 doi:10.20944/preprints201908.0197.v1

Article

Influence of Synoptic-Scale Airmass Conditions on Seasonal Precipitation Patterns over North Carolina

Christopher Zarzar [1*] and Jamie Dyer [2]

[1] Environmental Program, Department of Biology, Wake Forest University, Winston-Salem, North Carolina, USA; zarzarc@wfu.edu
[2] Department of Geosciences, Mississippi State University, Mississippi State, Mississippi, USA; jamie.dyer@msstate.edu
* Correspondence: zarzarc@wfu.edu

Abstract: This paper characterizes the influence of synoptic-scale airmass conditions on spatial and temporal patterns of precipitation in North Carolina over a 16-year period (2003-2018). National Center for Environmental Prediction Stage IV multi-sensor precipitation estimates were used to describe seasonal variations in precipitation in the context of prevailing airmass conditions classified using the spatial synoptic classification system. Spatial analyses identified significant clustering of high daily average precipitation amounts distributed along the lee side of the Appalachian Mountains and along the coastal plains. Significant and heterogenous clustering was prevalent in summer months and tended to coincide with land cover boundaries and complex terrain. Between the three geographic regions of North Carolina, highest precipitations amounts were received in western North Carolina during the winter and spring, but this signal shifted to eastern North Carolina in the summer and fall. Central North Carolina received the least amount of precipitation; however, there was substantial variability between regions due to prevailing airmass conditions. The summer months were dominated by maritime tropical airmass conditions with no clear shift in summertime airmass trends over the study period. Most days with recorded precipitation in the winter, spring, and fall occurred under dry moderate airmass conditions; however, the highest daily average precipitation and total precipitation occurred under the influence of maritime moderate airmasses. Importantly, there was an observed shift toward warmer and more humid airmass conditions in the winter, spring, and fall months throughout the study period (2003-2018), indicating a shift toward airmass conditions conducive to higher daily average rain rates in North Carolina.

Keywords: precipitation; seasonal; airmass; spatial patterns

1. Introduction

Knowledge of precipitation variability is essential to improving the forecasting and mitigation of hydrological hazards. Rapid population growth and increasing urban density act to both exacerbate human susceptibility to hydrological hazards and increase precipitation sensitivity to anthropogenic modifications to surface land cover conditions and climate change [1]. This is especially true in the Southeast United States which is home to some of the faster growing areas in the United States [2].

Precipitation in the southeastern United States has strong seasonal and regional sensitivity due to variations in midlatitude cyclone frequency [3], tropical cyclones [4], orographic processes [5], sea breeze circulations [6], and local-scale thermodynamic forcing [7]. Analysis of long-term precipitation patterns and trends over the Southeast United States tend to rely on dense rain-gauge network [8,9], although such data sources often have poor spatial coverage. Passive satellite remote sensing platforms have been used to explore the spatial characteristics of precipitation, especially around large metropolitan areas [10]; however, because precipitation distribution is known to vary with scale [11], studies have more recently used fine temporal and spatial radar-derived precipitation estimates for the analysis of spatio-temporal precipitation patterns at greater detail [12]. Furthermore, radar coverage in the Southeast United States has been shown to reproduce precipitation observations comparable to surface gauges [13,14]. The advent of radar-based multi-sensor precipitation datasets has further improved the accuracy of radar-based precipitation estimates. These multi-sensor datasets augment radar data with surface rain gauge and satellite precipitation estimates to address the caveats associated with radar estimates, especially over complex terrain. While these types of data and algorithms are becoming more viable for scientific analysis due to longer periods of record, the application of these multi-sensor precipitation data in characterizing precipitation patterns across the Southeast United States has been limited.

Precipitation in the Southeast United states has distinct seasonal and diurnal characteristics. Precipitation in the cool season tends to be associated with the passage of mid-latitude cyclones [3], while warm-season precipitation is often linked with local-scale thermodynamic forcing induced by variations in land-cover and soil characteristics [6,15] and tends to occur in the late afternoon and evening [16]. However, these signals are sensitive to both teleconnections and climate change. In a long-term study over North Carolina, Sayemuzzaman and Jha [9] noted that the majority of North Carolina rain gauge stations experienced a negative trend in wintertime precipitation and a positive trend in summertime precipitation. These seasonal precipitation trends may indicate a shift from more homogenous synoptically driven precipitation events to more heterogenous thermodynamically driven precipitation events. This would have consequences on community susceptibility to hydrometeorological hazards as well as negative impacts on water resource allocation and agricultural operations. Furthermore, there has been a notable increase in the urban heat island signal across the central portion of North Carolina [17]. The combined effect of increasing summertime precipitation and increasing urban heat island signals points toward more intense and spatially heterogenous precipitation patterns [18,19]; however, the magnitude of this signal will be dictated by the prevailing synoptic scale airmass [20]. For example, a seasonal shift in days under dry polar (dP) airmass regimes to days under moist tropical (mT) airmass regimes would exacerbate the thermodynamic forcing of precipitation by increasing the surface energy fluxes.

The objective of this study is to quantify the seasonal patterns of precipitation across North Carolina, USA in relation to airmass type. North Carolina is a unique natural laboratory for studying precipitation because of the distinct geographic features separating three regions across the state and because of natural variability in annual and seasonal precipitation regimes. The presented analysis uses multi-sensor data from the National Center for Environmental Prediction (NCEP) to define spatial precipitation patterns over a 16-year period (2003-2018). In addition to studying the seasonal spatial variability in precipitation, this paper will place the analysis in the context of prevailing airmass conditions to investigate how variations in synoptic scale forcing, or lack thereof, influences seasonal precipitation regimes across the study domain. This will be important for the forecasting and mitigation of hydrologic hazards, especially in response to rapid population and urbanization across North Carolina.

2. Materials and Methods

North Carolina offers a unique natural laboratory because it displays a large variety of topographic, soil type, and land use characteristics, including mountainous terrain, dense forests, agricultural lands, metropolitan cities, and low relief coastal regions (Figure 1).

