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TECHNICAL REPORT FOR THE ESTUARY AND BASIN

Climate Change

Partnership for the DELAWARE ESTUARY

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TECHNICAL REPORT FOR THE ESTUARY AND BASIN

2 Climate Change

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Table of Contents

2. Climate Change 75
2.1 Air Temperature 76
2.2 Precipitation 82
2.3 Extremes: Air Temperature & Precipitation 86
2.4 Streamflow 90
2.5 Ice Jams 95
2.6 Sea Level 97
Take-Home Messages 100
Redlining and Urban Heat Islands 107
Raymond Najjar, PhD
The Pennsylvania State University
Flooding in a Marginalized Community 109
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2. Climate Change

Abstract

Past and likely future changes in the climate of the Delaware Estuary and Basin are presented. From a historical analysis of air temperature, precipitation, streamflow, sea level, and ice and snow indicators, an overall picture of dramatic and accelerating climate change in the Delaware Estuary and Basin emerges, one that is largely consistent with expectations from increases in greenhouse gases. These climate trends are extremely likely to continue into the next few decades regardless of greenhouse gas emissions. Climate change beyond mid-century will depend strongly on the emissions pathway. Hence, a combination of aggressive local adaptation and global emissions reduction is needed to avoid the worst impacts of anthropogenic climate change in the Delaware Estuary and Basin. Adaptation planning should compensate for unjust policies, such as redlining, that have led climate impacts to fall disproportionately on the most vulnerable communities.

What is Climate Change?

Climate is among the most important factors determining the character of a watershed or an estuary. Climate influences the type of natural and managed vegetation growing on a landscape as well as the flora and fauna in tidal and non-tidal aquatic habitats. The abundance of fresh water available for human use is largely dictated by the balance of precipitation and evapotranspiration, which are driven by climate. One of the most serious impacts of climate change is flooding, which is worsening with warming via sea level rise and more extreme precipitation (Douville et al. 2022; Fox-Kemper et al. 2022). Though water quality is generally considered to be driven by human activity on the landscape, it is increasingly recognized that climate can act as a stress multiplier by, for example, exacerbating harmful algal blooms during unusually warm periods and reducing water clarity during extreme precipitation events (Paerl and Huisman 2008; Coffey et al. 2018). Because of the strong influence of climate, it must be considered in restoration planning. In summary, all the topics covered by this report—watersheds and landscapes, water quantity, water quality, sediments, aquatic habitat, living resources, and restoration—are all profoundly influenced by climate.

Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as changes in the mean and/or variability of climatic properties (e.g., air temperature and precipitation) that persist for an extended period, typically decades or longer, due to natural internal processes or external forcings. One of the main external forcings of climate change is the addition of greenhouse gases (GHGs) to the atmosphere via anthropogenic emissions (Myhre et al. 2013). Globally, there is an urgency to minimize potential future impacts of climate change through the reduction of anthropogenic GHG emissions, particularly carbon dioxide (CO_2), because of their ability to increase radiative forcing (Myhre et al. 2013). Since the beginning of the Industrial Age in the late 1700s to December 2021, the atmospheric CO_2 concentration has increased from about 280 ppm to 417 ppm (Joos and Spahni 2008; NOAA Global Monitoring Laboratory). Over the past decade, the atmospheric CO_2 concentration has increased at a rate of 2.5 ppm per year (Friedlingstein et al. 2022).

This chapter describes how the climate of the Delaware Estuary and Basin has changed in the past and discusses how it may change in the future. The focus is on air temperature and precipitation throughout the watershed with additional analysis of changes in streamflow, ice jams, and sea level. This chapter follows a similar structure as the corresponding chapter from the 2017 report, with a few differences. Sea level has been added as an indicator, given its importance to tidal wetlands, salt water intrusion, and flooding of coastal communities. Since the impacts of changes in climate and other environmental conditions are unequal across socioeconomic and racial groups, we have also included discussions that highlight two particular instances, redlining and nuisance flooding (Climate Features 1 and 2). Wind speed was removed as a climate change indicator as it has been found to be more dependent on land use change and management than climate change (Vautard et al. 2010). Snow cover is now included with precipitation in Section 2.2.

Methods

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). The statistical significance of each trend was tested using the nonparametric Mann-Kendall test (Mann 1945; Kendall 1955) at a significance level of α=0.05. For time series that exhibited statistically significant autocorrelation, which increases the likelihood of falsely identifying a spurious trend as significant, the trend and significance were corrected using the trend-free prewhitening method (Coen et al. 2020; Yue et al. 2002). These statistical methods were provided by the Python package "pyMannKendall" (Hussain et al. 2019). Trends were calculated for both the full extent of each time series and for the most recent 30 years (1992–2021). To merge data from multiple stations into a single time series, anomalies were calculated by subtracting each station's mean value over the standard 30-year climate normal time period (1991-2020) prior to averaging the station data.

Some of the indicator trends presented here are broken down by season and/or by sub-watershed, such as upper Basin or Estuary (i.e., Fig 2.1). 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 to reduce the potential biases caused by incomplete data.

2.1 Air Temperature

Description of Indicator

Air temperature is one of the most important climate change indicators as it directly influences snowpack, evapotranspiration, growing season, water temperature, and other fundamental characteristics of watersheds and estuaries.

Monthly mean near-surface air temperature was obtained from version 2.5 of the U.S. Historical Climatology Network (USHCN) database. 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 are at daily resolution. 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). As in the 2017 report, these adjustments are needed in order to correct for the substantial cooling effect of changes in equipment and observation times.

The 15 USHCN stations located in or near the Delaware Estuary and Basin were selected for analysis (Fig 2.1, Table 2.1). The analysis distinguished between the upper and lower portions of the Delaware Estuary watershed. The Delaware Estuary, also sometimes referred to here as the lower watershed, is defined by those basins that deliver freshwater directly to the tidal portion of the estuary, which is located below Trenton, NJ. The upper Basin, or upper watershed, drains to the Delaware River above Trenton. There are 8 USHCN stations in the Estuary and 7 in the upper Basin.

The period 1910–2021 was selected for analysis based on the monthly dataset because every station has a value during this time period (some being filled by interpolation).

Table 2.1 USHCN stations in the Delaware Estuary and Basin.

#	Name	State	ID number	Latitude (deg)	Longitude (deg)	Elevation (m)	Start–end
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	1926–2016
3	Port Jervis	NY	306774	41.3800	-74.6847	143.3	1910–2020
4	Stroudsburg	PA	368596	41.0125	-75.1906	140.2	1912–2021
5	Belvidere BRG	NJ	280734	40.8292	-75.0836	80.2	1983–2018
6	Palmerton	PA	366689	40.8000	-75.6167	125.0	1918–1997
7	Allentown AP	PA	360106	40.6508	-75.4492	118.9	1948–2021
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	1910–2016
10	Moorestown	NJ	285728	39.9511	-74.9697	13.7	1910–2008
11	Indian Mills 2 W	NJ	284229	39.8144	-74.7883	30.5	1910–2019
12	Wilmington Porter Res.	DE	079605	39.7739	-75.5414	82.3	1942–2020
13	Newark Univ. Farm	DE	076410	39.6694	-75.7514	27.4	1942–2020
14	Dover	DE	072730	39.2583	-75.5167	9.1	1910–2018
15	Milford 2 SE	DE	075915	38.8983	-75.4250	10.7	1916–2001

Past Trends

Annual-mean temperature has increased significantly at the 95% confidence interval over the last 112 years in both the upper and lower watersheds (Fig 2.2, Table 2.2). Based on these trends, temperature has increased by roughly 1.7 °C (3.0 °F) over the last 112 years. This rate is consistent with the predicted effect of GHGs (Najjar et al. 2009). The estimated trend in annual mean temperature during the past 30 years of about 0.06 °C (0.10 °F) per year is around four times greater than during the last 112 years, indicating an acceleration in warming.

Since 1910, significant warming trends were also present in both portions of the watersheds for all seasons (Fig 2.3, Table 2.2). In the recent 30-year period, both watersheds show significant temperature increases for all seasons except the winter.

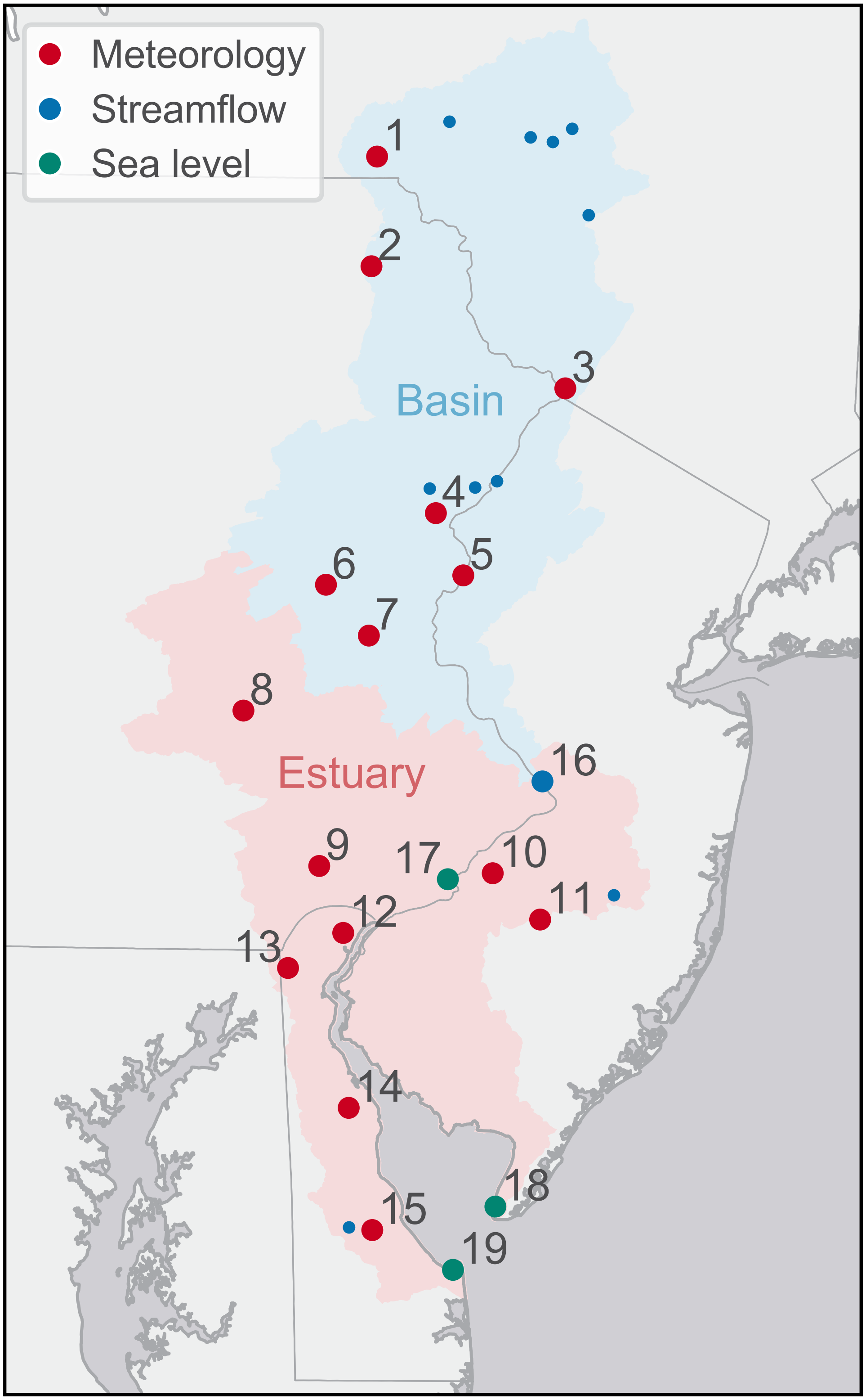


Figure 2.1 Stations in the Delaware Estuary (red shaded region) and Basin (blue shaded region) for: air temperature and precipitation (red circles - see Table 2.1), streamflow (blue circles - #16 is the Trenton gauge), and sea level (green circles - #17 is Philadelphia, #18 is Cape May, and #19 is Lewes tidal stations).

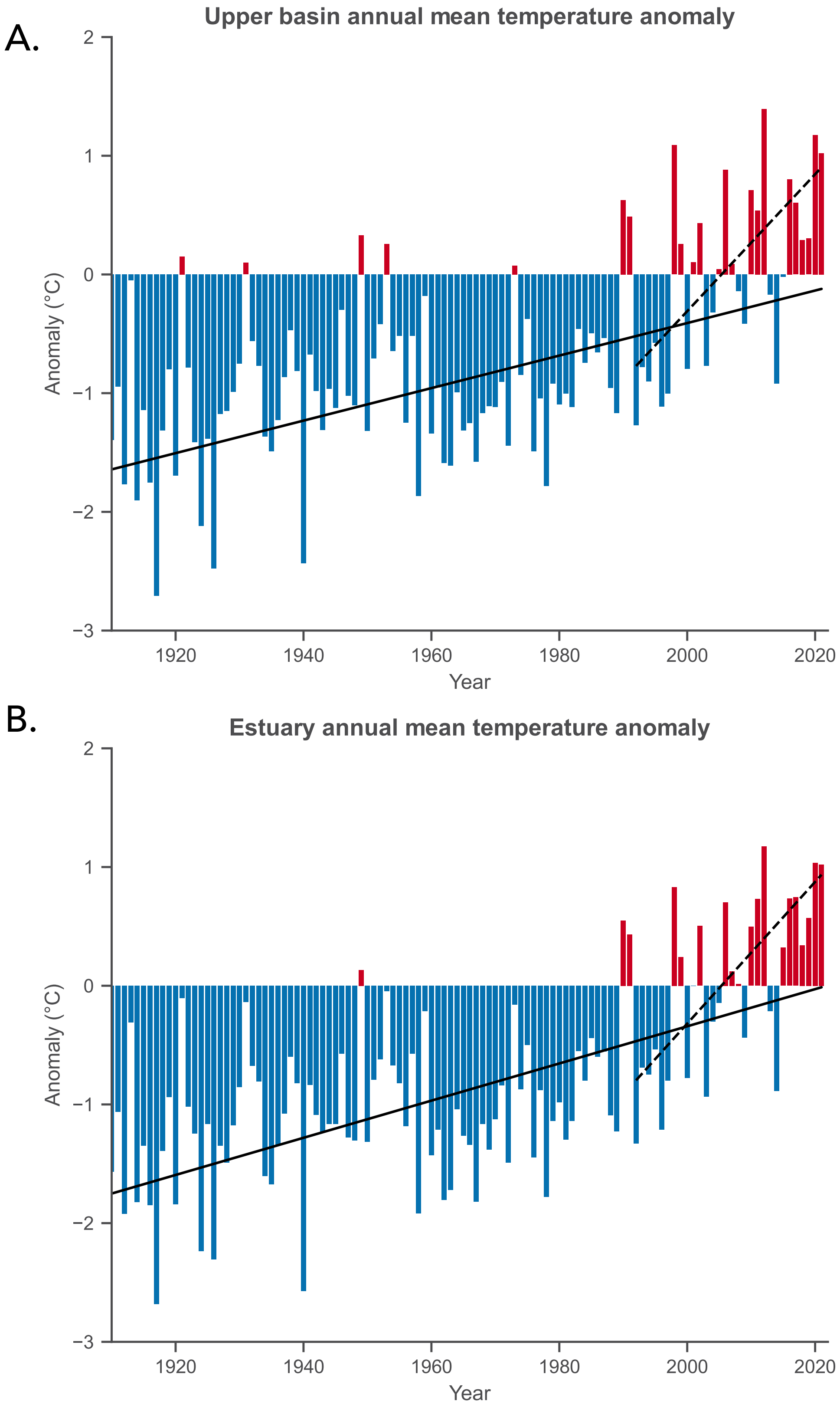


Figure 2.2 Annual mean temperature anomalies with respect to the 1991-2020 average in the Upper Basin (A) and Estuary (B). The solid and dashed lines are linear trends for the 1910–2021 and 1992–2021 periods, respectively.

