Observed Changes in Interannual Precipitation Variability in the United States

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Key Points

- We find widespread robust changes in two measures of interannual precipitation variability across the United States
- We detect robust increases (decreases) in annual precipitation and wet day frequency across the central and eastern (western) United States
- We explore the interaction of changes in precipitation frequency and wet day precipitation intensity on interannual variability

Abstract

Characterizing robust changes in precipitation patterns over time is critical for water resource management and agricultural planning. Here, we explore observed trends in interannual precipitation variability using a suite of metrics that describe changes in precipitation patterns over time. We analyze daily *in-situ* Global Historical Climatology Network precipitation data from 1970 to present over seventeen internally consistent sub-national United States domains using the regional Mann-Kendall trend test. We find increasing trends in annual precipitation and wet day frequency for most of the central and eastern U.S., but decreasing trends in the western U.S. Importantly, we also identify widespread significant trends in interannual precipitation variability with increasing variability in the southeast, decreasing variability in the far west, and mixed signals in the Rocky Mountains and north-central U.S. Our results provide important context for water resource management and a new observational standard for climate model performance assessments.

Plain Language Summary

While many studies have examined how annual precipitation and precipitation frequency have changed, few examine the variability, or consistency, of year-over-year precipitation. We test for these trends in daily observations from the Global Historical Climatology Network within seventeen regions within the U.S. We find changes in yearly precipitation variability for most regions, though results in the central U.S. are mixed. We also identify rising annual precipitation and precipitation frequency for the central and eastern U.S. and falling annual precipitation and frequency for the western U.S. Our results are important for agriculture and water resource management and can be compared against climate models to determine how well they reproduce our findings.

Keywords

precipitation, interannual variability, precipitation variability, GHCN, NEON, NCA

Introduction

Precipitation patterns are shifting globally due to climate change (Douville et al., 2021). These changes are broadly driven by increased moisture availability due to rising temperatures (i.e., the Clausius-Clapeyron relationship) and shifts in atmospheric circulation patterns (e.g., poleward expansion of the Hadley cell; Polade et al., 2014), and are constrained by Earth's energy budget (Pendergrass and Hartmann, 2014). Observationally-based historical studies and model-based future projections of precipitation commonly characterize changes across metrics like annual mean, wet day frequency, and measures of extremes. However, constraining the temporal variability of precipitation changes, using metrics such as interannual variability, is important to inform a number of societally-impactful realms. Interannual variability of precipitation describes the degree of consistency in year-over-year precipitation amounts: higher variability equates to greater irregularity about the annual mean, which brings increased challenges to fields like water resource management. Greater precipitation variability has been shown to reduce crop yields, including for staples like corn and rice (Shortridge, 2019; Rowhani et al., 2011), as well as decrease a grazing area's ability to support livestock (Sloat et al., 2018). Hydrologically, shifts in interannual precipitation variability may also be driving increased variability in Great Lake water levels (Gronewold et al., 2021) and water quality via increased agricultural runoff (Loecke et al., 2017). Despite the importance of interannual variability, summary assessments like the U.S. National Climate Assessment have not yet included characterizations of its changes, instead focusing on mean and extreme precipitation (Easterling et al., 2017). Here, to better constrain historical changes in the year over year distribution of precipitation across the U.S., we examine shifts in observed interannual precipitation variability, as well as annual precipitation amounts and precipitation frequency – two metrics useful for understanding and explaining observed changes in interannual precipitation variability.

How is interannual precipitation variability projected to change?

Global climate models project that interannual precipitation variability will increase with rising greenhouse gas concentrations (Boer, 2009; Polade et al., 2014; Berg and Hall, 2015). Increases in the interannual variability of precipitation of 3 to 5%/K are projected globally, with 4 to 5%/K projected over land (Pendergrass et al., 2017; Wood et al., 2021; Chou and Lan, 2012), though some projections estimate smaller increases (He and Li, 2018). He and Li (2018) explain that the drivers of changes in interannual precipitation variability vary spatially; the increase of mean state specific humidity leads to an increase in variability over areas of climatological ascent. Conversely, variability increases in areas of climatological descent are driven primarily by changes in mean state precipitation. Good et al. (2016) further tie interannual precipitation variability to wet season length, individual rainfall event intensity, and variability in interstorm wait times.