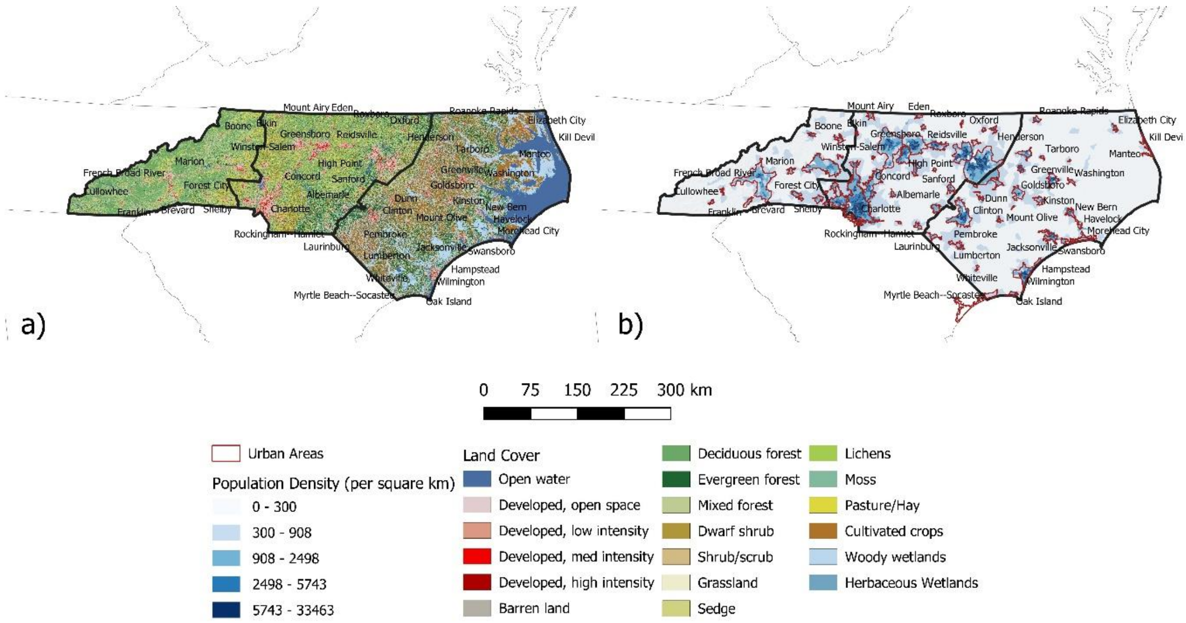

Figure 1. a) National Land Cover Database (NLCD) 2016 data and b) Census track population density per square kilometer. The three regions are delineated from left to right as western North Carolina, central North Carolina, and eastern North Carolina.

The state is broken into three geologically distinct regions. Western North Carolina (WNC) is characterized by complex terrain in the Appalachian Mountains covered by a mix of deciduous forests and boreal conifer forests with thick underbrush, as well as a sparse matrix of urban regions. The Piedmont region of central North Carolina (CNC) is a dramatic transition in both vegetation and soils characteristics from the western mountains to the eastern coastal lowlands. CNC transitions from the WNC deciduous and conifer forests to heavy agricultural landcover and urbanization. CNC has the highest population density and fastest population growth of the three regions leading to an increasing trend in impervious surfaces [17,21]. The coastal plains in eastern North Carolina (ENC) are characterized by sparsely populated cities, widespread livestock operations, and hardwood swamp forests in the eastern coastal lowlands.

The current study utilized 16 years (2003-2018) of the NCEP Stage IV multi-sensor precipitation estimates product. The NCEP Stage IV product is produced by mosaicking twelve National Weather Service (NWS) River Forecast Center (RFC) hourly Next Generation Weather Radar (NEXRAD) Stage III/Multi-sensor Precipitation Estimator (MPE) products. The Stage III/MPE product is a radar-based precipitation dataset that combines ground and space-derived precipitation estimates and is manually quality controlled at each RFC. As such, the final Stage IV product produces hourly and daily best estimate gridded precipitation products projected on the Hydrologic Rainfall Analysis Project (HRAP) polar stereographic coordinate system centered at 60°N/105°W with a nominal 4 x 4 km grid resolution. The daily NCEP Stage IV gridded binary (GRIB I) product was used in the current study.

The spatial synoptic classification (SSC) [20] data from the Greensboro station (KGSO) were used to identify the prevailing airmass conditions for each day in the dataset. The synoptic-scale airmass extent exceeds the spatial extent of North Carolina; therefore, KGSO was selected because it was a centrally located site in North Carolina that would be representative of the prevailing airmass conditions over all three regions. With the SSC system, it is possible to classify the prevailing airmass into one of seven categories: transitional (T), moist tropical (mT), moist moderate (mM), moist polar (mP), dry tropical (dT), dry moderate (dM), and dry polar (dP). For example, many urban heat island studies focus on mT days because this airmass is typically associated with synoptically benign days that experience conditional instability conducive to thermodynamically driven convection [18–20,22].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 August 2019 doi:10.20944/preprints201908.0197.v1

In the current study, we incorporated all classifications to consider the impact of the prevailing airmass on seasonal spatial and temporal precipitation patterns.

The NCEP Stage IV data were subset seasonally and by airmass. Statewide and regional values were extracted to calculate the daily average and total precipitation within the respective areas. Daily average precipitation represents the average daily precipitation that fell at each pixel contained within the respective area. The total accumulated precipitation values were averaged across the grid cells within the respective area. Averaging total precipitation across the respective area rather than adding precipitation accumulation of each pixel allowed for the comparison of precipitation accumulations between regions by normalizing differences in area. Maps produced from a Local Indicators of Spatial Association (LISA) [23] analysis facilitated the assessment of statistically significant high and low precipitation clusters within each of the three North Carolina regions. The LISA analysis was conducted on each North Carolina region independently to investigate clustering. A local Moran's I spatial statistic was calculated for each cell based on a queen contiguity spatial neighborhood weight object and one-sided (alpha = 0.05) hypothesis testing was performed.

3. Results and discussion

3.1. General Seasonal Patterns

The summer months produced the highest daily average and total rainfall across North Carolina whereas the winter months have the lowest (Figure 2a). This is consistent within all regions of North Carolina (Figure 2b). However, spatial comparisons of daily average precipitation between regions shows that there is a seasonal signal to precipitation maximums across regions (Figure 3). WNC received higher daily average precipitation than CNC and ENC in the winter and spring months, whereas CNC received higher daily average precipitation during the summer and fall months. Spatial patterns follow initial expectations where there tends to be a precipitation maximum on the lee side of the Appalachian Mountains and along the coastal sandhills (Figure 3). The lee mountain maximum is consistent with Letkewicz and Parker [24] who found that the maxima was associated with favorable thermodynamic conditions downstream of the mountains. However, this signal is minimized in the winter months (Figure 3a) where precipitation events tend to be driven by northwest flow events after the passage of midlatitude cyclones. This leads to conditions where the southwestern portion of the Appalachian Mountains observed statistically significant clustering of high daily precipitation amounts. Consistent with Koch and Ray [6], the precipitation maximum over eastern North Carolina is associated with sea breeze circulations that are further enhanced by distinct variations in soil composition.