Table 2.2 Temperature trends in the Delaware Estuary and Basin. Significant trends are bold (95% confidence).

Seasonal Subset	Temperature Trend (°C/decade)			
	1910-2021	p-value	1992-2021	p-value
		Upper Basin		
Annual	**0.14**	**$2.4e^{-10}$**	**0.58**	**0.002**
DJF	**0.19**	**0.00028**	0.35	0.39
MAM	**0.13**	**0.00013**	**0.54**	**0.019**
JJA	**0.13**	**$3.0e^{-07}$**	**0.49**	**0.011**
SON	**0.13**	**$2.5e^{-05}$**	**0.66**	**0.0029**
		Estuary		
Annual	**0.16**	**$1.6e^{-12}$**	**0.60**	**0.0012**
DJF	**0.19**	**0.00045**	0.36	0.43
MAM	**0.16**	**$5.7e^{-06}$**	**0.59**	**0.014**
JJA	**0.17**	**$5.5e^{-12}$**	**0.49**	**0.0027**
SON	**0.13**	**$1.2e^{-06}$**	**0.63**	**0.0013**

The addition of only six years of data since the 2017 report has changed the temperature trends substantially. Every p-value decreased and every trend increased. The decrease in p-values is notable for the 30-year trends, which were predominantly larger than 0.05 in the 2017 report (1986–2015) and are predominantly less than 0.05 here (1992–2021). The acceleration in warming is higher as well, a result of the 30-year trends in this analysis being nearly twice as large as the 30-year trends in the 2017 report.

The Delaware Estuary and Basin is part of the Northeastern United States coastal region, which has warmed more rapidly than regions just inland as well as the North American average and the Northern Hemisphere average, according to a study by Karmalkar and Horton (2021). This study also provided evidence indicating that the high rate of warming is associated with the warming of Northeastern United States coastal waters, which, in turn, appears to be related to the slowdown of the North Atlantic Ocean's overturning circulation and the northward movement of the Gulf Stream.

Future Predictions

Future temperature changes in the Delaware Estuary and Basin are strongly dependent on the amount of future GHG emissions (Hayhoe et al. 2018). If GHG emissions continue to increase throughout the 21 st century (represented by the IPCC's RCP8.5 emissions scenario), global climate models (GCMs) project that some parts of the DEB will be 7 °C (12.6 °F) warmer at the end of the 21st century compared to 1986-2015. On the other hand, if emissions peak by mid-century and then decline (the RCP4.5 scenario), the DEB is projected to be 4 °C (7.2 °F) warmer. The IPCC issued its latest and sixth assessment report (AR6) beginning in late 2021 with GHG scenarios now broken into Shared Socio-economic Pathways, cross-referenced by the approximate level of radiative forcing, and the use of updated GCMs (IPCC 2021). To our knowledge, the AR6 GCMs have not yet been applied to studies of the Delaware Estuary and Basin region, but an analysis comparing projections of the AR6 GCMs to those of the previous generation of GCMs for North America reveals a smaller spread among models across the continent and slightly cooler and wetter projections for the Northeast United States (Martel et al., 2022).

Studies concur that air temperatures will increase in all seasons, but there is less agreement in the seasonality of warming. One study using the CMIP5 GCMs and RCP8.5 scenario, the largest increase

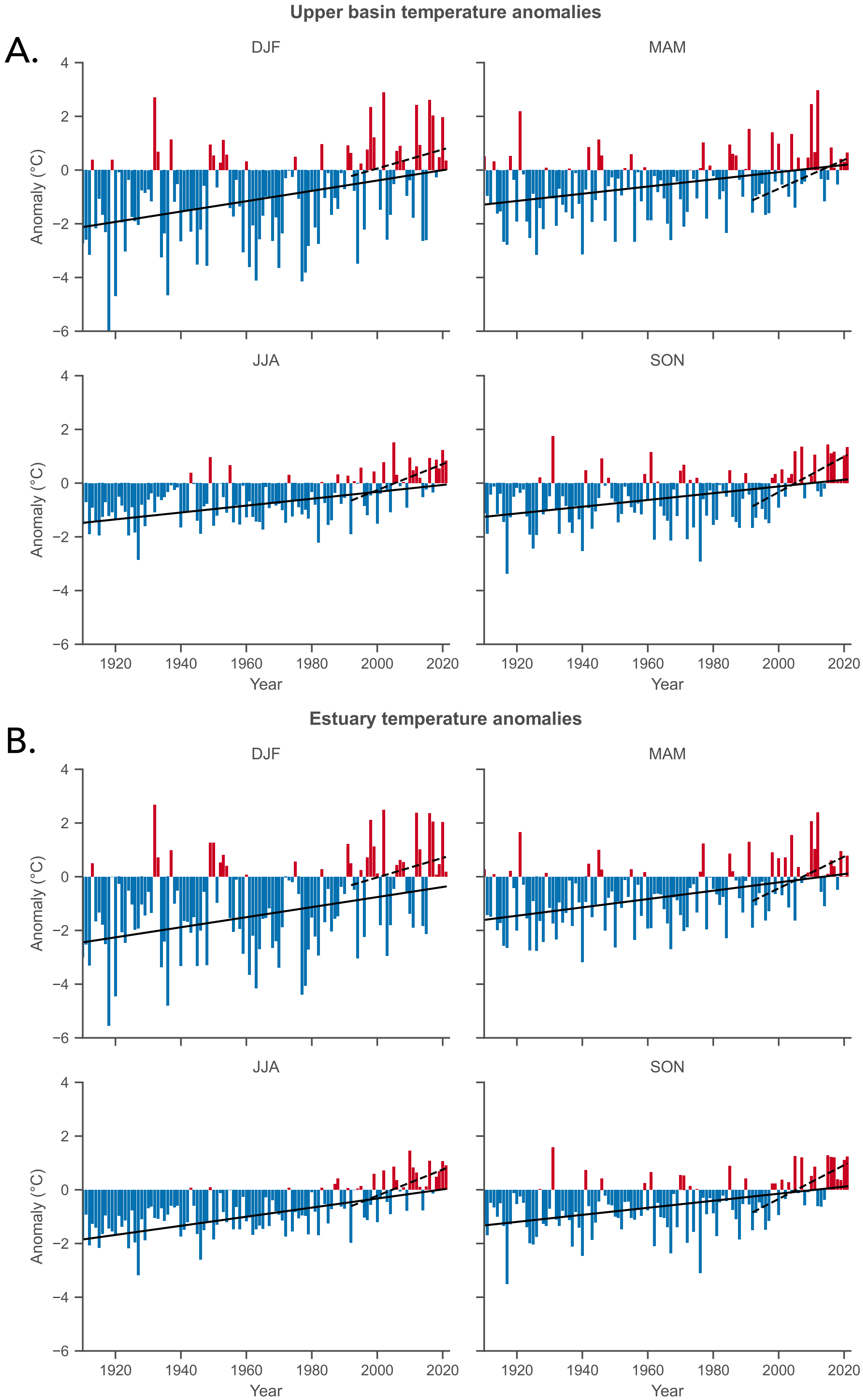


Figure 2.3 Seasonal mean temperature anomalies with respect to the 1991-2020 average in the Upper Basin (a) and Estuary (b). The solid and dashed lines are linear trends for the 1910–2021 and 1992–2021 periods, respectively.

in monthly mean air temperatures for 2041–2100, compared to means from 1971–2000, will occur in winter with a secondary peak in summer, but these changes will be more acute in the northern end of the Delaware Estuary and Basin (Lynch et al. 2016). A second study that employed a suite of regional climate models and the relatively high A2 emissions scenario produced a similar seasonal pattern that, on average, predicted greater winter warming in the northern region of the upper Basin, but higher summer warming in the Estuary region by the mid-21 st century (Rawlins et al. 2012). Finally, a third study that focused on a small watershed dominated by agriculture, located in the lower Estuary subregion of the Delaware Estuary and Basin, also predicted the greatest air temperature change during the winter months under both RCP4.5 and 8.5 climate scenarios for years 2021-2040, but with the least change occurring in the summer (Giri et al. 2020). The difference in future seasonal temperature predictions between these three studies could be due to several factors, such as the use of different GCMs, spatial resolution, climate scenarios, time periods, and land cover. Regardless, any increases in summer heating in the Estuary will have a greater impact on the more urbanized areas of the region, such as Philadelphia, which are already experiencing urban heat island (UHI) effects, especially in redlined communities (See Climate Feature 1).

Actions and Needs

The rapid rate of anthropogenic warming in the Delaware Estuary and Basin means that actions are needed now to adapt to climate change, which will only become more severe as GHG levels continue to increase. The analysis here has been focused on air temperature, but stream water temperatures are also increasing in the watershed by about 0.3 °C per decade (median of eight streams, Kaushal et al. 2010), similar to the air warming rates. It seems very likely that Delaware Bay is warming as well, like its estuarine neighbor just to the south, Chesapeake Bay (Hinson et al. 2022), but the underlying analysis has yet to be conducted.

Summary

The Delaware Estuary and Basin has warmed substantially over the past century, and the rate of warming has increased dramatically. This accelerated warming is probably the clearest and most dramatic indicator that the climate of the Delaware Estuary and Basin is changing rapidly. Identifying this rapid increase in temperatures is important because we are still striving to understand ecological responses to climate change, such as how increasing temperatures have affected vegetation and wildlife geographic range and species composition of communities, which will ultimately impact future ecosystem functions and longevity (Blois et al. 2013).

2.2 Precipitation

Description of Indicator

Precipitation, either as rain or snowfall, is important for maintaining terrestrial and aquatic habitats (see Chapter 6), as well as replenishing groundwater and drinking water reserves (see Chapter 3). However, too much precipitation causes flooding, which can be devastating to crops, infrastructure, and housing due to flooding.

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

Past Trends

Annual precipitation has increased by 1.2 cm per decade with 95% confidence in the upper Basin, but not in the Estuary (Fig 2.4, Table 2.3). The estimated trend in annual precipitation over the most recent 30 years in the upper Basin is about three times larger than over the last 112 years, but is not statistically significant. In contrast to the upper Basin, the estimated recent 30-year trend in annual precipitation of 0.56 cm per decade in the Estuary is roughly 30% less than the trend over the past 112 years. Precipitation totals have increased significantly in the fall in both the upper Basin and Estuary over the last 112 years, but have only increased significantly in the summer in the upper Basin over the last 30 years (Fig 2.5, Table 2.3). The precipitation trends reported here are qualitatively similar to those in the 2017 report. The trends appear to be driven, in part, by increases in atmospheric blocking over Greenland and the negative phase of the North Atlantic Oscillation, which lead to enhanced moisture transport from the south (Simonson et al. 2022).

Table 2.3 Precipitation trends in the Delaware Estuary and Basin. Significant trends are bold (95% confidence).

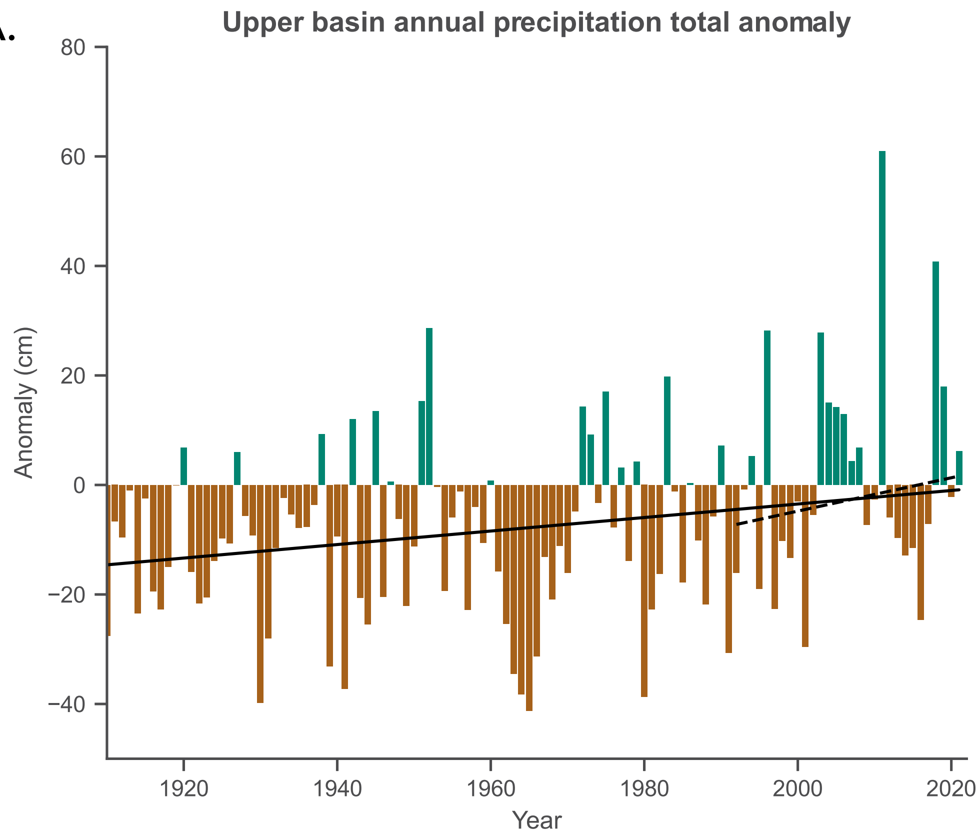
Seasonal Subset	Precipitation Trend (cm/decade) 1910-2021	p-value	1992-2021	p-value
		Upper Basin		
Annual	**1.2**	**0.013**	3.0	0.48
DJF	0.29	0.1	0.76	0.45
MAM	0.14	0.39	-0.77	0.69
JJA	0.27	0.36	**4.5**	**0.042**
SON	**0.69**	**0.012**	-0.59	0.75
		Estuary		
Annual	0.95	0.058	0.56	0.89
DJF	0.098	0.56	0.58	0.67
MAM	0.27	0.21	-1.3	0.35
JJA	0.12	0.71	3.8	0.087
SON	**0.69**	**0.0051**	-1.3	0.52

Warming has dramatically impacted snowfall and snow cover. The ratio of snow to total precipitation decreased throughout the northeast US, including the Delaware Estuary and Basin, from 1949 to 2005 (Feng and Hu 2007). A more recent study showed that the snow/rain event ratio declined by as much as 4% per decade between 1978 and 2019 (Shi and Liu 2021). Finally, days per year with snow cover declined by several days per decade from 1960 to 2019 (Ford et al. 2021).

