

1 **Observed Changes in Daily Precipitation Intensity in the United States**

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15 **Key Points**

- 16 • We find consistent shifts from lower to higher daily precipitation intensities, particularly
- 17 in the central and eastern United States
- 18 • All contiguous United States domains show significant changes in their distributions of
- 19 precipitation intensity from 1951-1980 to 1991-2020
- 20 • Mean and standard deviation of wet day precipitation intensities increase for nearly all
- 21 domains in the central and eastern United States
- 22

23 **Abstract**

24

25 The characterization of changes over the full distribution of precipitation intensities remains an  
26 overlooked and underexplored subject, despite their critical importance to hazard assessments  
27 and water resource management. Here, we aggregate daily *in situ* Global Historical Climatology  
28 Network precipitation observations within seventeen internally consistent domains in the  
29 United States for two time periods (1951-1980 and 1991-2020). We find statistically significant  
30 changes in wet day precipitation distributions in all domains – changes primarily driven by a  
31 shift from lower to higher wet day intensities. Patterns of robust change are geographically  
32 consistent, with increases in the mean (4.5-5.7%) and standard deviation (4.4-8.7%) of wet day  
33 intensity in the eastern U.S., but mixed signals in the western U.S. Beyond their critical  
34 importance to the aforementioned impact assessments, these observational results can also  
35 inform climate model performance evaluations.

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38 **Plain Language Summary**

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40 Lots of research has been done to see how precipitation event totals are affected by climate  
41 change. Instead of yearly totals or extreme precipitation, we look at how daily precipitation is  
42 changing at all intensities, which has effects on natural hazards and related risks. We group  
43 daily rain gauge measurements within seventeen climate regions in the United States for two  
44 thirty-year time periods: 1951-1980 and 1991-2020. We find changes in daily precipitation

45 intensity in all regions, changes that are mostly caused by a shift from lower to higher intensity  
46 events. We also identify a broad area within the central and eastern U.S. with consistent  
47 increases in average precipitation and its variability. Changes are mixed in the western U.S. In  
48 addition to the impacts mentioned above, our results can also be used to see how well climate  
49 models perform.

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## 52 **Keywords**

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54 daily precipitation, precipitation variability, precipitation intensity distribution, GHCN, NEON,  
55 NCA

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## 58 **1. Introduction**

59

60 Anthropogenic climate change is driving shifts in global precipitation patterns (Douville et al.,  
61 2021). Recent studies have characterized these shifts across a diversity of metrics and scales,  
62 including annual totals, frequencies of occurrence, and zonal distributions. At the daily scale,  
63 recent efforts have demonstrated robust changes in extreme precipitation intensities (i.e., the  
64 95th percentile and above; Seneviratne et al., 2021). However, characterization of changes in the  
65 full distribution of precipitation intensities – events which are, by definition, much more  
66 common – are often overlooked. While extreme precipitation events can produce outsized

67 damages given their exceptional nature, changes in non-extreme precipitation have critical  
68 impacts on many Earth systems, including agriculture (Shortridge, 2019), infrastructure (Cook  
69 et al., 2019), and natural hazards (Dinis et al., 2021; Cannon et al., 2008). For example, including  
70 increasing daily precipitation variability in projections of future crop yields resulted in a 2-6%  
71 reduction in relative yields compared to projections excluding this factor (Shortridge, 2019).  
72 Here, to more comprehensively characterize daily precipitation shifts, we explore changes in the  
73 full distribution of wet day precipitation intensities over seventeen climatically-distinct regions  
74 across the United States.

75

### 76 *1.1. Why is precipitation changing?*

77 Globally, mean annual precipitation is expected to increase  $\sim 2\%/K$  with warming (Trenberth,  
78 2003; Held and Soden, 2006; Wentz et al., 2007; Wood et al., 2021), though considerable  
79 observed and projected spatiotemporal variability underlie this estimate (e.g., Polade et al.  
80 (2014) globally; Caloiero et al. (2018) in Europe). Anthropogenic climate change is expected to  
81 alter precipitation patterns via both thermodynamic and dynamic processes. Thermodynamic  
82 changes are driven by an increase in atmospheric moisture content with warming, which occurs  
83 at a rate of  $\sim 6-7\%/K$  as described by the Clausius-Clapeyron relationship. An increase in  
84 atmospheric moisture content leads to an increase in globally averaged rainfall, though  
85 magnitude estimates of the corresponding increase depend on spatial and temporal scales  
86 (Westra et al., 2014; Cannon and Innocenti, 2019; Sun et al., 2021; Wood and Ludwig, 2020;  
87 Wood et al., 2021; Bador et al., 2018, Giorgi et al., 2019). Globally averaged precipitation  
88 increases are also constrained by Earth's energy budget, which leads to a discrepancy between

