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Geospatial Analysis of Historical Tropical Cyclone Intensity and Rainfall in Georgia, United States

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GEOSPATIAL ANALYSIS OF HISTORICAL TROPICAL CYCLONE INTENSITY AND RAINFALL IN GEORGIA, UNITED STATES

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For my mother, Cassie Taylor Corkran.

You raised me to be the woman I am today during your too short time on earth. I miss you more than words can say. You taught me that there is incredible beauty that comes from a woman who embodies strength, kindness, intelligence, and grace all at once.

I look forward to the day we meet again.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii

ABSTRACT vi

CHAPTER 1. INTRODUCTION 1
- 1.1. Tropical Cyclone Damage in Georgia 1
- 1.2. Hurricane Michael in Georgia 3
- 1.3. Research Problem and Purpose 5

CHAPTER 2. HURRICANES, TROPICAL STORMS, AND GEORGIA 9
- 2.1. Introduction into North Atlantic Tropical Cyclones 9
- 2.2. The State of Georgia 13
- 2.3. Georgia Tropical Cyclones 16

CHAPTER 3. METHODS AND DATA 24
- 3.1. HURDAT2 24
- 3.2. nClimGrid-Daily 25
- 3.3. Archival Data 27
- 3.4. Descriptive Statistics 27
- 3.5. Correlation and Regression Models 28
- 3.6. Rainfall Methods 30
- 3.7. Archival Methods 31

CHAPTER 4. RESULTS 33
- 4.1. Descriptive Statistics 33
- 4.2. Correlation and Regression 51
- 4.3. Annual Average Rainfall 55
- 4.4. Monthly Average Rainfall 58
- 4.5. October 1898 Hurricane 72
- 4.6. October 1940 Hurricane 78

CHAPTER 5. DISCUSSION AND CONCLUDING REMARKS 84
- 5.1. Discussion 84
- 5.2. Conclusion 85

APPENDIX A. HURRICANE AND TROPICAL STORMS OF GEORGIA 88

PERMISSIONS 91

REFERENCES 92

VITA 102

ABSTRACT

Tropical cyclones, characterized by their high wind speeds and heavy rainfall, cause widespread devastation, affecting millions of people and leading to economic losses worldwide. Tropical cyclone-specific research in Georgia is scarce, likely due to the coast's minimal geographical extent and the relative infrequency of direct landfalls. Research on Georgia tropical cyclones does not account for storms that make landfall in Florida and continue north, northeast, or northwest. In 2018, Hurricane Michael generated $4.7 billion in property, agriculture, and forestry damages across southwest Georgia as a Category 3 hurricane. With an increasing population, property development, and agriculture sector sensitive to tropical storms, it is imperative to update the state's tropical cyclone climatology. This study seeks to understand the spatiotemporal patterns of direct and indirect landfalling Georgia tropical storms ($\geq 17\ ms^{-1}$) from 1851–2021 using data from the North Atlantic Basin hurricane database (HURDAT2). This study considers tropical cyclone-induced rainfall using daily rainfall (nClimGrid-Daily and nClimGrid) from 1951–2021 to estimate the proportion of annual rainfall that is attributed to these storms. Using a multi-methodological approach of statistics, archival resources, and mapping to assess the trends of Georgia tropical cyclones and their attributed rainfall. The study, concentrating on 113 tropical cyclones from May–November, found that Georgia averages 0.66 tropical cyclones annually, with the bulk occurring in September and October. The study found that tropical cyclone-induced rainfall contributes a notable amount of annual rainfall totals.

CHAPTER 1. INTRODUCTION

1.1. Tropical Cyclone Damage in Georgia

The United States coastline stretches 5,955 kilometers (3,700 miles) along the Gulf of Mexico (GOM) and the Atlantic Seaboard, as reported in 1975 by the National Oceanic and Atmospheric Administration (NOAA). Within this extensive coastline, the state of Georgia accounts for 160 kilometers (100 miles). Coastal locations throughout the GOM and North Atlantic are often frequented by tropical cyclones, or low - pressure systems with strong rotating winds (Elsner and Jagger 2013).

Georgia has experienced 107 individual billion-dollar disaster events since 1980, making it the most of any southern state of the most billion-dollar events for any southeastern state, including Louisiana (NCEI 2024). Twenty-four of these disasters were tropical cyclones (TCs) (NCEI 2024). The TC events in Georgia were the costliest disasters for the state, estimated to cost around $10–20 billion. The most recent TC was Hurricane Idalia in August 2023. Hurricane Idalia is estimated to have resulted in $3.5 billion in damages due to strong winds, flooding, heavy rainfall, storm surge, and downed trees (NCEI 2024). Hurricane Idalia rapidly intensified, that is, the storms wind intensity increased by $\geq$ 30 knots in 24 hours, which left residents scrambling to evacuate (Cangialosi and Alaka 2024). Rapid intensification is defined as a one-minute maximum sustained surface wind speed that increases by 30 knots over a 24-hour period (Kaplan et al. 2015). Hurricane Idalia was predicted to travel through Savannah, Georgia, but ultimately proceeded on a more northward track. Many residents in the region who were not planning on evacuating experienced heavy rainfall, flooding, and intense winds (Hunter 2023). Valdosta, Georgia, experienced extensive infrastructure damage because the area lacked tropical cyclone resistant infrastructure (Hunter 2023).

Hurricane Irma in September 2017 caused $54 million in damage from falling trees, debris, strong winds, power outages, extensive flooding, and storm surge (NCEI 2017). The strong winds toppled trees onto homes and businesses. Two fatalities were reported in north Georgia due to falling trees, with many other reports involving major injuries (NOAA 2017). The rainfall covered the entire state ranging from30.48 mm (1.2 in) in northern Georgia – 341.9 mm (13.46 in) around Brunswick, Georgia. Due to drier than normal conditions before the storm, the state experienced extensive flooding in multiple regions (NOAA 2017). More than 900,000 residents lost power across the state, which took days to restore due to the damage around the region (Chappell 2017).

Hurricanes are a type of TC that forms over the Atlantic or the eastern Pacific Ocean, characterized by sustained winds of 33 ms^{-1} or higher. Over half (~60%) of all Georgia hurricanes travel from the south or southeast (Blake 2011). TCs infrequently make direct landfall in Georgia due to the short coastline. Over 161 years, only 14 hurricanes moved directly across Georgia's coastline (Bossak et al. 2014). TCs can indirectly affect Georgia after making initial landfall in Florida and continuing northward at tropical storm (17 ms^{-1}) or hurricane (33 ms^{-1}) intensity. A subset of storms will enter Georgia at hurricane intensity and quickly downgrade into tropical storms. These tropical storms can still cause immense damage for residents, as seen in Hurricanes Idalia, Irma, and Michael, which all became tropical storms shortly after entering Georgia. Indirect TCs entering the state at hurricane intensity through Florida should be considered part of Georgia's historical hurricane occurrences. TCs have made indirect landfall throughout Georgia's historical record. Observing the effects of the earlier occurring TCs may provide insight on the similarities and differences between modern day and historical TCs. The study will use archival resources such as news articles, historical weather maps, and photographs to investigate the impacts of these storms on Georgia.

1.2. Hurricane Michael in Georgia

Hurricane Michael (2018) was a Category 5 ($\geq$ 69 ms^{-1}) hurricane on the Saffir-Simpson Wind Scale while in the GOM, and it made landfall just southeast of Panama City, Florida, as a Category 5 storm. The system formed in the Caribbean Sea on 2 October 2018, as a convective burst. By October 7, the system formed into a tropical depression off the coast of Cozumel, Mexico. The system rapidly intensified before traveling off the west coast of Cuba, where maximum sustained winds reached 23.9 ms^{-1} (85 kt; 95 mph) (Beven et al. 2019). At landfall, Hurricane Michael exhibited maximum sustained wind speeds of 71.9 ms^{-1} (140 kt; 161 mph) (Beven et al. 2019). The event accelerated northeastward into Georgia as a Category 3 hurricane. Michael weakened into a tropical storm as it passed southeast of Macon, Georgia (~265 km north of the Florida border), and continued through Augusta, Georgia, and into the Carolinas. The remnant low of Michael traveled into the Atlantic, where it dissipated off the northern coast of Portugal on 15 October (Beven et al. 2019).

Donaldsonville, Georgia, reported a maximum wind gust of 44 ms^{-1} (100 kt; 100 mph). Hurricane Michael produced three tornadoes in Georgia. Two tornadoes were rated as EF –0 (105–137 km/h) in Fulton and Crawford County, and the EF –1 (138–177 km/h) tornado touched down in Peach County with minor damages reported (Beven et al. 2019). One fatality was reported due to a falling tree during the storm. Southwestern and Central Georgia reported wind damage in the agriculture/forestry sector, with Donaldsonville reporting damage to 99% of the homes and agriculture in the region. Dougherty County, Georgia, reported approximately 3,000 residential structures damaged and 49 destroyed. NOAA’s National Centers for Environmental

Information (NCEI) estimated $25 billion in damages from Hurricane Michael in the U.S. in 2018, with $4.7 billion occurring in Georgia from property, agricultural, and forestry losses.

As seen with Hurricane Michael, Irma, and Idalia, heavy rainfall is a common hazard associated with TCs. Intense, sustained rainfall can overwhelm rivers, streams, and drainage systems leading to flash floods and inundation of communities (Rogers et al. 2009). Floodwater can cause extensive damage to roadways and infrastructure. Rainfall can lead to the failure of some infrastructure, such as buildings, bridges, and roads (Terry 2007, Koetse and Rietveld 2009, Le Cozannet et al. 2013). Rainfall can cause erosion to undermine foundations and structures (Koetse and Rietveld 2009). TC rainfall can destroy crops through flooding or too much rainfall for the given plant (Loayza et al. 2012). Soil erosion and agricultural schedules are important to obtain a yield with certain crops and changes to these can affect the food supply chain (Loayza et al. 2012). Observing and analyzing the rainfall patterns associated with TCs on monthly and annual scales is critical to disaster preparedness and recovery planning. This systematic monitoring provides invaluable data, enabling state authorities to predict potential rainfall regions and estimate the precipitation likely to occur. Such predictive insights are instrumental in forming strategic responses and resource allocation for disaster mitigation and recovery after TCs. A proactive approach not only enhances the state's resilience against TCs but also aids in minimizing the overall impact on communities and infrastructure.

The aftermath of TCs often result in prolonged and unexpected impacts that extend far beyond the immediate damage. For instance, hurricane Micahel's passage through Georgia led to the downing of a vast number of trees that altered the landscape of Georgia. This accumulation of dried, fallen timber became the perfect fuel for a severe wildfire season the following year. The 2017 wildfire season witnessed the devastating West Mims Fire, ignited by a lightening strike in the Okefenokee National Wildlife Refuge (Darnell 2017). This fire caused massive mandatory evacuations in many towns in southern Georgia due to its severity (Darnell 2017). Spanning approximately 140,000 acres, the fire affected not just Georgia but also reached into Florida (Darnell 2017). It posed a major threat to residents, firefighters, homes, Georgia's landscape, and other species. The initial devastation caused by a TC can be just the beginning, with subsequent effects of wildfires, tornadoes, and more that add to the toll on ecosystems and communities.

These examples illustrate that a hurricane does not need to make direct landfall on the coast of Georgia to cause havoc in the state. Despite not making landfall on Georgia's Coastline, these TCs have inflicted considerable damage throughout many regions of the state. Research must encompass the effects of TCs on entire states, not just on specific regions. While regional-scale research is valuable, a statewide approach is equally important. The current deficit in research regarding the impact of TCs in Georgia is a significant concern and is thoroughly addressed in this study.

1.3. Research Problem and Purpose

TC research specific to Georgia is scarce, likely due to the coast's minimal geographical extent and relative infrequency of direct landfalls. This dearth of research affects the public's understanding of TCs in the state, which leaves residents without necessary planning information. TC research in the state focuses specifically on coastal Georgia (Bossak et al. 2014, Cederholm 2015, and Lard 2015). Concentrating on a specific region deprives the remainder of the state of essential information needed to prepare for a severe event.

A comprehensive evaluation of the spatiotemporal characteristics of TCs is imperative for Georgia to accurately assess and strategize against potential TC risk in specific regions. The analytical approach enables the state to identify and prioritize regions that may require targeted assistance, resources, or disaster recovery initiatives during the hurricane season. Regions historically prone to TCs are often equipped with infrastructure specifically engineered to withstand the multifaceted impacts of such storms, including storm surge, high-velocity wind gusts, intense rainfall, etc. However, the current lack of TC-related research within Georgia presents a significant challenge. Without detailed knowledge of the areas susceptible to TCs, there is a heightened risk that existing infrastructure may not be adequately fortified against the destructive nature of these extreme weather events. While Georgia may not frequently experience hurricanes, closely monitor and preparing for tropical storms remains critical. Tropical storms, though less intense than hurricanes, can still inflict considerable damage due to their potential association with heavy rainfall and strong winds to areas that are not used to them. Consequently, a thorough understanding of these weather events is essential for effective state-level planning and response strategies.

The research questions addressed in this thesis are:

1. What are the spatiotemporal characteristics (e.g., frequency, intensity, and rainfall) of tropical cyclones exceeding 17 ms^{-1}in Georgia?
    a. Are these spatiotemporal characteristics changing across time?
2. How much of Georgia's monthly and annual precipitation is attributed to tropical cyclones?

The research hypothesizes the existence of a concentrated area of coastal TC activity, and a distinct hotspot for TCs entering from the southwest region of Georgia. A notable frequency disparity is expected between tropical storms and hurricanes. It is anticipated that there has been a gradual decrease in the frequency of hurricanes, coupled with a significant increase in the overall intensity of hurricanes or tropical storms. The research anticipates observing a decreasing trend of hurricane occurrences, counterbalanced by an escalation in their intensity. Observing a decreasing trend of hurricane occurrences could suggest a dynamic change in TC activity patterns, warranting a further investigation into the underlying causes and potential implications.

This research hypothesizes that, within the state of Georgia, the coastal and southwest regions are likely to receive the highest levels of rainfall from TCs, both on a monthly and annual time scales. In contrast, the north Georgia region is anticipated to experience the least amount of TC rainfall. The study hypothesizes that the peak incidence of rainfall attributed to TCs mainly occurs in August, September, and October. These findings could provide critical insights for regional planning and preparedness strategies in relation to TC impacts.

This study uses a multi-methodological approach. Descriptive statistics and regression models (i.e., ordinary least squares (OLS), quantile, and loess) are used to observe the spatiotemporal characteristics and trends in Georgia TCs, including the seasonality, intensity, frequency, and distribution of TCs. The research then uses ArcGIS to aggregate monthly and annual precipitation to calculate the amount of TC rainfall in the state. Finally, historical archive documents are used to analyze and cross-reference TCs. This research aims to have a concise climatological history of tropical cyclones in Georgia across space and time (1851–2021).

The following chapters will cover the broad themes of TCs and their attributed rainfall. Chapter Two will provide an in-depth review of the existing literature on North Atlantic TCs, indicating the fundamental principles of TC formation and differentiating between tropical storms and hurricanes. This chapter will also delve into the specific literature regarding TCs in

Georgia, thereby establishing a foundation for the research conducted in this study. Chapter Three is dedicated to outlining the methodology employed in this research. It will comprehensively analyze the dataset used, detailing each method and its respective approach. Furthermore, this chapter will discuss the limitations inherent in the datasets and justify the rationale behind the selection of both the datasets and the methods for this study.

Chapter Four will present the study's findings, accompanied by maps and figures to illustrate the results. Finally, Chapter Five will thoroughly discuss the results, culminating in the conclusions drawn from this study.

CHAPTER 2. HURRICANES, TROPICAL STORMS, AND GEORGIA

2.1. Introduction to North Atlantic Tropical Cyclones

TCs are rotating, non-frontal, low pressure systems typically with a warm-core defined by strong winds and a grouping of thunderstorms with heavy rainfall potential (Maue 2004). A warm core often refers to the structure of the central region of a TC, where the air is warmer than its surroundings (Vigh and Schubert 2009). TCs depend on many atmospheric factors to form. These favorable conditions include high humidity in the troposphere, a warm sea surface temperature (SST) (> 27°C), low vertical shear (< 10.3 ms^{-1}), being at least 483 km (300 mi) from the equator due to the decreased Coriolis effect, increased relative vorticity in the troposphere, and a preexisting disturbance (NOAA 2020). Relative vorticity refers to the measure of rotation in the air at a specific point relative to the Earth's surface (Wu et al. 2020). It is a main characteristic of a TCs rotating structure. Low vertical wind shear is where there is little to no change in wind speed and direction at different altitudes (Latif et al. 2007). Low vertical wind shear is beneficial for TC development and determining TC intensity. TCs gain their energy from warm ocean water and latent heat exchange but can also gain energy from easterly waves, tropical upper tropospheric troughs, or West African disturbances (Lin et al. 2020). While these conditions help form a TC, not all factors must be present, nor does the existence of all conditions imply a TC will form.

North Atlantic TCs are categorized by the Saffir-Simpson Hurricane Wind Scale (SSHWS), which is based on the maximum wind speed of an individual TC (Table 1). The scale is utilized to assess TC intensity and to forecast the potentially destructive impacts. This evaluation is critical for preparedness and response planning in affected areas. The SSHWS's principal shortcoming is its lack of other critical factors, such as rainfall, flooding, and storm surge. These factors significantly contribute to the damage caused by TCs. The SSHWS falls short in adequately capturing the multifaceted nature of a TC, as it is predominantly focused on wind speed metrics and the attributed damage alone.

Table 1. Saffir-Simpson Hurricane Wind Scale (NOAA 2020)

Category	**Wind Speed (m/s^{-1})**	**Wind Speed (kt)**	**Wind Speed (mph)**	**Expected Damage**
Tropical Storm	17–32 ms^{-1}	33–63 kt	38–73	Dangerous winds will produce little damage
1	33–42 ms^{-1}	64–82 kt	74–95 mph	Dangerous winds will produce some damage
2	43–49 ms^{-1}	83–95 kt	96–110 mph	Extremely dangerous winds will produce extensive damage
3	50–58 ms^{-1}	96–112 kt	111–129 mph	Devastating damages will be produced by winds
4	59–69 ms^{-1}	113–136 kt	130–156 mph	Catastrophic damage will occur produced by winds
5	≥ 70 ms^{-1}	≥ 137 kt	≥ 157 mph	Catastrophic damage will occur produced by winds

When a 1-minute average of sustained winds (10-meters above the ground) reach 17 ms^{-1}, the TC is considered a tropical storm and given a name. A tropical storm forms from a tropical depression and occurs frequently near the Intertropical Convergence Zone (ITCZ). The ITCZ is the equatorial zone where trade winds converge. Tropical storms have a low-pressure center that spins counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Tropical storms are not categorized into different intensity levels, it is considered one intensity level until hurricane status is reached (33 ms^{-1}).

When the sustained wind speeds reach 33 ms^{-1}, the storm qualifies as a Category 1 on the SSHWS. This categorization marks the transition of the storm into a hurricane, indicating increased intensity and potential for damage. All winds in the SSHWS scale are considered life threatening (Rappaport 2000). Categories 3, 4, and 5 hurricanes are major hurricanes due to catastrophic damage and significant loss of life due to strength of the wind. TC intensity research is more complicated due to many types of intensities within the subject (average intensity, maximum potential intensity, etc.) (Pielke et al. 2005, Emanuel 2007). For this study, intensity of TCs will be categorized by the SSHWS (Table 1).

TCs occur in seven basins across the globe: North Atlantic, Eastern Pacific, Western Pacific, North Indian, Southwest Indian, Australian and South Pacific basin. This study focuses on the North Atlantic basin, including the Caribbean Sea and GOM. The official TC season spans from June 1 to November 30, during which approximately 97% of TCs occur (NWS 2023). However, it is important to note that about 3% of TCs develop outside of this designated season (NWS 2023). TCs have occurred as late as January following an active season, and as early as April (Shultz et al 2018).

In the North Atlantic Ocean Basin, storms commonly form at low latitudes off Africa's coast in the eastern region of the basin and are driven westward by trade winds. During this time, a TC could potentially form if there are enough environmental factors for genesis. The North Atlantic Oscillation (NAO) significantly influences the genesis frequency of TCs (Zhang et al. 2022). During a positive NAO (+NAO) the Icelandic Low and Azores High are well developed, and this is related to the strong westerly winds located over the North Atlantic (Wanner et al. 2001). This leads to TCs being directed toward the north or east, generally moving away from the eastern coast of the United States and heading toward the North Atlantic or Western Europe. During a negative NAO (-NAO) the Icelandic Low and Azores High are weaker, reducing the westerlies over the North Atlantic (Wanner et al. 2001). A negative, weaker NAO leads to more east coast landfalls. Baldini et al. (2016) found that the NAO and SST influence changes in the TC tracks and intensity of major TCs (category 3-5) in the Atlantic Basin over long-term periods. Additionally, the Atlantic Multidecadal Oscillation is a climatic pattern at periods of about 60–80 years that can affect the genesis of TCs. It is important to understand that SST anomalies and sea level pressure anomalies (SLPA) play critical roles in the AMO. When the AMO is positive, there tends to be heightened TC activity in the Atlantic Basin (Klotzbach and Gray 2008). Klotzbach and Gray (2008) found that in a positive phase, SST anomalies in the North Atlantic are warmer than usual, whereas SLPAs near the equator fall below normal levels. During a negative AMO phase TC activity tends to decrease. The opposite conditions occur in a negative AMO phase, SST anomalies are cooler than usual in the North Atlantic and SLPAs near the equator are above normal levels (Klotzbach and Gray 2008). Moreover, a positive AMO correlates with an increased occurrence of hurricanes making landfall on the U.S. eastern coastline (Klotzbach and Gray 2008).

Vertical wind shear is also an important factor for TC development. When a hurricane has formed and there is low vertical wind shear, it allows the hurricane to develop further without disruption of high wind shear. When high wind shear is present, it spreads the storm out over a larger area, which, in turn, distributes the latent heat over a larger area (Latif et al. 2007). Wind crossing over a tropical storm could deter it from developing into a hurricane by weakening the system or forcing it to dissipate (Elsberry and Jeffries 1996). Ting et al. (2019) found that the eastern coast of the United States may have a boundary of strong wind shear that varies between phases of intensity. This could potentially protect the Atlantic coast from major hurricanes. However, the researchers discussed how greenhouse gases may erode this boundary of high vertical wind shear leaving the coast without the barrier.

2.3. The State of Georgia

Georgia is in the southeastern United States and has a rich history. It was the last of the original 13 colonies established by Great Britain. Georgia is known for its diverse geography from the Appalachian Mountains in the north to the Coastal Plains in the south, and its vibrant culture, including major cities like Atlanta and Savannah.

The State of Georgia shares its borders with Florida, Alabama, Tennessee, North Carolina, South Carolina, and the Atlantic Ocean along the eastern coast. The geographic proximity of Georgia to the warm waters of the GOM contributes a climatic profile characterized by prolonged, hot, and humid summers, with brief winters. Annual rainfall totals vary from 1,778 mm (70 in) in the north to 1,143mm (45 in) in the Coastal Plains (Frankson et al. 2022). While snow is rare in most of Georgia, the northern region does see an average of approximately 127 mm (5 in) each year (Frankson et al. 2022).

Georgia is divided into five distinct regions including the Appalachian Plateau, the ridge and valley region, the blue ridge mountains, the Piedmont region, and the Coastal Plain (Figure 1). The Coastal Plain can be divided into the upper and lower regions. The Coastal Plain covers the largest area and is approximately 60% of the state (Alhadeff et al 2000).

