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Examining hurricane exposure on neonatal outcomes in North Carolina: A case study of hurricane Isabel in 2003

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A B S T R A C T

Exposure to tropical cyclones during pregnancy can adversely influence neonatal and birth outcomes, contributing to low birth weight and preterm birth. These outcomes could be impacted by the disruption of healthcare and infrastructure, as well as stress and injury. Although research has focused on the impacts on neonatal health from extreme tropical events, little is known about the neonatal health impacts of moderate-intensity hurricanes or hurricanes that reduce intensity before landfall. The aim of this study is to 1) assess the 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) identify differences in spatial patterns for the adverse birth outcomes LBW and PTB pre- and post-Hurricane Isabel, a Category 2 storm that impacted North Carolina in 2003. The geospatial analysis included multiple buffers of 30, 60, and 100 km to define exposure and local spatial autocorrelation statistics. The results were predominantly insignificant, with some key exceptions. The difference-in-difference analysis found a statistically negative association between hurricane exposure and preterm birth, suggesting an unexpected reduction in preterm births post-storm. We found that exposure to Hurricane Isabel (2003) and LWB were statistically significant at the 30 and 100-km spatial buffers; exposure was also associated with a decrease in PTB at the 30 km buffer. We also examined differences in potential impacts by trimester and found a significant negative association during the second and third trimesters. Significant differences in the clustering of LBW and PTB before and after Isabel made landfall were also found, with new clusters of higher PTB and LBW forming along the storm track. Results from our study highlight the need for further analysis of neonatal and birth outcomes across different hurricane types and the need for spatial analysis to understand fine-scale heterogeneity in hurricane risk.

1. Introduction

Research shows that hurricanes, which are also known as tropical cyclones or typhoons, impact pregnant women and newborns disproportionately through loss of housing, disrupted or lost prenatal and general healthcare, and impacted nutrition [1,2]. Common themes of maternal stress during hurricane exposure include concerns about infant feeding, evacuation logistics, family roles, and general stress surrounding the hurricane [3]. 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 [4–8].

Understanding the association between hurricanes and maternal/neonatal outcomes has become more of a priority as climate change models are projecting more frequent and severe hurricanes [9]. 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. For instance, positive associations between exposure to hurricanes and preterm birth have been found in multiple studies ([10,11]; Grabich et al.,

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2016a; [12–14]). However, limited studies focused on specific storms, like Hurricane Katrina, have found significant associations between hurricane exposure and low birth weight [11,15,16]. Additionally, Mendez-Figueroa [17], Harville et al. (2010a), and Hamilton et al. [18] found no associations between hurricane exposure and preterm birth, but results suggest that forced migration may be impacting null findings. Mixed results are also found with low birth weight, with numerous studies also finding no association between hurricane exposure for pregnant persons residing in the affected areas [10,13,18,19].

In addition, the overall association between hurricane exposure and neonatal outcomes is not well characterized, primarily due to varying methods, limited samples, and discrepancies in exposure definitions [20]. The aim of this study is to determine if an association exists between exposure to a moderate hurricane and the neonatal outcomes of low birth weight (LBW) and preterm birth (PTB). More specifically, this study will address the following research questions: does prenatal exposure to a moderate tropical cyclone negatively impact neonatal outcomes (e.g., low birth weight and preterm birth), and how does this effect vary spatially? Results from this study will enhance the literature on hurricane exposure and neonatal outcomes by analyzing a less intense hurricane, incorporating spatial analysis findings, and using a finer spatial resolution than previous studies.

2. Materials and methods

2.1. Data sources

We used administrative hospital delivery and infant records for all North Carolina births from the University of Notre Dame's Children's Environmental Health Initiative (CEHI) [21]. 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 age, and any congenital anomalies (such as gastrointestinal anomalies, musculoskeletal anomalies, or congenital heart disease). Maternal characteristics include 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. Inclusion criteria to be considered in the study

