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Tropical cyclones and risk of preterm birth: A retrospective analysis of 20 million births across 378 US counties

Shengzhi Sun[a,b,*], Kate R. Weinberger[b,c], Meilin Yan[d,e], G. Brooke Anderson[e], Gregory A. Wellenius[a,b]

[a] Department of Environmental Health, Boston University School of Public Health, Boston, MA, United States
[b] Department of Epidemiology and Center for Environmental Health and Technology, Brown University School of Public Health, Providence, RI, United States
[c] School of Population and Public Health, University of British Columbia, Vancouver, British Columbia, Canada
[d] Beijing Innovation Center for Engineering Science and Advanced Technology and State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing, China
[e] Department of Environmental & Radiological Health Sciences, Colorado State University, Fort Collins, CO, United States

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ABSTRACT

Background: The public health impacts of tropical cyclones (TCs) are expected to increase due to the continued growth of coastal populations and the increasing severity of these events. However, the impact of TCs on pregnant women, a vulnerable population, remains largely unknown. We aimed to estimate the association between prenatal exposure to TCs and risk of preterm birth in the eastern United States (US) and to assess whether the association varies by individual- and area-level characteristics.

Methods: We included data on 19,529,748 spontaneous singleton births from 1989 to 2002 across 378 US counties. In each county, we classified days as exposed to a TC when TC-associated peak sustained winds at the county's population-weighted center were > 17.2 m/s (gale-force winds or greater). We defined preterm birth as births delivered prior to 37 completed weeks of gestation. We used distributed lag log-linear mixed-effects models to estimate the relative risk (RR) and absolute risk difference (ARD) for TC exposure by comparing preterm births occurring in TC-periods (from 2 days before to 30 days after the TC's closest approach to the county's population center) to matched non-TC periods. We conducted secondary analyses using other wind thresholds (12 m/s and 22 m/s) and other exposure metrics: county distance to storm track (30 km, 60 km, and 100 km) and cumulative rainfall within the county (75 mm, 100 mm, and 125 mm).

Results: During the study period, there were 1,981,797 (10.1%) preterm births and 58 TCs that affected at least one US county on which we had birth data. The risk of preterm birth was positively associated with TC exposure defined as peak sustained wind speed > 17.2 m/s (gale-force winds or greater) [RR: 1.01 (95% CI: 0.99, 1.03); ARD: 9 (95% CI: −7, 25) per 10,000 pregnancies], distance to storm track < 60 km [RR: 1.02 (95% CI: 1.01, 1.04); ARD: 23 (95% CI: 9, 38) per 10,000 pregnancies], and cumulative rainfall > 100 mm [RR: 1.04 (95% CI: 1.02, 1.06); ARD: 36 (95% CI: 16, 56) per 10,000 pregnancies]. Results were comparable when considering other wind, distance, or rain thresholds. The association was more pronounced among early preterm births and mothers living in more socially vulnerable counties but did not vary across strata of other hypothesized risk factors.

Conclusions: Maternal exposure to TC was associated with a higher risk of preterm birth. Our findings provide initial evidence that severe storms may trigger preterm birth.

1. Introduction

Tropical cyclones (TCs) pose a significant threat to human health in the United States (US), and their adverse impacts are expected to increase due to projected growth in coastal populations and severity of storms (Crossett et al., 2013; Holland and Bruyère, 2014; Smith et al., 2009). It is estimated that in the last 30–40 years, the number of people living in coastal areas in the US has increased by 39% (Crossett et al.,

Abbreviations: TC, Tropical Cyclone; RR, Relative Risk; ARD, Absolute Risk Difference; LMP, Last Menstrual Period; SVI, Social Vulnerability Index; NWS, National Weather Service; IQR, Interquartile Range

* Corresponding author at: Department of Environmental Health, Boston University School of Public Health, 715 Albany Street, Boston, Massachusetts 02118, United States.

E-mail address: szsun@bu.edu (S. Sun).

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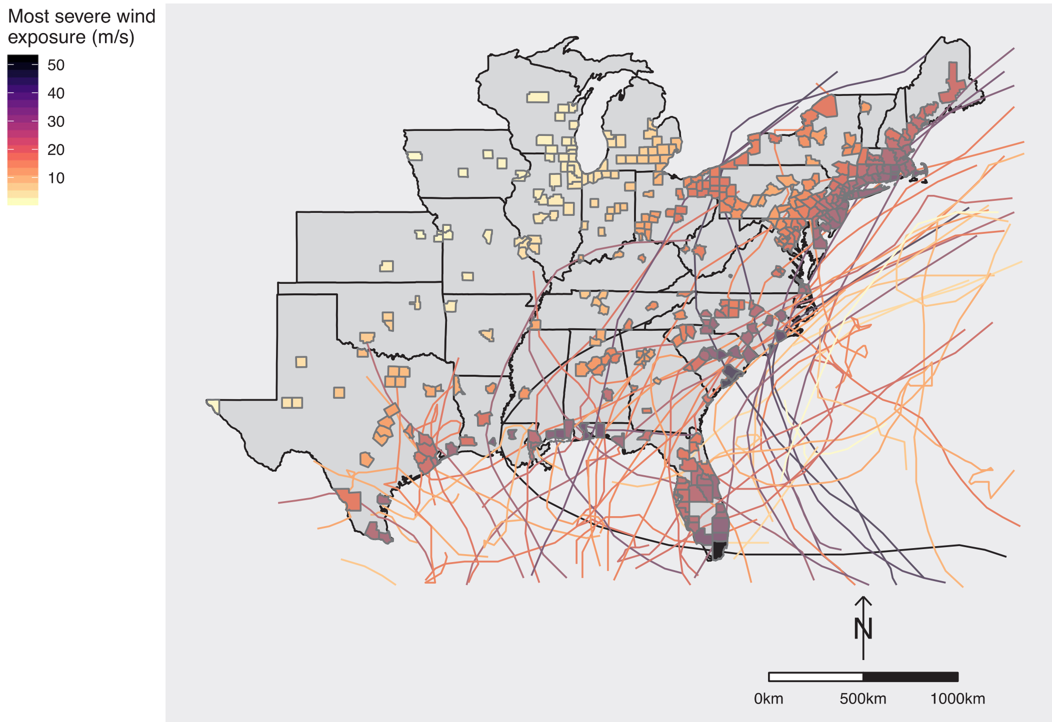


