Variations in Flash Flood–Producing Storm Characteristics Associated with Changes in Vertical Velocity in a Future Climate in the Mississippi River Basin

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ABSTRACT: The Mississippi River basin (MRB) is a flash flood hotspot receiving the most frequent flash floods and highest average rainfall accumulation of any region in the United States. Given the destruction flash floods cause in the current climate in the MRB, it is critical to understand how they will change in a future, warmer climate in order to prepare for these impacts. Recent work utilizing convection-permitting climate simulations to analyze future precipitation changes in flash flood–producing storms in the United States shows that the MRB experiences the greatest future increase in flash flood rainfall. This result motivates the goal of the present study to better understand the changes to precipitation characteristics and vertical velocity in flash flood–producing storms in the MRB. Specifically, the variations in flash flood–producing storm characteristics related to changes in vertical velocity in the MRB are examined by identifying 484 historical flash flood–producing storms from 2002 and 2013 and studying how they change in a future climate using 4-km convection-permitting simulations under a pseudo–global warming framework. In a future climate, precipitation and runoff increase by 17% and 32%, respectively, in flash flood–producing storms in the MRB. While rainfall increases in all flash flood–producing storms due to similar increases in moisture, it increases the most in storms with the strongest vertical velocity, suggesting that storm dynamics might modulate future changes in rainfall. These results are necessary to predict and prepare for the multifaceted impacts of climate change on flash flood–producing storms in order to create more resilient communities.

KEYWORDS: Flood events; Precipitation; Climate change; Hydrometeorology

1. Introduction

In the continental United States (CONUS), floods are the second deadliest weather-related natural disaster (Ashley and Ashley 2008) and accounted for over $123.5 billion in adjusted losses between 1980 and 2018 (Smith 2019). Deadly flash flooding in Texas and Arkansas from 9 to 11 June 2010 resulted in over $10 million in damage along the Guadalupe River in Texas and 20 fatalities at the Albert Pike Recreational Area in western Arkansas (Schumacher et al. 2013). This devastating flood was due to a mesoscale convective vortex (MCV) associated with a series of heavy rainfall-producing mesoscale convective systems (MCSs; Houze 2004; Schumacher et al. 2013). Such high-intensity, flash flood–producing storms are common to the Mississippi River basin (MRB), which are the most frequent and have the highest average rainfall accumulation of any region in the United States (Dougherty and Rasmussen 2019). This region has thus been identified as a flash flood hotspot (Saharia et al. 2017), with flash floods occurring year-round (Saharia et al. 2017; Dougherty and Rasmussen 2019). The deadliest of these flash floods in the MRB occur mainly due to fronts and MCSs (Ashley and Ashley 2008), particularly in the warm season (Schumacher and Johnson 2006; Ashley and Ashley 2008; Saharia et al. 2017). The risk posed by warm-season flooding in the MRB is exacerbated by the poor predictability of warm-season convective extreme rainfall events (Sukovich et al. 2014; Herman and Schumacher 2018) due to issues representing moist convection in operational models (Fritsch and Carbone 2004). Given the frequency and intensity with which flash floods impact the MRB, it is critical to better understand the factors causing these events in order to improve the predictability of such events in order to protect human life.

To help improve flash flood forecasting, Doswell et al. (1996) produced a seminal paper on the ingredients necessary for flash flood–producing storms to occur, as summarized by the following equation:

$$P = RD,$$

(1)

where $P$ is precipitation, $R$ is the average rainfall rate, and $D$ is the rainfall duration. This equation shows that for heavy precipitation and flash flooding to occur, either high rain rates or long-duration rainfall events are necessary (or both). Expanding Eq. (1) based on terms related to $R$ and $D$,

$$P = EwgL_s(C^{-1}),$$

(2)

where $E$ is precipitation efficiency, $w$ is vertical motion, $q$ is moisture, $L_s$ is the system size, and $C$ is the system motion vector. Most storms do not have all of these ingredients maximized, but MCSs often have many, making them major flood producers in the Midwest and the MRB (Fritsch et al. 1986; Schumacher and Johnson 2006; Ashley and Ashley 2008; Kunkel et al. 2012). MCSs typically occur in environments with a deep saturated layer, high relative humidity, moderate convective available potential energy (CAPE), little convective inhibition (CIN; Schumacher and Johnson 2009), and sometimes exhibit back-building—the repeated formation of...
convective cells upstream of their predecessors (Schumacher and Johnson 2005). Similarly, tropical cyclones are large systems with high moisture content that can sometimes move slowly, depending on the synoptic conditions. These same ingredients in tropical cyclones lead to flooding that affects the MRB in summer and fall (Schumacher and Johnson 2006; Ashley and Ashely 2008; Villarini et al. 2014). Convective airmass thunderstorms that are generated due to strong daytime surface heating in the summer also lead to flooding in the MRB (Ashley and Ashley 2008; Kunkel et al. 2012), but they tend to be smaller, more isolated, and more transient than other types of flood-producing storms in the MRB. Note that in addition to precipitation, nonatmospheric factors such as land-use types, terrain gradients, and antecedent soil moisture conditions can contribute to the occurrence of floods (Davis 2001; Kumar et al. 2014; Berghuijs et al. 2016; Schroeder et al. 2016; Saharia et al. 2017).

An understanding of the storm dynamics associated with flash floods in the MRB in the current climate is helpful, but it is also critical to investigate how a changing climate could affect storm behavior and precipitation in the future. This subject is even less well understood than the storm dynamics leading to flooding in the MRB region in the present climate. Previous studies have explored aspects of future floods (mainly fluvial flooding) in the MRB using hydrologic models and regional and global climate models (RCMs and GCMs, respectively). These studies present varying results, with Hirabayashi et al. (2013) and van der Wiel et al. (2018) projecting less frequent future floods, but Jha et al. (2004) and Frans et al. (2013) showing increased streamflow and runoff associated with more precipitation in the MRB in both the past and future climate.

