

# Expecting Mother Nature: Uncertain Hurricane Forecasts Disrupt Prenatal Care and Impair Birth Outcomes

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## Article

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# 1 Title Page

**Title:**

Expecting Mother Nature: Uncertain Hurricane Forecasts Disrupt Prenatal Care and Impair Birth Outcomes

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Hurricanes, Healthcare Services, Forecast Uncertainty, Birth Outcomes.

## 2 Abstract

Early forecasts give people in a storm's path time to prepare. Less is known about the cost to society when forecasts are incorrect. We examine over 700,000 births in the path of Hurricane Irene and find exposure led to a decrease in birth weights and increase in preterm and low birth weight outcomes. Additional warning time decreased preterm birth rates for women who experienced intense storm exposures documenting a benefit of avoiding a type II forecasting error. A larger share of this at-risk population experienced a type I forecasting error where severe physical storm impacts were anticipated but not experienced. Disaster anticipation disrupted healthcare services by delaying and canceling prenatal care leading to impaired birth outcomes. Recognizing storm damages depend on human responses to predicted storm paths is critical to supporting the next generation's developmental potential with judicious forecasts that ensure public warning systems mitigate rather than exacerbate climate damages.

### 3 Introduction

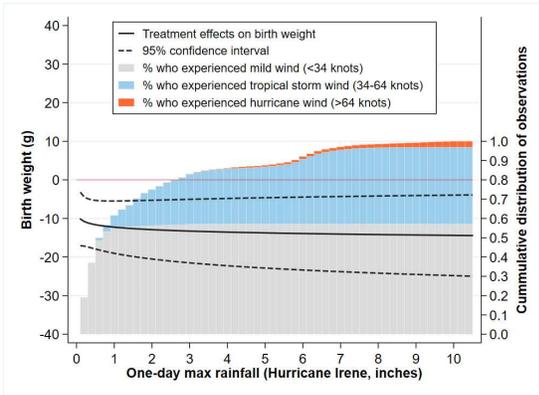
The best available climate science predicts an increase in high-intensity (1) and less predictable (2, 3) tropical storms. Despite the physical damages from these storms totaling over 500 billion dollars since 2004, National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (NHC) funding allocated to forecasting tropical storm threats continues to diminish (4). Media coverage supports advanced warning systems by forecasting potential threats to the masses. The goal of disaster forecasts is to avert damages to infrastructure, human health and well-being while recognizing that the broadcast itself will increase psychological stress in viewing populations (5). Yet, no large-scale study exists documenting the relationship between forecast accuracy and human health impacts in hurricane-threatened populations.

The release of highly uncertain disaster forecasts may represent a public health threat for several reasons. Disaster-related media coverage has long been shown to contribute to post-traumatic stress disorder symptoms in viewers (6, 7). New evidence reveals that forecasted posttraumatic stress symptoms, leading up to a hurricane event, influences the public's mental health before and after a hurricane event (5). Taken together, NHC storm forecasts, such as the "Cone of Uncertainty," which are often misinterpreted by the public (8) but widely disseminated by the media, may cause substantial distress to viewing populations. Such a public health threat is most preventable in communities that expect and prepare for a hurricane exposure that does not end up generating physical impacts - i.e., a type I forecasting error.

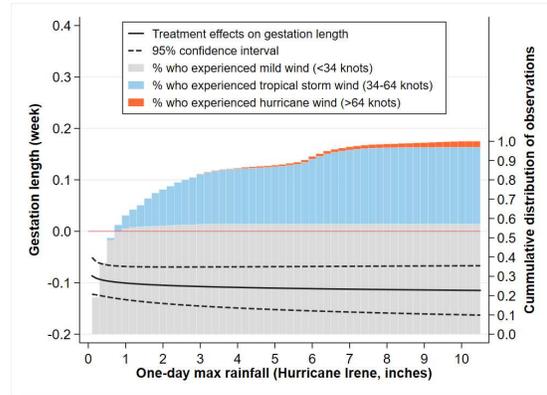
Experiencing a disaster during pregnancy can impair birth outcomes (9–12) and disrupt access to healthcare services (13–16), which may have long-run implications for the unborn child's livelihood (11, 17, 18). In utero exposure to stress (12), environmental toxins (19, 20) and disrupted access to health services (21) are leading explanations for observed reductions in birth weight and gestation lengths. Causal linkages between these birth outcomes and later life disease prevalence (22, 23), mental health (12), aptitude, educational attainment and future wages (17) have been established. No study to date has isolated these underlying mechanisms empirically and measured the extent to which institutions influence birth outcomes by disseminating uncertain disaster forecasts to the public.

### Results

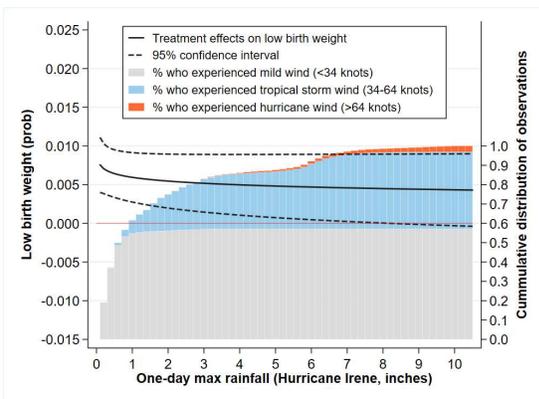
We find that *in utero* exposure to Hurricane Irene created widespread and detrimental impacts to birth outcomes. Herein we report birth impacts as an average across all rainfall intensity bands with associated 95% confidence intervals (CI) in parentheses. Importantly, we find that birth impacts do not vary meaningfully across storm exposure intensity, which is reinforced by overlaying a cumulative distribution of wind exposures and estimated treatment effects (Fig. 1). The average *in utero* exposure to Hurricane Irene reduced birth weights by 12.7g (5.4g to 20.0g), which represents a 0.17% to 0.61% reduction on the birth weight sample mean ( $\bar{x}^{bw}=3,263.7g$ ). The largest treatment effect of 14.4g (-3.9g to -25.0g) is estimated for populations receiving hurricane-force winds and a one-day maximum rainfall in excess of 10 inches and the smallest



