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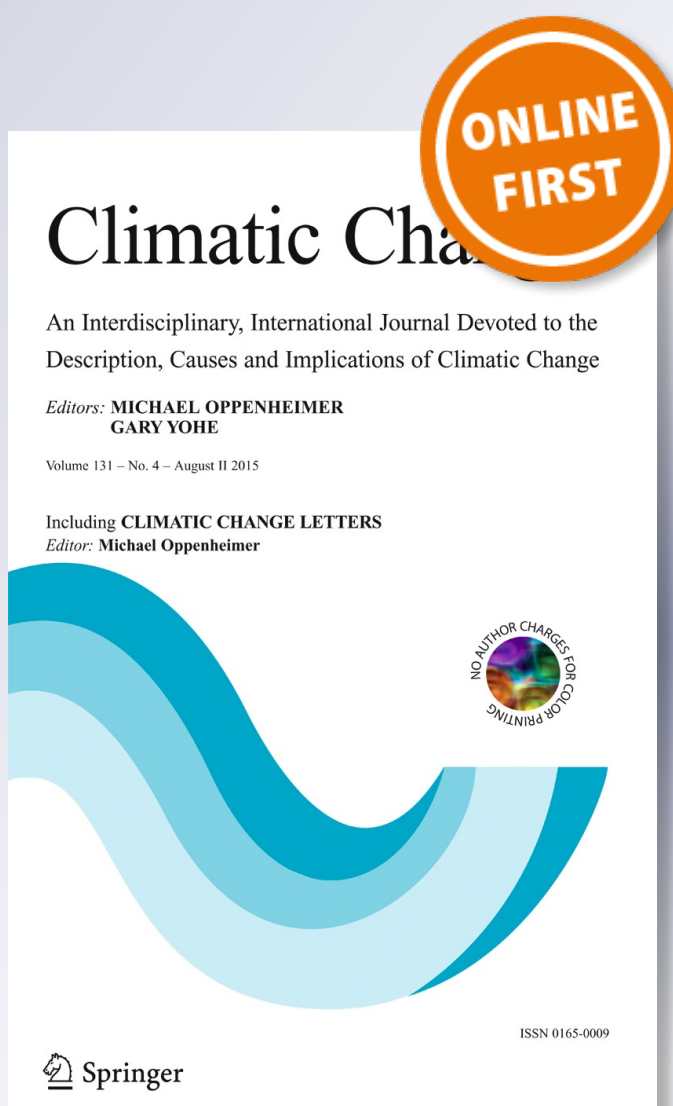
## **Climatic Change**

An Interdisciplinary, International  
Journal Devoted to the Description,  
Causes and Implications of Climatic  
Change

ISSN 0165-0009

Climatic Change

DOI 10.1007/s10584-015-1478-z



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## LETTER

# Future property damage from flooding: sensitivities to economy and climate change

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Received: 27 April 2015 / Accepted: 27 July 2015  
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**Abstract** Recent trends in the frequency and intensity of extreme weather events have raised the concern that climate change could increase flooding risks and property damage. However, a major challenge in attributing and projecting changes in disaster risk is that damage is influenced not only by the physical climate hazard, but also by non-climatic factors that shape exposure and vulnerability. Recent assessments of integrated disaster risk have been hampered by the paucity of literature analyzing local-scale interactions between hazard, exposure and vulnerability in the historical record. Here we develop an integrated empirical analysis of historical flood damage that emphasizes spatial and temporal heterogeneity in flood hazard, economic exposure and social vulnerability. Using the Midwestern United States as a testbed, we show that annual property damage from flooding is projected to increase by 13 to 17.4 % over the next two decades. At the state level, over half of the increase is driven by projected growth in housing units. However, at the county level, the dominant factor causing future damage varies, emphasizing the value of a fully integrated, spatially and temporally resolved approach to assessing flooding risk and control strategies.

Accumulating evidence indicates that, in addition to global-scale warming, the rising concentration of greenhouse gases in Earth's atmosphere has likely led to changes in the hydrologic cycle, including increasing precipitation intensity, increasing dry-spell length, and widespread

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**Electronic supplementary material** The online version of this article (doi:10.1007/s10584-015-1478-z) contains supplementary material, which is available to authorized users.

