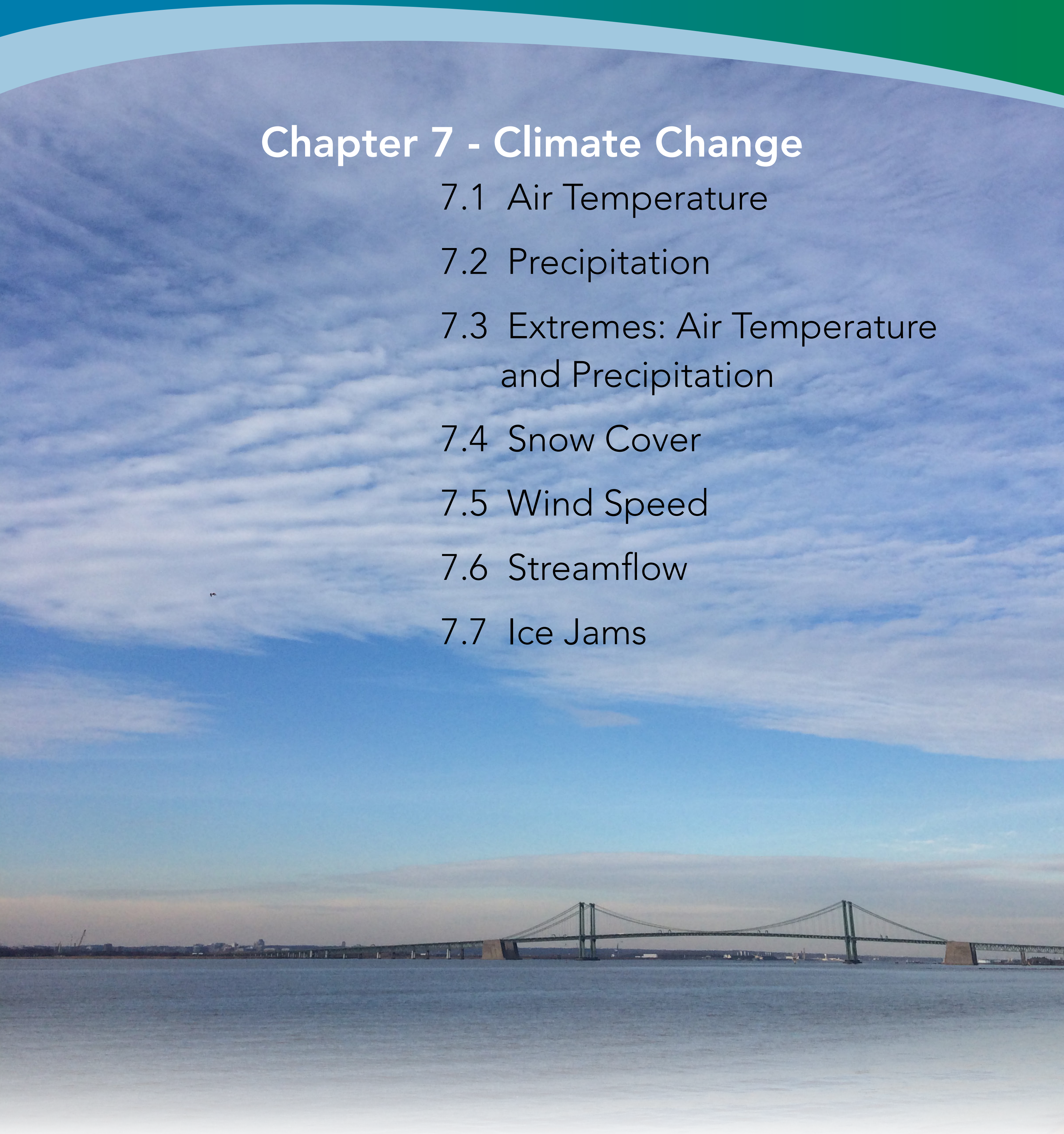
Chapter 7 - Climate Change



Partnership for the DELAWARE ESTUARY

December, 2017 | Report No.17-07

A publication of the Partnership for the Delaware Estuary—A National Estuary Program

7. Climate Change

Andrew Ross and Raymond Najjar
Pennsylvania State University

This chapter describes how the climate of the Delaware River Basin (DRB) has changed in the past and may change in the future. The focus is on air temperature and precipitation throughout the watershed with additional analyses of changes in snow cover, wind speed, and ice jams in the Delaware River.

All indicators presented in the previous report have been updated to use the most recent data available. All datasets and selected sites match those used in the previous report, aside from some minor differences. Trends in this report are calculated using a new, nonparametric method that accounts for autocorrelation (discussed next). Although different datasets and procedures were applied to analyze the different indicators, there were several common methods used in the analysis of most indicators. All trends were calculated using the nonparametric Theil-Sen slope estimator (Theil 1950; Sen 1968), and the statistical significance each trend was tested using the nonparametric Mann-Kendall test for trend (Mann 1945; Kendall 1955) with pre-whitening to reduce the impact of autocorrelation (Yue et al. 2002) at a significance level α =0.05. These statistical methods were provided by the R package "zyp" (Bronaugh and Werner 2013). Trends were calculated for both the full extent of each time series and for the most recent 30 years (1986–2015). To merge data from multiple stations into a single time series, anomalies were calculated by subtracting each station's 1981–2010 mean value prior to averaging the station data. Some of the indicator trends were broken down by season. The seasons were defined as December to February (DJF; winter), March to May (MAM; spring), June to August (JJA; summer) and September to November (SON; fall). Finally, for daily data (temperature and precipitation extremes and streamflow), if a year or season at a given station had more than 5 days of missing or flagged data in any month, the data from the entire year or season were excluded from the analysis.

7.1 Air Temperature

7.1.1 Description of Indicator

Monthly mean near-surface air temperature was obtained from version 2.5 of the U.S. Historical Climatology Network (USHCN) database (Fig 7.1.1). A complete description of the dataset and data processing is provided in Menne et al. (2009), Menne et al. (2015a), and Menne et al. (2015b); an abbreviated description is presented here. Most data in the USHCN are a subset of the data from the National Oceanographic and Atmospheric Administration's (NOAA's) Cooperative Observer Program (COOP). The COOP data stations included in the USHCN dataset are relatively long, stable, and amenable to adjustments for non-climatic changes (such as station relocations).

The COOP data consist of daily high and low temperatures. Daily mean temperature is computed as an average of the daily high and low temperature. During processing for inclusion in the USHCN dataset, the data are extensively screened for erroneous daily values. For example, data that show strong spatial or temporal inconsistency are flagged. The monthly USHCN dataset was derived from the daily dataset in several steps. First, means for a given month were computed if no more than nine daily values were flagged or missing for that month. Second, the monthly dataset was subjected to further consistency checks that are qualitatively similar to the checks for the daily data. Third, the data were adjusted for time of observation, which has undergone significant change in the U.S. Fourth, a "change-point" detection algorithm was used to adjust the temperature for other inhomogeneities, such as change in station location, change in instrumentation, and change in nearby land use (e.g., urbanization).

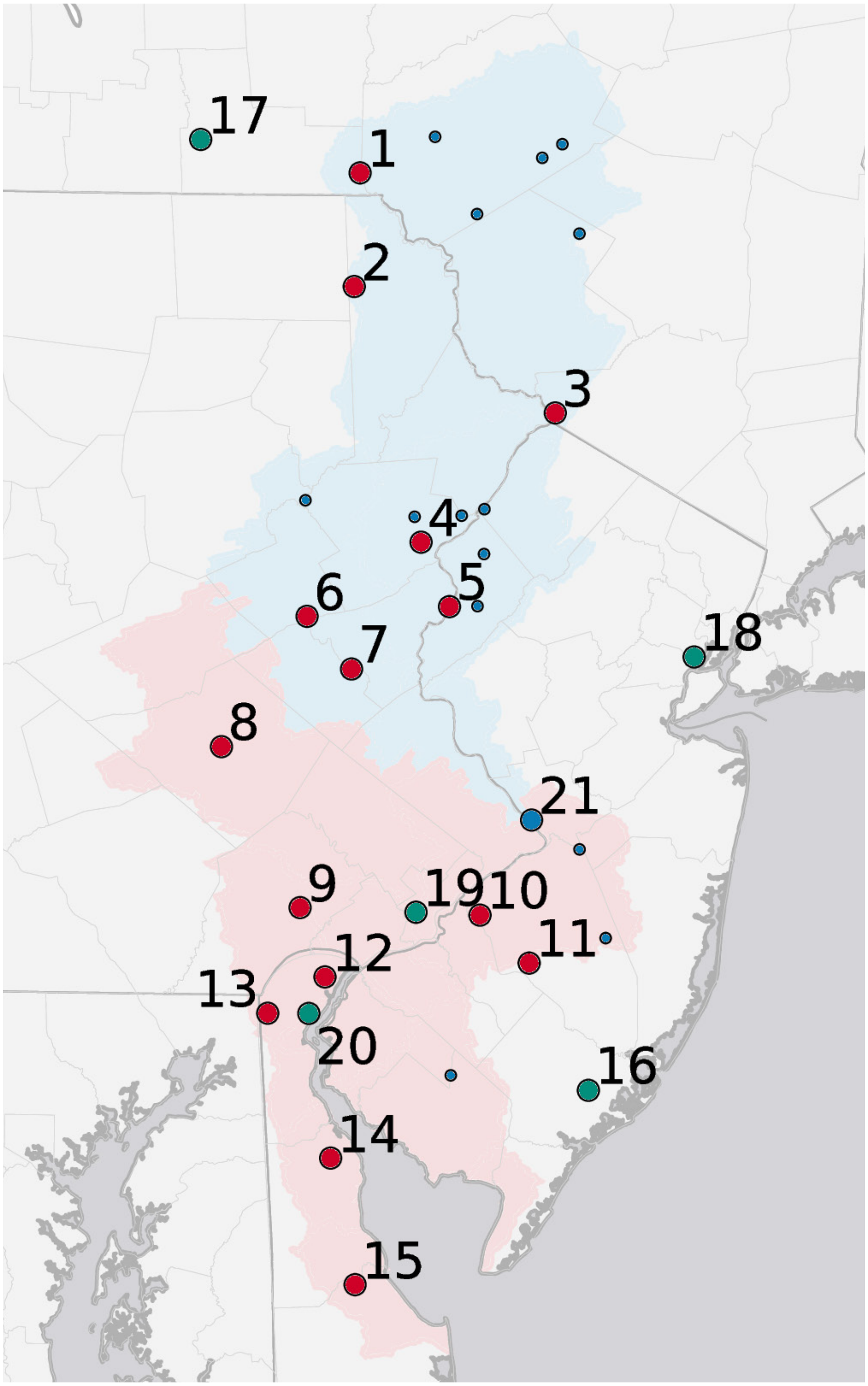


Figure 7.1.1 Location of meteorological and hydrological stations used in this analysis. Red dots (1–15) are the USHCN stations (section 7A); green dots (16–20) are the wind stations (7E); the blue dot (21) is the stream gauge at Trenton (7F).

The 15 USHCN stations located in or near the DRB were selected for analysis (Table 7.1.1). The analysis distinguished between the upper and lower portions of the watershed. The lower portion of the watershed is defined by those basins that deliver freshwater directly to tidal waters, which are located below Trenton, NJ. The upper portion of the watershed drains to the Delaware River above Trenton. There are 8 USHCN stations in the lower portion and 7 in the upper portion.

The period 1910–2015 was selected for analysis based on the monthly dataset because every station has a value during this time period (some data being estimated from an average of neighboring stations during the consistency check and homogenization procedures).

7.1.2 Past trends

Annual-mean temperature has increased significantly at the 95% confidence interval over the last 106 years (Fig 7.1.2-7.1.3, Table 7.1.2). Based on these trends, temperature has increased by roughly 1.0 to 1.2 °C over the last century. This rate is consistent with the predicted effect of greenhouse gases (Najjar et al. 2009). The estimated trend in annual mean temperature during the past 30 years is around three times greater than during the last century.

Since 1910, significant warming trends are also present in both portions of the watersheds for all seasons except for winter in the lower watershed (Fig 7.1.4, Table 7.1.2). In the recent 30-year period, both watersheds show significant fall temperature increases.

Substantial adjustments to the temperature data were necessary to account for changing observation times, station relocations, thermometer changes, and other causes of inhomogeneity (Fig 7.1.5). The effect of these adjustments is to increase the calculated temperature trend; adjustments increase the 1910–2015 temperature trend from from 0.015 to 0.099 °C/decade in the upper watershed and from 0.042 to 0.12 °C/decade in the lower watershed. Although these adjustments are large, they are necessary to account for the predominantly cooling effect of the thermometer and observation time changes. Studies of the U.S. temperature record have demonstrated that the adjustment algorithms are capable of significantly reducing errors and biases in data (Williams et al. 2012), and recent, high quality measurements of temperature are consistent with the adjusted data (Menne et al. 2010).

7.1.3 Future predictions

Future temperature changes in the DRB are strongly dependent on the amount of future global greenhouse gas (GHG) emissions. A variety of scenarios for future GHG emissions, or emissions scenarios, have been proposed. These can be broadly catagorized into high emissions scenarios that assume that emissions will continue at a pace similar to the present (the RCP 8.5 and A2 scenarios) and low emissions scenarios that assume significant global efforts to reduce emissions (the RCP 2.6, RCP 4.5 and B1 scenarios).

If GHG emissions remain high, the latest generation of global climate models (GCMs) project that some parts of the DRB will be 5 °C warmer at the end of the 21st century compared to the end of the 20th century (Walsh et al. 2014). On the other hand, if emissions are quickly and significantly reduced, the DRB is projected to be less than 2 °C warmer. The warming in the models is spread relatively evenly throughout the year, with the greatest warming in winter and a secondary peak in summer (Lynch et al. 2016). High-resolution regional climate models (RCMs) produce a similar seasonal pattern and, on average, predict greater winter warming in the northern region of the DRB and greater summer warming in the southern region (Rawlins et al. 2012). The historical climatology of temperature is relatively well-simulated by these RCMs, and all models agree that the future will be warmer, raising confidence in the model results (Rawlins et al. 2012).

7.1.4 Actions and needs

The cause of the substantial warming observed in the DRB requires further investigation. Though numerous studies have been conducted to determine the causes of long-term temperature trends at continental and global scales, there has only been one study specifically for the DRB (Najjar et al. 2009), which used GCMs from the 2001 Intergovernmental Panel on Climate Change report. Analysis of daily high and low temperatures may provide some insight as to the causes of long-term temperature change as these quantities respond differently to various types of radiative forcing, such as changes in greenhouse gases, aerosols, and cloudiness.

7.1.5 Summary

The DRB has warmed substantially over the past 106 years, and the rate of warming appears to be increasing. This change is qualitatively consistent with that expected from increases in greenhouse gases, but the large uncertainty in the temperature data combined with the limited attribution studies indicates that additional research is needed to better understand past temperature change. Future temperature change may be paradoxically more certain: not a single climate model projects cooling even under the low emissions scenario analyzed in Kreeger et al. (2010).

