Evidence for increasingly extreme and variable drought conditions in the contiguous United States between 1895 and 2012

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Abstract

Potential annual (January-December) and summertime (June-August) regional time trends and increasingly extreme and / or variable values of Palmer-based drought indices were investigated over the contiguous United States (US) between 1895 and the present. Although there has been no significant change in the annual or summertime Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), or Palmer Modified Drought Index (PMDI) for the contiguous US over this time frame, there is clear evidence of decreasing drought conditions in the eastern US (northeast, east north central, central, and southeast climate zones) and increasing drought conditions in the west climate region (California and Nevada). No significant time trends were found in the annual or summertime PDSI, PHDI, and PMDI for the spring and winter wheat belts and the cotton belt. The corn and soybean belts have significant increasing trends in both the annual and summertime PDSI, PHDI, and PMDI, indicating a tendency towards reduced drought conditions over time. Clear trends exist toward increasingly extreme (dry or wet) annual PDSI, PHDI, and PMDI values in the northeast, east north central, central, northwest, and west climate regions. The northeast, northwest, and west climate zones display significant temporal trends for increasingly extreme PDSI, PHDI, and PMDI values during the summertime. Trends toward increasingly variable annual and summertime drought index values are also apparent in the northeast, southwest, northwest, and west climate zones.

Keywords:
Drought, Time trends, Hydroclimatic change, United States, Palmer Drought Severity Index

Introduction

The severe ecological and socio-economic impacts of droughts have led many to consider the potential effects of climate change on the frequency, duration, and intensity of these phenomena [1]. At a global scale, drought is expected to increase in frequency and intensity during the twenty-first century [2–7], although there is modest disagreement as to the magnitude / direction of any recent trends [8, 9]. Various measures for assessing drought conditions have been developed [1, 2, 10–12], but the Palmer suite of indices (e.g., Palmer Drought Severity Index [PDSI], Palmer Hydrological Drought Index [PHDI], Palmer Modified Drought Index [PMDI]) remain in wide application. Flaws in the PDSI and related approaches for drought determination and prediction have been broadly discussed [1, 3, 5, 8–15], but the general consensus appears to be that these metrics still offer substantial utility for climate change studies.

In addition to possible anthropogenic forcings, various natural climate cycles (e.g., El Nino-Southern Oscillation [ENSO], Atlantic Multi-Decadal Oscillation [AMO],

Pacific Decadal Oscillation [PDO]) also affect time trend analyses of drought indices [2, 16–20]. Furthermore, evidence exists that pre-industrial drought extremes have been greater than that observed over the past century [21]. For these reasons, it is difficult to unequivocally link any temporal variations in drought conditions to anthropogenic influences, even with corroborating predictions from climate models. However, current observable trends in many regional drought indices are in reasonable agreement with climate models that associate at least some of the changes to anthropogenic causes, thereby warranting additional mechanistic and empirical studies. Consequently, in the current work, we assess potential regional (Figure 1) time trends in Palmer-based drought indices over the contiguous United States (US) between 1895 and the present, with particular attention to any trends in the occurrence of extreme drought index values and short-term variability in drought conditions.

Datasets and Methods

Data was obtained from the National Climatic Data Center of the National Oceanic and Atmospheric Administration online database (http://www.ncdc.noaa.gov/ temp-

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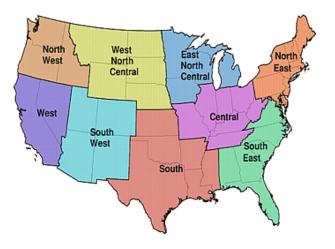
Figure 1: Map of the United States climate regions [22] (taken from http://www.ncdc.noaa.gov/crn/usrcrn/regionmap.html).

and-precip/time-series/). Statistical analyses of climate data were conducted using the nonparametric Mann-Kendall test for the trend and the nonparametric Sen's method for the magnitude of the trend [23–25] within the R Project for Statistical Computing environment [26].

Results and Discussion

There has been no significant ($p \leq 0.10$) change in the annual (January-December) PDSI, PHDI, and PMDI for the contiguous US (p=0.22 / 0.12 / 0.16) between 1895 and 2011. Significant temporal increases in the annual PDSI, PHDI, and PMDI have occurred in the northeast (p=3.5e-05 / 5.2e-05 / 1.8e-05), east north central (p=0.00039 / 0.00013 / 0.00024), central (p=0.022 / 0.0037 / 0.013), and southeast (p=0.016 / 0.011 / 0.0083) US climate regions during this period (Table 1), indicating reduced drought conditions over time. The south (p=0.080 / 0.063) climate region has also exhibited a significant temporal increase in the annual PDSI and PHDI, and a near significant (p=0.11) increase in annual PMDI. In contrast, there has been a significant decline in the annual PDSI, PHDI, and PMDI in the west climate region (p=0.015 / 0.055 / 0.043), reflecting increased drought conditions since 1895. No significant changes in these three drought indices were found for the west north central (p=0.68 / 0.44 / 0.51), southwest (p=0.31 / 0.14 / 0.30), and northwest (p=0.46 / 0.33 / 0.34) climate regions on an annual basis.

