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Precipitation Trends across the Commonwealth of Virginia (1947 – 2016)

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ABSTRACT

Water is an important resource for the Commonwealth of Virginia. Too much water increases runoff, disrupt transportation networks, and contributes to school closures. Too little water may adversely impact agricultural operations. To improve climate-related information to Virginia citizens, this study assesses means and changes in precipitation across the Commonwealth of Virginia (1947 – 2016). Using daily station-level precipitation data from the Global Historical Climate Network (GHCN), descriptive statistics were calculated for 43 locations in terms of total precipitation (inches decade^{-1}), precipitation days (x>0"), and heavy precipitation days (x>1.0"). On average, locations showed an overall increase in total precipitation across the time period. The frequency of heavy rainfall events has also increased across many of the analyzed locations. Precipitation has important ramifications for agriculture, storm water management, and hazard response, and improved coordination of atmospheric-related information may be beneficial to various stakeholders across the Commonwealth.

INTRODUCTION

Heavy rainfall can lead to numerous hazards including flooding, landslides, and loss of life. From 1980 – 2013, 19 flood-related, billion-dollar disasters occurred in the United States (Smith and Matthews 2015). Combined, these events averaged a price tag of $4.5 billion. Hurricane Agnes, Fran, and Irene coupled with non-tropical events such as rapid snowmelt and ravine flooding highlight the concern in the Commonwealth of Virginia. Of the 64 federal disaster declarations issued by FEMA for the Commonwealth, 27 highlighted flooding. Others explicitly reference tropical systems or hurricanes (FEMA 2018).

While tropical systems often impact the coastal plain, precipitation associated with hurricanes often leads to inland flooding (Rappaport 2000). Mesoscale features recently flooded parts of Cape Charles, and heavy rain associated with Tropical Storm

Michael flooded parts of southwest Virginia. Flooding and heavy precipitation events (HPE) are recognized as a major hazard across the Commonwealth.

While state legislature refers to some events as so-called *nuisance* or *sunny day flooding*, flooding disrupts transportation networks, leads to cancellation of school, and plays a role in more prolonged impacts such as mold and mildew (Wong et al. 2014; Chew et al. 2006). HPE intertwine land use policy, hazard mitigation awareness, and future climate change. Recent studies have indicated shifts in the frequency and intensity of precipitation events (Lewis et al. 2018; Kunkel 2003; Wuebbles et al. 2014; Heineman 2012). In the southeast, extreme rainfall events are increasing though many stations along the Appalachian Mountains show a downward trend (USGCRP 2018). While both natural and anthropogenic forcing mechanisms are associated, it is likely that increases in atmospheric water vapor content may lead to further increases in such heavy precipitation events (Kunkel 2003).

In the United States, Peterson et al. (2013) provides a comprehensive overview of weather- and climate-related extremes. While regional assessments exist (Agel et al. 2015; Sayemuzzaman et al. 2014; Boyles and Rama 2003), the existence of climatological reviews of HPE in Virginia are unknown. The Virginia Climate Office provides some information, but the data portal is based on a climatological period that may not adequately represent the most recent changes in our Virginia climate.

This research assesses the climatological trends associated with precipitation across the Commonwealth of Virginia and draws attention to the need to better coordinate weather-related information that may be beneficial in emergency management operations, planning of our cities, or minimizing the consequences of future weather/climate-related impacts.

DATA AND METHODS

The Global Historical Climate Network (GHCN) is a database of land-based stations around the world. Subjected to detailed quality control (Menne et al. 2012), these data include a wide range of atmospheric variables such as temperature and precipitation at a variety of temporal scales (e.g. hourly; daily). Using the Climate Data Online (CDO) tool, daily precipitation values were obtained through the National Centers for Environmental Information (NCEI; 1947 – 2016). Shorter, more recent sub-periods were analyzed (1987 – 2016), but due to the heterogeneity in precipitation and limited statistical significance, these results are not shown. For this research, stations located in Virginia were selected, and only stations with at least 90% complete record were included in the analysis. In total, 43 locations met this criterion (Figure 1; Appendix A).

Using SPSS 19, descriptive statistics were generated for annual precipitation totals, precipitation days, and precipitation days exceeding 1.0” (heavy precipitation days). While other studies may use a higher threshold (Pommerenk 2016) or a cumulative value (e.g. Smirov et al. 2017), precipitation characteristics were selected based upon previous thresholds defining high precipitation days (Boyles and Raman 2003).

