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Key Points:
- More rapid increases are found in more extreme precipitation events in response to warming
- The more rapid increases in more extreme events are caused by atmospheric circulation changes
- Thermodynamically induced changes have relatively uniform effects across extreme events

Supporting Information:
- Supporting Information S1

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Larger Increases in More Extreme Local Precipitation Events as Climate Warms

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Abstract Climate models project that extreme precipitation events will intensify in proportion to their intensity during the 21st century at large spatial scales. The identification of the causes of this phenomenon nevertheless remains tenuous. Using a large ensemble of North American regional climate simulations, we show that the more rapid intensification of more extreme events also appears as a robust feature at finer regional scales. The larger increases in more extreme events than in less extreme events are found to be primarily due to atmospheric circulation changes. Thermodynamically induced changes have relatively uniform effects across extreme events and regions. In contrast, circulation changes weaken moderate events over western interior regions of North America and enhance them elsewhere. The weakening effect decreases and even reverses for more extreme events, whereas there is further intensification over other parts of North America, creating an "intense gets intenser" pattern over most of the continent.

Plain Language Summary Climate models project that extreme precipitation events will intensify during the 21st century at large spatial scales, with several studies suggesting that the most extreme events will exhibit the highest rate of intensification. Identification of the causes of this phenomenon nevertheless remains tenuous, partly because estimating long-term changes in precipitation extremes is difficult, particularly for precipitation extremes at impact-relevant spatial scales. Robustly estimated changes in precipitation extremes at small spatial scales can only be obtained from large extreme precipitation data sets from large ensemble simulations. We employ a large ensemble regional climate simulation experiment performed for North America. The large volume of output from this experiment allows us to confidently obtain statistical evidence that precipitation intensification occurs more rapidly with warming for more extreme events at impact-relevant spatial scales, and secondly, to determine the causes for this phenomenon. The effect of atmospheric moisture increases caused by greenhouse gas warming is found to be similar for extreme precipitation events of different intensities, ranging from 2- to 50-year events. In contrast, atmospheric circulation change due to greenhouse gas warming tends to reduce the effect of the atmospheric moisture increases on less intense events rather than intensifying the effect on more extreme events.

1. Introduction

More rapid increases of extreme precipitation than mean precipitation in response to warming is both an observed and a projected aspect of climate change (Allen & Ingram, 2002; Kharin et al., 2007; Kharin et al., 2013; Trenberth, 1999; Westra et al., 2014; Zhang et al., 2013). It is therefore natural to ask whether the rate of change of extreme precipitation intensity varies from less extreme to more extreme events, and if so, how this occurs. At continental to global scales, global climate modeling studies suggest that extreme precipitation events will intensify in proportion to their intensity during the 21st century (Fischer & Knutti, 2016; O'Gorman & Schneider, 2009; Pendergrass, 2018), with the most extreme events exhibiting the highest rate of intensification. Using coarse-resolution Community Earth System Model large ensemble simulations, a recent study also projected more rapid intensification of more extreme precipitation events particularly in the tropics and subtropics due primarily to the influence of atmospheric circulation changes (Norris et al., 2019).

There is a much less robust understanding of how extreme precipitation of different intensities will change at local to regional scales. Although some studies have found that more extreme precipitation events tend to be more sensitive to daily temperature variations than less extreme events in some regions (e.g., Lenderink et al., 2011; Lenderink & van Meijgaard, 2008; Wasko et al., 2016), it has recently been recognized that the sensitivity to day-to-day temperature changes represents only an aspect of the variation in precipitation extremes that is distinct from the response of extreme precipitation to long-term warming (Guerreiro et al., 2017; Zhang et al., 2017). In fact, estimating long-term changes in precipitation extremes at local impact-relevant spatial scales is difficult because of the high inherent internal variability (Fischer et al., 2014; Guerreiro et al., 2017; Kendon et al., 2008; Li et al., 2018; Westra et al., 2013). This is particularly so for very rare precipitation extremes such as events that occur only once every 50 years. Further, physical reasons for the more rapid intensification of more extreme precipitation events remain elusive.