Table 7.1.1 USHCN stations used in the analysis. Numbers (first column) correspond to the numbers plotted on the map in figure 7.1.1. The start–end dates shown are defined as the first and last year for which precipitation data passed the quality-control procedures for precipitation extremes (See Section 4). Some stations have data before 1910, but are not listed as such because the present analysis begins in 1910. Stations above the horizontal line between Allentown and Reading are in the upper watershed, and stations below the line are in the lower watershed.

#	Name	State	ID number	Coordinates (dec. deg.)		Elev. m	Start–end
				Latitude	Longitude		
1	Deposit	NY	302060	42.0628	-75.4264	304.8	1963–2011
2	Pleasant Mt. 1 W	PA	367029	41.7394	-75.4464	548.6	1926–2014
3	Port Jervis	NY	306774	41.3800	-74.6847	143.3	1910–2014
4	Stroudsburg	PA	368596	41.0125	-75.1906	140.2	1912–2014
5	Belvidere BRG	NJ	280734	40.8292	-75.0836	80.2	1983–2014
6	Palmerton	PA	366689	40.8000	-75.6167	125.0	1918–1997
7	Allentown AP	PA	360106	40.6508	-75.4492	118.9	1948–2014
8	Reading 4 NNW	PA	367322	40.4269	-75.9319	109.7	1974–2007
9	West Chester 2 NW	PA	369464	39.9708	-75.6350	114.3	1911–2014
10	Moorestown	NJ	285728	39.9511	-74.9697	13.7	1911–2008
11	Indian Mills 2 W	NJ	284229	39.8144	-74.7883	30.5	1910–2014
12	Wilmington Porter Res.	DE	079605	39.7739	-75.5414	82.3	1942–2014
13	Newark Univ. Farm	DE	076410	39.6694	-75.7514	27.4	1942–1999
14	Dover	DE	072730	39.2583	-75.5167	9.1	1910–2011
15	Milford 2 SE	DE	075915	38.8983	-75.4250	10.7	1916–2001

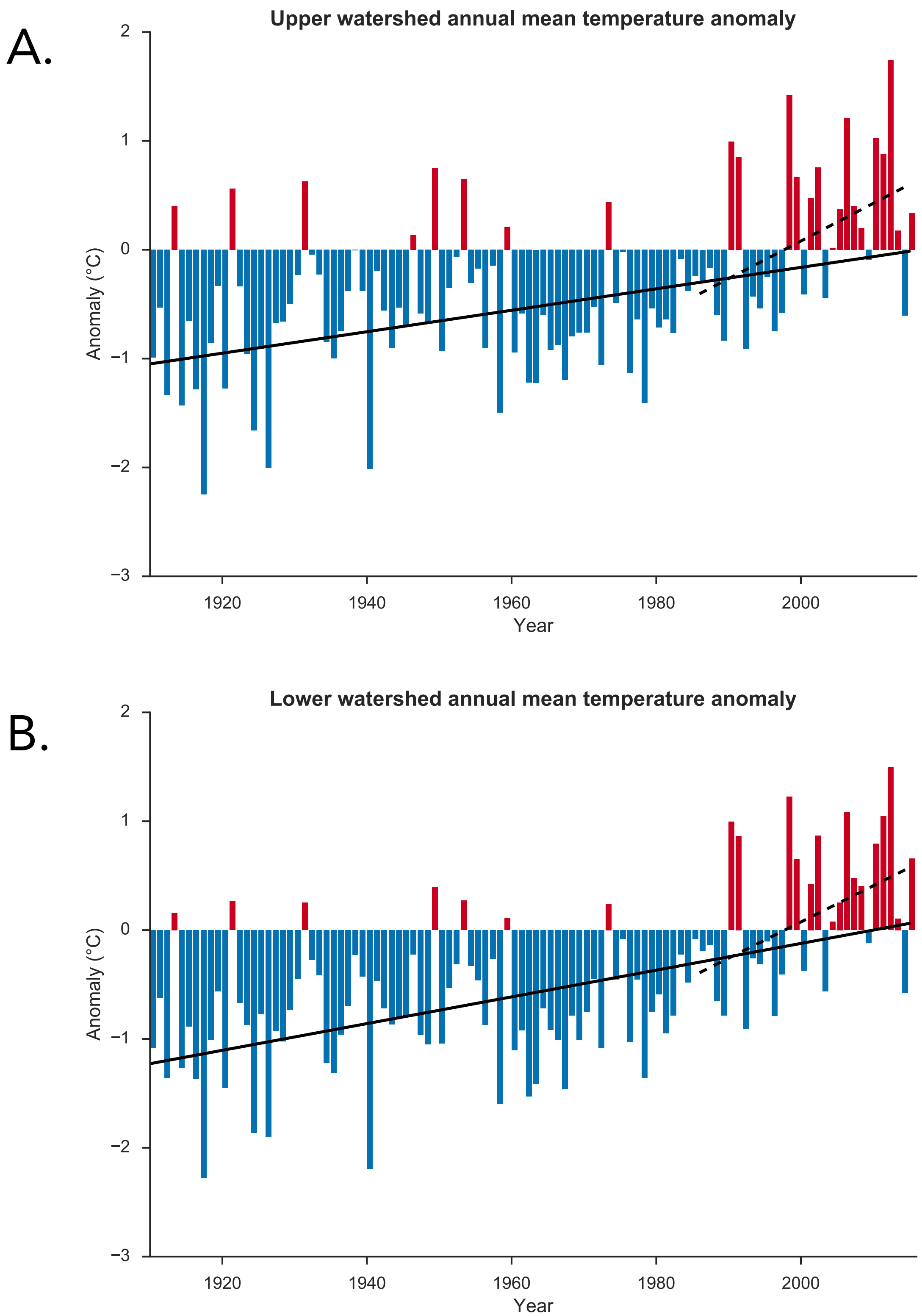


Figure 7.1.2 Anomalies (with respect to the 1981–2010 average) of annual-mean temperature for the upper (A) and lower (B) portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

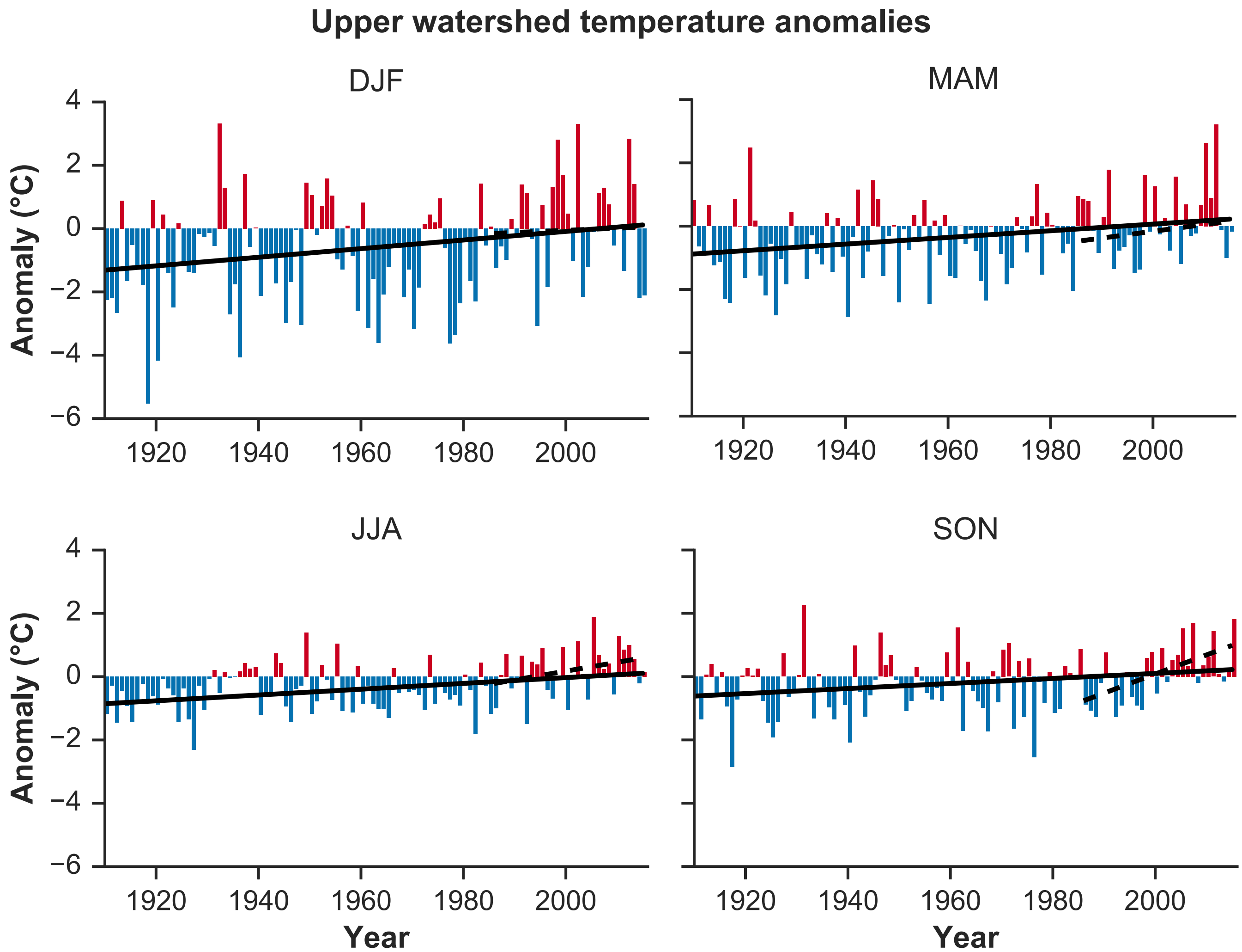


Figure 7.1.3 Anomalies (with respect to the 1981–2010 average) of seasonal-mean temperature for the upper portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

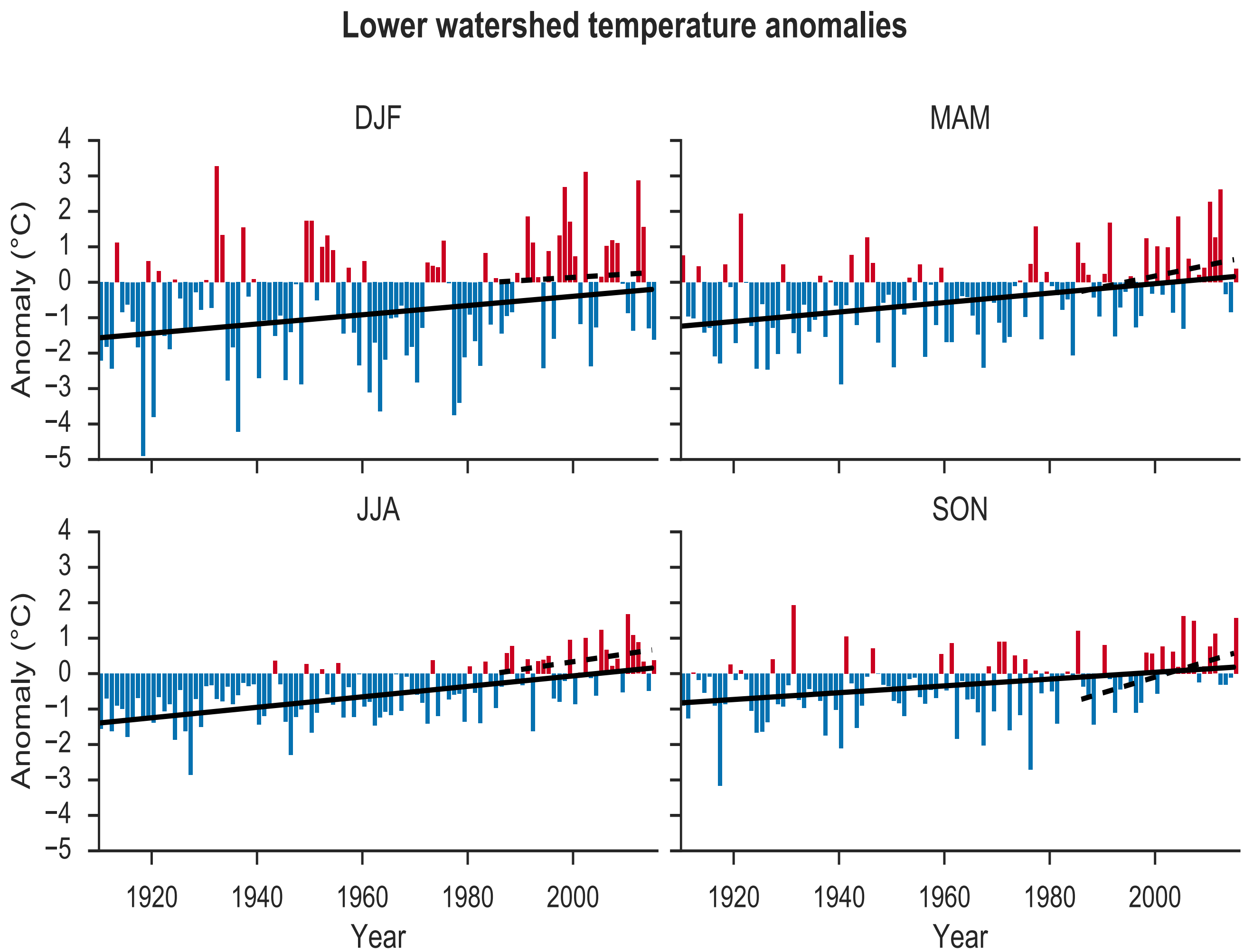


Figure 7.1.4 Anomalies (with respect to the 1981–2010 average) of seasonal-mean temperature for the lower portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

