7

Climate Change

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Chapter 7 – Climate Change

Introduction

This chapter describes how the climate of the Delaware River Basin (DRB) and sea level in the Delaware Estuary have changed and may change in the future. The focus is on air temperature and precipitation throughout the watershed with additional analysis of changes in snow cover, wind speed, barometric pressure, and ice jams in the Delaware River. Trends of water properties including surface water temperature and salinity can be found in Chapters 2 and 3.

1 - Air Temperature

1.1 Description of Indicator

Monthly surface air temperature from the U.S. Historical Climate Network (USHCN), Version 2 was used. The monthly data set is derived from a daily data set. A complete description of the data set and the quality control procedures is given in Menne et al. (2009; 2010a, b); an abbreviated description is presented here. The USHCN is a subset of the National Oceanographic and Atmospheric Administration's (NOAA's) Cooperative Observer Program (COOP). The COOP data stations extracted for the USHCN data set are relatively long, stable, and amenable to adjustments for non-climatic changes (such as station location).

Table 7.1. USHCN stations used in the analysis. The start-end dates shown are defined as the first and last year for which precipitation data passed the 19-day cutoff for calculations of precipitation extremes (see Section 3.1). Some stations have data before 1910, but are not listed as such because the present analysis begins in 1910. Stations in bold are in the lower watershed

#	Name	State	ID #	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Start-end years
1	**Dover**	DE	72730	39.2583	-75.5167	9.1	1910-2008
2	**Milford 2 SE**	DE	75915	38.8983	-75.4250	10.7	1910-2002
3	**Newark Univ. Farm**	DE	76410	39.6694	-75.7514	27.4	1942-1999
4	**Wilmington Porter Res.**	DE	79605	39.7739	-75.5414	82.3	1942-2009
5	Belvidere BRG	NJ	280734	40.8292	-75.0836	80.2	1983-2009
6	**Indian Mills 2 W**	NJ	284229	39.8144	-74.7883	30.5	1910-2008
7	**Moorestown**	NJ	285728	39.9511	-74.9697	13.7	1914-2008
8	Deposit	NY	302060	42.0628	-75.4264	304.8	1963-2009
9	Port Jervis	NY	306774	41.3800	-74.6847	143.3	1910-2009
10	Allentown AP	PA	360106	40.6508	-75.4492	118.9	1948-2009
11	Palmerton	PA	366689	40.8000	-75.6167	125.0	1918-1997
12	**Reading 4 NNW**	PA	367322	40.4269	-75.9319	109.7	1974-2007
13	Stroudsburg	PA	368596	41.0125	-75.1906	140.2	1911-2007
14	**West Chester 2 NW**	PA	369464	39.9708	-75.6350	114.3	1910-2008

The daily portion of the USHCN data has undergone extensive screening for erroneous values; there are 15 individual checks for temperature. For example, if daily data show strong spatial or temporal inconsistency, data are flagged. The daily dataset was not adjusted for biases due, for example, to changes in station location, time of observation, etc.

The monthly data set was derived from the daily data set 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 data set 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).

These adjustments significantly affect calculated trends. For the U.S. as a whole, the long-term (1895-2007) temperature trend in the unadjusted data is 0.036 °C per decade. Including the adjustment for time of observation increases the trend to 0.054 °C per decade. Remaining adjustments (e.g., station location) increase the trend further to 0.069 °C per decade. The fourth and final step in creating a monthly data set from daily data was to fill in missing days using information from surrounding stations.

The 14 USHCN stations located in the DRB were extracted (Fig. 7.1 and Table 7.1). 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 the tidal portion of the estuary, which is located below Trenton, NJ. The upper portion of the watershed drains to the Delaware River above Trenton. There are eight USHCN stations in the lower portion and six in the upper portion.

The period 1910-2009 was selected for analysis based on the monthly data set because every station during this time period had a value (some being filled in by interpolation). 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). Seasonal and annual averages were computed for each year and then anomalies were computed with respect to the 1961-1990 reference period. The upper and lower basin averages of the anomalies were then computed. The basin averages of the annual-mean temperature adjustment were also computed; this is simply the adjusted annual-mean temperature minus the raw annual-mean temperature, separate products that were supplied by NOAA.

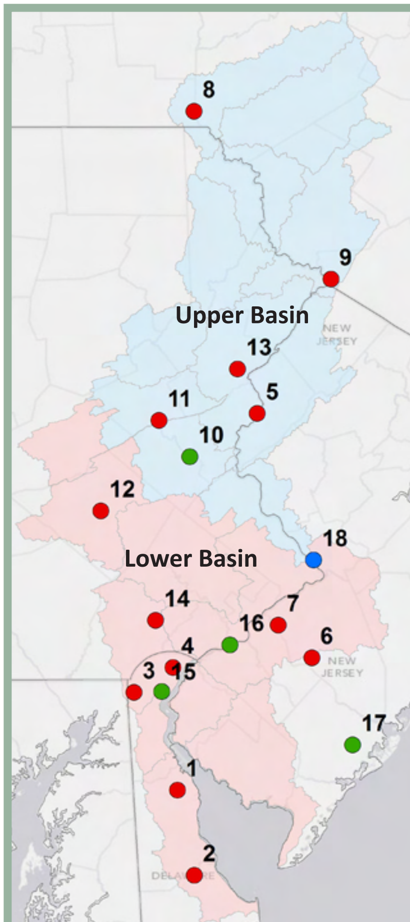

Fig. 7.1. Location of meteorological and hydrological stations used in this analysis. Red dots (1-14) are the USHCN stations; green dots (10, 15, 16, and 17) are the wind stations (Section 5.1); and the blue dot (18) is the stream gauge at Trenton (Section 6.1). The upper watershed is shaded blue and the lower watershed is shaded red

1.2 Past Trends

Annual-mean temperature has increased significantly at the 95% confidence level over the past 100 years, and this trend has increased over the past 30 years (Fig. 7.3. and Table 7.2). In both portions of the watershed, the centennial temperature change given by these trends is about 1.0 °C. The trend over past 30 years for temperature is more than two times the 100-year trend.

Temperature adjustments, which reveal a warm bias in the raw data that has generally decreased with time, are substantial over the past 100 years, accounting for about half of the overall warming trend in the lower watershed (Fig. 7.2). The impact of adjustments over the past 30 years is relatively small. The change in the temperature bias in the late 1960s and early 1970s is likely a result of the change in observation time made at many COOP stations at this time (David Robinson, Rutgers University, personal communication).

The warming observed in the DRB, about 1 °C per century, is consistent with that expected from increases in greenhouse gases according to Najjar et al. (2009), who analyzed temperature observations and global climate model simulations for the region.

Table 7.2 and Fig. 7.4 and 7.5 show that significant (95% confidence) warming trends are also evident for individual seasons during the past 100 years, though significant temperature trends over the past 30 years are only seen for fall (warming).

1.3 Future Predictions

In Kreeger et al. (2010) 14 21st-century temperature projections were averaged over the Delaware River Basin from simulations of global climate models (GCMs) under two greenhouse gas emissions scenarios: a higher emissions scenario (A2) in which atmospheric CO_2 is about three times its preindustrial value by the end of the century and a lower emissions scenario (B1) in which atmospheric CO_2 is about twice its preindustrial value by the end of the century. All of the GCMs simulated warming throughout the 21st century, with median warming by late century of 1.9 and 3.7 °C for the B1 and A2 scenario, respectively. The models project more warming in the summer than in the winter.

1.4 Actions and Needs

The large corrections made to the monthly temperature data, particularly in the early part of the century, reveal a poorly constrained uncertainty in the temperature trends in the DRB. Research is needed to better quantify this uncertainty, perhaps through the identification of temperature stations that have required minimal adjustments or can be cross-calibrated.

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 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.

Given the Delaware River Basin's proximity to the sea and its large north-south temperature gradient, the global climate models recently used to investigate climate change in the region (Najjar et al. 2009; Kreeger et al. 2010) may be inadequate. Regional climate model simulations, which have been recently made available by the North American Regional Climate Change Assessment Program (Mearns et al. 2009), represent a substantial improvement over existing GCM simulations in terms of resolution and should be investigated in detail.

1.5 Summary

The DRB has warmed substantially over the past 100 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 paradoxically be more certain: not a single climate model projects cooling even under the low emissions scenario analyzed in Kreeger et al. (2010).