89 increased moisture availability and precipitation change (Pendergrass and Hartmann, 2014a).  
90 Dynamically-driven precipitation changes are mostly associated with shifts in atmospheric  
91 circulation (e.g., Swain et al, 2016; Endo and Kitoh, 2014). Examples of these mechanisms  
92 include climatological shifts in cyclone and anticyclone tracks, baroclinic zones, and jets – which  
93 are driven by the reduction in the equator-pole temperature gradient – a poleward expansion of  
94 the descending branch of Hadley cells, and increases in land-sea temperature gradients (Polade  
95 et al., 2014). Altered precipitation totals can also be caused by more subtle changes, such as  
96 reductions in storm speeds (Kahraman et al., 2021). The relative importance of these factors  
97 varies widely depending on location.

98         Locally, the rate of increase of precipitation for smaller-scale and heavy precipitation  
99 events parallels and can even exceed Clausius-Clapeyron scaling, particularly during  
100 convective precipitation (Lenderink and van Meijgaard, 2008; Guerreiro et al., 2018; Risser and  
101 Wehner, 2017) or where local conditions shift from favoring stratiform to convective  
102 precipitation (Berg and Haerter, 2013; Berg et al., 2013; Ivancic and Shaw, 2016). Prein et al.  
103 (2017) project increases in extreme precipitation frequency and intensity with rising  
104 temperatures in moist, energy-limited environments, along with abrupt decreases in dry,  
105 moisture-limited environments. However, the precise scaling of extreme precipitation to rising  
106 temperatures and moisture availability is dependent on a multitude of factors, including  
107 characteristics of local convection, topography, and synoptic-scale dynamics (Moustakis et al.,  
108 2020).

109

110 *1.2 How is daily precipitation variability changing?*

111 Increases in the frequency and intensity of extreme daily precipitation have been widely  
112 observed (Westra et al., 2014; Donat et al., 2016; Asadieh and Krakauer, 2015; Sun et al., 2021;  
113 Wood et al., 2021; Alexander et al., 2006; Myhre et al., 2019) and generally agree with increases  
114 projected by climate model simulations (Moustakis et al., 2021; Toreti et al., 2013; Groisman et  
115 al., 2005; Fischer and Knutti, 2014; Fischer and Knutti, 2016; Myrhe et al., 2019; Min et al., 2011;  
116 O’Gorman, 2015). For example, Lehmann et al. (2015) found that record-breaking rainfall events  
117 occurred 12% more often than expected globally from 1981-2010 with an estimated 26% chance  
118 that a record-setting rainfall event is due to long-term climate change. Min et al. (2011)  
119 examined observed and modeled changes and found that climate change has contributed to the  
120 observed intensification of heavy precipitation events over two-thirds of the Northern  
121 Hemisphere. Sub-daily extreme precipitation is both observed and projected to increase at an  
122 even faster rate than daily extremes at regional and global scales (e.g., U.S., Prein et al., 2017;  
123 Netherlands, Lenderink and van Meijgaard, 2008; global, Westra et al., 2014).

124         Despite widespread research into precipitation extremes, changes over the full  
125 distribution of precipitation intensities are less well-characterized. For instance, Chou et al.  
126 (2012) find an increase in heavy precipitation events relative to light in the global tropics in  
127 model simulations. Giorgi et al. (2019) find similar results over extratropical land, including an  
128 overall reduction in lower intensity event frequency and increase in higher intensity event  
129 frequency. Hennessy et al. (1997) modeled changes in daily precipitation and found distribution  
130 shifts from low to high intensity at high latitudes along with increased heavier precipitation  
131 events coincident with a reduction of moderate events in the mid-latitudes. Despite the

132 identification of changes in distributions of precipitation intensity at broad global or zonal  
133 scales, studies at regional and local scales are sparse.

