Observed Changes in Daily Precipitation Intensity in the United States

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Key Points

- We observe consistent shifts from lower to higher daily precipitation intensity, particularly in the central and eastern United States
- Mean and standard deviation of wet day precipitation intensities increase for nearly all domains within the United States
- Fourteen of seventeen domains show differences in wet day precipitation intensity distributions between 1951-1980 and 1991-2020

Abstract

Relative to changes in annual mean and extreme precipitation, the characterization of changes in the full distribution of precipitation intensities remains overlooked and under-explored, despite their critical importance to natural hazard, agriculture, and infrastructure risk assessments. Here, we aggregate daily *in situ* Global Historical Climatology Network precipitation observations within seventeen internally consistent NEON domains in the United States for two time periods (1951-1980 and 1991-2020). We find statistically significant changes in wet day precipitation distributions in fourteen of the domains – changes primarily driven by a shift from lower to higher wet day intensities. Patterns of robust change are geographically consistent, with increases in the mean (4.6-7.1%) and standard deviation (20-31%) of wet day intensity in the eastern U.S., but mixed signals in the western U.S. Beyond their critical importance to the aforementioned societal impact realms, these observational results can also inform climate model performance evaluations.

Plain Language Summary

Lots of research has been done to see how rainfall and snowfall event totals are affected by climate change. While most studies look at yearly totals or extreme events, we look at how daily precipitation is changing at all intensity levels, which has effects on agriculture, infrastructure,

landslides, and flooding. We group daily rain gauge measurements within seventeen climate regions in the United States for two thirty-year time periods. We find changes in daily precipitation intensity in fourteen regions, changes that are mostly caused by a shift from lower to higher intensity rain and snow events. We also identify broader areas in the eastern U.S. with consistent increases in the average and daily variability of precipitation, but changes are mixed in the western U.S. In addition to the impacts mentioned above, our results can also be used to assess how well climate models perform.

Keywords

precipitation, precipitation variability, precipitation intensity distribution, daily, GHCN, NEON

1. Introduction

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

are often overlooked. While extreme precipitation events can produce outsized damages given their exceptional nature, changes in non-extreme precipitation have critical impacts on many Earth systems, including agriculture (Shortridge, 2019), infrastructure (Cook et al., 2019), and natural hazards (Dinis et al., 2021; Cannon et al., 2008). Here, to more comprehensively characterize daily precipitation shifts, we explore changes in the full distribution of wet day precipitation intensities over 17 climatically-distinct regions across the United States.

1.1. Why is precipitation changing?

Globally, mean annual precipitation is expected to increase ~2%/K with warming (Trenberth, 2003; Held and Soden, 2006; Wentz 2007; Wood et al., 2021), though considerable observed and projected regional and temporal variability underlie these projections (e.g., Polade et al. (2014) globally; Caloiero et al. (2018) in Europe). Changes in precipitation due to anthropogenic climate change is driven by combinations of thermodynamic and dynamic components. The thermodynamic component is caused by increases in atmospheric moisture content with atmospheric warming, which occurs at a rate of ~6-7%/K as described by the Clausius-Clapeyron equation. This increase in atmospheric moisture availability leads to an increase in globally averaged rainfall, though estimates of the magnitude of increase in precipitation vary depending on spatial and temporal scales (Westra, 2014; Cannon and Innocenti, 2019; Sun et al., 2021; Wood and Ludwig, 2000; Wood et al., 2021; Bador et al., 2018, Giorgi et al., 2019). Locally, the rate of increase of precipitation for smaller-scale events parallels and can even exceed Clausius-Clapeyron scaling, particularly during convective events (Lenderink and van Meijgaard, 2008; Guerreiro et al., 2018; Risser and Wehner, 2017) or where local conditions shift from favoring stratiform to convective precipitation (Berg and Haerter, 2013; Berg et al., 2013; Ivancic and Shaw, 2016). Generally, the Clausius-Clapeyron relationship leads to increases in extreme precipitation frequency and intensity with rising temperatures in moist, energy-limited environments, but abrupt decreases in dry, moisture-limited environments (Prein et al., 2017). Conversely, the dynamic component of precipitation changes is composed of shifts in atmospheric circulation (e.g., Swain et al, 2016) . Examples of these mechanisms include shifts in the climatologies of cyclone and anticyclone tracks, baroclinic zones, and jets, which are all driven by the reduction in the equator-pole temperature gradient, a poleward expansion of the descending branch of Hadley cells, and increases in land-sea temperature gradients (Polade et al., 2014). Increased precipitation totals can also be caused by more subtle changes, such as reductions in storm speeds (Kahraman et al., 2021) and weakening landfalling tropical cyclones (Touma et al, 2019). The relative importance of these factors varies widely depending on location.