Table 7.2. Linear trends of annual and seasonal temperature and precipitation for the upper and lower portions of the DRB. *p*-values, given in parentheses, are based on an F-test and calculated here and elsewhere in this chapter using the lm function in the programming language R. Trends significant at the 90% and 95% confidence levels are underlined once and twice, respectively. To put the precipitation trends in perspective, the annual and seasonal average totals in the lower & upper watershed for the 1961-1990 period are 112 & 110 cm (annual), 25 & 23 cm (DJF), 29 & 28 cm (MAM), 31 & 30 (JJA), and 27 & 27 cm (SON)

Upper water-shed	Temperature trend (°C decade^{-1})		Precipitation trend (cm decade^{-1})	
	1910-2009	1980-2009	1910-2009	1980-2009
Annual	0.09 (2.8×10^{-5})	0.28 (0.030)	1.4 (0.059)	6.6 (0.075)
DJF	0.14 (0.0080)	0.42 (0.20)	0.28 (0.20)	2.5 (0.12)
MAM	0.09 (0.015)	0.08 (0.69)	0.32 (0.17)	-1.9 (0.20)
JJA	0.08 (0.0022)	0.22 (0.21)	0.00 (0.99)	2.5 (0.17)
SON	0.06 (0.045)	0.40 (0.017)	0.83 (0.0027)	3.5 (0.072)
Lower water-shed	Temperature trend (°C decade^{-1})		Precipitation trend (cm decade^{-1})	
	1910-2009	1980-2009	1910-2009	1980-2009
Annual	0.10 (3.2×10^{-7})	0.26 (0.031)	1.1 (0.059)	6.3 (0.077)
DJF	0.13 (0.0057)	0.47 (0.14)	0.03 (0.90)	2.0 (0.15)
MAM	0.09 (0.0095)	0.17 (0.39)	0.30 (0.24)	-0.20 (0.24)
JJA	0.12 (9.5×10^{-8})	0.13 (0.38)	-0.21 (0.51)	2.9 (0.12)
SON	0.09 (0.0039)	0.28 (0.079)	0.94 (0.00081)	3.4 (0.074)

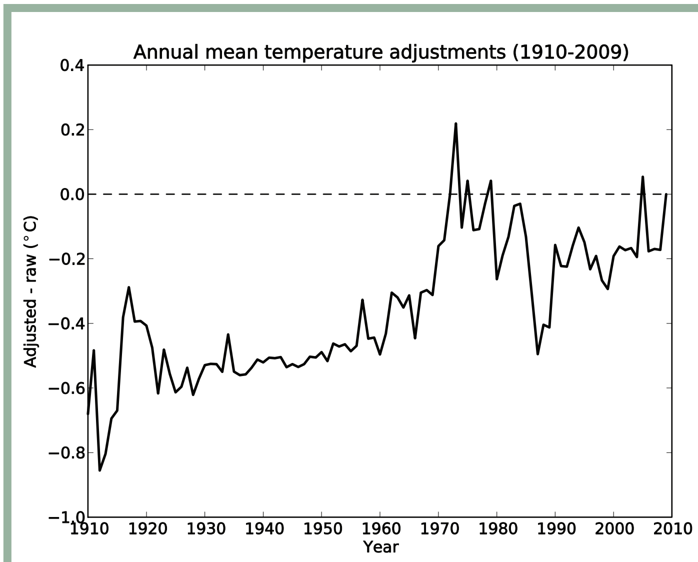

Fig. 7.2. Adjustments made to monthly temperature data. Shown is the adjusted temperature minus the raw (unadjusted) temperature for the lower portion of the watershed

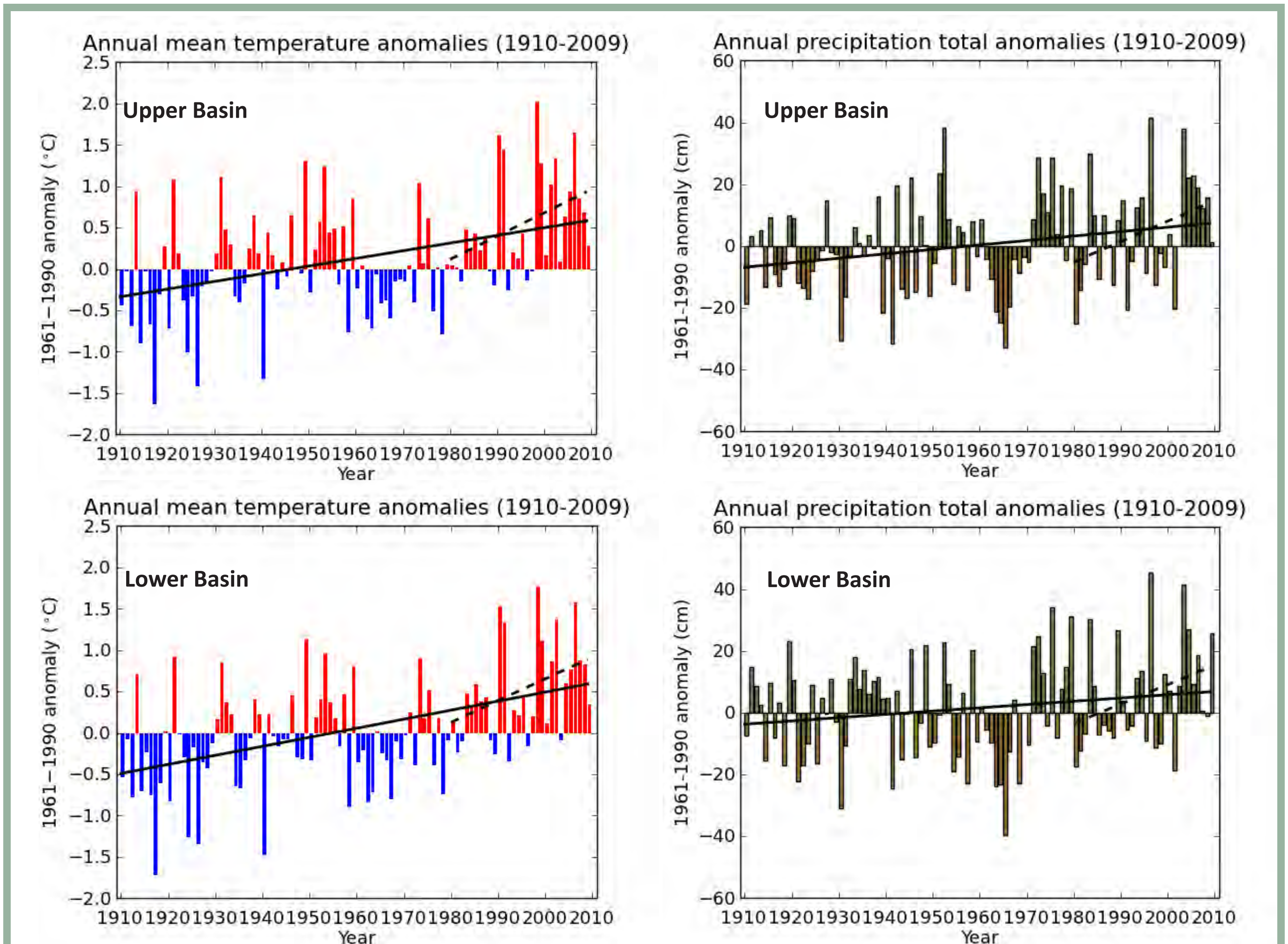

Fig. 7.3. Anomalies (with respect to the 1961-1990 average) of annual-mean temperature (left panels) and annual totals of precipitation (right panels) for the lower (bottom panels) and upper (top panels) portion of the DRB. The solid and dashed lines are the linear fits to the data for the 1910-2009 and 1980-2009 periods, respectively. To put the precipitation trends in perspective, the annual 1961-1990 avg. precipitation for the lower and upper watershed is 112 and 110 cm, respectively

2 - Precipitation

2.1 Description of Indicator

As with temperature, monthly precipitation from the USHCN, Version 2 was used. The data set description and screening procedures are the same as for temperature (Section 1.1), except that there are 12 screening checks for precipitation and no time-of-observation correction.