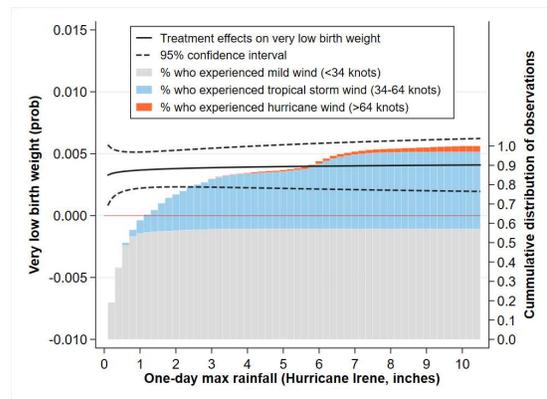
(a) Birth weight (g)



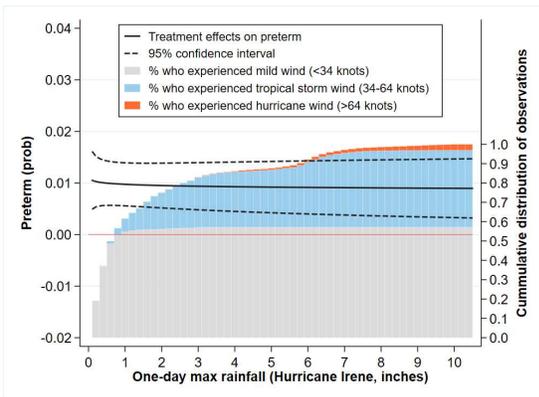
(b) Gestation length (wks)



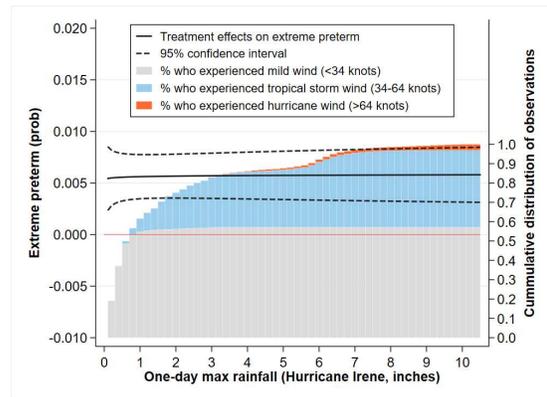
(c) Low birth weights (<2500 g)



(d) Very low birth weight (<1500 g)



(e) Preterm birth (<37 weeks)



(f) Extremely preterm birth (<34 weeks)

Figure 1: Estimated treatment effect of Hurricane Irene exposure on birth outcomes plotted across rainfall intensity at pregnant woman’s residential address. Rainfall at residential address is used as an indicator of exposure intensity represented by the one-day maximum rainfall from August 14, 2011 to September 4, 2011, which encompasses the hurricane event’s impact on North Carolina. Rainfall source: PRISM climate group Time Series Values for Individual Locations

treatment effect of 10.1g (-3.2g and -17.1g) is estimated for populations receiving less than 1 inch of rainfall and only mild winds (Fig. 1.a).

Gestation lengths were also shortened following *in utero* exposure by an average of 0.10 weeks (0.07 weeks to 0.14 weeks), which represents a 0.18% to 0.36% reduction on the gestation length sample mean ( $\bar{x}^{gest}=38.5$  weeks). The largest treatment effect of 0.11 weeks (0.07 weeks to 0.16 weeks) is estimated for populations receiving hurricane-force winds and a one-day maximum rainfall in excess of 10 inches and the smallest treatment effect of 0.09 weeks (0.05 weeks to 0.12 weeks) is estimated for populations receiving less than 1 inch of rainfall and only mild winds (Fig. 1.b).

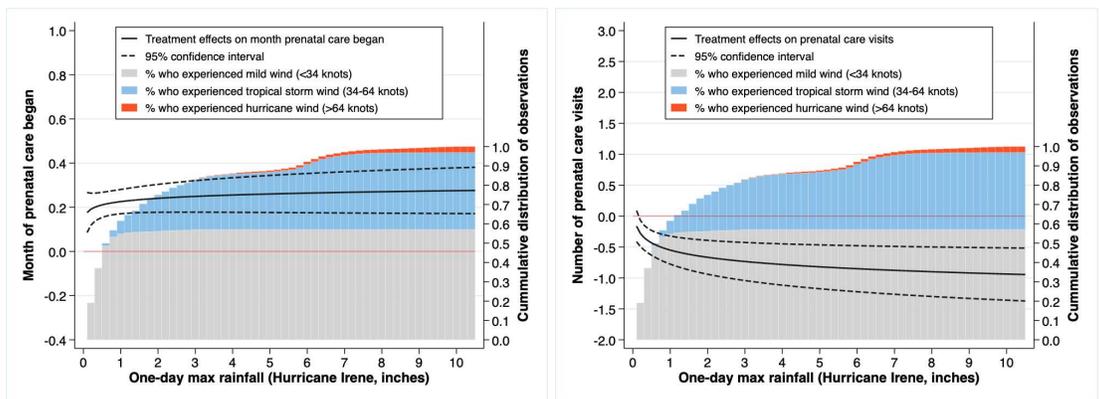
A similar pattern is revealed for increased likelihood of experiencing low birth weight, very low birth weight, preterm and extremely preterm birth outcomes following *in utero* exposure to Hurricane Irene. Each of these birth impacts are significant but statistically indistinguishable in magnitude across our wind and rainfall indicators for exposure intensity (Fig. 1). The incidence of low birth weight outcomes increased by 0.56 percentage points (0.22 percentage points to 0.90 percentage points), which represents a 2.52% to 10.34% increase in the likelihood of a low birth weight outcome on the sample mean ( $\bar{x}^{lbw}=0.087$ ) (Fig. 1.c). The incidence of very low birth weight outcomes increased by 0.38 percentage points (0.23 percentage points to 0.52 percentage points), which represents a 15.33% to 34.67% increase in the likelihood of a very low birth weight outcome on the sample mean ( $\bar{x}^{vlbw}=0.015$ ) (Fig. 1.d). The incidence of preterm births increased by 0.96 percentage points (0.53 percentage points to 1.38 percentage points), which represents a 5.20% to 13.53% increase in the likelihood of a preterm birth on the sample mean ( $\bar{x}^{pre}=0.102$ ) (Fig. 1.e). The incidence of extremely preterm births increased by 0.56 percentage points (0.35 percentage points to 0.78 percentage points), which represents a 12.07% to 26.90% increase in the likelihood of an extremely preterm birth on the sample mean ( $\bar{x}^{expre}=0.029$ ) (Fig. 1.f).

