EXAMINING HURRICANE EXPOSURE ON NEONATAL OUTCOMES IN NORTH CAROLINA: A PROSPECTIVE BIRTH COHORT STUDY

A Thesis
by
TAYLIN J. SPURLOCK

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Abstract

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Exposure to tropical storms and hurricanes during pregnancy can adversely influence neonatal and birth outcomes such as low birth weight and preterm birth. These outcomes could potentially be impacted by the disruption of healthcare and infrastructure, as well as stress, injury, and changes in nutrition. Little is known about how far from the storm center maternal and neonatal impacts occur, nor how storms affect spatial patterns of maternal health. The aim of this study is to 1) assess causal association between hurricane exposure and the adverse birth outcomes of low birth weight (LBW) and preterm birth (PTB) using a difference-in-difference analysis, and 2) find differences in spatial patterns for the adverse birth outcomes LBW and PTB pre- and post-Hurricane Isabel (2003). The geospatial analysis included multiple buffers of 30, 60, and 100 kilometers and local spatial autocorrelation statistics. The results were predominantly insignificant, with some key exceptions. The difference-in-difference analysis found a statistical association between hurricane exposure and preterm birth, with reductions, post-storm. Across all three models, we found exposure to Hurricane Isabel and low birth weight was statistically significant at the 30 and 100-km spatial buffers; exposure was also associated with preterm birth at the 30km buffer. Our fourth model was trimester specific, and we found significant results during the second and third trimesters. Significant differences in clustering of low birth weight and preterm birth before and after Isabel made landfall also were found, with new clusters forming along the storm track. Results from this study will enhance the literature analyzing hurricane exposure and neonatal outcomes.

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Throughout my academic career at Appalachian State, I have had the great pleasure of being surrounded and supported by incredible advisors. Dr. Maggie Sugg is the entire reason I chose to pursue my Master's at App. She has been a valuable resource and a great mentor throughout my time in graduate school. I aspire to half of the scholar she is. Dr. Jennifer Runkle's passion for research on every project we worked on was motivation on even the latest of nights. Dr. Dennis Guignet's endless knowledge of statistical analysis and expertise guidance while using the CEHI data was invaluable. I have also had the benefit of Dr. Derek Martin's understanding and guidance, even when I came to him out of nowhere wanting a minor in History. Without the mentorship of Dr. Saskia van de Gevel, I would not be the student I am today. She has inspired me with her strength and wisdom to pursue even the wildest of dreams. Lastly, I would like to thank Claire Osgood and Joshua Tootoo of Notre Dame's Children's Environmental Health Initiative for their direction and support.

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Mitchell Massey has been a phenomenal partner throughout my undergraduate and graduate careers. He has pushed me in ways I never thought possible, encouraged me to follow my dreams, and I would not be where I am today without his support.

Table of Contents

Foreword

The findings of this thesis will be submitted to *GeoHealth,* a transdisciplinary peer-reviewed journal dedicated to publishing research articles across the "intersection of the Earth and environmental sciences and health sciences." The format of this thesis has been adjusted accordingly.

Examining Hurricane Exposure on Neonatal Outcomes in North Carolina: A Case Study of Hurricane Isabel (2003)

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Key Points:

- The aim of this study is to 1) assess causal association between hurricane exposure and the adverse birth outcomes of low birth weight (LBW) and preterm birth (PTB) using a difference-in-difference analysis, and 2) find differences in spatial patterns for the adverse birth outcomes LBW and PTB pre and post-Hurricane Isabel (2003).
- We use difference-in-difference statistical and LISA spatial analysis to understand the impact of hurricane exposure on LBW and PTB.

Keywords: Hurricanes, neonatal health, maternal health, birth outcomes

Abstract

Exposure to tropical storms and hurricanes during pregnancy can adversely influence neonatal and birth outcomes such as low birth weight and preterm birth. These outcomes could potentially be impacted by the disruption of healthcare and infrastructure, as well as stress, injury, and changes in nutrition. Little is known about how far from the storm center maternal and neonatal impacts occur, nor how storms affect spatial patterns of maternal health. The aim of this study is to 1) assess causal association between hurricane exposure and the adverse birth outcomes of low birth weight (LBW) and preterm birth (PTB) using a difference-in-difference analysis, and 2) find differences in spatial patterns for the adverse birth outcomes LBW and PTB pre- and post-Hurricane Isabel (2003). The geospatial analysis included multiple buffers of 30, 60, and 100 kilometers and local spatial autocorrelation statistics. The results were predominantly insignificant, with some key exceptions. The difference-in-difference analysis found a statistical association between hurricane exposure and preterm birth, with reductions, post-storm. Across all three models, we found exposure to Hurricane Isabel and low birth weight was statistically significant at the 30 and 100-km spatial buffers; exposure was also associated with preterm birth at the 30km buffer. Our fourth model was trimester specific, and we found significant results during the second and third trimesters. Significant differences in clustering of low birth weight and preterm birth before and after Isabel made landfall also were found, with new clusters forming along the storm track. Results from this study will enhance the literature analyzing hurricane exposure and neonatal outcomes.

1. Introduction

Hurricanes, which are also known as tropical cyclones or typhoons, are strong storms that can have prolonged health impacts because of the disruption of livelihoods, healthcare, and infrastructure. The Federal Emergency Management Agency (FEMA) categorizes pregnant women as a socially vulnerable population. Research shows that hurricanes impact pregnant women and newborns disproportionately through loss of housing, disrupted or lost prenatal and general healthcare, and impacted nutrition (Sato et al., 2016; Subaiya et al., 2014). Common themes of maternal stress during hurricane exposure include concerns about infant feeding, evacuation logistics, family roles, and general stress surrounding the hurricane (DeYoung et al., 2022). Stress during pregnancy is associated with higher rates of hypertension and preeclampsia, and higher rates of distressed delivery, preterm birth, infant mortality, low birth weight, and suboptimal development in children (Cardwell, 2013; Rondo et al., 2003; Wadhwa et al., 2012; Witt et al., 2014; Van den Bergh, 2020).

Understanding the relationship between hurricanes and maternal/neonatal outcomes has become more of a priority as climate change models are projecting more severe hurricanes will increase in frequency (USGCRP, 2018). Currently, the literature linking natural disasters and birth outcomes has mixed results, but preterm birth has been linked to severe storms more consistently than low birth weight. Positive associations between exposure to hurricanes and preterm birth have been found in multiple studies (Antipova and Curtis, 2015; Chen et al., 2012; Grabich et al., 2016a; Oni et al., 2015; Parayiwa & Behie, 2018; Xiao et al., 2019). Only three studies, focused on Hurricane Katrina, have found significant associations between hurricane exposure and low birth weight (Chen et al., 2012; Harville et al., 2010a; and Xiong et al., 2008). Only Mendez-Figueroa (2019), Harville et al.

