



Multi-hazard climate risk projections for the United States

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Abstract

Climate risk is a consequence of climate hazards, exposure, and the vulnerability (IPCC 2014). Here, we assess future (2040–2049) climate risk for the entire contiguous US at the county level with a novel climate risk index integrating multiple hazards, exposures and vulnerabilities. Future, weather and climate hazards are characterized as frequency of heat wave, cold spells, dryer, and heavy precipitation events along with anomalies of temperature and precipitation using high resolution (4 km) downscaled climate projections. Exposure is characterized by projections of population, infrastructure, and built surfaces prone to multiple hazards including sea level rise and storm surges. Vulnerability is characterized by projections of demographic groups most sensitive to climate hazards. We found Florida, California, the central Gulf Coast, and North Atlantic at high climate risk in the future. However, the contributions to this risk vary regionally. Florida is projected to be equally hard hit by the three components of climate risk. The coastal counties in the Gulf states of Louisiana, Texas, Mississippi and Alabama are at high climate risk due to high exposure and hazard. High exposure and vulnerability drive high climate risk in California counties. This approach can guide planners in targeting counties at most risk and where adaptation strategies to reduce exposure or protect vulnerable populations might be best applied.

Keywords Climate risk · Projection · Sea level rise · Hazards · Exposure · Vulnerability

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1 Introduction

The IPCC's fifth assessment report (IPCC 2014) stresses the importance of three components in a climate risk model useful to policy makers: weather and climate hazards, exposure of people and assets to those hazards and the vulnerability of those exposed assets and people (Fig. 1). Single weather and climate events have their own risks (Hauer et al. 2016; Jones et al. 2015; Baum et al. 2008), but most locations are exposed to more than one type of extreme events. Each hazard is uniquely characterized by its impacts and consequences. For example, disaster events such as drought/heat wave and tropical storms are the leading cause of human casualties, but the economic losses from tropical storm damage far outweigh the loss caused by direct drought and heat wave events. NOAA's billion-dollar disaster report (NOAA 2019) shows that in the United States, from 1980 to 2019 drought/heat waves alone claimed around 3000 lives, and tropical cyclones similarly claimed 6500 lives, whereas the economic loss from these events accounted for 15 and 55% of the cumulative loss from all major disaster events, respectively, during this period.

In addition to the extreme events, changes in mean state (climate) can also contribute to risk. Ecosystems, for example, are adapted to a certain range of temperature and precipitation. A slight change in temperature and/or precipitation over a period of time can result in profound ecological impacts on ecosystem services. For example, change in precipitation affects fish production due to changes in runoff (Rijnsdorp et al. 2009). Similarly, biodiversity loss and decline in fish stock are positively correlated to change in mean temperature (Nunez et al. 2019; Tu et al. 2018). For instance, changes in mean temperature and precipitation impact species composition and timber yield of forests (Rasche et al. 2013). Rising temperatures lead to glacier melting, which is evident in the U.S.'s Glacier National Park and glacier watershed in Pacific Northwest (Hall and Fagre 2003; Frans et al. 2018). In the Midwest, warming of streams, rivers and lakes potentially affects cold-water fish, such

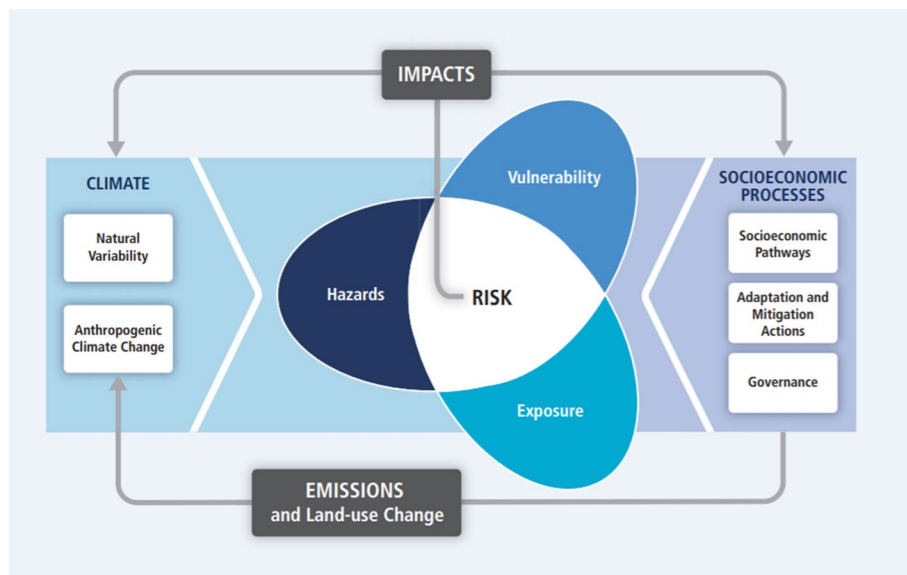


Fig. 1 Climate-related risk resulting from synergistic interaction of weather and climate hazards, vulnerability, and exposure of human and environment systems (Source: IPCC 2014)