The summertime (June-August) PDSI, PHDI, and PMDI for the contiguous US (p=0.59 / 0.79 / 0.76), as well as the southeast (p=0.40 / 0.18 / 0.44), west north central (p=0.40 / 0.40 / 0.35), and south (p=0.66 / 0.64 / 0.89) climate regions, have not changed significantly since 1895. Significant positive time trends in these indices exist in the northeast (p=0.00046 / 0.00056 / 0.0022) and east north central (p=0.010 / 0.0067 / 0.023) regions, and negative trends in the southwest (p=0.091 / 0.078 / 0.072) and

west (p=0.0066 / 0.043 / 0.029) zones). A significant positive trend exists in the summertime PHDI for the central region (p=0.055), whereas the corresponding PDSI and PMDI trends are non-significant (p=0.11 / 0.16). The northwest region has significant positive trends in summertime PHDI and PMDI (p=0.062 / 0.096) but not in PDSI (0.17). There is a clear indication of decreasing drought conditions over time in the eastern US (northeast, east north central, central, and southeast climate zones), whereas the west climate zone (California and Nevada) has a clear and unambiguous trend of increasing drought conditions. The remainder of the nation shows either no trends or a mixture of non-significant / significant trends depending on the index / time frame under consideration, reflecting a transition between the decreasing drought conditions in the US northeast and the increasing drought conditions in the southwestern US. Trend magnitudes and directions are not always uniform within each climate region, as the individual state analyses given in Supporting Information Tables S1-S6 illustrate.

These findings are in general agreement with prior work which has shown historical trends and predictions toward increasingly frequent and severe droughts and a generally drier hydroclimate in the western and southwestern US [7, 17, 27–32] and no clear changes, or reduced drought conditions, in the rest of the nation [3, 30, 33]. Recent modeling work suggests the PDSI overestimates future drought severity in the Great Plains region, with PDSI-based projections indicating that this region will be in semi-permanent severe drought over the coming century [14]. However, as discussed above, an analysis of PDSI time trends for this region gives no suggestion of a dramatic hydroclimatic regime change to more severe drought conditions. No significant time trends were found in the annual or summertime PDSI, PHDI, and PMDI for the spring and winter wheat belts and the cotton belt (Table 2). In the corn and soybean belts, both annual and summertime PDSI, PHDI, and PMDI have significant increasing trends, indicating a tendency towards reduced drought conditions over time.

Trends of increasingly extreme drought/anti-drought conditions (extreme dry or extreme wet) can be tested by examining whether the absolute values of each index are changing over time. This metric captures situations whereby either a region is becoming progressively drier or wetter in a pattern moving farther away from the index midrange (i.e., index value of zero) over time, or where a region does not exhibit any net temporal trends in the drought indices, but the year-to-year values of the indices are moving progressively farther away from the index midrange for both wet and dry years over time. The metric does not reflect cases whereby a region is becoming wetter or drier over time, but the index trend is either still toward the index midrange, or where recent index values are still closer to the index midrange than historical values. As shown in Table 3, no regions show significantly decreasing trends in extreme drought/anti-drought conditions. On an annual basis, there are clear trends for

2

increasingly extreme PDSI, PHDI, and PMDI values over time in the northeast (p=0.0031 / 0.00031 / 0.0028), east north central (p=0.094 / 0.15 / 0.085), central (p=0.054 / 0.081 / 0.085), northwest (p=0.11 / 0.025 / 0.025), and west (p=0.13 / 0.064 / 0.085). The northeast (p=0.031 / 0.0044 / 0.044), northwest (p=0.028 / 0.0033 / 0.0068), and west (p=0.033 / 0.028 / 0.061) display significant temporal trends for increasingly extreme PDSI, PHDI, and PMDI values during the summertime. All other regions have no significant trends in extreme drought index values.

Alterations over time in short-term climate variability can be investigated by considering trends in the absolute values of year-to-year drought index changes (Table 4), as well as five-year running interquartile ranges (Table 5) and five-year running minimum-maximum ranges (Table 6) in these indices. These metrics capture cases whereby widely varying drought conditions (e.g., an extreme dry year is followed by an extreme wet year) are becoming more prevalent. The metrics indicate that the northeast, southwest, northwest, and west climate zones are becoming increasingly variable over time with respect to the various drought indices on an annual basis and during the summertime. The west north central climate zone does not exhibit any variability trends, whereas the remaining climate regions generally exhibit no overall variability trends although some isolated trends for specific index / time frame combinations may exist.

Conclusions

Time trend analyses of annual and summertime drought indices for the contiguous US indicate that the western / southwestern US is becoming increasingly susceptible to drought conditions over time. The eastern US is transitioning to a wetter climate regime with reduced drought conditions. The north / south-central and northwestern / southeastern regions of the nation generally exhibit temporal trends that reflect a transition between the southwestern / northeastern coastal end members. Increasingly extreme drought index values (either extreme dry or extreme wet) are evident in the northeast, east north central, central, northwest, and west climate regions. Trends towards increasing drought index variability exist in the northeast, southwest, northwest, and west climate zones.

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Table 1: Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the annual (January-December 12-month average for each calendar year between 1895-2011) and summertime (June-August 3-month average for each calendar year between 1895-2012) Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), and Palmer Modified Drought Index (PMDI) by region in the contiguous United States.

| | Palmer Drought Severity Index (PDSI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance[a]	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.062/0.33	0.0057	NS/0.033/0.59	0.0032
Northeast	***/0.26/3.5e-05	0.020	***/0.22/0.00046	0.020
East North Central	***/0.22/0.00039	0.018	**/0.16/0.010	0.014
Central	*/0.14/0.022	0.010	NS/0.099/0.11	0.0089
Southeast	*/0.15/0.016	0.011	NS/0.052/0.40	0.0043
West North Central	NS/-0.026/0.68	-0.0033	NS/-0.053/0.40	-0.0092
South	+/0.11/0.080	0.0098	NS/0.027/0.66	0.0033
Southwest	NS/-0.064/0.31	-0.0082	+/-0.10/0.091	-0.015
Northwest	NS/0.046/0.46	0.0032	NS/0.086/0.17	0.0077
West	*/-0.15/0.015	-0.017	**/-0.17/0.0066	-0.023

