The Heat Is On

U.S. Temperature Trends

Claudia Tebaldi, PhD
Senior Scientist

Dennis Adams-Smith
Data Analyst

Nicole Heller, PhD
Collaborating Scientist

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Claudia Tebaldi, PhD
Dennis Adams-Smith
Nicole Heller, PhD (collaborator)

Princeton

One Palmer Square, Suite 330
Princeton, NJ 08542

Phone: +1 609 924-3800

Palo Alto

895 Emerson Street
Palo Alto, CA 94301

Phone: +1 877 425-4724

Call Toll Free

+1 877 4-CLI-SCI (877 425-4724)

www.climatecentral.org

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Report Authors

Claudia Tebaldi, PhD

Senior Scientist

Dr. Tebaldi leads research involving climate statistcs at Climate Central. Her research interests include the analysis of observations and climate model output in order to characterize observed and projected climatic changes and their uncertainties. She has published papers on detection and attribution of these changes, on extreme value analysis, future projections at regional levels, and impacts of climate change on agriculture and human health and she is currently a lead author for the IPCC Fifth Assessment Report, within Working Group 1. She has a Ph.D. in statistics from Duke University.

Dennis Adams-Smith

Data Analyst

Mr. Adams-Smith is Climate Central's lead data analyst, translating vast amounts of climate and energy data into more accessible, graphical, and interactive results. Previously, he developed statistical methods and tools used in design, testing and manufacturing at Michelin Americas Research Corporation, and he also taught industrial statistics courses and mathematics at Greenville Technical College and Clemson University. He holds a M.Sc. in Mathematical Sciences from Clemson University and a BA in Mathematics from Alfred University.

Nicole Heller, PhD

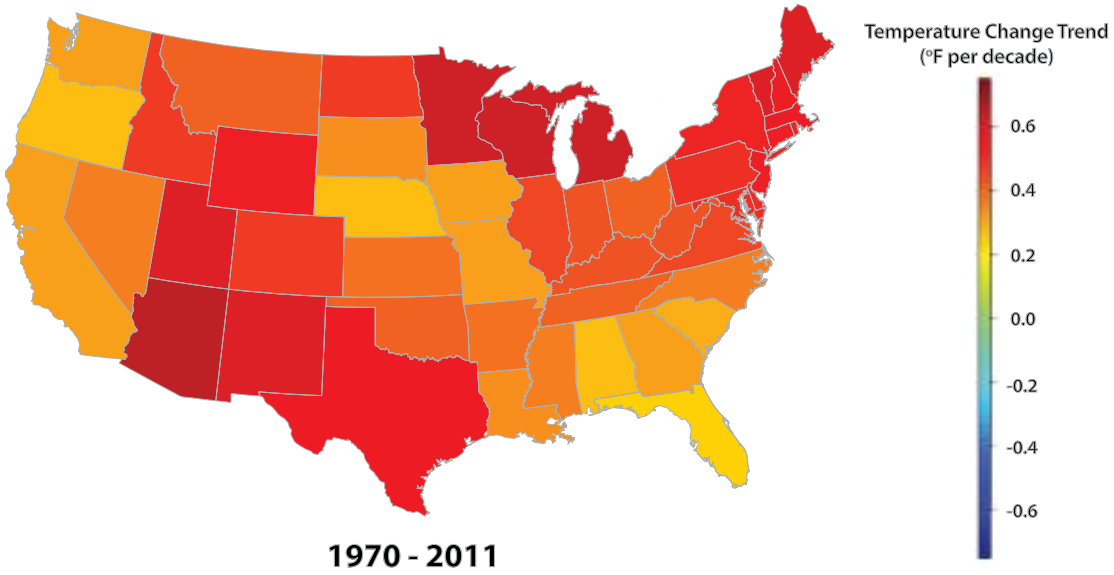
Collaborating Scientist

Dr. Heller studies the effects of global change on ecosystems and climate change adaptation. She was recently named a Google Science Communication Fellow and she is now collaborating with Climate Central on a project using Google Earth to help communities visualize the local impacts of climate change. She holds a Ph.D. in Biology from Stanford University and is a Visiting Assistant Professor at the Nicolas School of the Environment at Duke University.

Summary

Global warming isn't uniform. The continental U.S. has warmed by about 1.3°F over the past 100 years, but the temperature increase hasn't been the same everywhere: some places have warmed more than others, some less, and some not much at all. Natural variability explains some of the differences, and air pollution with fine aerosols screening incoming solar radiation could also be a factor.

Our state-by-state analysis of warming over the past 100 years shows where it warmed the most and where it warmed the least. We found that no matter how much or how little a given state warmed over that 100-year period, the *pace* of warming in *all* regions accelerated dramatically starting in the 1970s, coinciding with the time when the effect of greenhouse gases began to overwhelm the other natural and human influences on climate at the global and continental scales.



We looked at average daily temperatures for the continental 48 states from 1912 to the present, and also from 1970 to the present and found:

- Over the past 100 years, the top 10 states on average warmed **60 times faster** than the bottom 10 (0.26°F per decade vs. 0.004°F per decade), when looking at average mean temperatures. During this timeframe, 45 states showed warming trends, although 21 were not statistically significant. Three states experienced a slight cooling trend.
- Since 1970, warming began accelerating everywhere. The speed of warming across the lower 48 **more than tripled**, from 0.127°F per decade over the 100-year period, to 0.435°F per decade since 1970. In the last 42 years the 10 fastest-warming states heated up just twice as fast, not 60 times as fast as the 10 slowest-warming states (0.60°F vs. 0.30°F per decade). Over the past 42 years 17 states warmed more than half a degree F per decade.
- The states that have warmed the most — whether you look at the past 100 years or just the past 40 — include northern-tier states from Minnesota to Maine and the Southwest, particularly Arizona and New Mexico. Places that have warmed the least include Southeast states, like Florida, Alabama, Georgia and South Carolina, along with parts of the central Midwest, like Iowa and Nebraska.