A number of studies, while not U.S.-focused, have used global climate models to project changes in interannual precipitation variability over the U.S. Wood et al. (2021) used initial perturbation large ensemble projections and found increasing interannual variability over the U.S. by the end of the century, particularly in the winter months, under the RCP8.5 emissions scenario. Polade (2014) revealed a similar widespread, though slight, increase in interannual variability across the U.S. (up to 4%), with a hotspot of increased variability over the southwest. This finding is replicated by Berg and Hall (2015) for California using a suite of RCP8.5-driven CMIP5 models. Similarly, Swain et al. (2018) projected increases in annual precipitation "whiplash events" (i.e., sub-20th percentile annual precipitation followed by super-80th percentile in the next year) for California. Chou and Lan (2012) find an expanding range of projected annual precipitation under the A1B emissions scenario over the U.S. midwest, northeast, and northwest, driven by rising maximum annual totals. These findings are mirrored by Pendergrass et al. (2017), who noted a similar spatial pattern using projections from the RCP8.5 emissions scenario.

Despite numerous model projections of interannual precipitation variability change, there remains a dearth of observation-based analyses on the topic. Recently, Zhang et al. (2021) identified increases in the coefficient of variation of precipitation for regions of the southwestern and central United States using *in situ* observations from 1976-2019, however we are aware of no other U.S.-focused analyses. To address this deficiency of observation-based analyses and produce an observational standard for model studies, we explore changes in interannual variability and relevant precipitation metrics throughout the U.S. using a full complement of *in situ* measurements.

Methods

To characterize interannual precipitation variability in the U.S. we use daily *in-situ* station data from the Global Historical Climatology Network Daily (GHCN-D). The National Centers for Environmental Information curate the GHCN-D database, which consists of observations from over 80,000 stations from 180 countries and territories, including the most complete collection of U.S. daily data available (Menne et al., 2012). GHCN-D observations have a sensitivity of 0.1 mm and are subjected to a sequence of quality control tests to identify climatological outliers, duplicate data, and other inconsistencies (Durre et al., 2010). We subject available U.S. station records to additional constraints to determine station observations with sufficient length and completeness for trend analysis. Specifically, we require station records to consist of 90% or more complete station-years to qualify, where a station-year must contain 90% or more of all possible daily records within the year to be considered complete. These screenings filtered our set of available U.S. stations from 63,571 to 2,542 (using a 1970 start year); domain summary statistics of station availability are shown in Table S7. To overcome some of the limitations of individual station statistics, such as internal variability (e.g., Fischer et al., 2013), we center our analysis on regional trends and utilize the set of established domains determined by the National Ecological Observatory Network (NEON). These twenty domains were created to possess internally homogeneous climates but remain distinct across-domains, as determined by a multi-variable analysis using nine climate variables (Keller et al., 2008; Schimel et al., 2011). As labeled in Figure 1a, we use the seventeen domains that are predominantly within the contiguous United States. We also perform our analysis for U.S. National Climate Assessment regions (Easterling et al., 2017) with results included within the Supporting Information.

We employ the regional Mann-Kendall trend tests to identify trends in precipitation data at the NEON-domain level. The Mann-Kendall trend test is nonparametric and determines if a trend exists in the data regardless of underlying distribution or linearity (Mann, 1945; Kendall, 1975). As the Mann-Kendall trend test relies on the rank of values in place of actual values, it is less subject to outliers and is suitable for detecting robust trends in hydrological time series (Hamed, 2008). It is commonly used in studies assessing trends of precipitation over time (e.g., Zhang et al., 2021; Roque-Malo and Kumar, 2017). The regional Mann-Kendall trend test determines if a significant trend emerges across the collection of time series within a region (Helsel and Frans, 2006). We use the Theil-Sen slope estimator, which is similar in its underlying design to the Mann-Kendall trend test, to determine the slope of identified trends (Sen, 1968; Theil, 1950).

