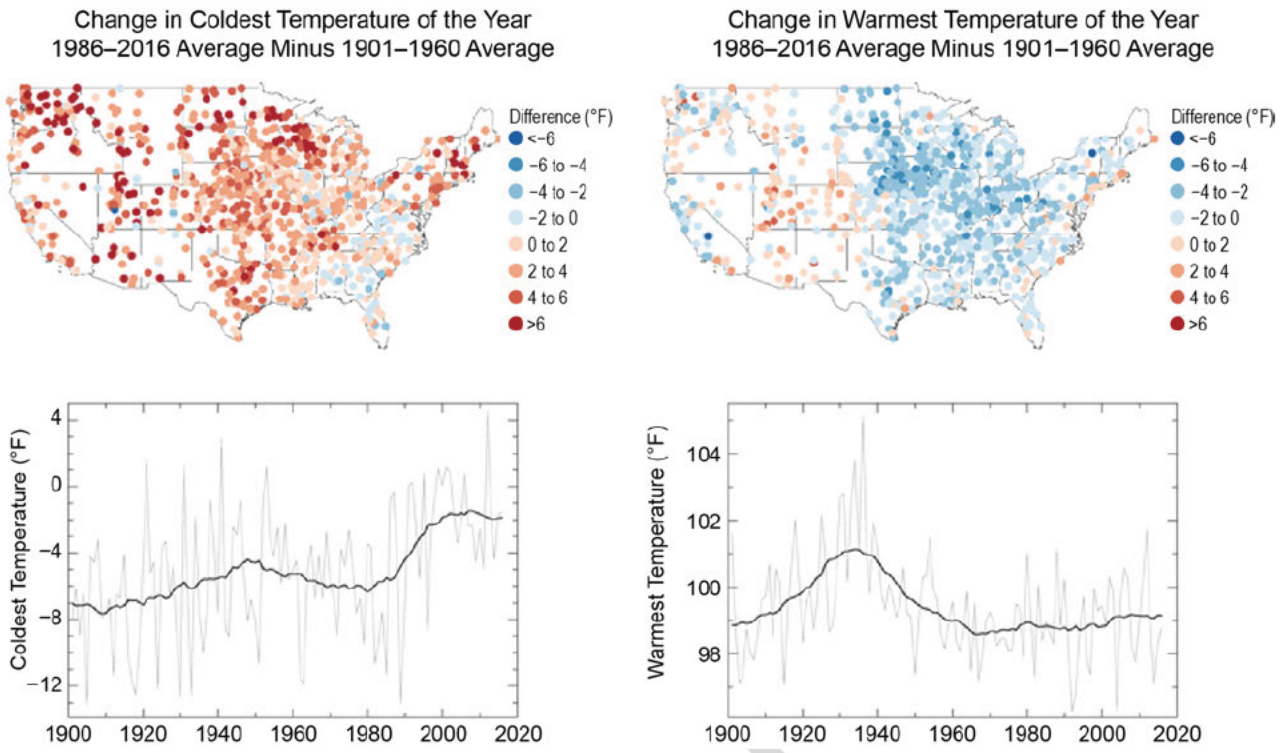

Figure 6.3. Observed changes in the coldest and warmest daily temperatures (°F) of the year in the contiguous United States. Maps (top) depict changes at stations; changes are the difference between the average for present-day (1986–2016) and the average for the first half of the last century (1901–1960). Time series (bottom) depict the area-weighted average for the contiguous United States. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset (Menne et al. 2012). (Figure source: NOAA/NCEI).

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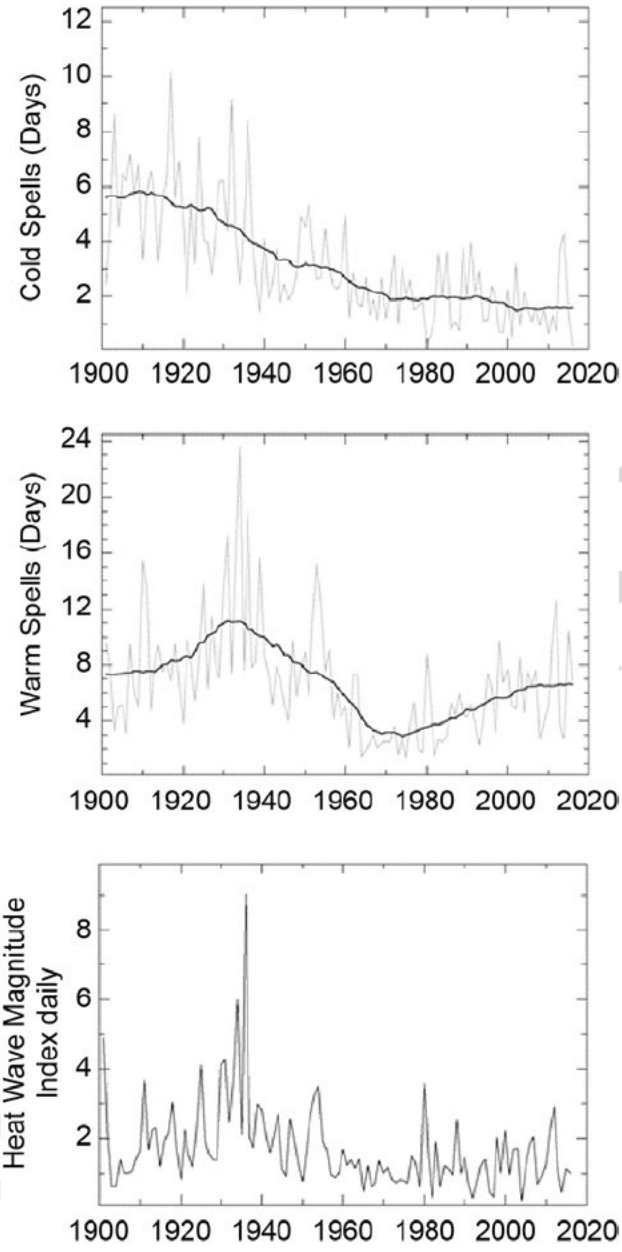

Figure 6.4. Observed changes in cold and heat waves in the contiguous United States. The top panel depicts changes in the frequency of cold waves; the middle panel depicts changes in the frequency of heat waves; and the bottom panel depicts changes in the intensity of heat waves. Cold and heat wave frequency indices are defined in Zhang et al. (2011), and the heat wave intensity index is defined in Russo et al. (2014). Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset (Menne et al. 2012). (Figure source: NOAA/NCEI).

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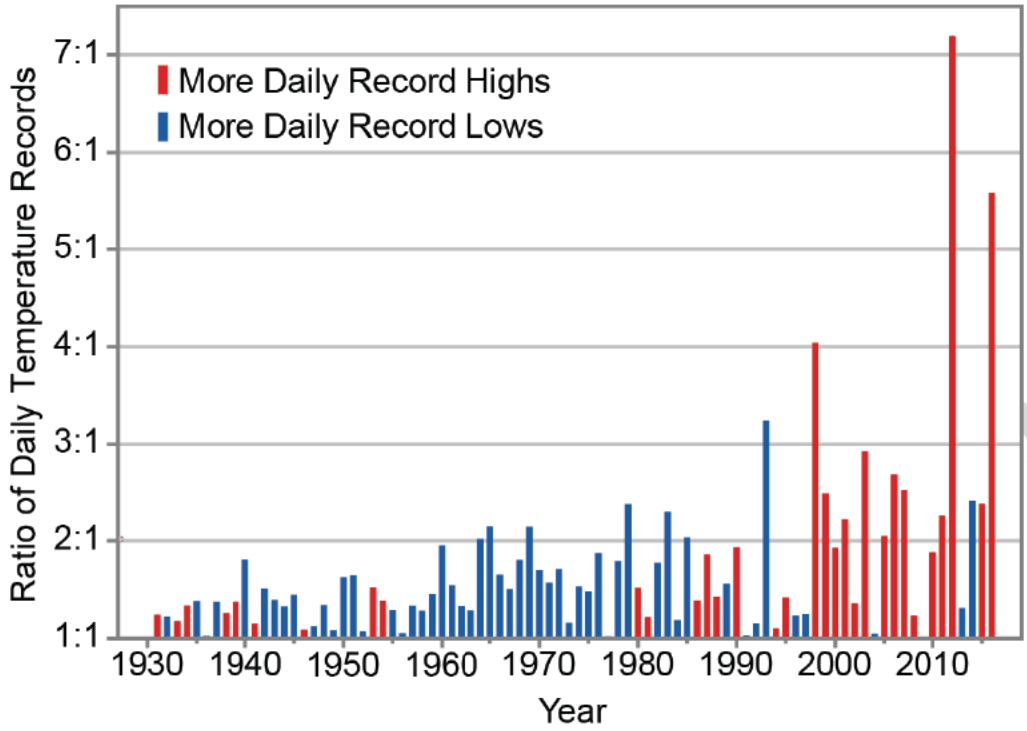

Figure 6.5. Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. Estimates are derived from long-term stations with minimal missing data in the Global Historical Climatology Network–Daily dataset (Menne et al. 2012). (Figure source: NOAA/NCEI).

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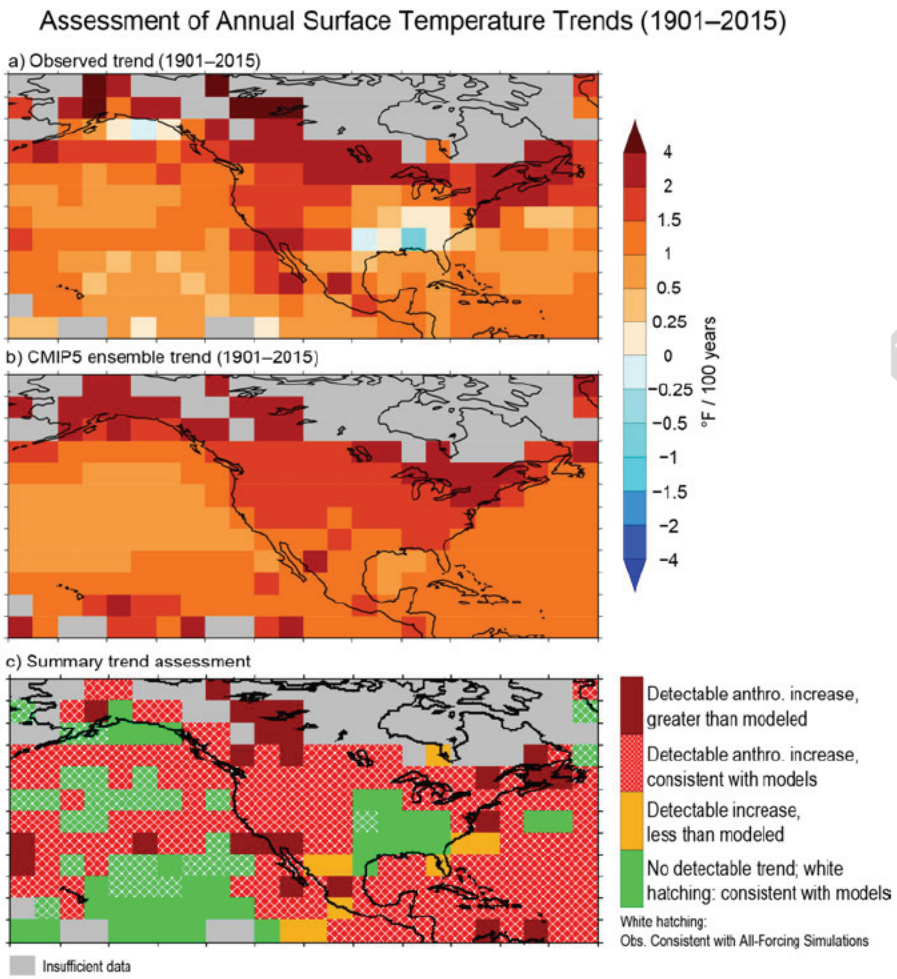

Figure 6.6. Detection and attribution assessment of trends in average annual temperature (°F). Grid-box values indicate whether linear trends for 1901–2015 are detectable (that is, distinct from natural variability) and/or consistent with CMIP5 historical All-Forcing runs. If the grid-box trend is found to be both detectable and either consistent with or greater than the warming in the All-Forcing runs, then the grid box is assessed as having a detectable anthropogenic contribution to warming over the period. Gray regions represent grid boxes with data that are too sparse for detection and attribution. (Figure source: updated from Knutson et al. 2013a; © American Meteorological Society. Used with permission.)

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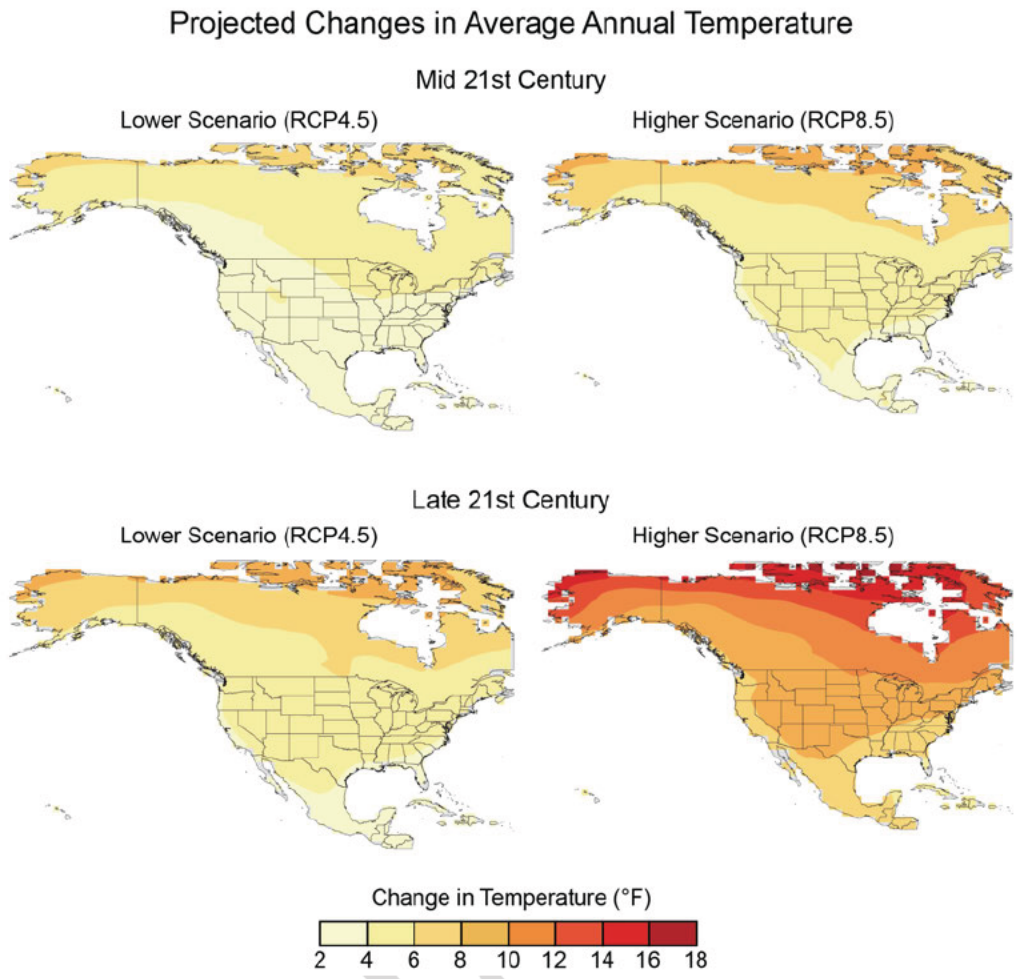

Figure 6.7. Projected changes in average annual temperatures (°F). Changes are the difference between the average for mid-century (2036–2065; top) or late-century (2071–2100, bottom) and the average for near-present (1976–2005). Each map depicts the weighted multimodel mean. Increases are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change; Sun et al. 2015). (Figure source: CICS-NC / NOAA/NCEI).

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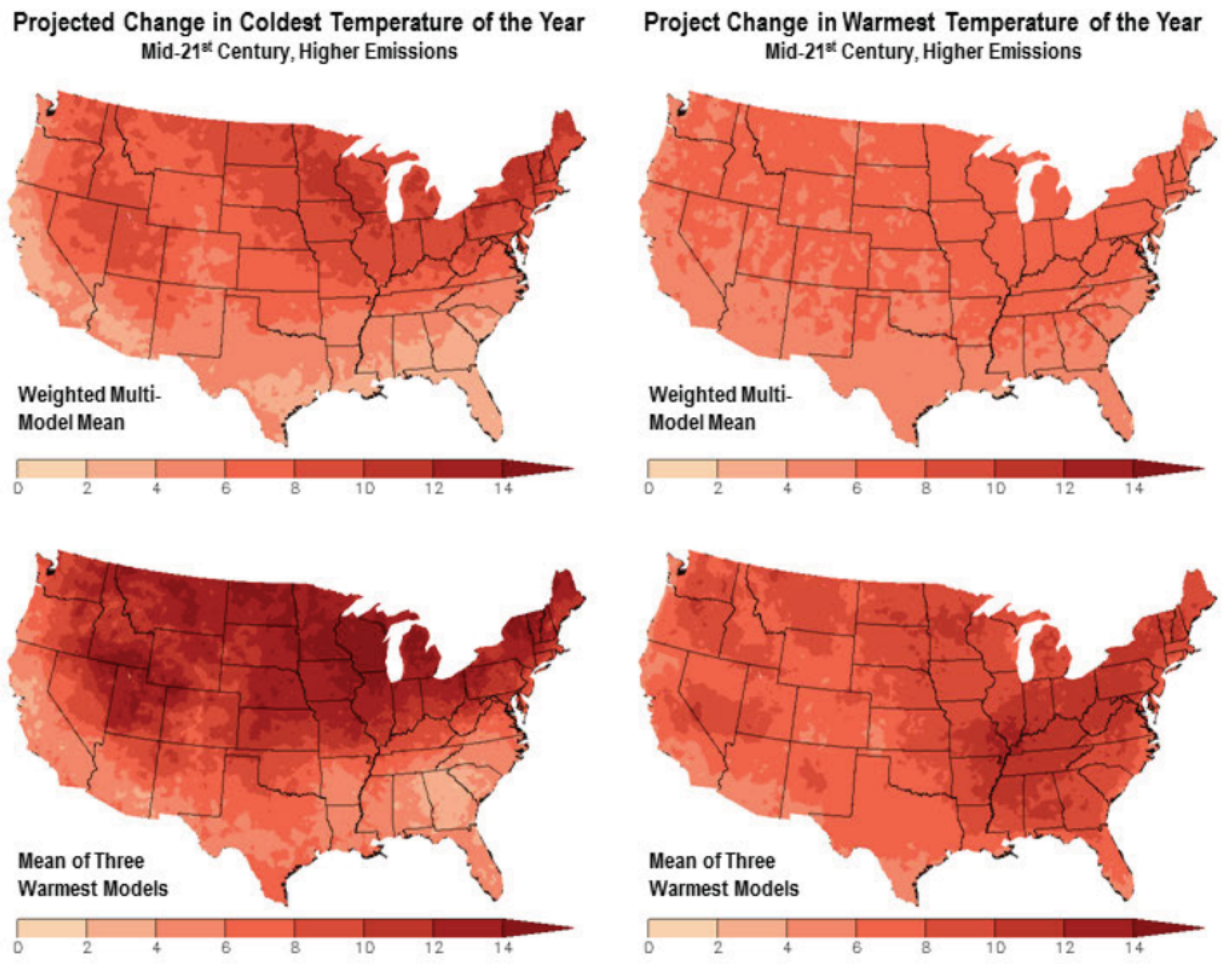

Figure 6.8. Projected changes in the coldest and warmest daily temperatures (°F) of the year in the contiguous United States. Changes are the difference between the average for mid-century (2036–2065) and the average for near-present (1976–2005) under RCP8.5. Maps in the top row depict the weighted multimodel mean whereas maps on the bottom row depict the mean of the three warmest models (that is, the models with the largest temperature increase). Maps are derived from 32 climate model projections that were statistically downscaled using the Localized Constructed Analogs technique (Pierce et al. 2014). Increases are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change; Sun et al. 2015). (Figure source: CICS-NC / NOAA/NCEI).

