LETTER • OPEN ACCESS

Examining the impact of emissions scenario on lower Mississippi River flood hazard projections

View the article online for updates and enhancements.

Environmental Research Communications

Examining the impact of emissions scenario on lower Mississippi River flood hazard projections

K B J Dunne[1,*] , S G Dee[2] , J Reinders[6], S E Muñoz[3,4] and J A Nittrouer[5]

1 Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, 91106, California, United States of America
2 Department of Earth, Environmental, and Planetary Sciences, Rice University, Houston, 77005, Texas, United States of America
3 Department of Marine and Environmental Sciences, Northeastern University, Nahant, 01908, Massachusetts, United States of America
4 Department of Civil and Environmental Engineering, Northeastern University, Boston, 02115, Massachusetts, United States of America
5 Department of Geosciences, Texas Tech University, Lubbock, 79409, Texas, United States of America
6 Leiden University College, Leiden University, P.O. Box 13228, 2501, EE, The Hague, the Netherlands
* Author to whom any correspondence should be addressed.

E-mail: kdunne@caltech.edu

Keywords: climate change impacts, flooding, Mississippi river

Supplementary material for this article is available online

Abstract

The Mississippi River is the largest commercial waterway in North America and one of the most heavily engineered rivers in the world. Future alteration of the river's hydrology by climate change may increase the vulnerability of flood mitigation and navigation infrastructure implemented to constrain 20th century discharge conditions. Here, we evaluate changes in Lower Mississippi River basin hydroclimate and discharge from 1920–2100 C.E. by integrating river gauge observations and climate model ensemble simulations from CESM1.2 under multiple greenhouse gas emissions scenarios. We show that the Lower Mississippi River's flood regime is highly sensitive to emissions scenario; specifically, the return period of flood discharge exceeding existing flood mitigation infrastructure decreases from approximately 1000 years to 31 years by the year 2100 under RCP8.5 forcing, primarily driven by increasing precipitation and runoff within the basin. Without aggressive reductions in greenhouse gas emissions, flood mitigation infrastructure may require substantial retrofitting to avoid disruptions to industries and communities along the Lower Mississippi River.

1. Introduction

Flooding is a deadly and costly natural disaster, resulting in more than $1 trillion in damages globally over the last 40 years [1]. Anthropogenic warming is likely to alter river flood regimes, greatly increasing risk to human life and socioeconomic prosperity around the world [2]. As the merits and costs of different greenhouse gas emission mitigation policies are deliberated, it is crucial to constrain changes to river flood regimes under different greenhouse gas emissions forcings scenarios, and to assess robustly the capacity of existing flood mitigation infrastructure to withstand future floods. The Mississippi River is a critical natural resource that provides hydroelectric power, fresh water, agricultural and industrial land, and serves as an artery for trade and commerce for the United States [3]. Efforts to understand, predict, and mitigate flooding along the main channel of the river have constituted an important research focus for over a century [3, 4]. The economic importance of the Mississippi River in combination with its extensive flood mitigation and navigation infrastructure makes it an important system to evaluate the impacts of climate change on river flood hazard.

A particularly devastating flood in 1927 prompted Congress to authorize the Mississippi River and Tributaries (MR&T) project, a system of earthen levees, cutoffs, and strategic spillways designed to contain discharge as high as 76,739 m³s⁻¹ at Vicksburg, Mississippi—a magnitude about 28% greater than the 2011 flood, the largest measured discharge on the Lower Mississippi [5–8]. Failure of the Old River Control Structure (ORCS), a major component of the MR&T Project that prevents the main channel of the Mississippi from

shifting to the Atchafalaya and circumventing the Port of South Louisiana and New Orleans, would be an economic and humanitarian disaster with damage estimates in the billions of dollars [9, 10]. The infrastructure of the MR&T project has withstood several high-magnitude events over the last century, but the hydroclimatic conditions of the next century are unlikely to resemble those of the 20th century as a result of greenhouse forcing [11–13]. Given the sensitivity of hydrologic systems to climatic change [14], the ability of the current flood mitigation system to contain the river over the next century is unclear, with potentially profound economic impacts [15–19].

Over the next century, extreme precipitation, a major driver to flood hazard, is projected to become more frequent over the Mississippi River basin [20–22]. At the same time, warming is expected to decrease hydrologic contributions from snow-melt and increase evaporative losses over the mid-continent [23, 24]—trends that have the potential to reduce flood hazard [19]. Modelling studies disagree over how greenhouse forcing will influence discharge of the Mississippi River, with projections ranging from decreases [19, 25, 26] to increases [27, 28] in mean and extreme flows through the mid- to late-21st century. This discrepancy reflects differences in model set-up and forcing scenarios, making it difficult to quantitatively compare projections and evaluate the sensitivity of flood hazard to climate change.

Here, we integrate climate model simulations (CESM1.2) with observations of Mississippi River basin discharge over the instrumental period to evaluate the past and future response of river discharge to climate change. We compute changing frequencies and magnitudes of flood discharge on the Lower Mississippi River, providing climate-driven projections of future flood hazard under high (RCP8.5) and moderate (RCP4.5) GHG emissions scenarios. Finally, we evaluate changes in basin hydroclimate to diagnose the drivers of changes in discharge projected for the 21st century. While the CESM1.2 medium and large ensembles provide insight into future changes in Mississippi River hydroclimate, additional work examining the sensitivity of projections to land-model hydrology and climate model physics is warranted. Our results provide an initial step toward understanding the impact of emissions scenario on the largest river in North America, with the goal of providing robust projections of flood hazard in the face of increasing atmospheric temperatures.

2. Data and methodology

We extracted daily post-processed river discharge data from simulations spanning 1920-2100 from the Community Earth System Model version 1.2 (CESM) [29]. CESM is a state-of-the-art, Intergovernmental Panel on Climate Change (IPCC)-class general circulation model (GCM) developed at the National Center for Atmospheric Research. CESM includes a coupled river transport model [30, 31] that has been employed in previous work to hindcast the Mississippi's behavior over the last millennium, and to evaluate its response climate variability [18, 32].

We evaluated discharge changes using two distinct greenhouse gas emissions scenarios, derived from IPCC representative concentration pathways (RCP): RCP4.5 and RCP8.5, which correspond to 4.5 and 8.5 W m^{-2} of radiative imbalance due to anthropogenic greenhouse gas emissions, respectively. RCP8.5 assumes a 'business as usual' radiative forcing consistent with minimal mitigation, whereas RCP4.5 represents medium-range mitigation of emissions. We chose to employ both the medium—and high-forcing model ensembles, though we note that emissions trends over the past few decades track slightly above RCP8.5 [33]. We additionally employ data from the CESM 1 CAM5 BGC Large Ensemble spanning the years 1920-2005 for comparison to instrumental data. The first five years of data were discarded to account for model spin-up. CESM 1.2 simulations include the CESM 1 CAM5 BGC Large Ensemble of simulations (n = 33) spanning the periods 1920–2005 and 2006–2100 under RCP8.5 forcing; however, only 15 simulations were produced for the CESM1 CAM5 BGC Medium Ensemble spanning the period 2006-2080 under RCP4.5 forcing. We thus employ 15 ensemble members from each simulation for consistency.

