Hurricane Charley Exposure and Hazard of Preterm Delivery, Florida 2004

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Abstract *Objective* Hurricanes are powerful tropical storm systems with high winds which influence many health effects. Few studies have examined whether hurricane exposure is associated with preterm delivery. We aimed to estimate associations between maternal hurricane exposure and hazard of preterm delivery. *Methods* We used data on 342,942 singleton births from Florida Vital Statistics Records 2004–2005 to capture pregnancies at risk of delivery during the 2004 hurricane season. Maternal exposure to Hurricane Charley was assigned based on maximum wind speed in maternal county of residence. We estimated hazards of overall preterm delivery (<37 gestational weeks) and extremely preterm delivery (<32 gestational weeks) in Cox regression models, adjusting for maternal/pregnancy characteristics. To evaluate heterogeneity among racial/ethnic subgroups, we performed analyses stratified by race/ethnicity. Additional models investigated whether exposure to multiples hurricanes increased hazard relative to exposure to one hurricane. *Results* Exposure to wind speeds $\geq$39 mph from Hurricane Charley was associated with a 9 % (95 % CI 3, 16 %) increase in hazard of extremely preterm delivery, while exposure to wind speed $\geq$74 mph was associated with a 21 % (95 % CI 6, 38 %) increase. Associations appeared greater for Hispanic mothers compared to non-Hispanic white mothers. Hurricane exposure did not appear to be associated with hazard of overall preterm delivery. Exposure to multiple hurricanes did not appear more harmful than exposure to a single hurricane. *Conclusions* Hurricane exposure may increase hazard of extremely preterm delivery. As US coastal populations and hurricane severity increase, the associations between hurricane and preterm delivery should be further studied.

Keywords Preterm birth · Cox regression · Time-varying · Hurricane · Race · Ethnicity · Vital statistics

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Significance

What is already known on this subject? Pregnant women and children may be disproportionately vulnerable to hurricane-related health effects. Preterm birth is a known potential consequence of intense disaster-related stress, although current literature is limited and associations are somewhat mixed. No research has evaluated differences by ethnicity and only few have evaluated racial disparities with hurricane exposure.

What this study adds? This study shows suggested association between hurricane and extremely preterm delivery (<32 weeks) exacerbated in the black/Hispanic subgroup compared to white/non-Hispanic. Multiple hurricane occurrences did not cumulatively exacerbate hazard of preterm.

Objectives

A hurricane is a powerful tropical storm system capable of extremely high winds which can result in loss of power and community services. As coastal populations and hurricane severity increase in the United States, the associations between hurricane exposure and preterm delivery need to be better understood. The southeastern quadrant of the US is most often and hardest hit by hurricanes. Specifically, Florida had the highest percent increase (approximately 18 %) in population compared to other states between 1990 and 2010 (Blake et al. 2011; Doocy et al. 2013). The adverse impacts of hurricane exposure on health outcomes such as injury, psychosocial stress and loss of community resources have been well documented (Doocy et al. 2013). However, relatively few studies have evaluated preterm delivery.

Children who are born preterm are more likely to experience many negative health consequences including increased respiratory illnesses and lower cognitive abilities (Beck et al. 2010). Death and disability rates among extremely preterm infants (<32 weeks) are more than 150 times higher than among term babies (Martin 2007). In the US, black women are consistently reported to be two to three times more likely to have a preterm delivery and three to four times more likely to have an extremely preterm delivery compared to other minorities or white women (Behrman and Butler 2007; Wilcox 2010). One potential mechanism by which hurricanes could affect the risk of preterm delivery is for stress to trigger early labor and delivery (Christian 2012; Harville et al. 2010; Mulder et al. 2002). Other mechanisms could include hurricane-related traumatic injury leading to early delivery or hurricane-related lapses in access to health care or prenatal care that increase the risk of preterm delivery (Harville et al. 2010).

An association between exposure to natural disasters and preterm delivery has been reported (Harville et al. 2010, #19; Harville et al. 2015, #317); however, the results of studies investigating hurricane exposure and preterm delivery have been mixed (Currie and Rossin-Slater 2013; Hamilton et al. 2009; Harville et al. 2010; Xiong et al. 2008). The aim of this study is to determine the association between hurricane exposure and hazard of preterm delivery overall and extremely preterm delivery using a time-to-event analysis of individual-level Florida birth data. Additionally we will examine differences among racial/ethnic subgroups.