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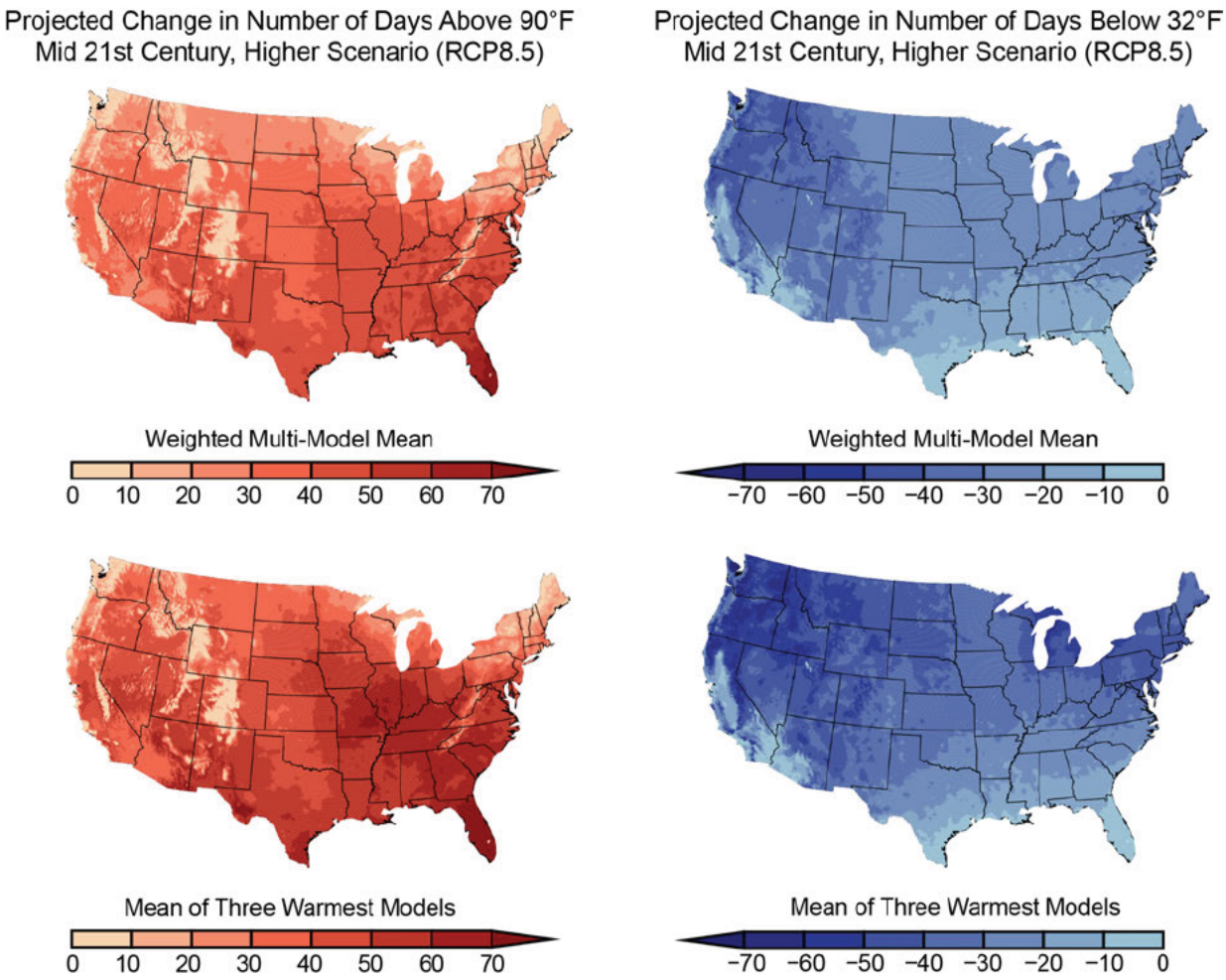

Figure 6.9. Projected changes in the number of days per year with a maximum temperature above 90°F and a minimum temperature below 32°F in the contiguous United States. Changes are the difference between the average for mid-century (2036–2065) and the average for near-present (1976–2005) under RCP8.5. Maps in the top row depict the weighted multimodel mean whereas maps on the bottom row depict the mean of the three warmest models (that is, the models with the largest temperature increase). Maps are derived from 32 climate model projections that were statistically downscaled using the Localized Constructed Analogs technique (Pierce et al. 2014). Changes are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change; Sun et al. 2015). (Figure source: CICS-NC / NOAA/NCEI).

FINAL

REFERENCES

Abatzoglou, J.T. and K.T. Redmond, 2007: Asymmetry between trends in spring and autumn temperature and circulation regimes over western North America. *Geophysical Research Letters,* **34,** L18808. http://dx.doi.org/10.1029/2007GL030891

Angélil, O., D. Stone, M. Wehner, C.J. Paciorek, H. Krishnan, and W. Collins, 2017: An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. *Journal of Climate,* **30,** 5-16. http://dx.doi.org/10.1175/JCLI-D-16-0077.1

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952. http://www.climatechange2013.org/report/full-report/

Bonfils, C., P.B. Duffy, B.D. Santer, T.M.L. Wigley, D.B. Lobell, T.J. Phillips, and C. Doutriaux, 2008: Identification of external influences on temperatures in California. *Climatic Change,* **87,** 43-55. http://dx.doi.org/10.1007/s10584-007-9374-9

Cattiaux, J. and P. Yiou, 2013: U.S. heat waves of spring and summer 2012 from the flow analogue perspective [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S10-S13. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

CCSP, 2006: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (Eds.). National Oceanic and Atmospheric Administration, Washington, D.C., 164 pp. http://www.globalchange.gov/browse/reports/sap-11-temperature-trends-lower-atmosphere-steps-understanding-reconciling

CCSP, 2008: *Weather and Climate Extremes in a Changing Climate - Regions of Focus - North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Karl, T.R., G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray, Eds. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C., 164 pp. http://downloads.globalchange.gov/sap/sap3-3/sap3-3-final-all.pdf

FINAL DRAFT

Christidis, N., P.A. Stott, F.W. Zwiers, H. Shiogama, and T. Nozawa, 2010: Probabilistic estimates of recent changes in temperature: A multi-scale attribution analysis. *Climate Dynamics,* **34,** 1139-1156. http://dx.doi.org/10.1007/s00382-009-0615-7

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

Diffenbaugh, N.S. and M. Scherer, 2013: Likelihood of July 2012 U.S. temperatures in pre-industrial and current forcing regimes [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S6-S9. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

Dole, R., M. Hoerling, A. Kumar, J. Eischeid, J. Perlwitz, X.-W. Quan, G. Kiladis, R. Webb, D. Murray, M. Chen, K. Wolter, and T. Zhang, 2014: The making of an extreme event: Putting the pieces together. *Bulletin of the American Meteorological Society,* **95,** 427-440. http://dx.doi.org/10.1175/BAMS-D-12-00069.1

Donat, M.G., A.D. King, J.T. Overpeck, L.V. Alexander, I. Durre, and D.J. Karoly, 2016: Extraordinary heat during the 1930s US Dust Bowl and associated large-scale conditions. *Climate Dynamics,* **46,** 413-426. http://dx.doi.org/10.1007/s00382-015-2590-5

Fischer, E.M., U. Beyerle, and R. Knutti, 2013: Robust spatially aggregated projections of climate extremes. *Nature Climate Change,* **3,** 1033-1038. http://dx.doi.org/10.1038/nclimate2051

Goldstein, A.H., C.D. Koven, C.L. Heald, and I.Y. Fung, 2009: Biogenic carbon and anthropogenic pollutants combine to form a cooling haze over the southeastern United States. *Proceedings of the National Academy of Sciences,* **106,** 8835-8840. http://dx.doi.org/10.1073/pnas.0904128106

Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J.W. Nielsen-Gammon, P. Pegion, J. Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of Climate,* **26,** 2811–2832. http://dx.doi.org/10.1175/JCLI-D-12-00270.1

Huang, B., V.F. Banzon, E. Freeman, J. Lawrimore, W. Liu, T.C. Peterson, T.M. Smith, P.W. Thorne, S.D. Woodruff, and H.-M. Zhang, 2015: Extended Reconstructed Sea Surface

FINAL DRAFT

Temperature Version 4 (ERSST.v4). Part I: Upgrades and intercomparisons. *Journal of Climate,* **28,** 911-930. http://dx.doi.org/10.1175/JCLI-D-14-00006.1

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.). Cambridge University Press, Cambridge, UK and New York, NY. 582 pp. http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf

Jeon, S., C.J. Paciorek, and M.F. Wehner, 2016: Quantile-based bias correction and uncertainty quantification of extreme event attribution statements. *Weather and Climate Extremes,* **12,** 24-32. http://dx.doi.org/10.1016/j.wace.2016.02.001

Karl, T.R., J.T. Melillo, and T.C. Peterson, eds., 2009: *Global Climate Change Impacts in the United States*. ed. Karl, T.R., J.T. Melillo, and T.C. Peterson. Cambridge University Press: New York, NY, 189 pp. http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf

Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth-century simulations. *Journal of Climate,* **26,** 8709-8743. http://dx.doi.org/10.1175/JCLI-D-12-00567.1

Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: The extreme March-May 2012 warm anomaly over the eastern United States: Global context and multimodel trend analysis [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S13-S17. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams, D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950-2050 changes in US anthropogenic aerosols – Part 1: Aerosol trends and radiative forcing. *Atmospheric Chemistry and Physics* **12,** 3333-3348. http://dx.doi.org/10.5194/acp-12-3333-2012

Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams, D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950–2050 changes in US anthropogenic aerosols – Part 2: Climate response. *Atmospheric Chemistry and Physics,* **12,** 3349-3362. http://dx.doi.org/10.5194/acp-12-3349-2012

Mascioli, N.R., M. Previdi, A.M. Fiore, and M. Ting, 2017: Timing and seasonality of the United States 'warming hole'. *Environmental Research Letters,* **12,** 034008. http://dx.doi.org/10.1088/1748-9326/aa5ef4

FINAL DRAFT

Mazdiyasni, O. and A. AghaKouchak, 2015: Substantial increase in concurrent droughts and heatwaves in the United States. *Proceedings of the National Academy of Sciences,* **112,** 11484-11489. http://dx.doi.org/10.1073/pnas.1422945112

Mears, C.A. and F.J. Wentz, 2016: Sensitivity of satellite-derived tropospheric temperature trends to the diurnal cycle adjustment. *Journal of Climate,* **29,** 3629-3646. http://dx.doi.org/10.1175/JCLI-D-15-0744.1

Meehl, G.A., J.M. Arblaster, and G. Branstator, 2012: Mechanisms contributing to the warming hole and the consequent US east–west differential of heat extremes. *Journal of Climate,* **25,** 6394-6408. http://dx.doi.org/10.1175/JCLI-D-11-00655.1

Meehl, G.A., C. Tebaldi, and D. Adams-Smith, 2016: US daily temperature records past, present, and future. *Proceedings of the National Academy of Sciences,* **113,** 13977-13982. http://dx.doi.org/10.1073/pnas.1606117113

Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program: Washington, DC, 842 pp. http://dx.doi.org/10.7930/J0Z31WJ2

Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston, 2012: An overview of the global historical climatology network-daily database. *Journal of Atmospheric and Oceanic Technology,* **29,** 897-910. http://dx.doi.org/10.1175/JTECH-D-11-00103.1

Min, S.-K., X. Zhang, F. Zwiers, H. Shiogama, Y.-S. Tung, and M. Wehner, 2013: Multimodel detection and attribution of extreme temperature changes. *Journal of Climate,* **26,** 7430-7451. http://dx.doi.org/10.1175/JCLI-D-12-00551.1

Mueller, N.D., E.E. Butler, K.A. McKinnon, A. Rhines, M. Tingley, N.M. Holbrook, and P. Huybers, 2016: Cooling of U.S. Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, **6**, 317-322, doi:10.1038/nclimate2825.

PAGES 2K Consortium, 2013: Continental-scale temperature variability during the past two millennia. *Nature Geoscience,* **6,** 339-346. http://dx.doi.org/10.1038/ngeo1797

Pan, Z., X. Liu, S. Kumar, Z. Gao, and J. Kinter, 2013: Intermodel variability and mechanism attribution of central and southeastern U.S. anomalous cooling in the twentieth century as simulated by CMIP5 models. *Journal of Climate,* **26,** 6215-6237. http://dx.doi.org/10.1175/JCLI-D-12-00559.1

Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P. Giovannettone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe, C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G. Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D.

FINAL DRAFT

Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society,* **94,** 821-834. http://dx.doi.org/10.1175/BAMS-D-12-00066.1

Pierce, D.W., T.P. Barnett, B.D. Santer, and P.J. Gleckler, 2009: Selecting global climate models for regional climate change studies. *Proceedings of the National Academy of Sciences,* **106,** 8441-8446. http://dx.doi.org/10.1073/pnas.0900094106

Pierce, D.W., D.R. Cayan, and B.L. Thrasher, 2014: Statistical downscaling using Localized Constructed Analogs (LOCA). *Journal of Hydrometeorology,* **15**, 2558-2585. http://dx.doi.org/10.1175/jhm-d-14-0082.1

Po-Chedley, S., T.J. Thorsen, and Q. Fu, 2015: Removing diurnal cycle contamination in satellite-derived tropospheric temperatures: Understanding tropical tropospheric trend discrepancies. *Journal of Climate,* **28,** 2274-2290. http://dx.doi.org/10.1175/JCLI-D-13-00767.1

Rupp, D.E., P.W. Mote, N. Massey, C.J. Rye, R. Jones, and M.R. Allen, 2012: Did human influence on climate make the 2011 Texas drought more probable? [in Explaining Extreme Events of 2011 from a Climate Perspective]. *Bulletin of the American Meteorological Society,* **93,** 1052-1054. http://dx.doi.org/10.1175/BAMS-D-12-00021.1

Russo, S., A. Dosio, R.G. Graversen, J. Sillmann, H. Carrao, M.B. Dunbar, A. Singleton, P. Montagna, P. Barbola, and J.V. Vogt, 2014: Magnitude of extreme heat waves in present climate and their projection in a warming world. *Journal of Geophysical Research: Atmospheres,* **119,** 12,500-12,512. http://dx.doi.org/10.1002/2014JD022098

Seager, R., M. Hoerling, D.S. Siegfried, h. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2014: Causes and Predictability of the 2011-14 California Drought. National Oceanic and Atmospheric Administration, Drought Task Force Narrative Team, 40 pp. http://dx.doi.org/10.7289/V58K771F

Sillmann, J., V.V. Kharin, F.W. Zwiers, X. Zhang, and D. Bronaugh, 2013: Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical Research: Atmospheres,* **118,** 2473-2493. http://dx.doi.org/10.1002/jgrd.50188

Smith, T.T., B.F. Zaitchik, and J.M. Gohlke, 2013: Heat waves in the United States: Definitions, patterns and trends. *Climatic Change,* **118,** 811-825. http://dx.doi.org/10.1007/s10584-012-0659-2

Spencer, R.W., J.R. Christy, and W.D. Braswell, 2017: UAH Version 6 global satellite temperature products: Methodology and results. *Asia-Pacific Journal of Atmospheric Sciences,* **53,** 121-130. http://dx.doi.org/10.1007/s13143-017-0010-y

FINAL DRAFT

Sun, L., K.E. Kunkel, L.E. Stevens, A. Buddenberg, J.G. Dobson, and D.R. Easterling, 2015: Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States: Differences, Similarities, and Implications for the U.S. National Climate Assessment. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 111 pp. http://dx.doi.org/10.7289/V5RB72KG

Thorne, P.W., M.G. Donat, R.J.H. Dunn, C.N. Williams, L.V. Alexander, J. Caesar, I. Durre, I. Harris, Z. Hausfather, P.D. Jones, M.J. Menne, R. Rohde, R.S. Vose, R. Davy, A.M.G. Klein-Tank, J.H. Lawrimore, T.C. Peterson, and J.J. Rennie, 2016: Reassessing changes in diurnal temperature range: Intercomparison and evaluation of existing global data set estimates. *Journal of Geophysical Research: Atmospheres,* **121,** 5138-5158. http://dx.doi.org/10.1002/2015JD024584

Trenary, L., T. DelSole, B. Doty, and M.K. Tippett, 2015: Was the cold eastern US Winter of 2014 due to increased variability? *Bulletin of the American Meteorological Society,* **96 (12),** S15-S19. http://dx.doi.org/10.1175/bams-d-15-00138.1

Trouet, V., H.F. Diaz, E.R. Wahl, A.E. Viau, R. Graham, N. Graham, and E.R. Cook, 2013: A 1500-year reconstruction of annual mean temperature for temperate North America on decadal-to-multidecadal time scales. *Environmental Research Letters,* **8,** 024008. http://dx.doi.org/10.1088/1748-9326/8/2/024008

Vose, R.S., D. Arndt, V.F. Banzon, D.R. Easterling, B. Gleason, B. Huang, E. Kearns, J.H. Lawrimore, M.J. Menne, T.C. Peterson, R.W. Reynolds, T.M. Smith, C.N. Williams, and D.L. Wuertz, 2012: NOAA's merged land-ocean surface temperature analysis. *Bulletin of the American Meteorological Society,* **93,** 1677-1685. http://dx.doi.org/10.1175/BAMS-D-11-00241.1

Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, Jr., C. Fenimore, K. Gleason, and D. Arndt, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology,* **53,** 1232-1251. http://dx.doi.org/10.1175/JAMC-D-13-0248.1

Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, C. Fenimore, K. Gleason, and D. Arndt, 2017: Improved historical temperature and precipitation time series for Alaska climate divisions. *Journal of Service Climatology (in press)*

Wahl, E.R. and J.E. Smerdon, 2012: Comparative performance of paleoclimate field and index reconstructions derived from climate proxies and noise-only predictors. *Geophysical Research Letters,* **39,** L06703. http://dx.doi.org/10.1029/2012GL051086

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F.