| | Palmer Hydrological Drought Index (PHDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.091/0.15	0.0090	NS/0.017/0.79	0.0016
Northeast	***/0.25/5.2e-05	0.022	***/0.22/0.00056	0.020
East North Central	***/0.24/0.00013	0.021	**/0.17/0.0067	0.015
Central	**/0.18/0.0037	0.014	+/0.12/0.055	0.010
Southeast	*/0.16/0.011	0.014	NS/0.084/0.18	0.0081
West North Central	NS/-0.049/0.44	-0.0072	NS/-0.053/0.40	-0.0091
South	+/0.12/0.063	0.012	NS/0.029/0.64	0.0033
Southwest	NS/-0.092/0.14	-0.012	+/-0.11/0.078	-0.018
Northwest	NS/0.061/0.33	0.0056	+/0.12/0.062	0.012
West	+/-0.12/0.055	-0.015	*/-0.13/0.043	-0.018

| | Palmer Modified Drought Index (PMDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.075/0.23	0.085	NS/0.019/0.76	0.0073
Northeast	***/0.27/1.8e-05	0.23	**/0.19/0.0022	0.050
East North Central	***/0.23/0.00024	0.21	*/0.14/0.023	0.036
Central	*/0.16/0.013	0.12	NS/0.088/0.16	0.025
Southeast	**/0.16/0.0083	0.14	NS/0.048/0.44	0.013
West North Central	NS/-0.041/0.51	-0.073	NS/-0.058/0.35	-0.027
South	NS/0.10/0.11	0.11	NS/0.0091/0.89	0.0032
Southwest	NS/-0.065/0.30	-0.088	+/-0.11/0.072	-0.049
Northwest	NS/0.060/0.34	0.058	+/0.10/0.096	0.029
West	*/-0.13/0.043	-0.16	*/-0.14/0.029	-0.057

[a] Presented as significance level (NS=not significant at p>0.10; +=p≤0.10; *=p≤0.05; **=p≤0.01; and ***=p≤0.001), τ, and 2-sided p-value.

Table 2: Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the annual (January-December 12-month average for each calendar year between 1895-2011) and summertime (June-August 3-month average for each calendar year between 1895-2012) Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), and Palmer Modified Drought Index (PMDI) by agricultural belt in the contiguous United States.

| | Palmer Drought Severity Index (PDSI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance[a]	Slope (y^{-1})	Significance	Slope (y^{-1})
Spring Wheat Belt	NS/-0.047/0.46	-0.0040	NS/-0.092/0.14	-0.0078
Winter Wheat Belt	NS/0.035/0.58	0.0017	NS/0.0089/0.89	0.00043
Corn Belt	**/0.20/0.0014	0.013	**/0.18/0.0050	0.011
Soybean Belt	***/0.22/0.00027	0.013	**/0.18/0.0044	0.011
Cotton Belt	NS/0.040/0.53	0.0016	NS/-0.028/0.66	-0.0017

| | Palmer Hydrological Drought Index (PHDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Spring Wheat Belt	NS/-0.048/0.45	-0.0036	NS/-0.067/0.28	-0.0065
Winter Wheat Belt	NS/0.037/0.56	0.0021	NS/-0.00072/0.99	0.00
Corn Belt	***/0.22/0.00055	0.015	**/0.16/0.0083	0.013
Soybean Belt	***/0.23/0.00017	0.015	**/0.18/0.0044	0.012
Cotton Belt	NS/0.052/0.41	0.0029	NS/-0.038/0.55	-0.0027

| | Palmer Modified Drought Index (PMDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Spring Wheat Belt	NS/-0.040/0.53	-0.038	NS/-0.082/0.19	-0.021
Winter Wheat Belt	NS/0.036/0.57	0.024	NS/-0.012/0.85	-0.0020
Corn Belt	**/0.20/0.0013	0.15	*/0.15/0.014	0.031
Soybean Belt	***/0.23/0.00024	0.15	*/0.15/0.014	0.029
Cotton Belt	NS/0.045/0.47	0.026	NS/-0.038/0.54	-0.0071

[a] Presented as significance level (NS=not significant at p>0.10; +=p≤0.10; *=p≤0.05; **=p≤0.01; and ***=p≤0.001), τ, and 2-sided p-value.

Table 3: Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the annual (January-December 12-month average for each calendar year between 1895-2011) and summertime (June-August 3-month average for each calendar year between 1895-2012) absolute values of the Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), and Palmer Modified Drought Index (PMDI) by region in the contiguous United States.

| | Palmer Drought Severity Index (PDSI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance[a]	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.052/0.41	0.0029	NS/0.020/0.75	0.0010
Northeast	**/0.19/0.0031	0.0071	*/0.13/0.031	0.0062
East North Central	+/0.10/0.094	0.0052	NS/0.087/0.16	0.0042
Central	+/0.12/0.054	0.0045	NS/0.041/0.52	0.0019
Southeast	NS/0.061/0.33	0.0024	NS/0.099/0.11	0.0044
West North Central	NS/0.085/0.18	0.0058	NS/0.080/0.20	0.0060
South	NS/0.0060/0.92	0.00033	NS/0.014/0.83	0.00094
Southwest	NS/0.027/0.67	0.0016	NS/0.043/0.49	0.0033
Northwest	NS/0.10/0.11	0.0044	*/0.14/0.028	0.0065
West	NS/0.095/0.13	0.0054	*/0.13/0.033	0.0085