Spatial precipitation patterns tend to be less consistent across central North Carolina. In the winter and spring months, there is clustering of high precipitation values in the northwest portion of CNC, possibly related to redevelopment of mesoscale convective systems (MCSs) on the lee side of the Appalachian Mountains [5]. In the summer months, this northwest clustering signal is overcome by a region of high precipitation near the Charlotte metropolitan area. It is possible that this is an area of precipitation enhancement downwind of the urban city center as noted by studies near similar metropolitan areas [15,18,19]; however, there is a need for future research detailing the urban influence on precipitation across North Carolina. The clustering of high precipitation values in the northern portion of CNC and in the southeastern portion of CNC return in the fall months. This is likely the return of synoptically driven organized MCS precipitation events propagating eastward across the state.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 August 2019 doi:10.20944/preprints201908.0197.v1

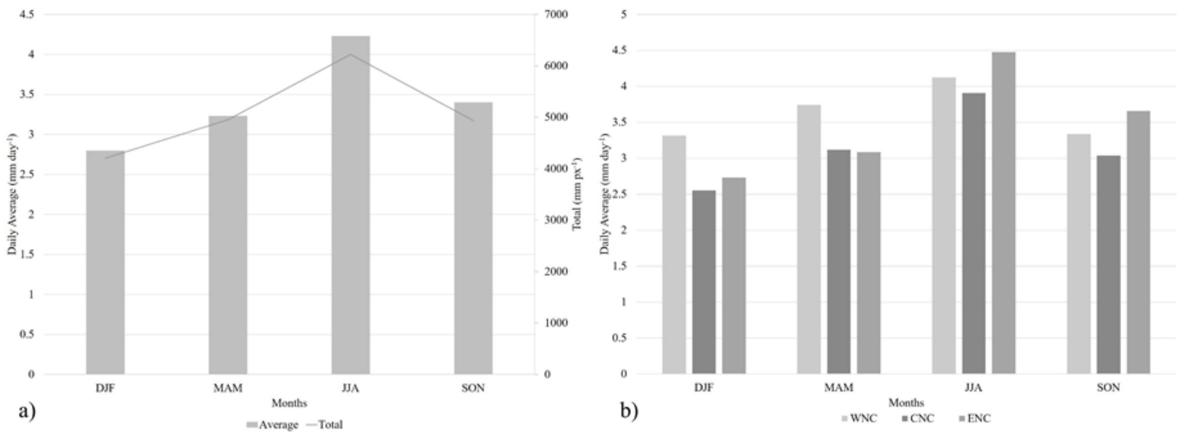

Figure 2. a) Statewide precipitation daily average and total precipitation and b) regional assessment of daily average precipitation for western North Carolina (WNC), central North Carolina (CNC), and eastern North Carolina (ENC).

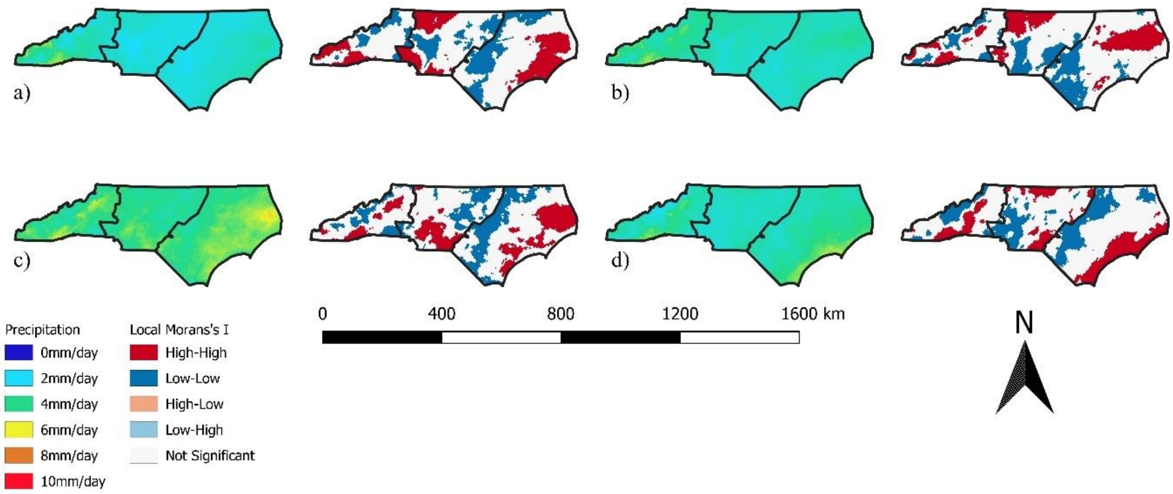

Figure 3. Daily average precipitation (left) and spatial clustering analysis of precipitation (right) for DJF (a), MAM (b), JJA (c), and SON (d) over the 2003-2018 study period. Local Moran's I was calculated within each region individually.

3.2. Seasonal and Airmass Precipitation Patterns

It was important to augment the seasonal analysis by focusing on prevailing synoptic-scale airmass conditions to distinguish between synoptically driven and local-scale thermodynamically driven precipitation events within each season. Whereas polar airmass conditions tend to be affiliated with kinetically-driven frontal precipitation, tropical airmass conditions are commonly used as a proxy for synoptically benign conditions and thermodynamically driven precipitation [18–20,22]. Also, changes in seasonal airmass frequency may play a role in precipitation distribution and intensity; therefore, it is important to quantify patterns of both in an effort to understand their relationship.

3.2.1. Winter

Winter months are characterized by dM and dP airmass conditions (Figure 3), although, while dM and dP dominate the frequency of precipitation, mM and mP conditions make important

 doi:10.20944/preprints201908.0197.v1

contributions to wintertime precipitation. However, this is not surprising because moist polar is often the result of a dP airmass acquiring additional moisture; therefore, it maintains that moist polar airmass are indicative of the passage of mid-latitude cyclones. mM airmass conditions produce similar conditions to the mP with the exception of having higher temperatures and higher humidity levels [20]. Furthermore, these mM airmass conditions can form independently to the south of mP airmasses, which likely associate them to the passage of deep midlatitude cyclones that tap into southerly Gulf moisture and can produce heavy precipitation and dangerous snow events in North Carolina. Overall, results are consistent with Nieto Ferreira et al. [3] indicating that airmass conditions typically associated with the passage of mid-latitude cyclones contribute nearly 80% of total precipitation across the study domain. Interestingly, however, is that the frequency of mM airmass conditions have steadily increased from 2010-2018 (Figure 4c). This tends to be at the expense of dP and mP airmass conditions, suggesting that there has been a gradual shift to warmer and more humid airmass conditions throughout the 16-year study period.

Spatial precipitation variations support the above assessment where the highest precipitation totals and significant clustering of high precipitation amounts occur in the southwest and across the southern portion of the study domain under mM conditions (Figure 5). Precipitation distribution tends to be most homogenous during dT, dP, and dM airmass conditions where there is a gradual west-to-east increasing gradient in precipitation across North Carolina. Furthermore, areas of significant clustering of high precipitation amounts tend to cluster across the northern portion of the study domain suggesting that these events originate poleward of the study domain. Highest rain amounts in ENC are associated with moist polar events.