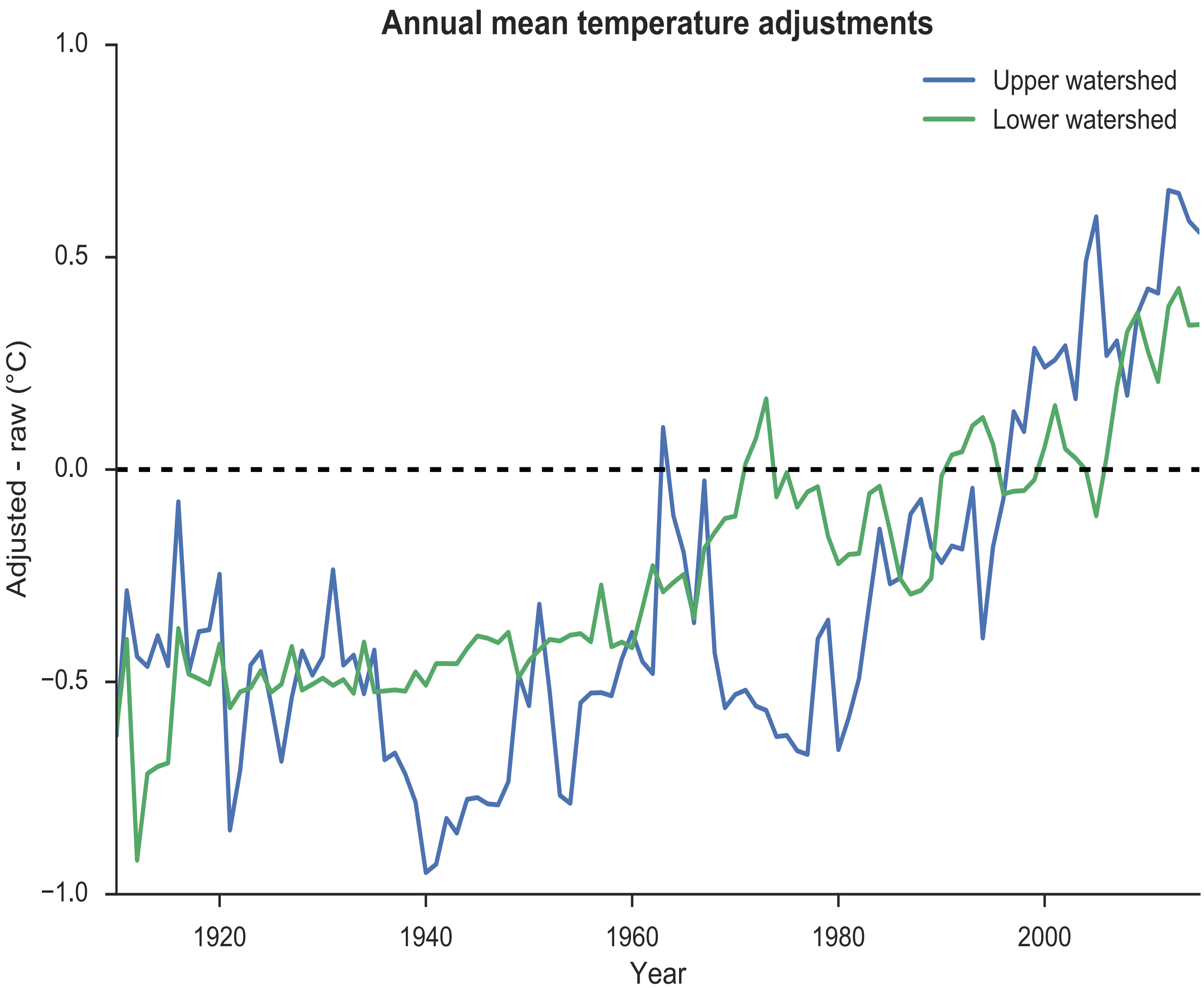


Figure 7.1.5 Impact of the adjustments to the monthly temperature data on the calculated annual mean temperatures. Shown is the difference between the time series of annual mean temperature calculated with the corrected data (as used in the text) and with the raw data for both subwatersheds.

Table 7.1.2 Linear trends of annual and seasonal mean temperature for the upper and lower portions of the DRB. p-values are in parentheses; trends significant at the 95% confidence level are bold.

	Seasonal Subset	Temperature Trend (°C/decade)	
		1910-2015	1986-2015
Upper Watershed	Annual	**0.099 (1.8×10^{-4})**	0.35 (0.088)
	DJF	**0.14 (0.036)**	0.068 (0.93)
	MAM	**0.11 (1.9×10^{-3})**	0.21 (0.28)
	JJA	**0.092 (2.0×10^{-4})**	0.28 (0.15)
	SON	**0.08 (0.011)**	**0.60 (4.1×10^{-3})**
Lower Watershed	Annual	**0.12 ($<10^{-4}$)**	0.33 (0.075)
	DJF	0.13 (0.055)	0.090 (0.93)
	MAM	**0.13 ($<10^{-4}$)**	0.31 (0.058)
	JJA	**0.15 ($<10^{-4}$)**	0.22 (0.22)
	SON	**0.096 (3.7×10^{-4})**	**0.45 (0.014)**

7.2 Precipitation

7.2.1 Description of Indicator

As with temperature, monthly precipitation totals were acquired from the USHCN version 2.5 dataset. The same stations were used, and the USHCN screening procedure was similar to the procedure for temperature except there is no time-of-observation correction.

7.2.2 Past trends

Annual precipitation totals have not increased with 95% confidence in either portion of the watershed (Fig 7.2.1-7.2.2, Table 7.2.1). Estimated trends in annual total precipitation over the most recent 30 years are about three times larger but are also not statistically significant. Seasonally (Figs 7.2.3-7.2.4, Table 7.3), fall precipitation totals have increased significantly in both watershed portions over the last 106 years.

7.2.3 Future predictions

There is a strong model consensus towards increased winter precipitation in the northern half of North America, including all of the DRB, in the future (Walsh et al. 2014; Lynch et al. 2016; Rawlins et al. 2012). A performance-weighted average of regional climate model simulations under a high emissions scenario yields a 10-14% increase in winter precipitation throughout the DRB by 2041–2070 (Rawlins et al. 2012). Most studies also show that increased spring precipitation is likely in the DRB, while changes in summer and fall precipitation are uncertain.

7.2.4 Actions and needs

The understanding of long-term changes in precipitation is poor. Observed precipitation trends in the DRB do not match model predictions of the effects of greenhouse gases on regional precipitation totals. Globally, most precipitation datasets show an increasing trend in mean precipitation during the last century, which is consistent with the expected effect of increasing greenhouse gases (Hartmann et al. 2013). However, observations vary widely between datasets, and the overall confidence in the trends is low (Hartmann et al. 2013). Finally, changes in extreme events should be studied, since model simulations of changes in extreme events show a stronger signal of climate change (Section 7.3).

7.2.5 Summary

There is some evidence that precipitation has increased in the DRB, particularly during the fall. Precipitation is projected to increase in the future, mainly during winter and spring. The projected precipitation changes are well within natural interannual variations (Najjar et al. 2009), which is possibly why the greenhouse gas signal has not been detected in the observations.

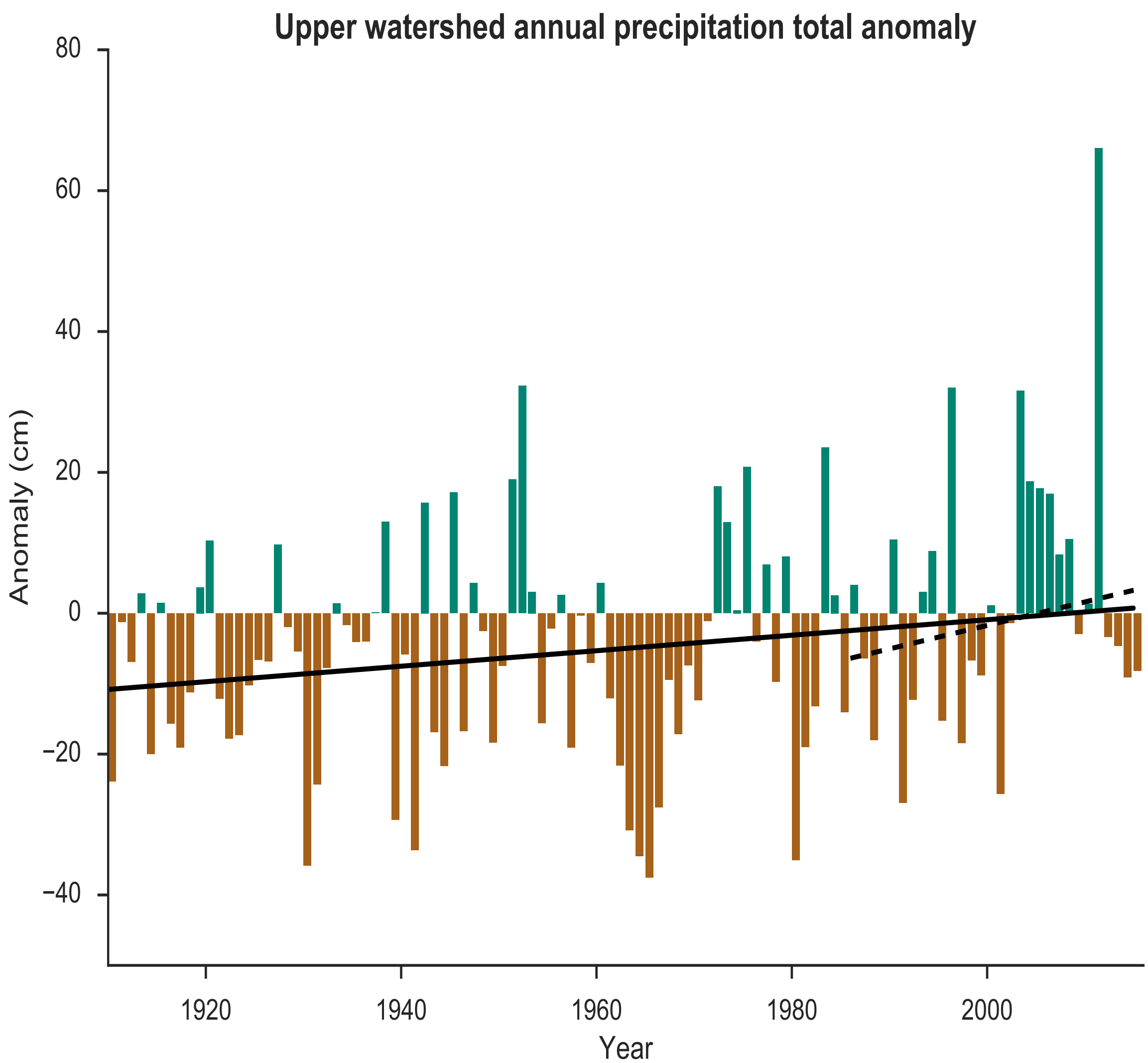


Figure 7.2.1 Anomalies (with respect to the 1981–2010 average) of annual precipitation totals for the upper portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

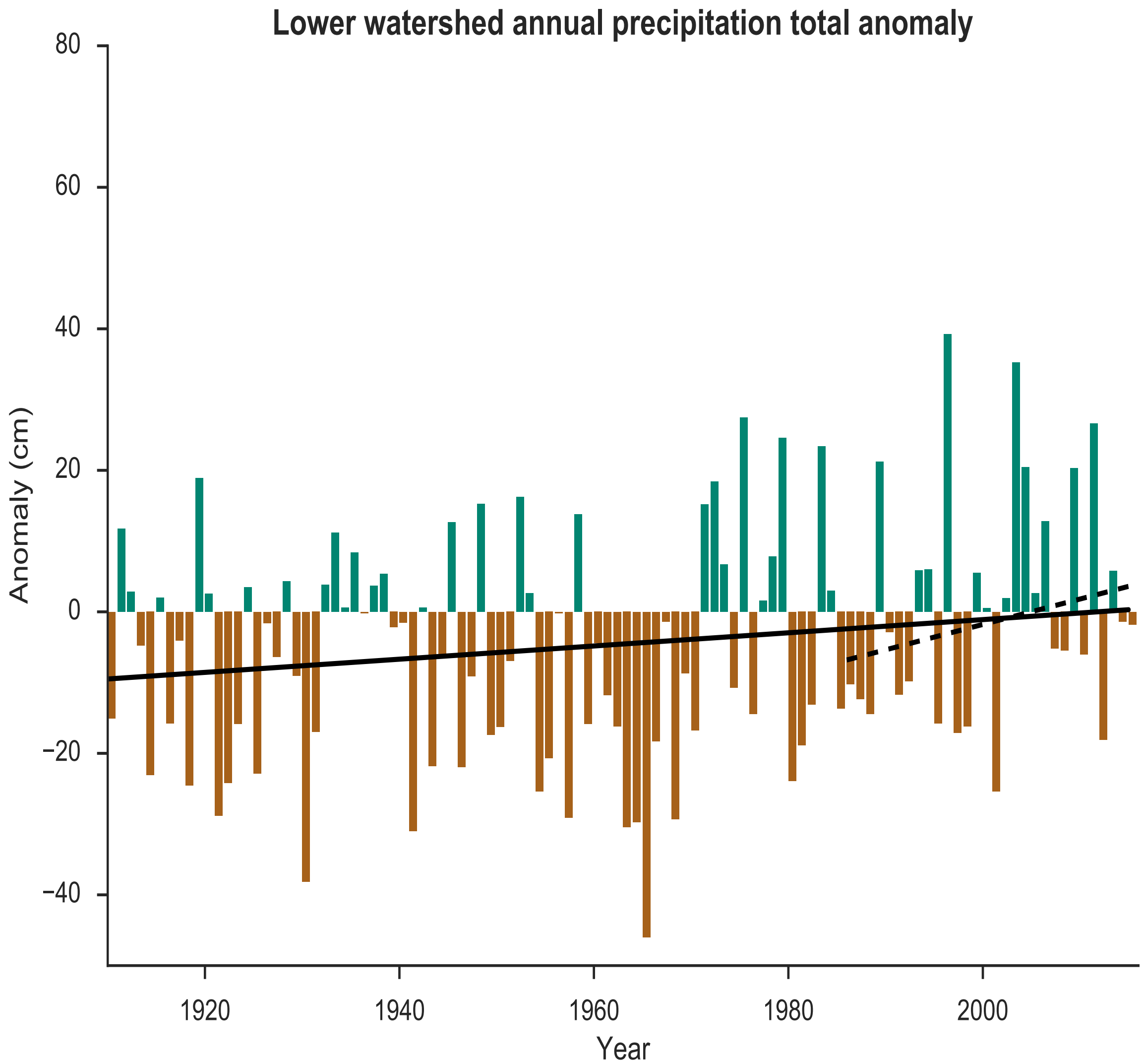


Figure 7.2.2 Anomalies (with respect to the 1981–2010 average) of annual precipitation totals for the lower portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