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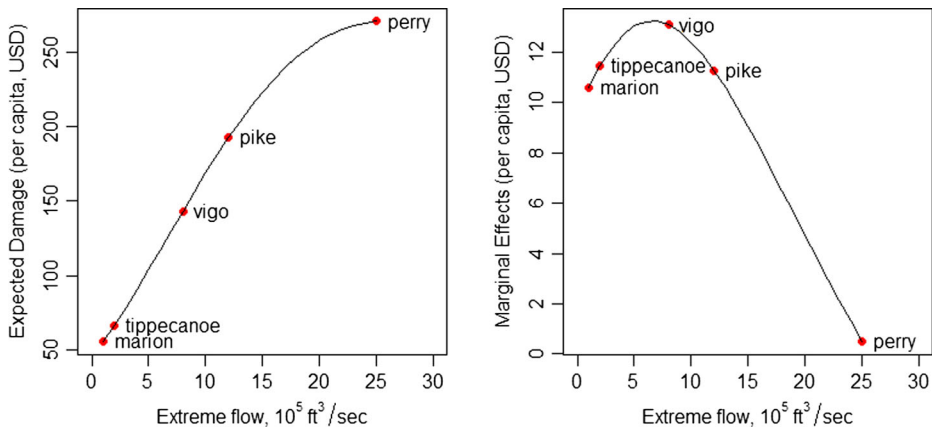
melting of snow and ice (Romero-Lankao et al. 2014; IPCC 2013, 2014; Peterson et al. 2013; Giorgi et al. 2011). These findings have raised concerns about rising damage from hydroclimatic extremes (Ashfaq et al. 2010; Giorgi et al. 2011), including both intense drought events (IPCC 2014; Touma et al. 2015; Diffenbaugh et al. 2015) and flooding disasters (IPCC 2014). Addressing this concern requires a careful assessment of the drivers of damage from extreme events, as well as the separation of damage attributable to changes in flooding hazard from damage attributable to changes in exposure and/or vulnerability.

The literature to date has had difficulty quantifying the impact of individual drivers (Mendelsohn et al. 2012; Mechler and Bouwer 2014). In order to develop more effective disaster management policies, empirical research is needed to provide a quantitative framework that is both comprehensive and sufficiently detailed in its treatment of space and time (Huggel et al. 2013; Bouwer 2013). On the one hand, research must consider the full range of environmental, economic and social risk factors. On the other hand, each dimension must be carefully assessed. Furthermore, effective policy must recognize the inherent uncertainty in forecasting future climate and economy. Thus, comparing disaster risks under different possible futures is necessary to explore policy implications in the presence of uncertainty (Pielke 2007).

This paper seeks to address these scientific challenges in the context of flood damages from extreme events. We focus initially on the Midwestern United States as a test-bed for our local-scale framework. While this may appear to be a narrow geographic focus, the controversy surrounding integrated, large-scale damage projections (Cramer et al. 2014) demands a new “bottom-up” approach to account for the spatial and temporal heterogeneity that determines damages at the local-scale. Our framework provides such an alternative, and is generalizable to other areas of the globe for which sufficient data are available.

The immediate goal of this research is to quantify the response of property damage from flooding to various combinations of hazard, exposure, and vulnerability conditions. A decomposition of this response allows for complete attribution of damage to each risk factor. The analytical framework we develop embraces fine-scale climate analysis, climate simulation and statistical modeling to reduce estimation bias. We first use a new historical data series (1995–2012) to uncover the statistical relationship between disaster loss and each flood risk factor. Next, assuming this empirical relationship remains stable in the future, losses are projected under a series of future scenarios. Each scenario combines three factors—hazard, exposure and vulnerability, which are successively evaluated during a baseline (the average of 1995–2012) and future time period (circa 2030). Applying this framework to a case study of counties in the State of Indiana, we assess the sensitivity of flooding damage to climate change and economic growth.

The relationship between flooding hazard and damage was estimated with respect to extreme events intensity while controlling for extreme events frequency. Figure 1 shows that damage climbs as the volume of water increases, but gradually flattens out as the realized damage approaches a maximum value of damaged assets. In addition to the total effect, it is useful to examine the damage caused by incremental flooding hazard, or the marginal effect. We find that the county-level marginal effect peaks at the volume of  $7 \times 10^5$  (ft<sup>3</sup>/sec), before which every unit increase in the flow volume leads to a larger increase in damage. Over 90 % of the analyzed Indiana counties fall within this regime, indicating that marginal flooding risk could rise faster in the future as flooding hazard increases. Beyond that point, more extreme flow still leads to higher total damage, but the marginal effect diminishes.