(2010a), and Hamilton et al. (2009) found no associations between hurricane exposure and preterm birth, but results suggest that forced migration may be impacting null findings. More studies have found no association between hurricane exposure and low birth weight for pregnant persons residing in the impacted areas (Parayiwa & Behie, 2018; Grabich et al., 2017; Antipova & Curtis, 2015; Hamilton et al., 2009).

The overall association between hurricane exposure and neonatal outcomes is not well characterized, largely due to varying methods, limited samples, and discrepancies in exposure definitions (Jeffers & Glass, 2020). While there have been a number of other studies in the Southeast United States, namely Florida, Louisiana, and Texas, there is still much that needs to be understood including the impacts of direct exposure, and to the author's knowledge, no study has examined this relationship in North Carolina. The aim of this study is to determine if an association exists between hurricane exposure and the neonatal outcomes of low birth weight (LBW) and preterm birth (PTB) using a prospective birth cohort. More specifically, this study will address the following research question: how does prenatal exposure to tropical cyclones negatively impact neonatal outcomes (e.g. low birth weight and preterm birth), and how does this vary spatially? Results from this study will enhance the literature between hurricane exposure and neonatal outcomes by analyzing a non-major hurricane and using a finer resolution than previous studies.

2. Materials and Methods

2.1 Data Sources

We used a prospective birth cohort composed of administrative hospital delivery and infant records for all North Carolina births from the University of Notre Dame's Children's

Environmental Health Initiative (CEHI) (Children's Environmental Health Initiative, 2020). This data consists of long-form birth records for children born in North Carolina from 2000 to 2009. Infant characteristics obtained from the birth records include infant sex, birth weight, date of birth, birth order, the estimate of gestational length, and any congenital anomalies (such as gastrointestinal anomalies, musculoskeletal anomalies, or congenital heart disease). Maternal characteristics include the age, marital status, race and ethnicity, educational attainment, the trimester in which prenatal care began, and the mother's residential address at the time of birth as well as many other characteristics. Inclusion criteria to be considered in the study are mothers between the ages of 20 and 39, and their births had to be at least 20 weeks gestation. This means we excluded teen mothers and mothers over the age of 40, as they are more likely to have complications (World Health Organization, 2022a; Wisner, 2022.)

2.2 Health Outcomes

We have chosen to analyze the birth outcomes of low birth weight (LBW) and preterm birth (PTB). These variables were selected as they were two of the most studied variables by prior studies (Waddell et al., 2021; Jeffers & Glass, 2020; Zotti et al., 2013; Harville et al., 2010b). Within our dataset, these outcomes were pre-defined as variables by CEHI. LBW has been defined as any newborn born under 2500 grams (5.5 pounds) (World Health Organization, n.d.). Any live birth before 37 completed weeks of gestation is defined as a PTB (World Health Organization, 2022b).

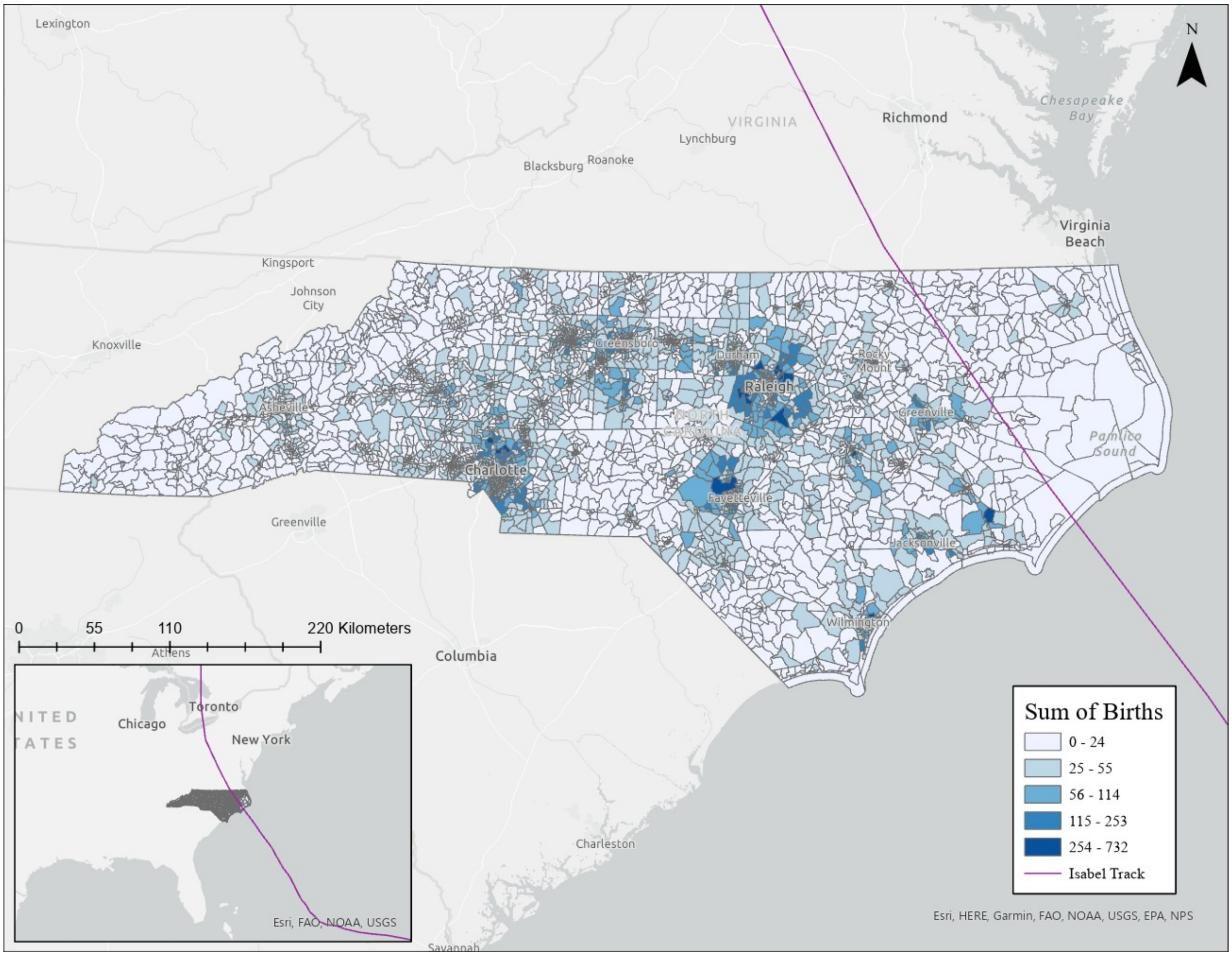
2.3 Hurricane Exposure

2.3.1 Setting

Hurricane Isabel made landfall on September 18th, 2003, on the North Carolina Outer Banks between Cape Lookout and Cape Hatteras as a Category 2 storm (Figure 1) bringing small storm tides of half a foot to one foot above normal (National Weather Service, n.d.).

