Technical Appendix

Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment

Contents

A.1. Ensuring Information Quality

The Technical Report and its underlying analyses were conducted in accordance with EPA's Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by the Environmental Protection Agency,[1] which follows Office of Management and Budget (OMB) guidelines[2] and implements the Information Quality Act (IQA) (Section 515 of Public Law 106–554).[3] Section A.3 of this Appendix describes the independent, external peer review that was performed on the report.

In accordance with OMB definitions, EPA defines the basic standard of information "quality" by the attributes objectivity, integrity, utility, and transparency. For products meeting a higher standard of quality, like this Technical Report, the Agency requires an appropriate level of transparency regarding data and methods in order to facilitate the reproducibility of information by qualified third parties. The EPA uses various established Agency processes (e.g., the Quality System, peer review requirements and processes) to ensure the appropriate level of objectivity, utility, integrity, and transparency for its products based on the intended use of the information and the resources available.

Objectivity focuses on whether the disseminated information is being presented in an accurate, clear, complete, and unbiased manner, and as a matter of substance, is accurate, reliable, and unbiased. The Technical Report meets the standard for objectivity, due to activities described in the following:

a) The information disseminated was determined to be complete, accurate, and reliable based on internal quality control measures adopted by the expert modeling teams. This included quality checks throughout the chain of analytic steps, including developing and processing climate projections, calibrating and validating the sectoral impact models, and checking data to ensure that no errors occurred in the process to compile and summarize results.

b) The information disseminated was determined to be clear, complete, and unbiased based on multiple rounds of independent review. Consistent with guidelines described in EPA's Peer Review Handbook,[4] the underlying sectoral modeling analyses of the CIRA project were peer-reviewed in the scientific literature. Section A.2 of this Appendix provides a comprehensive list of this literature. The content of the Technical Report was also subject to an independent, external peer review to ensure that the findings of the underlying CIRA literature were

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[1] EPA, 2002: Guidelines for ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the Environmental Protection Agency. United States Environmental Protection Agency, EPA/260R-02-008. Available online at http://www.epa.gov/quality/informationguidelines/documents/EPA_InfoQualityGuidelines.pdf

[2] OMB, 2002: Office of Management and Budget Information Quality Guidelines. Executive Office of the President, Office of Management and Budget. Available online at http://www.whitehouse.gov/sites/default/files/omb/inforeg/iqg_oct2002.pdf

[3] The IQA requires the Office of Management and Budget and federal agencies to issue guidelines that "ensur[e] and maximize[e] the quality, objectivity, utility, and integrity of information (including statistical information) disseminated by Federal agencies" (Public Law 106-554; 44 U.S.C. 3516, note). The IQA does not impose its own standard of "quality" on agency information; instead, it requires only that an agency "issue guidelines" ensuring data quality. Following guidelines issued by the Office of Management and Budget, EPA released its own guidelines to implement the IQA: "Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of Information Disseminated by the Environmental Protection Agency."

[4] EPA, 2015: Peer Review Handbook, 4th Edition, 2015. United States Environmental Protection Agency, Programs of the Office of the Science Advisor.

technically supported, competently summarized, properly documented, consistent with established quality criteria, and clearly communicated.

Integrity refers to security of information, such as the protection of information from unauthorized access or revision, to ensure that the information is not compromised through corruption or falsification. The Technical Report and its underlying analyses meet the standard for integrity by taking multiple steps to ensure that the data and information remained secure. These steps include the use of password protected data storage repositories, password protected data transfer technology, and multiple layers of data validation checks to ensure that the integrity was not compromised.

Utility is the usefulness of the information to the intended users. The Technical Report and its underlying analyses meet the standard for utility because the information disseminated provides insights (quantitative estimates in physical and economic terms) regarding the potential direction and magnitude of the impacts of climate change on the U.S. Understanding the risks posed by climate change in futures under alternative emissions scenarios can inform broader assessment reports and policy decisions designed to address these risks.

Transparency ensures access to and description of (1) the source of the data, (2) the various assumptions employed, (3) the analytic methods applied, and (4) the statistical procedures used. The Technical Report and its underlying analyses meet the standard for transparency for the following reasons:

a) The technical approaches and results of the sectoral impact analyses have been published with open access in the peer-reviewed scientific literature, and are cited throughout the Technical Report. These papers, along with their online supplementary materials, provide detailed information on the source of data used, assumptions employed, the analytic and statistical methods applied, and important limitations regarding the approaches and/or how the results should be interpreted.

b) Each sectoral impact described in the report has a brief description of the approach and assumptions used in developing the estimates, with citations to the underlying literature for more information.

c) The data from all figures and graphs shown in the Technical Report will be made available through the Global Change Information System at https://data.globalchange.gov/.

e) This Technical Report is intended to serve as input to the U.S. Global Change Research Program's (USGCRP) Fourth National Climate Assessment (NCA4) and will be made available at: http://www.globalchange.gov/nca4

A.2. Underlying Literature

As part of the process to ensure information quality, and consistent with guidelines described in EPA's Peer Review Handbook, the underlying modeling analyses of the CIRA project were peer-reviewed in the scientific literature. The CIRA project applies a large number of statistical and process-based models to quantify how risks and damages across multiple U.S. sectors (i.e., human health, infrastructure, water resources, electricity, ecosystems, etc.) may be avoided or reduced under different greenhouse gas emissions scenarios. To ensure that the methods and results of these modeling analyses are technically rigorous and supported, competently performed, properly documented, consistent with established quality criteria, and clearly communicated, independent evaluation of underlying literature was undertaken through the external peer review processes of scientific journals. This approach is consistent with OMB and EPA guidelines.[5]

Literature documenting the CIRA methods and results, which have been published with open access (i.e., free access to the public), are listed below:

CIRA Special Issue

EPA and collaborators published 11 papers as a special journal issue of *Climatic Change* describing the different elements of CIRA, including project objectives, scenario development, climate projection, and modeling of sectoral impacts and damages. A number of the special issue papers are listed below under the sectoral categories:

Martinich, J., J. Reilly, S. Waldhoff, M. Sarofim, and J. McFarland, Eds., 2015: Special Issue on "A Multi-Model Framework to Achieve Consistent Evaluation of Climate Change Impacts in the United States." *Climatic Change*, **131**, 1-181. Available online at http://link.springer.com/journal/10584/131/1/page/1

2015 CIRA Report

The 2015 CIRA report, *Climate Impacts in the United States: Benefits of Global Action*, summarizes multiple analyses that quantify the physical effects and economic damages of climate change under two global GHG emission scenarios.

EPA, 2015: *Climate Change in the United States: Benefits of Global Action*. United States Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001.[6]

[5] Peer review by a credible, refereed scientific journal is consistent with OMB's Final Information Quality Bulletin for Peer Review available online at http://www.whitehouse.gov/sites/default/files/omb/memoranda/fy2005/m05-03.pdf, EPA's Peer Review Handbook (4th Edition) available online at https://www.epa.gov/osa/peer-review-handbook-4th-edition-2015, and EPA's Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity, of Information Disseminated by the Environmental Protection Agency available online at http://www.epa.gov/quality/informationguidelines. The EPA Peer Review Handbook states "peer review of journal articles (written by EPA or non-EPA authors) performed by a credible, refereed scientific journal contributes to the scientific and technical credibility of the reviewed product. Generally, EPA considers peer review by such journals as adequate for reviewing the scientific credibility and validity of the findings (or data) in that article, and therefore, a satisfactory form of peer review" (page 56).

[6] Available online at https://www.epa.gov/cira

CIRA Framework Models

For a more comprehensive description of the models, scenarios, and projections used in this Technical Report, including sea level rise, atmospheric CO_2, and socioeconomic projections, see the Modeling Framework section in the Technical Report.

Method Papers on Individual CIRA Components

Separate from the CIRA special issue of *Climatic Change*, most of the underlying sectoral impacts models that serve as the basis for the CIRA project have been independently peer reviewed in the scientific literature. The following papers describe the underlying sectoral impacts models of the CIRA project. These papers represent the most relevant in-depth discussions of underlying methodologies, model calibration/validation, calculations, and other technical details.

Post-Processing Models:

Climate and Runoff Model (CLIRUN)

Strzepek, K., M. Jacobsen, B. Boehlert, and J. Neumann, 2013: Toward evaluating the effect of climate change on investments in the water resources sector: insights from the forecast and analysis of hydrological indicators in developing countries. *Environmental Research Letters*. doi: 10.1088/1748-9326/8/4/044014. Available online at http://iopscience.iop.org/1748-9326/8/4/044014

Kaczmarek, Z., 1993: Water balance model for climate impact assessment. *Acta Geophysica Polonica,* **41**, 423-437.

Integrated Climate and Land-Use Model (ICLUS)

EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (ICLUS) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

Bierwagen, B., D.M. Theobald, C.R. Pyke, A. Choate, P. Groth, J.V. Thomas, and P. Morefield, 2010: National housing and impervious surface scenarios for integrated climate impact assessments. *Proceedings of the National Academy of Sciences*, **107**, 20887-20892, doi: 10.1073/pnas.1002096107. Available online at http://www.pnas.org/content/early/2010/11/08/1002096107.abstract

CO2SYS

Lewis, E., and D. Wallace, 1998: Program developed for CO_2 system calculations. Oak Ridge National Laboratory – Carbon Dioxide Information Analysis Center, Pub. No. 4735. Available online at http://cdiac.ornl.gov/ftp/co2sys/CO2SYS_calc_DOS_v1.05/cdiac105.pdf

Health Sector Models:

Air Quality

Fann, N., C.G. Nolte, P. Dolwick, T.L. Spero, A. Curry Brown, S. Phillips, and S. Anenberg, 2015: The geographic distribution and economic value of climate change-related ozone health impacts

in the United States in 2030. *Journal of the Air & Waste Management Association*, **65**, 570-580. Available online at http://dx.doi.org/10.1080/10962247.2014.996270

EPA, 2014: Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE). United States Environmental Protection Agency, Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. Available online at www.epa.gov/benmap

Aeroallergens

Anenberg, S. C., K. R. Weinberger, H. Roman, J. E. Neumann, A. Crimmins, N. Fann, J. Martinich, and P. L. Kinney (2017), Impacts of oak pollen on allergic asthma in the United States and potential influence of future climate change, *GeoHealth*, **1**, doi:10.1002/2017GH000055.

Extreme Temperature Mortality

Mills, D., J. Schwartz, M. Lee, M. Sarofim, R. Jones, M. Lawson, and L. Deck, 2014: Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States. *Climatic Change*. doi: 10.1007/s10584-014-1154-8. Available online at http://link.springer.com/article/10.1007/s10584-014-1154-8

Labor

Graff Zivin, J. and M. Neidell, 2014: Temperature and the allocation of time: implications for climate change. *Journal of Labor Economics*. doi: 10.1086/671766. Available online at http://www.jstor.org/stable/10.1086/671766

EPA, 2015: Technical Appendix for Report: Climate Change in the United States: Benefits of Global Action. Section G: Technical Details Related to Labor Analysis. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001. Available online at https://www.epa.gov/cira/downloads-cira-report

West Nile Virus

Belova, A., Mills, D., Hall, R., Juliana, A.S., Crimmins, A., Barker, C. and Jones, R. (2017) Impacts of Increasing Temperature on the Future Incidence of West Nile Neuroinvasive Disease in the United States. *American Journal of Climate Change*, **6**, 166-216. Available online at https://doi.org/10.4236/ajcc.2017.61010

Harmful Algal Blooms

Chapra, S.C., B. Boehlert, C. Fant, J. Henderson, D. Mills, D.M.L. Mas, L. Rennels, L. Jantarasami, J. Martinich, K.M. Strzepek, V.J. Jr. Bierman, and H.W. Paerl, 2017: Climate change impacts on harmful algal blooms in U.S. freshwaters: a screening-level assessment. *Environmental Science and Technology*, doi: 10.1021/acs.est.7b01498. Available online at http://pubs.acs.org/doi/full/10.1021/acs.est.7b01498

Domestic Migration

EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (ICLUS) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479

Infrastructure Sector Models:

Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2014: Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change* **131**, 97-109, doi: 10.1007/s10584-013-1037-4. Available online at http://link.springer.com/article/10.1007/s10584-013-1037-4

Roads

Chinowsky, P., J. Price, and J. Neumann, 2013: Assessment of Climate Change Adaptation Costs for the U.S. Road Network. *Global Environment Change*. doi: 10.1016/j.gloenvcha.2013.03.004. Available online at http://www.sciencedirect.com/science/article/pii/S0959378013000514

Espinet, X., A. Schweikert, N. van den Heever, and P. Chinowsky, 2016: Planning resilient roads for the future environment and climate change: quantifying the vulnerability of the primary transport infrastructure system in Mexico. *Transport Policy*, **50**, 78-86. Available online at http://www.sciencedirect.com/science/article/pii/S0967070X1630316X

Chinowsky, P. and C. Arndt, 2012: Climate Change and Roads: A Dynamic Stressor–Response Model. *Review of Development Economics*, **16**, 448-462. Available online at http://onlinelibrary.wiley.com/doi/10.1111/j.1467-9361.2012.00673.x/abstract

Bridges

Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J.B. Smith, J. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, doi: 10.1007/s11027-011-9354-2. Available online at http://www.springerlink.com/content/080u67337157202k/

Rail

Chinowsky, P., J. Helman, S. Gulati, J. Neumann, and J. Martinich, 2017: Impacts of Climate Change on Operation of the US Rail Network. *Transport Policy*, doi: 10.1016/j.tranpol.2017.05.007. Available online at https://doi.org/10.1016/j.tranpol.2017.05.007

Alaska Infrastructure

Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, L. Rennels, A. Bothner, D.J. Nicolsky, and S.S. Marchenko, 2016: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academies of Sciences*, doi:10.1073/pnas.1611056113. Available online at http://www.pnas.org/content/early/2016/12/20/1611056113.abstract

Urban Drainage

Price, J., L. Wright, C. Fant, and K. Strzepek, 2014: Calibrated Methodology for Assessing Climate Change Adaptation Costs for Urban Drainage Systems. *Urban Water Journal*, doi: 10.1080/1573062X.2014.991740. Available online at http://www.tandfonline.com/doi/abs/10.1080/1573062X.2014.991740

Coastal Property

Neumann, J., K. Emanuel, S. Ravela, L. Ludwig, P. Kirshen, K. Bosma, and J. Martinich, 2014: Joint Effects of Storm Surge and Sea-level Rise on US Coasts. *Climatic Change*, doi: 10.1007/s10584-014-1304-z. Available online at http://link.springer.com/article/10.1007/s10584-014-1304-z

Neumann, J.E., D.E. Hudgens, J. Herter, and J. Martinich, 2010: Assessing Sea-Level Rise Impacts: A GIS-Based Framework and Application to Coastal New Jersey. *Coastal Management*. doi:10.1080/08920753.2010.496105. Available online at http://dx.doi.org/10.1080/08920753.2010.496105

Neumann, J.E., D.E. Hudgens, J. Herter, and J. Martinich, 2010: The economics of adaptation along developed coastlines. *Wiley Interdisciplinary Reviews (WIREs) Climate Change*, doi: 10.1002/wcc.90. Available online at http://onlinelibrary.wiley.com/doi/10.1002/wcc.90/full

Martinich, J., J.E. Neumann, L. Ludwig, and L. Jantarasami, 2012: Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*, doi: 10.1007/s11027-011-9356-0. Available online at http://www.springerlink.com/content/x411112212347762/

Electricity Sector Models

McFarland, J., Y. Zhou, L. Clarke, P. Schultz, P. Sullivan, J Colman J, P. Patel, J. Eom, S. Kim, G.P. Kyle, W. Jaglom, B. Venkatesh, J. Haydel, R. Miller, J. Creason, B. Perkins, and J Creason, 2015: Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Climatic Change*, **131**, 111-125, doi: 10.1007/s10584-015-1380-8. Available online at http://link.springer.com/article/10.1007/s10584-015-1380-8

GCAM-USA Model

Kyle, P., L. Clarke, F. Rong, and S.J. Smith, 2010: Climate policy and the long-term evolution of the U.S. buildings sector. *The Energy Journal*, **31**,145-172. Available online at https://www.jstor.org/stable/41323285?seq=1#page_scan_tab_contents

Zhou, Y., L. Clarke, J. Eom, P. Kyle, P. Patel, S. Kim, J. Dirks, E. Jensen, Y. Liu, J. Rice, L. Schmidt, and T. Seiple, 2014: Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. *Applied Energy*, **113**, 1077-1088, doi: 10.1016/j.apenergy.2013.08.034. Available online at http://dx.doi.org/10.1016/j.apenergy.2013.08.034

Zhou, Y., J. Eom, and L. Clarke, 2013: The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China. *Climatic Change*, **119**, 979-992, doi: 10.1007/s10584-013-0772-x. Available online at http://link.springer.com/article/10.1007%2Fs10584-013-0772-x

Regional Energy Deployment System (ReEDS)

Bird, L., C. Chapman, J. Logan, J. Sumner, and W. Short, 2011: Evaluating renewable portfolio standards and carbon cap scenarios in the U.S. electric sector. *Energy Policy*, doi: 10.1016/j.enpol.2011.02.025. Available online at http://www.sciencedirect.com/science/article/pii/S0301421511001054

Eurek, K., W. Cole, D. Bielen, N. Blair, S. Cohen, B. Frew, J. Ho, V. Krishnan, T. Mai, B. Sigrin and D. Steinberg, 2016: Regional Energy Deployment System (ReEDS) Model Documentation. Version 2016. National Renewable Energy Laboratory Technical Report NREL/TP-6A20-67067. Available online at http://www.nrel.gov/docs/fy17osti/67067.pdf

Sullivan, P., J. Colman, and E. Kalendra, 2015: Predicting the Response of Electricity Load to Climate Change. National Renewable Energy Laboratory Technical Report NREL/TP-6A20-64297. Available online at www.nrel.gov/docs/fy15osti/64297.pdf

Water Resource Sector Models:

Strzepek, K., J. Neumann, J. Smith, J. Martinich, B. Boehlert, M. Hejazi, J. Henderson, C. Wobus, R. Jones, K. Calvin, D. Johnson, E. Monier, J. Strzepek, and J. Yoon, 2014: Benefits of Greenhouse Gas Mitigation on the Supply, Management, and Use of Water Resources in the United States. *Climatic Change*, **131**, 127-141, doi: 10.1007/s10584-014-1279-9. Available online at http://link.springer.com/article/10.1007/s10584-014-1279-9

Inland Flooding

Wobus, C., E. Gutmann, R. Jones, M. Rissing, N. Mizukami, M. Lorie, H. Mahoney, and J. Martinich, 2017: Modeled changes in 100 year flood risk and asset damages within mapped floodplains of the contiguous United States. *Natural Hazards and Earth System Sciences*. doi: 10.5194/nhess-2017-152. Available online at http://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-152/

Water Quality

Boehlert, B., K.M. Strzepek, S.C. Chapra, Y. Gebretsadik, M. Lickley, C. Fant, R. Swanson, A. McCluskey, J.E. Neumann, and J. Martinich, 2016: Climate change impacts and greenhouse gas mitigation effects on U.S. water quality. *Journal of Advances in Modeling Earth Systems*, doi: 10.1002/2014MS000400. Available online at http://onlinelibrary.wiley.com/doi/10.1002/2014MS000400/full

Yen, H., P. Daggupati, M.J. White, R. Srinivasan, A. Gossel, D. Wells, and J.G. Arnold, 2016: Application of large-scale, multi-resolution watershed modeling framework using the hydrologic and water quality system (HAWQS). *Water*, **8**, 164. Available online at http://www.mdpi.com/2073-4441/8/4/164

Fant, C., R. Srinivasan, B. Boehlert, L. Rennels, S.C. Chapra, K.M. Strzepek, J. Corona, A. Allen, and J. Martinich, 2017: Climate change impacts on US water quality using two models: HAWQS and US Basins. *Water*, **9**, 118, doi:10.3390/w9020118. Available online at http://www.mdpi.com/2073-4441/9/2/118

Municipal and Industrial Water Supply

Boehlert, B., K. M. Strzepek, S. C. Chapra, C. Fant, Y. Gebretsadik, M. Lickley, R. Swanson, A. McCluskey, J. E. Neumann, and J. Martinich, 2015: Climate change impacts and greenhouse gas mitigation effects on U.S. water quality, *J. Adv. Model. Earth Syst.*, **7**, 1326–1338, doi:10.1002/2014MS000400. Available online at http://onlinelibrary.wiley.com/doi/10.1002/2014MS000400/full

Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, and J. Martinich, 2013: Economic Impacts of Climate Change on Water Resources in the Coterminous United States. *Mitigation* *and Adaptation Strategies for Global Change*, doi: 10.1007/s11027-013-9483-x. Available online at http://link.springer.com/article/10.1007%2Fs11027-013-9483-x

Winter Recreation

Wobus, C., E.E. Small, H. Hosterman, D. Mills, J. Stein, M. Rissing, R. Jones, M. Duckworth, R. Hall, M. Kolian, J. Creason, and J. Martinich, 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environmental Change*, doi: 10.1016/j.gloenvcha.2017.04.006. Available online at http://www.sciencedirect.com/science/article/pii/S0959378016305556

Agriculture Sector Models:

Yield and Welfare Effects

Environmental Policy Integrated Climate (EPIC)

Beach, R., Y. Cai, A. Thomson, X. Zhang, R. Jones, B. McCarl, A. Crimmins, J. Martinich, J. Cole, and S. Ohrel, 2015: Climate change impacts on US agriculture and forestry: benefits of global climate stabilization. *Environmental Research Letters*, doi: 10.1088/1748-9326/10/9/095004. Available online at http://iopscience.iop.org/article/10.1088/1748-9326/10/9/095004/pdf

Thomson, A.M., R.A. Brown, N.J. Rosenberg, R.C. Izaurralde, and V. Benson, 2005: Climate Change Impacts for the Conterminous USA. Part 3: Dryland production of grain and forage crops. *Climatic Change*, doi:10.1007/1-4020-3876-3. Available online at http://link.springer.com/article/10.1007/s10584-005-3612-9

Williams, J.R. 1995: The EPIC Model. In Computer Models in Watershed Hydrology, V.P. Singh (ed.), pp. 909-1000. Highlands Ranch, CO: Water Resources Publication.

Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG)

Beach, R., D. Adams, R. Alig, J. Baker, G. Latta, B. McCarl, B.C. Murray, S.K. Rose, and E. White, 2010: Model documentation for the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG). Prepared for U.S. Environmental Protection Agency. Available online at: http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf

Global Agriculture Interactions: Global Biosphere Management Model (GLOBIOM)

Havlík, P., Schneider, U.A., Schmid, E., Böttcher, H., S. Fritz, R. Skalsky, K. Aoki, S. De Cara, G. Kindermann, F. Kraxner, S. Leduc, I. McCallum, A. Mosnier, T. Sauer, and M. Obersteiner, 2011: Global land-use implications of first and second generation biofuel targets. *Energy Policy*, **39**, 5690-5702. Available online at http://www.sciencedirect.com/science/article/pii/S030142151000193X

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111**, 3709-3714. Available online at http://www.pnas.org/content/111/10/3709.abstract

Leclère, D., Havlík, P., Fuss, S., Schmid, E., Mosnier, A., Walsh, B., Valin, H., Herrero, M., Khabarov, N., Obersteiner, M., 2014: Climate change induced transformations of agricultural systems: insights from a global model. *Environmental Research Letters,* **9**, 1748-9326. Available online at http://iopscience.iop.org/article/10.1088/1748-9326/9/12/124018

Ecosystem Sector Models:

Coral: Coral Mortality and Bleaching Output (COMBO) Model

Lane, D., R. Jones, D. Mills, C. Wobus, R.C. Ready, R.W. Buddemeier, E. English, J. Martinich, K. Shouse, and H. Hosterman, 2014: Climate change impacts on freshwater fish, coral reefs, and related ecosystem services in the United States. *Climatic Change*, doi: 10.1007/s10584-014-1107-2. Available online at http://link.springer.com/article/10.1007/s10584-014-1107-2

Lane, D.R., R.C. Ready, R.W. Buddemeier, J.A. Martinich, K.C. Shouse, and C.W. Wobus, 2013: Quantifying and Valuing Potential Climate Change Impacts on Coral Reefs in the United States: Comparison of Two Scenarios. *PLOS ONE*, doi: 10.1371/journal.pone.0082579. Available online at http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0082579

Shellfish

Moore, C. and C. Griffiths, 2017: Welfare Analysis in a Two-Stage Inverse Demand Model: An Application to Harvest Changes in the Chesapeake Bay. *Empirical Economics*. 181:1-26. DOI 10.1007/s00181-017-1309-3 https://link.springer.com/content/pdf/10.1007%2Fs00181-017-1309-3.pdf

Moore, C. 2015: Welfare estimates of avoided ocean acidification in the U.S. mollusk market. *Journal of Agricultural and Resource Economics*, **40**, 50-62. Available online at http://www.waeaonline.org/UserFiles/file/JAREJan20154Moorepp50-62.pdf

Freshwater Fish

Lane, D., R. Jones, D. Mills, C. Wobus, R.C. Ready, R.W. Buddemeier, E. English, J. Martinich, K. Shouse, and H. Hosterman, 2014: Climate change impacts on freshwater fish, coral reefs, and related ecosystem services in the United States. *Climatic Change*, **131**, 143-157, doi: 10.1007/s10584-014-1107-2. Available online at http://link.springer.com/article/10.1007/s10584-014-1107-2

Jones, R., C. Travers, C. Rodgers, B. Lazar, E. English, J. Lipton, J. Vogel, K. Strzepek, and J. Martinich, 2012: Climate Change Impacts on Freshwater Recreational Fishing in the United States. *Mitigation and Adaptation Strategies for Global Change*, doi: 10.1007/s11027-012-9385-3. Available online at http://link.springer.com/article/10.1007/s11027-012-9385-3

Wildfire Response Costs

Mills, D., R. Jones, K. Carney, A. St Juliana, R. Ready, A. Crimmins, J. Martinich, K. Shouse, B. DeAngelo, and E. Monier, 2014: Quantifying and Monetizing Potential Climate Change Policy Impacts on Terrestrial Ecosystem Carbon Storage and Wildfires in the United States. *Climatic Change*, doi:10.1007/s10584-014-1118-z. Available online at http://link.springer.com/article/10.1007/s10584-014-1118-z

Melvin, A.M., J. Murray, B. Boehlert, J.A. Martinich, L. Rennels, and T.S. Rupp, 2017: Estimating wildfire response costs in Alaska's changing climate. *Climatic Change Letters*, doi: 10.1007/s10584-017-1923-2. Available online at http://link.springer.com/article/10.1007%2Fs10584-017-1923-2

Conklin, D.R., J.M. Lenihan, D. Bachelet, R.P. Neilson, and J.B. Kim, 2016: MCFire model technical description. Gen. Tech. Rep. PNW-GTR-926. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Available online at https://www.treesearch.fs.fed.us/pubs/52326

Drapek, R.J., J.B. Kim, and R.P Neilson, 2015: Continent-wide Simulations of a Dynamic Global Vegetation Model over the United States and Canada under Nine AR4 Future Scenarios. Global Vegetation Dynamics: Concepts and Applications in the MC1 Model, 73-90. Available online at http://onlinelibrary.wiley.com/doi/10.1002/9781119011705.ch6/summary

Rupp, T.S., A.M. Starfield, and F.S. Chapin III, 2000: A frame-based spatially explicit model of subarctic vegetation response to climatic change: comparison with a point model. Landscape *Ecology*, **15**, 383-400. Available online at http://link.springer.com/article/10.1023/A:1008168418778

A.3. Peer Review of the Technical Report

Consistent with guidelines described in EPA's Peer Review Handbook,[7, 8] this Technical Report was subject to an independent, external peer review. As described in Sections A.1 and A.2 of this Technical Appendix, the methods and results underlying the content of the Technical Report have been previously peer reviewed and published in the research literature. Since the Technical Report is a summary designed to inform the NCA4 (which has its own separate peer and other review processes), the peer review of this report was not intended to focus on reevaluating or reassessing the adequacy or rigor of those underlying peer-reviewed analytical modeling methods already in the literature. Rather, the charge was to carefully review and provide feedback on whether the findings of the underlying peer-reviewed literature are accurately summarized, technically supported, competently performed, properly documented, consistent with established quality criteria, and clearly communicated.

The review was managed by a contractor (Eastern Research Group, Inc.) under the direction of a designated EPA peer review leader, who prepared a peer review plan, the scope of work for the review contract, and the charge for the reviewers. Importantly, the EPA peer review leader played no role in producing any portion of the Technical Report. Reviewers worked individually (i.e., without contact with other reviewers, colleagues, or EPA) to prepare written comments in response to the charge questions.

The contractor identified, screened, and selected seven reviewers who had no conflict of interest in performing the review, and who collectively met the technical selection criteria provided by EPA.

The peer review charge directed reviewers to provide responses to the following questions during the main review:

1. Does the introductory chapter clearly explain the purpose of the report and provide appropriate context for the sector chapter results? If not, please provide recommendations for improvement.
2. Does the report adequately explain its relationship to other significant and well-known climate change risk analysis efforts, and are these descriptions properly placed in the report? If key citations are missing, please provide recommendations.
3. The report has been written for an educated and semi-technical audience. Are the writing level and graphics appropriate for these audiences?
4. Does the report adequately explain the overall analytic framework of the project, such that results across multiple sectors can be communicated in a consistent manner? Are the inputs and scenarios clearly explained and documented?

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[7] EPA, 2015: Peer Review Handbook, 4th Edition, 2015. United States Environmental Protection Agency, Programs of the Office of the Science Advisor. Available online at https://www.epa.gov/osa/peer-review-handbook-4th-edition-2015

[8] EPA has determined that this CIRA technical report falls under the classification of "Other Scientific and/or Technical Work Products." The report does not meet the criteria for "influential scientific information," as defined by OMB and further described in the EPA Peer Review Handbook, since it is not being used to support a regulatory program or policy position, and does not meet one or more of the factors listed in Section 2.2.3 of the EPA Peer Review Handbook for consideration as influential scientific information. As a corollary, the report also cannot be considered a "highly influential scientific assessment," as defined by OMB.

5. Do the text, figures and tables in the sector specific chapters clearly communicate the modeling results?
6. Sources of uncertainty across the modeling project are described upfront in the report, while the most important caveats for each sector are discussed in those respective sections (with references to the underlying research papers where these issues are described in more detail). With this in mind, does the report adequately inform the reader regarding how the results should be interpreted and used, given the limitations?
7. Are the conclusions in the Key Findings and Summary sections supported by the results of the sector specific chapters? Is the draft report missing important findings or messages based on your review of the report?
8. Sectoral modeling results for each sector have been aggregated to the NCA4 regions for the purpose of informing the development of the regional chapters of the NCA4 (see Regional Summaries). Would highlighting results for a sector with particularly meaningful impacts in each region be a helpful addition to these summaries (e.g., inland flooding damages in the Southeast)?
9. Report Format: Please comment on whether any aspects of the layout help or hinder the reader to understand the content and key messages of the report.
10. Please provide any recommendations on how this report can better inform or provide input to the NCA4 authors.