Large ensemble simulations with high-resolution regional climate model that enable very large samples of precipitation extremes may help to increase our understanding of projected changes in extreme precipitation at local to regional scales. Based on an ensemble of 35 regional climate simulations of North America, Li et al. (2018) found, consistent with lower-resolution global modeling studies, that more extreme hourly-to-daily local-scale precipitation events over most of North America also intensify more rapidly with warming than less extreme events. Here we investigate the role of thermodynamics and dynamics in driving the more rapid intensification of more extreme precipitation events. To do so, we adopt an alternative method for diagnosing the relationship between temperature and extreme precipitation to that used in Li et al. (2018) in order to more flexibly study the roles of both temperature and atmospheric circulation changes.

2. Data and Methods

We briefly describe the data and methods used in this study here, and provide more details in the online supporting information. We use output (precipitation and vertical velocity at 500 hPa) for the period 1981–2100 from a large ensemble of 35 regional climate simulations for North America performed with the Canadian Regional Climate Model (CanRCM4) at a horizontal resolution of ~50 km (Scinocca et al., 2016). These simulations are driven by a corresponding large initial-condition ensemble of global Canadian Earth System Model (CanESM2) simulations with historical forcing through 2005 and extended with the Representative Concentration Pathway 8.5 forcing scenario (van Vuuren et al., 2011). Comparisons with gridded observations find that the historical CanRCM4 simulations reasonably reproduce the observed intensity of precipitation extremes over most of North America, but with marked negative biases during May-November in the southeastern United States (Whan & Zwiers, 2016a, 2016b).

We use quantile regression to quantify the rate of intensification of extreme precipitation events with annual global mean surface air temperature (in %/°C). We estimate such scaling rates for annual maximum 6-, 12-, and 24-hr precipitation events of 5 different intensity levels corresponding respectively to annual probabilities of exceedance of 0.5, 0.2, 0.1, 0.05, and 0.02 (where the intensity levels evolve with warming). These levels can be interpreted as 2-, 5-, 10-, 20-, and 50-year return levels, respectively, under the climate state at the corresponding level of warming. We test whether more extreme precipitation events intensify more rapidly than less extreme events with warming by comparing the estimated scaling rates for different intensity levels in terms of a spatiotemporal block bootstrap test at the 5% significance level.

Quantile regression is a nonparametric technique that allows for estimation of trends in any quantile of a response variable distribution (Koenker, 2005). It can be considered as an extension of classical least squares regression. Compared to the method based on a generalized extreme value distribution with temperature-dependent parameters in Li et al. (2018), quantile regression can more flexibly represent the different responses of extreme precipitation events of different intensity levels. We perform quantile regression at each land grid cell by pooling data from the 35 simulations and 13 selected grid cells within a 7×7 grid cell region (see Figure S1 in the supporting information for the spatial pooling configuration). In doing so, we are assuming that all grid cells within a spatial pool have a common regression slope (i.e., scaling rate estimate). With these 35 simulations and the chosen spatial pooling, there is $35 \times 13 = 455$ times as much data involved

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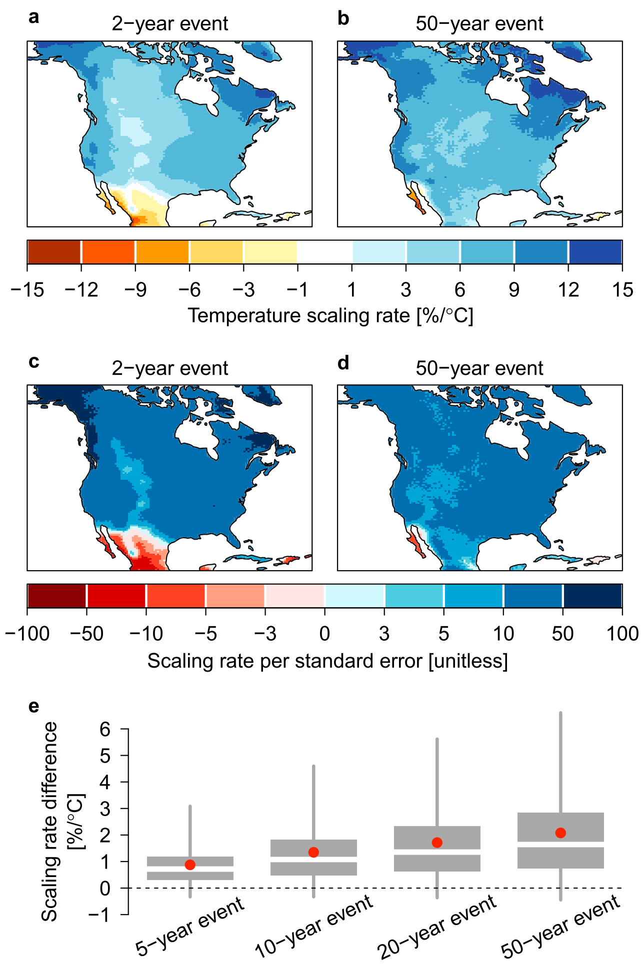