Figure 1.

Map of Study Area



Note: The map displays raw birth counts during the study period of 9/18/2003-6/18/2003 and 9/18/2003-6/18/2004.

2.3.2 Hurricane Exposure Measurement

We assessed hurricane exposure using spatial data on the specific storm trajectory (Powell et al., 1998; Grabich et al., 2015). The historical storm track data was derived from the Regional and Mesoscale Meteorology Branch Cooperative Institute for Research in the

Atmosphere from Colorado State University (Demuth et al., 2006). The track data is in the form of latitude (X), and longitude (Y) coordinates, which were imported into ArcGIS Pro (Esri Inc., 2022). We used a range of buffer distances (30, 60, and 100km) to define spatial exposure (Zahran et al., 2010; Currie & Rossin-Slater, 2013; Grabich et al., 2015). A non-exposure birth is defined as any birth that occurred outside of these buffers.

Maternal exposure to Hurricane Isabel has been derived from the mother's residential address at the time of birth and whether that location falls within 30, 60, or 100 kilometers from the storm track. The control period (i.e., pre-Isabel) includes the births from 9/18/2002 through 6/18/2003, and the treatment period (i.e., post-Isabel) has all of the births after 09/18/2003 until 06/18/2004. To identify the "hurricane exposed group (i.e., exposed pregnant persons)," we used "select by location" to select the births where the mother's residential address is within 100, 60, or 30 kilometers from Hurricane Isabel's storm track (Grabich et al., 2015). Each buffer was analyzed separately as the treatment factor in the difference-in-difference analysis models. The "control group (i.e., unexposed pregnant persons)" was defined as mothers outside of the spatial buffers.

We have further split the maternal exposure into trimesters (i.e., trimester 1, trimester 2, trimester 3) to estimate the differences between the timing of storm exposure during a pregnancy. An example of this would be a child born on January 1st, 2004, after Hurricane Isabel made landfall on September 18th, 2003. Since this child was born after the event, we can assume they were exposed in utero during their second trimester. The trimester of storm exposure was defined by subtracting the difference between the birth date and the landfall date from the gestational age. The same premise was applied to all births within the sample.

2.4 Analysis

2.4.1 Statistical Analysis

We used a difference in difference (DD) for our analytical approach. This statistical technique attempts to mimic an experimental research study design using observational data, and it estimates the effect of exposure on an outcome as the difference in the average change over time in the cases (exposed) and controls (unexposed). DD is a quasi-experimental design that allows for causal inference. For our study, this allows us to measure if hurricane exposure is causally associated with adverse birth outcomes. DD is often used in economics to measure the effect of exposure at a given period in time (Schwerdt & Woessmann, 2020; Grabich et al., 2017). Using difference-in-difference, like other models, allows us to also compare mothers of different races, socioeconomic status, and locations by adjusting for each within the model (Ramesh et al., 2022; Schnake-Mahl et al., 2020).

For our DD analysis, we have used the basic model set up of the birth outcome ~ time + treatment + time*treatment. The time variable corresponds to the date of landfall, so it separates the births that took place before landfall from after landfall. The treatment variables are the spatial buffers (i.e. the 30, 60, and 100-km buffers outlined above). This base formula stays the same throughout all four models. For the second model, we adjusted for several confounders, such as the mother's age, education, and race. The third model was completed using coarsened exact matched data. Coarsened exact matching is a design strategy that produces a good covariate balance between the control and treatment groups, and this is to reduce the impact of confounding (Ripollone et al., 2020). Finally, our fourth DD model was fit for each of the primary outcomes and each spatial buffer broken down by trimester using the matched data.

We also ran a sensitivity analysis using the FEMA Disaster declarations. This allowed us to compare the counties that had any type of four FEMA declarations (i.e. Individual and Household program, Individual Assistance program, Public Assistance program, or Hazard Mitigation program) to counties that were not exposed. We decided to complete this analysis because FEMA disaster declarations are commonly used to measure hurricane exposure (Grabich et al., 2016b; Hamilton et al., 2009; Parayiwa & Behie, 2018; Xiao et al., 2019).

2.5.2 Spatial Analysis

A spatial analysis using LISA or local clustering statistics from ArcGIS was conducted to identify changes in birth outcome clusters pre- and post- Isabel (Anselin, 1995). Geocoded births were aggregated to the census tract level using the sum. They were then normalized by the total number of births per tract. This table was then exported and used for further analysis in GeoDa (Anselin et al., 2006). Next, we created a Queen's spatial weights matrix using the ID codes of each tract. Finally, a LISA univariate cluster analysis was conducted to assess changes in the distribution of clusters pre- and post- Isabel.