Critical to this study, CESM1 includes a river transport module (RTM) which simulates daily discharge. Broadly, the RTM is a routing model. The RTM is connected to the Community Land Model (CLM) to route runoff through the land surface model toward seas and/or oceans to close the hydrological cycle water budget [30, 31]. All modelled data were extracted from the cell centered at 32.25N, 91.25W. No discernible difference was noted between the selected cell and those downstream. Importantly, CESM does not simulate the effects of engineering infrastructure (e.g., artificial levees, cutoffs, dams, and spillways), irrigation, or groundwater extraction on discharge, allowing us to evaluate the climate controls on discharge independently of the effects of most human alterations to the basin that confound analyses of instrumental data sets [5, 34, 35]; we thus focus on large-scale hydroclimate changes simulated by the model. In the analysis that follows, all values reported are given for the CESM ensemble mean, unless explicitly stated otherwise. By evaluating discharge changes in the RCP4.5 and RCP8.5 ensemble means, we effectively isolate the change in discharge driven by external forcing alone.
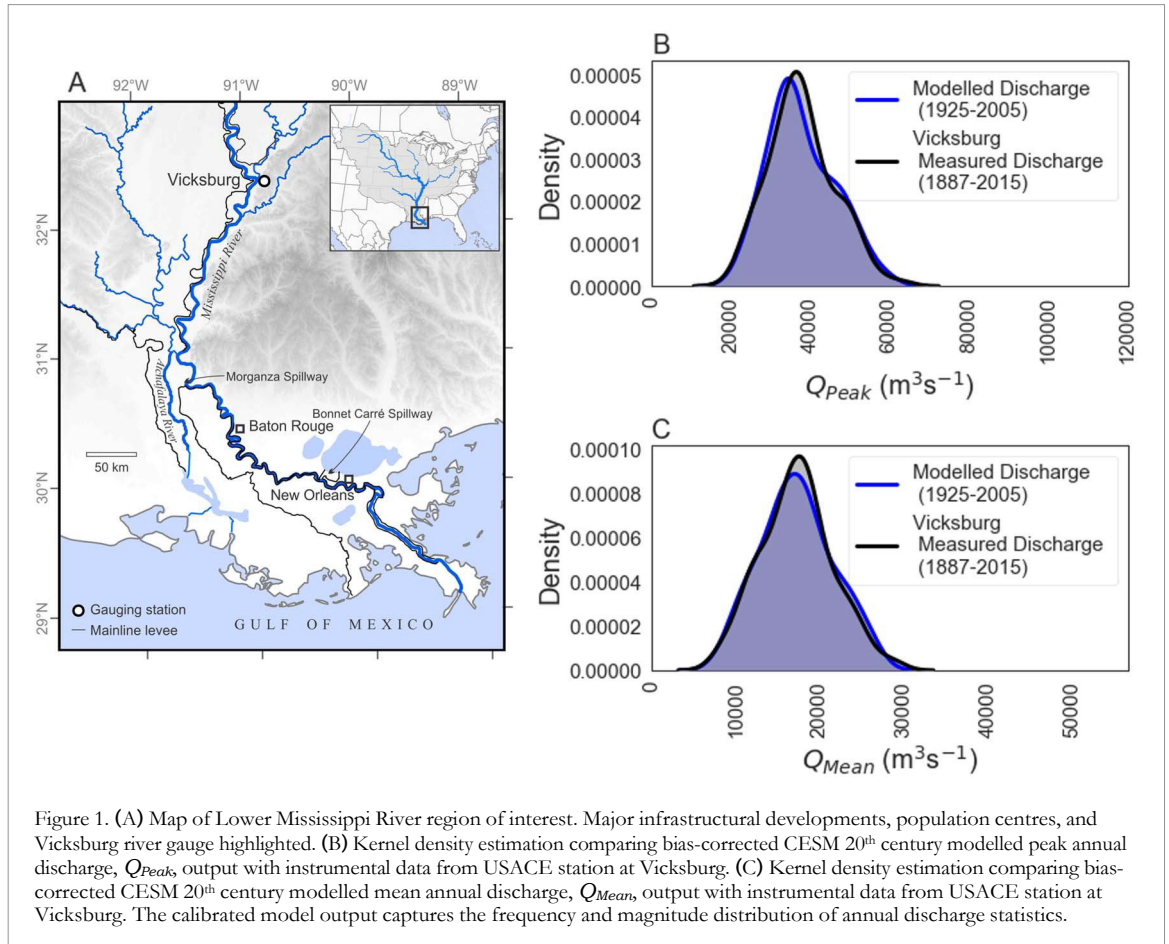
Figure 1. (A) Map of Lower Mississippi River region of interest. Major infrastructural developments, population centres, and Vicksburg river gauge highlighted. (B) Kernel density estimation comparing bias-corrected CESM 20th century modelled peak annual discharge, Q_{Peak}, output with instrumental data from USACE station at Vicksburg. (C) Kernel density estimation comparing bias-corrected CESM 20th century modelled mean annual discharge, Q_{Mean}, output with instrumental data from USACE station at Vicksburg. The calibrated model output captures the frequency and magnitude distribution of annual discharge statistics.

Errors in global climate model hydrology relative to observations are well documented, so modelled data are routinely bias-corrected to observations [36]. To bias-correct the simulated CESM discharge data, we utilize the daily discharge data for the Lower Mississippi River measured at Vicksburg from 1887–2015, obtained by the United States Army Corps of Engineers. The gauge at Vicksburg was chosen because of its long, continuous daily discharge record, its upstream position from Old River Control Structure, and because no major tributaries enter the main channel of the Mississippi downstream from its location (figure 1(A)). Furthermore, measured discharge data at Vicksburg reflect the influence of upstream flood mitigation infrastructure and human alteration of the basin on Lower Mississippi River discharge. As such, using this instrumental data to bias-correct the climate model output allows for these effects to be implicitly, albeit coarsely, incorporated into future discharge projections. To bias-correct the simulated discharge data, the mean and peak annual discharge values were calculated from the daily instrumental and daily modelled data, and the z-score of the modelled data was calculated and used to scale the modelled data by the mean and standard deviation of the instrumental data:

$$Z_{m_P} = \frac{X_{m_P} - m_{m_P}}{s_{m_P}}$$

$$C_{m_P} = Z_{m_P} \cdot s_I + m_I \qquad (1)$$

where Z_{m_P}, m_{m_P}, and s_{m_P} are the z-score, arithmetic mean, and standard deviation of the 1925-2005 modelled data, respectively; μ_I and σ_I are the arithmetic mean and standard deviation of the instrumental data, respectively; and C_{m_F} is the bias-corrected modelled data. The 21st century modelled data under both RCP8.5 and RCP4.5 conditions, X_{m_F}, were bias-corrected using the z-score of the 21st century data relative to the mean and the standard deviation of the 20th century modelled data, Z_{m} :

$$Z_{m_F} = \frac{X_{m_F} - m_{m_P}}{s_{m_P}}$$

$$C_{m_F} = Z_{m_F} \cdot s_I + m_I \qquad (2)$$

This bias-correction of the modelled data, C_{m_F}, preserves the variance and magnitude of the instrumental data while allowing for evaluation of the systematic deviation from the 20th century conditions as projected by the model, facilitating comparison of historical and projected discharge. This process was performed separately on both the peak and mean annual discharge data. Comparison between calibrated modelled and observed peak