We would expect that a higher intensity of rainfall and wind would be associated with more drastic birth impacts. The consistency in our measured birth impacts across storm exposure intensity is unexpected and may suggest that birth impacts are being driven by a mechanism other than physical storm exposures. We further investigate the nature of potential physical exposures by focusing on statewide groundwater contamination. During Hurricane Irene, over 2 million individuals that represent over 20% of North Carolina's population (24) relied on private wells that are federally unregulated and particularly vulnerable to contamination from severe weather and flooding events (25–28).

We examine over 17,000 private well water samples that were collected by county health offices statewide and processed through the North Carolina State Laboratory of Public Health. We focus on nitrate, manganese, lead, chromium, cadmium and arsenic results, which are all known to disrupt *in utero* development and have exposure pathways related to major storm events (29–34). While these samples are not taken from the same residences of our pregnant women sample, both data sets have statewide and residence-level coverage and use the same selection into treatment window around Hurricane Irene. This approach provides an indicator of potential environmental exposures that may explain the observed statewide hurricane-linked

birth impacts. Reinforcing our suspicion that observed birth impacts are driven by a mechanism other than the physical impacts of Hurricane Irene, we find no meaningful relationship between storm exposure intensity and private well water contamination rates (Fig. A.1).

We also examine a suite of medical risk factors reported for each pregnant woman within our data set (Fig. A.2). Systematic geographic sorting along socioeconomic lines, which may have occurred during our sample window, could reasonably explain observed birth impacts. In such a case, we would expect prediagnosed medical risk factors to vary systematically between our treatment and control groups. We focus on the incidence of prepregnancy hypertension and having previously had a poor pregnancy outcome for each individual within our sample. Previously poor pregnancies include those that resulted in perinatal death, small-for-gestational age or intrauterine growth restricted births. We find no relationship between selection into treatment (or intensity of treatment) and the presence of a prepregnancy hypertension or previous poor pregnancy diagnosis (Fig. A.2). We then focus on the incidence of gestational hypertension and eclampsia that may have developed during pregnancy. To the extent that maternal stress from experiencing a severe storm event is driving observed birth impacts, we might expect gestational hypertension and eclampsia rates to be elevated in our treatment group. We find no evidence of increased incidence of gestational hypertension or eclampsia relative to our baseline group (Fig. A.2).



(a) Month that prenatal care began (N=582,407)      (b) Number of prenatal care visits (N=702,336)

Figure 2: Estimated treatment effect of Hurricane Irene exposure on the month that prenatal care began and the number of prenatal care visits. Rainfall at residential address is used as an indicator of exposure intensity represented by the one-day maximum rainfall from August 14, 2011 to September 4, 2011, which encompasses the hurricane event’s impact on North Carolina. Rainfall source: PRISM climate group Time Series Values for Individual Locations

We turn our attention to the disruption of healthcare services from hurricane exposure that might impact birth outcomes. For each birth in our analysis, we examine the impact of hurricane exposure intensity on the month that prenatal care began following the clinically-determined conception date ( $N = 582,407$ ) and the total number of prenatal care visits that occurred

throughout the pregnancy ( $N = 702, 336$ ). Both prenatal care indicators suggest that hurricane exposure creates a disruption of access to healthcare services (Fig. 2). The average *in utero* exposure to Hurricane Irene delayed the first prenatal care appointment by 0.24 months (0.18 months to 0.30 months), which represents an approximate 1 week or 6.92% to 11.54% delay on the sample mean of when prenatal care was initiated ( $\bar{x}^{beg.}=2.60$ ). The total number of prenatal care appointments is reduced on average by 0.63 appointments (0.37 appointments to 0.89 appointments) following in utero exposure to Hurricane Irene, which represents a 3.03% to 7.29% reduction on the sample mean of total prenatal care appointments ( $\bar{x}^{app.}=12.21$ ). Similar to the observed impacts of Hurricane Irene on birth outcomes, we observe that prenatal care disruptions are significant but vary little across the intensity of storm exposures. Such a finding suggests that the anticipation of hurricane exposures and associated institutional responses to that anticipation, rather than the physical impacts from the storm itself, may be the driving force that disrupts healthcare services.

To better understand the connection between hurricane anticipation and observed birth impacts, we overlay the National Hurricane Center's "Cone of Uncertainty" forecasts for Hurricane Irene with the residential addresses of all pregnant women within our sample. The spatial extent of the Cone of Uncertainty represents a zone that will contain the "eye" of an impending hurricane with approximately 66% confidence. Variation in hurricane anticipation is given by the total hours that each residential address within our sample spends within this cone (Fig. 3). The cone first overlapped with North Carolina at 9:00am on August 22, 2011 and scraped across the state until the hurricane's eye was over the northeastern corner of the state at 9:00pm on August 27th (Fig. 3).

We stratify our sample into three categories that experienced light rainfall (<1 inch of rain within the most intensive 24 hour period), moderate rainfall (1-2 inches of rain within the most intensive 24 hour period) and heavy rainfall (>2 inches of rain within the most intensive 24 hour period) during Hurricane Irene. Following the same empirical approach as previous analyses, our baseline group of comparison represents births from residential addresses that *would have* experienced the same light, moderate and heavy rainfall conditions if their pregnancies had overlapped with Hurricane Irene - i.e, births occurred in the same location but at a slightly later time. Separating the sample into categories of physical exposure allows us to measure the additional benefit (or harm) that results from advanced warning that signals potential impact ahead of a storm event that ends up bringing either mild, moderate or severe weather.