1.2 How is daily precipitation variability changing?

Increases in the frequency and intensity of extreme daily precipitation have been widely observed around the globe (Westra et al., 2014; Donat et al., 2016; Asadieh and Krakauer, 2015; Sun et al., 2021; Wood et al., 2021; Alexander et al., 2006; Myrhe et al., 2019) and generally agree with increases projected by climate model simulations (Moustakis et al., 2021; Toreti et al., 2013; Groisman et al., 2005; Fischer and Knutti, 2014; Fischer and Knutti, 2016; Myrhe et al., 2019; Min et al., 2011; O'Gorman, 2015). For example, Lehmann et al. (2015) found that record-breaking rainfall events occurred 12% more often than expected from 1981-2010 with an estimated 26%

chance that a record-setting rainfall event is due to long-term climate change. Min et al. (2011) examined observed and modeled changes and found that climate change has contributed to the observed intensification of heavy precipitation events found over about two-thirds of the Northern Hemisphere. Sub-daily extreme precipitation is both observed and projected to increase at an even faster rate than daily extremes (Prein et al., 2017; Lenderink and van Meijgaard, 2008; Westra et al., 2014).

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

In the United States, increases in mean annual precipitation and extreme precipitation have been observed, though changes are not uniform (Easterling et al., 2017). Increases in heavy to extreme precipitation are well established in the central and eastern portions of the country (Groisman et al., 2012; Sun et al., 2021; Kunkel et al., 2013; Guilbert et al., 2015; Karl and Knight, 1998; Pryor et al., 2008; Groisman et al., 2001; Villarini et al., 2013; Contractor et al., 2021; Groisman et al., 2005). In addition, increases in light to moderate precipitation frequency are driving a general increase in precipitation frequency in the U.S. (Pal et al., 2013; Goodwell and Kumar, 2019; Karl and Knight, 1998; Roque and Kumar, 2021). However, the evolution of the proportion of lower vs higher intensity wet days is less understood with contradictory findings reported. For example, Groisman et al. (2012) focused on the central U.S. and found that moderate precipitation has become less frequent compared to heavy and extreme events, with higher intensity events increasing in frequency and moderate intensity events remaining unchanged. In contrast, Karl and Knight (1998) found an increasing frequency of events across most percentiles and U.S. regions, including an increase in moderate intensity events. While findings focused on the eastern and central U.S. are relatively consistent, studies focused on the western U.S. disagree and often unveil changes of a different sign. For example, Contractor et al. (2021) and Higgins and Kousky (2013) find generally increasing frequency and intensity of wet day events over the majority of the U.S. but decreasing moderate to heavy intensity events along the Pacific coast. This is inconsistent with findings of increasing or insignificant extreme precipitation on the U.S. west coast by Kunkel et al. (2013). Many previous analyses used gridded precipitation products (e.g., Contractor et al., 2021) that possess known inconsistencies across products (Alexander et al., 2020) and center on heavy-to-extreme precipitation or arbitrary light or moderate thresholds (e.g., 50th percentile or 10mm; Higgins and Kousky, 2013). To overcome methodological limitations and reconcile disparate findings, we examine changes over the complete distribution of precipitation intensities by spatially aggregating a large number of *in-situ* station observations across a high number of empirically determined, disparate local U.S. climate regimes.