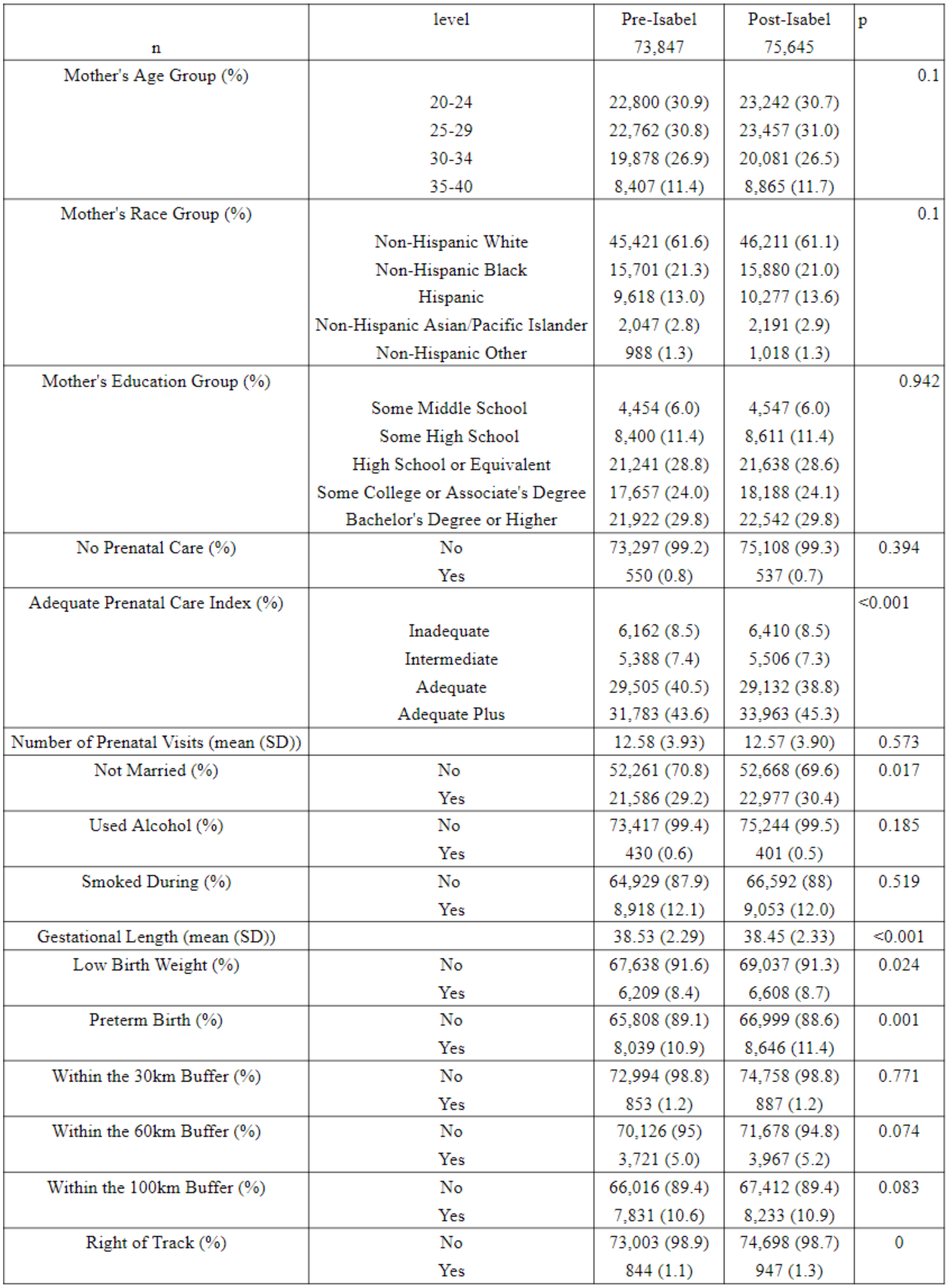
Local autocorrelation analysis is used to identify significant spatial clusters of observations, as well as spatial outliers (where the value does not match with its neighbors). The Local Moran's I was calculated as an indicator for spatial associations (Anselin, 1995). Our birth outcomes (LBW or PTB) were then classified into High-High, Low-Low, Low-High, or High-Low clusters based on if their local Moran's I was statistically significant ($p < 0.05$). These clusters can be broken down by the outcome's value and how that fits in compared to their neighbors. If a tract has a relatively high cluster value and is surrounded by other high cluster values, the cluster will be High-High. Low-Low tracts have low values of the birth outcome surrounded by other tracts that also have low values. Low-High tracts are tracts with low values surrounded by tracts with high values, and High-Low tracts have high values of the birth outcomes and are surrounded by tracts with low values. The last two combinations, Low-High and High-Low, indicate spatial outliers.

4. Results

4.1 Sample Characteristics

Table 1.

Demographics of Study Sample



	level	Pre-Isabel	Post-Isabel	p
n		73,847	75,645	
Mother's Age Group (%)				0.1
	20-24	22,800 (30.9)	23,242 (30.7)	
	25-29	22,762 (30.8)	23,457 (31.0)	
	30-34	19,878 (26.9)	20,081 (26.5)	
	35-40	8,407 (11.4)	8,865 (11.7)	
Mother's Race Group (%)				0.1
	Non-Hispanic White	45,421 (61.6)	46,211 (61.1)	
	Non-Hispanic Black	15,701 (21.3)	15,880 (21.0)	
	Hispanic	9,618 (13.0)	10,277 (13.6)	
	Non-Hispanic Asian/Pacific Islander	2,047 (2.8)	2,191 (2.9)	
	Non-Hispanic Other	988 (1.3)	1,018 (1.3)	
Mother's Education Group (%)				0.942
	Some Middle School	4,454 (6.0)	4,547 (6.0)	
	Some High School	8,400 (11.4)	8,611 (11.4)	
	High School or Equivalent	21,241 (28.8)	21,638 (28.6)	
	Some College or Associate's Degree	17,657 (24.0)	18,188 (24.1)	
	Bachelor's Degree or Higher	21,922 (29.8)	22,542 (29.8)	
No Prenatal Care (%)	No	73,297 (99.2)	75,108 (99.3)	0.394
	Yes	550 (0.8)	537 (0.7)	
Adequate Prenatal Care Index (%)				<0.001
	Inadequate	6,162 (8.5)	6,410 (8.5)	
	Intermediate	5,388 (7.4)	5,506 (7.3)	
	Adequate	29,505 (40.5)	29,132 (38.8)	
	Adequate Plus	31,783 (43.6)	33,963 (45.3)	
Number of Prenatal Visits (mean (SD))		12.58 (3.93)	12.57 (3.90)	0.573
Not Married (%)	No	52,261 (70.8)	52,668 (69.6)	0.017
	Yes	21,586 (29.2)	22,977 (30.4)	
Used Alcohol (%)	No	73,417 (99.4)	75,244 (99.5)	0.185
	Yes	430 (0.6)	401 (0.5)	
Smoked During (%)	No	64,929 (87.9)	66,592 (88)	0.519
	Yes	8,918 (12.1)	9,053 (12.0)	
Gestational Length (mean (SD))		38.53 (2.29)	38.45 (2.33)	<0.001
Low Birth Weight (%)	No	67,638 (91.6)	69,037 (91.3)	0.024
	Yes	6,209 (8.4)	6,608 (8.7)	
Preterm Birth (%)	No	65,808 (89.1)	66,999 (88.6)	0.001
	Yes	8,039 (10.9)	8,646 (11.4)	
Within the 30km Buffer (%)	No	72,994 (98.8)	74,758 (98.8)	0.771
	Yes	853 (1.2)	887 (1.2)	
Within the 60km Buffer (%)	No	70,126 (95)	71,678 (94.8)	0.074
	Yes	3,721 (5.0)	3,967 (5.2)	
Within the 100km Buffer (%)	No	66,016 (89.4)	67,412 (89.4)	0.083
	Yes	7,831 (10.6)	8,233 (10.9)	
Right of Track (%)	No	73,003 (98.9)	74,698 (98.7)	0
	Yes	844 (1.1)	947 (1.3)	

Note: The table can be interpreted as the count of the sample, then the percentage of the population (n,%), except where noted as the mean and standard deviation. The p-value corresponds to the two-sample t-test.