Future Predictions

There is a strong model consensus towards future increased winter precipitation in the northern half of North America, including all of the Delaware Estuary and Basin (Hayhoe et al. 2018; Lynch et al. 2016; Rawlins et al. 2012; Thibeault et al. 2014). A performance-weighted average of regional climate model simulations under the A2 emissions scenario yields a 10-14% increase in winter precipitation throughout the Delaware Estuary and Basin by 2041–2070 (Rawlins et al. 2012). Under the RCP8.5 scenario, precipitation is projected to increase by 15-20% in winter and 10-15% in spring for most of the northeastern US, including the Delaware Estuary and Basin, by the late 21st century compared to 1986-2015 (Hayhoe et al. 2018). However, winter precipitation as snowfall is projected to decrease by 42-84% by 2099 across the

A.



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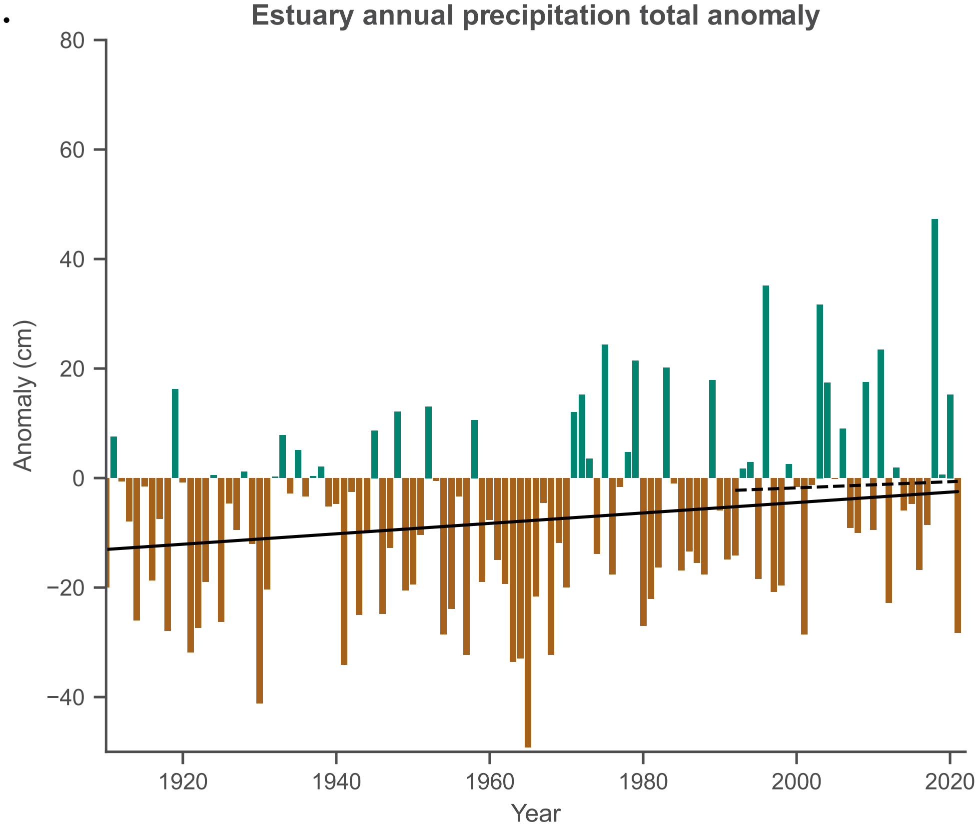

Figure 2.4 Annual mean precipitation anomalies with respect to the 1991-2021 average in the Upper Basin (a) and Estuary (b). The solid and dashed lines are linear trends for the 1910–2021 and 1992–2021 periods, respectively.

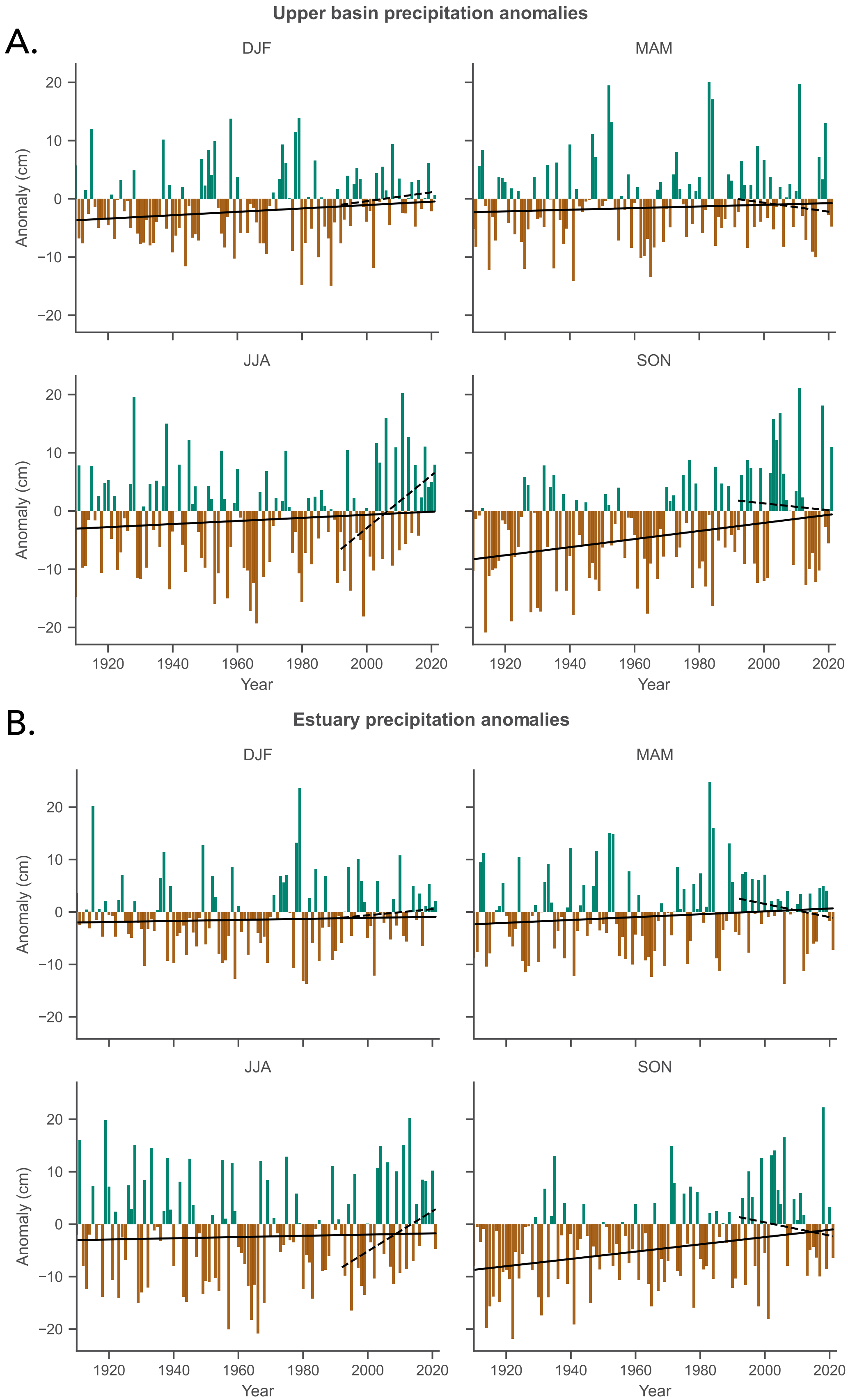

Figure 2.5 Seasonal mean precipitation anomalies with respect to the 1992-2021 average in the Upper Basin (a) and Estuary (b).

Delaware Estuary and Basin due to increasing temperatures causing a shift in the snow-rain transition zone (Ning and Bradley 2015; Hawkins and Woltemade 2021). Most studies also show that increased spring precipitation is likely in the Delaware Estuary and Basin, while there is less agreement in changes in summer and fall precipitation (Hayhoe et al. 2018; Hawkins and Woltemade 2021; Lynch et al. 2016; Rawlins et al. 2012).

Actions and Needs

The understanding of long-term changes in precipitation is not as clear as it is for temperature, where the effect of greenhouse gas emissions has been shown to be substantial. Although the increased annual precipitation observed in the Delaware Estuary and Basin and broader Northeast U.S. is consistent with the modeled effect of climate change on precipitation, the observed increase is greater than predicted by climate models (Knutson and Zeng 2018). Furthermore, climate models project that the largest increases in precipitation will occur in winter and spring, whereas the observed trends during the last century are largest in autumn. Understanding the causes of these differences is important for improving projections of future precipitation change in the Delaware Estuary and Basin.

The past decreases in snowfall and snow cover reported in the literature and continued declines that are projected indicate that dramatic changes in winter hydrology are underway. These changes not only represent a shift in the character of winter in the Delaware Estuary and Basin but should also be of concern to water resource managers and local economies that rely on winter recreation.

Summary

There is some evidence that annual and fall precipitation have increased in the Delaware Estuary and Basin (Table 2.3). Precipitation is projected to increase in the future, mainly during winter and spring. Several snow indicators have shown declines, which will likely continue into the future. Additional research is needed to reconcile the observed increase in autumn precipitation with climate model projections for increases in winter and spring.

2.3 Extremes: Air Temperature & Precipitation

Description of Indicator

Extreme air temperature and precipitation have direct impacts on human health and wellbeing, terrestrial and aquatic ecosystems, and infrastructure (see Chapters 1 and 3).

Trends in five extreme event indices were calculated: (1) Frost days, the number of days per year with low temperatures below 32 °F (0 °C); (2) Hot days, the number of days per year with high temperatures above 90 °F (32.2 °C); (3) consecutive dry days (CDD), the maximum number of successive days without precipitation per year; (4) R45, the number of days per year with heavy (> 4.5 cm or 1.78 in) precipitation; and (5) RX5day, the annual maximum five-day precipitation total (Figs 2.6 and 2.7, Table 2.4).

Daily data from the Berkeley Earth Surface Temperature (BEST; berkeleyearth.org) dataset were used to calculate the frost days and hot days indicators. Like the USHCN monthly temperature, and unlike most other daily temperature datasets, the BEST dataset contains daily station data that have been adjusted for relocations, changing observation times, and other inconsistencies. However, unlike other data used in this report, the BEST daily temperature data have been averaged onto a 1° x 1° latitude-longitude grid. The frost days and hot days indicators were calculated for each grid cell between latitude 39° to 42° N and longitude 76° to 74° W, which covers most of the Delaware Estuary and Basin, and then averaged over the grid cells. Both indicators used data from 1910 to 2021, consistent with the monthly temperature indicators.

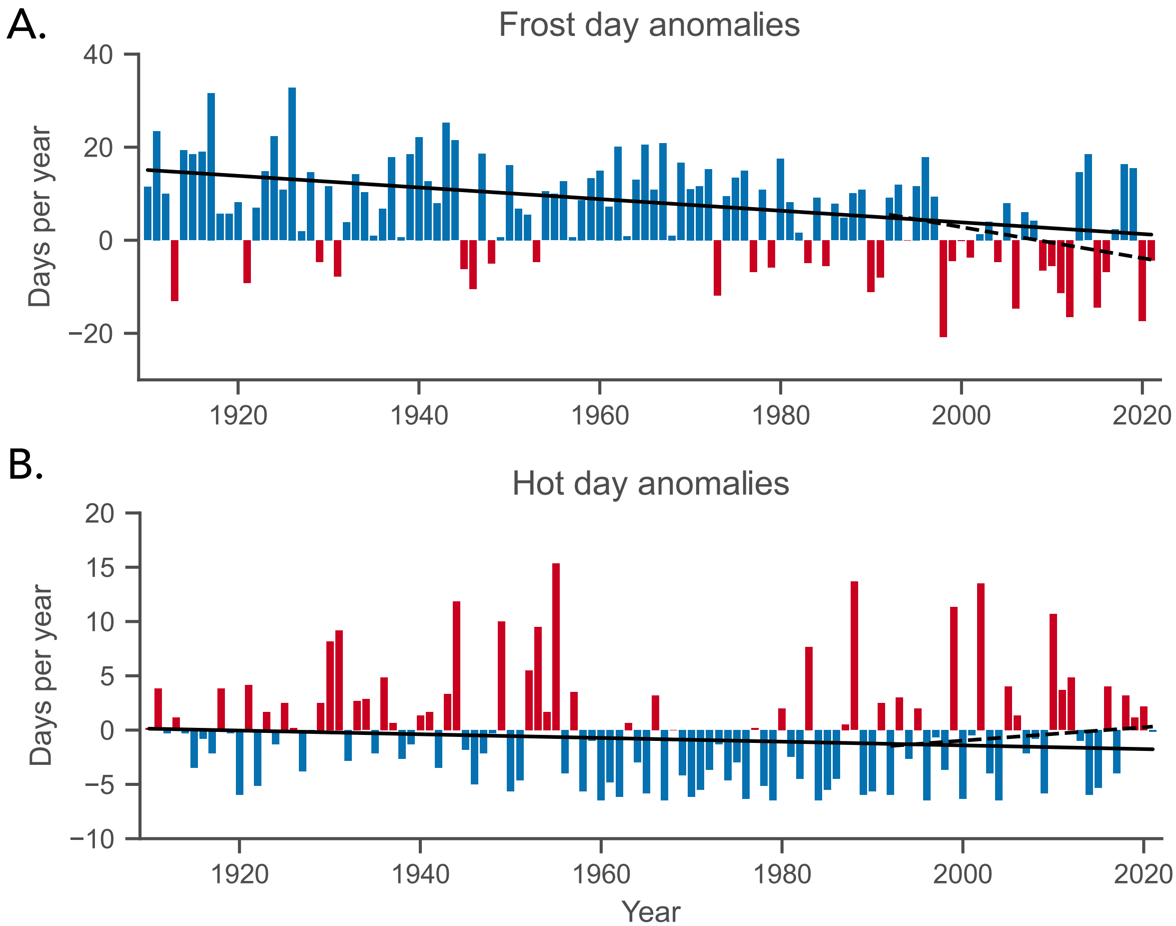

Figure 2.6 Temperature extremes: frost day (a) and hot day (b) anomalies.