| | Palmer Hydrological Drought Index (PHDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.074/0.24	0.0045	NS/0.015/0.81	0.00097
Northeast	***/0.23/0.00031	0.011	**/0.18/0.0044	0.0083
East North Central	NS/0.091/0.15	0.0050	NS/0.062/0.32	0.0026
Central	+/0.11/0.081	0.0046	NS/0.046/0.47	0.0024
Southeast	NS/0.074/0.24	0.0026	NS/0.070/0.26	0.0034
West North Central	NS/0.043/0.49	0.0032	NS/0.048/0.44	0.0037
South	NS/0.017/0.79	0.00098	NS/0.032/0.61	0.0021
Southwest	NS/-0.0084/0.90	-0.00076	NS/0.044/0.48	0.0033
Northwest	*/0.14/0.025	0.0066	**/0.18/0.0033	0.0089
West	+/0.12/0.064	0.0069	*/0.14/0.028	0.0094

| | Palmer Modified Drought Index (PMDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.068/0.28	0.044	NS/0.019/0.77	0.0033
Northeast	**/0.19/0.0028	0.089	*/0.13/0.044	0.017
East North Central	+/0.11/0.085	0.056	NS/0.056/0.37	0.0074
Central	NS/0.077/0.22	0.034	NS/0.025/0.69	0.0040
Southeast	NS/0.072/0.25	0.038	NS/0.039/0.53	0.0059
West North Central	NS/0.059/0.35	0.050	NS/0.039/0.53	0.0093
South	NS/0.0030/0.96	0.0016	NS/0.0016/0.98	0.00026
Southwest	NS/-0.012/0.86	-0.0075	NS/0.058/0.35	0.014
Northwest	*/0.14/0.025	0.065	**/0.17/0.0068	0.023
West	+/0.11/0.085	0.073	+/0.12/0.061	0.024

[a] Presented as significance level (NS=not significant at p>0.10; +=p≤0.10; *=p≤0.05; **=p≤0.01; and ***=p≤0.001), τ, and 2-sided p-value.

Table 4: Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the absolute value of the year-to-year change of the annual (January-December 12-month average for each calendar year between 1895-2011) and summertime (June-August 3-month average for each calendar year between 1895-2012) Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), and Palmer Modified Drought Index (PMDI) by region in the contiguous United States.

| | Palmer Drought Severity Index (PDSI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance[a]	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.014/0.83	0.00065	NS/0.053/0.39	0.0030
Northeast	NS/0.051/0.42	0.0019	+/0.10/0.097	0.0055
East North Central	NS/-0.030/0.64	-0.0012	NS/-0.018/0.77	-0.00095
Central	NS/0.0012/0.99	0.00	NS/-0.060/0.34	-0.0038
Southeast	NS/0.071/0.26	0.0031	NS/0.060/0.34	0.0040
West North Central	NS/-0.037/0.56	-0.0015	NS/0.079/0.21	0.0056
South	NS/-0.018/0.78	-0.0012	NS/0.0063/0.92	0.00053
Southwest	NS/0.085/0.18	0.0051	NS/0.10/0.11	0.0082
Northwest	NS/0.027/0.67	0.00095	NS/0.0047/0.94	0.00015
West	NS/0.066/0.30	0.0046	**/0.17/0.0058	0.015

| | Palmer Hydrological Drought Index (PHDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/-0.014/0.82	-0.00085	NS/0.042/0.51	0.0033
Northeast	NS/0.024/0.71	0.00098	NS/0.015/0.81	0.00076
East North Central	NS/-0.047/0.46	-0.0018	NS/-0.063/0.31	-0.0035
Central	NS/-0.062/0.33	-0.0028	*/-0.14/0.030	-0.0077
Southeast	NS/-0.048/0.44	-0.0024	NS/-0.0075/0.91	-0.00061
West North Central	NS/-0.035/0.58	-0.0017	NS/0.075/0.23	0.0050
South	NS/-0.031/0.62	-0.0017	NS/0.058/0.36	0.0044
Southwest	+/0.11/0.070	0.0079	+/0.10/0.10	0.0095
Northwest	NS/0.030/0.63	0.0012	NS/0.0037/0.95	0.00017
West	+/0.11/0.069	0.0075	**/0.20/0.0011	0.018

| | Palmer Modified Drought Index (PMDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.013/0.84	0.0092	NS/0.033/0.60	0.0060
Northeast	NS/0.071/0.26	0.028	+/0.12/0.055	0.021
East North Central	NS/-0.053/0.40	-0.026	NS/-0.029/0.64	-0.0038
Central	NS/-0.051/0.41	-0.028	NS/-0.086/0.17	-0.013
Southeast	NS/0.0092/0.89	0.0038	NS/0.061/0.33	0.010
West North Central	NS/-0.050/0.43	-0.024	NS/0.091/0.14	0.019
South	NS/-0.0015/0.98	-0.0012	NS/0.062/0.32	0.015
Southwest	NS/0.093/0.14	0.081	+/0.10/0.096	0.029
Northwest	NS/0.048/0.45	0.023	NS/0.058/0.36	0.0090
West	*/0.15/0.015	0.11	***/0.22/0.00048	0.058

[a] Presented as significance level (NS=not significant at p>0.10; +=p≤0.10; *=p≤0.05; **=p≤0.01; and ***=p≤0.001), τ, and 2-sided p-value.