After revising the report based on comments received, EPA asked the peer reviewers to conduct one round of re-review focused on the Executive Summary of the Technical Report. The re-review charge directed reviewers to provide responses to the following questions

1. Is the new "Executive Summary" (formerly Key Findings), including the updated figure, improved compared to the original version (both are being provided)?
2. Do you have any final comments or recommendations for this Executive Summary section?
3. To provide more regionally-relevant detail, we are considering the addition of similar graphics to each of the NCA4 regional summary sections (see example below), focusing on the ten sectors for each region with the largest economic damages. Your reactions to this would be appreciated as well.

A.4. Supplementary Information Regarding Scenarios, Projections, and Inputs

A.4.1. General Criteria for Selection of GCMs

As in many sectoral impact analyses, the selection of a subset of GCMs is necessary due to computational, time, and resource constraints. Table A.4.1 presents the five GCMs used in the sectoral analyses of the Technical Report.

Table A.4.1. CMIP5 GCMs Used in the Analyses of this Technical Report

Center (Modeling Group)	Model Acronym	Availability		References
		LOCA	SNAP	
Canadian Centre for Climate Modeling and Analysis	CanESM2	X		Von Salzen et al. 2013[9]
National Center for Atmospheric Research	CCSM4	X	X	Gent et al. 2011[10] Neale et al. 2013[11]
NASA Goddard Institute for Space Studies	GISS-E2-R[12]	X	X	Schmidt et al. 2006[13]
Met Office Hadley Centre	HadGEM2-ES	X		Collins et al., 2011[14] Davies et al. 2005[15]
Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	X		Watanabe et al. 2010[16]

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[9] von Salzen, K., J.F. Scinocca, N.A. McFarlane, J. Li, J.N. Cole, D. Plummer, D. Verseghy, M.C. Reader, X. Ma, M. Lazare, and L. Solheim, 2013: The Canadian fourth generation atmospheric global climate model (CanAM4). Part I: representation of physical processes. *Atmosphere-Ocean*, **51**, 104-125.

[10] Gent, P.R., G. Danabasoglu, L.J. Donner, M.M. Holland, E. Hunke, S. Jayne, D. Lawrence, R.B. Neale, P.J. Rasch, M. Vertenstein, and P.H. Worley, 2011: The community climate system model version 4. *Journal of Climate*, **24**, 4973-4991.

[11] Neale, R.B., J. Richter, S. Park, P.H. Lauritzen, S.J. Vavrus, P. Rasch, and M. Zhang, 2013: The mean climate of the community Atmosphere Model (CAM4) in forced SST and fully coupled experiments. *Journal of Climate*, **26**, 5150-5168.

[12] Some of the GCMs in the CMIP5 archive were run multiple times to develop individual initializations for each climate model. In general, the LOCA dataset provides projections using the first initialization of each GCM. However, for the GISS-E2-R model, the LOCA dataset provided data for RCP4.5 using run #r6i1p1 and run #r2i1p1 for RCP8.5. The main reasoning for this difference is that the GCM initializations (raw data from CMIP5) did not provide all of the climate data necessary for doing the LOCA constructed analog and bias correction technique. While the usage of different initializations for the GISS-ER-R model could introduce inconsistency, the statistical differences across runs of the same GCM are dramatically lower than across models, and those differences are further dampened by the LOCA bias correction. To evaluate the potential that these alternative initializations could introduce inconsistencies, an analysis was completed comparing the raw #r6i1p1 runs for both RCPs and the raw #r2i1p1 runs for both RCPs. The results of this comparative analysis confirmed that the differences are minimal and that it is reasonable to use the LOCA projections.

[13] Schmidt, G.A., R. Ruedy, J.E. Hansen, I. Aleinnov, N. Bell, M. Bauer, S. Bauer, B. Cairns, V. Canuto, Y Cheng, and A. Del Genio, 2006: Present-day atmospheric simulations using GISS ModelE: Comparison to in situ, satellite, and reanalysis data. *Journal of Climate*, **19**, 153-192.

[14] Collins, W.J., N. Bellouin, M. Doutriaux-Boucher, N. Gedney, P. Halloran, T. Hinton, J. Hughes, C. D. Jones, M. Joshi, S. Liddicoat, G. Martin, F. O'Connor, J. Rae, C. Senior, S. Sitch, I. Totterdell, A. Wiltshire, and S. Woodward, 2011: Development and evaluation of an Earth system model–HadGEM2. *Geoscience Model Development*, **4**, 1051-1075.

[15] Davies, T., M. J. P. Cullen, A. J. Malcolm, M. Mawson, A. Staniforth, A.A. White, N. Wood, 2005: A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Quarterly J. of the Royal Meteorological Society*, **131**, 1759-1782.

[16] Watanabe, M., T. Suzuki, R. O'ishi, Y. Komuro, S. Watanabe, S. Emori, T. Takemura, M. Chikira, T. Ogura, M. Sekiguchi, and K.

These GCMs were chosen based on the criteria described below:

A. Leverage existing dynamically-downscaled data

B. Available in the SNAP and LOCA datasets

C. Capture variability in temperature and precipitation outputs

D. Demonstrate independence and quality

Criterion A. Leverage existing dynamically-downscaled data

Analyses estimating the impacts of climate change on air quality require climate projections with high temporal resolution (e.g., hourly data). Most downscaled datasets for atmospheric chemistry modeling, including the LOCA and SNAP products, do not have this type of resolution (e.g., hourly data). Therefore, a dynamically-downscaled dataset is used to enable the inclusion of air quality in this Technical Report. Prior to beginning this Technical Report, EPA had dynamically-downscaled the CCSM4 GCM using the Weather Research and Forecast (WRF) model.[17] Additional reasons for including CCSM4 are described in the other criteria below.

Criterion B. Available in the SNAP and LOCA datasets

As all of the five GCMs downscaled by SNAP for Alaska are available in the LOCA dataset, it is preferable to represent at least two of the five SNAP GCMs (Table 1). While the differences in downscaled methodologies for the contiguous U.S. (LOCA) and Alaska (SNAP) datasets are not ideal, the use of consistent GCMs (or at least a subset) across sectoral analyses in both the contiguous U.S. and Alaska represents the most important focus for developing a consistent framework for this project.[18,19]

Criterion C. Capture variability in temperature and precipitation outputs

Because only five of the CMIP5 GCMs that produced daily data are being used in this project, one of the most important factors in selecting the GCMs is to ensure that the subset chosen captures a large range of the variability observed across the entire CMIP5 ensemble. While many different metrics could be used in this type of comparison, a logical and accepted approach is to compare the projections from CMIP5 GCMs for annual and seasonal temperature and precipitation outputs at national and regional (sub-national) scales.

Takata, 2010: Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. *Journal of Climate*, **23**, 6312-6335.

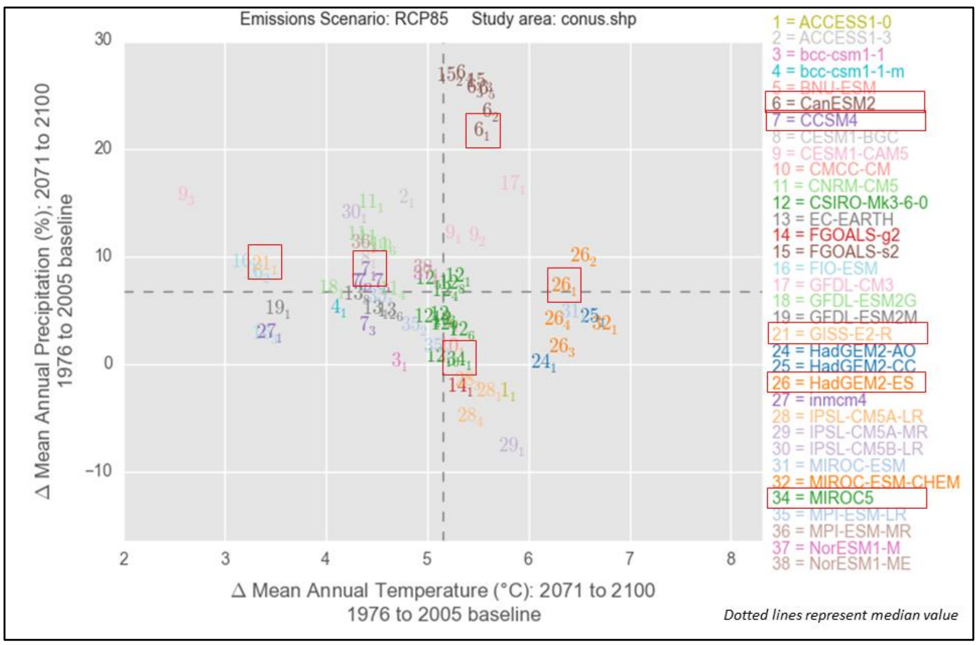
[17] Fann, N., C.G. Nolte, P. Dolwick, T.L. Spero, A. Curry-Brown, S. Phillips, and S. Anenberg, 2015: The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030. *Journal of the Air & Waste Management Association*, 65, 570-580. http://dx.doi.org/10.1080/10962247.2014.996270.

[18] Because only two of the five overall GCMs chosen for this project correspond with those available in the SNAP database, the sectoral impact analyses for Alaska present results for only these two models in the Technical Report. But the sectoral analyses for Alaska ran all five GCMs downscaled in the SNAP database as a separate sensitivity analysis.

[19] See section A.4.2 for a description of steps taken to bias correct SST data used in the Coral Reef and Shellfish analyses.

EPA has developed the LASSO climate tool to support these types of comparisons in the contiguous U.S. To aid in the selection of GCMs for this multi-sectoral analysis, LASSO was used to produce scatter plots showing the variability across the CMIP5 ensemble for projected changes (2071-2100 compared to 1976-2005 reference period) in annual and seasonal temperature and precipitation. The national-scale plots are shown directly below, while similar plots for all six NCA3 regions of the contiguous U.S. (Northern and Southern Plains are combined into one Great Plains region) are further below, following the last criterion. The five selected GCMs are displayed with boxes around them to highlight their location within the scatter plots.

Figure A.4.1. Variability of Projected Annual Temperature and Precipitation Change across the CMIP5 Ensemble for the Contiguous U.S. [20]



[20] A number of the GCMs in the Climate Tool plots contain multiple initializations that are designated with numbers in subscript. The dashed lines represent the median value for each axis.

Figure A.4.2. Variability of Projected Summertime (June, July, August) Temperature and Precipitation Change across the CMIP5 Ensemble for the Contiguous U.S.

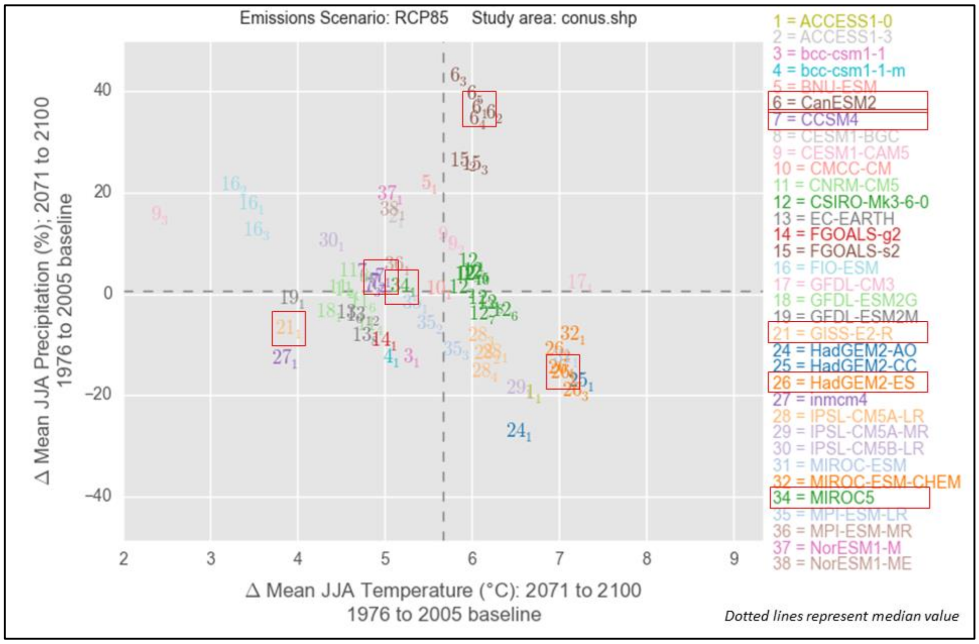
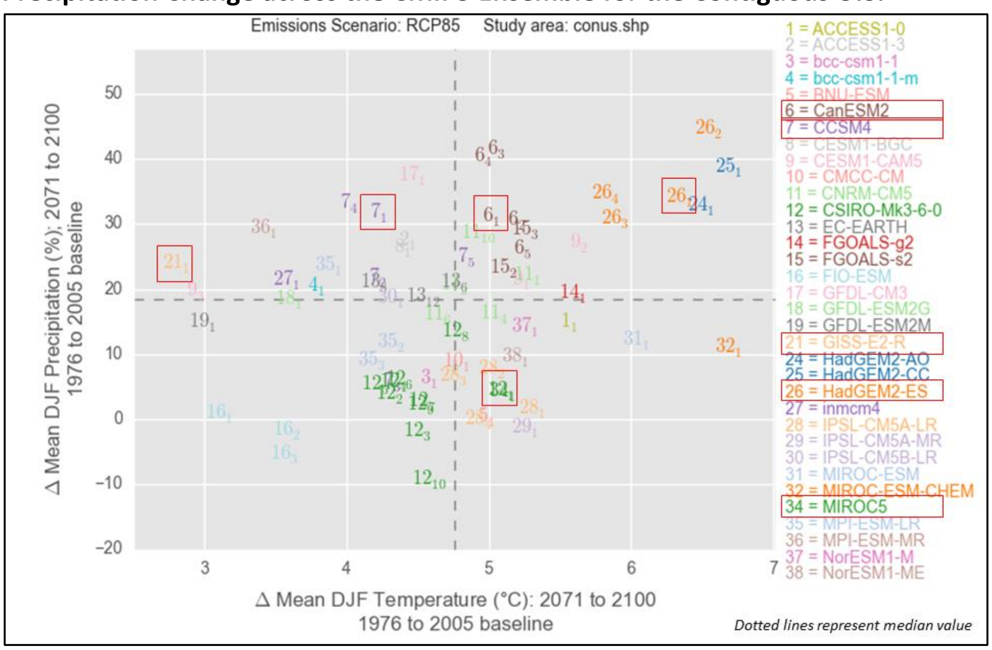


Figure A.4.3. Variability of Projected Wintertime (December, January, February) Temperature and Precipitation Change across the CMIP5 Ensemble for the Contiguous U.S.



As shown in Figures A.4.1 – A.4.3, the five selected GCMs (CCSM4, GISS-E2-R, CanESM2, HadGEM2-ES, and MIROC5) cover a large range of the variability across the entire ensemble. This selection also balances the range alongside considerations of model independence, broader usage by the scientific community, and skill, which are described in more detail in Criterion D.

While EPA's LASSO tool does not provide plots for Alaska due to unavailability of the underlying downscaled dataset, the following figures of this Section present the change in temperature and precipitation in the SNAP GCMs used in this Technical Report (see Figures A.4.21, A.4.22., A.4.28, A.4.29, A.4.35, A.4.42, A.4.43). The two SNAP GCMs selected (CCSM4 and GISS-E2-R) capture some of the variability across the five models included in the SNAP database.[21]

Criterion D. Demonstrate independence and quality

The CMIP5 archive is the largest assemblage of data ever produced from different GCMs and modeling teams. However, the models vary in their ability to resolve certain climate system processes, including those most relevant to the U.S. In addition, while over 60 different GCMs are represented, a number of the models share computer code or are parametrized in similar ways. Sanderson et al. (2015a[22] and b[23]) provided analysis of both model skill at the global scale and independence of underlying code. These criteria were considered in the selection process.

With insufficient time to conduct a U.S.-specific weighting analysis based on skill and independence, a qualitative consideration of these metrics is still valuable. For purposes of this project, the five GCMs selected were developed by different, well-known modeling groups whose models are frequently used in the literature.[24] In addition, two of the GCMs (CCSM4, GISS-E2-R) are developed by U.S.-based modeling groups (NCAR and NASA, respectively). There is some expectation that modeling teams may pay closer attention to the regional climate in the region where the team is based, and that therefore U.S.-based modeling groups might have comparatively greater skill for purposes of U.S. impacts analysis.

Plots of Variability across CMIP5 Ensemble for NCA3 Regions

The scatter plots starting on the following pages display the variability across the CMIP5 ensemble for projected changes (2071-2100 compared to 1976-2005 reference period) in annual and summertime

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[21] Melvin, A.M., P. Larsen, B. Boehlert, J.E. Neumann, P. Chinowsky, X. Espinet, J. Martinich, M.S. Baumann, L. Rennels, A. Bothner, D.J. Nicolsky, and S.S. Marchenko, 2016: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. Proceedings of the National Academies of Sciences, doi:10.1073/pnas.1611056113.

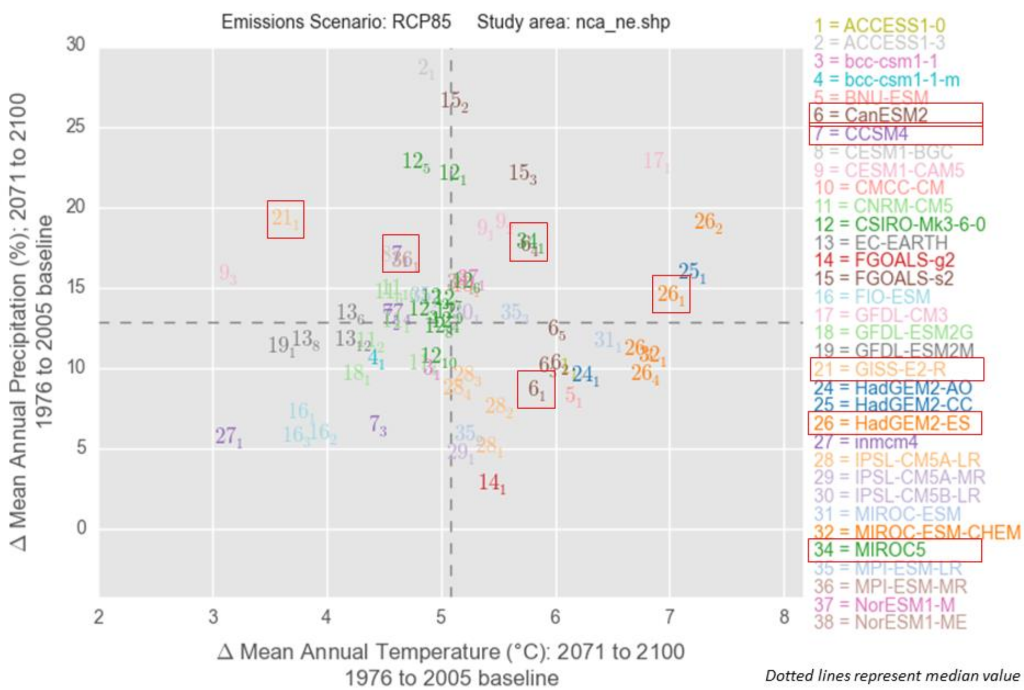
[22] Sanderson, B., R. Knutti, and P. Caldwell, 2015: A representative democracy to reduce interdependency in a multimodel ensemble. *Journal of Climate*, **28**, doi: 10.1175/JCLI-D-14-00362.1.

[23] Sanderson, B., R. Knutti, and P. Caldwell, 2015: Addressing interdependency in a multi-model ensemble by interpolation of model properties. *Journal of Climate*, **28**, doi: 10.1175/JCLI-D-14-00361.1.

[24] The fact that other impact modeling groups have also used these GCMs also allows for greater comparability of results across studies. For example, HadGEM2-ES was the primary model used in the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) fast track project. See: Warszawski, L., K. Frieler, V. Huber, F. Piontek, O. Serdeczny, and J. Schewe, 2013: The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework. *PNAS*, **111**, 3228-3232, doi: 10.1073/pnas.1312330110.

temperature and precipitation for each of the NCA3 regions of the contiguous U.S. The five selected GCMs are displayed with boxes around them to highlight their location within the scatter plots.[25]

Figure A.4.4. Variability of Projected Annual Temperature and Precipitation Change across the CMIP5 Ensemble for the Northeast



[25] A number of the GCMs in the LASSO climate tool plots contain multiple initializations that are designed with numbers in subscript.

Figure A.4.5. Variability of Projected Summertime Temperature and Precipitation Change across the CMIP5 Ensemble for the Northeast

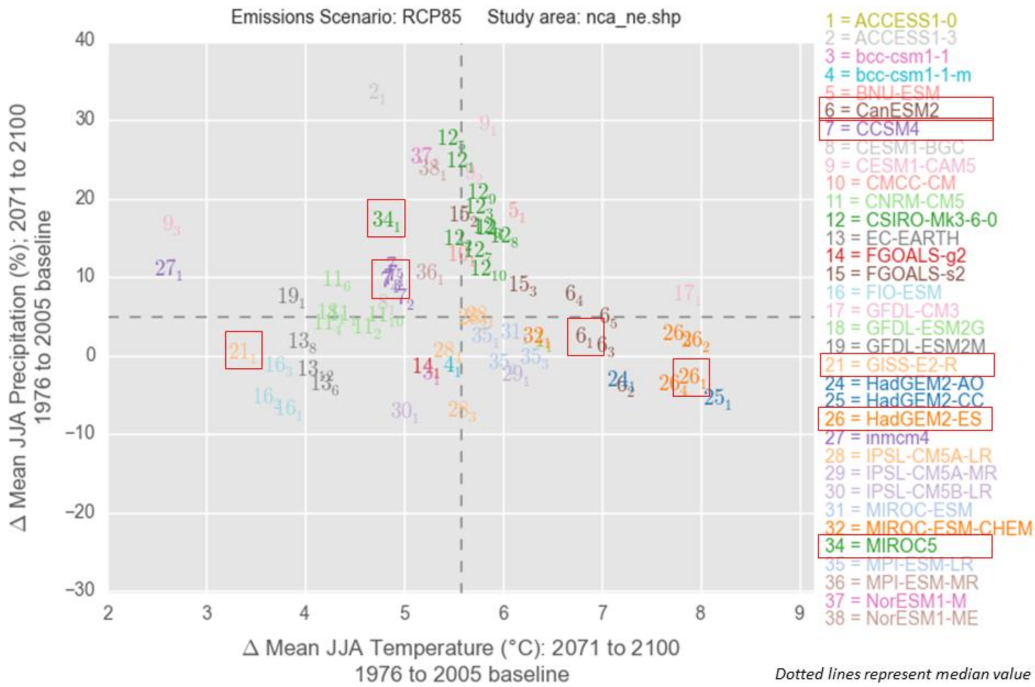


Figure A.4.6. Variability of Projected Annual Temperature and Precipitation Change across the CMIP5 Ensemble for the Southeast

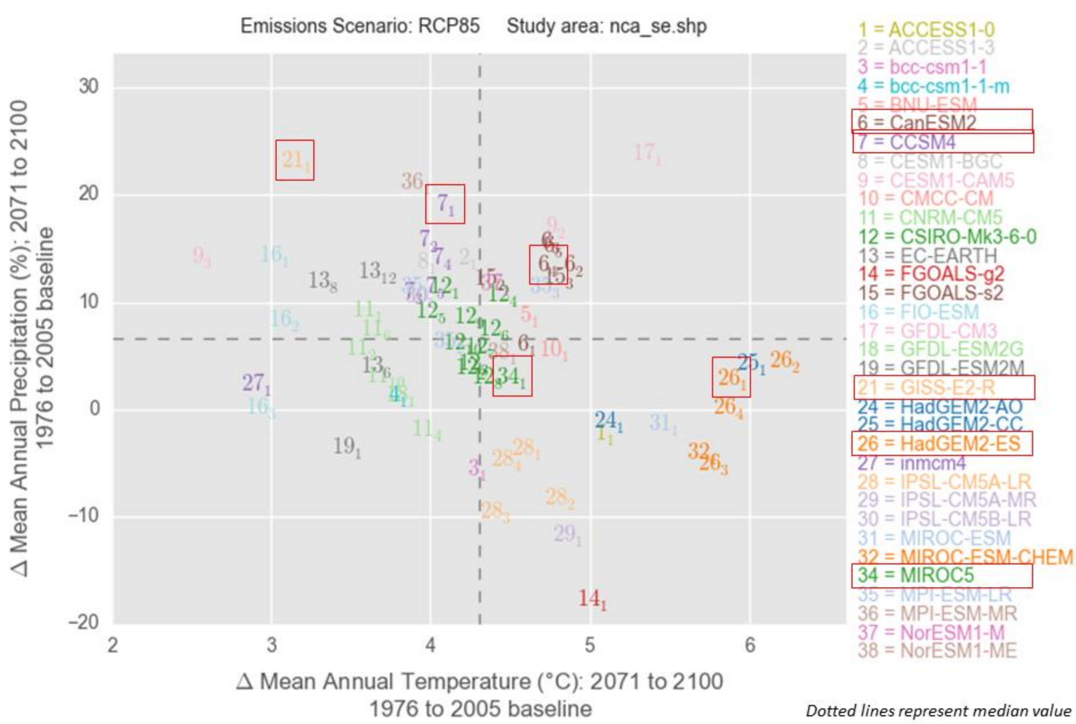


Figure A.4.7. Variability of Projected Summertime Temperature and Precipitation Change across the CMIP5 Ensemble for the Southeast

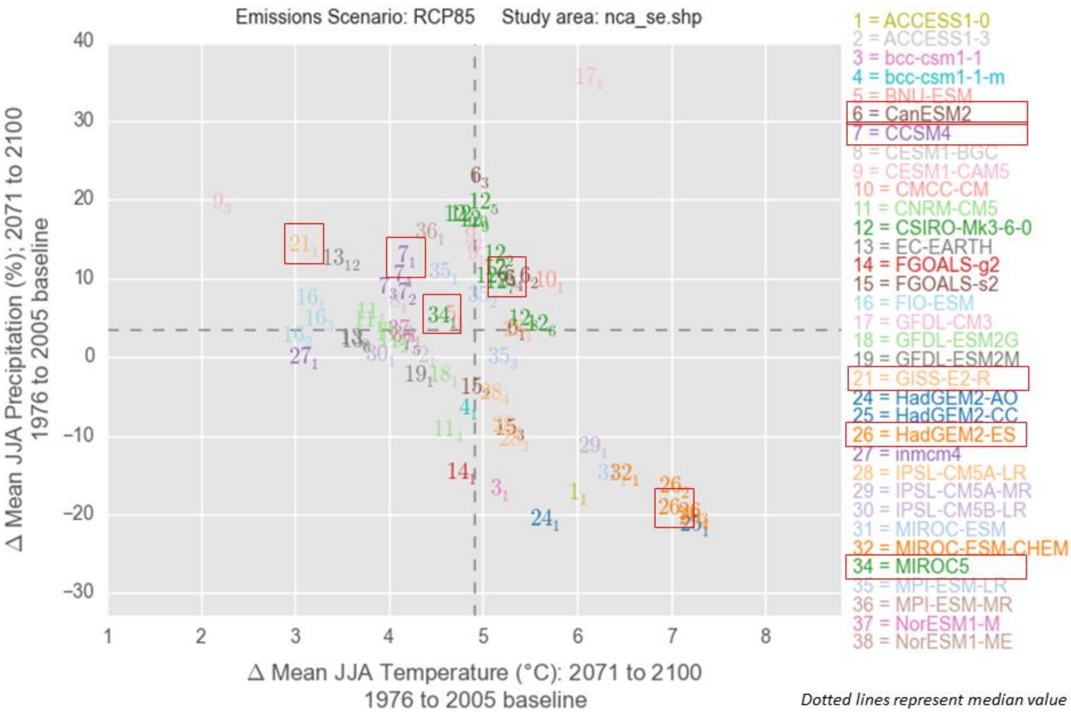


Figure A.4.8. Variability of Projected Annual Temperature and Precipitation Change across the CMIP5 Ensemble for the Midwest

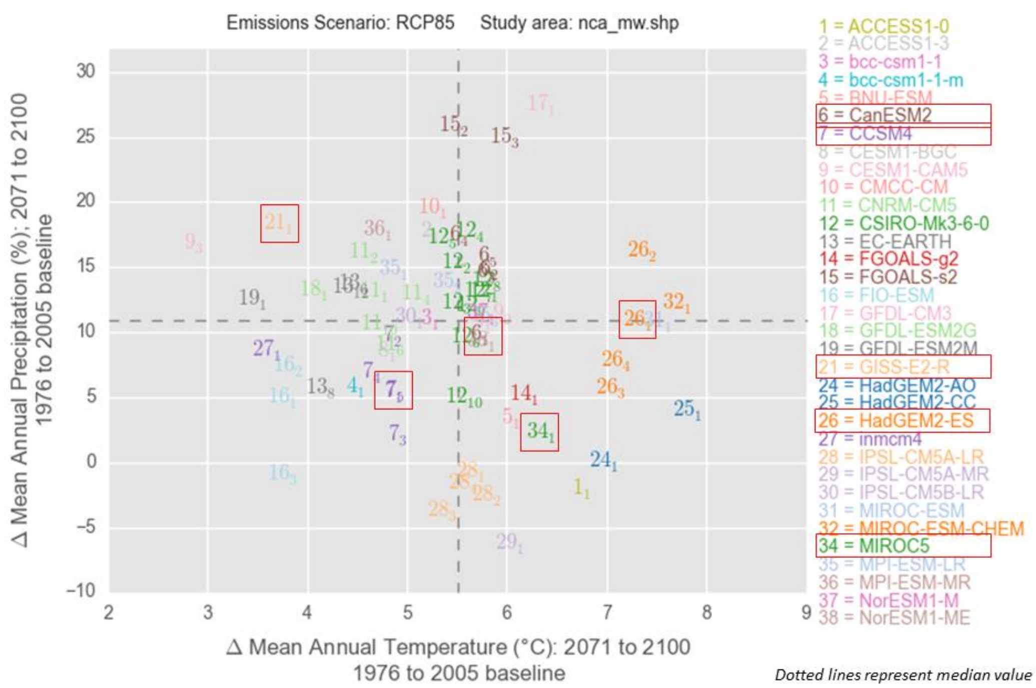


Figure A.4.9. Variability of Projected Summertime Temperature and Precipitation Change across the CMIP5 Ensemble for the Midwest