Table 2.4 Trends in extremes in the Delaware Estuary and Basin. P-values are in parentheses, and significant trends are bold (95% confidence).

Metric	1991-2020 Average	Trend (per decade)	
		1910-2021	1992-2021
Entire Watershed			
# of days below 32 °F	119	**-1.2 (0.00029)**	-3.3 (0.25)
# of days above 90 °F	6.49	-0.17 (0.19)	0.61 (0.45)
Upper Basin			
Annual max # consecutive dry days	15	-0.095 (0.26)	-0.3 (0.57)
# days/year with precip. >4.5 cm	3	**0.16 (0.00011)**	0.25 (0.41)
Annual max 5-day precip. total	11	0.057 (0.42)	-0.19 (0.8)
Estuary			
Annual max # consecutive dry days	18	0.13 (0.19)	-0.86 (0.53)
# days/year with precip. >4.5 cm	3.8	**0.20 (1.3e-06)**	0.36 (0.38)
Annual max 5-day precip. total	12	0.15 (0.055)	0.22 (0.71)

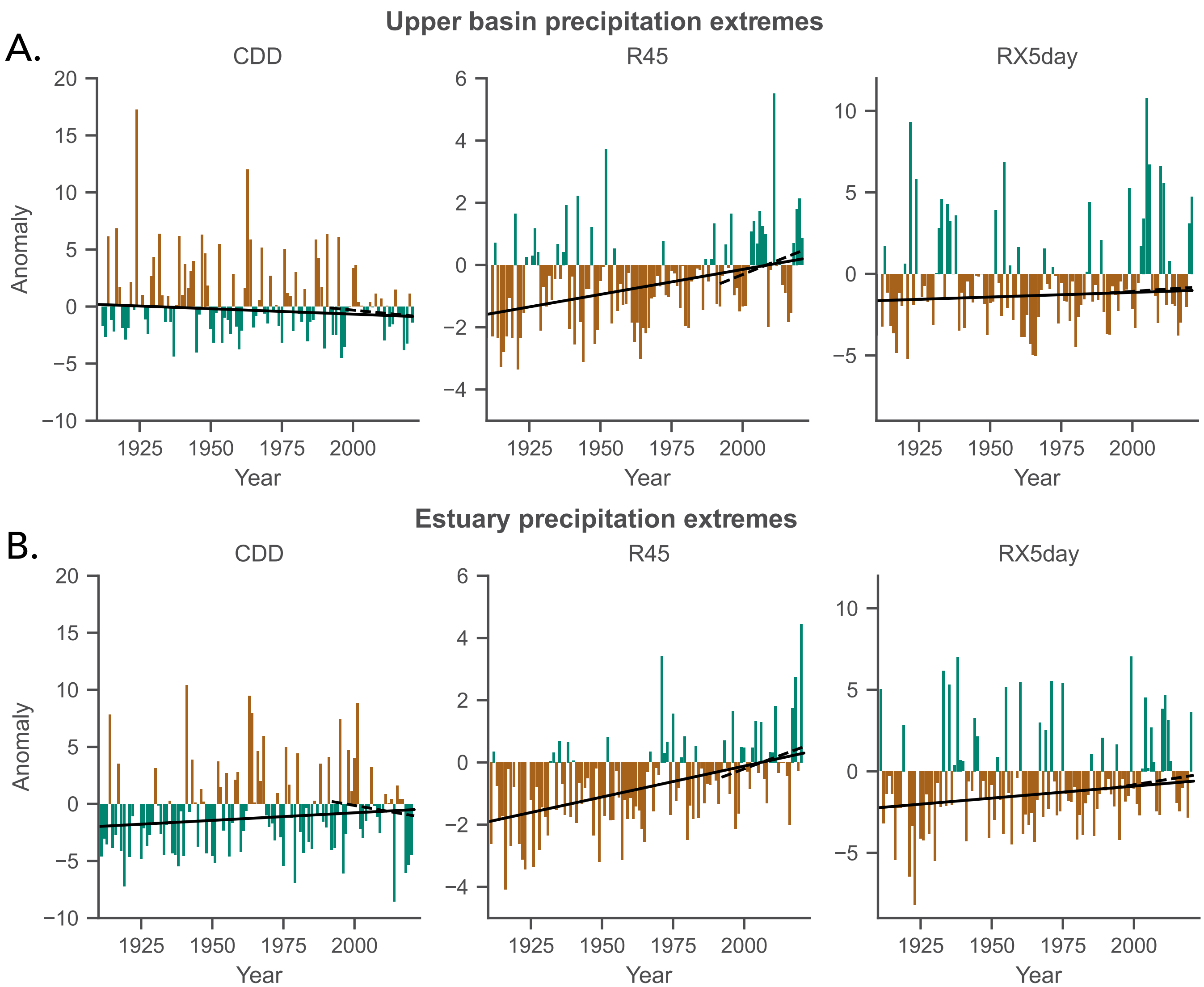

Figure 2.7 Precipitation extremes for the Upper Basin (a) and Estuary (b). Anomalies are with respect to the 1992-2021 average. CDD = annual maximum consecutive dry days, R45 = number of days per year with precipitation >4.5 cm, and RX45day = annual maximum 5-day precipitation total.

The Global Historical Climatology Network (GHCN) daily dataset collected at the USHCN stations (Table 2.1) was used for the precipitation analysis. Unlike the monthly data used for air temperature and precipitation analyses (see Sections 2.1 and 2.2), 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. Precipitation data that were given any quality control failure flags in the dataset were removed. 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. Precipitation extreme indices were averaged over the upper Basin and the Estuary.

Past Trends

Table 2.4 presents the trends for the two extreme temperature indices, which are generally consistent with a warming climate. For the entire Delaware Estuary and Basin watershed there is a significant decrease in the number of frost days over the last 112 years by 1.2 days per decade, but the rate of decline in the number of frost days during the more recent 30-year period is almost three times higher (Fig 2.6A). Consistent with these results is the trend towards fewer freezing days found throughout the Northeast U.S. (Brown et al. 2010; Thibault and Seth 2014) and a declining trend in cold winters (Ford et al. 2021). Thibeault and Seth (2014) further showed that the decline in frost days throughout the Northeast US is less than predicted by GCMs from 1951 to 2010. Trends in the number of days above 90 °F in the Delaware Estuary and Basin are negative over the past 112 years, but are positive over the recent 30-year period; however, both trends are not significant at the 95% confidence level. These equivocal results are consistent with those of Thibault and Seth (2014), who examined several high temperature indices (though none exactly like ours) and found both increasing and decreasing trends from 1951 to 2010.

The two heavy precipitation indices, R45 and RX5day, are increasing except for the maximum 5-day precipitation in the upper Basin over the last 30 years (Table 2.4). However, the only significant trend is in R45, which shows an upward trend over the past 112 years of 0.16 and 0.20 days per decade for the upper Basin and Estuary, respectively (Fig 2.7). This may appear to be a small change but is, in fact, substantial, because there are so few days of heavy precipitation. The average number of R45 days per year for the 1991–2020 reference period is about 3 to 4, which is an increase of about 50% compared to the average over the past 112 years (Table 2.4). Consistent with our results are the findings of increases in extreme precipitation in the Delaware Estuary and Basin by Howarth et al. (2019) and in the Northeast US by Thibault and Seth (2014), who also showed that the observed trends are of the same sign but about half the magnitude of those simulated by GCMs from 1951 to 2010.

Tropical systems appear to be responsible for the increases in extreme precipitation in the Delaware Estuary and Basin (Howarth et al. 2019), as they are for total precipitation (Simonson et al. 2022). Indeed, globally, as well as in the North Atlantic Ocean, the fraction of tropical cyclones that are major (sustained winds greater than 50 meters per second), have increased significantly since 1980 (Kossin et al. 2020). The same is true for the number of landfalling major tropical cyclones, though the trend is more significant at the global scale than for the North Atlantic (Wang and Toumi 2022).

There are no significant trends in the maximum number of consecutive dry days per year in the Delaware Estuary and Basin (Table 2.4), a result that is consistent with observations and GCM simulations of the Northeast US during 1951–2010m (Thibeault and Seth 2014).

In general, the trends in extremes reported here are similar to those in the 2017 report.

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; Hayhoe et al. 2018; Wuebbles et al. 2014; Janssen et al. 2014; Thibault and Seth 2014), with larger changes in scenarios of higher GHG emissions. The frequency and intensity of heavy precipitation events are projected to increase over 40% compared to events observed between 1986–2015 based on the high RCP8.5 scenario (Hayhoe et al. 2018). In addition, the frequency, intensity, and size of North Atlantic tropical cyclones that could impact the Delaware Estuary and Basin with heavy precipitation are predicted to increase by the year 2095 compared to tropical cyclones observed between the years 1980-2005 (Marsooli et al. 2019). Other sources of tropical moisture, including atmospheric rivers, are also projected to increase (Hsu and Chen 2020). By the middle of the 21st century, climate models also project a large increase in the number of days per year above 90 °F in the Northeast US, and a decrease in the number of days below freezing in the Delaware Estuary and Basin, even under moderately low emissions scenarios (Horton et al. 2014; Williamson et al. 2016; Vose et al. 2017).

Actions and Needs

The stronger warming signal in the minimum temperature metric (frost days) compared to the maximum temperature metric (hot days) is broadly consistent with other studies (DeGaetano and Allen 2002; Brown et al. 2010). However, other studies have also found that trends in extreme temperature metrics are highly sensitive to the choices of time period and data homogenization method, and more detailed analysis is needed to examine the historical drivers of extreme temperatures and whether the trends are consistent with climate model projections. In addition, due to the size and variable topography and land use of the Delaware Estuary and Basin, changes in temperature and precipitation extremes may have high spatial variability. Future climate trend analyses of temperature and precipitation extremes are needed at higher spatial resolution to identify immediate needs of communities at high risk of climate change impacts, such as the Eastwick community in southwestern Philadelphia, PA (see Climate Features 1 and 2). Despite any uncertainties, the threat of increasing extreme temperature and precipitation is great enough to warrant actions to limit negative impacts through actions including green infrastructure development in urban areas, which will decrease heat stress and flooding.

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 Delaware Estuary and Basin over the past century (see Section 2.1), 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, such as tropical cyclones in the North Atlantic, but there is still a lot of uncertainty in predicting changes at small scales, such as those of the Delaware Estuary and Basin.

2.4 Streamflow

Description of Indicator

Streamflow, the volume of water flowing in a stream, river, or channel, is influenced by climate change through changes in precipitation, the timing and volume of snowmelt, and evapotranspiration.

Daily streamflow data measured in the Delaware River at Trenton, New Jersey, from 1913 to 2020 were obtained from the United States Geological Survey. Since the flow at Trenton is significantly influenced by upstream reservoir releases to meet an established flow objective set by the Flexible Flow Management Program, data from ten smaller, unregulated (natural flow) tributaries were also included (Delaware River Basin Commission 2021; United States Geological Survey 2017; Table 2.5). The tributaries were selected from those that are noted in the Hydro-Climatic Data Network dataset (Slack et al. 1993) as measuring natural, unregulated streamflow and having a complete record of quality data. We further limited the selection to stations having complete daily data during 1981 to 2020. The gauges are concentrated in the upper Basin; only two are south of Trenton (see Fig 2.1). Data from the tributaries were analyzed for trends for the years 1958 to 2020 when data were available at every gauge. Like other daily data, flow data from 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 based on the years 1991-2020 for each gauge. The standardized anomaly Q’ was calculated as:

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

where Q is the time series of annual or seasonal mean streamflow, $\bar{Q}$ is the 1991–2020 mean of the time series, and Q_σ is the 1991–2019 standard deviation of the time series.

Table 2.5 Unregulated tributaries included in streamflow analyses.

Station 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

Past Trends

Streamflow at Trenton, NJ, has varied substantially over the past 109 years, with some years departing from the 1991-2020 mean of 365 m^3 per second, shown as anomalies, by more than 50% (Figs 2.8 and 2.9, Table 2.6). It is notable that the four largest positive anomalies in annual streamflow have occurred since 1998. Aside from a large increase in winter streamflow over the full time period (1913-2020), no trend in streamflow was statistically significant at the 95% confidence level. Despite lack of significance, the trends over the last century are generally consistent with trends over the last 30 years, with positive trends observed in winter and summer and negative trends in spring.

Since the streamflow at Trenton is highly regulated, trends at the natural flow tributary sites give insight to climate change effects on streamflow across the Delaware Estuary and Basin. Overall, the seasonal trends observed at Trenton are similar to the trends at the smaller tributaries (Fig 2.10). Most unregulated sites show increasing trends in streamflow in the winter, summer and fall, but negative in the spring. Although only a few trends are statistically significant, positive trends are present at every one of the 10 unregulated gauges except one in winter, two in summer, and one in autumn. Trends at all 10 gauges are negative in spring, although the spring trends tend to be closer to zero, meaning little change over time, than the trends in the other seasons.

The streamflow trends at Trenton and the unregulated site are qualitatively consistent with those in the 2017 report.

Low flows in streams can have negative ecological impacts and hence trends in associated indices, such as the 7-day period in a year with the lowest mean flow (annual 7-day low flow), are important for monitoring and management. According to Hammond and Fleming (2021), throughout most of the Delaware Estuary and Basin, annual 7-day low flows have increased as a result of increasing precipitation. The study showed, however, annual 7-day low flows decreased in the Coastal Plain province, where water use and impervious surface area have increased.

A notable feature of streamflow in the Delaware Estuary and Basin is the prominent drought of the 1960s (Fig 2.8), which can also be seen in precipitation (Fig 2.7). Indeed, a water budget analysis revealed that low precipitation, not high temperature, was the dominant driver of the very low streamflow of the 1960s (McCabe and Wolock 2020). The drought was dramatic in its impact, leading to saltwater intrusion that threatened drinking water supplies (Hull and Titus 1986). Nevertheless, a 1,500-year record of drought from tree rings revealed that the 1960s were not historically unusual (McCabe and Wolock 2020). Remarkably, the cause of the 1960s drought is still poorly understood. Using GCMs, Seager et al. (2012) argued that the drought was the result of natural variability of the atmosphere. Schulte et al. (2016), on the other hand, conducted a wavelet analysis that showed that the Southern Oscillation, a natural feature of the coupled ocean–atmosphere system, could account for 40% of the streamflow anomaly associated with the drought.