as economically important trout, through impacts on reproduction and food availability (Wenger et al. 2011; Williams et al. 2015). The abundance of fish species impact the population that depend on fishing for their livelihood (Kuczynski et al. 2017). When multiple hazards co-occur in time or space, the risk is exacerbated. Therefore, rather than focusing on the risk of a single hazard type, a multi-hazard framework can better serve a comprehensive understanding of future climate risk.

Multiple sectors of society are exposed to climate risks. Urban areas, for example, are highly susceptible to multiple hazards due to higher population concentrations, infrastructure, and other investments (Jones et al. 2015). In addition to temperature and precipitation changes, coastal areas must also contend with sea level rise and increased frequencies of storm surges (Hauer et al. 2016; Nicholls et al. 2008; Sweet et al. 2017a, b). Importantly, some socio-demographic groups are more vulnerable than others—for instance, the youngest and oldest age groups (i.e., those under 5 y of age and those over 70 y of age), natural resource-dependent populations (i.e., economies dependent on agriculture, forestry, fishery), and lower wealth groups bear a disproportionate burden of climate hazards (Emrich and Cutter 2011; Karl et al. 2008; Shepherd and KC 2015; Reams et al. 2012). Responding to the needs and challenges faced by the multiplicity of societal actors affected by a changing climate is the task at hand for governments at varying levels.

We project climate risk in the mid-century (2040–2049) for counties of the contiguous United States, integrating multiple hazards, exposures, and vulnerabilities. The weather and climate hazards are characterized by anomalies in mean temperature and precipitation coupled with extreme precipitation days, heat waves, cold spells, and wet–dry conditions for the ten-year period (KC et al. 2015). The weather and climate hazards are calculated for RCP 8.5, a “high” emission scenario, using climate projections from ten global climate models in the World Research Climate Program’s CMIP5 archive dynamically downscaled to 4 km resolution (Ashfaq et al. 2016) with a historic baseline period of 1981–2010. The “high” emission scenario was selected based on the assumption that these nominally “high” scenarios are unlikely to significantly diverge from “business-as-usual” before 2050 (Jay et al. 2018). We quantify exposure with projections of impervious surface area, population, and housing density in the 2040s, along with roads and housing exposed to 0.6 m (2 feet) of sea level rise and storm surge in the coastal counties. Vulnerability is the combination of socioeconomic projections of elderly and infant populations, natural resource-dependent populations of farming, forestry, and fishery, and personal income per capita. These individual quantifications are first transformed into normalized (0–1) indices of hazard, exposure and vulnerability and combined by multiplying the three components. This is the first time the IPCC (IPCC 2014) risk framework has been applied to a multi-hazard, multi-exposure, multi-vulnerability characterization of future climate risk for the entire contiguous US at the county level.

2 Data and methods

The climate risk projection is performed for the mid-century (2040–2049), the 2040s, and the dimensions of risk are explored in different physiographic domains in the conterminous United States. The 2040s were chosen because there are large uncertainties associated with the demographic projection toward the end of the century, and our primary focus is to provide a near-term climate risk that could be useful to planners and stakeholders. The IPCC (2014) model of risk (a function of hazards, exposure, and vulnerability) is adopted

to quantify climate risk. Hazards are the climate-related physical events and changes in mean temperature and precipitation. Exposure is the presence of people, livelihoods, and infrastructure, in places that could be adversely affected by the hazards and vulnerability is the sensitivity to the hazard and lack of capacity to cope and adapt (Table 1).