2. Methods

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

We filter available U.S. station records to curate a set of station observations of sufficient length and completeness for trend analysis. To do so, we impose a minimum length requirement of 50 years of complete data, where a complete year is defined as containing 95% or more of all available daily records after removal of any flagged entries. These thresholds are in general agreement with similar analyses (e.g., Anderson et al., 2015). In addition, a station record must consist of 90% or more complete data-years for inclusion. Applying these filters reduces the number of U.S. records available from an initial 63,571 to 934 that are potentially suitable for our analysis. Supporting information Figure S1 depicts station locations and additional summary statistics.

Our analysis focuses on regional changes in precipitation intensity distributions. To partition the U.S. into climatologically-distinct regions, we adopt the National Ecological Observatory Network (NEON) domains. These twenty domains were designed to be climatically homogeneous within-domains but distinct across-domains and were created using a multivariate geographic clustering analysis incorporating nine different temperature and precipitation variables (National Ecological Observatory Network, 2022; Schimel et al., 2011; Keller et al., 2008). We center our analysis on the seventeen domains that exist entirely or predominantly within the contiguous United States (Figure S1). Rather than analyze GHCN stations individually, we employ spatial aggregation to provide a larger sample size and better view of change over time given the inherent limitations of individual station statistics and internal climate variability. Spatial aggregation has frequently been employed in precipitation analyses (e.g., Fischer et al., 2013; Groisman et al., 2005; Kunkel et al., 2013).

To examine changes in the distribution of wet day precipitation intensities, we aggregate all wet day precipitation observations for all stations within each NEON domain, where a wet day is defined as a station-day observing 1 mm or more of precipitation. This is done for two thirty-year periods, 1951-1980 and 1991-2020, for all seventeen NEON domains under consideration. We choose the early time period (1951-1980) due to the proliferation of GHCN-D stations that peaked in this interval (see Fig. 3b, Menne et al., 2012); we selected the late time period (1991-2020) as it is the most recent 30-year interval with available data. The distributions are built around 30-year periods of reference to align with World Meteorological Organization guidelines for climate (World Meteorological Organization, 2017) and overcome known impacts of interannual modes of climate variability (e.g., Groisman et al., 2012). Data from a station is included if the station record spans the entirety of both the early and late periods, in addition to meeting the aforementioned quality control measures. Though this definition results in the exclusion of some stations that may otherwise have been included in either the early or late period but not the other, we err on the side of consistency, though results based on analysis that include stations that covered only the early or late period are included in the supporting information (Figure S2). The majority of stations span both periods (546, 58%), with 23% (161) and 18% (116) of stations covering either the early or late period, respectively. Each wet day observation is then aggregated into a corresponding early or late period daily precipitation intensity probability distribution.

The resultant probability distribution functions are then directly compared through two-sample Kolmogorov-Smirnov and Anderson-Darling tests, both of which are suitable for nonparametric analysis and are not sensitive to the number of events in the distributions (Chakravarti et al., 1967; Stephens, 1974). Despite the similarity of the two tests and the more common use of the Kolmogorov-Smirnov test in hydrometeorological analyses, we employed the Anderson-Darling test as well due to its higher sensitivity to extreme values, though results ultimately proved largely consistent regardless of test. While the two tests are able to determine if distributions are distinct, the Kolmogorov-Smirnov and Anderson-Darling tests do not provide descriptive information as to how the distributions differ. We thus also examine the statistical moments of each distribution (mean, standard deviation, skew, kurtosis) and employ a bootstrapping methodology to assess statistical confidence intervals. Our bootstrapping process resamples each distribution with replacement to create new distributions of the same size as the original distributions. This process is replicated 1,000 times and differences in each statistical moment between the distributions are recalculated for each resample to produce confidence intervals for each statistical moment change.