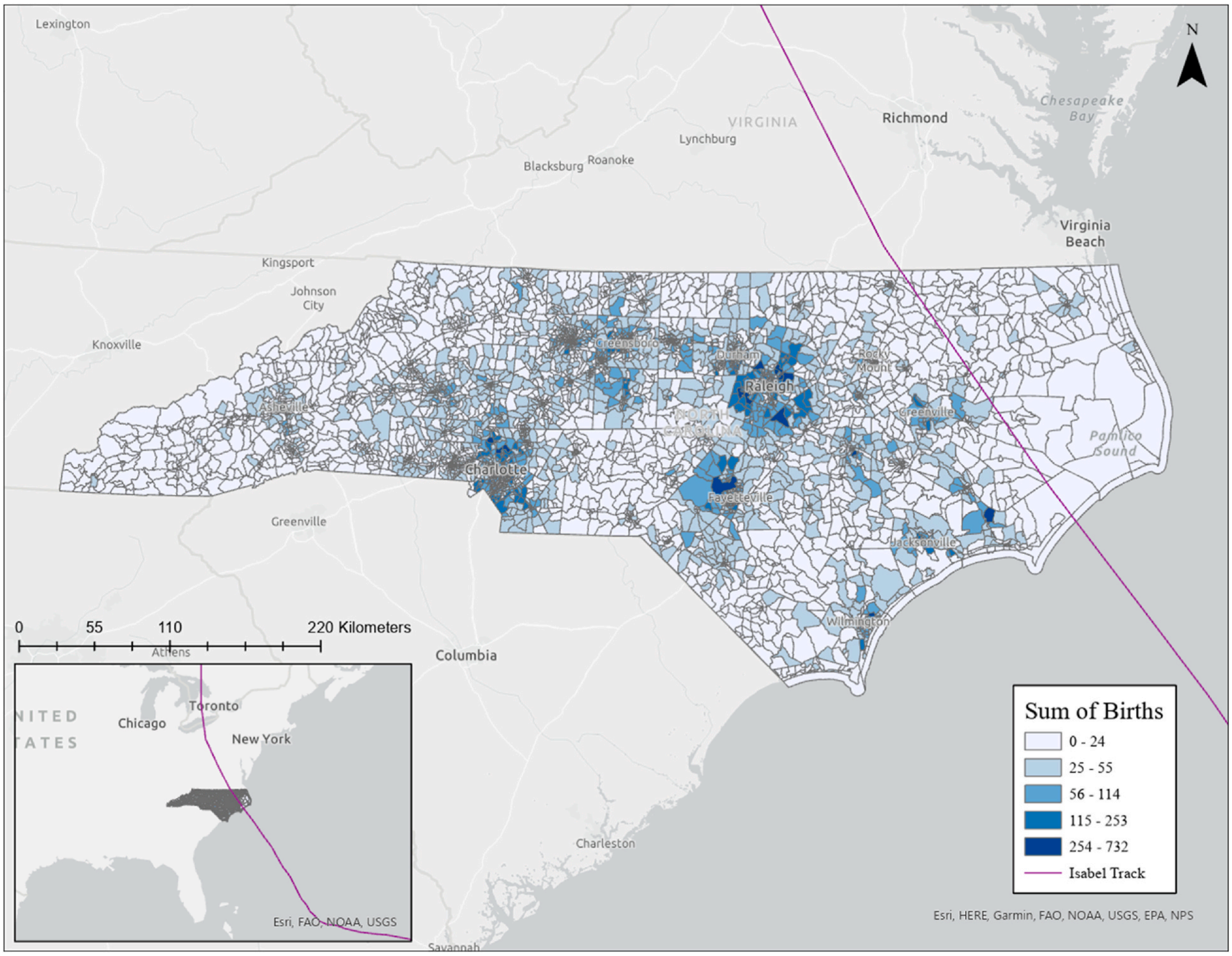

Fig. 1. Map of study area.

are mothers between the ages of 20 and 39, and their births had to be at least 20 weeks gestation. This analysis excluded teen mothers and mothers over the age of 40, as they are more likely to have complications [22,23].

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 outcomes in prior studies [20,24–26]. Within our dataset, these outcomes were pre-defined as variables by CEHI. LBW has been defined as any newborn born under 2500 g (5.5 pounds) [27–29]. Any live birth before 37 completed weeks of gestation is defined as a PTB [27–29].

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 (Fig. 1), bringing small storm tides of half a foot to one foot above normal [30]. Prior to landfall, Hurricane Isabel reached peak intensity as a Category 5 through September 14th but weakened to a Category 2 storm by September 16, 2003.

2.3.2. Hurricane exposure measurement

Hurricane exposure was assessed using spatial data on the specific storm trajectory [31,32]. 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 [33]. The track data is in the form of latitude (X) and longitude (Y) coordinates, which were imported into ArcGIS Pro [34]. We used a range of buffer distances (30, 60, and 100 km) to define spatial exposure ([35]; Currie & Rossin-Slater, 2013; [32]). A non-exposure birth is defined as any birth that occurred outside of these buffers.

Maternal exposure to Hurricane Isabel was derived from the mother's residential address at the time of birth, geocoded to a point location, and whether that location falls within 30, 60, or 100 km from the storm track. We consider the occurrence and path of Hurricane Isabel as the "treatment" event. The "pre-treatment" 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 deliveries after 09/18/2003 until 06/18/2004. We define the "treated" group (i.e., pregnant persons exposed to the hurricane) using alternative distance buffers; more specifically, mothers whose residential address at the time of their child's birth falls within 100, 60, or 30 km of Hurricane Isabel's storm track [32]. Each buffer was analyzed separately in the difference-in-difference analysis models. The "control" group was defined as mothers outside the spatial buffers (i.e., pregnant persons living outside the specified distance buffer). In a subsequent model, we split the maternal exposure measure into trimesters (i.e., trimester 1, trimester 2, and trimester 3) and estimate any differences in adverse birth outcomes based on the timing of storm exposure during pregnancy.