134 In the United States, increases in mean annual precipitation and extreme precipitation  
135 have been noted, though changes are non-uniform and have seasonal dependencies (Easterling  
136 et al., 2017; Goble et al., 2020). Here, we focus on observed changes in daily precipitation.  
137 Increases in heavy to extreme precipitation are well established in the central and eastern U.S.  
138 (Groisman et al., 2012; Sun et al., 2021; Kunkel et al., 2013; Guilbert et al., 2015; Karl and Knight,  
139 1998; Pryor et al., 2008; Groisman et al., 2001; Villarini et al., 2013; Contractor et al., 2021;  
140 Groisman et al., 2005). In addition, increases in light-to-moderate precipitation frequency are  
141 driving a general increase in precipitation frequency in the U.S. (Pal et al., 2013; Goodwell and  
142 Kumar, 2019; Karl and Knight, 1998; Roque-Malo and Kumar, 2017). However, the evolution of  
143 the proportion of lower vs higher intensity wet days is less resolved with contradictory findings  
144 reported. For example, Groisman et al. (2012) found more frequent higher intensity events over  
145 the central U.S. despite no change in moderate intensity events. In contrast, Karl and Knight  
146 (1998) identified an increasing frequency of events across most percentiles and U.S. regions,  
147 including an increase in moderate intensity events. While findings focused on the eastern and  
148 central U.S. are generally consistent, studies focused on the western U.S. disagree. For example,  
149 Contractor et al. (2021) and Higgins and Kousky (2013) find generally increasing frequency and  
150 intensity of wet day events over the majority of the U.S. but decreasing moderate to heavy  
151 intensity events along the Pacific coast. Their findings are inconsistent with findings of  
152 increasing or insignificant extreme precipitation change on the U.S. west coast by Kunkel et al.  
153 (2013). Many previous analyses used gridded precipitation products (e.g., Contractor et al.,

154 2021) that possess known inconsistencies across products (Alexander et al., 2020) and center on  
155 heavy-to-extreme precipitation or arbitrary light or moderate thresholds (e.g., 50th percentile or  
156 10mm; Higgins and Kousky, 2013; Kunkel et al., 2013). To overcome these methodological  
157 limitations and reconcile disparate findings, here we examine changes over the complete  
158 distribution of precipitation intensities by spatially aggregating a large number of *in-situ* station  
159 observations across a high number of empirically determined, distinct U.S. climate regions.

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161

## 162 2. Methods

163

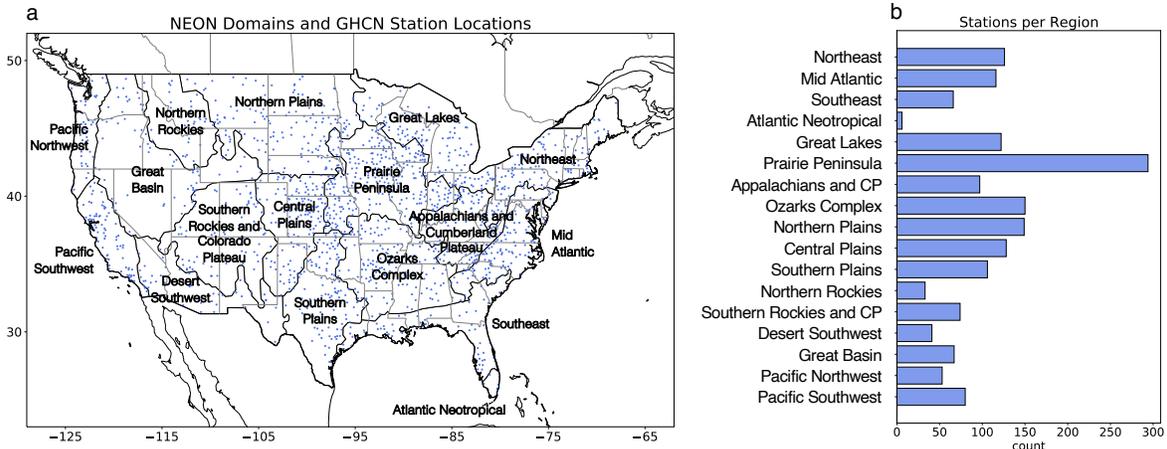
164 To partition the U.S. into climatologically-distinct regions, we adopt the National Ecological  
165 Observatory Network (NEON) domains. These twenty domains were designed to be  
166 climatically homogeneous within-domains but distinct across-domains and were created using  
167 a multivariate geographic clustering analysis incorporating nine different temperature and  
168 precipitation variables (National Ecological Observatory Network, n.d.; Schimel, 2011; Keller et  
169 al., 2008). We center our analysis on the seventeen domains that compose the contiguous United  
170 States (Figure 1). Rather than analyze station records individually, we employ spatial  
171 aggregation to provide a larger sample size and better view of change over time given the  
172 inherent limitations of individual station statistics and internal climate variability. Spatial  
173 aggregation has frequently been employed in precipitation analyses (e.g., Fischer et al., 2013;  
174 Groisman et al., 2005; Kunkel et al., 2013). In addition to the seventeen domains within the  
175 contiguous U.S., we include findings for the remaining three domains, as well as replicate our

176 analysis for the U.S. National Climate Assessment regions (NCA; Easterling et al., 2017), in the  
177 Supporting Information.