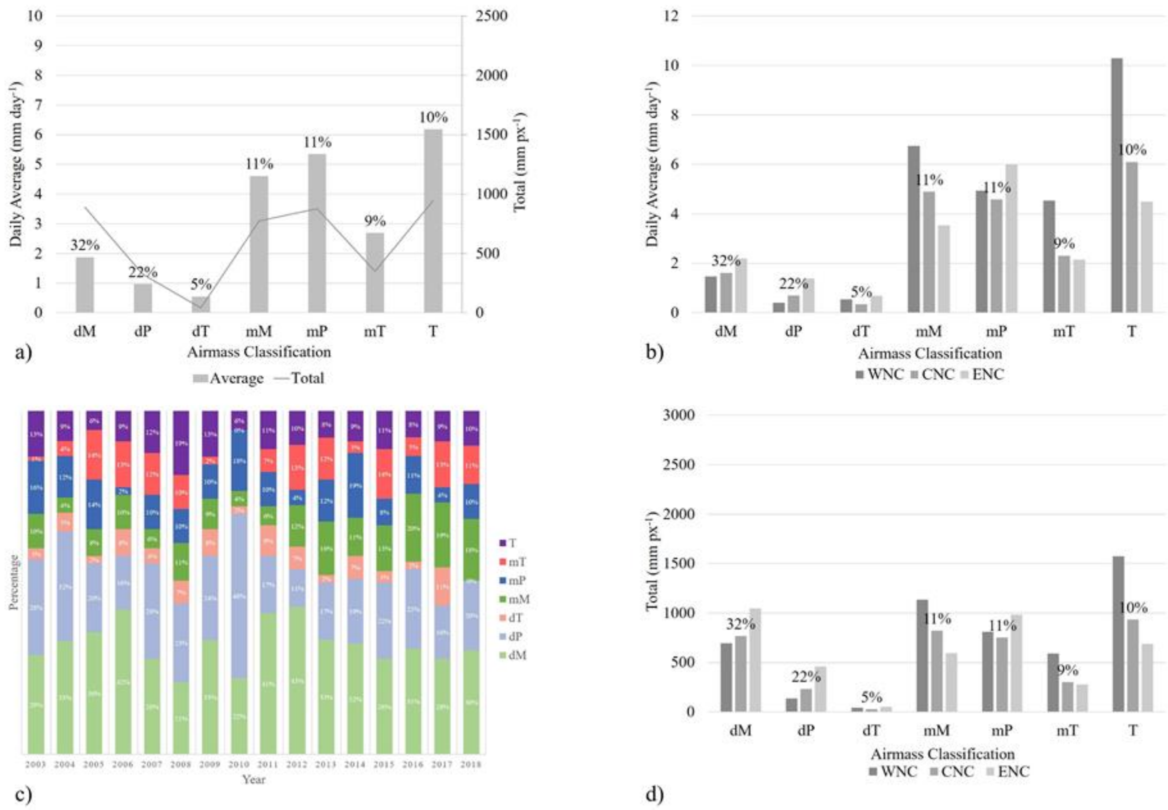

Figure 4. a) DJF statewide daily average precipitation total precipitation for each SSC airmass classification; b) daily average precipitation for each North Carolina region; c) frequency of each SSC airmass classification over the study period; d) total precipitation for each North Carolina Region. Percentages indicate the fraction of airmass classification for each season (a, b, d) or year (c).

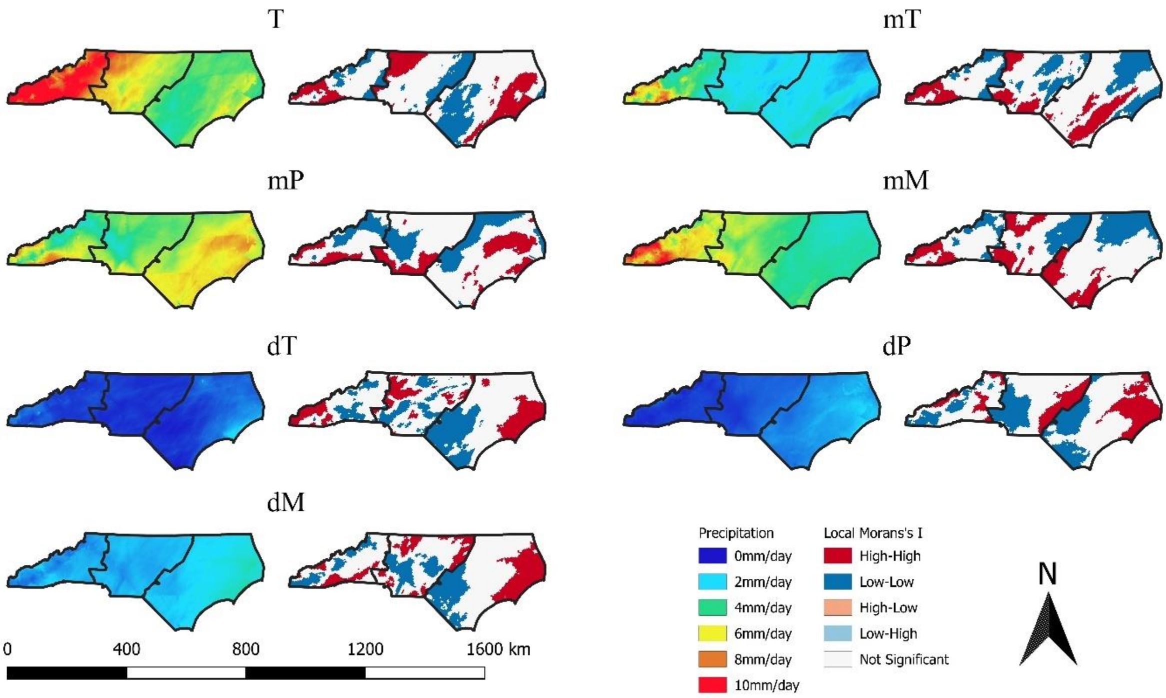

Figure 5. DJF daily average precipitation (left) and spatial clustering analysis of precipitation (right) for each SSC airmass classification.