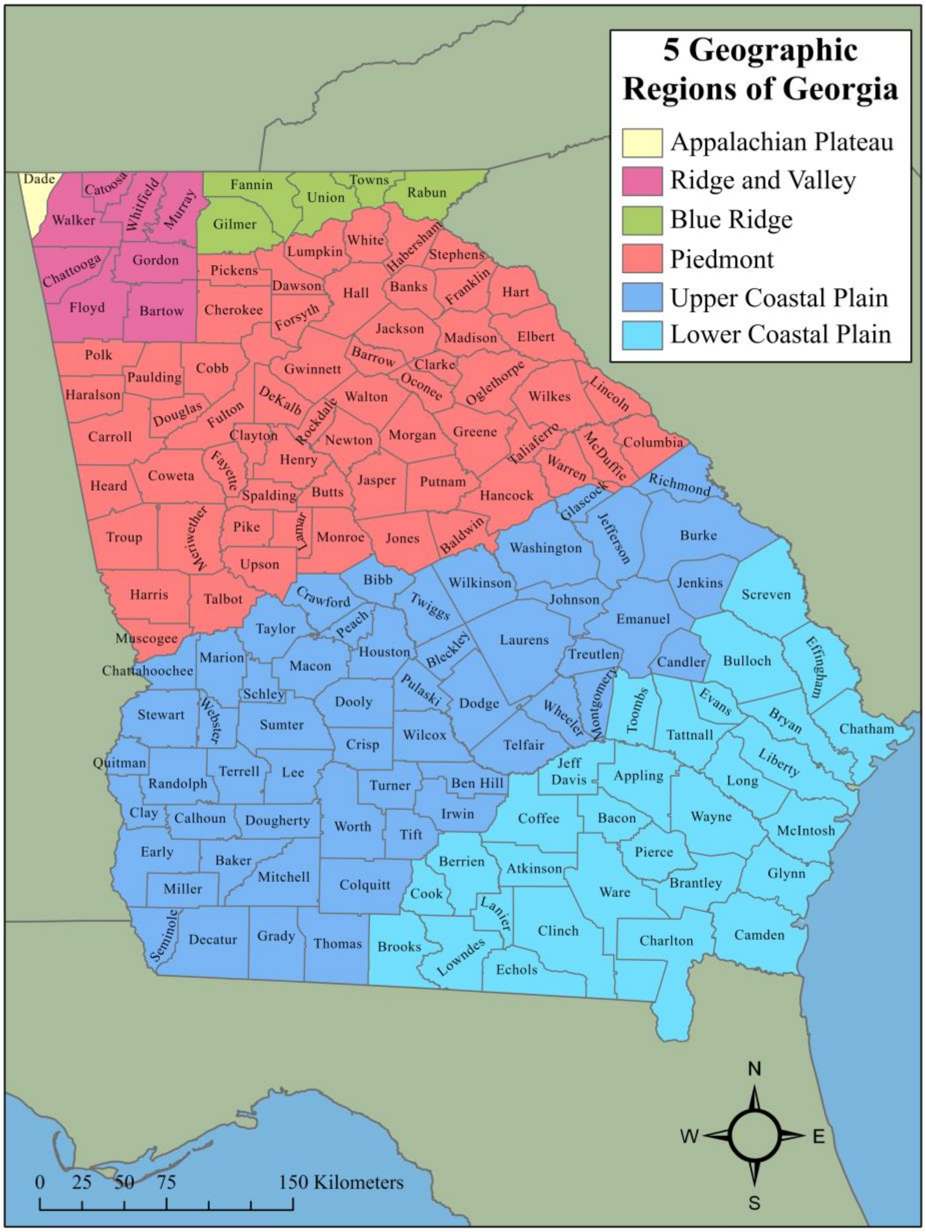


Figure 1. The five geographic regions of Georgia with county delineation and the Coastal Plain divided into the upper and lower regions.

Georgia's Coastal Plain features a 160 km (100 mi) coastline with 14 major barrier islands, extensive dunes, significant river systems, maritime forests, and roughly 400,000 acres of salt marshes (One Hundred Miles 2020). The coastline area includes six counties listed from south to north: Camden, Glynn, McIntosh, Liberty, Bryan, and Chatham. By 2060, the population in this region is expected to grow from 726,502 to 1,012,000 residents (Georgia Water Plan 2023). Table 2 shows population growth in Coastal Georgia counties using data from 1950–2020. There has been a consistent population increase over time across all coastal counties. This region is an economic driver of Georgia's economy through its major ports, tourism, and energy production sectors.

The Coastal Plain contains most of Georgia's agricultural land. Georgia's food and fiber production contributed $73.2 billion and 340,827 jobs to the state in 2021 (Kane 2023). Georgia's top ten agricultural commodities (in order of value) are chickens ($4.2 billion), cotton ($1.0 billion), peanuts ($776.7 million), timber ($660.6 million), beef ($658.6 million), greenhouses ($635.9 million), eggs ($635.1 million), corn ($509.1 million), pecans ($383.8 million), and blueberries ($348.7 million) (Kane 2023).

Table 2. Population Growth of Coastal Georgia Counties from 1950 to 2020 (Census Bureau 2020) listed from south to north.

County	1950	1960	1970	1980	1990	2000	2010	2020
Camden	7,339	9,975	11,334	13,371	30,167	43,664	50,513	54,513
Glynn	29,160	41,954	50,580	54,981	62,496	67,568	79,626	79,626
McIntosh	6,007	6,364	7,371	8,046	8,634	10,847	14,333	10,975
Liberty	8,467	14,487	17,569	37,583	52,745	61,610	63,453	65,256
Bryan	5,988	6,226	6,539	10,175	15,438	23,417	30,233	44,738
Chatham	150,946	188,299	187,767	202,226	216,935	232,048	265,128	295,291

According to Table 3, Georgia's population is 10,711,908. The piedmont region of Georgia is home to most of the state's population (~50%), largely because it includes Atlanta, the capital city, and a major metropolitan area. Atlanta is in Fulton County, along with 14 other cities. There are 1,066,710 people living within Fulton County as of the 2020 Census. Georgia is the ninth most diverse state in the US, boasting a diversity index of 64.1% (Lu 2024). Notably, four of the six most diverse counties are in the Piedmont region, including Gwinnett, Cobb, Fulton, and Dekalb County (Census 2020). The other two most diverse counties, Stewart and Liberty, are in the Coastal Plain (Census 2020). Among these, Gwinnet County, located east of Fulton County, is the most diverse in Georgia, with a diversity index of 75.1% (Census 2020).

Table 3. Race Demographics of the Georgia Population in 2020 (Census 2020)

Race	**Estimate**
White	5,555,483
Black	3,320,513
Two or More Races	743,908
Other Race	555,059
Asian	479,028
American Indian and Alaska Native	50,618
Native Hawaiian	7,299
Total Population	**10,711,908**

The Appalachian Plateau (Dade County) is in the northwest corner of the state, with a population of 14,895 people (Census 2020). The area is known for its scenic beauty, including Cloudland Canton State Park. The Valley and Ridge region, situated between the Blue Ridge Mountains and The Appalachian Plateau, is characterized by its abundance of rivers, valleys, and agricultural lands, making it the state's second most populated region according to the 2020 Census. The Blue Ridge region is home to Georgia's highest peak, Brasstown Bald (1,458 meters), and Springer Mountain (1,153 meters), marks the starting point for northbound hikers on the Appalachian Trail (GPB 2019). The region receives the highest annual precipitation compared to other areas in Georgia and features some of the state's largest rivers, including the Savannah, Chattahoochee, and Coose Rivers (GPB 2019).

2.2. Georgia Tropical Cyclones

Georgia is susceptible to landfalling hurricanes; however, due to its coasts geographical extent and curvature, such occurrences are uncommon compared to Florida. The Coastal Plain is where direct TCs travel because the region covers ~60% of the state and is closest to the GOM and the Atlantic Ocean. However, the state periodically experiences indirect TCs that have made initial landfall in Florida and travel through other portions of the state. The potential impacts of a TC, rather than its categorization, hold high importance, as evidenced by hurricanes like Michael, Irma, and Idalia, that continued to have lasting effects in Georgia even after being downgraded to tropical storms.

Numerous factors influence the frequency of TCs in Georgia. Arid conditions are known to increase wind shear, which can periodically inhibit TC genesis, whereas more humid conditions may enhance TC frequency due to reduced wind shear (Gray 1984, Goldenberg and Shapiro 1996, Wilson 1999, Chu 2004, Klotzbach 2007, Jin et al. 2014). Additionally, rainfall patterns over the Sahel and Sudan regions have been identified as significant contributors to intense Atlantic hurricane activity (Landsea and Gray 1992). The Bermuda High is pivotal as a primary steering mechanism for TCs. This system, characterized by its clockwise-rotating airmass, often drives TCs northward, or causes re-curvature into the North Atlantic (Hurricane Movement 2020). The strength and position of the Bermuda High are controlled by several factors including the NAO, AMO, SST, the jet stream, and El Niño-Southern Oscillation (ENSO). The El Niño-Southern Oscillation (ENSO) influences these factors, with its phases of warmer (El Niño) and cooler (La Niña) SSTs impacting global weather patterns, which in turn affect the formation and intensity of TCs. For the southeastern coast, especially Georgia, SST, NAO, and AMO are factors that can influence the strength and position of the Bermuda High. A strong Bermuda High tends to direct TCs westward before redirecting them toward Florida and into the GOM. Conversely, a weaker Bermuda High is more likely to allow TCs to travel along the east coast and then curve out to sea (Scowcroft et al. 2020). The TC track patterns are determined by whether this high-pressure system is located more to the west or east within the basin (Scowcroft et al. 2020).

Keim et al. (2007) examine the coastal strikes of TCs from Texas to Maine over a 105-year period, focusing on their frequency in various states including Georgia. Georgia experiences hurricanes infrequently, with some coastal regions seeing hurricanes only once in every +105 years. This rarity is linked to Georgia's coastline being somewhat sheltered, which helps to explain the lower infrequency of hurricane landfalls compared to other areas. Return intervals, or the expected time between TC occurrences, can be used to compare the frequency of storms between places. Saint Simons Island in Georgia, situated within 4.8 km (3 miles) of the southern portion of Georgia's coastline, has a 52–year return period for all TCs, while Tybee Island within 4.4 km (2.5 miles) of the northern portion of Georgia's coastline, has a 21–year return period (Keim et al. 2007).

Bettinger et al. (2009) investigate TC intensity along the southeastern coast, including Georgia, utilizing geographic information systems (GIS). It reveals that parts of the Georgia coast endure storms with higher average intensities compared to surrounding regions. Notably, it points out that storms originating from the Atlantic Ocean maintain their intensity upon landfall and can persist up to 100 km inland, whereas storms from the GOM tend to weaken more quickly.

There is a lack of research that focuses on all TC tracks that have impacted the state of Georgia. Research currently exists focusing on coastal counties and the geographic locations of direct hurricane landfalls (Bettinger et al. 2009, Bossak et al. 2014, and Welford et al. 2017). Researching direct landfall is important, but hurricanes have made landfall in the Florida panhandle and continued to progress into the state of Georgia at hurricane strength. Most research focuses on individual cities or counties on the coast, with a majority focusing on Savannah. The effects hurricanes have in Georgia beyond the coast occur in forest resources (Henderson et al. 2022, Cole et al. 2021), agriculture (Reighard et al. 2001), and throughout the economy (Dorfman et al. 2018 and Henderson et al. 2022).

Non-coastal counties may be affected by TCs due to the high wind speed and rainfall from these extreme storms. Huang et al. (2001) formulated a TC vulnerability model by integrating economic loss data from Hurricane Hugo in 1989 and Hurricane Andrew in 1992. The model establishes a clear correlation between the hurricane-induced damage and the maximum wind speed experienced throughout the storm. Increased wind speed can inflict considerable damage in forested areas due to the increased likelihood of tree falls (Huang et al. 2001). Trees in a state of decay or near death, already suffer from structural compromise, and are particularly vulnerable to collapse during episodes of intense rainfall (Huang et al. 2001). Excessive precipitation can result in soil saturation, diminishing the soil's capacity to securely anchor tree roots. Additionally, extended periods of moisture can lead to root rot and other diseases in crops and trees (Huang et al. 2001).

Georgia was found to have one of the highest amounts of damage from hurricane force winds to urban and rural forests in the U.S. (Cole et al. 2021). The state has the fifth-largest urban forest in the nation (Kilgore 2024). Atlanta's urban forest provides many benefits for the region such as sequestering carbon, reducing air pollution, and decreasing the heat island effect (Tran et al. 2017). The urban forest is a natural water management system, absorbing rainfall and reducing runoff. This function is particularly crucial in urban areas, where impervious surfaces are prevalent. These forests also serve as vital greenspaces, enhancing the well-being of residents by offering a sanctuary from urban life. They provide a serene environment for physical activity and relaxation. The urban forest can reduce energy costs by minimizing the reliance on air conditions and offering ample summer shade.

Furthermore, the potential loss of timber in Georgia's rural forests could impact both farmers and the state's economic wellbeing. Researchers studied whether long-leaf pine forests can completely recover from hurricane damage in Georgia (Henderson et al. 2022). They found that forests damaged by hurricanes will not be able to recover in their total growing stock or carbon removal. This affects consumers, as prices will jump rapidly once the demand for timber returns to normal after the initial recovery period (Henderson et al. 2022).

Hurricane Michael affected Georgia's agricultural division during the early cotton, vegetable, and peanut harvest season (Dorfman et al., 2018). Agricultural equipment and infrastructure were damaged due to hurricane-force winds of 35.8 – 53.6 ms^{-1}. The estimated total of direct losses (crop losses at a farm level) in the agricultural sector of Georgia due to Hurricane Michael was ~$2.4 billion, and indirect losses (value of product) were estimated as ~$360 million (Dorfman et al.2018). The largest direct and indirect loss came from timber.

Variability in rainfall greatly affects these industries. Reighard et al. (2001) found that peach production in south and central Georgia was affected by rainfall events enhanced by El Niño and TCs like Tropical Storm Alberto (1994). Excessive water or rain in the soil can rot the bark, roots, and limbs of plants (Reighard et al. 2001). Prat and Nelson (2013) analyzed precipitation of TCs from 1998–2009 in the southeast U.S. using tropical rainfall measurement mission. Annually TC rainfall contributed the highest amount along the GOM and Atlantic coasts. Inland, the proportion of rainfall from TCs ranged from 8–12% for regions situated 150–300 km away from the coasts. In the monthly analysis, it was found that Frances (2004) and Ivan (2004) together contributed to rainfall ≥ 200 mm, which was 30% more than the total seasonal rainfall in North Georgia. Knight and Davis (2009) analyzed data from 1972–2007 and discovered that rainfall from TCs in the southeastern U.S. had increased 5%–10% per decade.

Knight and Davis (2007) discovered that, on average, TCs contribute approximately 6–14% to the annual precipitation in June–November in the coastal plain and piedmont regions of Georgia. Monthly TC-induced rainfall averages were calculated with September having the largest range of 9–12% in the northwest to >24% occurring along the eastern border. They used 84 surface observation stations across the southeast, supplemented by additional stations from the Cooperative Observer program network, to ensure a uniform distribution of data across their study area. Of these, eight stations were located within Georgia's border. The study notes that the data set represents the maximum possible contribution of rainfall-induced by TC, leading to an overestimation of potential rainfall in the area.

The state identifies TCs as the most expensive type of natural disaster it experiences (GEMA 2019). The 2019 Georgia Hazard Mitigation Strategy lists the state's primary climate risks in the following order: tornadoes, inland flooding, hurricane wind, severe weather, and coastal hazards. It recognizes these major risks are primarily due to TCs. In 2013, 60% of the counties were impacted by "Tropical Cyclonic Events", slightly decreasing to 55% in 2017 (GEMA 2019).

In South Georgia, only two major interstates move travelers north in South Georgia: I-75 and I-16 (as seen in Figure 2). This limited infrastructure presents challenges during emergency evacuations. With Florida and Georgia residents potentially seeking refuge by moving northward simultaneously, these two interstates can quickly become overwhelmed. The convergence of evacuees from Florida into Georgia could exacerbate the situation, leading to severe traffic congestion. For example, Hurricane Irma caused traffic congestion on I-75 due to evacuees from

Florida and coastal Georgia (Brasch and Wickert 2017). Gas stations in Georgia were running out of gas due to the traffic influx, leaving evacuees stranded (Brasch and Wickert 2017). The Georgia Department of Transportation converted all lanes on I-16 to eastbound traffic to accommodate the evacuees from Georgia's coast (Brasch and Wickert 2017).

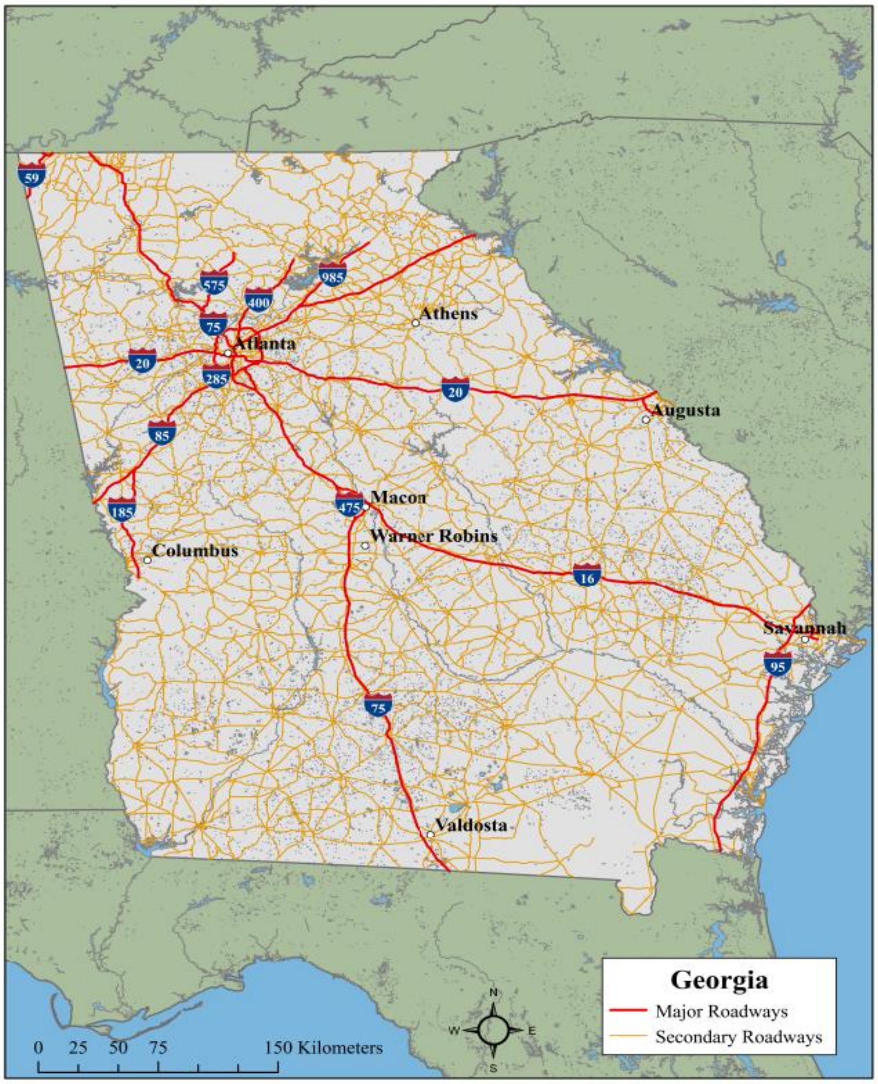


Figure 2. The State of Georgia with major interstates shown in red and secondary roadways shown in orange. Major cities of Georgia are also identified.

Protecting Georgia from natural disasters, such as TCs, is crucial due to its geographical location, historical significance, and economic significance. The state's coastline on the Atlantic Ocean and proximity to GOM makes it vulnerable to hurricanes and tropical storms, which can cause widespread damage to homes, infrastructure, and agriculture. The economic consequences of such disasters, as demonstrated by Hurricane Michael and Irma, are notable, impacting not only local communities but also the broader state economy.

CHAPTER 3. METHODS AND DATA

3.1. HURDAT2

TC data from the North Atlantic hurricane database (HURDAT2) consists of data on TCs that have occurred in the North Atlantic basin since 1851 (Landsea and Franklin 2013). HURDAT2 includes location and wind speed information at six-hourly increments for each known track in the basin. Beginning in 1961, synoptic observations at landfall were added outside the six–hour increments. Elsner and Jagger (2013) provided an interpolation method that produces hourly values along the known track using the six-hourly and synoptic data. The hourly interpolated data are generated through spline interpolation (Elsner and Jagger 2013). This method ensures the retention of values at the designated six-hour intervals, employing a piecewise polynomial to obtain the values between the 6-hour increments (Elsner and Jagger 2013). The geographic positions of the TCs are interpolated by using spherical geometry on the splines (Elsner and Jagger 2013). The data subset encompasses a comprehensive time frame from 1851–2021. Despite the acknowledged constraints inherent in earlier records, the inclusion of this extensive historical data are vital. This approach facilitates a thorough examination of potential trends in TCs in Georgia.

HURDAT2 has limited reporting before the pre–flight (1944–present) and pre–satellite (1966–present) era (Landsea and Franklin 2013). This leads to underestimations of storm frequency due to missing storms. TC intensities may be under-analyzed or categorized as lower than the actual event. This study uses archival research (e.g., photos) paired with the HURDAT2 data to provide context related to the historical experiences of people living through these earlier storms. This study focuses on storms once they have crossed the GA border, so many concerns over the earlier record (e.g., missed open ocean storms, landfall specifics) are not relevant here.

Confidence in the estimations increases when a storm has made landfall, as land observations become more straightforward compared to open ocean observations (Landsea and Franklin 2013).

This study only focuses on storms that are considered tropical storm (17 ms^{-1}) or hurricane (33 ms^{-1}) intensity within Georgia. The data are a subset to exclude storms that occurred only as tropical depressions, extratropical cyclones, subtropical depressions, subtropical storms, lows, tropical waves or disturbances. Due to this, TC rainfall in this study will be underrepresented. In the context of this thesis, the term ‘indirect’ will be used to describe TCs that did not make landfall on Georgia’s coastline. In contrast, the term ‘direct’ will describe storms that made landfall on Georgia’s coastline. The project uses the R Program for Statistical Computing for statistics and graphics (R Core Team 2023). ArcGIS Pro is used for data analysis and data mapping (Esri 2022).

3.2. nClimGrid–Daily

Daily precipitation data for this study are derived from the NCEI’s nClimGrid-Daily, which consists of daily high-resolution precipitation and temperature from 1951 to near present (Durre et al. 2022). The dataset includes information from the cooperative Observer Program (COOP), Automated Surface Observing System (ASOS), Snowpack Telemetry network (SNOTEL), and the Remote Automatic Weather Stations (RAWS) (Durre et al. 2022). RAWS stations are only used for temperature and are, thus, not used here. The thinplate smoothing splines method was used for a wide range of topographical and climatic features, and still shows the complexity of the terrain and coastal proximity (Durre et al. 2022). This approach collectively minimizes the likelihood of errors in interpolation. This method is good for interpolating daily temperature and precipitation at various spatial scales. Nclimgrid-Daily outperforms other precipitation datasets such as PRISM and DayMet (Durre et al. 2022).

A limitation of the nClimGrid-Daily is the variation in daily observation times across different stations. Such variations can lead to discrepancies in recorded precipitation values, as Janis (2002) noted. To minimize this impact, the dataset specifically includes measurements taken at midnight, 0500, 0600, 0700, 0800, and 0900 Local Time. These times were chosen because they are the most common for observations reports (Durre et al. 2022). Morning observations are combined with observations from the previous day at midnight to align the data further. This method enhances the consistency between two 24-hour observation periods ending at these times (Durre et al., 2022).

The observation time of nClimGrid-Daily creates a significant challenge to the dates when TCs occurred. TCs entered Georgia at varying hours throughout any given day. To align with the nClimGrid-Daily rainfall observation times, this study chose to reevaluate the days on which TCs occurred to account for the precipitation that was combined with the previous days' midnight observation. Since the morning observations occur between midnight and 9 am, making 9 am essentially the new midnight, the study reevaluated storms that entered or exited the state on or after 10 am. Figure 3 shows a schematic describing the way this decision was made for each storm.

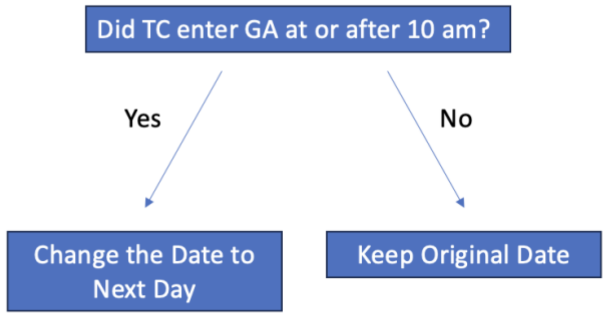


Figure 3. Decision Tree used in the reevaluation of the TC rainfall dates.

3.3 Archive Data

The study only focused on archives that occurred within 1851–2021. This was to unify any information found that would potentially match the HURDAT2 data set. The archives used were the Georgia Archives of the University System of Georgia and the Georgia Historical Society. Due to time constraints, only online archives were used. This limits the information available as there were letters, firsthand experiences, and ledgers that were documented to contain information on hurricanes in Georgia but were unable to be viewed unless in person. The study wishes to expand in the future to allow time for in-person analysis of archival documents. Using an archival approach for historical hurricanes assisted in further understanding the effects TCs had on the region, specifically in the late 1800s and early 1900s when HURDAT2 is least reliable (Kearney and Mullins, n.d.).

3.4. Descriptive Statistics

Descriptive statistics are used to summarize the entire database of TCs and provide the main characteristics of TCs in Georgia. By employing descriptive statistics, the study can determine the average frequency of TCs, analyze the occurrences distributed across different months, and identify the weakest and strongest wind intensities recorded in the state. The study uses descriptive statistics to calculate the average intensity of TCs and assess the years with the highest and lowest TC activity. This method illustrates the range and patterns of TCs in Georgia, laying a foundation for future assessments of the potential impacts on the region.