and mean annual discharge shows that the bias-corrected model output captures both the variance and magnitude of the natural system (figures 1(B), (C)), indicating its appropriateness for our analysis. Given the importance of checking the distribution fit for bias correction in hydrology [37], a bias-correction based on a log-normal distribution was tested; however, this did not result in a better fit. This facilitates comparison of changes in bias-corrected peak and mean annual discharge statistics, Q_{Peak} and Q_{Mean}, respectively, and mean climate change over time (figures 1(B), (C)). We note that the CESM RTM contains seasonal biases in its simulation of river discharge, specifically that the model shifts peak discharge into summer (May–July) while it is observed to peak in spring (March–May) (Supplementary Materials figure S1 (online available at: stacks.iop.org/ERC/4/091001/mmedia)). To circumvent this seasonal bias, we focused our analyses on the annual statistics of discharge rather than seasonal changes in hydrology. Modelled seasonal cycles of basin-averaged runoff, precipitation, evapotranspiration, and snow melt for the Mississippi River Basin are described in the supplemental materials (figure S3). In the analysis that follows, we focus on the simulated change in Q_{Peak}, but provide the same evaluation of Q_{Mean} for all figures in the Supplementary Materials (figure S4). Flood frequency analysis was done by fitting bias-corrected Q_{Peak} values from bias-corrected individual ensemble members to a General Extreme Value (GEV) distribution using the R package extRemes, which characterizes the distribution shape of extreme river flooding [38, 39]. As to not assume hydrological stationarity over the projected 21st century conditions, model predictions were extended with a non-stationary flood frequency analysis in which the location, scale, and shape parameters are linear functions of the CESM modeled average global temperatures [40, 41].
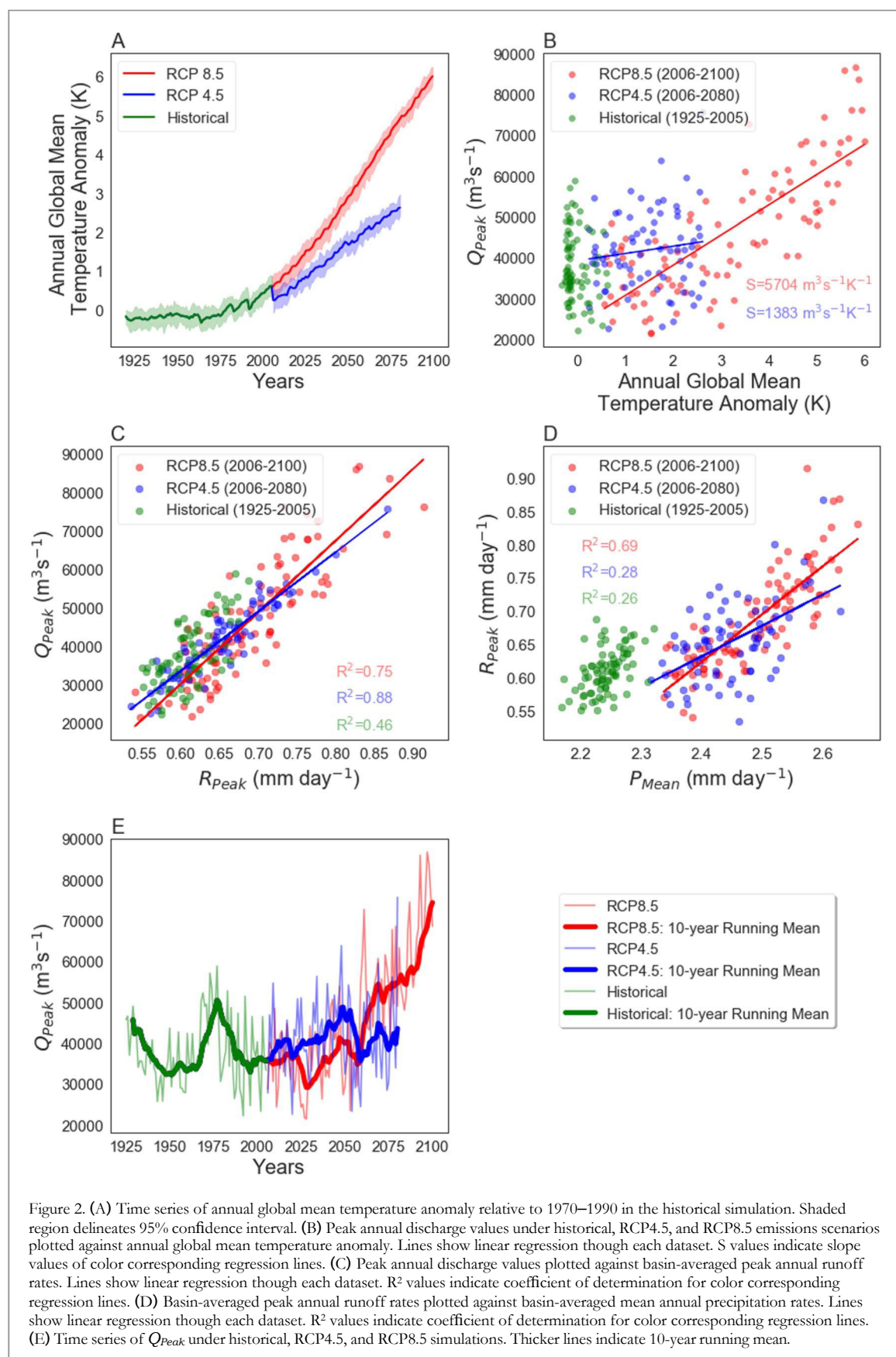
3. Results

