developing countries in addressing climate change impacts through

9. *See* CLIMATE CHANGE 2014, *supra* note 7; *See generally* U.S. GLOBAL CHANGE RES. PROGRAM *supra* note 7.

10. *See* CLIMATE CHANGE 2014, *supra* note 7; *See also* U.S. GLOBAL CHANGE RES. PROGRAM *supra* note 7.

11. *See* CLIMATE CHANGE 2014, *supra* note 7; *See also* U.S. GLOBAL CHANGE RES. PROGRAM *supra* note 7.

12. *See* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE: THE IPCC SCIENTIFIC ASSESSMENT (1990).

13. Guus J. M. Velders, et al., *The Importance of the Montreal Protocol in Protecting Climate*, 104 PROC. NAT'L ACAD. SCI. 4814, 4814 (2007).

14. Paul J. Crutzen, *The "Anthropocene," in* EARTH SYSTEM SCIENCE IN THE ANTHROPOCENE 13 (Eckart Ehlers & Thomas Kraft eds., 2006).

15. *See generally* Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec. 11, 1997, 2303 U.N.T.S. 30822.

16. Kuishuang Feng et al., *Outsourcing CO2 Within China*, 110 PROC. NAT'L ACAD. SCI. 11654, 11654 (2013).

17. Louise W. Bedsworth & Ellen Hanak, *Climate Policy at the Local Level: Insights from California,* 23 GLOBAL ENVTL. CHANGE 664 (2013).

financial support.[18] The NDCs themselves do not guarantee limiting warming by 2°C, however, the ability to curtail warming could be reached if countries used the Paris Agreement as a springboard to ratchet up mitigation efforts progressively over the twenty-first century.[19] While the Paris Agreement is ambitious like the Kyoto Protocol, there is optimism that the bottom-up approach to emission reductions of the Paris Agreement may be more effective than the Kyoto Protocol's top-down approach.[20] As of 2017, the US under the Trump administration began the process of withdrawing from the agreement, citing the detrimental economic impacts the US would face if abiding by the NDCs.[21]

Public perceptions on the topic of climate change in the US generally remain lukewarm for a variety of reasons including educational attainment, local rates of observed warming, and political leanings.[22] Climate change is often ranked near the bottom of concerns that US citizens face and thus is viewed as a less pressing issue compared to more immediate concerns such as the economy and war; further, many people do not see climate change as a direct, personal threat.[23] This may be linked to the multi-generational timescales of how climate change information is presented, mistrust of information sources, or misunderstanding in climate science, as well as the overall scale of the problem relative to other more localized concerns. Finally, climate science is a topic that most are never formally introduced to in an educational setting, leaving the public with insufficient tools to assess the quality of information on a topic that is typically filtered through the media or politicians.

Given the public discourse and perception surrounding the topic of climate change, it is instructive to briefly review the fundamental nature of science. Rarely does science produce absolute facts that are proved without a doubt. Instead, science is a meant to be open for revision and reinterpretation through the introduction of credible new evidence that advances scientific knowledge. Discourse in science often occurs in peer-reviewed literature using principles guided by the scientific method. By nature, scientists are skeptical, critically examine details, and strive to advance new theories and discoveries, including those that challenge the status quo. It is healthy for scientific fields to be challenged by new ideas or theories as they may promote advances in scientific knowledge. However, despite alternative hypotheses to recent changes in climate (e.g., solar cycles, cosmic rays, natural cycles), none has refuted human activities as the leading driver of observed climate

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18. *See* Steven K. Rose et al., *The Paris Agreement and Next Steps in Limiting Global Warming*, 142 CLIMATIC CHANGE 255, 256 (2017).

19. *Id.*

20. Jennifer Morgan & Eliza Northrop, Opinion, *Will the Paris Agreement Accelerate the Pace of Change*, 8 WIRES: CLIMATE CHANGE 1, 5 (2017).

21. Michael D. Shear, *Trump Will Withdraw U.S. From Paris Climate Agreement,* N.Y. TIMES (June 1, 2017), https://www.nytimes.com/2017/06/01/climate/trump-paris-climate-agreement.html.

22. Tien Ming Lee et al., *Predictors of Public Climate Change Awareness and Risk Perception Around the World*, 5 NATURE CLIMATE CHANGE 1014, 1016–17 (2015); Peter D Howe et al., *Geographic Variation in Opinions on Climate Change at State and Local Scales in the USA*, 5 NATURE CLIMATE CHANGE 596, 596 (2015).