2.2 Past Trends

Annual-mean precipitation in the DRB has increased significantly at the 90% confidence level over the past 100 years, and this trend has increased over the past 30 years (Fig. 7.2 and Table 7.2). In both portions of the watershed, the centennial precipitation change given by these trends is about 10%. The trend over the past 30 years for precipitation is more than five times the 100-year trend. Seasonal precipitation trends (Table 7.2 and Fig. 7.4 and 7.5) are positive but these are only significant in the fall, which has gotten dramatically wetter (more than 10% per decade over the past 30 years). Though a warmer atmosphere is expected to hold more moisture and have greater precipitation, Najjar et al. (2009) found that the precipitation increase over the 20th century in the Delaware River Basin was not captured by GCMs forced by the observed increase in greenhouse gases. Similarly, Seager et al. (2012) examined the cause of the 1960s drought and the subsequent rapid increase in precipitation in the Northeast U.S. They, too, found that simulations with GCMs forced by increased greenhouse gases were not able to capture these important hydrological changes. Seager et al. (2012) also found that GCMs forced from below by surface ocean temperature change did not reproduce the observed precipitation changes in the Northeast U.S. Together, these studies suggest that internal variability of the atmosphere (as opposed to variability forced from the

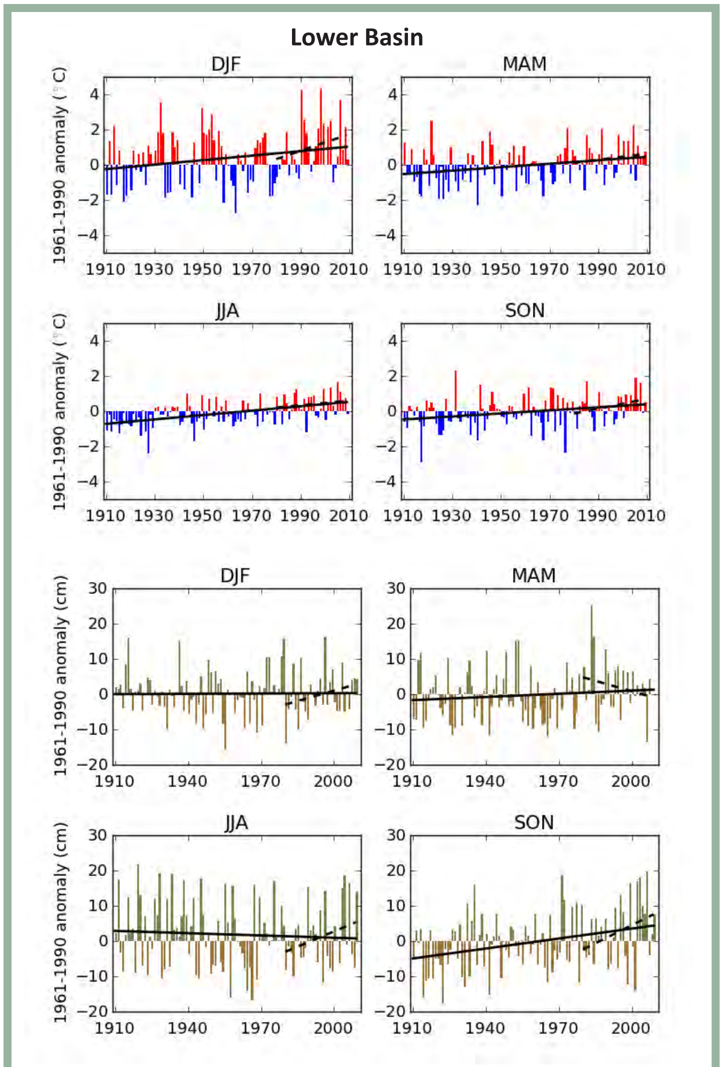

Fig. 7.4. Anomalies (with respect to the 1961-1990 average) of seasonal-mean temperature (top four panels) and seasonal totals of precipitation (bottom four panels) for the lower portion of the DRB. The solid and dashed lines are the linear fits to the data for the 1910-2009 and 1980-2009 periods, respectively

ocean or greenhouse gases) is the dominant influence on precipitation in the Delaware River Basin.

2.3 Future Predictions

Precipitation projections come from the same source as temperature projections (Kreeger et al. 2010). These show the DRB getting progressively wetter throughout the 21st century, particularly in the winter and spring. There is less consensus, however, than the temperature projections, as some models project precipitation declines. Median projected precipitation increases by the late 21st century for the B1 and A2 scenarios are 7 and 9%, respectively.

2.4 Actions and Needs

The understanding of long-term changes in DRB precipitation is poor. Greenhouse gas emissions, at least

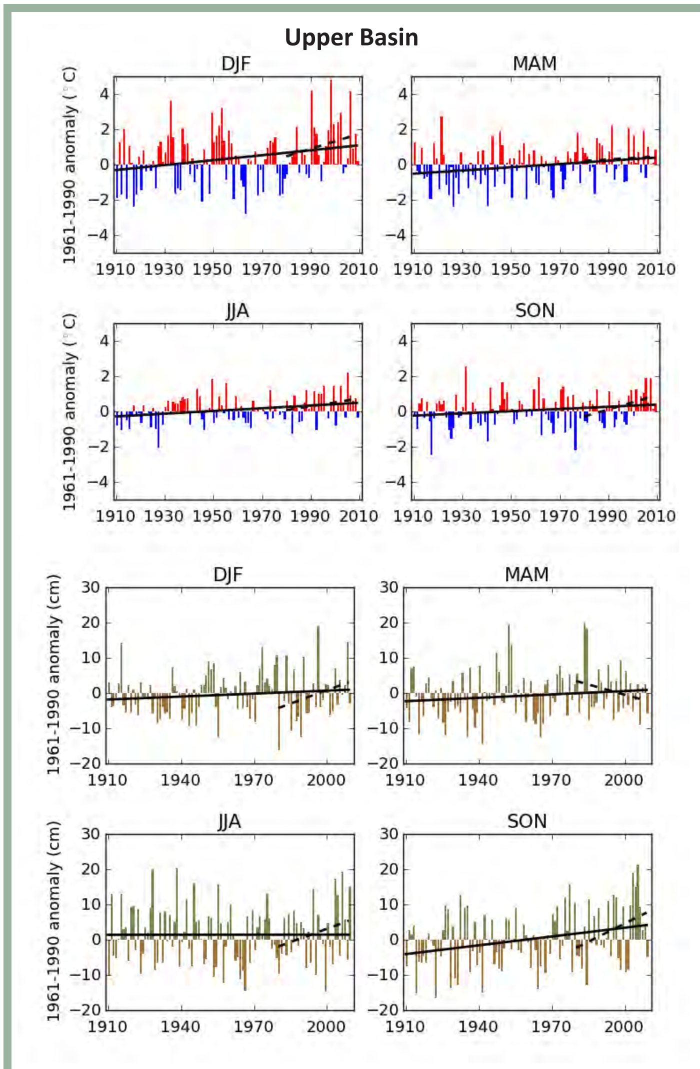

Fig. 7.5. Same as Fig. 7.4, except for the upper portion of the DRB

according to the limited studies available, do not appear to be the cause of such changes. However, as noted for air temperature (Section 1.3), climate simulations that have been analyzed are of very coarse resolution and are unable to capture the fine-scale processes, particularly in summer when convective activity is high, that drive the precipitation process in the DRB. Therefore, regional climate models or statistical downscaling techniques should be considered as tools for investigating past and future precipitation change.

2.5 Summary

Precipitation has increased in the DRB, mainly during fall, and is projected to increase in the future, mainly during winter and spring. 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 at regional scales, in contrast to studies showing a signal at continental and global scales (e.g., Hegerl et al. 2007).

3 - Extremes: Air Temperature and Precipitation

3.1 Description of Indicator

Trends in five extreme event indices were used: (1) the number of days per year with the high temperature above 90 °F (0°C), (2) the number of days per year with the low temperature below 32 °F (32.2°C), (3) the maximum number of consecutive dry days per year, (4) the annual maximum five-day precipitation total (cm), and (5) the number of days per year with heavy (>4.5 cm) precipitation. The USHCN daily data set was used for this analysis. Precipitation data that were flagged during screening were not used nor were any temperature data for a given day if the high, low, or average temperature was flagged. For the high-temperature metric, years from a given station were not used if it had more than 23 days of flagged or missing data during May-September of that year; the same threshold was used for the low-temperature metric during October-April. For the three precipitation extremes, a year from a given station was not used if it had more than 19 days of flagged or missing data. A day was deemed dry if precipitation was less than 1 mm; missing days were assumed to be wet. For the maximum five-day precipitation total, precipitation for any day with missing or bad data was assumed to be 0. Thus, the maximum five-day total period could include a missing day, though this was rare.

Plots of extreme event index anomalies were averaged over the watershed as follows. First, using only data from years that met the cutoff, time series of extreme index anomalies were created for each station, using 1974-1992 as the reference period (chosen subjectively based on data availability). Those stations were then averaged in a given year that passed the cutoff for that particular year.

