Extreme Rainfall Trends in the United States of America

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Abstract

The European Centre for Medium Range Weather Forecast (ECMWF) fifth-generation reanalysis of the global climate (ERA5) and the Climate Hazards Croup InfraRed Precipitation with Station (CHIPPS) daily measurements are used to examine extreme rainfall (1981-2022) in the contiguous U.S.A. Linear spatiotemporal trends in indicators of extreme rainfall frequency, magnitude, and duration recommended by WMO, as identified by the TheiI-Sen slope estimate and its Mann Kendall significance ($p < 0.05$), are calculated. Temporal trends in the annual number of days with rainfall 20 mm (R20) are most significant in the Ohio Valley and in parts of Florida (increasing), and isolated parts of Texas, Oklahoma, elsewhere in the Southwest and West (decreasing). Annual frequency of days having 10 mm (R1O) shows similar spatiotemporal patterns, but with broader areas of decreasing trends in the southern Great Plains and Southwest. Annual trends in total rainfall on the 5% of the most precipitating days (R95P) increased significantly in parts of Florida and from Louisiana to Maine and decreased significantly across much of the Southwest. Annual trends in maximum five-day rainfall (Rx5day) increased significantly in parts of the Appalachians and other isolated pockets and decreased significantly in parts of the Southwest. Annual maximum number of consecutive dry days (CDD) increased significantly in parts of California and adjacent western U.S. and decreased significantly in much of the south-central U.S. Trends in annual maximum number of consecutive wet days (CWD) changed significantly only in isolated areas, with Colorado having the most significantly decreasing trends. The area having >2.5 mm day^{-1} of rainfall over a given meteorological season expanded for DJF and MAM but shrunk for SON, from the 1981-1990 to 2011-2022 periods. If such trends continue, floods, landslides, and droughts may intensify.

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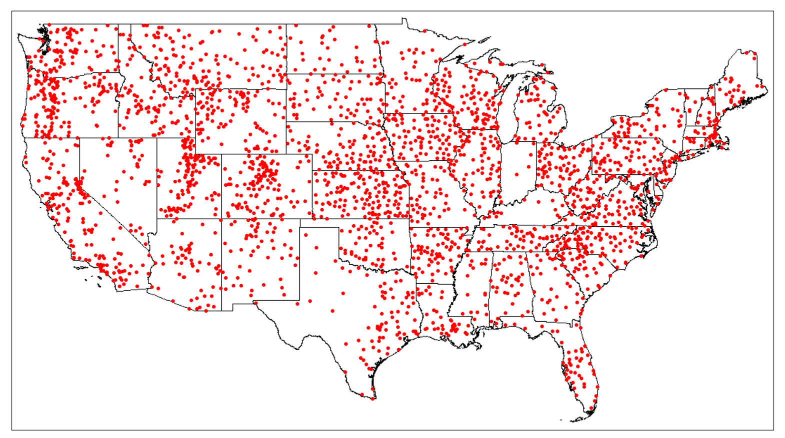
Introduction

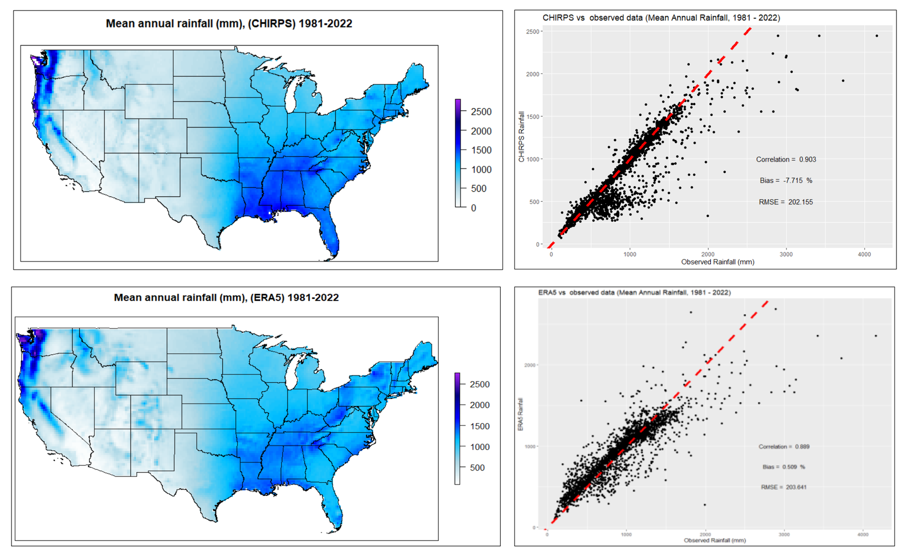
To characterize the spatiotemporal trends of extreme rainfall in the continental United States, 6 out of the 27 extreme climatic indices defined by the joint CCl/WCRP/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) were derived, analyzed, and visualized.