We focus our analysis on four precipitation metrics: changes in interannual precipitation variability, interannual coefficient of variation (a.k.a. relative interannual variability), annual precipitation, and annual wet day frequency, where a wet day is defined as a station-day observing 1 mm or more of precipitation (a threshold common in precipitation analyses; e.g., Vaittinada Ayar and Mailhot, 2021; Ye, 2018; Zolina et al., 2013; Giorgi et al., 2019). Collectively, these four variables either directly characterize interannual variability, or provide crucial information to explain shifts in interannual variability. The relationships between these variables are described in the discussion section and illustrated in the Supporting Information.

Here, we define interannual variability as the standard deviation in annual precipitation over a moving 11-year window. We use an 11-year window to limit the influence of known dominant modes of interannual climate variability (e.g., ENSO), though a sensitivity analysis reveals generally stable results for five to fifteen-year moving windows (Table S1-S2). We similarly determine the coefficient of variation by dividing the standard deviation by the mean annual precipitation over the concurrent 11-year moving window. The coefficient of variation is often used as a measure of precipitation variability as it removes the strong dependence of precipitation variability on the mean itself (e.g., Giorgi et al., 2019). For ease of understanding, we will refer to the coefficient of variation as the relative interannual variability for the remainder of this article.

In addition to performing a sensitivity analysis on the width of the moving window, we analyzed the stability of precipitation trends across time periods by choosing different starting dates in 10 year increments, such that calculations are performed every ten years from 1920 through 1980. We present findings using a 1970 starting date as it provides a balance of widespread station availability and length of observation record, but highlight discrepancies we identify within the sensitivity analysis in the discussion section. The full results of the sensitivity analysis presented in the Supporting Information (Tables S1-S8).

Results

To properly inform changes in interannual variability, we must also assess changes in annual precipitation and precipitation frequency over our domain. We find statistically significant ($p < 0.05$) increases in annual mean precipitation for all domains east of the Rocky Mountains. These increases in annual precipitation range from 5.2-23.7 mm/decade (0.4-2.5%/decade; excluding the Atlantic Neotropical domain), with larger increases for a subset of central and eastern domains (Northeast, Great Lakes, Prairie Peninsula, Appalachians and Cumberland Plateau) ranging from 18.4-23.7 mm/decade (1.6-2.5 %/decade) (Figures 1a and s, Tables S9-S10). We identify statistically significant negative trends in annual precipitation over the western U.S. between -9.6 to -2.7 mm/decade (-2.4 to -0.6 %/decade; excluding the non-significant Northern Rockies domain). Spatial patterns in changes in annual wet day frequency largely mirror changes in annual mean precipitation, with some additional non-significant domains (Figure 1b). We observe statistically significant increases in wet day frequency for northern domains east of the Rocky Mountains, and statistically significant decreases for most western domains, as well as the Southern Plains and Southeast domains. Changes in wet day frequency range from -1.0 to 0.9 wet days/decade (-3.3 to 1.0%/decade) with the greatest increases generally located in the most northern and southern domains (Figures 1b and 2, Tables S9-S10).

Given robust changes in observed annual precipitation, it is important to determine if these changes have been equitably distributed. To assess precipitation distribution, we quantify two metrics of year-over-year variability. We identify statistically significant trends in both the interannual variability and relative interannual variability of precipitation for most NEON domains in the United States (Figures 1c-d, 2, Tables S9-S10). Changes in interannual variability range from -1.1 to 2.0 mm/decade (-4.4 to 9.5%/decade), with changes not reaching statistical significance for five domains, predominantly in the north central U.S. Generally speaking, interannual variability is decreasing in domain clusters in the western U.S. (five domains), and increasing in the south central and northeastern U.S. (Figure 1c; seven domains). We observe broadly similar spatial patterns in trends of relative interannual variability, though seven domains switched from significant to non-significant trends or vice versa. Additionally, the direction of change in the Desert Southwest domain switched from significantly negative to significantly positive (Figures 1c-d, 3). We explore this discrepancy in the discussion section. Collectively, trends in relative interannual variability range from -3.2 to 9.6%/decade with statistically significant changes occurring in all but two domains (Great Basin and Northeast). Results for U.S. NCA regions reveal similar spatial patterns and can be found in the Supporting Information (Figures S1-S2, Tables S11-S12).