In other words, our approach isolates both (i) the reproductive health benefits of an advanced warning system that avoids a type II forecasting error - i.e., correctly provides additional warning time to vulnerable populations that receive intense physical exposures - and the reproductive health harm of an advanced warning system that commits a type I forecasting error - i.e., incorrectly provides additional warning to vulnerable populations that only receive mild physical exposures. In such a latter case, additional exposure anticipation may lead to the (*ex post unnecessary*) cancellation of prenatal care appointments, which may inadvertently cause harm to birth outcomes.

The average individual that received heavy rainfall experienced an average of 15.9 6-hour

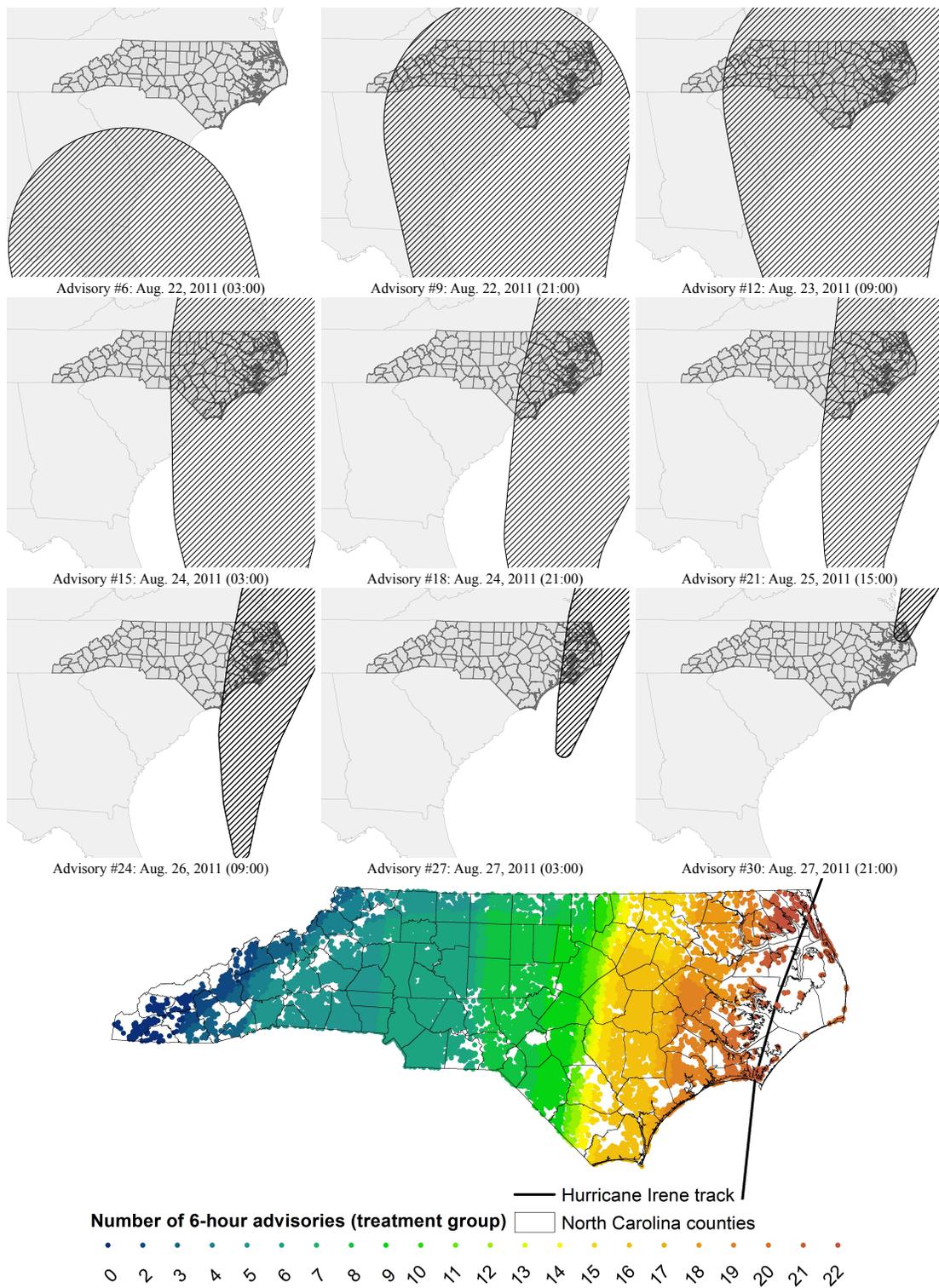


Figure 3: Total number of 6-hour advisories experienced within the Cone of Uncertainty for the residential address of each woman within Hurricane Irene’s treatment sample.

Table 1: Treatment effect of an additional six-hour ‘‘Cone of Uncertainty’’ advisory .

Birth outcomes	Effect of an additional advisory		
	Rain > 2in	1in < Rain ≤ 2in	Rain ≤ 1in
Birth weight (g)	1.391 (1.099)	-4.815 (3.023)	-4.111*** (1.449)
Mean dept. var.	3252.378	3281.767	3263.981
Gestation length (wk)	0.00357 (0.00304)	-0.0201 (0.0123)	-0.0201 (0.0131)
Mean dept. var.	38.526	38.544	38.543
Low birth weight (<2500g)	-0.000629 (0.000403)	0.00122 (0.00113)	0.00206* (0.00105)
Mean dept. var.	0.090	0.084	0.087
Very low birth weight (<1500g)	0.000131 (0.000218)	0.000488 (0.000579)	0.000846* (0.000484)
Mean dept. var.	0.016	0.015	0.015
Preterm (< 37 wks)	-0.00126** (0.000496)	0.00197 (0.00152)	0.00114* (0.000666)
Mean dept. var.	0.103	0.102	0.102
Extreme preterm (< 34 wks)	0.000273 (0.000290)	0.000514 (0.000898)	0.00139* (0.000703)
Mean dept. var.	0.030	0.030	0.029
Observations	177425	95056	436233

