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Maternal stress and birth outcomes: Evidence from the 1994 Northridge earthquake☆

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ABSTRACT

Psychological maternal stress is thought to be a factor in poor infant health, but direct evidence is difficult to obtain. We posit that the 1994 Northridge earthquake in Los Angeles, California provides a natural test of the effect of mothers' stress on infants' birth weight and gestation. The Northridge disaster featured a low rate of injury and a quick recovery, but long-lasting and well documented consequences for mental health. Difference-in-difference results show that infants born closest to the epicenter were 0.2 percentage points more likely to be born with low birth weight. Impacts were larger and more precisely identified for women who experienced the earthquake in their first or third trimester. Among the subsample of mothers most susceptible to stress – first-time, single mothers – low birth weight was 0.5 percentage points more likely to occur. We find little evidence that the earthquake affected preterm delivery.

1. Introduction

"It moved into every corner of the landscape, into every home, into every life." (Kennedy, 2014)

Poor health at birth, often signaled by low birth weight or prematurity, is strongly linked to weaker health and development later in life (Currie and Hyson, 1999; Black et al., 2007; Figlio et al., 2014). There are many known determinants of low birth weight and preterm birth, including maternal health, economic deprivation, and limited access to proper nutrition and prenatal care during pregnancy. Maternal psychological stress is also thought to be a key risk factor in birth outcomes. In clinical research, changes in hormone levels due to stress are linked to an increased probability of low birth weight and prematurity (Glynn et al., 2001; Hobel and Culhane, 2003; Hobel et al., 2008; Dunkel Schetter, 2011).[1] It is very difficult, however, to identify stress as a causal factor in infant health. The stylized correlation between mothers' stress and birth outcomes is complicated by the fact that many of the same conditions that result in stress (e.g., financial uncertainty, substance abuse, or single motherhood) likely have independent effects on infant health.

We are not the first to investigate the effects of plausibly exogenous and stressful events on birth outcomes. Armed conflict (Mansour and Rees, 2012), proximity to landmines (Camacho, 2008), the September 11th terrorist attacks (Brown, 2013),

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[1] Stress can also indirectly lead to low birth weight via smoking, drinking, unhealthy dietary habits, or other compensating behaviors by expectant mothers.

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job loss (Lindo, 2011), economic collapse (Bozzoli and Quintana-Domeque, 2014), and blackouts (Burlando, 2014) have all been shown to harm newborn health. A subset of this literature assesses the effect of natural disasters on infant outcomes, including hurricanes and tropical storms (Currie and Rossin-Slater, 2013), a major earthquake in a developing country (Torche, 2011), and other adverse weather events including smaller earthquakes (Simeonova, 2011). While estimated effects from these events vary considerably, the consensus is that disasters – both man made and natural – affect birth weight and gestation length. However, attributing a causal role for psychological stress alone is difficult because most disasters impose both physical and psychological stress by limiting access to nutrition, clean water, safe living conditions, prenatal care, or other inputs to maternal or fetal health. To the extent that any of these events are anticipated, results may in part reflect compositional changes in birth cohorts *prior* to the disaster in question.

We join Brown (2013) in assessing the *in utero* effects of a disaster that entailed far more psychological stress than bodily harm, but in a context where difference-in-difference identification is possible. The 1994 Northridge earthquake, registering a 6.7 moment magnitude and centered near Los Angeles, California, offers a source of exogenous variation in large-scale maternal stress that is minimally confounded by physical stress or endogenous *ex ante* migration. An earthquake is a purely unanticipated disaster that elicits stress (in varying degrees) among individuals in the affected area regardless of their socioeconomic status.

Using 1992–1995 data from the National Center for Health Statistics (NCHS), we analyze birth outcomes before and after the earthquake.[2] We evaluate how intertemporal variation in infants' birth weight and gestation differed by mothers' likely proximity to the epicenter. The Los Angeles area population tends to be more socioeconomically and environmentally challenged, but our empirical strategy balances characteristics of parents and expectations of newborn health with rich controls for city and seasonal fixed effects. Results of this difference-in-difference exercise show that infants born closest to the epicenter were 0.2 percentage points more likely to be born with low birth weight (less than 2500 g, or about 5 pounds and 8 ounces). These treatment effect estimates are approximately 11% of the estimated effect of smoking on birth weight (Abrevaya, 2006). One might expect that effects of a stressful event would be strongest among those who are more susceptible to stress, such as single and first-time mothers (Cairney et al., 2003). Indeed, for these women we find that the earthquake raised the likelihood of low birth weight by 0.5 percentage points, or 21% of the estimated effect of maternal smoking. Estimated effects are strongest for mothers who experienced the earthquake in their first or third trimester. Findings are limited to mild degrees of low birth weight and are broadly robust to changes in the delineation of treatment and the sample period in question. Under some specifications of the sample and estimating equations, we find that the Northridge earthquake affected preterm birth, although results are not as robust as estimates for low birth weight. These findings underscore psychological and medical research pointing to stress as an important factor in low birth weight, both at and below full gestation (Field et al., 2006; Dunkel Schetter and Lobel, 2010). We rule out the idea that reactive mobility after the earthquake could be driving results. Permutation tests strongly highlight the actual epicenter over placebo locations.