3.5. Correlation and Regression Models

Correlation is a statistical method used to evaluate the linear relationship of two continuous variables while testing for statistical significance. First, the study uses Shapiro-Wilk test to test for normality and to find the best fitted correlation test. The equation for Shapiro-Wilk is:

$$W = \frac{(\Sigma_{i=1}^{n} \alpha_i y_i)^2}{\Sigma_{i=1}^{n} (y_i - \overline{y})^2}$$

The study found that the maximum intensity of TCs and proceeded with the non-parametric Spearman's rank correlation test. This test is designed to assess the strength and direction of the relationship between the two variables ranked. The equation for Spearman rank correlation is:

$$\rho = 1 - \frac{6 \, \Sigma \, d_i^2}{n(n^2 - 1)}$$

This study examines the maximum intensity of TCs over time in the state of Georgia using OLS, quantile, and loess regression (Jacoby 2000, Elsner et al. 2008, Malmstadt et al. 2009). OLS is used in this study to fit a linear model to assess the relationship between time and hurricane intensity. The simplicity and interpretability of OLS makes it a useful tool to investigate the average trends in the state. The equation for OLS regression is:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

The explanatory variable (*x*) is year, and the response variable (*y*) is TC maximum wind intensity that occurred within Georgia's state boundary. This study does not consider the lifetime maximum intensity of the storm (i.e., over the entire track). Quantile regression is beneficial for this research because it provides insight into the conditions that lead to moderate and severe impacts and allows the user to specify which quantile of data to consider. A quantile regression model with two covariates is represented by:

$$Q_Y(q|X) = \beta_0(q) + \beta_1(q)X_1 + \beta_2(q)X_2$$

Quantile regression is a tool to comprehensively assess and illustrate the range of hurricane intensities that traditional mean-based approaches might overlook.

Finally, loess regression is considered. in which it does not make any assumptions about the overall structure or pattern of the data. This allows the line to curve with the data, giving more weight to points closer together with a smoother curve that estimates the relationship between the maximum intensity of TCs over time. It is useful for exploring complex relationships such as the maximum intensity of TCs over time and creates confidence intervals around the curve. This method is particularly effective for handling data outliers, which is crucial for TC data. Major Hurricanes can notably distort the results by causing an upward skew.

The models have tailored assumptions about normality, independence and the identical distribution of data points. The Shapiro-Wilk test is designed to assess whether the data is normally distributed and needs independent observations. Spearman's rank, however, does not require normal distribution because it is non-parametric, which focuses on the independence and ranking of data. OLS regression assumes the residuals are normally distributed but does not assume the variables are normally distributed. OLS regression focuses on each observation's residuals as being independent and identically distributed. Quantile regression assumes the residuals are not as affected as much as OLS but models' quantiles to view independent observations. Finally, Loess regression is a non-parametric method that does not assume normal or identical distributed data points but requires independence.

3.6. Rainfall Methods

The study applied a 500 km buffer (250 km buffer on each side of the point) to the HURDAT2 interpolated tracks to observe any TCs that possibly deposited rainfall. 'Select by Location' was used to observe buffers intersecting with the Georgia state border. The buffers that intersected with the borders were used in this study. This was done to ensure that all TCs near the state that may have deposited any precipitation were considered.

To determine the yearly accumulated rainfall from 1951– 2021, the total rainfall from each TC occurring within the timeframe was calculated. The 'Aggregate Multidimensional Raster' tool is used to perform statistical summaries over specified dimensions applied to the daily grids. The study used standard time as the dimension, sum as the aggregate method, and the aggregate definition was set to interval ranges (e.g., month or year). The range was set to the first day that the storm intersected Georgia to the last day the storm intersected with Georgia. Some storms spanned over two months. For example, Hurricane Ernesto in 2006 entered Georgia on 31 August and departed the state on 1 September. Using the 'Raster Calculator' tool, both days in those months' time were aggregated to sum the rainfall that occurred during the TC. The rainfall was then clipped to the Georgia state boundary. Each TC is then summed together using the 'Raster Calculator' tool to find the total amount of rainfall in Georgia from TCs. The TC rainfall was divided by the summed annual rainfall from 1951–2021. The daily rainfall grids were used to calculate the rainfall for each TC and were compared to the annual rainfall grids. The annual grids were calculated by summing the monthly gridded rainfall. The monthly gridded rainfall comes from the sister dataset – NClimGrid. The daily gridded rainfall is standardized with the monthly gridded rainfall to ensure consistency.

Similar procedures were used for both annual and monthly rainfall averages. The annual gridded rainfall total was obtained by summing the precipitation from each TC and then clipping this data to Georgia's State boundary. To determine the TCs attribution to the state's rainfall, this sum was divided by the total recorded rainfall from 1951–2021.

Monthly rainfall averages were calculated with the 'Aggregate Multidimensional Raster' tool to sum the precipitation data by month. TCs affecting Georgia across two months were divided, ensuring rainfall was attributed to the correct month of occurrence. This approach allowed for accurate monthly rainfall analysis, with the total precipitation for each month and TCs affecting Georgia were both divided by 71 years to adjust for months with no precipitation in the dataset. Finally, TC monthly averages were divided by the total monthly rainfall.

3.7. Archival Methods

This project uses archival research to construct the history of hurricanes, Georgia's changing physical geography, and the historic effect of hurricanes on the state and the affected population. Archival research is a method used to investigate and analyze historical documents. This is important to provide background on the state and a historical hurricane context. The research will use historical photo archives to identify and learn about hurricanes from a historical perspective. Using these archives will assist in increasing the human and social perspective on historical hurricanes and potentially map the geographic effects hurricanes had on Georgia in the past.

To narrow down the results of the archives only a small number of keywords were used to search through the archives. The words chosen for the search were: Hurricane, Tropical Storm, and Tropical Cyclone. 'Tropical Storm' and 'Tropical Cyclone' gave little to no results between both archive sites, likely due to online access. 'Hurricane' gave the most results on both archive sites and included letters, diaries, and ship logs containing experiences of potential hurricanes. There were some digitized documents about hurricanes that impacted Georgia, but it was before the allotted time range and, therefore, could not be used. Photographs are the dominant archival source, and two large collections from the Georgia Historical Society and the Georgia Archives gave detailed depictions of hurricane damage from the October 1898 Hurricane and 1940 Southeastern Hurricane. This thesis provides case studies on each hurricane influencing GA to give a combined climate, historical, and geographic background to better understand the impact on the historic communities. This gives insight into what TC variables historically damage Georgia the most.

CHAPTER 4. RESULTS

4.1. Descriptive Statistics

This study analyzes 113 tropical storms and hurricanes that occurred within the boundary of Georgia from 1851–2021 (Table 3). The classification of storm type is based on the intensity of the TCs at landfall, reflecting the varied intensities these systems have on the state.

Table 3. Tropical Cyclones in Georgia from 1851–2021 separated by landfall intensity and direct/indirect landfall. Percentage of total TCs relates to Georgia's total.

Event Type	Total Count	Hurricanes	Tropical Storms	Percentage of Total TCs
Direct Landfall	16	7	9	14%
Indirect Landfall	97	17	80	86%
Total Impact	**113**	**24**	**89**	**100%**

Figure 4a depicts the 16 direct landfalling TCs in Georgia categorized by storm type. The direct landfalling TCs all formed in the Atlantic Ocean, as opposed to the Caribbean or Gulf of Mexico. Figure 4b shows the 97 indirect landfalling TCs in Georgia categorized by storm type. These storms form within the Atlantic Basin, Caribbean Sea, and Gulf of Mexico, and the tracks make initial landfall in Florida or South Carolina. In both panels, TC tracks are varied in duration and total track length.

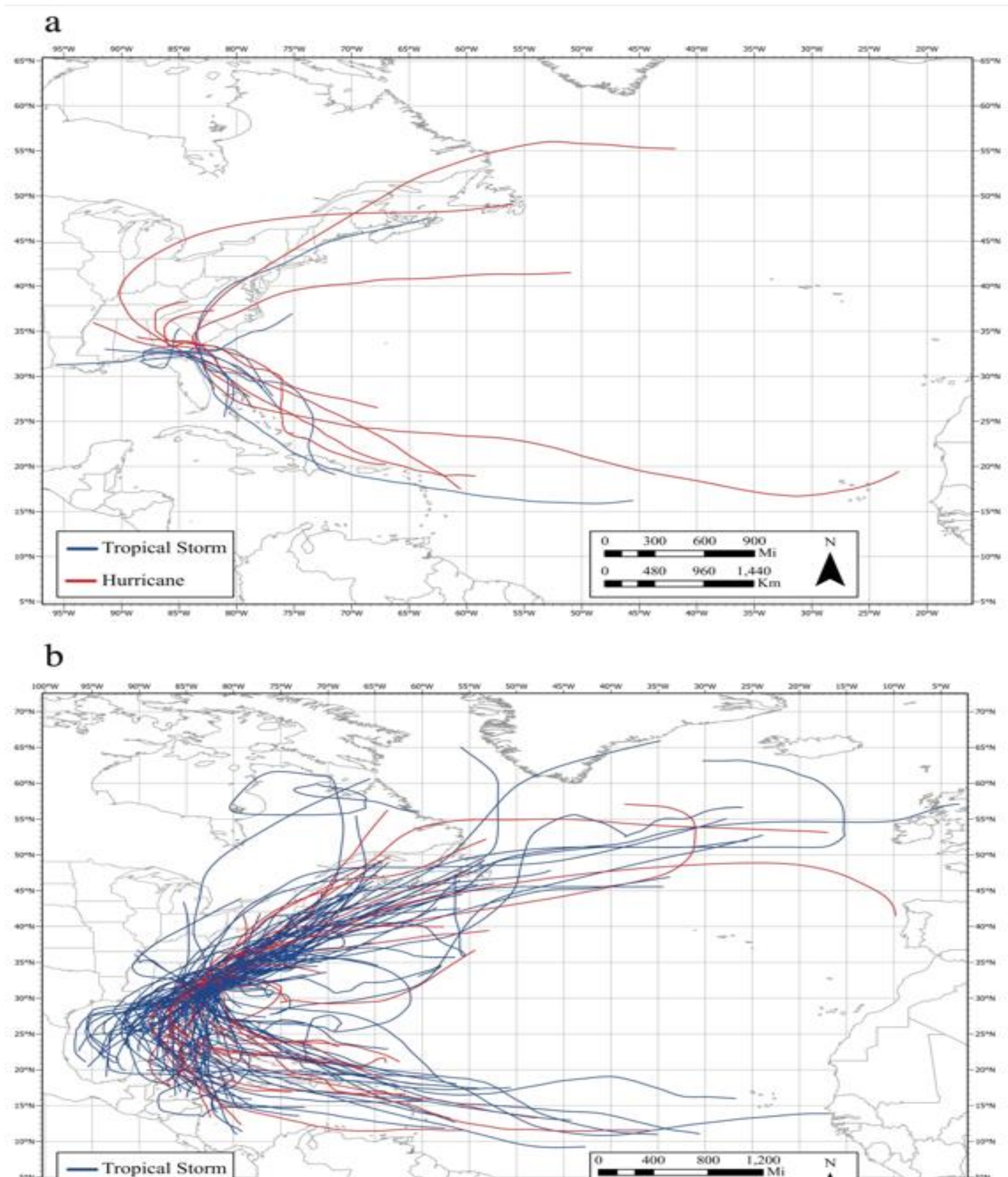


Figure 4a. Track map of direct landfalling tropical cyclones on the coastline of Georgia from 1851–2021. Figure 4b. Track map of indirect landfalling tropical cyclones in the state of Georgia from 1851–2021.

Figures 5 and 6 are density maps highlighting the specific locations where TCs have entered and exited the state. Each TC's point of entry or exit is marked with a black dot for precise identification. To symbolize the maps, each point was surrounded by a 40.3 km (25 mi) radius to determine the overlap among points, indicating areas where multiple points intersect. On the maps, red areas indicate regions with the highest density of entry points, while green represents the sparest areas of TC activity within a 40.3 km radius. Regions without color signify areas where TCs have not directly entered or exited. However, this does not imply that these areas have been completely unaffected by TCs.

Figure 5 is a heat map of TC entry points into the state. This map includes all direct and indirect landfalling TCs in Georgia. The densest area is along the southern border, where most tracks made landfall in Florida from the GOM and then continued into Georgia. The sparse area along the midwestern border is from TCs that travel further into the GOM but make a wide turn east to make landfall in Florida and then Georgia. One track from an Unnamed TC in 1947 entered the state multiple times due to the track's bending. The first entrance of this TC track into the state is the only point considered. Two TCs that had only one segment enter the state before leaving the state. These two storms (Unnamed 1874 and Eta 2020) will be included in the entrance and exit maps. TCs that make direct landfall on the coast tend to move westward, exiting along the state's western border.

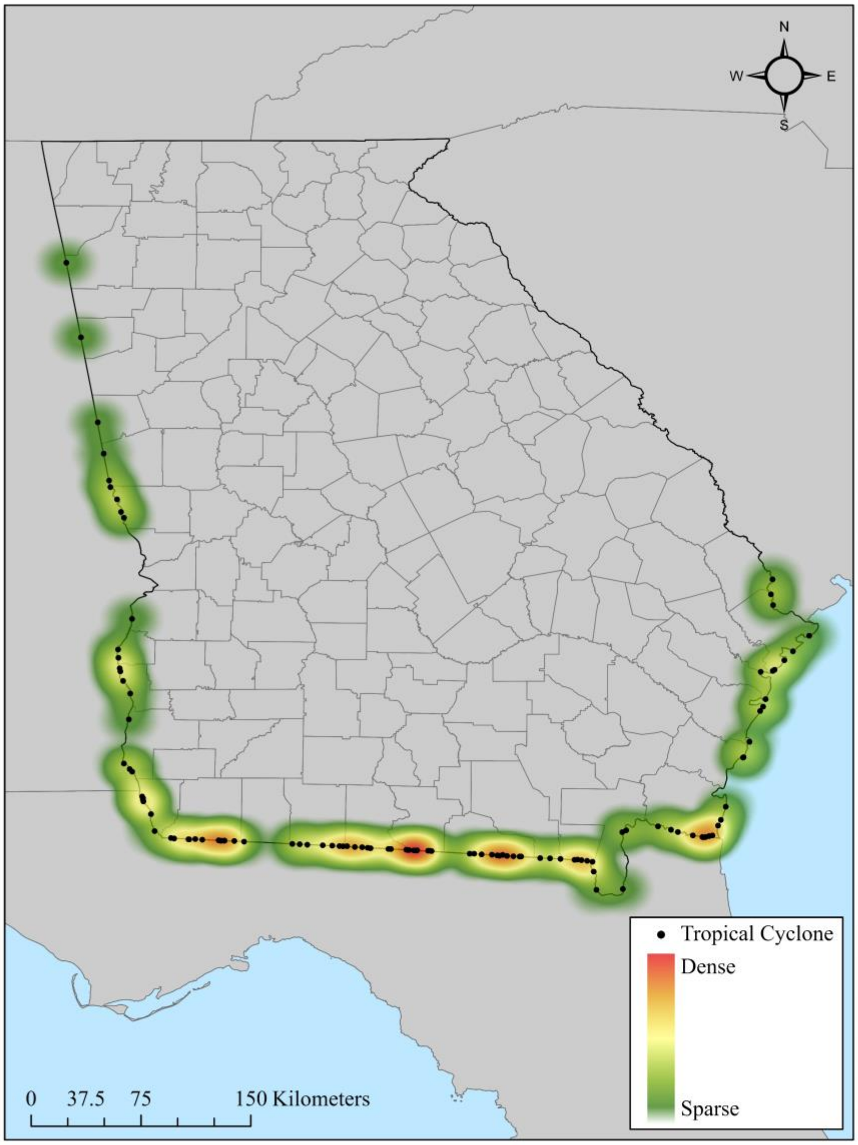


Figure 5. Heat map of first tropical cyclone entry points into Georgia, 1851–2021.

Figure 6 is a heat map for the exit points of TCs in Georgia from 1851–2021. There are nine TCs are not considered in this map as they dissipated within the state's borders. The storms that dissipate are Unnamed 1871, Unnamed 1873, Unnamed 1875, Unnamed1887, Unnamed 1916, Unnamed 1917, Unnamed 1933, Florence 1953, and Unnamed 1966. Most storms exit on the eastern edge of the state, with the densest area along the southeastern border. This is because most TCs enter from the south and travel eastward. There are TCs that continue North into Tennessee or North Carolina. TCs that make direct landfall on the coastal tend to move westward exiting along the state's western border.

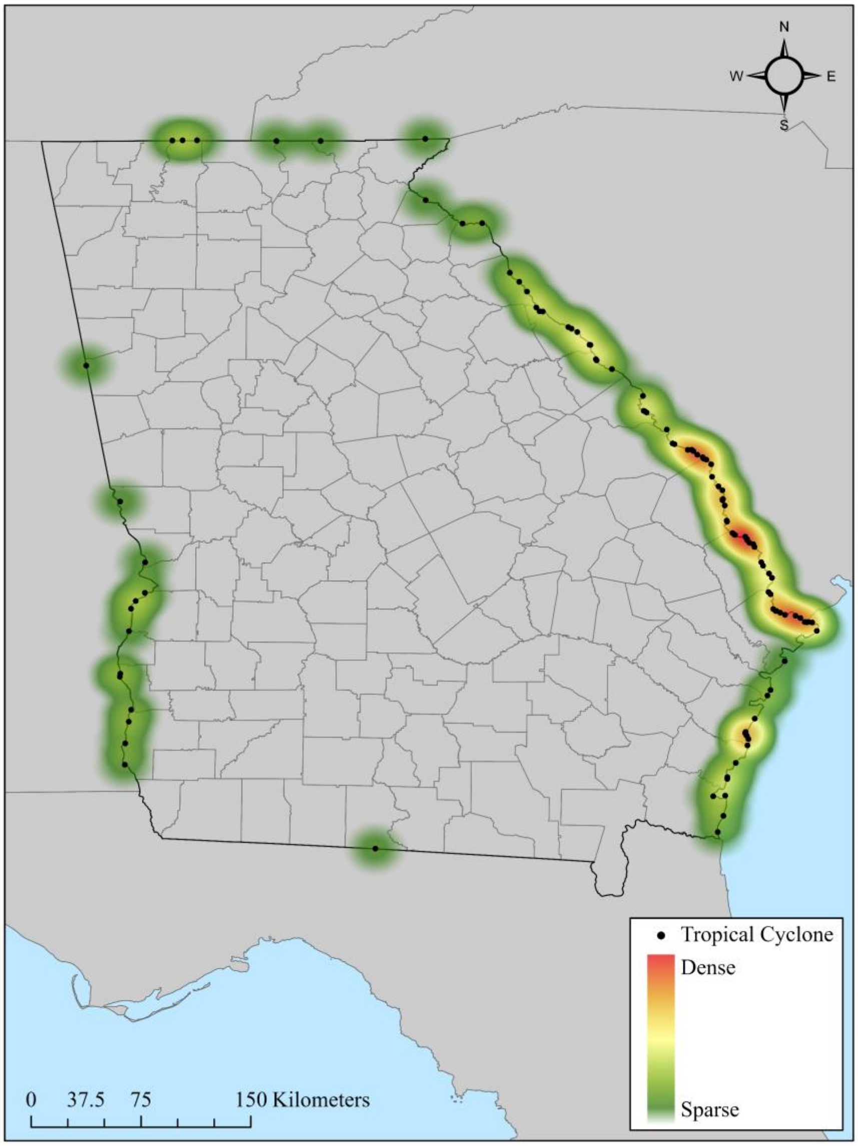


Figure 6. Heat map of tropical cyclone exit points along the Georgia border, 1851–2021.

Table 4 shows the distribution of annual Georgia TC counts categorized by the SSHWS (NOAA 2020). Category 4 and Category 5 hurricanes have not occurred in the state's known history. Hurricane Michael in 2018 and the Unnamed 1898 hurricane both maintained category three hurricane status as the tracks passed into and through Georgia. The Unnamed 1898 hurricane made landfall on 2 October from the Atlantic Ocean on the southern coastline of Georgia with a windspeed of 57 ms^{-1}. The Unnamed 1898 hurricane decayed and downgraded into a tropical storm around 125 miles into the Georgia from the coastline. Hurricane Michael entered the southwestern corner of Georgia from the GOM with a windspeed of 53 ms^{-1}. Hurricane Michael decayed and downgraded into a tropical storm around 90 miles into the states border.

Table 4. Category distribution of tropical cyclones in Georgia, 1851–2021.

Tropical Storm (17-32 ms^{-1})	**Category 1** (33-42 ms^{-1})	**Category 2** (43-49 ms^{-1})	**Category 3** (50-58 ms^{-1})	**Category 4** (59-70 ms^{-1})	**Category 5** ($\geq$70 ms^{-1})
89	15	7	2	0	0

Figure 7 illustrates the time series of annual Georgia TCs over a 171-year period. When considering all tropical cyclones over that time, the average rate is 0.66 TC/yr, with a variance of 0.65 σ^2. This rate is divided between tropical storms, 0.52 hur/yr (var = 0.56 σ^2) and hurricanes,0.14 hur/yr (var=0.145 σ^2). Most of the hurricanes (27%, n=21) occurred in the first one hundred years of the data set. Only three hurricanes occur after 1950.

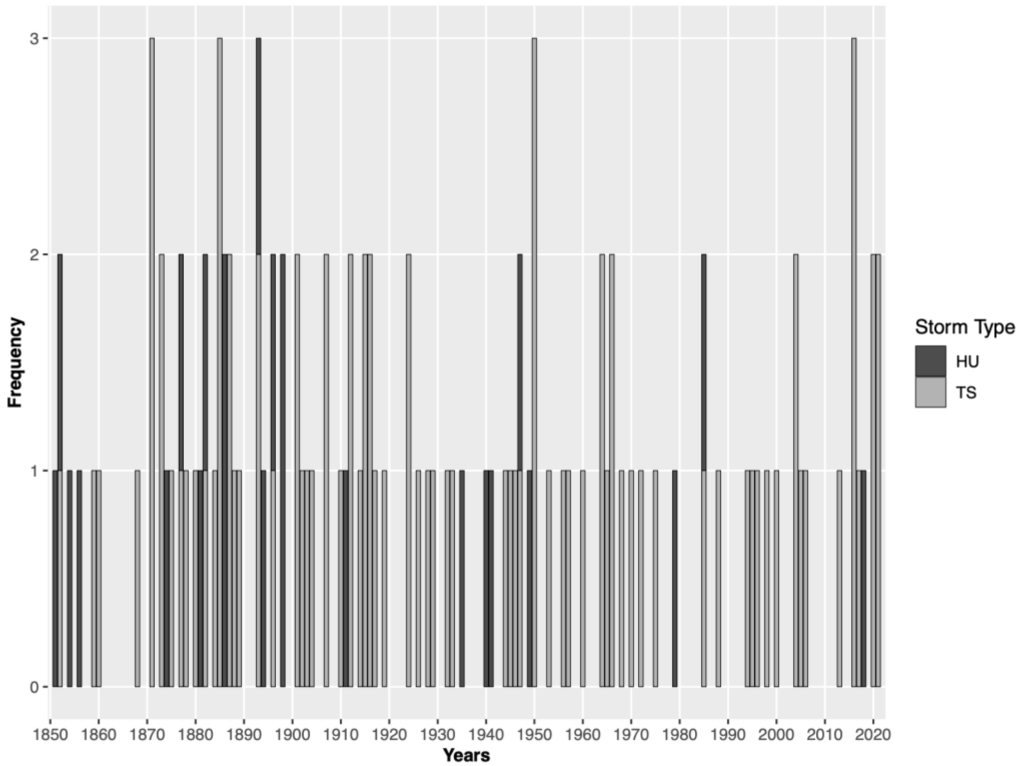


Figure 7. Georgia's annual tropical cyclone occurrence (1851–2021) categorized by intensity.

Figure 8 depicts the distribution of annual Georgia counts. There are 89 years without a Georgia TC and five years (1871, 1885, 1893, 1950, and 2016) where three TCs traveled through the state. The years with multiple storms are further analyzed by looking into historical records. Historical NOAA weather map's span the years in which most Georgia TCs occurred. There were only weather map records for the TCs occurring during the late 1800's that affected Georgia in August and December. No other months were available.

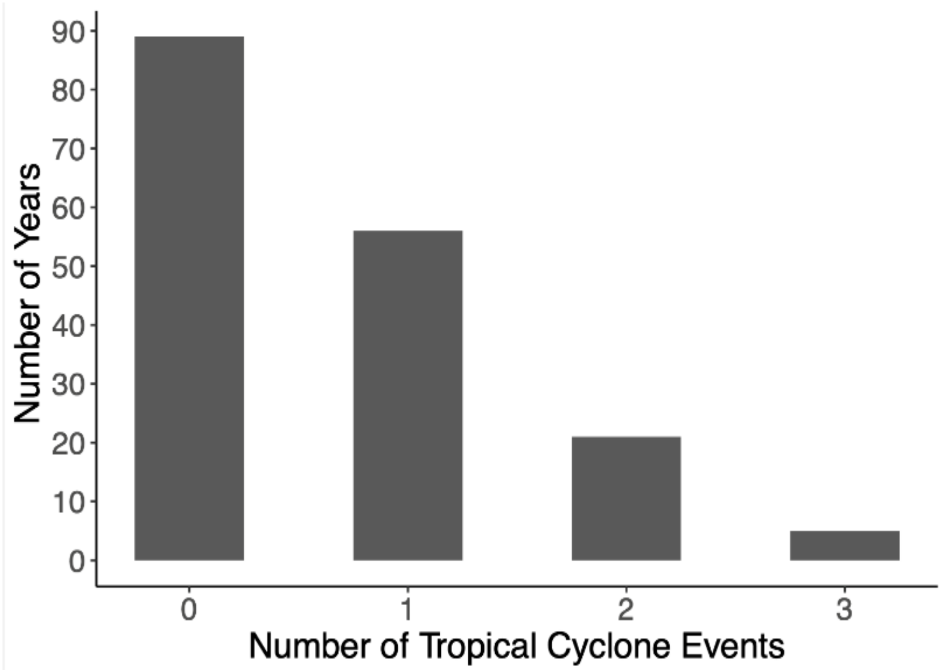


Figure 8. Distribution of annual Georgia tropical cyclone counts 1851–2021.