Introduction

Meteorologists and climatologists have long been aware that global warming doesn't happen uniformly over time; global temperatures rise more quickly during some decades than in others, and can even decline temporarily. Nor does it affect every place the same way. The Arctic, for example, is warming significantly faster than the tropics, for reasons scientists believe they understand.

In this report, we set out to document state-by-state differences in warming within the continental U.S. The country as a whole has warmed by 1.3°F over the past century, but the warming has not been uniform.

The rate of warming in each state depends on the time frame you consider. Over the past 100 years, some states have warmed more than others — and a few states do not show any statistically significant warming. But in the past 40 years — as the rate of global warming trends has increased — every state in the continental U.S. has experienced an overall rise in temperatures.

Rising Temperatures State-By-State

We collected the record of daily high (maximum) and low (minimum) temperatures from the National Climatic Data Center's U.S. Historical Climatology Network of weather stations. Combining the averages of these high and low temperatures from every station in each state, we calculated the average daily temperatures over the entire year, and then evaluated how much average daily temperatures changed each decade over the past 100 years by computing linear trends.

Based on these changes in annual average daily temperature, Table 1 lists the rate of warming for each state between 1912 and 2011. During that time, 45 states showed warming trends (though trends in 21 states were not statistically significant at the 5 percent level), and three — Alabama, Arkansas and Georgia — experienced a slight cooling (not statistically significant in any of the three).

The 10 fastest warming states during the 100-year period saw on average warming rates that were 60 times higher than the slowest warming states. The five fastest warming states — Rhode island, Massachusetts, New Jersey, Arizona and Maine — warmed at rates twice the U.S. average of 0.127°F per decade for the 100-year period.

Trends in changing daily high and low temperatures between 1912–2011 are tabulated in the Appendix (*Table A1* and *Table A2*).

Almost Every State Has Warmed In The Past 100 Years

Table 1. Since 1912, states experienced different rates of warming. Some warmed dramatically; others didn't warm at all.

Rank	State	Temperature Change (°F per decade)
1	Rhode Island	0.339
2	Massachusetts	0.300
3	New Jersey	0.280
4	Arizona	0.273
5	Maine	0.272
6	Connecticut	0.250
7	Michigan	0.245
8	Utah	0.233
9	Minnesota	0.229
10	Colorado	0.225
11	New Hampshire	0.215
12	Delaware	0.210
13	North Dakota	0.208
14	Wyoming	0.197
15	Nevada	0.196
16	Wisconsin	0.189
17	Montana	0.188
18	New York	0.181
19	New Mexico	0.177
20	Maryland	0.176
21	Vermont	0.172
22	Idaho	0.166
23	California	0.161
24	South Dakota	0.143
25	Pennsylvania	0.142
26	Washington	0.129
27	Oregon	0.128
28	Texas	0.114
29	Virginia	0.107
30	Kansas	0.103
31	Florida	0.081
32	Ohio	0.077
33	Illinois	0.076
34	Nebraska	0.072
35	Oklahoma	0.072
36	Indiana	0.059
37	North Carolina	0.054
38	Iowa	0.046
39	West Virginia	0.035
40	Missouri	0.029
41	South Carolina	0.024
42	Tennessee	0.021
43	Louisiana	0.019
44	Mississippi	0.014
45	Kentucky	0.008
46	Arkansas	-0.004
47	Georgia	-0.035
48	Alabama	-0.071

[a] *States ranked 25-48 have trends that are not statistically significant (at the five percent level).*

The 10 Fastest-Warming States Warmed 60 Times Faster Than the Slowest States Between 1912-2011