Fig. 1. Spatial distribution of the 378 eastern US counties that had data on preterm births and tracks of all Atlantic-basin tropical cyclones (n = 58) between 1989 and 2002. Color of county indicates the maximum sustained wind speed of all tropical cyclones a county experienced during the study period; color of storm track represents the maximum sustained wind speed of all counties among the 378 studied US counties that a storm passed.

2013), and the global proportion of category 4 and 5 hurricanes as defined by the Saffir-Simpson Hurricane Scale has increased by 13% (Knutson et al., 2019). The combination of these trends underscores a pressing need to understand and quantify the adverse health impacts of TCs. A growing body of literature suggests adverse impacts of TCs on hospitalizations or mortality (Becquart et al., 2019; Hendrickson et al., 1997; Kim et al., 2016; Platz et al., 2007; Smith and Graffeo, 2005; Swerdel et al., 2014), but only a few studies have examined the potential impacts of TCs on adverse pregnancy outcomes (Currie and Rossin-Slater, 2013; Grabich et al., 2016, 2017; Hamilton et al., 2009; Harville et al., 2010b; Xiong et al., 2008; Yu et al., 2018).

Preterm birth is the leading cause of infant death worldwide and is associated with higher risks of developing neurocognitive and cardiorespiratory diseases later in life (Blencowe et al., 2012; Liu et al., 2015). It is estimated that about 15 million infants worldwide are born prematurely each year, affecting over 11% of all deliveries (World Health Organization, 2018). Despite reductions in infant mortality, the preterm birth rate in the US remains higher (12%) than the rates in Europe and many other developed countries (5% to 9%) (Blencowe et al., 2012).

A variety of environmental risk factors may play a role in triggering preterm birth, including prenatal exposure to ambient air pollution (Kingsley et al., 2017; Malley et al., 2017), ambient temperature (Sun et al., 2019b), and environmental chemicals (Savitz et al., 2012). TCs may plausibly trigger preterm birth through multiple pathways, such as through increasing psychosocial stress, environmental contamination (e.g., water contamination) (Wilson, 2006), mold (Wilson, 2006), triggering pre-existing diseases (e.g., asthma) (Kelly et al., 1995), or disruption of health care services and loss of basic utilities (Akutagawa et al., 2007; Christian, 2012; Harville et al., 2010a). Few prior studies have examined the association between maternal exposure to TCs and risk of preterm birth (Table S1), and findings from these studies have been mixed (Grabich et al., 2016; Hamilton et al., 2009; Harville et al., 2010b; Xiong et al., 2008; Yu et al., 2018).

Given the potential public health significance, we sought to estimate the association between maternal exposure to TCs and risk of preterm birth among ~20 million spontaneous live singleton births from 1989 to 2002 across 378 eastern US counties using different exposure metrics (i.e., peak sustained wind speed within the county, distance from the county's center to the storm track, and cumulative rainfall within the county) and choice of thresholds. We also examined whether these associations varied by personal characteristics (infant sex, maternal age, marital status, maternal race, maternal education, and parity, and preterm birth sub-categories) and county's social vulnerability index.

2. Methods

2.1. Study participants

We obtained data on spontaneous live singleton births occurring in the US between 1989 and 2002 from the Centers for Disease Control and Prevention (CDC)'s National Center for Health Statistics (Centers for Disease Control and Prevention, 2017). Data were available only for US resident mothers living in counties with a population of ≥100,000. We restricted our analysis to counties in the eastern half of the US as this area is the part of the country typically affected by Atlantic-basin hurricanes. We included all US counties in the eastern half of the country for which birth outcomes data were available during the study period.

The exact date of birth is not directly available in these data, so we imputed this variable based on the last menstrual period (LMP), completed weeks of gestation, and the recorded weekday of birth as previously described (Sun et al., 2019a, 2019b). To minimize potential misclassification, we excluded births where the imputed month of birth differed from the recorded month of birth. We also excluded births with implausible combinations of birth weight and gestational age according to the Alexander criteria (Alexander et al., 1996). The final analytic sample consisted of 19,529,748 spontaneous live singleton births (Fig. S1).