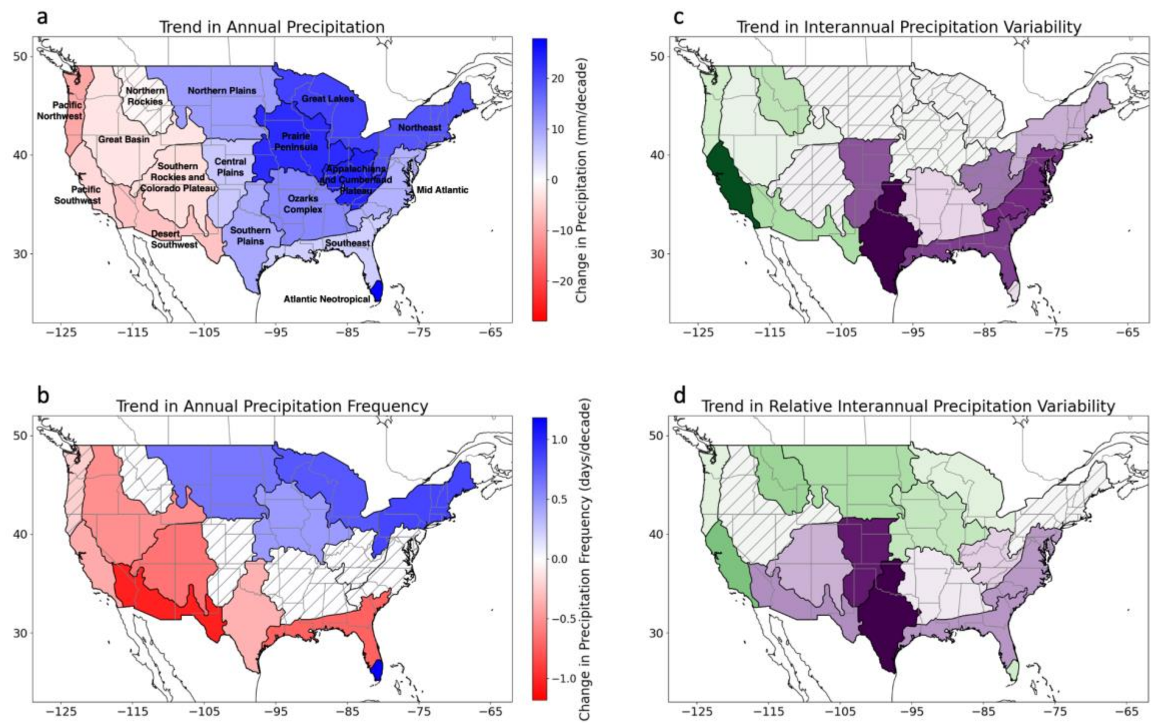