Between our study dates, there were 175,870 live births in the CEHI dataset. After excluding births to mothers outside of the ages 20 to 39 and any births less than 20 weeks gestation, we have 149,493 births in our study. The treatment and control groups were similar prior to matching (Table 1). The percentage of low birth weight births for the control group was 8.4% (n = 6,209), and the treatment group's percentage was 8.7% (n = 6,608). Preterm birth percentages were also similar between the control and treatment groups, 10.9% (n = 8,039) and 11.4% (n = 8,646), respectively. The majority of women in our sample held a high school diploma or higher and were between the ages of 20-34. Our sample was also majority white and had access to prenatal care.

Table 2.

Birth Outcomes per Buffer, Pre- and Post- Isabel

Health Outcome	Buffer	Pre-Isabel (%)	Post-Isabel (%)	p-value
LBW	30	95 (0.12)	76 (0.10)	0.08562
	60	369 (0.49)	389 (0.51)	0.8936
	100	746 (1.01)	733 (0.97)	0.1404
PTB	30	143 (0.19)	111 (0.15)	**0.0146**
	60	487 (0.65)	502 (0.66)	0.5879
	100	951 (1.28)	1007 (1.33)	0.9379

Note: In the pre- and post- Isabel columns, the number of cases is first, then followed by the percentage in the parentheses. The p-value responds to the Chi Square test.

Within our spatial buffers, around one percent of the control and treatment groups were within 30 kilometers of Hurricane Isabel's storm track. Around five percent were located within the 60-kilometer buffer, and almost 11% were located within 100 kilometers of the track. Table 2 illustrates how many of each birth outcome were located within each buffer. The only statistically significant change we see in the number of pre- and post- Isabel birth outcomes is for PTB at the 30-km buffer.

4.2 DD Model Assumptions

Table 3.

Assumption of Parallel Trends

		LBW		
		RR	*CI*	*p*
Landfall: 09/18/2002 (Control = 2001)	1st Trimester	1.06	0.89 – 1.27	0.52
	2nd Trimester	1.19	1.00 – 1.42	0.048
	3rd Trimester	0.9	0.71 – 1.15	0.407
		PTB		
		RR	*CI*	*p*
	1st Trimester	1	0.86 – 1.16	0.982
	2nd Trimester	1.06	0.91 – 1.24	0.465
	3rd Trimester	0.84	0.68 – 1.03	0.1
Landfall: 09/18/2003 (Control = 2002)		**LBW**		
		RR	*CI*	*p*
	1st Trimester	0.99	0.83 – 1.18	0.916
	2nd Trimester	0.72	0.61 – 0.87	<0.001
	3rd Trimester	0.78	0.61 – 0.99	0.046
		PTB		
		RR	*CI*	*p*
	1st Trimester	0.94	0.80 – 1.09	0.39
	2nd Trimester	0.87	0.74 – 1.01	0.071
	3rd Trimester	0.93	0.75 – 1.15	0.491

Monthly trends of birth outcomes during the before period and after can be found above. In all three models, exposure to Hurricane Isabel during pregnancy was associated with a slight improvement in LBW at the 30 kilometers and 100 kilometers buffers, and PTB was significant at the 30-kilometer buffer. Results for the DD models are summarized in Tables 4-7.

Table 4.

Model 1

Health Outcome	Buffer	Risk Ratio	95% Confidence Interval	p-value
LBW	30	0.74	0.55 – 0.98	**0.039**
	60	0.95	0.83 – 1.09	0.455
	100	0.88	0.80 – 0.98	**0.016**
PTB	30	0.71	0.56 – 0.89	**0.003**
	60	0.92	0.81 – 1.03	0.15
	100	0.95	0.87 – 1.04	0.264

Note: Bolded font indicates statistically significant. This model is the basic difference-in-difference (DD) model (time multiplied by treatment) without adjusting for confounding variables.

Table 5.

Model 2

Health Outcome	Buffer	Risk Ratio	95% Confidence Interval	p-value
LBW	30	0.74	0.55 – 0.98	**0.038**
	60	0.95	0.83 – 1.09	0.473
	100	0.88	0.80 – 0.98	**0.018**
PTB	30	0.71	0.56 – 0.89	**0.003**
	60	0.92	0.81 – 1.03	0.156
	100	0.95	0.87 – 1.04	0.276

Note: This model is also a basic DD model except we have adjusted for the mother’s age, race, and educational attainment.

Table 6.

Model 3

Health Outcome	Buffer	Risk Ratio	95% Confidence Interval	p-value
LBW	30	0.74	0.55 – 0.98	**0.039**
	60	0.95	0.82 – 1.09	0.444
	100	0.89	0.80 – 0.98	**0.021**
PTB	30	0.71	0.56 – 0.89	**0.003**
	60	0.91	0.81 – 1.03	0.139
	100	0.95	0.87 – 1.04	0.272

Note: This basic DD model utilizes coarsened exact matched data while adjusting for the mother's age, race, and educational attainment.

Table 7.

Model 4

Health Outcome	Trimester	Spatial Buffer	Risk Ratio	95% Confidence Interval	p-value
LBW	1	30	1.02	0.61 – 1.70	0.947
		60	0.96	0.76 – 1.23	0.763
		100	0.98	0.82 – 1.17	0.833
	2	30	0.41	0.22 – 0.73	**0.003**
		60	0.78	0.61 – 1.00	0.052
		100	0.74	0.62 – 0.89	**0.001**
	3	30	0.79	0.38 – 1.62	0.525
		60	0.99	0.71 – 1.38	0.941
		100	0.78	0.61 – 1.00	0.054
PTB	1	30	1.09	0.74 – 1.62	0.678
		60	1.01	0.82 – 1.24	0.961
		100	0.93	0.80 – 1.08	0.327
	2	30	0.45	0.27 – 0.71	**0.001**
		60	0.8	0.65 – 0.99	**0.042**
		100	0.88	0.75 – 1.03	0.113
	3	30	0.44	0.23 – 0.81	**0.011**
		60	0.75	0.56 – 0.99	**0.044**
		100	0.94	0.76 – 1.16	0.561

Note: This basic DD model is broken down by trimester, and it utilizes coarsened exact matched data that is adjusted for the mother's age, race, and educational attainment.