4.1.1. 1871

A historic map (Figure 9) from August 23, 1871, Figure 10 suggests a low barometer reading was observed with high winds and heavy rainfall across the state (NOAA 1871). The TC of August 26, 1871, (Figure 11) made initial landfall in Florida and then entered Georgia as a tropical storm in the southwestern region of the state (NOAA 1871).

4.1.2. 1885

While there is no mention of a TC in the August 1885 weather map, the days in which the storm is said to affect Georgia, records show a low barometer in the region, winds traveling north or northeast, and light rain with clouds (NOAA 1885).

4.1.3. 1893

For the August 28, 1893, TC, (Figure 12) records indicated the low traveled from the Atlantic up the eastern side of Florida and made landfall in Georgia (NOAA 1893). The map indicates a low-pressure system moving inland with a high-pressure system making its way into the Atlantic just north of the low-pressure system (NOAA 1893).

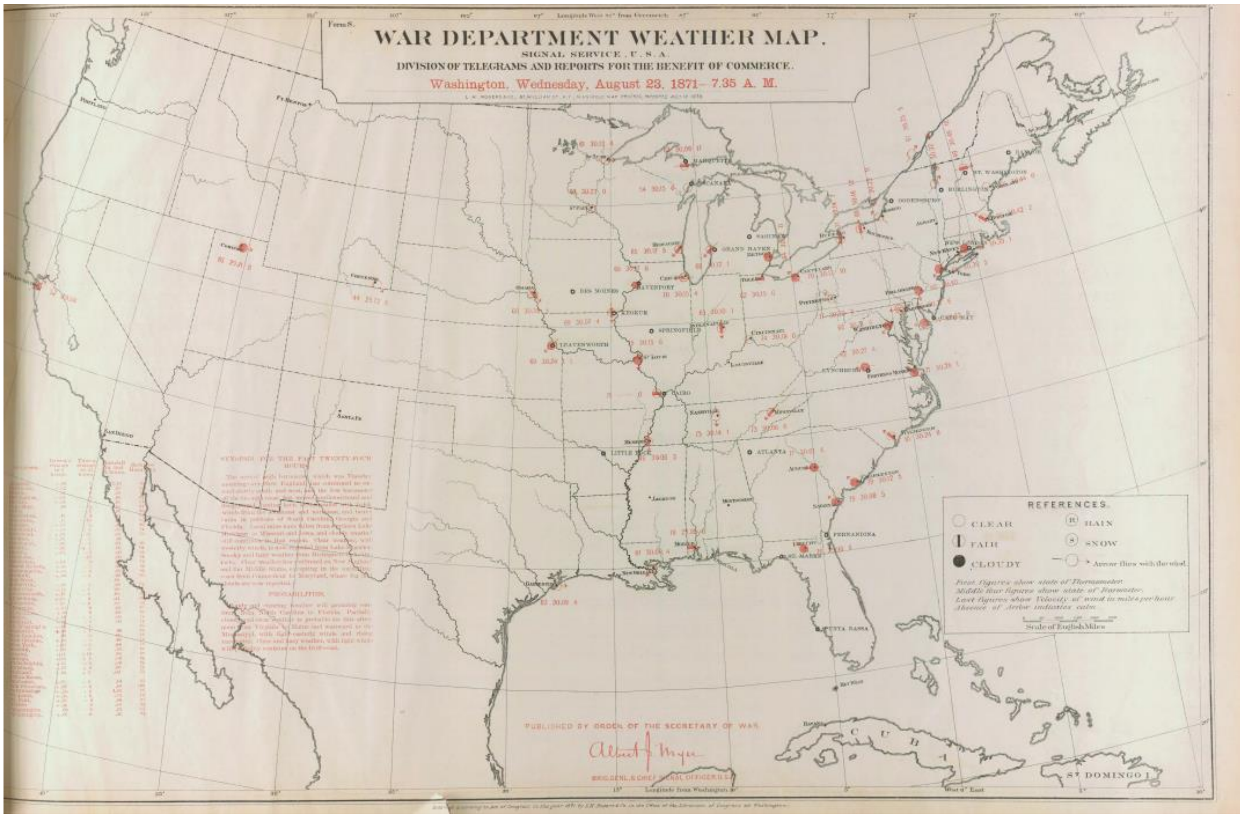
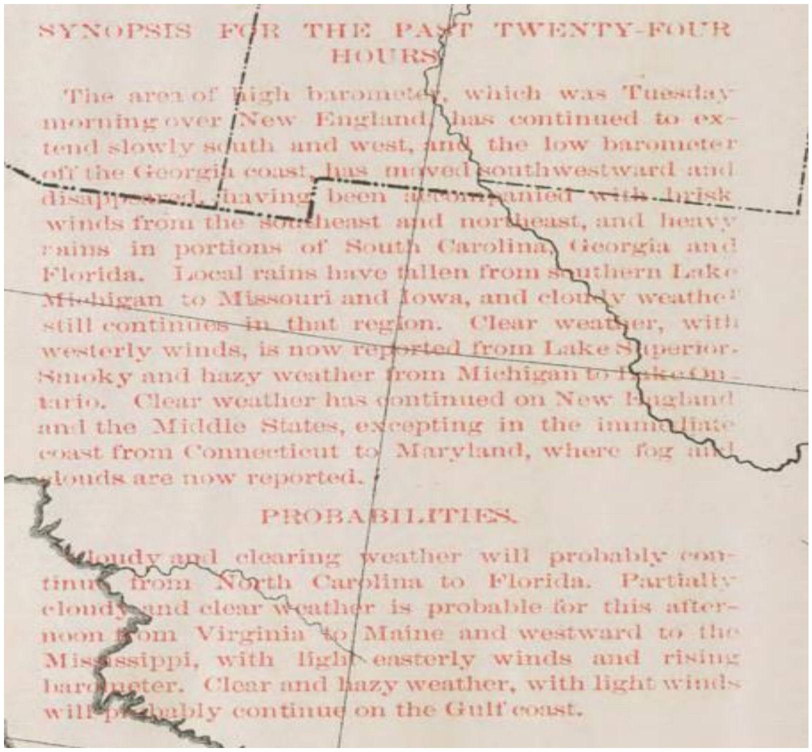


Figure 9. August 23, 1871, weather map from the Signal Service, U.S.A. *Source*: National Weather Service.



SYNOPSIS FOR THE PAST TWENTY-FOUR HOURS.

The area of high barometer, which was Tuesday morning over New England, has continued to extend slowly south and west, and the low barometer off the Georgia coast, has moved southwestward and disappeared, having been accompanied with brisk winds from the southeast and northeast, and heavy rains in portions of South Carolina, Georgia and Florida. Local rains have fallen from southern Lake Michigan to Missouri and Iowa, and cloudy weather still continues in that region. Clear weather, with westerly winds, is now reported from Lake Superior. Smoky and hazy weather from Michigan to Lake Ontario. Clear weather has continued on New England and the Middle States, excepting in the immediate coast from Connecticut to Maryland, where fog and clouds are now reported.

PROBABILITIES.

Cloudy and clearing weather will probably continue from North Carolina to Florida. Partially cloudy and clear weather is probable for this afternoon from Virginia to Maine and westward to the Mississippi, with light easterly winds and rising barometer. Clear and hazy weather, with light winds will probably continue on the Gulf coast.

Figure 10. Synopsis of the August 23, 1871, weather map from the Signal Service, U.S.A. *Source*: National Weather Service.

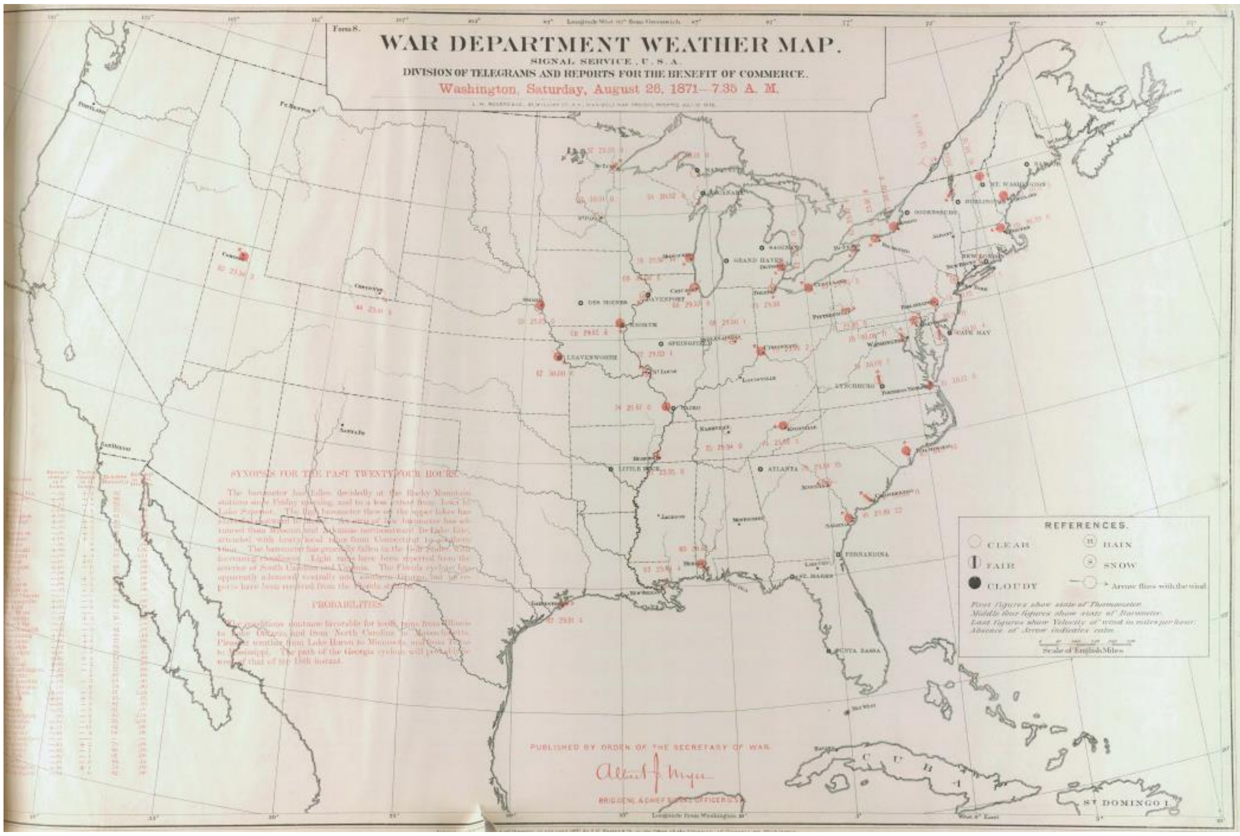


Figure 11. August 28, 1871, weather map from Signal Service, U.S.A. *Source*: National Weather Service.

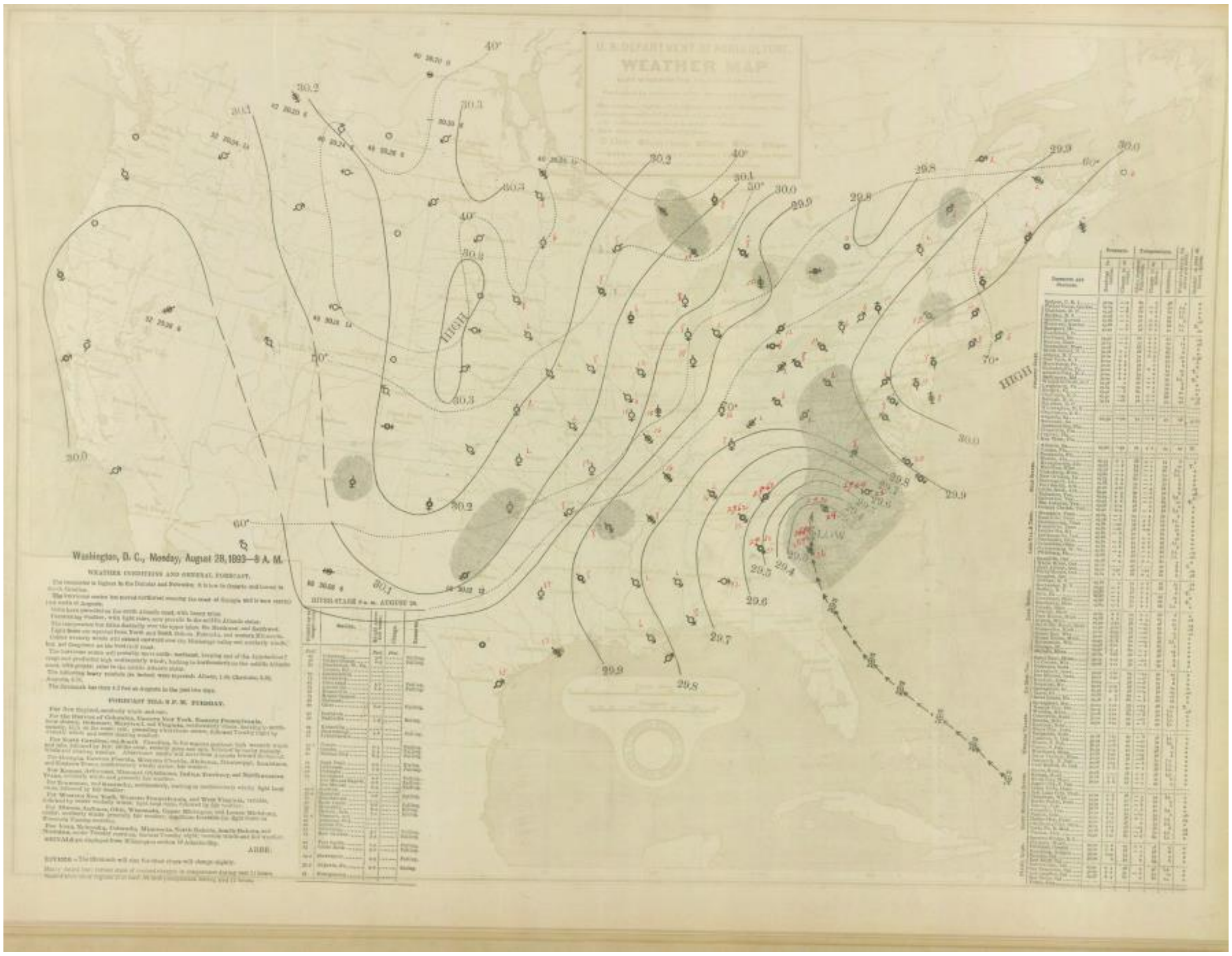


Figure 12. August 28, 1893, weather map from Signal Service, U.S.A. *Source*: National Weather Service.

4.1.4. 1950

The September 7, 1950 (Figure 13) TC was characterized as a low-pressure weather system, accompanied by a cyclonic system to its east over the Atlantic and a separate low-pressure system moving across northern Canada (NOAA 1950). Two high-pressure systems were in the northeast and mid-west (NOAA 1950). The TC on October 19, 1950, (Figure 14) was depicted traveling from the Atlantic through the middle of Florida and into southwest Georgia (NOAA 1950). A low-pressure system not depicted as a TC was directly southwest of the TC in the GOM off the coast of Louisiana and Texas (NOAA 1950).

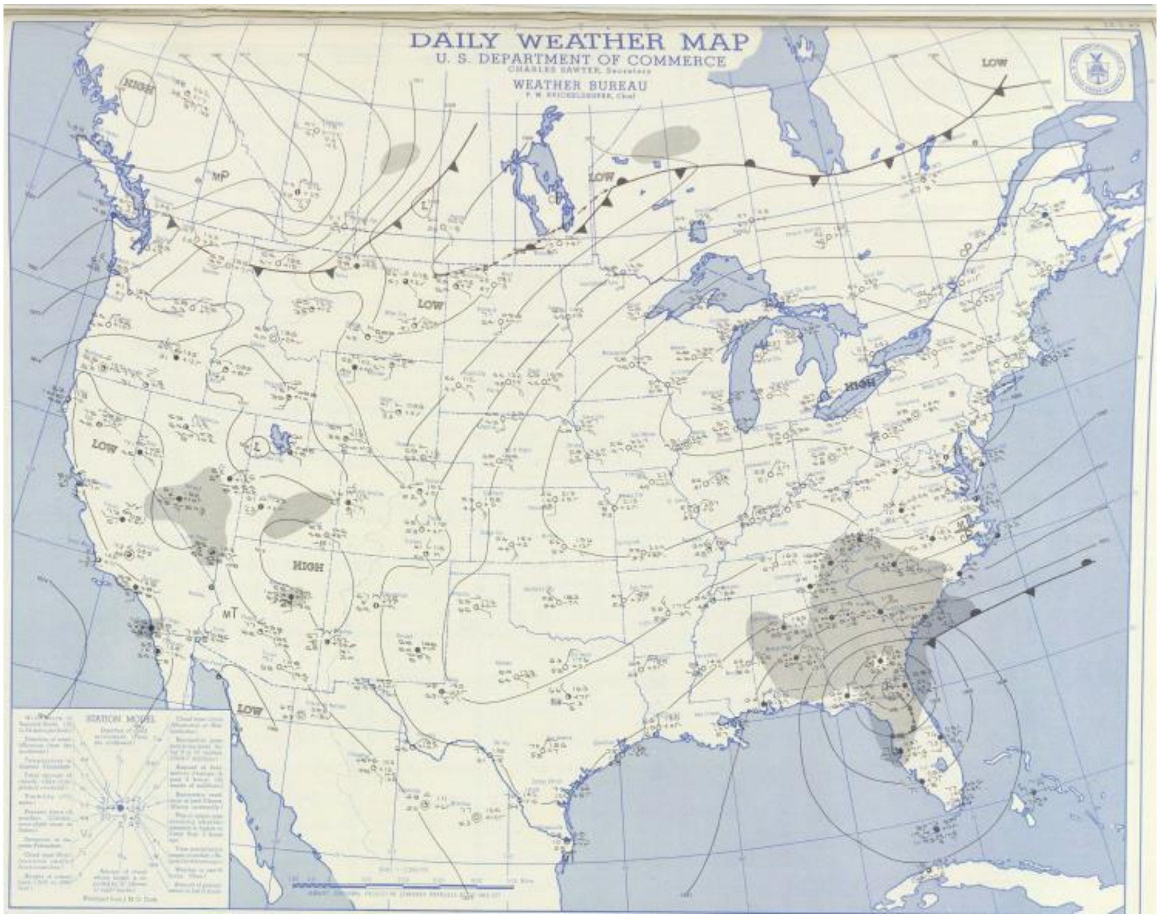


Figure 13. September 7, 1950, weather map from the U.S. Weather Bureau. *Source*: National Weather Service.

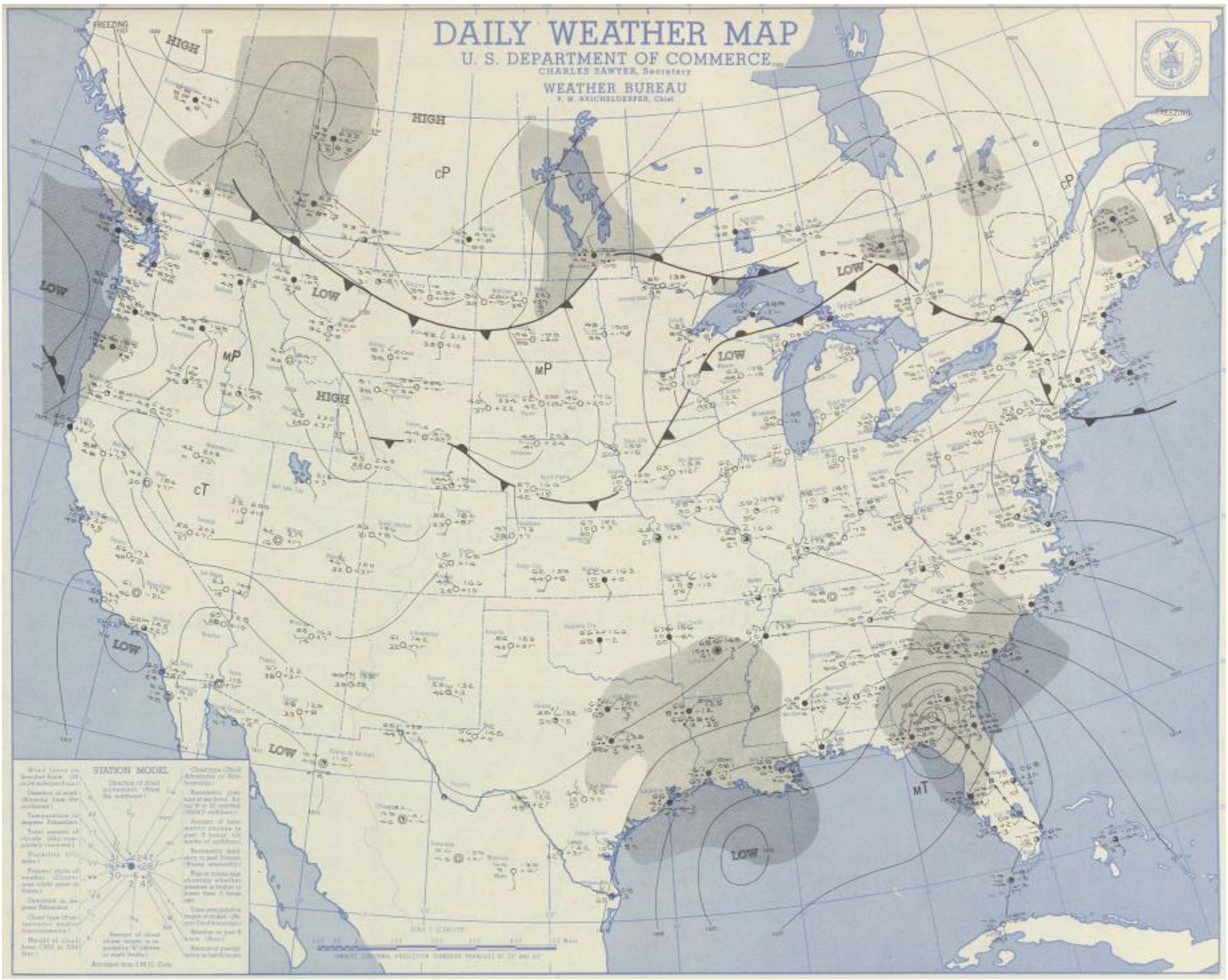


Figure 14. October 19, 1950, weather map from the U.S. Weather Bureau. *Source*: National Weather Service.

4.1.5. 2016

The June 2016 TC (Figure 15) had a stationary front moving through the state on June 6th as the TC was making its way through Georgia (NOAA 2016). A cold front was moving south from the mid-west toward the southeastern states with a low- and high-pressure system in front of it (NOAA 2016). On June 7^{th} (Figure 16), the cold front covered most of the U.S. as the TC was leaving Georgia with high pressure systems covering the U.S. (NOAA 2016). This northern coastal region of Georgia received a maximum of around 101.6 mm (4 in), with the surrounding area receiving around 50.8–76.2 mm (2–3 in) of rainfall in the 24-hour period (NOAA 2016).

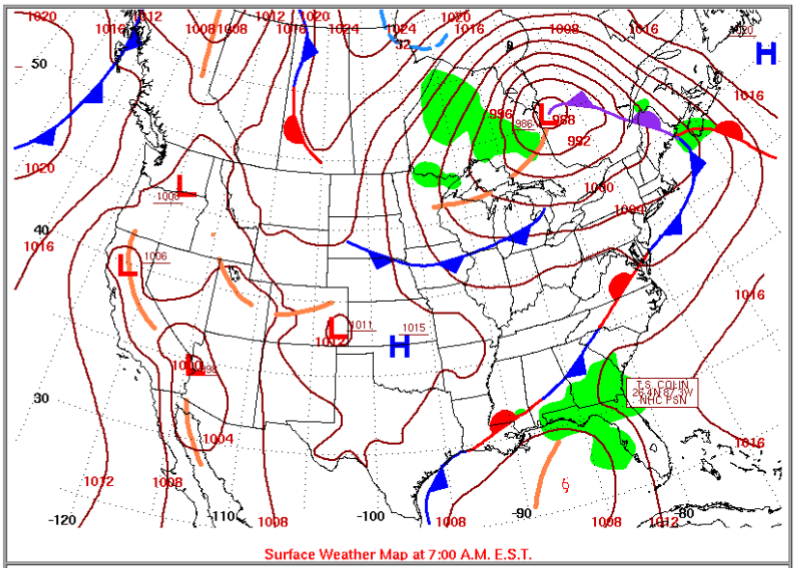


Figure 15. June 6, 2016, weather map from the Weather Prediction Center. *Source*: National Weather Service.