As an alternative to our 30, 60, and 100-km treatment bins, we also conducted a sensitivity analysis where "treatment" was defined using FEMA Disaster declarations, a standard methodology to measure hurricane exposure [13,14,18,36]. This sensitivity analysis allowed us to compare births in counties receiving hurricane-related FEMA declarations (i.e., Individual and Household programs, Individual Assistance programs, Public Assistance programs, or Hazard Mitigation programs) to those in counties that did not.

2.4. Analysis

2.4.1. Statistical Analysis

We used a difference in difference (DiD) for our analytical approach, a quasi-experimental design that facilitates causal inference. 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). DiD is a quasi-experimental design that leverages hurricane events as a natural experiment. The time variable corresponds to the date of landfall, separating the births that took place before and after. The treatment variables are the spatial buffers (i.e., the 30, 60, and 100-km buffers outlined above). We conduct four DiD models to incorporate different covariates and effects. The first DiD model included no covariates. The second model adjusted for several confounders, such as the mother's age, education, and race. Since the primary outcomes—preterm birth (PTB) and low birth weight (LBW)—are binary variables, we used logistic regression to estimate the odds of these outcomes based on hurricane exposure. In each DiD model, logistic regression was applied to model the likelihood of PTB and LBW as a function of proximity to the hurricane's impact and the relevant covariates. The logistic regression models provided odds ratios that indicate how the likelihood of adverse outcomes changes depending on the distance from the storm's landfall. We applied a propensity score matching technique for the third model using coarsened exact matching (CEM). Coarsened exact matching is a design strategy that produces a good covariate balance between the control and treatment groups, and this is meant to provide a cleaner quasi-experimental comparison and reduce the influence of otherwise confounding factors [37]. After matching the groups, logistic regression was applied to estimate the effects of hurricane exposure on PTB and LBW within the matched samples, providing more reliable estimates by controlling for confounding variables. Finally, the fourth model focused on trimester-specific outcomes, breaking down the spatial buffers by trimester to assess whether exposure at different stages of pregnancy has varying effects on neonatal health. For each trimester, we applied logistic regression to model the odds of PTB and LBW based on the proximity to the hurricane's landfall.

2.4.2. 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 [38]. Geocoded births were summed up at the census tract level and then normalized by the total number of births per tract during the pre- and post-Isabel time periods.

Local autocorrelation analysis was used to identify significant spatial clusters of observations and spatial outliers (where the value does not match its neighbors) using a Queen's spatial weights matrix [39]. The Local Moran's I was calculated as an indicator for spatial associations [38]. 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

Table 1
Demographics of study sample.

	level	Pre-Isabel	Post-Isabel	p-value
n		31,433	31,545	
Mother's Age Group (%)				0.186
	20–24	9515 (30.3)	9347 (29.6)	
	25–29	9576 (30.5)	9760 (30.9)	
	30–34	8614 (27.4)	8595 (27.2)	
	35–40	3728 (11.9)	3843 (12.2)	
Mother's Race Group (%)				0.145
	Non-Hispanic White	18498 (58.9)	18605 (59.0)	
	Non-Hispanic Black	7877 (25.1)	7687 (24.4)	
	Hispanic	3854 (12.3)	4005 (12.7)	
	Non-Hispanic Asian/Pacific Islander	978 (3.1)	1033 (3.3)	
	Non-Hispanic Other	188 (0.6)	193 (0.6)	
Mother's Education Group (%)				0.2
	Some Middle School	1713 (5.5)	1688 (5.4)	
	Some High School	3082 (9.8)	3153 (10.0)	
	High School or Equivalent	8558 (27.3)	8390 (26.7)	
	Some College or Associate's Degree	7435 (23.7)	7665 (24.3)	
	Bachelor's Degree or Higher	10587 (33.7)	10585 (33.6)	
No Prenatal Care (%)	No	31219 (99.3)	31359 (99.4)	0.16
	Yes	214 (0.7)	186 (0.6)	
Adequate Prenatal Care Index (%)				<0.001
	Inadequate	2577 (8.3)	2537 (8.1)	
	Intermediate	2696 (8.7)	2777 (8.9)	
	Adequate	12252 (39.5)	11840 (38.0)	
	Adequate Plus	13495 (43.5)	14018 (45.0)	
Number of Prenatal Visits (mean (SD))		12.70 (4.06)	12.67 (4.14)	0.28
	No	22637 (72)	22446 (71.2)	0.017
Not Married (%)				
	Yes	8796 (28.0)	9099 (28.8)	
Used Alcohol (%)	No	31223 (99.3)	31365 (99.4)	0.132
	Yes	210 (0.7)	180 (0.6)	
Smoked During (%)	No	28333 (90.1)	28364 (89.9)	0.352
	Yes	3100 (9.9)	3181 (10.1)	
Gestational Age in Weeks (mean (SD))		38.51 (2.37)	38.43 (2.43)	<0.001
	No	28744 (91.4)	28758 (91.2)	0.215
Low Birth Weight (%)				
	Yes	2689 (8.6)	2787 (8.8)	
Preterm Birth (%)	No	27915 (88.8)	27822 (88.2)	0.017
	Yes	3518 (11.2)	3723 (11.8)	
No Congenital Anomalies (%)	No	1571 (5)	1773 (5.6)	
	Yes	29862 (95.0)	29772 (94.4)	0.001
	No	30556 (97.2)	30652 (97.2)	
Within the 30 km Buffer (%)				
	Yes	877 (2.8)	893 (2.8)	0.775
	No	27585 (87.8)	27564 (87.4)	
Within the 60 km Buffer (%)				
	Yes	3848 (12.2)	3981 (12.6)	0.154
	No	23244 (73.9)	23284 (73.8)	
Within the 100 km Buffer (%)				
	Yes	8189 (26.1)	8261 (26.2)	0.705
	No	30535 (97.1)	30599 (97)	
Right of Track (%)				
	Yes	898 (2.9)	946 (3.0)	0.301