Table 5: Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the five-year running interquartile range of the annual (January-December 12-month average for each calendar year between 1895-2011) and summertime (June-August 3-month average for each calendar year between 1895-2012) Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), and Palmer Modified Drought Index (PMDI) by region in the contiguous United States.

| | Palmer Drought Severity Index (PDSI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance[a]	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/-0.0092/0.89	-0.00037	NS/0.035/0.59	0.0019
Northeast	NS/-0.013/0.84	-0.00018	NS/0.084/0.19	0.0040
East North Central	NS/0.026/0.69	0.00091	NS/0.018/0.77	0.00091
Central	**/0.19/0.0024	0.0089	NS/-0.0081/0.90	-0.00013
Southeast	NS/0.080/0.21	0.0030	NS/-0.024/0.71	-0.0012
West North Central	NS/0.049/0.44	0.0029	NS/0.023/0.72	0.0018
South	*/-0.16/0.012	-0.0084	NS/-0.096/0.13	-0.0046
Southwest	*/0.14/0.029	0.0082	**/0.17/0.0076	0.013
Northwest	**/0.17/0.0079	0.0068	NS/-0.044/0.49	-0.0012
West	*/0.15/0.019	0.0099	***/0.26/5.2e-05	0.018

| | Palmer Hydrological Drought Index (PHDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.092/0.15	0.0048	NS/0.036/0.58	0.0021
Northeast	NS/-0.040/0.53	-0.0011	NS/0.051/0.43	0.0024
East North Central	NS/-0.020/0.76	-0.00076	*/-0.13/0.046	-0.0067
Central	+/0.11/0.079	0.0058	NS/-0.069/0.28	-0.0044
Southeast	NS/-0.022/0.73	-0.00081	NS/-0.037/0.56	-0.0021
West North Central	NS/0.023/0.72	0.0016	NS/0.012/0.85	0.00077
South	*/-0.16/0.012	-0.0070	NS/-0.030/0.64	-0.0016
Southwest	NS/0.082/0.20	0.0041	*/0.16/0.014	0.013
Northwest	**/0.18/0.0054	0.0077	NS/0.020/0.75	0.0012
West	**/0.19/0.0033	0.012	***/0.21/0.00077	0.018

| | Palmer Modified Drought Index (PMDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.035/0.58	0.016	NS/0.034/0.59	0.0054
Northeast	NS/0.0098/0.88	0.0018	+/0.10/0.10	0.016
East North Central	NS/-0.059/0.36	-0.026	NS/-0.034/0.59	-0.0046
Central	*/0.16/0.015	0.091	NS/0.0023/0.97	0.00
Southeast	NS/0.059/0.36	0.026	NS/-0.0055/0.93	-0.00021
West North Central	NS/0.049/0.44	0.026	NS/0.026/0.68	0.0058
South	**/-0.16/0.010	-0.10	NS/-0.051/0.42	-0.0072
Southwest	*/0.15/0.021	0.098	*/0.16/0.013	0.043
Northwest	**/0.19/0.0030	0.097	NS/0.025/0.70	0.0026
West	**/0.19/0.0036	0.14	***/0.25/9.0e-05	0.060

[a] Presented as significance level (NS=not significant at p>0.10; +=p≤0.10; *=p≤0.05; **=p≤0.01; and ***=p≤0.001), τ, and 2-sided p-value.

Table 6: Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the five-year running range of the annual (January-December 12-month average for each calendar year between 1895-2011) and summertime (June-August 3-month average for each calendar year between 1895-2012) Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), and Palmer Modified Drought Index (PMDI) by region in the contiguous United States.

| | Palmer Drought Severity Index (PDSI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance[a]	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.013/0.84	0.00044	NS/0.018/0.78	0.00099
Northeast	NS/0.081/0.21	0.0043	*/0.15/0.017	0.0081
East North Central	NS/-0.0095/0.88	0.00	NS/-0.019/0.77	-0.00039
Central	NS/0.053/0.41	0.0021	NS/-0.043/0.50	-0.0031
Southeast	NS/0.097/0.13	0.0054	+/0.11/0.090	0.0069
West North Central	NS/0.0035/0.96	0.00	NS/0.062/0.33	0.0061
South	NS/-0.024/0.72	-0.0017	NS/-0.011/0.87	0.00
Southwest	+/0.10/0.10	0.010	**/0.17/0.0088	0.018
Northwest	**/0.17/0.0097	0.0083	**/0.18/0.0040	0.013
West	**/0.20/0.0022	0.018	***/0.27/3.0e-05	0.029

| | Palmer Hydrological Drought Index (PHDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.0022/0.97	0.00	NS/0.021/0.75	0.0010
Northeast	*/0.14/0.033	0.0070	*/0.16/0.013	0.0082
East North Central	NS/-0.078/0.22	-0.0052	NS/-0.034/0.60	-0.0027
Central	NS/-0.066/0.30	-0.0037	+/-0.12/0.055	-0.0087
Southeast	NS/0.069/0.28	0.0050	NS/0.068/0.29	0.0054
West North Central	NS/0.017/0.79	0.0011	NS/0.082/0.20	0.0096
South	NS/-0.028/0.66	-0.0019	NS/0.018/0.78	0.00099
Southwest	*/0.16/0.014	0.017	**/0.18/0.0040	0.021
Northwest	**/0.20/0.0020	0.012	**/0.18/0.0038	0.014
West	***/0.25/0.00010	0.022	***/0.28/7.7e-06	0.033

| | Palmer Modified Drought Index (PMDI) | | | |
| | Annual (January-December) | | Summertime (June-August) | |
Region	Significance	Slope (y^{-1})	Significance	Slope (y^{-1})
Contiguous US	NS/0.014/0.83	0.0063	NS/-0.0022/0.97	0.00
Northeast	*/0.14/0.025	0.079	***/0.23/0.00026	0.040
East North Central	NS/-0.024/0.71	-0.016	NS/-0.010/0.87	-0.00093
Central	NS/-0.025/0.69	-0.015	NS/-0.088/0.17	-0.016
Southeast	NS/0.064/0.32	0.048	NS/0.053/0.41	0.011
West North Central	NS/0.028/0.66	0.022	NS/0.086/0.18	0.027
South	NS/0.0022/0.97	0.00	NS/0.027/0.68	0.0074
Southwest	*/0.14/0.029	0.15	*/0.16/0.013	0.055
Northwest	***/0.25/0.00011	0.15	***/0.25/0.00011	0.057
West	***/0.24/0.00013	0.25	***/0.28/1.0e-05	0.089

[a] Presented as significance level (NS=not significant at p>0.10; +=p≤0.10; *=p≤0.05; **=p≤0.01; and ***=p≤0.001), τ, and 2-sided p-value.