periods within Hurricane Irene’s cone of uncertainty (approximately 95 hours). For these individuals, the prediction of direct hurricane exposure was *ex post* correct and additional time spent within the cone of uncertainty served as an accurate risk signal to prepare for imminent exposure. We find that the marginal effect of an additional six hour window of preparation for these heavily-exposed populations had no meaningful impact on birth outcomes, gestation length or the incidence of low birth weight, very low birth weight or extreme preterm birth outcomes. We find that additional advisories for this group of women led to a statistically significant decrease in the likelihood of having a preterm birth, which represents a 1.2% reduction on the heavily-exposed sample mean ( $\bar{x}^{pret}=0.103$ ).

The average individual that received light rainfall experienced an average of 6.5 6-hour periods within Hurricane Irene’s cone of uncertainty (approximately 39 hours). For these individuals, the prediction of direct hurricane exposure was *ex post* incorrect and additional time spent within the cone of uncertainty served as an inaccurate risk signal that may have disrupted unnecessarily planned healthcare services. We find that the marginal effect of residing within the cone for an additional six hour window decreased birth weights by 4.1 grams for this lightly-

exposed population, which represents a 0.13% reduction in birth weight on the lightly-exposed sample mean ( $\bar{x}^{bw}=3264.1$ ). For this group, we also find that an extended time of anticipating direct impact leads to a marginally significant increase in the incidence of low birth weight, very low birth weight, preterm and extreme preterm births. The marginal impact on low birth weight incidence is 0.0021, which represents a 2.4% increase in the likelihood of a low birth weight outcome on the lightly-exposed sample mean ( $\bar{x}^{lbw}=0.0869$ ). The impact on very low birth weight outcomes is relatively larger, 0.0008, which represents a 5.4% increase in the likelihood of a very low birth weight outcome on the lightly-exposed sample mean ( $\bar{x}^{vlbw}=0.0147$ ). We observe a similar trend for preterm and extreme preterm births. The marginal impact on preterm incidence is 0.0011, which represents a 1.1% increase in the likelihood of a preterm birth on the lightly-exposed sample mean ( $\bar{x}^{pret}=0.1016$ ). The impact on extreme preterm births is relatively larger, 0.0014, which represents a 4.9% increase in the likelihood of a very low birth weight outcome on the lightly-exposed sample mean ( $\bar{x}^{expret}=0.0287$ ).

## 4 Discussion

The findings represent the first evidence that uncertain hurricane forecasts lead to individual-level disruptions in healthcare services. These impacts on birth outcomes are similar in magnitude to those found in response to other traumatic events experienced during pregnancy, such as nearby terrorist attacks (35), bereavement (12) and financial hardship (36). A key distinction is that the driving mechanism of exposure is a public warning system that is designed to mitigate rather than exacerbate the impacts of storm events on threatened populations. Studies such as ours are a first step to timing the optimal dissemination of disaster forecasts.

Findings highlight the importance of understanding risk preferences of disaster-threatened populations and institutions. In the case of Hurricane Irene, the early release of the storm track forecast triggered a precautionary response by patients and healthcare providers. The decision to cancel healthcare appointments was driven by risk averse preferences among these groups. However, the spatial extent of those cancellations was determined by the amount of forecast uncertainty. As such, we discover that this combination of risk averse preferences and forecast uncertainty during Hurricane Irene disproportionately harmed the unborn. On the margin, delaying the release of Hurricane Irene's storm forecast release would have improved birth outcomes (birth weight, low birth weight and preterm outcomes) for 2.5 women relative to each woman for which the delay would have impaired birth outcomes (increased preterm births). Evaluating the impact of storm forecast uncertainty in this way has the potential to guide cost-benefit analyses for the research and development of improved storm prediction models.

The findings presented herein provide direction for several areas of future research. Empirically, heterogeneity in the estimated treatment effects should be explored to support future policy implications. Hurricane "experience" may mediate observed healthcare disruptions, which could be investigated by linking residential addresses with historical storm events and real estate records. Trimester of exposure should also be investigated to identify populations

that are most vulnerable to disruptions in health care. Behaviorally, our analysis is unable to predict the psychological impacts of a delayed storm forecast. The ambiguity (rather than uncertainty) surrounding a low-information scenario may trigger similar precautionary responses by individuals and institutions during the anticipation phase of delayed official storm forecasts. Here, future research should examine how public risk responses are likely to differ in disaster scenarios characterized by extreme ambiguity.

## Data and Methods

Our analysis is based on the North Carolina Department of Health and Human Services (NCDHHS) vital statistics data set for all North Carolina live and still births from August 26th, 2006 to June 14th, 2012. We construct a data set of 710,186 North Carolina birth outcomes with associated prenatal care and medical risk factor information that are georeferenced at the residential address level. Birth outcomes include birth weight (g) and gestation length (weeks) variables that are used to create binary indicators for low birth weight (<2,500 g), very low birth weight (<1,500 g), preterm (<37 weeks) and extreme preterm (<34 weeks) outcomes. Associated prenatal care indicators include the number of prenatal care visits and the gestational month in which prenatal care began. Medical risk factors include indicators for prepregnancy and gestational hypertension.

We focus on the North Carolina impacts of Hurricane Irene, which made landfall August 27, 2011. Births that occurred in the five years prior to the hurricane's impact serve as a baseline of comparison against births experiencing *in utero* exposure to Hurricane Irene. Incorporating zip code and monthly fixed effects ensures that our estimation procedure isolates the impact of hurricane exposure on birth outcomes rather than local social and institutional factors (37–40) and seasonal trends (41–44). An annual time trend is also included to control for background trends in birth outcomes from 2006 to 2012. In all analyses, standard errors are clustered at the county level, which is the level of public health services and data collection throughout North Carolina. Clustering at the county level allows for arbitrary serial correlation across births within the same county over time.