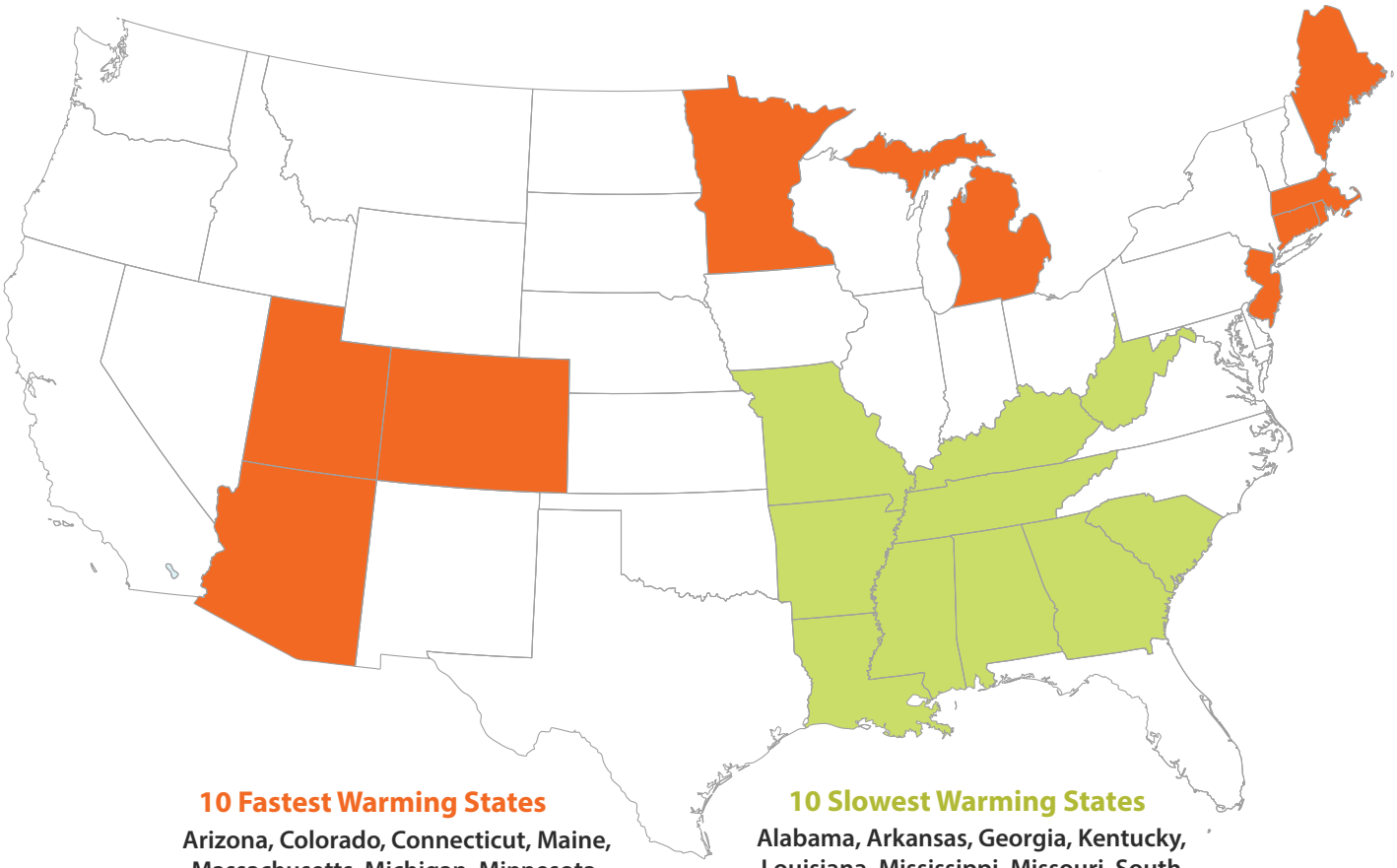


Figure 1. *From 1912-2011, the Southeast and Mississippi Valley warmed far more slowly than the rest of the country, a phenomenon described as the Warming Hole.*

From 1970 to the present, warming accelerated dramatically and there were rapid trends in warming for every state. Over this 42-year time span, all 48 states showed warming (*Table 2*), with temperatures increasing at more than twice the rate than during the 100-year time span (see Appendix *Table A3* and *Table A4* for 1970-2011 trends in daily high and low temperatures).

With every state showing significant warming trends from 1970–2011, the difference between the fast-warming states and more slowly warming states is smaller than when looking over the 100-year time period (*Figure 2*).

Every State Has Warmed Since 1970

Table 2. Since 1970, every state has experienced a warming and the rates of warming were faster than they were over the past 100 years.

Rank	State	Temperature Change (°F per decade)
1	Arizona	0.639
2	Michigan	0.622
3	Minnesota	0.620
4	Wisconsin	0.616
5	Vermont	0.607
6	New Mexico	0.603
7	Utah	0.588
8	Maine	0.587
9	Texas	0.575
10	Massachusetts	0.568
11	New Jersey	0.560
12	Connecticut	0.556
13	Wyoming	0.554
14	New Hampshire	0.553
15	New York	0.538
16	Rhode Island	0.520
17	Maryland	0.508
18	Pennsylvania	0.498
19	Delaware	0.494
20	Colorado	0.483
21	North Dakota	0.471
22	Idaho	0.470
23	Illinois	0.468
24	Virginia	0.456
25	Indiana	0.439
26	Kentucky	0.432
27	West Virginia	0.428
28	Ohio	0.420
29	Montana	0.420
30	Tennessee	0.416
31	Oklahoma	0.413
32	Arkansas	0.383
33	Kansas	0.378
34	Mississippi	0.375
35	North Carolina	0.370
36	Nevada	0.367
37	South Dakota	0.349
38	Louisiana	0.344
39	MIssouri	0.318
40	Washington	0.318
41	California	0.314
42	Iowa	0.310
43	Georgia	0.307
44	South Carolina	0.292
45	Oregon	0.277
46	Alabama	0.275
47	Nebraska	0.268
48	Florida	0.246

The Warming Hole in the Southeast Disappeared From 1970-2011, the Same Time That Warming Accelerated