Supporting Information

Table S1. Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the annual (January-December 12-month average for each calendar year) Palmer Drought Severity Index (PDSI) between 1895-2011 by state in the contiguous United States.

Region	Significance	τ	2-Sided p-value	Slope (y^{-1})
Alabama	***	0.35	2.9e-08	0.028
Arizona	NS	-0.064	0.31	-0.0077
Arkansas	NS	0.056	0.37	0.0038
California	**	-0.16	0.0091	-0.016
Colorado	**	-0.18	0.0031	-0.026
Connecticut	***	0.33	1.1e-07	0.024
Delaware	NS	0.0092	0.89	0.00050
Florida	NS	0.032	0.61	0.0026
Georgia	NS	0.048	0.45	0.0038
Idaho	NS	-0.055	0.38	-0.0052
Illinois	*	0.13	0.037	0.0084
Indiana	***	0.21	0.00068	0.014
Iowa	**	0.17	0.0075	0.014
Kansas	NS	0.082	0.19	0.0082
Kentucky	NS	0.098	0.12	0.0068
Louisiana	NS	0.095	0.13	0.0064
Maine	NS	-0.090	0.15	-0.0075
Maryland	NS	-0.013	0.83	-0.00090
Massachusetts	***	0.45	2.2e-16	0.031
Michigan	***	0.33	1.3e-07	0.023
Minnesota	**	0.17	0.0058	0.016
Mississippi	***	0.23	0.00029	0.017
Missouri	NS	0.073	0.25	0.0051
Montana	**	-0.19	0.0022	-0.022
Nebraska	NS	0.032	0.61	0.0044
Nevada	+	-0.10	0.10	-0.011
New Hampshire	NS	0.074	0.24	0.0045
New Jersey	NS	0.066	0.30	0.0036
New Mexico	NS	0.081	0.19	0.0079
New York	***	0.32	4.0e-07	0.022
North Carolina	NS	0.020	0.75	0.0011
North Dakota	NS	-0.039	0.53	-0.0047
Ohio	*	0.12	0.046	0.0092
Oklahoma	+	0.12	0.054	0.011
Oregon	NS	0.044	0.49	0.0033
Pennsylvania	***	0.38	6.1e-10	0.031
Rhode Island	***	0.32	2.6e-07	0.020
South Carolina	NS	0.064	0.31	0.0038
South Dakota	***	0.34	3.6e-08	0.046
Tennessee	*	0.13	0.041	0.0089
Texas	NS	0.019	0.77	0.0019
Utah	NS	0.0094	0.88	0.0010
Vermont	*	0.12	0.049	0.011
Virginia	NS	0.0087	0.89	0.00054
Washington	NS	0.086	0.17	0.0064
West Virginia	NS	0.098	0.12	0.0058
Wisconsin	NS	0.099	0.11	0.0070
Wyoming	***	-0.31	1.0e-06	-0.050

Table S2. Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the summertime (June-August 3-month average for each calendar year) Palmer Drought Severity Index (PDSI) between 1895-2012 by state in the contiguous United States.

Region	Significance	τ	2-Sided p-value	Slope (y^{-1})
Alabama	***	0.24	9.9e-05	0.025
Arizona	+	0.071	-0.11	-0.016
Arkansas	NS	-0.029	0.65	-0.0026
California	*	-0.16	0.011	-0.020
Colorado	**	-0.19	0.0020	-0.030
Connecticut	***	0.25	7.4e-05	0.021
Delaware	NS	-0.066	0.29	-0.0060
Florida	NS	0.029	0.64	0.0025
Georgia	NS	-0.020	0.76	-0.0020
Idaho	NS	-0.024	0.71	-0.0025
Illinois	+	0.10	0.10	0.0094
Indiana	**	0.20	0.0017	0.017
Iowa	*	0.14	0.027	0.014
Kansas	NS	0.076	0.22	0.0092
Kentucky	NS	0.074	0.24	0.0064
Louisiana	NS	0.016	0.81	0.0013
Maine	NS	-0.067	0.28	-0.0070
Maryland	NS	-0.097	0.12	-0.0081
Massachusetts	***	0.32	2.2e-07	0.027
Michigan	***	0.24	0.00017	0.019
Minnesota	*	0.13	0.043	0.013
Mississippi	*	0.13	0.042	0.012
Missouri	NS	0.012	0.85	0.0012
Montana	**	-0.18	0.0031	-0.028
Nebraska	NS	0.021	0.73	0.0036
Nevada	+	-0.10	0.094	-0.015
New Hampshire	NS	0.074	0.24	0.0068
New Jersey	NS	0.0028	0.97	0.00029
New Mexico	NS	0.00087	0.99	0.00023
New York	***	0.24	0.00014	0.022
North Carolina	+	-0.10	0.095	-0.0088
North Dakota	NS	-0.062	0.32	-0.0083
Ohio	+	0.10	0.092	0.0096
Oklahoma	NS	0.053	0.39	0.0068
Oregon	+	0.12	0.066	0.011
Pennsylvania	***	0.33	1.6e-07	0.031
Rhode Island	***	0.21	0.00089	0.015
South Carolina	NS	-0.016	0.79	-0.0013
South Dakota	***	0.29	2.9e-06	0.047
Tennessee	NS	0.077	0.22	0.0062
Texas	NS	-0.023	0.71	-0.0038
Utah	NS	-0.0096	0.88	-0.0015
Vermont	*	0.12	0.048	0.012
Virginia	NS	-0.076	0.22	-0.0062
Washington	+	0.11	0.082	0.0092
West Virginia	NS	0.059	0.34	0.0057
Wisconsin	NS	0.066	0.29	0.0052
Wyoming	***	-0.30	1.7e-06	-0.055

Table S3. Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the annual (January-December 12-month average for each calendar year) Palmer Hydrological Drought Index (PHDI) between 1895-2011 by state in the contiguous United States.