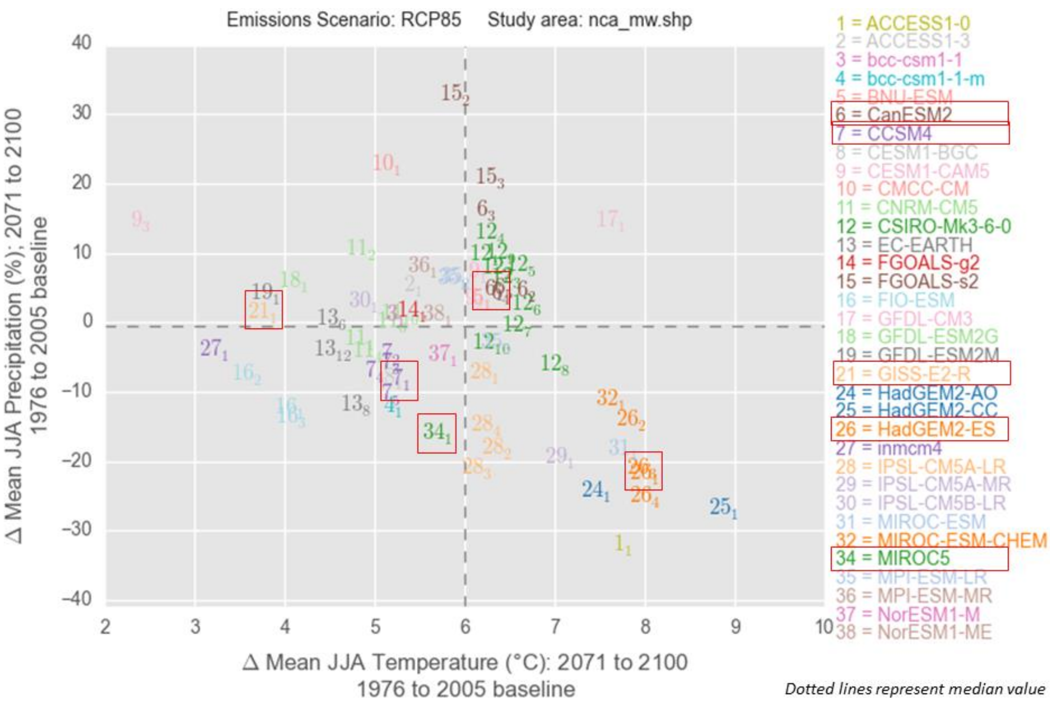


Figure A.4.10. Variability of Projected Annual Temperature and Precipitation Change across the CMIP5 Ensemble for the Great Plains

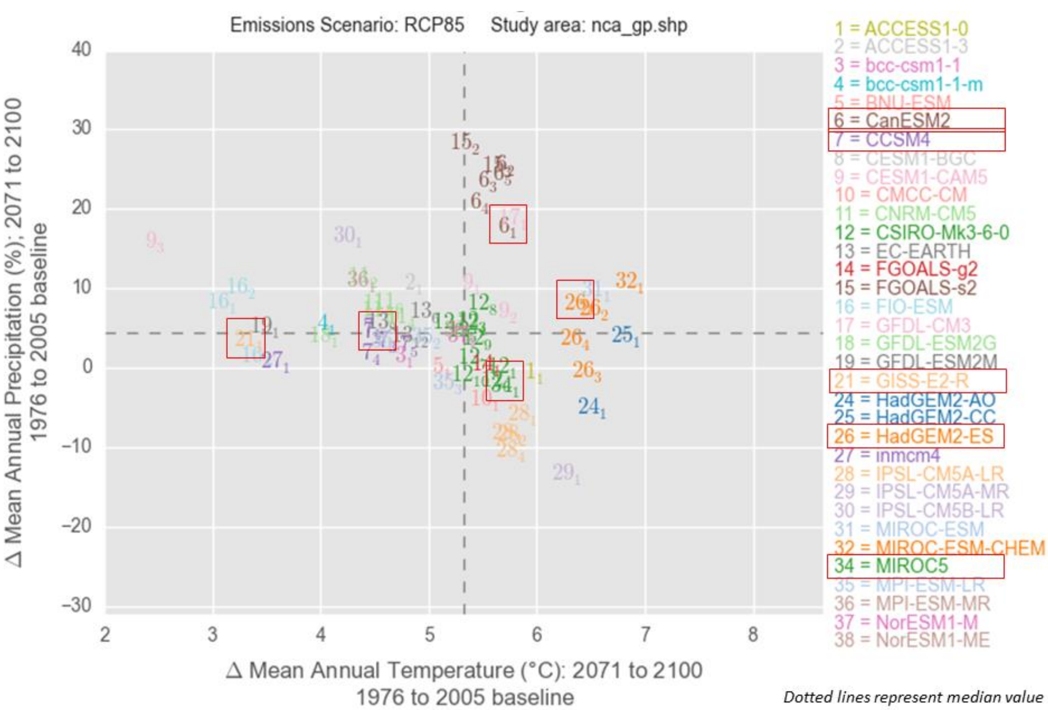
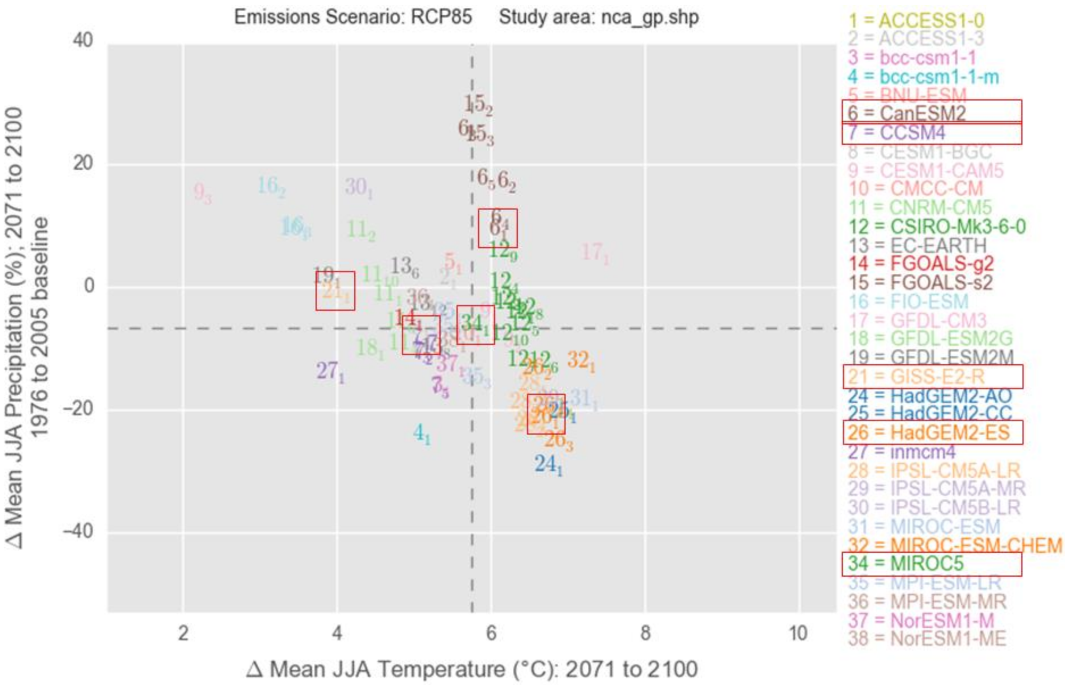
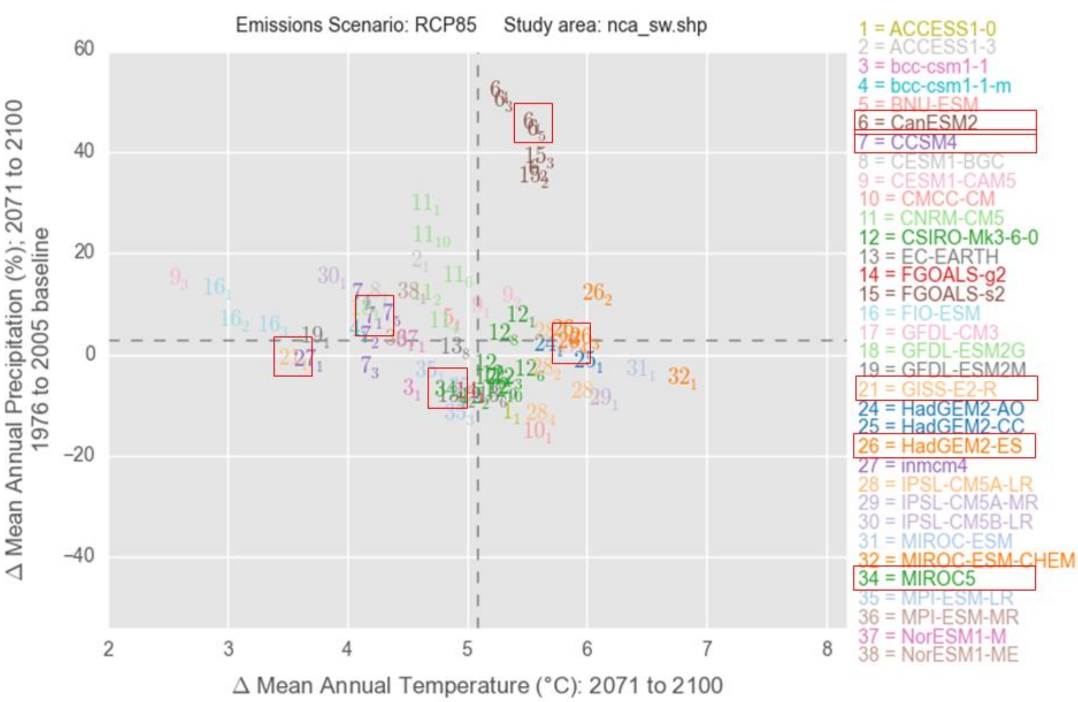


Figure A.4.11. Variability of Projected Summertime Temperature and Precipitation Change across the CMIP5 Ensemble for the Great Plains



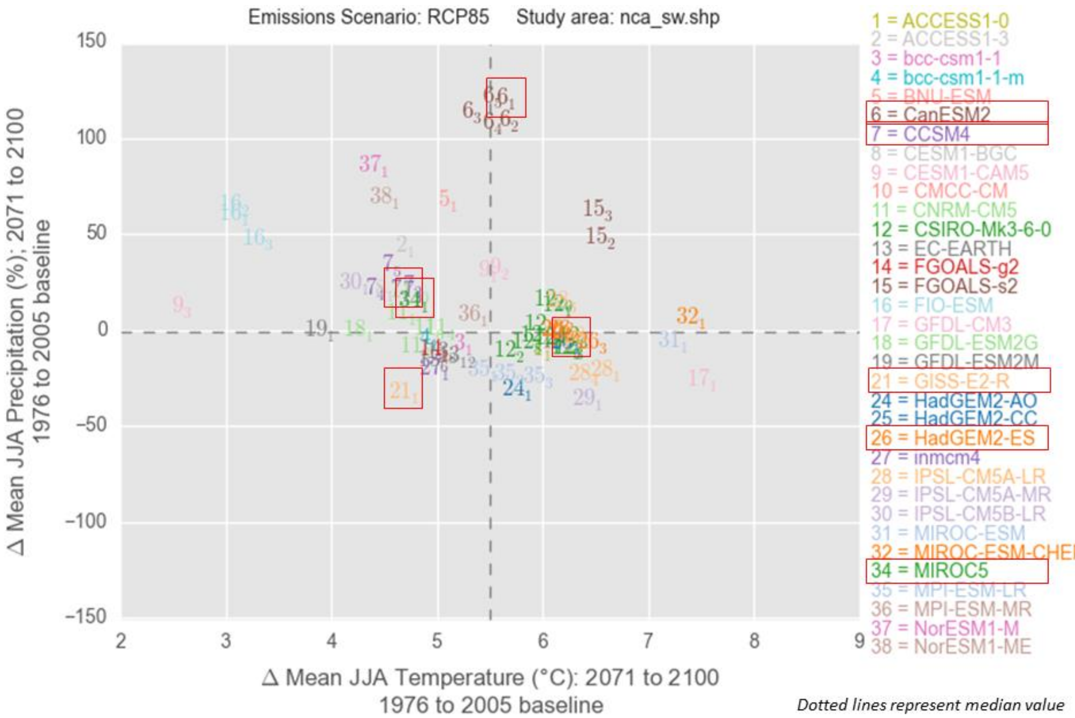
Dotted lines represent median value

Figure A.4.12. Variability of Projected Annual Temperature and Precipitation Change across the CMIP5 Ensemble for the Southwest



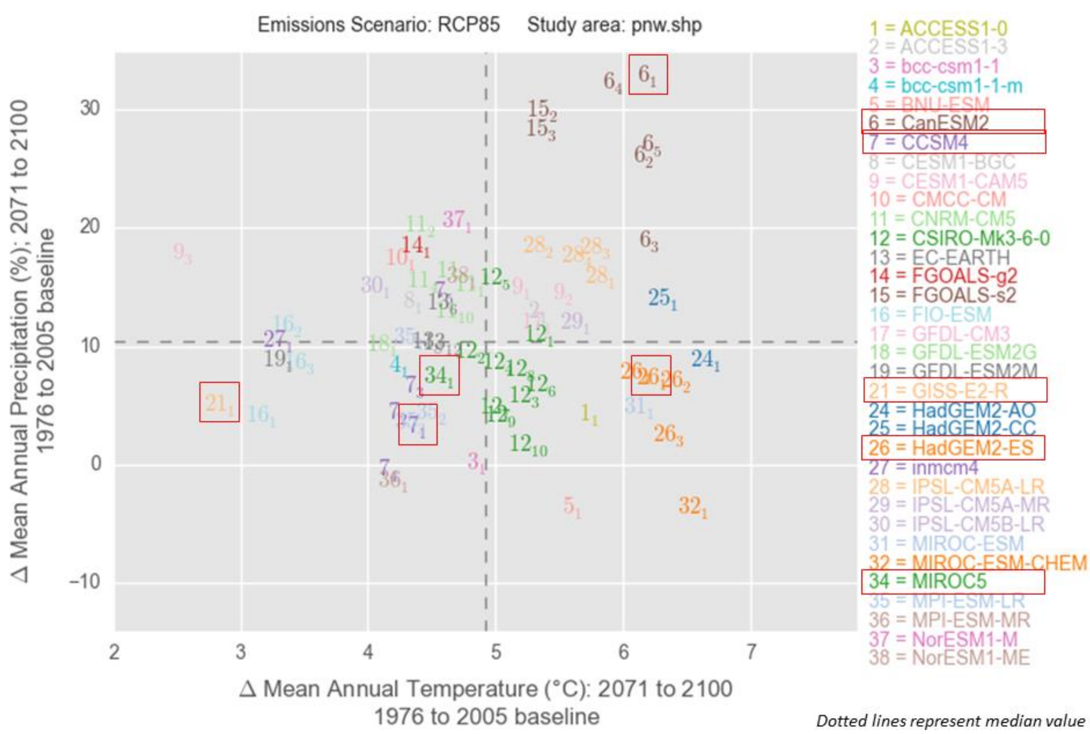
Dotted lines represent median value

Figure A.4.13. Variability of Projected Summertime Temperature and Precipitation Change across the CMIP5 Ensemble for the Southwest



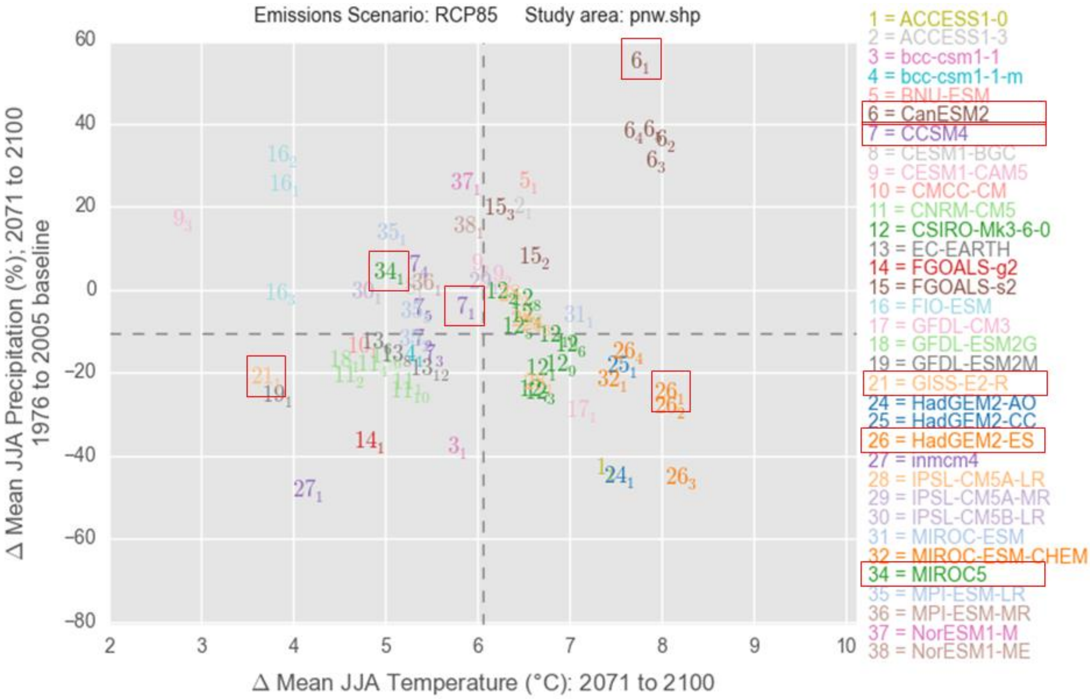
Dotted lines represent median value

Figure A.4.14. Variability of Projected Annual Temperature and Precipitation Change across the CMIP5 Ensemble for the Northwest



Dotted lines represent median value

Figure A.4.15. Variability of Projected Summertime Temperature and Precipitation Change across the CMIP5 Ensemble for the Northwest



Dotted lines represent median value

A.4.2. Additional Climate Variables Needed for Impacts Analysis

The LOCA dataset provides daily projections through 2100 at a 1/16th degree resolution for three variables: daily maximum temperature (tmax), daily minimum temperature (tmin), and daily precipitation. Some of the CIRA sectoral models require additional variables, for example:

- Many models require average daily temperature at various resolutions.
- EPIC (crop yield simulator) requires solar radiation, wind speed, and relative humidity at a 2 x 2.5 degree resolution.
- MC2 (vegetation/forestry model) requires vapor pressure and wind speed at a 0.5 x 0.5 degree resolution.

To generate average daily temperature, the widely-used and straightforward practice of taking an average of tmax and tmin will be used. This approach is commonly used for observational data, and therefore models which are calibrated against observed temperatures will often be based on the tmax/tmin average. However, some models may be based on the average temperature weighted by time over the course of the day. The precise relationship between this weighted average over time, tmax, and tmin is a function of latitude, range of daily temperature, and other factors. The benefits of methodological simplicity from using the average of tmax and tmin outweigh the slight loss in accuracy for those models that depend on a weighted average over time.

For pressure, wind speed, humidity, and solar radiation, the approach is more complex. The historical pattern of these four variables cannot be simply repeated to fill in the missing LOCA values, as the arrival times of the LOCA tmax, tmin, and precipitation outputs are drawn from the GCM projections rather than the historical time series. To fill in the missing values, the proposed approach starts with the assumption that there is some relationship between temperature/precipitation and these four variables.[26] With limited time to test multiple approaches, a straightforward, commonly-used, and robust approach has been identified to generate projections of these variables that is internally-consistent and relies on historically observed weather and climate conditions.

To start, all of the variables needed for the sectoral models are available historically from the Princeton Land Surface Hydrology Group[27] at a 0.5 x 0.5 degree resolution. The following steps for generating the 2 x 2.5 degree pressure, wind speed, humidity, and solar radiation projections for EPIC:

1. Spatially aggregate precipitation, tmean and the four missing variables from 0.5 degrees up to 2 x 2.5 degrees.
2. For each month and 2 x 2.5 degree grid in CONUS, divvy the roughly 900 historical daily tmean and precipitation values into 20th percentile bins for each variable, making a total of 25 precipitation/temperature bins for each month/grid combination.
3. Aggregate the daily LOCA projections of tmean and precipitation to 2 x 2.5 degree.
4. Within each month and grid, assign each day of the aggregated LOCA projections to one of the 25 historical temperature/precipitation bins. If the LOCA projection falls outside of the historical temperature and/or precipitation projections, assign that value to the nearest bin.
5. For each LOCA value, randomly choose one of the elements its assigned bin – this is the day from that month/grid combination that is assigned to that day of LOCA projections. The pressure, wind speed, humidity, and solar radiation of the selected historical day are then assigned to the projection day in the LOCA series.[28]

Because sea surface temperature (SST) is typically not provided in downscaled datasets, including LOCA, projections for this variable were obtained directly from the CMIP5 archive. For each of the five GCMs and two RCPs, modeled deltas were derived by subtracting the average monthly hindcast SST value for 1986-2005 from each modeled future month. These model deltas were added to an observed monthly average (based on NOAA ERSST v3b data[29]) from the period 1986-2005 by model cell, resulting in

[26] Alternatives to the absolute binning approach were considered, including relative (percent) binning, econometric analysis, and bias correction of these variables taken directly from the GCMs. While the latter approach may be the most desirable, it would require months of processing and testing. Econometric analysis would also require significant time and analytic resources.
[27] Sheffield, J., G. Goteti, and E. F. Wood, 2006: Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling. *J. Climate*, **19**, 3088-3111 Global Meteorological Forcing Dataset for Land Surface Modeling. Available online at: http://hydrology.princeton.edu/data.pgf.php
[28] Vapor pressure can be derived using values for specific humidity, atmospheric pressure, and temperature.
[29] Smith, T.M., R.W. Reynolds, T.C. Peterson, and J. Lawrimore, 2008: Improvements NOAAs Historical Merged Land–Ocean Temp Analysis (1880–2006). *Journal of Climate*, **21**, 2283-2296. Data available at https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v3b

modeled absolute temperatures.[30] The resulting data was used in the Coral Reef and Shellfish sectors of this Technical Report.

A.4.3. Individual Model Results for Projections of Future Climate

Temperature Change in the U.S.

This section presents the individual model projections of the change in mean temperature under RCP4.5 and RCP8.5 for four future time periods relative to the reference period across the lower 48 states (Figures A.4.16 through A.4.20) and Alaska (Figures A.4.21 and A.4.22).

Figure A.4.16. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across the Contiguous U.S. (CanESM2)

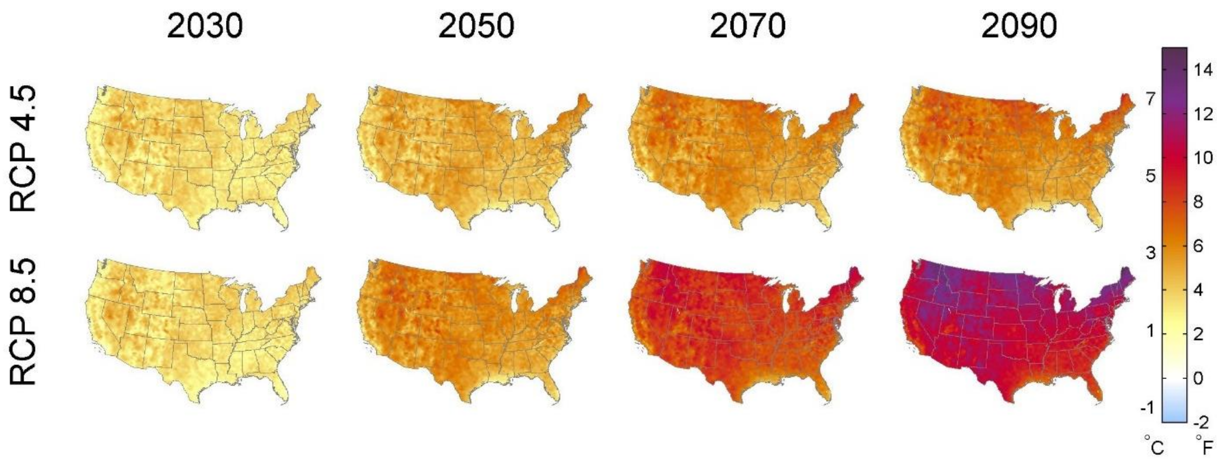
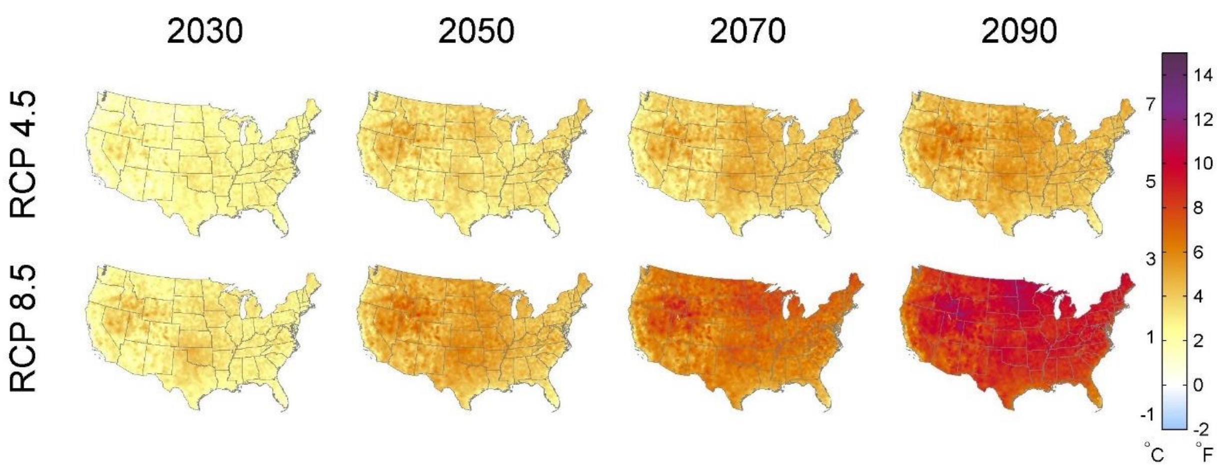


Figure A.4.17. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across the Contiguous U.S. (CCSM4)



[30] Because the HadGEM2-ES model was only simulated out to 2099 for the CMIP5 project, the values for the year 2099 were repeated in the year 2100 to provide data for that missing year.

Figure A.4.18. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across the Contiguous U.S. (GISS-E2-R)

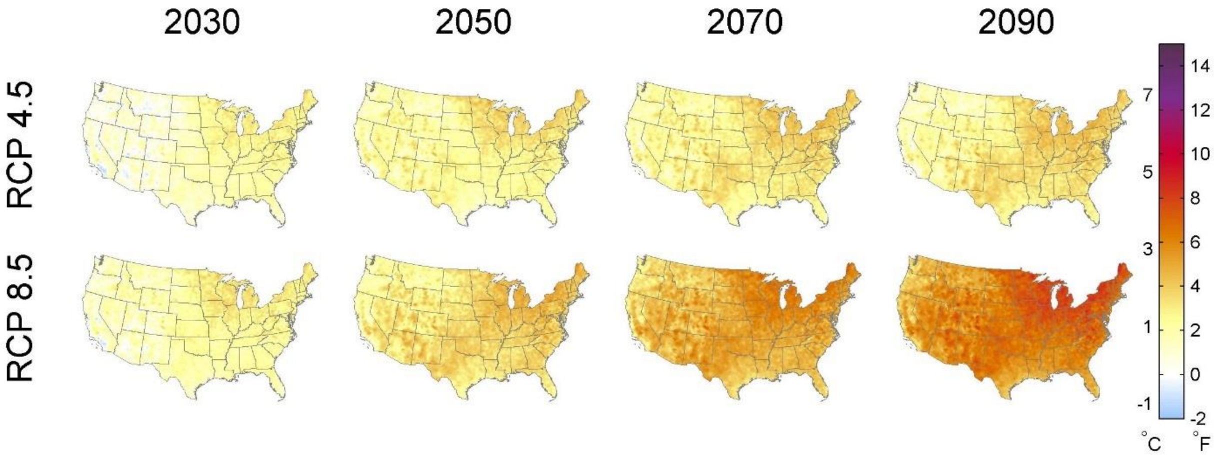


Figure A.4.19. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across the Contiguous U.S. (HadGEM2-ES)

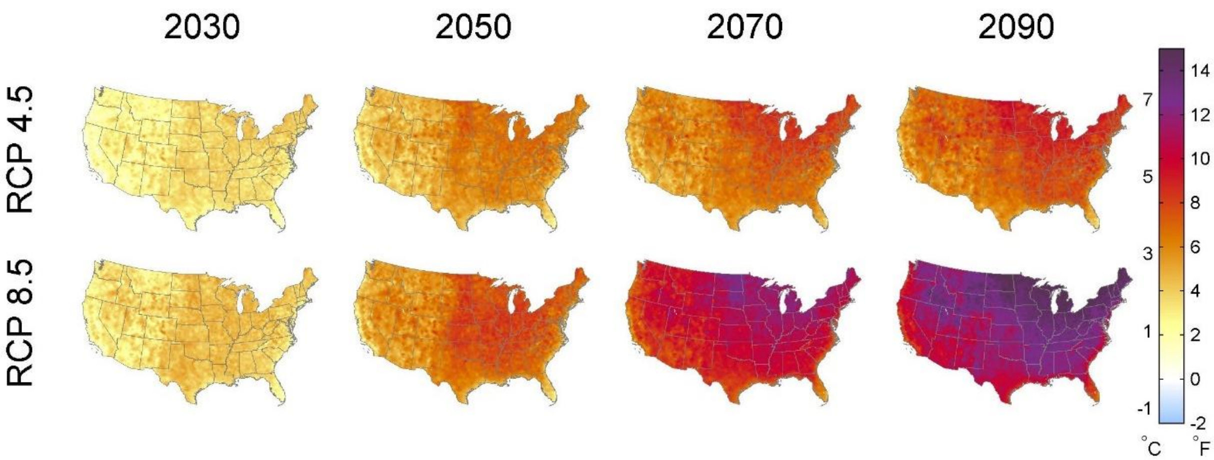


Figure A.4.20. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across the Contiguous U.S. (MIROC5)

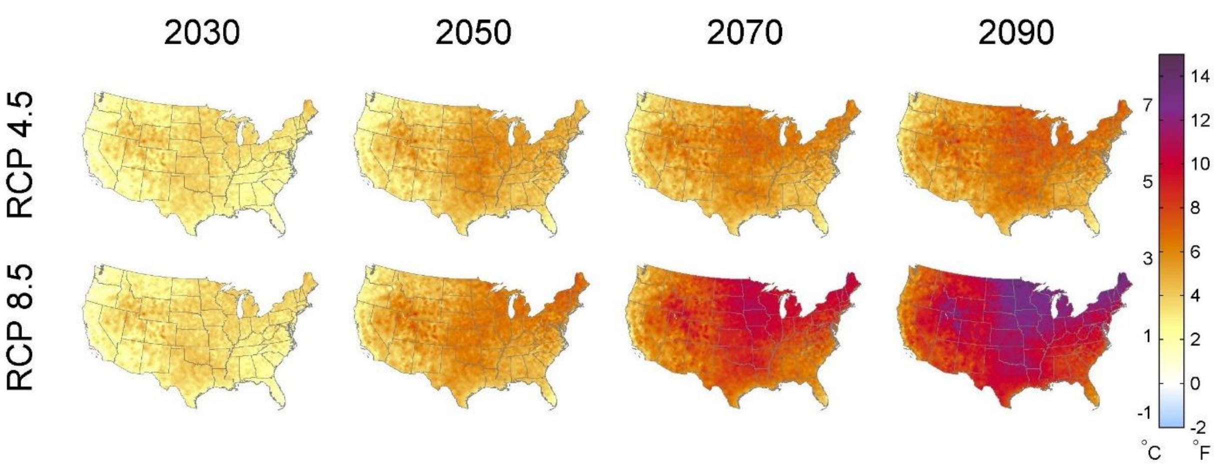


Figure A.4.21. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across Alaska (CCSM4)

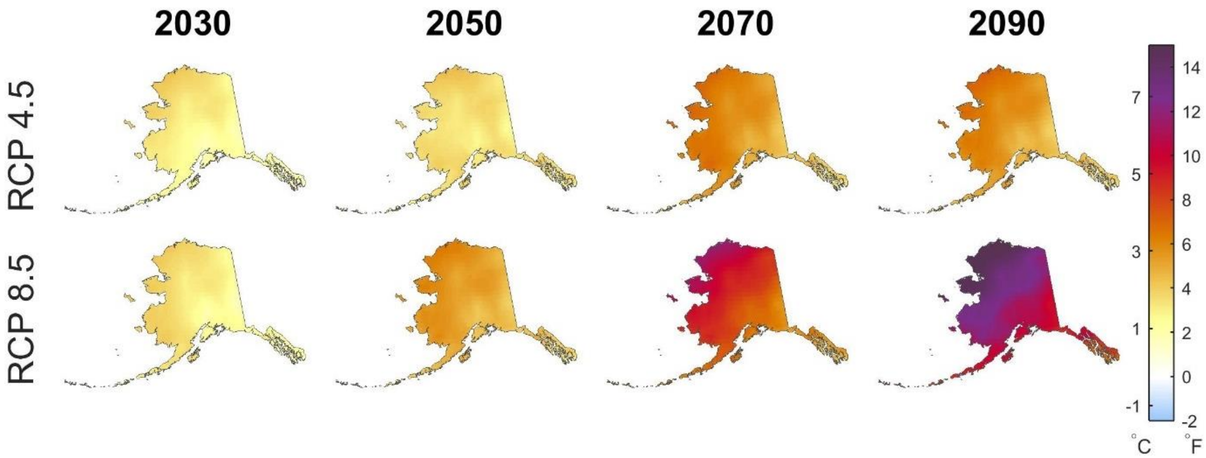
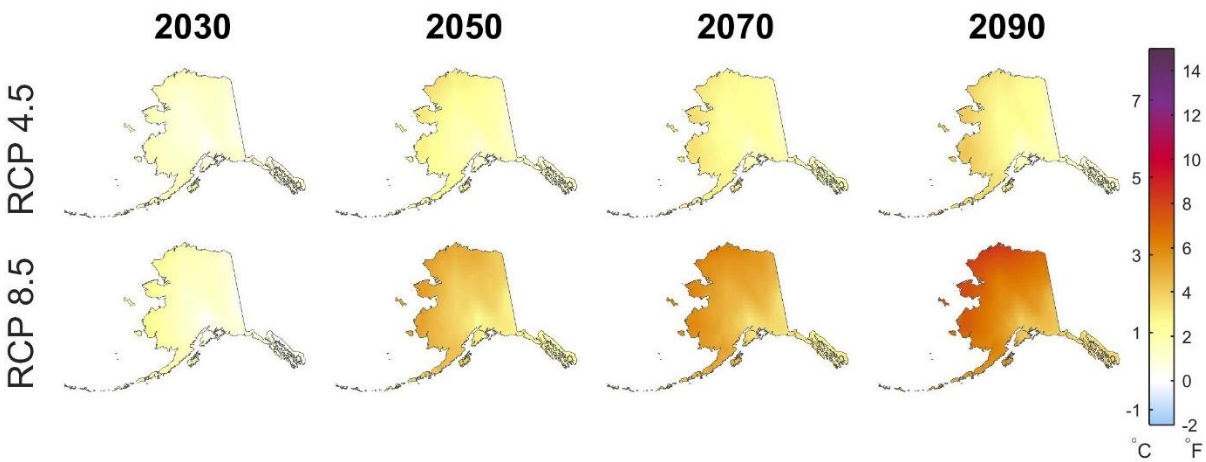


Figure A.4.22. Change in Mean Annual Temperature Relative to the Reference Period (1986-2005) across Alaska (GISS-E2-R)



This section presents the individual model projections of the number of days above 90°F under RCP4.5 and RCP8.5 for four future time periods relative to the reference period (1996-2005) across the lower 48 states (Figures A.4.23 through A.4.27) and the individual model projections of the number of days above 80°F under RCP4.5 and RCP8.5 for four future time periods relative to the reference period (1996-2005) across Alaska (Figures A.4.28 and A.4.29).