Pre-hurricane births serve as a control group for post-hurricane births. Constructing the data set in this way exploits the fact that pre-natal, but not post-natal, exposure to a disaster may influence birth outcomes. Our empirical strategy hinges on the assumption that pregnant women did not select into treatment. We present layers of evidence that this assumption is reasonable and that our results glean insight into the causal nature of *in utero* exposure to hurricanes on birth outcomes. Precise birth dates and residential addresses allow us to control for local neighborhood and seasonality effects that are known to otherwise influence birth outcomes. We then use variation in a woman's residential location relative to the NHC's *ex ante* "Cone of Uncertainty" forecasts and the hurricane's *ex post* storm track and associated rainfall intensities. We focus on the effects of *in utero* exposure to disaster stress by identifying women who anticipated direct hurricane impact but were not necessarily exposed to severe weather because of the storm's changing trajectory.

The selection of births includes each woman’s expected delivery date, which is defined as 280 days after the clinically-estimated date of conception. An expected delivery date within five years leading up to the Hurricane Irene disaster declaration date, August 25th, 2011, is placed into the control group and an expected birthdate within the 280 days following Hurricane Irene is placed into the treatment group. Constructing the sample in this way includes all births that experience pre-natal or post-natal exposure to Hurricane Irene within the relevant time window.

Construction of the data set follows convention in the literature (12, 45) and helps overcome two empirical challenges. First, opting to define the treatment window based on actual birth dates creates a mechanical correlation between gestation length and the likelihood that a pregnant woman experiences a hurricane – i.e., longer gestation lengths lead to larger birth weights and an increased likelihood that hurricane exposure occurred during the pregnancy. Second, a large literature and our findings suggest exposure to a disaster influences gestation length. Defining the treatment window based on expected birth dates, rather than actual birth dates, ensures that the treatment window is predetermined at the time of Hurricane Irene’s arrival – i.e., there is no selection of women into treatment from exposure (12, 45).

Formally, the sample selection contains a treatment group and a control group. The treatment group is all pregnant women residing in North Carolina during Hurricane Irene’s disaster declaration date and within the first 40 weeks following their approximate date of conception (*c*). We define the child’s expected birth date as  $e^b = c + 280$ . The control group contains all women whose births were within  $x$  days of Hurricane Irene. We include a full five years,  $x = 1, 825$ , of control group expected birth dates to ensure that we are able to account fully for seasonality effects in birth outcomes.

The sample selection of Hurricane Irene births follows (11) and (12) and is

$$S = \left\{ i : \mathbf{1}[c \leq \text{August 25, 2011} \leq b]_i = 1 \mid \mathbf{1}[b < \text{August 25, 2011} \leq b + x]_i = 1 \right\}.$$

Our data set includes the residential address and birth date for each observation. We geocode these residential addresses into (x,y) decimal degree coordinate using the ArcGIS geocoder application programming interface (API) for Python (1.5.2). The coordinates were then converted into georeferenced points and used to calculate the distance of each residential location to the nearest point along a dissolved version of NOAA’s preliminary best track from the National Hurricane Center’s Geographic Information System (GIS) Archive - “Tropical Cyclone Best Track”. Distance calculations were conducted using the UTM zone 17N projection. NOAA’s NHC GIS sources were also used to overlay Hurricane Irene’s “Cone of Uncertainty” predictions from advisory #7, which occurred on August 22, 2011 at 9:00am and represented the first time that the Hurricane Irene 5-day cone approached the border of North Carolina, to advisory number #30A, which occurred on August 27, 2011 at 11:00pm and represented the final intersection of North Carolina and Hurricane Irene’s 5-day “Cone of Uncertainty” (Figure 3).

We also merge the North Carolina State Laboratory of Public Health’s statewide private drinking water well samples that were collected and processed during our Hurricane Irene treatment and control time periods. Comprehensive samples for arsenic, cadmium, chromium, lead,

manganese and nitrate are all collected because they are known to cause adverse effects on birth outcomes when ingested during pregnancy. Further, each contaminant may be plausibly related to hurricane-exposure conditions or indicative of geographic sorting among pregnant women in response to risk. Together, these water samples help us determine the underlying cause of observed birth outcomes and rule out the selection of women into treatment by geographic sorting along socioeconomic lines. Each inorganic analyte is coded as a binary outcome based on whether the sample exceeded the U.S. EPA’s safe drinking water standards. Our NCDHHS data set also includes the number of prenatal visits that occurred during each woman’s gestation period, the month that prenatal care began and information on whether prepregnancy hypertension, gestational hypertension, eclampsia and having prior had a poor pregnancy (including perinatal death and small-for-gestational age/intrauterine growth restricted births) were diagnosed as a medical risk factor.

Consistent with prior work (46), we hypothesize that hurricane exposures lead to reduced birth weights and gestation lengths and an increased likelihood of a preterm and low birth weight outcomes. Rainfall at each residential address is used as an indicator of exposure intensity represented by the one-day maximum rainfall from August 14, 2011 to September 4, 2011, which encompasses the hurricane event’s impact on North Carolina. Rainfall data are from the PRISM climate group Time Series Values for Individual Locations. For the control group, rainfall data from Hurricane Irene are similarly overlaid with residential addresses *as if* these residences experienced physical exposures. However, our selection into treatment criteria ensures that only those women within our treatment group experienced uterine exposure whereas postnatal exposure in our control group cannot impact uterine conditions or birth outcomes of infants that were born before the hurricane’s arrival. Conditioning on rainfall intensity in this way enables a comparison of women in the treatment and control groups who presumably share similar socioeconomic and demographic characteristics because they reside in the regions that would have been similarly exposed to Hurricane Irene’s physical impacts.