In addition to means, simple linear regression was used to calculate observed changes in precipitation and whether such changes were significant ($p<0.05$). The study also evaluated other thresholds (e.g. 2” days), but due to the rarity of these events and limited statistical significance, the results are not shown.

RESULTS

a. Means

Across the Commonwealth, annual precipitation averaged 43.02” year^{-1} (Figure 2; Appendix B). Only three locations average more than 50” of precipitation: Wallaceton, Meadows of Dan, and Woolwine. With only 36.2”, Woodstock averaged the lowest mean annual precipitation of any station. Local topography may help explain the variability in precipitation.

From 1947 – 2016, an average of 111 precipitation days occurred at each of the locations (Figure 2; Appendix B). Burkes Garden averaged the most precipitation days (140 year^{-1}) while Clarksville the fewest (88 year^{-1}).

On average, Virginia locations experienced 10 days year^{-1} with precipitation exceeding 1.0” (Figure 2; Appendix B). Similar to annual precipitation statistics, Meadows of Dan and Woolwine observed the most 1” precipitation days, with both exceeding an average of 15 such days year^{-1}. Six locations (Blacksburg, Lafayette, Pulaski, Staffordsville, Woodstock, Wytheville) averaged less than 8, one-inch precipitation days year^{-1}.

b. Changes and Trends

Regression analysis indicates an upward trend in mean annual precipitation for 39 of the 43 locations (Figure 3; Appendix C). As a whole, precipitation increased in Virginia 0.57” decade^{-1}. Of the increases, the greatest change was found in Wallaceton (1.40 inches decade^{-1}). Several other locations observed a significant increase of more than 1.0” decade^{-1}. In total, eight significant changes were found across the Commonwealth, all indicating an upward trend.

On average, total precipitation days increased 1.69 days decade^{-1} across the commonwealth. Burkes Garden showed the largest shifts with nearly 10 more precipitation days per decade. Thirty six of the 43 stations analyzed showed an upward trend in total precipitation days. Seventeen were found to be significant ($p<0.05$).

While similar results were found for heavy precipitation days, the overall frequency of these heavy events reduced the statistical significance (Figure 2; Appendix C). All locations except two indicated a shift towards more frequent heavy precipitation days. Eight of these stations showed a significant trend. On average, heavy precipitation days increased 0.29 days decade^{-1}. With values in excess of 0.60 days decade^{-1}, Buena Vista and Hopewell showed the largest changes.

As an illustration, Figure 4 displays the annual observations and associated changes at Norfolk International Airport.

DISCUSSION AND RECOMMENDATIONS

Over the 70-year period (1947 – 2016), mean annual precipitation in Virginia seems to have increased. Additionally, both individual precipitation and heavy precipitation days, days exceeding 1.0”, have also increased across much of the Commonwealth. While some precipitations variations may be associated with orographic features, the changes support other findings that show similar increase in precipitation (Smirnov et al. 2017; Pommerenk 2016; USGCRP 2018; Lewis et al. 2018). Karl et al. (2009) showed at 27% increase in heavy precipitation events in the southeast United States. In North Carolina, Boyles and Raman (2003) showed increases in precipitation during the fall and winter seasons but decreases in the summertime. The 4th National Climate Assessment (Figure 19.3) showed similar increases in precipitation across the southeast region. Over the past 25 years, days with 3 inches or more of precipitation has been historically high though decreasing trends did exist along the Appalachian Mountains (USGCRP 2018). While these studies utilize different time periods and geographic domains, the general increases in frequency and intensity in rainfall is consistent with the presented findings for Virginia. Using NOAA climate divisions, Hoffman et al. (2019) recently showed spatial variability in terms of precipitation across the Commonwealth. Future studies may explore the seasonal variability in station-level precipitation changes to uncover how precipitation is changing over the course of the calendar year.