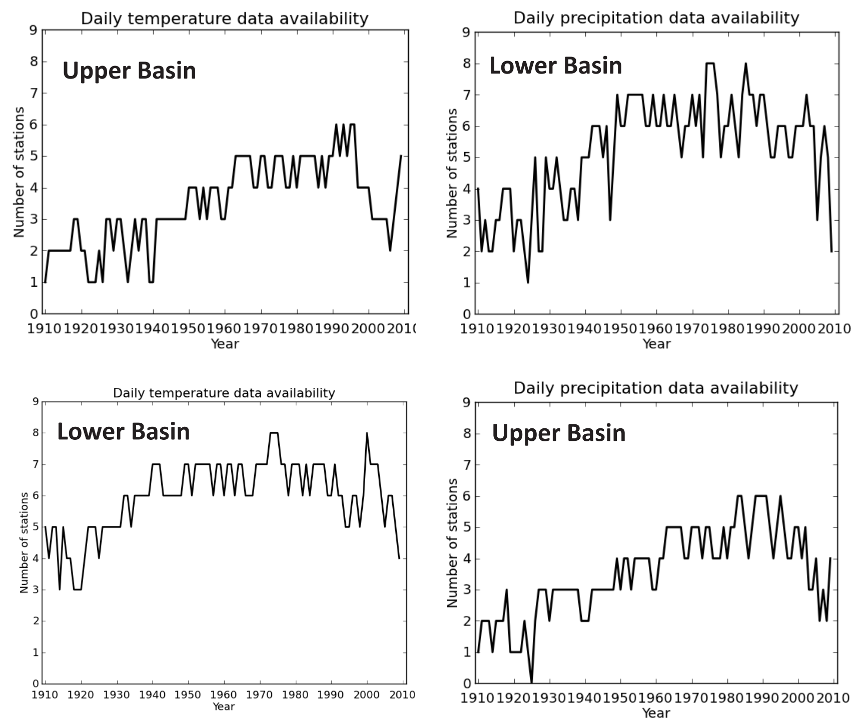

Fig. 7.6. Number of stations that passed the cutoffs for extreme event index calculations for temperature (left panels) and precipitation (right panels) in the lower (bottom panels) and upper (top panels) portion of the watershed

Table 7.3. Linear trends of extreme event indices for the upper and lower portions of the DRB. *p*-values are given in parentheses. Trends significant at the 90% and 95% confidence levels are underlined once and twice, respectively

Upper watershed	1974-1992 average	Trend (per decade)	
		1910-2009	1980-2009
# days per year above 90° F	10	-0.22 (0.42)	0.19 (0.91)
# days per year below 32° F	125	-0.43 (0.20)	1.5 (0.39)
Annual max # consecutive dry days	18	-0.097 (0.51)	-0.94 (0.20)
Annual max 5-day precip. total	10	0.10 (0.35)	1.2 (0.12)
# days/yr with precip. >4.5 cm	2.5	0.13 (0.0078)	0.47 (0.062)
Lower watershed	1974-1992 average	Trend (per decade)	
		1910-2009	1980-2009
# days per year above 90° F	18	0.37 (0.21)	-1.2 (0.59)
# days per year below 32° F	97	-0.84 (0.013)	-2.3 (0.16)
Annual max # of consecutive dry days	19	0.11 (0.50)	0.04 (0.96)
Annual max 5-day precipitation total	11	0.11 (0.30)	1.0 (0.04)
# days per year with precip. >4.5 cm	3.0	0.13 (0.0024)	0.47 (0.030)

3.2 Past Trends

Fig. 7.6 shows the number of stations that passed the cutoffs for temperature and precipitation described in Section 3.1. In most years, more than half of the stations meet the cutoffs. The greatest rejection rates are early in the 20th century and during the past few years; these are due, at least in part, to the start and end dates of the stations (Table 7.1).

Many of the trends in the five extreme event indices analyzed are insignificant, with the notable exception of the days per year of heavy precipitation, which shows a significant upward trend of 0.1 day per year per decade or 1 day per year per century in the upper and lower watersheds (Table 7.3 and Fig. 7.7 and 7.8). 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 1974-1992 reference period (3.0 days per year),

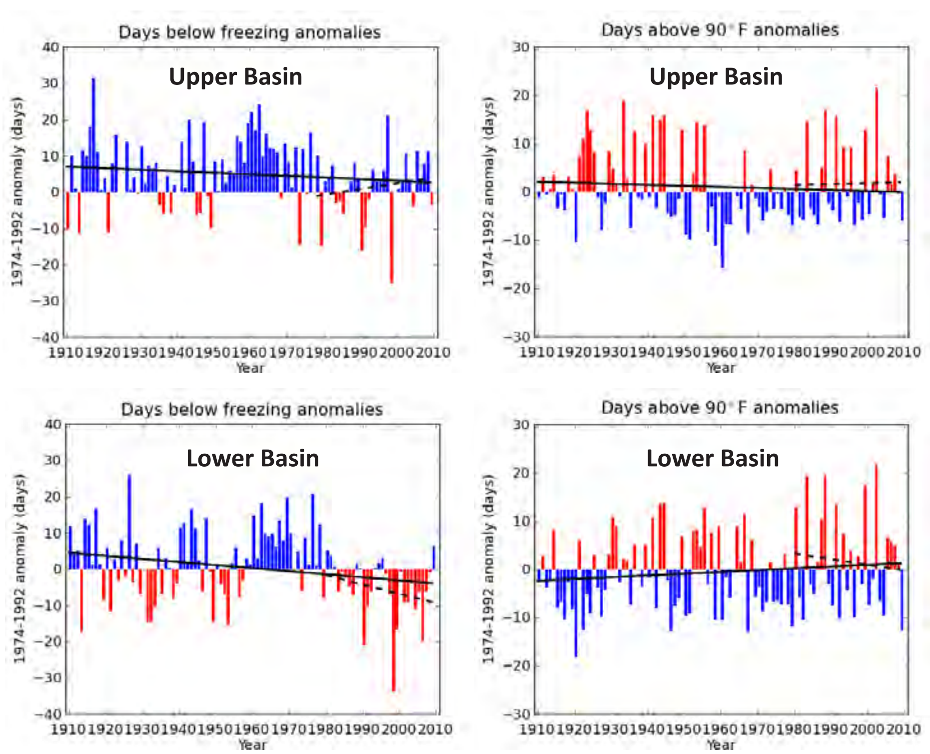

Fig. 7.7. Time series of the anomalies (with respect to the 1974-1992 average) of the number of days per year with low temperature below 32° F (0°C) (left panels) and high temperature above 90° F (32.2°C) (right panels) in the lower (bottom panels) and upper (top panels) portion of the watershed. Lines are least-squares linear fits to the 1910-2009 (solid) and 1980-2009 (dashed) periods

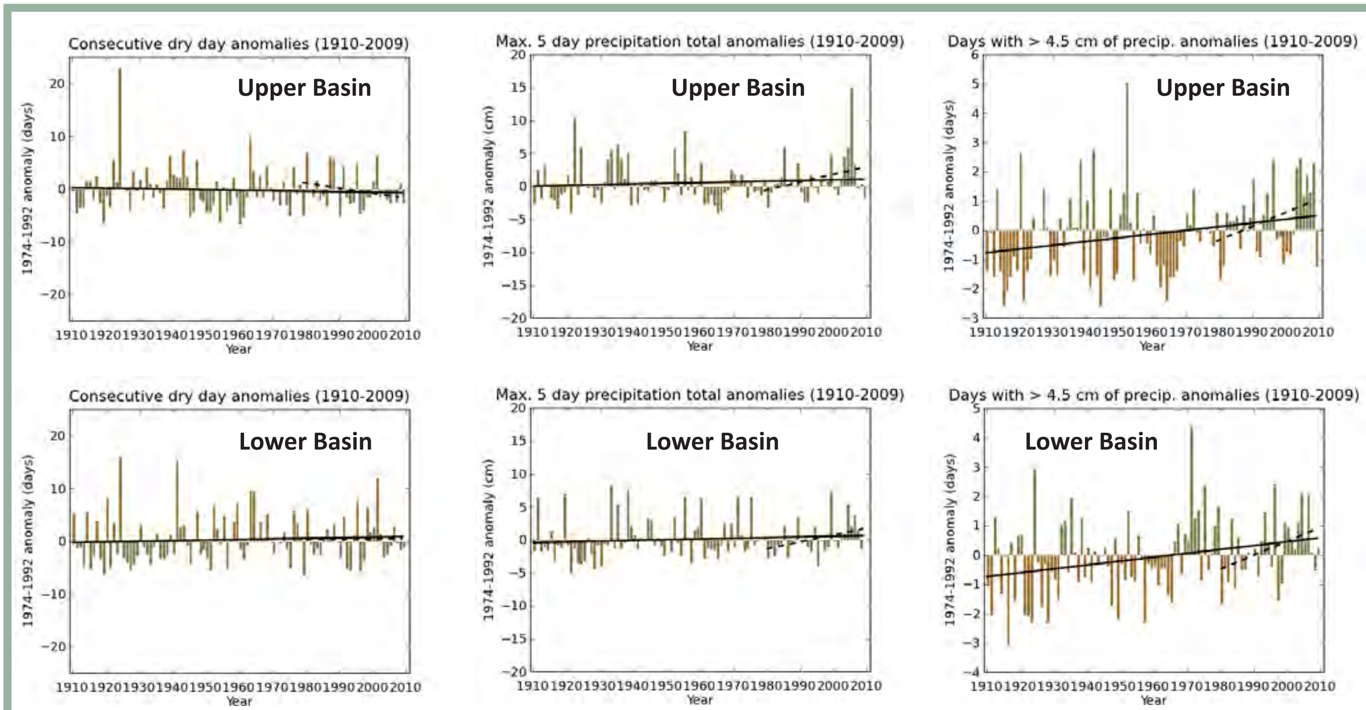

Fig. 7.8. Time series of precipitation extremes anomalies (with respect to the 1974-1992 average): annual maximum number of consecutive dry days per year (left panels), annual maximum 5-day precipitation total (middle panels), and number of days per year with precipitation exceeding 4.5 cm. Upper watershed is shown in upper panels and lower watershed in lower panels. Lines are least-squares linear fits to the 1910-2009 (solid) and 1980-2009 (dashed) periods

the increase is about 30%; an earlier reference period would give an even larger fractional increase. Also, in the lower watershed, we find a significant decline in the number of freezing days over the past 100 years, which is consistent with a similar decline found by Brown et al. (2010) throughout the Northeast U.S.