FINAL DRAFT

Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, D.C., 19-67. http://dx.doi.org/10.7930/J0KW5CXT

Wolter, K., J.K. Eischeid, X.-W. Quan, T.N. Chase, M. Hoerling, R.M. Dole, G.J.V. Oldenborgh, and J.E. Walsh, 2015: How unusual was the cold winter of 2013/14 in the Upper Midwest? [in "Explaining Extreme Events of 2014 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **96 (12),** S10-S14. http://dx.doi.org/10.1175/bams-d-15-00126.1

Wuebbles, D., G. Meehl, K. Hayhoe, T.R. Karl, K. Kunkel, B. Santer, M. Wehner, B. Colle, E.M. Fischer, R. Fu, A. Goodman, E. Janssen, V. Kharin, H. Lee, W. Li, L.N. Long, S.C. Olsen, Z. Pan, A. Seth, J. Sheffield, and L. Sun, 2014: CMIP5 climate model analyses: Climate extremes in the United States. *Bulletin of the American Meteorological Society,* **95,** 571-583. http://dx.doi.org/10.1175/BAMS-D-12-00172.1

Xu, L., H. Guo, C.M. Boyd, M. Klein, A. Bougiatioti, K.M. Cerully, J.R. Hite, G. Isaacman-VanWertz, N.M. Kreisberg, C. Knote, K. Olson, A. Koss, A.H. Goldstein, S.V. Hering, J. de Gouw, K. Baumann, S.-H. Lee, A. Nenes, R.J. Weber, and N.L. Ng, 2015: Effects of anthropogenic emissions on aerosol formation from isoprene and monoterpenes in the southeastern United States. *Proceedings of the National Academy of Sciences,* **112,** 37-42. http://dx.doi.org/10.1073/pnas.1417609112

Yu, S., K. Alapaty, R. Mathur, J. Pleim, Y. Zhang, C. Nolte, B. Eder, K. Foley, and T. Nagashima, 2014: Attribution of the United States “warming hole”: Aerosol indirect effect and precipitable water vapor. *Scientific Reports,* **4,** 6929. http://dx.doi.org/10.1038/srep06929

Zhang, X., L. Alexander, G.C. Hegerl, P. Jones, A.K. Tank, T.C. Peterson, B. Trewin, and F.W. Zwiers, 2011: Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews: Climate Change,* **2,** 851-870. http://dx.doi.org/10.1002/wcc.147

Zou, C.-Z. and J. Li, 2014: NOAA MSU Mean Layer Temperature. National Oceanic and Atmospheric Administration, Center for Satellite Applications and Research, 35 pp. http://www.star.nesdis.noaa.gov/smcd/emb/mscat/documents/MSU_TCDR_CATBD_Zou_Li.pdf

Zwiers, F.W., X.B. Zhang, and Y. Feng, 2011: Anthropogenic influence on long return period daily temperature extremes at regional scales. *Journal of Climate,* **24,** 881-892. http://dx.doi.org/10.1175/2010jcli3908.1

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7. Precipitation Change in the United States

KEY FINDINGS

1. Annual precipitation has decreased in much of the West, Southwest, and Southeast and increased in most of the Northern and Southern Plains, Midwest, and Northeast. A national average increase of 4% in annual precipitation since 1901 is mostly a result of large increases in the fall season. (*Medium confidence*)

2. Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 (*high confidence*). There are important regional differences in trends, with the largest increases occurring in the northeastern United States (*high confidence*). In particular, mesoscale convective systems (organized clusters of thunderstorms)—the main mechanism for warm season precipitation in the central part of the United States—have increased in occurrence and precipitation amounts since 1979 (*medium confidence*).

3. The frequency and intensity of heavy precipitation events are projected to continue to increase over the 21st century (*high confidence*). Mesoscale convective systems in the central United States, are expected to continue to increase in number and intensity in the future (*medium confidence*). There are, however, important regional and seasonal differences in projected changes in total precipitation: the northern United States, including Alaska, is projected to receive more precipitation in the winter and spring, and parts of the southwestern United States are projected to receive less precipitation in the winter and spring (*medium confidence*).

4. Northern Hemisphere spring snow cover extent, North America maximum snow depth, snow water equivalent in the western United States, and extreme snowfall years in the southern and western United States have all declined, while extreme snowfall years in parts of the northern United States have increased (*medium confidence*). Projections indicate large declines in snowpack in the western United States and shifts to more precipitation falling as rain than snow in the cold season in many parts of the central and eastern United States (*high confidence*).

Introduction

Changes in precipitation are one of the most important potential outcomes of a warming world because precipitation is integral to the very nature of society and ecosystems. These systems have developed and adapted to the past envelope of precipitation variations. Any large changes beyond the historical envelope may have profound societal and ecological impacts.

Historical variations in precipitation, as observed from both instrumental and proxy records, establish the context around which future projected changes can be interpreted, because it is

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within that context that systems have evolved. Long-term station observations from core climate networks serve as a primary source to establish observed changes in both means and extremes. Proxy records, which are used to reconstruct past climate conditions, are varied and include sources such as tree ring and ice core data. Projected changes are examined using the Coupled Model Intercomparison Project Phase 5 (CMIP5) suite of model simulations. They establish the likelihood of distinct regional and seasonal patterns of change.

7.1 Historical Changes

7.1.1 Mean Changes

Annual precipitation averaged across the United States has increased approximately 4% over the 1901–2015 period, slightly less than the 5% increase reported in the Third National Climate Assessment (NCA3) over the 1901–2012 period (Walsh et al. 2014). There continue to be important regional and seasonal differences in precipitation changes (Figure 7.1). Seasonally, national increases are largest in the fall, while little change is observed for winter. Regional differences are apparent, as the Northeast, Midwest, and Great Plains have had increases while parts of the Southwest and Southeast have had decreases. The slight decrease in the change in annual precipitation across the United States since NCA3 appears to be the result of the recent lingering droughts in the western and southwestern United States (NOAA 2016a; Barnston and Lyon 2016). However, the recent meteorological drought in California that began in late 2011 (Seager et al. 2015; NOAA 2016b) now appears to be largely over, due to the substantial precipitation and snowpack the state received in the winter of 2016–2017. The year 2015 was the third wettest on record, just behind 1973 and 1983 (all of which were years marked by El Niño events). Interannual variability is substantial, as evidenced by large multiyear meteorological and agricultural droughts in the 1930s and 1950s.

[INSERT FIGURE 7.1 HERE]

Changes in precipitation differ markedly across the seasons, as do regional patterns of increases and decreases. For the contiguous United States, fall exhibits the largest (10%) and most widespread increase, exceeding 15% in much of the Northern Great Plains, Southeast, and Northeast. Winter average for the United States has the smallest increase (2%), with drying over most of the western United States as well as parts of the Southeast. In particular, a reduction in streamflow in the northwestern United States has been linked to a decrease in orographic enhancement of precipitation since 1950 (Luce et al. 2013). Spring and summer have comparable increases (about 3.5%) but substantially different patterns. In spring, the northern half of the contiguous United States has become wetter, and the southern half has become drier. In summer, there is a mixture of increases and decreases across the Nation. Alaska shows little change in annual precipitation (+1.5%); however, in all seasons, central Alaska shows declines and the panhandle shows increases. Hawai‘i shows a decline of more than 15% in annual precipitation.

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7.1.2 Snow

Changes in snow cover extent (SCE) in the Northern Hemisphere exhibit a strong seasonal dependence (Vaughan et al. 2013). There has been little change in winter SCE since the 1960s (when the first satellite records became available), while fall SCE has increased. However, the decline in spring SCE is larger than the increase in fall and is due in part to higher temperatures that shorten the time snow spends on the ground in the spring. This tendency is highlighted by the recent occurrences of both unusually high and unusually low monthly (October–June) SCE values, including the top 5 highest and top 5 lowest values in the 48 years of data. From 2010 onward, 7 of the 45 highest monthly SCE values occurred, all in the fall or winter (mostly in November and December), while 9 of the 10 lowest May and June values occurred. This reflects the trend toward earlier spring snowmelt, particularly at high latitudes (Kunkel et al. 2016). An analysis of seasonal maximum snow depth for 1961–2015 over North America indicates a statistically significant downward trend of 0.11 standardized anomalies per decade and a trend toward the seasonal maximum snow depth occurring earlier—approximately one week earlier on average since the 1960s (Kunkel et al. 2016). There has been a statistically significant decrease over the period of 1930–2007 in the frequency of years with a large number of snowfall days (years exceeding the 90th percentile) in the southern United States and the U.S. Pacific Northwest and an increase in the northern United States (Kluver and Leathers 2015). In the snow belts of the Great Lakes, lake effect snowfall has increased overall since the early 20th century for Lakes Superior, Michigan-Huron, and Erie (Kunkel et al. 2010). However, individual studies for Lakes Michigan (Bard and Kristovich 2012) and Ontario (Harnett et al. 2014) indicate that this increase has not been continuous. In both cases, upward trends were observed till the 1970s/early 1980s. Since then, however, lake effect snowfall has decreased in these regions. Lake effect snows along the Great Lakes are affected greatly by ice cover extent and lake water temperatures. As ice cover diminishes in winter, the expectation is for more lake effect snow until temperatures increase enough such that much of what now falls as snow instead falls as rain (Wright et al. 2013; Vavrus et al. 2013).

End of season snow water equivalent (SWE)—especially important where water supply is dominated by spring snow melt (for example, in much of the American West)—has declined since 1980 in the western United States, based on analysis of in situ observations, and is associated with springtime warming (Pederson et al. 2013). Satellite measurements of SWE based on brightness temperature also show a decrease over this period (Gan et al. 2013). The variability of western United States SWE is largely driven by the most extreme events, with the top decile of events explaining 69% of the variability (Lute and Abatzoglou 2014). The recent drought in the western United States was highlighted by the extremely dry 2014–2015 winter that followed three previous dry winters. At Donner Summit, CA, (approximate elevation of 2,100 meters) in the Sierra Nevada Mountains, end-of-season SWE on April 1, 2015, was the lowest on record, based on survey measurements back to 1910, at only 0.51 inches (1.3 cm), or less than 2% of the long-term average. This followed the previous record low in 2014. The

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estimated return period of this drought is at least 500 years based on paleoclimatic reconstructions (Belmecheri et al. 2016).

7.1.3 Observed changes in U.S. seasonal extreme precipitation.

Extreme precipitation events occur when the air is nearly completely saturated. Hence, extreme precipitation events are generally observed to increase in intensity by about 6% to 7% for each degree Celsius of temperature increase, as dictated by the Clausius–Clapeyron relation. Figure 7.2 shows the observed change in the 20-year return value of the seasonal maximum 1-day precipitation totals over the period 1948–2015. A mix of increases and decreases is shown, with the Northwest showing very small changes in all seasons, the southern Great Plains showing a large increase in winter, and the Southeast showing a large increase in the fall.

[INSERT FIGURE 7.2 HERE]

A U.S. index of extreme precipitation from NCA3 was updated (Figure 7.3) through 2016. This is the number of 2-day precipitation events exceeding the threshold for a 5-year recurrence. The values were calculated by first arithmetically averaging the station data for all stations within each 1° by 1° latitude/longitude grid for each year and then averaging over the grid values across CONUS for each year during the period of 1896–2015. The number of events has been well above average for the last three decades. The slight drop from 2006–2010 to 2011–2016 reflects a below average number during the widespread severe meteorological drought year of 2012, while the other years in this pentad were well above average. The index value for 2015 was 80% above the 1901–1960 reference period average and the third highest value in the 120 years of record (after 1998 and 2008).

[INSERT FIGURE 7.3 HERE]

Maximum daily precipitation totals were calculated for consecutive 5-year blocks from 1901 (1901–1905, 1906–1910, 1911–1915, …, 2011–2016) for individual long-term stations. For each 5-year block, these values were aggregated to the regional scale by first arithmetically averaging the station 5-year maximum for all stations within each 2° by 2° latitude/longitude grid and then averaging across all grids within each region to create a regional time series. Finally, a trend was computed for the resulting regional time series. The difference between these two periods (Figure 7.4, upper left panel) indicates substantial increases over the eastern United States, particularly the northeastern United States with an increase of 27% since 1901. The increases are much smaller over the western United States, with the southwestern and northwestern United States showing little increase.

Another index of extreme precipitation from NCA3 (the total precipitation falling in the top 1% of all days with precipitation) was updated through 2016 (Figure 7.4, upper right panel). This analysis is for 1958–2016. There are increases in all regions, with the largest increases again in the northeastern United States. There are some changes in the values compared to NCA3, with

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small increases in some regions such as the Midwest and Southwest and small decreases in others such as the Northeast, but the overall picture of changes is the same.

The national results shown in Figure 7.3 were disaggregated into regional values for two periods: 1901–2016 (Figure 7.4, lower left panel) and 1958–2016 (Figure 7.4, lower right panel) for comparison with Figure 7.4, upper right panel. As with the other metrics, there are large increases over the eastern half of the United States while the increases in the western United States are smaller and there are actually small decreases in the Southwest.

There are differences in the magnitude of changes among the four different regional metrics in Figure 7.4, but the overall picture is the same: large increases in the eastern half of the United States and smaller increases, or slight decreases, in the western United States.

[INSERT FIGURE 7.4 HERE]

7.1.4 Extratropical Cyclones and Mesoscale Convective Systems

As described in Chapter 9: Extreme Storms, there is uncertainty about future changes in winter extratropical cyclones (ETCs) (Colle et al. 2013). Thus, the potential effects on winter extreme precipitation events is also uncertain. Summertime ETC activity across North America has decreased since 1979, with a reduction of more than 35% in the number of strong summertime ETCs (Chang et al. 2016). Most climate models simulate little change over this same historical period, but they project a decrease in summer ETC activity during the remainder of the 21st century (Chang et al. 2016). This is potentially relevant to extreme precipitation in the northeastern quadrant of the United States because a large percentage of the extreme precipitation events in this region are caused by ETCs and their associated fronts (Kunkel et al. 2012). This suggests that in the future there may be fewer opportunities in the summer for extreme precipitation, although increases in water vapor are likely to overcompensate for any decreases in ETCs by increasing the likelihood that an ETC will produce excessive rainfall amounts. A very idealized set of climate simulations (Pfahl et al. 2015) suggests that substantial projected warming will lead to a decrease in the number of ETCs but an increase in the intensity of the strongest ETCs. One factor potentially causing this model ETC intensification is an increase in latent heat release in these storms related to a moister atmosphere. Because of the idealized nature of these simulations, the implications of these results for the real earth–atmosphere system is uncertain. However, the increased latent heat mechanism is likely to occur given the high confidence in a future moister atmosphere. For eastern North America, CMIP5 simulations of the future indicate an increase in strong ETCs (Colle et al. 2013). Thus, it is possible that the most extreme precipitation events associated with ETCs may increase in the future.

Mesoscale convective systems (MCSs), which contribute substantially to warm season precipitation in the tropics and subtropics (Nesbitt et al. 2006), account for about half of rainfall in the central United States (Frisch et al. 1986). Schumacher and Johnson (2006) reported that

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74% of all warm season extreme rain events over the eastern two-thirds of the United States during the period 1999–2003 were associated with an MCS. Feng et al. (2016) found that large regions of the central United States experienced statistically significant upward trends in April–June MCS rainfall of 0.4–0.8 mm per day (approximately 20%–40%) per decade from 1979 to 2014. They further found upward trends in MCS frequency of occurrence, lifetime, and precipitation amount, which they attribute to an enhanced west-to-east pressure gradient (enhanced Great Plains Low-Level Jet) and enhanced specific humidity throughout the eastern Great Plains.

7.1.5 Detection and Attribution

TRENDS

Detectability of trends (compared to internal variability) for a number of precipitation metrics over the continental United States has been examined; however, trends identified for the U.S. regions have not been clearly attributed to anthropogenic forcing (Anderson et al. 2015; Easterling et al. 2016). One study concluded that increasing precipitation trends in some north-central U.S. regions and the extreme annual anomalies there in 2013 were at least partly attributable to the combination of anthropogenic and natural forcing (Knutson et al. 2014).

There is *medium confidence* that anthropogenic forcing has contributed to global-scale intensification of heavy precipitation over land regions with sufficient data coverage (Bindoff et al. 2013). Global changes in extreme precipitation have been attributed to anthropogenically forced climate change (Min et al. 2011, 2013), including annual maximum 1-day and 5-day accumulated precipitation over northern hemisphere land regions and (relevant to this report) over the North American continent (Zhang et al. 2013). Although the United States was not separately assessed, the parts of North America with sufficient data for analysis included the continental United States and parts of southern Canada, Mexico, and Central America. Since the covered region was predominantly over the United States, these detection/attribution findings are applicable to the continental United States.

Analyses of precipitation extreme changes over the United States by region (20-year return values of seasonal daily precipitation over 1948–2015, Figure 7.2) show statistically significant increases consistent with theoretical expectations and previous analyses (Westra et al. 2013). Further, a significant increase in the area affected by precipitation extremes over North America has also been detected (Dittus et al. 2015). There is likely an anthropogenic influence on the upward trend in heavy precipitation (Dittus et al. 2016), although models underestimate the magnitude of the trend. Extreme rainfall from U.S. landfalling tropical cyclones has been higher in recent years (1994–2008) than the long-term historical average, even accounting for temporal changes in storm frequency (Kunkel et al. 2010).

Based on current evidence, it is concluded that detectable but not attributable increases in mean precipitation have occurred over parts of the central United States. Formal detection-attribution

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studies indicate a human contribution to extreme precipitation increases over the continental United States, but confidence is *low* based on those studies alone due to the short observational period, high natural variability, and model uncertainty.

In summary, based on available studies, it is concluded that for the continental United States there is *high confidence* in the detection of extreme precipitation increases, while there is *low confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing. There is stronger evidence for a human contribution (*medium confidence*) when taking into account process-based understanding (increased water vapor in a warmer atmosphere), evidence from weather and climate models, and trends in other parts of the world.

EVENT ATTRIBUTION

A number of recent heavy precipitation events have been examined to determine the degree to which their occurrence and severity can be attributed to human-induced climate change. Table 7.1 summarizes available attribution statements for recent extreme U.S. precipitation events. Seasonal and annual precipitation extremes occurring in the north-central and eastern U.S. regions in 2013 were examined for evidence of an anthropogenic influence on their occurrence (Knutson et al. 2014). Increasing trends in annual precipitation were detected in the northern tier of states, March–May precipitation in the upper Midwest, and June–August precipitation in the eastern United States since 1900. These trends are attributed to external forcing (anthropogenic and natural) but could not be directly attributed to anthropogenic forcing alone. However, based on this analysis, it is concluded that the probability of these kinds of extremes has increased due to anthropogenic forcing.

The human influence on individual storms has been investigated with conflicting results. For example, in examining the attribution of the 2013 Colorado floods, one study finds that despite the expected human-induced increase in available moisture, the GEOS-5 model produces fewer extreme storms in the 1983–2012 period compared to the 1871–1900 period in Colorado during the fall season; the study attributes that behavior to changes in the large-scale circulation (Hoerling et al. 2014). However, another study finds that such coarse models cannot produce the observed magnitude of precipitation due to resolution constraints (Pall et al. 2017). Based on a highly conditional set of hindcast simulations imposing the large-scale meteorology and a substantial increase in both the probability and magnitude of the observed precipitation accumulation magnitudes in that particular meteorological situation, the study could not address the question of whether such situations have become more or less probable. Extreme precipitation event attribution is inherently limited by the rarity of the necessary meteorological conditions and the limited number of model simulations that can be performed to examine rare events. This remains an open and active area of research. However, based on these two studies, the anthropogenic contribution to the 2013 Colorado heavy rainfall-flood event is unclear.