23. CLIMATE CHANGE IN THE AMERICAN MIND: AMERICANS' GLOBAL WARMING BELIEFS AND ATTITUDES IN APRIL 2013 8–13 (Yale Project on Climate Change Communication et al., 2013).

change.[24] While nearly all peer-reviewed studies acknowledge human-caused factors in recent changes in global climate,[25] several outstanding scientific questions remain in the field of climate science.

II. OBSERVED CHANGES IN CLIMATE: FROM THE GLOBE TO THE AMERICAN WEST

Global CO_2 concentrations have been actively measured since 1958 and can be reconstructed using a variety of proxy collection methods such as ancient air preserved in ice cores.[26] Prior to the industrial revolution, atmospheric CO_2 oscillated between 180-280 parts per million (ppm) during glacial and interglacial periods over the past several hundred thousand years.[27] As of March 2015, CO_2 at Mauna Loa was greater than 400 ppm, over 45% higher than levels from 150 years ago.[28] There are many ways that carbon is sent into the atmosphere, including respiration from vegetation, outgassing from the ocean, and volcanic emissions.[29] Likewise, carbon is removed from the atmosphere through processes including vegetative productivity (i.e., photosynthesis) and the ocean.[30] Since 1850 human activity has sent 550 gigatons (Gt) of carbon into the atmosphere through the burning of fossil fuels and land use changes such as deforestation.[31] This has disrupted the homeostasis of atmospheric carbon fluxes that had maintained a remarkably stable climate for the past 10,000 years.[32] Over the past decade, about 45% of the man-made carbon emitted to the atmosphere (approximately 10 Gt per year) has remained there, with the rest being taken up by the terrestrial biosphere and the oceans.[33] The fact that vegetation and oceans have been net sinks for the anthropogenic carbon burden highlight an Earth system process that mitigates the rate of climate change. Yet, the uptick of CO_2 by the ocean has resulted in a slight acidification of the global oceans with detrimental impacts to some species.[34]

Global mean surface temperatures have increased approximately 1°C since the 1700s, with most of the increase observed since 1970.[35] Increases in surface air

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24. John Cook et al., *Consensus on Consensus: A Synthesis of Consensus Estimates on Human-Caused Global Warming*, 11 ENVTL. RES. LETTERS 1, 2–5 (2016).
25. *Id.* at 2.
26. H. Friedli et al., *Ice Core Record of the 13C/12C Ratio of Atmospheric CO2 in the Past Two Centuries*, 324 NATURE 237, 237–38 (1986); Dieter Lüthi et al., *High-Resolution Carbon Dioxide Concentration Record 650,000-800,000 Years Before Present*, 453 NATURE 379 (2008).
27. *See* F. Joos, *The Atmospheric Carbon Dioxide Perturbation,* 27 EUROPHYSICS NEWS 213, 217 (1996).
28. C. Le Quéré et al., *Global Carbon Budget 2015*, 7 EARTH SYS. SCI. DATA 349, 351 (2015).
29. *See id.*
30. Tim White, *Carbon Cycle and Atmospheric CO2*, PENN ST. C. EARTH & MIN. SCI. (2017), https://www.e-education.psu.edu/earth530/content/l3_p4.html.
31. Le Quéré et al., *supra* note 28, at 377.
32. *See* Shaun A. Marcott et al., *A Reconstruction of Regional and Global Temperature for the Past 11,300 Years*, 339 SCIENCE 1198 (2013).
33. *See* Le Quéré, *supra* note 28, at 351.
34. Scott Doney, *Oceans of Acid: How Fossil Fuels Could Destroy Marine Ecosystems*, NOVA NEXT (Feb. 12, 2014), http://www.pbs.org/wgbh/nova/next/earth/ocean-acidification/.
35. *See* Ed Hawkins et al., *Estimating Changes in Global Temperature Since the Preindustrial Period*, 2017 BULL. AM. METEOROLGICAL SOC'Y 1841.

temperature have primarily tracked with climate model projections,[36] with seventeen of the eighteen warmest years in the instrumental record from 1850-2017 occurring since 2000.[37] That said, the increase in global mean surface temperature has not been monotonic but rather embedded within natural interannual to decadal climate variability that can amplify or moderate the pace of warming. For example, the so-called warming hiatus evident in global temperature records from 1998-2012 corresponds to a period where the rate of observed warming was less than that seen over the previous fifty years and less than that projected by climate models.[38] Scientific efforts to reconcile the subdued warming rate have suggested several factors that may have contributed to the hiatus, including issues with observational records, natural climate variability, and the lowest period of solar activity in a half-century.[39] Another possibility remains that the climate sensitivity—defined as the amount of warming globally due to a doubling of atmospheric CO2—is overestimated by climate models, which may render future climate projections less credible.[40] Although this is an active field of research, the latter appears unlikely given estimates of climate sensitivity compiled from paleoclimatic records, modern observations, and several modeling experiments.[41]