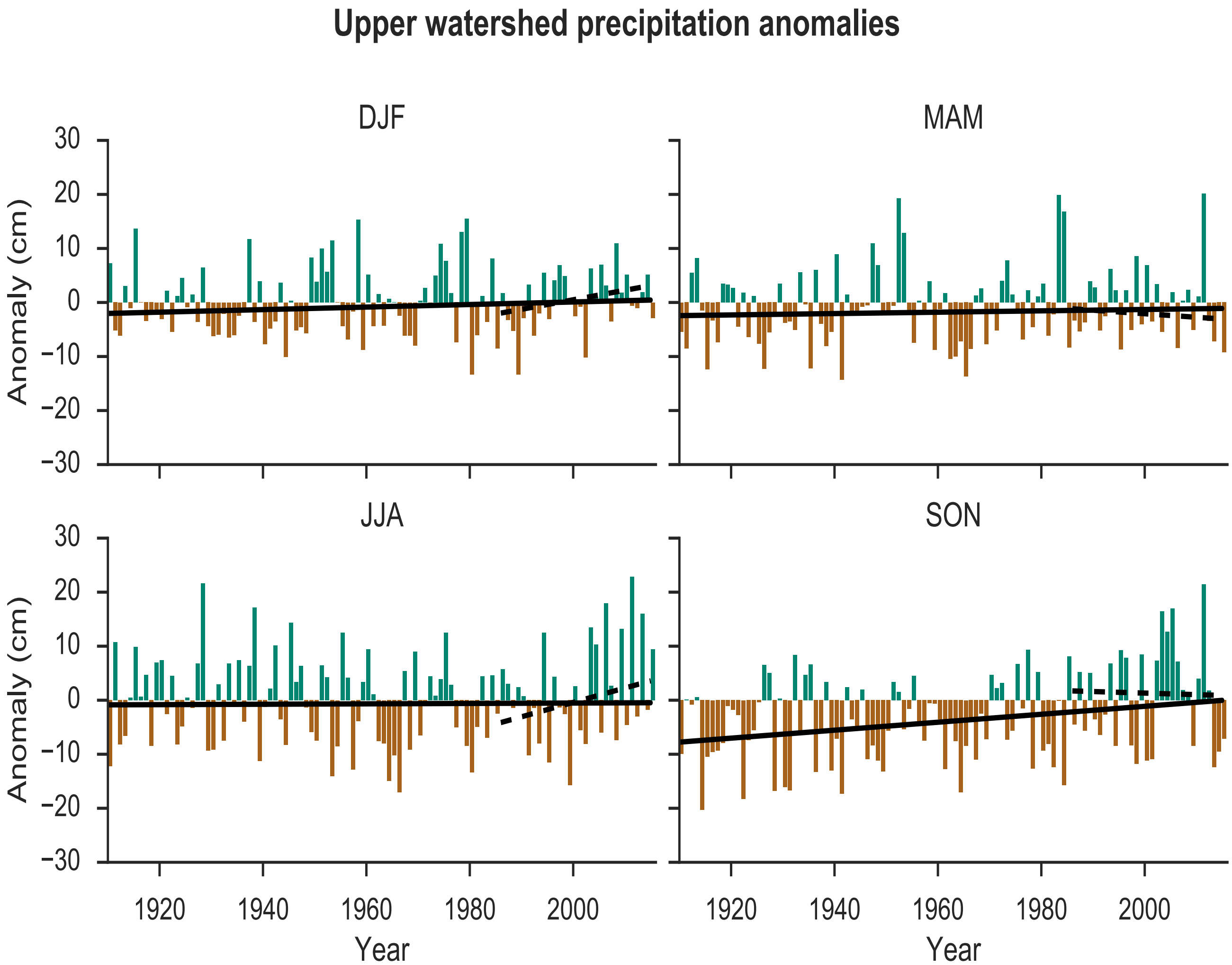


Figure 7.2.3 Anomalies (with respect to the 1981–2010 average) of seasonal precipitation totals for the upper portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

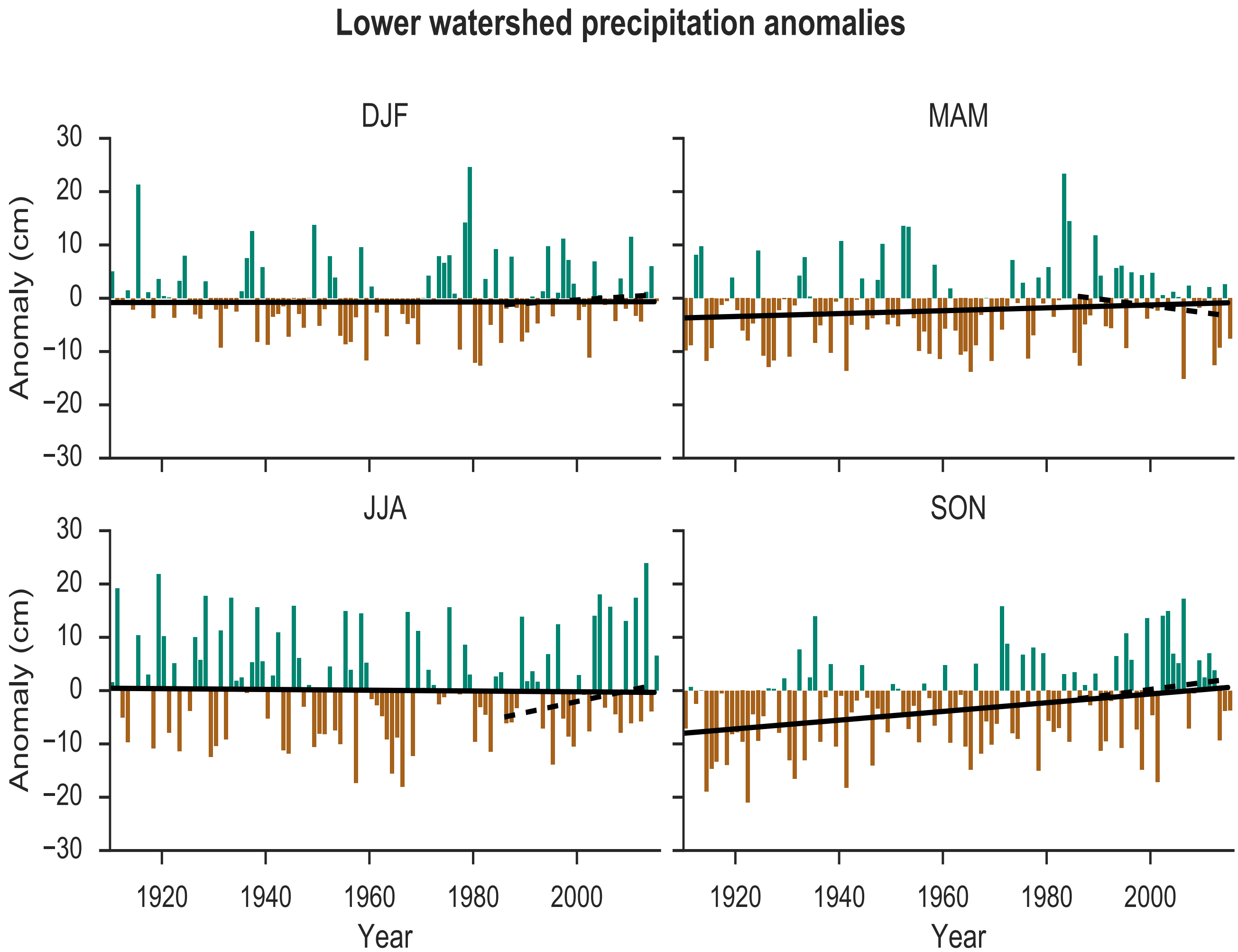


Figure 7.2.4 Anomalies (with respect to the 1981–2010 average) of seasonal precipitation totals for the lower portion of the DRB. The solid and dashed lines are linear trends for the 1910–2015 and 1986–2015 periods, respectively.

Table 7.2.1 Linear trends of annual and seasonal precipitation totals for the upper and lower portions of the DRB. p-values are in parentheses; trends significant at the 95% confidence level are bold.

	Seasonal Subset	Precipitation Trend (cm/decade)	
		1910-2015	1986-2015
Upper Watershed	Annual	1.1 (0.084)	3.3 (0.28)
	DJF	0.24 (0.14)	1.8 (0.063)
	MAM	0.13 (0.71)	-0.65 (0.64)
	JJA	0.037 (0.97)	2.7 (0.053)
	SON	**0.74 (0.032)**	-0.29 (0.96)
Lower Watershed	Annual	0.93 (0.11)	3.6 (0.32)
	DJF	0.015 (0.84)	0.63 (0.78)
	MAM	0.27 (0.43)	-1.3 (0.20)
	JJA	-0.073 (0.91)	2.1 (0.16)
	SON	**0.82 (1.2×10^{-3})**	1.3 (0.56)

7.3 Extremes: Air Temperature and Precipitation

7.3.1 Description of indicator

Trends in five extreme event indices were calculated: (1) T90, the number of days per year with high temperatures above 90 °F (32.2 °C); (2) FD, the number of frost days per year (days with low temperatures below 32 °C (0 °C); (3) CDD, the maximum number of consecutive dry days per year; (4) RX5day, the annual maximum five-day precipitation total in centimeters; (5) R45, the number of days per year with heavy (> 4.5 cm) precipitation.

The USHCN daily dataset was used for this analysis. Unlike the monthly data, the daily data are not adjusted for changes in station location, instrumentation, or time of observation, which may result in significant biases and artificial trends, particularly in the temperature data.

Temperature and precipitation data that were given any quality control failure flags in the dataset were removed. For precipitation data, a day was deemed dry if the reported precipitation total was less than 1 mm. Missing days were assumed to be wet for the CDD metric and dry for the RX5day metric.

7.3.2 Past trends

Many of the trends in the five extreme events indices are not statistically significant, with the notable exception of the days per year of heavy precipitation (R45) which shows an upward trend of 0.17-0.19 days per decade or slightly less than 2 days per century in both watersheds (Figs 7.3.1-7.3.2, Table 7.3.1). This may appear to be a small change but is, in fact, substantial, because there are so few days of heavy precipitation. Compared to the average for the 1981-2010 reference period (about 3 days per year), the increase is over 50%.

Both watersheds show decreases in the number of freezing days over the last century, although neither watershed reaches the bar of statistical significance. A trend towards fewer freezing days was found throughout the Northeast U.S. by Brown et al. (2010). Trends in the number of days above 90 °F are also positive but insignificant in both subwatersheds.

7.3.3 Future predictions

Both extreme wet and extreme dry events are expected to become more common by the end of the 21st century (Kreeger et al. 2010; Walsh et al. 2014; Wuebbles et al. 2014; Janssen et al. 2014), with larger changes in scenarios of high GHG emissions. By the middle of the 21st century, climate models also project a large increase in the number of days per year above 90 °C in the Northeast U.S., and a decrease in the number of days below freezing in the DRB, even under low emissions scenarios (Horton et al. 2014; Williamson et al. 2016).

7.3.4 Actions and needs

A more thorough analysis and literature review is needed for past trends in extremes in the DRB. A central issue is the homogenization and correction for non-climatic trends in the daily temperature data. Other studies, with different treatments of the data and different metrics (DeGaetano and Allen 2002; Brown et al. 2010), show some substantial differences with our analysis, and these need to be resolved. Recently developed datasets that apply adjustments at the daily level may provide a better picture of changing temperature extremes. In addition, due to the size and variable topography and land use of the DRB,

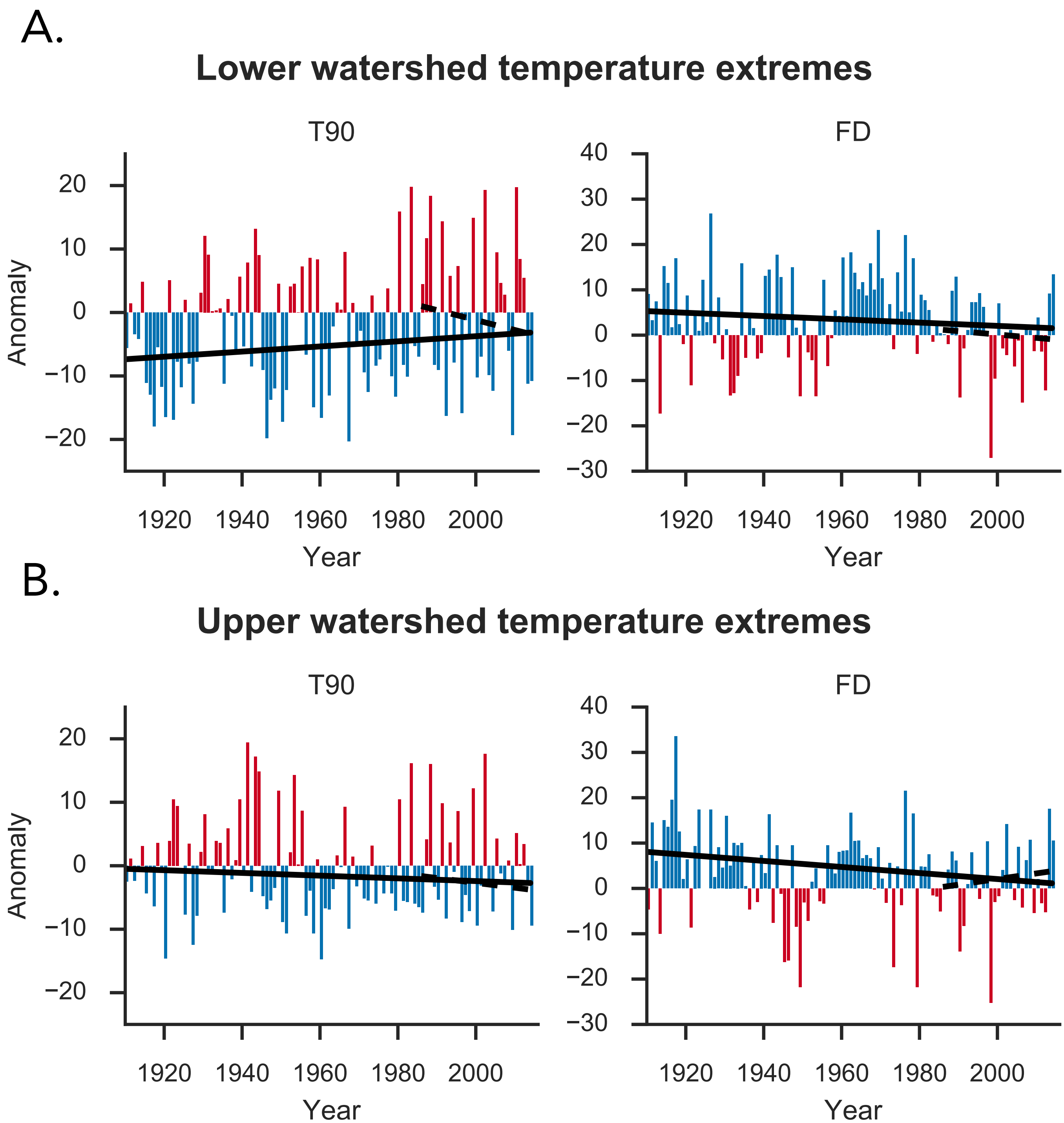


Figure 7.3.1 Time series of the anomalies (with respect to the 1981–2010 average) of the number of days per year with low temperature below 32 °F (0 °C) and high temperature above 90 °F (32.2 °C) in the A) upper and B) lower portions of the watershed. The solid and dashed lines are linear trends for the 1910–2014 and 1986–2014 periods, respectively.