Despite the conflicting results of the above studies, none use high-resolution convection-permitting RCMs that more accurately simulate precipitation and storm characteristics by explicitly resolving convection that obviates the need for a convective parameterization. Given the complex storm dynamics and morphology that lead to the wide variety of storms producing floods, it is necessary to use such high-resolution simulations to understand future changes in flood-producing storms in the MRB in addition to changes in fluvial floods. Recently, studies have used high-resolution convection-permitting RCM simulations over the CONUS to examine changes in precipitation in a future climate. Such simulations more accurately depict the diurnal cycle, structure, and intensity of precipitation (especially convectively driven) on regional scales compared to coarser GCMs (Kendon et al. 2012, 2017; Prein et al. 2017b; Rasmussen et al. 2017). These simulations show that in a future warmer climate, precipitation in convective storms (Prein et al. 2017b,c; Rasmussen et al. 2017), heavy rainfall events (Prein et al. 2017a; Dai et al. 2017), and hurricanes (Guttmann et al. 2018) will become more intense. In 584 flash flood–producing storms specifically, Dougherty and Rasmussen (2020) used high-resolution RCM simulations to show that the accumulated flash flood rainfall over the whole CONUS increases by 21%, on average, in a future warmer climate. Notably, the greatest future increase in the rainfall per storm was located in the MRB, where rainfall increased up to 50 mm per storm.

Motivated by the results from Dougherty and Rasmussen (2020), the goal of the present study is to understand the detailed changes in precipitation characteristics and storm dynamics in flash flood–producing storms in the MRB in a future warmer climate. Specifically, the role that flash flood–producing storm vertical velocity changes have on modulating future precipitation changes are examined by grouping storms with similar vertical velocities. As suggested by O’Gorman (2015), changes in precipitation extremes due to warming are a function of 1) precipitation efficiency (microphysics), 2) vertical motion (dynamics), and 3) condensation rate (thermodynamics). This study examines the role of dynamics and thermodynamics in modulating future changes in flood-producing storm precipitation by studying changes in storm dynamics in hundreds of historical storms using convection-permitting simulations. While other nonatmospheric factors affect flood occurrence, the focus on storm dynamics as it relates to precipitation changes in a future, warmer climate is important to understand given the devastating impacts flood-producing storm precipitation has in the current climate. This examination may help better prepare the flood-prone region of the MRB for the impacts of climate change on flash flood–producing storms of varying intensities. Additionally, understanding how storm dynamics in flood-producing storms may change and modulate future precipitation behavior in a warmer climate may provide a greater understanding of how convection might change in a future warmer climate in general.

2. Data and methods

To study the role vertical velocity in flash flood–producing storms plays in a current and future climate in the MRB, 4-km convection-permitting simulations provide representations of a current and future warmer climate over this region. Only storms that are well represented in the simulations are used, as quantified by a structural similarity index (section 2a). These flash flood–producing storm cases are based on a climatology from 2002 to 2013 (Dougherty and Rasmussen 2019) over the CONUS that merges storm reports with stream gauge information and Stage IV rainfall data (section 2b). Flash flood–producing storms influenced by tropical cyclones are separated out from the rest of the storms to understand the changes in the different types of storms (section 2c). The storms were then categorized by their vertical velocity to understand the role this “ingredient” has on future rainfall changes (section 2d).

a. Convection-permitting simulations

High-resolution, convection-permitting simulations run by scientists at the National Center for Atmospheric Research (NCAR) are utilized to analyze flash floods in the MRB in a current and future climate. Though Liu et al. (2017) describes these simulations in detail, here, a brief overview of the simulations is discussed. The simulations were run using the Weather Research and Forecasting (WRF) Model v3.4.1 over a 1360 × 1016 grid point domain covering North America, centered on the CONUS. Due to the domain covered, these simulations will hereafter be referred to as the WRF-CONUS simulations. The horizontal grid spacing is 4 km, and the vertical resolution is comprised of 51 levels up to 50 hPa, with the
highest resolution in the boundary layer. The parameterization schemes used in the simulations include the Thompson aerosol-aware microphysics (Thompson and Eidhammer 2014), the Yonsei University (YSU) planetary boundary scheme (Hong et al. 2006), the Rapid Radiative Transfer Model (RRTMG) (Iacono et al. 2008), and the Noah-MP land surface model (Niu et al. 2011), which was specifically improved for these simulations (Liu et al. 2017). On horizontal scales greater than 2000 km above the boundary layer, spectral nudging was applied in order to avoid long-term climate drift (Feser et al. 2011) and to minimize deviations from the forcing data. However, on horizontal scales less than 2000 km and within the boundary level, the flow was allowed to freely evolve, thus enabling changes in sub-synoptic-scale weather to occur.

The WRF-CONUS simulations were comprised of two sets of simulations—one of the current climate and the other representing the future climate. The current climate simulations (CTRL) were forced with ERA-Interim (ERA-I) reanalysis data every 6 h over a continuous 13-yr period from 2000 to 2013. The future simulations were also forced every 6 h by ERA-I over the same 13-yr period, except a “pseudo–global warming” (PGW) signal was added to represent a future warmer climate, as given by the following:

\[
WRF_{\text{input}} = \text{ERA-Interim} + \Delta \text{CMIP5}_{2071-2100} - \text{CMIP5}_{1976-2005}
\]

where \(\Delta \text{CMIP5}_{2071-2100} \) is the climate delta signal, which is the 95-yr multimodel ensemble-mean monthly change in Coupled Model Intercomparison Project phase 5 (CMIP5) under the representative concentration pathway 8.5 (RCP8.5) emission scenario:

\[
\Delta \text{CMIP5}_{2071-2100} = \text{CMIP5}_{2071-2100} - \text{CMIP5}_{1976-2005}
\]

The perturbed fields in the PGW simulations include horizontal wind, geopotential, temperature, specific humidity, sea surface temperature, soil temperature, sea level pressure, and sea ice. Over the CONUS, this PGW approach results in a +3°C–6°C warming and an increase in water vapor mixing ratio of ~20%–40%, consistent with the Clausius–Clapeyron theory (Trenberth et al. 2003; Liu et al. 2017). This PGW approach has been similarly utilized in future regional climate change studies all over the world (Schär et al. 1996; Ban et al. 2015; Rasmussen et al. 2011, 2014; Prein et al. 2015, 2017a–c; Liu et al. 2017; Rasmussen et al. 2017; Dai et al. 2017; Gutmann et al. 2018), including case studies of floods in a future climate (Lackmann 2013; Mahoney et al. 2018).