Our estimating equation is

$$y_{iy mz} = \beta_0 + \beta_1 E_{iy mz} + \beta_2 \ln R_{iy mz} + \beta_3 E_{iy mz} \times \ln R_{iy mz} + \mu_m + Year + \zeta_z + \varepsilon_{iy mz}, \quad (1)$$

for a woman  $i$  who resided in zipcode  $z$  whose birth took place in month  $m$  of year  $y$ . The variable  $E_{iy mz}$  is a binary variable that takes the value of 1 if her birth is in the treatment group and 0 otherwise. That is,  $E_{iy mz} = \mathbf{1}[c \leq August\ 25, 2011 \leq e^b]_{iy mz}$ . The variable  $\ln R_{iy mz}$  is the natural logarithm of the 24-hour maximum rainfall that the woman experienced during the hurricane week. The variables  $\mu_m$  and  $\zeta_z$  are month and zip code fixed effects. The variable  $Year$  is a linear year trend. The dependent variable,  $y_{iy mz}$  is the birth outcome of each woman. Our estimating equation resembles (12) but includes an exposure intensity variable that is interacted with the treatment group binary variable. Mediating the intensity of exposure in this way allows us to estimate non-linear impacts of hurricane exposure, across rainfall intensity, on North Carolina’s birth outcomes. Standard errors for all regressions are clustered across the State of North Carolina’s 100 counties, which is the level of public health services and data

collection throughout North Carolina. Clustering at the county level allows for arbitrary serial correlation across births within the same county over time.

After Equation (1) is estimated, we calculate the treatment effect of hurricane exposure on birth outcome,  $\psi$ , as a function of  $R_{iy mz}$

$$\psi(R_{iy mz}) = y|_{E=1} - y|_{E=0} = \beta_1 + \beta_3 \ln R_{iy mz}, \quad (2)$$

which is the basis for Figures 1, 2, A.1, A.2 and Table 1 with expanded summary statistics available in Table A.1. To examine the effect of hurricane anticipation on birth outcomes, we augment the estimating equation as follows

$$y_{iy mz} = \beta_0 + \beta_1 E_{iy mz} + \beta_2 \ln R_{iy mz} + \beta_3 C_{iy mz} + \beta_4 E_{iy mz} \times C_{iy mz} + \mu_m + Year + \zeta_z + \varepsilon_{iy mz}, \quad (3)$$

where  $\ln R_{iy mz}$  is the natural logarithm of the 24-hour maximum rainfall that the woman experienced (or would have experienced) at her residential address,  $E_{iy mz}$  is the treatment binary variable and  $y_{iy mz}$  is the birth outcome. The variable  $C_{iy mz}$  is the number of six hour advisories for which a woman's residence was within Hurricane Irene's cone of uncertainty. Such variation in advisories reveals the intensity of type I errors for those locations that experienced only mild weather exposures. The coefficient  $\beta_4$  is the marginal effect of an additional advisory at the residence of an individual in the treatment group. While no advisories occurred for women in the control group, we calculate these advisories using the same approach to ensure that geographic factors are fully controlled. This approach, and interacting our advisory variable with our exposure indicator, ensures that our estimated marginal effects are unique to exposed women, not driven by other geographic factors local to where advisories were issued.

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## Supplementary Material

Table A.1: Full sample summary statistics (inclusive of treatment and control groups).

<b>Variable</b>	<b>Mean</b>	<b>Std. Dev.</b>	<b>Min.</b>	<b>Max.</b>	<b>N</b>
Birth weight (g)	3263	601	28	6435	710186
Gestation length (wk)	38.54	2.13	23	45	710310
Low birth weight (<2500g)	0.087	0.282	0	1	710310
Very low birth weight (<1500g)	0.015	0.122	0	1	710310
Preterm (< 37 wks)	0.102	0.302	0	1	710310
Extreme preterm (< 34 wks)	0.029	0.168	0	1	710310
Month prenatal care began	2.6	1.447	0	9	582407
Number of prenatal care visits	12.21	4.01	0	49	702336
One-day max rainfall	1.60	2.11	0	10.21	709613
Number of 6-hour advisories	9.27	4.64	0	22	710310