The challenge with attributing disaster-induced changes in birth outcomes to stress is that higher stress coincides with other barriers to physical health and health care. Much of the related literature on the effects of disasters on birth outcomes either abstracts from specific causal mechanisms or relies on contextual information to claim that factors other than stress are unlikely to drive the result. In most disasters, however, at least some of the aftermath includes event-specific non-psychological factors, making it difficult to quantify the effect of stress alone. There is considerable variation in the severity of disasters reviewed by this literature. It is therefore unsurprising that estimated effects on the probability of low birth weight range from zero to 2.7 percentage points, or that estimated changes in birth weight range from zero to 70 g (see Table 1 in Section 2.2). While we also rely on contextual knowledge to understand the possible extent of physical mechanisms, features of the Northridge earthquake make it uniquely well suited to isolate the effect of stress following a natural disaster. The earthquake occurred recently in a large and developed metropolitan area, and there was extensive media coverage and scientific documentation of both the damage and recovery. The record indicates that access to nutrition and basic needs was largely unaffected, infrastructure in the area was constrained but intact, and the retail and grocery sectors were similarly spared. With plentiful access to food, water, medical care, and safe housing, remaining candidates for why disasters may affect birth outcomes include physical injury, stress, and changes in physical health as a result of lasting structural damage (which may plausibly affect mental health as well). In some models, we control for spatial variation in damages and injuries to more tightly bound the effect of stress within this single event, a departure from the related literature.[3] Spatial variation in injury and structural damage reduces the precision of estimates but leaves at least 45% of the effect of proximity unexplained. We attribute this residual effect to psychological stress, acknowledging that the true effect may be larger if we account for the effect of damage itself on maternal stress.

Evidence from the Northridge earthquake suggests that physical harm to expectant mothers was limited. Relief efforts were immediate and successful, reducing the possibility that material deprivation, access to nutritious food and clean water,

[2] We do not consider births after 1995 because of the possibility of endogenous longer-term mobility following the earthquake. Results are broadly robust to including 1991 births or excluding 1995 births (see Section 5.1).

[3] A close exception is provided by Simeonova (2011), who controls for property damage and fatalities across a wide variety of disasters. Differences in damages across disasters, however, do not necessarily align with differences in the physical challenges faced by expectant mothers. By way of example, Hurricane Ike wrought $29 billion in damages in 2008, much less than Northridge's $44 billion before correcting for inflation. But Ike entailed weeks of power outages for millions of people in the late summer alongside widespread difficulties obtaining food and medical care (Centers for Disease Control, 2008), whereas the Los Angeles area returned to normal daily activities within days of the Northridge earthquake.

or unsanitary conditions contributed to the results to follow. Although the immediate aftermath of the earthquake saw power outages, gas leaks, crowded hospitals, and road and overpass destruction, normal business activity resumed within a week. Utilities were restored within four days and the vast majority of surface streets were navigable, evidenced by the fact that public transit saw little to no disruption (EQE International, 1994; Kandel, 2014). We find no evidence that access to prenatal care was hindered. On the contrary, mothers may have consumed more prenatal care as compensatory behavior (see Table 12 and related discussion). As discussed in Section 2.2, injuries resulting from the Northridge earthquake were too infrequent to explain our findings. Results are impervious to controls for air quality during pregnancy, ruling out particulate matter, smoke, and pollution as mechanisms.[4] The scope of structural damage included eleven hospitals and health facilities where one or more buildings were "red-tagged" and deemed unsafe to enter.[5] Nevertheless, we find no differential change in the likelihood of a hospital birth among more affected mothers, and results to follow are robust to controls for hospital birth (see Table S3).

Though casualties were relatively low and there was little disruption to health care or basic needs, damages from the earthquake were extraordinarily large compared to other natural disasters in the United States. The financial measure of damages was a nominal $44 billion and 90,000 buildings were damaged or destroyed (Eguchi et al., 1998). Destruction of this degree, even with minimal accompanying effects on physical health, may have exacerbated and extended the short-term stress mothers experienced during and immediately after the earthquake. Exposure to destruction from natural disasters is associated with lasting psychological stress, including symptoms of depression and post-traumatic stress disorder (Nolen-Hoeksema and Morrow, 1991; McMillen et al., 2000). Just ten of about 2000 bridges and overpasses were damaged beyond repair in the region, but this still affected major freeways and created "severe hardships for the traveling public" (Cooper et al., 1994). Kahneman et al. (2004) found commuting to be the least satisfying of all daily activities in a sample of working women, associated with elevated levels of impatience and fatigue. Heightened traffic has been shown to increase physical markers of stress across non-experimental and experimental settings (Evans and Carrere, 1991; Drews et al., 2003).

