Environmental Research Letters

LETTER • **OPEN ACCESS**

Increasing exposure of energy infrastructure to compound hazards: cascading wildfires and extreme rainfall

To cite this article: Hamed Moftakhari and Amir AghaKouchak 2019 *Environ. Res. Lett.* **14** 104018

IOP Publishing Environ. Res. Lett. 14 (2019) 104018 https://doi.org/10.1088/1748-9326/ab41a6

Environmental Research Letters

OPEN ACCESS

RECEIVED
21 December 2018

REVISED
14 August 2019

ACCEPTED FOR PUBLICATION
5 September 2019

PUBLISHED
18 October 2019

LETTER

Increasing exposure of energy infrastructure to compound hazards: cascading wildfires and extreme rainfall

Hamed Moftakhari[1,2] and **Amir AghaKouchak**[1,3]

[1] University of California, Irvine, United States of America
[2] The University of Alabama, United States of America
[3] Author to whom any correspondence should be addressed.

E-mail: amir.a@uci.edu

Keywords: energy infrastructure, climate change, natural hazards, energy security

Supplementary material for this article is available online

Abstract

Floods and debris flows pose a significant threat, especially when extreme rain falls over burned areas. This is an example of a compound event in which two concurrent or consecutive events lead to extreme societal impacts. Compound and cascading hazards are becoming increasingly important and have notable impacts on threatened communities across the world. Wildfire followed by an intense precipitation event can result in a large flood under which the combined impacts of hazard drivers are much more intense than those from individual drivers. Here, we first quantify the change in exposure of natural gas infrastructure to individual hazards, wildfire and floods in the future relative to past. We, then quantify the compound hazards as coincidence likelihood of intense rain over burned areas and analyze the spatial patterns across the State of California, USA. Our results show that not only the exposure of natural gas infrastructure to individual hazards would be higher, the likelihood of compound hazards is expected to increase substantially in a warming climate.

Introduction

Floods and debris flows pose a significant threat to energy infrastructure, especially when extreme rain falls over burned areas. A recent example was the devastating debris flow in Montecito, California that killed at least 20 people and injured many more. The event occurred about a month after a major wildfire that scorched over 440 square miles in Southern California. This is an example of compound events in which two consecutive or cascading events lead to extreme impacts (AghaKouchak *et al* 2018). Though there is considerable variability in the ways to define/discuss extreme events across disciplines (McPhillips *et al* 2018), in general, compound events (or compound hazards) correspond to combinations of two or more dependent drivers that yield extreme impacts and pose significant societal or environmental risk (Leonard *et al* 2014, Zscheischler and Seneviratne 2017). The compounding impacts can be grouped into the following categories: (i) two or more extreme events occurring simultaneously or successively (the latter is known as cascading event), (ii) combinations of extreme events with underlying conditions that amplify the impact of the events, (iii) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined (IPCC 2012). In these situations, the resulting impacts due to compounding effects are expected to be significantly more severe than those due to individual hazard drivers in isolation, and thus ignoring these compounding effects may yield inappropriate characterization of posed risk (Sadegh *et al* 2018).

Wildfires followed by severe flooding in the western United States are examples of compound and cascading hazards, under which the impacts are intensified by succession of two natural hazards (NFIP 2012). Both the frequency and intensity of wildfires in the western US have significantly increased over the last few decades (Dennison *et al* 2014). This rise is associated with many factors including human-caused climate change, and more specifically climate warming and drought severity (Abatzoglou and Williams 2016, Westerling 2016). This extensive wildfire during the dry season may enhance the risk of flooding by increased hydrologic vulnerability stemming from elevating soil exposure to runoff and erosion processes (Williams *et al* 2014). Indeed, wildfires by disturbing the hydrologic characteristics of the watershed such as, evapotranspiration (Poon and Kinoshita 2018), baseflow (Kinoshita and Hogue 2011) and surface water yield (Kinoshita and Hogue 2015) not only affect the quantity of the delivered runoff, but also the quality and concentration of suspended materials (Burke *et al* 2013, Florsheim *et al* 2017). That makes debris-flow activity among the most destructive consequences of post-wildfire effects during which erosion and entrainment of material by surface runoff, and infiltration-triggered failure and mobilization of a discrete, shallow landslide mass intensify fire-related debris flows (Parise and Cannon 2017).