3. Results

Early and late period wet day precipitation intensity distributions are statistically significantly different for all but three NEON domains (Figure 1a; Northern Rockies, Great Basin, and Southern Rockies and Colorado Plateau) with broadly consistent changes observed in central and eastern domains. Specifically, mean wet day precipitation increases in all domains east or the Rocky Mountains (Figure 1a), with an intensification in mean wet day precipitation between 4.6-7.1% for all but two of these domains (Figure 1b). Similarly, the standard deviation of wet day precipitation intensity increased between 20-31% for each domain in this grouping (Figure 1c). Changes are less consistent for western domains, with an increase in mean wet day precipitation in one domain (Desert Southwest), a decrease in mean wet day precipitation in two domains (Pacific Northwest and Pacific Southwest), and no statistically significant change in the remaining domains. Despite the inconsistencies, the standard deviation of wet day precipitation intensity increased in all western domains, though the magnitude of increases vary more widely than in the eastern U.S. Supporting information Table S1 shows the differences in mean, standard deviation, skew, and kurtosis across all domains.

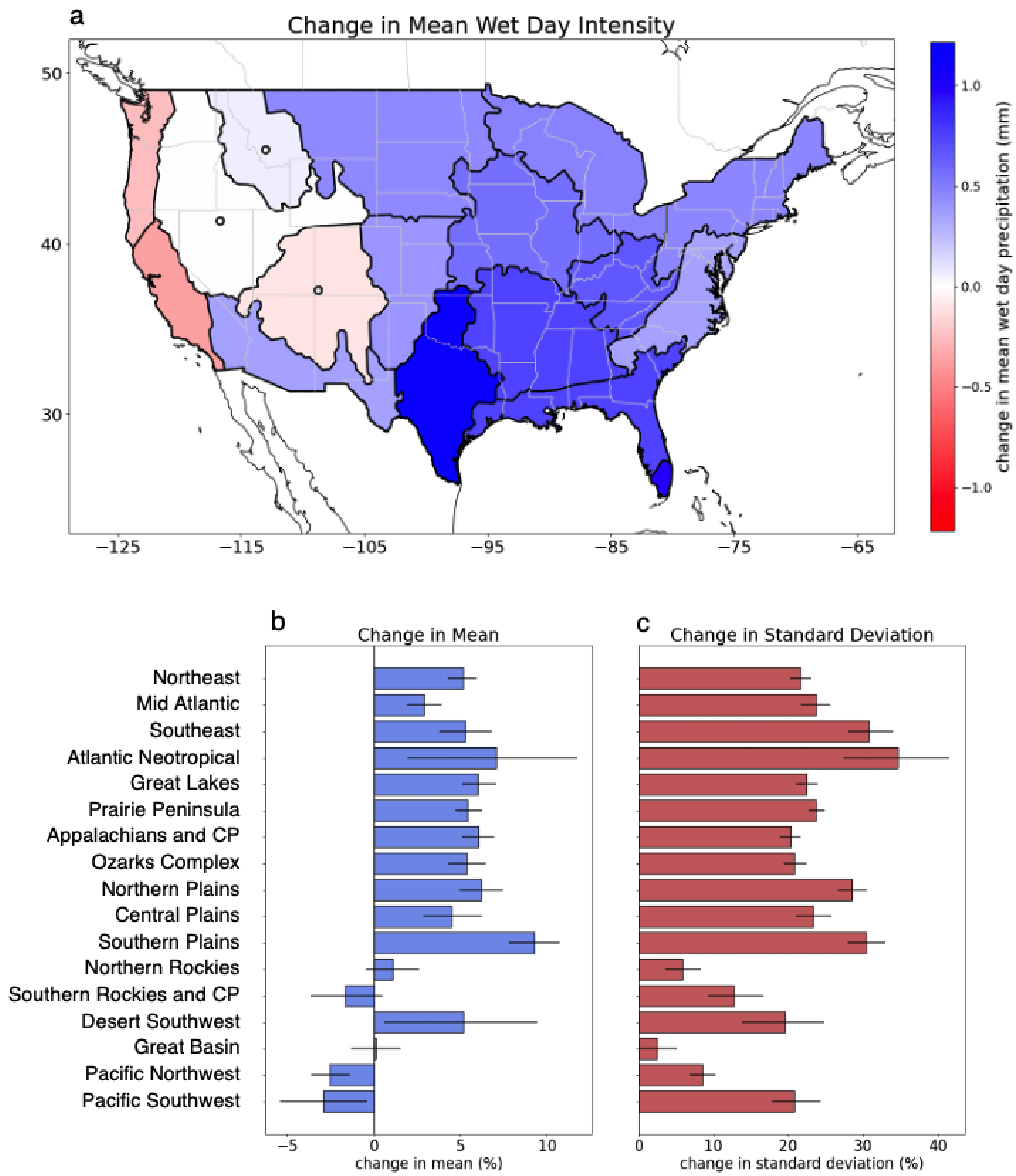

Figure 1: Changes in Wet Day Precipitation Intensity. (a) Map of changes in mean wet day precipitation for NEON domains. Red-blue fill indicates change in precipitation intensity (mm/day) within domains (dark grey borders) on top of state boundaries (light grey borders). Grey circle with white fill denotes

domains without a statistically significant change. (b) Changes in mean wet day precipitation for NEON domains. Blue bars show percentage change of mean and horizontal black line shows 95% confidence interval. (c) Same as (b) but with red bars and standard deviation of wet day precipitation.

In addition to changes in mean and standard deviation, we also quantified shifts in the underlying distributions between the early and late periods, allowing for a more nuanced characterization of observed distribution changes (Figures 2, 3). Figure 2 illustrates how the precipitation intensity distribution changes between the early and late periods for two example domains. We characterize absolute differences in wet day intensities in Figures 3b and 3e along with relative differences in Figures 2c and 2f. For example, in Figure 2b, we demonstrate that the Great Lakes domain has experienced a robust shift from lower to higher precipitation intensities across the full distribution of intensities, which becomes clearer when compared against the initial frequencies in the early period (Figure 2c). To illustrate, the likelihood of 40 mm or greater events in the Great Lakes domain is roughly 30-40% greater in the later period of observation. Changes over the Great Lakes domain contrast with the lack of a consistent response in the Great Basin domain (Figures 2d-f). The observed shift from lower- to higher-intensity wet day totals in the Great Lakes domain is broadly consistent with findings across the central and eastern U.S. (see blue filled regions, Figure 3).