Region	Significance	τ	2-Sided p-value	Slope (y^{-1})
Alabama	***	0.39	6.3e-10	0.033
Arizona	NS	-0.075	0.23	-0.010
Arkansas	NS	0.092	0.14	0.0072
California	*	-0.13	0.040	-0.015
Colorado	**	-0.19	0.0024	-0.028
Connecticut	***	0.34	3.8e-08	0.027
Delaware	NS	0.047	0.46	0.0036
Florida	NS	0.043	0.49	0.0035
Georgia	NS	0.066	0.29	0.0055
Idaho	NS	-0.051	0.41	-0.0051
Illinois	*	0.16	0.013	0.013
Indiana	***	0.28	7.2e-06	0.020
Iowa	**	0.18	0.0043	0.017
Kansas	NS	0.089	0.16	0.0082
Kentucky	+	0.12	0.055	0.0091
Louisiana	+	0.11	0.090	0.0084
Maine	+	-0.11	0.090	-0.0095
Maryland	NS	-0.0046	0.94	-0.00042
Massachusetts	***	0.46	2.2e-16	0.036
Michigan	***	0.36	1.1e-08	0.029
Minnesota	**	0.18	0.0033	0.018
Mississippi	***	0.25	8.1e-05	0.021
Missouri	NS	0.078	0.21	0.0065
Montana	**	-0.19	0.0024	-0.024
Nebraska	NS	0.033	0.60	0.0044
Nevada	NS	-0.078	0.21	-0.010
New Hampshire	NS	0.055	0.38	0.0042
New Jersey	NS	0.062	0.33	0.0036
New Mexico	NS	0.062	0.33	0.0065
New York	***	0.34	7.3e-08	0.027
North Carolina	NS	0.0015	0.98	0.00
North Dakota	NS	-0.048	0.44	-0.0062
Ohio	**	0.17	0.0082	0.013
Oklahoma	+	0.12	0.061	0.011
Oregon	NS	0.056	0.38	0.0050
Pennsylvania	***	0.42	1.5e-11	0.037
Rhode Island	***	0.35	2.5e-08	0.026
South Carolina	NS	0.076	0.23	0.0057
South Dakota	***	0.34	5.2e-08	0.048
Tennessee	*	0.15	0.019	0.012
Texas	NS	0.026	0.68	0.0032
Utah	NS	0.0091	0.89	0.0012
Vermont	NS	0.10	0.11	0.0093
Virginia	NS	0.028	0.65	0.0021
Washington	+	0.10	0.10	0.0089
West Virginia	+	0.10	0.098	0.0084
Wisconsin	*	0.14	0.028	0.011
Wyoming	***	-0.32	3.7e-07	-0.053

Table S4. Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the summertime (June-August 3-month average for each calendar year) Palmer Hydrological Drought Index (PHDI) between 1895-2012 by state in the contiguous United States.

Region	Significance	τ	2-Sided p-value	Slope (y^{-1})
Alabama	***	0.28	5.7e-06	0.030
Arizona	NS	-0.096	0.12	-0.014
Arkansas	NS	0.0080	0.90	0.00083
California	*	-0.13	0.034	-0.018
Colorado	***	-0.22	0.00052	-0.033
Connecticut	***	0.29	4.3e-06	0.026
Delaware	NS	-0.012	0.85	-0.0012
Florida	NS	0.039	0.54	0.0039
Georgia	NS	0.0048	0.94	0.00042
Idaho	NS	-0.012	0.84	-0.0012
Illinois	+	0.10	0.10	0.0097
Indiana	***	0.24	0.00012	0.020
Iowa	*	0.15	0.017	0.015
Kansas	NS	0.055	0.38	0.0059
Kentucky	+	0.10	0.10	0.010
Louisiana	NS	0.025	0.69	0.0021
Maine	NS	-0.094	0.13	-0.0091
Maryland	NS	-0.028	0.65	-0.0027
Massachusetts	***	0.40	2.4e-10	0.036
Michigan	***	0.25	6.8e-05	0.022
Minnesota	+	0.12	0.061	0.012
Mississippi	*	0.16	0.012	0.016
Missouri	NS	0.040	0.52	0.0037
Montana	**	-0.19	0.0019	-0.031
Nebraska	NS	0.0098	0.88	0.0018
Nevada	NS	-0.10	0.11	-0.014
New Hampshire	NS	0.054	0.39	0.0049
New Jersey	NS	0.020	0.75	0.0016
New Mexico	NS	-0.0086	0.89	-0.0011
New York	***	0.25	5.0e-05	0.023
North Carolina	NS	-0.087	0.16	-0.0072
North Dakota	NS	-0.045	0.48	-0.0054
Ohio	+	0.12	0.058	0.011
Oklahoma	NS	0.072	0.25	0.0071
Oregon	+	0.11	0.068	0.011
Pennsylvania	***	0.36	1.2e-08	0.035
Rhode Island	***	0.27	1.1e-05	0.023
South Carolina	NS	-0.024	0.71	-0.0024
South Dakota	***	0.29	2.3e-06	0.049
Tennessee	NS	0.068	0.27	0.0061
Texas	NS	-0.034	0.58	-0.0048
Utah	NS	-0.018	0.78	-0.0027
Vermont	NS	0.044	0.48	0.0051
Virginia	NS	-0.029	0.65	-0.0022
Washington	*	0.13	0.037	0.011
West Virginia	NS	0.089	0.16	0.0077
Wisconsin	+	0.10	0.10	0.0082
Wyoming	***	-0.32	4.4e-07	-0.060

Table S5. Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the annual (January-December 12-month average for each calendar year) Palmer Modified Drought Index (PMDI) between 1895-2011 by state in the contiguous United States.