[INSERT TABLE 7.1 HERE]

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7.2 Projections

Changes in precipitation in a warmer climate are governed by many factors. Although energy constraints can be used to understand global changes in precipitation, projecting regional changes is much more difficult because of uncertainty in projecting changes in the large-scale circulation that plays important roles in the formation of clouds and precipitation (Shepherd 2014). For the contiguous United States (CONUS), future changes in seasonal average precipitation will include a mix of increases, decreases, or little change, depending on location and season (Figure 7.5). High-latitude regions are generally projected to become wetter while the subtropical zone is projected to become drier. As the CONUS lies between these two regions, there is significant uncertainty about the sign and magnitude of future anthropogenic changes to seasonal precipitation in much of the region, particularly in the middle latitudes of the Nation. However, because the physical mechanisms controlling extreme precipitation differ from those controlling seasonal average precipitation (Section 7.1.4), in particular atmospheric water vapor will increase with increasing temperatures, confidence is *high* that precipitation extremes will increase in frequency and intensity in the future throughout the CONUS.

Global climate models used to project precipitation changes exhibit varying degrees of fidelity in capturing the observed climatology and seasonal variations of precipitation across the United States. Global or regional climate models with higher horizontal resolution generally achieve better skill than the CMIP5 models in capturing the spatial patterns and magnitude of winter precipitation in the western and southeastern United States (e.g., Mearns et al. 2012; Wehner 2013; Bacmeister et al. 2014; Wehner et al. 2014), leading to improved simulations of snowpack and runoff (e.g., Rauscher et al. 2008; Rasmussen et al. 2011). Simulation of present and future summer precipitation remains a significant challenge, as current convective parameterizations fail to properly represent the statistics of mesoscale convective systems (Boyle and Klein 2010). As a result, high-resolution models that still require the parameterization of deep convection exhibit mixed results (Wehner et al. 2014; Sakaguchi et al. 2015). Advances in computing technology are beginning to enable regional climate modeling at the higher resolutions (1–4 km), permitting the direct simulation of convective clouds systems (e.g., Ban et al. 2014) and eliminating the need for this class of parameterization. However, projections from such models are not yet ready for inclusion in this report.

Important progress has been made by the climate modeling community in providing multimodel ensembles such as CMIP5 (Taylor et al. 2012) and NARCCAP (Mearns et al. 2012) to characterize projection uncertainty arising from model differences and large ensemble simulations such as CESM-LE (Kay et al. 2015) to characterize uncertainty inherent in the climate system due to internal variability. These provide an important resource for examining the uncertainties in future precipitation projections.

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7.2.1 Future Changes in U.S. Seasonal Mean Precipitation

In the United States, projected changes in seasonal mean precipitation span the range from profound decreases to profound increases. And in many regions and seasons, projected changes in precipitation are not large compared to natural variations. The general pattern of change is clear and consistent with theoretical expectations. Figure 7.5 shows the weighted CMIP5 multimodel average seasonal change at the end of the century compared to the present under the RCP8.5 scenario (see Ch. 4: Projections for discussion of RCPs). In this figure, changes projected with high confidence to be larger than natural variations are stippled. Regions where future changes are projected with high confidence to be smaller than natural variations are hatched. In winter and spring, the northern part of the country is projected to become wetter as the global climate warms. In the early to middle parts of this century, this will likely be manifested as increases in snowfall (O'Gorman 2014). By the latter half of the century, as temperature continues to increase, it will be too warm to snow in many current snow-producing situations, and precipitation will mostly be rainfall. In the southwestern United States, precipitation will decrease in the spring but the changes are only a little larger than natural variations. Many other regions of the country will not experience significant changes in average precipitation. This is also the case over most of the country in the summer and fall.

[INSERT FIGURE 7.5 HERE]

This pattern of projected precipitation change arises because of changes in locally available water vapor and weather system shifts. In the northern part of the continent, increases in water vapor, together with changes in circulation that are the result of expansion of the Hadley cell, bring more moisture to these latitudes while maintaining or increasing the frequency of precipitation-producing weather systems. This change in the Hadley circulation (see Ch. 5: Circulation and Variability for discussion of circulation changes) also causes the subtropics, the region between the northern and southern edges of the tropics and the midlatitudes (about 35° of latitude), to be drier in warmer climates as well as moving the mean storm track northward and away from the subtropics, decreasing the frequency of precipitation-producing systems. The combination of these two factors results in precipitation decreases in the southwestern United States, Mexico, and the Caribbean (Collins et al. 2013).

PROJECTED CHANGES IN SNOW

The Third National Climate Assessment (Georgakakos et al. 2014) projected reductions in annual snowpack of up to 40% in the western United States based on the SRES A2 emissions scenario in the CMIP3 suite of climate model projections. Recent research using the CMIP5 suite of climate model projections forced with the RCP8.5 scenario and statistically downscaled for the western United States continues to show the expected declines in various snow metrics, including snow water equivalent, the number of extreme snowfall events, and number of snowfall days (Lute et al. 2015). A northward shift in the rain–snow transition zone in the central

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and eastern United States was found using statistically downscaled CMIP5 simulations forced with RCP8.5. By the end of the 21st century, large areas that are currently snow-dominated in the cold season are expected to be rainfall dominated (Ning and Bradley 2015).

The Variable Infiltration Capacity (VIC) model has been used to investigate the potential effects of climate change on SWE. Declines in SWE are projected in all western U.S. mountain ranges during the 21st century with the virtual disappearance of snowpack in the southernmost mountains by the end of the 21st century under both the RCP4.5 and RCP8.5 scenarios (Gergel et al. 2017). The projected decreases are most robust at the lower elevations of areas where snowpack accumulation is now reliable (for example, the Cascades and northern Sierra Nevada ranges). In these areas, future decreases in SWE are largely driven by increases in temperature. At higher (colder) elevations, projections are driven more by precipitation changes and are thus more uncertain.

7.2.2 Extremes

HEAVY PRECIPITATION EVENTS

Studies project that the observed increase in heavy precipitation events will continue in the future (e.g. Janssen et al. 2014, 2016). Similar to observed changes, increases are expected in all regions, even those regions where total precipitation is projected to decline, such as the southwestern United States. Under the RCP8.5 scenario the number of extreme events (exceeding a 5-year return period) increases by two to three times the historical average in every region (Figure 7.6) by the end of the 21st century, with the largest increases in the Northeast. Under the RCP4.5 scenario, increases are 50%–100%. Research shows that there is strong evidence, both from the observed record and modeling studies, that increased water vapor resulting from higher temperatures is the primary cause of the increases (Kunkel et al. 2013a,b; Wehner 2013). Additional effects on extreme precipitation due to changes in dynamical processes are poorly understood. However atmospheric rivers (ARs), especially along the West Coast of the United States, are projected to increase in number and water vapor transport (Dettinger 2011) and experience landfall at lower latitudes (Shields and Kiehl 2016) by the end of the 21st century.

[INSERT FIGURE 7.6 HERE]

Projections of changes in the 20-year return period amount for daily precipitation (Figure 7.7) using Locally Constructed Analogs (LOCA) downscaled data also show large percentage increases for both the middle and late 21st century. The lower emissions projections (RCP4.5) show increases of around 10% for mid-century and up to 14% for the late century projections. The higher emissions projections show even larger increases for both mid-century and late century projections, with increases of around 20% by late 20th century. No region in either emissions scenario shows a decline in heavy precipitation. The increases in extreme precipitation

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tend to increase with return level, such that increases for the 100-year return level are about 30% by the end of the century under a high emissions scenario.

[INSERT FIGURE 7.7 HERE]

Projections of changes in the distribution of daily precipitation amounts (Figure 7.8) indicate an overall more extreme precipitation climate. Specifically, the projections indicate a slight increase in the numbers of dry days and the very lightest precipitation days and a large increase in the heaviest days. The number of days with precipitation amounts greater than the 95th percentile of all non-zero precipitation days increases by more than 25%. At the same time, the number of days with precipitation amounts in the 10th–80th percentile range decreases.

[INSERT FIGURE 7.8 HERE]

Most global climate models lack sufficient resolution to project changes in MCSs in a changing climate (Kooperman et al. 2013). However, research by Cook et al. (2008) attempted to identify clues to changes in dynamical forcing that create MCSs. To do this, they examined the ability of 18 coupled ocean–atmosphere global climate models (GCMs) to simulate potential 21st century changes in warm-season flow and the associated U.S. Midwest hydrology resulting from increases in greenhouse gases. They selected a subset of six models that best captured the low-level flow and associated dynamics of the present-day climate of the central United States and then analyzed these models for changes due to enhanced greenhouse gas forcing. In each of these models, springtime precipitation increases significantly (by 20%–40%) in the upper Mississippi Valley and decreases to the south. The enhanced moisture convergence leading to modeled future climate rainfall increases in the U.S. Midwest is caused by meridional convergence at 850 hPa, connecting the rainfall changes with the Great Plains Low-Level Jet intensification (Higgins et al. 1997). This is consistent with findings from Feng et al. (2016) in the observational record for the period 1979–2014 and by Pan et al. (2004) by use of a regional climate model.

Changes in intense hourly precipitation events were simulated by Prein et al. 2017 where they found the most intense hourly events (99.9 percentile) in the central United States increase at the expense of moderate intense (97.5 percentile) hourly events in the warm season. They also found the frequency of seasonal hourly precipitation extremes is expected to increase in all regions by up to five times in the same areas that show the highest increases in extreme precipitation rates.

HURRICANE PRECIPITATION

Regional model projections of precipitation from landfalling tropical cyclones over the United States, based on downscaling of CMIP5 model climate changes, suggest that the occurrence frequency of post-landfall tropical cyclones over the United States will change little compared to present day during the 21st century, as the reduced frequency of tropical cyclones over the Atlantic domain is mostly offset by a greater landfalling fraction. However, when downscaling from CMIP3 model climate changes, projections showed a reduced occurrence frequency over

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U.S. land, indicating uncertainty about future outcomes. The average tropical cyclone rainfall rates within 500 km (about 311 miles) of the storm center increased by 8% to 17% in the simulations, which was at least as much as expected from the water vapor content increase factor alone.

Several studies have projected increases of precipitation rates within hurricanes over ocean regions (Knutson et al. 2010), particularly for the Atlantic basin (Knutson et al. 2013). The primary physical mechanism for this increase is the enhanced water vapor content in the warmer atmosphere, which enhances moisture convergence into the storm for a given circulation strength, although a more intense circulation can also contribute (Wang et al. 2015). Since hurricanes are responsible for many of the most extreme precipitation events in the southeastern United States (Kunkel et al. 2010, 2012), such events are likely to be even heavier in the future. In a set of idealized forcing experiments, this effect was partly offset by differences in warming rates at the surface and at altitude (Villarini et al. 2014).

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TRACEABLE ACCOUNTS

Key Finding 1

Annual precipitation has decreased in much of the West, Southwest, and Southeast and increased in most of the Northern and Southern Plains, Midwest, and Northeast. A national average increase of 4% in annual precipitation since 1901 is mostly a result of large increases in the fall season. (*Medium confidence*)

Description of evidence base

The key finding and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Evidence of long-term changes in precipitation is based on analysis of daily precipitation observations from the U.S. Cooperative Observer Network (http://www.nws.noaa.gov/om/coop/) and shown in Figure 7.1. Published work, such as the Third National Climate Assessment (Melillo et al. 2014), and Figure 7.1 show important regional and seasonal differences in U.S. precipitation change since 1901.

Major uncertainties

The main source of uncertainty is the sensitivity of observed precipitation trends to the spatial distribution of observing stations and to historical changes in station location, rain gauges, the local landscape, and observing practices. These issues are mitigated somewhat by new methods to produce spatial grids through time (Vose et al. 2014).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Based on the evidence and understanding of the issues leading to uncertainties, confidence is *medium* that average annual precipitation has increased in the United States. Furthermore, confidence is also *medium* that the important regional and seasonal differences in changes documented in the text and in Figure 7.1 are robust.

Summary sentence or paragraph that integrates the above information

Based on the patterns shown in Figure 7.1 and numerous additional studies of precipitation changes in the United States, there is *medium confidence* in the observed changes in annual and seasonal precipitation over the various regions and the United States as a whole.

Key Finding 2

Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 (*high confidence*). There are important regional differences in trends, with

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the largest increases occurring in the northeastern United States (*high confidence*). In particular, mesoscale convective systems (organized clusters of thunderstorms)—the main mechanism for warm season precipitation in the central part of the United States—have increased in occurrence and precipitation amounts since 1979 (*medium confidence*).

Description of evidence base

The key finding and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. Numerous papers have been written documenting observed changes in heavy precipitation events in the United States, including those cited in the Third National Climate Assessment and in this assessment. Although station based analyses (e.g., Westra et al. 2013) do not show large numbers of statistically significant station-based trends, area averaging reduces the noise inherent in station-based data and produces robust increasing signals (see Figures 7.2 and 7.3). Evidence of long-term changes in precipitation is based on analysis of daily precipitation observations from the U.S. Cooperative Observer Network (http://www.nws.noaa.gov/om/coop/) and shown in Figures 7.2, 7.3, and 7.4.

Major uncertainties

The main source of uncertainty is the sensitivity of observed precipitation trends to the spatial distribution of observing stations and to historical changes in station location, rain gauges, and observing practices. These issues are mitigated somewhat by methods used to produce spatial grids through gridbox averaging.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Based on the evidence and understanding of the issues leading to uncertainties, confidence is *high* that heavy precipitation events have increased in the United States. Furthermore, confidence is also *high* that the important regional and seasonal differences in changes documented in the text and in Figures 7.2, 7.3, and 7.4 are robust.

Summary sentence or paragraph that integrates the above information

Based on numerous analyses of the observed record in the United States there is *high confidence* in the observed changes in heavy precipitation events, and *medium confidence* in observed changes in mesoscale convective systems.

Key Finding 3

The frequency and intensity of heavy precipitation events are projected to continue to increase over the 21st century (*high confidence*). Mesoscale convective systems in the central United

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States, are expected to continue to increase in number and intensity in the future (*medium confidence*). There are, however, important regional and seasonal differences in projected changes in total precipitation: the northern United States, including Alaska, is projected to receive more precipitation in the winter and spring, and parts of the southwestern United States are projected to receive less precipitation in the winter and spring (*medium confidence*).

Description of evidence base

Evidence for future changes in precipitation is based on climate model projections and our understanding of the climate system's response to increasing greenhouse gases and of regional mechanisms behind the projected changes. In particular, Figure 7.7 documents projected changes in the 20-year return period amount using the LOCA data, and Figure 7.6 shows changes in 2 day totals for the 5-year return period using the CMIP5 suite of models. Each figure shows robust changes in extreme precipitation events as they are defined in the figure. However, Figure 7.5, which shows changes in seasonal and annual precipitation, indicate where confidence in the changes is higher based on consistency between the models and that there are large areas where the projected change is uncertain.

Major uncertainties

A key issue is how well climate models simulate precipitation, which is one of the more challenging aspects of weather and climate simulation. In particular, comparisons of model projections for total precipitation (from both CMIP3 and CMIP5, see Sun et al. 2015) by NCA3 region show a spread of responses in some regions (for example, the Southwest) such that they are opposite from the ensemble average response. The continental United States is positioned in the transition zone between expected drying in the sub-tropics and wetting in the mid- and higher-latitudes. There are some differences in the location of this transition between CMIP3 and CMIP5 models and thus there remains uncertainty in the exact location of the transition zone.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Based on evidence from climate model simulations and our fundamental understanding of the relationship of water vapor to temperature, confidence is *high* that extreme precipitation will increase in all regions of the United States. However, based on the evidence and understanding of the issues leading to uncertainties, confidence is *medium* that that more total precipitation is projected for the northern U.S. and less for the Southwest.

Summary sentence or paragraph that integrates the above information

Based on numerous analyses of model simulations and our understanding of the climate system there is *high confidence* in the projected changes in precipitation extremes and *medium confidence* in projected changes in total precipitation over the United States.

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Key Finding 4

Northern Hemisphere spring snow cover extent, North America maximum snow depth, snow water equivalent in the western United States, and extreme snowfall years in the southern and western United States have all declined, while extreme snowfall years in parts of the northern United States have increased (*medium confidence*). Projections indicate large declines in snowpack in the western United States and shifts to more precipitation falling as rain than snow in the cold season in many parts of the central and eastern United States (*high confidence*).

Description of evidence base

Evidence of historical changes in snow cover extent and a reduction in extreme snowfall years is consistent with our understanding of the climate system's response to increasing greenhouse gases. Furthermore, climate models continue to consistently show future declines in snowpack in the western United States. Recent model projections for the eastern United States also confirm a future shift from snowfall to rainfall during the cold season in colder portions of the central and eastern United States. Each of these changes is documented in the peer-reviewed literature and are cited in the main text of this chapter.

Major uncertainties

The main source of uncertainty is the sensitivity of observed snow changes to the spatial distribution of observing stations and to historical changes in station location, rain gauges, and observing practices, particularly for snow. Another key issue is the ability of climate models to simulate precipitation, particularly snow. Future changes in the frequency and intensity of meteorological systems causing heavy snow are less certain than temperature changes.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Given the evidence base and uncertainties, confidence is *medium* that snow cover extent has declined in the United States and *medium* that extreme snowfall years have declined in recent years. Confidence is *high* that western United States snowpack will decline in the future, and confidence is *medium* that a shift from snow domination to rain domination will occur in the parts of the central and eastern United States cited in the text.

Summary sentence or paragraph that integrates the above information

Based on observational analyses of snow cover, depth and water equivalent there is *medium confidence* in the observed changes, and based on model simulations for the future there is *high confidence* in snowpack declines in the Western United States and *medium confidence* in the shift to rain from snow in the eastern United States.

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TABLE

Table 7.1: A list of U.S. extreme precipitation events for which attribution statements have been made. In the last column, "+" indicates that an attributable human-induced increase in frequency and/or magnitude was found, "-" indicates that an attributable human-induced decrease in frequency and/or magnitude was found, "0" indicates no attributable human contribution was identified. As in tables 6.1 and 8.2, several of the events were originally examined in the *Bulletin of the American Meteorological Society's* (BAMS) State of the Climate Reports and reexamined by Angélil et al. (2017). In these cases, both attribution statements are listed with the original authors first. Source: M. Wehner.