The Liu et al. (2017) simulations are particularly well suited to study changes to flood-producing storms in a future climate over the CONUS. In the CTRL simulations, precipitation totals over the mountainous West outperform 25 other gridded precipitation datasets and show the best precipitation variability compared to uncorrected datasets (Beck et al. 2019). Dougherty and Rasmussen (2020) also showed that the CTRL precipitation compares well to that observed by the Stage IV precipitation dataset (Lin and Mitchell 2005) within 584 of the most intense historical flash flood–producing storms over the CONUS, as well as 45 flood-producing atmospheric rivers in California (Dougherty et al. 2020). A structural similarity index (SSIM; Wang et al. 2004) quantifies the structural differences in rainfall accumulation within these flash flood–producing storms between Stage IV and CTRL, as well as CTRL and PGW (Dougherty and Rasmussen 2020, Dougherty et al. 2020), as given by the following equation:

\[
\text{SSIM}(x, y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}
\]

where \(x, y\) is the pixel location, \(\mu\) is the mean pixel intensity, \(\sigma\) is the variance of intensity, and \(c_1\) and \(c_2\) are constants to avoid instability when the other terms in the denominator are close to zero (Wang et al. 2004). SSIM is used in the image-processing community to compare the similarity between two images’ contrast, luminance, and structure, but in this study, it is used to compare the difference in rainfall structure and accumulation in flash flood–producing storms between Stage IV observations and CTRL simulations, as well as CTRL and PGW simulations.

SSIM is calculated for all 484 flash flood–producing storms in the MRB, with a mean value of 0.89 between Stage IV and CTRL simulations, and 0.91 between CTRL and PGW simulations (Fig. 1). For both comparisons, SSIM ranges from approximately 0.7 to 0.98. Values closer to 1 indicate that flash flood–producing storm rainfall has a more similar structure and accumulation, so mean values of 0.89 and 0.91 between Stage IV and CTRL simulations and CTRL and PGW simulations, respectively, indicate a high similarity between flash flood–producing storm rainfall intensity and structure compared to observations and future simulations. A perfect agreement of 1 is not expected for either comparison, due to deficiencies in Stage IV observations (Dougherty and Rasmussen 2020; Nelson et al. 2016), and a different thermodynamic environment in the PGW simulations (Liu et al. 2017). However, the high values observed in the SSIM distribution indicate that rainfall is being reasonably well simulated in both CTRL and
PGW simulations, likely due to the spectral nudging used in the simulations that reproduces the synoptic conditions associated with flash floods in the current and future climate [see an example of a case study in Dougherty and Rasmussen (2020)].

However, the WRF-CONUS simulations cannot explore all aspects of a future climate. At this high resolution, the computational constraint does not allow for the generation of multimember ensembles, therefore only a single deterministic representation of a future climate can be run and the range in model uncertainty or internal variability cannot be assessed. Such a limitation was mitigated in part by taking the mean of a 19-member ensemble from the CMIP5 simulations used to force the PGW simulations, rather than use a single model run as in Rasmussen et al. (2011, 2014). Additionally, while the use of spectral nudging in the PGW method in the WRF-CONUS simulations is beneficial for reproducing specific weather events, it does not allow for substantial future changes in large-scale synoptic dynamics, especially since this signal is smoothed out by taking the future monthly average mean. This large-scale dynamical change is more uncertain than the thermodynamic change in a future climate, which is why the WRF-CONUS simulations focus on the more robust thermodynamic change (Liu et al. 2017). Therefore, the main utility of the WRF-CONUS simulations is to understand how today’s weather would change in a warmer, moister future environment. Thus, these simulations are well suited to understand how historical flash flood–producing storms will change in a warmer, moister climate in the MRB.

b. Flash flood cases

Historical flash flood–producing storms in the MRB are identified from a climatology of flood-producing storms over the CONUS from 2002 to 2013 (Dougherty and Rasmussen, 2019). This climatology merges National Center for Environmental Information (NCEI) storm reports with flooded stream gauges (Shen et al. 2017) and Stage IV precipitation data (Lin and Mitchell 2005) to analyze the rainfall characteristics associated with flood-producing storms that had a notable hydrologic response. Stage IV precipitation is analyzed over a ±5° latitude/longitude domain from the flood centroid over the whole duration of the flood (plus a buffer of several hours). To isolate the likely flood-contributing rainfall, only the largest contiguous object with rainfall accumulations that met or exceeded the 75th percentile is utilized for each flood.

Using the above methodology, Dougherty and Rasmussen (2019) identified 3436 flash flood–producing storms (including the hybrid category of floods) over the CONUS. Any flash flood report that occurred in states directly along the Mississippi River—Minnesota, Wisconsin, Iowa, Illinois, Missouri, Kentucky, Tennessee, Arkansas, Mississippi, and Louisiana—are utilized in the current study. However, flash flood rainfall associated with the flood reports sometimes extends into bordering states, which are also included in the analysis. Not including the entire MRB in the present study is due to the different character of flood-producing storms, especially in the western part of the basin (i.e., the Missouri River basin), in which floods generated by rain-on-snow/snowmelt comprise a large portion of floods (Dougherty and Rasmussen 2019). Based on these criteria, 1182 flash flood–producing storms in the MRB are identified (Fig. 2). These flash floods are well distributed in the MRB, occurring both in the northern and southern portion of the basin. They mainly occur in the warm season from April to July (Fig. 3), consistent with previous work, and are thus likely associated with convective storms, like MCSs (Maddox et al. 1979; Schumacher and Johnson 2006; Dougherty and Rasmussen 2019).

To ensure that only cases well represented in the WRF-CONUS simulations are utilized, flash floods in which the area-average rainfall difference between Stage IV and CTRL exceeded 30% are excluded. This results in 484 flash flood–producing storms in the MRB in which CTRL and PGW rainfall differences are examined. Using the same time and location of flood rainfall as the observations results in well-represented flash flood–producing storms in the MRB in both the CTRL and PGW simulations, as shown by the SSIM results (Fig. 1). While the flash flood–producing storm rainfall compares well between CTRL and PGW simulations and it is likely this rainfall could result in a future flood, it cannot be said with certainty, as future changes in land use, soil moisture content, and streamflow were not examined and could influence future flash flood occurrence. Such a caveat is important to consider and could only be specifically addressed by coupling the
simulations with a more detailed hydrologic model, which will occur in future work. For details on how specific flash flood–producing storm quantities were calculated in the CTRL and PGW simulations, please refer to Dougherty and Rasmussen (2020).

c. Identification of tropical cyclone-related floods

A nonnegligible source of flooding in the MRB is due to landfalling tropical cyclones (TCs), especially in the lower MRB near the Gulf of Mexico (Schumacher and Johnson 2006; Ashley and Ashley 2008). Therefore, among the 484 flash floods included in this study, all are examined to see if a TC contributed to the flood. Note that the Dougherty and Rasmussen (2019) climatology from which the flash floods in this study are based excludes coastal flood reports and tropical cyclone reports, due to the nonflooding related hazards that could merit a storm report. Thus, the TC influence is only considered in respect to flash floods.