3.3 Future Predictions

Although there is considerable uncertainty in predicting future climate extremes, the current consensus is that the increased annual-mean precipitation (Section 2.3) projected for this century will be associated with more frequent extreme events. Three quarters of the climate models analyzed by Kreeger et al. (2010) predicted increases in the frequency of extreme hydrological metrics, including heavy precipitation and consecutive dry days. The U.S. Global Climate Research Program also predicted increases in extreme weather events and associated risks from storm surges (GCRP 2009).

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 bias adjustment in daily precipitation and mean, minimum, and maximum temperature. 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. The science and management community in the DRB should stay abreast of regional and national climate studies that predict extreme events and storm intensity and frequency. Understanding of complex global and regional climate cycles and oceanic feedbacks is rapidly evolving but is still very limited. Nevertheless, warmer and wetter air masses are expected to provide suitable conditions to fuel stronger and more frequent weather events.

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. There was, however, a significant decrease in the number of extreme cold events in the lower watershed. On the other hand, heavy precipitation events increased in frequency in both the upper and lower basin. This upward trend in extreme precipitation events was more striking for the recent past (1980-2009) than over the past century (1910-2009). Similarly, 5-day rainfall totals increased during the last 30 years in the lower basin, which also had less frost days. Most climate scientists predict increasing extreme events in the future, but there is still a lot of uncertainty in this facet of climate science.

4 - Snow Cover

4.1 Description of Indicator

The snow cover product used here, The Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent Version 3, is from the National Snow and Ice Data Center (NSIDC, Armstrong and Brodzik 2005). This 25-km resolution product was created by the NSIDC by re-gridding data products from the Rutgers University Global Snow Lab (much of which actually has a resolution coarser than 25 km). Data are binary, with 0 indicating no snow and 1 indicating snow. Continuous data are available for the period 1967-2006. For each of the approximately 60 grid points in the DRB, the fraction of weeks each year with snow cover was computed. Those fractions were then averaged to arrive at the DRB-wide snow cover fraction for each year. The anomaly of the snow fraction was computed relative to the 1974-1992 average (for consistency with the extremes metrics) and expressed as a percent difference.

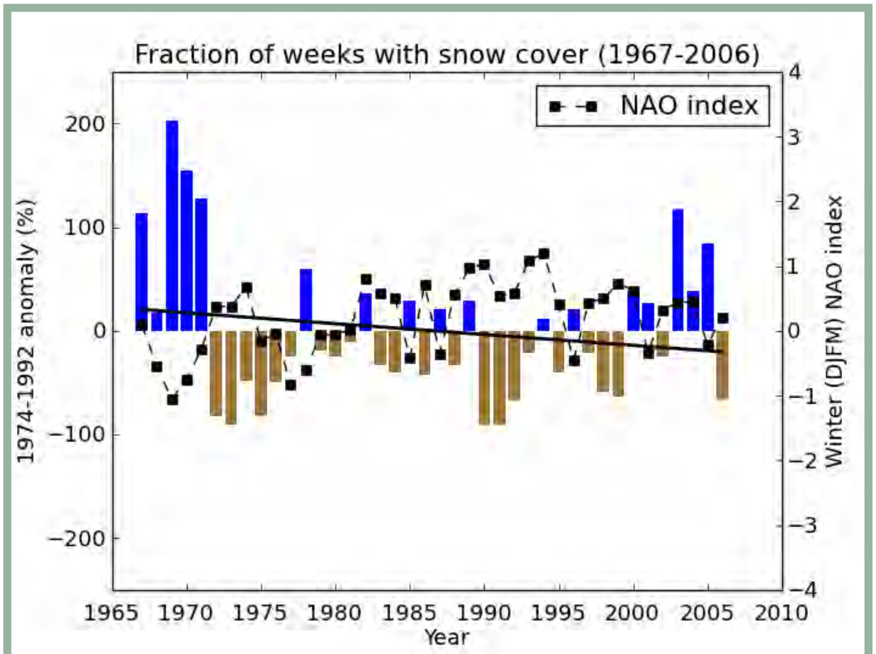

Fig. 7.9. Time series of snow cover anomaly (with respect to the 1974-1992 average) in the Delaware River Basin (bars) and the winter NAO index (squares). The solid line is a linear fit to the snow cover data

4.2 Past Trends

Figure 7.9 shows that snow cover in the DRB has varied dramatically, with some years having twice the mean snow cover and some years with essentially zero snow cover. The linear trend is negative and about 10% per decade but is not significant (p = 0.029). The winter North Atlantic Oscillation (NAO) index, acquired from the Climate Prediction Center, is significantly (p = 0.001) negatively correlated (r = -0.50) with DRB snow cover (Fig. 7.9). This result is consistent with analyses showing a negative correlation between the winter NAO index and snowfall in the eastern United States (Seager et al. 2010).

4.3 Future Predictions

Approximately 20 fewer frost days per year are predicted by mid-century and 40 fewer frost days by the end of the century under a "A2" emission scenario (Kreeger et al. 2010). With fewer frost days, the snowpack in DRB is predicted to be smaller and melt earlier (UCS 2008). The reduction or loss of the winter snowpack, combined with higher winter precipitation, will contribute to greater winter flooding and lower amounts of springtime snowmelt runoff.

4.4 Actions and Needs

Snowfall depends on many factors in addition to temperature, such as the status of the NAO; 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. For example, stronger winter storms such as occurred during the winters of 2010 and 2011 were sufficient to entrain cold air into the DRB, resulting in record snowfall despite overall warming conditions.

4.5 Summary

Snowfall is highly variable from year to year, influenced by many factors that govern upper air movements, storm intensity, and temperature of course. 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 Delaware River Basin. 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.

5 - Wind Speed

5.1 Description of Indicator

Wind speed data were acquired from the National Climatic Data Center for four stations in the region (Fig. 7.1): Wilmington, DE (1948-2009); Allentown, PA (1948-1994); Philadelphia, PA (1955-1994); and Atlantic City, NJ (1971-2010). The 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). To compute a seasonal average, at least 63 observations were required from each of the 4 hours. Annual averages were computed when all seasonal averages were defined. Statistical quality control procedures of Vautard et al. (2010) were followed to eliminate outliers. Anomalies were computed with respect to the 1974-1992 average and then averaged

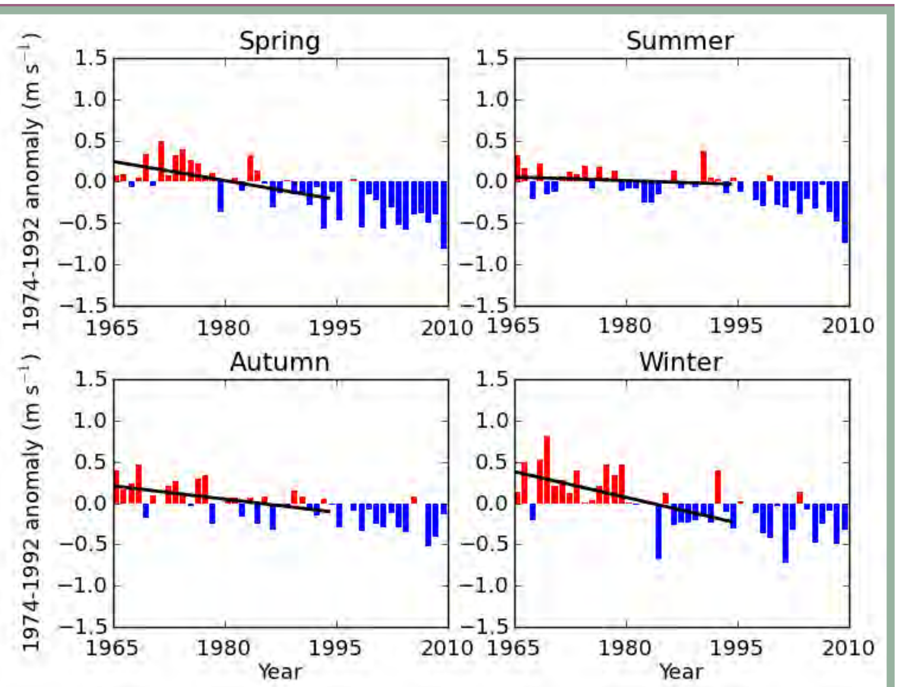

Fig. 7.10. Time series of wind speed anomalies (with respect to 1974 -1992 average) for each of the seasons averaged over the four wind stations (see text). Solid lines show least-squares linear fits between 1965 and 1995

over the four stations. 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 1998). 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. (2000), such a change resulted in low winds reported lower and high winds reported higher; calm wind reports nearly doubled. Post-1995 data are presented, but the trend analysis is restricted to 1965-1995.