In a warmer climate, intense rainfall hazard is also expected to be higher due to the increased water vapor holding capacity of the atmosphere and change in precipitation pattern (Hirabayashi *et al* 2013, Pendergrass *et al* 2017). In parts of the western US the same trend is expected (Hamlet and Lettenmaier 2007, DeFlorio *et al* 2013, Salathé *et al* 2014). California is expected to experience increased heavy and extreme precipitation in the following decades (Polade *et al* 2017, Ragno *et al* 2018); with more than threefold increase in sub-seasonal events at the order of greatest recorded historic floods (Swain *et al* 2018). Berg and Hall (2015) found a statistically significant increase (~2×), between 2020 and 2060, in historical frequency of wet extremes. Thus, the expected climate change-induced alteration in heavy-precipitation and high-temperature extremes (Fischer and Knutti 2015) may yield growing susceptibility to compound hazards. The more intense/frequent extreme compound hazards tremendously threaten infrastructures, depending on their vulnerability to each specific hazard (Forzieri *et al* 2018).

Energy infrastructure in numerous ways are vulnerable to climate conditions (Schaeffer *et al* 2012, Cruz and Krausmann 2013, Forrest *et al* 2018, Mukherjee *et al* 2018, Tarroja *et al* 2018, 2019). In Europe by the 2080s, for example, an overall climate risk of 8.2 € million/year to energy sector is expected (Forzieri *et al* 2018). In California by the end of 21st century, substantial new investment is required for an additional 38.5% peak generation capacity to compensate the decreased efficiency of generators and substations, and the increased demand (Sathaye *et al* 2012). Among all, natural gas pipelines are notably sensitive to extreme flooding and wildfires (and the consequent hazards such as landslides and land erosion) that might expose the underground pipes (Schaeffer *et al* 2012, Forzieri *et al* 2018). Pipelines at water crossings may experience scouring, damage from debris, and/or damage or potential rupture due to landslides (Bruzgul *et al* 2018). The above-ground natural gas transmission-related facilities in California are vulnerable to direct impacts of wildfires. Even if the pipelines would be underground, and so less threatened directly by wildfire, measurements and control assets are highly vulnerable (meters in several locations had melted away in California wildfire incidents in October 2018) and disruptions/shutoffs are required before fire reaches houses (ICF 2018). Beyond these, the exposure of natural gas pipelines to compound hazards yet to be studied, otherwise the failure probability will be under/overestimated (Moftakhari *et al* 2017, 2019). In January 2018, for example Montecito community in California experienced one of a kind compound hazards (wildfire followed by intense rainfall) that each of drivers in isolation may not produce such extensive mudslide-driven damage yielding federal Major Disaster Declaration (ICF 2018).

In this study we first quantify the exposure of natural gas pipelines to individual hazards, wildfire and estimated runoff and also the change in exposure in the future relative to past. We then quantify the compounding patterns and likelihood that extreme precipitation falls over burned areas of the state of California. Then, we analyze the projections and determine the regions with higher projected hazard.

Materials and methods

The data used in this study are all based on the downscaled climate simulations/projections from localized constructed analogs (LOCA) by Scripps Institution of Oceanography (Pierce *et al* 2014). The Cal-Adapt tool (http://cal-adapt.org) provides access to LOCA climate data including precipitation and generated total runoff at spatial resolution of 1/16° (approximately 6 km) and daily temporal resolution all over the State of California. LOCA data have also been used as input to models for wildfire intensity projections (Westerling 2018). The projections from four general circulation models (GCMs) prioritized by California 4th Climate Assessment, namely HadGEM2-ES, CNRM-CM5, CanESM2 and MIROC5 under representative concentration pathways (RCP) 4.5 and 8.5 are obtained to represent warm/dry, cool/wet, average and complement climate conditions in California. While the daily values for precipitation and runoff are provided in $\mathrm{kg\,m^{-2}\,s^{-1}}$ and $\mathrm{m^3\,s^{-1}}$, respectively, the annual average wildfire intensity is estimated in *hectares* under medium population growth scenarios.

In this study for compound hazard assessment we take the product of annual average wildfire and the 99.5th percentile of daily precipitation in the following year as a representative of compound wildfire-flooding hazard. We assume that a watershed hit by wildfire can recover after a year and so the history of fire experience (i.e. lag times greater than one year) is not transferred to calculate the compound hazard. For infrastructure exposure assessment we obtain data about the distribution of natural gas pipelines of