The extended best track dataset, which contains 6-hourly data of Atlantic TC pressure, winds, and location coordinates (Demuth et al. 2006), is utilized to identify floods with a TC influence. Specifically, any flood in which the 34-kt (1 kt ≈ 0.51 m s⁻¹) wind radii of a TC overlaps with the flood domain (±5° latitude/longitude) and occurs within 24 h of the TC entering the flood domain is classified as having a TC influence. An example of this identification is shown in Fig. 4, which shows Hurricane Katrina’s 34-kt wind radii squarely in the flood domain of a particular flash flood. Using these criteria, 25 MRB flash floods are associated with 11 unique TCs—Isidore (2002), Bill (2003), Ivan (2004), Katrina (2005), Rita (2005), Humberto (2007), Gustav (2008), Ike (2008), Lee (2011), Isaac (2012), and Andrea (2013). However, after a manual inspection of the overlap between the 34-kt wind radii and the flood domain, three TCs (Ike, Lee, and Andrea) are removed, due to barely being located in the flood domain. This leaves 19 MRB flash floods associated with eight unique TCs (Table 1), with a majority of the flash floods associated with Hurricane Gustav (2008), followed by Isidore (2003), and Bill (2003).

To ensure that the TCs were well represented in the WRF-CONUS simulations, the eight TCs in Table 1 are compared to

![Fig. 3. The seasonality of flash flood–producing storms shown in Fig. 2.](image)

![Fig. 4. Example of the methodology used to classify a flash flood–producing storm as having a tropical storm influence. In this case, the domain of a flash flood–producing storm is outlined by the red box, while the 34-kt wind radii (storm center) of Hurricane Katrina (2005) are shown by the turquoise ellipses (black dots). Any flash flood–producing storm, such as this example, where the 34-kt wind radii intersect the flood domain < 24 h prior to the flood was classified as having a tropical influence.](image)

### Table 1. Names and years of hurricanes that were associated with flash flood events (and the number of flood episodes) in the Mississippi River basin from the Dougherty and Rasmussen (2019) climatology.

<table>
<thead>
<tr>
<th>Hurricane name</th>
<th>Year</th>
<th>No. of flood episodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isidore</td>
<td>2002</td>
<td>3</td>
</tr>
<tr>
<td>Bill</td>
<td>2003</td>
<td>3</td>
</tr>
<tr>
<td>Ivan</td>
<td>2004</td>
<td>1</td>
</tr>
<tr>
<td>Katrina</td>
<td>2005</td>
<td>1</td>
</tr>
<tr>
<td>Rita</td>
<td>2005</td>
<td>1</td>
</tr>
<tr>
<td>Humberto</td>
<td>2007</td>
<td>1</td>
</tr>
<tr>
<td>Gustav</td>
<td>2008</td>
<td>7</td>
</tr>
<tr>
<td>Isaac</td>
<td>2012</td>
<td>2</td>
</tr>
</tbody>
</table>
observations and between CTRL and PGW simulations. The TC track and the minimum pressure from the best track dataset is plotted over the CTRL surface pressure and reflectivity to ensure that CTRL simulations produced a TC-looking structure at a similar location and intensity. The CTRL reflectivity and pressure is then compared to that in the PGW simulations for each TC to ensure the TCs are captured in the future simulations. These comparisons are done qualitatively, similar to the manual comparison of observed and simulated tracks in Gutmann et al. (2018) used to exclude hurricanes from their analysis using the same set of simulations.

Most of the eight TCs are well captured in the CTRL and PGW simulations, though Bill (2003), Katrina (2005), and Humberto (2007) have slight deviations in track and intensity. However, when comparing the CTRL and PGW rainfall in the flash floods associated with these three TCs, they are adequately similar in rainfall structure and location to include in the analysis. These results are consistent with Gutmann et al. (2018) who used to the WRF-CONUS simulations to specifically study future changes to 22 landfalling TCs. They included all TCs in Table 1, except for Bill, Katrina, and Humberto, based on not being well represented in the simulations. However, the criteria from Gutmann et al. (2018) were stricter since they specifically focused on changes to TCs, whereas the present study allows some leeway in the representation of TCs since the main focus is on flooding. In general, these eight TCs are adequately represented in the WRF-CONUS simulations, especially in regard to the flash flood rainfall associated with the TCs, which is the main interest of the study.

d. Categorization of flash flood vertical velocity

To further understand changes in flash flood–producing storms in the MRB in a future climate, storms are categorized by vertical velocity. This is motivated by the “ingredients-based
approach” of forecasting flash floods by Doswell et al. (1996). Recall, that among other factors being equal, stronger vertical velocity results in heavier rainfall [Eqs. (1) and (2)]. Additionally, changing precipitation extremes in a warmer climate are related to changes in vertical velocity, as well as precipitation efficiency, and condensation rate (O’Gorman 2015). This leads to the hypothesis that flash flood–producing storms in the MRB, which are largely convective in nature (Fig. 3), will produce different rainfall amounts in a future climate based on their vertical velocity. In this case, the average vertical velocity $\bar{w}$ over a flash flood–producing storm’s lifetime and heavy rainfall area (see section 2b) in the CTRL simulations is used to group storms into different categories. This provides just one metric for categorizing the convective strength of flash flood–producing storms, and thus one aspect of quantifying the role of storm dynamics in modulating future changes in rainfall. However, it is recognized that there are other dynamical metrics that are related to convective strength and precipitation potential, such as low-level vertical wind shear (Nielsen and Schumacher 2018).

After calculating $\bar{w}$ in the 484 flash flood–producing storms in the MRB using the CTRL simulations, three different $\bar{w}$ categories are created based on percentiles of the $\bar{w}$ distribution. The weak $\bar{w}$ flash floods include 125 flash floods below the 25th percentile ($0.03 \, \text{m s}^{-1}$) of $\bar{w}$ (Fig. 5), moderate includes 224 flash floods between the 25th and 75th percentile ($0.03–0.06 \, \text{m s}^{-1}$), and strong $\bar{w}$ flash floods are the 135 floods with $\bar{w}$ over the 75th percentile ($0.06 \, \text{m s}^{-1}$). Note that the relatively low values of $\bar{w}$ are due to spatial and temporal averaging.