Weather and climate hazards in the 2040s are quantified as anomalies in mean temperature and precipitation, coupled with frequency of extreme events. Daily maximum and minimum air temperature and precipitation projections from the World Research Climate Program's CMIP5 are used to project future hazards for RCP 8.5 scenario. Ten global climate models, Australian Community Climate and Earth System Simulator (ACCESS1-0), Beijing Climate Center Climate System Model (BCC-CSM1-1), Community Climate System Model Version 4 (CCSM4), Centro Euro-Mediterraneo sui Cambiamenti Climatici Climate (CMCC-CM), Flexible Global Ocean–Atmosphere–Land System Model Grid-point Version 2 (FGOALS-g2), Geophysical Fluid Dynamics Laboratory Earth System Models (GFDL-ESM2M), Institut Pierre Simon Laplace Climate Model 5A, Low-Resolution (IPSL-CM5A-LR), Norwegian Earth System Model (NorESM1-M), Meteorological Research Institute Coupled Global Climate Model Version 3 (MRI-CGCM3), and Max Planck Institute for Meteorology Earth System Model Mixed Resolution (MPI-ESM-MR), dynamically downscaled to 4 km (Li and Bou-Zeid 2013), are used to project future weather and climate hazards. Data processing is performed in R and ArcMap 10.3.1 to calculate the daily minimum and maximum temperature and precipitation of each model as the spatial mean for counties in the United

Table 1 The variables used to quantify hazard, exposure, and vulnerability components of climate risk

<i>Hazard</i>	
Temperature change	Mean temperature in the 2040s compared to baseline temperature
Precipitation change	Mean precipitation in the 2040s compared to baseline precipitation
Extreme precipitation	Days exceeding 98th percentile of daily baseline precipitation
Extreme cold	Days below 2 percentiles of the minimum baseline temperature
Heat wave	Days exceeding the 97.5 percentile of daily maximum baseline temperature for 3 consecutive days
Dry condition	Standard precipitation index: standardized z score of monthly precipitation in the 2040s compared to baseline
<i>Exposure</i>	
Impervious surface	EPA's ICLUS
Population	EPA's ICLUS
Housing density	EPA's ICLUS
Low-lying infrastructure	Houses and roads < 0.6 m sea level rise and/or storm surges using surging seas
<i>Vulnerability</i>	
Elderly population	Woods and Poole (2009)
Infant population	Woods and Poole (2009)
Farming jobs	Woods and Poole (2009)
Forestry and fishery jobs	Woods and Poole (2009)
Personal income per capita	Woods and Poole (2009)
African American (non-Hispanic)	Woods and Poole (2009)
Hispanic	Woods and Poole (2009)

States. The daily minimum and maximum temperature and precipitation of each county are calculated for individual models for the ten-year period (2040–2049). Similarly, historic baseline temperature and precipitation are calculated for counties in the United States by aggregating the 1 km Daymet gridded temperature and precipitation (Thorn-ton et al. 2018) to county level from 1981 to 2010.

The anomalies in temperature and precipitation and frequency of extreme events in the 2040s are calculated for individual models. Changes in mean temperature and precipitation for the decade (2040s) compared to the historic baseline period are calculated. An extreme temperature event (defined as a heat wave) is calculated as the number of events exceeding the 97.5th percentile of daily maximum baseline temperature for three consecutive days in the 2040s (Anderson and Bell 2011; Kysely et al. 2011; Zacharias et al. 2014). Cold events are calculated as the number of days in the 2040s below 2 percentiles of the minimum temperature in the baseline period. Extreme precipitation events were calculated as the number of days in the 2040s exceeding 98th percentile of daily baseline precipitation. Similarly, dry conditions are quantified using the monthly standard precipitation index (SPI), which is the standardized z score of monthly precipitation in the 2040s compared to the historic baseline precipitation. Low SPI values indicate drier conditions, whereas higher SPI values indicate wetter conditions. To capture drier conditions, we averaged the SPI for each month over a ten-years period and extracted the minimum average SPI value. A negative SPI indicates drought condition; however, to build the hazard index, the SPI values are reversed so that high SPI values represent high hazard.

The climate anomalies and extreme events over the 10-year period 2040–2049 are averaged for the ten individual models to calculate the average frequency. Changes in mean temperature, precipitation, extreme precipitation days, heat waves, cold spells, and SPI are rescaled to 0 to 1 (Eq. 1):

$$X = (x - \min(x)) / (\max(x) - \min(x)) \quad (1)$$

The rescaled variables are summed, and divided by number of hazard components to obtain the weather and climate hazard index for the 2040s (Eq. 2):

$$H(0, 1) = \sum X_{H,i}(0, 1) / k \quad (2)$$

where H is the hazard index, $X_{H,i}$ is the i th normalized hazard variable, \sum indicates the summation from $i=0$ to k and k is the number of metrics.