Other observational indicators of a warming planet include increases in sea level and ocean acidification, and declines in sea ice and glaciers. For example, the rate of sea level rise from 1990-2012 of 3.1 mm/yr was three times that from 1900-1990.[42] Other indicators have changed at a rate faster than many climate simulations projected. For example, the extent of Arctic sea ice has dwindled rapidly over the past couple of decades at a rate exceeding most climate model projections.[43] The magnitude of decline in Arctic sea ice in recent decades may be a consequence of an alignment of natural variability with man-made climate change.[44] Alternatively, climate models may systematically under predict the sensitivity of the Arctic to warming, which could have further ramifications for global climate.

Similar to the documented warming of global average mean temperature, air temperature across the American West has warmed over the past century.[45] From 1895-2016 the western eleven states of the contiguous US have seen an increase in

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36. Ed Hawkins & Rowan Sutton, *Connecting Climate Model Projections of Global Temperature Change with the Real World*, 2016 BULL. AM. METEOROLOGICAL SOC'Y 963, 977.

37. *See State of the Climate in 2016*, 98 BULL. AM. METEOROLOGICAL SOC'Y 1 (2017).

38. *See generally* Hawkins & Sutton, *supra* note 36.

39. Thomas R. Karl et al., *Possible Artifacts of Data Biases in the Recent Global Surface Warming Hiatus*, 348 SCIENCE 1469, 1469–70 (2015); John C. Fyfe et al., *Making Sense of the Early-2000s Warming Slowdown*, 6 NATURE CLIMATE CHANGE 224, 224 (2016).

40. Nicholas Lewis & Judith A. Curry, *The Implications for Climate Sensitivity of AR5 Forcing and Heat Uptake Estimates*, 45 CLIMATE DYNAMICS 1009, 1009–10 (2015).

41. Mark Richardson et al., *Reconciled Climate Response Estimates from Climate Models and the Energy Budget of Earth*, 6 NATURE CLIMATE CHANGE 931, 931 (2016).

42. *See* Sönke Dangendorf et al., *Reassessment of 20th Century Global Mean Sea Level Rise*, 114 PROC. NAT'L ACAD. SCI. 5946, 5946–47 (2017).

43. James E. Overland & Muyin Wang, *When Will the Summer Arctic be Nearly Sea Ice Free?*, 40 GEOPHYSICAL RES. LETTERS 2097, 2097 (2013).

44. Neil C. Swart et al., *Commentary: Influence of Internal Variability on Arctic Sea-Ice Trends*, 5 NATURE CLIMATE CHANGE 86, 86-87 (2015).

45. KELLY T. REDMOND & JOHN T. ABATZOGLOU, CLIMATE CHANGE IN NORTH AMERICA ch. 2, p. 53–94 (George Ohring ed., 2014); U.S. GLOBAL CHANGE RES. PROGRAM, *supra* note 7, at 419–20.

air temperature of approximately 1.3°C with most of the warming occurring since the 1970s, and four of the five warmest years occurring since 2010.[46] The rate of warming has varied geographically, seasonally, and diurnally. While these asymmetries in warming trends have not been fully explained, changes in land-use,[47] internal climate variability,[48] atmospheric dynamics, and land-surface feedbacks[49] have been implicated in the tapestry of warming trends across the landscape.