3.2.2. Spring

The springtime distribution of airmass conditions are similar to the winter; however, there is a decrease in the frequency of dM and dP airmass days and an increase in the number of mT and dT days (Figure 6.). This is consistent with the expected transition from a strong synoptic winter regime toward the relatively week synoptic summer regime. There is a notable shift to more intense precipitation conditions (Figure 6b) due to a higher frequency of mT and dT airmass conditions. Thus, there is an affiliated increased risk for hazardous hydrometeorological events due to the shift to airmass conditions conducive to high intensity precipitation events. While the dry airmass conditions maintain significant clustering of high precipitation toward the northern portion of North Carolina, moist airmass conditions no longer have a southern tendency in the clustering of high precipitation amounts (Figure 7). mT days are characterized by a northern distribution of high precipitation cluster; however, the clusters are more localized and sporadic for all moist airmass regimes suggesting a shift toward thermodynamically driven precipitation events and enhanced connectivity between land-cover conditions and precipitation. This is an important consideration because it also appears that there is an increasing trend in the frequency of mT days during spring months (Figure 6c). This comes as the expense of fewer dM, dP, and dT days suggesting that North Carolina is experiencing a shift to more humid springtime airmass conditions conducive to thermodynamically driven precipitation events.

 doi:10.20944/preprints201908.0197.v1

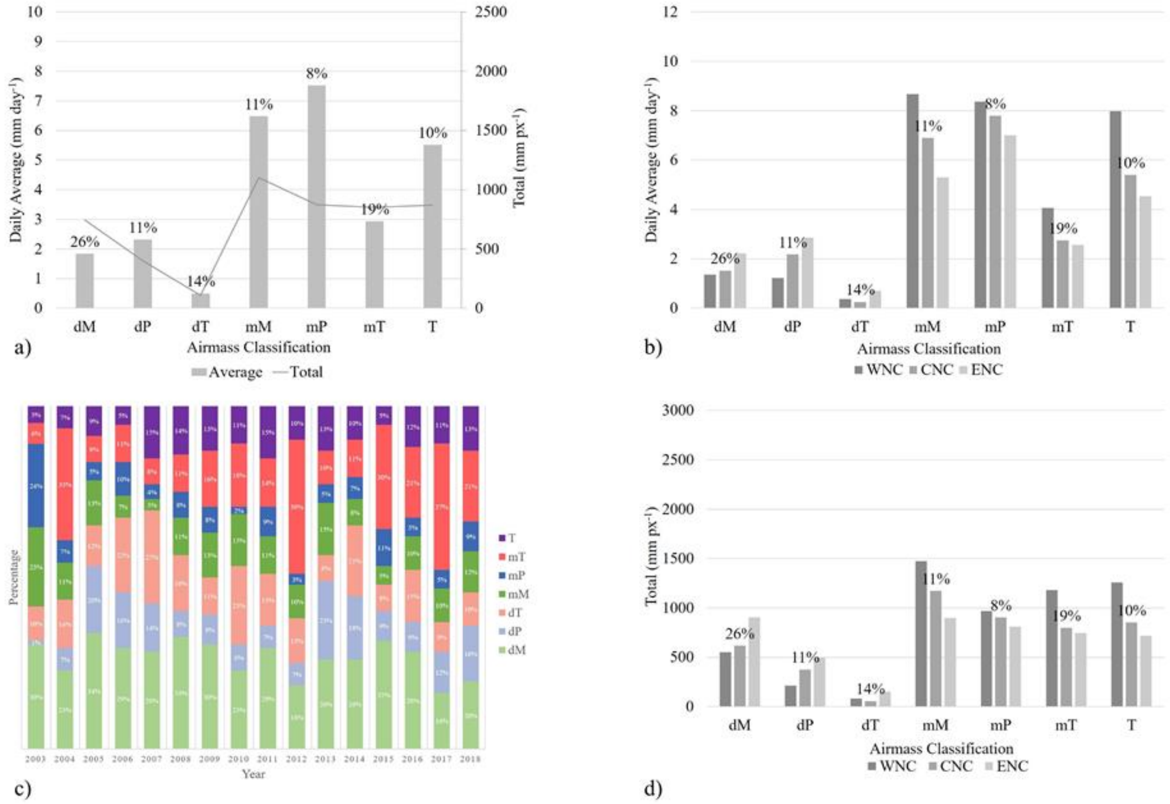

Figure 6. Same as figure 4 but for MAM.

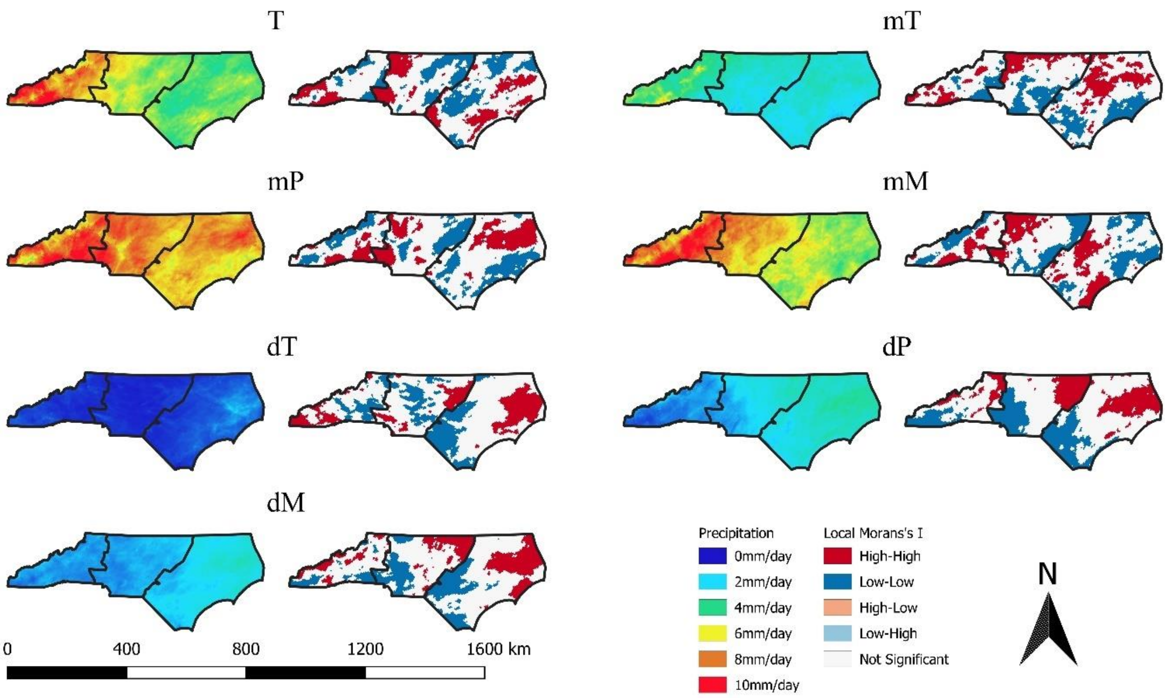

Figure 7. Same as Figure 5 but for MAM

3.2.3. Summer

There is an abrupt increase in daily average rainfall in the summer months and a shift to a higher frequency of synoptically benign mT days (Figure 8). These mT days make up 41% of the daily

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 August 2019 doi:10.20944/preprints201908.0197.v1

summertime airmass regimes. mT airmass conditions exhibit moderate rainfall rates and contribute a substantial amount of precipitation to the summertime total precipitation. While there are a limited number of days subject to mP airmass conditions (2%), these airmass conditions in the summer are conducive to intense precipitation events (Figure 8b & Figure 9). Also notable was the substantial contributions to total precipitation from mM airmass conditions. While moist moderate airmass conditions make up only 17% of summertime days, they contribute the second largest amount to total precipitation (Figure 8b). Unlike the winter and spring, there was not clear shift in the frequency of airmass conditions over the period of the study. The variations in airmass regimes in Figure 8c appear to be more consistent with interannual teleconnections such as the Southern Oscillation [3]; however, further research is required to assess the strength of these potential correlations with specific SSC airmasses.