Figure A.4.23. Number of Days above 90°F across the Contiguous U.S (CanESM2)

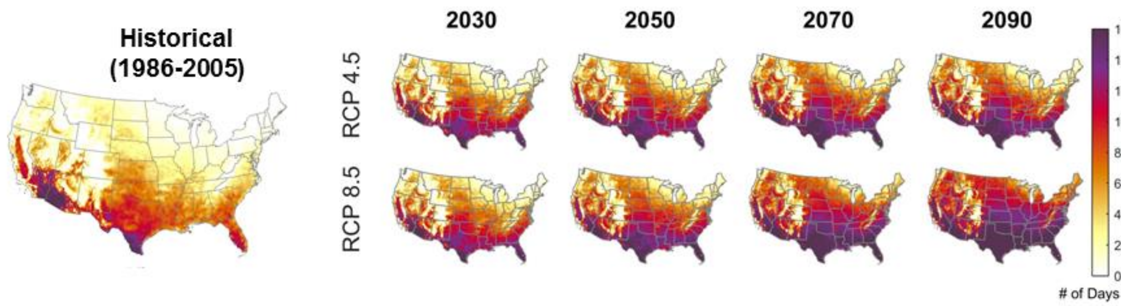


Figure A.4.24. Number of Days above 90°F across the Contiguous U.S (CCSM4)

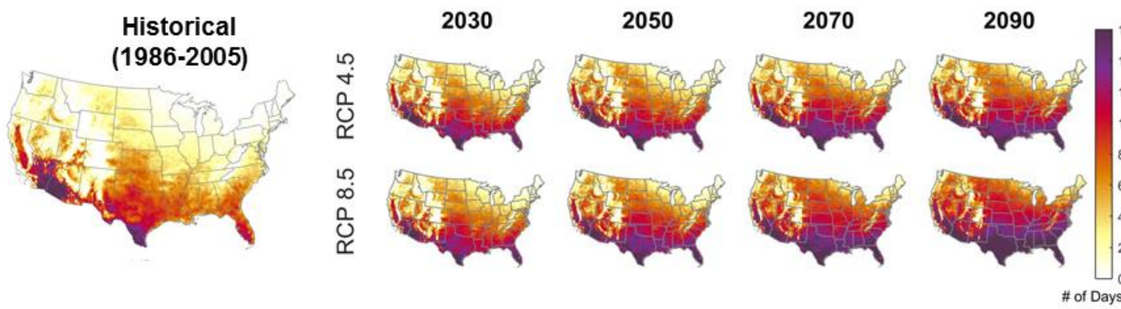


Figure A.4.25. Number of Days above 90°F across the Contiguous U.S (GISS-E2-R)

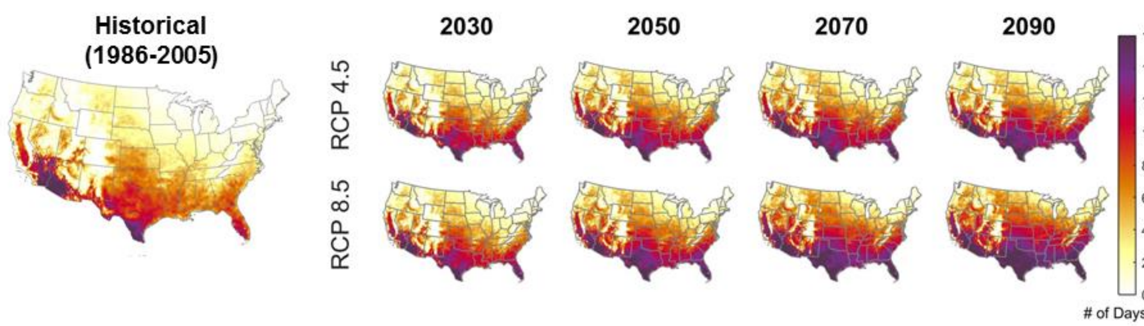


Figure A.4.26. Number of Days above 90°F across the Contiguous U.S (HadGEM2-ES)

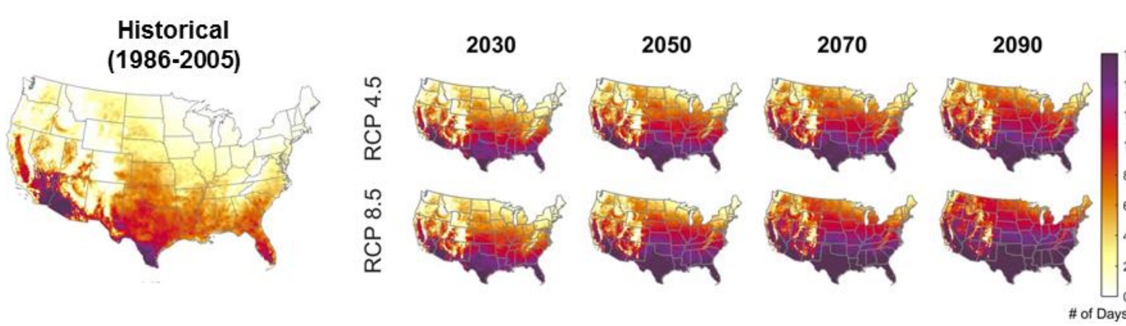


Figure A.4.27. Number of Days above 90°F across the Contiguous U.S (MIROC5)

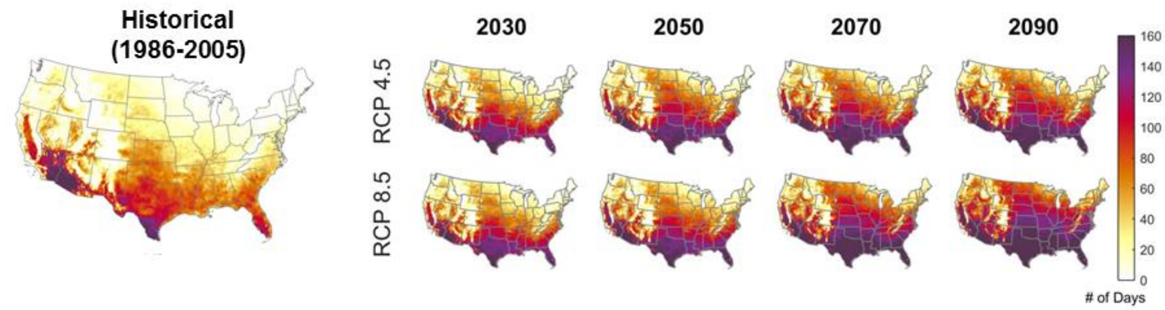


Figure A.4.28. Number of Days above 80°F across Alaska (CCSM4)

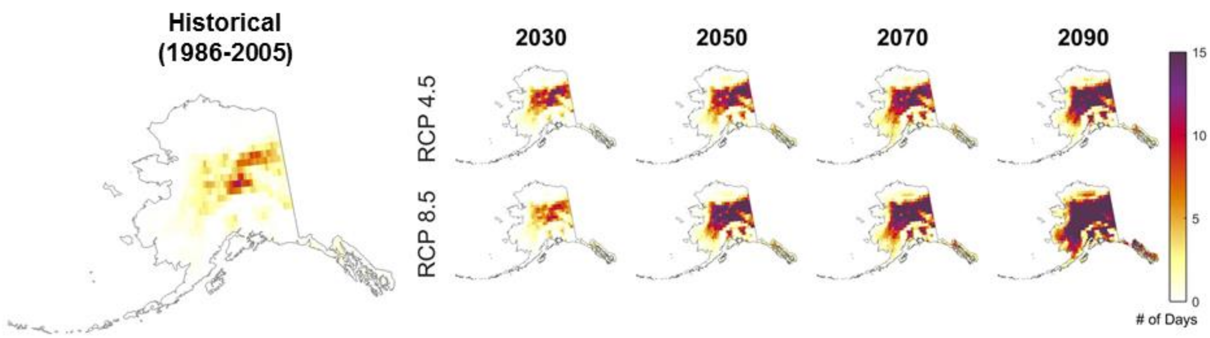
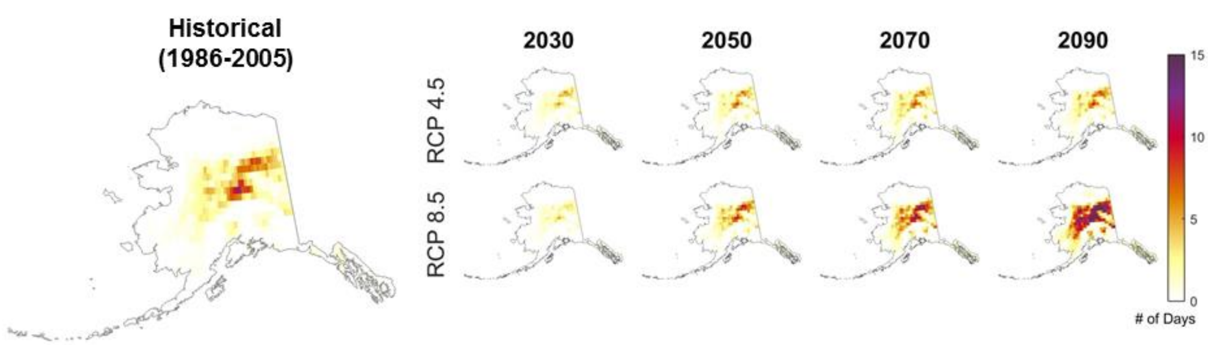


Figure A.4.29. Number of Days above 80°F across Alaska (GISS-E2-R)



Precipitation Change in the U.S.

This section presents the individual model projections of the percent change in mean annual precipitation under RCP4.5 and RCP8.5 across the lower 48 states (Figure A.4.30 through A.4.34) and Alaska (Figure A.4.34 and A.4.36) for four future time periods.

Figure A.4.30. Percent Change in Mean Annual Precipitation across the Contiguous U.S. (CanESM2)

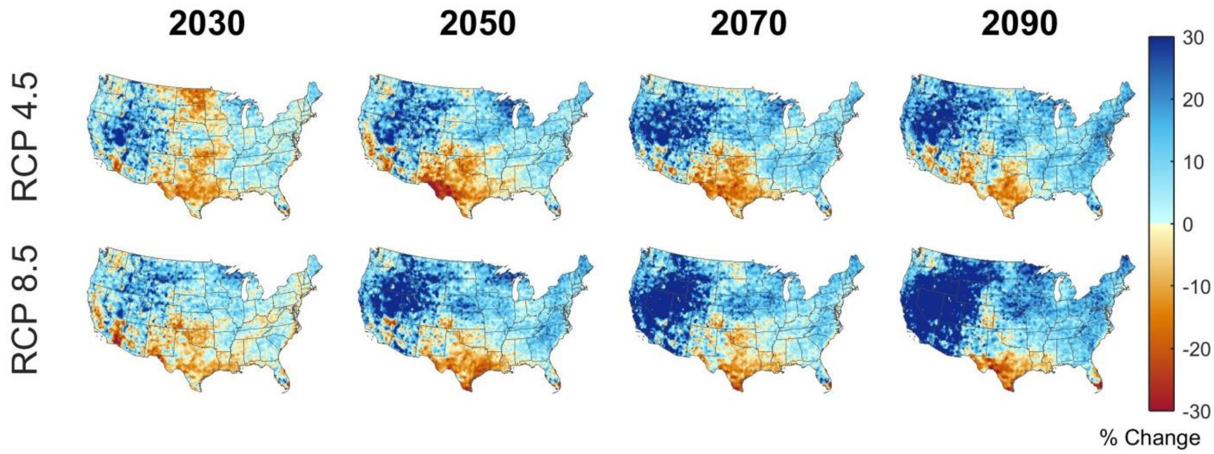


Figure A.4.31. Percent Change in Mean Annual Precipitation across the Contiguous U.S. (CCSM4)

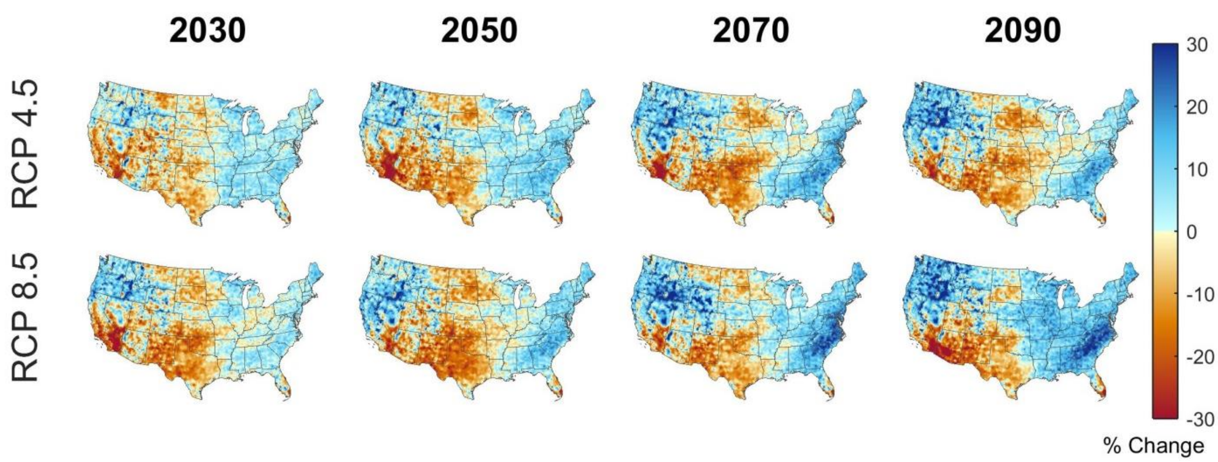


Figure A.4.32. Percent Change in Mean Annual Precipitation across the Contiguous U.S. (GISS-E2-r)

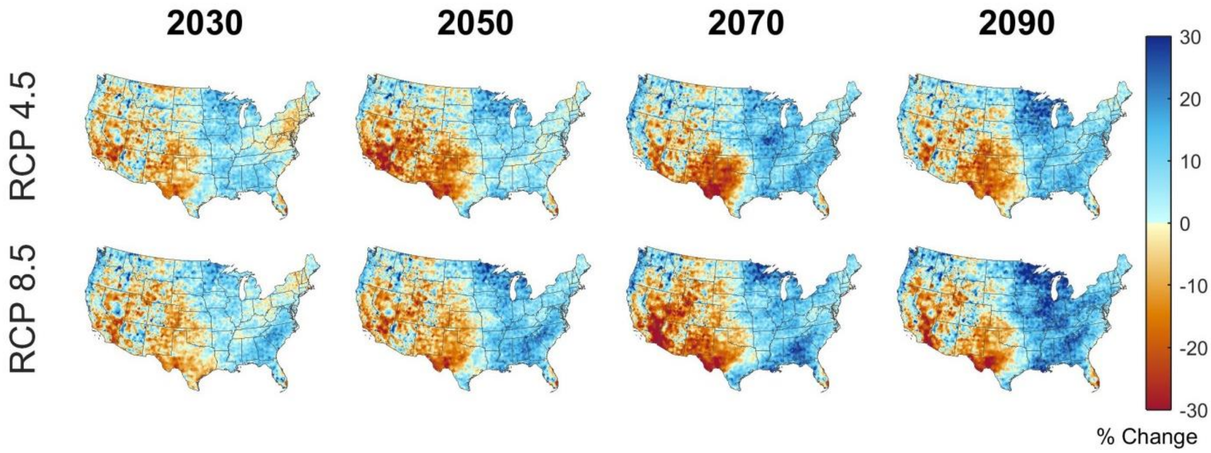


Figure A.4.33. Percent Change in Mean Annual Precipitation across the Contiguous U.S. (HadGEM2-ES)

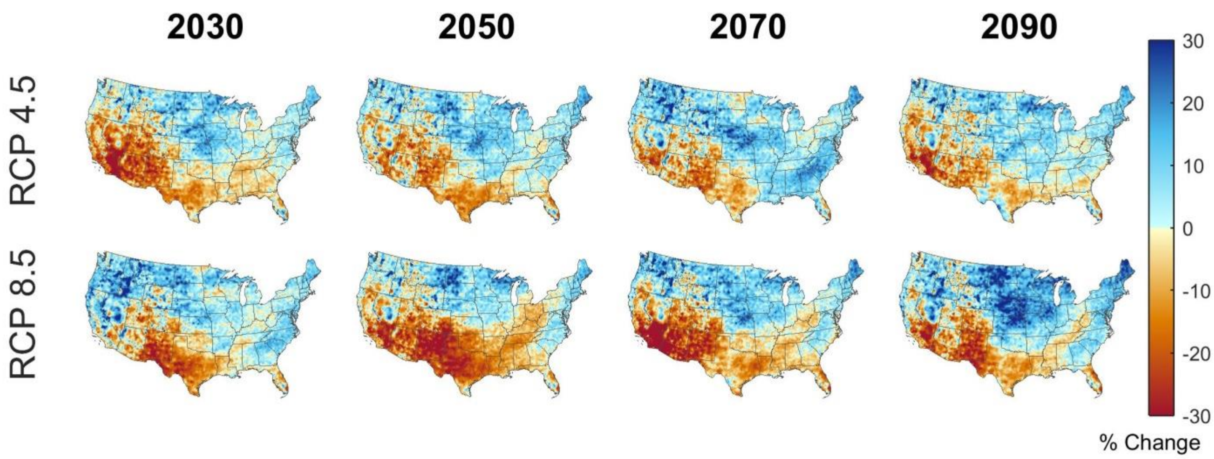


Figure A.4.34. Percent Change in Mean Annual Precipitation across the Contiguous U.S. (MIROC5)

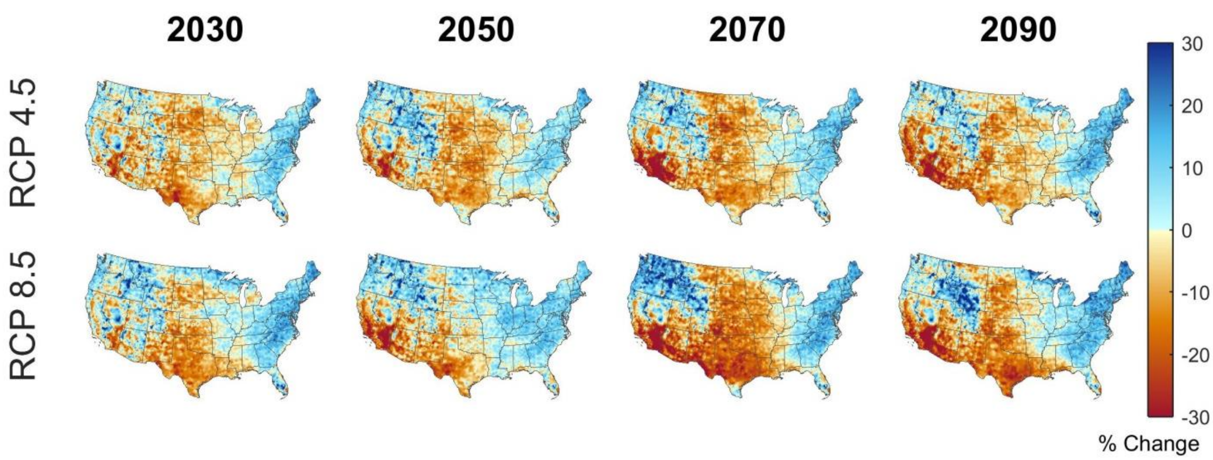


Figure A.4.35. Percent Change in Mean Annual Precipitation across Alaska (CCSM4)

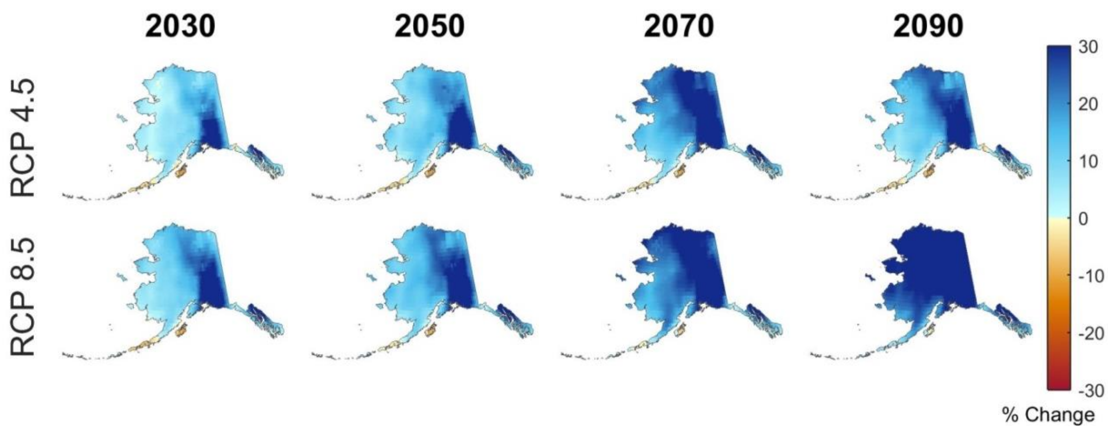
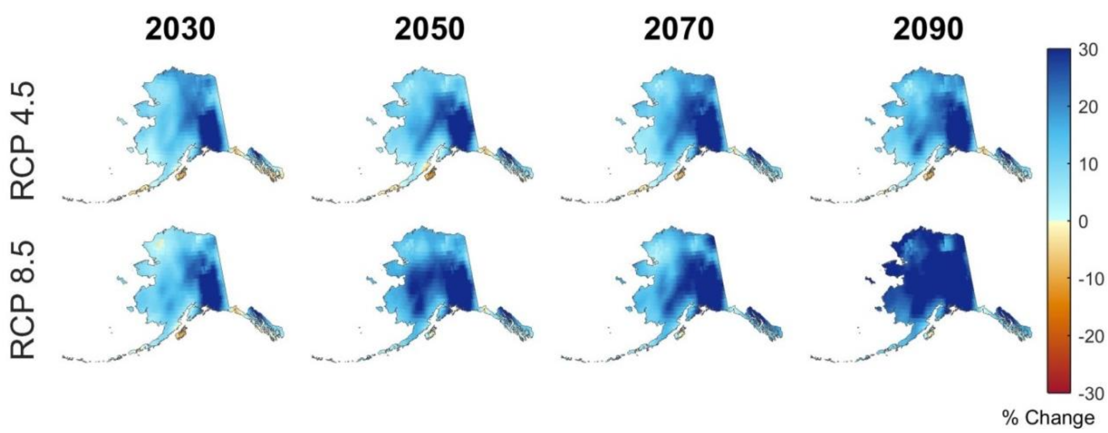


Figure A.4.36. Percent Change in Mean Annual Precipitation across Alaska (GISS-E2-R)



This section presents the individual model projections for the percent change in the maximum daily precipitation across the lower 48 states under both RCP4.5 and RCP8.5 across the contiguous U.S. (Figures A.4.37 through A.4.41) and the percent change in maximum monthly precipitation in Alaska under both RCP4.5 and RCP8.5 (Figures A.4.42 and A.4.43).