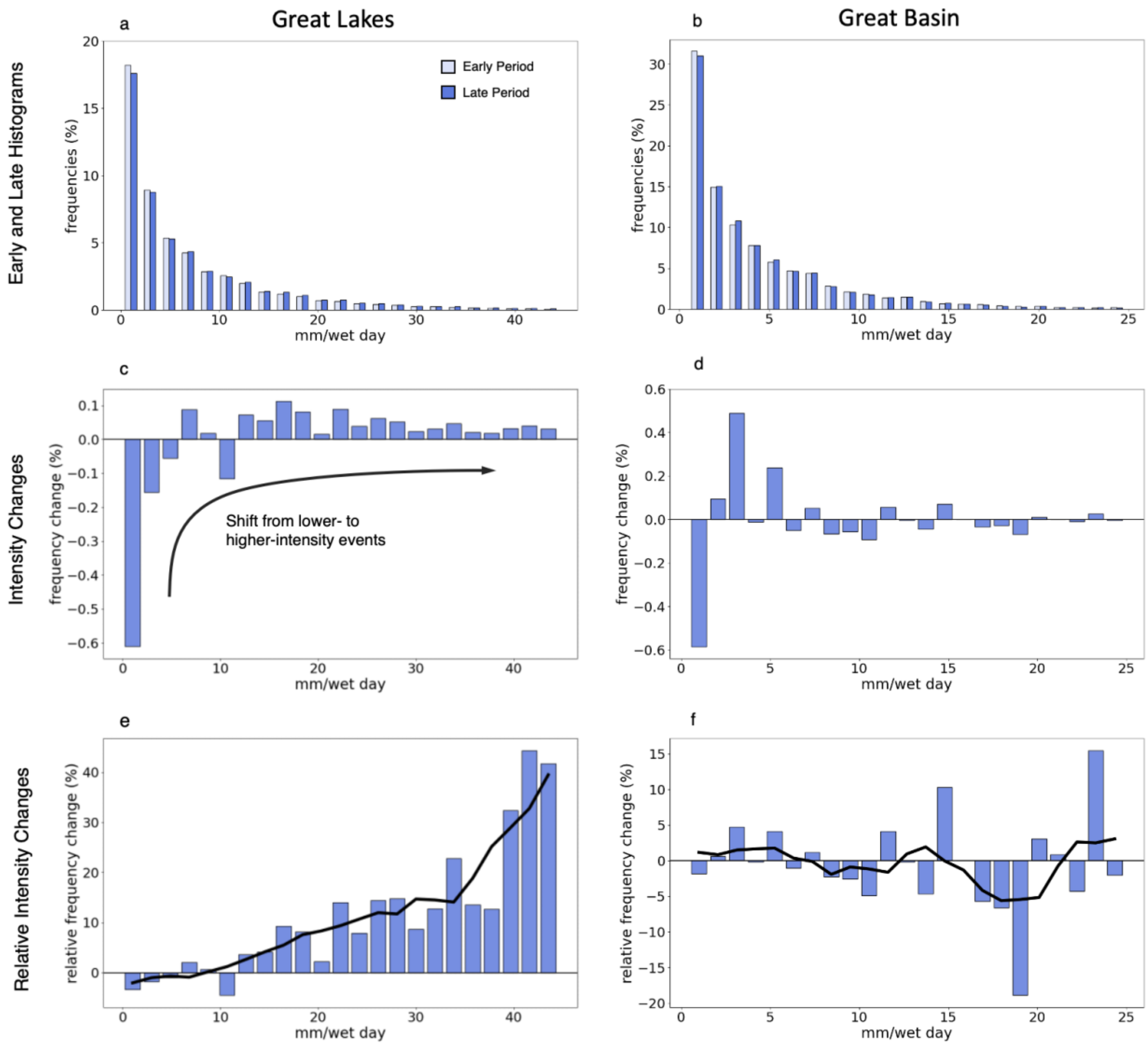

Figure 2: Change in Precipitation Intensity between Early and Late Periods. (a) Histograms of wet day precipitation intensity in the Great Lakes domain for the early (light blue; 1951-1980) and late (dark blue; 1991-2020) periods for sub-99th percentile daily precipitation totals. Histogram values represent the percentage of all wet-day events within the binned intensity. (b) Absolute difference in wet day precipitation intensity frequency between the late and early periods for the Great Lakes NEON domain for sub-99th percentile daily precipitation events. (c) Same as (b) but the change has been normalized by

dividing by the early period frequency. Thick black line denotes average change of the five nearest bins centered on a given bin. (d-f) Same as (a-c) but for the Great Basin domain. This figure is replicated for all domains in supporting information Figures S3-S17.*