The spatial patterns of summer precipitation exhibit a heterogenous distribution of precipitation across North Carolina (Figure 9). There maintains significant clustering in the coastal plains, but the previously strong clustering lee of the Appalachian Mountains weakened, and precipitation appears to be heavily impacted by local-scale orographic processes in western North Carolina. Under the majority of summertime airmass conditions, there is significant clustering near the urbanized Triad region in CNC. While the influence of urban areas on precipitation has yet to be explored in detail across North Carolina, it has been documented that population growth and urbanization across the CNC have contributed to increasing trends in urban heat island signatures [17]. As such, it is possible that the pockets of significant precipitation clustering, especially across CNC, are associated with local-scale thermodynamic forcing and land cover boundaries.

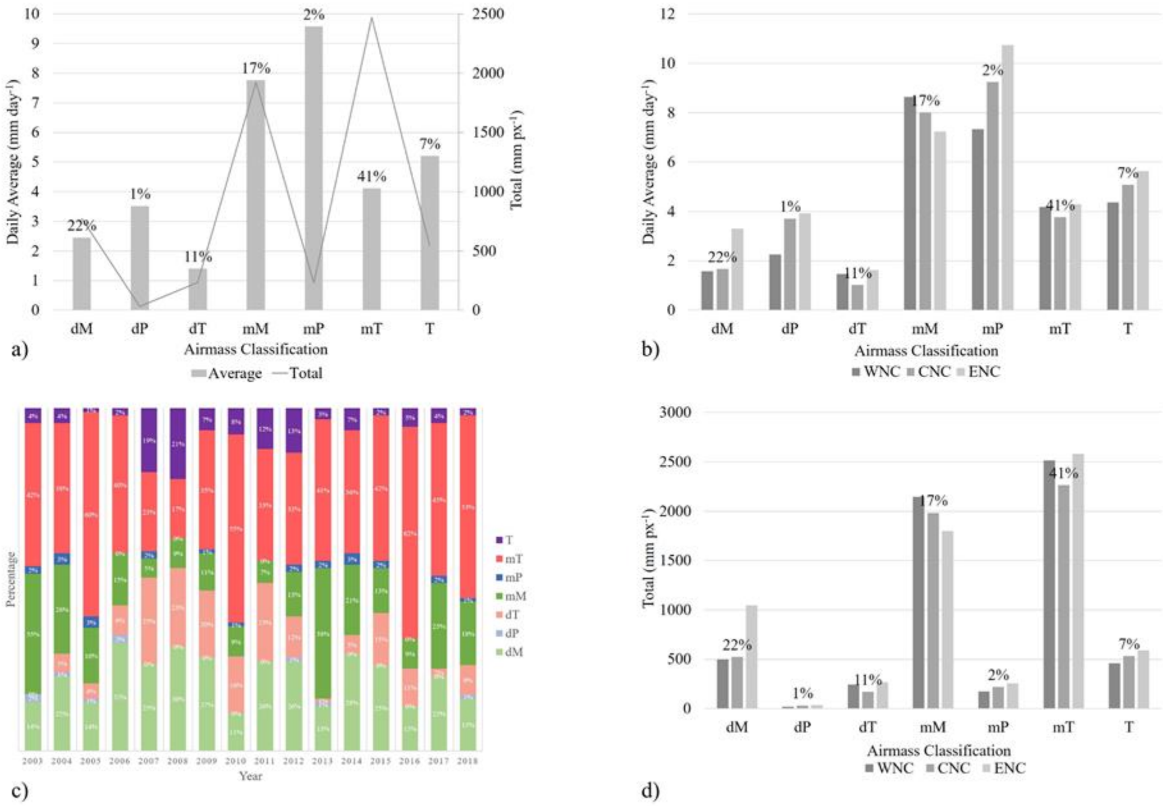

Figure 8. Same as figure 4 but for JJA.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 August 2019 doi:10.20944/preprints201908.0197.v1

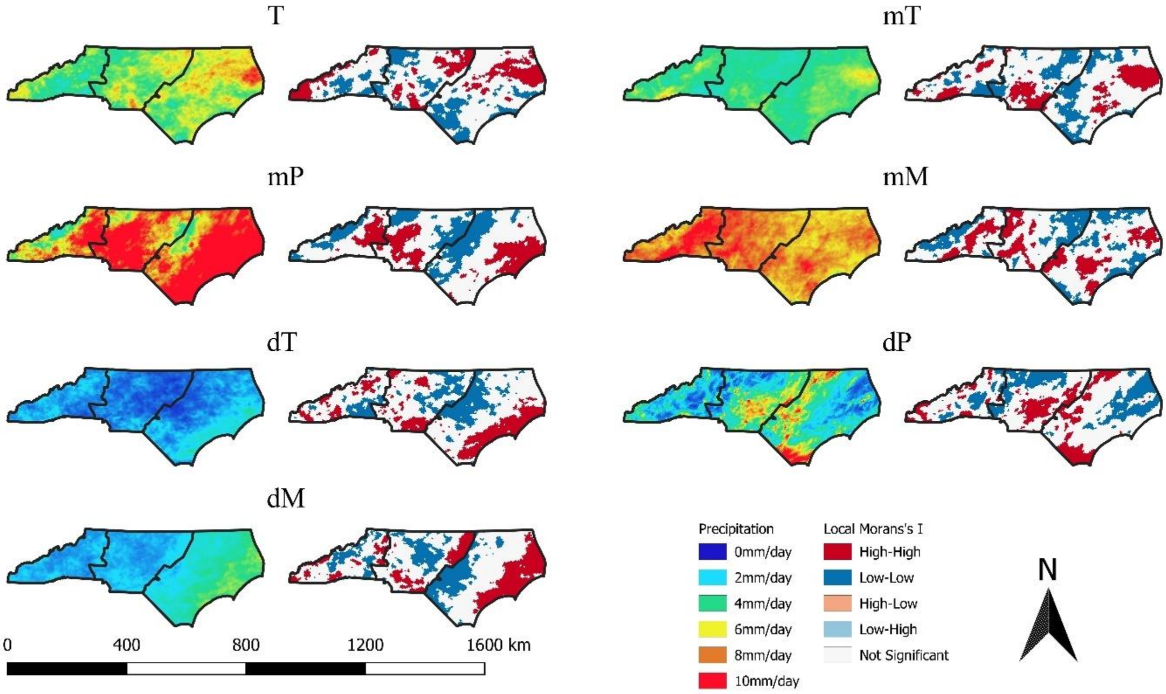

Figure 9. Same as Figure 5 but for JJA

3.2.4. Fall

Fall is indicative of a shift away from synoptically benign conditions in the summer to the typical strong synoptic scale forcing in the winter (Figure 10). There is a shift from mT airmass conditions to a higher frequency of mP and dM airmass conditions. The signal in daily average and total precipitation is similar to the spring months, including an increasing number of days under mT tropical airmass conditions and fewer days under dM and dP conditions from 2010-2018. This is an important outcome because it appears the transitional and winter month airmass conditions are becoming warmer and more humid over the period of the study. A signal that distinguishes the fall from the spring months is an area of high precipitation amounts clustered over the east and southeast portions of the domain (Figure 11). This is most likely associated with the passage of tropical cyclones, whereas the southeastern clustering during dT and dM are likely associated with the formation and passage of Hatteras Lows.