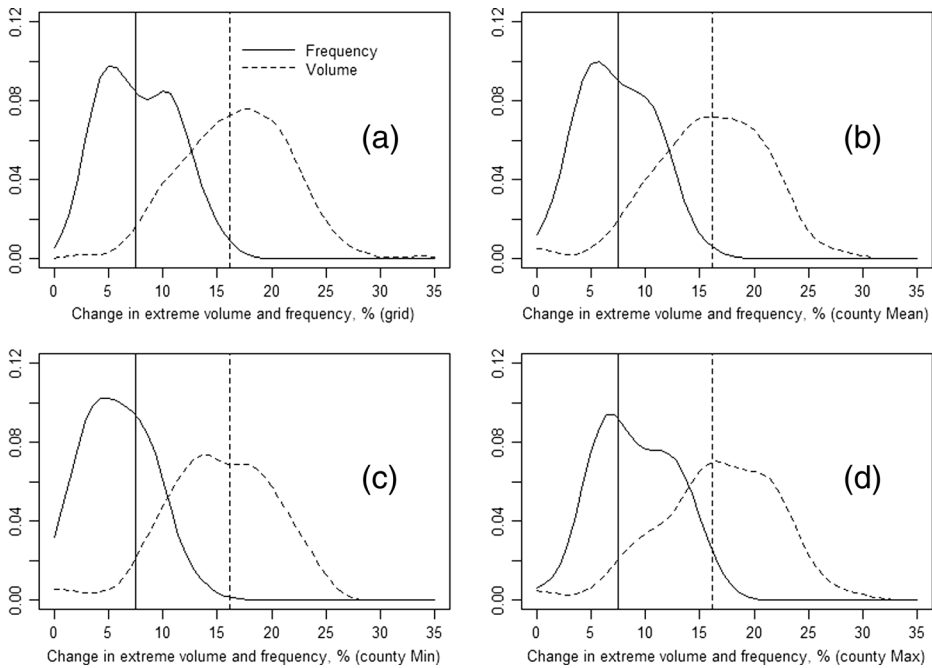


**Fig. 1** Estimated property damage function with respect to accumulative extreme flow volume (*left*), and the estimated marginal effect of increasing extreme flow volume on property damage (*right*) (Dots mark the position of representative counties along the curve)

The measurement of flooding hazard focuses on extreme events. An extreme event is defined by the peaks-over-threshold method (Mallakpour and Villarini 2015), using a threshold set at 97.5 percentile of the daily records in the baseline period. The accumulated number of extreme days describes the *frequency* of extreme events, and the accumulated flow volume from the extreme days describes the *intensity* of extreme events. Fine-scale daily discharge is simulated by a high-resolution macroscale hydrological model (VIC), forced with the bias-corrected ensemble of hydro-meteorological fields from a regional climate model (RegCM3) (Ashfaq et al. 2013). The model experiment consists of a five-member ensemble of simulations covering 1960–1999 in the baseline period and 2000–2039 in the A1B future scenario (see Methods). Comparisons of the distributions of daily values in the baseline and future ensemble simulations suggest that Indiana counties will experience more intense and more frequent extreme runoff events in the future, with a larger degree of increase in the intensity (Fig. 2).