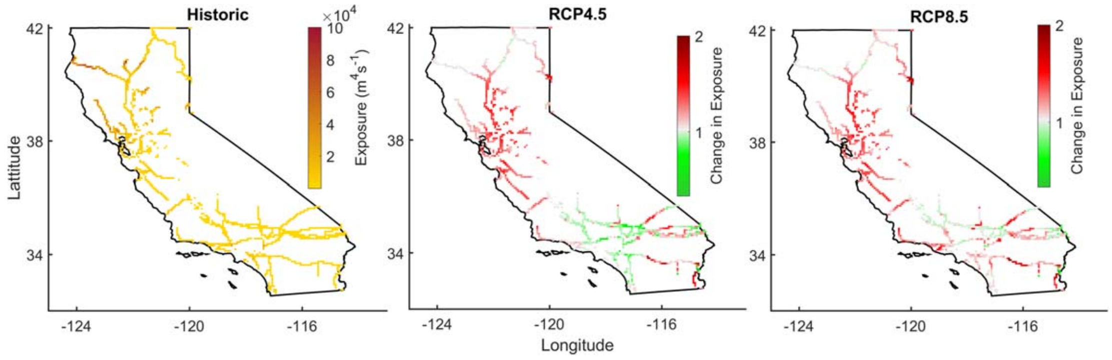

Figure 1. Natural gas pipeline exposure to runoff in the past (left; 1953–2005), and its expected change in the future (2047–2099) under RCPs 4.5 (middle) and 8.5 (right). Red (green) means increased (decreased) exposure to runoff.

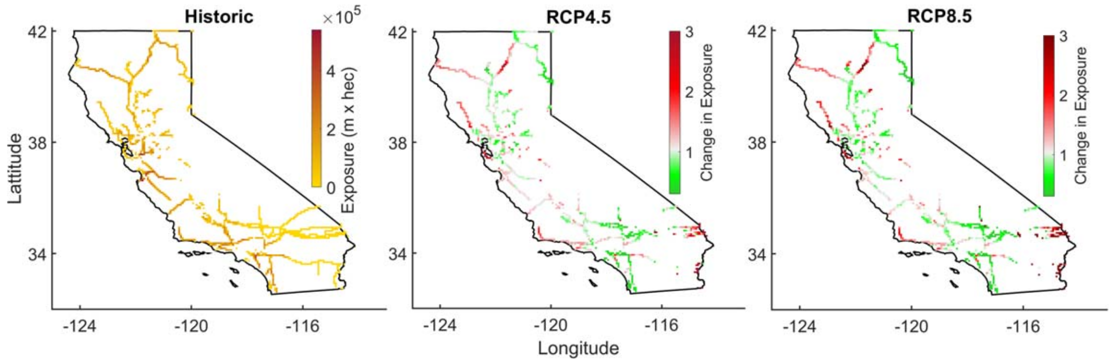

Figure 2. Natural gas pipeline exposure to wildfire in the past (left; 1953–2005), and its expected change in the future (2047–2099) under RCPs 4.5 (middle) and 8.5 (right). Red (green) means increased (decreased) exposure to wildfire.

California from US Energy Information Administration (https://eia.gov). Using this data we quantify the length of pipelines located in each pixel with wildfire intensity and runoff projection. Then the exposure of pipelines to natural hazards is calculated by multiplying the length of pipeline to the estimated intensity of the given natural hazard, that is the median and 90th quantile over the study period for wildfire (in *hectares*) and runoff (in $m^3\ s^{-1}$), respectively.

To obtain the probability density function (PDF) of the compound hazards, first the ensemble mean of estimated compound hazards from the four studied GCMs are calculated, and then the empirical distribution of median of estimated hazards for the pixels all around California is calculated using kernel density estimation method (Silverman 1998). Then, the mean of historic values is considered as a threshold to calculate the exceedance likelihood above the given threshold.

Results and discussions

Analysis of exposure of energy infrastructure to the projected hazards may provide a better understanding of the expected change in risk towards these infrastructure in the future (2047–2099) relative to the past (1953–2005). For this purpose, we calculate the length of pipelines within each pixel with runoff and wildfire estimates. Then the product of hazard intensity and pipeline length in each pixel provides an estimate of the exposure of the natural gas pipelines to these hazard drivers. Figures 1 and 2 show the results for ensemble mean estimates, and results for individual GCMs are provided in the supplementary Information is available online at stacks.iop.org/ERL/14/104018/mmedia.

The estimated exposure of pipelines to runoff (figure 1) is notably higher in the north. Since our analysis shows no notable difference between average lengths of pipelines per pixel between south and north, we conclude that the exposure difference between northern and southern California can be attributed to variation in received precipitation across state (Jones 2000). The exposures have been highest in the Northwest and lowest in the deserts of the south (e.g. Mojave and Sonoran; with respect to the characterized bioregions in California by Lenihan *et al* (2003)). In the future, however, the infrastructure in north of Central Valley, Modoc Plateau, and the San Francisco Bay area along with parts of the South (e.g. Southwestern, Mojave Desert and Sonoran Desert) will