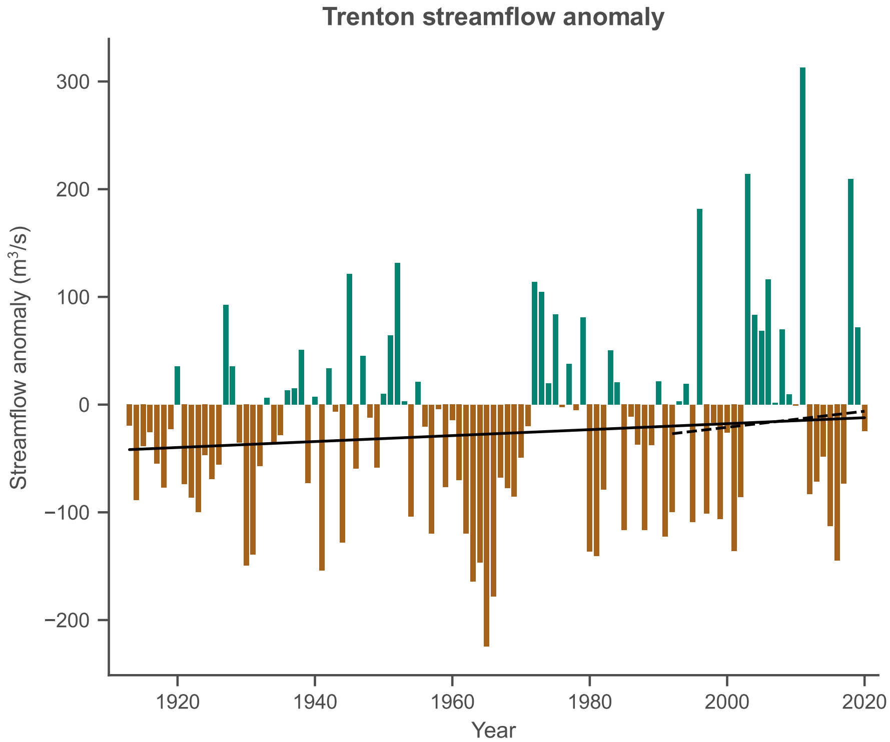

Figure 2.8 Time series of annual average streamflow anomalies (with respect to the 1991-2020 average of 365 m³ per second) at Trenton, NJ. The solid and dashed lines are linear trends for the 1913-2020 and 1991-2020 periods, respectively.

Future Predictions

Hydrological model simulations forced by GCMs project decreasing runoff from April through November in some areas of the Delaware Estuary and Basin (Williamson et al. 2016). Annual mean runoff, however, is predicted to increase, primarily as a result of increased winter precipitation (Williamson et al. 2016, Hawkins and Woltemade 2021). The positive trend observed in winter streamflow, which is consistent with the previous 2017 report but also now statistically significant, is in line with climate projections for increased winter precipitation and decreased snow storage (see Section 2.2). 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). The application of GCM projections to hydrologic and hydraulic models in Pennsylvania revealed that flood hazards and exposure are projected to increase, especially in the central Delaware River Basin (Sharma et al. 2021).

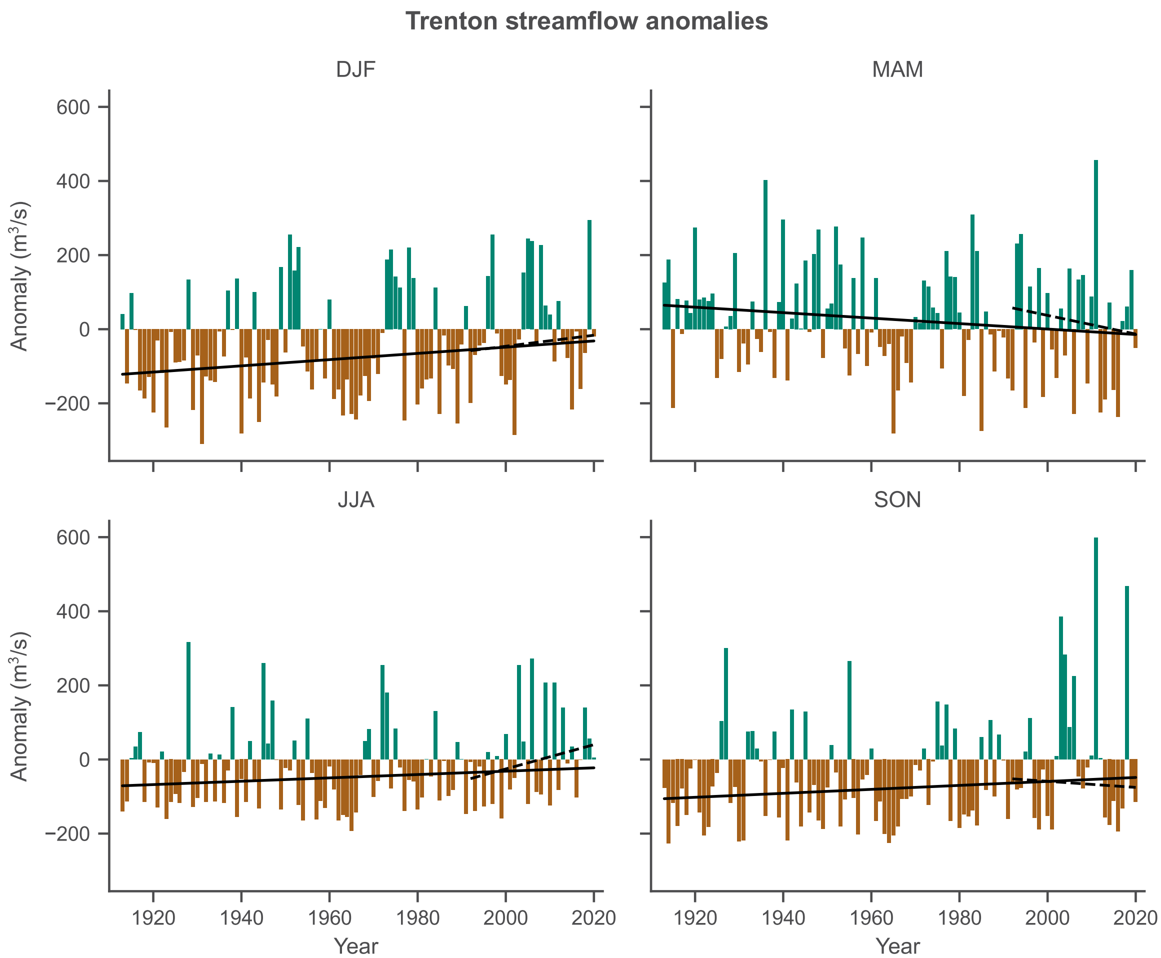

Figure 2.9 Time series of seasonal mean streamflow anomalies (with respect to the 1991-2020 average) at Trenton, NJ. The solid and dashed lines are linear trends for the 1913-2020 and 1991-2020 periods, respectively.

Table 2.6 Streamflow trends. Significant trends are bold (95% confidence).

Seasonal Subset	Streamflow (m^3 per second per decade)			
	1910-2020	p-value	1991-2020	p-value
Annual	2.8	0.29	7.5	0.81
DJF	**8.4**	**0.028**	15	0.69
MAM	-7.4	0.12	-25	0.44
JJA	4.5	0.1	33	0.061
SON	5.4	0.15	-8.2	0.72

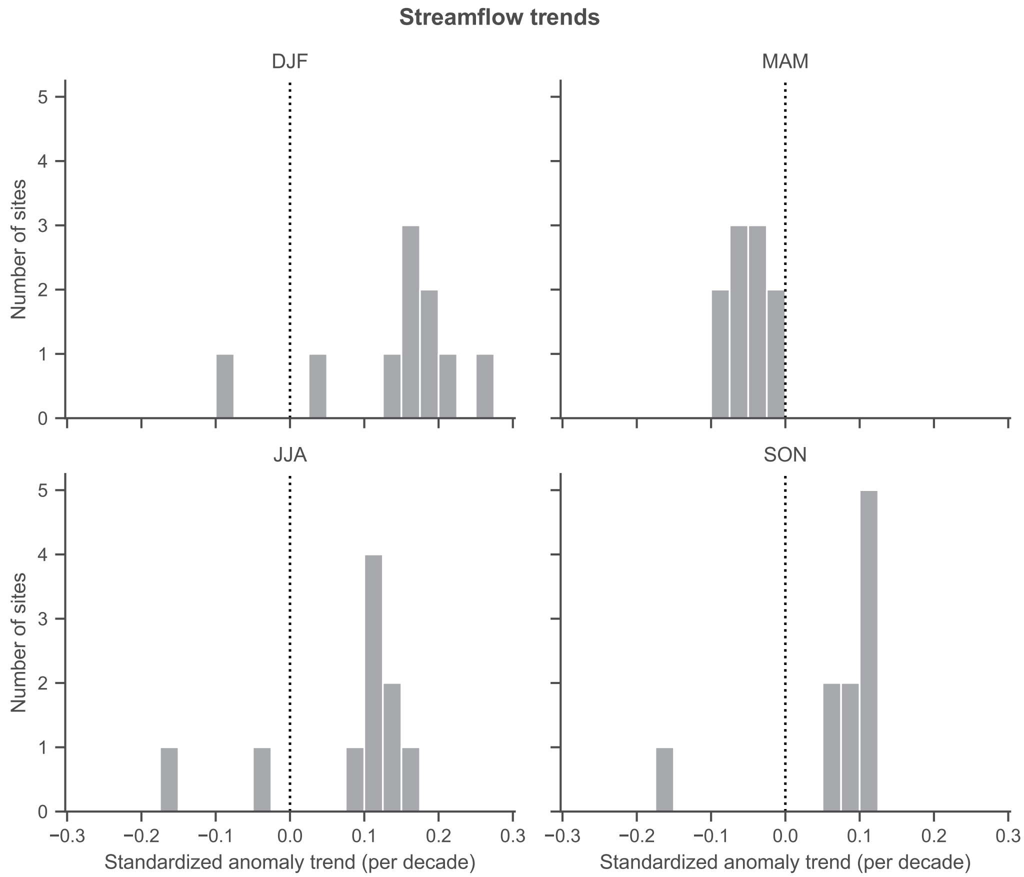

Figure 2.10 Histograms of trends in standardized seasonal streamflow anomaly at the 10 tributary sites during 1958-2020.

Actions and Needs

Continued monitoring of stream and river flows is critically important to track changes in the water budget of the Delaware Estuary and Basin, especially within the Estuary where there are only a few monitoring stations, which affects estuarine salinity and freshwater availability for people and the environment (see Chapter 3). Future changes in flow, particularly in winter and summer, are likely to be driven by a combination of the amount and type of precipitation (see Sections 2.2 and 2.3) and evapotranspiration changes, which may not be simulated well by global climate models, so understanding and accounting for uncertainty in future flow is necessary.

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 in the form of rainfall, and reduced streamflow in the summer is possible.

2.5 Ice Jams

Description of Indicator

Ice jams occur primarily when chunks of ice flowing down river clump together, eventually blocking the flow of the river and causing sudden flooding of river banks and the surrounding areas. They are considered a secondary indicator of climate change as ice jams are influenced by air temperature and precipitation.

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. Analyzed here are annual counts (by water year) of ice jams occurring anywhere on the Delaware River from Trenton upstream, including the West and East Branches.

Past Trends

The number of ice jams that have been reported over the past century in the Delaware River has been declining (Fig 2.11). 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 (see Section 2.1, Table 2.2), which is expected to lead to fewer ice jams. Indeed, as Fig 2.12 shows, there is a moderate negative correlation between the number of ice jams and the upper Basin winter mean temperature. Using the same non-parametric Mann-Kendall method that was used to determine the trend in other indicators, the correlation between upper watershed winter mean temperature and the number of reported ice jams is -0.33 ($p < 1x10^{-4}$).

Future Predictions

It is reasonable to expect fewer ice jams in the future due to predicted higher winter temperatures (see Section 2.1) and decreases in the number of frost days (see Section 2.3).

Actions and Needs

Declining ice jams may be one of the clearer impacts of a warming winter climate, but reporting issues make ice jams a problematic indicator. Other indicators of changing winter climate should be considered in future TREBs, including the snow/rain event ratio (Shi and Liu 2021) and days per year with snow cover (Ford et al. 2021).

Summary

The frequency of ice jams along the Delaware River has decreased, 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 less frequent. Inconsistent ice jam reporting suggests that other indicators of winter climate, such as snowfall and snow cover, may be more robust.

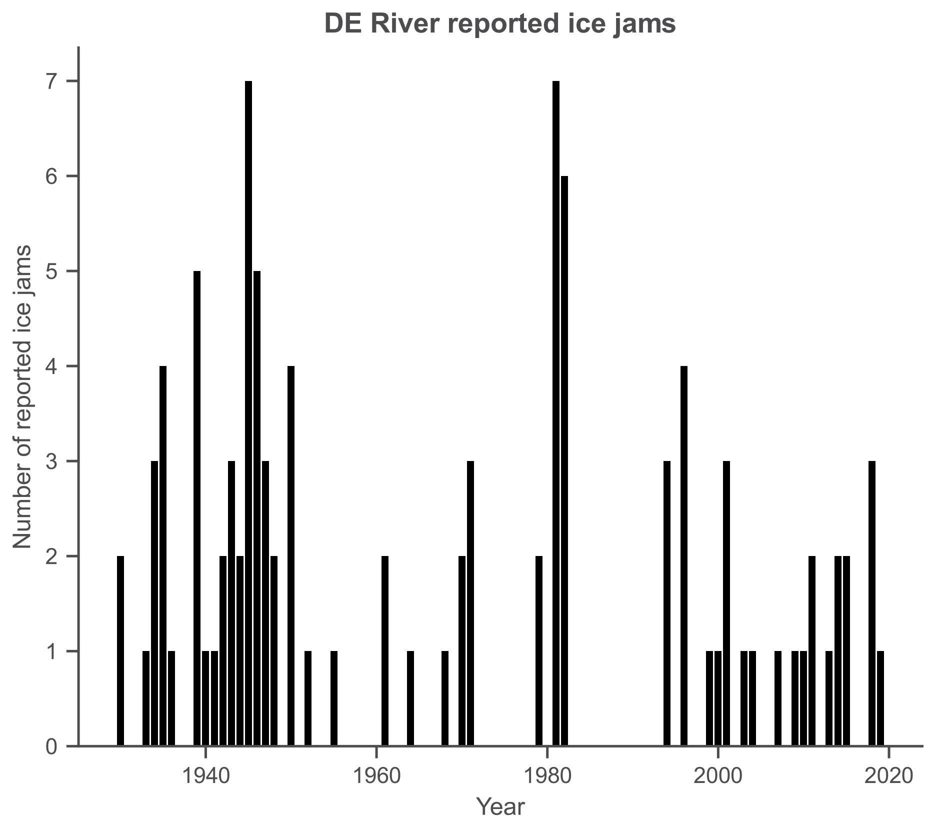

Figure 2.11 Reported ice jams on the Delaware River.