Note: The table can be interpreted as the count of the sample and then the percentage of the population (n,%), except where noted as the mean and standard deviation. The p-value corresponds to the chi-squared test. Women under 20 and over 40 were excluded from the cohort. Rates per 1000 were 15.3 (under 20) and 11.7 (over 40) per 1000 women, which were significantly lower than the rates of age groups within the inclusion criteria for 82.5 (20–29) and 74.5 (30–39).

outcome's rate and how that fits in compared to their neighbors. If a tract has a relatively high cluster rate and is surrounded by other high cluster rates (e.g., a tract with a high rate of LBW or PTB is surrounded by other tracts with high rates of LBW or PTB), then the cluster will be High-High. Low-low tracts have low rates of birth outcome, surrounded by other tracts that also have low rates. Low-High tracts are tracts with low rates surrounded by tracts with high rates, and High-Low tracts have high rates of birth outcomes and are surrounded by tracts with low rates. The last two combinations, Low-High and High-Low, indicate spatial outliers.

3. Results

3.1. Sample characteristics

According to the data, there were 175,870 live births in NC between our study dates. After excluding births to mothers outside of the ages 20 to 39 and any deliveries less than 20 weeks gestation, we have 149,493 births in our study. The pre-and post-Isabel groups are fairly similar (Table 1). The percentage of low birth weight births for the control group was 8.4 % (n = 6209), and the treatment group's percentage was 8.7 % (n = 6608). Preterm birth percentages were also similar between the control and treatment groups, 10.9 % (n = 8039) and 11.4 % (n = 8646), 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.

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

3.2. DiD model

In all three models, exposure to Hurricane Isabel during pregnancy was associated with a slight improvement in LBW at the 30-km and 100-km buffers, and PTB was significant at the 30-km buffer. Results for the DiD models are summarized in Tables 3–6.

Model 1 (Table 3) is a basic DiD model (exposed*treatment) without adjusting for potentially important covariates such as the mother's age, race, or educational status. We found a slight reduction in each adverse birth 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), PTB was significant at 30-km (RR = 0.71, CI: 0.56–0.89). Model 2 (Table 4) adjusts for important covariates, including the mother's age, race, and education. The results from Model 2 are similar to the previous model; 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 5) is a DiD 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 previous models. 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 6) uses the same matched data, but it breaks down the basic DiD 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).

To further assess our exposure metrics for hurricane damage, we conducted a secondary sensitivity analysis of outcomes for FEMA declarations as our exposure variable (Table 7). Therefore, we assigned observations to the treated group based on counties that received a FEMA disaster declaration rather than based on distance to the storm track. In other words, hurricane exposure is now defined as living in a county that received a FEMA declaration while the mother was pregnant. There were no significant results.

Lastly, we also examined different temporal periods before the storm to test the assumption of equal trends using a placebo test. For this test, we performed an additional difference-in-difference estimation using a "placebo" treatment group (i.e., not exposed to the storm). This difference-in-difference estimation used a hypothetical landfall date of 09/18/2002. Across an entire pregnancy, the

Table 2
Sample size of Birth Outcomes per Buffer Distance for Pre- and Post- Isabel; Low Birth Weight (LBW); Preterm Birth (PTB).

Health Outcome	Buffer (m)	Pre-Isabel[b] (%)	Post-Isabel[b] (%)	*p*-value[a]
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

[a] The *p*-value responds to the Chi-Square test.