178 Our analysis uses daily *in-situ* observations of precipitation from the Global Historical  
179 Climatology Network Daily (GHCN-D). The GHCN-D database is compiled by NOAA's  
180 National Centers for Environmental Information and consists of records from over 80,000  
181 stations and 180 countries and territories, including the most complete collection of daily U.S.  
182 data available (Menne et al., 2012). Observations in GHCN-D have a sensitivity of 0.1 mm and  
183 undergo a series of nineteen quality control tests to flag duplicate data, climatological outliers,  
184 and other inconsistencies, as detailed in Durre et al. (2010).

185 To examine changes in the distribution of wet day precipitation intensities, we aggregate  
186 all wet day precipitation observations for all qualifying stations within each domain, where a  
187 wet day is defined as a station-day observing 1 mm or more of precipitation. This is done for  
188 two thirty-year periods: 1951-1980 and 1991-2020. We choose the early time period (1951-1980)  
189 due to the proliferation of GHCN-D stations that peaked in this interval (see Fig. 3b; Menne et  
190 al., 2012); we selected the late time period (1991-2020) as the most recent 30-year interval with  
191 available data. The distributions are built around 30-year periods of reference to overcome  
192 known impacts of interannual modes of climate variability (e.g., Groisman et al., 2012) and align  
193 with World Meteorological Organization guidelines (World Meteorological Organization, 2017).  
194 To ensure quality of record and consistency in stations across periods, we include data from a  
195 station if 90% of the station-years in both periods are complete, where a complete year is  
196 defined as containing 90% or more of all available daily records after removal of any flagged  
197 entries. Applying this filter reduces available records from an initial 63,571 to 1,742 that are

198 suitable for our analysis. Figure 1 depicts station locations and stations per domain. Finally, we  
 199 manually check extreme outliers against historical records (e.g., state records, U.S. National  
 200 Weather Service records), to corroborate their validity. This final check identified 32  
 201 unverifiable records that we remove from our analysis (Table S1).



202  
 203 *Figure 1: Station Locations and Domain Station Counts. (a) Map of qualifying GHCN-D stations (blue*  
 204 *dots) overlaid on the United States with NEON domain boundaries in thick black and state borders in*  
 205 *thin grey. (b) Histogram of the number of qualifying stations within each NEON domain.*

206  
 207 Qualifying wet day observations are aggregated into early or late period daily  
 208 precipitation intensity probability distributions via block bootstrapping. Raw observations from  
 209 qualifying stations are parsed into two-year station-segments, resampled with replacement, and  
 210 combined. The resultant two-year aggregations are then stacked to produce a single 30-year  
 211 precipitation intensity distribution sample for each domain; this process is replicated 1,000  
 212 times for each period in each domain. We then calculate differences between early and late  
 213 period distributions across four statistical moments (mean, standard deviation, skew, kurtosis).

214 This process is replicated for each bootstrap resample to determine statistical confidence  
215 intervals for changes in statistical moments. In addition, we characterize changes in the full  
216 precipitation intensity distributions by quantifying changes in the number of wet day events  
217 within each five percentile increment bin (e.g., 50th-55th percentile), where percentile bin  
218 ranges are determined by values in the early period distribution sample.

219 Finally, the initial early and late precipitation intensity distributions are directly  
220 compared through two-sample Kolmogorov-Smirnov and Anderson-Darling tests, both of  
221 which are suitable for nonparametric analysis and are insensitive to the number of events in the  
222 distributions (Chakravarti et al., 1967; Stephens, 1974). These tests were performed on all  
223 available station data within a domain (i.e., not bootstrapped). We employed the Anderson-  
224 Darling test in addition to the more common Kolmogorov-Smirnov due to its higher sensitivity  
225 to extreme values, though results proved largely consistent. While both tests can determine if  
226 distributions are distinct, they do not provide descriptive information as to how the  
227 distributions differ. We thus characterize early and late period distribution differences by  
228 computing differences in wet day intensity distributions and their statistical moments.  
229 However, it should be noted that statistical moments do not comprehensively characterize a  
230 distribution. As such, statistically significant changes identified by the Kolmogorov-Smirnov  
231 and Anderson-Darling two-sample tests, may not be discernible via the moment difference  
232 analysis.