Table 1
Demographic characteristics of spontaneous preterm births in 378 eastern US counties between 1989 and 2002.

Characteristics, No. (%)	All Births (20–44 weeks)	Preterm Births (20–36 weeks)	% of Births Born Preterm
Total birth	19,529,748	1,981,797	10.1
Gestational weeks, median (IQR)	38.9 ± 2.4	33.9 ± 3.0	–
Sub-categories of preterm birth			
Early preterm birth (< 34 weeks)	538,394 (2.8)	538,394 (27.2)	100.0
Late preterm birth (34–36 weeks)	1,443,403 (7.4)	1,443,403 (72.8)	100.0
Child sex			
Male	9,983,814 (51.1)	1,064,004 (53.7)	10.7
Female	9,545,934 (48.9)	917,793 (46.3)	9.6
Maternal age, years			
< 30	12,266,998 (62.8)	1,297,302 (65.5)	10.6
≥30	7,262,750 (37.2)	684,495 (34.5)	9.4
Marital status			
Married	13,276,220 (68)	1,107,724 (55.9)	8.3
Unmarried	6,253,528 (32)	874,073 (44.1)	14.0
Maternal race			
White	14,507,437 (74.3)	1,236,610 (62.4)	8.5
Non-white	5,022,311 (25.7)	745,187 (37.6)	14.8
Years of education, years			
< 13	10,242,197 (52.4)	1,197,540 (60.4)	11.7
13–17	8,849,463 (45.3)	738,663 (37.3)	8.3
Unknown	438,088 (2.2)	45,594 (2.3)	10.4
Parity			
0	8,051,030 (41.2)	830,891 (41.9)	10.3
≥1	11,394,189 (58.3)	1,141,776 (57.6)	10.0
Unknown	84,529 (0.4)	9,130 (0.5)	10.8
Social vulnerability index			
Lower tertile	5,119,911 (26.2)	434,601 (21.9)	8.5
Middle	5,425,928 (27.8)	521,045 (26.3)	9.6
Upper tertile	8,983,909 (46.0)	1,026,151 (51.8)	11.4

Abbreviation: IQR = interquartile range.

2.2. Tropical cyclone exposure classification

There is no consensus regarding which exposure metric should be used to define TC exposure for epidemiological research (Grabich et al., 2015). As TC intensity is typically quantified by wind speed (WMO, 2005), we decided a *priori* to use sustained wind speed as the primary exposure metric. We also considered distance from county to storm track and cumulative rainfall as secondary exposure metrics.

We obtained county-level TC-associated sustained wind speed, distance from the storm track, and rain between 1989 and 2002 for counties in the eastern US from the R *hurricaneexposure* package (Version: 0.1.0) (Anderson et al., 2017). Briefly, all Atlantic-basin TCs that passed within 250 km of at least one eastern US county were identified using the National Hurricane Center's revised Atlantic hurricane database (HURDAT2), and this set of TCs was further assessed for county-level wind-, distance-, and rain-based exposure metrics (Landsea and Franklin, 2013). Ground-level peak sustained winds at each county's population mean center for each TC were estimated using a parametric wind speed model, with winds at each county center estimated every 15 min along the TC's track and the maximum within each county taken as the county's peak value (Anderson et al., 2018; Willoughby et al., 2006). Cumulative rainfall from one day before to one day after the TC's closest approach to the county was calculated using precipitation data from the North American Land Data Assimilation System, phase 2 (NLDAS-2) (Rui and Mocko, 2013). In the main analysis, for each county we classified a day as exposed to a TC if the estimated peak sustained wind was > 17.2 m/s at the county's population center (classified as gale-force winds or greater based on the Beaufort wind scale) (Met Office, 2020). In secondary analyses, we classified as TC-exposed day using other wind speed thresholds (12 m/s and 22 m/s), as well as exposure defined by distance from the storm track (30 km, 60 km, and 100 km) or cumulative rainfall (75 mm, 100 mm, and 125 mm) (Currie and Rossin-Slater, 2013; Grabich et al., 2015).

2.3. Outcome measures

Preterm birth was defined as births delivered prior to 37 completed weeks of gestation. We further categorized preterm birth into early (20–33 weeks) and late preterm birth (34–36 weeks).

2.4. Social vulnerability index

We obtained 2000 census-tract level data from the CDC. We calculated Social Vulnerability Index (SVI) values following the methodology described in Flanagnan et al. (2011). The overall SVI includes themes of socioeconomic status, household composition and disability, minority status and language, and housing and transportation. The SVI was expressed as percentiles scaled from 0 to 1: a value of 0.0 means that it is the least vulnerable administrative unit while 1.0 means that it is the most vulnerable.

2.5. Statistical analysis

Within each county exposed to one or more TCs, we matched each day exposed to a TC (TC-exposed days) to four days on which a TC did not occur (non-TC days) (Bobb et al., 2014; Liu et al., 2017; Yan et al., 2020). More specifically, we randomly selected four non-TC

Table 2
Characteristics of tropical cyclones across 378 US counties during the study period, 1989 to 2002[a].