Future projections indicate continued increases to the frequency and magnitude of heavy precipitation in the eastern United States (USGCRP 2018; IPCC 2014; Castellano and DeGaetano 2017; Kunkel et al. 2013; Wuebbles et al. 2014). Warmer air contains more water vapor, and research has shown the amount of water vapor has increased over both land and the ocean (Santer et al. 2007; Dai 2006). With changing precipitation intensity and frequency, *rain bombs* play an important role in groundwater recharge and agricultural runoff (e.g., Mohan et al. 2018), transportation systems (Suarez et al. 2005), and longer-term implications such as vector habitat or respiratory issues (Rochlin et al. 2013; Chew et al. 2006; IMO 2011). Such heavy rain events are important in the design of urban stormwater systems and mitigation of flood risk. Understanding the interconnectivity in precipitation changes, these events are also relevant in the context of a warmer world, rising sea level, and future hazard planning.

As with any study, limitations exist. While studies have used station-level data, other approaches such as fine-scale climate models (D’Onofrio et al. 2014; Maurer et al. 2007) may better represent larger geographical areas. Hydrologic watershed modeling may also help identify at-risk assets based on future precipitation scenarios (Balstrøm 2018; Larsen et al. 2010 Pedtrozo-Acuna et al. 2017). The physical mechanisms governing precipitation trends are not explicitly examined. Other studies have shown relationship between ocean circulation and atmospheric characteristics (Hoerling et al. 2016; Maleski and Martinez 2018). Variability in precipitation may be associated with larger scale phenomenon such as ENSO (el-Askary et al. 2004) and synoptic climatological approaches may be a useful approach to investigating spatial patterns in Virginia (Hewitson and Crane 2002; Dixon et al. 2016). Bindoff et al. (2013) showed *medium confidence* that anthropogenic forcing has contributed to heavy precipitation intensification. Other studies showed similar results in terms of anthropogenic climate change attribution (Easterling et al. 2016; Janssen et al. 2014; Balan Sarojini et al. 2012). Land-use modifications (Shepherd 2005; Mahmood et al. 2010) are also areas of potential future research.

Recent events associated with Hurricane Matthew and Florence draw attention to the need for robust data and state-level support for the Virginia Climate Office. A recent report suggested agricultural damage associated with Hurricane Michael topped $1.3 billion (Daniels 2018). In Central Virginia, prolonged rainfall disrupted transportation networks (Fox 2018). Changes in the intensity, duration, or seasonal timing of heavy precipitation events presents a wide range of challenges. These multi-sector challenges crisscross Virginia and require collaboration across disciplines, and decision-makers must rely upon updated, real-time information and the full body of peer-reviewed evidence. As local climate change impacts become more apparent, additional data and tools such as Geographic Information Systems, downscaled climate models, and advanced remote sensing tools should be leveraged to provide up-to-date information to stakeholders through the Virginia Climate Office.

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Figure 1. Virginia observation locations (Appendix A).