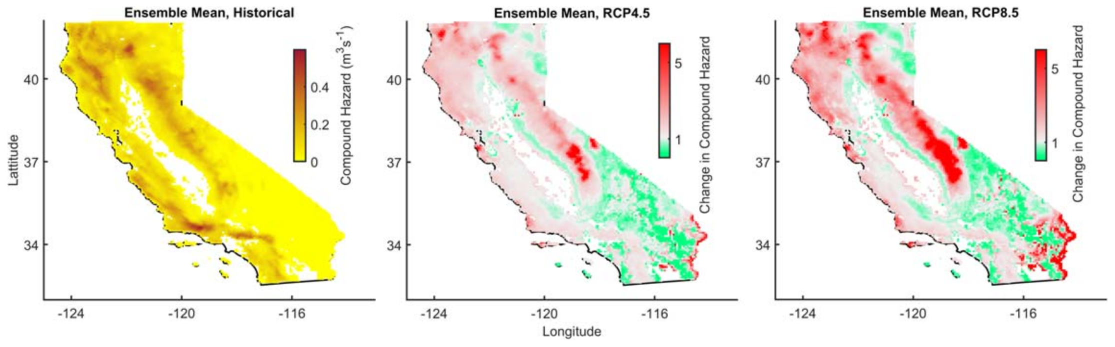

Figure 3. Relative change in compound hazard (burned area × precipitation intensity) in the future (2047–2099) compared with the past (1953–2005) based on ensemble mean of climate models. Red (green) means increased (decreased) likelihood of compound hazards.

experience an increased (2× times) exposure to runoff. It should be noted that this raise is estimated based on the assumption that no flood mitigation measures will be implemented and thus (if available) the effects of runoff control projects (i.e. storm water drainage systems implementation) must be taken into account for more accurate projections.

The exposure to wildfire is different than runoff and is expected to vary across space and time. The exposure is relatively higher (up to three times) in coastal regions (e.g. Northwest, Central Western and Southwestern) and cascade ranges and relatively low in the deserts of the South. While expected to rise in the Northwest, the Cascade ranges and east of the Mojave and Sonoran deserts, there is no significant change. It is projected to decrease in the future for the rest of the state. A considerable decreasing trend (down to one-third) is expected in Modoc Plateau, the north of Central Valley and the Bay area, west of Mojave and Sonoran deserts and Southwestern regions.

Figure 3 shows the change in expected compound wildfire and intense precipitation events in the future (2047–2099) relative to the past (1953–2005). The shading on the left panel (Historic) shows the intensity of estimated compound hazard over the historic period. In this panel, white regions (no data) are the areas excluded from wildfire projections. This exclusion is either due to the fact that these regions are outside the current combined fire state and federal protection responsibility areas, including landscape intensively converted to human uses or primarily desert areas (Westerling 2018). The intensity of compound hazards is generally larger (~2× on-average) in the North (above 37° latitude) compared to the Southern California (below 37° latitude). This difference can be attributed to the significant spatial variability of precipitation across the State. The total rainfall amounts received during a typical winter season in northern California could be 2–4 times higher than in the southern California (Jones 2000). This yields large differences in vegetation types and pattern and so the wildfire dynamics, combined with precipitation variability, explain the aforementioned spatial pattern in compound hazard intensity. Another detectable pattern is the difference between coastal watersheds and mountain ranges with low lying inland watersheds. Indeed, out of various known bioregions in California (Lenihan *et al* 2003), forests (Northwest, Cascade Ranges, and Sierra Nevada) and coastal shrublands/woodlands (Central Western and Southwestern) are experiencing more intense compound hazards. In the future, forests are expected to experience even more severe compound hazards (up to 6×), with the southern part of Sierra Nevada experiencing the highest rise under both RCPs 4.5 and 8.5. Coastal shrublands/woodlands though expect to experience either low-to-moderate rise (i.e. Central Western) or no-considerable rise (i.e. Southwestern). Interestingly, East of Sierra Nevada, South of Mojave Desert and Sonoran Desert, which in the current situation show relatively low potential for compound hazards, are projected to experience notably more intense compound events in the future. This may stem from the potential for land cover change due to change in climatic patterns.

Figure 4 shows the temporal evolution in the distribution of compound hazard intensities. The left panel shows the empirical probability distribution function (PDF) of the median values. The shaded area (and the percentage associated with that) represent the likelihood that the historic mean will be surpassed by above-average events. The right panel shows the empirical PDFs of 90th quantiles. The distributions of compound hazards are expected to be notably different in the future relative to the past. While, in the past there has been a 38% chance that the historic mean of median values will be exceeded, this likelihood is projected to double in the future under both RCPs 4.5 (68%) and 8.5 (73%). The difference between distributions becomes even more considerable for extreme events. The likelihood that the mean of 90th quantiles will be exceeded in the future is almost three times higher than the past (34%), under both RCPs 4.5 (90%) and 8.5 (91%). These results show that statistics