Figure 1. Larger increases in more extreme precipitation events than in less extreme events in response to global warming. (a, b) Estimated scaling rates (%/°C) for the (a) 2- and (b) 50-year 6-hr precipitation events with respect to annual global mean surface air temperature. (c, d) Uncertainties (unitless) in the estimated scaling rates shown in (a) and (b) expressed as "scaling rate per standard error." Standard error is estimated via a bootstrap approach (see online supporting information). (e) Spatial probability distributions of the estimated scaling rate differences between more extreme precipitation events (shown along the horizontal axis) and the moderate 2-year events. The white line and red dot represent the spatial median and mean over North America, respectively. The height of the box represents the interquartile range across the domain, while the whisker extends to the 5–95% range. See Figures S2 and S3 for 12 and 24-hr extreme precipitation events.

in the scaling rate estimation as is available from a single simulation for an individual grid cell, which can substantially reduce uncertainty in the estimates of the scaling rate caused by internal variability. We select a subset of grid cells from the 7 × 7 region so as to make computations manageable.

We diagnose the thermodynamic and dynamic scaling rates for precipitation extremes using the method in Emori and Brown (2005), which is based on the empirical relationship between precipitation intensity and vertical velocity at 500 hPa. The diagnosed thermodynamic scaling rate represents the response of extreme precipitation to changes in atmospheric moisture conditional on the present-day circulation, while the diagnosed dynamic scaling rate represents its response to circulation changes acting on the present-day moisture distribution. We consider the sum of these thermodynamic and dynamic scaling rates as the diagnosed total scaling rate. We note that the diagnosed total scaling rate in the CanRCM4 simulations agrees well with the direct estimate from the simulations by quantile regression (e.g., Figures 1a and 1b vs. Figures 2a and 2d).

The choice of an empirical method for diagnosing thermodynamic and dynamic scaling rates is necessary here since vertical velocities were only archived from the CanRCM4 simulations at three vertical levels (i.e., 800, 500, and 200 hPa), which is insufficient for the implementation of more physically based approaches such as the diagnostic of O'Gorman and Schneider (2009) or the moisture budget analysis of Norris et al. (2019). As this statistical method is based on the empirical correlation between precipitation intensity and vertical velocity at 500 hPa, it can become less reliable in regions where the correlation is weak. It is verified that for all land grid cells in North America, the correlation between precipitation and vertical velocity at 500 hPa is greater than 0.3 for all studied accumulation durations in the CanRCM4 simulations when the vertical velocity is upward, that is, when precipitation is expected to occur.

3. Results

3.1. Larger Increases in More Extreme Local Precipitation Events in Response to Warming

Consider as an example the estimated scaling rates for 6-hr extreme precipitation events. The magnitude of extreme 6-hr precipitation events increases almost everywhere across North America regardless of their intensity (Figures 1a and 1b), except for southern subtropical regions around Mexico and Greater Antilles where moderate events become less intense (e.g., Figure 1a for 2-year events). In general, the rate of increase is smaller over western interior regions than elsewhere. This is the case for all studied intensity levels, though spatial gradients are somewhat sharper for relatively less extreme events (Figure 1a vs. 1b). Similar results are found for extreme precipitation events of longer durations (Figures S2 and S3). These results are consistent with those reported in our previous study (Li et al., 2018), where a generalized extreme value distribution with temperature-dependent parameters is used for scaling rate estimation. The size of the large ensemble simulation, with its 35 runs, ensures that the estimated scaling rates are robustly constrained across almost all of North America for all studied extreme precipitation events, with the absolute value of the ratio between the scaling rate estimate and its standard error being substantially greater than 5 (e.g., Figures 1c and 1d and Figures S2 and S3). These robustly constrained estimates provide a basis for a rigorous statistical test of whether more extreme precipitation events indeed intensify more rapidly than less extreme events with global warming in CanRCM4 (see online supporting information for details).