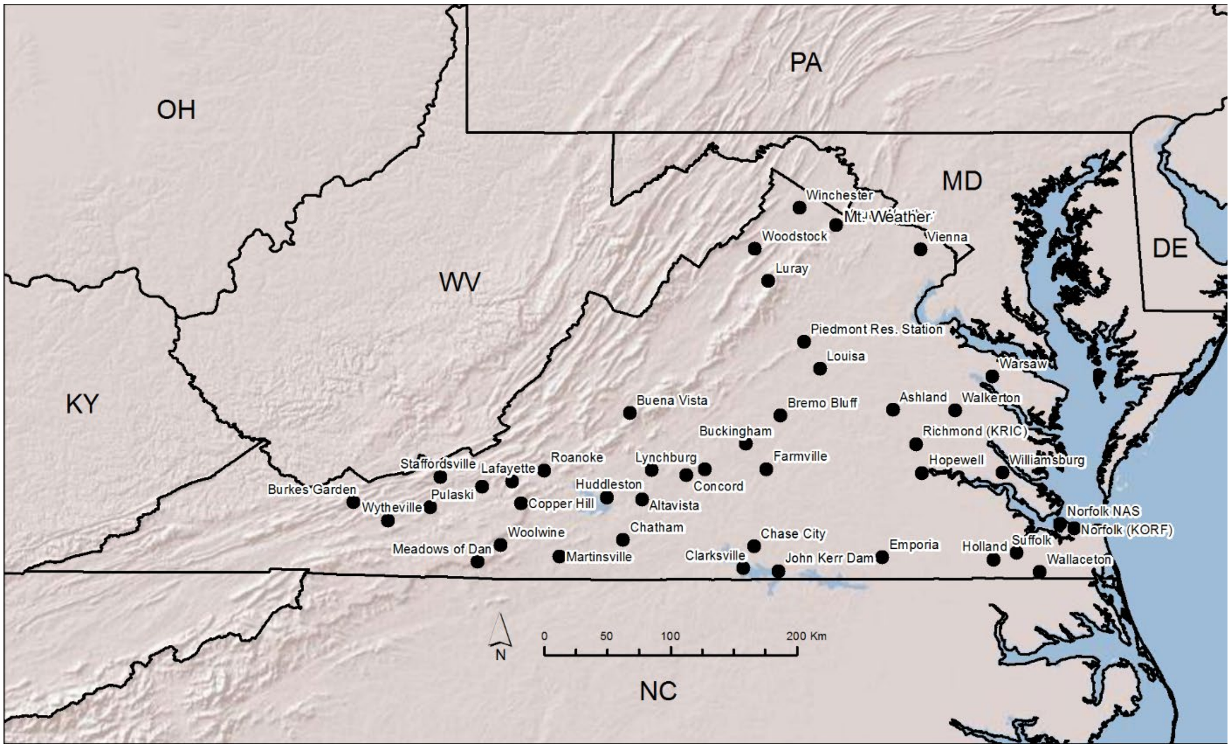


Figure 2. (top to bottom) Mean total Precipitation (inches), precipitation days, and heavy precipitation days (See Appendix B).