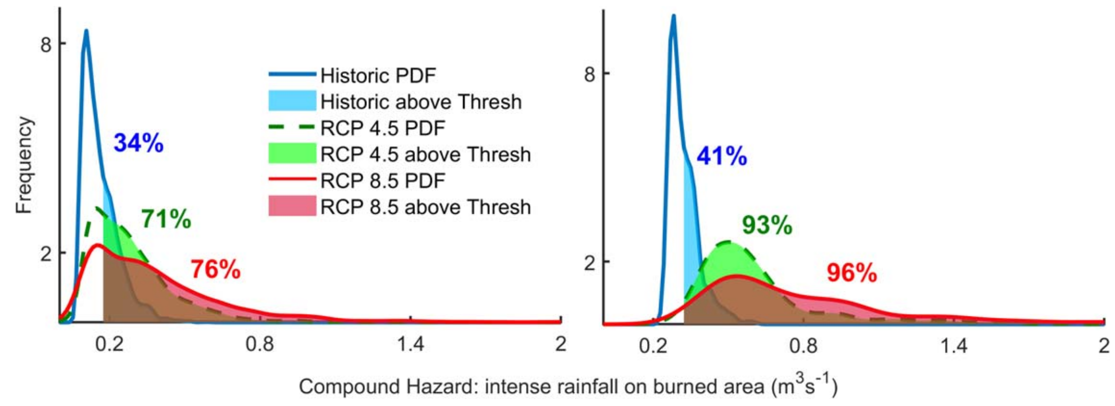

Figure 4. Distribution of median (left panel) and 90th quantile (right panel) of the ensemble average estimates of compound hazards. The shaded areas represent the exceedance likelihood with respect to the mean of the historic distribution.

of compound hazards will be notably different in the future relative to the past. Thus, for appropriate characterization of compound hazards in the future we need to take non-stationarity of statistics into account (Cheng *et al* 2014, Ragno *et al* 2018, 2019).

We can further explore the uncertainty associated with these estimates. Figure 5 shows the boxplot of estimates for three distinct pixels in the north, middle and south of California (left, middle and right columns, respectively) under historic climate, and RCPs 4.5 and 8.5 (panels (a)–(c), (d)–(f), (g)–(i), respectively). This is just an example of uncertainty analysis that integrates uncertainty from different sources (e.g. climate models and RCP scenarios).

In summary, regional patterns of exposure of natural gas pipelines to individual/compounding effects of hazards are considerably different. The results of this work shows Northwest and Cascade ranges are the regions with highest exposure and they are more likely to experience notably higher rates of compound hazards in the future. The Mojave and Sonoran deserts, which are relatively low in exposure to hazards, will likely experience considerably higher rates of compounding hazards, though there are regions where compound hazards are expected to decrease in the future (e.g. Southwestern and the west of Mojave Desert).

We should clarify the difference between hazards and their drivers (Zscheischler *et al* 2018). For a comprehensive compound hazard assessment, would have been ideal if we have estimated runoff under given scenarios that not only take the change in precipitation into account, but also update the hydrologic characteristics of the watershed under given wildfire scenarios. This way, we may robustly quantify the compounding impacts with the underlying nonlinear relationships. In the absence of such data, we have to analyze the exposure of pipelines to each hazard (e.g. runoff and wildfire) and then, to obtain an understanding of future trends in compounding impacts, analyze the likelihood that hazard drivers (e.g. rainfall and prior wildfire experience) might coincide.

It should be noted that, not all pipeline infrastructure equally exposed to the aforementioned hazards. Indeed, depending upon proximity to rivers, debris flow basins, urban areas, and/or steep topography and their position relative to ground level (above-/under-ground) natural gas pipelines would experience differential levels of risk. For a comprehensive assessment of risk associated with compound hazards consideration of these modulating factors is necessary.

In these analyses, interactions between hazard drivers and anthropogenic effects (i.e. risk prevention/mitigation measures) are not included. A more thorough understanding of risk in the future needs holistic approaches that take the post-disaster dynamic interactions between natural and human processes into account (Di Baldassarre *et al* 2015, Kinoshita *et al* 2016). This is even more important when we are dealing with aging infrastructure with declining resilience to natural hazards. The United States for example, needs to spend $4.5 trillion by 2025 on aging infrastructure to secure their serviceability (American Society of Civil Engineers 2018). More specifically, a large percentage of US natural gas pipelines were installed before 1980, and without appropriate maintenance measures Americans may experience more frequent power interruptions (American Society of Civil Engineers 2018). This is even more important in the case of post-wildfire flooding, which is an example of cascading hazards (AghaKouchak *et al* 2018). The chain of such adverse events are expected to become more common in the future and without appropriate consideration the web of connections between hazard drivers, devastating events like the disastrous situation that southern California experienced in January 2018 (ICF 2018) will cost more and more in the future.