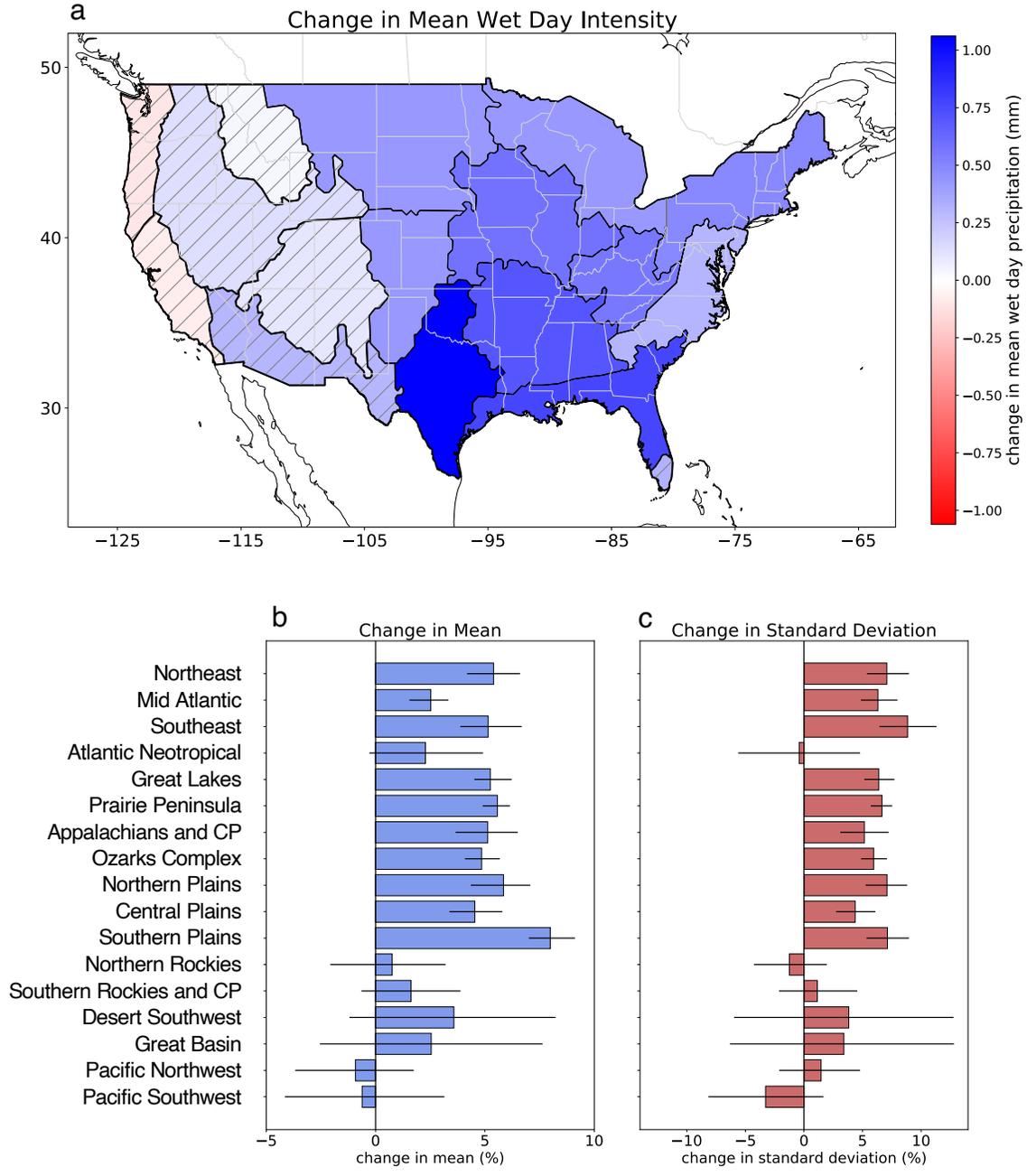
233

### 234 3. Results

235

236 Early and late period distributions of wet day precipitation intensity are statistically  
237 significantly different ( $p < 0.05$ ) for all NEON domains in the contiguous U.S. (Table S2), with  
238 broadly consistent changes observed across central and eastern domains. Specifically, mean wet  
239 day precipitation increases in all domains east of the Rocky Mountains (Figure 2a-b) except for  
240 one (Atlantic Neotropical), with an intensification in mean wet day precipitation between 4.5-  
241 5.7% for the majority of these eastern domains (Figure 2b). Similarly, the standard deviation of  
242 wet day precipitation intensity increased between 4.4-8.7% for each eastern domain (Figure 2c)  
243 outside of the Atlantic Neotropical. Changes in mean and standard deviation for western  
244 domains are mixed in sign and not statistically significant. Table S2 shows the differences in  
245 mean, standard deviation, skew, and kurtosis across all NEON domains (results for NCA  
246 regions are reported in Figure S2 and Table S3).