Model 1 (Table 4) is a basic DD model (exposed*treatment) without adjusting for important covariates such as age, race, or educational status. We found a slight reduction in each outcome after exposure to Hurricane Isabel for LBW at 30 km (RR = 0.74, CI: 0.55 - 0.98) and 100 km (RR =0.88, CI: 0.80 – 0.98), Preterm birth was significant at 30-km (RR = 0.71, CI: 0.56 – 0.89). Model 2 (Table 5) adjusts for important covariates, including mother's age, race, and education status. Model 2's results are the same as the model before; LBW is significant at 30-km (RR = 0.74, CI: 0.55 – 0.98) and 100-km (RR = 0.88, CI: 0.80 – 0.98) and PTB is significant at 30-km (RR = 0.71, CI: 0.56 – 0.89). Model 3 (Table 6) is a DD using the coarsened exact matched data. The matching was completed using the same covariates that were adjusted for in Model 2. This model had the same significant results as the models before. LBW at the 30-km (RR = 0.74, CI: 0.55 – 0.98) and 100-km (RR = 0.89, CI: 0.80 – 0.98) buffers and PTB at the 30-km (RR = 0.71, CI: 0.56 – 0.89) buffer were all significant. Model 4 (Table 7) uses the same matched data, but it breaks down the basic DD by trimester of exposure. Our significant results are as follows: LBW during the 2nd trimester at the 30-km buffer (RR = 0.41, CI: 0.22 – 0.73), LBW during the 2nd trimester at the 100-km buffer (RR = 0.74, CI: 0.62 – 0.89), PTB during the 2nd trimester at 30-km buffer (RR = 0.45, CI: 0.27 – 0.71) and at the 60-km buffer (RR = 0.80, CI: 0.65 – 0.99), and finally, PTB during the 3rd trimester at the 30-km (RR = 0.44, CI: 0.23 – 0.81) and 60-km buffers (RR = 0.75, CI: 0.56 – 0.99).

Table 8.

FEMA Sensitivity Analysis

Health Outcome	Risk Ratio	95% Confidence Interval	p-value
LBW	1.03	0.97 – 1.11	0.338
PTB	1	0.94 – 1.06	0.98

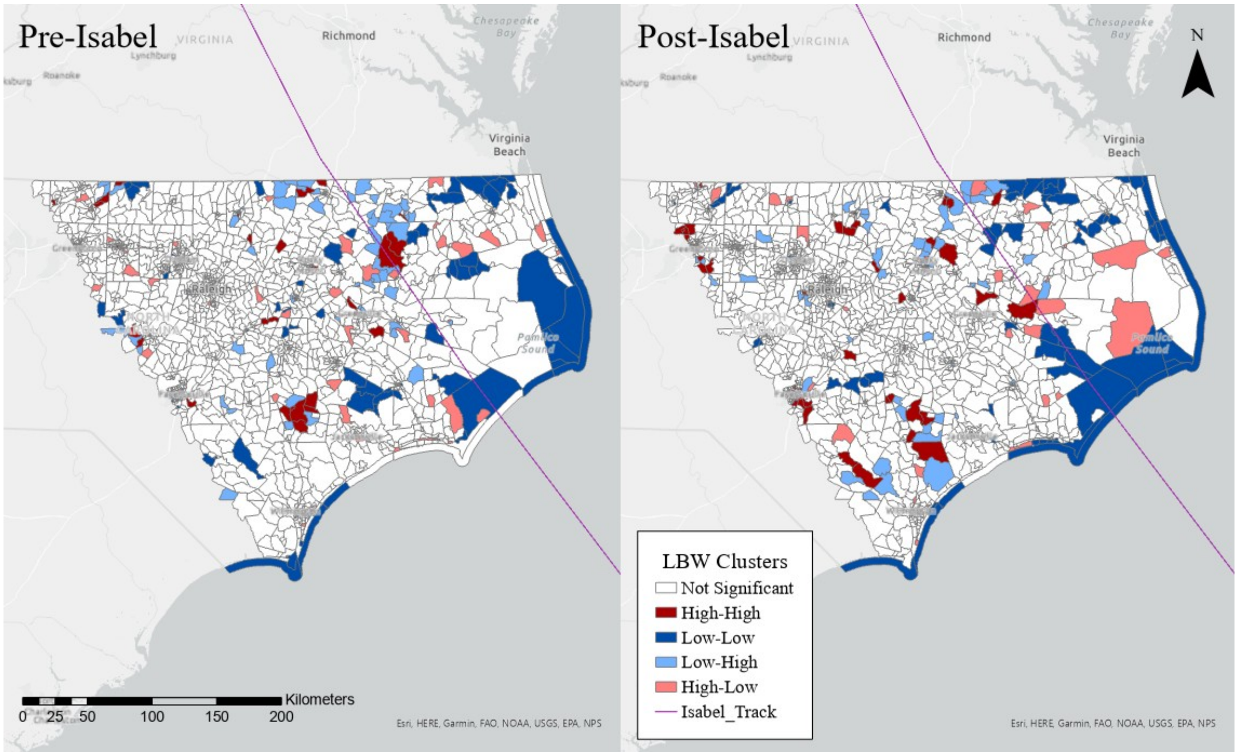
Note: This basic DD model utilizes FEMA Disaster Declarations as the "treatment."

The FEMA sensitivity analysis (Table 8) assigned counties with a declaration as the "exposed" group, and it compared their outcomes to counties without any declarations. There were no significant results.

4.3 Spatial Analysis

Figure 3.