Methods

Birth Cohort

Data on singleton live births from 2003 to 2005 were obtained from the Florida Department of Health, Vital Statistics Department. The study population included births with an estimated date of conception between October 24, 2003 and September 26, 2004. Therefore, the study period encompasses births that were conceived before Hurricane Charley (on August 13, 2004) and the last hurricane of 2004 (September 26, 2004). We excluded births to non-Florida residents as they did not have an address to link to Florida hurricane exposure. Additionally, congenital anomalies, births with gestational age <20 weeks and births of mother <16 or >45 years of age at delivery were also excluded. The age exclusion was implemented because of both potential differences in prenatal care and possible difference mechanisms influencing preterm birth.

Exposures

Hurricane exposure was classified by the hurricane's maximum wind speed in a specific Florida county extracted from National Oceanic and Atmospheric Administration, Hurricane Research Division public databases (Grabich et al. 2015; NOAA, http://www.nhc.noaa.gov/dcmi.shtml). The Saffir Simpson Hurricane Scale categorizes hurricanes into five distinct categories of wind severity: Category 1 (74–95 miles per hour [mph]), 2 (96–110 mph), 3 (111–129 mph), 4 (130–156 mph), and 5 (157 and higher mph) while tropical storm wind speeds are classified as 39–73 mph (Zandbergen 2009). We categorized maximum wind speed using two binary categorizations based on the Saffir–Simpson wind scale: ≥39 mph to indicate tropical storm wind speed and ≥74 mph to indicate hurricane wind speed.

The 2004 hurricane season in Florida was atypical, as four hurricanes made landfall. Our analysis was primarily focused on the first hurricane of 2004, Hurricane Charley. Focusing on the first hurricane avoided bias that could affect analyses of later storms. For instance, for a later storm, women in counties unaffected by that storm could have been affected by an earlier storm that hit their county only a few weeks earlier. Classifying women in these counties as unaffected could inaccurately attenuate associations between storm exposure and preterm outcomes. We additionally performed analysis adjusting for subsequent hurricane occurrences. Finally, we conducted analyses to investigate associations with exposure to multiple storms by that report hazard ratios for Hurricane Charley-only exposure versus no hurricane exposure and hazard ratios comparing exposure to Hurricane Charley plus subsequent hurricanes to no exposure to any hurricanes.

Outcomes

We assessed two outcomes: extremely preterm delivery (<32 completed gestational weeks) and overall preterm delivery (<37 completed gestational weeks). Gestational age was determined based on clinical estimate of gestational age as reported on vital statistics record. Although the National Center for Health Statistic (NCHS) recommends that gestational age be estimated by self-reported last menstrual period (Roth 2003–2005; Wier et al. 2007), we assumed that hurricane exposure could be differentially associated with self-reported recall of last menstrual period. Validity of the estimate was assessed using the NCHS method of comparing gestational age with birth weight; estimates were excluded when implausible (Wier et al. 2007).

Covariates

Maternal and infant characteristics were available from vital statistic records. The following variables were chosen for adjustment *a priori* based on the current literature and variable availability: maternal age (<18, 18–24, 25–34, 35–39 or 40–45 years), maternal education (< high school degree, high school degree, some college/associates, bachelor's degree or graduate/professional degree), maternal race (black, white, Asian/Pacific islander and other/multiracial), maternal ethnicity (Hispanic or non-Hispanic), marital status (legally married or not legally married), maternal tobacco consumption during pregnancy (yes or no) and maternal gestational diabetes (yes or no). Maternal age was categorized as a categorical variable due to non-linear associations with the outcome. We created a composite race/ethnicity variable for analysis of white non-Hispanic, white Hispanic, black non-Hispanic, black Hispanic and Asian/Pacific Islander subgroups.