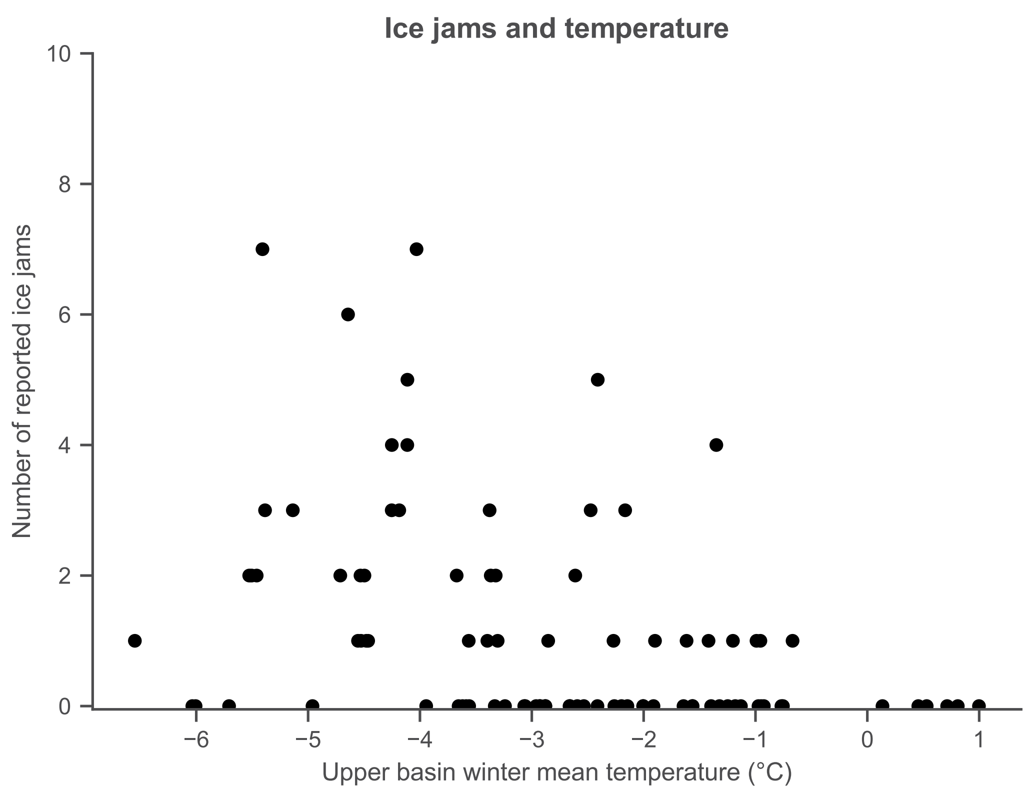

Figure 2.12 Comparison of the number of ice jams and winter temperatures.

2.6 Sea Level

Description of Indicator

Sea level is an indicator of climate change as it is impacted by increasing global air temperatures in a variety of ways, such as the addition of water to the oceans by ice-mass loss and by thermal expansion. Relative sea level is also affected by other factors, such as isostatic rebound and subsidence due to groundwater and oil withdrawals. Rising sea levels are a major threat to global coastal communities and estuarine habitats because of increased high tide flooding, infiltration of saline water into groundwater systems, and upstream progression of the salt front which can impact drinking water intakes (see Chapter 3). The long-term rate of global sea level rise from 1900 to 2018 is about 1.6 cm per decade, but more recent rates (1993–2018) indicate global mean sea level is increasing at 3.4 cm per decade (Frederikse et al. 2020).

Mean sea levels within the Estuary were obtained from the Permanent Service for Mean Sea Level database for three locations: (1) Philadelphia, Pennsylvania (Station ID: 135), (2) Cape May, New Jersey (Station ID: 1153), and (3) Lewes, Delaware (Station ID: 224) (Fig 2.1). Sea level data are annual means calculated from monthly means with gaps of up to 3 months filled using linear interpolation. Recent publications were also reviewed to identify historical trends in tidal range, connections to mean sea level, and projected changes.

Past Trends

Within the Delaware Estuary, both the long-term and recent sea level trends are positive and significant at the 95% confidence level (Table 2.7). Over the past 120 years, sea level at Philadelphia has been rising at a rate of 3.07 cm per decade (Fig 2.13). From 1992 to 2021, sea level at Philadelphia has increased at a rate of 4.7 cm per decade, indicating that the rate of sea-level rise is increasing in the Delaware Estuary, as it is globally. At the mouth of Delaware Bay, sea level has risen at an average rate of 5.7 cm per decade over the past 30 years, for a total of about 17 cm (7 inches). These high rates of sea-level rise are exacerbated by geologic contributions of around 2 cm per decade (Kopp 2013). Sea-level rise has contributed to increasing salinity throughout much of the estuary (Ross et al. 2015).

Table 2.7 Sea level trends in the Delaware Estuary. P-values are in parentheses and significant trends are bold (95% confidence).

Station	Sea level trends (cm per decade)	
	1901-2021	1992-2021
Philadelphia, PA	**3.07 (< $1e^{-4}$)**	**4.7 (0.00025)**
Cape May, NJ	-	**5.8 ($3.9e^{-08}$)**
Lewes, DE	-	**5.6 ($1.1e^{-07}$)**

Tidal amplitudes and overall tidal ranges in the Estuary have also varied historically, in part due to sea-level rise (Ross et al. 2017). Anomalies in the highest astronomical tide at tide gauges throughout the Estuary have been positively correlated with anomalies in mean sea level (Devlin et al. 2019). Channel deepening has also influenced tidal range, causing it to more than double over the first half of the 20th century in the upper estuary, between Philadelphia and Trenton (DiLorenzo et al. 1993; Pareja-Roman et al. 2020).

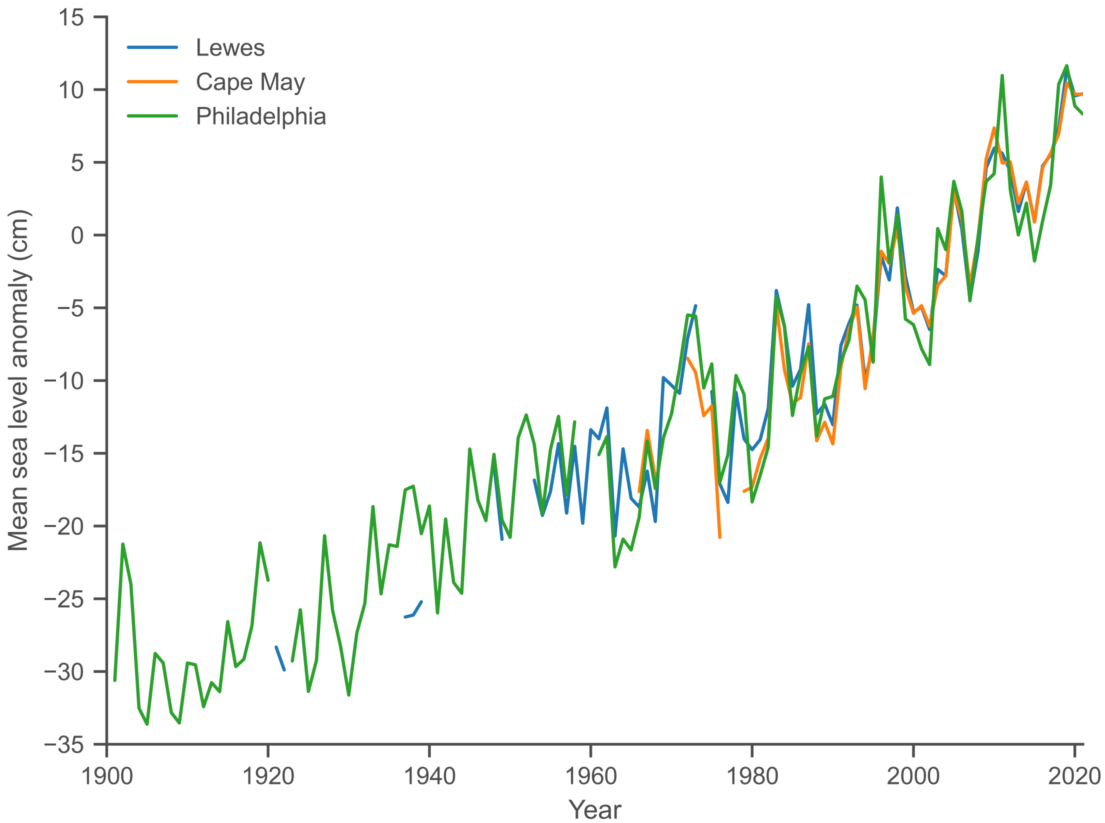

Figure 2.13 Annual mean sea level anomalies with respect to the 1991-2020 means.

Increases in tidal range have increased the frequency of "nuisance flooding" during high tides at Philadelphia (Li et al. 2021). The water level height when nuisance flooding occurs is based on the mean high high water level at each station, which is about 1.9 ft (0.58 meters) above sea level for the locations discussed here (Sweet et al. 2022). At Philadelphia, nuisance flooding events have been increasing over the past 20 years with a peak of 15 instances in 2011 alone (National Ocean Service). The monitoring stations at Lewes, Delaware, and Cape May, New Jersey, have also experienced increases in high tide flooding events since the 1980s (National Ocean Service).

Future Predictions

Mean sea level along the contiguous United States is predicted to increase by 30 cm by the year 2050 (Sweet et al. 2022). Based on the RCP8.5 low and high probability scenarios, sea level in Delaware Bay is projected to increase between 52 cm and 153 cm by the year 2100 when compared to mean sea level observed in the year 2000 (Callahan et al. 2017). In the near term, rising mean sea level and an increase in tidal range associated with a regular 18.6-year tidal cycle are projected to result in a substantial increase in nuisance flooding in the 2030s and moderate flooding in the 2050s (Thompson et al. 2021).

The positive historical correlation between tidal range and mean sea level suggests that future sea level rise is likely to continue to cause increased tidal range beyond the expected cyclical increase in the 2030s. Model simulations agree with this hypothesis; Lee et al. (2017) projected that 1 m of sea-level rise would cause mean tidal range in the upper Estuary to increase by 25 cm, with smaller increases in the Bay. However, Lee et al. (2017) found that the simulations were sensitive to the treatment of shorelines in the model. Sea-level rise increased tidal range when the coast was modeled like a hardened shoreline; if instead low-lying coastal land was inundated as the sea level rose, the model tidal range decreased.

Saltwater intrusion is likely to increase in the Delaware Estuary as a result of sea-level rise (Ross et al. 2015). Such salinity increases are projected to negatively impact industry, including electricity generation (Shirazi et al. 2019), and reduce the large tidal-fresh portion of the estuary, which harbors important and unique species.

Actions and Needs

Coastal communities across the United States are already feeling the impacts of rising sea levels. Adaptations currently used to prevent or reduce flooding due to rising sea levels range from sandbags to living shorelines to higher seawalls, even including elevating structures. However, future predicted sea levels compounded with increasing storm intensities will likely be devastating to coastal communities, regardless of adaptations (see Climate Feature 2). For example, the heights of peak storm tides of cool-season storms, like Nor'easters, are predicted to increase in counties along the Delaware River by the late 21st century because of more intense storms tracking further inland (Pringle et al. 2021). With a projected additional increase in sea level of over 1 meter along the Delaware River, tropical and cool-season storms will become more damaging and far reaching. The Delaware Estuary and Basin is already starting to experience unprecedented storms and their impacts. After landfall in Louisiana as a category 4 storm, Hurricane Ida stalled over the northeastern US in September 2021, causing flash flood events and a storm surge of up to a meter above normal tides (Beven II et al. 2022). Increases in tidal range due to sea-level rise and periods of higher range in the 2030s and 2050s will exacerbate due to flooding storms, particularly in the upper Estuary; detailed projections of these changes and adaptations to cope with regular flooding are urgently needed.

Severe flooding may occur when multiple flood types, such as pluvial flooding (directly due to heavy local precipitation), fluvial flooding (due overflowing river banks), and coastal flooding (due to high tides and storm surge), happen simultaneously. Such compound flooding is likely to increase in the future in many parts of the world, including the Delaware Estuary, as a result of heavy precipitation, higher sea-levels, and stronger storms. Most of the United States is expected to see increases in flooded area from 2020 to 2050 (Bates et al. 2021) that will disproportionately impact Black communities (Wing et al. 2022). Coastal areas, including the Delaware Estuary, are expected to be hardest hit, and the effects by the end of the century under high emissions are projected to be dramatic. Specifically, a severe compound pluvial and storm surge flood, which is when 100-year extreme rainfall occurs simultaneously with 100-year extreme sea level, is projected to change from an occurrence every 270 years to every 7 years on average throughout the Delaware Estuary, a 36-fold increase in likelihood (Gori et al. 2022).

Summary

Changes on decadal to century time scales in sea level and tidal range are indicators of climate change and can have drastic impacts on coastal communities along the Delaware Bay and within the tidal reach of the lower Delaware River. At Philadelphia, the rate of sea level rise has increased and is correlated with increases in tidal range. These and future projected increases will impact other climate change indicators, such as flooding events, particularly within communities already impacted by nuisance flooding (see Climate Feature 2), changes in coastal habitats (see Chapter 6), and movement of the salt front (see Chapter 3). Without an appreciable reduction in GHG emissions, in addition to adaptations to modern increases in sea level, communities and habitats along the Delaware Bay and River will likely experience severe negative impacts.

Take-Home Messages

This chapter describes how the climate of the Delaware Estuary and Basin has changed in the past using historical data collected across the watershed and bay and discusses how climate may change in the future based on model projections from scientific literature. By conducting our own data analysis for past changes and using the peer-reviewed literature for past and future changes, an overall picture of dramatic climate change in the Delaware Estuary and Basin emerges, one that is largely consistent with expectations from increases in greenhouse gases (Table 2.8). The influence of global warming on primary indicators (temperature, precipitation, and sea level) and secondary indicators (ice, snow, and coastal flooding) is clear.

The three primary indicators that most closely track expectations from global warming are mean air temperature, frost days, and sea level, which are not only increasing but also accelerating, trends that are extremely likely to continue. Historic trends in hot days are more equivocal, but future increases are all but certain. Although our analysis of historic extreme precipitation trends depends on the particular metric considered, the totality of evidence, including published studies, indicates that very strong rain events are increasing. Future increases in such extremes are very likely. Winter streamflow is increasing and is predicted to continue to increase, but changes in streamflow throughout the year and by how much will depend on changes in precipitation, air temperature, water use, and impervious land cover.

Coastal flooding and ice and snow indices are considered secondary indicators of climate change because they are directly influenced by primary indicators, such as air temperature and precipitation. Nuisance flooding events along the coast have increased in frequency and are expected to further increase with rising sea levels, and storm surges and heavy precipitation caused by increasingly stronger storms. Ice and snow indicators, such as ice jams and snowfall, have decreased in extent and frequency due to warming and will be further reduced in the future.