Gridded daily rainfall values from the fifth generation ECMWF atmospheric reanalysis of the global climate (ERA5; Hersbach et al., 2020) and the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS; Funk et al., 2015) were used to calculate the indices. CHIRPS and ERA5 outperform other satellite and reanalysis rainfall data in capturing extreme rainfall upon validation with gauge-based measurements (Bhattacharyya et al., 2022).

Moreover, the areal extents of mean daily rainfall above a specific threshold have been compared for the current and the past decade, classified by meteorological seasons, following a similar approach to Safdar et al. (2023).

Data and Methods





- Number of Global Historical Climatology Network daily (GHCNd) meteorological stations having at least 95% (Crossett et al., 2020) of daily observations (1981-2022) : 2643

- Analyzed daily rainfall data downloaded from ERA5, CHIRPS, and GHCNd; 1/1/1981 – 12/31/2022
- Study area: continental United States; spatial resolution of both gridded rainfall data sets: 0.25°x 0.25°
- GHCNd data were used for validation of the two gridded rainfall datasets.

Extreme rainfall indices considered in this study:

Index	Index name	Description	Unit	Type of index
R20mm	Number of 20 mm or more rainfall days	Annual count of days when daily rainfall ≥ 20 mm	days	Frequency
R10mm	Number of 10 mm or more rainfall days	Annual count of days when daily rainfall ≥ 10 mm		
R95p	Very wet days	Annual rainfall above long-term 95th percentile	mm	Intensity
Rx5day	Maximum 5-day rainfall	Annual 5-day maximum rainfall		
CDD	Maximum length of consecutive dry days	Maximum number of consecutive days with daily rainfall <1 mm	days	Duration
CWD	Maximum length of consecutive wet days	Maximum number of consecutive days with daily rainfall ≥1 mm		

- Magnitude of the temporal trend for each index was calculated using the Theil–Sen slope estimate, and its statistical significance ($p < 0.05$) was computed using the nonparametric Mann–Kendall's significance test (Mann, 1945; Sen, 1968).
- A comparison (1981-1990 vs. 2011-2022) was made to reflect changes in the average areal extent of rainfall >2.5 mm/day for the meterological seasons.

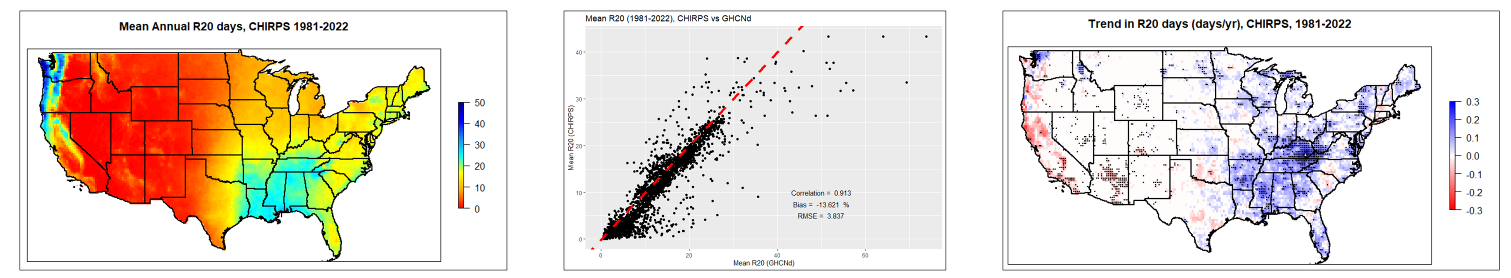
Results

The performance of the ERA5 and CHIRPS data sets in terms of the mean annual values of the calculated extreme rainfall indices with respect to GHCNd data is compared in the table below. Green shading indicates better performance (higher correlation coefficient and lower bias and RMSE).