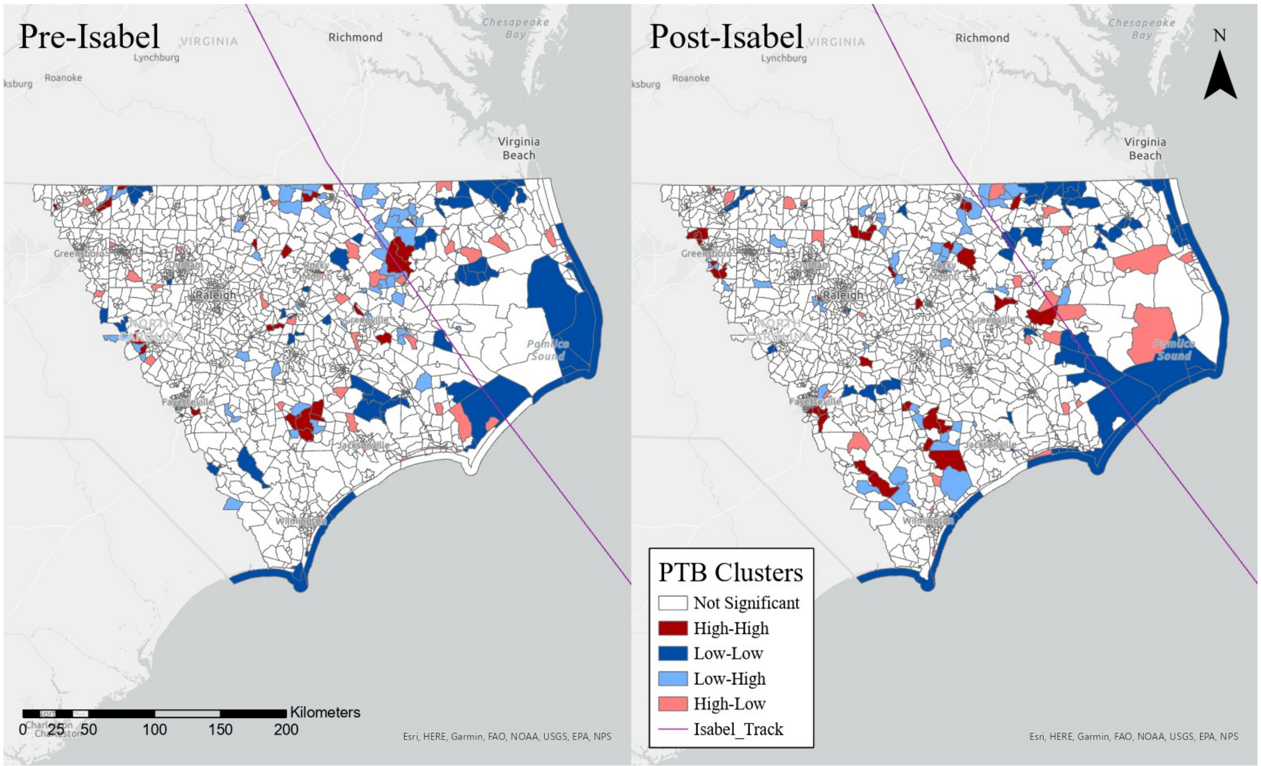
Map of LISA for LBW, Pre- and Post-Isabel.



Note: Pre-Isabel dates are births between 9/18/2002-6/18/2003, and post-Isabel births are between the dates of 9/18/2003-6/18/2003. High-High tracts have high values of LBW rates and are surrounded by other tracts with high rates. Low-Low tracts have low rates of LBW and are surrounded by other tracts with low rates. Low-High tracts have low rates of LBW but are surrounded by tracts with high rates. High-Low tracts have high rates of LBW but are surrounded by tracts with low rates.

Figure 4.

Map of LISA for PTB, Pre- and Post-Isabel.



Our univariate local Moran's I analysis is based on the number of birth outcomes per tract. We found significant changes in clustering before and after Hurricane Isabel made landfall for both LBW and PTB (Figures 3 and 4). High value tracts are red and pink, whereas low value tracts are dark blue and light blue. To interpret the map, High-High tracts are highlighted in dark red; they correspond to high counts of the birth outcome surrounded by other tracts with high counts of the birth outcome. Low-Low tracts (dark blue) are low value tracts surrounded by other low value tracts. Low-High tracts (light blue) are low value tracts surrounded by high value tracts, and High-Low tracts (pink) are high value tracts surrounded by low value tracts. Both of these, Low-High and High-Low, are indications of outliers.

For both outcomes, we see a development of Low-Low clusters along the track and to the right of the track in the Outer Banks of North Carolina. We also see a new High-Low tract in the Pamlico Sound, next to where there was a notable cluster of Low-Low tracts in the before Isabel period. There is also a new formation of high values of PTB births just East of Greenville along Isabel's Track. Before Isabel made landfall, there was a cluster of high values along the track (East of Rocky Mount), but we do not see this cluster after, instead we see a small patch of low values.

5. Discussion

We examined the effects of exposure to Hurricane Isabel (2003) in North Carolina on low birth weight and preterm birth. To do this, we implemented a difference-in-differences and geospatial cluster analyses on the population of live births from December of 2002 to June of 2004 throughout the state. Overall, we found that prenatal exposure to the hurricane was negatively associated with low birth weight (LBW) at the 30 and 100 km spatial buffers and preterm birth (PTB) at the 30km buffer.

Currently, there is no consensus on how exposure to hurricanes impacts neonatal outcomes (Jeffers & Glass, 2020; Harville et al., 2010b; Waddell et al., 2021; Zotti et al., 2013;). There are multiple reasons for this, as most studies have a variety of exposure definitions (e.g., FEMA Disaster Declarations for county-level exposure, spatial buffers), limited study populations (e.g., small sample sizes), and varied methods (e.g., difference-in-difference models, Breslow-Day statistics, binary logistic regression models). Most studies say there is an increase in adverse neonatal outcomes post-storm (Antipova & Curtis, 2015; Chen et al., 2012; Grabich et al., 2016a; Hamilton et al, 2009; Harville et al., 2010a; Harville et al., 2015; Harville et al., 2022; Parayiwa & Behie, 2018; Xiao et al., 2019; 2010; Xiong et al., 2008), but some have insignificant results after analyzing how hurricanes impact birth outcomes (Antipova & Curtis, 2015; Currie & Rossin-Slater, 2013; Grabich et al., 2017; Harville et al., 2015; Parayiwa & Behie, 2018), and a select few studies find decreases in adverse birth outcomes (Grabich et al., 2016b; Hamilton et al., 2009).