We performed a comparison of projected river flows under two greenhouse gas emissions scenarios, RCP8.5 and RCP4.5. Note that the model simulation spans 2006–2080 in the RCP4.5 medium ensemble and 2006–2100 in the RCP8.5 large ensemble. The model forecasts large increases in annual global mean temperature anomalies (relative to the 1970–1990 model mean). Under RCP8.5 forcing, both the rate and magnitude of warming are significantly higher than under RCP4.5. (figure 2(A)). Increasing temperatures are associated with increases in Q_{Peak} and Q_{Mean} when simulations exceed a temperature anomaly of 3°C (figure 2(B)); for RCP8.5, the rate and magnitude of changes in discharge are nonlinear. As mentioned above, a simulation spanning 2080–2100 is unavailable for RCP4.5; however, under RCP4.5 forcing, emissions peak around 2040 and subsequently decline [42], likely dampening the large increases in discharge simulated under the warmer RCP8.5 conditions.
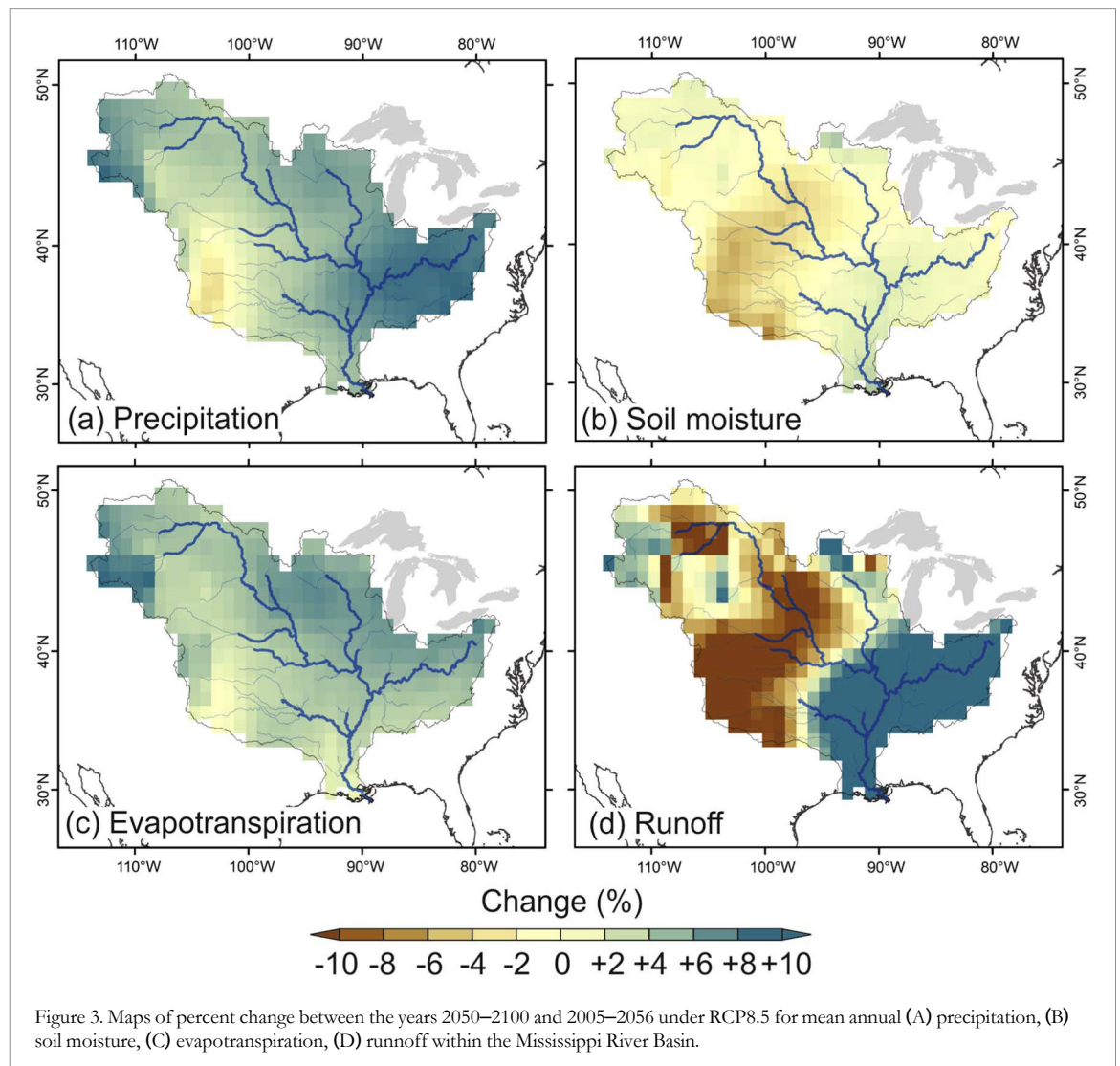
Under both RCP scenarios, peak discharge for the Lower Mississippi River is primarily driven by the basin-averaged peak annual runoff rate, R_{Peak}, which is calculated as a spatial average over the entire Mississippi River Basin (figure 2(C), Supplemental Materials figure S2). In turn, R_{Peak} is primarily driven by basin-averaged mean annual precipitation rate, P_{Mean}, also calculated as a spatial average over the entire Mississippi River Basin (figure 2(D)) [43]. It is notable that the correlation between P_{Mean} and R_{Peak} is stronger under RCP8.5 than under RCP4.5 or under 20th century conditions. This is possibly illustrative of the diminishing influence of snow melt on runoff as snow accumulation and melt volumes decrease, and increase in precipitation rates under the warming climate within the Mississippi River Basin.

To illustrate the spatial structure of hydroclimatic changes over the Mississippi basin as a whole over the 21st century, we examine spatial changes to mean annual precipitation, runoff, evapotranspiration, snow melt, and soil moisture for between the years 2006–2056 and 2050–2100 under RCP8.5. Figure 3 shows that some changes to basin hydrology are spatially heterogeneous, with large increases in precipitation and runoff occurring over the Ohio River and Lower Mississippi River sub-basins, and decreases precipitation and runoff over the Missouri sub-basin (figures 3(A), (D)). Total evapotranspiration increases in the upper Mississippi River, Missouri, and Ohio sub-basins (figure 3(C)), and soil moisture content decreases over all sub-basins with the exception of the lower Mississippi River sub-basin. Note however that changes to mean annual soil moisture are relatively minor in comparison to the other hydrological variables (figure 3(B)).

To further diagnose the hydrological drivers of elevated discharge in the 21st century, we computed the mean, seasonal, and spatial changes in precipitation, runoff, snowmelt, evapotranspiration (ET), and soil moisture for both RCP8.5 and 4.5 (Supplemental Materials figures S3, S5, S6). Figure S3 shows the basin-average seasonal changes in key hydrological variables; in both forcing scenarios, springtime precipitation (FMAM) increases are accompanied by an increase in runoff in the same months. Snowmelt decreases in winter and spring (JFMAM), and spring ET (figure S4). Spatial structure of change in hydrological variables shows greatest differences between RCP8.5 and RCP4.5 by the end of the 21st century are in increases to both mean annual precipitation and runoff over the Ohio River Basin (figure S5). Scatter plots of all hydrological variables with discharge (figure S6) show runoff to be a strong control on discharge. There is also some correlation with mean annual soil moisture content, and with mean annual precipitation. Finally, figure S7 shows a comparison

Figure 2. (A) Time series of annual global mean temperature anomaly relative to 1970–1990 in the historical simulation. Shaded region delineates 95% confidence interval. (B) Peak annual discharge values under historical, RCP4.5, and RCP8.5 emissions scenarios plotted against annual global mean temperature anomaly. Lines show linear regression though each dataset. S values indicate slope values of color corresponding regression lines. (C) Peak annual discharge values plotted against basin-averaged peak annual runoff rates. Lines show linear regression though each dataset. R^2 values indicate coefficient of determination for color corresponding regression lines. (D) Basin-averaged peak annual runoff rates plotted against basin-averaged mean annual precipitation rates. Lines show linear regression though each dataset. R^2 values indicate coefficient of determination for color corresponding regression lines. (E) Time series of Q_{Peak} under historical, RCP4.5, and RCP8.5 simulations. Thicker lines indicate 10-year running mean.

between these values from 2030-2080 in RCP4.5 *versus* 8.5. Discharge, mean annual precipitation, runoff, and ET are all higher in RCP8.5 compared to 4.5, while snow depth, snow melt are both reduced in RCP8.5 compared to 4.5 (figure S7). Distributions of soil moisture are very similar in the two scenarios; soil moisture

Figure 3. Maps of percent change between the years 2050–2100 and 2005–2056 under RCP8.5 for mean annual (A) precipitation, (B) soil moisture, (C) evapotranspiration, (D) runnoff within the Mississippi River Basin.

exhibits little seasonal change from the early to the late 21st century, implying a limited role for soil moisture in changing peak discharge.

Given the simulated impact of greenhouse forcing on the peak annual flows of the Lower Mississippi River, hydrological stationarity cannot be assumed throughout the 21st century. To explore this transition, we examined changes in the frequency and magnitude of Q_{Peak} distributions over 50-year periods throughout the 21st century compared to the 20th century (figure 4). The kernel density estimations show a significant increase in Q_{Peak} distributions between the historical period (1925–2005) and projections for 2030–2080 under both RCP8.5 and 4.5 scenarios ($p < 0.0001$ and $p < 0.01$, respectively). Distributions were determined to be statistically different based on a two-tailed t-test. RCP8.5 projections spanning 2050-2100 show a pronounced increase in the average magnitude and variance of Q_{Peak} (figures 4(A), (B)). Differences in the distributions of Q_{Peak} for RCP4.5 and RCP8.5 in the second half of the 21st century correspond to a greater increase in the magnitude of the distribution of P_{Mean} under RCP8.5 than under RCP4.5 for the years 2030–2080 ($p < 0.01$) (figures 4(C)). This difference is primarily driven by a larger increase in P_{Mean} (figure 4(D)) over the Ohio River basin under RCP8.5 than under RCP4.5. (Supplementary figure S5).