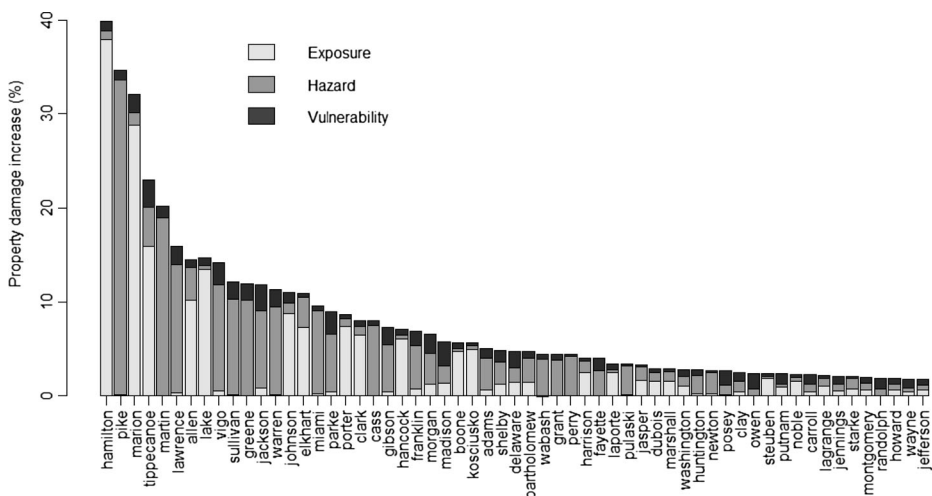
The potential increase in property damage, at the *county* level, varies from +2 to +40 % in the future period, with the dominant driver of damages varying greatly by location (Fig. 3). For some large counties such as Hamilton, Marion and Lake Counties, economic exposure is more influential than the other two factors in explaining the increased damages. Many of these counties are also among the fastest-growing counties of Indiana. Conversely, other counties will experience more damages due to the increased flooding hazard. These include Pike, Martin and Miami Counties where the increase in extreme flow volume is around 20 %.

At the *state* level, annual total damages increase by 13.0 to 17.4 % relative to the baseline, if all risk factors are updated to their 2030 levels. The upper and lower bounds of this range are determined by the results from different statistical models (models 1–4, Fig. 4a). In model 1, damage is predicted to increase by 17.4 %. Of this 17.4 %, increasing exposure contributes 13.6 % (obtained by assuming that only exposure to flooding changes to its 2030 level, while keeping other risk factors unchanged), flooding hazard contributes 2.4 % (assuming only hazard changes), and vulnerability contributes 1.1 % (assuming only vulnerability changes). The predominance of increasing economic exposure in total state-wide losses persists across all of the model specifications. More severe flooding hazard ranks as the second leading cause of rising damages.

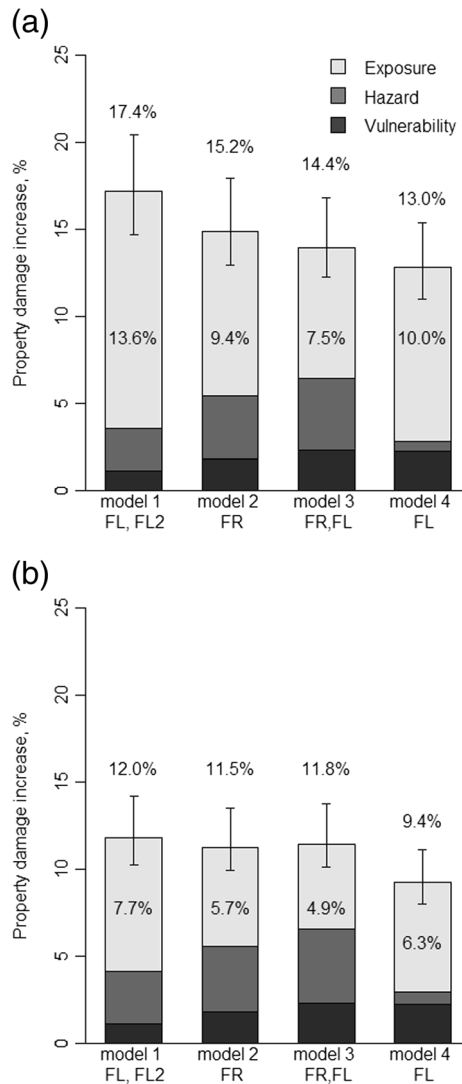


**Fig. 2** Kernel density plot of change in extreme flow volume and frequency (2000–2039 vs. 1960–1999), based on grid-level change (a) and county-level change represented by the mean (b), the minimum (c) and the maximum (d). Vertical lines refer to the average increase in flow volume and frequency at the state-level

To what extent does the analysis benefit from using more disaggregated data? This is a key question facing those seeking to undertake continental-, or even global-scale integrated assessment of climate change. For this purpose, we replace the county-specific risk factor



**Fig. 3** Projected increase in property damage from flooding and its decomposition at the county-level (circa 2030 vs. the average of 1995–2012). Segments denote the contribution of each factor to the total increase