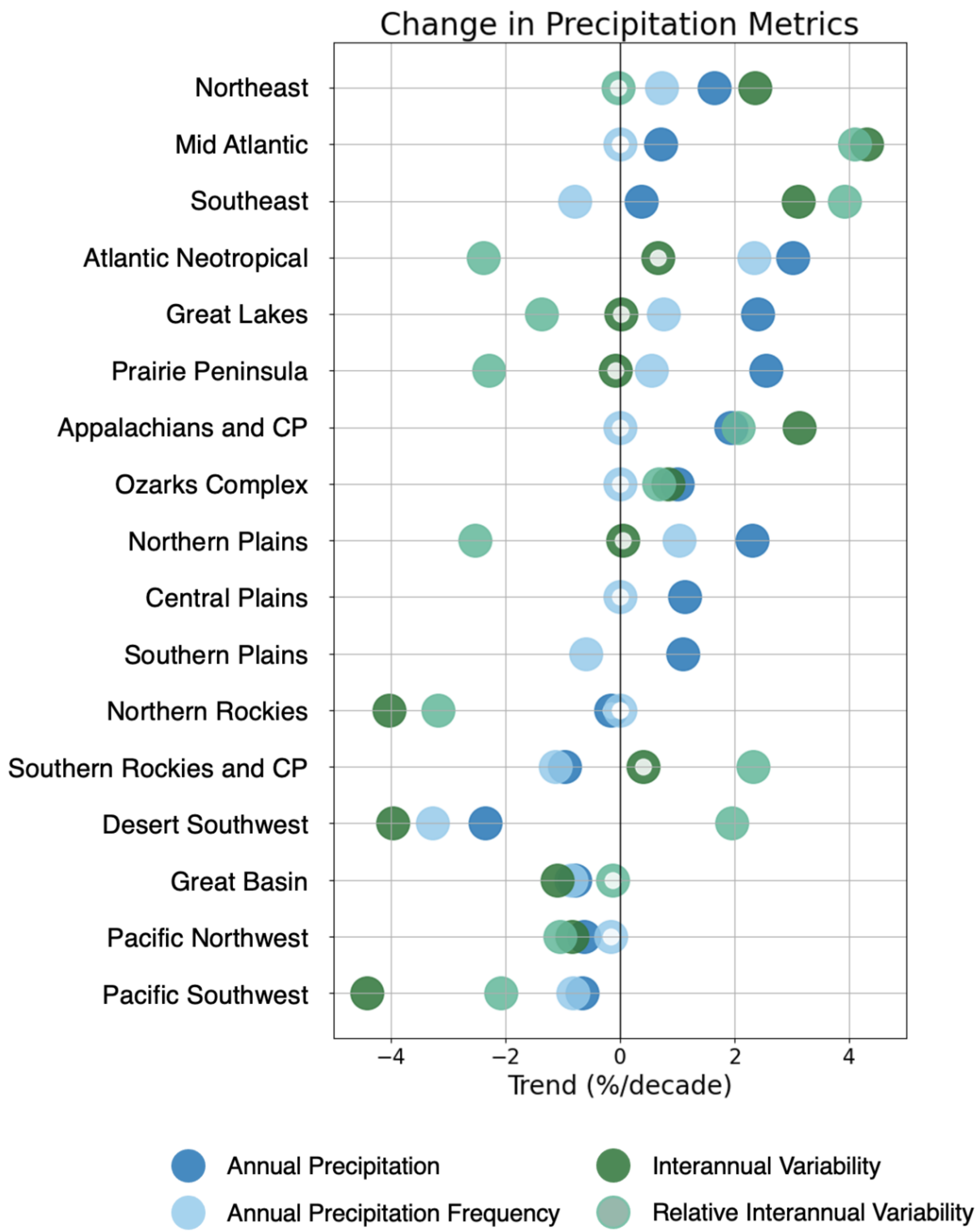