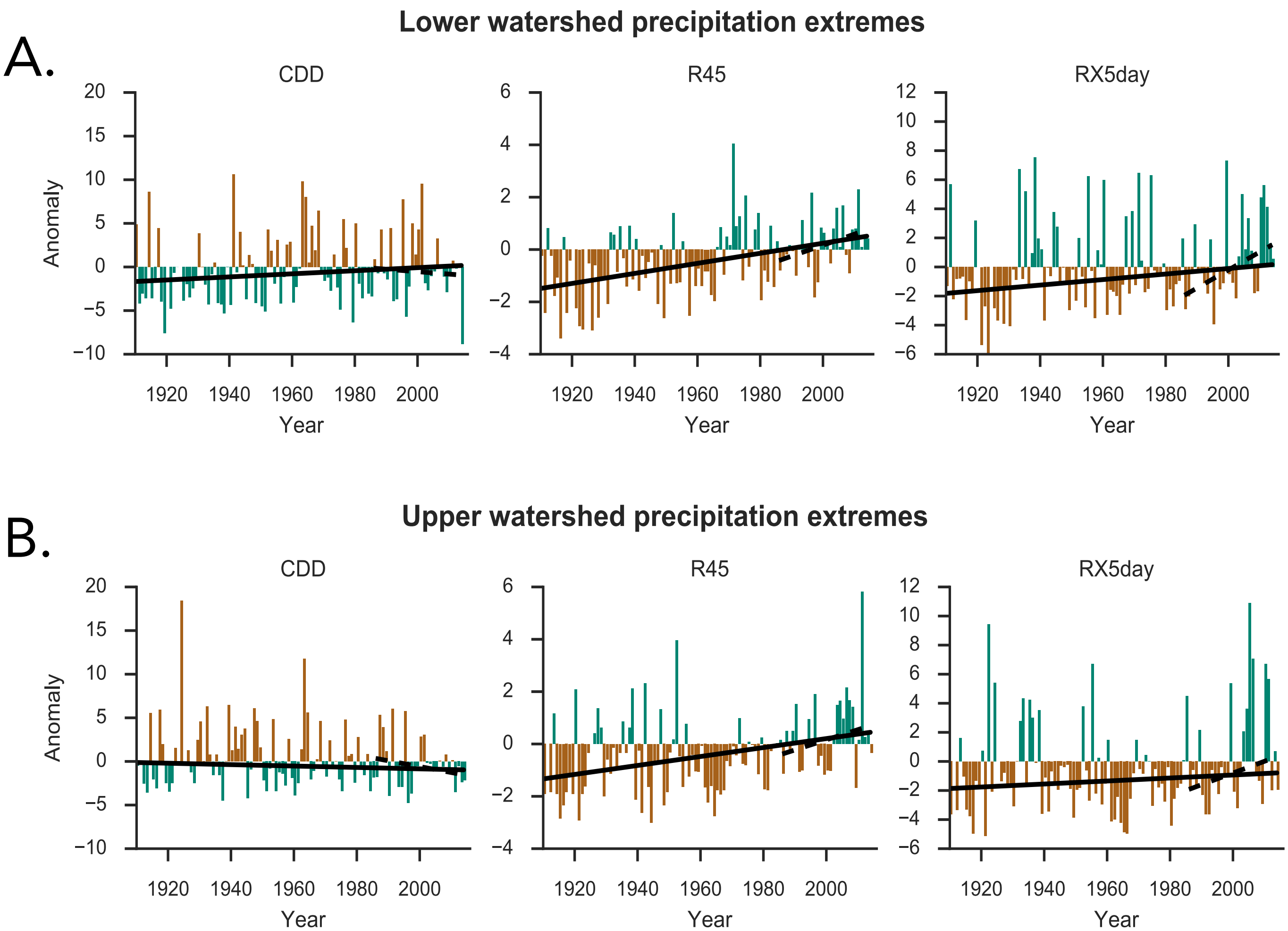


Figure 7.3.2 Time series of the anomalies (with respect to the 1981–2010 average) of the precipitation extreme metrics in the A) upper and B) lower portions of the watershed. The solid and dashed lines are linear trends for the 1910–2014 and 1986–2014 periods, respectively.

changes in temperature and precipitation extremes may have high spatial variability. Future work could analyze trends at the scale of individual stations and apply high-resolution regional climate models or other downscaling techniques.

7.3.5 Summary

The intensity and frequency of extreme temperature and precipitation events are difficult to examine directly and even harder to predict. Despite increased overall temperatures in the DRB over the past century, no significant increase in high temperature extreme events was detected in this analysis. On the other hand, heavy precipitation events increased in frequency in both the Upper and Lower Basin. Most climate scientists predict increasing extreme events in the future, but there is still a lot of uncertainty in this facet of climate science.

Table 7.3.1 Linear trends of extreme event indices for the upper and lower portions of the DRB. p-values are in parentheses; trends significant at the 95% confidence level are bold.

	Metric	1981-2010 Average	Trend (per decade)	
			1910-2015	1986-2015
Upper Watershed	# days per year above 90 °F	14	-0.21 (0.28)	-1.4 (0.28)
	# days per year below 32 °F	130	**-0.67 (0.043)**	1.1 (0.56)
	Annual max # consecutive dry days	15	-0.081 (0.35)	-0.96 (0.28)
	# days/year with precip >4.5 cm	2.8	**0.17 (5×10^{-4})**	0.3 (0.32)
	Annual max 5-day precip. total	11	0.1 (0.4)	0.78 (0.28)
Lower Watershed	# days per year above 90 °F	26	0.4 (0.12)	-1.4 (0.77)
	# days per year below 32 °F	93	-0.36 (0.42)	-1.3 (0.50)
	Annual max # consecutive dry days	17	0.18 (0.13)	-0.17(0.68)
	# days/year with precip >4.5 cm	3.3	**0.19 (<10^{-4})**	0.38 (0.087)
	Annual max 5-day precip. total	11	0.19 (0.078)	1 (0.18)

7.4 Snow Cover

7.4.1 Description

Snow cover data was obtained from the NOAA Climate Data Record of Northern Hemisphere Snow Cover Extent, Version 1 (https://data.noaa.gov/dataset/noaa-climate-data-record-cdr-of-northern-hemisphere-nh-snow-cover-extent-sce-version-1). This dataset provides gridded, satellite-derived observations of snow cover at weekly intervals. Snow cover is provided as a binary variable, indicating either the presence or absence of snow; no information about snow depth is available. For this analysis, three grid cells within the DRB were selected. Within a given snow year (year ending in July), the percent of weeks where at least one of the three cells had snow cover was calculated.

7.4.2 Past trends

Figure 7.4.1 shows that snow cover in the DRB has varied dramatically, with some years having several months of snow cover and other years having nearly zero snow cover. The linear trend during 1967–2016 is essentially zero. The trend for winters starting in 1986 and ending in 2016 is significantly positive at a rate of 3.7% per decade (p=0.018).

Climate oscillations have a large role in determining winter snow cover. Figure 7.4.1 also shows the winter mean North Atlantic Oscillation (NAO) index, acquired from the Climate Prediction Center. Snow cover percentage and mean NAO index are significantly negatively correlated (correlation coefficient =-0.45), and the fluctuations in the NAO index clearly align with anomalous snow cover periods such as the low snow cover during the late 1980s and early 90s and the high snow cover during the late 1960s and 70s. Since 2000, the NAO index has primarily been neutral or positive, yet snow cover has mostly been unusually high.

7.4.3 Future predictions

In the upper Delaware River watershed, snowpack during December through March is projected to be approximately half of the present-day snowpack by the mid-21st century under several different GHG emissions scenarios (Matonse et al. 2011). Global climate model simulations suggest that average snowfall in the mid-Atlantic region is not yet statistically different from early 20th century snowfall, but a detectable difference will emerge within the next two decades (Krasting et al. 2013).

7.4.4 Actions and needs

Snowfall depends on many factors in addition to temperature, such as the status of the NAO, El Niño-Southern Oscillation (ENSO), and other climate oscillations (Seager et al. 2010);

Therefore, the understanding of how climate affects snowfall would benefit from a more robust analysis of how local and regional weather events are affected by changing climate and associated weather patterns. Research would also benefit from additional datasets of observed snow-related variables, including measurements of snow depth.

7.4.5 Summary

Snowfall is highly variable from year to year, influenced by many factors that govern upper air movements, storm intensity, and temperature. It is just as related to short-term weather patterns as it is to long-term climate patterns. It is plausible that snowfall could actually increase in the future if deeper winter storms more routinely entrain cold northern air that would normally stay north of the DRB. On the other hand, warmer winters are predicted to cause a decrease in the depth, range, and duration of the snowpack. Therefore, it may snow just as much in the future but it may not stick around for as long as in the past, leading to faster freshwater runoff in streams and rivers.

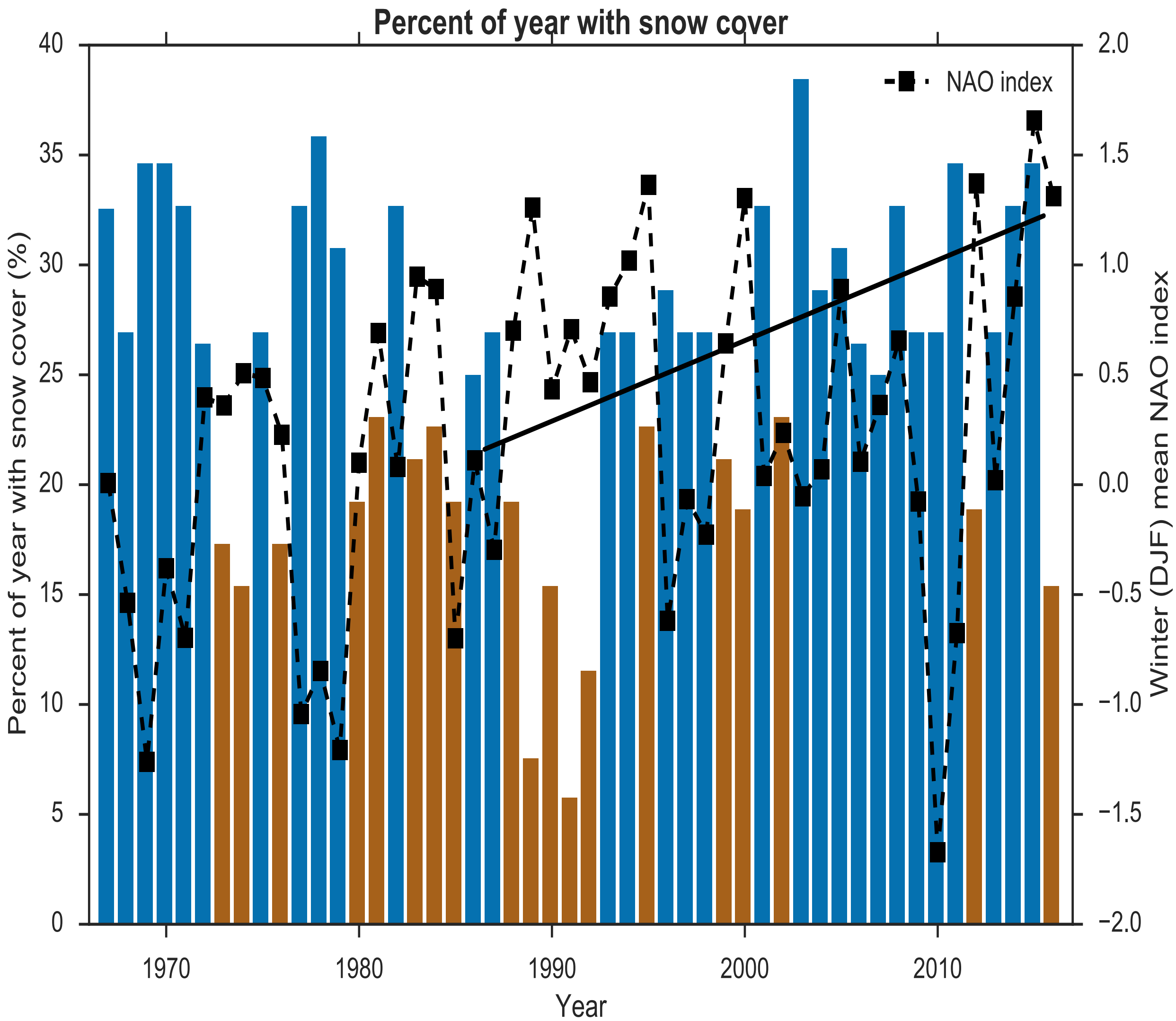


Figure 7.4.1 Time series of percent of the year with snow cover in the Delaware River Basin. Blue bars indicate a year with a greater snow cover percentage than the 1981–2010 mean of 24%; brown bars indicate a year with less snow cover. The solid line is the linear trend for the 1986–2016 period; the trend for the full time series is near zero. The dashed line is the winter mean NAO index.

7.5 Wind speed

7.5.1 Description of Indicator

Wind speed data were acquired from the National Climatic Data Center (NCDC) for five stations in the region (see Fig 7.1.1): Atlantic City, NJ (1973-2015); Binghamton, NY (1973-2015); Newark, NJ (1973-2015); Philadelphia, PA (1965-2015); and Wilmington, DE (1973-2009). The data processing and methods of analysis are similar to those of Vautard et al. (2010). Hourly averages at four times per day were acquired (00, 06, 12, and 18 UTC). Values flagged as suspect or erroneous by the NCDC were removed. The data were filtered using the came criteria as for the daily data: if for any month in a season or year contained more than five measurements missing from any of the four hours, the entire season or year from that station was considered missing.

The analysis was restricted to the period after 1965 because of a change in the reporting of low wind speeds in the early 1960s (DeGaetano and Allen 2002). A change in instrumentation occurred in 1995, when the stations became part of the Automated Surface Observing System (ASOS) of the National Weather Service. According to McKee et al. (1996), such a change resulted in low winds reported lower and high winds reported higher; calm wind reports nearly doubled. To avoid including the effects of this instrumentation switch, trends were calculated separately for the 1965-1994 and 1996–2015 periods.

Anomalies for wind speed were calculated with respect to the 1974–1992 average, during which most stations have data and were using consistent instrumentation, and averaged over the five stations. Anomalies were calculated for both the annual and seasonal mean wind speeds and for the annual and seasonal percent of hours with wind speeds exceeding 2, 5, and 7 $m \cdot s^{-1}$.

7.5.2 Past trends

Annual mean wind speed has declined by about 0.8 $m \cdot s^{-1}$ over the last 51 years (Fig 7.5.1). This trend is remarkably large compared to the 1974–1992 mean value of 4.3 $m \cdot s^{-1}$. The trend is relatively uniform across the seasons (Table 7.5.1, Fig 7.5.2), with the exception of a weaker summer trend before 1995. However, summer trends may be particularly affected by instrumentation and reporting standards, since calm winds are most common in summer.

The wind speed declines are consistently negative across the wind speed distribution (Figs 7.5.3 and 7.5.4). The trend in wind speeds exceeding 5 $m \cdot s^{-1}$ is the most negative trend both before and after 1995. Most of the plotted trend lines are statistically significant, including all of the annual trends. After 1995, all seasonal trends are significant except for the winter trends at all thresholds and the autumn trend in winds above 7 $m \cdot s^{-1}$. Before 1995, summer trends at all thresholds are not significant, along with autumn winds above 7 $m \cdot s^{-1}$ and spring and winter winds above 2 $m \cdot s^{-1}$.

These results are consistent with studies showing declining near-surface wind speeds in the tropical and mid-latitude regions of both the Northern and Southern Hemispheres over at least the last 30 years (Pryor et al. 2009; Vautard et al. 2010; McVicar et al. 2012). These declines are not matched by wind declines aloft, suggesting that surface roughness changes, perhaps resulting from land-use change, were responsible for the surface wind declines (Vautard et al. 2010). In fact, winds above the surface (at a pressure of 850 mb) have increased over much of North America, including the northeastern U.S. (Vautard et al. 2010).