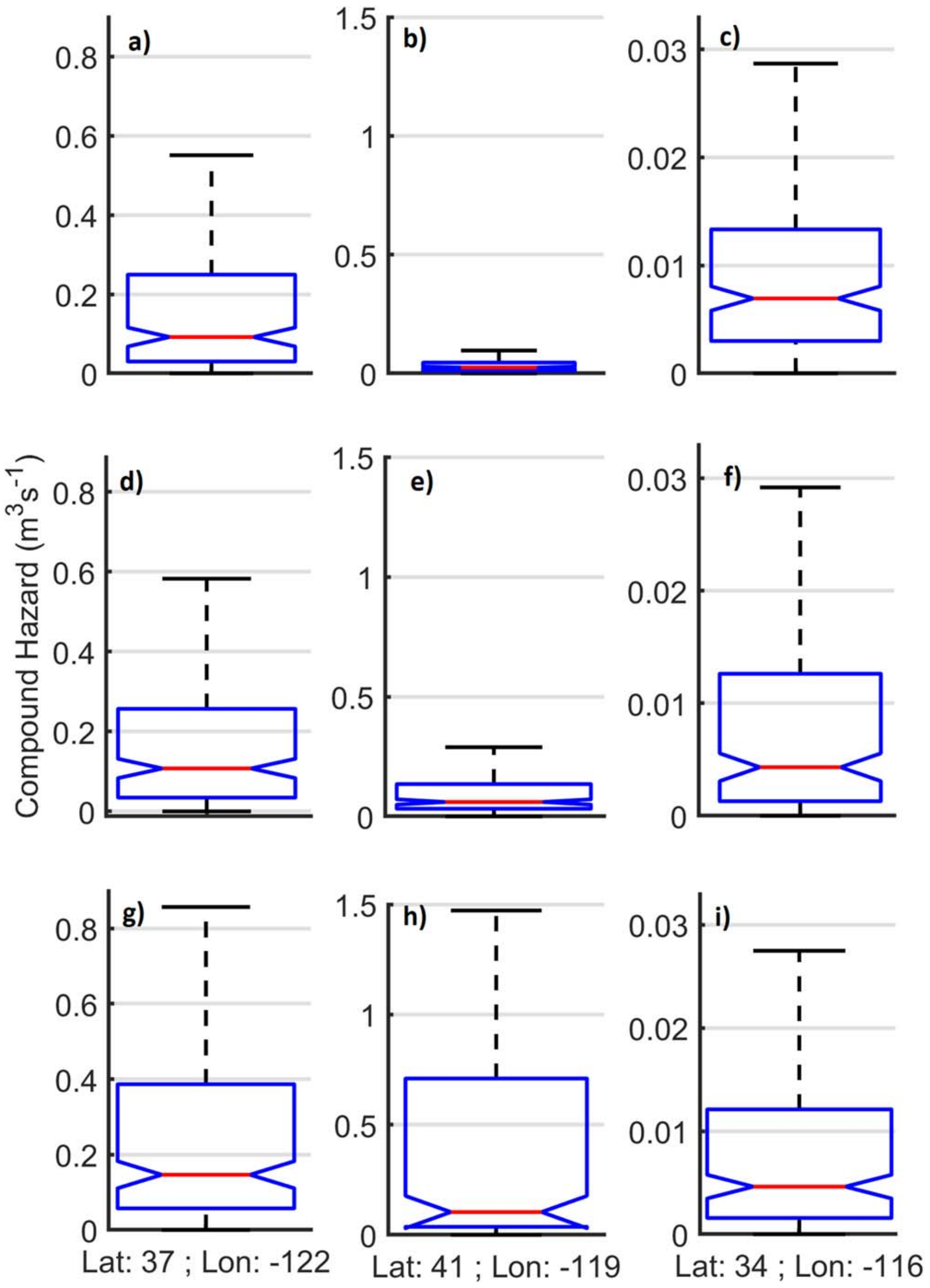

Figure 5. Uncertainty estimates for three distinct pixels in the north, middle and south of California (left, middle and right columns, respectively) under historic climate, and RCPs 4.5 and 8.5 (first, second and third rows, respectively).

Acknowledgments

This study is partially supported by the California Energy Commission grant No. 500-15-005 and National Science Foundation Grant No. CMMI-1635797. The hazard data used in this study, including precipitation, runoff and wildfire, are available through the Cal-Adapt tool (http://cal-adapt.org). Also, natural gas pipelines data for California are provided by US Energy Information Administration and available at https://eia.gov.