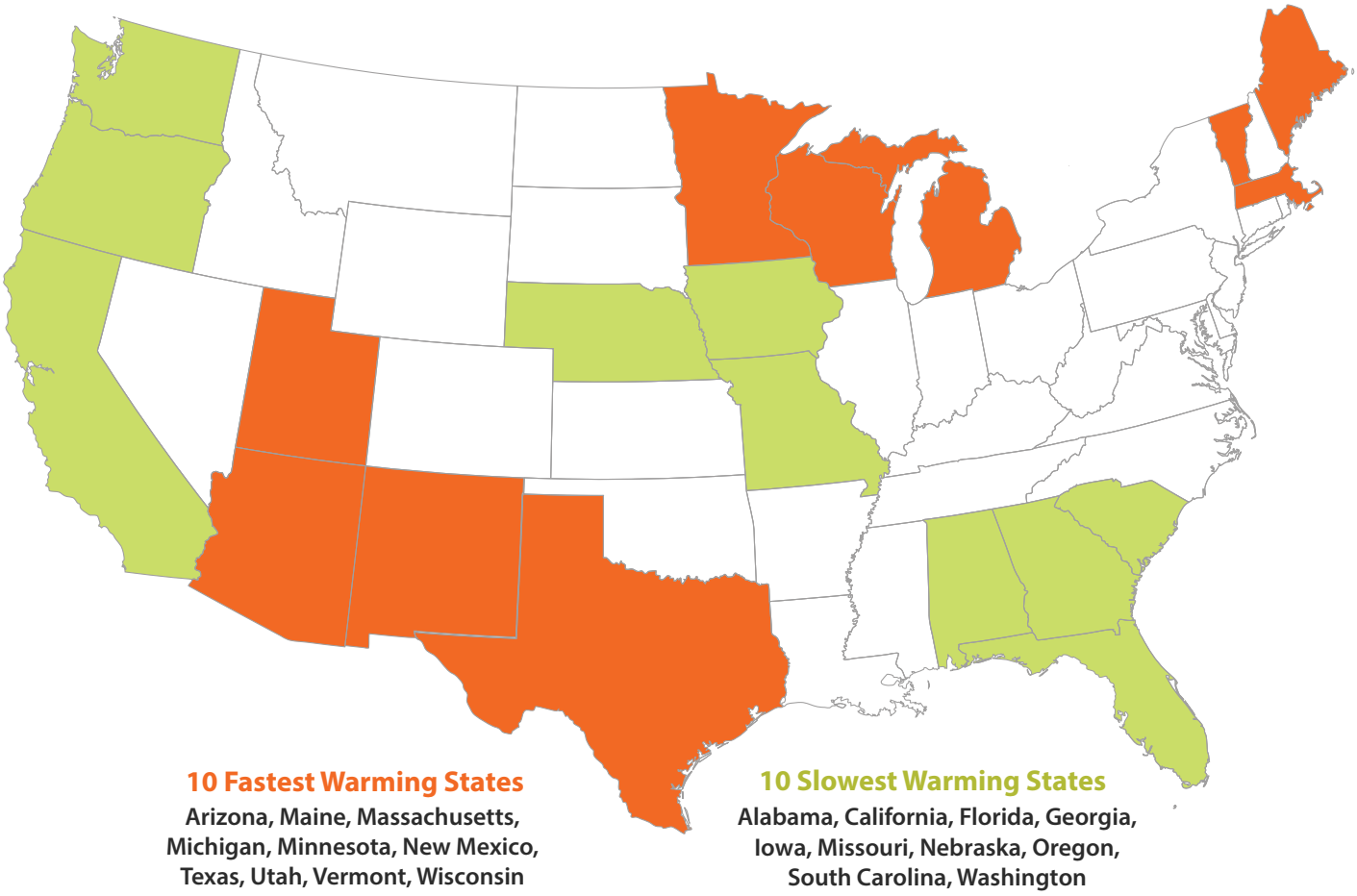


Figure 2. *From 1970-2011 every state experienced warming trends. The 10 fastest warming states remained in the Northeast, Upper Midwest and the Southwest, while the 10 slowest warming states (green) were evenly distributed through the Southeast, Midwest, and along the Pacific Coast.*

While not every state has seen steady temperature increases over the entire period of the past 100 years, every state has seen a significant warming trend in the past 30–40 years (since 1970). States like Alabama and Georgia, which have been among the slowest to warm (and have experienced slight cooling over the past 100 years), have nevertheless seen steady warming since the mid-1970s (*Figure 3*). States that have warmed consistently over the entire 100-year period, such as Arizona and New Mexico, saw their rate of warming accelerate even further (*Figure 4*).

Even States With No Temperature Change in the Past 100 Years Have Seen Steady Warming Trends Since 1970

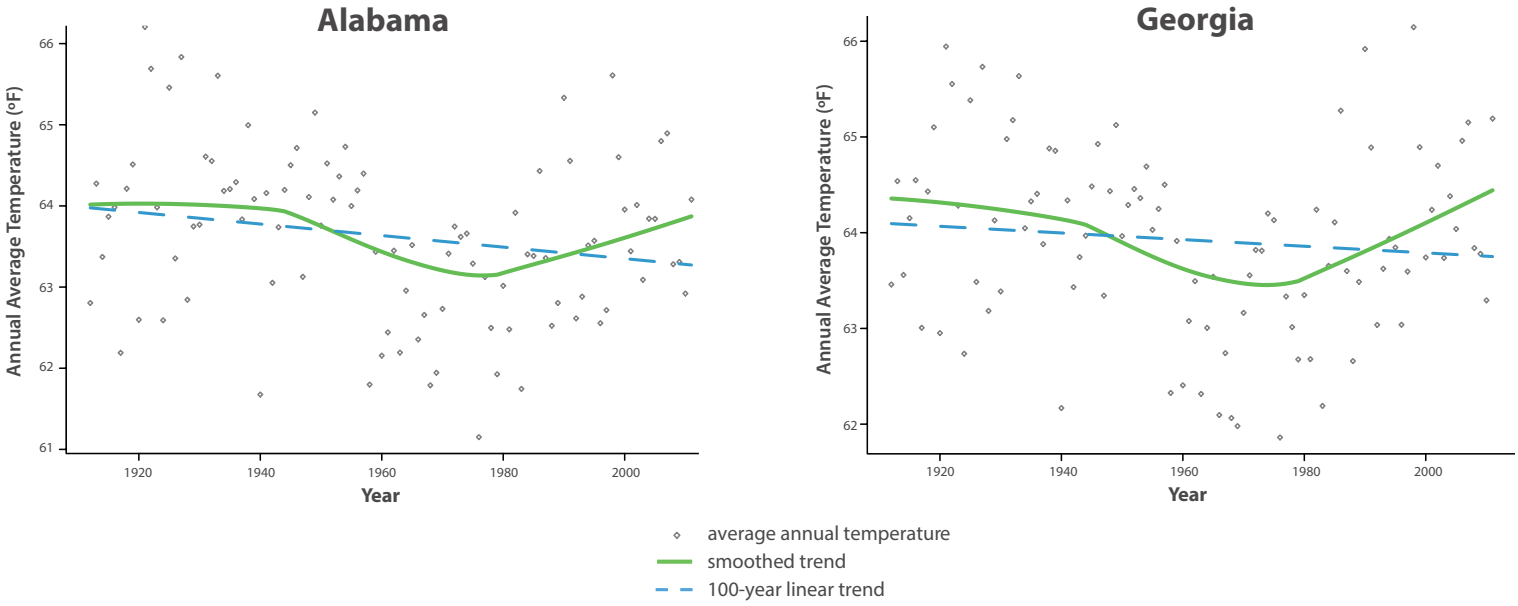


Figure 3. *All states have seen steady warming rates since 1970, including states that have seen little overall warming in the past 100 years, like Alabama and Georgia. The graphs show trends in average annual temperatures over the past 100 years.*