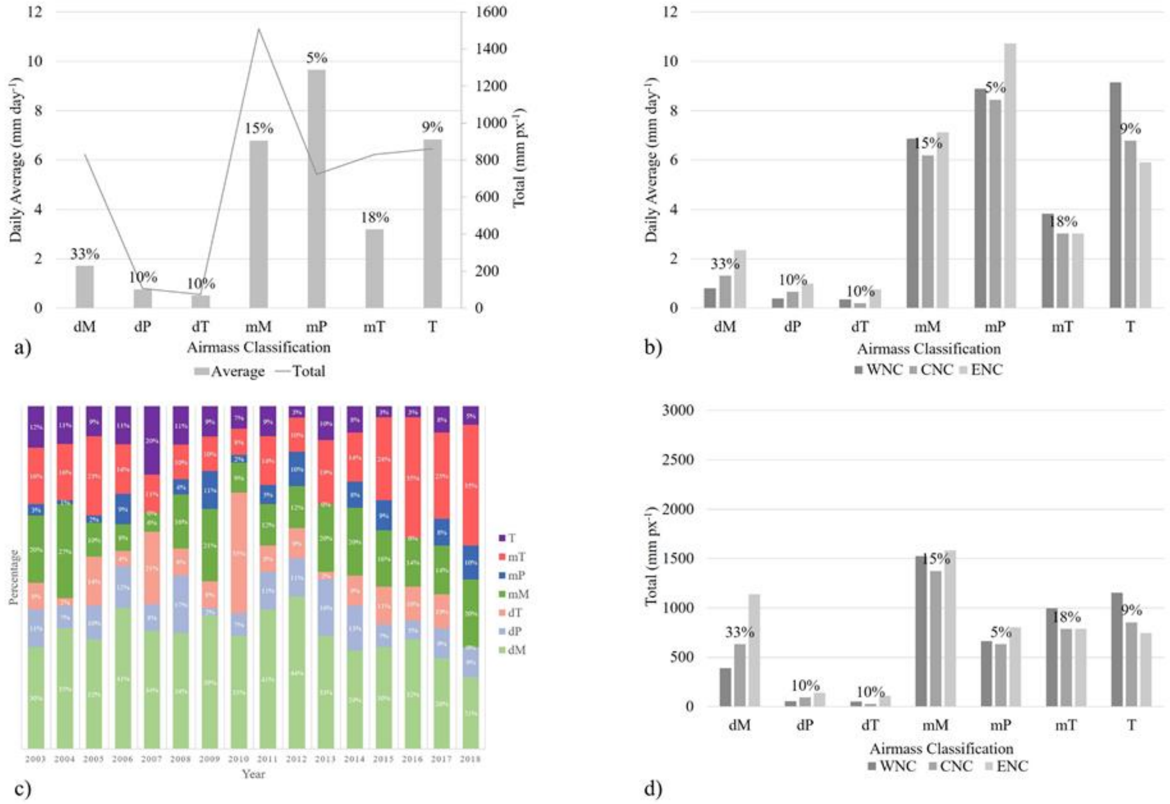

Figure 10. Same as figure 4 but for SON.

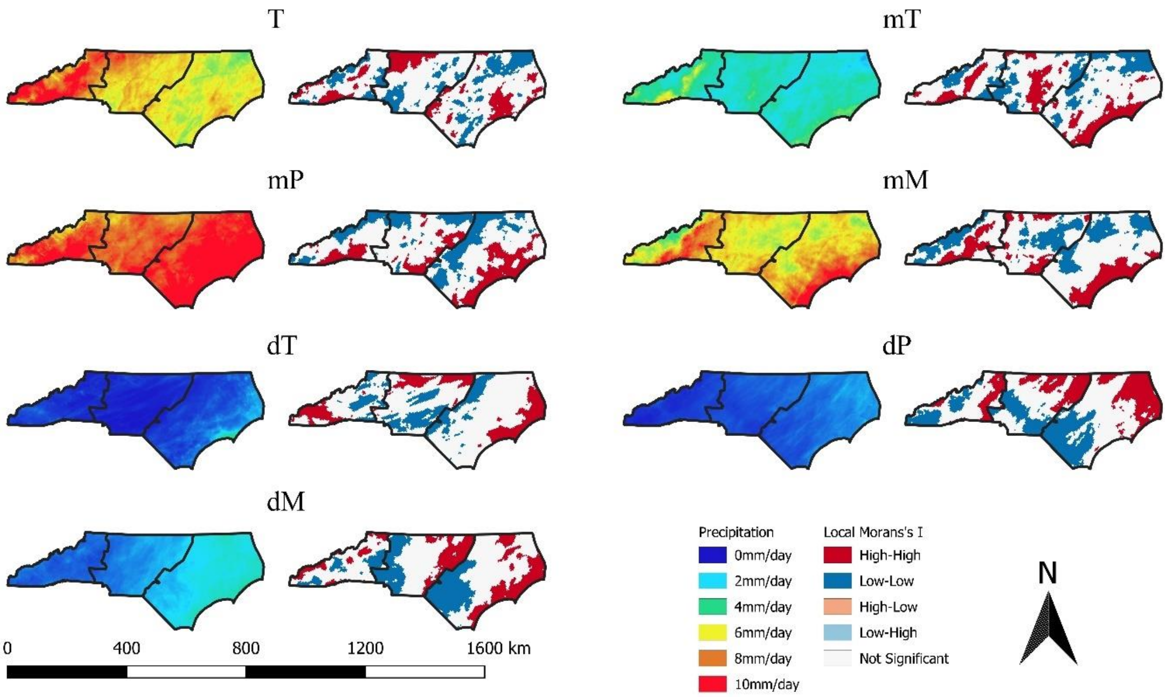

Figure 11. Same as Figure 5 but for SON

5. Conclusions

The current study used 16-years (2003-2018) of the National Center of Environmental Prediction (NCEP) Stage IV precipitation dataset to characterize the impact of airmass conditions on seasonal precipitation patterns in North Carolina. Results from the current study aid forecasting and mitigation of hydrometeorological hazards in North Carolina by documenting the spatial and temporal patterns of precipitation magnitude in the context of prevailing airmass conditions. It was found that winter is dominated by dry moderate (dM) and dry polar (dP) airmass conditions indicative of synoptically-driven precipitation events. Spatial clustering confirms this conclusion where there is clustering of high precipitation amounts in the lee of the Appalachian Mountains and along the Coastal Plains. Summertime precipitation is more heterogenous due to prevailing moist tropical (mT) airmass conditions indicating a tendency toward localized and more intense thermodynamically driven precipitation events. Furthermore, it was discovered that while moist moderate (mM) and moist polar (mP) airmass conditions were less frequent, they exhibited the highest daily average rainfall rates suggesting that mM and mP airmass conditions are conducive to hazardous hydrometeorological events.