Authors	Event year and duration	Region	Type	Attribution statement
Knutson et al. 2014 / Angélil et al. 2017	ANN 2013	U.S. Northern Tier	Wet	+/0
Knutson et al. 2014 / Angélil et al. 2017	MAM 2013	U.S. Upper Midwest	Wet	+/+
Knutson et al. 2014 / Angélil et al. 2017	JJA 2013	Eastern U.S. Region	Wet	+/-
Edwards et al. 2014	October 4-5, 2013	South Dakota	Blizzard	0
Hoerling et al. 2014	September 10-14, 2013	Colorado	Wet	0
Pall et al. 2017	September 10-14, 2013	Colorado	Wet	+

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FIGURES

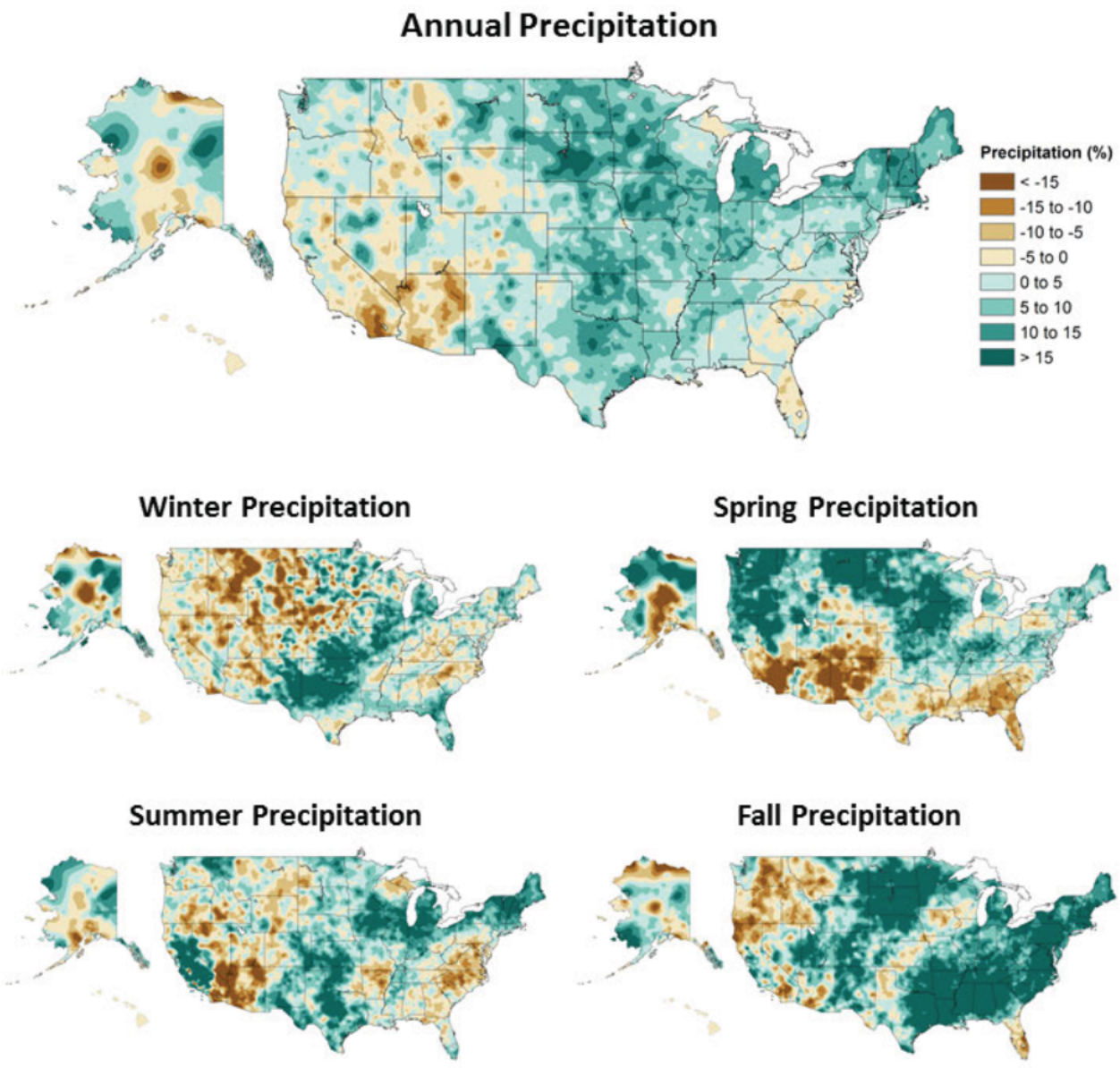

Figure 7.1: Annual and seasonal changes in precipitation over the contiguous United States. Changes are the average for present-day (1986–2015) minus the average for the first half of the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska and Hawaii) divided by the average for the first half of the century. (Figure source: [top panel] adapted from Peterson et al. 2013, © American Meteorological Society. Used with permission; [bottom four panels] NOAA NCEI, data source: nCLIMDiv].

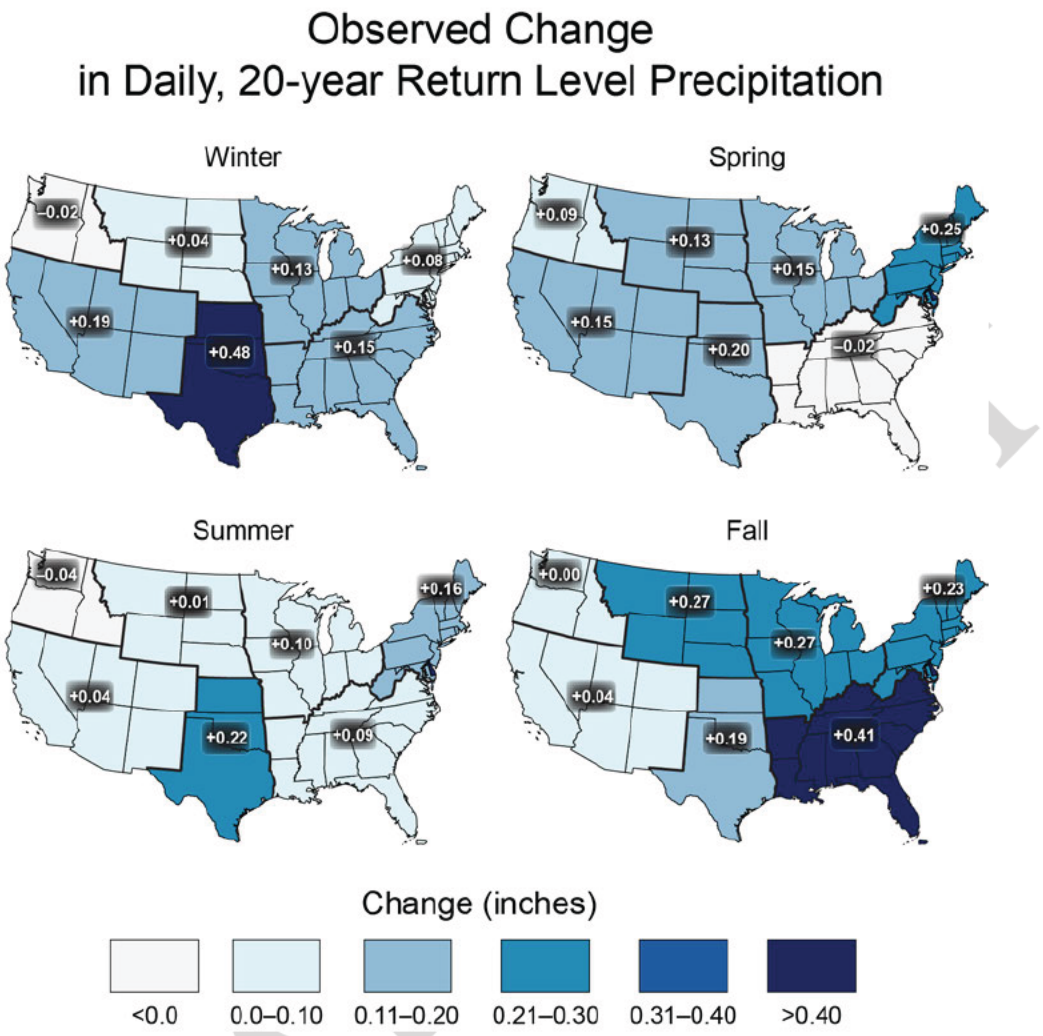

Figure 7.2: Observed changes in the 20-year return value of the seasonal daily precipitation totals over the period 1948 to 2015 using data from the Global Historical Climatology Network (GHCN) dataset. (Figure source: adapted from Kunkel et al. 2013; © American Meteorological Society. Used with permission.)

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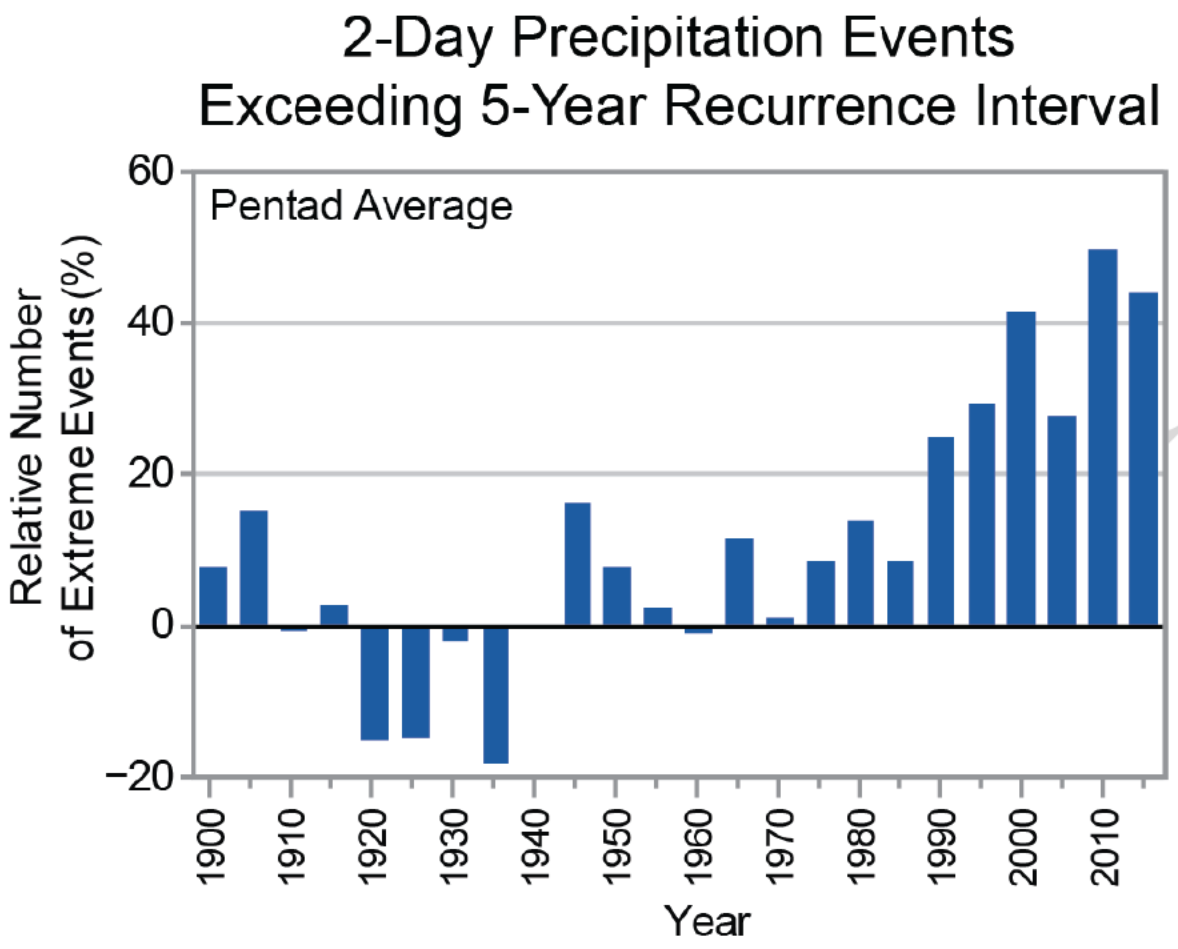

Figure 7.3: Index of the number of 2-day precipitation events exceeding the station-specific threshold for a 5-year recurrence interval, expressed as a percentage difference from the 1901–1960 mean. The annual values are averaged over 5-year periods, with the pentad label indicating the ending year of the period. Annual time series of the number of events are first calculated at individual stations. Next, the grid box time series are calculated as the average of all stations in the grid box. Finally, a national time series is calculated as the average of the grid box time series. Data source: GHCN-Daily. (Figure source: CICS-NC / NOAA NCEI).

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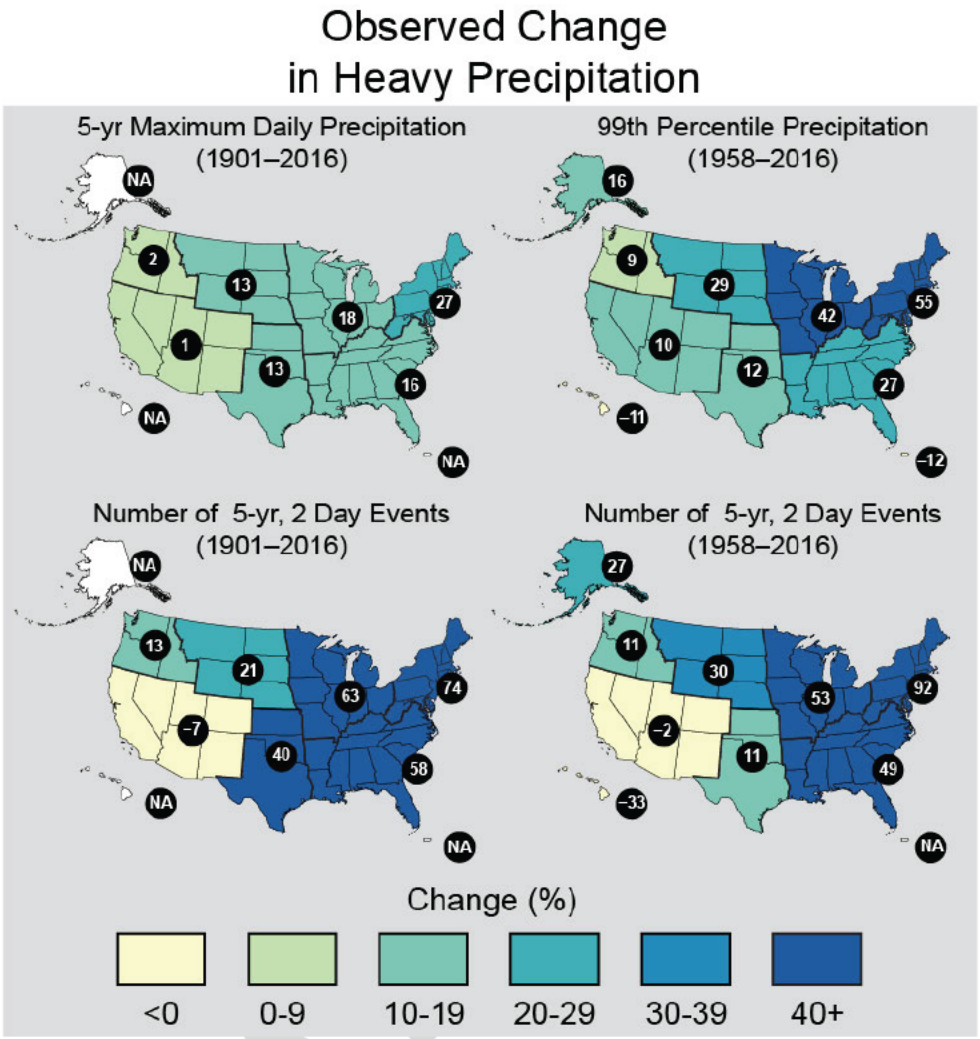

Figure 7.4: These maps show the change in several metrics of extreme precipitation by NCA4 region, including (upper left) the maximum daily precipitation in consecutive 5-year blocks, (upper right) the amount of precipitation falling in daily events that exceed the 99th percentile of all non-zero precipitation days, (lower left) the number of 2-day events with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average, only once every 5 years, as calculated over 1901–2016, and (lower right) the number of 2-day events with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average, only once every 5 years, as calculated over 1958–2016. The numerical value is the percent change over the entire period, either 1901–2016 or 1958–2016. The percentages are first calculated for individual stations, then averaged over 2° latitude by 2° longitude grid boxes, and finally averaged over each NCA4 region. Note that Alaska and Hawai'i are not included in the 1901–2016 maps owing to a lack of observations in the earlier part of the 20th century. (Figure source: CICS-NC / NOAA NCEI).

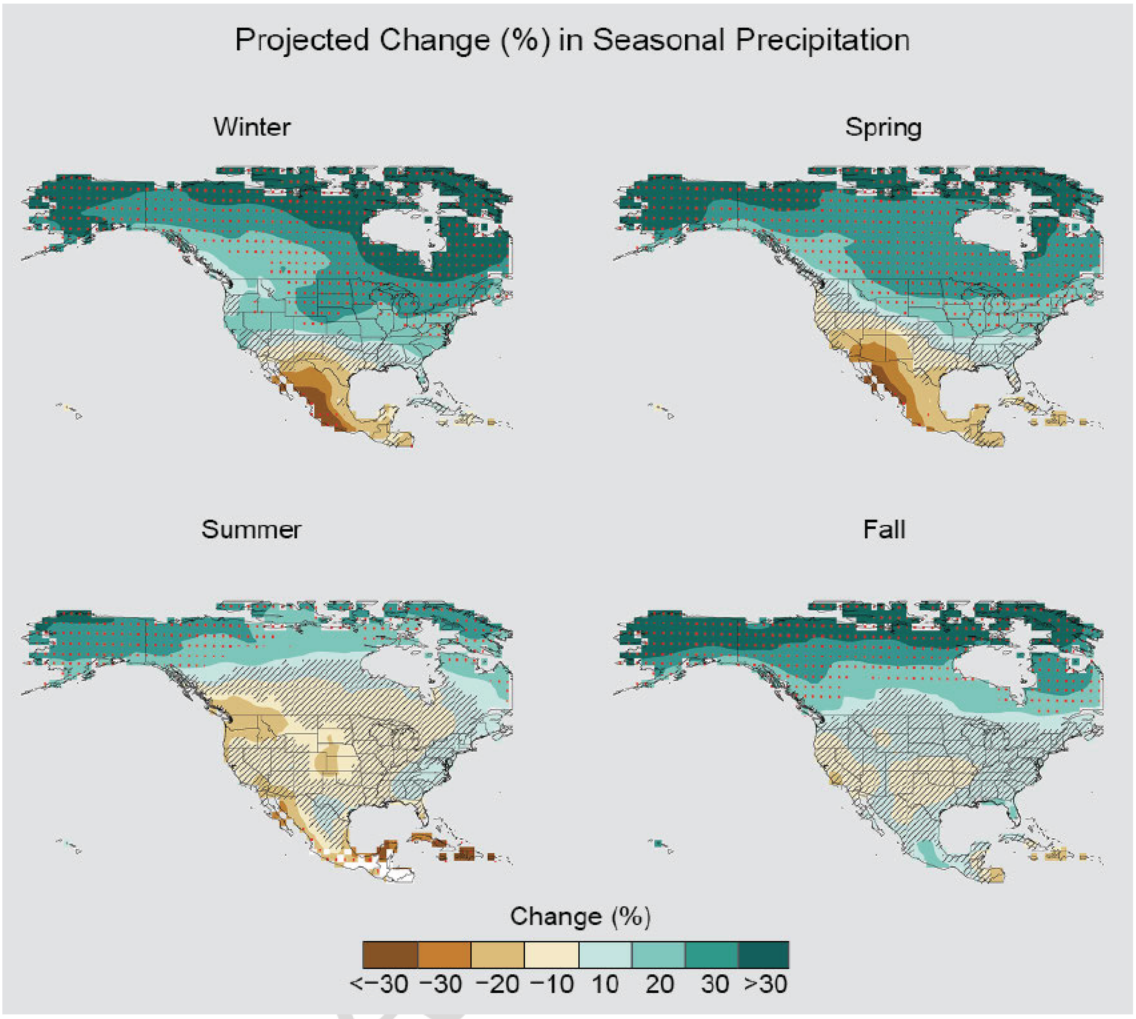

Figure 7.5: Projected change (%) in total seasonal precipitation from CMIP5 simulations for 2070-2099. The values are weighted multimodel means and expressed as the percent change relative to the 1976–2005 average. These are results for the RCP8.5 pathway. Stippling indicates that changes are assessed to be large compared to natural variations. Hatching indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive. Data source: World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project. (Figure source: NOAA NCEI).