Flood frequency analysis of the simulated peak annual discharge values [41] compared to the observed instrumental data at Vicksburg shows a significant shift in the frequency-magnitude distribution of floods under RCP4.5 and 8.5 scenarios from that of measured discharge throughout the 20th century (figure 5(A)). We find that under RCP4.5 conditions, the discharge of floods at all return periods greater than 10 years increases relative to 20th century observations. Similarly, under RCP8.5 conditions, discharge increases for all return periods greater than 2 years relative to 20th century observations. Of particular concern is that under the RCP8.5 forcing scenario, the ~50-year flood discharge values exceed the Project Design Flood, the maximum probable peak discharge for the MR&T Project [4, 44] (figure 5(A)). A likelihood ratio test shows that a model with three non-stationary parameters performed statistically significantly better than models with only one or two non-stationary parameters. The non-stationary flood frequency analysis shows that the effective return levels for the
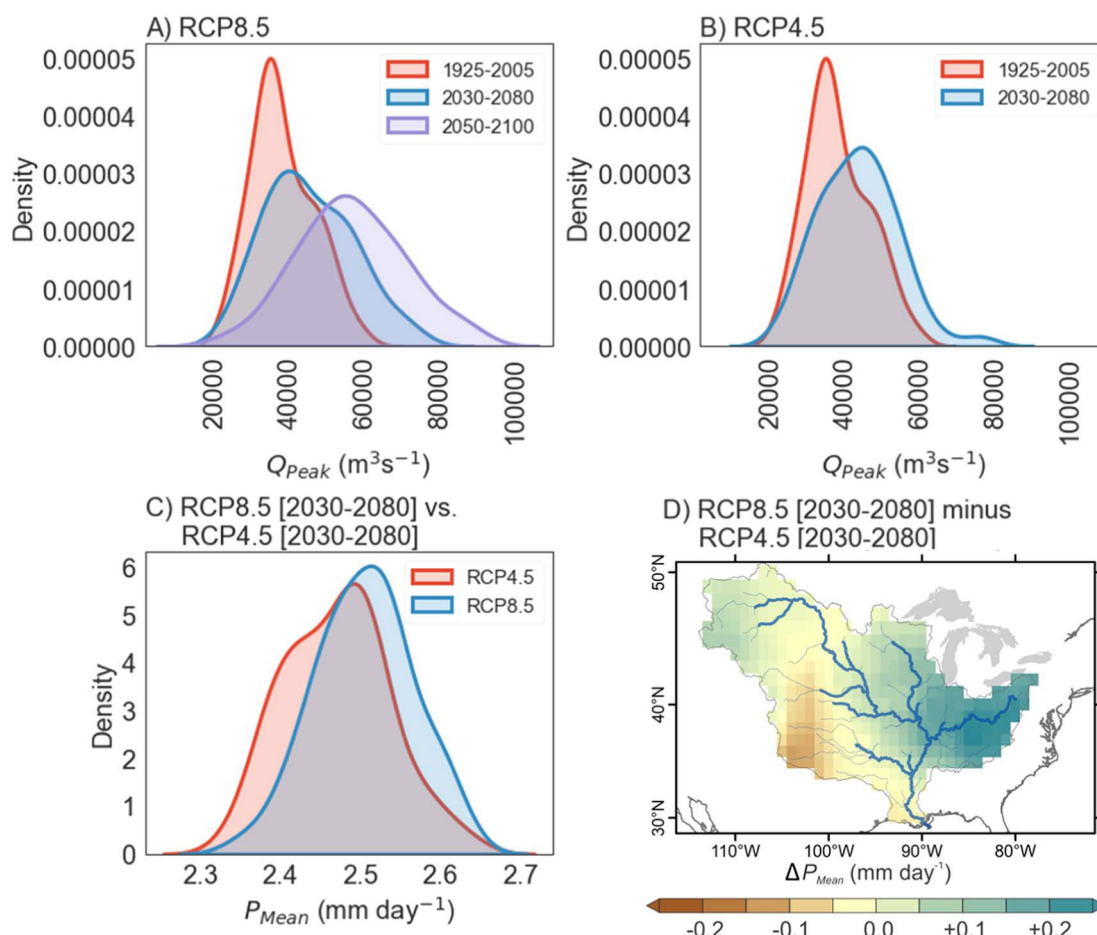
Figure 4. (A) Kernel density estimation of modelled peak annual discharge for 20th century and for years 2030–2080 and 2050–2100 under RCP8.5 projection. (B) Kernel density estimation of modelled peak annual discharge for 20th century and for years 2030-2080 under RCP4.5 projection. (C) Kernel density estimation of modelled basin-averaged mean annual precipitation for years 2030-2080 under RCP4.5 and RCP8.5 projections. (D) Map of spatial distribution of mean annual precipitation difference under RCP8.5 versus RCP4.5 throughout the Mississippi River Basin for years 2030-2080.
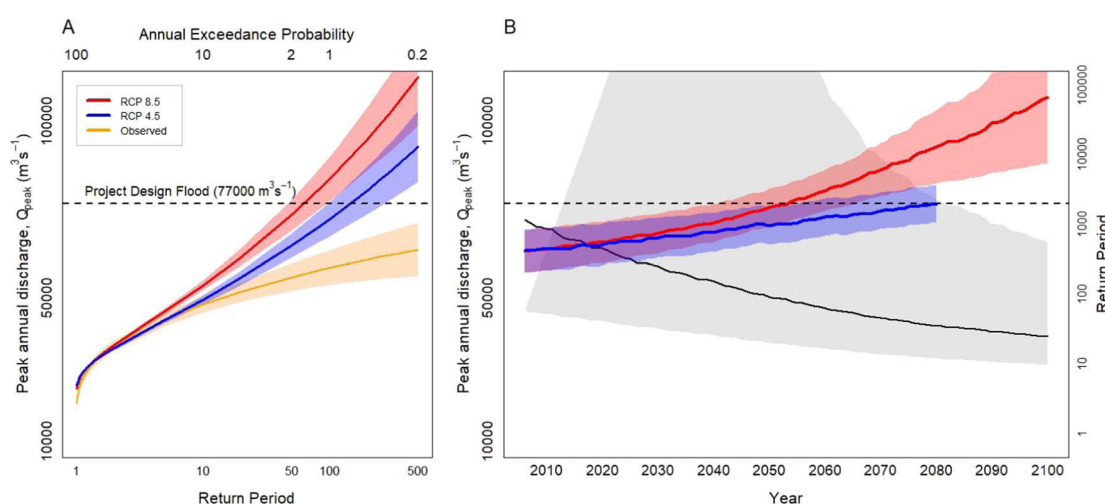

Figure 5. (A) Annual peak flow and return period for the Lower Mississippi River at Vicksburg for observed instrumental discharge data (yellow), RCP8.5 years 2006 to 2100 (red) and RCP4.5 years 2006 to 2080 (blue), and the 95% confidence intervals for the model ensemble. The Mississippi Project Design Flood capacity at Vicksburg is demarcated with a dashed line. (B) The 100-year-flood effective return level under RCP8.5 (red) and 4.5 (blue) forcing changes over time (left y-axis). The black line denotes the return period of the Mississippi Project Design Flood discharge at Vicksburg over time under RCP8.5 with shaded gray area denoting 95% confidence interval (right y-axis). Note the return period axis is plotted on a logarithmic scale. Note that the flood frequency analysis employs all of the individual model ensemble members (n = 15), not the ensemble mean.