| TABLE 2. Mean values of rainfall characteristics for all 484 flash flood–producing storms in the Mississippi River basin for CTRL and PGW simulations, the future difference (PGW – CTRL), future percent difference (% change), and future percent difference per degree of warming (% change K$^{-1}$). |
|-----------------|----------|----------|---------------|----------|----------|
| Area averaged rainfall (mm) | 34.1 | 40.2 | 6.1 | 16.6 | 5.7 |
| Average rain rate (mm h$^{-1}$) | 2.4 | 2.9 | 0.4 | 16.3 | 5.6 |
| Max rain rate (mm h$^{-1}$) | 72 | 86.7 | 14.7 | 26.9 | 8 |
| Duration (h) | 17.8 | 17.8 | 0 | 0 | 0 |
| Area (km$^2$) | $1.5 \times 10^5$ | $1.4 \times 10^5$ | $-9753$ | $-4$ | 0.22 |
| Runoff (mm) | 1.7 | 2.2 | 0.5 | 31.8 | — |

Fig. 7. Rainfall per flash flood–producing storm (mm storm$^{-1}$) in the (a) CTRL simulations, (b) PGW simulations, and (c) PGW – CTRL difference, where blue (red) indicates a future increase (decrease) in mm storm$^{-1}$. 
Weak flash flood–producing storms have a summertime maximum, smaller updraft and downdraft areas, a smaller area of heavy rainfall, and higher maximum instantaneous rain rates in both the CTRL and PGW simulations (as shown in section 3b). These characteristics imply that weak flash flood–producing storms are likely isolated summertime convection, though a full radar analysis would be needed to confirm this result. Strong flash flood–producing storms display a springtime maximum, larger updraft and downdraft areas, a larger area of heavy rainfall, and lower maximum instantaneous rain rates in the CTRL and PGW simulations compared to weak and moderate storms, though moderate storm characteristics are more similar to strong storms. Additionally, moderate storms include 10 out of 19 floods associated with TCs, while 8 out of 19 strong storms are associated with TCs. In general, these storm characteristics suggest that flash flood–producing storms with moderate and strong vertical velocity are due to larger, more organized convection. While a more detailed analysis of the relationship between future changes in vertical velocity and rainfall in storms is needed, examining the broad changes within the heavy rainfall region of flash flood–producing storms provides a foundation for understanding these changes.

Using these categories of flash flood–producing storm vertical velocity, future changes in rainfall are assessed to understand how different storm dynamics might change in a future climate and how this plays a role in modulating future changes in rainfall, which has not been examined in the context of historical flash flood–producing storms before. Such an examination is motivated by future increases in rainfall exceeding the theoretical Clausius–Clapeyron rate of increase of 7% K⁻¹ (Trenberth et al. 2003), which Trenberth (1999) hypothesized could be possible in intense convective storms with additional latent heat release. Dougherty and Rasmussen (2020) observed this phenomenon in some flash flood–producing storms over the CONUS that displayed increases in future hourly maximum rain rates above the Clausius–Clapeyron increase, increasing on average by 10.5% K⁻¹. The reason for this increase and dependence on vertical velocity thus warrants further investigation.

3. Results

a. Future changes in all flash flood–producing storms

In a future climate, the location of rainfall associated with flash flood–producing storms in the MRB does not change noticeably (Fig. 6). The flash flood rainfall is slightly more concentrated in Missouri and Arkansas in the PGW simulations, but over most of the basin, there is no obvious change. Such a result is likely due to the similar synoptic conditions in the PGW simulations, which results in similar flash flood–producing storms in the future in terms of duration, location, and rainfall structure as mentioned in section 2b. However, changes in rainfall characteristics do occur in the
MRB flash flood–producing storms in a future climate, due to the warmer and moister environment.

The amount of rainfall per storm (i.e., total accumulated rainfall at each grid point divided by the total number of storms at that grid point) increases over most of the MRB, especially in the lower part of the basin near the Gulf of Mexico. Here, flash flood rainfall increases up to 50 mm per storm in the PGW simulations (Fig. 7). This result is consistent with large increases in future precipitable water amounts over the Gulf of Mexico (Rasmussen et al. 2017). As will be shown later, some of this increased rainfall in the lower MRB is attributable to TCs. Elsewhere, flash flood rainfall increases exceed 20 mm per storm, though areas of slight decrease are observed. Some of these decreases are due to less rainfall from flash floods in a future climate, which could be related to the central CONUS dry bias in these simulations (Liu et al. 2017). Another contribution is due to slight shifts in the heavy rainfall area associated with flash floods in the PGW simulations. Overall, the dominant signal is increased flash flood rainfall, which increases by 16.6% (5.7% K\(^{-1}\) of warming) in the future (Table 2).

Consistent with future increased flash flood rainfall is an increase in flash flood runoff, which increases by 31.8% in the PGW simulations (Table 2). These increases generally follow the spatial patterns of increased future flash flood rainfall, with the greatest future increase in the lower MRB where future runoff increases up to 40 mm per storm (Fig. 8). Similarly, the locations of future decreased flash flood rainfall, such as western Wisconsin and central Minnesota, also exhibit decreased flash flood runoff. The average increase in future runoff exceeding the average increase in future rainfall in flash flood–producing storms implies more efficient runoff generation, as Dougherty and Rasmussen (2020) found, which could be due to more intense rainfall rates that promote more runoff via the precipitation excess mechanism as suggested by Yin et al. (2018). Other factors, such as changes in evaporation and soil moisture could influence this result as well, but a detailed hydrologic model would be needed to investigate such changes. However, as shown by Ma et al. (2017), the runoff from Noah-MP in these simulations performs well in the MRB. Therefore, an increase in both flash flood–producing storm rainfall and runoff suggest more intense flood-producing storms and a hydrologic response in a future climate over most of the MRB.

When separating out the flash flood rainfall contributed by TCs, most of the rainfall occurs in the lower MRB (Fig. 9). The occurrence of the flash flood rainfall from TCs is similar in the CTRL and PGW simulations, except for slight shifts. This is particularly noticeable in the western shift of flash flood rainfall over Arkansas, which is due to the shift of Hurricane Gustav in the PGW simulations—the dominant TC signal associated with seven different flash floods (Table 1). This shift in Hurricane Gustav in the PGW simulations is also evident in the future change in millimeters per storm, with a dipole of increasing (decreasing) rainfall over western (eastern) Arkansas (Fig. 10).
However, the change in rainfall due to Gustav in the PGW simulations is not just a pure shift, as there is a 27.6% increase in flash flood rainfall associated with Gustav in the future (not shown), consistent with Gutmann et al. (2018) findings that Gustav’s rain rate increased by 21 mm h\(^{-1}\) in the future. An increase in future flash flood rainfall is also observed in all other TCs, with area average rainfall increasing in the PGW simulations from 2.2% to 36.8%. Thus, while Hurricane Gustav exhibits a large signal of both increased rainfall and shift in rainfall in the future in the MRB, even after removing Gustav, area-average rainfall in TCs still increases by 17.8% on average, suggesting this is a robust future change. However, the dominant mode of change in future rainfall appears to be that from other types of flash flood–producing storms in the MRB, given that the TC signal is dampened when averaged with all storms in the MRB (Fig. 7).