Tropical cyclone definition		Counties with ≥ 1 tropical cyclone event, No. (%)	Frequency of tropical cyclones, Mean No. per Year (IQR)
Exposure metric	Threshold		
Peak sustained winds	> 12.0 m/s	265 (70)	3.1 (0.0, 4.0)
Peak sustained winds	> 17.2 m/s	202 (53)	3.0 (0.0, 3.0)
Peak sustained winds	> 22.0 m/s	127 (34)	0.7 (0.0, 1.0)
Distance to storm track	< 30 km	174 (46)	0.9 (0.0, 1.8)
Distance to storm track	< 60 km	243 (64)	1.7 (0.0, 3.0)
Distance to storm track	< 100 km	277 (73)	2.8 (0.0, 4.0)
Cumulative rainfall	> 75 mm	255 (67)	2.0 (0.0, 3.0)
Cumulative rainfall	> 100 mm	181 (48)	0.9 (0.0, 1.0)
Cumulative rainfall	> 125 mm	122 (32)	0.4 (0.0, 1.0)

Abbreviation: IQR = interquartile range.
[a] Not all of the counties have complete year-round birth data during the study period.

Table 3
Number of preterm births for tropical cyclone-exposed days and matched referent days across different exposure metrics and the tropical cyclone-period relative risk and absolute risk difference of preterm birth associated with tropical cyclone[a].

Exposure metric and threshold	No. of Exposed Counties	No. of Preterm Births (per 10,000 pregnancies at risk)		Relative Risk[d]	Absolute Risk Difference, No. per 10,000 pregnancies[e]
		TC Period[b]	Matched Referent Period[c]		
Peak sustained winds					
12.0 m/s	265	1,026	1,008	1.02 (1.01, 1.03)	21 (10, 32)
17.2 m/s	202	984	979	1.01 (0.99, 1.03)	9 (-7, 25)
22.0 m/s	127	953	932	1.03 (1.00, 1.05)	27 (4, 50)
Distance to storm track					
30 km	174	1,014	973	1.05 (1.02, 1.07)	45 (24, 66)
60 km	243	1,012	993	1.02 (1.01, 1.04)	23 (9, 38)
100 km	277	1,010	991	1.02 (1.01, 1.04)	24 (12, 35)
Cumulative rainfall					
75 mm	255	1,042	1,014	1.03 (1.02, 1.04)	30 (17, 43)
100 mm	181	1,067	1,028	1.04 (1.02, 1.06)	36 (16, 56)
125 mm	122	1,036	1,006	1.03 (1.00, 1.06)	28 (-1, 57)

Abbreviations: TC = tropical cyclone.
[a] Estimates over the entire tropical cyclone period, from 2 days before to 30 days after the tropical cyclone's closest approach to the county's population mean center.
[b] Number of preterm births were summed up across 33 days of the entire tropical cyclone period for all exposed counties under a certain exposure definition.
[c] Number of preterm births (divided by four to scale to the number of matched unexposed days per exposed day) were summed up across 33 days of the entire tropical cyclone period for all exposed counties under a certain exposure definition.
[d] Models were adjusted for federal holiday, day of week, year, and the number of daily expected count of preterm births.
[e] Absolute risk difference was calculated by α × (relative risk – 1)/relative risk where α denotes the proportion of preterm births, which was 1,015 per 10,000 pregnancies.

("referent") days from a set of candidate non-TC days, defined as all days within seven days of the day of year and within 5 years of the TC-exposed day (Fig. S2). We excluded non-TC days from consideration if they fell within a thirty-three-day window (from 2 days before to 30 days after the TC's closest approach to the county's population center) of a different TC-exposed day for that county, as well as days in the period from September 11 to 24, 2001.

To estimate the association between maternal exposure to TC and risk of preterm birth, we compared the number of preterm births observed on TC-exposed days versus on matched non-TC days in the same county using log-linear mixed-effects models with a county-specific random intercept to account for within-county correlation of the observations (Supplemental Material). We applied a constrained distributed lag function of TC exposure to estimate lag day-specific relative risk (RR) of TC from 2 days before (lag −2) to 30 days after (lag 30) the TC's closest approach to the county's population center. We included in this window 2 days before the TC landfall as the US National Weather Service (NWS) issues hurricane watches and warnings in advance of the anticipated onset of TC (National Weather Service, 2020), and individuals and communities may take preparatory actions in response to such forecasts that may be associated with changing risk of preterm birth. We considered maximum lags up to 30 days based on exploratory analysis suggesting that the effects of TC could be protracted. To explore the lag day-effects of TC, we used a *strata* function on the lag scale with breaks at 0, 1, 8, 15, and 22 days relative to the TC-exposure day in order to model the TC effects before, on, and 1 to 4 weeks after the date of TC landfall (Gasparrini, 2011). To account for long-term and weekday changes in the preterm birth rate, we included indicator variables for year and day of week in the models. We also calculated and applied an offset to account for the variation in daily expected number of preterm births, as previously described (Sun et al., 2019b; Vicedo-Cabrera et al., 2014). We estimated the overall RR of preterm birth over the entire TC-period (defined as 2 day before to 30 days after the TC's closest approach to the county's population center) by $1/33\sum_{l=-2}^{30}\exp(\beta_l)$ where β_l is the coefficient on lag l (Bobb et al., 2017, 2014). The TC-period RR compares the total number of preterm births in the two days before through 30 days following a TC with the total number of preterm births in the same time window relative to non-TC periods in the same county conditional on the expected number of preterm births. We also calculated the absolute risk difference (ARD) of preterm birth over the TC-period as α × (RR − 1)/RR, where α denotes the proportion of births that were born preterm (Di et al., 2017). In secondary analyses, we applied the same analytic approach but using other wind speed thresholds or exposure metrics.