Warming Has Accelerated Since 1970, Even in States That Were Already Warming

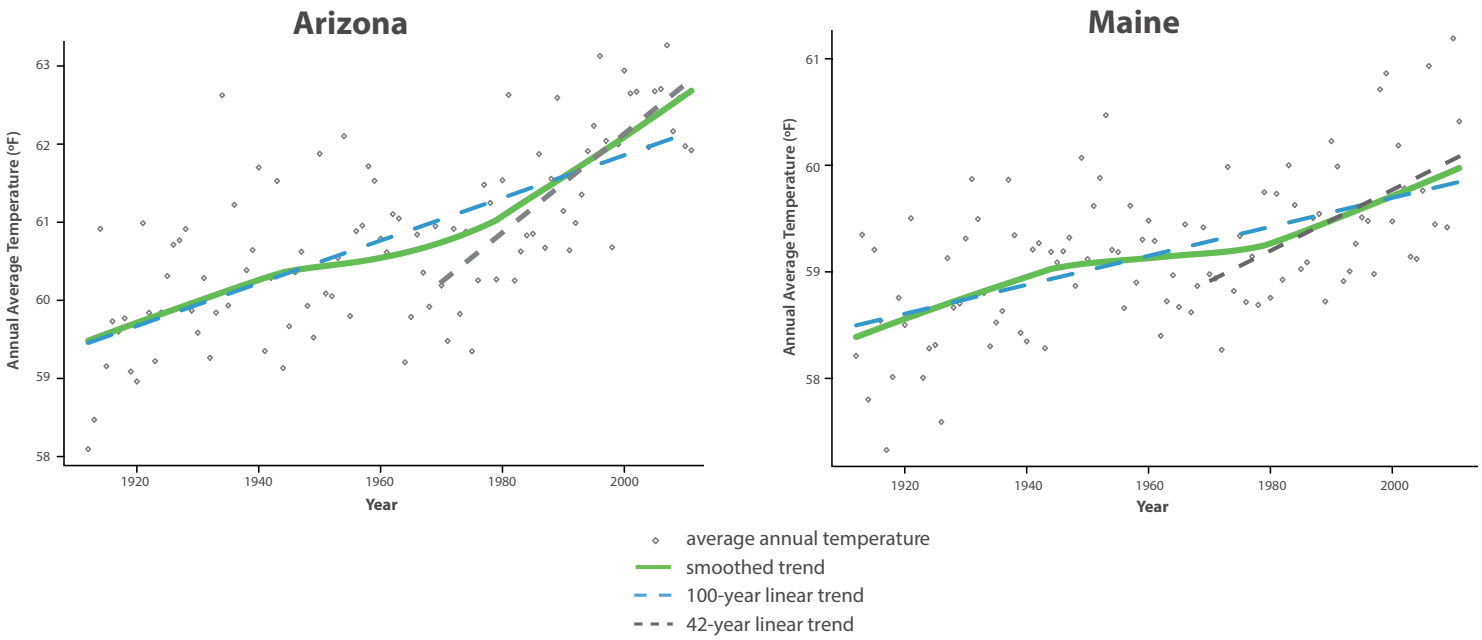


Figure 4. *In every state, the rate of warming has increased since 1970, even in states like Arizona and Maine, which have warmed for the last 100 years. The graphs show trends in average annual temperatures over the past 100 years.*

Warming Trends By Region

Our state-by-state analysis of warming over the past 100 and 42 years reveals some clear regional trends (*Figure 5*). The fastest-warming states are in the Southwest, Northeast, Upper Midwest, and Northern Rockies. On the other hand, states in the Southeast and Midwest regions tended to warm much slower. Other analyses refer to the overall lack of warming in these regions over the past century as the warming hole.

Between 1912-2011, in a large portion of the country — including parts of the Upper Midwest, South, and Southeast — trends in the rate of warming are not statistically significant. In other words, within this region, the warming trends in some states were so small that they were indistinguishable from random variability in the data.

Over this 100-year period, roughly half the states warmed faster than the U.S. average rate; roughly half warmed more slowly, and a handful did not warm at all (*Figure 6,* top).

Looking at the changing temperature trends from 1970, however, shows that not only are the increasing temperature trends significant, but also that the warming hole in the South, Southeast and Upper Midwest disappears. Over the past 42 years, all states have experienced increasing average annual temperatures (though some states in the Southeast and along the West Coast warmed slower than the national average pace). Although the pace of warming accelerated during this recent 42-year period, the ratio of faster than average to slower than average warming states stayed about the same (*Figure 6,* bottom).