Region	Significance	τ	2-Sided p-value	Slope (y^{-1})
Alabama	***	0.38	1.8e-09	0.32
Arizona	NS	-0.067	0.29	-0.084
Arkansas	NS	0.078	0.21	0.062
California	*	-0.13	0.035	-0.15
Colorado	**	-0.19	0.0024	-0.33
Connecticut	***	0.34	4.9e-08	0.26
Delaware	NS	0.026	0.67	0.020
Florida	NS	0.040	0.52	0.032
Georgia	NS	0.069	0.27	0.056
Idaho	NS	-0.043	0.49	-0.045
Illinois	*	0.14	0.027	0.11
Indiana	***	0.28	1.1e-05	0.19
Iowa	**	0.18	0.0052	0.17
Kansas	NS	0.080	0.20	0.088
Kentucky	+	0.12	0.062	0.085
Louisiana	NS	0.098	0.12	0.081
Maine	NS	-0.076	0.22	-0.073
Maryland	NS	0.00030	1.00	0.00065
Massachusetts	***	0.45	2.2e-16	0.35
Michigan	***	0.35	2.1e-08	0.29
Minnesota	**	0.18	0.0044	0.20
Mississippi	***	0.24	0.00013	0.20
Missouri	NS	0.062	0.32	0.063
Montana	**	-0.19	0.0023	-0.26
Nebraska	NS	0.034	0.58	0.047
Nevada	NS	-0.081	0.20	-0.11
New Hampshire	NS	0.064	0.31	0.051
New Jersey	NS	0.068	0.28	0.042
New Mexico	NS	0.078	0.21	0.090
New York	***	0.34	8.0e-08	0.27
North Carolina	NS	0.028	0.65	0.017
North Dakota	NS	-0.044	0.48	-0.060
Ohio	*	0.15	0.020	0.12
Oklahoma	+	0.11	0.089	0.11
Oregon	NS	0.066	0.29	0.056
Pennsylvania	***	0.40	2.9e-10	0.36
Rhode Island	***	0.35	2.5e-08	0.24
South Carolina	NS	0.072	0.25	0.063
South Dakota	***	0.33	1.1e-07	0.51
Tennessee	*	0.14	0.030	0.11
Texas	NS	0.023	0.72	0.028
Utah	NS	0.014	0.83	0.015
Vermont	+	0.11	0.084	0.10
Virginia	NS	0.045	0.47	0.026
Washington	+	0.12	0.061	0.096
West Virginia	NS	0.093	0.14	0.075
Wisconsin	*	0.13	0.043	0.10
Wyoming	***	-0.31	9.9e-07	-0.58

Table S6. Results of Mann-Kendall trend tests and Theil-Sen estimate of the slope for time trends in the summertime (June-August 3-month average for each calendar year) Palmer Modified Drought Index (PMDI) between 1895-2012 by state in the contiguous United States.

Region	Significance	τ	2-Sided p-value	Slope (y^{-1})
Alabama	***	0.24	0.00015	0.071
Arizona	NS	-0.094	0.13	-0.041
Arkansas	NS	-0.036	0.56	-0.0083
California	*	-0.13	0.037	-0.050
Colorado	***	-0.22	0.00035	-0.10
Connecticut	***	0.24	8.2e-05	0.058
Delaware	NS	-0.054	0.39	-0.013
Florida	NS	0.032	0.61	0.010
Georgia	NS	-0.018	0.77	-0.0057
Idaho	NS	-0.00044	1.00	0.00
Illinois	NS	0.094	0.13	0.027
Indiana	***	0.21	0.00068	0.051
Iowa	*	0.15	0.019	0.043
Kansas	NS	0.045	0.47	0.015
Kentucky	NS	0.080	0.20	0.020
Louisiana	NS	0.010	0.87	0.0027
Maine	NS	-0.049	0.43	-0.015
Maryland	NS	-0.064	0.31	-0.017
Massachusetts	***	0.32	4.5e-07	0.079
Michigan	***	0.24	0.00013	0.058
Minnesota	*	0.12	0.050	0.038
Mississippi	*	0.13	0.034	0.038
Missouri	NS	0.0072	0.91	0.0021
Montana	**	-0.19	0.0020	-0.086
Nebraska	NS	0.0042	0.95	0.0025
Nevada	+	-0.10	0.098	-0.046
New Hampshire	NS	0.065	0.30	0.016
New Jersey	NS	0.021	0.74	0.0056
New Mexico	NS	-0.0087	0.89	-0.0039
New York	***	0.21	0.00073	0.053
North Carolina	+	-0.10	0.10	-0.025
North Dakota	NS	-0.049	0.43	-0.023
Ohio	NS	0.091	0.14	0.026
Oklahoma	NS	0.035	0.57	0.011
Oregon	*	0.14	0.023	0.038
Pennsylvania	***	0.31	6.8e-07	0.079
Rhode Island	***	0.24	9.4e-05	0.052
South Carolina	NS	-0.024	0.70	-0.0055
South Dakota	***	0.28	4.9e-06	0.14
Tennessee	NS	0.061	0.33	0.014
Texas	NS	-0.035	0.58	-0.015
Utah	NS	-0.015	0.81	-0.0065
Vermont	NS	0.062	0.32	0.018
Virginia	NS	-0.074	0.23	-0.018
Washington	+	0.11	0.081	0.029
West Virginia	NS	0.066	0.29	0.016
Wisconsin	NS	0.062	0.32	0.016
Wyoming	***	-0.29	2.4e-06	-0.17