**Fig. 4** Projected increase in property damage from flooding and its decomposition at the state level (circa 2030 vs. the average of 1995–2012). Panels compare the predictions resulted from the county-specific (a) and the uniform state-wide (b) risk factor changes. The vertical lines represent the 90 % confidence intervals for the estimation. Four bars represent results from four econometric models whereby flooding hazard is measured by streamflow volume and its quadratic term (model 1), frequency (model 2), streamflow volume and frequency (model 3) and streamflow volume (model 4)

changes with the state-average changes, and recalculate the damage based on these uniform shocks. Removing the spatial heterogeneity leads us to underestimate the overall effects (Fig. 4b) due to the presence of a few large damages caused by the more dramatic changes (distributed along the right-skewed tail in Fig. 2), which are lost when only the state-wide mean is used. The contribution of exposure to the total effect, relative to that of hazard, is also dampened, although exposure remains the dominant factor at the state level.



Several interesting points emerge from our results. First, aligned with other aggregated studies (Changnon et al. 2000; Mendelsohn et al. 2012), we find that growing wealth exposed to flooding hazard is a more pivotal factor than the growing climate hazard per se in driving state-wide damages. It suggests that floodplain landscape management holds the greatest potential for limiting flood damage. Real estate wealth will certainly continue to accumulate over the coming decades, and will probably do so even faster on floodplains (Jongman et al. 2012). This could be due to the “safe development paradox”—a (false) sense of security brought by regulations that inadvertently increases the tendency of residing on flood-prone areas. Our results reinforce the importance of building code implementation and land-use planning.

A second finding relates to the need for greater spatial and temporal detail in flooding risk analysis. High-resolution climate modeling is essential to capture the impact of extreme floods (Ashfaq et al. 2010). The use of daily runoff data enables the emphasis to be placed on extreme events defined by volume and frequency. Both are critical metrics for changing precipitation patterns (Mallakpour and Villarini 2015). The high-resolution, high-frequency runoff data also permit us to capture the spatial and temporal heterogeneity of flood hazard, which if ignored could underestimate the consequences of flooding risks, fail to uncover the differential responses to flood risks across locations, and provide misleading scientific and policy implications.

Finally, our statistical analysis offers empirical support for an S-shaped flow-damage function, whereby damages from extreme events increase sharply initially, but eventually the marginal damage from extreme events diminishes as the flows increase. Increased flooding hazard corresponds to larger damage, regardless of whether the degree of hazard is measured by the volume or frequency of extremes. The trend, however, is not linear. In the area we studied, more frequent extreme rainfall events with the same intensity would cause more damage. On the other hand, even if the total amount of precipitation remains unchanged, the changing distribution of rainfall (Diffenbaugh et al. 2005; Ashfaq et al. 2010; Giorgi et al. 2011; Romero-Lankao et al. 2014) can still increase total damage as long as the impact of each individual event is above the respective threshold. From a policy point of view, there are two potential points of entry—reducing the damage per flooding event, and reducing the frequency of damaging flooding events.

Although our work significantly advances methods for assessing future damage from extreme rainfall events, there remain some important limitations. Our current measurement of exposure assumes that, within a county, the units and value of houses located in floodplain and non-floodplain areas grow at a same rate, which may not be true in some areas (Knutson et al. 2010). Future research should combine flood zone maps with property distribution data to track separately the pattern of asset accumulation in both the high and low flood risk zones. When data are available, a longer time series should be used to verify the trends and statistical relationships that we identify. Community vulnerability can be better measured if flood insurance and community rating system data are available. Further, we have used only one high-resolution climate-hydrology modeling system. Although multi-realization ensembles of high-resolution climate-hydrology projections remain extremely rare in the literature, it is very likely that alternative model formulations would yield a spread in projected extreme runoff changes. The importance of local-scale extreme flooding identified in our results provides motivation for continued development and deployment of high-resolution modeling systems that can accurately simulate the response of extreme rainfall and runoff to changes in greenhouse forcing.



While this paper has focused on the pattern of future damages from extreme rainfall events in the Midwestern United States, the methodology laid out in this paper can be readily applied at national, continental and even global scale, as the necessary spatial data and fine-scale climate and runoff projections become available. Our findings clearly demonstrate that future damages from extreme events will vary greatly by location, with the damages from increased runoff depending critically on the county's position along the estimated S-shaped flooding damage function. We find that the estimated damages from extreme events, as well as their attributions, can be misleading in models which operate at higher levels of aggregation. Adding geospatial detail to future integrated assessments of extreme rainfall events will improve the accuracy and reliability of such estimates. Such improvement will not only greatly enhance the relevance of damage assessments for decision making at the state and local levels, but is also likely to improve the quantification of continental- and global-scale damages, for which accurate assessments have remained elusive (IPCC 2014).