Figure A.4.37. Percent Change in Maximum Daily Precipitation across the Contiguous U.S. (CanESM2)

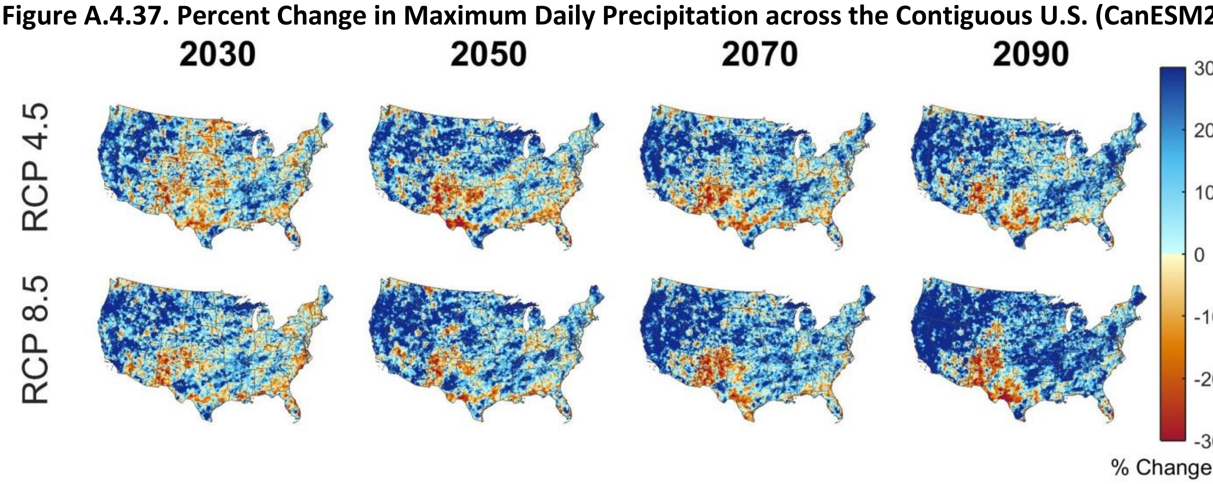


Figure A.4.38. Percent Change in Maximum Daily Precipitation across the Contiguous U.S. (CCSM4)

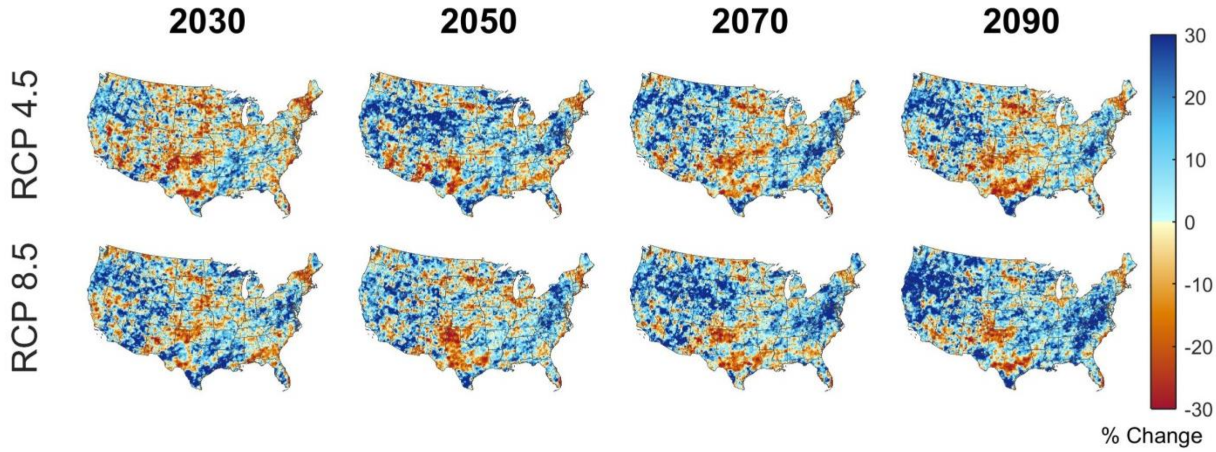


Figure A.4.39. Percent Change in Maximum Daily Precipitation across the Contiguous U.S. (GISS-E2-R)

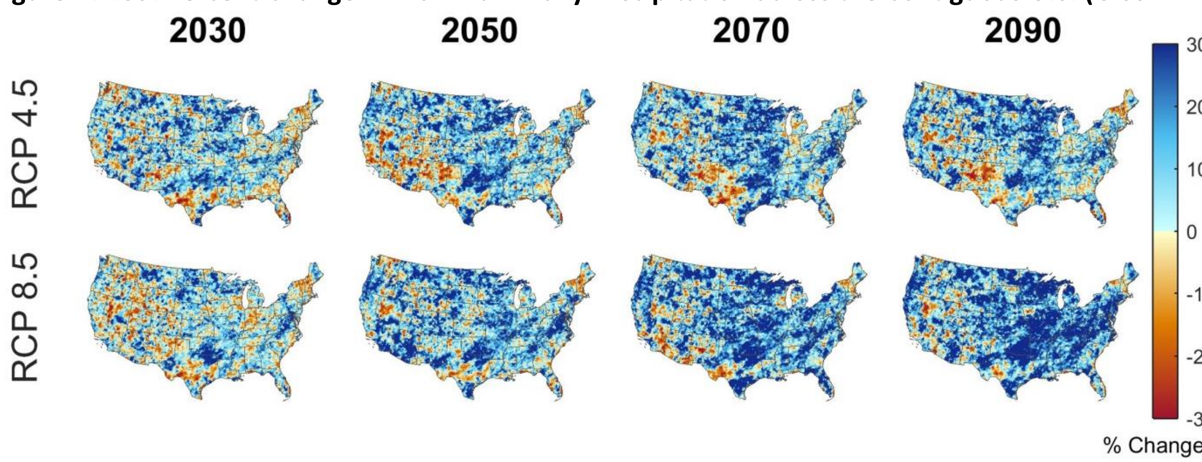


Figure A.4.40. Percent Change in Maximum Daily Precipitation across the Contiguous U.S. (HadGEM2-ES)

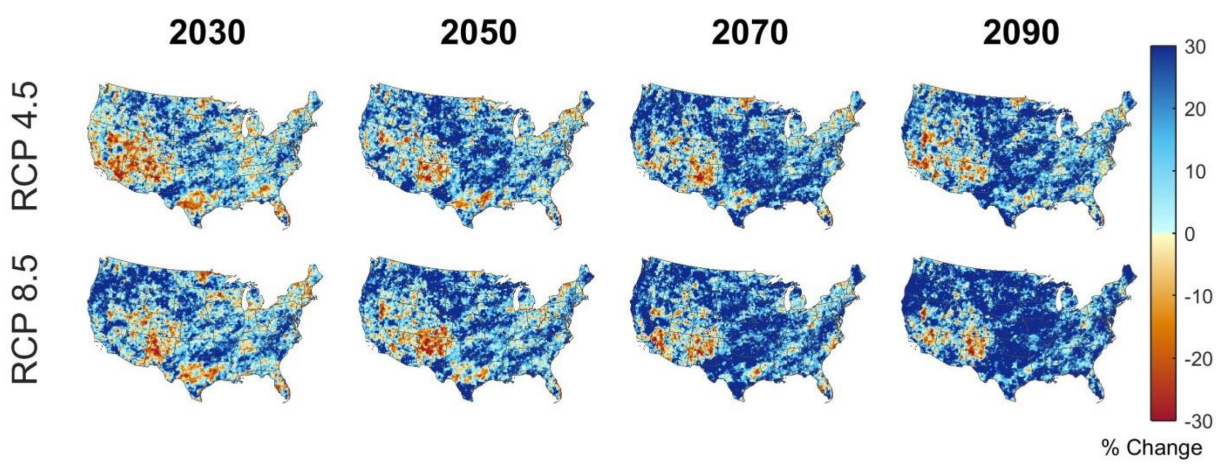


Figure A.4.41. Percent Change in Maximum Daily Precipitation across the Contiguous U.S. (MIROC5)

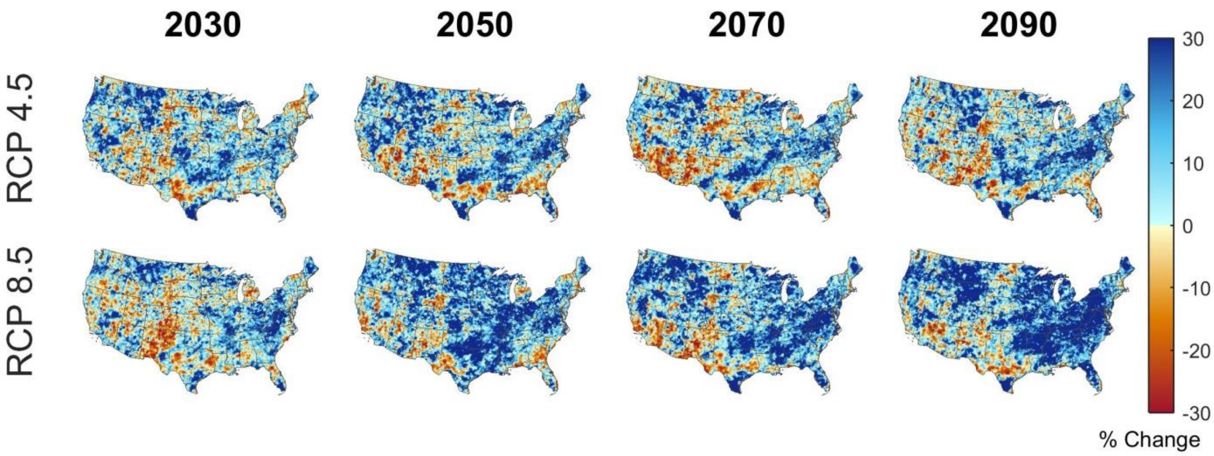


Figure A.4.42. Percent Change in Maximum Monthly Precipitation across Alaska (CCSM4)

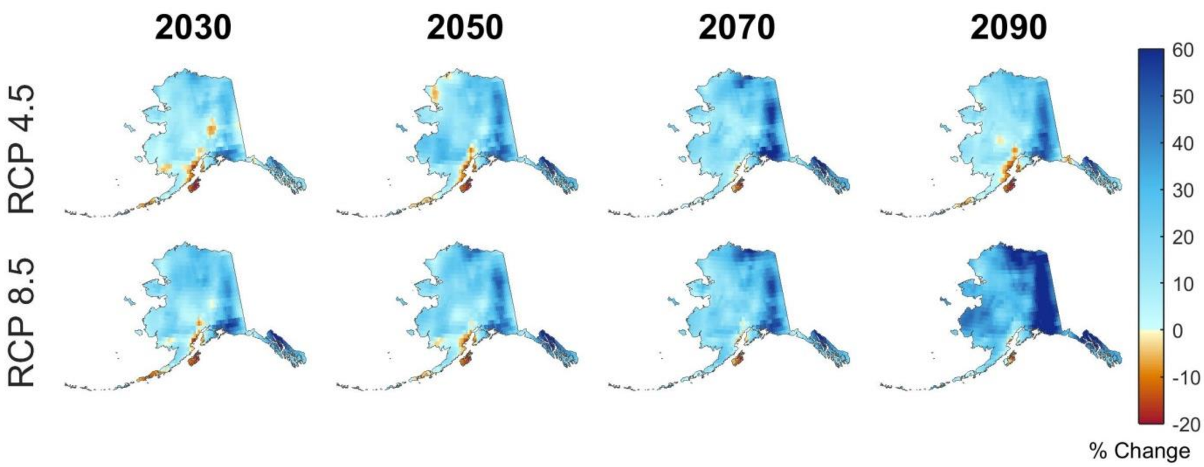
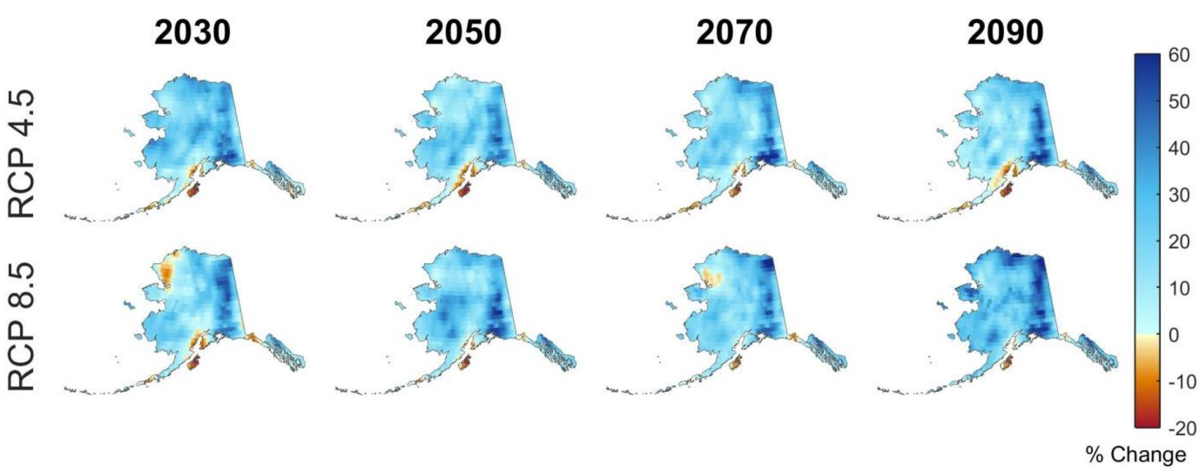


Figure A.4.43. Percent Change in Maximum Monthly Precipitation across Alaska (GISS-E2-R)



This section presents the projected percent change in consecutive dry days across the lower 48 states for each model under both RCP4.5 and RCP8.5 across 4 time periods (Figures A.4.44 and A.4.48).

Figure A.4.44. Percent Change in Consecutive Dry Days across the Contiguous U.S. (CanESM2)

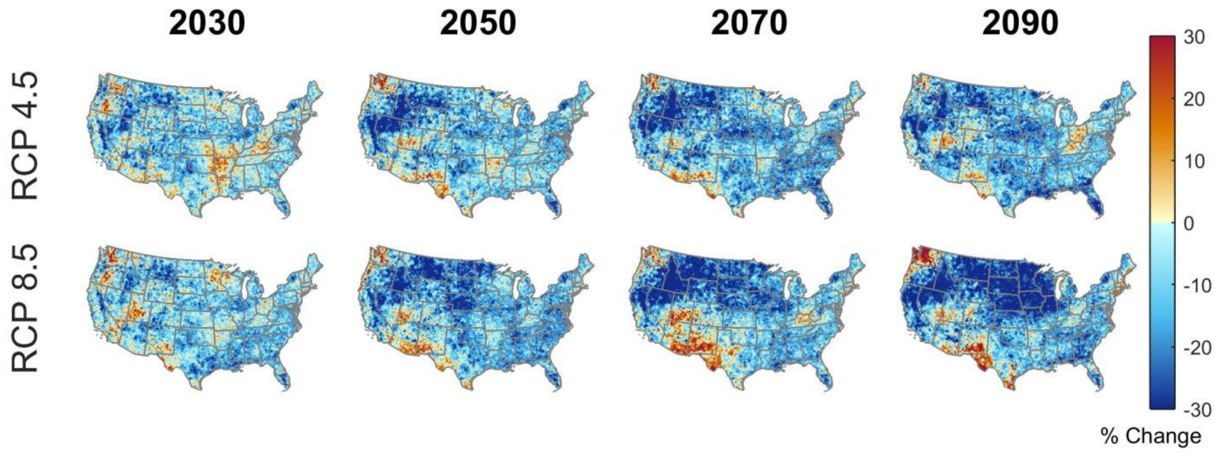


Figure A.4.45. Percent Change in Consecutive Dry Days across the Contiguous U.S. (CCSM4)

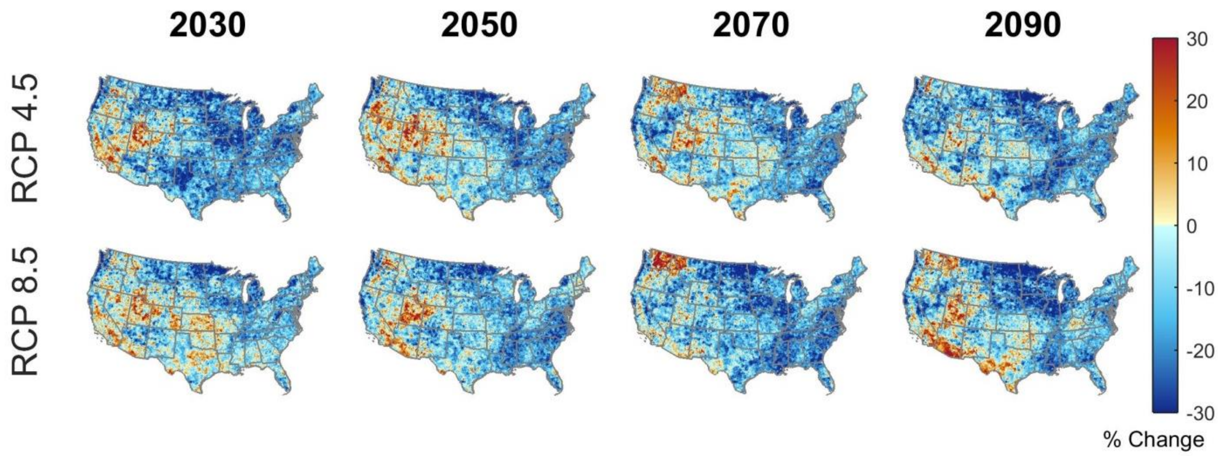


Figure A.4.46. Percent Change in Consecutive Dry Days across the Contiguous U.S. (GISS-E2-R)

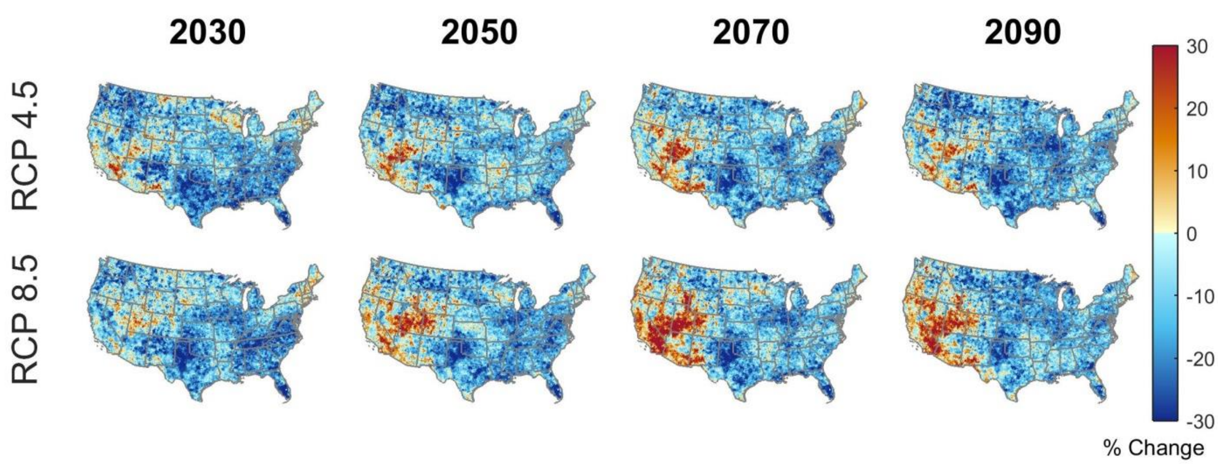


Figure A.4.47. Percent Change in Consecutive Dry Days across the Contiguous U.S. (HadGEM2-ES)

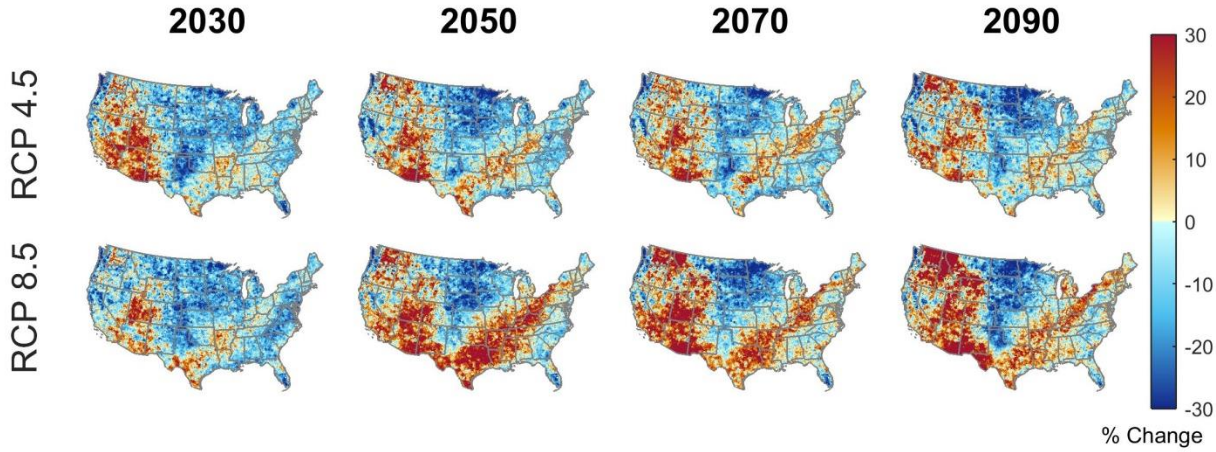
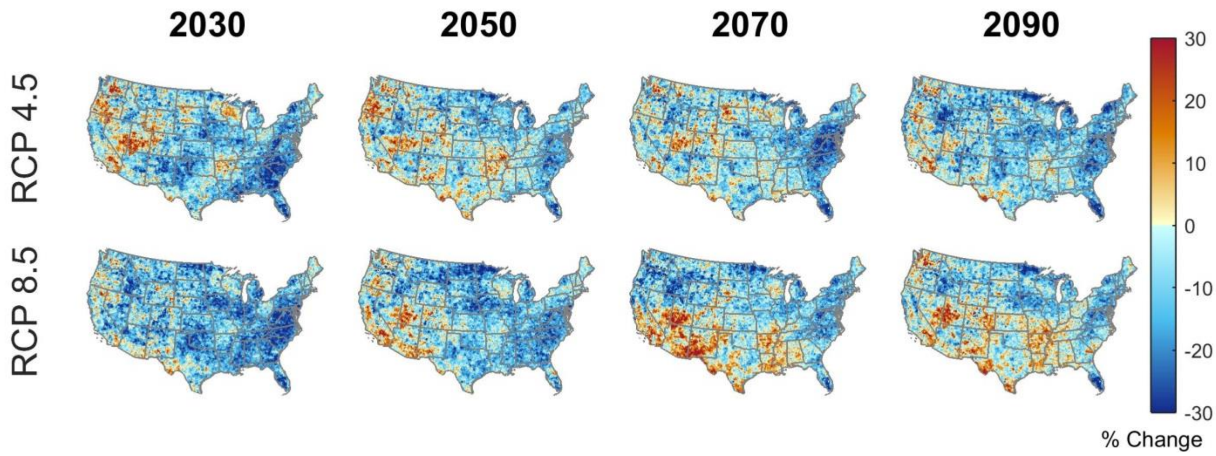


Figure A.4.48. Percent Change in Consecutive Dry Days across the Contiguous U.S. (MIROC5)



A.5. Summary of Multi-Model Climate Change Impact Studies and Key Features

Study	Modeling Framework			Geographic Coverage			Forcing Scenarios (Representative Concentration Pathways)					Socioeconomic Scenarios	Impact Sectors*	Adaptation Analysis
	Model Comparison	Multi-Sector	Multi-Model	US	EU	Global	RCP8.5	RCP6.0	RCP4.5	RCP2.6	Other	SSPs		
CIRA1.0		✓	✓	✓							RCP 8.6; RCP3.2		Agriculture, Coastal, Health, Energy, Water, Infrastructure, Forestry, Ecosystems	✓
CIRA2.0		✓	✓	✓			✓		✓			✓	Agriculture, Coastal, Health, Energy, Water, Infrastructure, Forestry, Ecosystems	✓
ACP		✓		✓			✓	✓	✓	✓			Agriculture, Coastal, Health, Energy, Productivity, Crime	
ISI-MIP	✓	✓	✓			✓	✓	✓	✓	✓		✓	Agriculture, Coastal, Health, Energy, Water	
AgMIP	✓		✓			✓	✓			✓		✓	Agriculture	
BRACE		✓	✓	✓		✓	✓		✓			✓	Agriculture, Health, Storms	
CIRCLE		✓				✓	✓				SRES A1B	✓	Agriculture, Coastal, Health, Energy, Productivity, Storms, Ecosystems	
PESETA		✓			✓		✓				SRES A1B, E1		Agriculture, Coastal, Health, Energy, Water, Infrastructure, Forestry, Ecosystems	
QUEST-GSI		✓	✓		✓	✓					SRES		Agriculture, Coastal, Health, Energy, Water, Infrastructure, Forestry, Ecosystems	
RISES-AM			✓		✓	✓	✓		✓			✓	Coastal	✓
IMPRESSIONS		✓	✓		✓	✓	✓		✓			✓	Agriculture, Coastal, Health, Energy, Water, Infrastructure, Forestry, Ecosystems	✓
HELIX		✓			✓	✓					2°, 3°, 4°+	✓	Agriculture, Coastal, Health, Energy, Water, Infrastructure, Forestry, Ecosystems	✓

* Multiple and varying impact categories are included in each of the sectors in different studies.

Legend:

Agriculture Coastal Health Energy Water Infrastructure Forestry

Ecosystems Crime Storms Productivity

A.6. Air Quality Appendix

Please refer to the Air Quality section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

A.6.1. Regional Climate

Figure A.6.1 shows projected changes in daily maximum summer temperature using the WRF dynamically downscaled projections. Under both RCPs, daily maximum summer temperatures are projected to increase across the contiguous U.S. At 2050, increases of 2-5°C are projected under RCP8.5, with the greatest impacts over the central U.S. Temperature increases of 1-4°C are projected under RCP4.5. The increases in summer temperatures generally are projected to intensify through late-century under both scenarios. At 2090, summer daily maximum near-surface temperatures are projected to rise by 3-7°C under RCP8.5. Although warmer than conditions in the reference period, the summer daily maximum temperatures at 2090 under RCP4.5 are less than those projected in 2050 under RCP8.5.

Figure A.6.2 shows the changes from the reference period in annual precipitation for the two future periods and two climate scenarios. Previous assessments of climate-driven changes in regional precipitation patterns have shown larger model-to-model differences than for temperature.[31,32] The lack of consensus in precipitation projections is, in part, because the scale-dependent features that influence precipitation are difficult to model. This analysis suggests that precipitation will increase in the Northwest, Southeast, and Northeast, but decrease in the Southwest and Southern Plains. The magnitudes and geographic distributions of the changes differ between the RCP scenarios and the time periods.

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[31] Jacob, D. J., and D. A. Winner, 2009: Effect of climate change on air quality. *Atmospheric Environment*, **43**, 51–63.
[32] 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. In: *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, pp. 1029–1136, doi:10.1017/CBO9781107415324.024

Figure A.6.1. Projected Change in Summer Maximum Temperatures

Model-estimated change in summer daily maximum near-surface air temperatures (°C) relative to the reference period, averaged over the 11 years within each period.

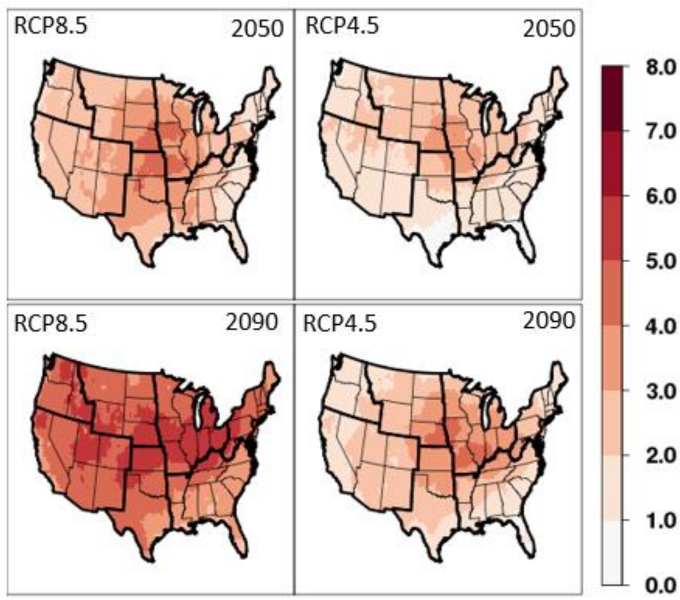
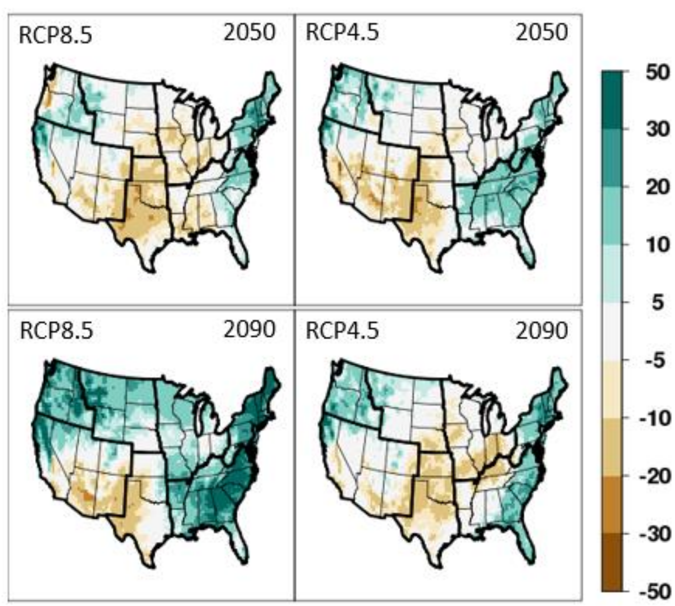


Figure A.6.2. Projected Change in Annual Precipitation

Model-estimated change in annual precipitation (mm) relative to the reference period, averaged over the 11 years within each period.



A.6.2. Ozone Morbidity

Populations exposed to ground level ozone are at greater risk of dying prematurely, being admitted to the hospital for respiratory hospital admissions, being admitted to the emergency department, and suffering from aggravated asthma, among other impacts. Premature deaths associated with climate-driven changes in ozone are presented in the Air Quality section with estimated damages. Table A.6.1 demonstrates ozone-related morbidity effects. These values are consistent with the existing literature, which find that future ozone-related human health impacts attributable to climate change are projected to lead to hundreds to thousands of premature deaths, hospital admissions, and cases of acute respiratory illnesses per year in the United States in 2030.[33]

Table A.6.1. Incurred Additional (or Avoided) Ozone-related Premature Deaths and Illnesses

Estimates for 2050 and 2090 under RCP8.5 and RCP4.5 are compared to a reference year of 2000. The second line in each table cell indicates the 95th percentile confidence intervals.

Human Health Impact (age)	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Premature death (0-99)[34]	790 420 to 1,200	550 300 to 810	1,700 920 to 2,500	1,200 630 to 1,700
Respiratory hospital admission (65-99)	1,000 -240) to 2,300	740 -170) to 1,700	1,700 -410 to 3,900	1,200 -280 to 2,700
Emergency department visit (0-99)	2,400 230-5,800	1,800 170-4,400	4,300 410-11,000	2,700 260-6,500
Exacerbated asthma (6-18)	710,000 -600,000 to 1,700,000	510,000 -440,000 to 1,200,000	1,200,000 -1,000,000 to 3,000,000	810,000 -690,000to 2,000,000
Minor restricted activity day (18-64)	1,600,000 670,000 to 2,600,000	1,200,000 490,000 to 1,900,000	2,800,000 1,100,000 to 4,400,000	1,900,000 770,000 to 3,000,000
Lost school day (5-17)	580,000 210,000 to 1,300,000	420,000 150,000 to 950,000	990,000 350,000 to 2,300,000	660,000 240,000 to 1,500,000

[33] Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero, and L. Ziska, 2016: Ch. 3: Air Quality Impacts. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 69–98. http://dx.doi.org/10.7930/J0GQ6VP6

[34] Estimated using effect coefficient from Zanobetti & Schwartz (2008). Source: Zanobetti, A., and J. Schwartz, 2008: Is there adaptation in the ozone mortality relationship: a multi-city case-crossover analysis. *Environ. Health*, **7**, 22.

A.6.3. Particulate Matter ($PM_{2.5}$)

Climate-driven changes in meteorological patterns will also impact $PM_{2.5}$ concentrations throughout the U.S. However, unlike ozone, there is no current consensus as to whether these changes will result in increasing or decreasing $PM_{2.5}$ levels.[35, 36] Because fine particle concentrations are comprised of a complex mixture of individual substances with many possible sources and formation pathways, it is difficult to quantify the net climate signal. There is consensus that specific sources of $PM_{2.5}$, such as wildfire smoke,[37] will increase in response to climate change. Conversely, increased precipitation in some regions, combined with warmer springtime temperatures and deeper mixed layers, may lead to future $PM_{2.5}$ decreases. The interactions of some sources of $PM_{2.5}$ with sunlight, clouds, and radiation are also uncertain.[38]

The modeled climate impacts on $PM_{2.5}$ concentrations shown in Figure A.6.3 do not include wildfire sources. Excepting wildfire, the projections suggest that climate change could result in small but regionally-varying $PM_{2.5}$ response in the future. At 2050 and 2090 in both scenarios, the climate impacts are less than ±1.0 $\mu g\ m^{-3}$ throughout the contiguous U.S. However, even small predicted changes in $PM_{2.5}$ in urban areas can yield large numbers of estimated deaths. Though not quantified in this analysis, the existing literature finds that $PM_{2.5}$ is associated with serious chronic and acute health effects, including lung cancer, chronic obstructive pulmonary disease (COPD), cardiovascular disease, and asthma development and exacerbation. Older adults are particularly sensitive to short-term particle exposure, with a higher risk of hospitalization and death.[39] Because this analysis uses one GCM and the climate-driven signal in $PM_{2.5}$ trends remains uncertain in the literature, and because this analysis excludes wildfire impacts, projected health impacts of these changes are not presented here.

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[35] Dawson, J. P., B. J. Bloomer, D. A. Winner, and C. P. Weaver, 2014: Understanding the meteorological drivers of U.S. particulate matter concentrations in a changing climate. *Bulletin of the American Meteorological Society*, **95**, 521–532.

[36] Fiore, A. M., V. Naik, and E. M. Leibensperger, 2015: Air quality and climate connections. *Journal of the Air & Waste Management Association*, **65**, 645–685. doi:10.1080/10962247.2015.1040526.

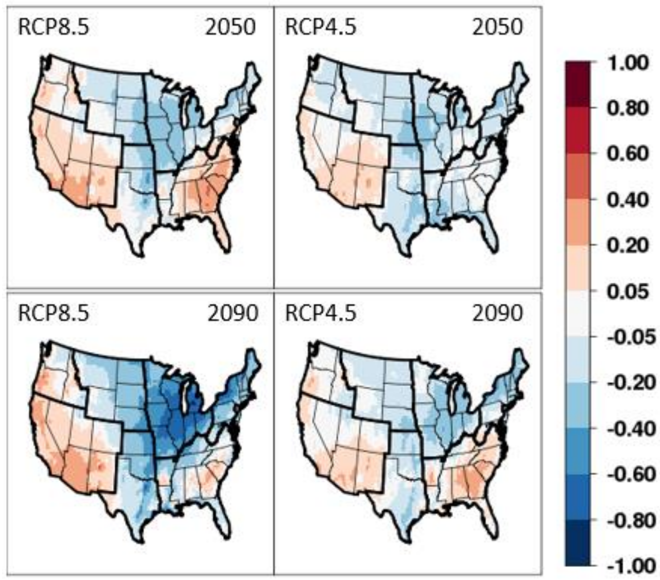
[37] USGCRP, 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp.