[b] 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.

Table 3
Model 1 unadjusted difference-in-difference for low birth weight (LBW) and preterm birth (PTB).

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 (DiD) model (time multiplied by treatment) without adjusting for confounding variables.

Table 4
Model 2: Adjusted Difference-in-Difference for Low Birth Weight (LBW) And
280 Preterm Birth (PTB). The model is adjusted by the mother's race, age, and education.

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 DiD model, except we have adjusted for the mother's age, race, and educational attainment.

Table 5
Model 3: Difference-in-Difference using coarsened exact, matched data for data matched on the mother's age, race, and educational attainment.

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 DiD model utilizes coarsened exact matched data while adjusting for the mother's age, race, and educational attainment.

Table 6
Model 4: Difference-in-Difference using coarsened exact, matched data for data matched on the mother's age, race, and educational attainment across the different trimesters of pregnancy.

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 DiD 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.

Table 7
FEMA sensitivity analysis unadjusted difference-in-difference for low Birth 302 weight (LBW) and preterm birth (PTB).

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 DiD model utilizes FEMA Disaster Declarations as the "treatment."

difference-in-difference estimator was insignificant ($p > 0.20$) for both LBW (RR: 1.07, CI: 0.96–1.28) and PTB (RR: 0.99, CI: 0.91–1.08). We also performed a separate test for trimester-specific difference-in-difference estimators (Table 8), and the results were predominately insignificant, with the exception of LBW in the second trimester (RR: 1.19, CI: 1.00–1.42).

3.3. Spatial analysis

Our univariate local Moran's I analysis is based on the rate of birth outcomes per tract. We found significant changes in clustering before and after Hurricane Isabel made landfall for both LBW and PTB (Figs. 2 and 3). High-value tracts (i.e., tracts with a relatively high rate of LBW or PTB) 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 and are 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 local 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 a notable cluster of low-low tracts from before the Isabel period. After landfall, there is also a new formation of high PTB birth values 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. Consistent with the DiD results, spatial trends highlight a reduction in LBW and PTB; however, this decline is spatially heterogeneous and not uniform along the hurricane track.

4. Discussion

We examined the effects of exposure to Hurricane Isabel in 2003 on low birth weight and preterm births in North Carolina. Our results contribute to a growing understanding of the impacts of hurricanes on maternal and neonatal outcomes; unlike other studies, our work focuses on a less intense hurricane, a category two at landfall, and includes spatial analysis of birth outcomes pre and post-storm. We implemented difference-in-differences and geospatial cluster analyses on the population of live births from December 2002 to June 2004 throughout the state. Overall, we found little evidence that prenatal exposure to the hurricane adversely impacted low birth weight (LBW) and preterm births (PTB). The results were generally statistically insignificant, and in the cases where we did identify significant impacts, the results suggested a negative association with LBW and PTB, particularly in the second and third trimesters.

Hurricanes may affect maternal health outcomes through a variety of mechanisms, including disruptions to healthcare access, increased psychological stress, and environmental factors such as poor air quality or exposure to infectious agents [20,40–42]. Currently, there are mixed results on how exposure to hurricanes impacts neonatal outcomes [20,25,26,43,26]. There are multiple reasons for these differences, 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). The majority of studies note there is an increase in adverse neonatal outcomes post-storm [10,11,13–16,18,44,45]. Nonetheless, some research finds insignificant results between hurricane impact and birth outcomes [10,13,19,44,46] and a limited sample notes a decrease in adverse birth outcomes [18,36], as observed in

Table 8
The difference in Difference Estimators for Hypothetical Treatment Time period to assess the assumption of Parallel Trends.

Landfall: 09/18/2002 (Control = 2001)			
	LBW		
	RR	*CI*	*p*
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		
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