	ERA5 vs GHCNd			CHIRPS vs GHCNd		
Index	Correlation	Bias	RMSE	Correlation	Bias	RMSE
R20mm	0.87	-26.68	5.36	0.91	-13.62	3.83
R10mm	0.85	-4.92	7.76	0.83	-4.34	8.72
R95P	0.89	-17.76	135.58	0.90	-11.70	104.33
Rx5day	0.86	-19.37	30.85	0.89	-19.82	28.25
CDD	0.96	-23.23	10.34	0.931	-16.97	10.59
CWD	0.70	39.96	3.33	0.513	-9.86	2.26

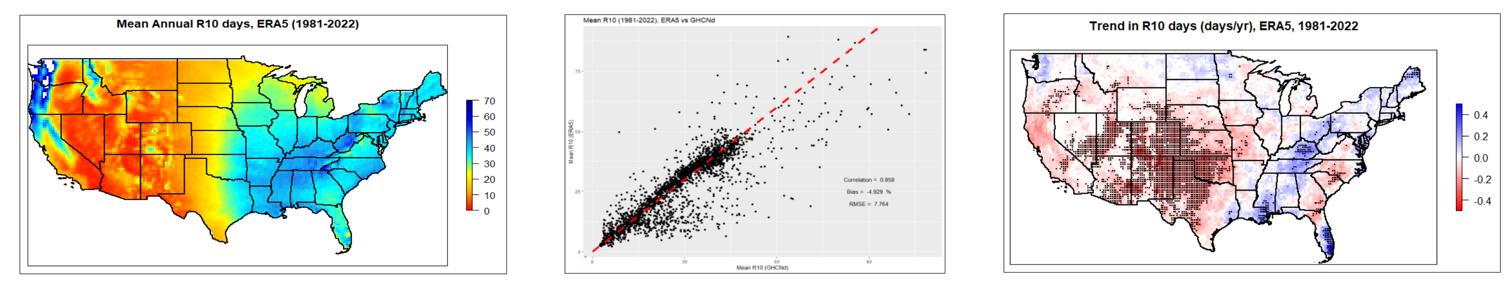
Results

Heavy Rainfall Days (R20)



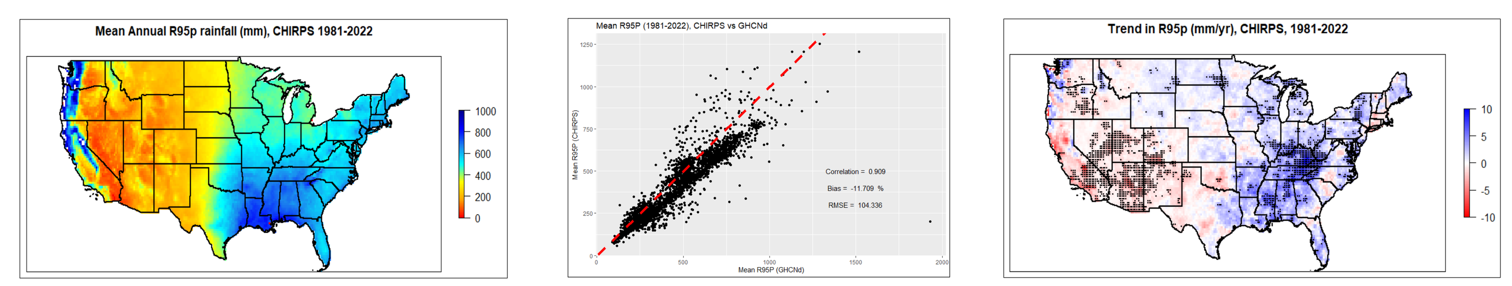
- Mississippi, Louisiana, Alabama, and Tennessee show the maximum R20 (>22 days), while Utah, Nevada, and Wyoming show the minimum R20 (<1.5 days).
- Significant positive temporal trends in Ohio Valley and in isolated parts of the Southeast, Northeast, and upper Midwest
- Significant negative temporal trends in discrete regions of the Southwest and the West