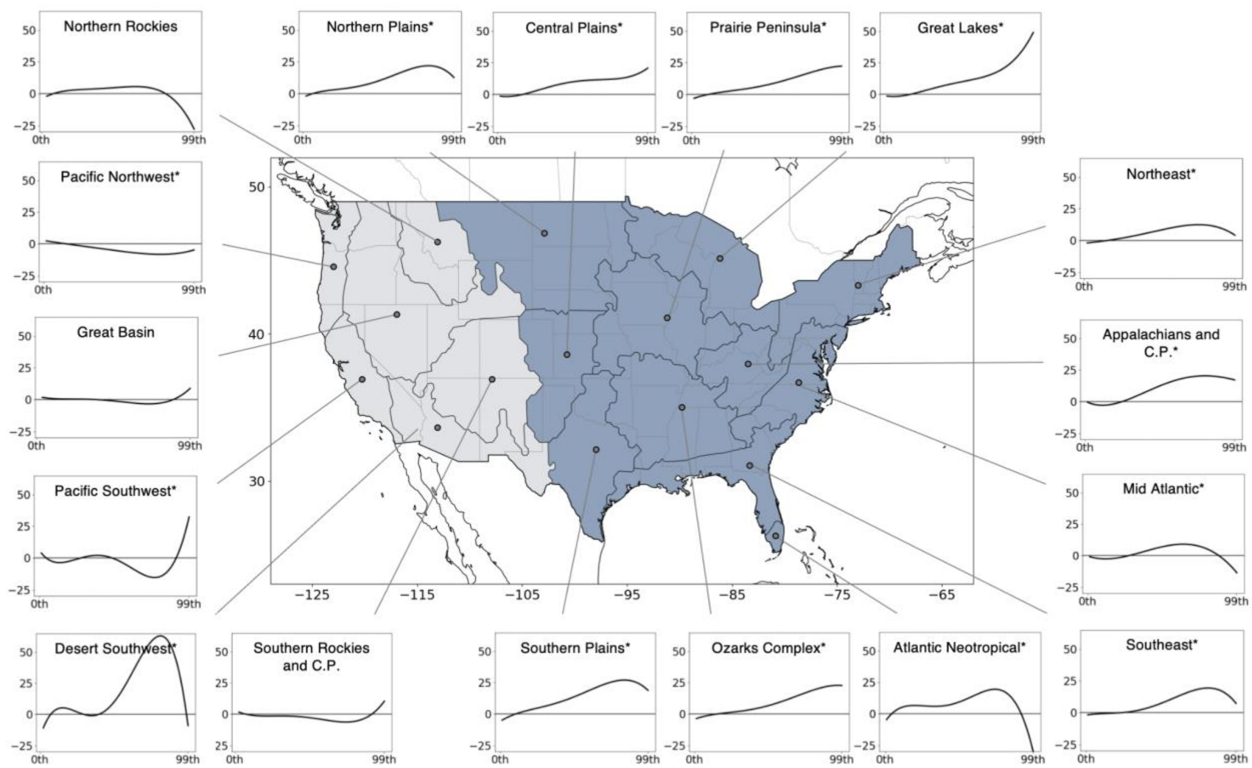

Figure 3: Smoothed Relativized Frequency Change for Each Domain. (map) The United States with NEON domain boundaries (thick dark grey) and state borders (thin light grey). Blue fill denotes the cluster of central and eastern domains with a predominantly consistent change in frequency across intensities. Conversely, grey fill denotes the cluster of western domains with inconsistent changes in frequency across intensities. (domain subplots) Smoothed change in frequency of intensity for each domain. See Figures 2c, 2f for demonstration of underlying data and calculations. Displayed change is for

the 0th-99th percentile of wet day intensities. Asterisked name indicates domains with a statistically significant change in their distributions.

The shift from lower- to higher-intensity events is largely consistent in the central and eastern U.S., with lower-intensity events decreasing in relative frequency for all eleven domains (blue filled regions, Figure 3). However, while higher-intensity events generally increase for all central and eastern domains and intensities, this change is not uniform, with a reduction in the most intense events in the Atlantic Neotropical and Mid Atlantic domains. Similarly, while across-domain responses converge on an approximately linear increase peaking at an ~25% increase in the relative frequency of highest intensity events, there is a lesser increase in the relative frequency of highest intensity events compared to heavy precipitation events in several domains (e.g., the Northeast domain). Similar to the mixed responses in wet day mean precipitation changes, changes across distribution frequencies vary between domains in the western U.S. (see grey filled regions, Figure 3). For example, the greatest increase in higher-intensity, non-extreme event frequency of all domains is in the Desert Southwest. This change is juxtaposed against nearby regions such as the Pacific Southwest, Southern Rockies and Colorado Plateau, Great Basin, and Pacific Northwest, with generally consistent shifts consisting of an increase in lowest and highest-intensity events but decreases in moderate and heavy precipitation events. It should be noted that the muted changes within the Great Basin, Southern Rockies and Colorado Plateau, and Northern Rockies domains are not statistically significant.

4. Discussion

Here, we examine the full extent of wet day precipitation intensity distributions and reveal statistically robust changes throughout the United States. Broadly, our analysis reveals an increase in mean wet day precipitation from 1951-1980 to 1991-2020 driven by a shift from lower to higher intensity wet day events in the central and eastern U.S. Changes in mean wet day precipitation and underlying wet day intensity distribution shifts are varied in the western U.S., though standard deviation of wet day precipitation totals increases for all domains investigated. This combination of changes leads to a statistically significant change in the underlying wet day precipitation intensity distributions for all but three of the domains analyzed across the U.S. (Northern Rockies, Southern Rockies and Colorado Plateau, and Great Basin). In summary, our analysis generally reveals observed increases in both wet day precipitation intensity and intensity variability.