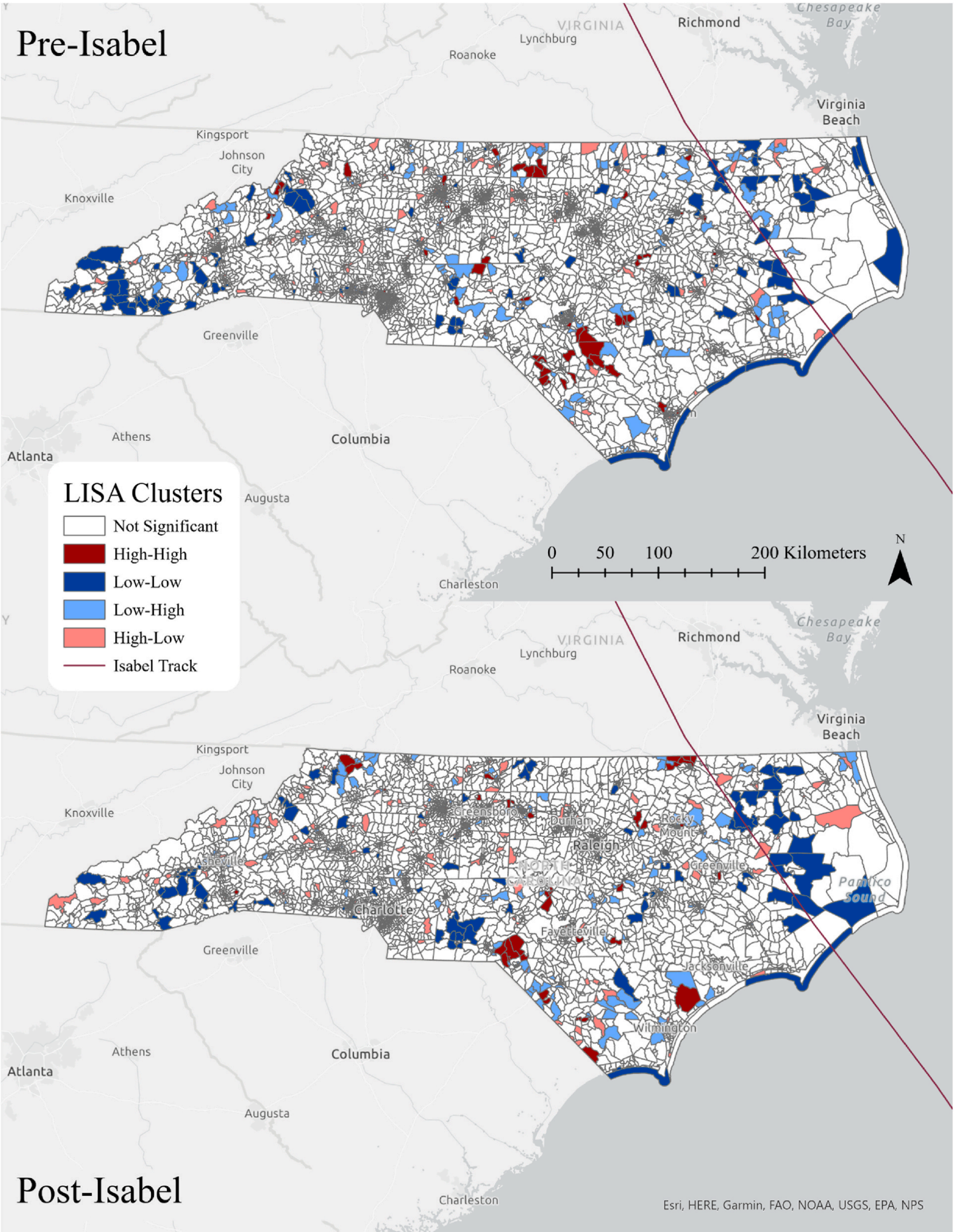

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Fig. 2. Map of LISA for LBW, pre- and post-Isabel.
Note: Pre-Isabel dates are births between 9/18/2002-6/18/2003, and post-Isabel births are between 9/18/2003-6/18/2003. High-High tracts have high values of LBW rates and are surrounded by other tracts 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.

this study.

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 to Grabich et al. (2016b) and Hamilton et al. [18]. 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 three of the four hurricanes they analyzed. Hamilton et al. analyzed how Hurricane Katrina impacted Alabama, Mississippi, and Louisiana and found large decreases in very preterm birth and very low birth weight rates in the selected parishes of Louisiana. Still, they found a large increase in very preterm births in the selected counties of Alabama [18], highlighting that hurricane exposure may influence maternal populations differently. Our work provides a new, unique perspective as we examine the impact of a hurricane relative to a mother's residential location for the DiD estimators and a sub-county scale for our spatial analysis (e.g., census tract), also finding both null and negative associations depending on the method and location examined. In addition, unlike Gabrich et al. and Hamilton et al., our case study of Hurricane Isabel was a lower-impact storm that produced moderate to heavy damage, totaling $450 million (2003 USD, $562 million in 2013 USD) (NWS, n.d.). More work is needed for major hurricanes that produce lower impact damage totals than catastrophic storms like Katrina and the multiple hurricanes of 2004.

In general, our DiD results align with other studies that have found no association between exposure to disasters and poor birth outcomes [10,13,19,46,47]. Furthermore, our study design is similar to those of Hetherington et al. [47] and Grabich et al. [19], as they also used DiD, a causal analytic framework, as their study design and found null results. Hetherington et al. [47] found no increased risk for small gestational age (SGA) or preterm birth from a large-scale flood event in Calgary, Canada. Grabich et al. [19] found no association between exposure to hurricane weather and reproductive health outcomes, including low birth weight.