[38] Bond, T. C., and Coauthors, 2013: Bounding the role of black carbon in the climate system: a scientific assessment. *Journal of Geophysical Research – Atmospheres*, **118**, 5380–5552.

[39] Fann, N., T. Brennan, P. Dolwick, J.L. Gamble, V. Ilacqua, L. Kolb, C.G. Nolte, T.L. Spero, and L. Ziska, 2016: Ch. 3: Air Quality Impacts. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 69–98. http://dx.doi.org/10.7930/J0GQ6VP6

Figure A.6.3. Projected Changes in Fine Particulates

Model-estimated change in annual-average $PM_{2.5}$ concentrations ($\mu g\ m^{-3}$) relative to the reference period, averaged over the 11 years for each period.

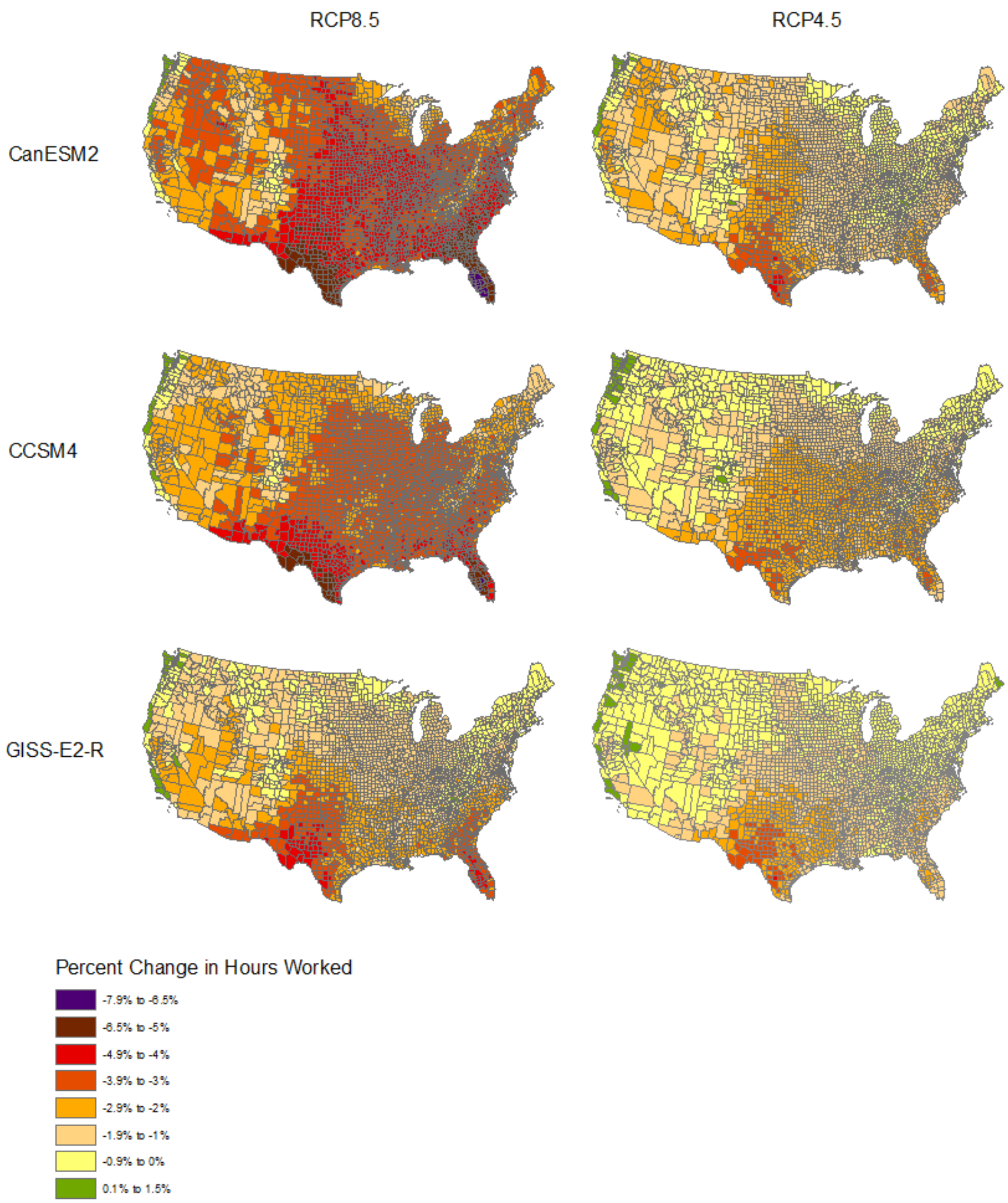


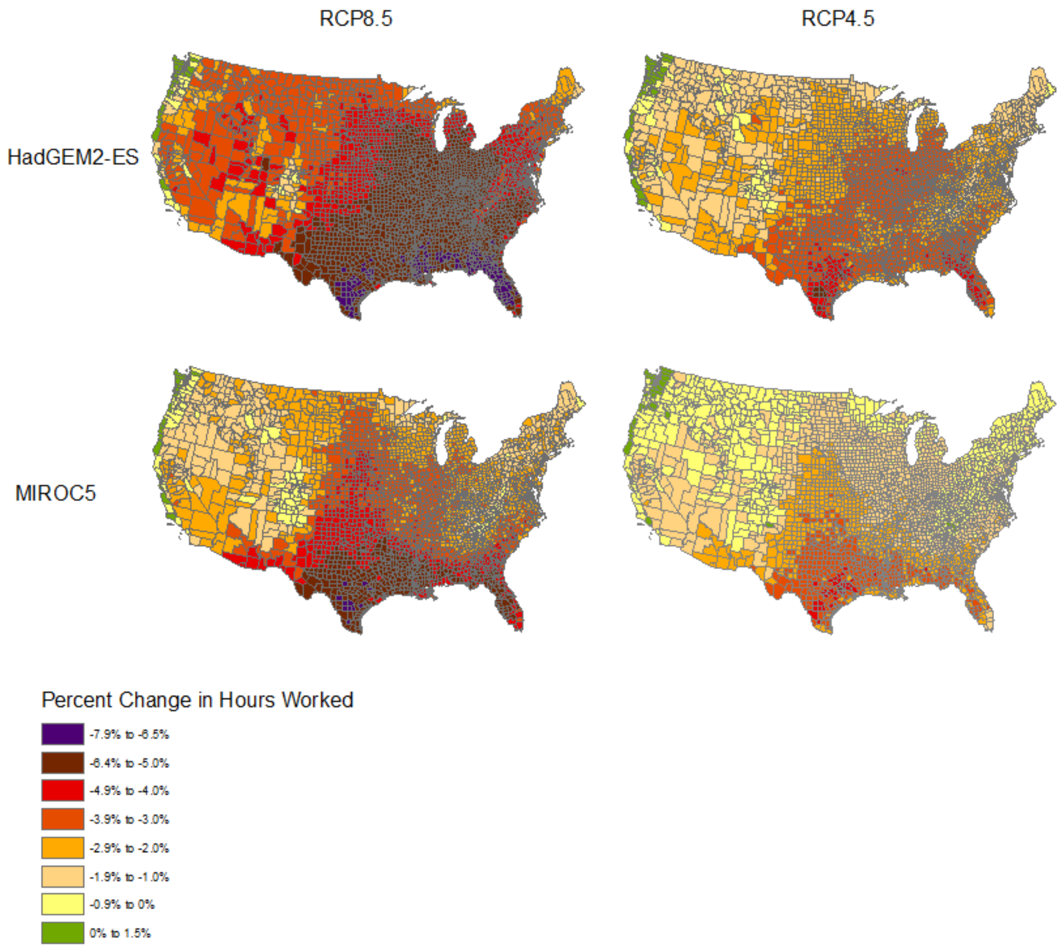
A.7. Labor Appendix

Please refer to the Labor section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

Figure A.7.1. Percent Change in Labor Hours Worked for High-Risk Industries

Percent change in hours work shown by county under RCP8.5 and RCP4.5 in 2090 for CanESM2, CCSM4, GISS-E2-R, HadGEM2-ES, and MIROC5.




RCP8.5
RCP4.5
HadGEM2-ES
MIROC5
Percent Change in Hours Worked
-7.9% to -6.5%
-6.4% to -5.0%
-4.9% to -4.0%
-3.9% to -3.0%
-2.9% to -2.0%
-1.9% to -1.0%
-0.9% to 0%
0% to 1.5%

A.8. Domestic Migration Appendix

Please refer to the Domestic Migration section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

Figure A.8.1. Variability in County Population Projections across Climate Models

These maps show the range in values for each county projected under the five GCMs (each compared to a "no climate change" reference). Higher values for percent change indicate greater variability across the reported GCM values.

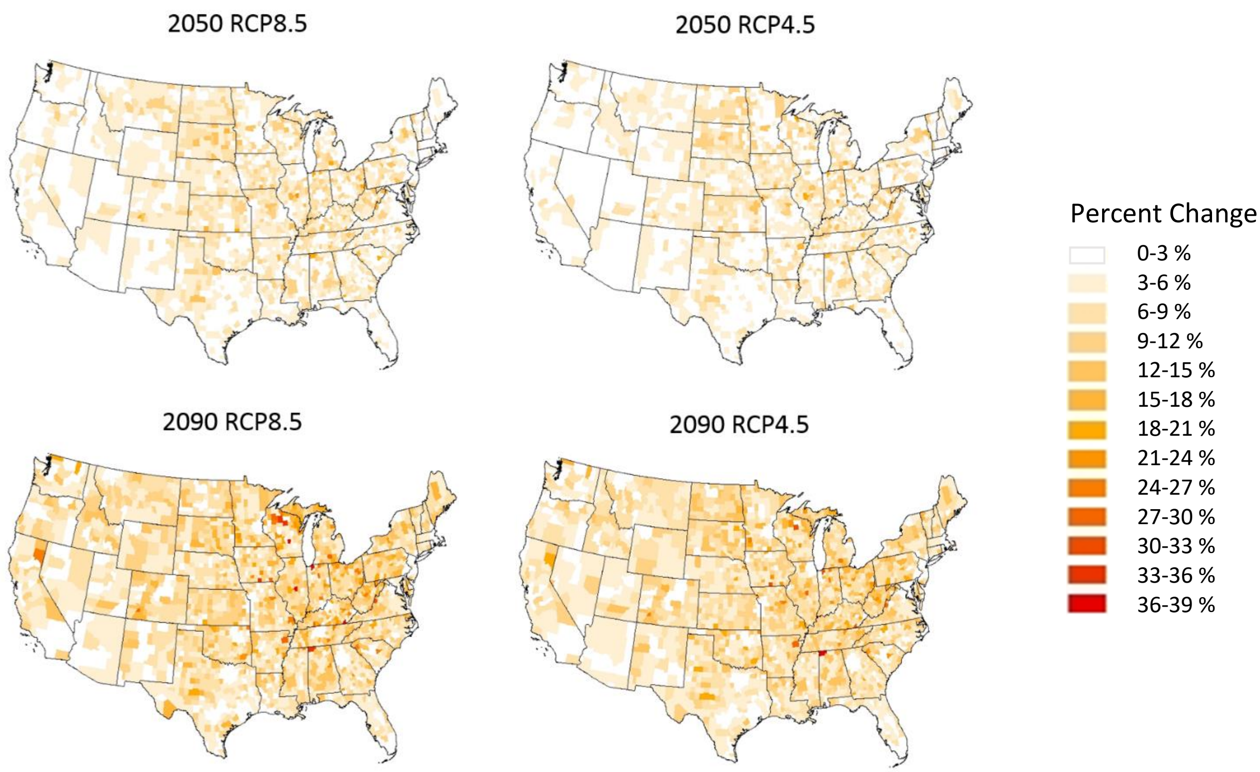
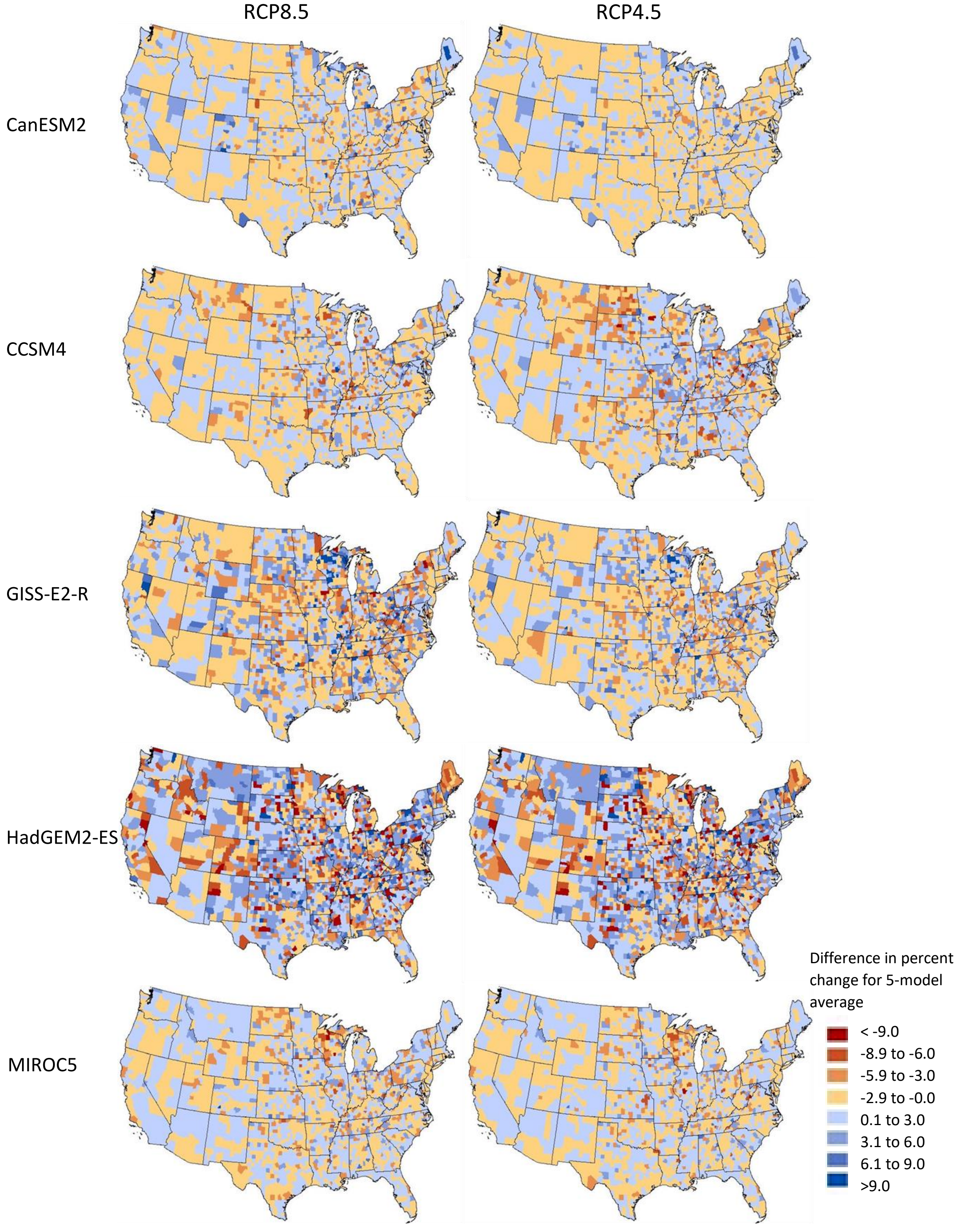


Figure A.8.2. Climate Change-Induced Domestic Migration across RCPs and Climate Models.

Values represent the percentage change from a "no climate change" reference scenario.



A.9. Rail Appendix

Please refer to the Rail section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

Table A.9.1. Projected Cumulative Costs of Climate Change by GCM with and without Adaptation

The table presents the incremental impacts of climate change on the U.S. rail system by GCM for the period 2016-2099 relative to the reference period (five-model average, billions 2015$, discounted at 3%).

	RCP8.5	RCP4.5
Without Adaptation		
CanESM2	$45	$56
CCSM4	$36	$47
GISS-E2-R	$27	$37
HadGEM2-ES	$48	$62
MIROC5	$42	$50
5-GCM Average	**$40**	**$50**
With Adaptation		
CanESM2	$3.1	$8.3
CCSM4	$4.3	$12
GISS-E2-R	$1.1	$3.6
HadGEM2-ES	$9.6	$26
MIROC5	$4.6	$7.9
5-GCM Average	**$4.5**	**$12**

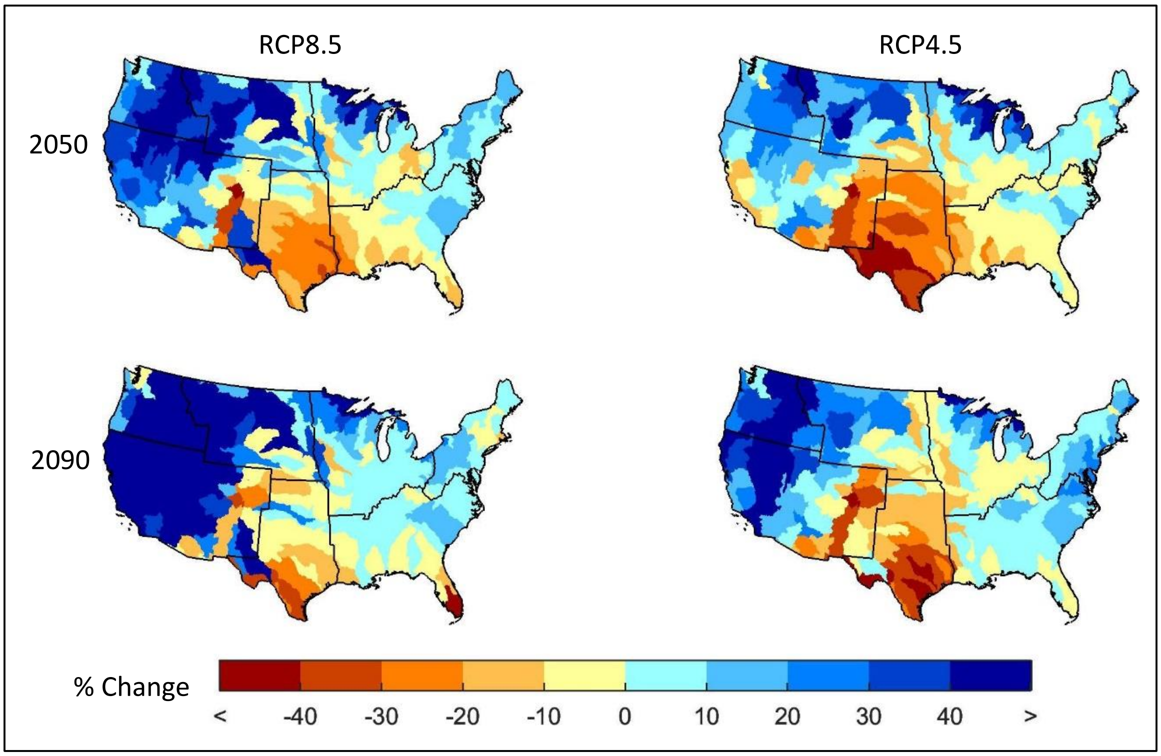
A.10. Electricity Demand and Supply Appendix

Please refer to the Electricity Demand and Supply section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature. Figure A.10.1 shows projected percent change in streamflow under both RCPs in 2050 and 2090. Figure A.10.2 shows national and regional percent change in electricity demand.

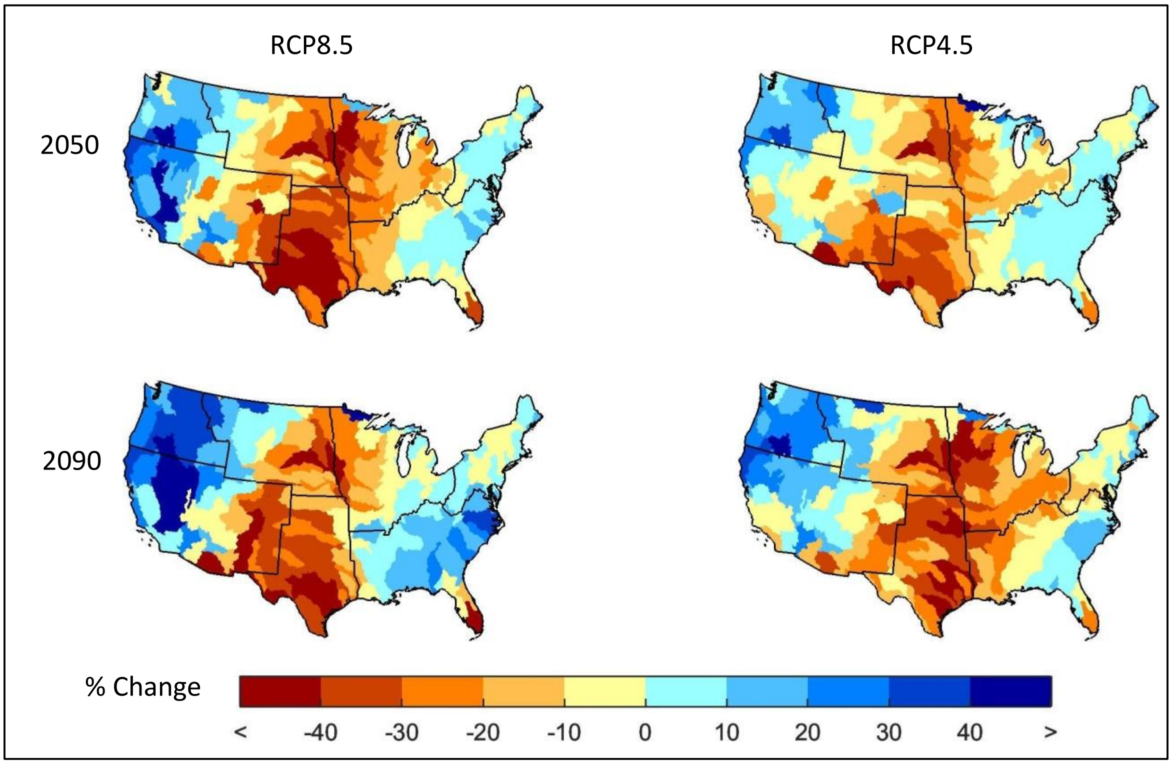
Figure A.10.1. Projected Percentage Change in Flow Compared to the Reference Period

Results are shown for the four-digit HUC level for each of the five GCMs and the five-GCM average.