While this work does not assess mechanistic drivers of observed changes, we note that the consistency of the increase in mean wet day precipitation across an area as broad as the eastern two-thirds of the U.S. (Figures 1, 3) is consistent with an underlying thermodynamic shift. The varying response along the U.S. west coast does not clearly align with thermodynamic explanations and we do not attempt to further explain underlying mechanisms here. However, we do note earlier work by Pfahl et al. (2017) found an omnipresent increase in thermodynamic influences across the country, but an east-west dichotomy in dynamic influences with dynamic mechanisms enhancing precipitation in the eastern U.S. and diminishing precipitation along the Pacific coast.

Though existing literature largely focuses on heavy-to-extreme precipitation or arbitrary light or moderate thresholds, our findings largely coincide and complement earlier findings such as the east-west division of changes in extreme precipitation described in the Fourth National Climate Assessment (Easterling et al., 2017). The relative increases in moderate and heavy precipitation in the eastern U.S. mirrors well-established increases in precipitation extremes, as well as annual precipitation, over the central and northeastern portions of the country (e.g., Groisman et al., 2012). We highlight the high consistency in the shift in precipitation intensities across the precipitation intensity distributions in this area (Figure 3) as well as the rising mean (~4.6-7.1%) and standard deviation (20-31%) of wet day precipitation. The inconsistent pattern of results for the western U.S. mirrors earlier results as well (Contractor et al., 2021; Higgins and Kousky, 2013; Rosenberg et al., 2010), though our analysis builds off earlier work by using a large number of *in situ* measurements instead of gridded observational products or studies that focus on a limited number of stations.

There are some potential limitations of this study, beginning with the underlying assumption that NEON domains are internally consistent. While NEON domains are empirically designed to possess internally homogeneous climates, there exists some measure of variability within domains and inconsistent station availability may impact domain-level findings. Further, we find slight differences in domain-level changes if all qualifying stations are included in the analysis as opposed to only stations which span both the early and late periods, though the vast majority of changes remain the same regardless of this methodological decision (see supporting information Figure S2 for findings with all stations). While not a limitation of our work, it should be explicitly noted that our analysis focuses on changes in *wet day* precipitation intensity and, therefore, does not consider underlying changes in precipitation frequency. This distinction is important for considering the impacts of these findings in the scope of annual precipitation totals, for instance. Finally, although we examine trends in precipitation through a period of time of increasing greenhouse gas emissions and resultant climate impacts, the analysis presented here is insufficient to directly attribute changes to ongoing anthropogenic climate change, although our findings are largely consistent with expected changes (e.g. Pfahl et al., 2017) and such an analysis could be performed using a robust attribution methodology (e.g., Diffenbaugh et al, 2017) .

5. Conclusion

We use curated daily *in situ* precipitation measurements from the GHCN to examine regional trends in wet day precipitation distributions from 1951-1980 to 1991-2020. We reveal significant changes in wet day intensity distributions for fourteen of seventeen domains around the United States, including all domains in the central and eastern U.S. These nearly ubiquitous changes are driven by a general shift from lower to higher intensity wet day precipitation totals around the U.S. and are largely manifested as increases in the mean wet day precipitation intensity and in the standard deviation of wet day precipitation intensity, though we identify an east-west split. Our findings can help inform the understanding of how natural hazard risk has changed over time, such as how shifting rates of moderate and heavy intensity precipitation may be interacting with increased wildfire burn areas in the western U.S. to affect water resources and landslide risk (Williams et al., 2022). These results also have important implications for research and applications surrounding agricultural yields and infrastructure design. Additionally, these results can be compared with climate model output to examine the abilities of climate models to reproduce the spatial patterns in changes in daily precipitation intensities.

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Open Research and Availability Statement

Global Historical Climatology Network Daily data is publicly available through the National Centers for Environmental Information at https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily. Code developed by the authors to conduct the analysis and produce the figures within this study is available at 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, at which time the finalized link to archive, DOI, and data citation will be added to this statement.

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