At the same time, our study contrasts with the majority of studies that have found an increased risk of adverse birth outcomes after exposure to a hurricane [10,11,13,15,44,48]. Sun et al. [48] employed the same spatial buffers we have used and found maternal exposure to a tropical cyclone was associated with a higher risk of preterm birth in 378 counties across the United States from 1989 to 2002. Otherwise, most current literature focuses on Gulf states (e.g., Texas, Louisiana, Alabama, and Florida), and our work highlights the need for studies in other hurricane-prone locations like North Carolina, which experiences significant tropical cyclone landfalls (NWS 2005) but remains primarily underrepresented in the literature.

Unlike previous DiD analysis, we paired our DiD results with spatial analysis examining the clustering of LBW and PTM before and after Hurricane Isabel. In general we found that the post-Isabel LBW and PTB clusters have a similar distribution. The co-occurrence of geographic clusters at the community level makes sense as there is an estimated 67 % overlap between individual preterm birth and low birth weight newborns [49,50]. In addition, although we noted insignificant and negative associations in PTB and LBW after Isabel, our spatial analysis did detect select regions with higher incidence, highlighting that some populations may still be at higher risk for adverse outcomes post-hurricane, and further analysis is needed. Our results highlight the importance of geospatial analysis alongside more traditional causal methods like DiD to provide a more comprehensive understanding of how disasters like hurricanes can impact maternal and neonatal health outcomes. While causal methods like Difference-in-Differences (DiD) are essential for estimating average treatment effects, our findings highlight the added value of spatial analysis in uncovering localized risk and clustering. Spatial analysis offers a more nuanced picture by identifying regions or communities that may be disproportionately affected, even when overall associations appear insignificant. This approach helps to pinpoint areas of heightened vulnerability and potential disparities that might be overlooked with traditional causal methods alone. By integrating these techniques, we can better inform targeted interventions, resource allocation, and future research aimed at mitigating localized health risks in disaster-prone areas.

From a public health perspective, our findings underscore the importance of integrating geospatial methods into disaster health research and response planning. Spatial analysis can help public health practitioners identify "hot spots" of risk often obscured in aggregate-level analyses like DiD. This knowledge is vital for targeting interventions, such as allocating resources to vulnerable communities, improving disaster preparedness, and strengthening healthcare systems in areas prone to hurricanes. Furthermore, the null or negative associations identified in our DiD analysis suggest that resilience factors—such as access to healthcare and emergency preparedness measures—might mitigate some adverse outcomes. Future research should comprehensively explore these protective factors to inform policy and program development. Continued research in diverse geographic regions across different hurricane intensities and using causal and geospatial methods will be critical for designing equitable and effective public health responses for maternal health during natural disasters like Hurricane Isabel.

4.1. Strengths and limitations

Important strengths of our study include the use of the DiD study design and the use of a finer resolution scale (i.e., the use of census tracts in spatial analysis and the mother's geocoded residence in other analyses). While DiD provides a robust research design for