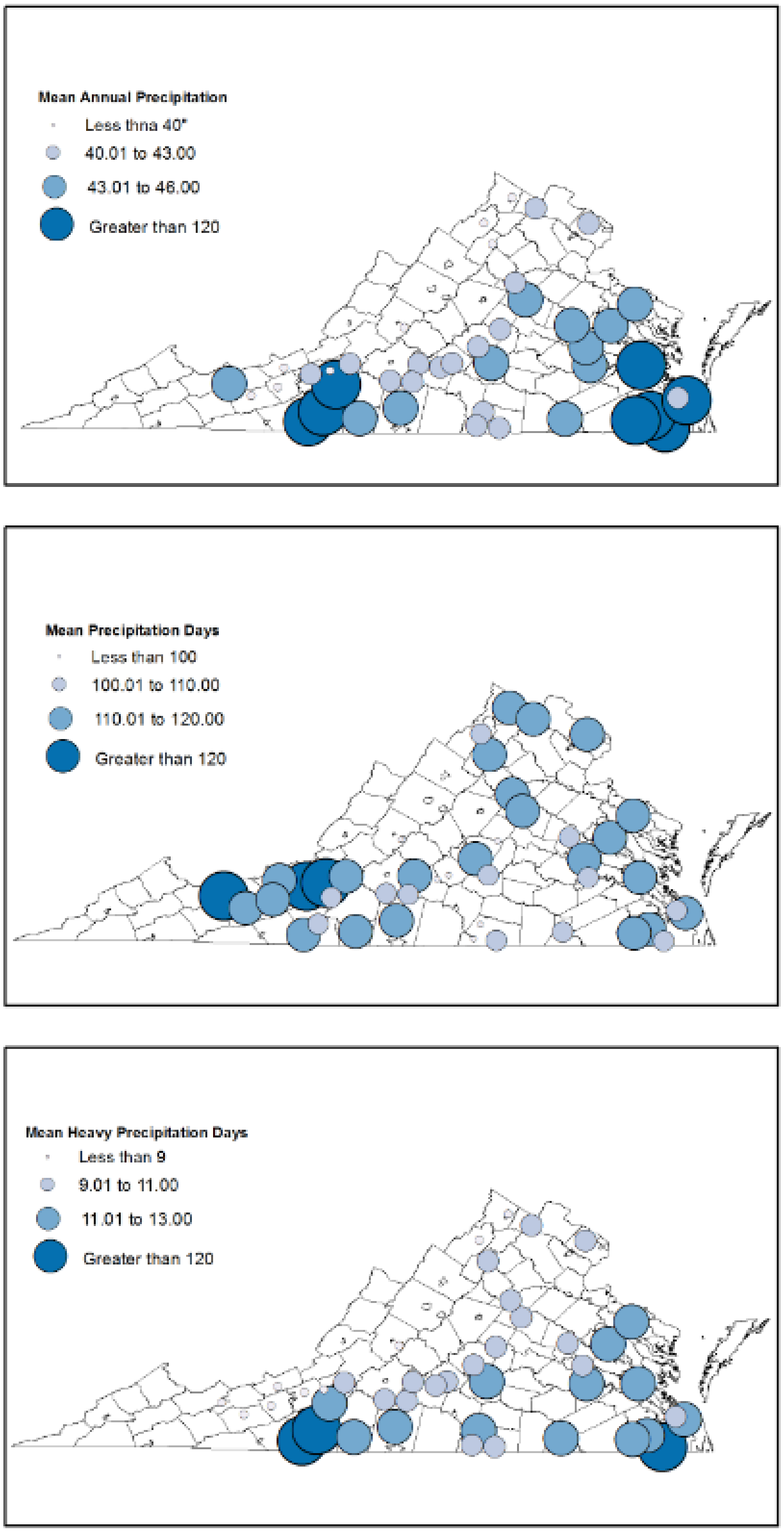


Figure 3. (top to bottom) Changes (decade^{-1}) in total precipitation (inches), precipitation days, and heavy precipitation days (Appendix C).