We quantify exposure with projections of impervious surface, population, and housing density in the 2040s and houses and roads exposed to 0.6 m (2 feet) sea level rise and/or storm surges. The population, housing density, and impervious surface projections are obtained from the United States Environmental Protection Agency's Integrated Climate and Land-Use Scenarios (ICLUS) projection that are based on the IPCC's A2 (medium-high to high emission) scenario, comparable to RCP 8.5 (EPA 2009). Sea level rise in the United States is likely to be higher than the projected global sea level rise of 0.15–0.38 m by 2050 (Sweet et al. 2017a). The U.S. Interagency sea level rise task force revised global mean sea level rise scenarios for the United States, project 0.63 m sea level rise by 2050 under the extreme scenario, also known as physically possible “worst case” scenario (Sweet et al. 2017b). Hence, we used 0.6 m (2 feet) sea level rise to derive the infrastructure exposure in the 2040s using an online tool, called surging seas (Climate Central 2014). Again, the individual metrics are rescaled to 0 to 1 (Eq. 1), summed and divided by the number of metrics to obtain the exposure index E (Eq. 3)

$$E(0, 1) = \sum X_{E,i}(0, 1)/k \quad (3)$$

where E is the exposure index, $X_{E,i}$ is the i th normalized exposure variable, \sum indicates the summation from $i=0$ to k and k is the number of metrics.

We quantify vulnerability using socioeconomic projections of vulnerable populations using Woods and Poole projections (Woods and Poole 2009). Woods and Poole's demographic projections are "cohort component projections" based on fertility and mortality in each county. The economic projections are based on an "Export-Base" model. Both are basically "business-as-usual" projections. The RCP 8.5 and SRES A2, mid-high scenario broadly comparable to RCP 8.5, define the hazard and exposure projections, respectively. Thus, our projections of hazard, exposure, and vulnerability are in reasonable harmony for near future projections of the 2040s. The socially isolated populations of elderly and infant populations, farming population, natural resource-dependent populations of forestry and fishery, and personal income per capita, racial/ethnic minorities. African American and Hispanic population are rescaled to 0 to 1 (Eq. 1) and summed and divided by the number of components to obtain the vulnerability index V for the 2040s (Eq. 4)

$$V(0, 1) = \sum X_{V,i}(0, 1)/k \quad (4)$$

where V is the vulnerability index, $X_{V,i}$ is the i th normalized vulnerability variable, \sum indicates the summation from $i=0$ to k and k is the number of metrics.

The future hazard, exposure and vulnerability indices are combined to derive a composite index of climate risk in the 2040s. In our coupling, we assign equal weights to each of our risk components and combine them through multiplication (Eq. 5).

$$R = H \times E \times V \quad (5)$$

where R is the risk index and H , E and V are the hazard, exposure and vulnerability indices, respectively. As any of the individual component indices approach zero, risk approaches zero. As hazard, exposure and vulnerability approach their individual maxima, risk increases with R approaching a maximum value of 1.

3 Results

We find Florida, California, the central Gulf Coast and North Atlantic to be at highest risk to climate change in the 2040s (Fig. 2). Florida is projected to be equally hard hit by the three components of climate risk: vulnerability, exposure, and climate hazards. Projected frequent heat waves, and extreme precipitation contribute to increased climate hazard in Florida and Gulf Coast counties (SI Figs. 5, 6, 7) even though the overall hazard index is only moderately high relative to other counties with an extreme hazard index (Fig. 3). A recent study by Raymond et al. (2020) noted that the Gulf Coast region has frequently surpassed the heat-humidity habitable limits and our findings further reinforce that in future heat waves will be more common in the region. The concentration of population and infrastructure in urban counties and coastal areas increase exposure (Fig. 4). Similarly, vulnerability in Florida is driven by a high elderly population (Fig. 5) as elderly populations suffering from chronic illness often have limited mobility, diminished sensory awareness, and are socially isolated, all which interfere with their ability to cope with climate hazards,