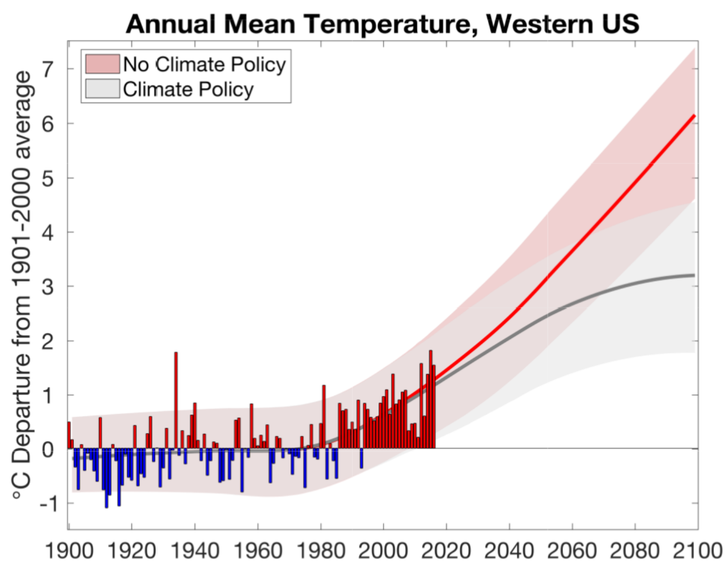

Figure 1: Annual mean temperature anomalies averaged across the western 11 states of the contiguous United States expressed as a departure from twentieth century average. Observed data acquired from the National Center for Environmental Information are depicted by the bars. Climate model projections from 20 different global climate models from the Fifth phase of the Coupled Model Intercomparison Project for two different scenarios, representative concentration pathway (RCP) 8.5 herein referred to as the "No Climate Policy" scenario, and RCP 4.5 referred to as the "Climate Policy" scenario. Plotted in solid red and grey lines are the multi-model mean projected changes using a loess smoothing filter, whereas the shading shows the smoothed range of annual data from the models.

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46. *See infra* Figure 1.
47. Benjamin I. Cook et al., *Irrigation as an Historical Climate Forcing*, 44 CLIMATE DYNAMICS 1715, 1723 (2015).
48. John T. Abatzoglou et al., *Seasonal Climate Variability and Change in the Pacific Northwest of the United States*, 27 J. CLIMATE 2125, 2126 (2014).
49. N. Pepin et al., *Elevation-Dependent Warming in Mountain Regions of the World*, 5 NATURE CLIMATE CHANGE 424, 425 (2015).

Much of the American West receives the bulk of its annual precipitation during the cool season, with the largest amounts falling in westward-facing higher elevation regions due to the orographic ascent of westerly flow coming from the Pacific.[50] Whereas water storage exists in groundwater or in man-made reservoirs, particularly in places like California, mountain snowpack is the most important source of water storage, and water from snowfall currently constitutes approximately 53% of runoff across the region.[51] This natural storage of winter precipitation is released as snowmelt runoff in spring and early summer and is a critical source of water that is available during the drier summer months.[52] Runoff provides benefits to both natural systems (e.g., cool water for aquatic species) and managed landscapes (e.g., irrigation). However, the spring snowpack has declined substantially across the American West over the past half-century,[53] concomitant with rising temperatures. Declines in spring snowpack and an earlier pulse of spring snowmelt are widely observed across the region, irrespective of changes in precipitation, which are regionally and temporally disparate.[54] The consequences of reduced spring snowpack are declines in snowmelt and runoff in late spring and summer when water availability is limited.[55] This has resulted in widespread declines in the fraction of annual runoff occurring during the summer months, as well as lower minimum flows.[56] There is some evidence that suggests that human-caused climate change has increased the intensity of drought events as warming increases evapotranspiration demands.[57] However, observational and paleoclimatic records also suggest that interannual-to-decadal variability in drought has been primarily associated with precipitation deficits, which to date have not been well linked to man-made climate change in the region.[58]

Climate impacts have also been realized across ecosystems of the American West. Over the past several decades concomitant with substantial warming have been widespread documented increases in wildfire activity,[59] insect outbreaks,[60]

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50. *See generally* Dongyue Li et al., *How Much Runoff Originates as Snow in the Western United States, and How Will That Change in the Future?*, 44 GEOPHYSICAL RES. LETTERS 6163 (2017).

51. *Id.* at 6167.

52. *Id.*

53. Philip W. Mote et al., *Perspectives on the Causes of Exceptionally Low 2015 Snowpack in the Western United States*, 43 GEOPHYSICAL RES. LETTERS 10,980, 10,987 (2016).

54. Abatzoglou et al., *supra* note 48.

55. *See* Patrick R. Kormos et al., *Trends and Sensitivities of Low Streamflow Extremes to Discharge Timing and Magnitude in Pacific Northwest Mountain Streams*, 52 WATER RESOURCES RES. 4990 (2016).

56. *Id.* at 4991.

57. *See* A. Park Williams et al., *Contribution of Anthropogenic Warming to California Drought During 2012–2014*, 42 GEOPHYSICAL RES. LETTERS 6819 (2015); *See* Noah S. Diffenbaugh et al., *Anthropogenic Warming Has Increased Drought Risk in California*, 112 PROC. NAT'L ACAD. SCI. 3931 (2015).