247



248

249 *Figure 2: Changes in Wet Day Precipitation Intensity Between Early and Late Periods. (a) Map of*  
 250 *changes in mean wet day precipitation intensity for NEON domains. Red-blue fill indicates change in*  
 251 *precipitation intensity (mm/day) within domains (dark grey borders) on top of state boundaries (light*

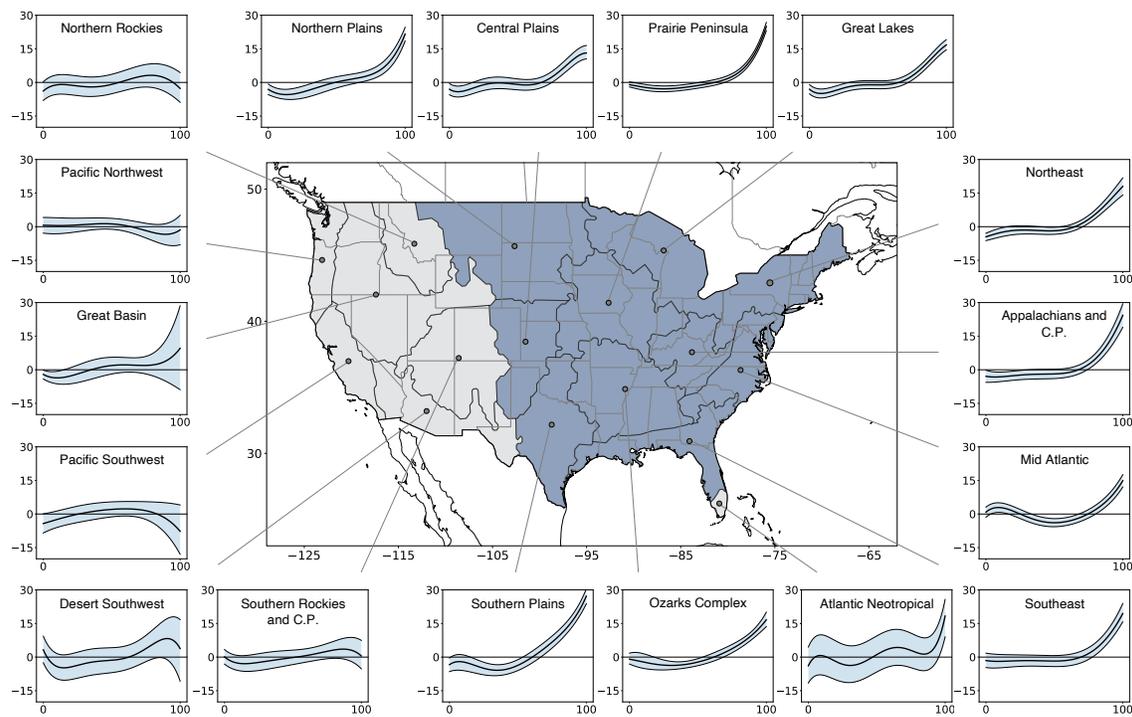
252 *grey borders). Hatching denotes domains without statistically significant changes. (b) Percentage*  
253 *changes in mean wet day precipitation for NEON domains. Blue bars show percentage change of mean*  
254 *and horizontal black line shows 95% confidence interval. (c) Same as (b) but for standard deviation of wet*  
255 *day precipitation and with red bars.*

256

257 In addition to changes in mean and standard deviation, we also quantify shifts in the  
258 underlying distributions across all precipitation intensities, allowing for a more nuanced  
259 characterization of observed distribution changes. Figure 3 illustrates smoothed observed shifts  
260 as determined by block bootstrapping. There is a broadly consistent shift from lower- to higher-  
261 intensity wet days across the central and eastern U.S. (blue filled regions, Figure 3). These  
262 changes are determined for five percentile increments and a demonstration of the calculations  
263 for two bootstrap iterations is available in supporting information (Figure S3). We characterize  
264 absolute differences in wet day intensities in Figures S3c-d, along with relative differences in  
265 Figures S3e-f. For example, in Figure S3c, we demonstrate that in this iteration, the Great Lakes  
266 domain has experienced a robust shift from lower to higher precipitation intensities across the  
267 full distribution of intensities, which becomes clearer when relativized against the initial early  
268 period frequencies in the early period (Figure S3e). To illustrate, the likelihood of a 95-100th  
269 percentile event has increased by roughly 15% in the Great Lakes in the later period of  
270 observation (Figure S3e-f).