Other changes in flash flood–producing storm characteristic were examined, including the change in heavy rainfall area and duration, both of which showed little future change (Table 2). Flash flood rainfall area showed a 4% future decrease and duration showed no change. The lack of duration change among all MRB flash flood–producing storms is partially due to the methodology, which examines floods over the same dates in the CTRL and PGW simulations. This a potential limitation of this study, but as previously demonstrated, a lack of change in flash flood duration could also be due to the ability of the PGW simulations to reproduce a similar flash flood in the future.

b. Future changes in flash flood–producing storms by vertical velocity

1) DYNAMICAL CHANGE

Changes between CTRL and PGW simulations among the different \(w\) categories (defined by values in the CTRL simulations) of flash flood–producing storms show that the mean \(w\) decreases in all categories in the future (Fig. 11). Values of \(w\) are lowest in the CTRL and PGW simulations in the weak storms (Fig. 11) and exhibit the greatest percent future decrease of \(-33\%\) (Table 3). Conversely, strong storms display

![Fig. 10. As in Fig. 7, but only for flash flood–producing storms with a tropical cyclone influence.](image URL)

![Fig. 11. Boxplots of average vertical velocity \(w\) in weak (blue), moderate (purple), and strong (red) flash flood–producing storms. Boxes with lighter (darker) shades indicate storms in the CTRL (PGW) simulations.](image URL)
the highest $\bar{w}$ in both CTRL and PGW simulations (Fig. 11) with the least future decrease of $-2.4\%$ (Table 3), despite showing a larger range in future $\bar{w}$ values. Moderate storms exhibit a future decrease in $\bar{w}$ that is between the values of weaker and stronger storms. Thus, the greatest (least) future decrease in $\bar{w}$ is in weak (strong) flash flood–producing storms.

To explain future changes in the $\bar{w}$ magnitude, changes in updraft ($>1 \text{ m s}^{-1}$) and downdraft ($<-1 \text{ m s}^{-1}$) characteristics are examined (Table 4). In a warmer climate, the maximum instantaneous updrafts increase in all categories of $\bar{w}$ (Fig. 12). In strong storms, maximum updrafts are the strongest in both the CTRL and PGW simulations at 25.5 and 29.8 m s$^{-1}$, respectively. However, moderate storms exhibit the largest future increase of 27.1% in maximum updrafts in the future (Table 4). The increase in maximum updrafts in these flash flood–producing storms is consistent with the projected increase in future CAPE in convective storms (Hoogewind et al. 2017; Prein et al. 2017c; Rasmussen et al. 2017), since CAPE is proportional to the theoretical maximum updraft velocity. Results from Prein et al. (2017c) support these results, finding that MCSs exhibit stronger maximum updrafts above 2 km in a future climate over the CONUS.

Changes in updrafts and downdrafts averaged over the duration of each flood-producing storm and the heavy rainfall region (the largest contiguous region with rainfall accumulations $>75$th percentile) suggest that flash flood–producing storms could intensify in the future in the MRB (Fig. 13). However, this intensification depends on the category of flash flood–producing storm. Average updraft magnitudes only increase by 1.9% in the future in weak flash flood–producing storms, while they increase by 5.5% in strong flash flood–producing storms (Table 4). It is possible that the larger increase in updraft magnitude in strong flash flood–producing storms is related to an increase in updraft area in the future, which increases by 3.6%, but decreases by 1.1% in both weak and moderate flash flood–producing storms (Table 4). Both Prein et al. (2017c) and Trapp et al. (2019) similarly found an increase in future updraft area in MCSs and hail-producing storms, respectively, while Grabowski and Prein (2019) showed stronger updrafts in the future compared to the current climate. While the results from the present study are consistent with previous studies, changes in future updrafts within a range of vertical velocities in flash flood–producing storms has not been previously documented.

Supporting the future increase in updraft magnitudes in flash flood–producing storms in the MRB are stronger downdrafts within these storms as well (Fig. 13). Weak, moderate, and strong flash flood–producing storms display similar CTRL and PGW average downdrafts ranging from $-1.33 \text{ to } -1.42 \text{ m s}^{-1}$, though downdraft magnitudes strengthen most in the future in strong flash flood–producing storms by 4.5% (Table 4). The change in downdraft area does not seem to play much of a role in explaining the change in downdraft magnitude, as it increases only slightly from 0.2% to 0.3% in all categories of flash flood–producing storms (Table 4). This is in contrast to Prein et al. (2017c), who found a broadening of downdrafts among MCSs, though they support the finding of stronger downdrafts in a future climate.

The strengthening of average updrafts, average downdrafts, and maximum updrafts in flash flood–producing storms, especially in strong storms, suggests more intense mesoscale dynamics operating in a future, warmer climate. The greater intensification of stronger flash flood–producing storms in a future climate is consistent with more CAPE and CIN in a future climate that is due to temperature and moisture increases throughout much of the troposphere (Rasmussen et al. 2017; Chen et al. 2020). While future warming could be greatest in the upper troposphere and enhance stability, acting to suppress storms (Keller et al. 2018), Prein et al. (2017c) suggested that increases in lower level moisture and temperature along with a higher tropopause help to increase CAPE and fuel more intense convective storms in a future climate. Thus, the storms with strong vertical velocity are likely able to overcome stronger CIN in a future climate (Rasmussen et al. 2017),

<table>
<thead>
<tr>
<th>Variable</th>
<th>Weak $\bar{w}$ (% K$^{-1}$)</th>
<th>Moderate $\bar{w}$ (% K$^{-1}$)</th>
<th>Strong $\bar{w}$ (% K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum updraft (m s$^{-1}$)</td>
<td>17.9 (3.3)</td>
<td><strong>27.1 (7.4)</strong></td>
<td>19.9 (6.5)</td>
</tr>
<tr>
<td>Average updraft (m s$^{-1}$)</td>
<td>1.9 (0.6)</td>
<td>3.9 (1.0)</td>
<td><strong>5.5 (1.3)</strong></td>
</tr>
<tr>
<td>Average downdraft (m s$^{-1}$)</td>
<td>3.7 (0.9)</td>
<td>4.0 (1.0)</td>
<td><strong>4.5 (1.5)</strong></td>
</tr>
<tr>
<td>Updraft area (km$^2$)</td>
<td>$-1.1$ (0.6)</td>
<td>$-1.1$ (1.0)</td>
<td><strong>3.6 (1.3)</strong></td>
</tr>
<tr>
<td>Downdraft area (km$^2$)</td>
<td>0.2 (0.9)</td>
<td>0.2 (1.0)</td>
<td><strong>0.3 (1.4)</strong></td>
</tr>
</tbody>
</table>

Table 4. As in Table 3, but for changes in updraft and downdraft characteristics.
Unlike the weak storms, allowing them to tap into the increased CAPE and further intensify in the future.