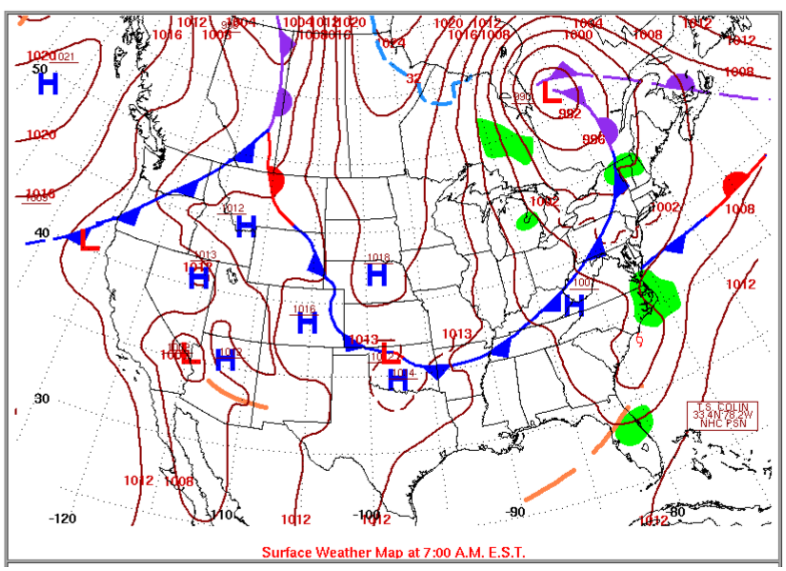


Figure 16. June 7, 2016, weather map from the Weather Prediction Center. *Source*: National Weather Service.

The September 2 TC (Figure 17) had a warm front directly to the north of the system, with the rest of the front being a low front moving off the eastern coast into the Atlantic Ocean

(NOAA 2016). The coastal region received around 76.2–101.6 mm (3–4 in) of rain within a 48-hour period (NOAA 2016). The area did receive two tornadoes in the southeast region of Georgia and South Carolina. The September 14 TC (Figure 18) was small and had an area of high pressure directly north of the cyclone with a stationary front covering the length of the US moving southeast (NOAA 2016).

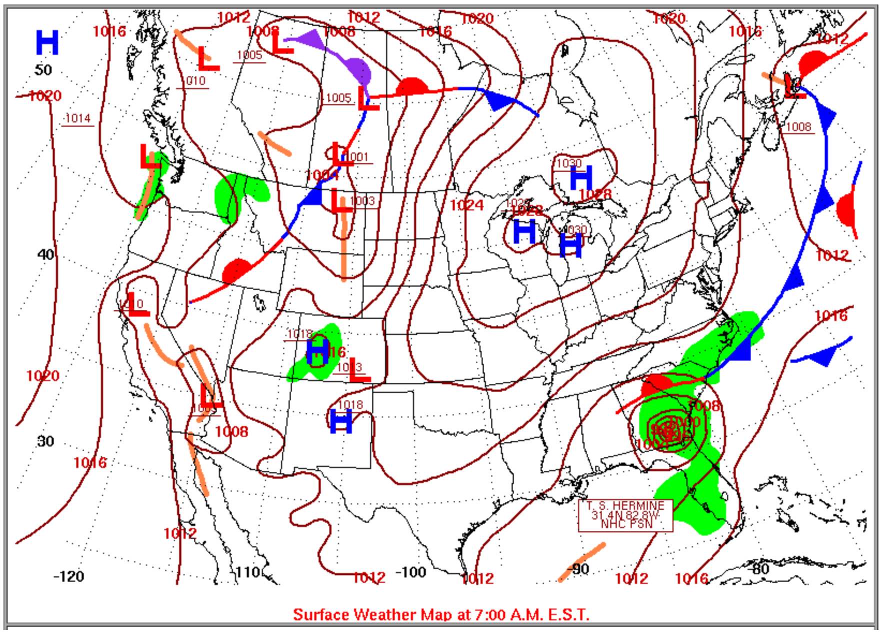


Figure 17. September 2, 2016, weather map from the Weather Prediction Center. *Source*: National Weather Service.

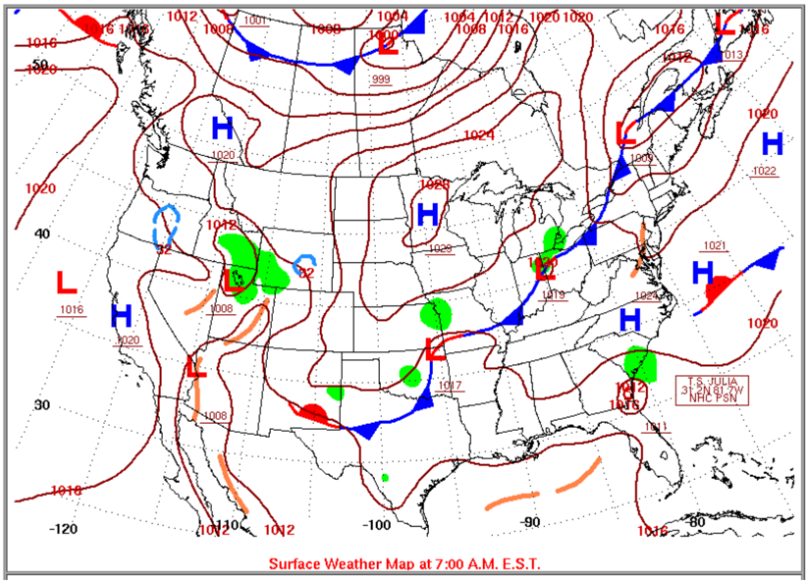


Figure 18. September 14, 2016, weather map from the Weather Prediction Center. *Source*: National Weather Service.

4.1.6. TC Seasonality

TC seasonality in Georgia is shown in Figure 19. The most active months of the hurricane season are August, September, and October (Klotzbach and Gray 2003). September is the most active month for TCs in Georgia (n=40; 35%), followed by October (n=27; 23%). August was the most active hurricane month (n=8; 7%). May has two recorded tropical storms outside of the official hurricane season. This is not uncommon, and further analysis of the storms is included below. Unexpectedly, there was an early batch of TCs in June (n=15; 13%).

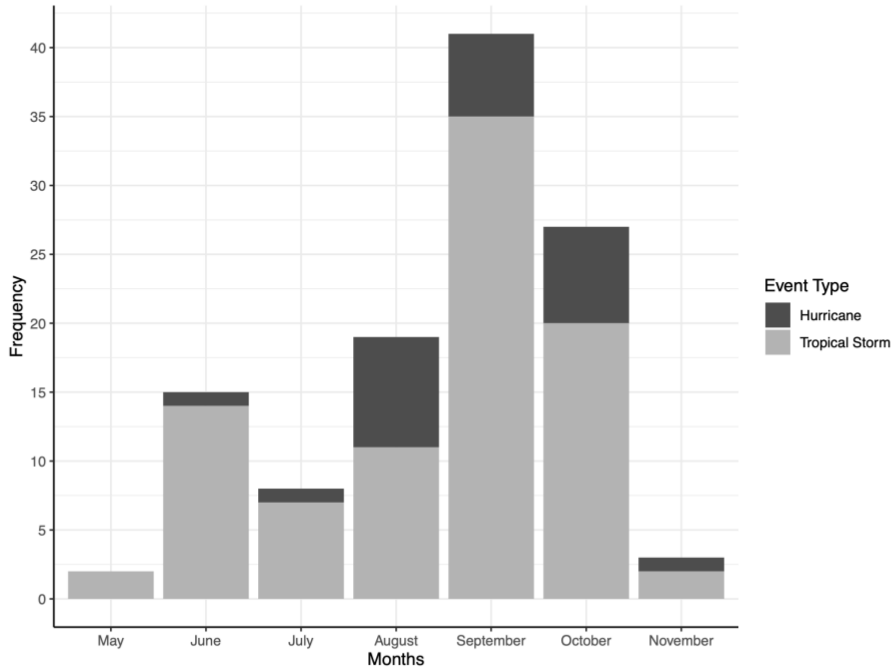


Figure 19. The seasonality of tropical cyclone strikes within the Georgia state boundary separated by intensity.

4.1.7. Wind Intensity

Figure 20 illustrates the distribution of maximum wind speeds (ms^{-1}) of TCs in Georgia once they entered the state. Most TCs reach their highest wind speeds along Georgia's border as they enter the state. However, five TCs were found to have higher wind speeds further into the state. Two TCs reached their peak wind speeds approximately 50 miles north of the southern border of Georgia, with the intensity of a tropical storm and tropical depression. Another two storms originating from the GOM passed through Florida and into Georgia, achieving their maximum wind speeds as tropical storms at the Georgia-South Carolina border. These storms traveled about 225 km (140 mi) northeast from their entry point into Georgia. Additionally, Hurricane Dora (1964) made landfall in Florida from the Atlantic, moved west, and then turned northeast through western Georgia, covering about 410 km (260 mi) of the state before its highest wind speed was recorded as it crossed into South Carolina. The minimum wind speed recorded is 16.3 ms^{-1} by an Unnamed tropical storm in 1904. The maximum wind speed is 54.6 ms^{-1} by an Unnamed Category 3 hurricane in 1898. The mean wind speed is 27.2 ms^{-1} with a variance of 75.8 σ^2.

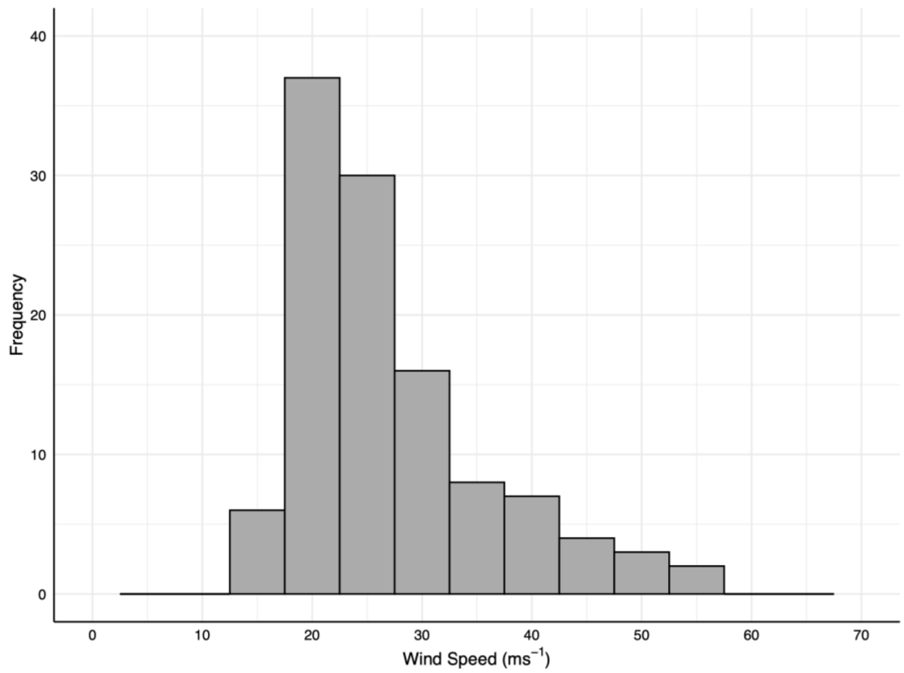


Figure 20. Distribution of tropical cyclone maximum intensity within the state of Georgia from 1851–2021.

4.2. Correlation and Regression

Many locations are experiencing changes in TC wind speeds compared to their historical normal (Garner 2024). The distribution of maximum wind speeds in Georgia is tested for normality using the Shapiro-Wilk's Test for Normality. The null hypothesis of this test is that the data are normally distributed. The p-value of <0.01 provides conclusive evidence to reject the null hypothesis of normality. The Spearman's rank correlation test is used because it is suitable for nonparametric data. The null hypothesis is no monotonic association between the *x* (year) and *y* (maximum wind speed) variables. The Spearman's ρ value is –0.184, this indicates a weak negative relationship between time and speed. With a p-value of 0.0507, which is marginally significant, and suggests evidence that the relationship between wind speed and time should be further explored.

The OLS regression using the entire subset of data has a -0.34 ms^{-1} change for every one-year increase with a p-value of 0.039 (red line in Figure 21). This suggests that TC maximum wind speed within the state of Georgia is decreasing over time. The adjusted R^2 is 0.029, suggesting 2.9% of the variability of wind speed is explained by year. However, an assumption of OLS regression is that the residuals of the model are normally distributed. Using the Shapiro-Wilks Test for normality, it is found that the regression residuals for this model are not normally distributed, and thus, it is an inadequate model. Further exploration is required.

Figure 21 shows the linear quantile trend of the TC maximum wind speed in Georgia and time. Decreasing trends are found throughout the relationship at various quantiles. Table 5 depicts the 5 quantiles; their confidence bounds and their trend. Significant decreasing trends are found in the 90th percentile, followed by the 75^{th} percentile (i.e., confidence bounds do not overlap zero). A decreasing trend occurs in the 10th, 25th, and 50th percentile, but they are not significant (Table 4).

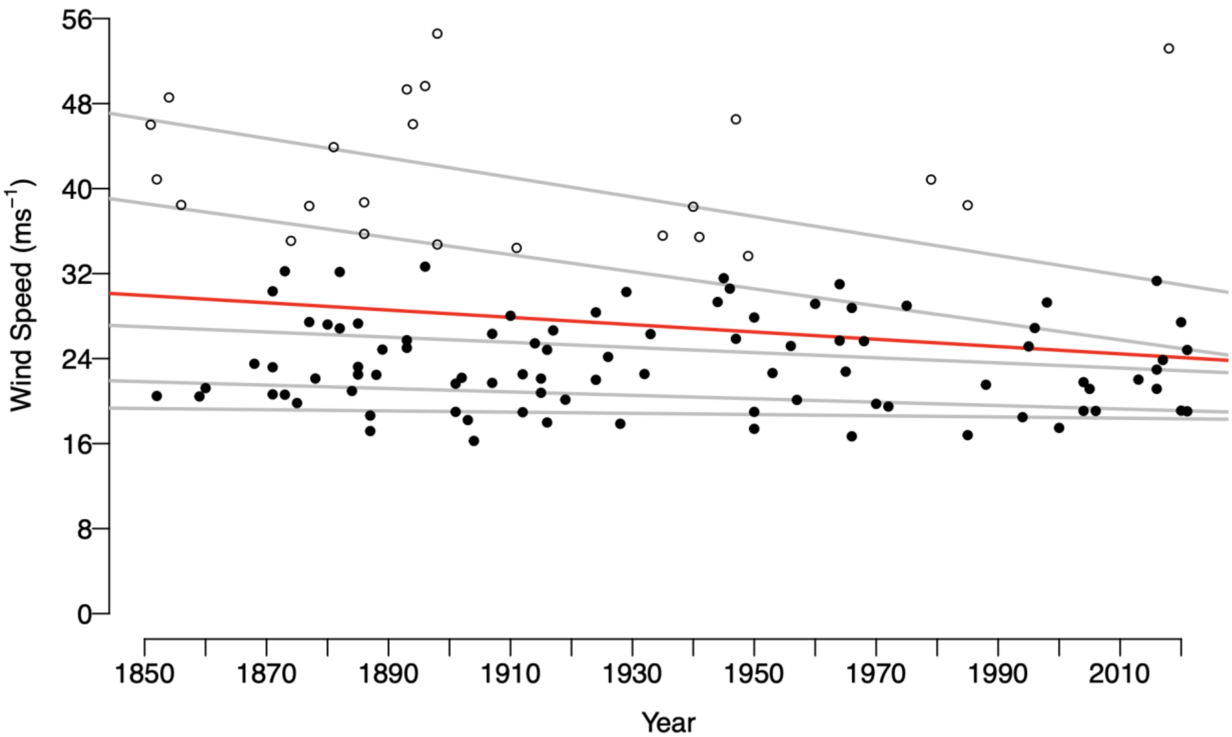


Figure 21. Georgia's tropical cyclone trend between maximum wind speed in the state and year 1851–2021. The hollow points are hurricanes, and the black points are tropical storms. The red line is ordinary least squares line (i.e., line of best fit) for the entire sample, and the quantile regression trend lines in gray are shown at the 10th percentile, 25th percentile, 50th percentile, 75th percentile and 90th percentile.

Table 5. Trend statistics for the relationship between maximum windspeed and year for tropical cyclones in Georgia from 1851–2021.

Quantile	**Lower Limit**	**Trend**	**Upper Limit**
90th percentile	-0.13	-0.092 **	-0.01
75th percentile	-0.11	-0.08 **	-0.03
50th percentile	-0.05	-0.02	0.009
25th percentile	-0.03	-0.016	0.004
10th percentile	-0.03	-0.006	0.003

The relationships all point to a decreasing trend but violate key assumptions and therefore the model is not valid. It is obvious the TCs are not distributed evenly throughout time in Georgia. Based on this observation, loess regression is used to further investigate the relationship. Figure 22 shows the TC count in Georgia with a loess regression line in blue and outlined in grey are the upper and lower confidence intervals.

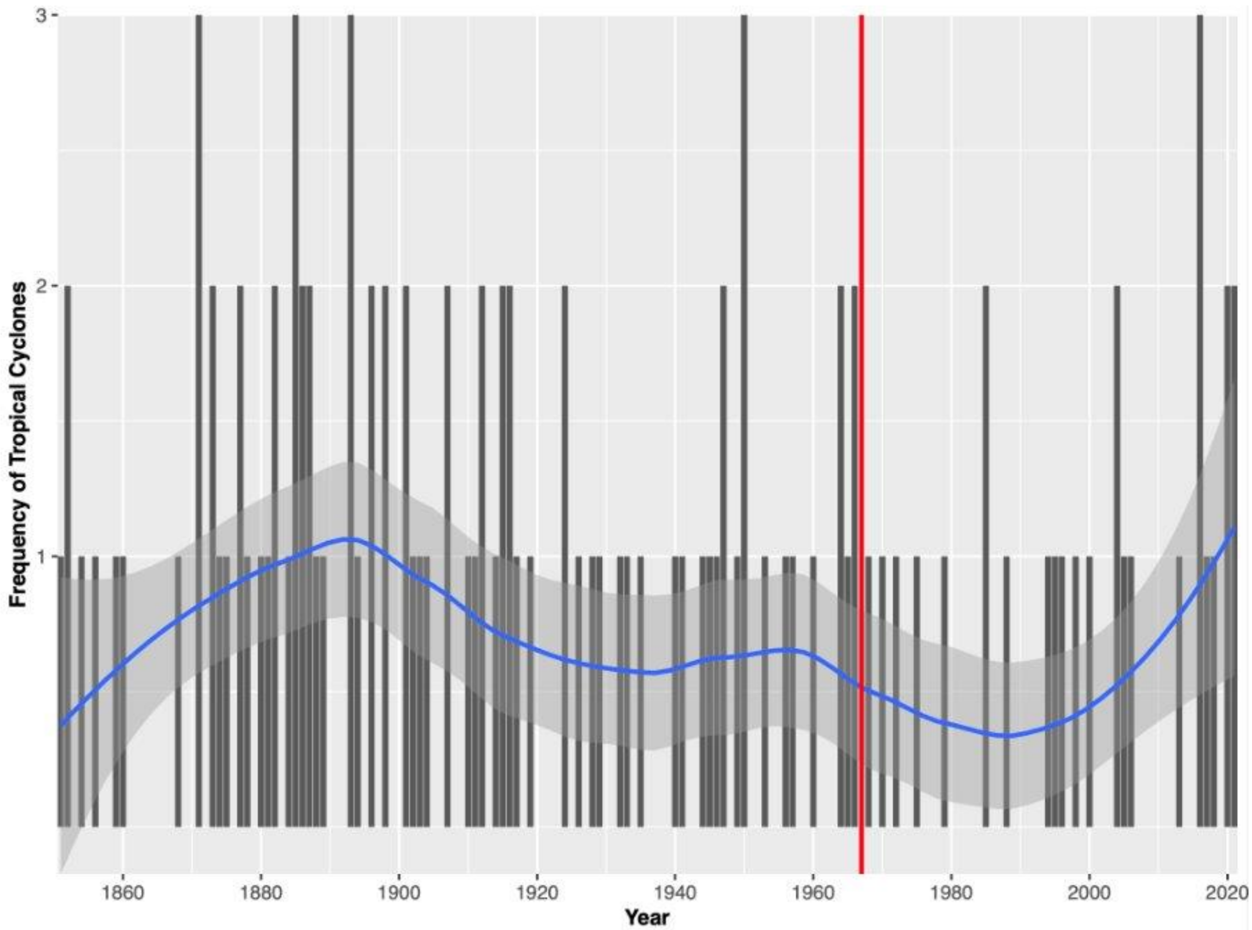


Figure 22. Annual Count of tropical cyclones in Georgia from 1851–2021. The blue line represents the loess regression with the grey as its upper and lower confidence bounds. The red line represents the start of the satellite era when observations of tropical cyclones became more reliable.

Based on the variability in trend showcased in Figure 22 there are multiple changes throughout time related to increases/decreases in TC count. This is potentially due to regional and/or global scale patterns in pressure and sea surface temperature. The pattern in Figure 22 is like the pattern in the AMO and suggests that it could be one of the many factors that plays into the intensity of Georgia TCs. The AMO's influence is tied to its effect on SST in the Atlantic Ocean. During the AMO's positive phase, higher SSTs can increase cyclone intensity by providing more energy and conducive conditions for cyclone development (Klotzbach and Gray 2008). Conversely, in the AMO's negative phase, lower SSTs can result in less intense storms, as

SST variations alter the atmospheric heat and moisture essential for cyclone formation and strength. While the loess line in Figure 22 does not follow the exact pattern of the AMO index, it follows a similar pattern. The difference is the AMO index has a positive phase around the mid 1920's to mid 1960's that Figure 22 does not follow. This idea is prompted for further investigation in future studies. In addition to the AMO, the study suggests that the NAO could be an influence on the track of Georgia TCs, as mentioned earlier.

4.3 Annual Average Rainfall

The study analyzed 119 storms that occurred between 1951–2021 based on the available rainfall data. Figure 23 shows the TC tracks during this time period when rainfall was available. A 500-km buffer was added around each track to determine the possible area where rainfall might have occurred from the storm. When the buffer overlaps with Georgia, the TC and associated rainfall are included. TCs were, again, categorized into tropical storms and hurricanes based on the highest maximum sustained wind recorded within the buffer area. There are 42 (35%) hurricanes and 77 (65%) are tropical storms. Across the 119 TCs, there are 295 days of observed precipitation within the state's border.

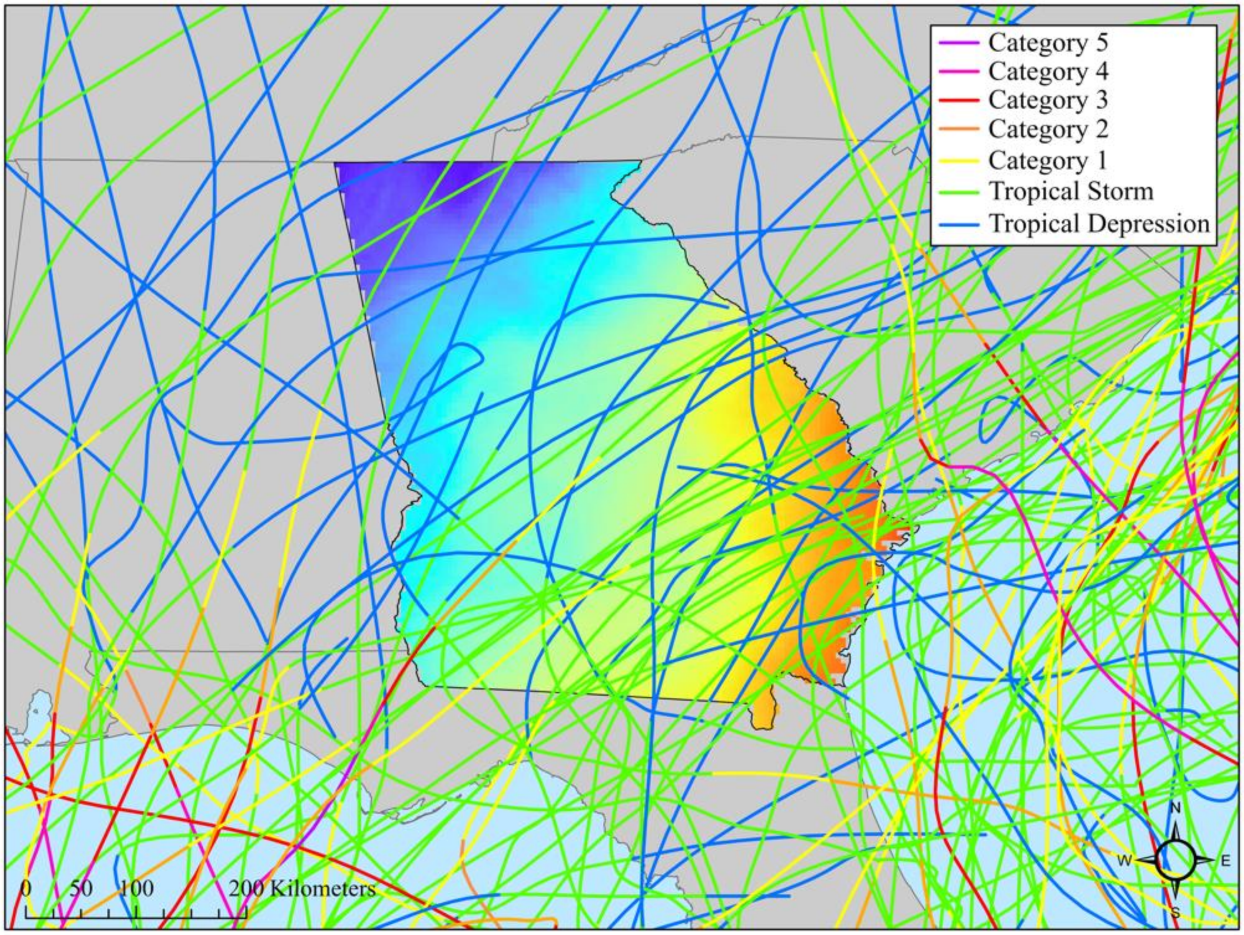


Figure 23. Tropical cyclone tracks used to find the annual TC precipitation in Georgia from 1951–2021.