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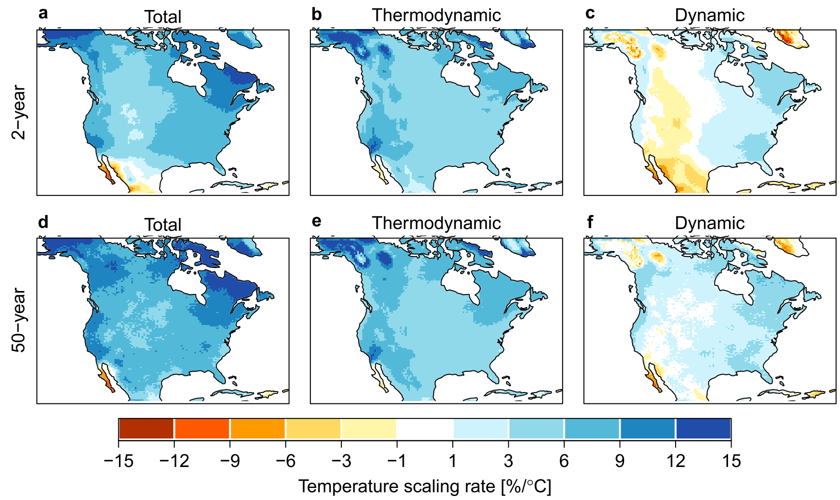

Figure 2. The response of extreme precipitation to warming and its thermodynamic and dynamic components. Panels show the diagnosed total (a, d), thermodynamic (b, e), and dynamic (c, f) scaling rates for the 2- (a–c) and 50-year (d–f) 6-hr precipitation events with respect to annual global mean surface air temperature. See Figures S4 and S5 for 12 and 24-hr extreme precipitation events.

We find for all durations that the estimated scaling rates for more extreme events are significantly larger than those for less extreme events at the 5% significance level over most of North America, particularly when the two intensity levels in the comparison are well separated in terms of their relative frequencies of occurrence and when the scaling rates are well constrained (Table S1). For example, for 6-hr precipitation events, ~75% of the land area exhibits a significantly larger rate of intensification in 50-year events than in 2-year events. The most pronounced scaling rate differences occur along the Rockies and in the southern subtropical regions around Mexico and the Greater Antilles for all paired comparisons. On average over North America, there are clear upward shifts of the probability distributions of the estimated scaling rates for more extreme precipitation events to high values relative to the moderate 2-year events, with the shift magnitude increasing with precipitation intensity (Figure 1e and Figures S2 and S3).

The increase in mean precipitation in a climate warmed by rising greenhouse gas concentrations is energetically constrained to ~2%/°C (Allen & Ingram, 2002). In contrast, it has been argued that extreme precipitation should be free to intensify at higher rates, such the Clausius-Clapeyron (CC) rate of ~7%/°C or greater depending on the duration of the event and the processes involved (Trenberth, 1999). Based on this, one might expect a continuum of responses to greenhouse gas-induced warming across the precipitation distribution, with smaller increases that are close to the mean for frequent events, and larger increases for extreme events of increasing rarity. The systematic increase of the estimated scaling rate with precipitation intensity in Figure 1e shows no sign of leveling off, implying that there may not be an upper bound on intensity change for events of increasing rarity, at least for the extreme levels (up to 50-year events) examined here. These results emphasize that CC scaling may be too idealized to provide detailed guidance to practitioners such as engineers about the expected intensification of future precipitation extremes at local impact-relevant scales; instead, the intensification rate varies spatially and with precipitation intensity and may depart considerably from the CC rate.

3.2. Causes for the Larger Increases in More Extreme Local Precipitation Events

To gain insight into the physical mechanisms causing the differences in the intensification across the frequency distribution of extreme precipitation events, we study the thermodynamic and dynamic scaling rates of extreme precipitation (see online supporting information for details). We find that the thermodynamic scaling rates are positive and dominate the total scaling rates almost everywhere across North America for the 2- to 50-year extreme precipitation events considered (Figures 2b and 2e; Figures S4 and S5), consistent with the expectation that the intensification of extreme precipitation is driven primarily by the increase in atmospheric moisture. The thermodynamic scaling rates are relatively homogeneous in space, in line with