100-year flood increases under the high emissions scenario over the 21st century (figure 5(B)). Notably, the non-stationary analysis shows that the probability of a flood exceeding the Project Design Flood shifts from a >1000-year event (<0.1% chance of occurrence in any given year) at the beginning of the 21st century to a 31-year event (12–644 years) (3.3% chance of occurrence in any given year) by the end of the 21st century under RCP8.5 (figure 5(B)). The projected change in peak annual discharge under both the high emissions scenarios are indicative of a significant shift in the hydrologic regime of the Lower Mississippi River over the 21st century.

4. Discussion and conclusions

Our study investigates the response of Lower Mississippi River streamflow to two different emissions scenarios over the next century using ensemble simulations from a state-of-the-art general circulation model with a river transport module (CESM). We demonstrate that peak annual flows increase significantly under greenhouse forcing. We also find that the simulated increase in peak annual discharge is more rapid and severe under RCP8.5 (49% increase) compared to RCP4.5 forcing (14% increase) by the end of the 21st century (figure 2(E)). These changes are primarily driven by an increase in mean annual precipitation, and result in a marked increase in the probability of catastrophic flooding exceeding the capacity of existing flood mitigation infrastructure, particularly under the high emissions (RCP8.5) scenario.

The model output used in this study (CESM) presents only one version of our prospective future, and contains important biases in land model structure and scale, land-atmosphere coupling, and channel routing that represent critical components of this region's hydrology. Disentangling the effects of model dynamics, emissions pathways, and physical mechanisms requires hydrologic projections to compare across multiple GCMs and scenarios [45]. To compare our results to a multi-model baseline, we compared the hydrological projections in CESM1.2 to other CMIP5-class GCMs. Spatial patterns and magnitudes of CESM's discharge are consistent with other CMIP5 models (within 10%) in future projections, as shown in [46]; the CMIP5 mean indicates increases in Q_{Peak} over much of the globe, with the notable exception of western North America. Furthermore, [47] show that CESM's simulation of runoff falls within the central range of CMIP5 simulations [47]. In addition, [48] compared preindustrial and warmer last interglacial simulations of precipitation, runoff, discharge, flood volume, and flood area in an ensemble of models that includes CESM and CESM2. In all cases, CESM's simulations of the warmer interglacial climate were more conservative than others in the ensemble. This is noteworthy given that comparisons to an older version of CESM1 (CCSM4) indicate that there is a greater increase in precipitation with future warming in the updated CESM1 [49]; this is consistent with [50, 51], which found increased global runoff sensitivity to temperature change in CMIP5 models compared to CMIP3 simulations. Taken together, these results suggest that CESM simulates projections of the hydrological cycle that are broadly consistent with other CMIP5/6-class models, and representative of plausible and credible changes in Mississippi basin hydrology.

To provide a more focused inter-model comparison, we compared our findings to recently published results using a different GCM, NOAA's Geophysical Fluid Dynamics Lab (GFDL) model [19]. Projections from CESM show elevated future Mississippi River discharge, but [19] use GFDL to show a reduction in discharge under RCP4.5 due to substantial reductions in snow melt. Why do CESM and GFDL diverge? In GFDL, reductions in basin total snow melt contribute to reduced discharge on the lower Mississippi by the end of the 21st century under RCP4.5 forcing [19], while we show that in CESM discharge increases modestly under RCP4.5 due primarily to elevated precipitation (figure 2). In CESM, decreased winter-spring snow melt within the Mississippi River basin is compensated by a larger increase in spring precipitation (Supplementary Materials, figure S3). A detailed land model physics inter-model comparison is needed to further diagnose the drivers of this difference, including a full quantification of model uncertainties and hydrologic biases within the basin.

Broadly, we note that, to date, streamflow and runoff have not been widely validated in CMIP5 or CMIP6, especially over the Missisppi Basin. In other regions, [47] have illustrated the limitations of GCM hydrology (specifically in simulations of runoff) for the Western U.S.; for the Pacific Northwest, CESM tends to outperform other GCMs in terms of simulated hydroclimate ([52]), but recent work evaluating temperature and precipitation simulations spanning the entire U.S. shows that CESM may fall short compared to other CMIP6 models ([53]). While the metrics applied in these studies vary widely, it is clear that the choice of GCM matters; the next steps of this work will necessarily require an evaluation of CESM's runoff generation and river transport model routing alongside other CMIP6 models. Recent work has employed techniques such as Bayesian Model Averaging (BMA) to weight GCM projections according to agreement with observations of streamflow and historical floods [54]. GCM projections could also be weighted by evaluating agreement with hydrological or hydraulic models, designed for smaller spatial scales.

Our analysis provides an evaluation of the sensitivity of the Lower Mississippi River to greenhouse forcing, and demonstrates that the rate and magnitude of increased peak flows is closely tied to emissions scenario. This

finding is broadly consistent with prior modeling studies projecting lower Mississippi River discharge, where models run under lower emissions scenarios tend towards decreases to moderate increases in flows [19, 25], while higher emissions scenarios result in larger increases in flows [27, 28]—though the hydrological drivers of these changes warrant further examination. River discharge is influenced by a range of hydroclimatic processes including precipitation, snow-melt, and evapotranspiration—all of which are influenced by greenhouse forcing through its effect on temperature [13]. Observations and model projections show that precipitation has increased, and will continue to increase, under greenhouse forcing [55], while snowpack is expected to decrease in response to warming [56]. Under the RCP4.5 emissions scenario, reduced contributions from snowmelt and enhanced evapotranspiration partially offset the increase in precipitation to moderate changes in peak annual discharge on the Lower Mississippi River. However, our work demonstrates that under the high RCP8.5 emissions scenario, increases in precipitation overwhelm hydrologic losses from snow-melt and evapotranspiration, enhancing peak annual flows beyond those observed in the 20th century.

The model employed in our study does not simulate the influence of human modifications to the river channel (i.e., levees, dykes, spillways, dams) on discharge, providing a unique opportunity to evaluate the relationships between climate change and regional hydrology independently of human modification of the river. The Lower Mississippi River was artificially channelized and straightened in the early 20th century [5], and these changes have affected river stages [34], sediment loads [57], and discharge [15]. Our approach directly compares the last century to future projections, and facilitates evaluation of the river discharge response to climate change because it allows us to isolate the contribution of regional hydroclimate changes to extreme discharge. The river channel and its basin will continue to change over the next century (via both natural and engineering pathways), with the potential to influence river stages and discharge. These geomorphic processes are not captured in simulations, but due to their importance on hydrology and channel hydraulics, offer a potential means to mitigate the effects of climate change on flood hazard and inundation extent.

Finally, a significant fraction of the rainfall and runoff that flow over the Mississippi River Basin is generated by tropical and extra-tropical cyclones [58]. Yet, GCMs do not have sufficient spatial resolution to simulate tropical cyclones and hurricanes [59]. Thus, the reliability of GCM-simulated rainfall and runoff necessarily excludes these storm systems, generating further uncertainty in the projections evaluated here. Furthermore, future tropical cyclones projections for the Atlantic show increased storm intensity (wind speeds), rainfall, sea level rise and inundation [60–64]. Elevated rainfall and storm surge will generate higher floodwaters. Continued modeling efforts should incorporate statistical downscaling tropical cyclone models [65, 66] to simulate synthetic storm tracks and intensities for a given region, using climate model output (e.g., CESM) as a boundary condition [59]. While such modeling is outside the scope of work presented here, studies using such approaches to evaluate tropical cyclone response to climate change is ongoing [67, 68], and these synthetic storms forced with future SSTs could lend insight into shifts in future flood hazard.