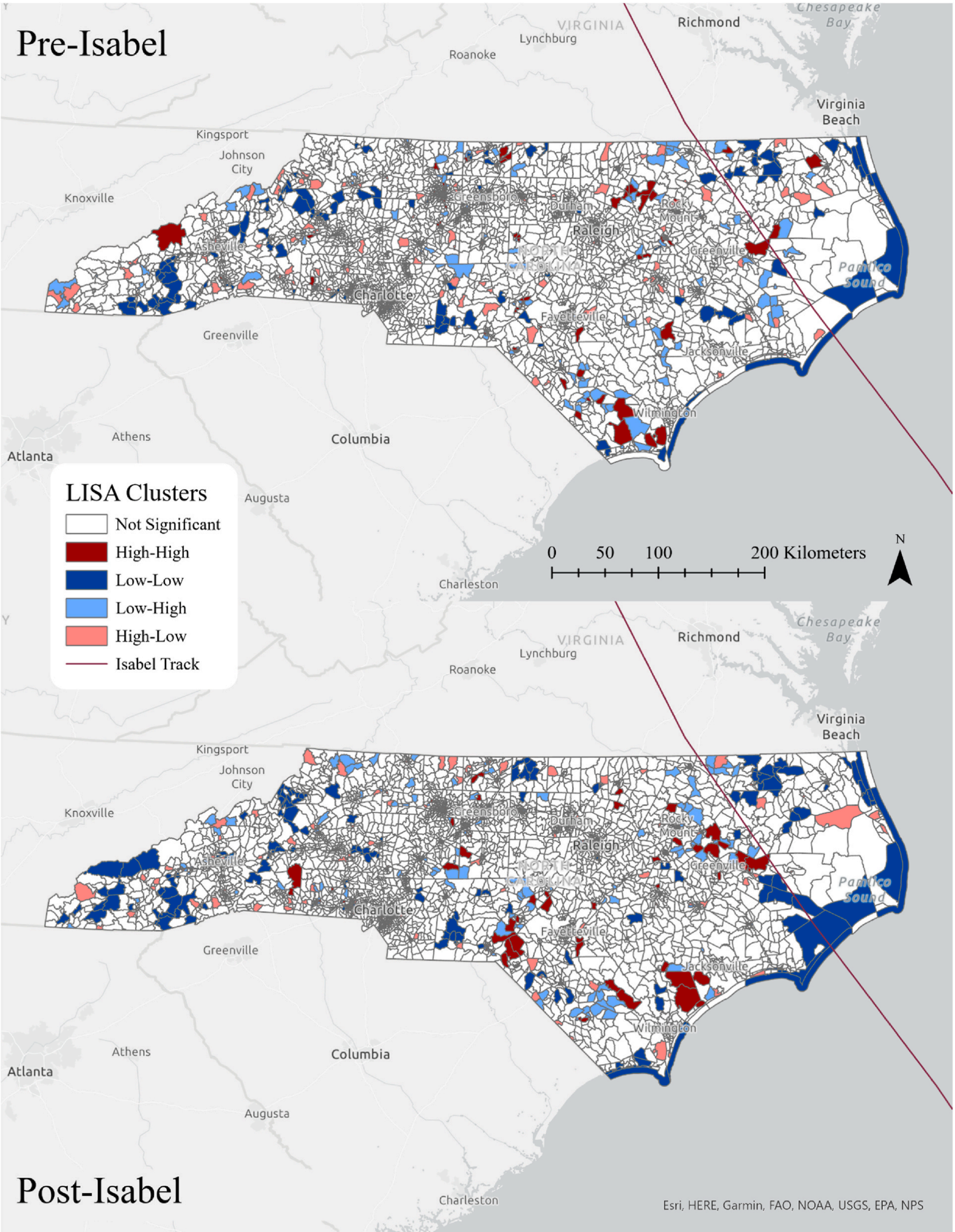

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Fig. 3. Map of LISA for PTB, pre- and post-Isabel.
Note: Pre-Isabel dates are births between 9/18/2002-6/18/2003, and post-Isabel births are between 9/18/2003-6/18/2003. High-High tracts have high values of LBW rates and are surrounded by other tracts 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.

natural experiments like hurricanes, DiD analyses rely on the assumption of common or parallel trends, and this assumption can be challenging to test for and prove [51]. To test this assumption, we used a hypothetical time period and also found insignificant results. Furthermore, integrating geospatial data into our DiD analysis provides a unique perspective, enabling a more nuanced understanding of localized risks associated with Hurricane Isabel.

Exposure to a disaster is difficult to quantify, and we chose to define exposure based on alternative distances of 30, 60, and 100 km of the storm track based on the mother's residential geocoded location. This location was based on the mother's residence at the time of birth, which may have changed during the pregnancy window. We also did not control for the mother's health or if the mother had access to prenatal care, which could be influenced by exposure to the disaster [52]. Furthermore, Hurricane Isabel was a less intense hurricane (category 2) when it made landfall in North Carolina; this could be a key reason why we find no evidence of adverse effects on neonatal health, particularly compared to other studies that focus on the more intense hurricane (e.g., Katrina) [18]. Another limitation is that our analysis relied on birth dates rather than gestational age, which researchers should use when available as it can provide a more accurate temporal measure of control vs. exposure windows for maternal populations. Despite this limitation, our study compensates by leveraging fine-scale spatial data, such as census tract-level patterns and geocoded maternal residences, which may enhance the accuracy and precision of exposure classification.

Although our study found limited evidence of adverse neonatal outcomes from a moderate hurricane, the focus on a single storm limits the generalizability of the results. Future work should analyze multiple hurricanes across varying intensities and geographies to better understand disaster-associated health risks. Nonetheless, our findings underscore the importance of incorporating spatial effects into disaster health research. Localized patternings allow for a deeper understanding of population-level heterogeneity and help identify specific communities at greater risk, guiding more targeted interventions and resource allocation.

5. Conclusions

This study in North Carolina examines the relationship between a moderate-intensity hurricane (Category 2) and neonatal outcomes, focusing on preterm birth and low birth weight. Using birth records and spatial buffers to measure exposure, our DiD analysis revealed null or negative associations between proximity to the storm's impact and these outcomes. However, our spatial analysis uncovered significant clustering of PTB and LBW in certain areas, emphasizing the importance of incorporating spatial factors in future studies. Future research is needed across hurricane types and spatial locations to understand the full association between hurricane exposure and neonatal outcomes.

CRediT authorship contribution statement

Taylin Spurlock: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Dennis Guignet:** Writing – review & editing, Visualization, Supervision, Project administration. **Jennifer D. Runkle:** Supervision, Methodology, Funding acquisition. **Margaret M. Sugg:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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