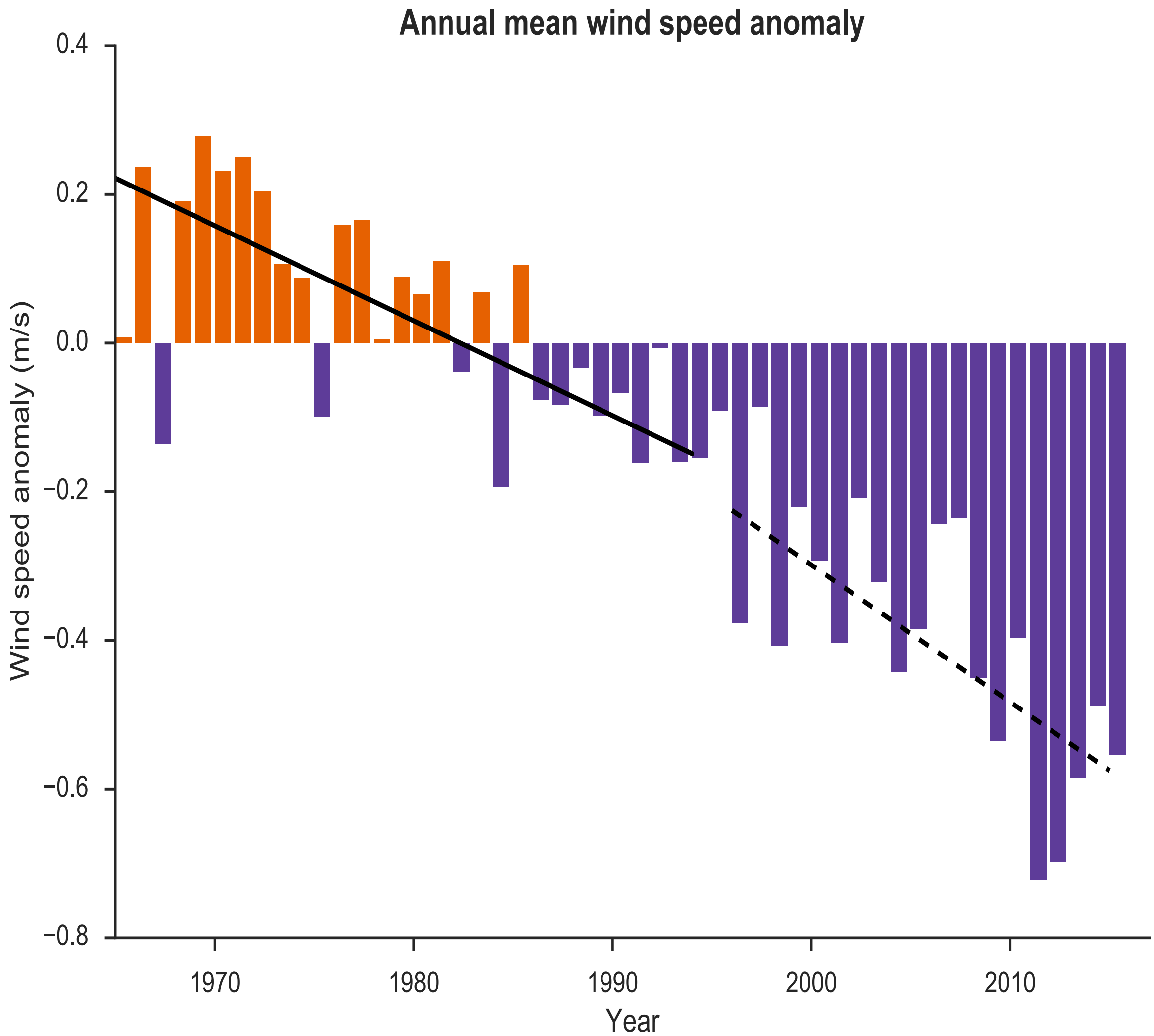


Figure 7.5.1 Time series of annual mean wind speed anomalies (with respect to 1974–1992 mean) averaged over the five wind stations. The solid line denotes the 1965–1994 trend, and the dashed line denotes the 1996–2015 trend.

Table 7.5.1 Mean and linear trends of annual and seasonal mean wind speed averaged over the five wind speed stations (see text).

Seasonal Subset	Wind Speed	
	Mean (m/s)	Trend (m/s/decade)
Annual	4.3	-0.18
DJF	4.6	-0.20
MAM	4.7	-0.22
JJA	3.8	-0.21
SON	4.0	-0.16

7.5.3 Future predictions

Future predictions of wind speed have not been analyzed in the DRB specifically. Across the United States, regional climate models have different projections about the sign and magnitude of future wind speed changes (Pryor and Barthelmie 2011). Since land-use and management changes are thought to have driven past changes, future winds may also depend more on land-use and management than on climate.

7.5.4 Actions and needs

Wind speeds are decreasing, which could have diverse effects on weather, agriculture, and other topics important to people and the environment. More study is needed to examine, for example, whether weaker winds might reduce evapotranspiration, promote slower-moving thunderstorms and more persistent fog, thereby affecting the water budget and growing conditions for plants and animals. Future work should also investigate whether wind direction has been changing or is predicted to change, and what effects changes in both wind speed and direction could have on the DRB.

7.5.5 Summary

Wind speeds have been declining across the Delaware River Basin. The cause of the wind speed decline is not known, but it may result from changes in surface properties, such as land use. Augmenting the current wind speed analysis with data on land use change and a regional climate model should be helpful in determining the cause of wind speed change in the DRB.

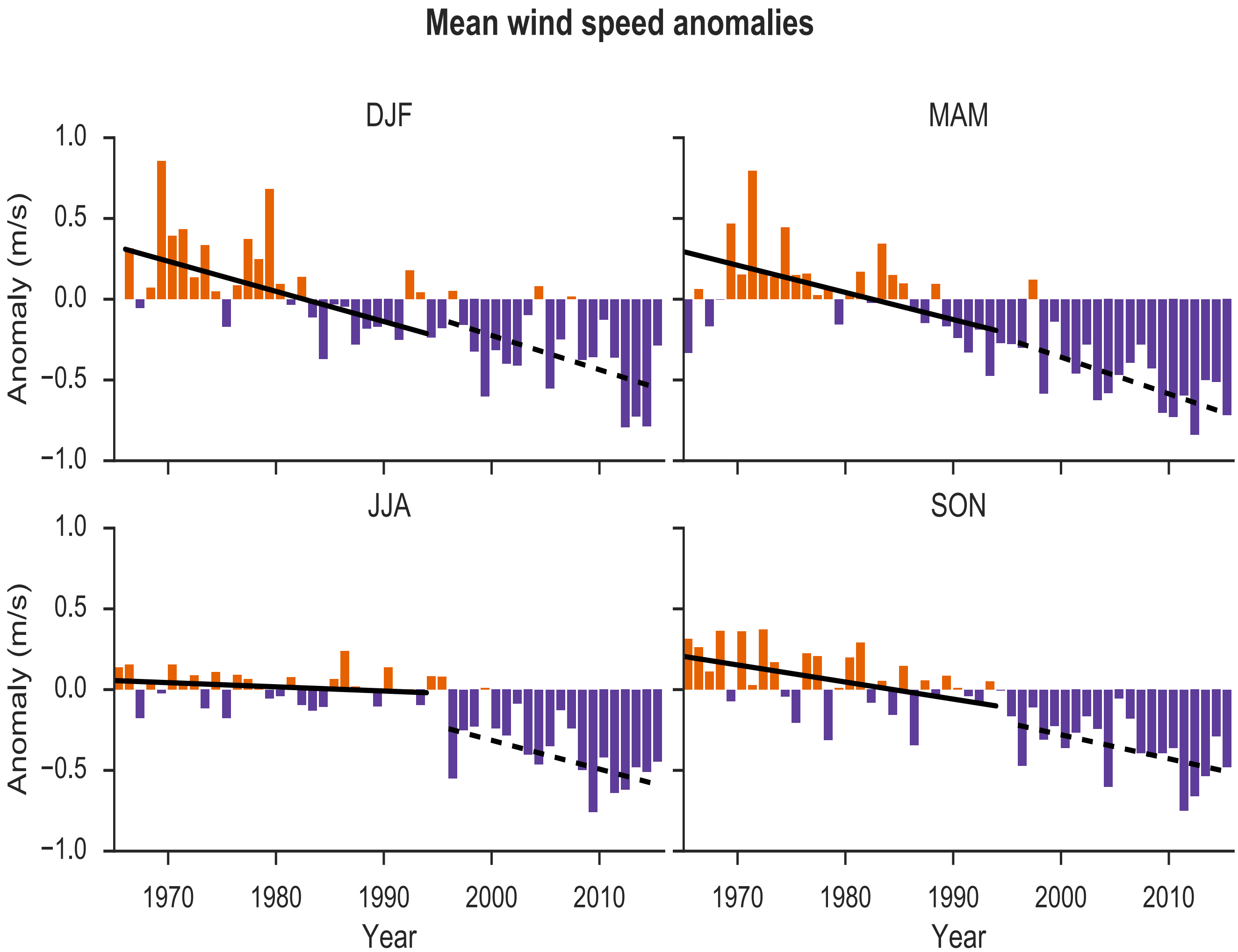


Figure 7.5.2 Time series of wind speed anomalies (with respect to 1974–1992 mean) averaged over the five wind stations. The solid lines denote the 1965–1994 trends, and the dashed lines denote the 1996–2015 trends.

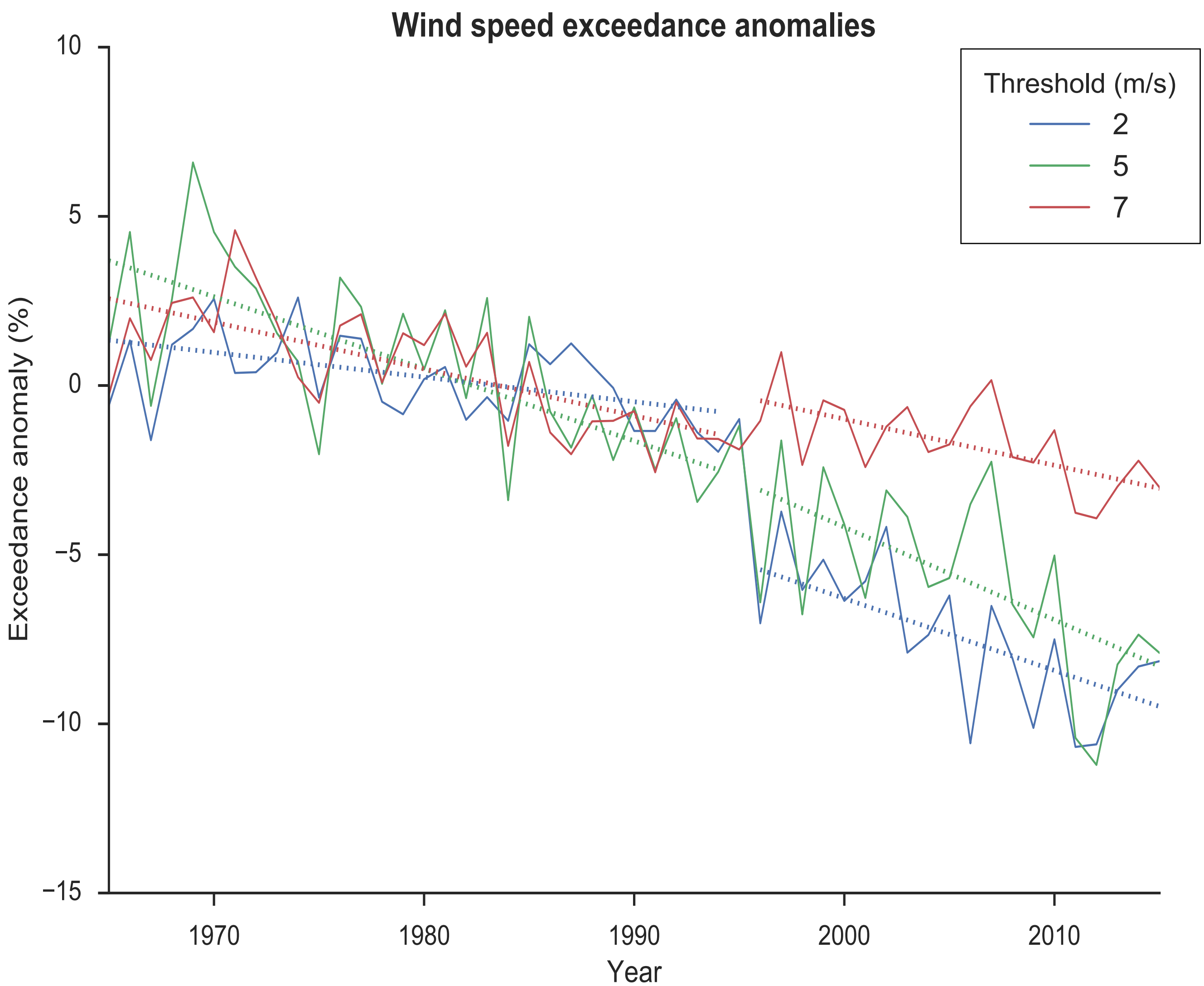


Figure 7.5.3 Time series of the wind speed exceedance anomalies (with respect to the 1974–1992 mean) averaged over the five wind stations. The dashed lines denote the 1965–1994 trends and 1996–2015 trends.