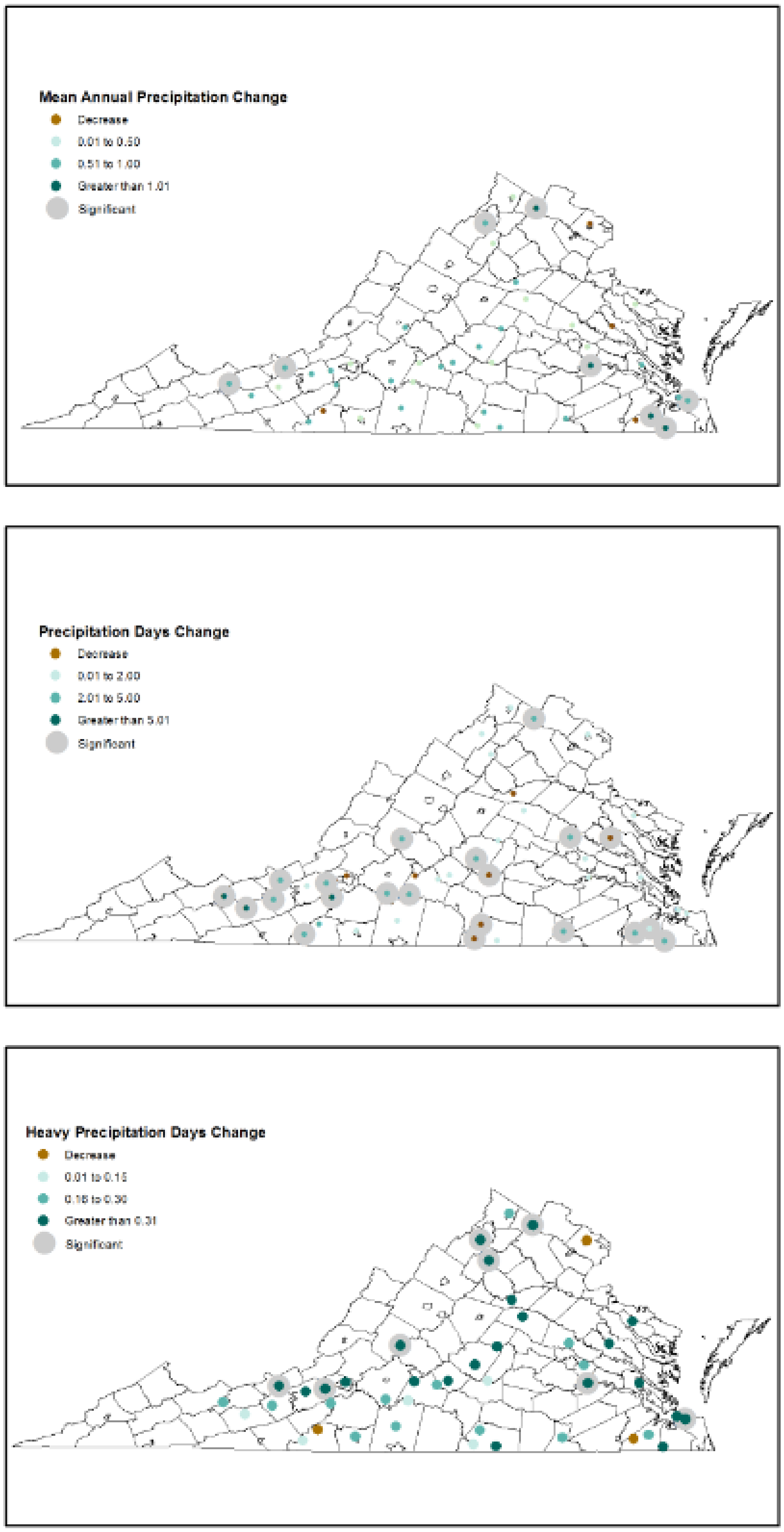
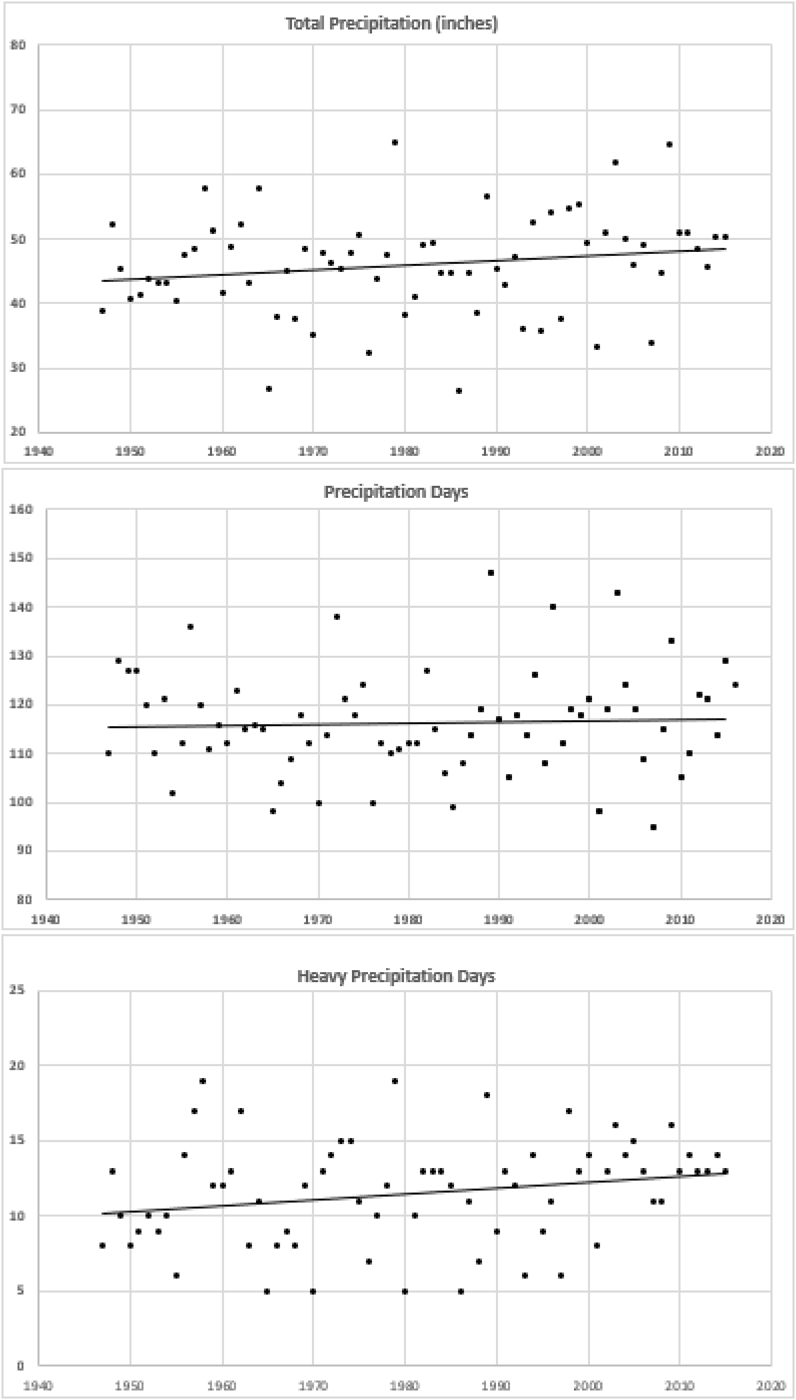


Figure 4. Annual total precipitation, precipitation days, and heavy precipitation days at Norfolk International Airport. Trend line associated with the observations.