2) Rainfall change

Future rainfall characteristics also exhibit changes as a function of storm π, with weak storms exhibiting the least area-average rainfall in the CTRL and PGW simulations (Fig. 14), along with the lowest percentage future increase of 13% and lowest scaling rate of 3.9% K\textsuperscript{−1} (Table 3). Strong flash flood–producing storms display the highest CTRL and PGW area-average rainfall and greatest future increase of 18.4% (5.8% K\textsuperscript{−1}) likely due to their stronger vertical velocity (Figs. 12 and 13)—an ingredient promoting heavy rainfall (Doswell et al. 1996) [Eq. (2)]. However, all flash flood–producing storms display an overall increase in future area-average rainfall, associated with a more favorable thermodynamic environment in the PGW simulations.

Similar to changes in maximum updrafts, maximum hourly rain rates increase at higher rates than the area-average rainfall in the future (Table 3). Maximum rain rates increase the most in the future in strong flash flood–producing storms by 29.1% and increase the least in weak storms by 22.5%. While weak and moderate storms’ maximum rain rates increase near the Clausius–Clapeyron rate at 8.6% K\textsuperscript{−1} (Table 3), strong storms increase slightly above this rate at 8.6% K\textsuperscript{−1} (Table 3).

Changes in volumetric rainfall and area by π category differ from future trends in π and area-average rainfall. While strong storms have the largest volumetric rain in the CTRL and PGW simulations (Fig. 15), the greatest future increase of 12.2% occurs in moderate storms (Table 3). Similar scaling rates in volumetric rainfall are observed in weak and moderate storms of 3.9% and 3.8% K\textsuperscript{−1}, respectively, which is higher than the 2.6% K\textsuperscript{−1} increase in strong storms. The future changes in volumetric rainfall are likely due to a competition between future decreases in area and future increases in rainfall amount, since volumetric rainfall, by definition, is the amount of total rainfall multiplied by area divided by the storm duration. Therefore, since area shows the least future decrease in moderate storms of −2.8%, this is likely the reason for greater increase in volumetric rainfall compared to weak and strong storms (Table 3).

3) Combined dynamic–thermodynamic change

To understand the mechanisms behind the future changes in rainfall characteristics among the different vertical velocity groups, vertical moisture flux \(wq\) and its individual components are examined. All components—\(wq\), \(w\), and \(q\)—are computed by temporally and spatially averaging these values over the heavy rainfall region of each storm. Only \(wq\) is presented in terms of a vertically integrated quantity to capture the entire atmospheric quantity. The spatially averaged \(wq\) increases in PGW simulations compared to CTRL simulations in all categories of flash flood–producing storms (Fig. 16a). Vertically integrated CTRL \(wq\) is highest in flash flood–producing storms with moderate π (Table 5), but it exhibits the greatest rate of future increase of 36.5% (12.0% K\textsuperscript{−1}) in storms with strong π. In storms with weak π, future vertically integrated \(wq\) increases at a lower rate of 23.4% (5.5% K\textsuperscript{−1}), though it decreases at low levels below 800 hPa (Fig. 16a), unlike moderate and strong storms that exhibit increases at all levels.

Breaking down \(wq\) by its individual components, \(w\) and \(q\), explains what is contributing to the future \(wq\) changes. Vertical profiles of \(q\) are fairly similar among π categories (Fig. 16b), though storms with weak π display the highest 1000–850-hPa values (Table 5). The future increase in \(q\) is similar among all storms, increasing between 22.9% and 24.5% (6.3%–7.0% K\textsuperscript{−1}), adhering to the Clausius–Clapeyron rate of increase (Table 5). In contrast to \(q\), \(w\) shows large differences among the π categories. Consistent with results in Table 3 and 4 and Figs. 11–13, vertical profiles of \(w\) are highest in storms with strong π (Fig. 16c), in which 850–1000-hPa \(w\) increases in the future as opposed storms with weak π that exhibit a decrease (Fig. 16c, inset). Given the similar increase in \(q\) among all π categories, but greater increase in future \(w\) in storms with strong π, this suggests that changes in low-level \(w\) influence future changes in \(wq\) more. This dynamical piece is thus likely responsible for the greater...
increase in future rainfall in storms with strong $w$ as seen in Fig. 14. However, more uniform increases in $q$ contribute to future increases in rainfall in all categories of $w$ (Table 3) due to the more favorable thermodynamic conditions.

The future changes in $wq$ in relation to rainfall are consistent with the hypothesis from Trenberth (1999) and Trenberth et al. (2003), who suggested that future scaling rates could exceed the Clausius–Clapeyron rate of increase in intense storms that have additional latent heat release.

This is supported by preliminary results from Loriaux et al. (2017) who suggested that a strong dynamical component leads to intensification of rain rates above Clausius–Clapeyron in high percentiles of precipitation. However, as O’Gorman (2015) stated, the thermodynamic change likely dominates the future change in precipitation, which explains a consistent future increase in maximum rain rates above 20% in all flash flood-producing storms, with the dynamical piece (i.e., vertical velocity) playing a secondary role and contributing to the greater intensification of rain rates in storms with strong $w$.

The future changes in $w$ and rainfall among the different $w$ categories of flash flood–producing storms are summarized in Fig. 17. The future change in $w$ (m s$^{-1}$) and area-average rainfall (%) is shown in terms of probability density functions (PDFs) for each $w$ category, where positive values indicate a future increase in $w$ or rainfall. The weak storms display a narrow PDF of $w$ with a negative skew, and a median value (dashed line) below zero, indicating a small median decrease of 0.005 m s$^{-1}$. As shown in Figs. 12 and 13 and Table 4, this is likely due to a greater future increase in downdraft magnitude compared to updraft magnitude, along with a decrease in updraft area. Strong storms, on the other hand, display a broad PDF, indicating a large variability in future $w$ ranging from $\pm 0.1$ m s$^{-1}$, with a median decrease of 0.002 m s$^{-1}$. However, most of the distribution is centered around zero, likely due to stronger future downdrafts being balanced by stronger future updrafts. Moderate storms exhibit a PDF between values of the weak and strong storms, with a median decrease of 0.005 m s$^{-1}$.