To identify susceptible subpopulations, we conducted analyses by infant sex (male versus female), maternal age (< 30 y versus ≥ 30 y), marital status (married versus unmarried), maternal race (white versus non-white), maternal education (< 13 y versus ≥ 13 y), parity (0 versus ≥ 1), preterm birth sub-categories (early versus late) and county's social vulnerability index (lower, middle, and upper tertile). We tested the differences in the estimated RR and ARD between categories within each subgroup (e.g., male versus female) by:

$$(\widehat{Q_{male}} - \widehat{Q_{female}}) \Big/ \sqrt{(\widehat{SE_{male}})^2 + (\widehat{SE_{female}})^2}$$

where $\widehat{Q_{male}}$ and $\widehat{Q_{female}}$ are the point estimates of the estimated RR and ARD for males and females, and $\widehat{SE_{male}}$ and $\widehat{SE_{female}}$ are their corresponding standard errors (Altman and Bland, 2003; Zeka et al., 2006).

All analyses were conducted in R version 3.6.1 with the "dlnm" package (Version 2.3.9) for the distributed lag non-linear model and the "lme4" package (Version 1.1–211.7.4) for the log-linear mixed-effects model. We considered a 2-sided p-value < 0.05 as statistically significant.

3. Results

Between 1989 and 2002, 58 TCs impacted at least one of the 378 studied US counties (Fig. 1 and Table S2). Our analysis included 19,529,748 spontaneous singleton births, of which 1,981,797 (10.1%) were born preterm (Table 1). About three-quarters (72.8%) of preterm births were delivered between 34 and 36 weeks. The median gestational ages at delivery for all births were 38.9 (Interquartile range, IQR: 2.4) weeks and 33.9 (IQR: 3.0) weeks for preterm births. The fraction of preterm births was higher among male infants (10.7%) and among mothers aged < 30 years old (10.6%), unmarried (14.0%), non-white (14.8%), having lower level of education (11.7%), and living in

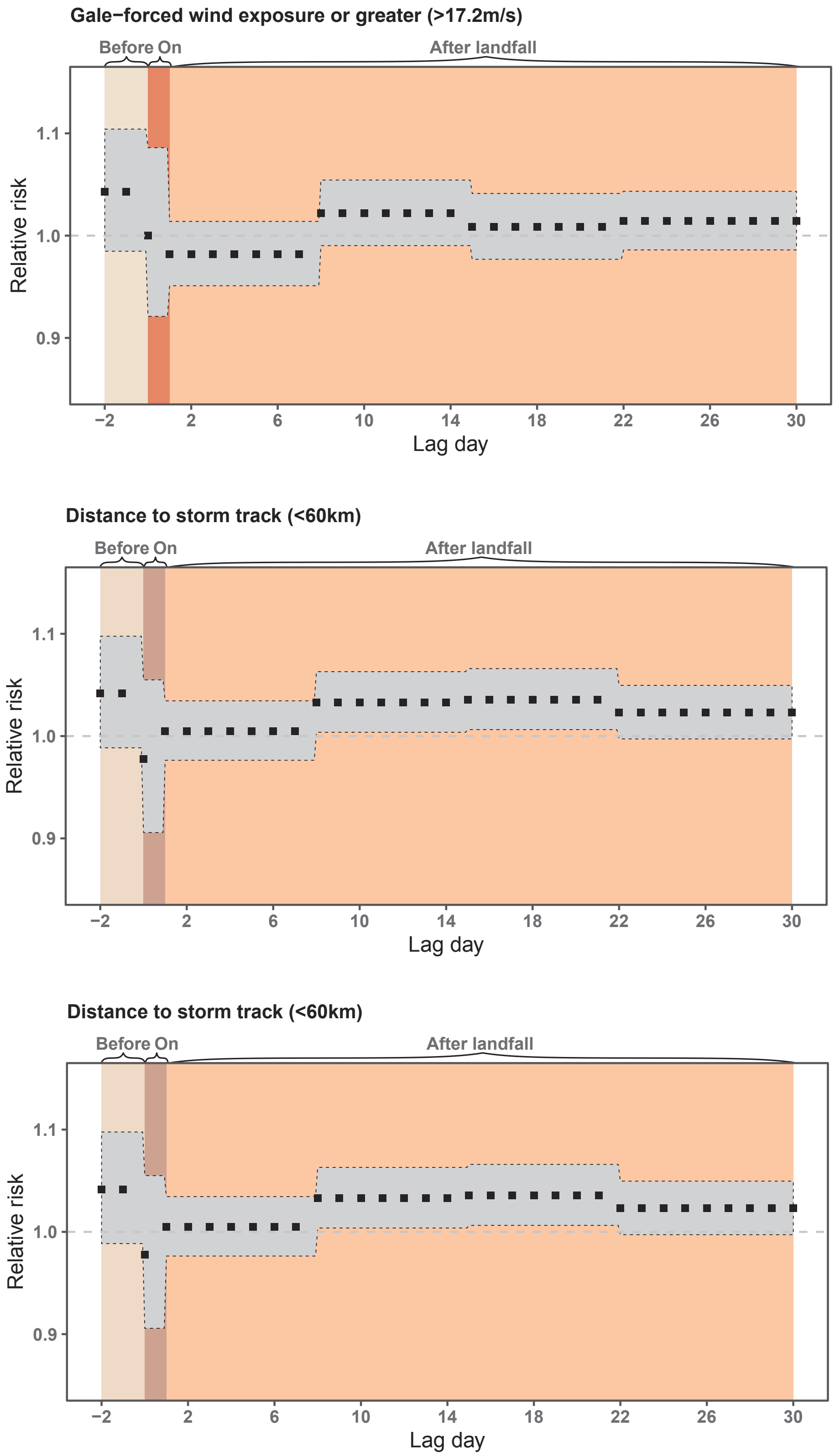
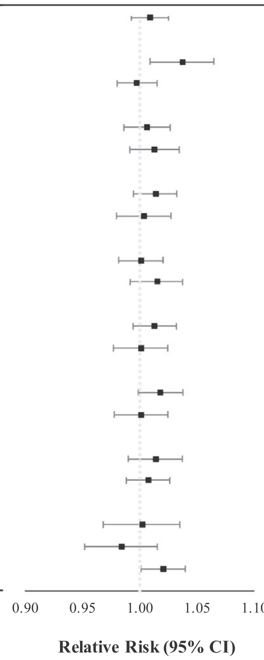