Figure 1: Domain Trends in Various Precipitation Metrics. (a) Map of changes in annual precipitation for each NEON domain within the contiguous U.S. Red-blue fill indicates domain-level trends in annual precipitation in mm/decade (dark grey borders). Hatching indicates domain trends of zero or those not reaching statistical significance. (b) Same as (a) but for annual precipitation frequency and units of days/decade. (c) Same as (a) but for interannual precipitation variability with purple-green fill and units of mm/decade. (d) Same as (c) but for relative interannual precipitation variability and units of decade^{-1}.



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231 *Figure 2: Domain Trends in Annual Precipitation Metrics. Trends in annual precipitation (dark blue),*

232 *annual precipitation frequency (light blue), interannual precipitation variability (dark green), and*

relative interannual precipitation variability (light green) for each domain. Trends are normalized against the mean value within each domain to produce trends in percent change/decade. Non-filled circles indicate non-significant domain-trends ($p < 0.05$). Note outlying trends in both metrics of interannual variability for the Central and Southern Plains are not displayed.

Discussion

Broadly, our analysis of precipitation trends in the United States reveals increasing interannual variability for the south-central and eastern U.S., decreasing interannual variability for the Pacific coast, and mixed trends in the north-central and Rocky Mountain portions of the U.S., depending on the variability metric of interest. These changes are side-by-side with rising annual precipitation and wet day frequency over the central and eastern United States, with falling trends in the western United States.

One result of particular interest is the finding that interannual variability *increased* but relative interannual variability *decreased* at a statistically significant level in the Desert Southwest. In addition, regardless of directionality, the trends in variability differed across metrics by one percent or more for eight domains. We explain this between-metric discrepancy through an examination of the components which influence interannual variability.

Interannual variability vs relative interannual variability

Together, changes in frequency and daily precipitation intensity drive changes in interannual and relative interannual precipitation variability. We demonstrate the underlying principles of these interactions using theoretical examples in Figures 3 and S3-S5. These examples apply 10% increases in precipitation frequency and intensity along with three different possible transformations of the underlying precipitation distribution – (1) a uniform increase at all intensities (Figures 3 and S3), (2) increases in the higher intensities (Figure S4), and (3) increases in the lower and medium intensities (Figure S5) – to demonstrate the interplay between annual variability metrics and wet day frequency and intensity.

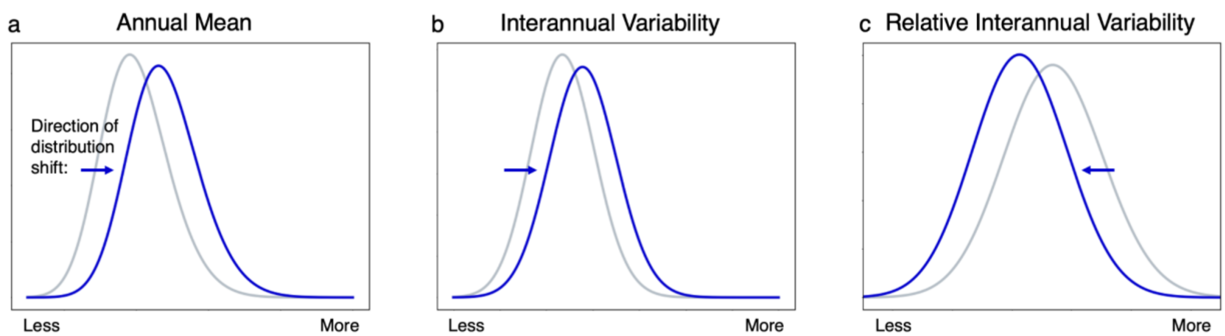

Figure 3: Response of Annual Mean Precipitation and Interannual Variability of Precipitation to Changes in Wet Day Frequency. (a) Initial probability distribution function (light grey) of annual precipitation based on Great Lakes domain precipitation intensity distribution. Projected probability distribution function (blue) after incorporating 10% increase in wet day frequency. (b) Same as (a) but for interannual variability of precipitation. (c) Same as (a) but for relative interannual variability of precipitation. Figure is replicated within the full combination of changes in Figures S3-S5.

Holding intensity constant (1), an increase in wet day frequency leads to an increase in interannual variability but a *decrease* in relative interannual variability (Figure 3 and Figures S3b-c, S4b-c, S5b-c). As would be expected, an increase in wet day frequency produces an increase in annual precipitation totals (Figures S3a, S4a, S5a). This rise in mean state leads to a corresponding increase in interannual variability as larger annual totals provide greater flexibility for interannual fluctuations. However, when accounting for the shift in baseline, *relative* interannual variability decreases. As wet day frequency rises, the contribution of extreme events toward annual totals is reduced, along with the likelihood that a given year of precipitation will be unduly influenced by extreme outlier events. Consequently, year-over-year annual precipitation totals become more consistent with more frequent precipitation. This scenario can be seen in reverse for the Desert Southwest domain: interannual variability decreases and relative interannual variability increases (Harp and Horton (*in review*) found no shift in underlying precipitation intensities for the Desert Southwest). A similar, abbreviated discussion of precipitation frequency on interannual variability can be found in Polade et al. (2014).