58. Diffenbaugh et al., *supra* note at 57, at 3934.

59. Anthony LeRoy Westerling, *Increasing Western US Forest Wildfire Activity: Sensitivity to Changes in the Timing of Spring*, 371 PHIL. TRANSACTIONS ROYAL SOC'Y B 1, 9 (2016).

60. Jeffrey A. Hicke et al., *Carbon Stocks of Trees Killed by Bark Beetles and Wildfire in the Western United States*, 8 ENVTL. RES. LETTERS 1, 2 (2013).

and tree mortality,[61] which have collectively impacted carbon storage and emissions from western forests.[62] While factors exogenous to climate such as the legacy of fire suppression and land management have fostered some of the changes,[63] increased temperature, aridity, and fire danger[64]—a portion of which have been tied to human-caused climate change—have likely contributed to increases in such ecological disturbances in forested regions.[65] The advancement in the timing of snowmelt juxtaposed with warmer summer temperatures has additionally impacted cold-water fisheries across much of the northwestern US,[66] and declines in mountain snowpack have threatened habitat for snow obligate and heat intolerant species who reside in the Mountain West such as the wolverine and the American pika.[67]

III. THE FUTURE: CLIMATE PROJECTIONS AND IMPACTS FOR THE AMERICAN WEST

The western US is projected to warm substantially over the next century irrespective of what climate policies are enacted. Under a business as usual scenario where the globe continues to rely primarily on carbon-based energy and no global climate policy is enacted, the American West is projected to warm 4-7°C over twentieth century temperatures by 2100.[68] By contrast, a future where policies are enacted to globally curtail greenhouse gas emissions in the vein of the Paris Agreement may reduce the magnitude of warming by half.[69] Geographic and seasonal variability in the rate of warming is evident, with the interior portions of the western US warming more than coastal locales, areas with reductions in seasonal snow cover incurring additional warming,[70] and summer warming faster than other seasons.[71]

Models tend to favor a slight increase in annual precipitation totals for much of the American West by the mid-to-late-twenty-first century.[72] However, model

61. William R. L. Anderegg et al., *Tree Mortality From Drought, Insects, and Their Interactions in a Changing Climate*, 208 NEW PHYTOLOGIST 674, 675 (2015).

62. Logan T. Berner et al., *Tree Mortality From Fires, Bark Beetles, and Timber Harvest During a Hot and Dry Decade in the Western United States (2003–2012)*, 12 ENVTL. RES. LETTERS 1, 2 (2017).

63. Jennifer R. Marlon et al., *Long-Term Perspective on Wildfires in the Western USA*, 109 PROC. NAT'L ACAD. SCI. E535, E536 (2012).

64. W. Matt Jolly et al., *Climate-Induced Variations in Global Wildfire Danger From 1979 to 2013*, 6 NATURE COMM. 1, 2 (2015).

65. A. Park Williams et al., *Temperature as a Potent Driver of Regional Forest Drought Stress and Tree Mortality*, 3 NATURE CLIMATE CHANGE 292, 293 (2013); John T. Abatzoglou & A. Park Williams, *Impact of Anthropogenic Climate Change on Wildfire Across Western US Forests*, 113 PROC. NAT'L ACAD. SCI. 11770, 11772 (2016).

66. D. J. Isaak et al., *Climate Change Effects on Stream and River Temperatures Across the Northwest US From 1980–2009 and Implications for Salmonid Fishes*, 113 CLIMATIC CHANGE 499, 501 (2012).

67. J. P. Copeland et al., *The Bioclimatic Envelope of the Wolverine (Gulo gulo): Do Climatic Constraints Limit Its Geographic Distribution?*, 88 CAN. J. ZOOLOGY 233, 237 (2010).

68. *See supra* Figure 1.

69. *See supra* Figure 1.

70. David E. Rupp et al., *Seasonal Spatial Patterns of Projected Anthropogenic Warming in Complex Terrain: A Modeling Study of the Western US*, 48 CLIMATE DYNAMICS 2191, 2192 (2016).

71. David E. Rupp et al., *Projections of 21st Century Climate of the Columbia River Basin.* 49 CLIMATE DYNAMICS 1783, 1797 (2017).