Climate across the Delaware Estuary and Basin is rapidly changing. Although climate change will affect every corner of the Delaware Estuary and Basin, vulnerable communities, such as redlined neighborhoods and residents living within high-risk flood zones, will experience the biggest impacts. To decrease the severity of future climate change, emissions of greenhouse gases into the atmosphere must be immediately reduced. Now is also the time to enact adaptation strategies to prepare for the changes to come. Communities, natural habitats, and infrastructure must be made more resilient to these future changes through, for example, the creation of green spaces, increased protections of ecosystems, reduction of impervious surfaces, increased access to public health services, and prioritizing affordable housing in low risk areas.

Table 2.8 Summary of historical and future climate impacts on the Delaware Estuary and Basin.

Climate Change Indicator	Trends: Historical	Trends: Future	Main Messages
Air Temperature	⇧ (High)	⇧ (High)	Warming is occurring in all seasons.
Days over 90 °F	⇧ (Low)	⇧ (High)	
Days under 32 °F	⇩ (High)	⇩ (High)	
Precipitation	⇧ (Medium)	⇧ (Medium)	Precipitation is increasing and becoming more intense.
Extreme Precipitation	⇧ (Medium)	⇧ (High)	
Streamflow	⇧ (Low)	⇧ (Low)	Winter streamflow is increasing.
Sea Level	⇧ (High)	⇧ (High)	Sea level is increasing rapidly.
Coastal Flooding	⇧ (High)	⇧ (High)	Occurrences of flooding are increasing.
Ice and Snow	⇩ (Medium)	⇩ (High)	Ice and snow indices are decreasing due to warming.

Confidence in Trend

- ⇧ Low
- ⇧ Medium
- ⇧ High

References

Bates, P. D., N. Quinn, C. Sampson, A. Smith, O. Wing, J. Sosa, J. Savage, G. Olcese, J. Neal, G. Schumann, L. Giustarini, G. Coxon, J. R. Porter, M. F. Amodeo, Z. Chu, S. Lewis-Gruss, N. B. Freeman, T. Houser, M. Delgado, A. Hamidi, I. Bolliger, K. E. McCusker, K. Emanuel, C. M. Ferreira, A. Khalid, I. D. Haigh, A. Couasnon, R. E. Kopp, S. Hsiang, and W. F. Krajewski. 2021. Combined modeling of US fluvial, pluvial, and coastal flood hazard under current and future climates. Water Resources Research, 57(2), e2020WR028673

Beven II, J. L., A. Hagen, and R. Berg. 2022. Hurricane Ida (AL902021). National Hurricane Center Tropical Cyclone Report. National Oceanic and Atmospheric Administration and National Weather Service

Blois, J. L., P. L. Zarnetske, M. C. Fitzpatrick, and S. Finnegan. 2013. Climate change and the past, present, and future of biotic interactions. Science, 341(6145), 499-504

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

Callahan, J. A., B. P. Horton, D. L. Nikitina, C. K. Sommerfield, T. E. McKenna, and D. Swallow. 2017. Recommendation of sea-level rise planning scenarios for Delaware: Technical Report, prepared for Delaware Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs. 116pp

Coen, M. C., E. Andrews, A. Bigi, G. Martucci, G. Romanens, F. P. A. Vogt, and L. Vuilleumier. 2020. Effects of the prewhitening method, the time granularity, and the time segmentation on the Mann–Kendall trend detection and the associated Sen's slope. Atmospheric Measurement Techniques, 13, 6945-6964

Coffey, R., M.J. Paul, J. Stamp, A. Hamilton, and T. Johnson. 2018. A review of water quality responses to air temperature and precipitation changes 2: Nutrients, algal blooms, sediment, and pathogens. Journal of American Water Resources Association, 5(4), 844-868.

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

Delaware River Basin Commision. 2021. Flow Management. <https://www.nj.gov/drbc/programs/flow/flow-mgmt.html> (accessed 06-08-2022)

Devlin, A. T., J. Pan, and H. Lin. 2019. Extended spectral analysis of tidal variability in the North Atlantic Ocean. Journal of Geophysical Research: Oceans, 124, 506-526

DiLorenzo, J. L., P. Huang, M. L. Thatcher, and T. O. Najarian. 1993. Dredging impacts on Delaware Estuary tides. In Estuarine and Coastal Modeling III: Proceedings of the 3rd International Conference, pp. 86-104

Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina. 2021. Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1055–1210.

Feng, S. and Q. Hu. 2007. Changes in winter snowfall/precipitation ratio in the contiguous United States. Journal of Geophysical Research: Atmospheres 112

Ford, C. M., A. D. Kendall, and D.W. Hyndman. 2021. Snowpacks decrease and streamflows shift across the eastern US as winters warm. Science of The Total Environment 793, 148483

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu. 2021. Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362

Frederikse, T., F. Landerer, L. Caron, S. Adhikari, D. Parkes, V. W. Humphrey, S. Dangendorf, P. Hogarth, L. Zanna, L. Cheng, and Y. Wu. 2020. The causes of sea-level rise since 1900. Nature, 584, 393-397

Friedlingstein, P., M. O'Sullivan, M.W. Jones, R.M. Andrew, L. Gregor, J. Hauck, C. Le Quéré, I.T. Luijkx, A. Olsen, G.P. Peters, W. Peters, et al. 2022. Global carbon budget 2022. Earth System Science Data, 14(11), 4811-4900.

Giri, S., R. G. Lathrop, and C. C. Obropta. 2020. Climate change vulnerability assessment and adaptation strategies through best management practices. Journal of Hydrology, 580, 124311

Gori, A., N. Lin, D. Xi, and K. Emanuel. 2022. Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. Nature Climate Change, 12(2), 171-178

Hammond, J. C. and B. J. Fleming. 2021. Evaluating low flow patterns, drivers and trends in the Delaware River Basin. Journal of Hydrology, 598, 126246

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

Hawkins, T. W. and C. J. Woltemade. 2021. Impact of projected 21st century climate change on basin hydrology and runoff in the Delaware River Basin, USA. Journal of Water and Climate Change, 12.1, 60-81

Hayhoe, K., D. J. Wuebbles, D. R. Easterling, D. W. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, and M. Wehner, 2018. Our Changing Climate. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 72–144

Hinson, K. E., M. A. Friedrichs, P. St-Laurent, F. Da, and R. G. Najjar. 2021. Extent and causes of Chesapeake Bay warming. JAWRA Journal of the American Water Resources Association, doi: 10.1111/1752-1688.12916

Howarth, M. E., C. D. Thorncroft, and L. F. Bosart. 2019. Changes in extreme precipitation in the northeast United States: 1979–2014. Journal of Hydrometeorology, 20(4): 673-689

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, J. M. Melillo, Terese (T. C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 317–395

Hsu, H.-H. and Y.-T. Chen. 2020. Simulation and projection of circulations associated with atmospheric rivers along the North American northeast coast. Journal of Climate, 33(13): 5673-5695

Hull, C. and J. G. Titus. 1986. Greenhouse effect, sea level rise, and salinity in the Delaware Estuary. United States Environmental Protection Agency. 36pp

Hussain, M. M. and I. Mahmud. 2019. pyMannKendall: a python package for non parametric Mann Kendall family of trend tests. The Journal of Open Source Software, 4, 1556

IPCC. 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32.

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

Joos, F. and R. Spahni. 2008. Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. Proceedings of the National Academy of Sciences, 105(5), 1425-1430

Karmalkar, A. V., and R. M. Horton. 2021. Drivers of exceptional coastal warming in the northeastern United States. Nature Climate Change, 11(10), 854-860

Kaushal, S. S., G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T. Belt, D. H. Secor, and R. Wingate. 2010. Rising stream and river temperatures in the United States. Frontiers in Ecology and the Environment, 8(9), 461-466

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

Kopp, R. E. 2013. Does the mid-Atlantic United States sea level acceleration hotspot reflect ocean dynamic variability? Geophysical Research Letters, 40(15), 3981-3985

Kossin, J. P., K. R. Knapp, T. L. Olander, and C. S. Velden. 2020. Global increase in major tropical cyclone exceedance probability over the past four decades. Proceedings of the National Academy of Sciences, 117(22), 11975-11980

Knutson, T. R. and F. Zeng. 2018. Model Assessment of observed precipitation trends over land regions: Detectable human influences and possible low bias in model trends. Journal of Climate, 31(12), 4617-4637

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. Partnership for the Delaware Estuary, PDE Report No. 10-01, 1-117 pp

Lee, S. B., M. Li, and F. Zhang. 2017. Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. Journal of Geophysical Research: Oceans, 122, 3917-3938

Li, S., T. Wahl, S. A. Talke, D. A. Jay, P. M. Orton, X. Liang, G. Wang, and L. Liu. 2021. Evolving tides aggravate nuisance flooding along the U.S. coastline. Science Advances, 7, eabe2412

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

Marsooli, R., N. Lin, K. Emanuel, and K. Feng. 2019. Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications, 10:3785

McCabe, G. J. and D. M. Wolock. 2020. Hydro-climatic drought in the Delaware River Basin. Journal of the American Water Resources Association, 56(6), 981-994

Menne, M. J., C. N. Williams, and R. Vose. 2015a. U.S. Historical Climatology Network (USHCN). <https://www.ncei.noaa.gov/products/land-based-station/us-historical-climatology-network>

——, ——, and ——. 2015b. United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data. <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

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang. 2013. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

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

National Ocean Service. Center for Operational Oceanographic Products and Services. NOAA Tides and Currents, Coastal Inundation Dashboard. <https://tidesandcurrents.noaa.gov/inundationdb/> (accessed 07/12/2022)

Ning, L. and R. S. Bradley. 2015. Snow occurrence changes over the central and eastern United States under future warming scenarios. Scientific Reports, 5(1), 1-8

NOAA Global Monitoring Laboratory. Trends in Atmospheric Carbon Dioxide, Global Monthly Mean CO2 (Full Record). <gml.noaa.gov/ccgg/trends/global.html> (accessed 03/08/2022).

Paerl, H.W. and J. Huisman. 2008. Blooms like it hot. Science, 320(5872), 57-58.

Pareja-Roman, L. F., R. J. Chant, and C. K. Sommerfield. 2020. Impact of historical channel deepening on tidal hydraulics in the Delaware Estuary. Journal of Geophysical Research: Oceans, 125, e2020JC016256

Pringle, W. J., J. Wang, K. J. Roberts, and V. R. Kotamarthi. 2021. Projected changes to cool-season storm tides in the 21st century along the Northeastern United States coast. Earth's Future, 9, e2020EF001940

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, D23112, doi:10.1029/2012JD018137

Ross, A. C., R. G. Najjar, M. Li, M. E. Mann, S. E. Ford, and B. Katz. 2015. Sea-level rise and other influences on decadal-scale variations of salinity in a coastal plain estuary. Estuarine Coastal and Shelf Science, 157, 79-92

Ross, A. C., R. G. Najjar, M. Li, S. B. Lee, F. Zhang, and W. Liu. 2017. Fingerprints of sea-level rise on changing tides in the Chesapeake and Delaware Bays. Journal of Geophysical Research: Oceans, 122, 8102–8125

Schulte, J., R. G. Najjar, and M. Li. 2016. The influence of climate modes on streamflow in the Mid-Atlantic Region of the United States. Journal of Hydrology: Regional Studies, 5, 80-99

Seager, R., N. Pederson, Y. Kushnir, J. Nakamura, and S. Jurburg. 2012. The 1960s drought and the subsequent shift to a wetter climate in the Catskill Mountains Region of the New York City Watershed. Journal of Climate, 25(19), 6721-6742

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

Sharma, S., M. Gomez, K. Keller, R. E. Nicholas, and A. Mejia. 2021. Regional flood risk projections under climate change. Journal of Hydrometeorology, 22(9), 2259-2274

Shi, S., and G. Liu. 2021. The latitudinal dependence in the trend of snow event to precipitation event ratio. Scientific Reports 11, 18112

Shirazi, Y. A., E. W. Carr, G. R. Parsons, P. Hoagland, D. K. Ralston, and J. Chen. 2019. Increased operational costs of electricity generation in the Delaware River and Estuary from salinity increases due to sea-level rise and a deepened channel. Journal of Environmental Management, 244, 228-234

Simonson, J. M., S. D. Birkel, K. A. Maasch, P. A. Mayewski, B. Lyon, and A. M. Carleton. 2022. Association between recent U.S. northeast precipitation trends and Greenland blocking. International Journal of Climatology

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, Reston, VA

Sweet, W. V., B. D. Hamlington, R. E. Kopp, C. P. Weaver, P. L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A. S. Genz, J. P. Krasting, E. Larour, D. Marcy, J. J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak. 2022. Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD

Theil, H. 1950. A rank-invariant method of linear and polynomial regression analysis, i, ii, and iii. Proceedings of the Koninklijke Nederlandse Akademie Wetenschappen, Series A Mathematical Sciences, 53, 386-392, 521-525, 1397-1412

Thibeault, J. M. and A. Seth. 2014. Changing climate extremes in the Northeast United States: observations and projections from CMIP5. Climatic Change, 127, 273-287

Thompson, P. R, M. J. Widlansky, B. D. Hamlington, M. A. Merrifield, J. J. Marra, G. T. Mitchum, and W. Sweet. 2021. Rapid increases and extreme months in projections of United States high-tide flooding. Nature Climate Change, 11, 584-590

United States Geological Survey. 2017. Flexible Flow Management Program. Office of the Delaware River Master. <https://webapps.usgs.gov/odrm/ffmp/flexible-flow-management-program> (accessed 06-08-2022)

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

Vose, R. S., D. R. Easterling, K. E. Kunkle, A. N. LeGrande, and M. F. Wehner. 2017. Temperature changes in the United States. Climate Science Special Report: Fourth National Climate Assessment, Volume I. [Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock (eds.)], U.S. Global Change Research Program, Washington, DC, USA, 185-206

Wang, S., and R. Toumi. 2022. More tropical cyclones are striking coasts with major intensities at landfall. Scientific Reports, 12(1), 5236

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

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, 139(2), 1–14

Wing, O. E. J., W. Lehman, P. D. Bates, C. C. Sampson, N. Quinn, A. M. Smith, J. C. Neal, J. R. Porter, and C. Kousky. 2022. Inequitable patterns of US flood risk in the Anthropocene. Nature Climate Change, 12(2), 156-162

Wuebbles, D., G. Meehl, K. Hayhoe, T. R. Karl, K. Kunkel, B. Santer, M. Wehner, B. Colle, E. M. Fischer, R. Fu, A. Goodman, E. Janssen, V. Kharin, H. Lee, W. Li, L.N. Long, S. C. Olsen, Z. Pan, A. Seth, J. Sheffield, and L. Sun. 2014. CMIP5 climate model analyses: Climate extremes in the United States. Bulletin of the American Meteorological Society, 95, 571–583

Yue, S. and C. Y Wang. 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. Water Resources Research, 38, doi: 10.1029/2001WR000861

Redlining and Urban Heat Islands

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Racist housing policies, such as redlining, have left poor neighborhoods in many cities more susceptible than wealthier neighborhoods to the urban heat island effect and air pollution (Hoffmann et al., 2020; Locke et al., 2021; Lane et al., 2022). The term "redlining" derives from discriminatory practices of the federal government's Home Owners' Loan Corporation (HOLC), which developed maps in the 1930s for use by mortgage lenders to assign grades to different neighborhoods; those deemed unfavorable were outlined in red. In 1968 the Fair Housing Act brought an end to redlining, in addition to other discriminatory home-lending policies, as part of the Civil Rights Act (United States Federal Reserve, 2017).