Appendix A. Virginia observation locations

Station	Latitude	Longitude	GHCND ID	Elevation (m)
Altavista	37.1	-79.3	USC00440166	161.2
Appomattox	37.3	-78.8	USC00440243	259.1
Ashland	37.8	-77.5	USC00440327	67.1
Blacksburg	37.2	-80.4	USC00440766	641
Bremo Bluff	37.7	-78.3	USC00440993	68.6
Buckingham	37.5	-78.5	USC00441136	176.8
Buena Vista	37.7	-79.4	USC00441159	256
Burkes Garden	37.1	-81.3	USC00441209	935.1
Chase City	36.8	-78.5	USC00441606	155.4
Chatham	36.8	-79.4	USC00441614	198.4
Clarksville	36.6	-78.6	USC00441746	100.6
Concord	37.3	-79.0	USC00441955	248.4
Copper Hill	37.1	-80.1	USC00441999	870.8
Emporia	36.7	-77.6	USC00442790	30.5
Farmville	37.3	-78.4	USC00442941	137.2
Holland	36.7	-76.8	USC00444044	24.4
Hopewell	37.3	-77.3	USC00444101	12.2
Huddleston	37.1	-79.5	USC00444148	273.4
John Kerr Dam	36.6	-78.3	USC00444414	76.2
Lafayette	37.2	-80.2	USC00444676	402.3
Louisa	38.0	-78.0	USC00445050	128
Luray	38.7	-78.4	USC00445096	426.7
Lynchburg	37.3	-79.2	USW00013733	286.5
Martinsville	36.7	-79.9	USC00445300	231.6
Meadows of Dan	36.7	-80.4	USC00445453	678.2
Mount Weather	39.1	-77.9	USC00445851	505.7
Norfolk (KORF)	36.9	-76.2	USW00013737	9.1
Norfolk NAS	36.9	-76.3	USW00013750	5.2
Piedmont Research Station	38.2	-78.1	USC00446712	158.5
Pulaski	37.1	-80.8	USC00446955	563.9
Richmond (KRIC)	37.5	-77.3	USW00013740	50
Roanoke	37.3	-80.0	USW00013741	358.1
Staffordsville	37.3	-80.7	USC00448022	594.4
Suffolk	36.7	-76.6	USC00448192	6.7
Vienna	38.9	-77.3	USC00448737	127.4
Walkerton	37.7	-77.0	USC00448829	15.2
Wallaceton	36.6	-76.4	USC00448837	6.1
Warsaw	38.0	-76.8	USC00448894	42.7
Williamsburg	37.3	-76.7	USC00449151	21.3
Winchester	39.2	-78.1	USC00449186	207.3
Woodstock	38.9	-78.5	USC00449263	205.7
Woolwine	36.8	-80.3	USC00449272	457.2
Wytheville	37.0	-81.1	USC00449301	749.2

Appendix B. Annual mean precipitation, precipitation days, and heavy precipitation (1.0”+) days (1947 – 2016).