271

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273  
 274 *Figure 3: Smoothed Relativized Frequency Change for Each Domain. (map) The United States with*  
 275 *NEON domain boundaries (thick dark grey) and state borders (thin light grey). Blue fill denotes the*  
 276 *cluster of central and eastern domains with a predominantly consistent significant change in frequency*  
 277 *across intensities. Conversely, grey fill denotes the cluster of western domains with inconsistent or non-*  
 278 *significant changes in frequency across intensities. (domain subplots) Smoothed change in relative*  
 279 *frequency of wet day intensity for each domain. Relative frequency change is determined at five percentile*  
 280 *increments before smoothing is performed across three increments; a fifth-order polynomial is fit to the*  
 281 *subsequent smoothed data. This is shown for the median (thick black) and 90% confidence bounds (thin*  
 282 *black line and light blue shading) as determined by block bootstrapping. See Figure S3 for demonstration*  
 283 *of underlying calculations and Figure S4 for raw (non-smoothed) results.*

284           The shift from lower- to higher-intensity events is largely consistent in the central and  
285 eastern U.S., with lower-intensity events decreasing in relative frequency for all but one domain  
286 (Atlantic Neotropical; blue filled regions, Figure 3) and a broadly consistent increase of ~15% in  
287 the relative frequency of highest intensity events. However, while higher-intensity events  
288 generally increase for all central and eastern domains and intensities, this change is not  
289 uniform. For example, we observe no increase in the Atlantic Neotropical domain and a  
290 decrease in moderate intensity events in the Mid Atlantic domain. Similar to the mixed  
291 responses in mean wet day precipitation changes, changes across distribution frequencies vary  
292 between domains in the western U.S. (see grey filled regions, Figure 3), though they are  
293 generally not statistically significant. For example, shifts within the Southern Rockies and  
294 Colorado Plateau, Desert Southwest, and Great Basin domains show similar, but muted, low- to  
295 high-intensity shifts like the eastern U.S. This change is juxtaposed against nearby regions such  
296 as the Pacific Northwest, where a decrease in the highest-intensity events is observed. We also  
297 find similar spatial patterns in intensity shift for extreme events (99-100th percentile), though  
298 the increase in relative frequency of events in the eastern U.S. are higher (~20%). Additionally,  
299 we include findings for NCA regions and 99th-plus percentile events in Supporting Information  
300 (Figures S5-S10).

301

302

#### 303 **4. Discussion**

304

305 Here, we examine the full extent of wet day precipitation intensity distributions and reveal  
306 statistically robust changes throughout the United States. Broadly, our analysis reveals an  
307 increase in mean wet day precipitation in the central and eastern U.S. from 1951-1980 to 1991-  
308 2020 driven by a shift from lower- to higher-intensity wet day events. Changes in the mean and  
309 standard deviation of wet day precipitation and underlying wet day intensity distribution shifts  
310 are mixed and do not reach statistical significance in the western U.S. Despite these western U.S.  
311 results, there is a statistically significant change in underlying wet day precipitation intensity  
312 distributions for all seventeen domains analyzed.

313         Though existing observation-based literature largely focuses on heavy-to-extreme  
314 precipitation or arbitrary light or moderate thresholds, our findings largely complement earlier  
315 findings, such as an east-west division of changes in extreme precipitation (Easterling et al.,  
316 2017). The relative increases in moderate and heavy precipitation we observe in the eastern U.S.  
317 mirror well-established increases in precipitation extremes, as well as annual precipitation,  
318 previously found over central and northeastern portions of the country (e.g., Groisman et al.,  
319 2012). We highlight the strong consistency in the shift in precipitation intensities across the  
320 distributions in this area (Figure 2) as well as the rising mean (~4.5-5.7%) and standard  
321 deviation (~4.4-8.7%) of wet day precipitation. While not a perfect parallel, the consistent shift  
322 from lower to higher intensity events in the central and eastern U.S. generally agrees with  
323 model-based findings from Dai et al. (2017), who examined U.S. precipitation intensities using  
324 historical and end-of-the-21st century RCP8.5 projections as boundary conditions in convection-  
325 permitting simulations (Liu et al., 2017). Dai et al. found robust increases in precipitation  
326 intensity across the U.S., a pattern we observe only in the central and eastern U.S. The mixed

327 pattern of results we find for the western U.S. mirrors earlier observation-based results  
328 (Contractor et al., 2021; Higgins and Kousky, 2013; Rosenberg et al., 2010). Our analysis furthers  
329 this earlier work by using a large number of in situ measurements instead of limited stations or  
330 gridded products. In addition, we note that Dai et al., along with other modeling studies we  
331 reference hereafter, use the RCP8.5 high emissions scenario, a pathway viewed as unlikely  
332 given societal trends (Hausfather and Peters, 2020). Despite its unlikelihood, we find it notable  
333 that the patterns of observed precipitation change presented here parallel RCP8.5-forced  
334 projections.