Warming Rates Accelerated Everywhere After 1970

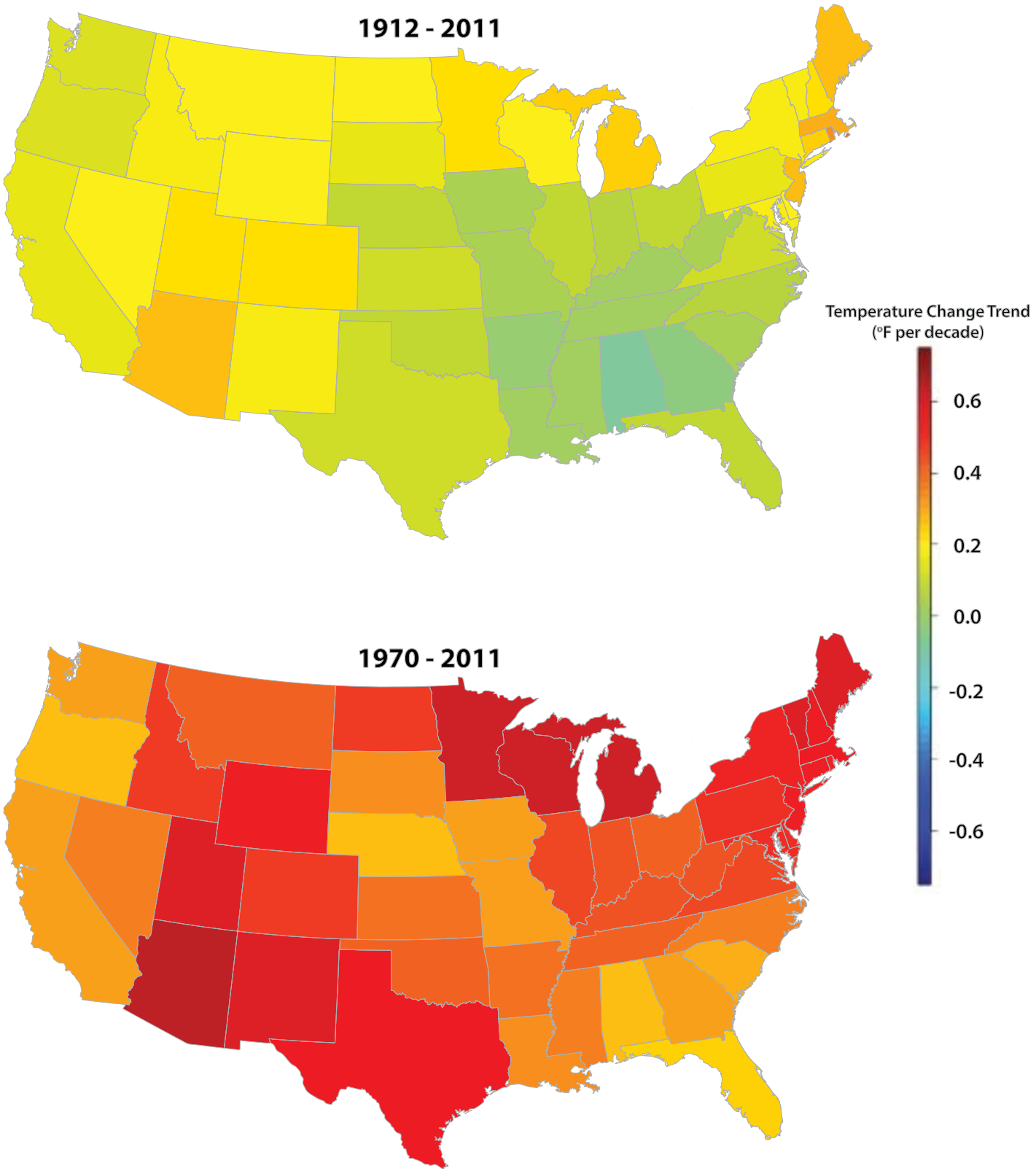


Figure 5. *Rates of warming for average annual temperatures (degrees Fahrenheit per decade) for each state: 1912-2011 (top) and 1970-2011 (bottom).*