Statistical Analysis

We estimated the hazard of preterm delivery among women who conceived between October 24, 2003, and September 26, 2004, and who successfully carried the pregnancy to 20 weeks. For all outcomes, the risk period begins at 20 completed weeks gestation because pregnancies that resulted in loss prior to 20 weeks are not captured in vital statistics data. The hazards of extremely and overall preterm delivery were modeled individually using Cox proportional hazards with gestational age in weeks as the time-scale (Henriksen et al. 1997). Pregnancies were right censored at 32 and 37 weeks for each outcome respectively. PROC PHREG (SAS 9.2 Cary, NC) was used to estimate hazard ratios (HRs) and 95 % confidence intervals (95 % CI) with time-varying hurricane exposure. A tabular method was used so that each pregnancy had two records, one representing unexposed time and one exposed time, with a variable to describe the amount of pregnancy-weeks contributed to each timeframe. For instance, a woman who delivered at 36 weeks residing in a county with Hurricane Charley exposure at 34 weeks and 5 days gestation would have 13 weeks unexposed (from 20 to 33 weeks) and 3 weeks exposed (34–36 weeks). In contrast women who delivered at 28 weeks in a county unexposed to Hurricane Charley would have 0 weeks exposed and 8 weeks unexposed. Exposure prior to 20 weeks gestation would be counted only from the start of the 20-week risk period. Individual analyses were conducted for each exposure ($\geq$34 mph wind speed and $\geq$79 mph wind speed) to estimate the hazards of extremely and overall preterm delivery comparing exposed pregnancy-weeks to unexposed pregnancy-weeks.

To investigate race/ethnicity differences we conducted individual stratified analyses by each race/ethnicity subgroup and performed tested for modification by race/ethnicity using formal test of an exposure-by-race/ethnicity interaction term. We used *a priori* criteria for a hazard ratio modification (Wald heterogeneity test alpha of 0.20 (Selvin 2004). In models of multiple hurricane exposure (Hurricane Charley and subsequent hurricane occurrence), we estimated the hazard of multiple exposures to no exposure and compare to estimates of Hurricane Charley exposure.

All analyses were conducted in SAS 9.2 (Cary, NC). This research was approved by the Florida Department of Health Institutional Review Board (IRB) (#H13049) and the IRB of the University of North Carolina at Chapel Hill (#13-0784).

Results

Study Population

Table 1 displays covariate distributions by preterm delivery outcomes in our study population. The mean maternal age at the time of childbirth was 32 years. The racial/ethnic distribution of the Florida cohort included non-Hispanic white (45 %), Hispanic white (28 %), non-Hispanic black (17 %), and Hispanic black (4 %) mothers. There was little difference in the maternal and delivery covariates between the extremely preterm (<32 weeks) and preterm (<37 weeks) deliveries. Each covariate used in adjusted analysis had <2 % missing information. A total of 15,740 of 342,942 records were excluded from the initial study population due to missing information on one or more covariates.

Hurricane Charley Cox Proportional Hazard Models

Overall, a positive association was observed between exposure to Hurricane Charley and hazard of extremely preterm delivery, but not for preterm delivery (Table 2). The associations with extremely preterm delivery were observed for exposure defined as $\geq$39 mph wind speed and for exposure defined as $\geq$74 mph wind speed (HR = 1.09,

Table 1 Descriptive characteristics of study population 2004 and 2005 live births by extremely preterm (<32 weeks), and preterm (32–36 weeks) status (n = 342,942)