In conclusion, our findings underscore the potential for greenhouse forcing to enhance the magnitude and frequency of extreme discharge events on the Lower Mississippi River—floods with the ability to catastrophically disrupt shipping, agriculture, and industry in the United States. The Lower Mississippi River is home to one of the busiest ports in the United States, and billions of dollars have been invested in flood mitigation and navigation infrastructure, with billions more proposed over the coming decades [69]. This infrastructure is designed to withstand hydrologic extremes of the 20th century, but our findings imply that this infrastructure may be poorly suited for the 21st century—particularly if greenhouse gas emissions continue unabated. If the project design flood were exceeded, and the Old River Control Complex were to fail, the economic and human costs would be catastrophic [10]. Floods remain costly even when river infrastructure is not overwhelmed. For example, major flooding in the spring of 2011 remained within the confines of the MR&T system but disrupted trade and transportation, and caused nearly $2 billion in damages [70], while the more recent 2019 floods resulted in a slowdown of barge traffic that led to agricultural losses exceeding $900 million [71]. Our findings imply that the vulnerability of the existing MR&T Project design and associated infrastructure warrants further investigation by engineers, hydrologists, climate scientists, and regulatory agencies. Key components of this investigatory process would include the validation of GCM discharge forecasts within the Mississippi River basin, as well as the development of higher-fidelity hydrological models with greater capacity to directly incorporate the influences for upstream flood mitigation infrastructure. Such an effort would be costly, and the cost of more aggressive mitigation of greenhouse gas emissions needs to be considered against the costs of retrofitting flood mitigation infrastructure in preparation for the hydroclimate of the future, as well as the potential economic and societal consequences of enhanced flood hazard.

Acknowledgments

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI:https://doi.org/https://osf.io/zv8eg/.

ORCID iDs

K B J Dunne ⦾ https://orcid.org/0000-0003-0995-7629
S G Dee ⦾ https://orcid.org/https://orcid.org/0000-0002-2140-785X

References

[1] Winsemius H C *et al* 2016 Global drivers of future river flood risk *Nat. Clim. Change* 6 381–5
[2] 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
[3] Barry J M 2007 *Rising Tide: The Great Mississippi Flood of 1927 and How it Changed America* (New York, NY: Simon and Schuster)
[4] Camillo C A 2012 *Divine Providence: The 2011 Flood in the Mississippi River and Tributaries Project* (Mississippi, United States of America : Mississippi River Commission)
[5] Smith L M and Winkley B R 1996 The response of the Lower Mississippi River to river engineering *Eng. Geol.* 45 433–55
[6] Alexander J S, Wilson R C and Green W R 2012 *A Brief History and Summary of the Effects of River Engineering and Dams on the Mississippi River System and Delta* (US Geological Survey: US Department of the Interior)
[7] Knox J C 2007 The Mississippi river system *Large Rivers: Geomorphology and Management* 145–82
[8] DeHaan H *et al* 2012 Mississippi River and Tributaries System 2011 post-flood report: Documenting the 2011 Flood, the Corps' response, and the performance of the MR&T System
[9] McPhee J 1989 Atchafalaya *The Control of Nature* 3–92
[10] Kazmann R G and Johnson D B 1980 If the Old River Control Structure Fails? *Bulletin 12, Louisiana, Water Resources Research Institute*
[11] Milly P C D, Wetherald R T, Dunne K and Delworth T L 2002 Increasing risk of great floods in a changing climate *Nature* 415 514–7
[12] Field C B, Barros V, Stocker T F and Dahe Q 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK: Cambridge University Press)
[13] Kundzewicz Z W *et al* 2014 Flood risk and climate change: global and regional perspectives *Hydrol. Sci. J.* 59 1–28
[14] Milly P, Betancourt J, Falkenmark M, Hirsch R M, Kundzewicz Z W, Lettenmaier D P and Stouffer R J 2008 Stationarity is dead: Whither water management? *Earth* 4 20
[15] Munoz S E, Giosan L, Therrell M D, Remo J W, Shen Z, Sullivan R M, Wiman C, O'Donnell M and Donnelly J P 2018 Climatic control of Mississippi River flood hazard amplified by river engineering *Nature* 556 95–8
[16] George S St+ 2018 Mississippi rising *Nature* 556 34–5
[17] Laurent A, Fennel K, Ko D S and Lehrter J 2018 Climate change projected to exacerbate impacts of coastal eutrophication in the northern Gulf of Mexico *Journal of Geophysical Research: Oceans* 123 3408–26
[18] Munoz S E and Dee S G 2017 El Niño increases the risk of lower Mississippi River flooding *Sci. Rep.* 7 1772
[19] Van der Wiel K, Kapnick S B, Vecchi G A, Smith J A, Milly P C and Jia L 2018 100-year Lower Mississippi floods in a global climate model: characteristics and future changes *Journal of Hydrometeorology* 19 1547–63
[20] Trenberth K E 1999 Conceptual framework for changes of extremes of the hydrological cycle with climate change *Weather and Climate Extremes* (Springer) 327–39
[21] Prudhomme C *et al* 2014 Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment *Proc. Natl Acad. Sci.* 111 3262–7
[22] Lewis J W, Tavakoly A A, Martin C A and Moore C D 2019 Mississippi River and Tributaries future flood conditions
[23] Peterson T C *et al* 2013 Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: state of knowledge *Bull. Am. Meteorol. Soc.* 94 821–34
[24] Georgakakos A *et al* 2014 Ch 3: Water Resources' in M Melillo, Terese (TC) Richmond and G W Yohe *Climate Change Impacts in the United States: The Third National Climate Assessment*
[25] Arnell N W and Gosling S N 2013 The impacts of climate change on river flow regimes at the global scale *J. Hydrol.* 486 351–64
[26] van Vliet M T, Franssen W H, Yearsley J R, Ludwig F, Haddeland I, Lettenmaier D P and Kabat P 2013 Global river discharge and water temperature under climate change *Global Environ. Change* 23 450–64
[27] Hirabayashi Y, Kanae S, Emori S, Oki T and Kimoto M 2008 Global projections of changing risks of floods and droughts in a changing climate *Hydrol. Sci. J.* 53 754–72
[28] Tao B, Tian H, Ren W, Yang J, Yang Q, He R, Cai W and Lohrenz S 2014 Increasing Mississippi river discharge throughout the 21st century influenced by changes in climate, land use, and atmospheric CO2 *Geophys. Res. Lett.* 41 4978–86
[29] Kay J E *et al* 2015 The Community Earth System Model (CESM) large ensemble project: a community resource for studying climate change in the presence of internal climate variability *Bull. Am. Meteorol. Soc.* 96 1333–49
[30] Branstetter M L 2001 *Development of a parallel river transport algorithm and applications to climate studies*

[31] Branstetter M L and Famiglietti J S 1999 Testing the sensitivity of GCM-simulated runoff to climate model resolution using a parallel river transport algorithm *in Preprints, 14th Conf. on Hydrology, Dallas, TX, Amer. Meteor. Soc.* 391–2

[32] Wiman C, Hamilton B, Dee S G and Muñoz S E 2021 Reduced lower mississippi river discharge during the medieval era *Geophys. Res. Lett.* 48 e2020GL091182

[33] Peters G P, Andrew R M, Boden T, Canadell J G, Ciais P, Le Quéré C, Marland G, Raupach M R and Wilson C 2013 The challenge to keep global warming below 2 C *Nat. Clim. Change* 3 4–6