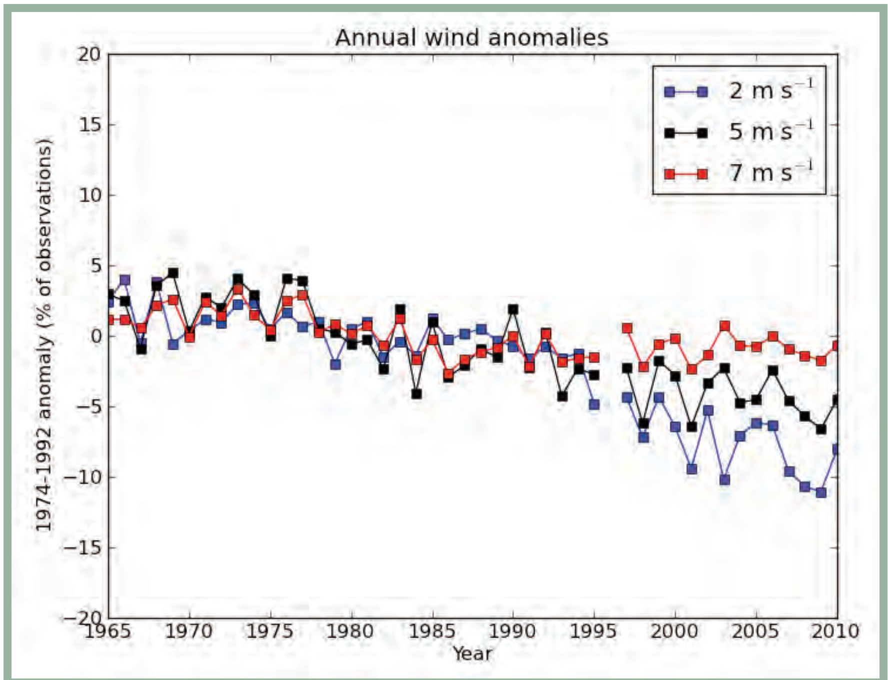

Fig. 7.11. Time series of the four-station average (see text) of the annual anomaly (with respect to the 1975-1992 average) of the percent of observations exceeding wind speed thresholds of 2, 5, and 7 m s^{-1}

5.2 Past Trends

Annual-mean wind speeds in the region decreased 0.12 m s^{-1} per decade between 1965 and 1995, a decline of 9% in 30 years (Table 7.4 and Fig. 7.10). Winter and spring declines are even larger. Declines are relatively uniform across the wind speed distribution (Fig. 7.11). The divergence in the trends for different wind speeds, which begins in 1995, is likely a result of the switch to the ASOS network. Over the past 30 years, long-term wind speed declines have occurred over much of the Northern Hemisphere's land masses, and such 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). Pryor et al. (2009) found differences among U.S. wind speed trends in observations, regional climate models, and reanalysis products (a blending of models and data), and were not able to determine the cause of the observed wind speed decline.

Table 7.4. Means and linear trends (1965-1995) of annual and seasonal wind speed averaged over the four wind speed stations (see text)

	Mean (m s^{-1})	Trend (m s^{-1} decade^{-1})
Annual	4.0	-0.12
DJF	4.4	-0.21
MAM	4.6	-0.15
JJA	3.5	-0.03
SON	3.7	-0.11

5.3 Future Predictions

Future predictions of wind speed have not been analyzed in the DRB. However, if recent trends are any indication, future winds may depend more on land use management than climate.

5.4 Actions and Needs

Since wind speeds are decreasing, this 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.

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 Delaware River Basin.

6 - Streamflow

6.1 Description of Indicator

Daily streamflow at Trenton, NJ was obtained from the United States Geological Survey (USGS) and was averaged by season and year. Anomalies were computed with respect to 1974-1992 averages.

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% (Fig. 7.12). Trenton streamflow is highly correlated with DRB precipitation (Najjar et al. 2009) and shows increases of 4.2 m^3s^{-1} per decade over 1913-2009 ($p = 0.16$) and 47 m^3s^{-1} per decade over 1980-2009 ($p = 0.015$). Seasonal trends over 1913-2009 and 1980-2009 are positive and significant at the 90% level for autumn and winter but not for the other seasons (Fig. 7.13).

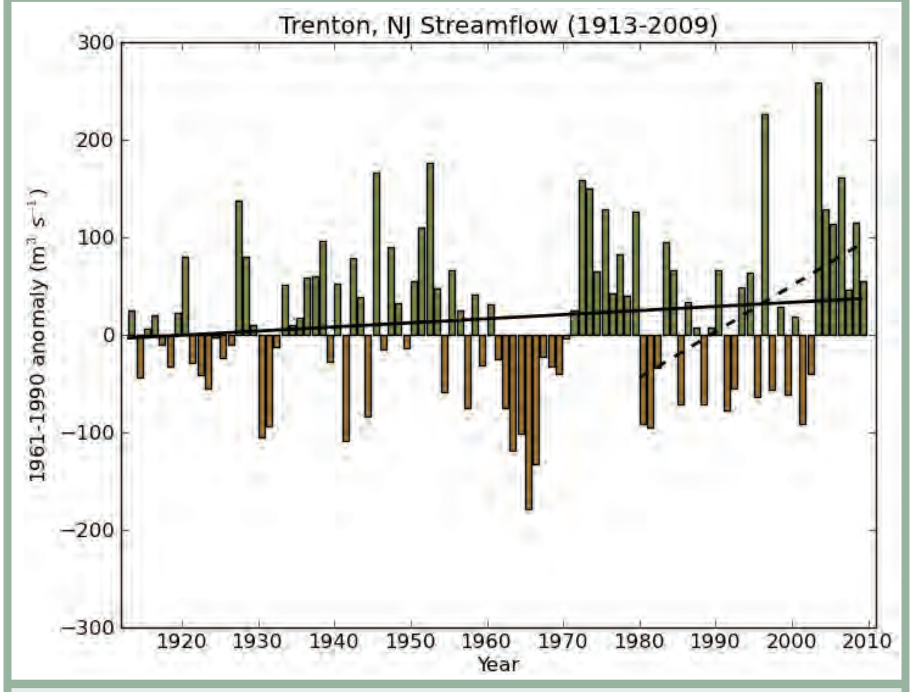

Fig. 7.12. Time series of annual average streamflow anomaly (with respect to 1974-1992 average) at Trenton, NJ. Lines are linear fits over the periods 1913-2009 (solid) and 1980-2009 (dashed). The anomaly is the departure from the 1961-1990 average, which is 320 m^3s^{-1}

6.3 Future Predictions

Streamflow is tightly correlated with precipitation even though much of the runoff in the DRB is regulated by reservoirs. Future predicted increases in precipitation may lead to greater runoff, particularly if less water infiltrates because of reduced snowpack and more flashy storm events. However, increased temperature will increase evapotranspiration, making less water available for runoff. Therefore, annual streamflow changes are highly uncertain in the mid-Atlantic region (Najjar et al. 2009); increases in winter and spring flow, however, are likely.