Station	Total Precipitation (inches year^{-1})	Precipitation Days (days year^{-1})	Heavy Precipitation Days (days year^{-1})
ALTAVISTA	40.9	101.7	10.6
APPOMATTOX	41.9	99.3	10.7
ASHLAND	43.0	101.2	10.9
BLACKSBURG NWS	40.7	129.5	7.7
BREMO BLUFF	40.2	98.1	10.1
BUCKINGHAM	42.6	111.3	10.7
BUENA VISTA	38.7	99.2	8.6
BURKES GARDEN	44.9	140.6	8.5
CHASE CITY	42.5	92.3	11.2
CHATHAM	44.2	116.6	11.1
CLARKSVILLE	40.8	88.8	10.1
CONCORD	42.4	99.3	10.6
COPPER HILL	46.5	107.1	11.6
EMPORIA	43.6	104.7	11.2
FARMVILLE	43.2	101.2	11.0
HOLLAND	48.3	114.3	12.3
HOPEWELL	44.9	109.3	11.5
HUDDLESTON	41.3	108.8	10.1
JOHN KERR DAM	42.0	108.9	11.0
LAFAYETTE	38.9	123.1	7.8
LOUISA	43.1	112.1	10.8
LURAY	39.8	114.9	9.4
LYNCHBURG	41.0	118.1	9.3
MARTINSVILLE	44.4	112.7	11.2
MEADOWS OF DAN	55.8	118.9	15.9
MOUNT WEATHER	41.5	111.7	10.0
NORFOLK (KORF)	46.3	116.4	11.5
NORFOLK NAS	41.1	109.8	9.4
PIEDMONT RES. STATION	41.5	114.7	10.5
PULASKI	37.1	113.1	7.9
RICHMOND (KRIC)	44.0	114.2	11.0
ROANOKE	41.1	119.0	9.6
STAFFORDSVILLE	38.6	116.6	7.9
SUFFOLK	48.6	116.6	12.8
VIENNA	42.9	117.5	10.2
WALKERTON	43.8	115.1	11.4
WALLACETON	50.4	100.5	13.4
WARSAW	43.2	110.4	11.1
WILLIAMSBURG	48.3	118.8	12.5
WINCHESTER	38.2	114.6	8.6
WOODSTOCK	36.3	106.6	7.0
WOOLWINE	53.4	107.6	15.5
WYTHEVILLE	38.2	119.0	7.6

Appendix C. Decade^{-1} changes in total precipitation, precipitation days, and heavy precipitation days (1947 – 2016). Significant values are bold and underlined ($p<0.05$).

Station	Total Precipitation (inches decade-1)	Precipitation Days (days decade-1)	Heavy Precipitation Days (days decade-1)
ALTAVISTA	0.40	**4.56**	0.10
APPOMATTOX	0.74	1.79	0.36
ASHLAND	0.47	**3.56**	0.24
BLACKSBURG NWS	0.71	1.86	0.57
BREMO BLUFF	0.53	1.05	0.37
BUCKINGHAM	0.87	**3.11**	0.40
BUENA VISTA	0.84	**2.76**	**0.69**
BURKES GARDEN	**0.94**	**9.67**	0.18
CHASE CITY	0.70	**-3.09**	0.28
CHATHAM	0.76	0.35	0.17
CLARKSVILLE	0.41	**-3.90**	0.07
CONCORD	1.00	1.33	0.24
COPPER HILL	0.73	**8.94**	0.20
EMPORIA	0.76	**2.69**	0.15
FARMVILLE	0.05	**-1.69**	0.14
HOLLAND	-0.22	**2.61**	0.00
HOPEWELL	**1.28**	1.70	**0.66**
HUDDLESTON	0.60	**3.05**	0.24
JOHN KERR DAM	0.53	1.49	0.31
LAFAYETTE	0.69	**2.59**	**0.45**
LOUISA	0.22	0.80	0.32
LURAY	0.25	0.14	**0.42**
LYNCHBURG	0.30	-0.70	0.37
MARTINSVILLE	0.13	0.41	0.21
MEADOWS OF DAN	0.72	**3.16**	0.13
MOUNT WEATHER	**1.25**	**3.96**	**0.59**
NORFOLK (KORF)	**0.95**	0.31	**0.45**
NORFOLK NAS	0.81	0.54	0.33
PIEDMONT RES. STATION	0.59	-1.23	0.30
PULASKI	0.34	**2.41**	0.30
RICHMOND (KRIC)	0.26	0.49	0.19
ROANOKE	0.48	-0.82	0.37
STAFFORDSVILLE	**0.87**	**4.59**	**0.51**
SUFFOLK	**1.20**	**1.53**	0.19
VIENNA	-0.54	1.39	-0.20
WALKERTON	-0.19	**-2.47**	0.35
WALLACETON	**1.40**	**3.72**	0.52
WARSAW	0.41	0.53	0.40
WILLIAMSBURG	1.00	1.30	0.30
WINCHESTER	0.23	0.64	0.15
WOODSTOCK	**0.86**	0.04	**0.32**
WOOLWINE	-0.26	2.09	-0.08
WYTHEVILLE	0.58	**5.23**	0.10