Hoffman et al. (2020) studied the effect of redlining on temperature and land use in 108 US cities, finding that neighborhoods with low HOLC grades are much hotter that those with high grades, a result that reflects the greater density of parks, trees, and other green infrastructure in wealthier neighborhoods, which experienced a greater infusion of funds for development. Specifically, redlined urban neighborhoods in the United States (grade D: hazardous) have land surface temperatures that are, on average, 2.6 °C higher than non-redlined areas (grade A: desirable). In Philadelphia, Camden, and Trenton, the same study found these differences to be much larger: 5.2, 4.3, and 4.6 °C, respectively (Fig 2.14).

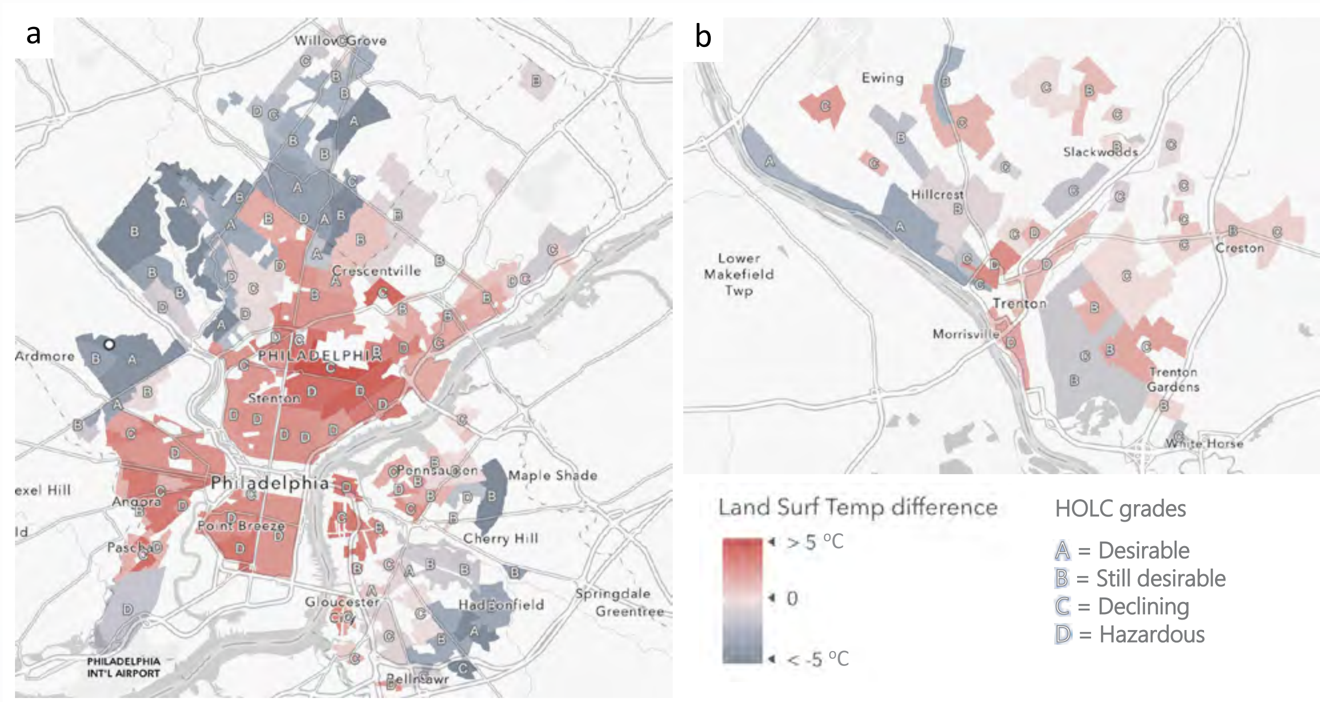

Figure 2.14 Maps of a) Philadelphia, Camden, and b) Trenton indicating the deviation of land surface temperature from the city-wide average (colors) and grades by the Home Owners' Loan Corporation (HOLC; letters). Source: Science Museum of Virginia and Esri. Data from Hoffman et al. (2020). https://www.arcgis.com/apps/dashboards/73e329457b6644e7aeff13ecce43c8d8

References

Hoffman, J. S., Shandas, V., & Pendleton, N. (2020). The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. Climate, 8(1), 12.

Lane, H. M., Morello-Frosch, R., Marshall, J. D., & Apte, J. S. (2022). Historical Redlining Is Associated with Present-Day Air Pollution Disparities in US Cities. Environmental Science & Technology Letters. https://doi.org/10.1021/acs.estlett.1c01012

Locke, D. H., Hall, B., Grove, J. M., Pickett, S. T. A., Ogden, L. A., Aoki, C., Boone, C. G., & O'Neil-Dunne, J. P. M. (2021). Residential housing segregation and urban tree canopy in 37 US Cities. npj Urban Sustainability, 1(1), 15. https://doi.org/10.1038/s42949-021-00022-0

United States Federal Reserve (2017). Consumer Compliance Handbook. V. Federal Fair Lending Regulations and Statutes. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/boarddocs/supmanual/cch/fair_lend_fhact.pdf

Climate Feature 2

Flooding in a Marginalized Community

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An example of the interaction between systemic racism and climate change is the Eastwick neighborhood in Southwest Philadelphia, Pennsylvania (Fig 2.15). Eastwick resides at low elevations, mostly below 10 feet (~3 meters) above sea level, borders the John Heinz Wildlife Refuge and the Philadelphia International Airport, and is nestled between the Delaware River, Schuylkill River, Cobbs Creek, and Darby Creek. A majority of what is now Eastwick was once a freshwater tidal marsh that was drained and diked for farming and horticulture in the 18th and 19th centuries, then later filled with dredged material to create land for housing and the airport in the 20th century (Krulikowski 2014). In this era, the community was subjected to redlining (also see Climate Feature 1), a racist housing policy that devalued property in neighborhoods of color, by Federal mortgage agencies who cited both African-American residents and flood risk as reasons to disinvest in the neighborhood (Nelson et al.). Today, the majority of the Eastwick public land parcel is within a Special Flood Hazard Area that consists of a 1% annual chance flood zone, otherwise known as the 100-year floodplain, and a 0.2% annual chance flood zone, or the 500-year floodplain (Fig 2.15)(FEMA 2021).

Although Eastwick has predominantly been a low-density neighborhood due to the difficulty of building in the neighborhood's wetland conditions, early 20th century Eastwick still managed to be one of the few racially integrated neighborhoods in Philadelphia (Cahn 2014). Before the urban renewal era in the 1950's, Eastwick was valued by the local residents for its pastoral qualities and was affectionately termed "The Meadows." However, the neighborhood struggled with environmental justice issues, including blight, a fire in a local landfill, and nuisance and major flooding events (McKee 2001). In 1958 the city of Philadelphia implemented large-scale redevelopment urban renewal projects in Eastwick centered around seizing private property using eminent domain. The city then proceeded to contract out creation of new housing tracts and relocate African American residents from other developing areas of Philadelphia into Eastwick (Cahn 2014). Most of this development plan failed, resulting in demolition of 2,000 acres of neighborhoods and the displacement of 8,000 residents (McKee 2001). Much of the housing that was constructed during redevelopment did not account for the low-lying nature of the landscape and resulted in buildings that are regularly flooded or are sinking into the marsh. The attempted redevelopment of Eastwick also destroyed acres of tidal wetlands, which provide a natural ecosystem service of mitigating flooding and storm surges (Cahn 2014).

In addition to discriminatory policy and planning, climate change is seriously threatening the continued existence of the neighborhood as increasing heavy rain and rising sea levels (see sections 2.3 and 2.5) have been dramatically intensifying flooding in residential neighborhoods (Phillips 2021). Today, the interaction of climate adaptation and environmental justice can still be observed in Eastwick. For example, there are ongoing discussions on rehousing current residents to new city-owned housing as Philadelphia's first climate migrants (Phillips 2021). This move is controversial, not only because of the history of development in the neighborhood (McKee 2001), but because the new housing still resides in a 500-year flood plain (Phillips 2021) and there are conflicting stakeholder interests between future economic development and flood mitigation of the vacated land. Despite activism by a neighborhood coalition and extensive community participation in city planning processes, the priorities of Eastwick residents have not been addressed in city land management decisions. Eastwick community groups continue to express concern that any development outside of conservation as open land will result in increased flooding in the surrounding neighborhood, especially under the threat of climate change.

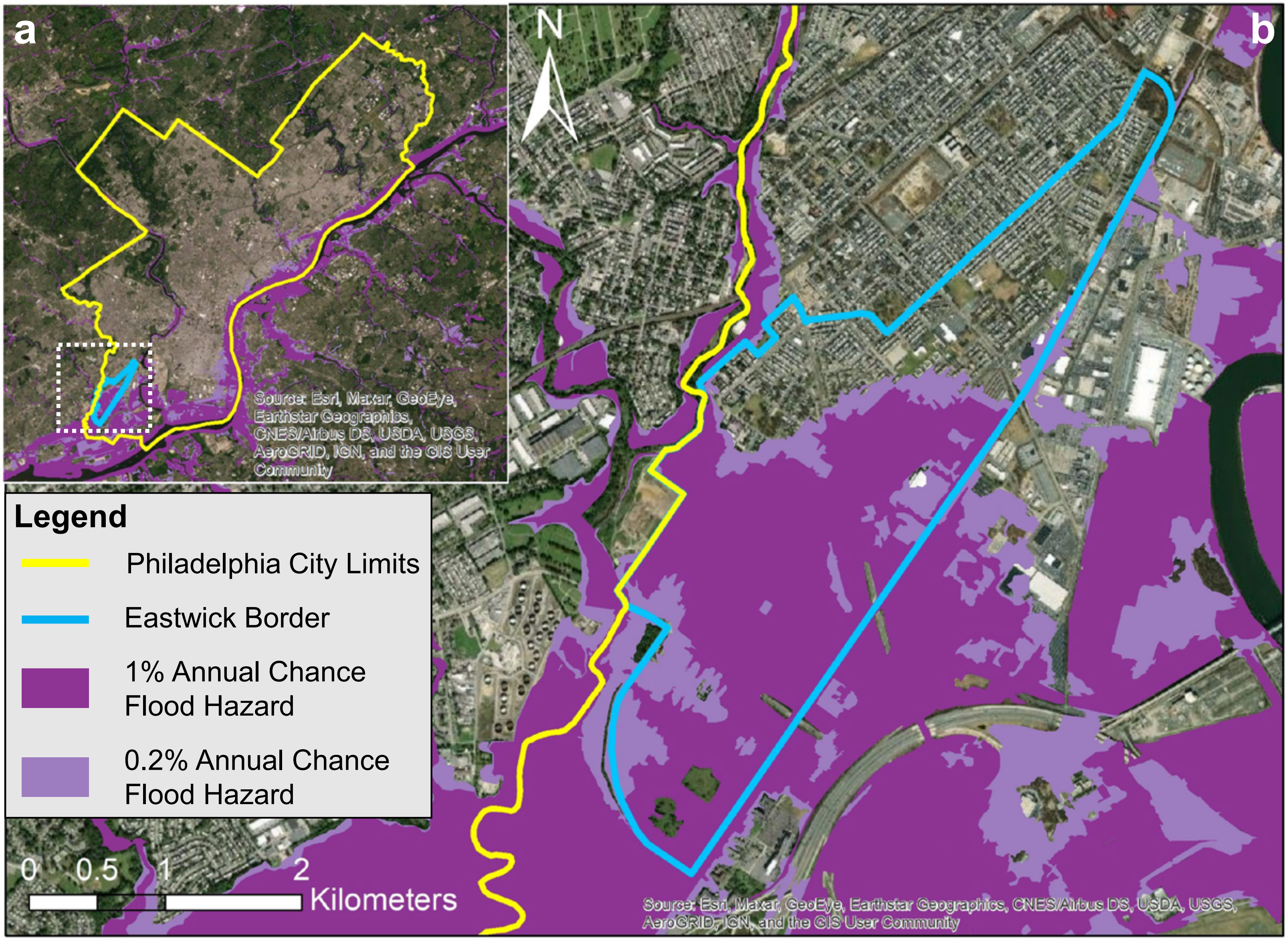

Figure 2.15 a) The Eastwick neighborhood (blue outline) resides in the southwest corner of Philadelphia (yellow outline). The 1 and 0.2 % annual chance flood hazard zones (dark and light purple, respectively) fall mainly along the Delaware River on the south and east sides of the city. b) A closer view of Eastwick and its vulnerability to major flooding events. (Sources: ESRI, FEMA, and pasda.psu.edu)

References

Cahn, A.L., 2014: On retiring blight as policy and making Eastwick whole. Harvard Civil Liberties Law Review, 49, 449-492.

Federal Emergency Management Agency (FEMA), 2021: Pennsylvania Releases New Mapping Tool to Show Flood Risk. https://www.fema.gov/press-release/20210607/pennsylvania-releases-new-mapping-tool-show-flood-risk (Accessed 03-22-2022).

Krulikowski, A.E. 2014. Southwest Philadelphia. The Encyclopedia of Greater Philadelphia. https://philadelphiaencyclopedia.org/locations/southwest-philadelphia/ (Accessed 03-22-22).

Martel, J.-L., F. Brissette, M. Troin, M., R. Arsenault, J. Chen, T. Su and P. Lucas-Picher. 2022. CMIP5 and CMIP6 model projection comparison for hydrological impacts over North America. Geophysical Research Letters, 49(15): e2022GL098364

McKee, G. A., 2001: Liberal ends through illiberal means: Race, urban renewal, and community in the Eastwick section of Philadelphia, 1949-1990. Journal of Urban History, 27(5), 547-583.

Nelson, R.K., Winling, L., Marciano, R., Connolly, N. et al., "Mapping Inequality," American Panorama, ed. Robert K. Nelson and Edward L. Ayers. Accessed March 28, 2022, https://dsl.richmond.edu/panorama/redlining/#loc=12/39.932/-75.267&city=philadelphia-pa&area=D23&adview=full&adimage=2/67.676/-165.938.

Phillips, S., 2021: Eastwick residents could become Philly's first climate migrants. A new plan sees them moving to city-owned higher ground. https://whyy.org/articles/eastwick-residents-could-become-phillys-first-climate-migrants-a-new-plan-sees-them-moving-to-city-owned-higher-ground/ (Accessed 03-22-22).