Figure 24 depicts the number of storms that occurred within a given year. There were 19 years where 0 TCs occurred. In 2004, there were 7 TC occurrences. One TC occurred in July, three occurred in August, and three occurred in September.

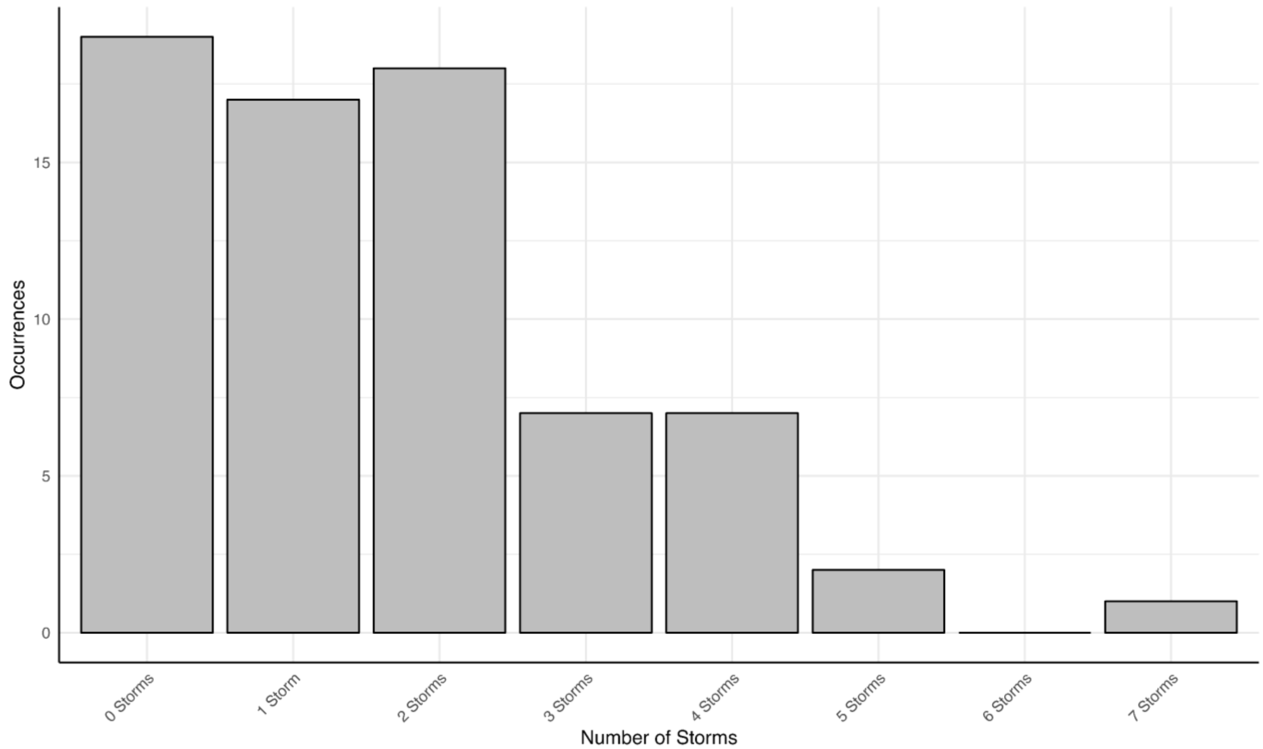


Figure 24. TC occurrences across the 71 years of rainfall data.

Figure 25 shows the rainfall that was attributed by TCs across the state by the percent of Georgia annual rainfall. Along the coastline, approximately 5–6% of annual rainfall is attributed to TCs. This value gradually diminishes moving toward the northwest. The Piedmont and upper Coastal Plain regions receive an average of 2–4% of annual rainfall from TCs. The northwestern portion of the state receives ≤ 1% annual rainfall from TCs.

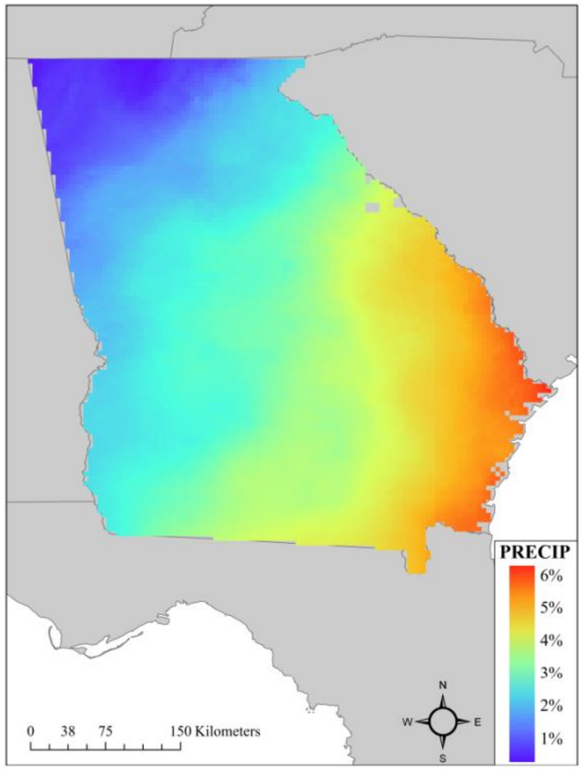


Figure 25. Annual TC precipitation percentage in Georgia from 1951–2021.

4.4 Monthly Rainfall

Understanding the distribution of TC rainfall across months of the TC season, and the proportion of annual rainfall, is important for planning purposes. May is not considered a part of the TC season, but of the 119 TCs in this study, 7 TCs occur in May (Figure 26). Five of these pre-season May TCs (all tropical storm strength) have taken place since 2012.

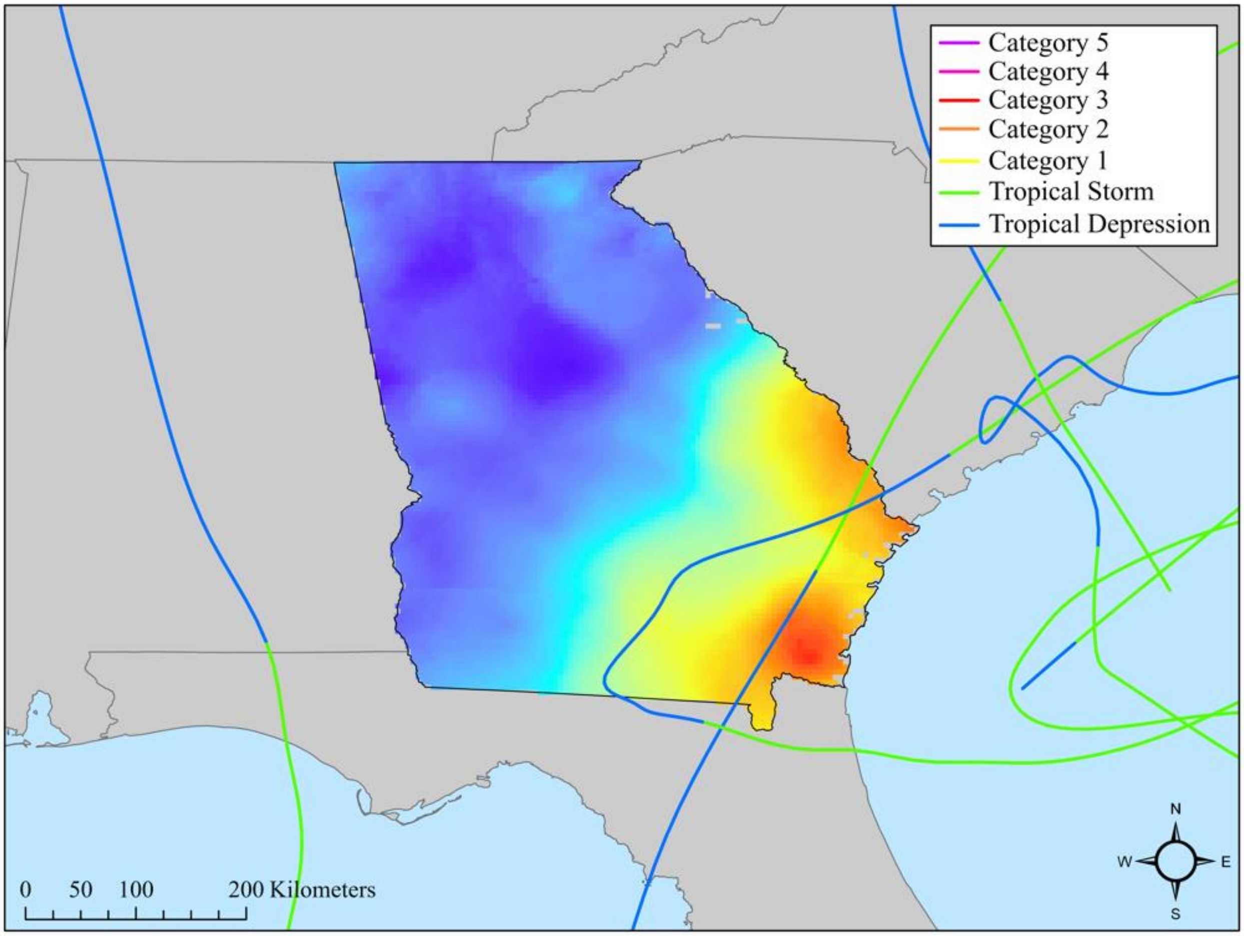


Figure 26. TC Tracks that occurred in May in Georgia from 1951–2021. Monthly average rainfall data attributed to tropical cyclones in May.

May has a high precipitation concentration from TCs in the Lower Coastal Plain, ~3-5% (Figure 27). This is not surprising as most of the tracks for May occur in this region. The rest of the state has an average of ~0–2% annual precipitation from TCs.

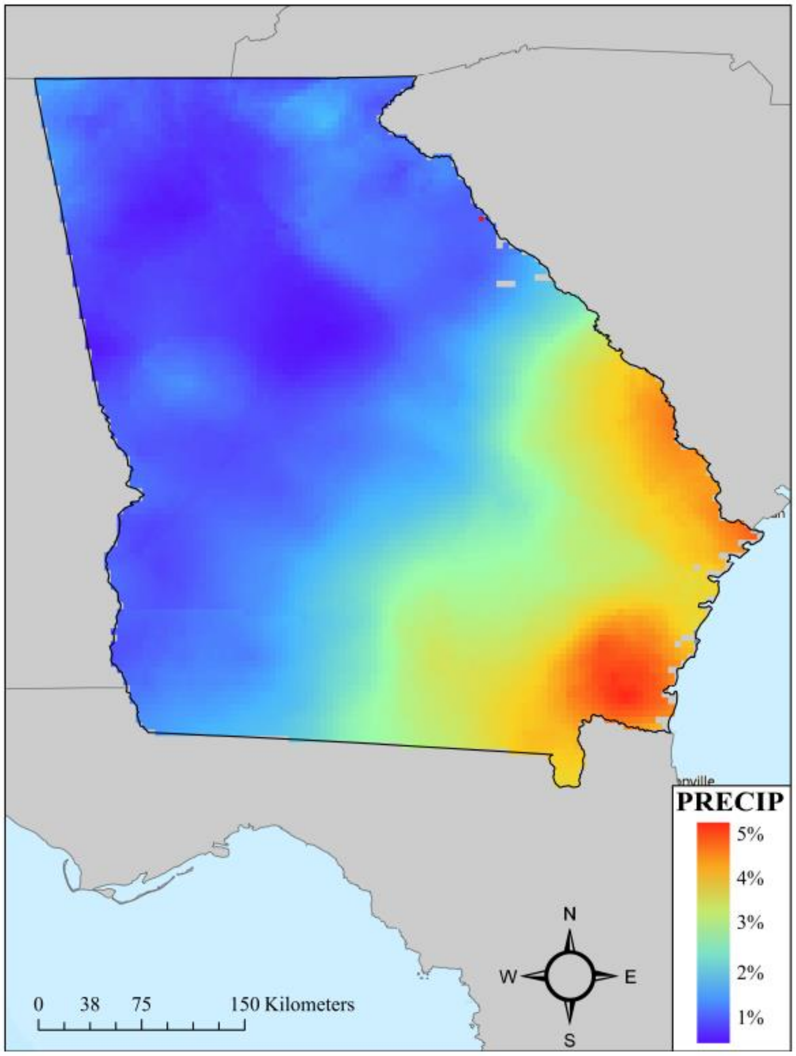


Figure 27. May average TC precipitation percentage in Georgia from 1951–2021.

There are 19 TCs have occurred in June since 1951 (Figure 28). Of the 19 TCs in June, three are hurricanes and 16 are tropical storms. Most of the June tracks form in the GOM. The western Caribbean is known for retaining its warmth well into the later part of the hurricane season. However, Figure 28 suggests that this region also starts to warm up earlier in the season than previously thought, potentially indicating a longer period of elevated temperatures. Most of the TCs travel into Georgia from the GOM traveling northeast into the Atlantic.

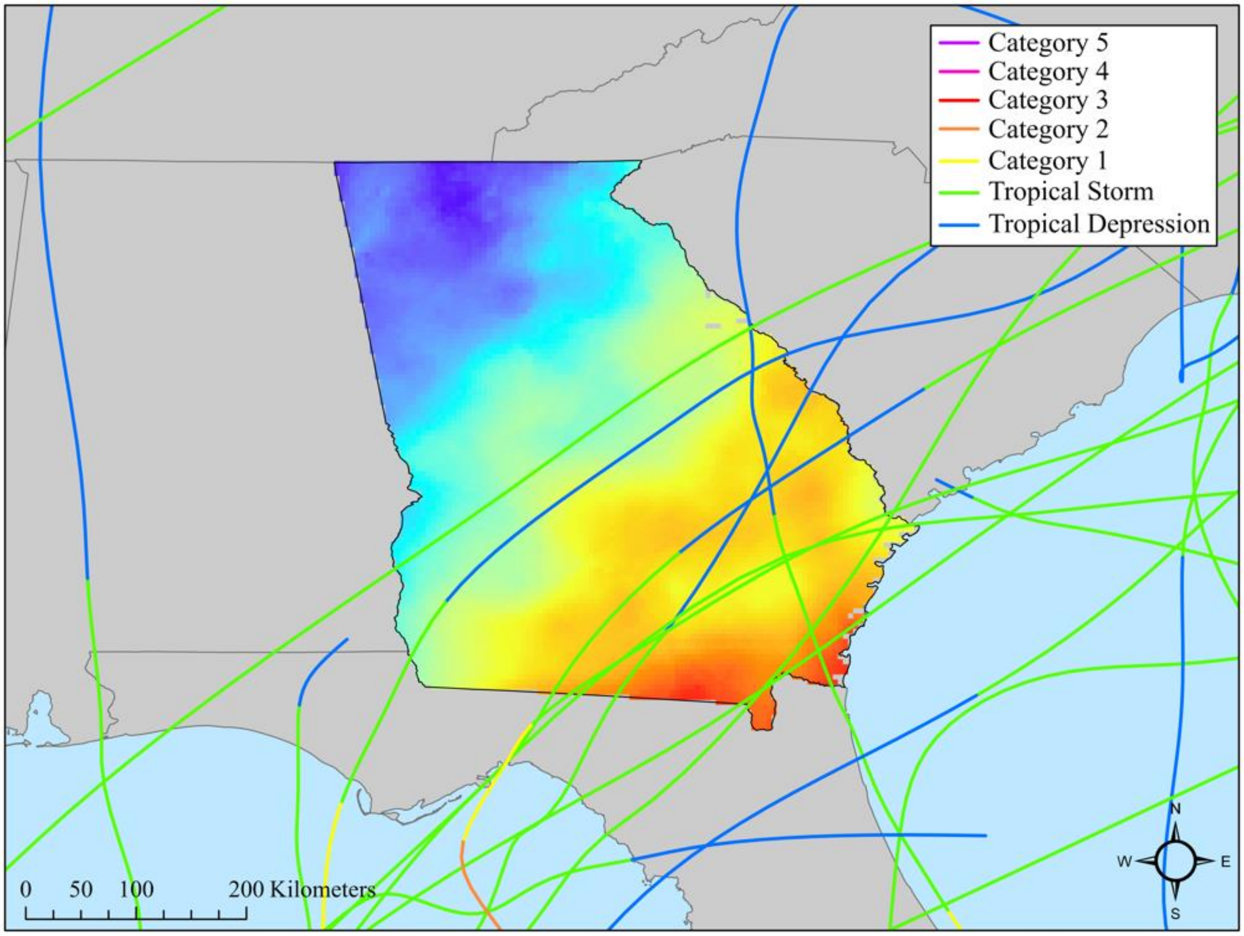


Figure 28. TC Tracks that occurred in June in Georgia from 1951–2021. Monthly average rainfall data attributed to tropical cyclones in June.

June has the highest precipitation concentration along the southeastern border with ~11% of its annual precipitation from TCs (Figure 29). The Lower Coastal Plain receives a range of ~7–11% of average annual precipitation from TCs. The Upper Coastal Plain and Piedmont region receives a range of ~7–2%, with the remainder of the state receiving 0–4%.

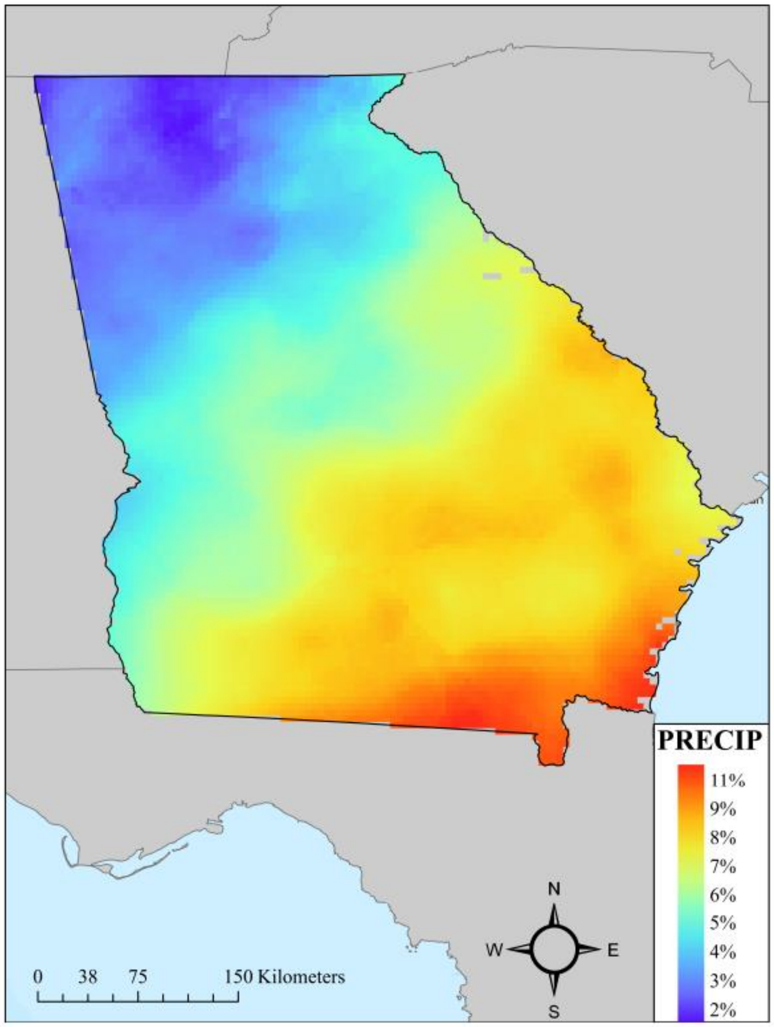


Figure 29. June average TC Precipitation percentage in Georgia from 1951–2021.

July has 13 TC occurrences with five hurricanes and eight tropical storms (Figure 30). Three TCs formed out in the Southern Atlantic, six in the GOM, and four east of Georgia's border in the Atlantic.

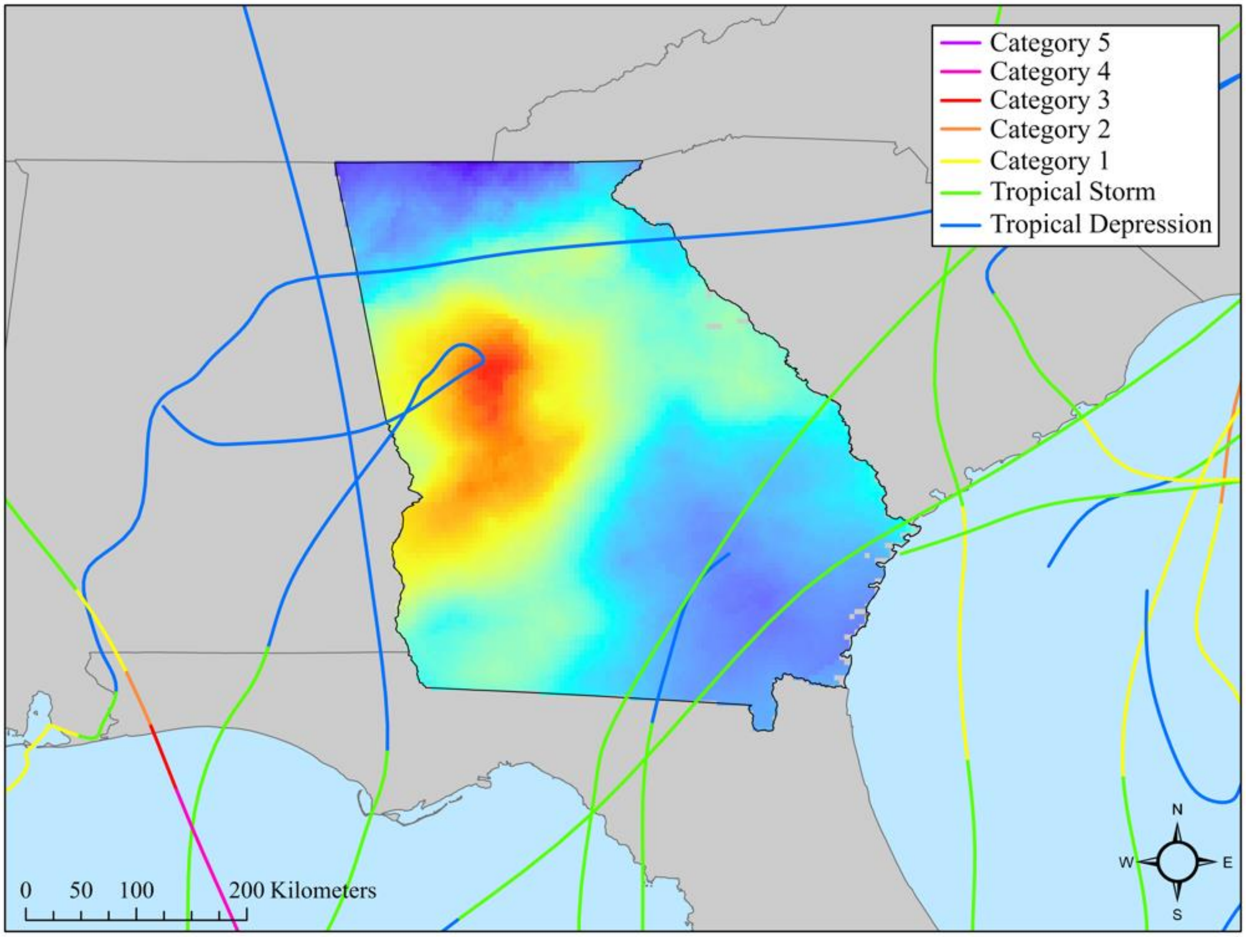


Figure 30. TC Tracks that occurred in July in Georgia from 1951–2021. Monthly average rainfall data attributed to tropical cyclones in July.