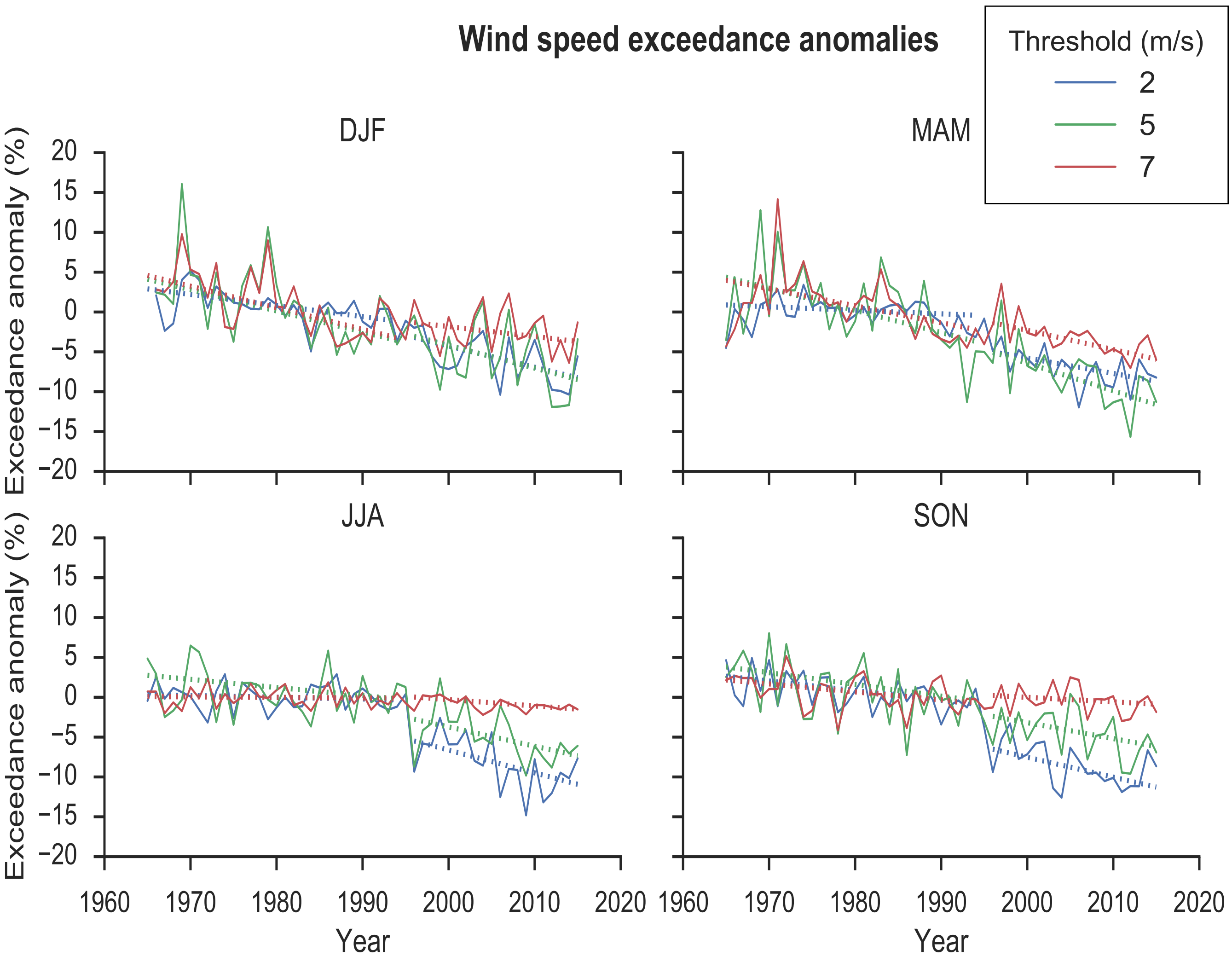


Figure 7.5.4 Time series of the wind speed exceedance anomalies (with respect to the 1974–1992 mean) averaged over the five wind stations. The dashed lines denote the 1965–1994 trends and 1996–2015 trends.

7.6 Streamflow

7.6.1 Description of Indicator

Daily streamflow data were obtained from the United States Geological Survey. The analysis primarily focuses on the streamflow measured in the Delaware River at Trenton, NJ. However, since the flow at Trenton is highly regulated, a set of data from smaller, unregulated, tributaries was also included. The tributaries were selected from those that are noted in the 2009 version of the Hydro-Climatic Data Network (HCDN) dataset (Slack et al. 1993) as having a complete record of acceptable data and that include complete daily data during 1981 to 2010. Sites listed in the HCDN dataset have passed a number of checks to ensure that the flow data from the sites are not affected by human activity such as dams, impervious surfaces, and water withdrawal and discharge. Information about the 10 selected gauges is provided in Table 7.6.1. The gauges are concentrated in the northern portion of the DRB; only three are south of Trenton. Data from the tributaries were analyzed during years 1958 to 2014 when data were available at every gauge. Like other daily data, flow data from both the Delaware River and the tributaries were filtered to remove years and seasons with more than 5 days of data missing in any month.

To homogenize the tributary river data, standardized anomalies were calculated for each gauge. The standardized anomaly Q′ was calculated as

$$Q' = \frac{Q - \overline{Q}}{Q_\sigma}$$

where Q is the time series of annual or seasonal mean streamflow, $\overline{Q}$ is the 1981–2010 mean of the time series, and Q_σ is the 1981–2010 standard deviation of the time series.

7.6.2 Past trends

Streamflow at Trenton, NJ has varied substantially over the past century, with many years departing from the long-term mean by more than 50% (Figs 7.6.1-7.6.2). Aside from a large increase in summer streamflow over the last 30 years, no trend in streamflow is statistically significant. Despite lack of significance, the estimated values of the trends over the last century are generally consistent with trends over the last 30 years, with positive trends in winter, summer, and fall and negative trends in spring.

Table 7.6.1 Metadata for the tributary flow gages.

ID	Name
01413500	East Br Delaware R at Margaretville, NY
01414500	Mill Brook near Dunraven, NY
01415000	Tremper Kill near Andes, NY
01423000	West Branch Delaware River at Walton, NY
01435000	Neversink River near Claryville, NY
01439500	Bush Kill at Shoemakers, PA
01440000	Flat Brook near Flatbrookville, NJ
01440400	Brodhead Creek near Analomink, PA
01466500	McDonalds Branch in Lebanon State Forest, NJ
01484100	Beaverdam Branch at Houston, DE

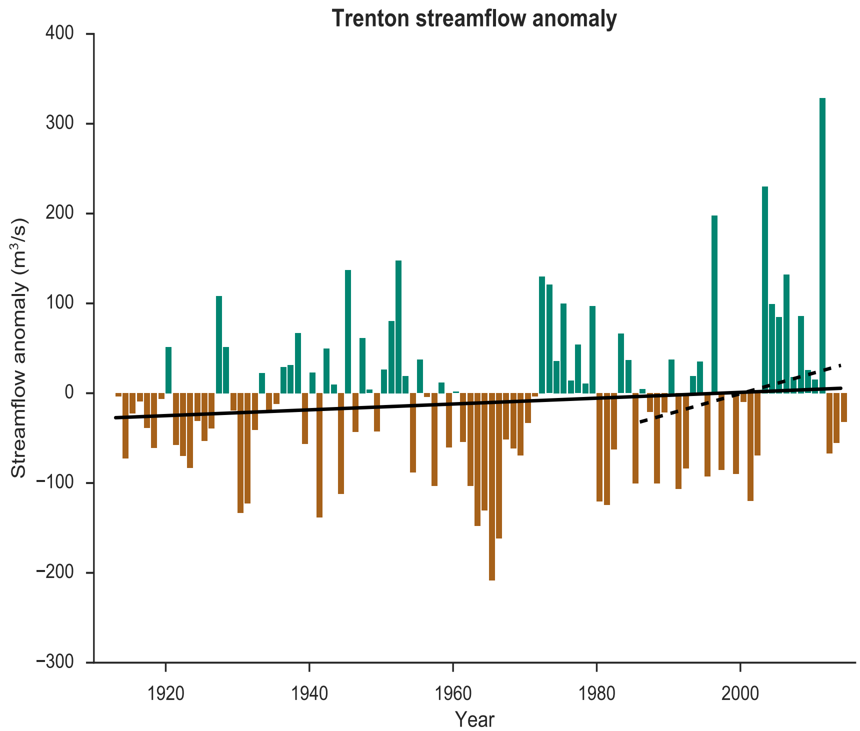


Figure 7.6.1 Time series of annual average streamflow anomaly (with respect to the 1981–2010 average of 349 $m^3 \cdot s^{-1}$ at Trenton, NJ. The solid and dashed lines are linear trends for the 1913–2015 and 1986–2015 periods, respectively.

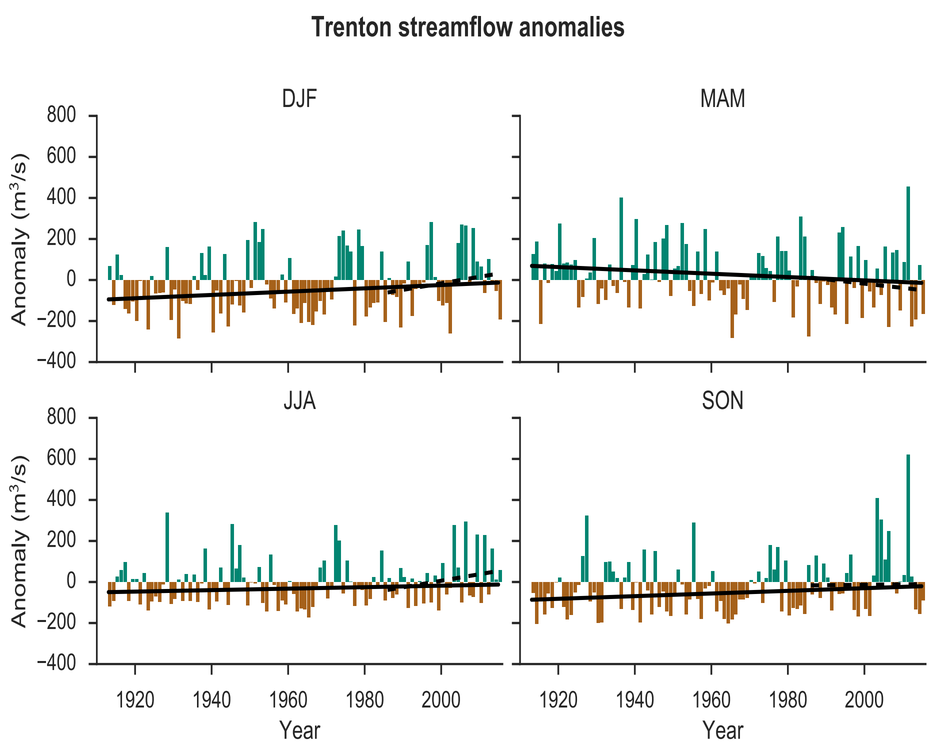


Figure 7.6.2 Time series of seasonal mean streamflow anomaly (with respect to the 1981–2010 average) at Trenton, NJ. The solid and dashed lines are linear trends for the 1913–2015 and 1986–2015 periods, respectively.

The trends at Trenton are similar to the trends observed at the smaller tributaries (Fig 7.6.3). Although only a few trends are statistically significant, negative trends in spring mean streamflow are present at all ten gauges. In the remaining seasons, positive trends are present at every one of the ten gauges except one in winter and two in summer.

7.6.3 Future predictions

Hydrological model simulations forced by global climate models project decreasing runoff from April through November in some areas of the DRB (Williamson et al. 2016). Annual mean runoff, however, is predicted to increase, primarily as a result of increased winter precipitation (Williamson et al. 2016). Model simulations of the nearby Chesapeake Bay watershed also show increasing winter runoff, although a decrease in annual mean runoff becomes more likely with higher emissions scenarios and later time periods (Hawkins 2015).

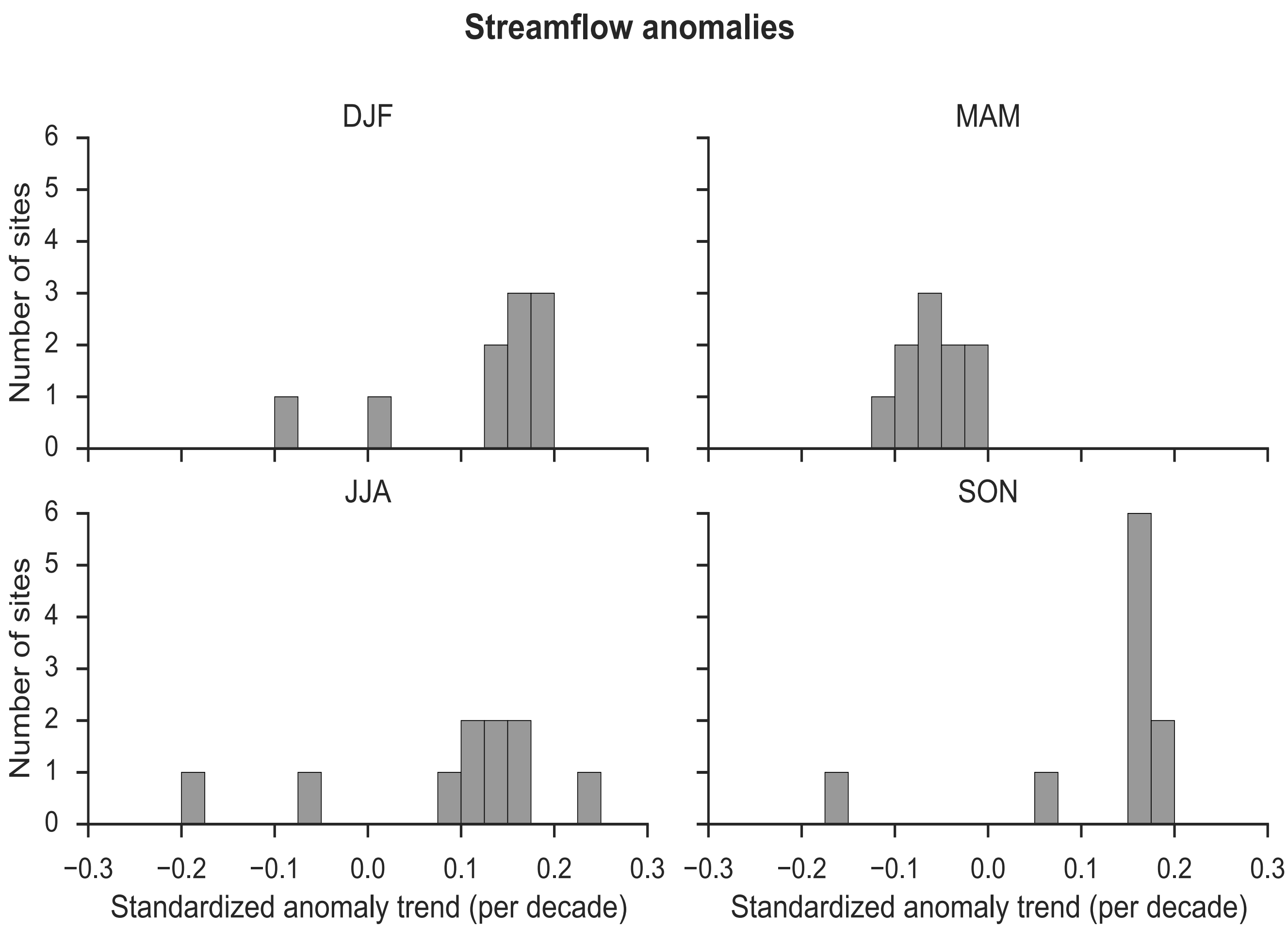


Figure 7.6.3 Histograms of trends in standardized seasonal streamflow anomaly at the 14 tributary sites during 1958-2014.

7.6.4 Actions and needs

Continued monitoring of stream and river flows is critically important to track changes in the water budget of the DRB, which affects estuarine salinity and freshwater availability for people and the environment. Future changes in flow, particularly in summer, are likely to be driven by a combination of precipitation and evapotranspiration changes, which may not be simulated well by global climate models, so understanding and accounting for uncertainty in future flow is necessary.

7.6.5 Summary

Most streamflow trends in the Delaware River and its tributaries are not statistically significant. In the future, increased streamflow is expected in winter and early spring, primarily as a result of increased precipitation, and reduced streamflow in the summer is possible.