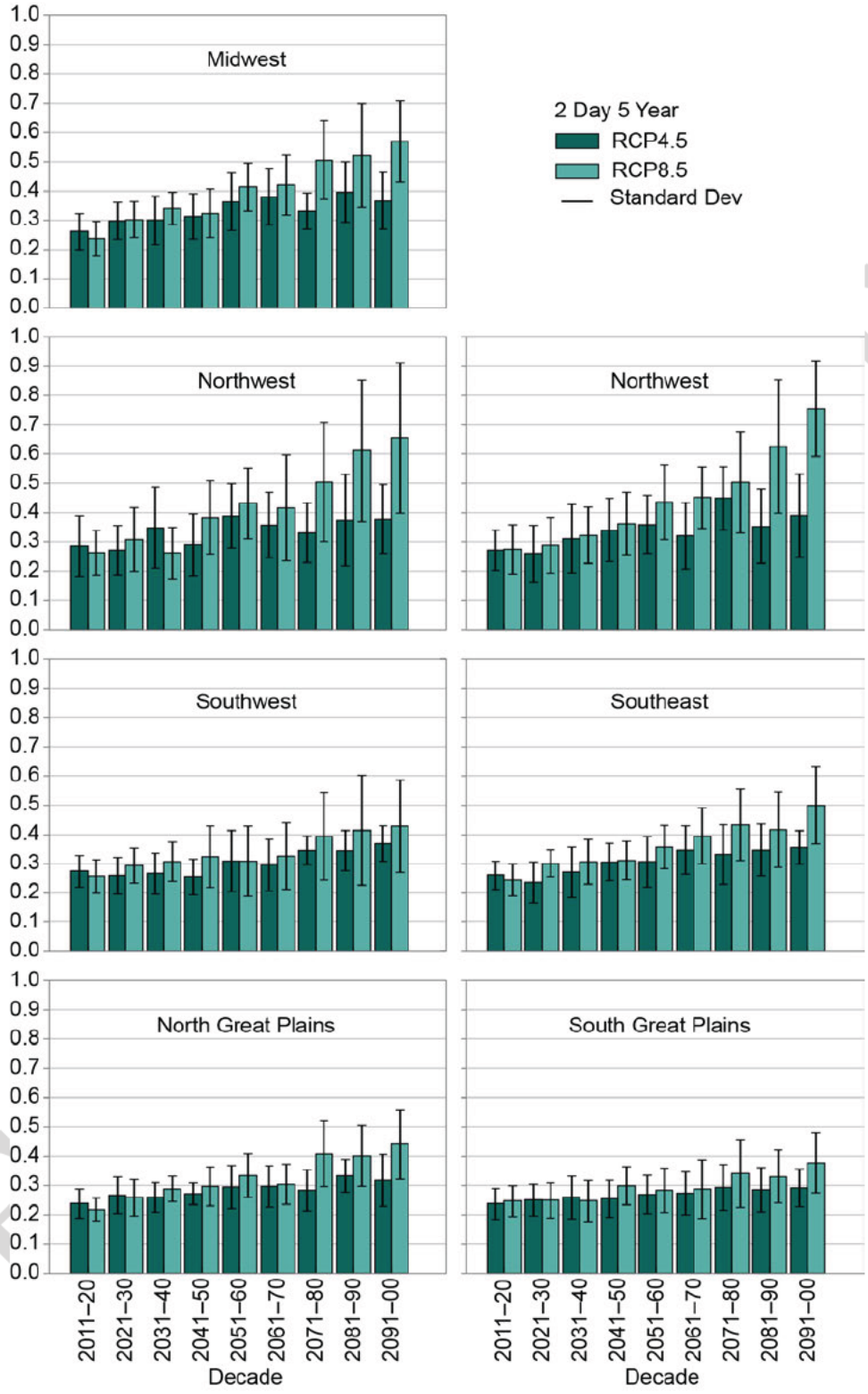

Figure 7.6: Regional extreme precipitation event frequency for RCP4.5 (green; 16 CMIP5 models) and RCP8.5 (blue; 14 CMIP5 models) for a 2-day duration and 5-year return. Calculated for 2006–2100 but decadal anomalies begin in 2011. Error bars are ±1 standard deviation;

standard deviation is calculated from the 14 or 16 model values that represent the aggregated average over the regions, over the decades, and over the ensemble members of each model. The average frequency for the historical reference period is 0.2 by definition and the values in this graph should be interpreted with respect to a comparison with this historical average value. (Figure source: Janssen et al. 2014).

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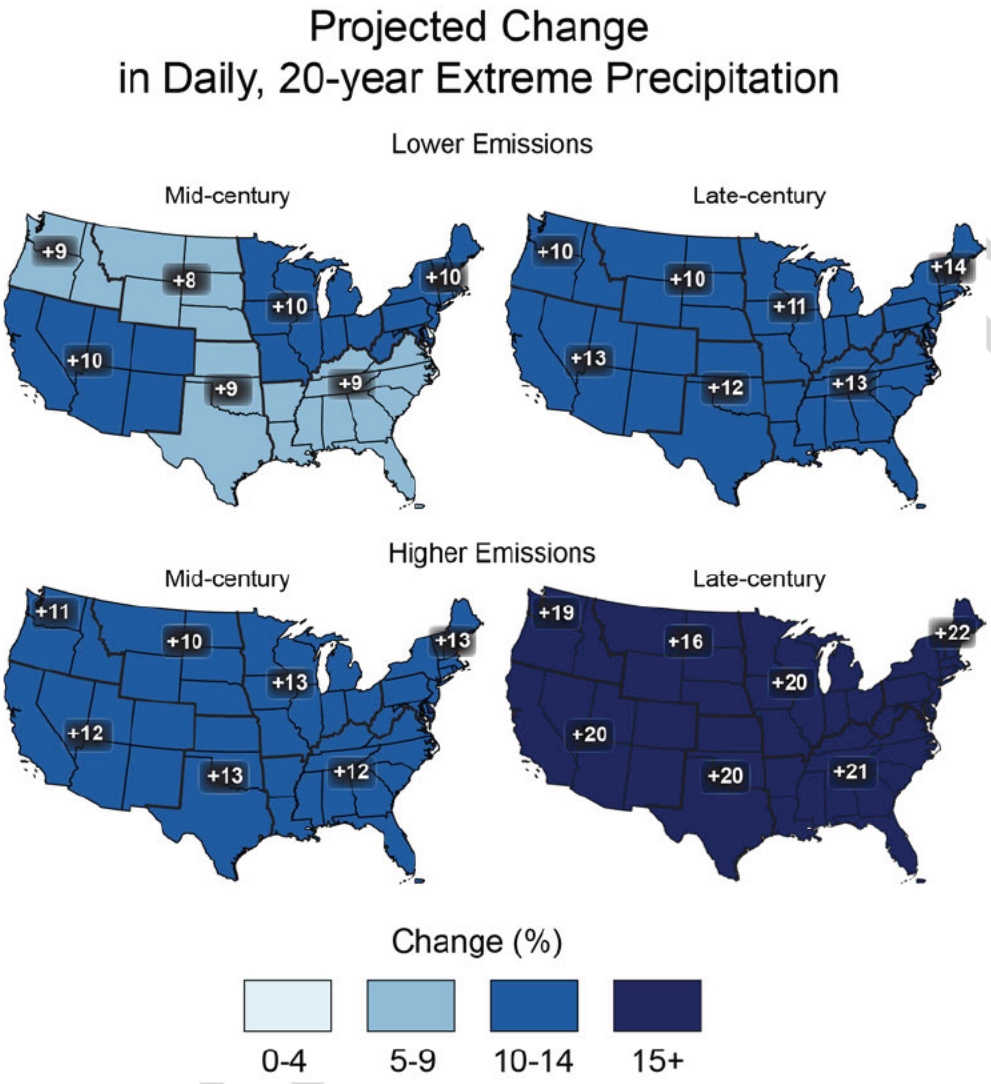

Figure 7.7: Projected change in the 20-year return period amount for daily precipitation for mid- (left maps) and late-21st century (right maps). Results are shown for a lower emissions scenario (top maps; RCP4.5) and for a higher emissions scenario (bottom maps, RCP8.5). These results are calculated from the LOCA downscaled data. (Figure source: CICS-NC / NOAA NCEI).

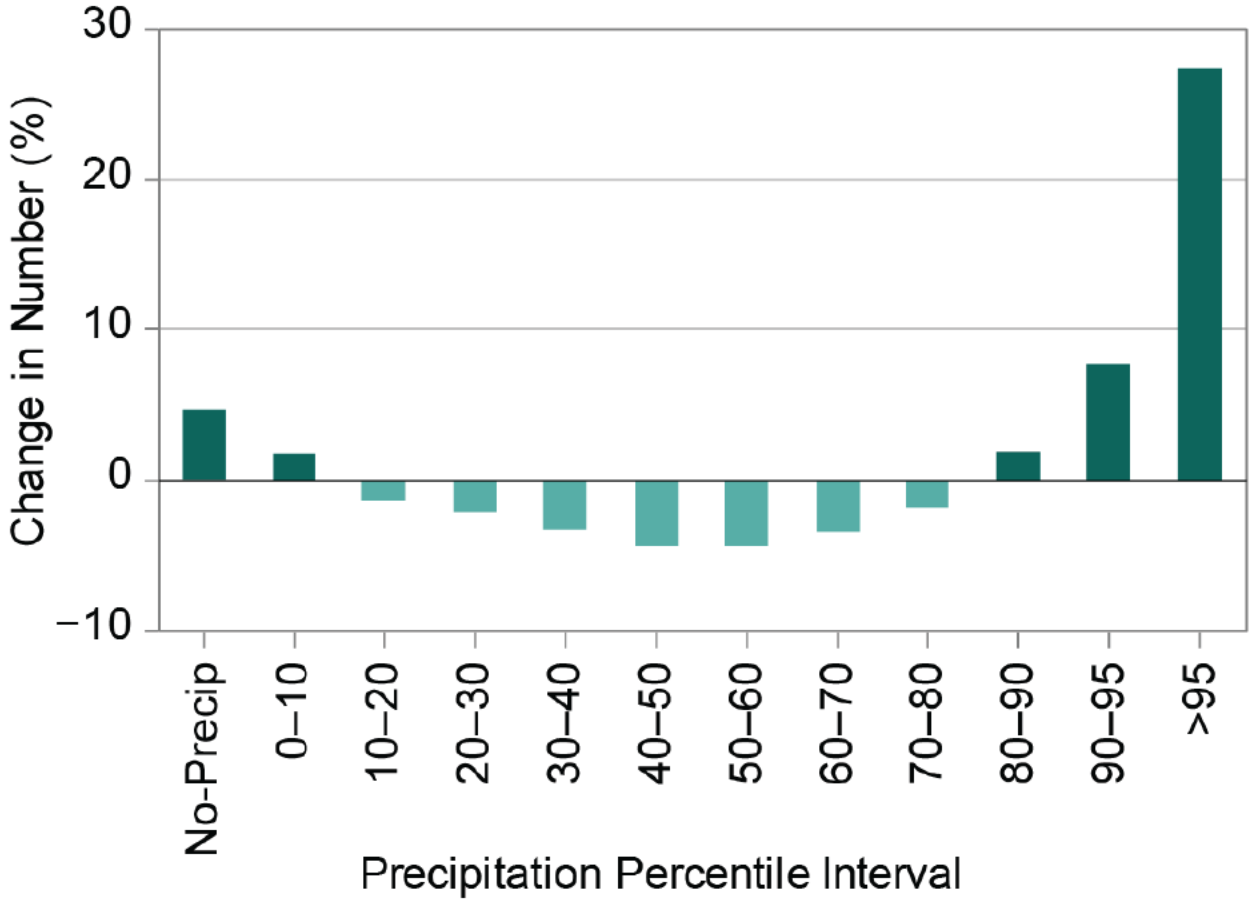

Figure 7.8: Projected change (percentage change relative to the 1976–2005 reference period average) in the number of daily zero ("No-Precip") and non-zero precipitation days (by percentile bins) for late-21st century under a high emissions scenario (RCP8.5). The precipitation percentile bin thresholds are based on daily non-zero precipitation amounts from the 1976–2005 reference period that have been ranked from low to high. These results are calculated from the LOCA downscaled data. (Figure source: CICS-NC / NOAA NCEI).

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REFERENCES

Anderson, B.T., D.J. Gianotti, and G.D. Salvucci, 2015: Detectability of historical trends in station-based precipitation characteristics over the continental United States. *Journal of Geophysical Research: Atmospheres,* **120,** 4842-4859. http://dx.doi.org/10.1002/2014JD022960

Angélil, O., D. Stone, M. Wehner, C.J. Paciorek, H. Krishnan, and W. Collins, 2017: An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. *Journal of Climate,* **30,** 5-16. http://dx.doi.org/10.1175/JCLI-D-16-0077.1

Bacmeister, J.T., M.F. Wehner, R.B. Neale, A. Gettelman, C. Hannay, P.H. Lauritzen, J.M. Caron, and J.E. Truesdale, 2014: Exploratory high-resolution climate simulations using the Community Atmosphere Model (CAM). *Journal of Climate,* **27,** 3073-3099. http://dx.doi.org/10.1175/JCLI-D-13-00387.1

Ban, N., J. Schmidli, and C. Schär, 2014: Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. *Journal of Geophysical Research: Atmospheres,* **119,** 7889-7907. http://dx.doi.org/10.1002/2014JD021478

Bard, L. and D.A.R. Kristovich, 2012: Trend reversal in Lake Michigan contribution to snowfall. *Journal of Applied Meteorology and Climatology,* **51,** 2038-2046. http://dx.doi.org/10.1175/jamc-d-12-064.1

Barnston, A.G. and B. Lyon, 2016: Does the NMME capture a recent decadal shift toward increasing drought occurrence in the southwestern United States? *Journal of Climate,* **29,** 561-581. http://dx.doi.org/10.1175/JCLI-D-15-0311.1

Belmecheri, S., F. Babst, E.R. Wahl, D.W. Stahle, and V. Trouet, 2016: Multi-century evaluation of Sierra Nevada snowpack. *Nature Climate Change,* **6,** 2-3. http://dx.doi.org/10.1038/nclimate2809

Boyle, J., and Stephen A. Klein, 2010: Impact of horizontal resolution on climate model forecasts of tropical convection and diabatic heating for the TWP-ICE period *Journal of Geophysical Research*, **115**, D23113, doi: 10.1029/2010JD014262 .

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.

FINAL DRAFT

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952. http://www.climatechange2013.org/report/full-report/

Chang, E.K.M., C.-G. Ma, C. Zheng, and A.M.W. Yau, 2016: Observed and projected decrease in Northern Hemisphere extratropical cyclone activity in summer and its impacts on maximum temperature. *Geophysical Research Letters,* **43,** 2200-2208. http://dx.doi.org/10.1002/2016GL068172

Colle, B.A., Z. Zhang, K.A. Lombardo, E. Chang, P. Liu, and M. Zhang, 2013: Historical evaluation and future prediction of eastern North American and western Atlantic extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate,* **26,** 6882-6903. http://dx.doi.org/10.1175/JCLI-D-12-00498.1

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

Cook, K.H., E.K. Vizy, Z.S. Launer, and C.M. Patricola, 2008: Springtime intensification of the Great Plains low-level jet and midwest precipitation in GCM simulations of the twenty-first century. *Journal of Climate,* **21,** 6321-6340. http://dx.doi.org/10.1175/2008jcli2355.1

Dettinger, M., 2011: Climate change, atmospheric rivers, and floods in California–a multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association,* **47,** 514-523. http://dx.doi.org/10.1111/j.1752-1688.2011.00546.x

Dittus, A.J., D.J. Karoly, S.C. Lewis, and L.V. Alexander, 2015: A multiregion assessment of observed changes in the areal extent of temperature and precipitation extremes. *Journal of Climate,* **28,** 9206-9220. http://dx.doi.org/10.1175/JCLI-D-14-00753.1

Dittus, A.J., D.J. Karoly, S.C. Lewis, L.V. Alexander, and M.G. Donat, 2016: A multiregion model evaluation and attribution study of historical changes in the area affected by temperature and precipitation extremes. *Journal of Climate,* **29**, 8285-8299. http://dx.doi.org/10.1175/jcli-d-16-0164.1

Easterling, D.R., K.E. Kunkel, M.F. Wehner, and L. Sun, 2016: Detection and attribution of climate extremes in the observed record. *Weather and Climate Extremes,* **11,** 17-27. http://dx.doi.org/10.1016/j.wace.2016.01.001

FINAL DRAFT

Edwards, L.M., M. Bunkers, J.T. Abatzoglou, D.P. Todey, and L.E. Parker, 2014: October 2013 blizzard in western South Dakota [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S23-S26. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Feng, Z., L.R. Leung, S. Hagos, R.A. Houze, C.D. Burleyson, and K. Balaguru, 2016: More frequent intense and long-lived storms dominate the springtime trend in central US rainfall. *Nature Communications,* **7,** 13429. http://dx.doi.org/10.1038/ncomms13429

Fritsch, J.M., R.J. Kane, and C.R. Chelius, 1986: The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. *Journal of Climate and Applied Meteorology,* **25,** 1333-1345. http://dx.doi.org/10.1175/1520-0450(1986)025<1333:tcomcw>2.0.co;2

Gan, T.Y., R.G. Barry, M. Gizaw, A. Gobena, and R. Balaji, 2013: Changes in North American snowpacks for 1979–2007 detected from the snow water equivalent data of SMMR and SSM/I passive microwave and related climatic factors. *Journal of Geophysical Research: Atmospheres,* **118,** 7682–7697. http://dx.doi.org/10.1002/jgrd.50507

Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, T.C. Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water resources. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, D.C., 69-112. http://dx.doi.org/10.7930/J0G44N6T

Gergel, D.R., B. Nijssen, J.T. Abatzoglou, D.P. Lettenmaier, and M.R. Stumbaugh, 2017: Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change,* **141,** 287-299. http://dx.doi.org/10.1007/s10584-017-1899-y

Hartnett, J.J., J.M. Collins, M.A. Baxter, and D.P. Chambers, 2014: Spatiotemporal snowfall trends in central New York. *Journal of Applied Meteorology and Climatology,* **53,** 2685-2697. http://dx.doi.org/10.1175/jamc-d-14-0084.1

Higgins, R.W., Y. Yao, E.S. Yarosh, J.E. Janowiak, and K.C. Mo, 1997: Influence of the Great Plains low-level jet on summertime precipitation and moisture transport over the central United States. *Journal of Climate,* **10,** 481-507. http://dx.doi.org/10.1175/1520-0442(1997)010<0481:iotgpl>2.0.co;2

Hoerling, M., K. Wolter, J. Perlwitz, X. Quan, J. Eischeid, H. Want, S. Schubert, H. Diaz, and R. Dole, 2014: Northeast Colorado extreme rains interpreted in a climate change context [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S15-S18. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

FINAL DRAFT

Janssen, E., D.J. Wuebbles, K.E. Kunkel, S.C. Olsen, and A. Goodman, 2014: Observational- and model-based trends and projections of extreme precipitation over the contiguous United States. *Earth's Future,* **2,** 99-113. http://dx.doi.org/10.1002/2013EF000185

Janssen, E., R.L. Sriver, D.J. Wuebbles, and K.E. Kunkel, 2016: Seasonal and regional variations in extreme precipitation event frequency using CMIP5. *Geophysical Research Letters,* **43,** 5385-5393. http://dx.doi.org/10.1002/2016GL069151

Kay, J.E., C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J.M. Arblaster, S.C. Bates, G. Danabasoglu, J. Edwards, M. Holland, P. Kushner, J.-F. Lamarque, D. Lawrence, K. Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, and M. Vertenstein, 2015: The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society,* **96 (12),** 1333-1349. http://dx.doi.org/10.1175/BAMS-D-13-00255.1