Heavy Rainfall Days (R10)



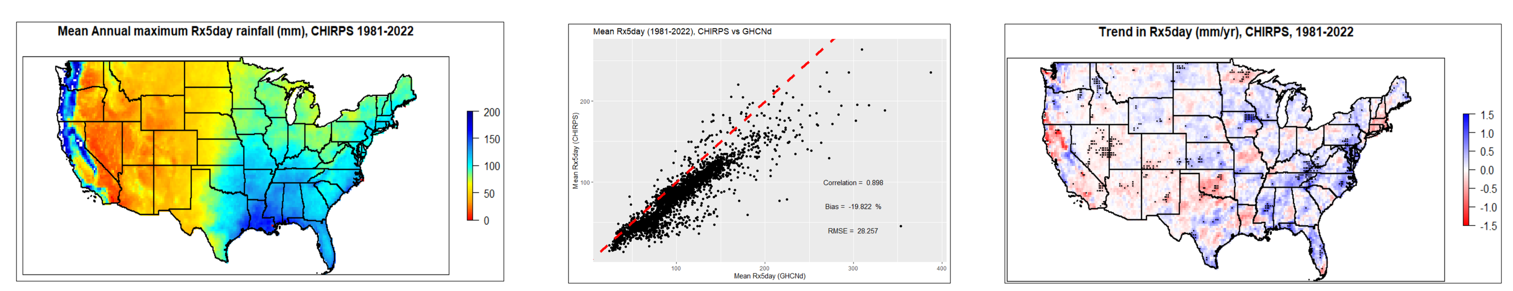
- In addition to Mississippi, Louisiana, Alabama, and Tennessee, West Virginia and Kentucky show the maximum R10 (>40 days), while Utah, Nevada, and Arizona have the minimum R10 (<8 days).
- Similar spatial patterns compared to R20 for increasing temporal trends, but with broader areas of significantly decreasing trends in the southern Great Plains and Southwest
- Significant negative temporal trends throughout New Mexico and Colorado

Wet Days Precipitation (R95P)



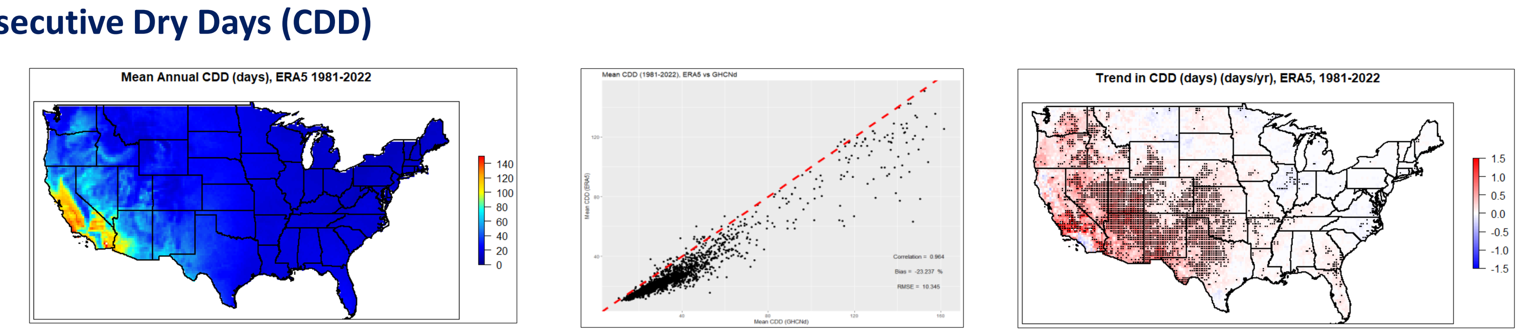
- Mississippi and Louisiana show the maximum R95P (>720 mm), while Utah and Nevada have the minimum R95P (<180 mm).
- R95P increased significantly in parts of the South, Ohio Valley, upper Midwest, and the East Coast.
- Significant negative temporal trends across much of the Southwest