Our results build upon a small subset of the literature that finds negative and null associations between hurricane exposure and birth outcomes. Our study finds similar reductions in adverse birth outcomes like Grabich et al. (2016b) and Hamilton et al. (2009). For instance, Gabrich et al. applied three different methods to assess hurricane exposure: using the spatial data with buffers, like we employed, FEMA Disaster Declarations, and a novel meteorological measure based on the Saffir-Simpson hurricane intensity scale. They implemented linear models and found the association between hurricane exposure and the county's preterm birth rate were negative for each of three of the four hurricanes they analyzed. Hamilton et al. analyzed how Hurricane Katrina impacted Alabama, Mississippi, and Louisiana found large decreases in very preterm birth and very low birthweight rates in the selected parishes of Louisiana, but they found a large increase in very preterm births in the selected counties of Alabama (Hamilton et al., 2009), highlighting that hurricane exposure may influence maternal populations differently.

Our results align with other studies that have found no association between the exposure to disasters and poor birth outcomes (Antipova and Curtis, 2015; Currie & Rossin-Slater, 2013; Grabich et al., 2017; Hetherington et al., 2021; Parayiwa & Behie, 2018). Furthermore, our study design is similar to those of Hetherington et al. (2021) and Grabich et al. (2017) as they also used DD, a causal analytic framework, as their study design and found null results. Hetherington et al. found no increased risk for small for gestational age (SGA) or preterm birth from a large-scale flood event in Calgary, Canada (Hetherington et al., 2021). Grabich et al. (2017) found no association between exposure to hurricane weather and reproductive health outcomes, including low birth weight.

While our study contrast with other studies that have found an increased risk of adverse birth outcomes after exposure to a hurricane (Antipova and Curtis, 2015; Chen et al., 2012, Harville et al., 2010a; Harville et al., 2015; Parayiwa & Behie, 2018; Sun et al., 2020). Sun et al. (2020) also employed the same spatial buffers we have used and found maternal exposure to a tropical cyclone was associated with higher risk of preterm birth in 378 counties across the United States from 1989 to 2002 found a significant association between maternal exposure to tropical cyclones and preterm birth. Our work was restricted to a single event, Hurricane Isabel, for a limited geographic population, highlighting that associations may change based on the population exposed, analytical strategies employed, and the exposure itself. Most of the current literature focuses on Gulf states (e.g. Texas, Louisiana, Alabama, and Florida).

We sought to identify where spatial clusters of LBW and PTB occurred both before and after Hurricane Isabel made in North Carolina. We aimed to learn more about the geography of clusters, and we found the post-Isabel LBW and PTB clusters have the same distribution. This is because there is an estimated 67% overlap between preterm birth and low birth weight newborns, and this select subset is at the highest risk for adverse neonatal outcomes (Katz et al., 2013; Lee et al., 2013). Our analysis provides evidence that there were spatial differences pre- and post- Isabel for rates of LBW and PTB with most of the changes being to the right of the tract. Due to the way hurricanes form, areas on the right of the track experiences more negative impacts because of the higher wind speeds (Slagel, n.d.). This could be in part to the relatively low rates of births in this region of North Carolina, as most of this region is covered by water (Pamlico Sound).

5.1 Strengths and Limitations

Important strengths of our study include the use of the DD causal study design, a prospective birth cohort, an analysis of a finer resolution scale (i.e. the use of Census tracts).There are multiple advantages to using a prospective birth cohort, such as it allows for the study of exposures when randomization is not practical and for the study of multiple outcomes (De Rango, 2016; Levin, 2006). All DD analyses rely on the assumption of common or parallel trends, and this assumption can be difficult to test for and prove (Wing et al., 2018). During our study, there were no major changes in the independent variables of our sample between the control and the treatment, which suggests that the unmeasured confounder was likely consistent as well (Hetherington et al., 2021).

Exposure to a disaster is difficult to quantify, and we chose to define exposure as births born within 30, 60, or 100km of the storm track after Hurricane Isabel made landfall. This was based on the mother's residence at the time of birth, but if the mother was not living at that residence during the hurricane exposure, it could introduce errors into our analysis. We also did not control for the mother's health or if the mother had access to prenatal care, and these could both be influenced by exposure to the disaster (Bui et al., 2022). Furthermore, Hurricane Isabel was a relatively minor disaster when it made landfall in North Carolina; this could be why we see no evidence of adverse effects on neonatal health.

Future research should explore how distance from natural disasters impacts neonatal outcomes. We suggest analyzing multiple storms and using a variety of exposure metrics (e.g., wind speed, precipitation, flooding). We made a priori assumptions regarding the spatial buffers, but further research should use the exact distance from the track (Bui et al., 2022). This would take into account whether one side of the track is affected more severely than the other, as the right side tends to be the most dangerous in terms of tornadoes, winds, and storm surge.

6. Conclusions

To our knowledge, this is the first study based on North Carolina evaluating associations between hurricane exposure and neonatal outcomes. We also believe this is the first study to use higher resolution census tracts as its scale for exposure; other studies like Grabich et al. used county level exposure to quantify the impacts Hurricane Ivan had on birth outcomes (Grabich et al., 2015). We also believe this to be the first study to analyze a non-major hurricane, as many studies have focused on the impacts of Hurricane Katrina. While we used a prospective birth cohort and used spatial buffers as our exposure metric, our results found a negative association between proximity to storm impact and PTB and LBW. While our study found mixed results on the impact of hurricane exposure on birth outcomes, we believe our results have contributed to the literature through the study of a non-major hurricane, analysis of spatial patterns, and using a new study location. Since we found significant differences in clustering before and after the storm, more research is needed to understand the nature of this relationship. Further studies on the impact of more severe tropical storms and adverse neonatal outcomes are needed to protect mom and baby in the face of more frequent and intense hurricanes in a changing climate.

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Vita

Taylin Spurlock was raised in the small town of Folkston, Georgia before moving to Murfreesboro, Tennessee at the start of her freshman year of high school. She attended Blackman High School, and through the Blackman Collegiate Academy program, she was able to explore career and research options while completing her senior capstone. When she graduated in 2017, she moved to Knoxville, Tennessee to attend the University of Tennessee.

During her time at UT, she studied abroad with Semester at Sea, and halfway through her program, she emailed her advisor from the ship to tell her she was changing her major again to be a geography student. This was the best decision she ever made because she was able to complete undergraduate research on a variety of topics, which inspired her to attend graduate school. After graduating in May of 2021 with a Bachelor of Arts in Geography, Taylin moved to Boone, North Carolina to attend Appalachian State University. She chose App to pursue research with Dr. Maggie Sugg, and throughout her time in the program, she has been able to work on several projects regarding public health and climate. Taylin will graduate with a Master of Arts in Geography in May of 2023. She has already accepted a job with the National Park Service to be an Interpretive Park Ranger, and she will begin shortly after graduation.