72. *Id.* at 1783.

changes are generally small compared to interannual-to-decadal precipitation variability and there is a lack of agreement among models.[73] When globally, models and paleoclimatic records averaged suggests that a warmer world is a wetter world due to greater water holding capacity of the atmosphere and enhanced evaporation rates.[74] However, realized changes in regional and seasonal precipitation patterns in the mid-latitudes will be dictated by changes in atmospheric circulation.[75] Declines in global precipitation under climate change scenarios are primarily confined to regions near the equatorward flanks of the jet stream,[76] including portions of the southwestern US. Complementary to changes in overall precipitation, models project a more robust increase in heavy precipitation events[77] for much of the western US, and an increase in the intensity of atmospheric river events,[78] which contribute substantially to western water resources while also posing flooding hazards.

Continued recession of mountain snowpack in the West is expected over the twenty-first century.[79] April 1 mountain snowpack storage is projected to decline by around 40% for the Cascades and Sierra ranges, and around 25% for the Rockies by the mid-twenty-first century,[80] although some modeling studies suggest more rapid declines.[81] The magnitude of changes in snowpack loss is expected to vary across the region as a function of the temperature sensitivity of individual watersheds.[82] Whereas some of the higher-elevation continental locations could see an increase in spring snowpack as a consequence of increased precipitation, snowpack in lower-to-mid elevation watersheds is particularly vulnerable to warming.[83]

The reduction in snowpack storage efficiency means that runoff will shift seasonally—with a relatively greater portion occurring during the cool season as more precipitation falls as rain rather than snow, and less snowmelt will occur in late spring and summer—leading to declines in streamflow during the dry season.[84] The transition from snow to rain coupled with increases in evaporation rates is also ex-

73. *Id.* at 1786.

74. Jack Scheff & Dargan M. W. Frierson, *Robust Future Precipitation Declines in CMIP5 Largely Reflect the Poleward Expansion of Model Subtropical Dry Zones*, 39 GEOPHYSICAL RES. LETTERS 1, 5 (2012).

75. *Id.*

76. *Id.* at 1.

77. Andreas F. Prein et al., *The Future Intensification of Hourly Precipitation Extremes*, 7 NATURE CLIMATE CHANGE 48, 49 (2017).

78. Michael D. Warner et al., *Changes in Winter Atmospheric Rivers Along the North American West Coast in CMIP5 Climate Models*, 16 J. HYDROMETEOROLOGY 118, 125 (2015).

79. Diana R. Gergel et al., *Effects of Climate Change on Snowpack and Fire Potential in the Western USA*, 141 CLIMATE CHANGE 287, 288 (2017).

80. *Id.* at 293, 295.

81. John C. Fyfe et al., *Large Near-Term Projected Snowpack Loss over the Western United States*, 8 NATURE COMM. 1, 2 (2017).

82. P. Zion Klos et al., *Extent of the Rain-Snow Transition Zone in the Western US Under Historic and Projected Climate*, 41 GEOPHYSICAL RES. LETTERS 4560, 4563 (2014); Jason Scalzitti et al., *Climate Change Impact on the Roles of Temperature and Precipitation in Western US Snowpack Variability*, 43 GEOPHYSICAL RES. LETTERS 5361, 5361 (2016).

83. *Id.*

84. Julie A. Vano et al., *Seasonal Hydrologic Responses to Climate Change in the Pacific Northwest*, 51 WATER RESOURCES RES. 1959, 1961 (2015).

pected to reduce the proportion of precipitation that runs off into the regions' rivers and streams,[85] leading to increased surface water scarcity, particularly in the semi-arid southwestern US.[86] Declines in water availability in a water-limited region may have significant implications for sectors ranging from agriculture to energy production. Agricultural irrigation water demand is projected to increase despite advancements in irrigation technology; increases in water use efficiency by vegetation with rising CO_2;[87] and the potential for groundwater availability to partially buffer declines in surface water availability in some watersheds.[88] Summertime electrical demands are projected to rise with growing residential demand for cooling, while declines in summer streamflow may reduce hydropower generating capacity.[89] Further, reductions in runoff may negatively impact municipal water supplies as reduced streamflow may decrease water availability, as well as diminish water quality due to higher concentrations of pollutants.