	Total cohort		<32 weeks [n = 11,681 (3.4 %)]		32–36 weeks [n = 29,344 (8.6 %)]	
	N	%	N	%	N	%
Maternal age						
<18	10,035	2.9	589	5.0	1051	3.6
18–25	114,002	33.2	4210	36.0	10,049	34.2
25–35	167,904	49.0	5015	42.9	13,502	46.0
35–45	50,593	14.8	1845	15.8	4696	16.0
Missing	408	0.1	22	0.2	46	0.2
Maternal education						
High school diploma	72,172	21.0	3072	26.3	7097	24.2
Some college/associates degree	86,601	25.3	4153	35.6	9750	33.2
Bachelor's degree	110,093	32.1	2680	22.9	7072	24.1
Professional/graduate degree	70,898	20.7	1543	13.2	5131	17.5
Missing	3178	0.9	233	2.0	294	1.0
Maternal race/ethnicity						
White non-Hispanic	155,736	45.4	3957	33.9	11,959	40.8
White Hispanic	94,875	27.7	2913	24.9	7918	27.0
Asian/Pacific Islander	9276	2.7	249	2.1	781	2.7
American Indian	7494	2.2	220	1.9	632	2.2
Other/multiracial[a]	762	0.2	23	0.2	93	0.3
Black non-Hispanic	59,044	17.2	3474	29.7	6445	22.0
Black Hispanic	12,476	3.6	679	5.8	1226	4.2
Missing	3279	1.0	166	1.4	290	1.0
Maternal marital status						
Married	201,441	58.7	5380	46.1	15,956	54.4
Single	141,002	41.1	6260	53.6	13,333	45.4
Missing	499	0.1	41	0.4	55	0.2
Maternal tobacco						
Yes	24,341	7.1	1064	9.1	2294	7.8
No	311,961	91.0	10,322	88.4	26,455	90.2
Missing	6640	1.9	295	2.5	595	2.0
Gestational diabetes						
Yes	12,949	3.8	385	3.3	1467	5.0
No	328,860	95.9	11,182	95.7	27,752	94.6
Missing	1133	0.3	114	1.0	125	0.4

[a] Other/multi racial includes mothers whom selected multiple races or other on the birth certificate

95 % CI [1.03, 1.16] and HR = 1.21, 95 % CI [1.06, 1.38] respectively).

We conducted stratified analysis to explore variation in the association between exposure to hurricane winds and preterm delivery by race/ethnicity. In stratified analysis of race/ethnicity, associations between ≥39 mph hurricane wind speed and extremely preterm delivery (<32 weeks) were positive among white Hispanics and black Hispanics (HR = 1.14, 95 % CI [1.01, 1.27] and HR = 1.49, 95 % CI [1.17, 1.87], respectively). The race/ethnicity stratified models suggested an association between ≥74 mph hurricane wind speed and extremely preterm delivery among white Hispanics (HR = 1.32, 95 % CI [1.04, 1.69]) and suggestions of positive associations in black Hispanic and white non-Hispanic subgroups (HR = 1.56, 95 % CI [0.85, 2.85] and HR = 1.18, 95% CI [0.97, 1.45], respectively). In race/ethnicity stratified analysis of hurricane and preterm delivery (<37 weeks), there was little evidence of an association in either ≥39 mph wind speed or ≥74 mph wind speed models.

Table 2 Florida 2004 unadjusted and adjusted[a] hazard ratio (HR) of Hurricane Charley wind exposure on extremely preterm (<32 weeks) and overall preterm (<37 weeks) delivery

Wind speed exposure (mph)	Model description	Outcome			
		<32 weeks (n = 11,681)		<37 weeks (n = 41,025)	
		HR	(95 % CI)	HR	(95 % CI)
≥39	Unadjusted	1.12	(1.06 1.19)	1.05	(1.02 1.07)
	Adjusted	1.09	(1.03 1.16)	0.99	(0.96 1.01)
≥74	Unadjusted	1.18	(1.04 1.35)	1.07	(1.01 1.13)
	Adjusted	1.21	(1.06 1.38)	1.06	(1.00 1.12)

[a] Adjusted for gestational diabetes, maternal age, maternal race, maternal ethnicity, maternal education, and maternal pregnancy tobacco use

Table 3 Florida 2004 adjusted[a] hazard ratio (HR) of Hurricane Charley race/ethnicity stratified hurricane wind exposure on extremely preterm (<32 weeks) and overall preterm (<37 weeks) delivery and *p* value for interaction in exposure by race/ethnicity model term