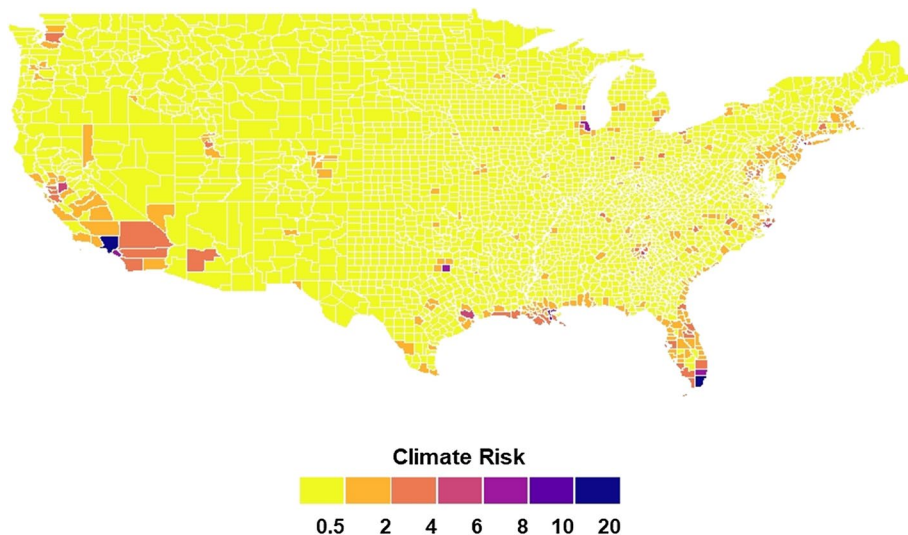


Fig. 2 Climate risk in the 2040s. Indices of climate hazard, exposure, and vulnerability of Figs. 3, 4 and 5, respectively, are multiplied to derive the climate risk index. Orange, red, and darker colors indicate high climate risk counties. The risk index is highly skewed to the right. The risk index is multiplied by 100 for clarity

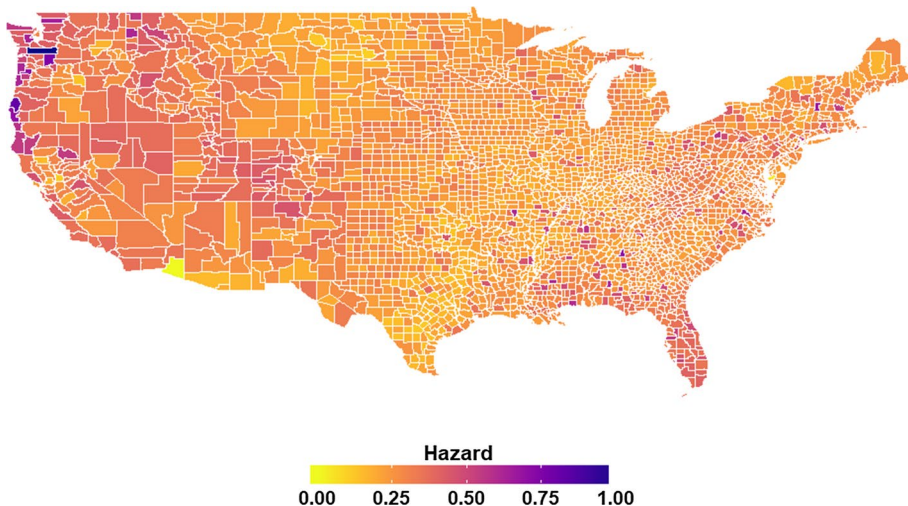


Fig. 3 Climate hazard in the 2040s obtained by merging the anomalies in temperature and precipitation and extreme events measured as—heat wave, cold spells, dry conditions, and extreme precipitation days (see Methods). The hazard index is rescaled 0 to 1

prepare for disasters, and respond during emergency evacuations (Aldrich and Benson 2008; O'Neill and Ebi 2009; Maier et al. 2014).

The coastal counties in the Gulf states of Louisiana, Texas, Mississippi, and Alabama, are at high climate risk (Fig. 2) due to exposure of infrastructure, population, and wealth to