Kluver, D. and D. Leathers, 2015: Regionalization of snowfall frequency and trends over the contiguous United States. *International Journal of Climatology,* **35,** 4348-4358. http://dx.doi.org/10.1002/joc.4292

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature Geoscience,* **3,** 157-163. http://dx.doi.org/10.1038/ngeo779

Knutson, T.R., J.J. Sirutis, G.A. Vecchi, S. Garner, M. Zhao, H.-S. Kim, M. Bender, R.E. Tuleya, I.M. Held, and G. Villarini, 2013: Dynamical downscaling projections of twenty-first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal of Climate,* **27,** 6591-6617. http://dx.doi.org/10.1175/jcli-d-12-00539.1

Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2014: Seasonal and annual mean precipitation extremes occurring during 2013: A U.S. focused analysis [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S19-S23. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Kooperman, G.J., M.S. Pritchard, and R.C.J. Somerville, 2013: Robustness and sensitivities of central U.S. summer convection in the super-parameterized CAM: Multi-model intercomparison with a new regional EOF index. *Geophysical Research Letters,* **40,** 3287-3291. http://dx.doi.org/10.1002/grl.50597

Kunkel, K.E., D.R. Easterling, D.A.R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2010: Recent increases in U.S. heavy precipitation associated with tropical cyclones. *Geophysical Research Letters,* **37,** L24706. http://dx.doi.org/10.1029/2010GL045164

FINAL DRAFT

Kunkel, K.E., D.R. Easterling, D.A. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012: Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. *Journal of Hydrometeorology,* **13,** 1131-1141. http://dx.doi.org/10.1175/JHM-D-11-0108.1

Kunkel, K.E., T.R. Karl, H. Brooks, J. Kossin, J. Lawrimore, D. Arndt, L. Bosart, D. Changnon, S.L. Cutter, N. Doesken, K. Emanuel, P.Y. Groisman, R.W. Katz, T. Knutson, J. O'Brien, C.J. Paciorek, T.C. Peterson, K. Redmond, D. Robinson, J. Trapp, R. Vose, S. Weaver, M. Wehner, K. Wolter, and D. Wuebbles, 2013: Monitoring and understanding trends in extreme storms: State of knowledge. *Bulletin of the American Meteorological Society,* **94**. http://dx.doi.org/10.1175/BAMS-D-11-00262.1

Kunkel, K.E., T.R. Karl, D.R. Easterling, K. Redmond, J. Young, X. Yin, and P. Hennon, 2013: Probable maximum precipitation and climate change. *Geophysical Research Letters,* **40,** 1402-1408. http://dx.doi.org/10.1002/grl.50334

Kunkel, K.E., D.A. Robinson, S. Champion, X. Yin, T. Estilow, and R.M. Frankson, 2016: Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change Reports,* **2,** 65-73. http://dx.doi.org/10.1007/s40641-016-0036-8

Luce, C.H., J.T. Abatzoglou and Z.A. Holden, Z.A., 2013: The missing mountain water: Slower westerlies decrease orographic enhancement in the Pacific Northwest USA. *Science*, **342**, 1360-1364

Lute, A.C. and J.T. Abatzoglou, 2014: Role of extreme snowfall events in interannual variability of snowfall accumulation in the western United States. *Water Resources Research,* **50,** 2874-2888. http://dx.doi.org/10.1002/2013WR014465

Lute, A.C., J.T. Abatzoglou, and K.C. Hegewisch, 2015: Projected changes in snowfall extremes and interannual variability of snowfall in the western United States. *Water Resources Research,* **51,** 960-972. http://dx.doi.org/10.1002/2014WR016267

Mearns, L.O., R. Arritt, S. Biner, M.S. Bukovsky, S. Stain, S. Sain, D. Caya, J. Correia, Jr., D. Flory, W. Gutowski, E.S. Takle, R. Jones, R. Leung, W. Moufouma-Okia, L. McDaniel, A.M.B. Nunes, Y. Qian, J. Roads, L. Sloan, and M. Snyder, 2012: The North American regional climate change assessment program: Overview of phase I results. *Bulletin of the American Meteorological Society,* **93,** 1337-1362. http://dx.doi.org/10.1175/BAMS-D-11-00223.1

Melillo, J. M., T. C. Richmond, and G. W. Yohe, Eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, 841 pp.

FINAL DRAFT

Min, S.K., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature,* **470,** 378-381. http://dx.doi.org/10.1038/nature09763

Min, S.-K., X. Zhang, F. Zwiers, H. Shiogama, Y.-S. Tung, and M. Wehner, 2013: Multimodel detection and attribution of extreme temperature changes. *Journal of Climate,* **26,** 7430-7451. http://dx.doi.org/10.1175/JCLI-D-12-00551.1

Nesbitt, S.W., R. Cifelli, and S.A. Rutledge, 2006: Storm morphology and rainfall characteristics of TRMM precipitation features. *Monthly Weather Review,* **134,** 2702-2721. http://dx.doi.org/10.1175/mwr3200.1

Ning, L. and R.S. Bradley, 2015: Snow occurrence changes over the central and eastern United States under future warming scenarios. *Scientific Reports,* **5,** 17073. http://dx.doi.org/10.1038/srep17073

NOAA, 2016: Climate at a Glance. http://www.ncdc.noaa.gov/cag/time-series/us/107/0/pdsi/12/12/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000

NOAA, 2016: Climate at a Glance. http://www.ncdc.noaa.gov/cag/time-series/us/4/0/pdsi/12/9/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000

O'Gorman, P.A., 2014: Contrasting responses of mean and extreme snowfall to climate change. *Nature,* **512,** 416-418. http://dx.doi.org/10.1038/nature13625

Pall, P.C.M.P., M.F. Wehner, D.A. Stone, C.J. Paciorek, and W.D. Collins, 2017: Diagnosing anthropogenic contributions to heavy Colorado rainfall in September 2013. *Weather and Climate Extremes,* **In Press**. http://dx.doi.org/10.1016/j.wace.2017.03.004

Pan, Z., R.W. Arritt, E.S. Takle, W.J. Gutowski, Jr., C.J. Anderson, and M. Segal, 2004: Altered hydrologic feedback in a warming climate introduces a "warming hole". *Geophysical Research Letters,* **31,** L17109. http://dx.doi.org/10.1029/2004GL020528

Pederson, G.T., J.L. Betancourt, and G.J. McCabe, 2013: Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S. *Geophysical Research Letters,* **40,** 1811-1816. http://dx.doi.org/10.1002/grl.50424

Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P. Giovannettone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe, C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G. Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D. Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society,* **94,** 821-834. http://dx.doi.org/10.1175/BAMS-D-12-00066.1

FINAL DRAFT

Pfahl, S., P.A. O'Gorman, and M.S. Singh, 2015: Extratropical cyclones in idealized simulations of changed climates. *Journal of Climate,* **28,** 9373-9392. http://dx.doi.org/10.1175/JCLI-D-14-00816.1

Prein, A.F., R.M. Rasmussen, K. Ikeda, C. Liu, M.P. Clark, and G.J. Holland, 2017: The future intensification of hourly precipitation extremes. *Nature Climate Change,* **7,** 48-52. http://dx.doi.org/10.1038/nclimate3168

Rasmussen, R., C. Liu, K. Ikeda, D. Gochis, D. Yates, F. Chen, M. Tewari, M. Barlage, J. Dudhia, W. Yu, K. Miller, K. Arsenault, V. Grubišić, G. Thompson, and E. Gutmann, 2011: High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. *Journal of Climate,* **24,** 3015-3048. http://dx.doi.org/10.1175/2010JCLI3985.1

Rauscher, S.A., J.S. Pal, N.S. Diffenbaugh, and M.M. Benedetti, 2008: Future changes in snowmelt-driven runoff timing over the western US. *Geophysical Research Letters,* **35,** L16703. http://dx.doi.org/10.1029/2008GL034424

Sakaguchi, K., L.R. Leung, C. Zhao, Q. Yang, J. Lu, S. Hagos, S.A. Rauscher, L. Dong, T.D. Ringler, and P.H. Lauritzen, 2015: Exploring a multiresolution approach using AMIP simulations. *Journal of Climate,* **28,** 5549-5574. http://dx.doi.org/10.1175/JCLI-D-14-00729.1

Schumacher, R.S. and R.H. Johnson, 2006: Characteristics of U.S. extreme rain events during 1999–2003. *Weather and Forecasting,* **21,** 69-85. http://dx.doi.org/10.1175/waf900.1

Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate,* **28,** 6997-7024. http://dx.doi.org/10.1175/JCLI-D-14-00860.1

Shepherd, T.G., 2014: Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geoscience,* **7,** 703-708. http://dx.doi.org/10.1038/ngeo2253

Shields, C.A. and J.T. Kiehl, 2016: Atmospheric river landfall-latitude changes in future climate simulations. *Geophysical Research Letters,* **43,** 8775-8782. http://dx.doi.org/10.1002/2016GL070470

Sun, L., K.E. Kunkel, L.E. Stevens, A. Buddenberg, J.G. Dobson, and D.R. Easterling, 2015: Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States: Differences, Similarities, and Implications for the U.S. National Climate Assessment. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 111 pp. http://dx.doi.org/10.7289/V5RB72KG

FINAL DRAFT

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society,* **93,** 485-498. http://dx.doi.org/10.1175/BAMS-D-11-00094.1

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang, 2013: Observations: Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 317–382. http://www.climatechange2013.org/report/full-report/

Vavrus, S., M. Notaro, and A. Zarrin, 2013: The role of ice cover in heavy lake-effect snowstorms over the Great Lakes Basin as simulated by RegCM4. *Monthly Weather Review,* **141,** 148-165. http://dx.doi.org/10.1175/mwr-d-12-00107.1

Villarini, G., D.A. Lavers, E. Scoccimarro, M. Zhao, M.F. Wehner, G.A. Vecchi, T.R. Knutson, and K.A. Reed, 2014: Sensitivity of tropical cyclone rainfall to idealized global-scale forcings. *Journal of Climate,* **27,** 4622-4641. http://dx.doi.org/10.1175/JCLI-D-13-00780.1

Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, Jr., C. Fenimore, K. Gleason, and D. Arndt, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology,* **53,** 1232-1251. http://dx.doi.org/10.1175/JAMC-D-13-0248.1

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, D.C., 19-67. http://dx.doi.org/10.7930/J0KW5CXT

Wang, C.-C., B.-X. Lin, C.-T. Chen, and S.-H. Lo, 2015: Quantifying the effects of long-term climate change on tropical cyclone rainfall using a cloud-resolving model: Examples of two landfall typhoons in Taiwan. *Journal of Climate,* **28,** 66-85. http://dx.doi.org/10.1175/JCLI-D-14-00044.1

Wehner, M.F., 2013: Very extreme seasonal precipitation in the NARCCAP ensemble: Model performance and projections. *Climate Dynamics,* **40,** 59-80. http://dx.doi.org/10.1007/s00382-012-1393-1

Wehner, M.F., K.A. Reed, F. Li, Prabhat, J. Bacmeister, C.-T. Chen, C. Paciorek, P.J. Gleckler, K.R. Sperber, W.D. Collins, A. Gettelman, and C. Jablonowski, 2014: The effect of

FINAL DRAFT

horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1. *Journal of Advances in Modeling Earth Systems,* **6,** 980-997. http://dx.doi.org/10.1002/2013MS000276

Westra, S., L.V. Alexander, and F.W. Zwiers, 2013: Global increasing trends in annual maximum daily precipitation. *Journal of Climate,* **26,** 3904-3918. http://dx.doi.org/10.1175/JCLI-D-12-00502.1

Wright, D.M., D.J. Posselt, and A.L. Steiner, 2013: Sensitivity of lake-effect snowfall to lake ice cover and temperature in the Great Lakes region. *Monthly Weather Review,* **141,** 670-689. http://dx.doi.org/10.1175/mwr-d-12-00038.1

Zhang, X., H. Wan, F.W. Zwiers, G.C. Hegerl, and S.-K. Min, 2013: Attributing intensification of precipitation extremes to human influence. *Geophysical Research Letters,* **40,** 5252-5257. http://dx.doi.org/10.1002/grl.51010

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8. Droughts, Floods, and Wildfires

KEY FINDINGS

1. Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*very high confidence*). While by some measures, drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

2. The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

3. Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*)

4. Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

5. Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases. Extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change, and the timing of any emergence of a future detectable anthropogenic change in flooding is unclear. (*Medium confidence*)

6. The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms, with profound changes to certain ecosystems (*medium confidence*).

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8.1. Drought

The word "drought" brings to mind abnormally dry conditions. However, the meaning of "dry" can be ambiguous and lead to confusion in how drought is actually defined. Three different classes of droughts are defined by NOAA and describe a useful hierarchal set of water deficit characterization, each with different impacts. "Meteorological drought" describes conditions of precipitation deficit. "Agricultural drought" describes conditions of soil moisture deficit. "Hydrological drought" describes conditions of deficit in runoff (NOAA 2008). Clearly these three characterizations of drought are related but are also different descriptions of water shortages with different target audiences and different timescales. In particular, agricultural drought is of concern to producers of food while hydrological drought is of concern to water system managers. Soil moisture is a function of both precipitation and evapotranspiration. Because potential evapotranspiration increases with temperature, anthropogenic climate change generally results in drier soils and often less runoff in the long term. In fact, under the RCP8.5 scenario (see Ch. 4: Projections for a description of the RCP scenarios) at the end of the 21st century, no region of the planet is projected to experience significantly higher levels of annual average surface soil moisture due to the sensitivity of evapotranspiration to temperature, even though much higher precipitation is projected in some regions (Collins et al. 2013). Seasonal and annual total runoff, on the other hand, are projected to either increase or decrease, depending on location and season under the same conditions (Collins et al. 2013), illustrating the complex relationships between the various components of the hydrological system. Meteorological drought can occur on a range of timescales, in addition to seasonal or annual timescales. "Flash droughts" can result from just a few weeks of dry weather (Mo and Lettenmaier 2015), and the paleoclimate record contains droughts of several decades. Hence, it is vital to describe precisely the definition of drought in any public discussion to avoid confusion due to this complexity. As the climate changes, conditions currently considered "abnormally" dry may become relatively "normal" in those regions undergoing aridification, or extremely unlikely in those regions becoming wetter. Hence, the reference conditions defining drought may need to be modified from those currently used in practice.

8.1.1. Historical Context

The United States has experienced all three types of droughts in the past, always driven, at least in some part, by natural variations in seasonal and/or annual precipitation amounts. As the climate changes, we can expect that human activities will alter the effect of these natural variations. The "Dust Bowl" drought of the 1930s is still the most significant meteorological and agricultural drought experienced in the United States in terms of its geographic and temporal extent. However, even though it happened prior to most of the current global warming, human activities exacerbated the dryness of the soil by the farming practices of the time (Bennet et al. 1936). Tree ring archives reveal that such droughts (in the agricultural sense) have occurred occasionally over the last 1,000 years (Cook et al. 2004). Climate model simulations suggest that

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droughts lasting several years to decades occur naturally in the southwestern United States (Coats et al. 2015). The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5; Bindoff et al. 2013) concluded "there is low confidence in detection and attribution of changes in (meteorological) drought over global land areas since the mid-20th century, owing to observational uncertainties and difficulties in distinguishing decadal-scale variability in drought from long-term trends." As they noted, this was a weaker attribution statement than in the Fourth Assessment Report (Hegerl et al. 2007), which had concluded "that an increased risk of drought was *more likely than not* due to anthropogenic forcing during the second half of the 20th century." The weaker statement in AR5 reflected additional studies with conflicting conclusions on global drought trends (e.g., Sheffield et al. 2012; Dai 2013). Western North America was noted as a region where determining if observed recent droughts were unusual compared to natural variability was particularly difficult. This was due to evidence from paleoclimate proxies of cases of central U.S. droughts during the past 1,000 years that were longer and more intense than historical U.S. droughts (Masson-Delmotte et al. 2013). Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined (Andreadis and Lettenmaier 2006; Mo and Lettenmaier 2015). Furthermore, there is no detectable change in meteorological drought at the global scale (Sheffield et al. 2012). However, a number of individual event attribution studies suggest that if a drought occurs, anthropogenic temperature increases can exacerbate soil moisture deficits (e.g., Seager et al. 2015; Trenberth et al. 2014). Future projections of the anthropogenic contribution to changes in drought risk and severity must be considered in the context of the significant role of natural variability.

8.1.2. Recent Major U.S. Droughts

METEOROLOGICAL AND AGRICULTURAL DROUGHT

The United States has suffered a number of very significant droughts of all types since 2011. Each of these droughts was a result of different persistent, large-scale meteorological patterns of mostly natural origins, with varying degrees of attributable human influence. Table 8.1 summarizes available attribution statements for recent extreme U.S. droughts. Statements about meteorological drought are decidedly mixed, revealing the complexities in interpreting the low tail of the distribution of precipitation. Statements about agricultural drought consistently maintain a human influence if only surface soil moisture measures are considered. The single agricultural drought attribution study at root depth comes to the opposite conclusion (Cheng et al. 2016). In all cases, these attribution statements are examples of attribution without detection (see Appendix C). The absence of moisture during the 2011 Texas/Oklahoma drought and heat wave was found to be an event whose likelihood was enhanced by the La Niña state of the ocean, but the human interference in the climate system still doubled the chances of reaching such high

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temperatures (Hoerling et al. 2013). This study illustrates that the effect of human-induced climate change is combined with natural variations and can compound or inhibit the realized severity of any given extreme weather event.

[INSERT TABLE 8.1 HERE]

The Great Plains/Midwest drought of 2012 was the most severe summer meteorological drought in the observational record for that region (Hoerling et al. 2014). An unfortunate string of three different patterns of large-scale meteorology from May through August 2012 precluded the normal frequency of summer thunderstorms, and was not predicted by the NOAA seasonal forecasts (Hoerling et al. 2014). Little influence of the global sea surface temperature (SST) pattern on meteorological drought frequency has been found in model simulations (Hoerling et al. 2014). No evidence of a human contribution to the 2012 precipitation deficit in the Great Plains and Midwest is found in numerous studies (Rupp et al. 2013; Hoerling et al. 2014; Angélil et al. 2017). However, an alternative view is that the 2012 central U.S. drought can be classified as a "heat wave flash drought" (Mo and Lettenmaier 2016), a type of rapidly evolving drought that has decreased in frequency over the past century (Mo and Lettenmaier 2015). Also, an increase in the chances of the unusually high temperatures seen in the United States in 2012, partly associated with resultant dry summer soil moisture anomalies, was attributed to the human interference with the climate system (Diffenbaugh and Scherer 2013), indicating the strong feedback between lower soil moisture and higher surface air temperatures during periods of low precipitation. One study found that most, but not all, of the 2012 surface moisture deficit in the Great Plains was attributable to the precipitation deficit (Livneh and Hoerling 2016). That study also noted that Great Plains root depth and deeper soil moisture was higher than normal in 2012 despite the surface drying, due to wet conditions in prior years, indicating the long timescales relevant below the surface (Livneh and Hoerling 2016).