Wind speed exposure (mph)	Race/ethnicity stratified models	Outcome					
		<32 weeks		Interaction *p* values[b]	<37 weeks		Interaction *p* values[b]
		HR	95 % CI		HR	95 % CI	
≥39	White non-Hispanic	1.06	(0.96 1.19)	Referent	0.99	(0.95 1.04)	Referent
	White Hispanic	1.14	(1.01 1.27)	0.52	0.98	(0.98 1.02)	0.26
	Asian/Pacific Islander	0.97	(0.60 1.57)	0.76	0.90	(0.77 1.07)	0.27
	Black Non-Hispanic	1.02	(0.90 1.14)	0.35	0.98	(0.93 1.04)	0.32
	Black Hispanic	1.49	(1.17 1.87)	0.05	1.06	(0.94 1.18)	0.80
≥74	White non-Hispanic	1.18	(0.97 1.45)	Referent	1.08	(0.99 1.17)	Referent
	White Hispanic	1.32	(1.04 1.69)	0.50	1.07	(0.96 1.18)	0.82
	Asian/Pacific Islander	1.50	(0.55 4.08)	0.71	1.09	(0.74 1.63)	0.88
	Black non-Hispanic	1.03	(0.76 1.40)	0.37	0.95	(0.82 1.10)	0.18
	Black Hispanic	1.56	(0.85 2.85)	0.43	1.33	(0.99 1.79)	0.22

[a] Adjusted for gestational diabetes, maternal age, maternal race, maternal ethnicity, maternal education and maternal pregnancy tobacco use

[b] Interaction *p* values were generated by fitting single models which included interaction terms for each five race/ethnicity subgroups explored in Table 3 with the main effect of exposure. Therefore, reported *p* values are from a single model which included each exposure outcome interaction

Table 4 Florida 2004 sample size description for multiple hurricane exposures hazard ratio models

Exposure	≥39 mph exposure			≥74 mph exposure		
	N of Counties	<32 week events	<37 week events	N of Counties	<32 week events	<37 week events
0 Hurricane exposure	4	259	1433	50	9902	50,054
1 Hurricane exposure	26	2391	11,844	9	1206	6534
2 Hurricane exposures	11	3737	17,999	7	2171	10,855
3 Hurricane exposures	26	7355	39,845	1	185	1110

Multiple Hurricane Cox Proportional Hazard Models

Of the 67 Florida counties, 37 counties were exposed to multiple hurricanes (Hurricane Charley and one or more subsequent hurricanes) when categorized by ≥39 mph wind speed, and 8 counties were exposed to multiple hurricanes when applying the ≥74 mph wind speed (Table 4). In all models, there was no evidence of an increased hazard of extremely preterm or overall preterm delivery with exposure to more than one hurricane (Table 5). For example, compared to no exposure to any hurricanes, the hazard ratios of extremely preterm and preterm delivery among those exposed to ≥74 mph winds

Table 5 Florida 2004 adjusted[a] hazard ratio (HR) of multiple hurricane exposure and single Hurricane Charley exposure to no hurricane exposure on extremely preterm (<32 weeks) and overall preterm (<37 weeks) delivery

Wind speed exposure (mph)	Multiple hurricane models	Outcome			
		<32 weeks gestation		<37 weeks gestation	
		HR	95 % CI	HR	95 % CI
≥39	Hurricane Charley compared to no hurricane exposure	1.09	(1.03 1.16)	0.99	(0.91 1.08)
	Charley and subsequent hurricane compared to no hurricane exposure	1.13	(1.06 1.22)	1.08	(1.00 1.17)
≥74	Hurricane Charley compared to no hurricane exposure	1.21	(1.06 1.38)	1.06	(1.00 1.12)
	Charley and subsequent hurricane compared to no hurricane exposure	1.20	(0.98 1.46)	1.07	(1.04 1.10)

[a] Adjusted for gestational diabetes, maternal age, maternal race, maternal ethnicity, maternal education, maternal pregnancy tobacco use

were similar when assessing only Hurricane Charley exposure and when assessing exposure to Charley plus a subsequent hurricane (extremely preterm (HR = 1.21, 95% CI [1.06, 1.38] and HR = 1.20, 95 % CI [0.98, 1.46], respectively; overall preterm (HR = 1.06, 95% CI [1.00, 1.12] and HR = 1.07, 95 % CI [1.04, 1.10], respectively).