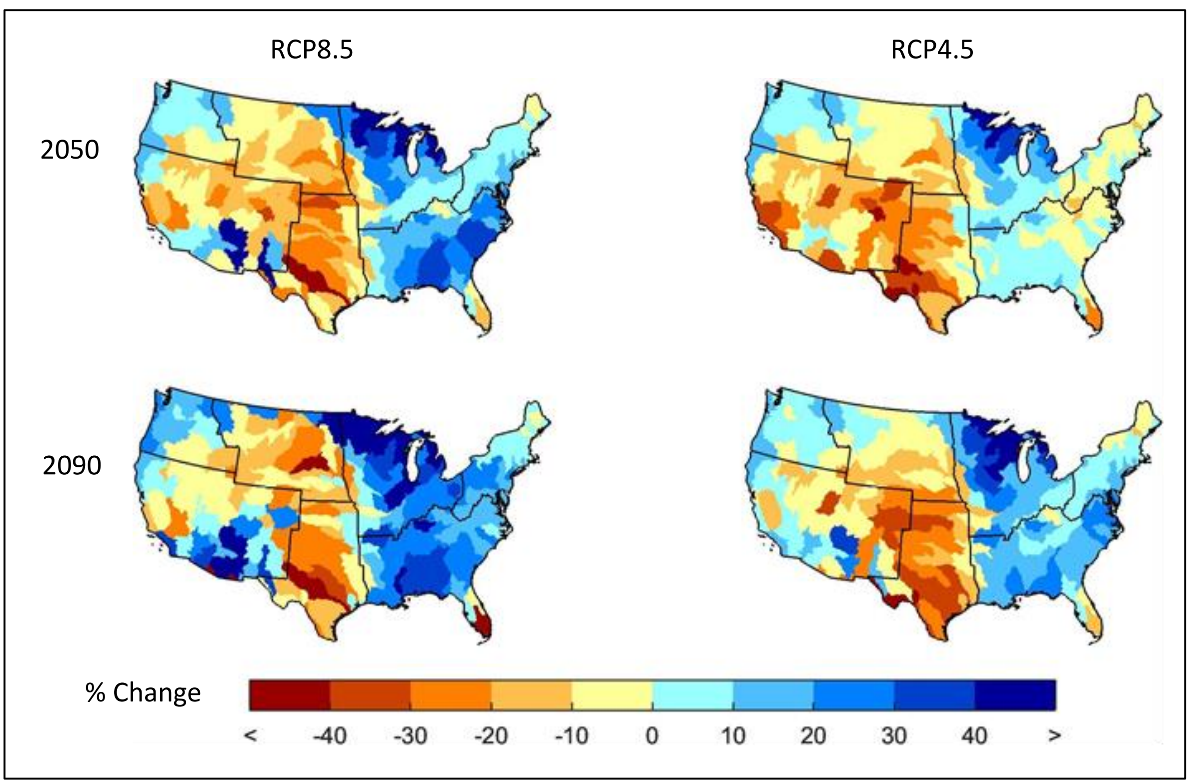
a) CanESM2



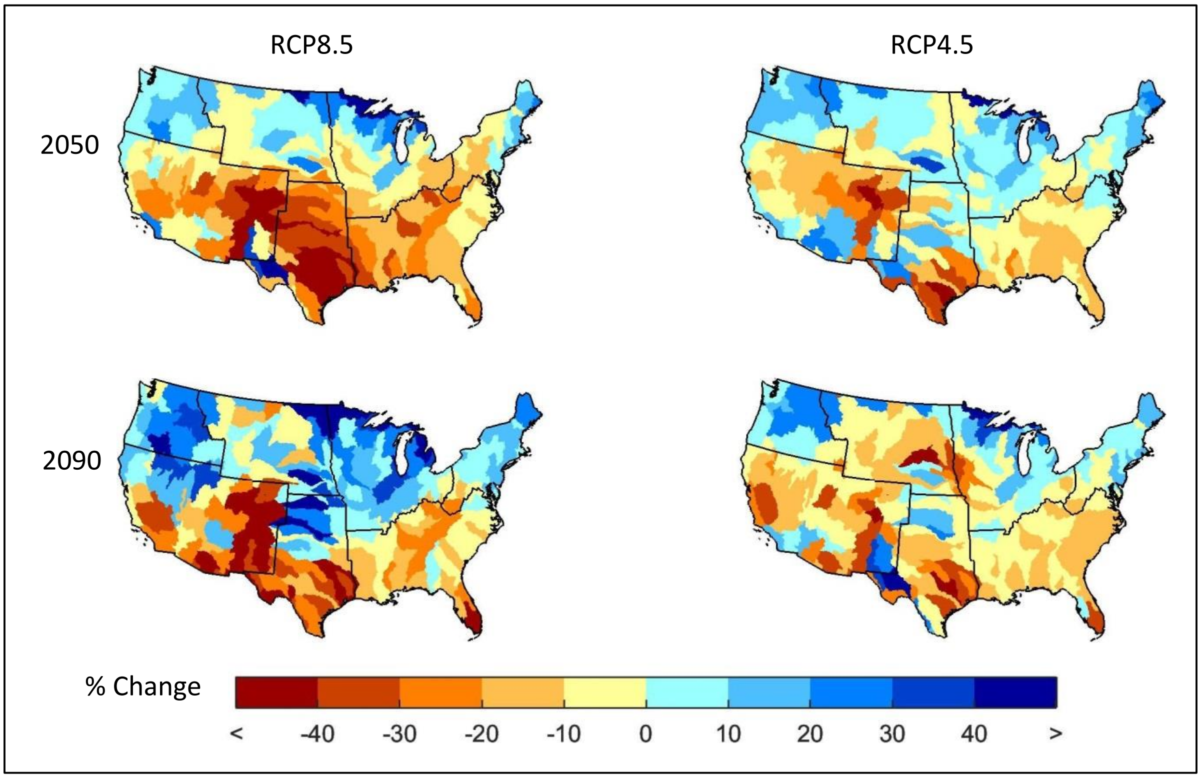
b) CCSM4



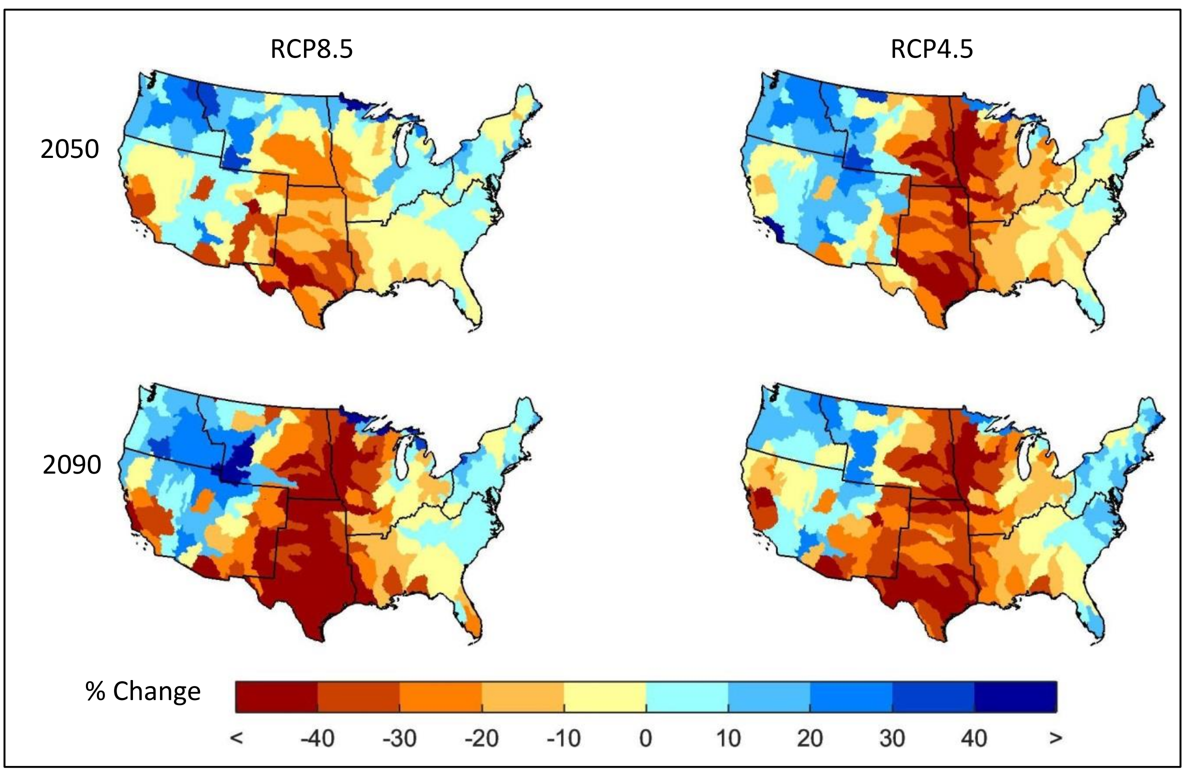
c) GISS-E2-R



d) HadGEM2-ES



e) MIROC5



f) Five-GCM Average

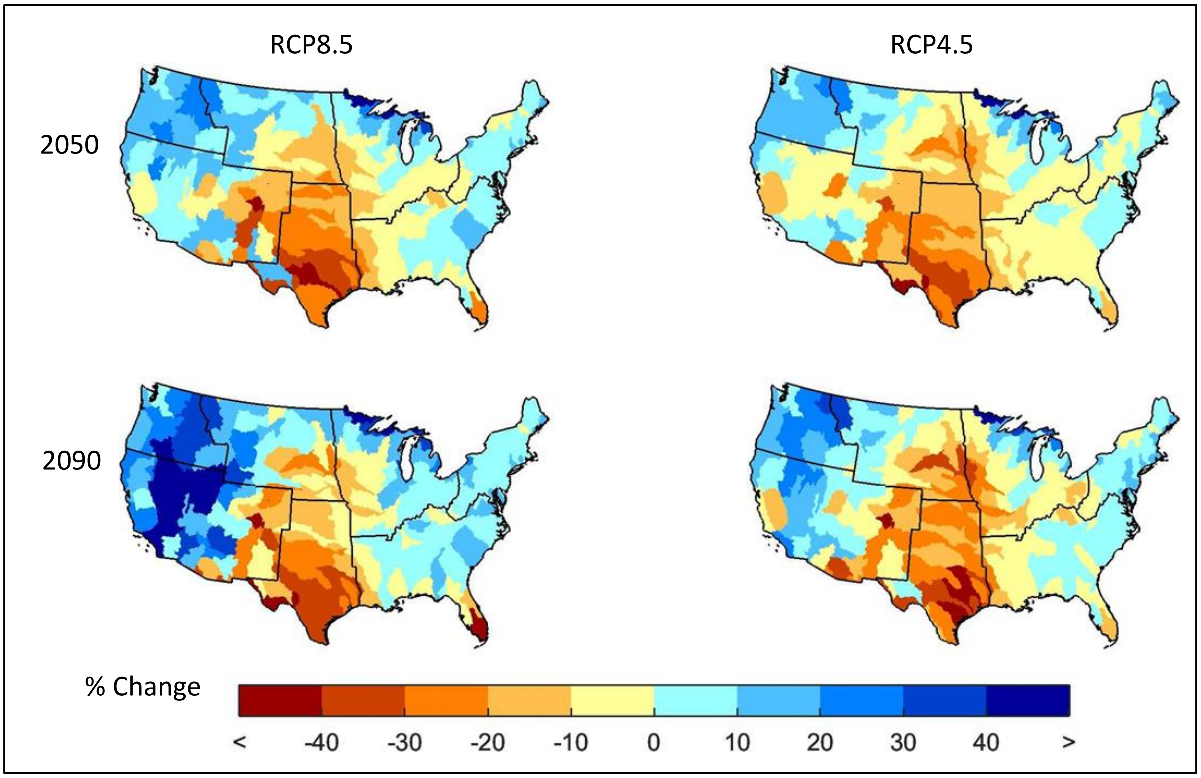
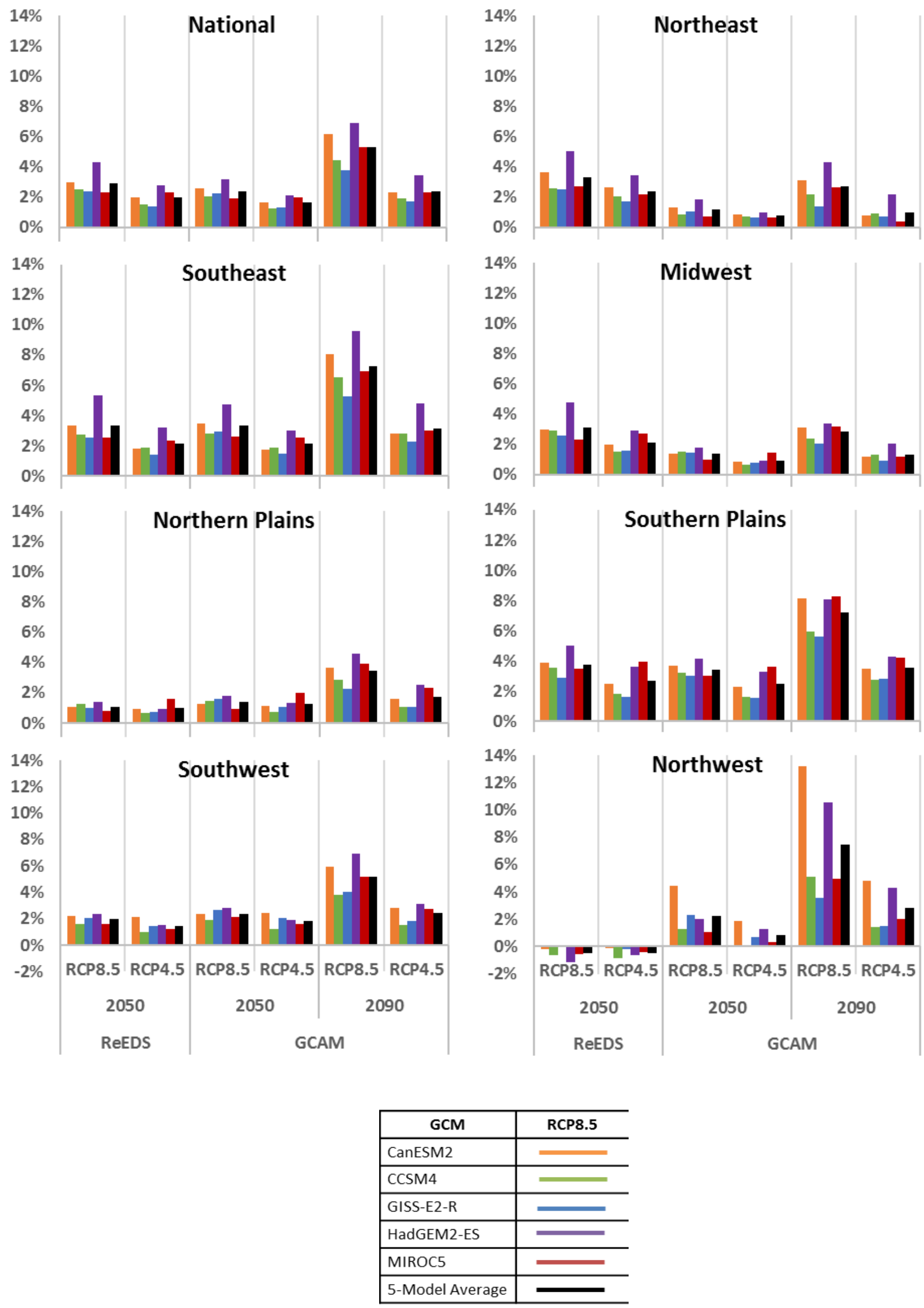


Fig A.10.2. Percentage Change in Electricity Demand

Values are shown across the five GCMS, under RCP8.5 and RCP4.5, in ReEDS (2050 only) and GCAM (2050, 2090)



A.11. Flooding Damages Appendix

Please refer to the Flooding Damages section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

Figure A.11.1. Map of Average Annual Max Flow by Node in the Reference Period

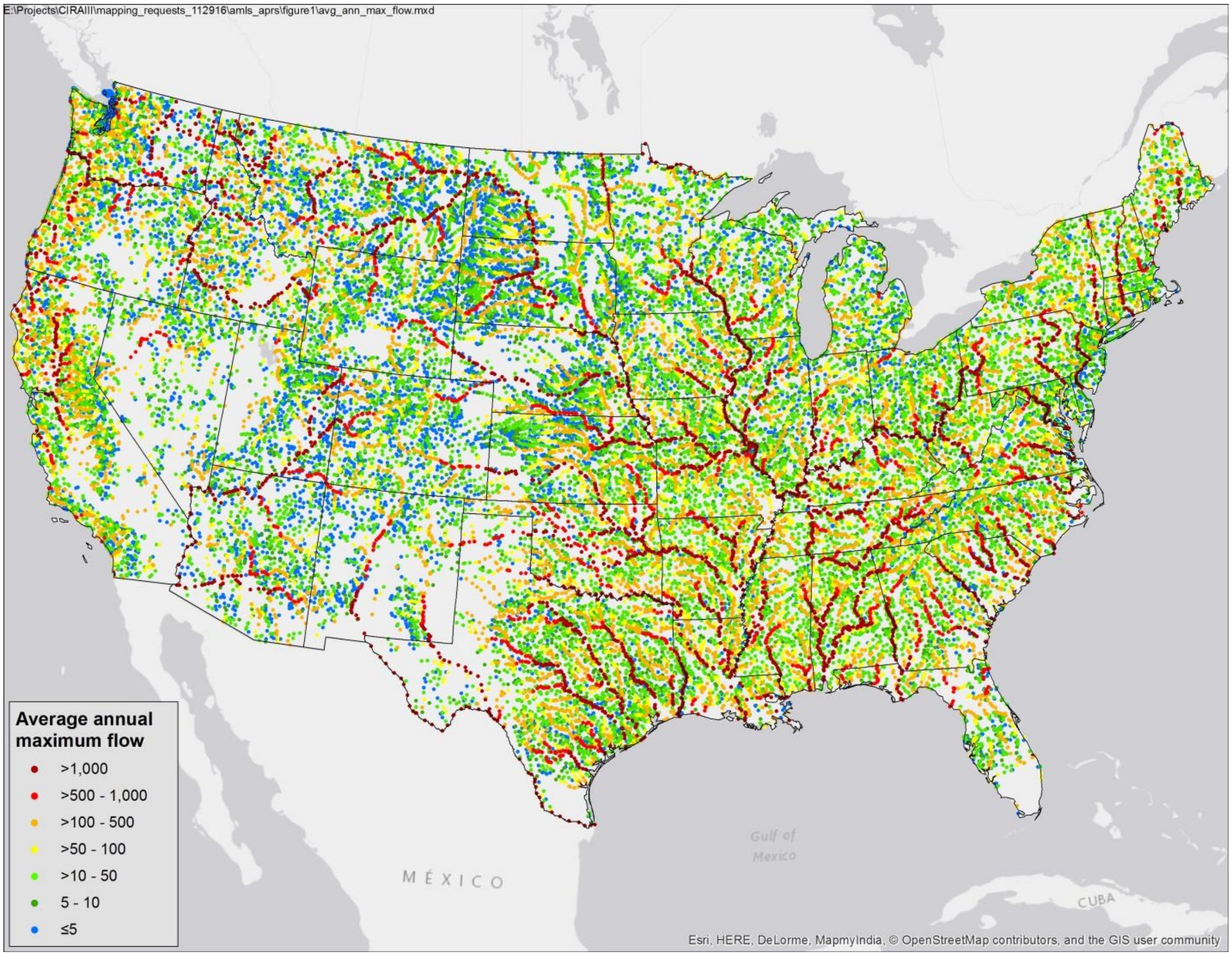
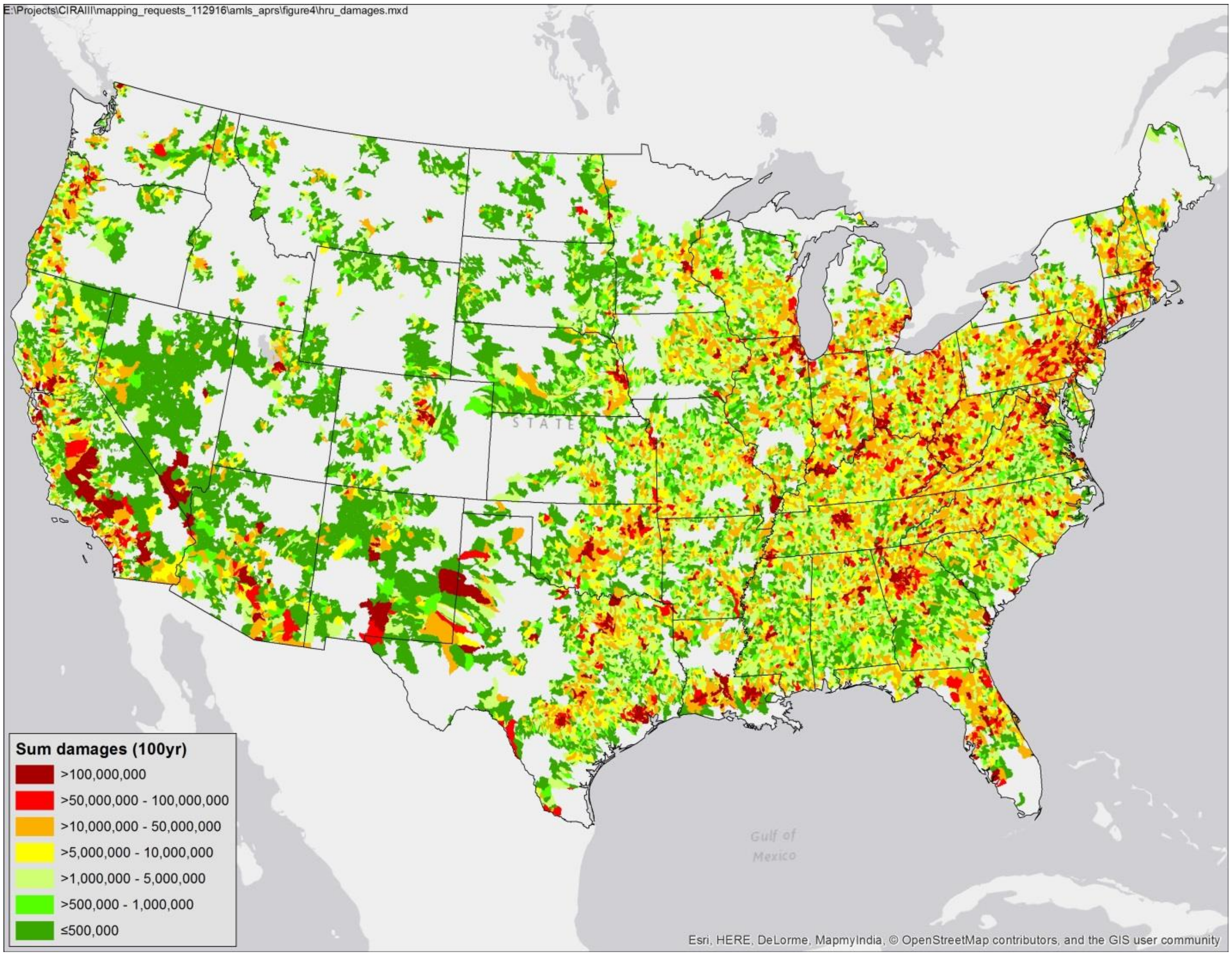


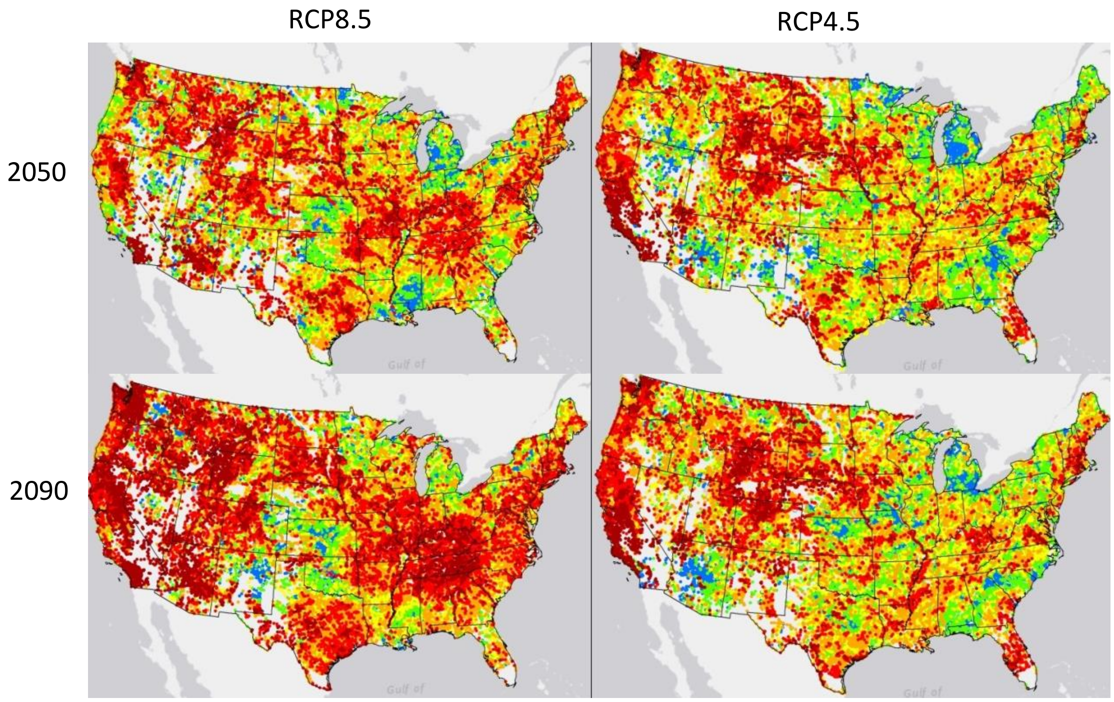
Figure A.11.2. Total Expected Damages from a 1% AEP Flood Event in each 12-digit HUC of the CONUS



Climate-driven changes in flood risk are not evenly distributed across the contiguous U.S., and results indicate some spatially coherent patterns of increased risk. Figure A.11.3 shows the change in the frequency of 100-year flood events throughout the contiguous U.S. in 2050 and 2090 based on the full CMIP-5 ensemble projections (i.e., not just the five GCMs used throughout the Technical Report). As shown, the largest fractional changes in flood frequency across the contiguous U.S. occur in the southern Appalachians and Ohio River valley, the northern and central Rocky Mountains, and the Northwest. In each of these regions, the ensemble average across GCMs suggests that historical 1% AEP events could become 2-5x more frequent by the end of the century. In some regions of the U.S., such as the southern Appalachians and northern Rocky Mountains, the spatial patterns of increased flood frequency can be explained by the increased occurrence of extreme precipitation events projected under the downscaled climate projections. In other regions, such as the Sierras and the Cascades, increases in the frequency of flood events are not as easily explained by changes in precipitation alone. In these locations, the increase in frequency of extreme floods more likely reflects changes in the type of winter precipitation (rain versus snow) compared to reference period conditions.

Figure A.11.3. Change in Frequency of Historical 1% AEP (100-year) Flood Events

Calculations are based on individual nodes over 20-year periods centered on 2050 and 2090 compared to the historic period (2001-2020), with values representing average results across the five GCMs. Values are expressed as ratios, for example a value of 2 corresponds to a doubling in frequency of the historical 1% AEP event.



A.12. Agriculture Yield and Welfare Effects Appendix

Please refer to the Agriculture Yield and Welfare Effects section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

Figure A.12.1. Percent Change in U.S. Crop Yields under RCP8.5 with and without CO_2 Fertilization

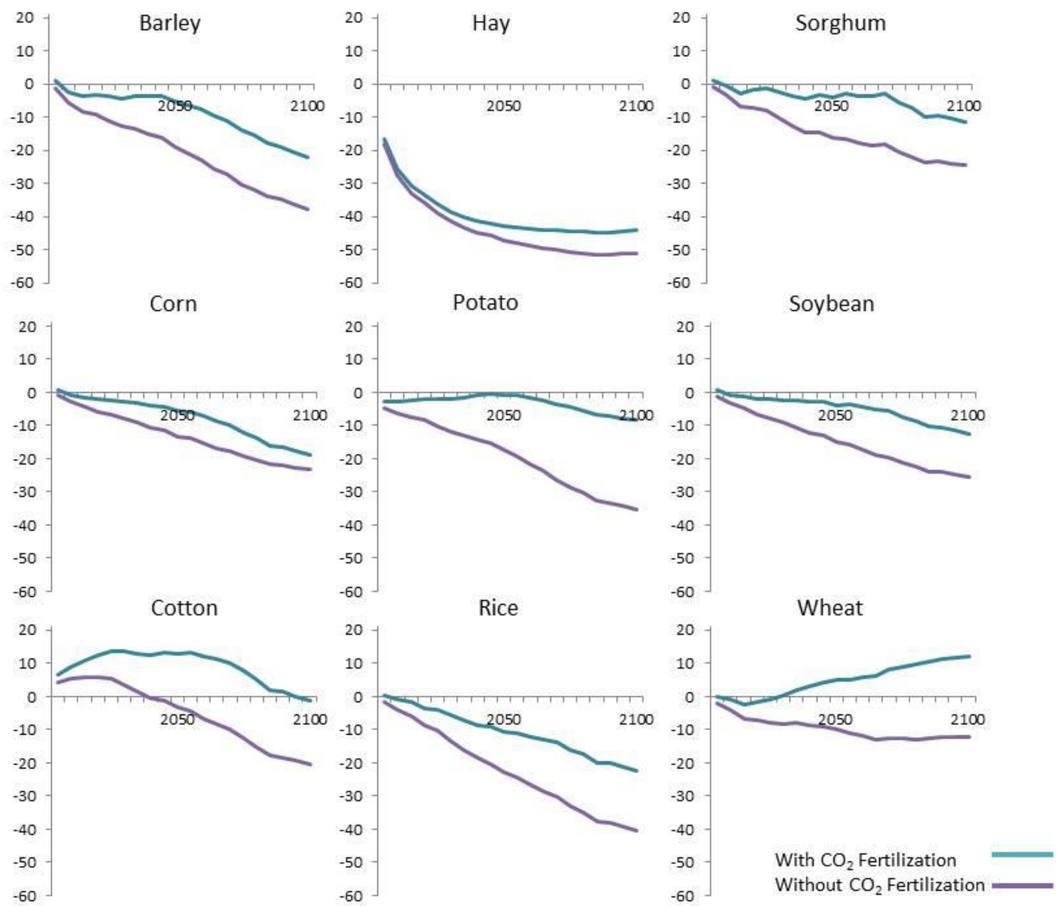


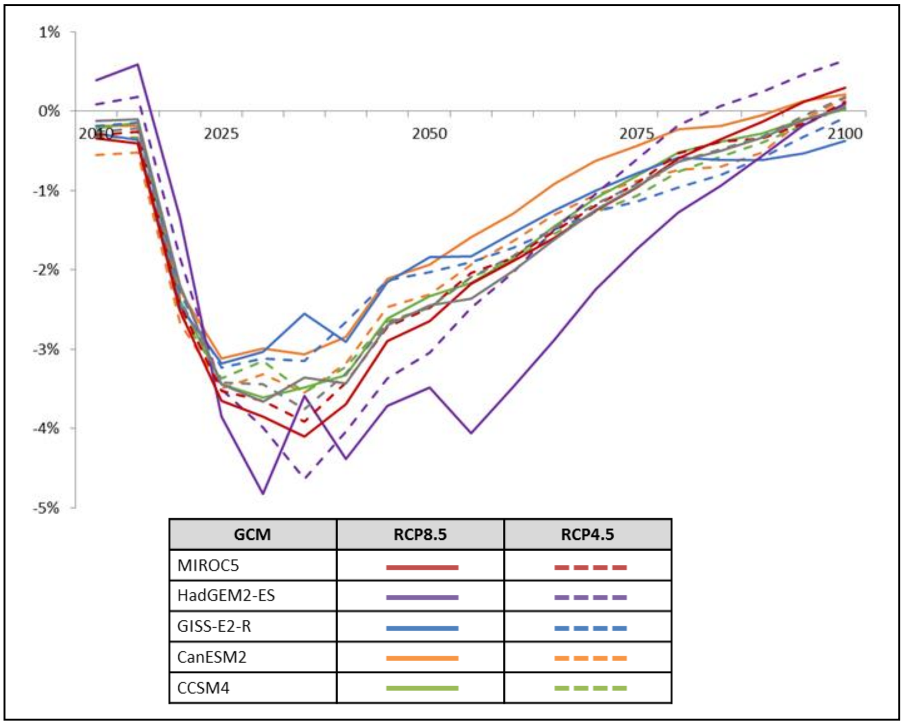
Table A.12.1. Projected Percent Change in U.S. Crop Yields with and without CO_2 fertilization

		2050		2090	
		With CO_2 Fertilization	Without CO_2 Fertilization	With CO_2 Fertilization	Without CO_2 Fertilization
Barley	RCP8.5	-5.0	-19	-19	-35
	RCP4.5	-7.0	-18	-6.4	-20
Corn	RCP8.5	-5.3	-13	-17	-22
	RCP4.5	-3.6	-10	-5	-12
Cotton	RCP8.5	13	-3.0	1.1	-19
	RCP4.5	16	2.7	18	0.9
Hay	RCP8.5	-43	-47	-44	-51
	RCP4.5	-43	-47	-48	-52
Potato	RCP8.5	-0.7	-17	-7.2	-33
	RCP4.5	7.0	-9	4.4	-15
Rice	RCP8.5	-10	-23	-20	-38
	RCP4.5	-5.0	-15	-6.1	-19
Sorghum	RCP8.5	-3.2	-16	-10	-24
	RCP4.5	-1.4	-12	0.1	-13
Soybean	RCP8.5	-3.4	-15	-11	-24
	RCP4.5	-2.5	-12	-2.7	-14
Wheat	RCP8.5	4.8	-10	11	-12
	RCP4.5	1.0	-10	4.6	-10

Changes in land allocation, crop mix, and production practices in turn affect GHG emissions from agriculture. Figure A.12.2 shows the estimated changes in cumulative GHG emissions under both RCPs for each of the 5 GCMs. In general, estimated GHG emissions decrease by 3-5% through 2035, and thereafter increase through 2100, eventually reaching levels consistent with those in 2010. Similar to the pattern seen in projected prices, the hotter GCMs, including HadGEM2-ES and MIROC5, show the largest declines in emissions, though the differences among RCPs and GCMs is relatively modest. The dynamics of the changes in GHG emissions are closely related to crop prices. The majority of the reduction in cumulative GHG emissions over the first few decades is associated with reduced emission from enteric fermentation and manure management. Higher prices for hay, feed grains, and grazing (due to land use shifts as lands used for grazing move into crop production) lead to a reduction in the number of livestock, particularly cattle, which reduces livestock GHG emissions. As prices for these commodities begin to fall after 2035, the number of livestock begins to increase again and the net cumulative emissions from agriculture begin to increase as well. By the end of the century, cumulative emissions have approximately caught up to reference period levels as the reduced livestock emissions from the first few decades are increasingly offset by higher CO_2 emissions from greater energy use both on-farm and to produce fertilizer for use on the higher area devoted to crop production and reduced carbon sequestration on cropland relative to pasture. Importantly, these results do not include interacting effects of changes in land use devoted to forest management. As such, the expansion of agricultural lands in response to declining yields could have competing effects on changes in forest management, which could in turn affect forestry-related emissions that are not accounted for in this analysis.

Figure A.12.2. Percent Change in Cumulative Net GHG Emissions from Agriculture 2010-2100

Emissions include carbon dioxide and methane, but exclude nitrous oxide.



A.13. Coral Appendix

Please refer to the Coral section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

The coral reef analyses described in the main report present COMBO (Coral Mortality and Bleaching Output) model projections for shallow-water reefs in Hawaii, South Florida, and Puerto Rico. As a sensitivity analysis, COMBO was also simulated using explicit modeling of three types of coral that have different responses to bleaching: feeders, switchers, and optimizers. Each coral type has its own bleaching threshold, mortality, and growth parameters, which together help to account for the potential variability in biological response to future bleaching events. These coral types are coded within the model to respond to bleaching events in the following ways:

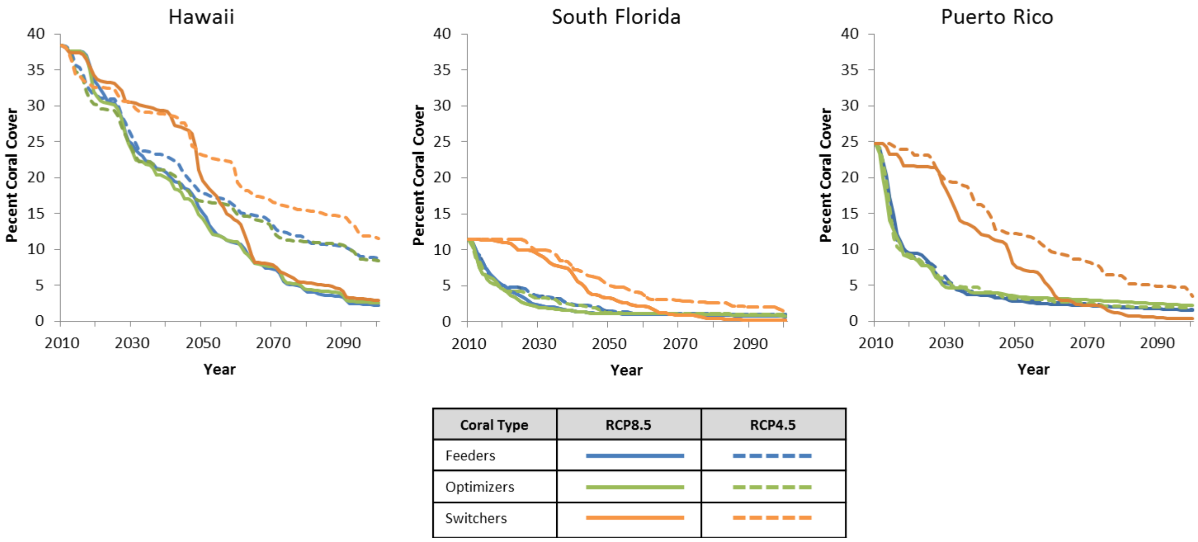
a) Feeders increase feeding rates to increase the probability of surviving through the event, but have little short- or long-term adaptability;

b) Switchers permanently change to more heat-resistant, but less productive symbionts, therefore experiencing reduced long-term growth but greater ability to survive successive bleaching events.

c) Optimizers reduce respiration and survive off of lipid stores, therefore increasing the probability of surviving an initial bleaching event, but leading to reduced abilities of surviving another event that occurs within 4 years of the previous occurrence.

Figure A.13.1 shows projected changes in coral cover for each coral type in the three regions of analysis. Each type and scenario combination represents the average results for the five GCMs analyzed as part of the broader project. As shown, the percent cover of all three coral types is projected to decline substantially over the course of the century. The effect of reduced climate change under RCP4.5 has a positive effect on reducing coral loss for all coral types in Hawaii, but only with the switchers type in South Florida and Puerto Rico. For all three locations, the switchers coral type indicates an elevated resilience to the effects from bleaching compared to the other two types. This sensitivity analysis is useful for investigating potential variability in biological response to future bleaching events, however, important caveats exist. In particular, coral reefs in Hawaii, South Florida, and Puerto Rico experienced intense, wide-spread bleaching events in 2015 and 2016. As a result, it is likely that much of the existing coral diversity prior to these events has been reduced, resulting in a low likelihood that these different coral types actually exist. The coral that does exist in these locations is likely to have already gone through natural selection, such that only the most resilient species remain. As such, the coral cover results presented in the main section of the Technical Report provide the most accurate results given the capabilities of the COMBO model.