ORCID iDs

Hamed Moftakhari https://orcid.org/0000-0003-3170-8653

References

Abatzoglou J T and Williams A P 2016 Impact of anthropogenic climate change on wildfire across western US forests *Proc. Natl Acad. Sci.* **113** 11770–5

AghaKouchak A, Huning L S, Chiang F, Sadegh M, Vahedifard F, Mazdiyasni O, Moftakhari H and Mallakpour I 2018 How do natural hazards cascade to cause disasters? *Nature* **561** 458–60

American Society of Civil Engineers 2018 2017 Infrastructure Report Card; A Comprehensive Assessment of America's Infrastructure (Reston, VA: American Society of Civil Engineers) (https://www.infrastructurereportcard.org/wp-content/uploads/2019/02/Full-2017-Report-Card-FINAL.pdf)

Berg N and Hall A 2015 Increased interannual precipitation extremes over California under climate change *J. Clim.* **28** 6324–34

Bruzgul J, Kay R, Rodehorst B, Petrow A and Hendrickson T 2018 *Potential Climate Change Impacts and Adaptation Actions for Gas Assets in the San Diego Gas and Electric Ccompany Service Area* (Sacramento, California: California Energy Commission) (http://climateassessment.ca.gov/techreports/docs/20180827-Energy_CCCA4-CEC-2018-009.pdf)

Burke M P, Hogue T S, Kinoshita A M, Barco J, Wessel C and Stein E D 2013 Pre- and post-fire pollutant loads in an urban fringe watershed in Southern California *Environ. Monit. Assess.* **185** 10131–45

Cheng L, AghaKouchak A, Gilleland E and Katz R W 2014 Non-stationary extreme value analysis in a changing climate *Clim. Change* **127** 353–69

Cruz A M and Krausmann E 2013 Vulnerability of the oil and gas sector to climate change and extreme weather events *Clim. Change* **121** 41–53

DeFlorio M J, Pierce D W, Cayan D R and Miller A J 2013 Western US extreme precipitation events and their relation to ENSO and PDO in CCSM4 *J. Clim.* **26** 4231–43

Dennison P E, Brewer S C, Arnold J D and Moritz M A 2014 Large wildfire trends in the western United States, 1984–2011 *Geophys. Res. Lett.* **41** 2928–33

Di Baldassarre G, Viglione A, Carr G, Kuil L, Yan K, Brandimarte L and Blöschl G 2015 Debates-perspectives on socio-hydrology: capturing feedbacks between physical and social processes: a socio-hydrological approach to explore flood risk changes *Water Resour. Res.* **51** 4770–81

Fischer E M and Knutti R 2015 Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes *Nat. Clim. Change* **5** 560–4

Florsheim J L, Chin A, Kinoshita A M and Nourbakhshbeidokhti S 2017 Effect of storms during drought on post-wildfire recovery of channel sediment dynamics and habitat in the southern California chaparral, USA: effect of storms on post-wildfire sediment dynamics and habitat *Earth Surf. Process. Landf.* **42** 1482–92

Forrest K *et al* 2018 Assessing climate change impacts on California hydropower generation and ancillary services provision *Clim. Change* **151** 395–412

Forzieri G, Bianchi A, Silva F B E, Marin Herrera M A, Leblois A, Lavalle C, Aerts J C J H and Feyen L 2018 Escalating impacts of climate extremes on critical infrastructures in Europe *Glob. Environ. Change* **48** 97–107

Hamlet A F and Lettenmaier D P 2007 Effects of 20th century warming and climate variability on flood risk in the western US *Water Resour. Res.* **43** W06427

Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H and Kanae S 2013 Global flood risk under climate change *Nat. Clim. Change* **3** 816–21

ICF 2018 *Case Studies of Natural Gas Sector Resilience Following Four Climate-Related Disasters in 2017* (Los Angeles, CA: SoCalGas)

IPCC 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption: Special Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press)

Jones C 2000 Occurrence of extreme precipitation events in California and relationships with the Madden–Julian oscillation *J. Clim.* **13** 3576–87

Kinoshita A M, Chin A, Simon G L, Briles C, Hogue T S, O'Dowd A P, Gerlak A K and Albornoz A U 2016 Wildfire, water, and society: toward integrative research in the 'Anthropocene' *Anthropocene* **16** 16–27

Kinoshita A M and Hogue T S 2011 Spatial and temporal controls on post-fire hydrologic recovery in Southern California watersheds *CATENA* **87** 240–52

Kinoshita A M and Hogue T S 2015 Increased dry season water yield in burned watersheds in Southern California *Environ. Res. Lett.* **10** 014003

Lenihan J M, Drapek R, Bachelet D and Neilson R P 2003 Climate change effects on vegetation distribution, carbon, and fire in California *Ecol. Appl.* **13** 1667–81

Leonard M, Westra S, Phatak A, Lambert M, van den Hurk B, McInnes K, Risbey J, Schuster S, Jakob D and Stafford-Smith M 2014 A compound event framework for understanding extreme impacts *Wiley Interdiscip. Rev. Clim. Change* **5** 113–28

McPhillips L E *et al* 2018 Defining extreme events: a cross-disciplinary review *Earths Future* **6** 441–55

Moftakhari H, Schubert J E, AghaKouchak A, Matthew R and Sanders B F 2019 Linking statistical and hydrodynamic modeling for compound flood hazard assessment in tidal channels and estuaries *Adv. Water Resour.* **128** 28–38