Agriculture in the western US is a multi-billion-dollar industry, providing roughly one million jobs across all agricultural sectors and exporting agricultural products around the country and the world. Climate change is anticipated to have both positive and negative consequences for agricultural production, with impacts and adaptive strategies varying by crop and geographic location.[90] Climate change may be beneficial to aspects of the agricultural sector through carbon dioxide fertilization;[91] a longer growing season;[92] and potential reductions in mortality caused by declines in extreme cold.[93] However, these changes may also be beneficial for weeds and pests, which may lead to the reduced efficacy of biological control of pests, requiring mitigation efforts such as increased herbicide and pesticide use.[94]

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85. W. R. Berghuijs et al., *A Precipitation Shift from Snow Towards Rain Leads to a Decrease in Streamflow*, 4 NATURE CLIMATE CHANGE 583, 583–84 (2014); Daniel R. Cayan et al., *Natural Variability, Anthropogenic Climate Change, and Impacts on Water Availability and Flood Extremes in the Western United States*, *in* WATER POL'Y & PLAN. VARIABLE & CHANGING CLIMATE 17, 17–19 (Kathleen A. Miller et al., eds., CRC Press 2016); John T. Abatzoglou & Darren L. Ficklin, *Climatic and Physiographic Controls of Spatial Variability in Surface Water Balance Over the Contiguous United States Using the Budyko Relationship* 53 WATER RESOURCES RES., 7630, 7639–40 (2017).

86. Richard Seager et al., *Projections of Declining Surface-Water Availability for the Southwestern United States*, 3 NATURE CLIMATE CHANGE 482, 482–83 (2013).

87. Abigail L. S. Swann et al., *Plant Responses to Increasing CO2 Reduce Estimates of Climate Impacts on Drought Severity*, 113 PROC. NAT'L ACAD. SCI. 10019, 10019 (2016).

88. Yoshihide Wada et al., *Multimodel Projections and Uncertainties of Irrigation Water Demand Under Climate Change*, 40 GEOPHYSICAL RES. LETTERS 4626, 4626 (2013).

89. Matthew D. Bartos & Mikhail V. Chester, *Impacts of Climate Change on Electric Power Supply in the Western United States*, 5 NATURE CLIMATE CHANGE 748, 748 (2015).

90. Cynthia Rosenzweig et al., *Assessing Agricultural Risks of Climate Change in the 21st Century in a Global Gridded Crop Model Intercomparison*, 111 PROC. NAT'L ACAD. SCI. 3268, 3269 (2014).

91. *See generally* Claudio O. Stöckle et al., *Evaluating Opportunities for an Increased Role of Winter Crops as Adaptation to Climate Change in Dryland Cropping Systems of the US Inland Pacific Northwest*, CLIMATIC CHANGE 1 (2017).

92. *See generally* Gregory J. McCabe et al., *Variability in the Start, End, and Length of Frost-Free Periods Across the Conterminous United States During the Past Century*, 35 INT'L J CLIMATOLOGY 4678 (2015); *See also* Michael A. Rawlins et al., *Future Decreases in Freezing Days Across North America,* 29 J. CLIMATE 6923 (2016).

93. Lauren E. Parker & John T. Abatzoglou, *Projected Changes in Cold Hardiness Zones and Suitable Overwinter Ranges of Perennial Crops over the United States*, 11 ENVT'L RES. LETTERS 4 (2016).

94. Sanford D. Eigenbrode et al., *Climate Change and Biological Control in Agricultural Systems: Principles and Examples from North America*, *in* CLIMATE CHANGE & INSECT PESTS 119 (2015) (ebook).

Warming winter temperatures may also impact crop yield and quality for orchard crops, which require cool winter temperatures for proper development.[95] Similarly, warming summer temperatures—particularly warmer and more frequent extreme heat events—increase heat stress to plants and livestock, can reduce milk production in dairy cows,[96] and decrease crop yield for staple crops such as wheat and corn.[97] Collectively, it is anticipated that the combined impacts of these projected changes will result in the geographic redistribution of crop cultivation, necessitate changes in the management of existing cropping systems, and open opportunities for novel cropping regions as climatically suitable locations for cultivation—particularly for sensitive perennials and crops with narrow climatic tolerance.[98]

While climate change may provide some benefits to agricultural systems, forest ecosystem impacts are largely projected to be negative. The advancement in the timing of snowmelt will promote a decline in soil moisture across snowmelt dependent ecosystems,[99] which have implications for ecological disturbance in forests.[100] Climate change may increase the severity of mountain pine beetle outbreaks and subsequent mortality, particularly in cold regions of the western US where winter minimum temperatures have previously limited beetle impacts.[101] Similarly, increased drought stress is projected to increase forest mortality[102] and wildfires.[103] The ramifications of climate change on forests have broader scale implications for ecosystems, water quality, and recreational opportunities.[104] Likewise, projected increases in the probability of very large wildfires and associated smoke emissions under climate change have far-reaching consequences for air quality and human health.[105]

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95. *See* Eike Luedeling, *Climate Change Impacts on Winter Chill for Temperate Fruit and Nut Production*, 144 SCIENTIA HORTICULTURAE 218, 220 (2012).