Fig. 2. Lag day-specific relative risk of preterm birth associated with tropical cyclones for different exposure metrics.

counties within the upper tertile of the social vulnerability index (11.4%).

As expected, tropical cyclone activity peaks in the months of August, September, and October across the 378 US counties (Fig. S3). Storms are heterogeneous in terms of their characteristics (e.g., wind speed or rainfall) and the locations or populations affected (Table 2 & Table S2). Thus, exposures defined according to different TC characteristics likely represent different populations at risk. For example, the number of pregnancies considered “exposed” was 3,024,973, 2,920,536, and 2,030,423 when defining TC exposure using peak sustained winds > 12 m/s, distance to storm track < 100 km, and cumulative rainfall > 75 mm, respectively. Moreover, populations at risk

Subgroup	Relative Risk (95% CI)	P Value for Effect Modification	Absolute Risk Difference, No. per 10,000 pregnancies (95% CI)	P Value for Effect Modification
All PTB	1.01 (0.99, 1.03)		9 (-7, 25)	
Sub-categories of PTB				
Early (<34 weeks)	1.04 (1.01, 1.07)	[Reference]	36 (10, 63)	[Reference]
Late (34-36 weeks)	1.00 (0.98, 1.02)	0.018	-2 (-20, 15)	0.017
Infant sex				
Male	1.01 (0.99, 1.03)	[Reference]	7 (-14, 28)	[Reference]
Female	1.01 (0.99, 1.03)	0.666	12 (-8, 33)	0.715
Maternal age, y				
<30	1.01 (0.99, 1.03)	[Reference]	14 (-5, 33)	[Reference]
≥30	1.00 (0.98, 1.03)	0.532	3 (-19, 26)	0.486
Marital status				
Married	1.00 (0.98, 1.02)	[Reference]	1 (-15, 17)	[Reference]
Unmarried	1.01 (0.99, 1.04)	0.368	20 (-11, 51)	0.274
Maternal race				
White	1.01 (0.99, 1.03)	[Reference]	11 (-5, 27)	[Reference]
Non-white	1.00 (0.98, 1.02)	0.429	1 (-34, 36)	0.619
Maternal education, y				
<13	1.02 (1.00, 1.04)	[Reference]	21 (-1, 43)	[Reference]
≥13	1.00 (0.98, 1.02)	0.273	1 (-18, 21)	0.182
Parity				
0	1.01 (0.99, 1.04)	[Reference]	14 (-10, 38)	[Reference]
≥1	1.01 (0.99, 1.03)	0.679	7 (-11, 26)	0.665
Social vulerability index				
Lower tertile	1.00 (0.97, 1.04)	0.442	2 (-26, 30)	0.421
Middle	0.98 (0.95, 1.02)	[Reference]	-16 (-47, 16)	[Reference]
Upper tertile	1.02 (1.00, 1.04)	0.055	23 (2, 44)	0.045