[34] Pinter N, Jemberie A A, Remo J W, Heine R A and Ickes B S 2008 Flood trends and river engineering on the Mississippi River system *Geophysical Research Letters* 35 L23404

[35] Remo J W, Pinter N and Heine R 2009 The use of retro-and scenario-modeling to assess effects of 100+ years river of engineering and land-cover change on Middle and Lower Mississippi River flood stages *J. Hydrol.* 376 403–16

[36] Hawkins E, Osborne T M, Ho C K and Challinor A J 2013 Calibration and bias correction of climate projections for crop modelling: an idealised case study over europe *Agric. For. Meteorol.* 170 19–31

[37] Piani C, Weedon G, Best M, Gomes S, Viterbo P, Hagemann S and Haerter J 2010 Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models *J. Hydrol.* 395 199–215

[38] Gilleland E and Katz R W 2011 New software to analyze how extremes change over time *Eos, Trans. Am. Geophys. Union* 92 13–4

[39] Salinas J L, Castellarin A, Viglione A, Kohnova S and Kjeldsen T 2014 Regional parent flood frequency distributions in Europe-Part 1: Is the GEV model suitable as a pan-European parent? *Hydrol. Earth Syst. Sci.* 18 4381

[40] Philip S *et al* 2020 A protocol for probabilistic extreme event attribution analyses *Advances in Statistical Climatology, Meteorology and Oceanography* 6 177–203

[41] Fix M J, Cooley D, Sain S R and Tebaldi C 2018 A comparison of US precipitation extremes under RCP8.5 and RCP4.5 with an application of pattern scaling *Clim. Change* 146 335–47

[42] Meinshausen M *et al* 2011 The RCP greenhouse gas concentrations and their extensions from 1765 to 2300 *Clim. Change* 109 213

[43] Pitlick J 1994 Relation between peak flows, precipitation, and physiography for five mountainous regions in the western usa *J. Hydrol.* 158 219–40

[44] McWilliams C D and Hayes G W III 2017 Comparison of the 2011 Mississippi River Flood to the MR-T project design flood *J. Hydrol. Eng.* 22 E5015002

[45] Hawkins E and Sutton R 2009 The potential to narrow uncertainty in regional climate predictions *Bull. Am. Meteorol. Soc.* 90 1095–108

[46] Fowler M D, Kooperman G J, Randerson J T and Pritchard M S 2019 The effect of plant physiological responses to rising co 2 on global streamflow *Nat. Clim. Change* 9 873–9

[47] Lehner F, Wood A W, Vano J A, Lawrence D M, Clark M P and Mankin J S 2019 The potential to reduce uncertainty in regional runoff projections from climate models *Nat. Clim. Change* 9 926–33

[48] Scussolini P *et al* 2020 Global river discharge and floods in the warmer climate of the last interglacial *Geophys. Res. Lett.* 47 e2020GL089375

[49] Meehl G A, Washington W M, Arblaster J M, Hu A, Teng H, Kay J E, Gettelman A, Lawrence D M, Sanderson B M and Strand W G 2013 Climate change projections in cesm1 (cam5) compared to ccsm4 *J. Clim.* 26 6287–308

[50] Zhang X, Tang Q, Zhang X and Lettenmaier D P 2014 Runoff sensitivity to global mean temperature change in the cmip5 models *Geophys. Res. Lett.* 41 5492–8

[51] Zhang X, Tang Q, Liu X, Leng G and Di C 2018 Nonlinearity of runoff response to global mean temperature change over major global river basins *Geophys. Res. Lett.* 45 6109–16

[52] Rupp D E, Abatzoglou J T, Hegewisch K C and Mote P W 2013 Evaluation of cmip5 20th century climate simulations for the Pacific Northwest USA *Journal of Geophysical Research: Atmospheres* 118 10–884

[53] Almazroui M *et al* 2021 Projected changes in temperature and precipitation over the united states, central america, and the caribbean in cmip6 gcms *Earth Systems and Environment* 5 1–24

[54] Konapala G, Mishra A K, Wada Y and Mann M E 2020 Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation *Nat. Commun.* 11 1–10

[55] Easterling D R, Kunkel K, Arnold J, Knutson T, LeGrande A, Leung L R, Vose R, Waliser D and Wehner M 2017 Precipitation change in the United States

[56] Harpold A A and Brooks P D 2018 Humidity determines snowpack ablation under a warming climate *Proc. Natl Acad. Sci.* 115 1215–20

[57] Meade R H and Moody J A 2010 Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007 *Hydrological Processes: An International Journal* 24 35–49

[58] Knight D B and Davis R E 2009 Contribution of tropical cyclones to extreme rainfall events in the Southeastern United States *Journal of Geophysical Research: Atmospheres* 114

[59] Camargo S J and Wing A A 2016 Tropical cyclones in climate models *Wiley Interdiscip. Rev. Clim. Change* 7 211–37

[60] Balaguru K, Foltz G R and Leung L R 2018 Increasing magnitude of hurricane rapid intensification in the central and eastern tropical Atlantic *Geophys. Res. Lett.* 45 4238–47

[61] Klotzbach P J, Bowen S G, Pielke R Jr and Bell M 2018 Continental us hurricane landfall frequency and associated damage: observations and future risks *Bull. Am. Meteorol. Soc.* 99 1359–76

[62] Trenberth K E, Cheng L, Jacobs P, Zhang Y and Fasullo J 2018 Hurricane Harvey links to ocean heat content and climate change adaptation *Earth's Future* 6 730–44

[63] Ting M, Kossin J P, Camargo S J and Li C 2019 Past and future hurricane intensity change along the us east coast *Sci. Rep.* 9 7795

[64] Knutson T *et al* 2020 Tropical cyclones and climate change assessment: part II: Projected response to anthropogenic warming *Bull. Am. Meteorol. Soc.* 101 E303–22

[65] Emanuel K, Ravela S, Vivant E and Risi C 2006 A statistical deterministic approach to hurricane risk assessment *Bull. Am. Meteorol. Soc.* 87 299–314

[66] Lee C-Y, Tippett M K, Sobel A H and Camargo S J 2018 An environmentally forced tropical cyclone hazard model *Journal of Advances in Modeling Earth Systems* 10 223–41

[67] Garner A J, Kopp R E and Horton B P 2021 Evolving tropical cyclone tracks in the north atlantic in a warming climate *Earth's Future* 9 e2021EF002326

[68] Wallace E J, Dee S G and Emanuel K A 2021 Resolving long-term variations in north atlantic tropical cyclone activity using a pseudo proxy paleotempestology network approach *Geophys. Res. Lett.* 48 e2021GL094891

[69] Peyronnin N, Green M, Richards C P, Owens A, Reed D, Chamberlain J, Groves D G, Rhinehart W K and Belhadjali K 2013 Louisiana's 2012 Coastal Master Plan: overview of a science-based and publicly informed decision-making process *J. Coast. Res.* 67 1–15

[70] Alfortish M, Brandon T, Gilbert R, Stark T and Westerink J 2012 Geotechnical reconnaissance of the 2011 flood on the Lower Mississippi River *Geo-Engineering Extreme Event Response Rep.* (Alexandria, VA: National Science Foundation)

[71] Fahie M 2019 Impacts of the 2019 Upper Mississippi River flooding on barge movements in the Upper Midwest Region *USCG Sector Upper Mississippi River* https://www.dco.uscg.mil/Portals/9/Impacts%20of%202019%20UMR%20Flooding_Barge%20Movements_Fahie_1.pdf