Figure A.13.1. Percent Change in Regional Coral Reef Cover for Each Coral Type

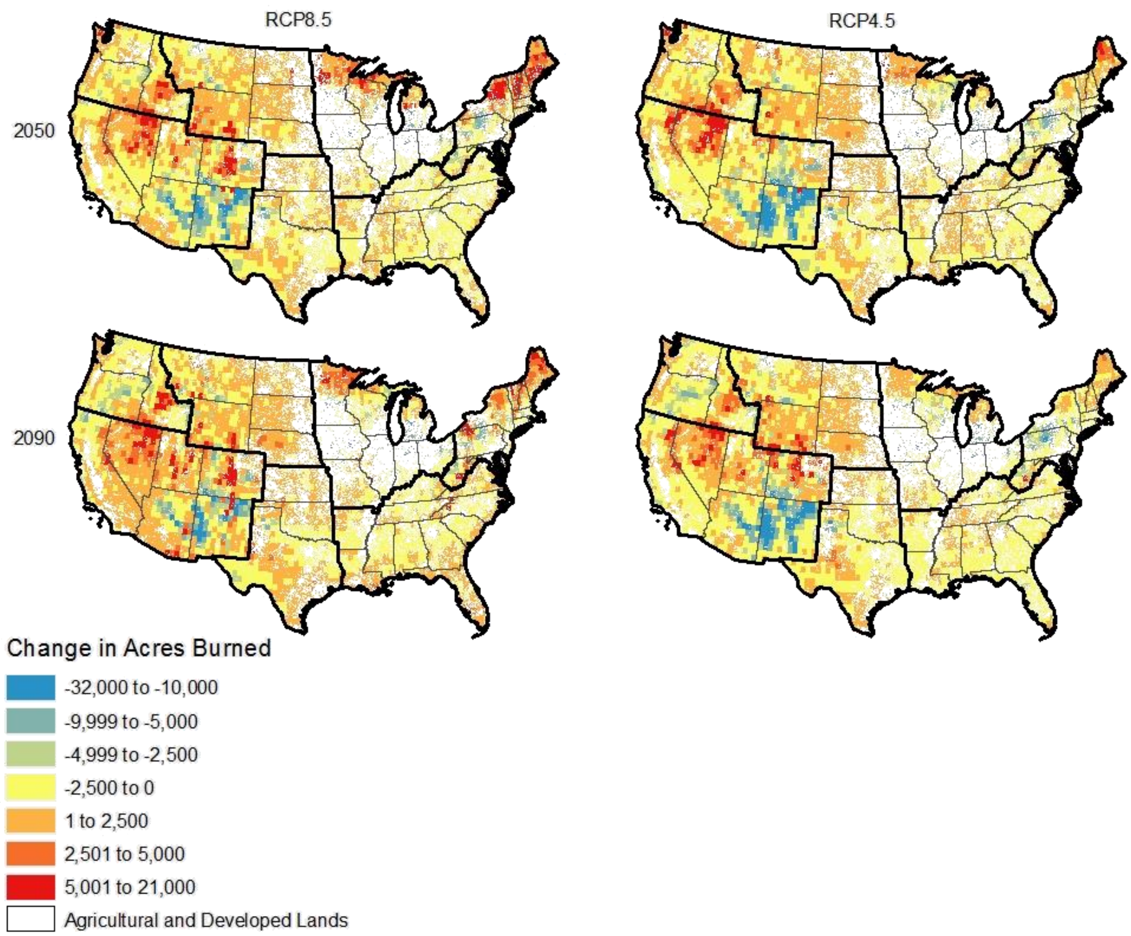


A.14. Wildfire Appendix

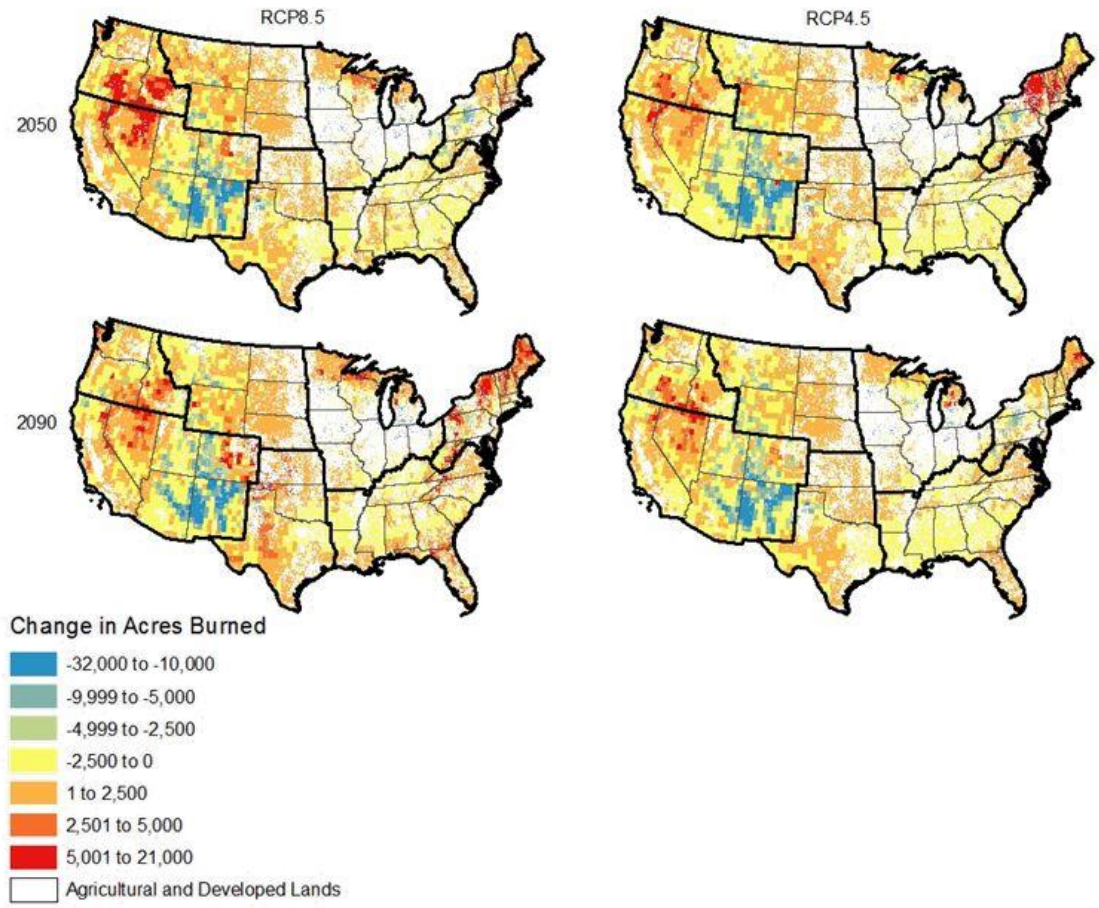
Please refer to the Wildfire section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

Figure A.14.1: Wildfire Maps by GCM

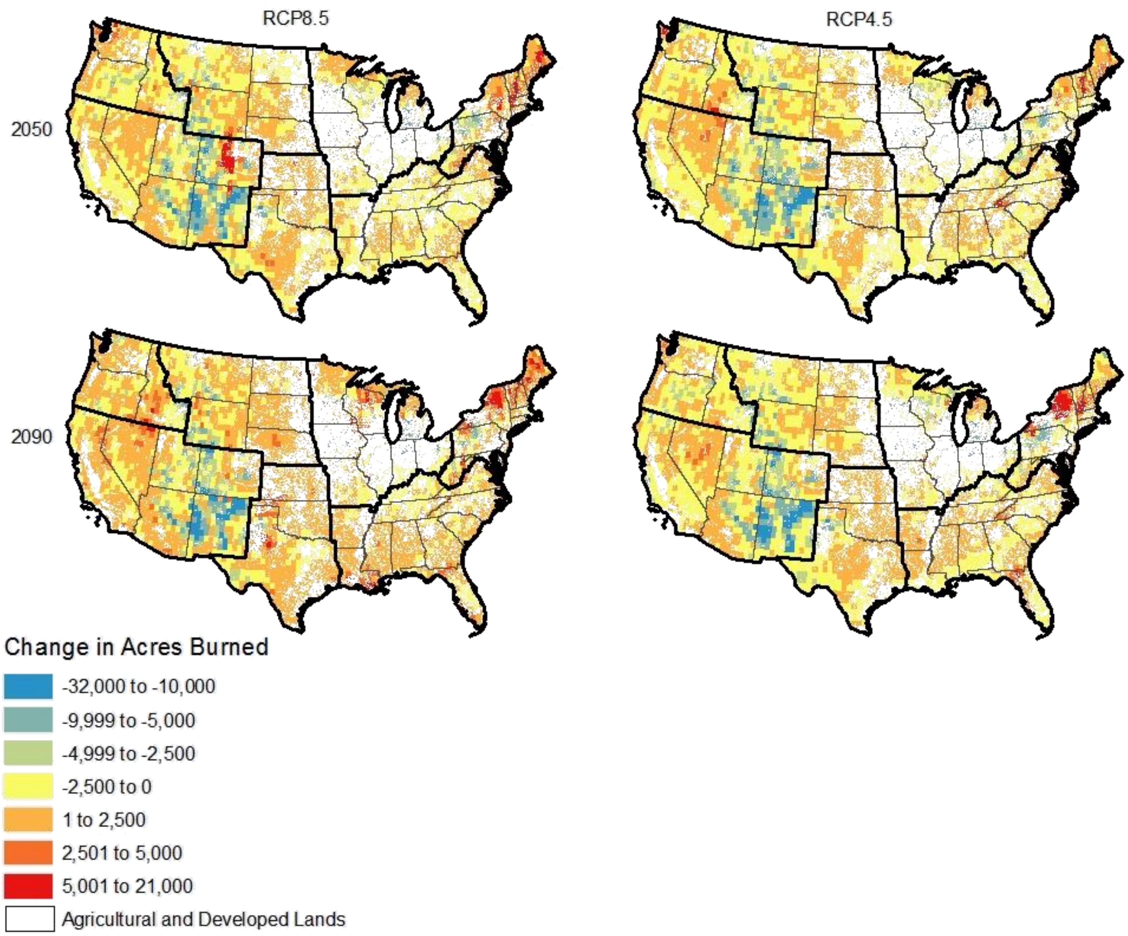
a) Change in Acres Burned across the Contiguous U.S. (CanESM2)



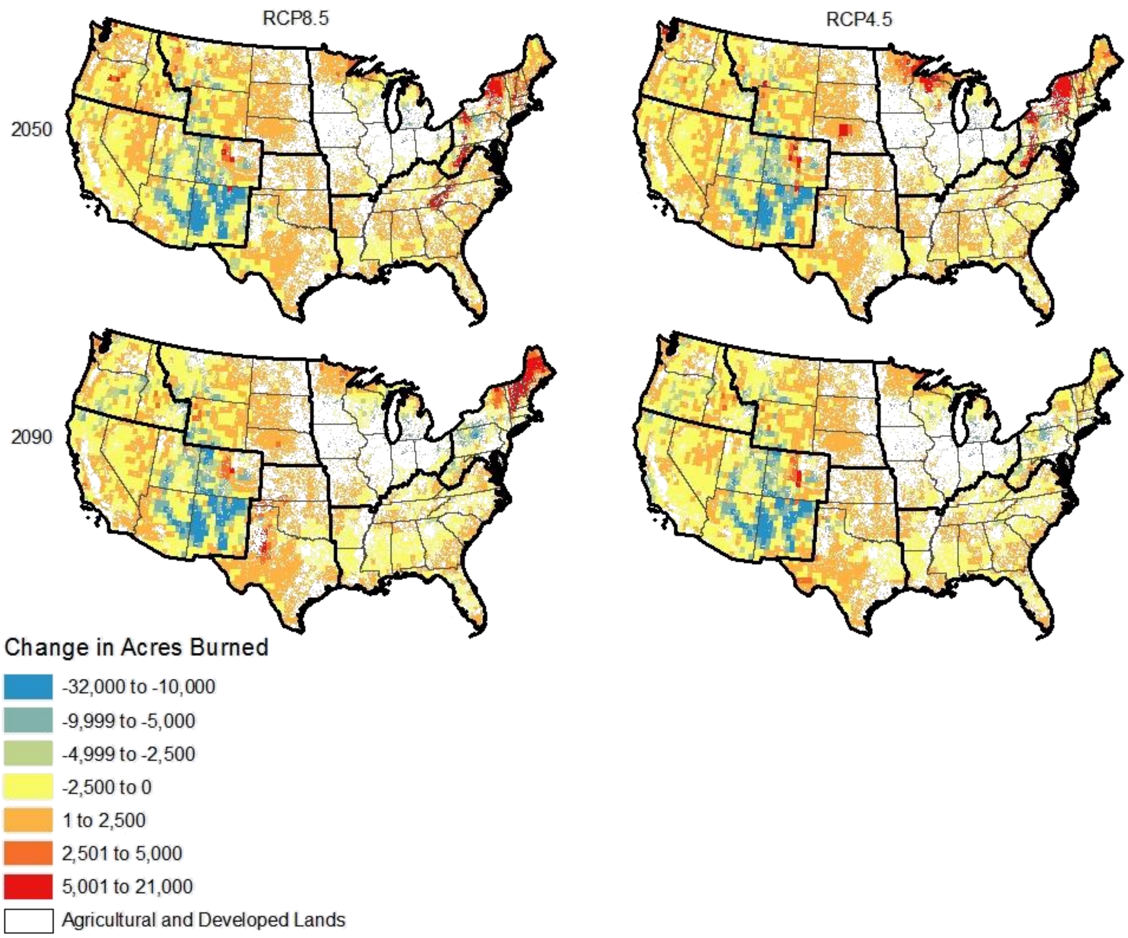
b) Change in Acres Burned across the Contiguous U.S. (CCSM4)



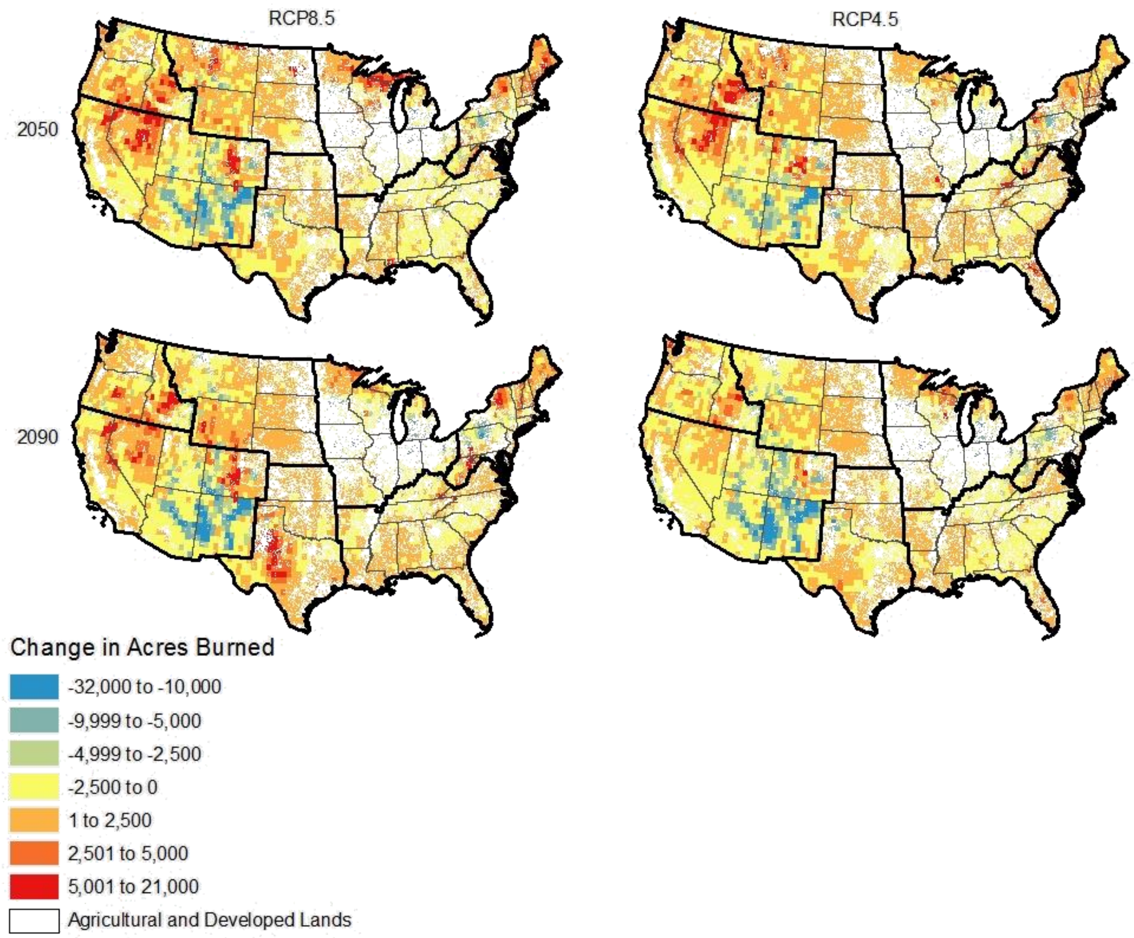
c) Change in Acres Burned across the Contiguous U.S. (GISS-E2-R)



d) Change in Acres Burned across the Contiguous U.S. (HadGEM2-ES)



e) Change in Acres Burned across the Contiguous U.S. (MIROC5)

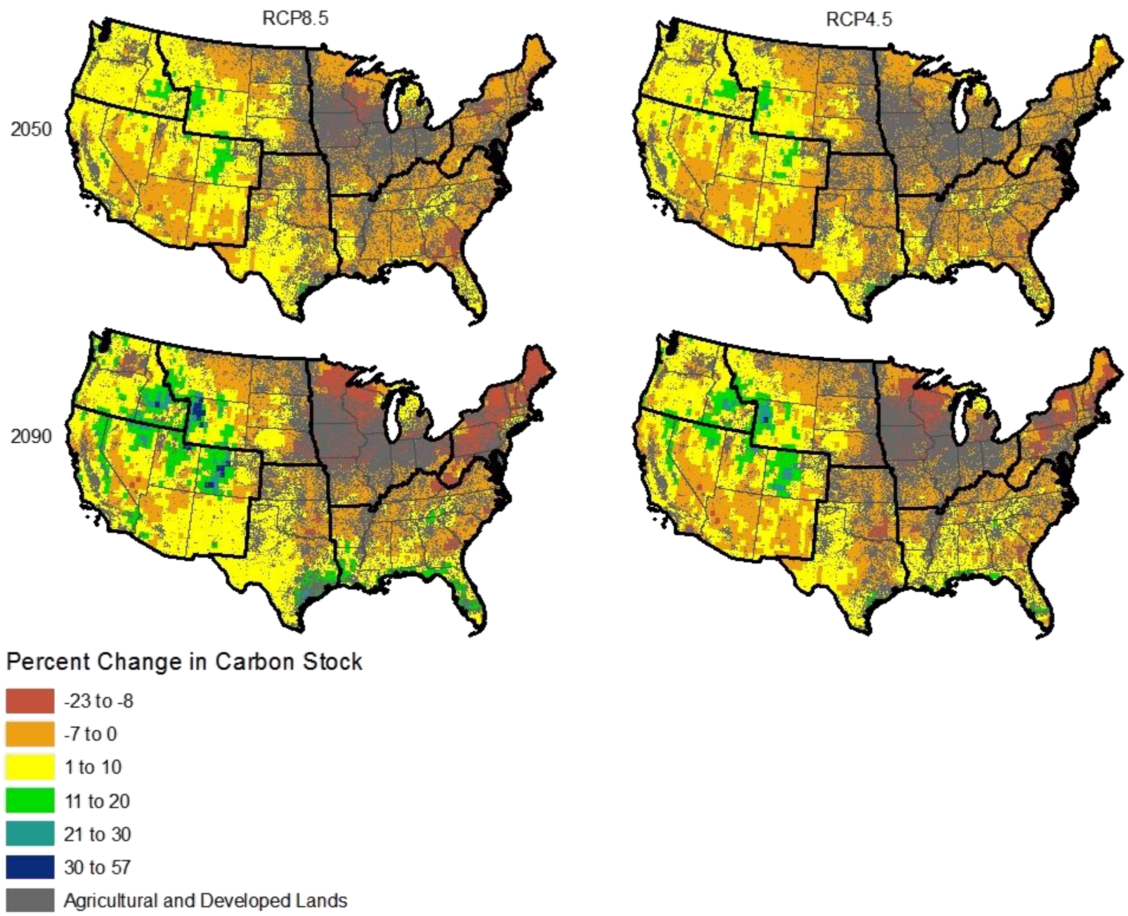


A.15. Carbon Storage Appendix

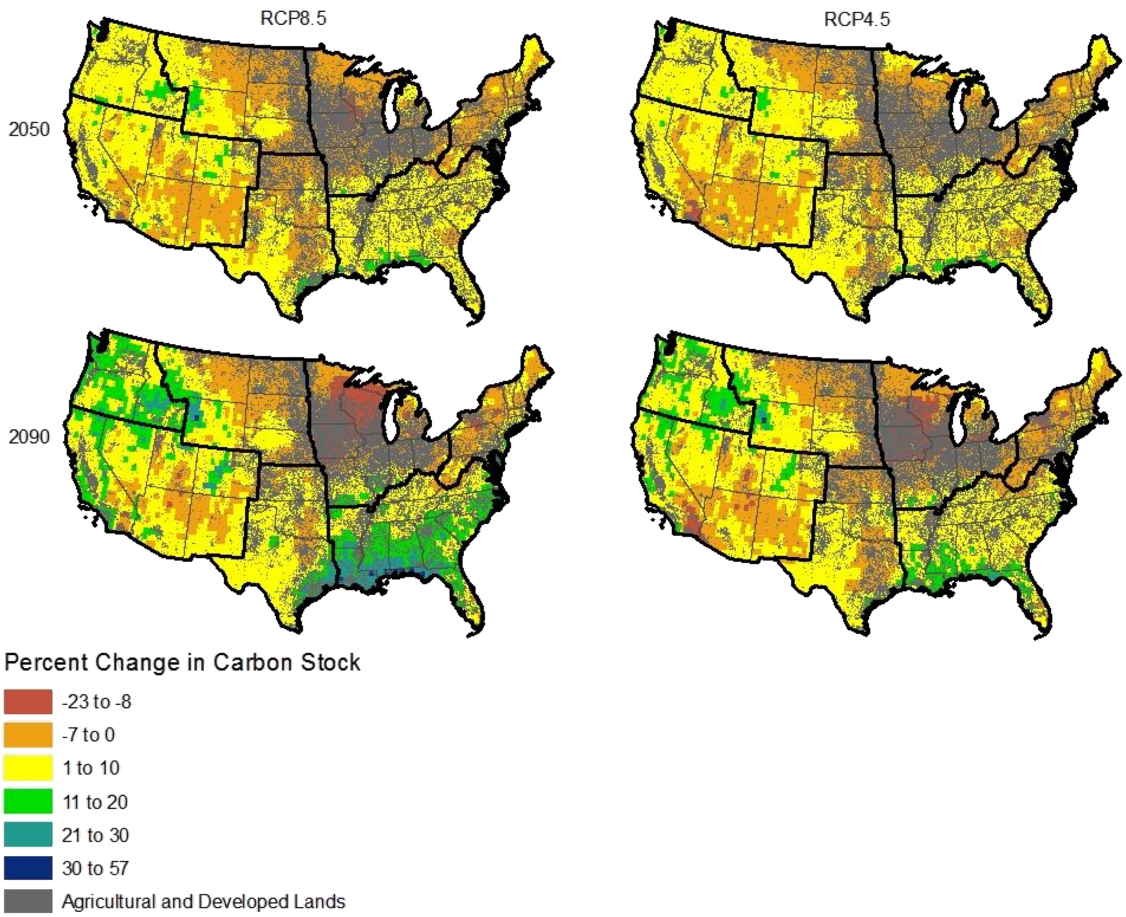
Please refer to the Carbon Storage section of the main Technical Report for detailed information on the results, a summary of the methodologies used, and references to the supporting peer-reviewed literature.

Figure A.15.1: Carbon Maps by GCM

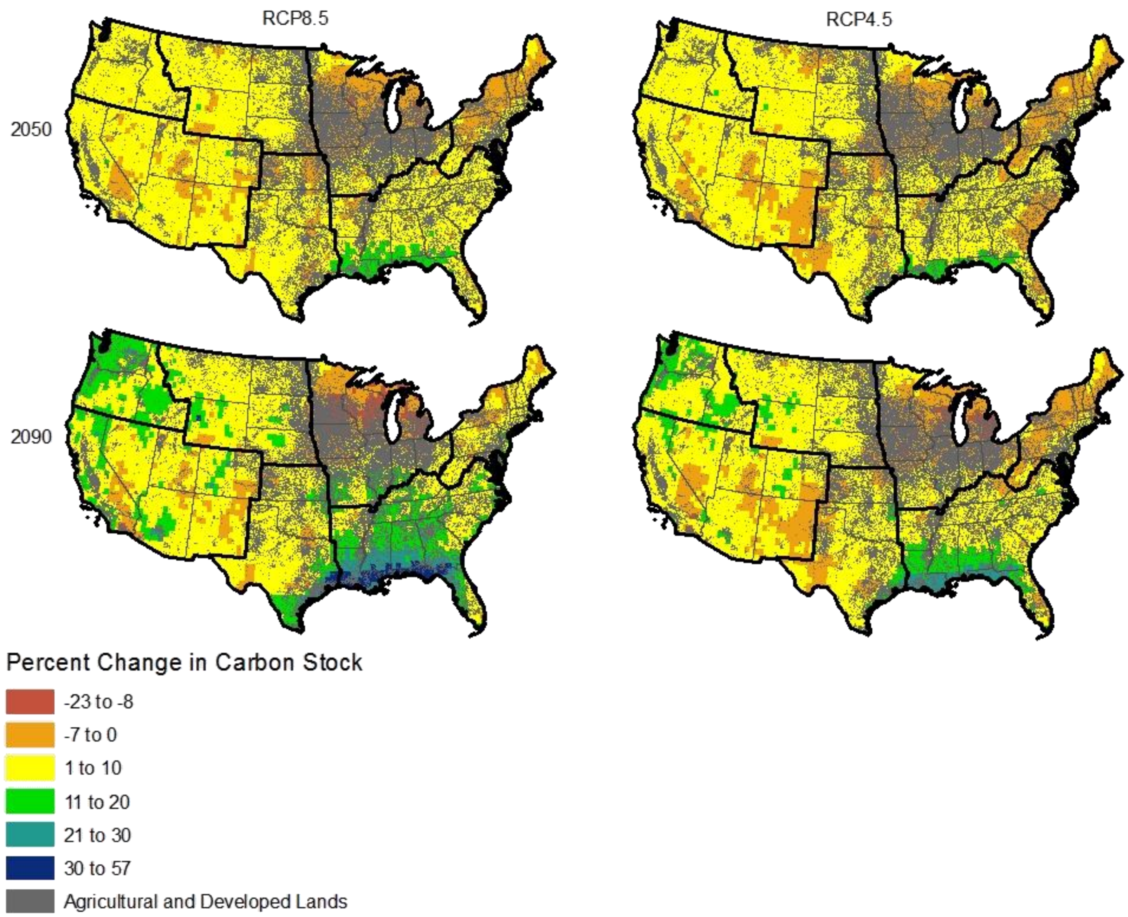
a) Percent Change in Carbon Stock across the Contiguous U.S. (CanESM2)



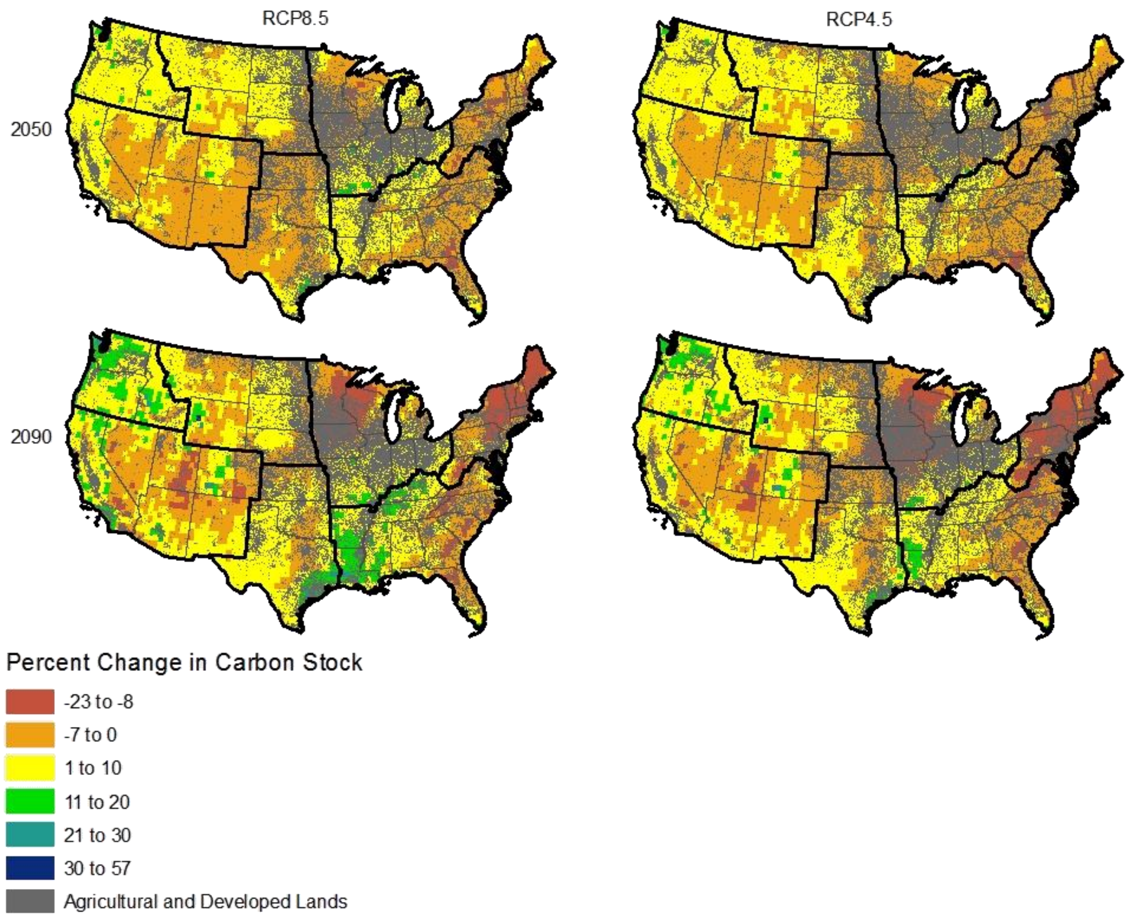
b) Percent Change in Carbon Stock across the Contiguous U.S. (CCSM4)



c) Percent Change in Carbon Stock across the Contiguous U.S. (GISS-E2-R)



d) Percent Change in Carbon Stock across the Contiguous U.S. (HadGEM2-ES)



e) Percent Change in Carbon Stock across the Contiguous U.S. (MIROC5)