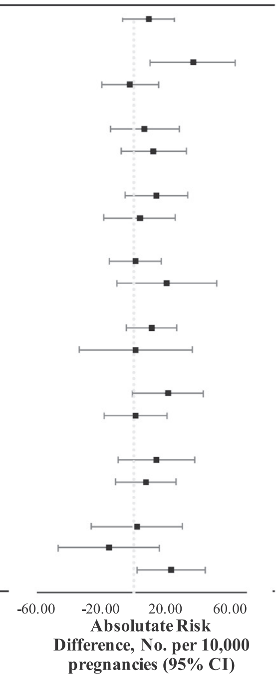


Fig. 3. The tropical cyclone-period relative risk of preterm birth associated with exposure to tropical cyclones that bring gale-force winds or greater by personal characteristics. Estimates over the entire storm period, from 2 days before to 30 days after the tropical cyclone's closest approach to the county's population mean center.

varied substantially by storms. For example, Hurricane Floyd in 1999 was the most pervasive TC for our study when defining TC exposure using cumulative rainfall > 75 mm, affecting 110 US counties and 349,069 pregnancies, while Tropical Storm Edouard in 2002 was affected 948 pregnancies in 2 US counties.

More preterm births were observed during TC periods versus matched non-TC periods, irrespective of which exposure definitions were used (Table 3). For example, there were 5 excess preterm births per 10,000 pregnancies at risk associated with exposure to TCs defined as having peak sustained winds > 17.2 m/s, 19 associated with exposure defined as < 60 km from the storm track, and 39 associated with exposure defined as > 100 mm cumulative rainfall.

In models adjusted for federal holiday, day of week, year, and the daily expected number of preterm births, the RR of preterm birth associated with TCs when using the exposure metric of peak sustained wind speeds > 17.2 m/s was 1.01 (95% CI: 0.99, 1.03) over the TC-period, or 9 (95% CI: −7, 25) additional preterm births per 10,000 pregnancies. A higher risk of preterm birth was observed when defining exposure based on distance to storm track or cumulative rainfall. For example, the RR and ARD per 10,000 pregnancies over the TC-period for exposure to TCs with tracks < 60 km from the counties were 1.02 (95% CI: 1.01, 1.04) and 23 (95% CI: 9, 38) and for TCs that bring > 100 mm rainfall were 1.04 (95% CI: 1.02, 1.06) and 36 (95% CI: 16, 56), respectively.

We next examined the time course of the association between TCs and risk of preterm birth by further examining the distributed lag function (Fig. 2). We observed an elevated RR before the TC and again one week after the date of TC landfall for wind- and distance-based TC exposures. For rainfall-based TC exposure, we observed a higher risk of preterm birth one week after the date of TC landfall.

To identify groups of expectant mothers that may be particularly susceptible to preterm delivery around the time of a TC, we conducted stratified analysis by personal characteristics and county's social vulnerability index (Fig. 3). We found the association between maternal exposure to TC and risk of preterm birth was more pronounced among early preterm births [RR: 1.04 (95% CI: 1.01, 1.07); *p*-value for interaction = 0.018; ARD: 36 (95% CI: 10, 63) per 10,000 pregnancies; *p*-value for effect interaction = 0.017] and mothers living in the tertile with the highest social vulnerability index [RR: 1.02 (95% CI: 1.00, 1.04); *p*-value for interaction = 0.055; ARD: 23 (95% CI: 2, 44) per 10,000 pregnancies; *p*-value for interaction = 0.045]. Results were not materially different across strata of infant sex, maternal age, marital status, education, race, or parity.

4. Discussion

This retrospective observational study of birth records from ∼20 million spontaneous live singleton births across 14 years and 378 counties in the eastern US provides suggestive evidence that maternal exposure to TC is associated with a higher risk of preterm birth. The association was stronger when focused on risk of early preterm birth and those mothers living in more socially venerable counties, but consistent across strata of individual-level demographic factors.

To our knowledge, only five prior epidemiologic studies have examined the association between TC exposure and risk of preterm birth, and results from these studies have been mixed. Our findings of a positive association between maternal TC exposure and risk of preterm birth are consistent with results from three of these studies (Grabich et al., 2016; Xiong et al., 2008; Yu et al., 2018). Grabich et al (2016) found that exposure of Florida residents to Hurricane Charley was associated with a higher risk of extremely preterm delivery (20–31 weeks of gestation), but not associated with a higher risk of any preterm birth (Grabich et al., 2016). Xiong et al. (2008) investigated adverse birth outcomes after Hurricane Katrina by comparing rates of preterm birth among pregnant women who had hurricane experience (self-reported "feeling that one's life was in danger") collected by questionnaire in

New Orleans (exposed to Hurricane Katrina) with pregnant women lived in Baton Rouge (nearly, but less exposed to Hurricane Katrina) (Xiong et al., 2008). They found women with versus without proximal hurricane experience had a 2.4-fold (95% CI: 1.00, 6.10) higher odds of preterm birth. The only published study of more than one hurricane (Yu et al., 2018) found exposure to high frequency of storm events during pregnancy was associated with a higher relative risk of preterm birth in Puerto Rico. On the other hand, our findings stand in contrast to the results from two pre-post analyses that found no evidence suggesting that exposure to Hurricane Katrina was associated with a higher risk of preterm birth (Hamilton et al., 2009; Harville et al., 2010b).