Future research should use the spatial clustering outcomes to identify and examine areas where small-scale clustering of high precipitation amounts coincides with local-scale variations in land cover conditions. In addition, there is a need to understand the magnitude of correlations between summertime airmass conditions and large-scale teleconnections. A notable result of this study was that winter, spring, and fall months exhibit a shift to warmer and more humid mM and mT airmass conditions over the 2003-2018 study period. This shift could lead to more thermodynamically driven and more intense precipitation events, especially during the spring and fall transitional seasons; however, a more detailed assessment of airmass trends across North Carolina is needed to substantiate this finding. It is recommended that future research explore spatial synoptic classification sites beyond the single Greensboro site used in the current study to determine whether the observed airmass trends are statistically significant and whether the trends are consistent across all North Carolina spatial synoptic classification system sites.

Funding: This research received no external funding

Conflicts of Interest: The authors declare no conflict of interest

Author Contributions: Conceptualization, Christopher Zarzar and Jamie Dyer; Data curation, Christopher Zarzar and Jamie Dyer; Formal analysis, Christopher Zarzar; Investigation, Christopher Zarzar; Methodology, Christopher Zarzar and Jamie Dyer; Project administration, Christopher Zarzar; Resources, Christopher Zarzar; Writing – original draft, Christopher Zarzar; Writing – review & editing, Jamie Dyer.

References

1. Seto, K.C.; Shepherd, J.M. Global urban land-use trends and climate impacts. *Curr. Opin. Environ. Sustain.* **2009**, *1*, 89–95.
2. Bureau, U.C. Fastest-Growing Cities Primarily in the South and West Available online: https://www.census.gov/newsroom/press-releases/2019/subcounty-population-estimates.html (accessed on 14 August 2019).
3. Ferreira, R.N.; Hall, L.; Rickenbach, T.M. A climatology of the structure, evolution, and propagation of midlatitude cyclones in the southeast united states. *J. Clim.* **2013**, *26*, 8406–8421.
4. Shepherd, J.M.; Grundstein, A.; Mote, T.L. Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States. *Geophys. Res. Lett.* **2007**, *34*, 1–5.
5. Parker, M.D.; Ahijevych, D.A. Convective Episodes in the East-Central United States. *Mon. Weather Rev.* **2007**, *135*, 3707–3727.
6. Koch, S.E.; Ray, C. Mesoanalysis of Summertime Convergence Zones in Central and Eastern North Carolina. *Weather Forecast.* **1997**, *12*, 56–77.
7. Dyer, J. Analysis of a Warm-Season Surface-Influenced Mesoscale Convective Boundary in Northwest Mississippi. *J. Hydrometeorol.* **2011**, *12*, 1007–1023.
8. Boyles, R.P.; Raman, S. Analysis of climate trends in North Carolina (1949-1998). *Environ. Int.* 2003, *29*,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 August 2019 doi:10.20944/preprints201908.0197.v1

263–275.

9. Sayemuzzaman, M.; Jha, M.K. Seasonal and annual precipitation time series trend analysis in North Carolina, United States. *Atmos. Res.* **2014**, *137*, 183–194.
10. Shepherd, J.M.; Burian, S.J. Detection of Urban-Induced Rainfall Anomalies in a Major Coastal City. *Earth Interact.* **2003**, *7*, 1–17.
11. Krajewski, W.F.; Ciach, G.J.; Habib, E. An analysis of small-scale rainfall variability in different climatic regimes. *Hydrol. Sci. J.* **2003**, *48*, 151–162.
12. Parker, M.D.; Knievel, J.C. Do meteorologists suppress-thunderstorms? Radar-derived statistics and the behavior of moist convection. *Bull. Am. Meteorol. Soc.* **2005**, *86*, 341–358.
13. Dyer, J.L.; Garza, R.C. A Comparison of Precipitation Estimation Techniques over Lake Okeechobee, Florida. *Weather Forecast.* **2004**, *19*, 1029–1043.
14. Dyer, J. Evaluation of Surface and Radar-Estimated Precipitation Data Sources Over the Lower Mississippi River Alluvial Plain. *Phys. Geogr.* **2009**, *30*, 430–452.
15. Dixon, P.G.; Mote, T.L. Patterns and Causes of Atlanta's Urban Heat Island–Initiated Precipitation. *J. Appl. Meteorol.* **2003**, *42*, 1273–1284.
16. Rickenbach, T.M.; Nieto-Ferreira, R.; Zarzar, C.; Nelson, B. A seasonal and diurnal climatology of precipitation organization in the southeastern United States. *Q. J. R. Meteorol. Soc.* **2015**, *141*, 1938–1956.
17. Doran, E.M.B.; Golden, J.S. Climate & Sustainability Implications of Land Use Alterations in an Urbanizing Region: Raleigh-Durham, North Carolina. *J. Environ. Prot.* **2015**, *07*, 1072–1088.
18. Ashley, W.S.; Bentley, M.L.; Stallins, J.A. Urban-induced thunderstorm modification in the Southeast United States. *Clim. Change* **2012**, *113*, 481–498.
19. Haberlie, A.M.; Ashley, W.S.; Pingel, T.J. The effect of urbanisation on the climatology of thunderstorm initiation. *Q. J. R. Meteorol. Soc.* **2015**, *141*, 663–675.
20. Sheridan, S.C. The redevelopment of a weather-type classification scheme for North America. *Int. J. Climatol.* **2002**, *22*, 51–68.
21. Tippett, R. NC Demographic Trends Through 2035. House Select Committee on Strategic Transportation Planning and Long Term Funding Solutions. 2016.
22. Mote, T.L.; Lacke, M.C.; Shepherd, J.M. Radar signatures of the urban effect on precipitation distribution: A case study for Atlanta, Georgia. *Geophys. Res. Lett.* **2007**, *34*, 2–5.
23. Anselin, L. Local Indicators of Spatial Association—LISA. *Geogr. Anal.* **1995**, *27*, 93–115.
24. Letkewicz, C.E.; Parker, M.D. Impact of Environmental Variations on Simulated Squall Lines Interacting with Terrain. *Mon. Weather Rev.* **2011**, *139*, 3163–3183.