96. U.S. DEP'T OF AGRIC. CLIMATE CHANGE, HEAT STRESS, AND US DAIRY PRODUCTION, ECON. RES. REPORT NO. 175 (2014).

97. *See generally* David B. Lobell et al., *The Critical Role of Extreme Heat for Maize Production in the United States*, 3 NATURE CLIMATE CHANGE 497 (2013); *See also* Bernhard Schauberger et al., *Consistent Negative Response of US Crops to High Temperatures in Observations and Crop Models*, 8 NATURE COMM. 13931 (2017).

98. *See* Gregory V. Jones & Hans R. Schultz, *Climate Change and Emerging Cool Climate Wine Regions*, 31 WINE & VITICULTURE J. 51 (2016); Parker & Abatzoglou, *supra* note 93.

99. Diana R. Gergel et al., *Effects of Climate Change on Snowpack and Fire Potential in the Western USA*, 141 CLIMATIC CHANGE 287, 295 (2017).

100. Charles H. Luce et al., *Contributing Factors for Drought in United States Forest Ecosystems Under Projected Future Climates and Their Uncertainty*, 380 U.S. FOREST ECOLOGY AND MGMT. 299, 305 (2016).

101. Polly C. Buotte et al., *Climate Influences on Whitebark Pine Mortality From Mountain Pine Beetle in the Greater Yellowstone Ecosystem*, 26 ECOLOGICAL APPLICATIONS 2507, 2509 (2016).

102. Nathan G. McDowell et al., *Multi-Scale Predictions of Massive Conifer Mortality Due to Chronic Temperature Rise*, 6 NATURE CLIMATE CHANGE 295, 298 (2016); Williams et al., *supra* note 65.

103. Donald McKenzie & Jeremy S. Littell, *Climate Change and the Eco-hydrology of Fire: Will Area Burned Increase in a Warming Western USA?*, 27 ECOLOGICAL APPLICATIONS 26, 34 (2017).

104. *Id.*

105. *See* R. Barbero et al., *Climate Change Presents Increased Potential for Very Large Fires in the Contiguous United States*, 24 INT'L J. WILDLAND FIRE 892 (2015); *See also* David M. J. S. Bowman et al., *Human Exposure and Sensitivity to Globally Extreme Wildfire Events*, 1 NATURE ECOLOGY & EVOLUTION 58 (2017).

IV. THE FUTURE: POLICIES TO MINIMIZE HUMAN-CAUSED CLIMATE CHANGE

While the fundamental climate science regarding the global response to increased CO_2 has been established, additional research will continue to fill in details and possibly uncover new science on the climate system and its response to anthropogenic forcing. It is a fallacy to expect that climate models will converge on a single answer of what our future climate will look like. Rather, we must be open to coping with uncertainty in climate projections when developing science-based policies for climate adaptation and mitigation. While international treaties like the Paris Agreement wrangle with the logistics and challenges of monitoring and policing emissions, communities and countries can proactively develop adaptation strategies to become more climate-resilient to both contemporary climate impacts and those projected to become more frequent or intense with climate change.

While adaptation efforts can minimize detrimental impacts at local scales, they fail to address the crux of the global problem. Cumulative anthropogenic carbon emissions from the year 2015 onward must not surpass an additional 350 Gt if we hope to limit global average warming to 2°C above pre-industrial conditions.[106] Notably, while the Paris Agreement was developed with this goal in mind, continued stagnation of mitigation policies – even if the NDC goals were achieved – would lead to warming of 2.9°C by 2100,[107] thus emphasizing the need to strengthen mitigation efforts throughout the twenty-first century. How these goals will be met requires a multipronged effort across countries and corporations, spanning fields from agricultural emissions to energy use, while delicately balancing economic development concerns. Climate change is one of the most imposing risks facing the globe in the twenty-first century, and the development and implementation of effective climate policies is one of the grand challenges that society currently faces.

106. Joeri Rogelj et al., *Paris Agreement Climate Proposals Need a Boost to Keep Warming Well Below 2°C*, 534 NATURE 631, 634 (2016).

107. *Id.*