Conclusions

To our knowledge, our Florida-based study population is the only example of evaluating associations between hurricane and preterm delivery in ethnic subgroups and is only the second study to evaluate hurricane influence on a full state population of births. While some hurricane studies are done at aggregate levels, we were able to control for individual-level confounders in our analysis using Vital Statistics data. Overall we found that pregnant women living in a county exposed to Hurricane Charley experienced increased hazard of extremely preterm delivery (<32 weeks) but not preterm delivery (<37 weeks) in Florida during the 2004 hurricane season.

Our results for Hurricane Charley are similar to several preterm delivery studies that focused on Hurricane Katrina. A smaller study conducted after Hurricane Katrina examined the effect of the hurricane on racial disparities by comparing county preterm delivery rates before and after Hurricane Katrina. Similar to our study, overall preterm delivery rates did not increase in the 2 years after Katrina. However, this study did not find significantly different hazard or preterm comparing black to white women (Harville et al. 2010). Another Harville et al. (2015) study of Hurricane Katrina showed that injury was associated with preterm delivery. In another study investigating poor fetal outcomes in US Gulf Coast states after Katrina, higher rates of extremely preterm delivery were reported in Alabama (Hamilton et al. 2009).

In contrast to our Hurricane Charley results, Hamilton et al. (2009) found lower rates of extremely preterm delivery in Louisiana after Hurricane Katrina (Hamilton et al. 2009). In addition, a study by Xiong et al. (2008), collected data in New Orleans and Baton Rouge after Hurricane Katrina related to hurricane "experiences" (e.g. feeling that one's life was in danger or having a loved one die). This study found a higher frequency of overall preterm delivery in women with three or more subjective hurricane experiences versus women with less than three, but did not explore extremely preterm delivery (Xiong et al. 2008). The only non-Katrina hurricane study, Currie and Rossin-Slater (2013), investigated Texas birth records over a 12-year period and found that exposure to a hurricane during pregnancy, as determined by disaster declaration, was not associated with gestational age at delivery even at the extremely preterm delivery period where we found suggested associations (Currie and Rossin-Slater 2013).

Prior research demonstrates that socially vulnerable populations, including women and members of racial/ethnic minorities, suffer disproportionately from disasters (Cutter et al. 2003; Perry and Lindell 1978). However, our study is the first to have investigated the hazard of preterm delivery among understudied racial/ethnic subgroups including Asians and Hispanics. Published studies of hurricane exposure and reproductive health show that black women may have an increased risk of adverse reproductive outcomes that are persistent but not necessarily exacerbated by hurricane exposure. These studies have not evaluated differences by ethnicity. In our race/ethnicity analysis, it appeared that there may be some differences among race/ethnicity subgroups. We felt that the effect of confounding factors on preterm delivery could vary in different racial/ethnic strata and therefore multivariable-adjusted associations could be better described in stratified models. Additionally, two of our interaction models did suggest multiplicative interactions comparing black Hispanic and black non-Hispanic to white non-Hispanic subgroups. Overall, more research is needed on racial/ethnic subgroups to better target vulnerable groups for public health intervention where appropriate.

Although underpowered, due to the racial and ethnic diversity of the State of Florida, we were able to describe more associations among racial/ethnic groups than other published analyses. Supplemental modification analyses were additionally performed for race and ethnicity separately and as a composite variable. These subgroup analyses may help public health officials in Florida and other states better prepare for future hurricanes, as well as better understand the hazards of preterm delivery in particularly vulnerable population subgroups.

In the US, the growing coastal population is one reason for increasing importance of studies that directly investigate health effects of hurricane exposures. In addition, there is substantial evidence that the intensity and frequency of hurricanes making landfall in the US has increased in recent years (Bettinger et al. 2009; Elsner et al. 2008; Webster et al. 2005). Current disaster reproductive health literature has not investigated the association of multiple hurricanes on delivery outcomes. Four hurricanes made landfall in Florida in rapid succession between August 13, 2004, and September 26, 2004. Hurricane Charley was the first hurricane of the 2004 hurricane season and therefore is the only hurricane not potentially biased by prior evacuation and changes in residence from previous hurricanes. In our analysis, we found that the hazard of preterm delivery did not differ when comparing multiple hurricane exposure to only Hurricane Charley exposure. In addition, we conducted analyses to examine the interaction between Charley and each subsequent hurricane. Because of power limitations, only interaction between Charley and the second hurricane of the 2004 season, Frances, could be described. We found no evidence of interaction between Hurricane Charley and Frances. We also investigated each hurricane of the 2004 season independently and found similar results to the Hurricane Charley analysis presented here. This may suggest that individual hurricanes could have an association with health but maybe not the compounded influence of multiple hurricanes as shown in our cumulative hurricane analyses. Future studies should consider evaluated the individual and cumulative effect of hurricanes when multiple disasters occur in a short time span.