The Fastest Warming States Are Concentrated in the Southwest and Northern Tier

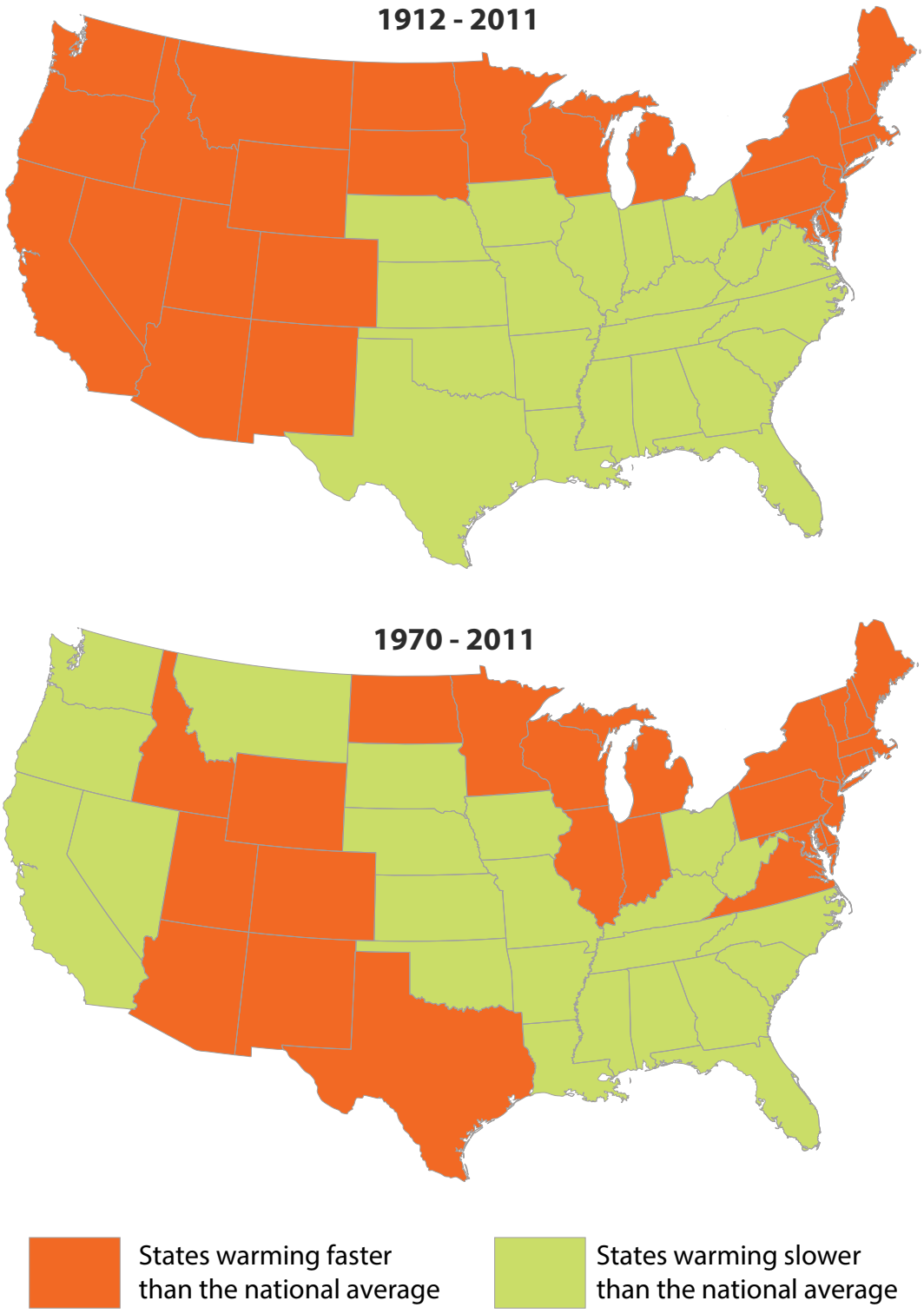


Figure 6. *Regional differences in where states have warmed more or less than the national average have changed over time. Over the past 100 years, states warming slower than the national average were concentrated towards the Southeast and Ohio/Mississippi River Valleys (top) but in the last 42 years, some of the westernmost states have been warming slower than the national average (bottom).*

These differences in warming across various regions of the U.S. have been previously documented. An earlier study[1] showed that when considering extreme high temperatures (rather than averages), parts of the western U.S., the Great Lakes region and the Atlantic coast are warming faster and more significantly (from a statistical point of view) than the Ohio Valley, South, Southeast and Northwest.

A more recent study[2] showed via climate model simulations that aerosol pollutants emitted into the atmosphere over the past 60 years from industrial and power plants in the eastern U.S. would be expected to create a cooling pattern similar to the warming hole that we see in the observed record. Even though this study could not conclude that aerosol emissions caused cooling observed across parts of the Midwest, South, and Southeast, it does suggest that the lack of cooling in those regions may not have been entirely natural.

The study also points out that since clean-air regulations have dramatically reduced these emissions over the past 20-30 years, the cooling effect has already disappeared and will no longer be a factor in the future. If the study's findings turn out to be applicable to the warming hole, then it is possible that without aerosols screening solar radiation these regions will catch up.

Although aerosol emissions may have contributed to flat trends, natural climate variability is also an important component in the slow warming observed in some regions.[3,4]

Several previous studies[5-9] looked at the warming hole in the Southeast, and traced its cause to the influence of slow varying natural oscillations in sea surface temperatures in the Pacific Ocean and the North Atlantic Ocean. Other researchers have suggested[10,11] that the ways we've changed the land over parts of the U.S. (with agriculture development and reforestation) may influence temperature changes from one region to another.

More generally, we should point out that just as in every statistical analysis of trend patterns, the magnitude of the trend can depend strongly on the starting point. For example, the 1930s were an unusually warm decade in much of the U.S., so if we had started there, the warming trends would have looked weaker over subsequent decades. The 1970s were a relatively cooler period in some parts of the U.S., making some of the 40-year trends especially striking.

We do not expect that future trends will be a simple extrapolation of current patterns, since natural variability and the future emissions -- of both heat-trapping greenhouse gases and cooling aerosol pollutants -- will shape future rates of warming. The rates of warming we've seen in various regions of the U.S. could be different in the future from what they've been in the past.

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Methodology

This analysis is based on data collected from stations that make up the United States Historical Climatological Network (USHCN). These stations, covering the contiguous U.S., are maintained by the National Climatic Data Center and contribute to the Global Historical Climatology Network (GHCN).

From this network of 1221 American stations, we collected minimum and maximum daily temperature records. Mean temperatures (ie. average daily temperatures) were calculated by averaging the daily minimum and maximum temperatures. We then aggregated all the stations in a given state to form state average values.

Using state average values, we computed linear trends for annual averages of minimum, maximum and mean temperatures. Given the long record at our disposal, we computed trends using two different starting points. The oldest date available with sufficiently complete coverage across the contiguous U.S. was 1912, which conveniently covered the past 100 years, so our first set of analyses cover the time between 1912 and 2011. Our second set of analyses spans 1970-2011.

We chose the latter 42-year period guided by the knowledge of a well known acceleration of the warming, at the global level, that began in the seventies. This accelerated global warming has been attributed to a concurrence of natural factors (changes in ocean temperatures according to intrinsic multi-decadal variability of the system) and the effect of clean-air regulation in countries of the industrialized world, reducing the amount of pollution particles (aerosols) in the air, known to have a cooling effect (see above).

In Figure 3 and Figure 4, the smoothed trend is obtained by a quadatic curve modeled using local fitting (akin to computing a moving average along the time series). The fit is performed using the loess() function in the R statistical software package (freely available at http://www.r-project.org/).

Statistical significance was computed assuming an autoregressive process of order 1 for the residuals of the linear regression, applying Generalized Least Squares. When we rank states according to the values of their respective trends, however, we do not consider the statistical significance of their differences. Rather, we use the trend magnitudes at their face value.

Appendix:
Detailed Data Tables and Figures

Table A1. State ranking of (annual) average maximum daily temperature trends, from 1912-2011.