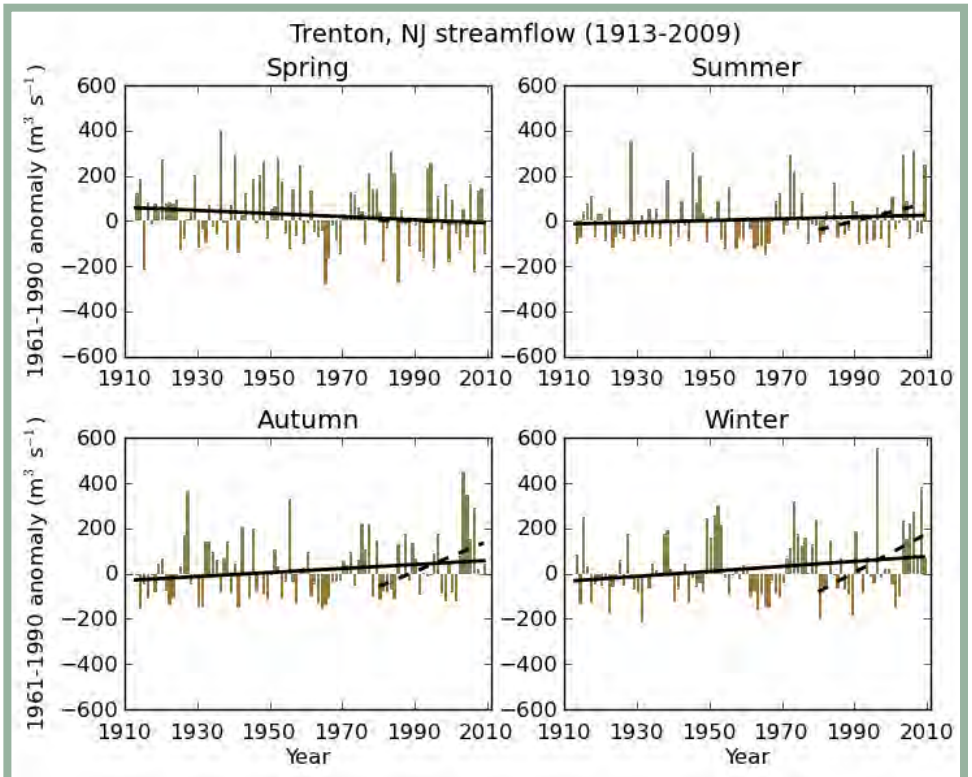

Fig. 7.13. Time series of Trenton, NJ streamflow anomalies (with respect to 1974-1992 average) for each of the seasons. Lines are least-squares linear fits to the 1910-2009 (solid) and 1980-2009 (dashed) periods

6.4 Actions and Needs

Funding cutbacks threaten to diminish USGS monitoring capabilities for streamflow. Continued monitoring of stream and river flows is critically important to track changes in the water budget of the DRB, which affects estuarine salinty and freshwater availability for people and the environment.

6.5 Summary

Increased fall and winter streamflow has occurred across the Delaware River Basin, particularly in recent decades, due to increases in precipitation (Section 2). In the future, this upward trend in runoff, particularly in the winter, is expected to continue as a result of predicted further increases in precipitation, more episodic events, and reduced snowpack.

7 - Ice Jams

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 data base contains occurrences of ice jams in numerous rivers of the northern United States. This section summed the occurrences in the DRB and in the Delaware River alone.

7.2 Past Trends

The top panel of Fig. 7.14 shows that the number of ice jams that have been reported over the past 80 years in the DRB and in the Delaware River has been declining. 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 during this time (Fig. 7.4), which is expected to lead to fewer ice jams. Indeed, as the bottom panel of Fig. 7.14 shows, there is a strong negative correlation between the number of ice jams and the mean winter temperature.

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 inverse correlation with mean winter temperatures in the DRB.

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.

7.5 Summary

Ice jams represents 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 Delaware River Basin has appeared to decrease significantly, and the decline is directly associated with the mean winter temperature across the watershed. Since winter temperatures are predicted to increase markedly in the future, ice jams are expected to become still less frequent.

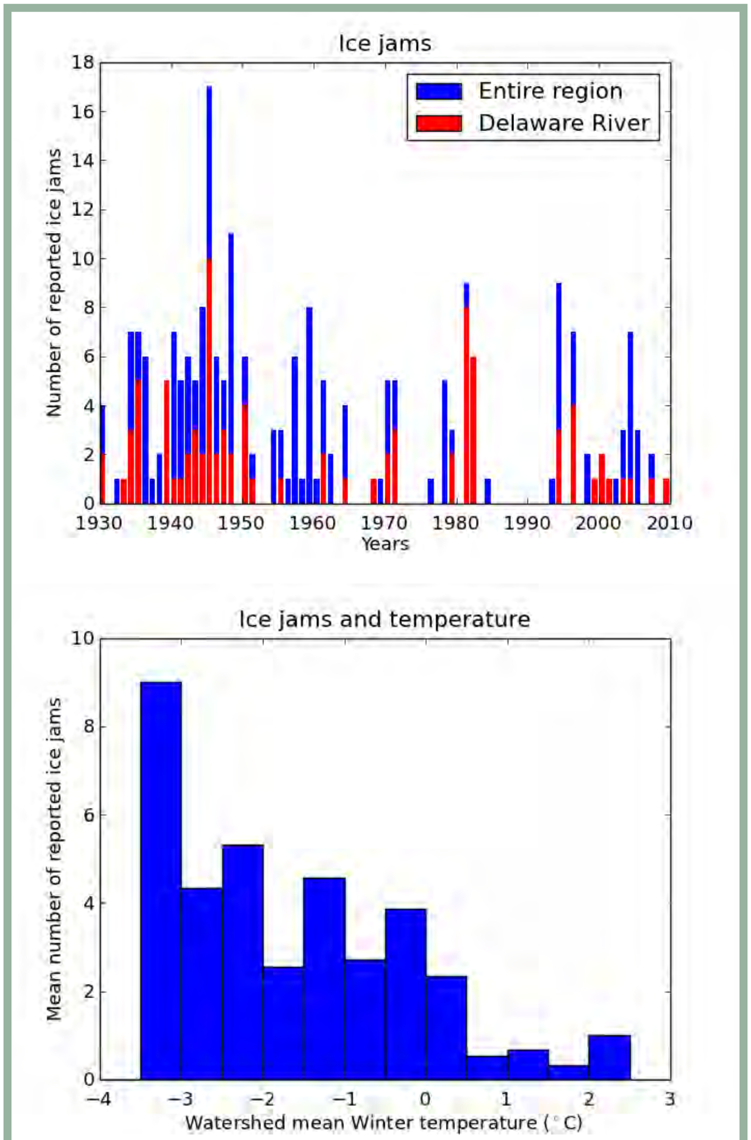

Fig. 7.14. Top panel: annual ice jam reports in the entire Delaware River Basin and in the Delaware River. Bottom panel: the number of reported ice jams binned into mean watershed temperature intervals of 0.5° C. Watershed-mean winter temperature is taken to be the average of the upper and lower watershed temperature

8 - Sea-level Rise

8.1 Description of Indicator

The coastline around the Delaware Estuary extends from Trenton, New Jersey, to Cape Henlopen in Delaware and to Cape May in New Jersey. Rising sea level is a growing concern with some Delaware and New Jersey Bayshore communities already calling the associated flooding an emergency situation. When combined with prospects for an increased frequency of intense storms (e.g., Lambert and Fyfe 2006), coastal flooding will become even more severe. Increased sea level is also expected to lead to greater loss of coastal wetlands, increased intrusion of saltwater into groundwater, and higher salinities, all of which threaten many important natural resources (Kreeger et al. 2010).

Sea-level rise is a natural phenomenon and natural resources and people have long adapted; however, an increase in the rate of sea-level rise will force more rapid adaptation in the future. This is why sea-level rise rate is the focus of this section.

8.2 Past Trends

The current rate of sea-level rise in the Delaware Estuary is 3.5-4.0 mm yr^{-1}, up from about 1.8 mm yr^{-1} in the early portion of the 20^{th} century (Gill et al. 2011). In the geologic history of the region, rates as high as 6-8 mm yr^{-1} have been estimated (Psuty 1986; Psuty and Collins 1996). Dr. Norbert Psuty (Rutgers University, Personal Communication) notes that during the Holocene when rates were most recently that fast, there were few tidal wetlands along the Mid-Atlantic coast. Reconstructions in the Delaware Estuary indicate that sea-level rise was approximately 1-2 mm yr^{-1} for the past 1,500 years until it more than doubled over the past 100 years (Engelhart et al. 2009).

8.3 Future Predictions

Absolute sea-level rise refers to the global rise of water resulting from melting ice sheets and expanding water as it warms. In the Delaware Estuary, two other factors will contribute to relative sea-level rise, which refers to the sea-level rise an observer fixed to the land surface would experience. These two factors are changing ocean currents and subsidence.

Regional variation in absolute sea level occurs because of gravitational forces, wind, and water circulation patterns. A decrease in current velocity of the Gulf Stream is an example, whereby less water will be pushed offshore by abated Coriolis Effect forcing. Under a “A2” greenhouse gas emissions scenario, changing water circulation patterns such as this are expected to increase sea-level by approximately 10 cm by 2100 in coastal regions of the northeast U.S. (Yin et al. 2009).