July has a high precipitation concentration from TCs in the Western Piedmont region, around ~5–9% (Figure 31). This is surprising as most of the track's travel near the state's southeastern region. This could be because the tracks closest to this region did not produce much rainfall. This could also be because most of the storms off the coast of Georgia had recently formed, not allowing much precipitation to fall at the beginning of their life cycle. The southeast and northern regions receive an average of 0–5% of their annual rainfall from TCs.

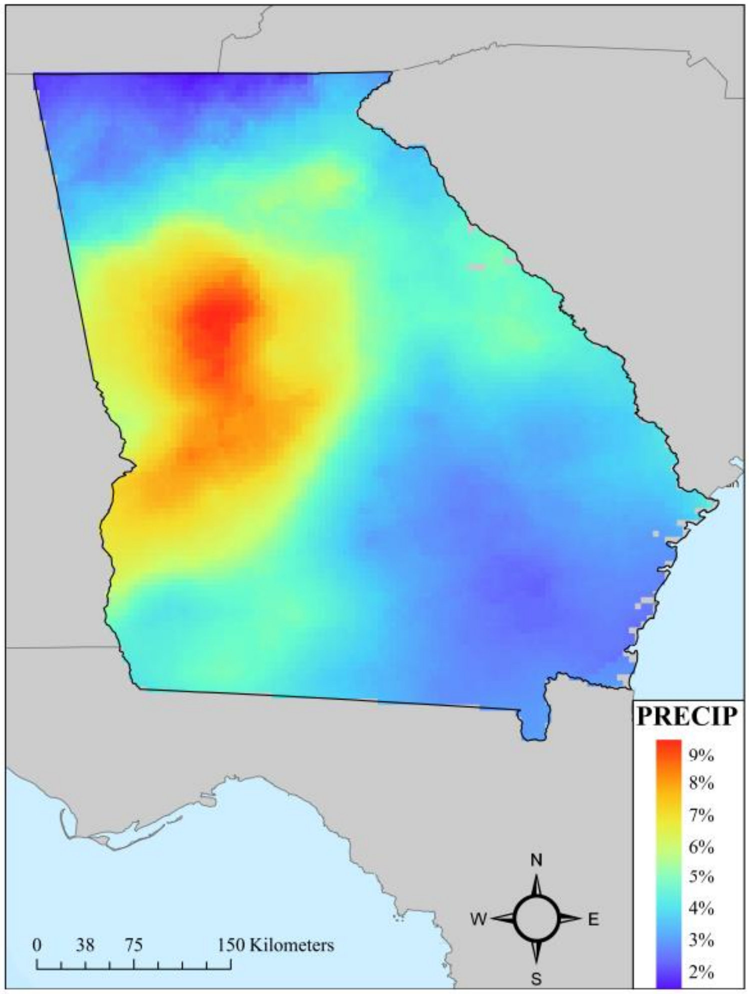


Figure 31. July average TC Precipitation percentage in Georgia from 1951–2021.

Figure 32 depicts the tracks that occurred in August. Three tracks in Figure 31 are also shown in September's track map (Figure 34). This is because the three storms overlapped August and September. There are 25 TCs that occurred in August with six hurricanes and 19 tropical storms. Twenty of the August TCs form in the Atlantic with seven forming near the coast of Florida and/or South Carolina.

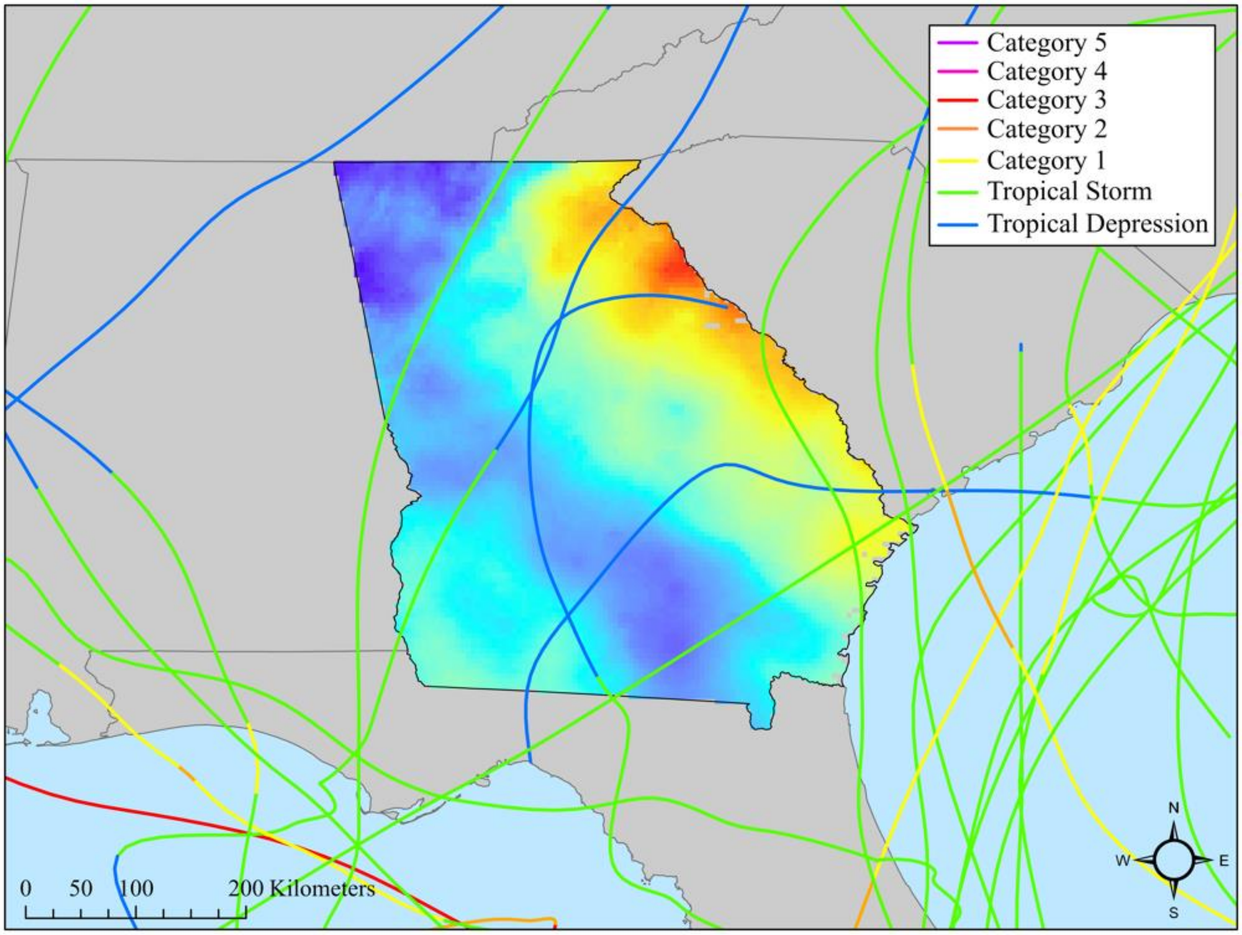


Figure 32. TC Tracks that occurred in August in Georgia from 1951–2021. Monthly average rainfall data attributed to tropical cyclones in August.

August has a high concentration of TC rainfall along the eastern border of Georgia (Figure 33). This is likely due to the number of storms traveling through Georgia and South Carolina. The Southwestern portion of the state has a region of ~6–9% of average TC precipitation per year. This is not surprising since the TC tracks passed through this portion of the state.

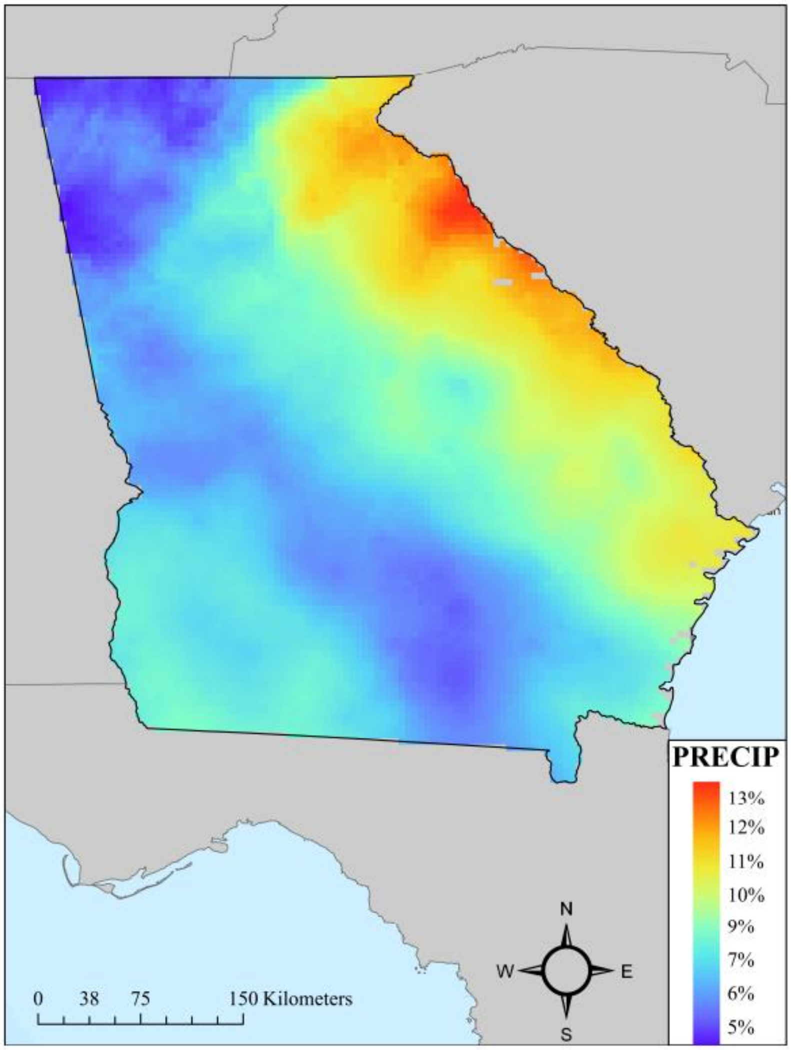


Figure 33. August average TC precipitation percentage in Georgia from 1951–2021.

There are 35 TCs that occurred in September. Historically, the September storms have the most erratic tracks, with six TCs having distinct loops throughout their tracks while over the state of Georgia. September also has the most severe storms, with 19 hurricanes. In addition, there are 16 tropical storms in September. There is one TC that is also represented in October's track map because it overlapped the two months. Most of the storms formed in the Atlantic with only six TCs forming in the GOM.

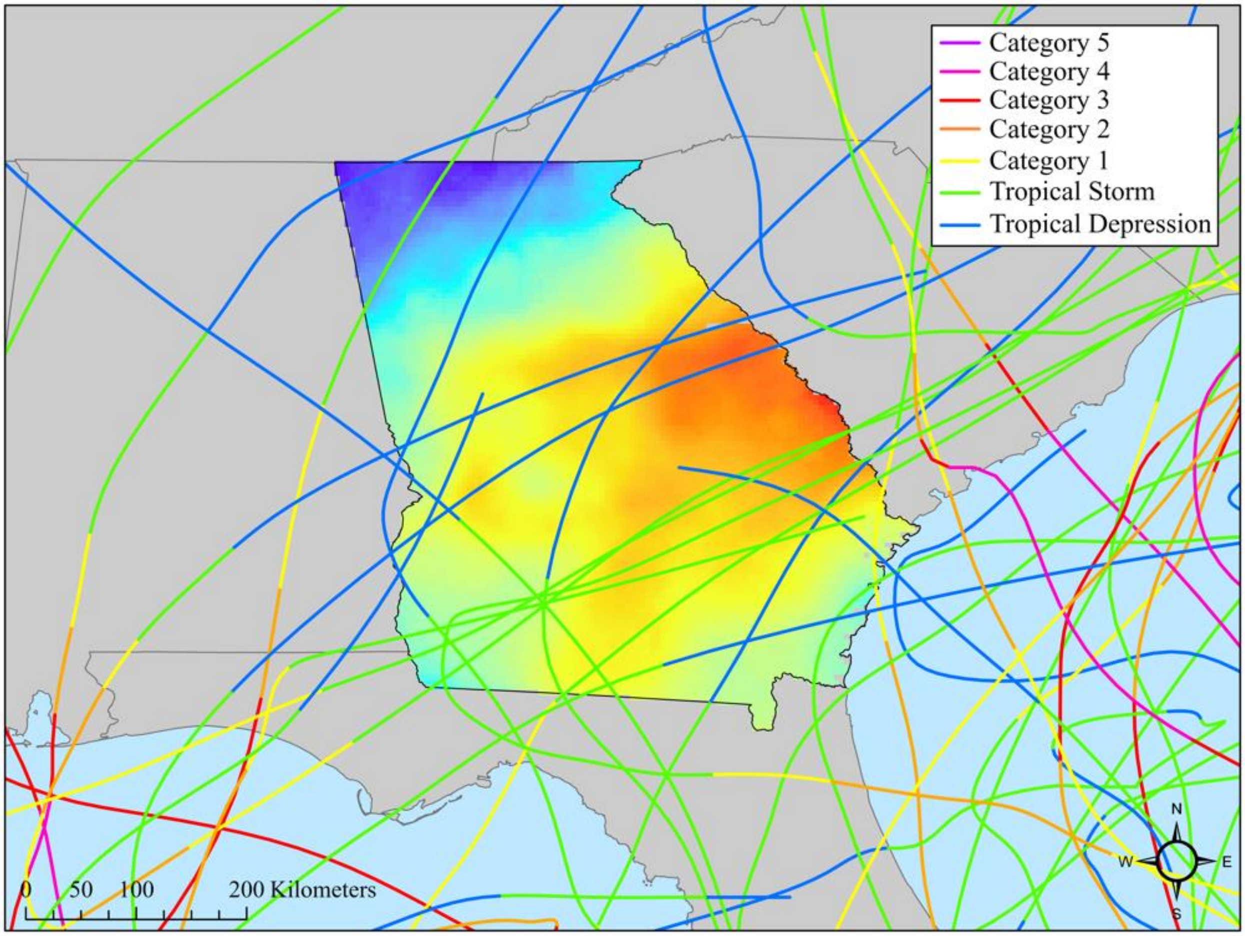


Figure 34. TC Tracks that occurred in September in Georgia from 1951–2021. Monthly average rainfall data attributed to tropical cyclones in September.

Figure 35 shows that September had the highest rainfall average compared to the other months. The highest concentration of precipitation is attributed to TCs along the eastern border moving inland within the Coastal Plain and Piedmont regions. This could be due to the high traffic area of TCs that traveled specifically in that area. Most of the state receives an average of ~15% of its annual rainfall from TCs in September. The only exception is the northern region which receives ~8%, and is the highest concentration of rainfall averages for this region compared to the other months.

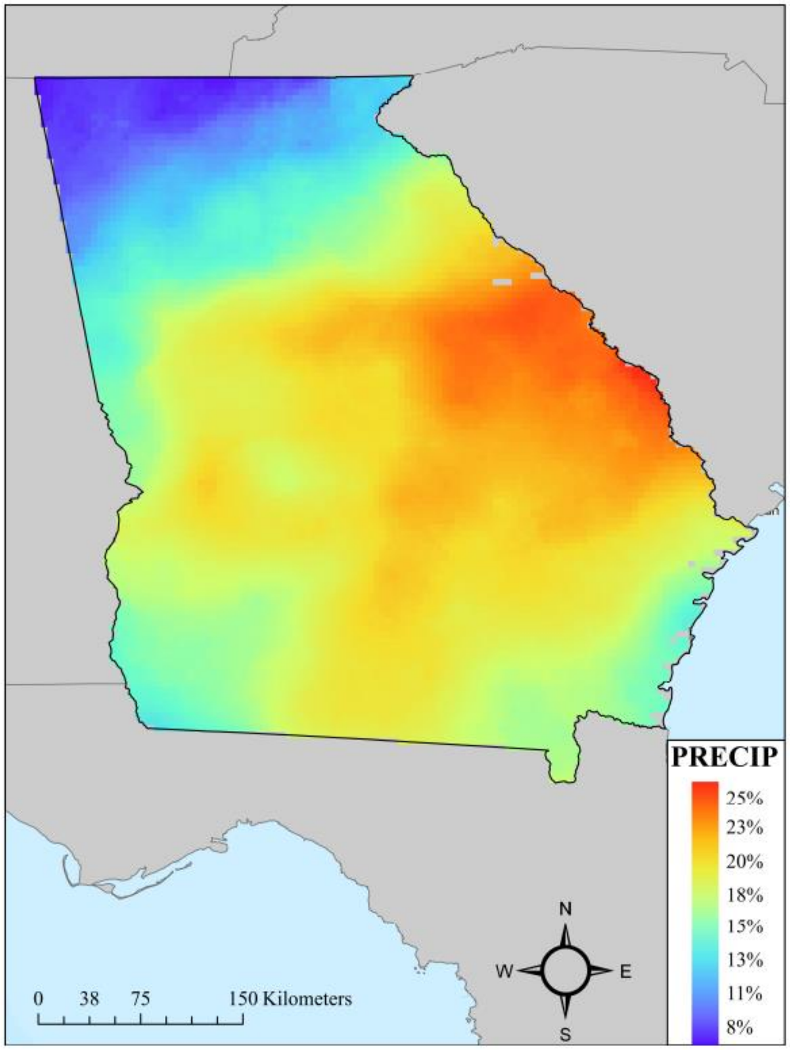


Figure 35. September average TC precipitation percentage in Georgia from 1951–2021.

Figure 36 shows that October has 18 TCs with eight hurricanes and ten tropical storms. One TC forms in the middle of the Atlantic Ocean while the rest form in the GOM, Caribbean Sea, or the southern portion of the Atlantic Ocean.

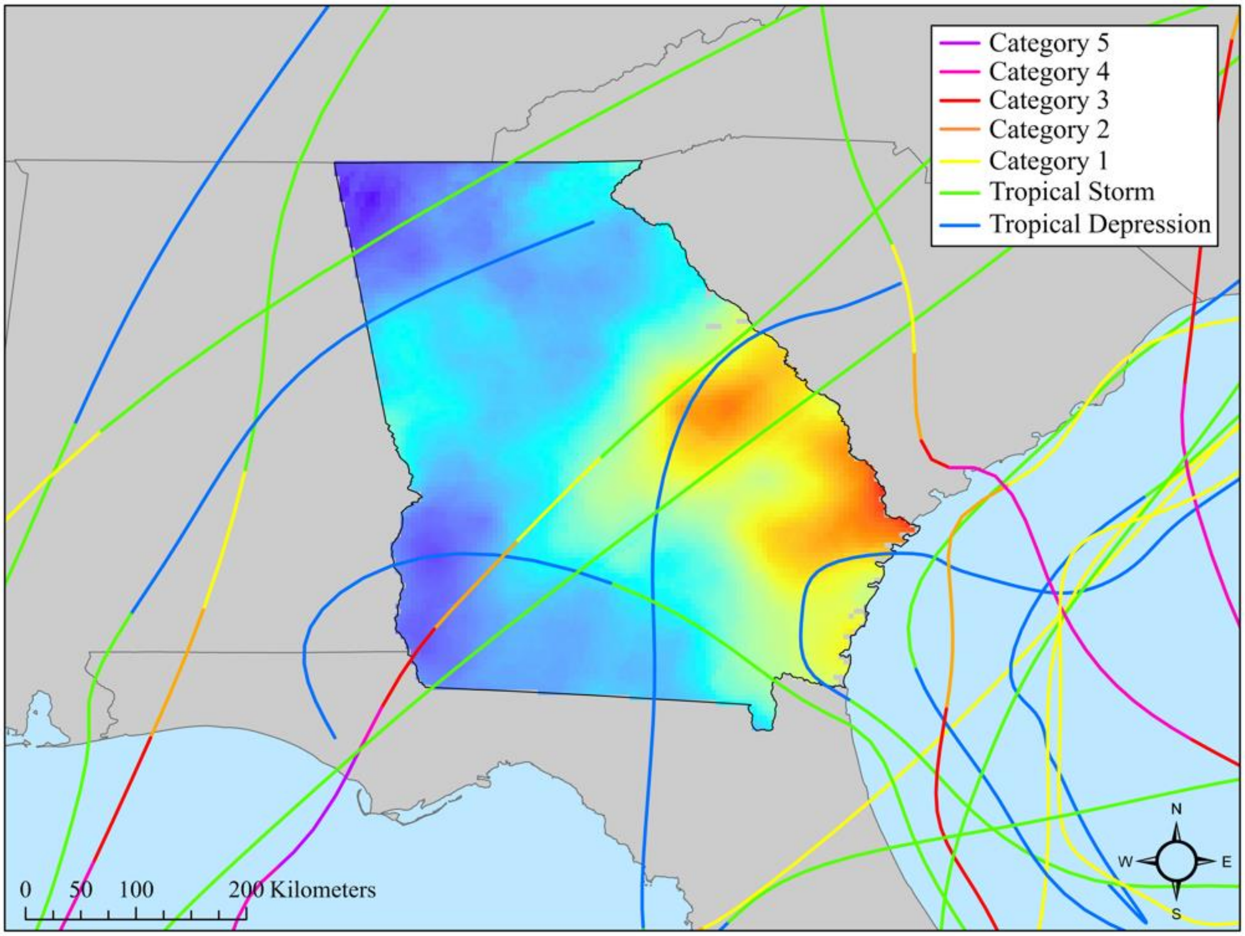


Figure 36. TC Tracks that occurred in October in Georgia from 1951–2021. Monthly average rainfall data attributed to tropical cyclones in October.

Figure 37 shows that the highest concentration of 14% of rainfall in October occurs along the eastern border within the Coastal Plain. The rest of the state sees varying concentrations of around 4% or less of its rainfall from TCs.

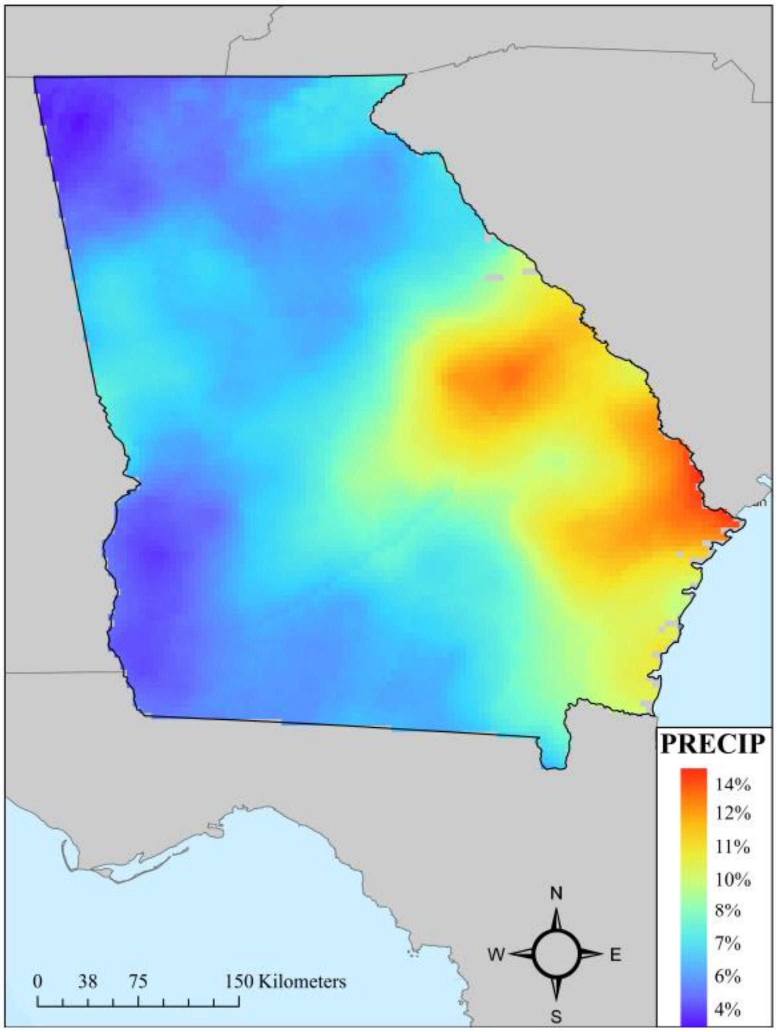


Figure 37. October average TC precipitation percentage in Georgia from 1951–2021.

Figure 38 shows that November only had 2 TCs with one hurricane and one tropical storm. Hurricane Kate (1985) travel through Georgia from the GOM where it had formed in the Atlantic Ocean. Tropical storm Juan (1985) formed in the GOM and traveled within the buffer, so it never actually moved over any part of Georgia. The majority of the rainfall this month is attributed to Hurricane Kate.