7.7 Ice jams

7.7.1 Description of indicator

Occurrences of ice jams were obtained from the Ice Jam Database of the U.S. Army Cold Regions Research and Engineering Laboratory (White 1996). The database contains reports of ice jams in numerous rivers of the northern United States. This section analyzed annual counts (by water year) of ice jams occurring on any river within the DRB and counts of ice jams occurring only on the Delaware River.

7.7.2 Past trends

The number of ice jams that have been reported over the past 85 years in the DRB and in the Delaware River has been declining (Fig 7.7.1). This is possibly a result of underreporting of ice jams in the more recent past (White 1996). However, winter warming of the watershed has occurred, which is expected to lead to fewer ice jams. Indeed, as figure 7.7.2 shows, there is a strong negative correlation between the number of ice jams and the winter mean temperature.

7.7.3 Future predictions

It is reasonable to expect fewer ice jams in the future due to predicted higher winter temperatures. Ice jam frequency shows a strong negative correlation with mean winter temperatures in the DRB.

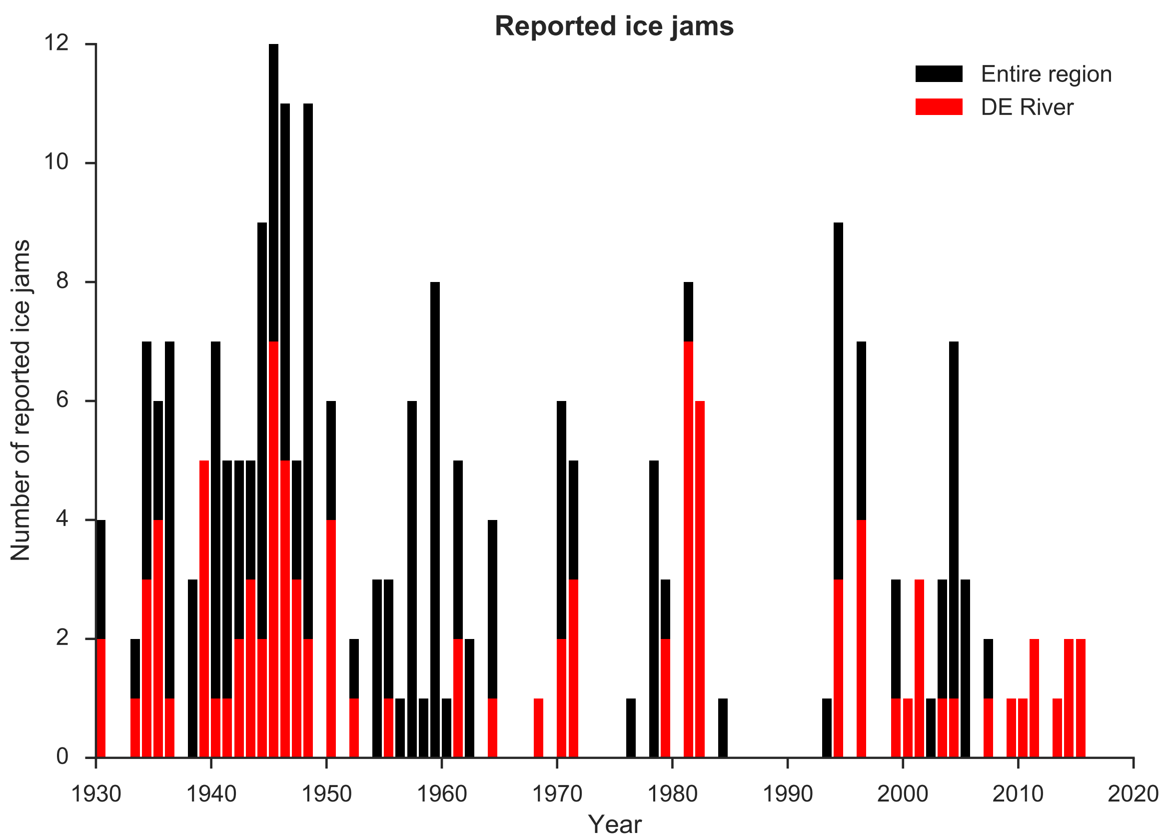


Figure 7.7.1 Annual count of ice jam reports anywhere in the Delaware River Basin (black) and only in the Delaware River (red).

7.7.4 Actions and needs

More analysis is warranted to understand the connection between temperature, river flow, snowfall, and ice jam data quality and consistency. This indicator appears to serve as a useful indicator of a climate change "outcome" and should be further explored.

7.7.5 Summary

Ice jams represent an interesting "outcome" indicator for tracking climate change effects, but the tracking of ice jams has potentially been inconsistent and so the analysis here should be considered as preliminary. Nevertheless, the frequency of ice jams in the DRB has apparently decreased significantly, and the decline is directly correlated with the increasing mean winter temperature across the watershed. Since winter temperatures are predicted to increase markedly in the future, ice jams are likely to become still less frequent.

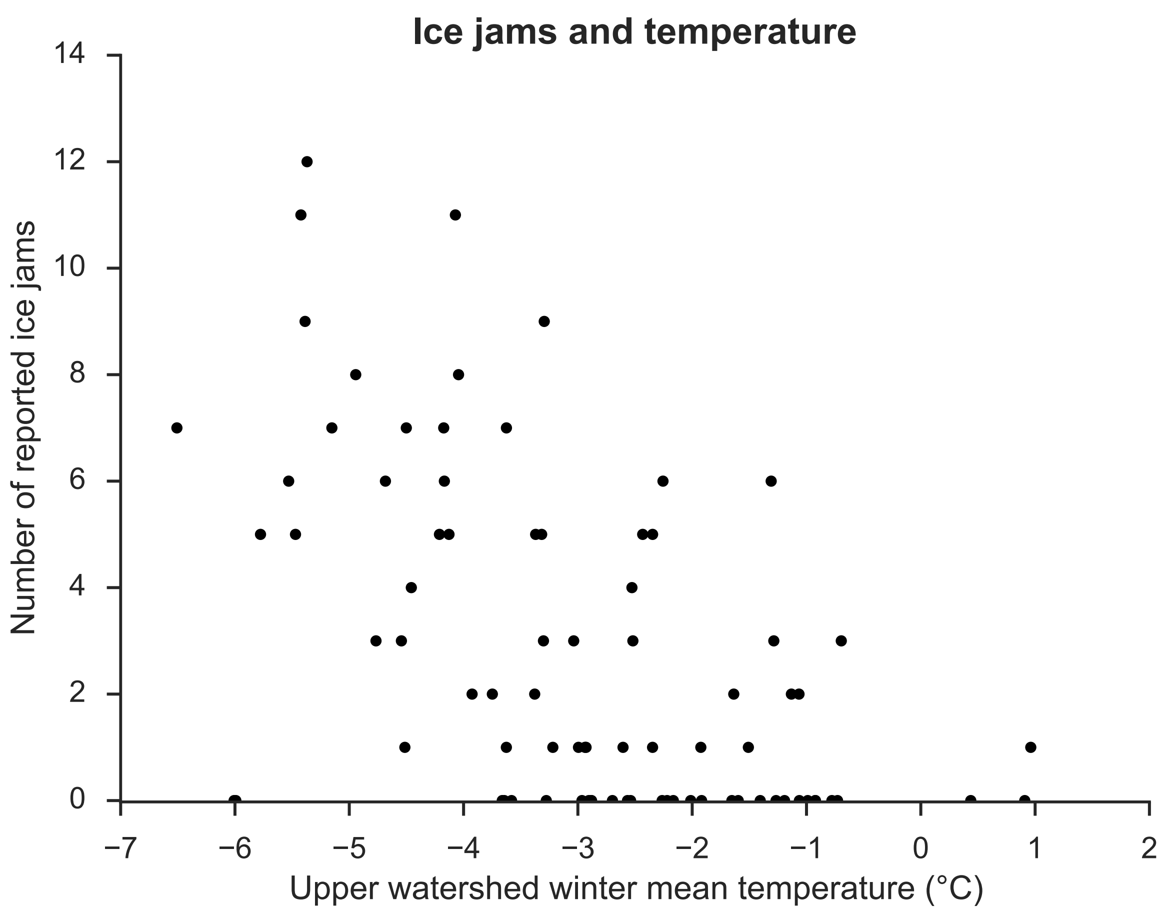


Figure 7.7.2 Annual count of ice jam reports anywhere in the DRB versus upper watershed winter mean temperature.

References

Bronaugh, D., and A. Werner, 2013: Zyp: Zhang + yue-pilon trends package. <https://CRAN.R-project.org/package=zyp.>

Brown, P. J., R. S. Bradley, and F. T. Keimig, 2010: Changes in Extreme Climate Indices for the Northeastern United States, 18702005. Journal of Climate, 23, 6555–6572.

DeGaetano, A. T., and R. J. Allen, 2002: Trends in twentieth-century temperature extremes across the United States. Journal of Climate, 15, 3188–3205.

Hartmann, D. and Coauthors, 2013: Observations: Atmosphere and surface. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridgue University Press, Cambridge; New York.

Hawkins, T. W., 2015: Simulating the Impacts of Projected Climate Change on Streamflow Hydrology for the Chesapeake Bay Watershed. Annals of the Association of American Geographers, 105, 627–648.

Horton, R., W. Easterling, R. Kates, M. Ruth, E. Sussman, A. Whelchel, D. Wolfe, and F. Lipschultz, 2014: Ch. 16: Northeast. Climate change impacts in the United States: The Third National Climate Assessment, U.S. Global Change Research Program, 317–395.

Janssen, E., D. J. Wuebbles, K. E. Kunkel, S. C. Olsen, and A. Goodman, 2014: Observational- and model-based trends and projections of extreme precipitation over the contiguous United States. Earth's Future, 2, 99–113.

Kendall, M. G., 1955: Rank Correlation Methods. 2nd ed. Hafner, New York,

Krasting, J. P., A. J. Broccoli, K. W. Dixon, and J. R. Lanzante, 2013: Future Changes in Northern Hemisphere Snowfall. Journal of Climate, 26, 7813–7828.

Kreeger, D., J. Adkins, P. Cole, R. Najjar, D. Velinsky, P. Conolly, and J. Kraeuter, 2010: Climate change and the Delaware Estuary: Three case studies in vulnerability assessment and adaptation planning.

Lynch, C., A. Seth, and J. Thibeault, 2016: Recent and Projected Annual Cycles of Temperature and Precipitation in the Northeast United States from CMIP5. Journal of Climate, 29, 347–365.

Mann, H. B., 1945: Nonparametric Tests Against Trend. Econometrica, 13, 245–259.

Matonse, A. H., D. C. Pierson, A. Frei, M. S. Zion, E. M. Schneiderman, A. Anandhi, R. Mukundan, and S. M. Pradhanang, 2011: Effects of changes in snow pattern and the timing of runoff on NYC water supply system. Hydrological Processes, 25, 3278–3288.

McKee, T. B., N. J. Doesken, and J. Kleist, 1996: Climate data continuity with ASOS: Report for the period September 1994-March 1996. Colorado Climate Center, Department of Atmospheric Science, Colorado State University, Fort Collins, CO,

McVicar, T. R. and Coauthors, 2012: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. Journal of Hydrology, 416-417, 182–205.

Menne, M., C. J. Willains, and R. Vose, 2015a: The USHCN Version 2 Serial Monthly Datasets. https://www.ncdc.noaa.gov/oa/climate/research/ushcn/.

M. J. Menne, C. N. Williams, Jr., and R. S. Vose, 2015. United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.<http://cdiac.ornl.gov/epubs/ndp/ushcn/daily_doc.html.>

Menne, M. J., C. N. Williams Jr., and R. S. Vose, 2009: The U.S. Historical Climatology Network Monthly Temperature Data, Version 2. Bulletin of the American Meteorological Society, 90, 993–1007.

Menne, M.J, C.N. Williams Jr., and M. A. Palecki, 2010: On the reliability of the U.S. surface temperature record. Journal of Geophysical Research, 115, D11108–9.

Najjar, R., L. Patterson, and S. Graham, 2009: Climate simulations of major estuarine watersheds in the Mid-Atlantic region of the U.S.. Climatic Change, 95, 139–168.

Pryor, S. C., and R. J. Barthelmie, 2011: Assessing climate change impacts on the near-term stability of the wind energy resource over the United States. Proceedings of the National Academy of Sciences, 8167–8171.

Pryor, S. C., R. J. Barthelmie, D. T. Young, E. S. Takle, R. W. Arritt, D. Flory, W. J. Gutowski Jr., A. Nunes, and J. Roads (2009), Wind speed trends over the contiguous United States, J. Geophys. Res., 114, D14105, doi:10.1029/2008JD011416.

Rawlins, M. A., R. S. Bradley, and H. F. Diaz, 2012: Assessment of regional climate model simulation estimates over the northeast United States. Journal of Geophysical Research Atmospheres, 117.

Seager, R., Y. Kushnir, J. Nakamura, M. Ting, and N. Naik, 2010: Northern Hemishpere winter snow anomalies: ENSO, NAO and the winter of 2009/10. Geophysical Research Letters, 37.

Sen, P. K., 1968: Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association, 63, 1379–1389.

Slack, J. R., A. M. Lumb, and J. M. Landwehr, 1993: Hydro-Climatic Data Network (HCDN) Streamflow Data Set, 1874-1988. U.S. Geological Survey,

Theil, H., 1950: A Rank-Invariant Method of Linear and Polynomial Regression Analysis, 1, 2, and 3. Ned. Akad. Wetensch Proc., 23, 386–392–521–525–and 1397–1412.

Vautard, R., J. Cattiaux, P. Yiou, J.-N. Thepaut, and P. Ciais, 2010: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. Nature Geoscience, 3, 756–761.

Walsh, J. and Coauthors, 2014: Ch. 2: Our changing climate. Climate change impacts in the United States: The Third National Climate Assessment, U.S. Global Change Research Program, 19–67.

White, K. D., 1996: A new ice jam database. Water Resources Bulletin, 32, 341–348.

Williams, C. N., M. J. Menne, and P. W. Thorne, 2012: Benchmarking the performance of pairwise homogenization of surface temperatures in the United States. Journal of Geophysical Research Atmospheres, 117.

Williamson, T. N., E. A. Nystrom, and P. C. D. Milly, 2016: Sensitivity of the projected hydroclimatic environment of the Delaware River basin to formulation of potential evapotranspiration. Climatic Change, 1–14.

Wuebbles, D. and Coauthors, 2014: CMIP5 Climate Model Analyses: Climate Extremes in the United States. Bulletin of the American Meteorological Society, 95, 571–583.

Yue, S., P. Pilon, B. Phinney, and G. Cavadias, 2002: The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes, 16, 1807–1829.

Suggested Citation for this Chapter

Ross, A., R. Najjar. 2017. "Chapter 7 - Climate Change" in the Technical Report for the Delaware Estuary and Basin. Partnership for the Delaware Estuary. PDE Report No. 17-07 pp. 300-334.

Back to Table of Contents