The impacts of shifts in wet day precipitation intensity are more nuanced (compare across Figures S3-S5). Generally, increases in mean wet day precipitation intensity alone (2) will lead to increases in interannual variability, however, the standard deviation of the underlying wet day precipitation intensity distribution has critical impacts on relative interannual variability (Figures S3d-f, S4d-f, S5d-f). For example, if the standard deviation of wet day precipitation intensity does not change, then an increase in the mean wet day precipitation intensity leads to negligible impacts on relative interannual variability (Figure S3f). However, an increase in standard deviation leads to an increase in relative interannual variability and vice versa (Figures S4f, S5f). Ultimately, changing interannual variability is a byproduct of changes in wet day frequency and the underlying precipitation distribution – both the change in mean and standard deviation of the distribution are important – which can combine to produce differential impacts on interannual variability and relative interannual variability. This is illustrated by observed changes over the Northeast domain. Here, both wet day frequency and intensity increase (Harp and Horton, *in review*) leading to a 2.4% rise in interannual variability but no change in relative interannual variability, mirroring the hypothetical shown in Figures S4h-i.

Highlighted Domains: Northern Rockies, Central/Southern Plains

As discussed above, generally speaking, the paths to shifting interannual precipitation variability are driven by a combination of changes in precipitation frequency or the underlying precipitation intensity distribution. Intriguingly, the Northern Rockies domain displays decreases in both interannual variability and relative interannual variability despite observing no statistically significant change in annual precipitation or wet day frequency. One potential explanation for these discrepancies is that underlying trends exist in one or more of these variables that do not rise to the level of statistical significance based on the data analyzed here. It is also possible that there are shifts in circulation patterns or storm tracks which are persistent *within* years but vary *between* years, such as a shift in atmospheric river frequency tied to modes of climate variability. For instance, shifts in El Nino Southern Oscillation teleconnection patterns could explain increased interannual variability in precipitation metrics, despite no long-term trends in precipitation or the underlying intensity. We leave this as an avenue for future research.

A second pair of notable domains are the Central and Southern Plains. These two domains have the most substantial changes in both interannual variability (6.2% and 9.5%, respectively) and relative interannual variability (6.1% and 9.6%, respectively) in either direction despite modest changes in annual precipitation and wet day frequency. These changes are likely driven by strong shifts in the underlying distribution of precipitation intensity toward heavier rainfall (Harp and Horton, *in review*) with increases in mean wet day intensity of 4.6% and 8%, respectively.

Comparison with earlier literature

Our results on changes in observed annual precipitation largely mirror earlier findings from the fourth National Climate Assessment (Easterling et al., 2017) with subtle differences over the southeastern and northwestern U.S. Additionally, we find similar trends in wet day frequency as earlier *in-situ*, station-based observational studies such as Pal et al. (2013), though there is some discrepancy in findings over the western U.S. Despite a similar observation-driven and interannual variability-focused methodology, we identify differences between our findings and those of Zhang et al. (2021), where a similar methodology was applied to observations in NEON domains in the western U.S. Specifically, within the domains of overlap in our studies, we find statistically significant changes in relative interannual variability for all domains except for the Great Basin, while Zhang et al. find statistically significant changes in just three domains. The identified trends for these three domains do, however, agree with our results. We similarly find significant results across more domains for annual precipitation and wet day frequency than Zhang et al., though the directions of any identified trends nearly perfectly overlap. These discrepancies may be a byproduct of methodological decisions. For example, despite also using GHCN-D data, Zhang et al. focus their analysis on the period from 1976-2019 and use a shorter moving window (five years) for calculation of relative interannual variability, though our sensitivity analysis did not reveal strong window width dependency.