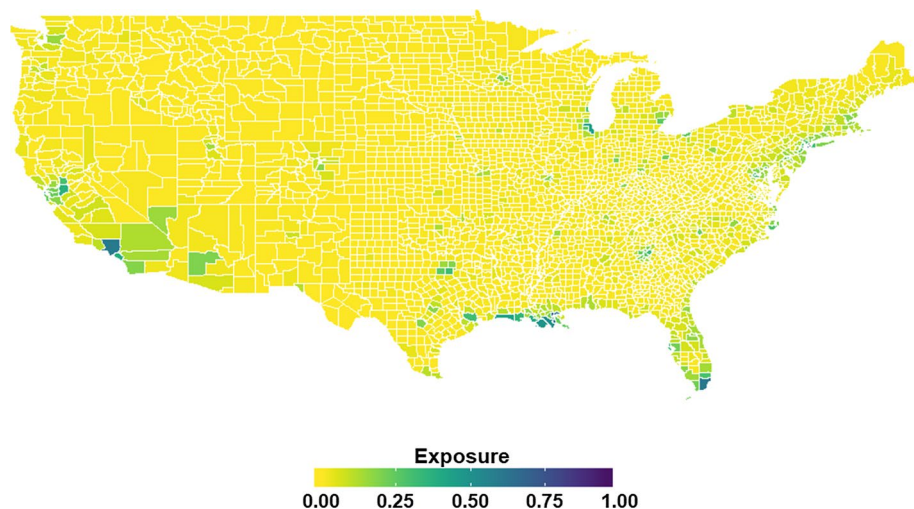


Fig. 4 Population and infrastructure exposure in the 2040s. Impervious surface, population and housing density in 2040s are combined with the infrastructure and homes inundated by 0.6 m (2 feet) sea level rise. Exposure index is rescaled 0 to 1

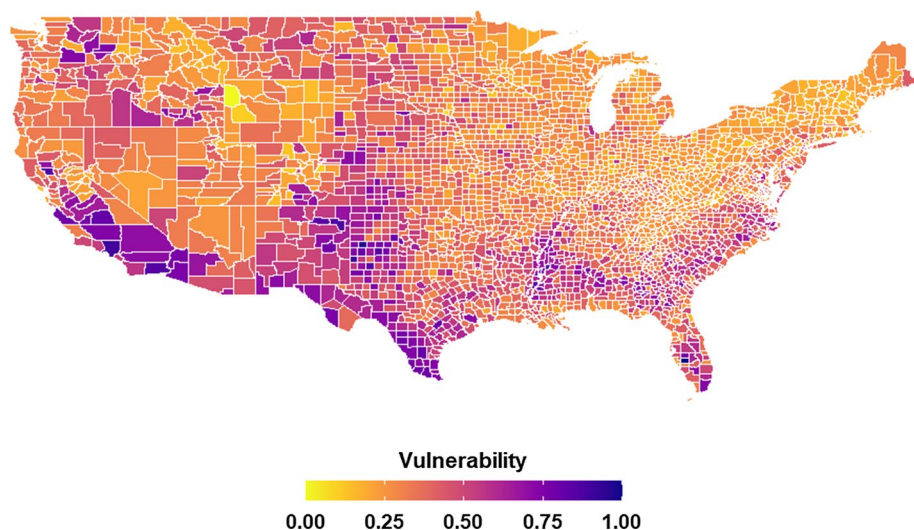


Fig. 5 Socioeconomic vulnerability in 2040. Socioeconomic variables are merged to obtain the vulnerability of the population in 2040. Vulnerability index is rescaled 0 to 1

sea level rise and storm surges coupled with climate hazards such as frequent heat waves (SI Fig. 3). Cold spells and extreme precipitation are projected for the Pacific Northwest (SI Figs. 4, 5). While cold spells are not new to the Pacific Northwest region, for example, the cold spell of 2002 that had adverse economic and ecological consequences (Knapp and Soulé 2005), the National Climate Assessment (May et al. 2018) projects increase

in temperature and decrease in snow cover in the region, which could mean decrease in cold spells. Therefore, the reason behind projected increase in cold spells in the Pacific Northwest is beyond the scope of this paper and warrants further research. Furthermore, the unique topography of the Cascade Range in the Pacific Northwest triggers more landslides during extreme precipitation events (Henn et al. 2015). High exposure (Fig. 3) and vulnerability (Fig. 4) alone drive high climate risk in California counties (Fig. 2). Although our model shows low hazard index in California, the hazard could be higher in this region in future as the warmer and drier conditions provide fuel to wildfire events (SI Figs. 1, 2). However, our hazard projections do not include wildfire risk as the SPI index is not a proxy or indicator for areas burned by wildfire. Non-coastal Southern California will be vulnerable because of populations that are highly dependent on farming for their livelihood. These farming communities will be highly sensitive to projected warmer and drier conditions. Although the climate hazard is relatively low in these and other Southern California counties (Fig. 3), high vulnerability along with exposure in urban and coastal areas puts these counties at high climate risk in the future. In contrast, the climatologically hazardous counties in the western US (Southern Rocky Mountains and Intermountain West (Fig. 3) with moderate vulnerability (Fig. 5) will have low climate risk due low exposure (Fig. 4).