These distributions in future $w$ indicate that weak storms mostly experience a decrease in future $w$, while strong storms experience little to a slight decrease in future $w$. These overall changes in future vertical velocity are likely related to future increases in CAPE and CIN that suppress weak convection and promote more frequent strong convection in a future climate over the CONUS (Rasmussen et al. 2017; Prein et al. 2017c; Hoogewind et al. 2017) and globally (Chen et al. 2020).

Future changes in rainfall show an increase among all $w$ categories (Fig. 17b). A positive skew in future rainfall change exists in all $w$ categories, but strong storms exhibit the largest positive skew and median increase in future rainfall of 18.4%. Therefore, while future rainfall increases in all flash flood–producing storms in the MRB due to increases in $q$, it increases the most in strong flash flood–producing storms that exhibit
least future decrease in \( w \). These results suggest that in a warmer and moister future climate, storms with stronger \( w \) dynamically intensify more than weak storms, leading to a thermodynamic feedback in which greater latent heating occurs to produce more rainfall and higher rain rates above that predicted by Clausius–Clapeyron theory, as suggested by Trenberth (1999) and Trenberth et al. (2003). Such a finding has not been documented before within the context of varying storm vertical velocities in convection-permitting RCMs, especially in flood-producing storms, where future changes in dynamics play a nonnegligible role in modulating future rainfall behavior.

4. Conclusions

This study examines changes in 484 flash flood–producing storms in the MRB in a future climate using high-resolution convection-permitting simulations (Liu et al. 2017) that adequately reproduce the rainfall structure, timing, and location of historical flash flood events in CTRL and PGW simulations. While storms in the current climate are associated with flash floods and are likely associated with flash floods in the future due to increases in rainfall and runoff, this cannot be said with certainty, as future changes in soil moisture, land use, and streamflow could all influence flood occurrence in the future. Thus, the focus of the study is on the characteristics of the storms producing the flash floods, rather than the floods themselves. The flash flood–producing storms in the MRB are mostly due to warm-season convection, but a small proportion (19/484 storms) are associated with TCs. The change in future rainfall specifically in floods associated with TCs is separated from the rest of the flash floods, which are mainly confined to the lower MRB.

Flash flood–producing storms in a future climate display a widespread increase in area-average precipitation and runoff, with an average increase of 17% and 32%, respectively. Some of

<table>
<thead>
<tr>
<th></th>
<th>Vertically integrated ( wq ) (kg m(^{-1}) s(^{-1}))</th>
<th>1000–850-hPa ( q ) (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weak</td>
<td>Moderate</td>
</tr>
<tr>
<td>CTRL</td>
<td>0.43</td>
<td>0.98</td>
</tr>
<tr>
<td>PGW</td>
<td>0.88</td>
<td>1.89</td>
</tr>
<tr>
<td>Percent change (% K(^{-1}))</td>
<td>23.4 (5.5)</td>
<td>35.9 (10.2)</td>
</tr>
</tbody>
</table>

FIG. 17. PDF of the future (PGW – CTRL) change in (a) average vertical velocity \( w \) (m s\(^{-1}\)) and (b) area-average rainfall (%) in weak (blue), moderate (purple), and strong (red) flash flood–producing storms. The dashed line at zero distinguishes a future increase/decrease in \( w \) and rain, with anything to the right of the zero line indicating a future increase. Colored dashed lines indicate the median of the distribution.
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this increase is due to the future increase in flash flood rainfall associated with TCs, mainly due to contributions from Hurricane Gustav (2008), which is associated with 7 out of 19 flash floods. While the TC signal is evident in the future rainfall change among all flash flood-producing storms, this signal is diminished, suggesting the predominant change in flash flood-producing storm rainfall in the MRB comes from other types of flood-producing storms, namely, warm-season convection.

Given the convection nature of flash flood-producing storms in the MRB, the influence of vertical velocity on changes in future rainfall is examined. This is motivated by Doswell et al. (1996) who showed that heavy rainfall partially depends on vertical velocity, and O’Gorman (2015) who suggested that changes in precipitation extremes are related to changes in vertical velocity. This is achieved by categorizing flash flood-producing storms as “weak,” “moderate,” or “strong” based on percentiles of spatially and temporally averaged vertical velocity $\bar{w}$ in the CTRL simulations. While all flash flood-producing storms exhibit increased future area-average rainfall amounts due to similar increases in $q$ consistent with the Clausius–Clapeyron rate of increase, flash flood-producing storms with strong vertical velocity display the greatest future increase and storms with weak vertical velocity the least future increase in rainfall. The strong flash flood-producing storms also exhibit the least decrease in future $\bar{w}$, decreasing slightly on average ($-2.4\%$), while weak storms, display the largest future decrease in $\bar{w}$ of $-33\%$. These results qualitatively suggest that changes in storm dynamics might modulate future changes in rainfall amounts in convective storms in the MRB, though the large increases rainfall are dominated by the thermodynamic change (O’Gorman 2015). However, more future work is necessary to explore these results, in order to more fully understand changes in storm dynamics and thermodynamics (i.e., changes in CAPE, CIN, vertical wind shear, etc.).

Overall, results suggest that flash flood–producing storms might be more intense in a future, warmer climate over the MRB—a flash flood hotspot in the CONUS (Saharia et al. 2017; Dougherty and Rasmussen 2019). Flash flood-producing storms with stronger $\bar{w}$ in the MRB display a greater future increase in rainfall and exhibit stronger updrafts and downdraft magnitudes in the future. Stronger storm dynamics (i.e., stronger updrafts) in more intense storms associated with a greater increase in future rainfall amounts suggests a feedback between future changes in storm dynamics and thermodynamics. This link between future changes in storm dynamics, thermodynamics, and rainfall has not been previously examined within the context of flash flood–producing storms of varying vertical velocities in convection-permitting RCMs. The results from this study contribute to an important understanding of how a warmer and moister climate state influences a range of future convective storm behavior within the context of destructive flood-producing storms. Such insight could improve the prediction and preparation of these climate change impacts to create more resilient communities.

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Data availability statement. The WRF–CONUS dataset was accessed through the Cheyenne supercomputer, with an online listing through the Research Data Archive site (https://rda.ucar.edu/datasets/ds612.0/). Flood cases in the Mississippi River Valley are from Dougherty and Rasmussen (2019) and available upon request. Hourly runoff data was obtained through personal communication with Kyoko Ikeda (NCAR).

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