Annual Maximum 5-Day Rainfall (Rx5day)



- Mississippi, Louisiana, Alabama, and Florida show the maximum Rx5day (>120 mm), while Utah, Nevada, and Wyoming have the minimum Rx5day (<40 mm).
- Annual trends in Rx5day increased significantly in parts of the Appalachians and other isolated pockets.
- Decreased significantly in small segments of the Southwest and the upper Midwest

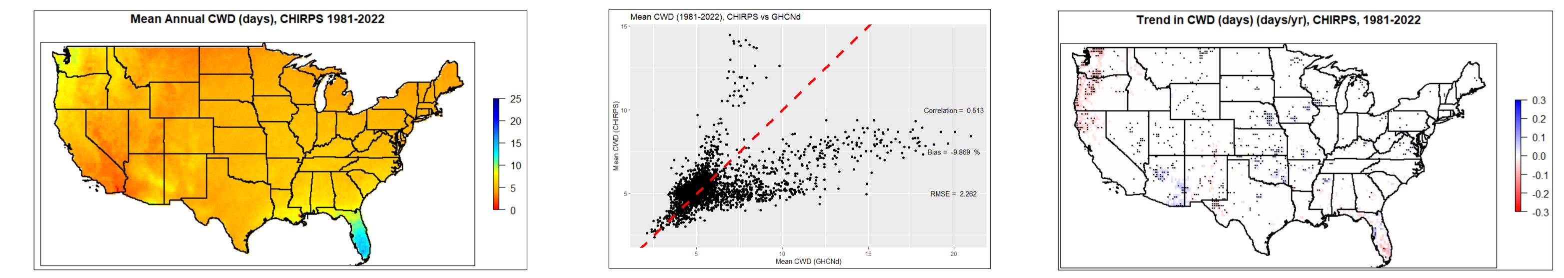
Consecutive Dry Days (CDD)



- California, Arizona, and Nevada show the maximum CDD (86, 61, and 54 days) whereas the New England region has the minimum CDD (<14 days).
- CDD shows positive statistically significant trends per year over all of Utah and in considerable parts of the Southwest and the western states, while not demonstrating negative temporal trend in any part of the continent.

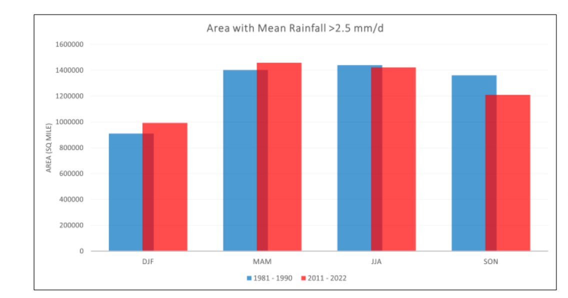
Results

Consecutive Wet Days (CWD)