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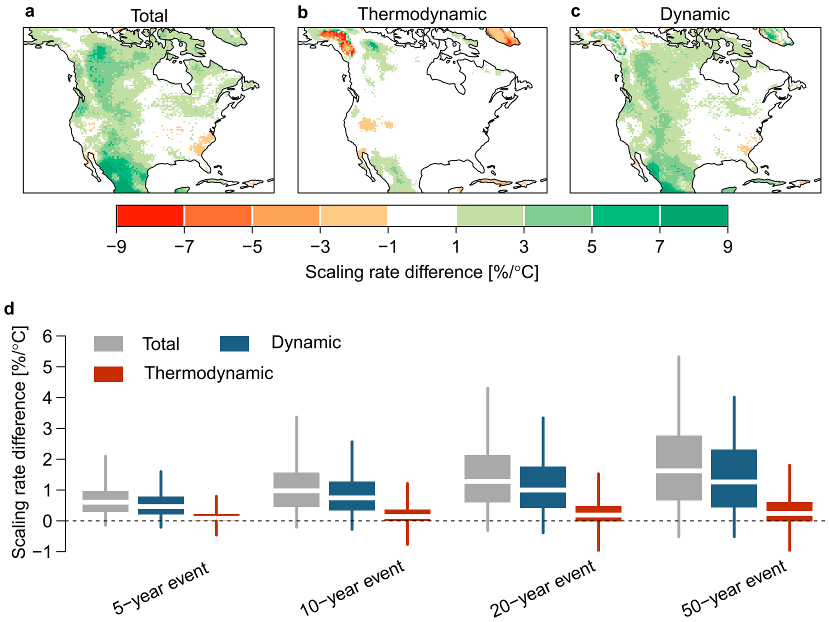

Figure 3. Changes in atmospheric circulation drive the larger increases in more extreme precipitation events in response to global warming. Differences in the diagnosed total (a), thermodynamic (b), and dynamic (c) scaling rates between the extreme 50-year 6-hr precipitation events and the moderate 2-year events. (d) Spatial probability distributions of the differences in the diagnosed total (gray bars), thermodynamic (orange bars), and dynamic (blue bars) scaling rates between more extreme precipitation events (shown along the horizontal axis) and the moderate 2-year events. The white line denotes the spatial median over North America. The height of the box represents the interquartile range across the domain, while the whisker extends to the 5–95% range. See Figures S6 and S7 for 12 and 24-hr extreme precipitation events.

the thermodynamic responses of daily precipitation extremes diagnosed from lower-resolution Coupled Model Intercomparison Project Phase 5 models (Pfahl et al., 2017). Surprisingly, the thermodynamic scaling rates are even more homogeneous among extreme precipitation events (of a given duration; Figure 2b vs. 2e; Figures S4 and S5), suggesting that direct thermodynamic effects are unlikely to explain the increasing intensification rate of extreme precipitation events with precipitation intensity.

The dynamic scaling rates exhibit complex variations both in space and among precipitation events of differing frequencies (Figures 2c and 2f; Figures S4 and S5). For example, moderate 2-year 6-hr precipitation accumulations exhibit negative dynamic scaling rates in a wide swath extending from the southernmost subtropics to Alaska along the Rockies and the central Great Plains, while positive but relatively small dynamic scaling rates are found elsewhere (Figure 2c), broadly consistent with the spatial patterns of the dynamic changes daily precipitation extremes diagnosed from different global models (Pfahl et al., 2017). The negative dynamic scaling rates offset and even outweigh the positive thermodynamic scaling rates, leading to the relatively weak intensification of the moderate 2-year events over western interior regions and the decline in the subtropics (Figures 1a and 2a). Moving toward more extreme events, areas with negative dynamic scaling rates reduce and eventually disappear almost completely in the extreme 50-year events (Figure 2c vs. 2f), while simultaneously, the positive dynamic scaling rates increase somewhat. Given the relatively uniform thermodynamic scaling among precipitation events, this leads to the more rapid intensification of more extreme events compared to less extreme events. Similar findings are observed in extreme precipitation events of longer durations (Figures S4 and S5).