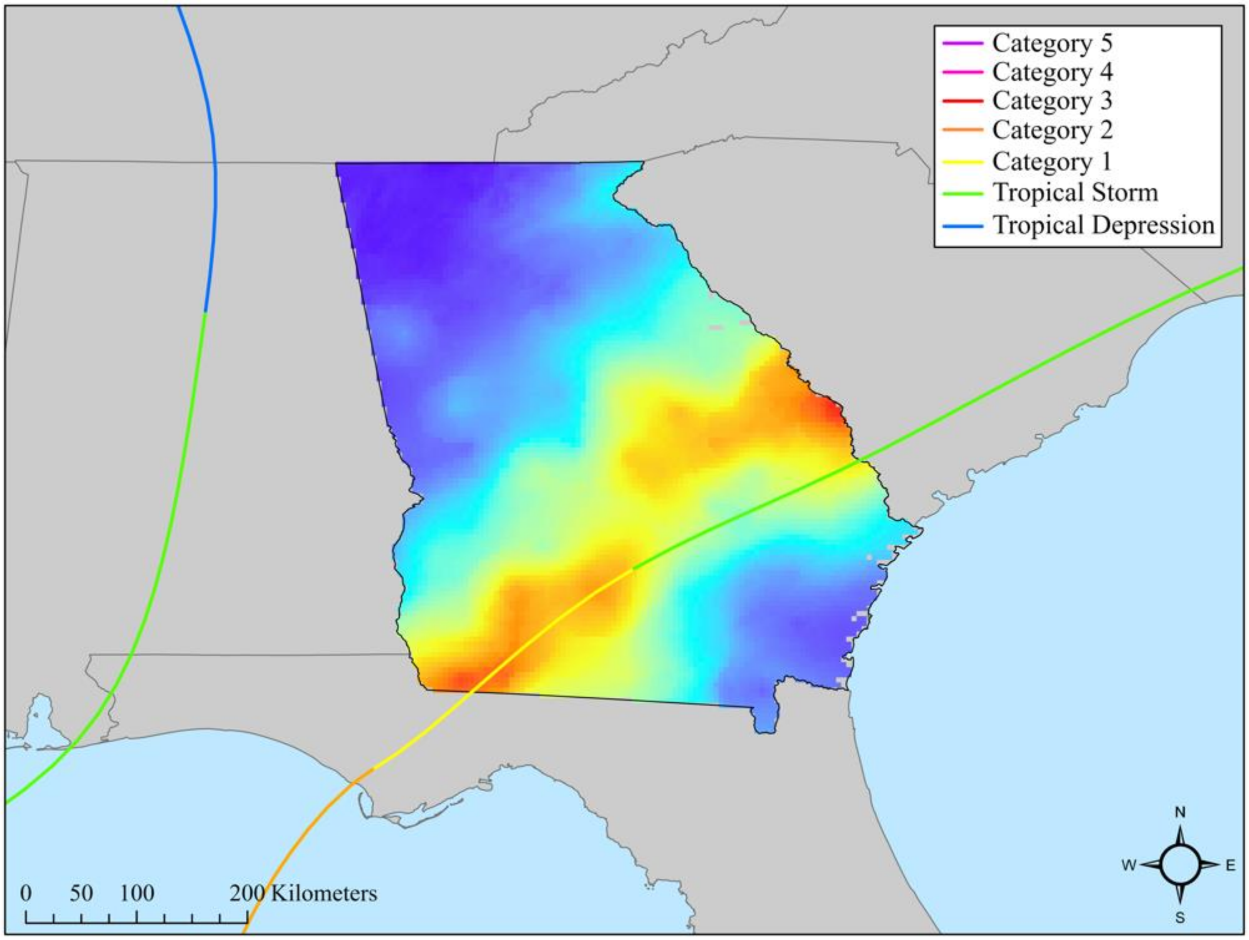


Figure 38. TC Tracks that occurred in November in Georgia from 1951–2021. Monthly average rainfall data attributed to tropical cyclones in November.

Figure 39 shows the highest concentration of precipitation occurred due to hurricane Kate. The rainfall is highest as the hurricane entered the southwest region and exited along the middle of the eastern border. This precipitation is mainly focused in the Upper Coastal Plain. The southern coastline and the northern portion of the state received no rainfall from TCs during this month.

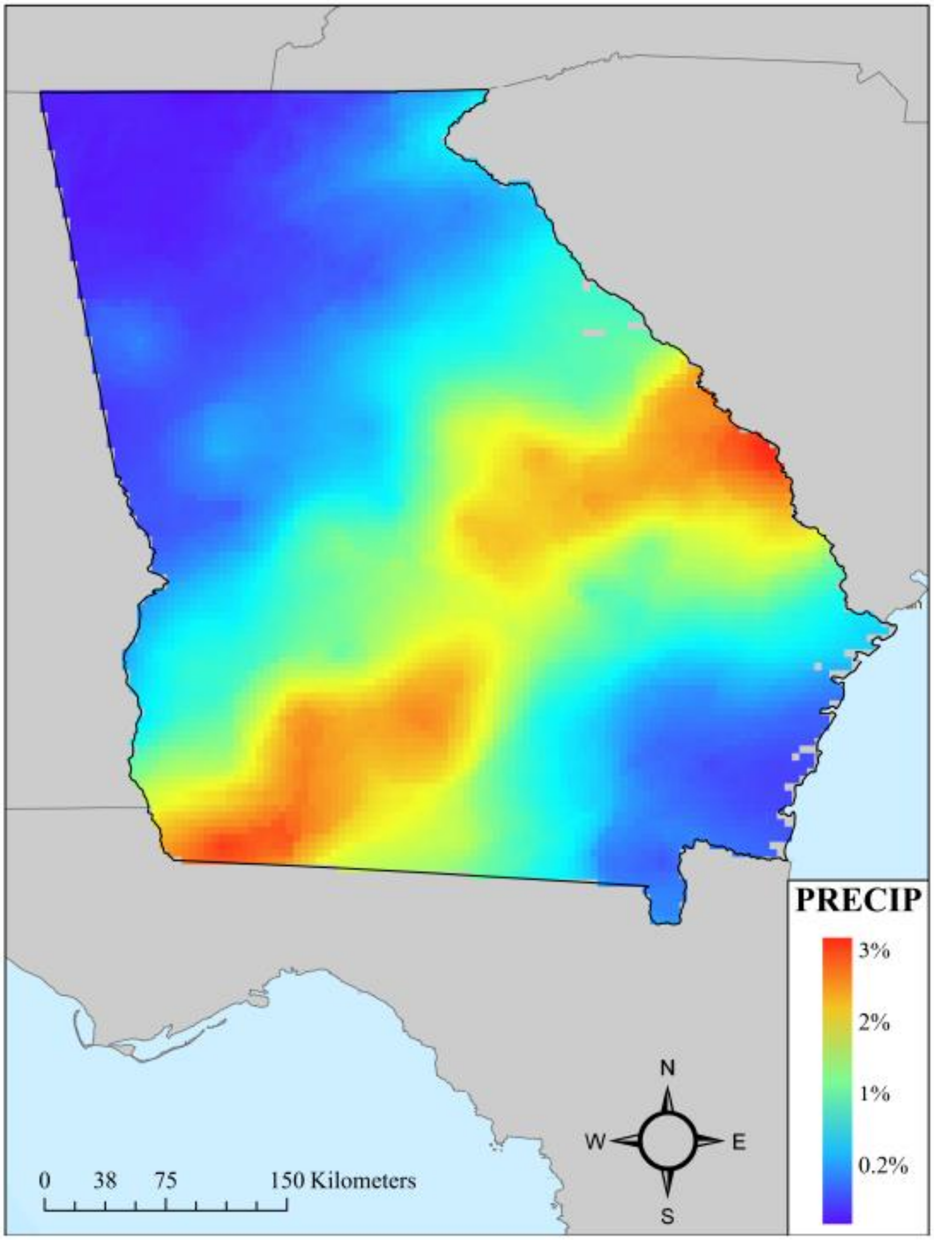


Figure 39. November average TC precipitation percentage of annual in Georgia from 1951–2021.

4.5. October 1898 Hurricane

The 1898 Georgia Hurricane, initially a category 4 storm, made landfall on Georgia's coast as a category 3. This ranks it as one of the most intense hurricanes to ever hit Georgia. The hurricane made landfall on Cumberland Island, one of Georgia's 14 barrier islands and then continued moving west. The October 2nd NOAA weather map documented a pressure of 29.62

inHg (1003.05 mb) in Savannah, Georgia just before the hurricane made landfall. The hurricane traveled through Georgia and made its way into Alabama. Around 179 people were reportedly killed from the hurricane (Dunn and Miller 1968). Sandrik and Jarvinen (1999) reevaluated the hurricane and determined the system had a central pressure of 27.7 inHg (938 mb) and a radius of maximum winds of 18 nmi. The storm possibly caused 16 feet of storm surge (Sandrik and Landsea 2003). Water flooded the streets in Brunswick, Georgia and flooding was so intense a boat found on a 20 ft high bluff pictured in Figure 40 (Sandrik and Landsea 2003).

Figure 40. A photo of a marooned ship in Brunswick, Georgia from the Hurricane of 1898. *Source*: Georgia Archives.

The hurricane impacted northeastern Florida, specifically Fernandina Beach, due to the 12-storm surge and extensive flooding. The October Monthly Weather Review of 1898 describes the city of Fernandina as “nearly destroyed” (NOAA 1898). The 1898 monthly weather report described the flooding in Brunswick, Georgia as the worst it had seen since 1812 (NOAA 1898).

The aftermath of flooding can be seen in Figures 41 and 42.

Figure 41. This photo shows flooding along Newcastle Street. Residents are walking through the flood waters with floating debris. The tall clock tower building on the right is Brunswick City Hall, which still stands to this day. *Source*: Georgia Archives.

Figure 42. This photo is another angle of Newcastle Street. Men on horses are seen riding through the flood waters. *Source*: Georgia Archives.

Buildings on the street have extensive damage. Debris floats through the water and gets stuck on high wires (Georgia Archives). The damage extended to warehouses and hospitals. Approximately 5,000 barrels of rosin were dispersed and damaged across the coast (Figure 43). A temporary hospital for individuals plagued with yellow fever was destroyed (Clayton 1992). The storm was estimated to cost $1.5 million (1898 USD), which would be worth about $55.4 million in today's dollars (Garriott 1898). A family, The Dart's, lived along the coast of Brunswick, Georgia, when the hurricane made landfall. Horace Dart's family home, pictured in Figure 44, had marsh grass washed up in by the flooding or storm surge in the front yard. Debris is scattered across the yard with sheets and clothing laid out to dry. The home of W.R. Dart's family home allegedly had flooding or storm surge that came up to six inches above the windowsills pictured in Figure 45. The family has laid various items out to dry.

Figure 43. Workers prepare to clean off the damage caused to the resin docks of the Downing Company. *Source*: Georgia Archives.

Figure 44. Home of Horace Dart. People are assessing the damage caused by the hurricane. *Source*: Georgia Archives.

Figure 45. Home of W.R. Dart. At 1601 Glynn Avenue in Brunswick. *Source*: Georgia Archives.

4.6. October 1940 Hurricane

The October 1940 hurricane, or the Southeast Hurricane, made landfall in South Carolina before quickly turning west into Georgia between 11 August and 12 August 1940. Despite the hurricane landfalling with Category 1 wind speeds, the extensive damage evident in the following photos underscores the potential destructiveness of any hurricane. After making landfall in South Carolina, the track moved through the center of Georgia, then proceeded northeast into Tennessee and Kentucky where it stalled (NOAA 2009). From there, it veered west toward Virginia, followed by a turn into North Carolina, before eventually reaching the Atlantic Ocean (NOAA 2009). The maximum recorded wind speed was sustained for 5 minutes at 75 mph in Savannah with gusts up to 90 mph (Gallenne 1940). The wind caused extensive damage to infrastructure evident in Figures 46 and 47. Many buildings were destroyed, including Rourke’s Iron Works (Figure 47). The roof, doors, and windows are missing from the factory.

Figure 46. Hurricane damage to Rourke’s Iron Works in Savannah, Georgia. *Source*: Harr 1940.

Figure 47. A clocktower fell onto a building's roof with the streets covered in other roofing and debris from the hurricane in Savannah, Georgia. *Source*: Harr 1940.

The highest reported rainfall in Georgia was recorded at 13.68 inches in Savannah (Roth 2022). The rain produced by the system caused major flash flooding across the Appalachian Mountains (NOAA 2009). The damage caused by flooding and storm surge can be seen in Figures 48 and 49. With the combined rain, flooding, and high wind speeds many trees fell (Figure 50). The hurricane caused a considerable loss of life with 50 reported deaths due to flooding or storm surge (Blake et al. 2011). The number of deaths was low in relation to the severity of the hurricane's rainfall, thanks to a timely issuance of evacuation notices (Gallenne 1940 and Blake et al. 2011). Savannah had over $1 million (1940 USD) worth in damages, totaling around $22 million today (Griner 2020).

Figure 48. Flooding and tree debris pictured outside of Holsum's Bread. *Source*: Harr 1940.

Figure 49. A sign for Hotel Savannah still stands with a building that has been uprooted from its foundation and moved onto the railroad tracks. *Source*: Harr 1940.

Figure 50. Uprooted tree falls into a home in Savannah, Georgia. *Source*: Harr 1940.

CHAPTER 5. DISCUSSION AND CONCLUDING REMARKS

5.1. Discussion

This thesis focuses on the spatial and temporal trends of tropical cyclone frequency, intensity, and rainfall in Georgia, U.S.A. The study found that 113 TCs have entered the state of Georgia from 1851–2021. Of the 113 TCs, 24 were categorized as hurricanes and 89 were categorized as tropical storms as they entered the states borders. September had the highest TC frequency (n=40; 35%), October had the second highest TC frequency (n=27; 23%) and August had the highest frequency of hurricanes (n=8; 7%). A surprising early batch of June TCs (n=15; 13%) was seen within the data. The maximum wind speed observed was 54.6 ms^{-1} by an Unnamed hurricane in 1898. The minimum wind speed observed was 16.3 ms^{-1} but an Unnamed storm in 1904. The mean wind speed observed across the data set was 27.2 ms^{-1}.

There appears to be a decreasing trend in Georgia over-land TC intensity, contrary to the intensification associated with anthropogenic warming. Many studies primarily concentrate on assessing their lifetime maximum intensity of TCs over the open ocean, rather than their strength when they reach land, which complicates making direct comparisons. These findings challenge prevailing assumptions about the impact of changing climate conditions on hurricane behavior in the North Atlantic Basin. In the dataset, most hurricanes (87%) occurred in the first 100 years of the data. This is likely causing the decreasing trend in intensity. Another probable factor contributing to the decrease in TC intensity is the transformation of Georgia's landscape. The region's transformation has been shaped by a confluence of factors including natural processes, natural disasters, demographic changes, and economic developments. Georgia has continually increased in urbanization, which can disrupt the essential conditions required for a TC to maintain or increase in intensity. Georgia was less urban in 1851 compared to modern day. There was a shift towards urbanization, which could have affected the conditions necessary for sustaining the intensity of severe TCs. Severe storms still exist within the later years, including Hurricane Michael in 2018. Further statistical analysis should be conducted to focus in on the modern (flight/satellite era to the present) tropical cyclone in Georgia. This will assist to see what the trends and characteristics for modern tropical cyclones.

Georgia TCS occur most often in September, which aligns with the most active month for TCs throughout the basin. This has implications for disaster preparedness and resource allocation, emphasizing the importance of heightened vigilance and readiness during September. On average, Georgia experiences 0.66 TCs (0.52 tropical storms and 0.14 hurricanes) per year. While it is not expected to be an annual occurrence, the threat of TCs remains within Georgia and is heightened in the middle of the season.

TC-induced rainfall was seen at high percentages across the coastal plains and the piedmont region when compared to annual rainfall totals. The study found that 5–6% of TC-induced rainfall occurs on average along the coastline and the inland counties. The 1% or lower TC induced rainfall was seen in the northwestern portion of the state. This makes sense as it is the furthest from the coast and furthest from the GOM. July and November have the lowest TC-induced rainfall amounts, with 14% and 2%, respectively. Only two TCs were recorded in November. The most TC-induced rainfall occurred in October and June, with 39% and 32%, respectively.

The hurricanes of 1898, 1940, and hurricane Michael in 2018 have provided valuable insight into the potential effects of such events on the state. Integrating archival resources, including news articles, and photographs, with climatological data on hurricanes offers a comprehensive understanding of these complex meteorological systems. Despite the 120-year difference in occurrence, the 1898 hurricane and hurricane Michael exhibited similarities, such as their maximum wind speeds, occurrence in October, and the extensive damage inflicted upon Georgia. A notable distinction was the 1898 hurricane made direct landfall on the coast, whereas hurricane Michael affected southwest Georgia. The 1940 hurricane, though less intense than the others, still caused notable damage as a category 1 hurricane.

The impact of TCs on regions in Georgia can vary based on whether the landfall was direct or indirect. Direct landfilling TCs are typically associated with greater damage due to storm surge and flooding from ocean waters, while indirect landfilling TCs may cause more damage due to rainfall. Nonetheless, both scenarios entail considerable risks of flash floods and intense winds. This study also acknowledges indirect TC related impacts not previously or extensively mentioned, such as tornadoes and wildfires. This exploration of archival resources further promotes the idea that severe TCs can affect any part of Georgia, whether coastal or inland. Furthermore, a severe hurricane is not limited by whether a TC makes a direct or indirect landfall in a region.

5.2. Conclusion

The comprehensive examination of TCs in Georgia from 1851 to 2021 highlights the state's susceptibility to both direct and indirect TC impacts. While the study reveals a general decrease in the frequency and maximum wind speeds of TCs over Georgia, it does not diminish the historical or potential future threat posed by high intensity hurricanes, particularly those that do not make direct landfalls. The significant damage wrought by TCs and the severe implications for Georgia's coastal and inland area underscore the importance of continued vigilance and preparedness in the face of TCs.

The spatial and temporal patterns of TC induced rainfall further emphasize the varied impacts these storms have across different regions of Georgia. The coastline and the Piedmont regions are experiencing a higher percentage of TC-induced precipitation. This variability in impact allows for an approach in disaster preparedness and response, tailored to the specific vulnerabilities of each region.

These results challenge existing assumptions, necessitating a reevaluation of the factors influencing hurricane behavior in Georgia. The unexpected downward trend in hurricane intensity prompts a reconsideration of the relationship between environmental variables controlling the wind speed of TCs in the region. Additionally, the emphasis on September as a peak month for TCs underscores the need for targeted preparedness efforts during this period. The provided annual averages contribute to a comprehensive characterization of Georgia's tropical weather patterns, providing valuable insights for future research and policy considerations. This research aims to represent the people who are underrepresented in literature and in planning practices to create a safer environment and to spread information to better protect the public. Hurricane Idalia and Hurricane Michael prove that hurricanes make their way into Georgia and have major impact on the region, yet the public focuses on the hurricane impact in Florida, South Carolina, and North Carolina. Hurricanes and tropical storms continue to impact Georgia, and this research serves as an updated climatology to help protect Georgia’s history, natural beauty, and the people within.

APPENDIX A. HURRICANE AND TROPICAL STORMS OF GEORGIA

Table 6. Tropical Cyclone of Georgia from 1851− 2021 Information.

Year	Storm Name	Category	Classification
1851	Unnamed	2	Hurricane
1852	Unnamed	1	Hurricane
1852	Unnamed	0	Tropical Storm
1854	Unnamed	2	Hurricane
1856	Unnamed	1	Hurricane
1859	Unnamed	0	Tropical Storm
1860	Unnamed	0	Tropical Storm
1868	Unnamed	0	Tropical Storm
1871	Unnamed	0	Tropical Storm
1871	Unnamed	0	Tropical Storm
1871	Unnamed	0	Tropical Storm
1873	Unnamed	0	Tropical Storm
1973	Unnamed	0	Tropical Storm
1974	Unnamed	1	Hurricane
1875	Unnamed	0	Tropical Storm
1877	Unnamed	1	Hurricane
1877	Unnamed	0	Tropical Storm
1878	Unnamed	0	Tropical Storm
1880	Unnamed	0	Tropical Storm
1881	Unnamed	2	Hurricane
1882	Unnamed	1	Hurricane
1882	Unnamed	0	Tropical Storm
1884	Unnamed	0	Tropical Storm
1885	Unnamed	0	Tropical Storm
1885	Unnamed	0	Tropical Storm
1885	Unnamed	0	Tropical Storm
1886	Unnamed	1	Hurricane
1886	Unnamed	1	Hurricane
1887	Unnamed	0	Tropical Storm
1887	Unnamed	0	Tropical Storm
1888	Unnamed	0	Tropical Storm
1889	Unnamed	0	Tropical Storm
1893	Unnamed	2	Hurricane
1893	Unnamed	0	Tropical Storm
1893	Unnamed	0	Tropical Storm
1894	Unnamed	2	Hurricane
1896	Unnamed	2	Hurricane
1896	Unnamed	0	Tropical Storm

(table cont'd.)

Year	Storm Name	Category	Classification
1898	Unnamed	3	Hurricane
1898	Unnamed	1	Hurricane
1901	Unnamed	0	Tropical Storm
1902	Unnamed	0	Tropical Storm
1903	Unnamed	0	Tropical Storm
1904	Unnamed	0	Tropical Storm
1907	Unnamed	0	Tropical Storm
1907	Unnamed	0	Tropical Storm
1910	Unnamed	0	Tropical Storm
1911	Unnamed	1	Hurricane
1912	Unnamed	0	Tropical Storm
1912	Unnamed	0	Tropical Storm
1914	Unnamed	0	Tropical Storm
1915	Unnamed	0	Tropical Storm
1915	Unnamed	0	Tropical Storm
1916	Unnamed	0	Tropical Storm
1916	Unnamed	0	Tropical Storm
1917	Unnamed	0	Tropical Storm
1919	Unnamed	0	Tropical Storm
1924	Unnamed	0	Tropical Storm
1924	Unnamed	0	Tropical Storm
1926	Unnamed	0	Tropical Storm
1928	Unnamed	0	Tropical Storm
1929	Unnamed	0	Tropical Storm
1932	Unnamed	0	Tropical Storm
1933	Unnamed	0	Tropical Storm
1935	Unnamed	1	Hurricane
1940	Unnamed	1	Hurricane
1941	Unnamed	1	Hurricane
1944	Unnamed	0	Tropical Storm
1945	Unnamed	0	Tropical Storm
1946	Unnamed	0	Tropical Storm
1947	Unnamed	2	Hurricane
1947	Unnamed	0	Tropical Storm
1949	Unnamed	1	Hurricane
1950	Love	0	Tropical Storm
1950	King	0	Tropical Storm

(table cont'd.)

Year	Storm Name	Category	Classification
1950	Easy	0	Tropical Storm
1953	Florence	0	Tropical Storm
1956	Flossy	0	Tropical Storm
1957	Unnamed	0	Tropical Storm
1960	Brenda	0	Tropical Storm
1964	Dora	0	Tropical Storm
1964	Cleo	0	Tropical Storm
1965	Unnamed	0	Tropical Storm
1966	Unnamed	0	Tropical Storm
1966	Alma	0	Tropical Storm
1968	Abby	0	Tropical Storm
1970	Alma	0	Tropical Storm
1972	Agnes	0	Tropical Storm
1975	Eloise	0	Tropical Storm
1979	David	1	Hurricane
1985	Kate	1	Hurricane
1985	Isabel	0	Tropical Storm
1988	Chris	0	Tropical Storm
1994	Beryl	0	Tropical Storm
1995	Allison	0	Tropical Storm
1996	Josephine	0	Tropical Storm
1998	Earl	0	Tropical Storm
2000	Gordon	0	Tropical Storm
2004	Jeanne	0	Tropical Storm
2004	Frances	0	Tropical Storm
2005	Tammy	0	Tropical Storm
2006	Alberto	0	Tropical Storm
2013	Andrea	0	Tropical Storm
2016	Julia	0	Tropical Storm
2016	Hermine	0	Tropical Storm
2016	Colin	0	Tropical Storm
2017	Irma	0	Tropical Storm
2018	Michael	3	Hurricane
2020	Eta	0	Tropical Storm
2020	Zeta	0	Tropical Storm
2021	Mindy	0	Tropical Storm
2021	Elsa	0	Tropical Storm

PERMISSIONS

Image Request

Haar, John M. Hurricane damage near Hotel Savannah. August 1940. GHS 2834 Haar collection of Savannah hurricane damage photographs. GHS 2834-PH-0011. Georgia Historical Society, Savannah, Georgia.

Haar, John M. Hurricane damage, fallen clocktower. August 1940. GHS 2834 Haar collection of Savannah hurricane damage photographs. GHS 2834-PH-0006. Georgia Historical Society, Savannah, Georgia.

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Haar, John M. Hurricane flooding and damage. August 1940. GHS 2834 Haar collection of Savannah hurricane damage photographs. GHS 2834-PH-0008. Georgia Historical Society, Savannah, Georgia.

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