TCs vary substantially in terms of strength and related hazards (i.e., rainfall, flooding), and previous studies have used different exposure definitions (e.g., date of storm, sustained wind speed, hurricane experiences) to identify populations exposed to TCs. Both of these factors may contribute to the heterogeneity across prior studies. Furthermore, most previous studies focused on a single storm (Grabich et al., 2016; Hamilton et al., 2009; Harville et al., 2010b; Xiong et al., 2008). Due to differences in storm characteristics, populations affected, and community resilience, findings from any given single storm may not be generalizable to other storms, populations, or time periods. Finally, statistical analyses involving pre-post comparisons (Hamilton et al., 2009; Harville et al., 2010b) or using unexposed neighboring areas as controls (Xiong et al., 2008) may lead to residual confounding by either temporal trends or spatial gradients in the risk of preterm birth.

To our knowledge, this study is the first to examine the time course of the association between TCs and risk of preterm birth. We found that the risk of preterm birth was higher before TC landfall for the wind- and distance-based TC exposure, a finding that may be explained by excess psychological stress caused by TC (Zotti et al., 2013). Prior studies reported excess stress could alter maternal-placental-fetal endocrine function and functions of immune and vascular systems (Mulder et al., 2002; Wadhwa et al., 2011). Elevated maternal psychosocial stress is associated with a rise in placental corticotrophin-releasing hormone in late pregnancy (Mancuso et al., 2004; Sandman et al., 2006), higher circulating levels of inflammatory markers (e.g., IL-6, TNF-α) (Coussons-Read et al., 2007), and increased risk of hypertensive disorders in pregnancy (Yu et al., 2013), potentially leading to preterm labor.

We found the associations between TC exposure and risk of preterm birth were stronger for exposure metrics defined by distance from the storm track and cumulative rainfall versus wind speed-based metrics. Numerous factors potentially contributed to this pattern of results, including heterogeneity in TCs and heterogeneity in the populations affected by or community responses to different types of storms. The lack of a strong association with wind speed-based exposure metric might also be due to greater exposure misclassification for wind versus our other exposure metrics. If so, such exposure misclassification would be expected to be non-differential and on average bias our results towards the null hypothesis of no association. Finally, the infrastructure damage and health risks can also differ across different elements. For example, the delayed effects of rainfall associated with TC on preterm birth might plausibly be explained by environmental contamination (e.g., water contamination) (Wilson, 2006), mold (Wilson, 2006), and exacerbated by pre-existing diseases (e.g., asthma) (Kelly et al., 1995).

We found that the association between TC and risk of preterm birth was more pronounced among early versus preterm births. This finding is consistent with a study examining the effects of Hurricane Charley in Florida (Grabich et al., 2016). We speculate that this finding may be explained either by higher vulnerability to TC-related exposures for pregnant women earlier in gestation (Selevan et al., 2000), by higher probability of evacuation among pregnant women at later stage of pregnancy (Grabich et al., 2016), or some combination of these factors.

Our study has several potential limitations. First, lacking information on residential mobility during pregnancy may lead to exposure misclassification. However, rates of residential mobility during pregnancy are relatively low, with most moves being within the same county (Bell and Belanger, 2012; Pennington et al., 2017). Nevertheless, we expect that any potential exposure misclassification would be non-differential and on average tend to bias our results towards the null. Second, although we restricted our analyses to births identified as spontaneous deliveries, the sensitivity and specificity of this information is unknown (Schoendorf and Branum, 2006). If TCs play a larger role in spontaneous than induced preterm births, our results might be biased towards the null of no association. Third, although our analysis included 58 TCs across 14 years and 378 more populous eastern US counties, our results may not be generalizable to other storms or time periods due to heterogeneity of TC in terms of TC characteristics and affected locations and populations. Similarly, our results may not be generalizable to other counties with smaller populations or to more recent time periods. Fourth, as there is no consensus regarding which exposure metric should be used to define TC exposure, we used wind speed, distance to storm track, and cumulative rainfall. Future studies that characterize storms or storm damage more comprehensively or derive improved summary metrics combining multiple facets of storm and their impacts may be useful. Notwithstanding the above limitations, to our knowledge, this is the largest analysis of TC exposure and risk of preterm birth to date among ~20 million US spontaneous live singleton births and is one of the first to examine the time course of the association between TCs and risk of preterm birth.

5. Conclusions

In this large retrospective observational study, we found that maternal exposure to tropical cyclones was associated with a higher risk of preterm birth. If causal, our findings may be useful to the public, public health officials, and clinicians, especially in light of continued climate change and the expected increase in coastal populations in the coming century.

CRediT authorship contribution statement

Shengzhi Sun: Conceptualization, Writing - original draft, Formal analysis, Data curation, Investigation. **Kate R. Weinberger:** Methodology, Writing - review & editing. **Meilin Yan:** Methodology, Writing - review & editing. **G. Brooke Anderson:** Methodology, Resources, Writing - review & editing, Funding acquisition. **Gregory A. Wellenius:** Conceptualization, Methodology, Resources, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

Dr. Wellenius has served as a paid member of multiple expert panels for the Health Effects institute (Boston, MA) providing expertise on the health effects of air pollution. Dr. Wellenius currently serves as a paid visiting scientist at Google Research.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105825.

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