Moftakhari S G, AghaKouchak A, Sanders B F and Matthew R A 2017 Compounding effects of sea level rise and fluvial flooding *Proc. Natl Acad. Sci.* **114** 9785–90

Mukherjee S, Nateghi R and Hastak M 2018 A multi-hazard approach to assess severe weather-induced major power outage risks in the US *Reliab. Eng. Syst. Saf.* **175** 283–305

NFIP 2012 *Flood After Fire Fact Sheet (FEMA)* (https://ready.gov/sites/default/files/Flood_After_Fire_Fact_Sheet.pdf)

Parise M and Cannon S H 2017 Debris flow generation in burned catchments *Advancing Culture of Living with Landslides* ed M Mikoš *et al* (Berlin: Springer) pp 643–50

Pendergrass A G, Knutti R, Lehner F, Deser C and Sanderson B M 2017 Precipitation variability increases in a warmer climate *Sci. Rep.* **7**

Pierce D W, Cayan D R and Thrasher B L 2014 Statistical downscaling using localized constructed analogs (LOCA)* *J. Hydrometeorol.* **15** 2558–85

Polade S D, Gershunov A, Cayan D R, Dettinger M D and Pierce D W 2017 Precipitation in a warming world: assessing projected hydro-climate changes in California and other mediterranean climate regions *Sci. Rep.* **7**

Poon P K and Kinoshita A M 2018 Spatial and temporal evapotranspiration trends after wildfire in semi-arid landscapes *J. Hydrol.* **559** 71–83

Ragno E, AghaKouchak A, Cheng L and Sadegh M 2019 A generalized framework for process-informed nonstationary extreme value analysis *Adv. Water Resour.* **130** 270–82

Ragno E, AghaKouchak A, Love C A, Cheng L, Vahedifard F and Lima C H R 2018 Quantifying changes in future intensity-duration-frequency curves using multimodel ensemble simulations *Water Resour. Res.* **54** 1751–64

Sadegh M, Moftakhari H, Gupta H V, Ragno E, Mazdiyasni O, Sanders B, Matthew R and AghaKouchak A 2018 Multi-hazard scenarios for analysis of compound extreme events *Geophys. Res. Lett.* **45** 5470–80

Salathé E P, Hamlet A F, Mass C F, Lee S-Y, Stumbaugh M and Steed R 2014 Estimates of twenty-first-century flood risk in the pacific northwest based on regional climate model simulations *J. Hydrometeorol.* **15** 1881–99

Sathaye J, Dale L, Larsen P, Fitts G, Ko K, Lewis S and Lucena A 2012 *Estimating Risk to California Energy Infrastructure From Projected Climate Change* (Berkeley, CA: California Energy Commission) (http://energy.ca.gov/2012publications/CEC-500-2012-057/CEC-500-2012-057.pdf)

Schaeffer R, Szklo A S, Pereira de Lucena A F, Moreira Cesar Borba B S, Pupo Nogueira L P, Fleming F P, Troccoli A, Harrison M and Boulahya M S 2012 Energy sector vulnerability to climate change: a review *Energy* **38** 1–12

Silverman B W 1998 The kernel method for univariate data *Density Estimation for Statistics and Data Analysis* (Boca Raton, FL: CRC Press) pp 34–72

Swain D L, Langenbrunner B, Neelin J D and Hall A 2018 Increasing precipitation volatility in twenty-first-century California *Nat. Clim. Change* **8** 427–33

Tarroja B *et al* 2018 Translating climate change and heating system electrification impacts on building energy use to future greenhouse gas emissions and electric grid capacity requirements in California *Appl. Energy* **225** 522–34

Tarroja B *et al* 2019 Implications of hydropower variability from climate change for a future, highly-renewable electric grid in California *Appl. Energy* **237** 353–66

Westerling A L 2016 Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring *Phil. Trans. R. Soc.* B **371** 20150178

Westerling A L 2018 *Wildfire Simulations for California's Fourth Climate Change Assessment: Projecting Changes in Extreme Wildfire Events with a Warming Climate* (California Energy Commission) (http://climateassessment.ca.gov/techreports/docs/20180827-Projections_CCCA4-CEC-2018-014.pdf)

Williams C J, Pierson F B, Robichaud P R and Boll J 2014 Hydrologic and erosion responses to wildfire along the rangeland-xeric forest continuum in the western US: a review and model of hydrologic vulnerability *Int. J. Wildland Fire* **23** 155

Zscheischler J and Seneviratne S I 2017 Dependence of drivers affects risks associated with compound events *Sci. Adv.* **3** e1700263

Zscheischler J *et al* 2018 Future climate risk from compound events *Nat. Clim. Change* **8** 469–77