The recent California drought, which began in 2011, is unusual in different respects. In this case, the precipitation deficit from 2011 to 2014 was a result of the "ridiculously resilient ridge" of high pressure. This very stable high pressure system steered storms towards the north, away from the highly engineered California water resource system (Swain et al. 2014; Seager et al. 2014, 2015). The ridge itself was due to a slow-moving high sea surface temperature (SST) anomaly, referred to as "The Blob"—which was caused by a persistent ridge that weakened the normal cooling mechanisms for that region of the upper ocean (Bond et al. 2015). Atmospheric modeling studies showed that the ridge that caused the Blob was favored by a pattern of persistent tropical SST anomalies that were warm in the western equatorial Pacific and simultaneously cool in the far eastern equatorial Pacific (Hartman 2015; Seager et al. 2014). It was also favored by reduced arctic sea ice and from feedbacks with "The Blob" SST anomalies (Lee et al. 2015). These studies also suggest that internal variability likely played a prominent role in the persistence of the 2013–2014 ridge off the west coast of North America. A principal attribution question regarding the precipitation deficit concerns the causes of this SST anomaly.

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Observational records are not long enough and the anomaly was unusual enough that similarly long-lived patterns have not been often seen before. Hence, attribution statements, such as that about an increasing anthropogenic influence on the frequency of geopotential height anomalies similar to 2012–2014 (e.g., Swain et al. 2014), are without associated detection (Ch. 3: Detection and Attribution). A secondary attribution question concerns the anthropogenic precipitation response in the presence of this SST anomaly. In attribution studies with a prescribed 2013 SST anomaly, a consistent increase in the human influence on the chances of very dry California conditions was found (Angélil et al. 2017).

Anthropogenic climate change did increase the risk of the high temperatures in California in the winters of 2013–2014 and 2014–2015, especially the latter (Seager et al. 2015; Diffenbaugh et al. 2015; Wang and Schubert 2014), further exacerbating the soil moisture deficit and the associated stress on irrigation systems. This raises the question, as yet unanswered, of whether droughts in the western United States are shifting from precipitation control (Mao et al. 2015) to temperature control. There is some evidence to support a relationship between mild winter and/or warm spring temperatures and drought occurrence (Mote et al. 2016), but long-term warming trends in the tropical and North Pacific do not appear to have led to trends toward less precipitation over California (Funk et al. 2014). An anthropogenic contribution to commonly used measures of agricultural drought, including the Palmer Drought Severity Index (PDSI), was found in California (Diffenbaugh et al. 2015; Williams et al. 2015) and is consistent with previous projections of changes in PDSI (Dai 2013; Wehner et al. 2011; Walsh et al. 2014) and with an attribution study (Brown et al. 2008). Due to its simplicity, the PDSI has been criticized as being overly sensitive to higher temperatures and thus may exaggerate the human contribution to soil dryness (Milly and Dunne 2016). In fact, this study also finds that formulations of potential evaporation used in more complicated hydrologic models are similarly biased, undermining confidence in the magnitude but not the sign of projected surface soil moisture changes in a warmer climate. Seager et al. (2015) analyzed climate model output directly, finding that precipitation minus evaporation in the southwestern United States is projected to experience significant decreases in surface water availability, leading to surface runoff decreases in California, Nevada, Texas, and the Colorado River headwaters even in the near term. However, the criticisms of PDSI also apply to most of the CMIP5 land surface model evapotranspiration formulations. Analysis of soil moisture in the CMIP5 models at deeper levels is complicated by the wide variety in sophistication of their component land models. A pair of studies reveals less sensitivity at depth to surface air temperature increases than at near surface levels (Cook et al. 2015; Cheng et al. 2016). Berg et al. (2017) adjust for the differences in land component model vertical treatments, finding projected change in vertically integrated soil moisture down to 3 meters depth is mixed, with projected decreases in the Southwest and in the south central United States, but increases over the northern plains. Nonetheless, the warming trend has led to declines in a number of indicators, including Sierra snow water equivalent, that are relevant to hydrological drought (Mao et al. 2015). Attribution of the California drought and heat wave remains an interesting and controversial research topic.

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In summary, there has not yet been a formal identification of a human influence on past changes in United States meteorological drought through the analysis of precipitation trends. Some, but not all, U.S. meteorological drought event attribution studies, largely in the "without detection" class, exhibit a human influence. Attribution of a human influence on past changes in U.S. agricultural drought are limited both by availability of soil moisture observations and a lack of sub-surface modeling studies. While a human influence on surface soil moisture trends has been identified with *medium confidence*, its relevance to agriculture may be exaggerated.

RUNOFF AND HYDROLOGICAL DROUGHT

Several studies focused on the Colorado River basin in the United States that used more sophisticated runoff models driven by the CMIP3 models (Christensen and Lettenmaier 2007; McCabe and Wolock 2007; Barnett and Pierce 2009; Barnett et al. 2008; Hoerling et al. 2009) showed that annual runoff reductions in a warmer western Unites States climate occur through a combination of evapotranspiration increases and precipitation decreases, with the overall reduction in river flow exacerbated by human water demands on the basin's supply. Reduced U.S. snowfall accumulations in much warmer future climates are virtually certain as frozen precipitation is replaced by rain regardless of the projected changes in total precipitation amounts discussed in Chapter 7: Precipitation Change (Figure 7.6). The profound change in the hydrology of snowmelt-driven flows in the western United States is well documented. Earlier spring runoff (Stewart et al. 2005) reduced the fraction of precipitation falling as snow (Knowles et al. 2006) and the snowpack water content at the end of winter (Mote 2003; Mote et al. 2005), consistent with warmer temperatures. Formal detection and attribution (Ch. 3: Detection and Attribution) of the observed shift towards earlier snowmelt driven flows in the western United States reveals that the shift is detectably different from natural variability and attributable to anthropogenic climate change (Hidalgo et al 2009). Similarly, observed declines in the snow water equivalent in the region have been formally attributed to anthropogenic climate change (Pierce et al. 2008) as have temperature, river flow, and snow pack (Barnett et al. 2008; Bonfils et al. 2008). As a harbinger of things to come, the unusually low western U.S. snowpack of 2015 may become the norm (Mote et al. 2016).

In the northwestern United States, long-term trends in streamflow have seen declines, with the strongest trends in drought years (Luce and Holden 2009) that are attributed to a decline in winter precipitation (Luce et al. 2013). These reductions in precipitation are linked to decreased westerly wind speeds in winter over the region. Furthermore, the trends in westerlies are consistent with CMIP5-projected wind speed changes due to a decreasing meridional temperature and pressure gradients rather than low-frequency climate variability modes. Such precipitation changes have been a primary source of change in hydrological drought in the Northwest over the last 60 years (Kormos et al. 2016) and are in addition to changes in snowpack properties.

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We conclude with *high confidence* that these observed in changes temperature controlled aspects of western U.S. hydrology are *likely* a consequence of human changes to the climate system.

8.1.3. Projections of Future Droughts

The future changes in seasonal precipitation shown in Chapter 7: Precipitation Change (Figure 7.6) indicate that the southwestern United States may experience chronic future precipitation deficits, particularly in the spring. In much warmer climates, expansion of the tropics and subtropics, traceable to changes in the Hadley circulation, cause shifts in seasonal precipitation that are particularly evident in such arid and semi-arid regions and increase the risk of meteorological drought. However, uncertainty in the magnitude and timing of future southwestern drying is high. We note that the weighted and downscaled projections of Figure 7.6 exhibit significantly less drying and are assessed to be less significant in comparison to natural variations than the original unweighted CMIP5 projections (Walsh et al. 2014).

Western U.S. hydrological drought is currently controlled by the frequency and intensity of extreme precipitation events, particularly atmospheric rivers, as these events represent the source of nearly half of the annual water supply and snowpack for the western coastal states (Dettinger 2011; Guan et al. 2013). Climate projections indicate greater frequency of atmospheric rivers in the future (e.g., Dettinger 2011; Warner et al. 2015; Gao et al. 2015; see further discussion in Ch. 9: Extreme Storms). Sequences of these extreme storms have played a critical role in ending recent hydrological droughts along the U.S. West Coast (Dettinger 2013). However, as winter temperatures increase, the fraction of precipitation falling as snow will decrease, potentially disrupting western U.S. water management practices.

Significant U.S. seasonal precipitation deficits are not confidently projected outside of the Southwest. However, future higher temperatures will *likely* lead to greater frequencies and magnitudes of agricultural droughts throughout the continental United States as the resulting increases in evapotranspiration outpace projected precipitation increases (Collins et al. 2013). Figure 8.1 shows the weighted multimodel projection of the percent change in near-surface soil moisture at the end of the 21st century under the RCP8.5 scenario, indicating widespread drying over the entire continental United States. Previous National Climate Assessments (Karl et al. 2009; Walsh et al. 2014) have discussed the implication of these future drier conditions in the context of the Palmer Drought Severity Index (PDSI), finding that the future normal condition would be considered drought at the present time, and that the incidence of "extreme drought" (PDSI < –4) would be significantly increased. However, as described below, the PDSI may overestimate future soil moisture drying.

This projection is made "without attribution" (Ch. 4: Projections), but confidence that future soils will generally be drier at the surface is *medium*, as the mechanisms leading to increased evapotranspiration in a warmer climate are elementary scientific facts. However, the land surface component models in the CMIP5 climate models vary greatly in their sophistication, causing the

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projected magnitude of both the average soil moisture decrease and the increased risk for agricultural drought to be less certain. The weighted projected seasonal decreases in surface soil moisture are generally towards drier conditions, even in regions and seasons where precipitation is projected to experience large increases (Figure 7.6) due to increases in the evapotranspiration associated with higher temperature. Drying is assessed to be large relative to natural variations in much of the CONUS region in the summer. Significant spring and fall drying is also projected in the mountainous western states, with potential implications for forest and wildfire risk. Also, the combination of significant summer and fall drying in the midwestern states has potential agricultural implications. The largest percent changes are projected in the southwestern United States and are consistent in magnitude with an earlier study of the Colorado River Basin using more sophisticated macroscale hydrological models (Christensen and Lettenmaier 2007).

In this assessment, we limit the direct CMIP5 weighted multimodel projection of soil moisture shown in Figure 8.1 to the surface (defined as the top 10 cm of the soil), as the land surface component sub-models vary greatly in their representation of the total depth of the soil. A more relevant projection to agricultural drought would be the soil moisture at the root depth of typical U.S. crops. Cook et al. (2015) find that future drying at a depth of 30 cm will be less than at 2 cm, but still significant and comparable to a modified PDSI formulation. Few of the CMIP5 land models have detailed ecological representations of evapotranspiration processes, causing the simulation of the soil moisture budget to be less constrained than reality (Williams and Torn 2015). Over the western United States, unrealistically low elevations in the CMIP5 models due to resolution constraints present a further challenge in interpreting evapotranspiration changes. Nonetheless, Figure 8.1 shows a projected drying of surface soil moisture across nearly all of the coterminous United States in all seasons, even in regions and seasons where precipitation is projected to increase, consistent with increased evapotranspiration due to elevated temperatures (Cook et al. 2015).

Widespread reductions in mean snowfall across North America are projected by the CMIP5 models (O'Gorman 2014). Together with earlier snowmelt at altitudes high enough for snow, disruptions in western U.S. water delivery systems are expected to lead to more frequent hydrological drought conditions (Barnett et al. 2008; Pierce et al. 2008; Barnett and Pierce 2009; Cayan et al. 2010; Das et al. 2011). Due to resolution constraints, the elevation of mountains as represented in the CMIP5 models is too low to adequately represent the effects of future temperature on snowpacks. However, increased model resolution has been demonstrated to have important impacts on future projections of snowpack water content in warmer climates and is enabled by recent advances in high performance computing (Kapnick and Delworth 2013). Figure 8.2 and Table 8.2 show a projection of changes in western U.S. mountain winter (December, January, and February) hydrology obtained from a different high-resolution atmospheric model at the middle and end of the 21st century under the RCP8.5 scenario. These projections indicate dramatic reductions in all aspects of snow (Rhoades et al. 2017) and are similar to previous statistically downscaled projections (Cayan et al. 2013; Klos et al. 2014).

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Table 8.2 reveals that the reductions in snow water equivalent accelerate in the latter half of this century under this emissions scenario and with substantial variations across the western United States. Changes in snow residence time, an alternative measure of snowpack relevant to the timing of runoff, is also shown to be sensitive to elevation, with widespread reductions across this region (Luce et al. 2014). Given the larger projected increases in temperature at high altitudes compared to adjacent lower altitudes (Pierce and Cayan 2013) and the resulting changes in both snowpack depth and melt timing in very warm future scenarios such as RCP8.5, and assuming no change to water resource management practices, several important western U.S. snowpack reservoirs effectively disappear by 2100 in this dynamical projection, resulting in chronic, long-lasting hydrological drought. This dramatic statement is also supported by two climate model studies: a multimodel statistical downscaling of the CMIP5 RCP8.5 ensemble that finds large areal reductions in snow dominated regions of the western United States by mid-century and complete elimination of snow-dominated regions in certain watersheds (Klos et al. 2014), and a large ensemble simulation of a global climate model (Fyfe et al. 2017).

As earlier spring melt and reduced snow water equivalent has been formally attributed to human induced warming, substantial reductions in western U.S. winter and spring snowpack are projected (with attribution) to be *very likely* as the climate warms as the climate continues to warm (*very high confidence*). Under higher emissions scenarios and assuming no change to current water-resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

[INSERT FIGURES 8.1 AND 8.2 HERE]

8.2. Floods

Flooding damage in the United States can come from flash floods of smaller rivers and creeks, prolonged flooding along major rivers, urban flooding unassociated with proximity to a riverway, coastal flooding from storm surge which may be exacerbated by sea level rise, and the confluence of coastal storms and inland riverine flooding from the same precipitation event (Ch. 12: Sea Level Rise). Flash flooding is associated with extreme precipitation somewhere along the river which may occur upstream of the regions at risk. Flooding of major rivers in the United States with substantial winter snow accumulations usually occurs in the late winter or spring and can result from an unusually heavy seasonal snowfall followed by a "rain on snow" event or from a rapid onset of higher temperatures that leads to rapid snow melting within the river basin. In the western coastal states, most flooding occurs in conjunction with extreme precipitation events referred to as "atmospheric rivers" (see Ch. 9: Extreme Storms) (Ralph and Dettinger 2011; Neiman et al. 2011), with mountain snowpack being vulnerable to these typically warmer-than-normal storms and their potential for rain on existing snow cover (Guan et al. 2016). Hurricanes and tropical storms are an important driver of flooding events in the eastern United States. Changes in streamflow rates depend on many factors, both human and natural, in addition to climate change. Deforestation, urbanization, dams, floodwater management activities,

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and changes in agricultural practices can all play a role in past and future changes in flood statistics. Projection of future changes is thus a complex multivariate problem (Walsh et al. 2014).

The IPCC AR5 (Bindoff et al. 2013) did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration or frequency. Trends in extreme high values of streamflow are mixed across the United States (Walsh et al. 2014; Archfield et al. 2016; EPA 2016). Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude (Hirsch and Ryberg 2012) but does not provide robust evidence that these trends are attributable to human influences. Significant increases in flood frequency have been detected in about one-third of stream gauge stations examined for the central United States, with a much stronger signal of frequency change than is found for changes in flood magnitude in these gauges (Mallakpour and Villarini 2015). This apparent disparity with ubiquitous increases in observed extreme precipitation (Figure 7.2) can be partly explained by the seasonality of the two phenomena. Extreme precipitation events in the eastern half of the CONUS are larger in the summer and fall when soil moisture and seasonal streamflow levels are low and less favorable for flooding (Wehner 2013). By contrast, high streamflow events are often larger in the spring and winter when soil moisture is high and snowmelt and frozen ground can enhance runoff (Frei et al. 2015). Furthermore, floods may be poorly explained by daily precipitation characteristics alone; the relevant mechanisms are more complex, involving processes that are seasonally and geographically variable, including the seasonal cycles of soil moisture content and snowfall/snowmelt (Berghuijs et al. 2016).

Recent analysis of annual maximum streamflow shows statistically significant trends in the upper Mississippi River valley (increasing) and in the Northwest (decreasing) (McCabe and Wolock 2014). In fact, across the midwestern United States, statistically significant increases in flooding are well documented (Groisman et al. 2001; Novotny and Stefan 2007; Tomer and Schilling 2009; Ryberg et al. 2014; Villarini and Strong 2014; Slater et al. 2015; Mallakpour and Villarini 2015, 2016). These increases in flood risk and severity are not attributed to 20th century changes in agricultural practices (Tomer and Schilling 2009; Frans et al. 2013) but instead are attributed mostly to the observed increases in precipitation shown in Figures 7.1 through 7.4 (Novotny and Stefan 2007; Wang and Hejazi 2011; Frans et al. 2013; Mallakpour and Villarini 2015). Trends in maximum streamflow in the northeastern United States are less dramatic and less spatially coherent (McCabe and Wolock 2014; Frei et al. 2015), although one study found mostly increasing trends (Armstrong et al. 2014) in that region, consistent with the increasing trends in observed extreme precipitation in the region (Ch. 6: Temperature Change; Walsh et al. 2014; Frei et al. 2015).

The nature of the proxy archives complicates the reconstruction of past flood events in a gridded fashion as has been done with droughts. However, reconstructions of past river outflows do exist. For instance, it has been suggested that the mid-20th century river allocations for the Colorado

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River were made during one of the wettest periods of the past five centuries (Woodhouse et al. 2006). For the eastern United States, the Mississippi River has undergone century-scale variability in flood frequency—perhaps linked to the moisture availability in the central United States and the temperature structure of the Atlantic Ocean (Munoz et al. 2015).

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies (Merz et al. 2012). As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed (Mallakpour and Villarini 2015).

A projection study based on coupling an ensemble of regional climate model output to a hydrology model (Najafi and Moradkhani 2015) finds that the magnitude of future very extreme runoff (which can lead to flooding) is decreased in most of the summer months in Washington State, Oregon, Idaho, and western Montana but substantially increases in the other seasons. Projected weighted increases in extreme runoff from the coast to the Cascade Mountains are particularly large in that study during the fall and winter which are not evident in the weighted seasonal averaged CMIP5 runoff projections (Collins et al. 2013). For the West Coast of the United States, extremely heavy precipitation from intense atmospheric river storms is an important factor in flood frequency and severity (Dettinger 2011; Dettinger et al. 2011). Projections indicate greater frequency of heavy atmospheric rivers in the future (e.g., Dettinger et al. 2011; Warner et al. 2015; Gao et al. 2015; see further discussion in Ch. 9: Extreme Storms). Translating these increases in atmospheric river frequency to their impact on flood frequency requires a detailed representation of western states topography in the global projection models and/or via dynamic downscaling to regional models and is a rapidly developing science. In a report prepared for the Federal Insurance and Mitigation Administration of the Federal Emergency Management Agency, a regression-based approach of scaling river gauge data based on seven commonly used climate change indices from the CMIP3 database (Tebaldi et al. 2006) found that at the end of the 21st century the 1% annual chance floodplain area would increase in area by about 30%, with larger changes in the Northeast and Great Lakes regions and smaller changes in central part of the country and the Gulf Coast (AECOM 2013).

Urban flooding results from heavy precipitation events that overwhelm the existing sewer infrastructure's ability to convey the resulting stormwater. Future increases in daily and sub-daily extreme precipitation rates will require significant upgrades to many communities' storm sewer systems, as will sea level rise in coastal cities and towns (SFPUC 2016; Winters et al. 2015).

No studies have formally attributed (see Ch. 3: Detection and Attribution) long-term changes in observed flooding of major rivers in the United States to anthropogenic forcing. We conclude

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