The spatial patterns of differences between dynamic scaling rates for more and less extreme events agree closely with the corresponding total scaling rate differences (Figure 3a vs. 3c; Figures S6 and S7), with the spatial correlation being >0.8 for all paired comparisons of extreme precipitation events of all durations considered, whereas the thermodynamic scaling rate differences are near zero with some localized exceptions (Figure 3b; Figures S6 and S7). On average, the differences in the dynamic scaling rate for more extreme events compared to 2-year events (blue bars in Figure 3d) vary in accord with the corresponding total

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scaling rate differences as precipitation intensity increases (gray bars in Figure 3d). In contrast, the thermodynamic scaling rates change little with intensity (red bars in Figure 3d). These results point again to the importance of circulation change in modulating the thermodynamic influence on extreme precipitation. This influence enhances thermodynamic increases in more extreme events over almost all of North America but dampens the increases in less extreme events over substantial parts of the continent. Consequently, more extreme events are seen to intensify more with warming than less extreme events. A moisture budget analysis of the coarse-resolution Community Earth System Model large ensemble produces qualitatively consistent conclusions on average over North America, though with considerable differences in the magnitudes of diagnosed scaling rates, which are likely due to the use of different climate models with different resolutions (Figure S8).

What processes alter the thermodynamic influence on extreme precipitation events? Typical midlatitude synoptic-scale weather events are described by the omega equation (Holton, 2004), which indicates that large-scale ascent associated with convergence will be amplified by the diabatic heating from increased precipitation (Nie et al., 2019; Tandon, Zhang, et al., 2018), thus producing a positive feedback. Updraft speed may also be affected by changes in eddy length scales (i.e., the horizontal length scales of ascending anomalies during extreme precipitation events; Tandon, Zhang, et al., 2018, Tandon, Nie, et al., 2018), transient eddy activity, and other diabatic processes at regional scales. These processes, which result in changes in midtropospheric vertical motion, evidently have widespread influences on more extreme precipitation events over North America (e.g., Figure 2f), suggesting that the intensification of precipitation extremes beyond a purely thermodynamic response is not strongly constrained by local processes. These processes also appear to weaken the thermodynamic response in less extreme precipitation events over substantial parts of North America. Hence, we argue our results may be explained by changes in vertical motion, with positive feedback from latent heat release being part, but certainly not all of the story. Further study will be required to gain additional insight into the processes that are responsible for the modulation of the thermodynamic influence on precipitation extremes.

4. Discussion and Conclusions

We note that robust evaluation of differences in the responses of extreme precipitation events of different intensity levels and diagnosis of the underlying mechanisms requires very large extreme precipitation data sets such as those that are available from large ensemble simulations. Unfortunately, to date, it has only been possible to produce large ensemble simulations using conventional models with parameterized representations of convection, such as the CanESM2/CanRCM4 combination of models used in this study. While questions remain about whether such models can adequately represent subdaily to daily extreme precipitation at the scales that the models resolve, we think that our separation of dynamical and thermodynamic influences on the extremes simulated by the CanESM2/CanRCM4 combination of models provides provocative insights into the processes that may be responsible for intensifying the most extreme precipitation events more rapidly with warming. Coordinated multimodel multimember high-resolution convection-permitting regional model experiments, though computationally expensive, will be needed to better understand the complex interactions among changes in precipitation extremes, atmospheric moisture, and circulation in a warming climate. In addition, model experiments based on individual extreme event cases that deliberately control different aspects of atmospheric circulation change may also help to better understand its role in modulating the effect of the atmospheric moisture increases on extreme precipitation events of different intensities. Changes in precipitation extremes may exhibit seasonal characteristics. Further studies are needed to explore the seasonality of changes in precipitation events of different extreme levels.

In summary, projections based on a large ensemble of regional climate simulations indicate that the more extreme precipitation events of hourly-to-daily durations will intensify more rapidly than less extreme events over most of North America. The more rapid intensification of rarer, more extreme, events is primarily a consequence of circulation change. The direct thermodynamic influence on the intensity of extreme precipitation appears to be relatively constant across the frequency distribution for the range of extremes (2 to 50-year events) that we have examined. The dynamical influence, on the other hand, is complex, offsetting the thermodynamic effect on less extreme precipitation events over a substantial part

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of North America, while combining with the thermodynamic effect on more extreme events over almost all of the continent.

Author Contributions

C. L., F. Z., and X. Z. initiated the project and designed the study. G. C. and J. L. helped with the study design. C. L. conducted the analysis. G. L., J. N., and Y. T. helped in data processing and computing. All authors contributed substantially to the interpretation of results. C. L. and F. Z. wrote the paper with input from all authors.

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