The Southeast region is projected to have a cooler and wetter climate based on decadal anomalies in temperature and precipitation. Despite the generally cooler and wetter conditions, frequent heat waves make the Southeast more climatologically hazardous than the Midwest with a projected drier climate (SI Figs. 1, 2, 3). Overall climate risk is also high in the Midwestern counties (Fig. 2). The Midwest, which is the farming “powerhouse” of the country, is potentially prone to flood as indicated by frequent extreme precipitation days (SI Fig. 5) which is in alignment with the Fourth National Climate Assessment (Wehner et al. 2017). These precipitation events could hard hit small farming communities in the Midwest. Portions of the North Atlantic-New England region are at moderate risk (Fig. 2) primarily due to warmer conditions (SI Fig. 1) and exposure in coastal counties (Fig. 4). Moreover, the warmer conditions in the North Atlantic and Norwest, particularly Northern Rockies will lead to warming of stream water and lake and increase evaporation and reduced lake level of high-altitude lakes which could potentially decrease trout and salmonids population (Flebbe et al. 2006; Schindler and Bruce 2012). The wetter conditions in the Eastern United States and far Northwest counties (SI Fig. 2) accompanied by frequent extreme precipitation events (SI Fig. 5) could lead to increase in stream flow and could potentially harm the cold-water fish by depositing sediment loads and degrade water quality. Additionally, densely built areas in these regions (SI Fig. 7) fragment the streams, the habitat of cold-water fish (Schindler and Bruce 2012). The Northeast United States is also prone to flood indicated by extreme precipitation days (SI Fig. 5). The flooding events, such as the one brought by hurricane Sandy, can be devastating in the population centers of Northeast, due to massive infrastructures failures. It is important to note that the climate projections themselves don’t specifically account for hurricanes. Extreme precipitation days are a proxy for potential flood events associated with the heavy rainfall that hurricanes can bring. However, depending on the topography, floods may occur only when there are consecutive extreme precipitation days.”

At present, the Southeast, mostly the Gulf Coast region, suffers the most economic loss to weather and climate-related disasters in the country with contributions from drought, flood, freeze, and tropical storms from 1980 to 2019 according to NOAA (NOAA 2019). In the 2040s, we find that counties in Florida and California (especially Miami-Dade and Los Angeles counties, respectively), along with the coastal counties of Louisiana, Mississippi, Alabama and Texas and major urban centers across the US are the most climatologically

risk prone areas (Fig. 2). One of the most socially vulnerable regions in the Southeast is the “Black Belt,” where the African American population exceeds national averages. This southern sub-region includes a band of rural counties stretching from southern Virginia to east Texas (McDaniel and Casanova 2003; Wimberley and Morris 1997). Despite high social vulnerability in this area, the Southeast region as a whole, except for some coastal areas in the Gulf Coast and Florida, does not rank high in climate risk in the 2040s. This is likely in part due to the fact that the climate projections do not explicitly consider hurricanes. Rather there is a projected regional shift to the West Coast (primarily southern California), with smaller regions in the Southeast (Florida and coastal Louisiana) still at high risk. This shift is a consequence of projected changes in climate hazards and vulnerability (Figs. 3 and 5, respectively). The projected West Coast shift in climate hazards includes the Pacific Northwest (Fig. 3), but without projected high exposure (Fig. 4) or vulnerability (Fig. 5), future climate risk for the region is comparatively moderate (Fig. 2). King County (Seattle) with higher exposure and vulnerability is something of an exception to this general pattern.

4 Conclusions

We find both rural and urban counties are at future risk. However, for a climate hazard, the mechanism through which its impacts are felt depends on whether the community is urban or rural. The future risk in urban counties is primarily attributable to high exposure, while in rural counties the risk is a consequence of vulnerability. In urban counties, a single hazard event can cause cascading effects through infrastructure failure, which may not be the case in rural counties. In rural counties, the hazards impact the livelihood of people through loss of lives, crops, and property, and rural counties are usually low in adaptive capacity. More and more populations are projected to migrate to urban areas in the 2040s (Jones et al. 2015; Jones and O’Neill BC 2013). The surge of urban population due to migration will be accompanied by increased impervious surface in the future, as seen in Atlanta and Denver, to meet the infrastructure demands (SI Fig. 7). Increased impervious surface amplifies the climate hazards due to increase in runoff and urban heat island effect exacerbating heat wave conditions (Basara et al. 2010; Tan et al. 2010; Zhao et al. 2018; Li and Bou-Zeid 2013). Despite relatively low climate hazards, urban counties of the Atlanta, New York, Boston, Chicago, Dallas, Houston, and Detroit metropolitan areas will have cascading effects due to high exposure, and hence have high climatic risk in the future (Figs. 2–5). The coastal counties in some of these metropolitan areas are at the brink of damaging sea level rise and storm surges which puts vast wealth, infrastructure, and lives at risk.