## 1 Method

The statistical relationship between damage and risk factors is estimated using a Tobit model because not every county suffered damage every year (Wooldridge 2010). County indicators are added to control for time-invariant variables (e.g., county geographic features). The estimated model is

$$y_{it}^* = X_{it}\beta + u_i + \varepsilon_{it}$$

$$y_{it} = \begin{cases} y_{it}^* & \text{if } y_{it}^* > 0 \\ 0 & \text{if } y_{it}^* = 0 \end{cases} \quad (1)$$

where  $y_{it}^*$  is a latent variable used to separate out the distribution of the non-zero damages.  $y_{it}$  is the observed damage.  $X_{it}$  contains a set of variables that measure flooding hazard, wealth exposure, and vulnerability by county and year.  $\beta$  is a vector of coefficients associated with flood risk factors.  $u_i$  is the time-invariant county-specific effect.  $\varepsilon_{it} \sim N(0, \sigma^2)$  is the disturbance term.

County-level damage data comes from the Spatial Hazard Events and Losses Database for the United States (SHELDUS) (Hazards & Vulnerability Research Institute 2013). Losses are adjusted to 2011 US dollars to allow for comparability between years. The flooding hazard in a particular year for each county is described by the accumulated volume and frequency of extreme events within a year. These two metrics are calculated from the daily maximum streamflow data provided by the US Geological Survey (USGS). Both are normalized by the number of sites within a county to avoid any inflation caused by the uneven distribution of the monitoring stations. We use total housing units of the county and the poverty rate from the US Census to approximate assets exposed to flooding risks. Vulnerability is captured by a synthetic indicator—the number of flood damage events reported during the past 5 years. It is important to bear in mind that our statistical model contains county indicators, which can effectively eliminate estimation bias as long as county-specific adaptability does not change significantly over time.

To construct the flooding risk scenarios, three factors—hazard (H), exposure (E), and vulnerability (V), are varied across two levels—historical (0) and future (1). We focus on H1E0V0, H0E1V0, H0E0V1 (the specific effect of each individual factor) and H1E1V1

(the overall effect of all factors). To construct future exposure, county-level housing units and poverty rates are linearly extrapolated based on the observed evolving pattern during 1995–2012. Future vulnerability, however, is more difficult to gauge given its multidimensional nature and the substantial uncertainty associated with it. We adopt a conservative 10 % increase in this variable to capture the likely rise in vulnerability in this region. A sensitivity analysis on this assumption is presented in the supplementary online material (SOM).

To assess future hazard, we use a high-resolution climate modeling system consisting of a global atmosphere-ocean general circulation model, a nested high-resolution atmospheric model, and a hydrological model. The importance of resolving fine-scale climate processes for the simulation of extreme events has been repeatedly confirmed in the literature (see SOM). Given the importance of both fine-scale processes and natural climate variability for extreme rainfall and flooding events, we use water runoff simulated by a five-member ensemble of high-resolution macroscale hydrological model (VIC) forced with the bias-corrected daily hydro-meteorological fields from a nested high-resolution climate model (RegCM3), which was nested in five realizations of a single GCM (CCSM3). The simulation period in each ensemble covers 1960–1999 in the baseline and 2000–2039 in the A1B future scenario. Because the five model realizations are physically uniform (and therefore equally likely), we pool the realizations to create a single 200-year baseline (1960–1999) population and a single 200-year future (2000–2039) population. We then calculate the extreme threshold value, the accumulated extreme days, and the accumulated flow volume based on the 200 years of daily data in each period.

**Acknowledgments** This work was supported by the Program on Integrated Assessment Model Development, Diagnostics, and Intercomparison (PIAMDDI) funded by the US DOE, award No. DE-SC0005171-001. Research conducted at Oak Ridge National Laboratory was supported by the Regional and Global Climate Modeling Program funded by the DOE office of science. The authors would like to thank the anonymous reviewers for their helpful comments on the manuscript.

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