335         While our work does not assess the drivers of observed precipitation changes, we  
336 compare our findings with modeling studies to provide mechanistic context, though analogs to  
337 our retrospective, observation-based methodology and time periods of analysis are indirect.  
338 Pfahl et al. (2017) combine historical (1950-2005) CMIP5 output with RCP8.5 emissions scenario  
339 (2006-2100) simulations to project a positive scaling of moisture content (thermodynamic factor)  
340 with temperature throughout the U.S., with enhanced vertical motion (dynamic factor) over the  
341 western and far eastern U.S. (see Figure S5 in Pfahl et al., 2017). Similarly, Zhang et al. (2021)  
342 compare historical HadGEM3 output (1900-1959) to end-of-century RCP8.5 emissions scenario  
343 projections (2040-2099) to find that increases in synoptic-scale precipitation variability over the  
344 U.S. are driven by thermodynamic and non-linear mechanisms but dampened by dynamic  
345 drivers (see Figure 6 in Zhang et al., 2021). Broadly, these findings demonstrate a consistent  
346 increase in precipitation and synoptic-scale precipitation variability over the U.S. driven by  
347 thermodynamic influences and a mixture of dynamical influences. While some of the scaling  
348 unveiled in these previously published model analyses mirror our findings, such as an overlap

349 between thermodynamic drivers and the increases in precipitation intensity we observe across  
350 the eastern half of the U.S., further work is necessary to explain the mechanisms driving the  
351 changes in observed wet day precipitation intensity that we find. However, the overall pattern  
352 we identify – of a transition from lower- to higher-intensity events – mirrors findings from  
353 Pendergrass and Hartmann (2014b) for a modeled doubled-CO<sub>2</sub> world.

354         Although we examine precipitation trends during a time of increasing greenhouse gas  
355 concentrations, and find similarities with greenhouse gas-forced model projections, our analysis  
356 is insufficient to directly attribute observed changes to ongoing anthropogenic climate change.  
357 Such an analysis would require use of a robust attribution methodology (e.g., Hegerl et al.,  
358 1996). In addition, while considering our results, it is important to bear in mind that our  
359 analysis focuses on changes in *wet day* precipitation intensity, and therefore does not consider  
360 underlying changes in precipitation frequency. This distinction is important for considering the  
361 impacts of these findings in the scope of total annual precipitation, for example. In regions  
362 where precipitation intensity has increased but precipitation frequency has decreased by an  
363 offsetting or greater amount, changes to total annual precipitation may appear to run counter to  
364 the changes we describe here (e.g., Markonis et al., 2019). It is also important to consider  
365 potential limitations of this study, beginning with the underlying assumption that NEON  
366 domains are internally consistent. While NEON domains are empirically designed to possess  
367 internally homogeneous climates, there exists some measure of variability within domains,  
368 particularly within the varied topography of mountainous domains (e.g., Southern Rockies and  
369 Colorado Plateau). Additionally, inconsistent station availability may impact domain-level  
370 findings and variable station density may inadvertently weight domain-level results.

371

372 **5. Conclusion**

373

374 We use curated daily *in situ* precipitation measurements from the GHCN to examine regional  
375 trends in wet day precipitation distributions from 1951-1980 to 1991-2020. We reveal significant  
376 changes in wet day intensity distributions for all seventeen NEON domains in the contiguous  
377 United States. These nearly ubiquitous changes are driven by a general shift from lower to  
378 higher intensity wet day precipitation totals particularly within the central and eastern U.S. and  
379 are largely manifested as increases in the mean and standard deviation of wet day precipitation  
380 intensity, though findings are mixed in the western U.S. Our findings can help inform an  
381 understanding of how natural hazards and associated risks have changed over time.

382 Additionally, these results can be compared with climate model output to examine the ability of  
383 climate models to accurately reproduce observed patterns of precipitation change.

384

385

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396 Provost, the Office for Research, and Northwestern University Information Technology.

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### 399 **Open Research and Availability Statement**

400 Global Historical Climatology Network Daily data is publicly available through the National  
401 Centers for Environmental Information at [https://www.ncei.noaa.gov/products/land-based-](https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily)  
402 [station/global-historical-climatology-network-daily](https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily). Code developed by the authors to conduct  
403 the analysis and produce the figures within this study is available at  
404 [https://github.com/ryandharp/Observed Changes in Daily Precipitation Intensity in the Uni](https://github.com/ryandharp/Observed_Changes_in_Daily_Precipitation_Intensity_in_the_United_States)  
405 [ted States](https://github.com/ryandharp/Observed_Changes_in_Daily_Precipitation_Intensity_in_the_United_States). This code will be archived on Zenodo upon completion of the peer review process,  
406 at which time the finalized link to archive, DOI, and data citation will be added to this  
407 statement.

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