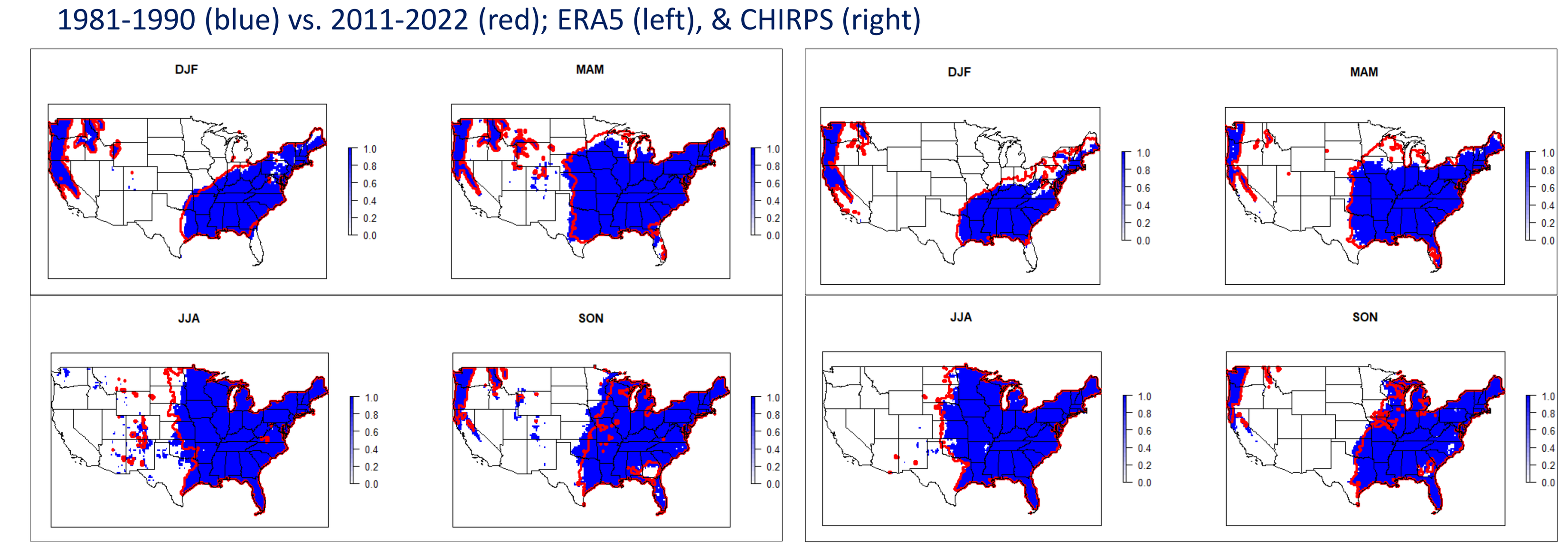
- Florida and Louisiana show the maximum CWD (11 and 7 days), while Nevada and North Dakota have the minimum CWD (~4 days).
- Temporal trends in CWD changed significantly only in isolated areas (both increasing and decreasing).

Change in Heavy Rainfall Extent by Season (1981 – 2022 vs. 2011 – 2022)



- A general increase in the area affected by rainfall > 2.5 mm/day from 1981-1990 to 2011-2022 for DJF and MAM
- For SON, this areal extent decreased significantly.

Areal extent of average rainfall >2.5 mm/day for the winter (DJF), spring (MAM), summer (JJA), and autumn (SON); 1981-1990 (blue) vs. 2011-2022 (red); ERA5 (left), & CHIRPS (right)



For DJF and MAM, the areal extent of mean rainfall >2.5 mm/day increased in the Northeast and the upper Midwest, while it decreased along much of the Midwest and the South.

Conclusions

- CHIRPS performed better than ERA5 for R20, R95P, Rx5day, and CWD. Of all the indices, the agreement of the CWD is the least when compared to gauge-based observations.
- Temporal trends in the frequency indices (R20 & R10) generally increased significantly in the Ohio Valley and the northeastern, southeastern, and southern States and decreased significantly in the Southwest. R10 shows a broader spatial pattern of significant annual decrease.
- The intensity indices (R95P and Rx5day) have similar spatial patterns to the frequency indices in terms of annual increase/decrease.
- The duration indices (CDD & CWD) show considerably less spatial clusters of significant annual change except for increasing CDD along much of the Southwest and the West.
- The general trend that can be inferred from our analysis is that the dry states are becoming much drier at a relatively faster rate than the wet states are becoming wetter. Some areas of the wet states are becoming drier to some extent, but the reverse has not been observed.
- Comparison of seasonal shifts of areal rainfall patterns between 2011–2022 and 1981–1990 averaging periods suggests that general increases in hydroclimatological extremes have occurred. If such trends continue, floods, landslides, and droughts may intensify.

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Acknowledgments

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