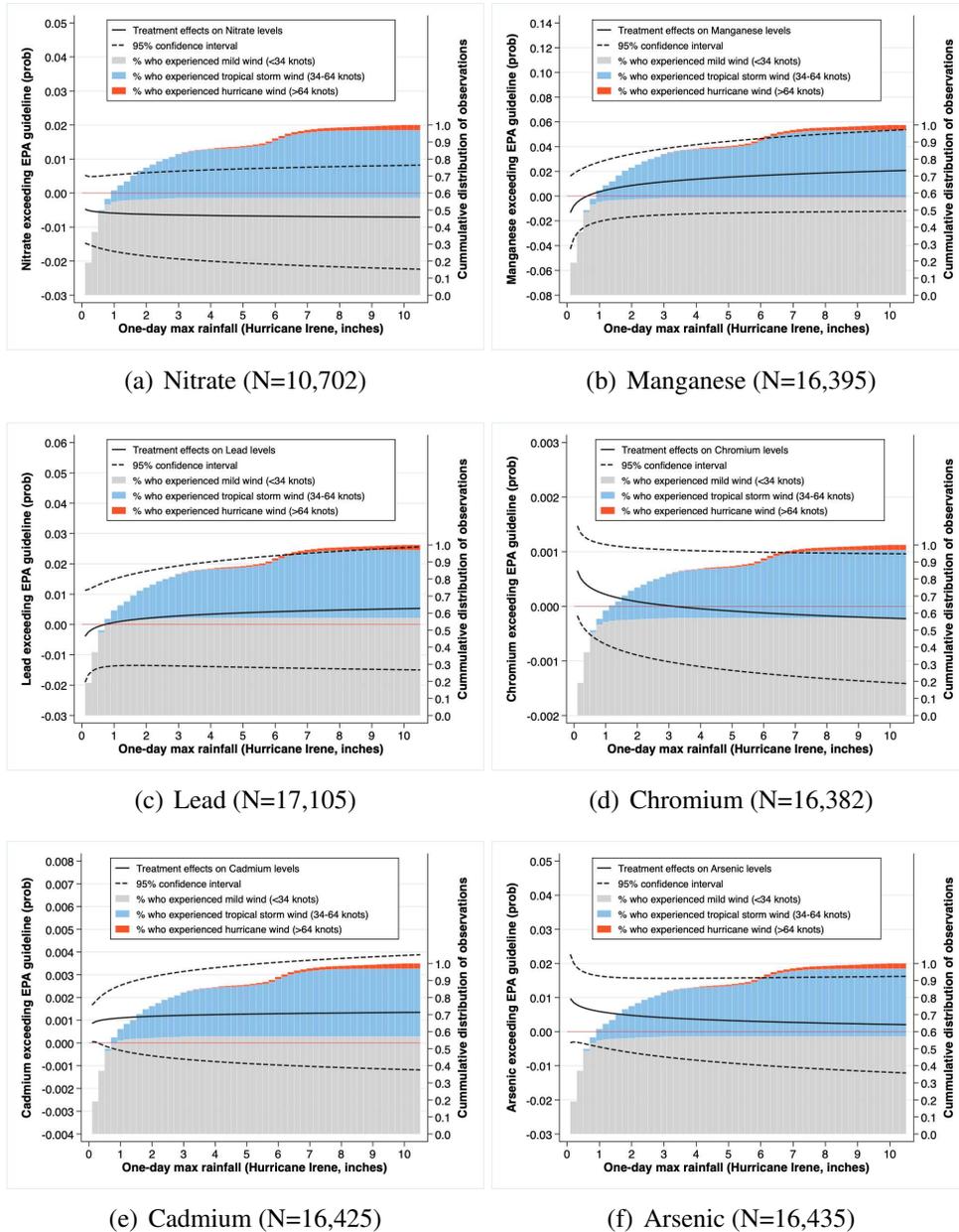
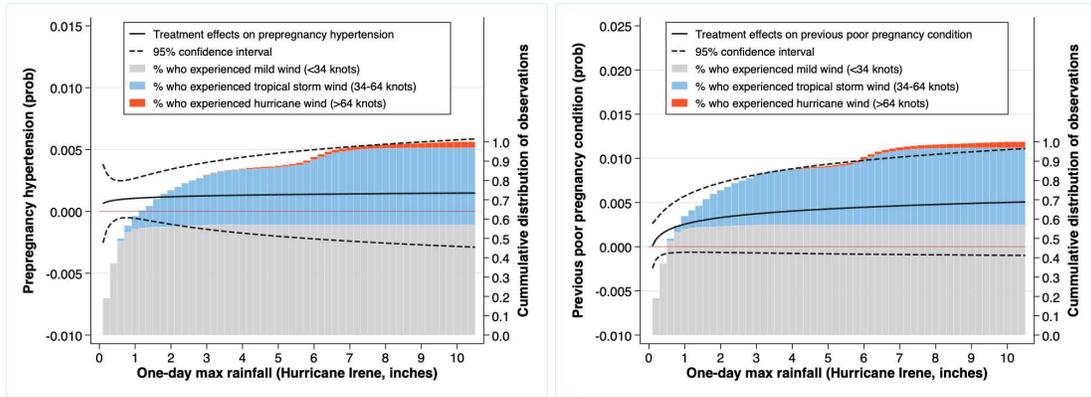
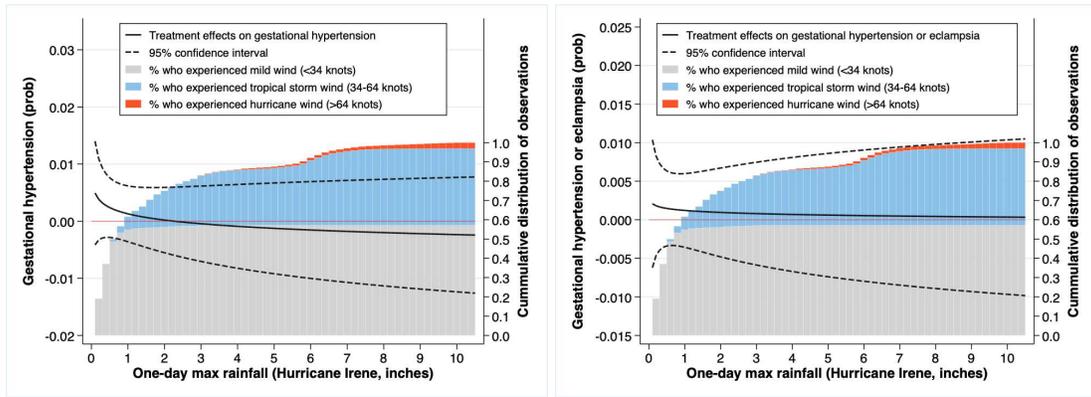


Figure A.1: Estimated treatment effect of Hurricane Irene exposure on the likelihood of a private well water sample exceeding EPA guidelines for nitrate, manganese, lead, chromium, cadmium and arsenic. Rainfall at residential address where well water sample was taken is used as an indicator of exposure intensity represented by the one-day maximum rainfall from August 14, 2011 to September 4, 2011, which encompasses the hurricane event's impact on North Carolina. While well water samples were not taken from the same residences as our pregnant women sample, the same selection into treatment criteria was used for sampling date, rather than conception date. Rainfall source: PRISM climate group Time Series Values for Individual Locations.



(a) Diagnosed with prepregnancy hypertension (b) Previously experienced a poor pregnancy outcome



(c) Diagnosed with gestational hypertension (d) Diagnosed with gestational hypertension or eclampsia

Figure A.2: Estimated treatment effect of Hurricane Irene exposure on the likelihood of being diagnosed with various medical risk factors (prepregnancy hypertension, previous poor pregnancy, gestational hypertension or gestational hypertension/eclampsia). Rainfall at residential address where well water sample was taken is used as an indicator of exposure intensity represented by the one-day maximum rainfall from August 14, 2011 to September 4, 2011, which encompasses the hurricane event’s impact on North Carolina. Rainfall source: PRISM climate group Time Series Values for Individual Locations.