While an imperfect comparison, we also compare our results of observed interannual variability with a suite of studies using high emission scenario model projections to determine if trends emerging in historical observations mirror future estimates. Our findings of increasing interannual variability of precipitation in the midwest and northeast match those of Chou and Lan (2012) and Pendergrass et al. (2017), though we disagree over the sign of change in the northwest U.S. Both Chou and Lan (2012) and Pendergrass et al. (2017) attribute rising interannual precipitation variability to greater moisture availability connected with increasing temperatures. The spatial patterns in interannual variability shifts we identify also differ from the generally uniform nationwide-increases projected by Wood et al. (2021) and Polade (2014), particularly in the western U.S. Similarly, our findings of falling interannual variability in California disagree with the modeled increases presented in multiple studies Berg and Hall (2015) and Swain et al. (2018), though both studies do not predict an emergence of signal until the middle 21st century. It should be noted that while our study examines changes in interannual variability over a period of rapidly increasing greenhouse gas concentrations and subsequent climate impacts, unlike the above studies, we do not explicitly examine the effects of climate change on interannual variability.

Limitations and Sensitivity Analysis Implications

There are potential limitations of our study, beginning with an underlying assumption that stations within NEON domains are relatively homogeneous. While NEON domains were created to possess internally consistent climates, within-domain variability may exist and inconsistent station availability may influence domain-level findings. The quantity of qualifying stations varies also between domains and can impact the reliability of results, this is especially true for the Atlantic Neotropical domain with only six qualifying stations.

Our sensitivity analysis revealed two domain clusters with start year-dependent results, in agreement with Kunkel (2003) which describes the importance of length of record for analysis, and notes that shorter time series may exhibit different trends than a greater length of record for a similar location. First, the direction of interannual variability trends over the three Plains domains and the Ozarks Complex between a 1950 and 1960 start date. Similarly, results for the western U.S. show a distinct shift in precipitation trends between a 1950 or earlier start date and a 1960 or 1970 start date. This shift occurs in trends for all metrics and across at least half of the western NEON domains (Tables S3-S6). Thus, while we have focused on results using a 1970 start date and 11-year moving window, we highlight that this combination should not be considered definitive. We further include results of analysis based on a 1950 start date in the Supporting Information (Figures S6-S9, Tables S13-S16). Finally, it should again be noted that although we examine trends in precipitation through a period of time of increasing greenhouse gas emissions and resultant climate impacts, we do not claim to directly attribute changes to anthropogenic climate change.

Conclusion

We use curated daily *in situ* precipitation measurements from the GHCN to examine domain-level trends in annual precipitation metrics, with a focus on interannual variability. We identify rises in annual precipitation in the central and eastern U.S. and declines in the western U.S. Trends in wet day frequency broadly mirror those of annual precipitation. We also reveal significant trends in interannual precipitation variability and relative precipitation variability across the United States, though with some differences in within-domain trends depending on the variability metric of interest. Broadly, we find an increase in precipitation variability across both metrics for the southeastern U.S., a decrease along the west coast, and mixed signals in the central U.S. These findings have important implications for understanding the impact of changing precipitation variability on agriculture and water resource planning. The full complement of our results can be compared against climate model projections to inform climate model analyses across the full spectrum of precipitation metrics. Finally, we recommend that future studies carefully consider how interannual precipitation variability is characterized (i.e., interannual variability vs relative interannual variability) and any subsequent implications.

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Open Research and Availability Statement

The National Centers for Environmental Information hosts publicly available Global Historical Climatology Network Daily data 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 github.com/ryandharp/Observed_Changes_in_Interannual_Precipitation_Variability_in_the_United_States. Analysis code will be placed and archived on Zenodo upon completion of the peer review process, at which time the finalized link to archive, DOI, and data citation will be included in this statement.

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