Our vulnerability proxy included projections of socio-demographic variables, which are important for understanding general categories of vulnerable populations, for example, racial/ethnic minorities and age-related factors. However, these data do not account for another critical indicator of vulnerability, security of homeownership. This issue differs from the exposure problem of housing density or location discussed in this paper. Neither does it relate to renter versus homeowner status but rather to the security of titles associated with homeownership. When families own homes as a collective or as “tenants in common,” this means that the home is owned by multiple, unnamed or informally documented heirs (Johnson Gaither et al. 2019). In these cases, it can be very difficult or perhaps impossible for families devastated by natural disasters to qualify for federal or state

funding to rebuild their homes. This problem became apparent in the aftermath of Hurricane Katrina on the Gulf Coast in the early 2000s when people affected by the storm tried to apply for the federal government's Road Home program (Kluckow 2014). Initially, many were denied funding because they could not substantiate their ownership of affected properties. Subsequent vulnerability analyses should account for the problem of tenuous land and homeownership, as this factor represents a more precise indicator of the vulnerabilities faced by people in the post-disaster recovery phase.

Future, climate risk varies geographically irrespective of urban–rural settings and the components of climate risk vary by region. Based on the projections used here, future vulnerability is the most dominant component of climate risk in California, while in coastal counties in Louisiana exposure is the most dominating component. Much of the western interior United States is hazard prone (primarily to increase in mean temperature and precipitation), but future exposure is projected to be low and consequently risk is moderated. In Florida counties, all three components of exposure, vulnerability, and hazards dominate. Many of the areas in the United States currently at risk to climate hazards remain so in this relatively new future (2040s). However, our projections also point to increased moderate to high risk in the Pacific Northwest.

As recognized by the turn toward a risk framework for considering the consequences of present and future climate change (e.g., IPCC 2014), a comprehensive characterization of future climate risks requires attention to each of the components of climate risk: hazard, exposure, and vulnerability. Moreover, the components of risk are themselves combinations of multiple factors: multiple and diverse hazards, exposure of various and multiple assets, and differential vulnerability of different subpopulations. Our risk index approach allows for combining multiple factors and components into an integrated characterization of future climate risk. As climate projections are updated, as new hazards are identified, additional assets are found to be exposed to these hazards, and new vulnerabilities are identified, they can be readily integrated into this framework. Our multi-component approach, a first for the entire contiguous US at the county level, can help planners develop state, regional and national adaptation strategies to target counties that will be hit by multiple hazards, future hazard-prone counties, and vulnerable and exposed populations in an integrated evaluation of future risk to climate change.

We reiterate that multiple hazards may be in the form of compound events which occur at the same time or in rapid succession (Kopp et al. 2017) or the same location may be subject to different hazards at different times. Portions of Texas, for example, may experience extreme drought in some years and extreme precipitation in others, similarly in California. Addressing the co-occurrence could be an avenue for future study by introducing synchronicity factors into the equation based on whether events were occurring at the same time or in sequence.

Furthermore, our climate risk provides equal weights to the individual climate hazards. The impact of disaster events translates in terms of loss of lives accompanied by economic loss. It is very challenging to determine the balance point between economic loss and loss of lives or species diversity for a given event and provide weights accordingly. This is a subject for further research and analysis. We derived a climate risk index based on SRES A2 and RCP 8.5 scenarios for exposure and hazard, respectively. The high emission scenario was selected based on the assumption that these nominally “high” scenarios are unlikely to significantly diverge from “business-as-usual” before 2050. By using RCP8.5 scenario, we are not suggesting “RCP8.5” as the “business as usual” scenario, and we do acknowledge that RCP2.6 and RCP4.5 scenarios are equally important for comparative study.

The historical to future climate anomalies are calculated as differences between the GCM projections and historical observations from Daymet data. Ashfaq et al. (2016), source of the dynamically downscaled GCM projections, concluded that overall, their simulations provide a comprehensive and detailed understanding of the potential changes in climate for the US. This conclusion came in part from their comparison of historical simulations with Daymet data in which biases were modest. We accordingly believe that use of the Daymet historical data as the historical baseline is justified as generating one potential future climate change. Use of the historical GCM simulations as the baseline for the climate change projections would generate another potential future. Our risk assessment is for only one potential future. Examination of the sensitivity of our risk assessment methodology to alternative future climate change is worthy of future research.

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