Subsidence is the sinking of the land surface due to post-glacial settling, which has occurred in the Delaware system since the last Ice Age. This settling causes a steady loss of elevation. Withdrawals of groundwater for irrigation and other uses are believed by some scientists to increase subsidence. Through the next century, natural subsidence is estimated to hold at an average 1-2 mm of land elevation loss per year (Engelhart et al. 2009), but perhaps greater if water withdrawals increase.

For these reasons, the Mid-Atlantic States are anticipated to experience sea-level rise greater than the global average (GCRP 2009). In its 2010 report, the Partnership for the Delaware Estuary noted that sea-level projections are being updated frequently and it decided to plan for an increase in sea level of 0.5 m, 1 m and 1.5 m without predicting the date. Most agencies in the region are currently planning for either 1 or 1.5 m by 2100. For every 1 m of global absolute sea-level rise, it is plausible to expect 1.2 m (or more) of relative sea-level rise in the Delaware Estuary.

Sediment accretion from accumulated plant matter and trapped sediments can act locally to offset this sinking and help land keep pace with sea-level rise. However natural accretion rates are rarely more than 5 mm yr^{-1}. If sea level rises 1 m by 2100, at some point the rate must become greater than 10 mm yr^{-1}, and so accretion is unlikely to be sufficient to offset sea level rise and subsidence in most areas.

8.4 Actions and Needs

Predicting rates of sea-level rise is critically important for coastal planners and resource managers due to the tremendous consequences for people and the environment, which depend on the timeline. Natural ecosystems and living resources all have tolerance limits for the rate of change to which they can adapt. Tipping points might be breached for some habitats such as salt marshes, a hallmark feature of the Delaware Estuary.

More research and monitoring is needed to track whether sea-level rise is contributing to or will contribute to increased salinity in the estuary and intrusion into groundwater. Since relative sea-level rise differs from absolute sea level rise, some of the elevation benchmarks may need to be replaced around the estuary due to past subsidence causing potential inaccuracies.

8.5 Summary

Sea levels in the Delaware Estuary have risen by about a foot in the last century (~0.3 m), which was a faster rate of increase than the previous 15 centuries when it was about half a foot per century. Over the next 90 years, most agencies are now planning for at least a 3 foot (0.9 m) rise, perhaps more. The science is still evolving, and scientists and managers will need to stay abreast of new developments and plan carefully and accordingly because of the potential severe effects of this scenario on coastal flooding and natural resource sustainability.

9 - Additional Considerations & Indicator Needs

9.1 Storm Intensity and Frequency

Climate change is expected to lead to environmental conditions that would support more frequent intense storm events, including both warm-season tropical cyclones (Kerr 2010) and cool-season extratropical cyclones (Lambert and Fyfe 2006). However, there is considerable scientific uncertainty in predicting future storminess. Looking at past trends, it is unclear whether storm intensity or frequency have increased, although as noted previously there is some evidence from surrogate indicators (extreme precipitation events) that storms may be on the increase.

As a proxy for storm intensity, barometric pressure data was examined from Atlantic City for the period 1947-2010 (except for 1965-1972 when data were not available). Daily mean atmospheric pressures were adjusted to sea-level, which is done to standardize pressure data collected from different stations that have different altitudes (Atlantic City station is located at 18 m elevation). The number of days per year with mean pressures below 1000, 990, and 980 millibars (mb) were counted, as well as the number of two-day events below 1000 mb. The number of days per year with low pressure was then contrasted among decades. No trends were apparent in any of these low-pressure proxies for storm intensity or frequency (e.g., Fig. 7.15). Since Atlantic City is not situated within the DRB and the long-term dataset is incomplete, it may be worth identifying and analyzing other relevant long-term datasets for atmospheric pressure or other direct indicators of storm severity for the Mid-Atlantic region.

9.2 Biological Indicators of Climate Change

This chapter summarizes past and predicted changes in physical conditions that are related to climate because these have generally been monitored and reported for a long time and because they serve as ecological drivers that govern biological activity. However, there is also a need to identify and develop biological indicators of climate change, which document ecological responses to changes in physical conditions. Biological indicators of climate change can take the form of altered species-species relationships (e.g., pollinators, shorebirds/horseshoe crab eggs), altered functionality and ecosystem services (e.g., water filtration by suspension-feeders, carbon sequestration by wetlands), and shifting species ranges (all major taxa), life history strategies (e.g., subtidal versus intertidal oysters) or physiological ecology (e.g., thermal stress, and oxygen consumption rates).

The Delaware Estuary and River Basin have high biodiversity, and preservation of this diversity is important for many reasons. However, a limited subset of plants and animals are often the functional dominants in terrestrial and aquatic habitats. These dominant biota and their associated habitats perform numerous life-sustaining services to people and natural resources (e.g., clean air and water, fish and wildlife habitat, nutrient and carbon sequestration, primary production of food, and microbial remineralization). Therefore, it will become increasingly important to sustain these key resources despite changing climate conditions and increasing pressures from human population growth and continued development.

To report the status and trends of future biological indicators of climate change, investments are needed in research and development of the indicators and associated monitoring infrastructure in cases where appropriate metrics are not currently being tracked.

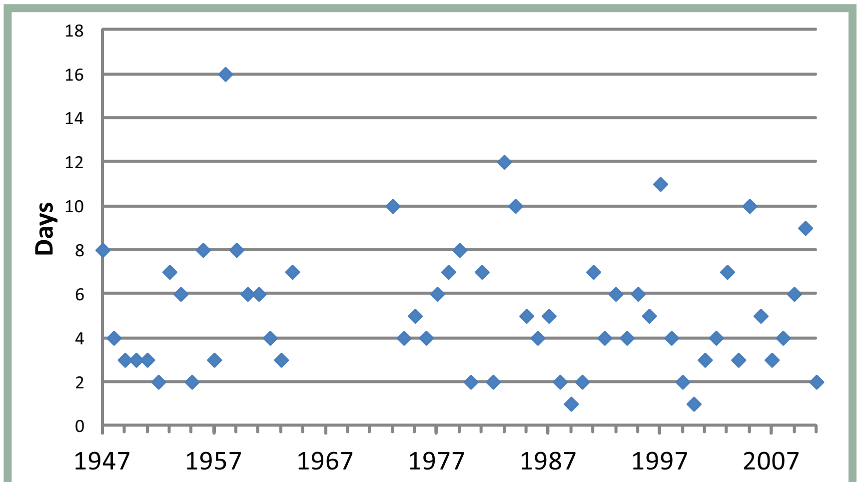

Fig. 7.15. Number of days per year for which the mean atmospheric pressure was less than 1000 mb at Atlantic City, NJ

9.3 Interactions Between Climate Change and Watershed Change

The consequences of future climate change for people and natural resources in the DRB are expected to vary in severity and rapidity. Some changes are expected to occur gradually, whereas others will appear suddenly when thresholds are breached. At the same time, the human population is expected to increase by 80% by 2100 (Kreeger et al. 2010). Until improvements are made to tracking of status and trends, it may be challenging to attribute specific changes to climate change because of complex interactions in the region's ecosystem. Living resources and habitats that are stressed because of direct anthropogenic impacts (e.g., development and pollution) are likely to be more vulnerable to the negative aspects of climate change. On the other hand, the longer growing season and increased plant productivity could impart some added resilience to buffer changes.

To discern between watershed change and climate change as drivers for future changes in environmental conditions, it will be increasingly important to monitor key ecosystem conditions. Currently, resource managers in the Delaware Estuary and River Basin are hampered by a lack of an ecosystem-based, watershed-based model that describes the basic physical, chemical and biological interactions that currently exist. Although cross-sector communication has increased in recent years, managers continue to focus on particular aspects of the system without a holistic context that would be provided by an ecosystem model. Development of an ecosystem-based model would help today's and tomorrow's managers more effectively address and discern the effects of climate and watershed change and to strategically respond to negative stressors with countermeasures.

10 – Summary

An analysis has been conducted of changes in a wide variety of climate metrics in the Delaware River Basin and sea level in the Delaware Estuary. It was found that the watershed is getting warmer and wetter, as expected given the observed increase in greenhouse gases. However, the magnitude and timing of the precipitation change is not consistent with climate model simulations and thus may be a result of natural variability. Some metrics of extreme temperature and precipitation are following changes in mean conditions. For example, decreases in ice-jam and frost day frequency and an increase in the number of heavy precipitation days were found. However, many metrics of extremes, including storminess, do not show significant trends. Wind speeds have declined substantially but the causes are not well understood. Streamflow is generally on the increase, and is consistent with the precipitation change. Finally, sea level is on the rise in the Delaware Estuary, exceeding the global average rate due, at least in part, to local subsidence. In summary, many aspects of the climate of the Delaware estuary and its watershed are undergoing change, and there is some understanding of these changes. A modeling framework that links the atmosphere to the watershed and its estuary will not only help to improve understanding of past change but allow for more robust future predictions.

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