Rank	State	Temperature Change (°F per decade)
1	Rhode Island	0.369
2	Massachusetts	0.317
3	Arizona	0.279
4	Utah	0.244
5	Wyoming	0.241
6	New Jersey	0.236
7	Montana	0.229
8	Michigan	0.225
9	New Mexico	0.219
10	Colorado	0.217
11	Connecticut	0.214
12	Delaware	0.205
13	Maine	0.198
14	New Hampshire	0.185
15	Vermont	0.180
16	New York	0.156
17	Wisconsin	0.151
18	North Dakota	0.151
19	Minnesota	0.139
20	Nevada	0.135
21	Idaho	0.134
22	Pennsylvania	0.115
23	Oregon	0.114
24	Texas	0.114
25	Florida	0.111
26	Maryland	0.105
27	Oklahoma	0.088
28	California	0.088
29	Virginia	0.077
30	South Carolina	0.056
31	Washington	0.047
32	Kansas	0.046
33	South Dakota	0.045
34	West Virgina	0.019
35	Illinois	0.018
36	North Carolina	0.015
37	Ohio	0.001
38	Louisiana	0.001
39	Nebraska	-0.002
40	Kentucky	-0.021
41	Georgia	-0.021
42	Missouri	-0.038
43	Tennessee	-0.043
44	Iowa	-0.046
45	Mississippi	-0.054
46	Arkansas	-0.061
47	Indiana	-0.064
48	Alabama	-0.085

Table A2. State ranking of (annual) average minimum daily temperature trends, from 1912-2011.

Rank	State	Temperature Change (°F per decade)
1	Maine	0.346
2	New Jersey	0.323
3	Minnesota	0.319
4	Rhode Island	0.309
5	Connecticut	0.287
6	Massachusetts	0.285
7	Arizona	0.269
8	North Dakota	0.265
9	Michigan	0.265
10	Nevada	0.256
11	Maryland	0.248
12	New Hampshire	0.246
13	South Dakota	0.241
14	California	0.234
15	Colorada	0.234
16	Wisconsin	0.227
17	Utah	0.223
18	Delaware	0.214
19	Washington	0.211
20	New York	0.205
21	Idaho	0.198
22	Indiana	0.182
23	Pennsylvania	0.169
24	Vermont	0.165
25	Kansas	0.157
26	Wyoming	0.154
27	Ohio	0.154
28	Montana	0.148
29	Nebraska	0.146
30	Oregon	0.143
31	Iowa	0.139
32	Virginia	0.139
33	Illinois	0.133
34	New Mexico	0.133
35	Texas	0.113
36	Missouri	0.096
37	North Carolina	0.093
38	Tennessee	0.084
39	Mississippi	0.084
40	West Virginia	0.054
41	Oklahoma	0.054
42	Arkansas	0.052
43	Florida	0.050
44	Kentucky	0.038
45	Louisiana	0.038
46	South Carolina	-0.007
47	Georgia	-0.051
48	Alabama	-0.058

Table A3. State ranking of (annual) average maximum daily temperature trends, from 1970-2011.

Rank	State	Temperature Change (°F per decade)
1	New Mexico	0.678
2	Arizona	0.629
3	Utah	0.608
4	New Jersey	0.603
5	Texas	0.602
6	Michigan	0.594
7	Wyoming	0.575
8	Vermont	0.557
9	Idaho	0.548
10	Pennsylvania	0.537
11	Maryland	0.532
12	Colorado	0.523
13	Delaware	0.523
14	Wisconsin	0.497
15	Rhode Island	0.495
16	Minnesota	0.493
17	Montana	0.486
18	Connecticut	0.472
19	New York	0.471
20	New Hampshire	0.470
21	Oklahoma	0.465
22	Massachusetts	0.464
23	Illinois	0.451
24	Nevada	0.442
25	Maine	0.433
26	Kentucky	0.420
27	Tennessee	0.411
28	Mississippi	0.399
29	Virginia	0.388
30	West Virginia	0.382
31	Louisiana	0.351
32	Kansas	0.346
33	South Carolina	0.339
34	Indiana	0.336
35	North Dakota	0.335
36	Ohio	0.327
37	Oregon	0.325
38	North Carolina	0.320
39	Georgia	0.320
40	California	0.307
41	Arkansas	0.280
42	Florida	0.225
43	Washington	0.205
44	Alabama	0.201
45	Missouri	0.200
46	Iowa	0.197
47	Nebraska	0.185
48	South Dakota	0.108

Table A4. State ranking of (annual) average minimum daily temperature trends, from 1970-2011.

Rank	State	Temperature Change (°F per decade)
1	Minnestoa	0.748
2	Maine	0.741
3	Wisconsin	0.730
4	Massachusetts	0.672
5	Vermont	0.656
6	Michigan	0.647
7	Arizona	0.641
8	Connecticut	0.639
9	New Hampshire	0.636
10	North Dakota	0.606
11	New York	0.604
12	South Dakota	0.586
13	Utah	0.557
14	Texas	0.548
15	Rhode Island	0.547
16	Indiana	0.543
17	Wyoming	0.529
18	New Mexico	0.526
19	Virginia	0.523
20	New Jersey	0.518
21	Ohio	0.513
22	Arkansas	0.486
23	Maryland	0.484
24	Illinois	0.484
25	West Virginia	0.474
26	Delaware	0.463
27	Pennsylvania	0.460
28	Kentucky	0.444
29	Missouri	0.439
30	Colorado	0.438
31	Washington	0.433
32	Iowa	0.425
33	Tennessee	0.422
34	North Carolina	0.419
35	Kansas	0.411
36	Idaho	0.388
37	Oklahoma	0.356
38	Montana	0.353
39	Mississippi	0.352
40	Alabama	0.351
41	Nebraska	0.347
42	Louisiana	0.340
43	California	0.308
44	Georgia	0.296
45	Nevada	0.283
46	Florida	0.270
47	South Carolina	0.246
48	Oregon	0.221

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Princeton

One Palmer Square, Suite 330
Princeton, NJ 08542

Phone: +1 609 924-3800

Palo Alto

895 Emerson Street
Palo Alto, CA 94301

Phone: +1 877 425-4724

Call Toll Free

+1 877 4-CLI-SCI (877 425-4724)

www.climatecentral.org