A major strength of our analysis is the use of the individual-level outcomes and covariates. The current literature on hurricane and preterm delivery use mostly pre-post analyses of county-level preterm delivery rates. Findings from these studies have been mixed, possibly due to biases inherent to pre-post analysis such as ecological fallacy. Our analyses used of Cox proportional hazard models to conduct a fetus-at-risk approach to evaluate preterm delivery. This method has been advocated as more appropriate in perinatal epidemiology, as opposed to cohorts of births when investigating time varying exposure and pregnancy-time dependent outcomes like gestational age (Klein and Moeschberger 2003; Platt et al. 2004; Louis and Platt 2011). Since the risk of delivery increases with gestational age, a model using traditional dichotomous (yes/no) exposure and not time contributed to exposure, may inflate the risk of delivery as it becomes imminent. This method also can account for fetuses-at-risk of hurricane exposure and the preterm delivery event, creating a better counterfactual contrast. Future research using time-to-event analysis on disaster exposure and preterm delivery could benefit by using a cohort design with time-varying confounders to account for changes in care or comorbidities during the course of pregnancy.

Our study had several limitations. Using vital statistics data, we could not distinguish spontaneous preterm delivery from other subtypes. Fetal deaths, although rare, were not included in adjusted analysis due to a lack of complete covariate information. Although overall missingness was not a concern, many potential confounders were not available from fetal death records. Fetal deaths made up less than 1 % of total births and when included in crude analysis did not show a difference in estimate from adjusted analysis. The addition of fetal deaths which occur after 20 weeks gestation in future analysis would strengthen the fetus-at-risk approach using time-to-event modeling. Additionally, hurricane exposure was determined based on residence reported at time of delivery. Women may have moved out of exposed areas if barriers to access to care or other damages occurred in their community. This would likely bias associations towards the null.

Another limitation is the current lack of ability to target the mechanisms that influence the hurricane to preterm delivery causal pathway, which may not be the same for extremely and overall preterm delivery. One hypothesis for the consistent association in the <32 week deliveries is the possibility that pregnancy at this stage could be more vulnerable to some short-term mechanisms, including access to care or injury. Our wind speed exposure measurement may be better at capturing these acute effects and not necessarily capturing accumulation of stress. Future research should try to target these mechanisms. Additionally, unmeasured confounding may be a larger issue in this extremely preterm analysis, where less reliable or unknown variables may have a greater impact compared to the overall preterm analysis. An additional possibility is that pregnant women are more likely to evacuate at later stages of pregnancy. This could drive the association in the overall preterm analysis toward the null if they move from exposed to unexposed areas. Also, using residence at delivery as a proxy to assign hurricane exposure could lead to exposure misclassification in our study. While research has not been done on evacuation trends during pregnancy, during the 2004 hurricane season 1 in 4 individuals of the total Florida population evacuated their primary residence during one or more hurricane events (Smith and McCarty 2009). Individuals most often relocate or return to the same county within a relatively short period of time (Kim and Oh 2014).

Associations between hurricane exposure and preterm delivery need to be better understood as coastal populations and hurricane severity increase in the United States. Preterm children, in particular extremely preterm, are more likely to experience negative consequences such as respiratory and cognitive impairment. We found that Hurricane Charley exposure in Florida in 2004 was consistently associated with the hazard of extremely preterm delivery (<32 weeks gestation). This association with extremely preterm delivery is shown with other published research, although limited to few studies. These results should potentially be considered by public health leaders in recommendations for evacuation procedures or prenatal care. Future studies of hurricane and preterm delivery should further evaluate race/ethnicity subgroups and use individual-data with methods such as time-to-event analysis to provide more accurate estimates than ecological and pre-post analysis.

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