The context of the Northridge earthquake enables us to contribute to the literature on disasters, stress, and birth outcomes in two ways. First, this paper serves as a bridge between two literatures: largely medical research on maternal stress and newborn health, and predominantly economic research on disasters and the same.[6] Documentation from the disaster and recovery enables us to eliminate many alternative physical mechanisms (i.e., access to lifelines and nutrition) and more directly control for physical stressors, thus we are better able to bound the role of psychological stress in affecting neonatal health. The estimated impact of Northridge is similar in magnitude to impacts of purely psychological events – the loss of a parent (Black et al., 2016) or the announcement of future layoffs (Carlson, 2015) – and smaller than the effects of more sweeping disasters. These comparisons imply that much of the variation in estimated impacts of large disasters on birth outcomes stems from event-specific factors.

Second, we are among the first to examine the impact of a massive earthquake in an urban, developed environment on newborn outcomes. Our analyses benefit from data on over 2 million California births as well as both spatial and temporal variation in earthquake exposure.[7] Results speak to the importance of infrastructure, relief, and recovery in mitigating the health consequences of disasters. Our findings, when viewed through the lens of a quick recovery, stand in marked contrast to the 2005 Tarapaca earthquake in Chile, which Torche (2011) credits with a 1.7 percentage point rise in the likelihood of low birth weight and a 2.6 percentage point higher probability of preterm delivery.[8]

2. Background

2.1. Mechanisms connecting maternal stress and birth outcomes

The pathophysiology connecting maternal stress and birth outcomes is not definitive, but is thought to involve mothers' hypothalamic-pituitary-adrenocortical axis and/or early placental development (Dunkel Schetter and Glynn, 2010). In

[4] After Northridge, airborne fungal spores from landslides resulted in a noted increase in coccidioidomycosis or "valley fever" in Ventura county.

[5] Six of these facilities provided labor and delivery care; three were fully operational within two weeks, and three were closed in whole or part for an extended period of time.

[6] In addition to studies cited in Section 1, Simeonova (2011) studies a broad set of adverse weather events in the United States, including some smaller earthquakes, and finds that experiencing a natural disaster in the second or third trimester decreases county-level gestational age and birth weight. Others examining the impact of negative *in utero* shocks on long term individual outcomes include Almond (2006), Chen and Zhou (2007), Almond et al. (2009), Field et al. (2009), Sanders (2012), Lee (2014), and Bharadwaj et al. (2013).

[7] See Harville et al. (2010) for a review of medical research on the impact of earthquakes and other disasters on birth outcomes. Earthquake studies therein focus on small samples of births ($N \leq 115$), the impact of direct injury (e.g., being buried in rubble), and/or inferences from intertemporal variation alone. This literature includes work by Glynn et al. (2001), a clinical analysis of 40 pregnant or post-partum women who experienced the Northridge earthquake. Results indicate that stress was strongest among women who experienced the tremor in their first trimester, who tended to have shorter gestation by 1.2 weeks. In a larger hospital-based study of 13,003 births, Tan et al. (2009) found that neonates *in utero* during the Wenchuan, China earthquake of May 2008 gestated 0.6 fewer weeks than infants born before the earthquake. In contrast to these two pre/post analyses, our difference-in-difference findings for the impact of Northridge on gestation are considerably smaller (from Table 8: 0.02–0.05 fewer weeks).

[8] The 7.8-magnitude Tarapaca earthquake affected a rural area in the Andes and entailed infrastructure damage so severe that power and water services were interrupted. Thirty power generating substations were destroyed, meaning water could not be pumped to the nearby town of Iquique. Relief supplies had to be delivered by air (Rondinel-Oviedo, 2005).

response to psychological stress, the body engages a hormonal chain reaction to enhance metabolic function in support of a "fight or flight" response. Specifically, the neuropeptide corticotrophin-releasing hormone (CRH) activates the adrenocorticotrophic hormone (ACTH), which initiates cortisol production. Cortisol has been shown to increase metabolic rates, suppress the immune system, and decrease bone formation (Sapolsky, 2004; Davis and Sandman, 2006). To the question at hand, CRH is particularly active during pregnancy, and elevated placental CRH levels, measured as early as the second trimester, are consistently linked to preterm birth (Hobel et al., 1999). Preterm birth is also associated with the presence of abnormally high rates of placental lesions, which may have roots in stress and poor placental development early in pregnancy.

Preterm birth clearly goes hand in hand with low birth weight, but there are several other possible links between maternal stress and low birth weight outside of gestation length. Chronic stress leads to the release of catecholamines, which hinder uterine perfusion and reduce fetal growth (Rakers et al., 2015). Another hypothesis suggests that increased cortisol levels from chronic stress lead to increases in glucocorticoids, which diminish the cardiovascular and metabolic function of the fetus.[9] Lobel et al. (2008) find empirical support for the idea that maternal behaviors (e.g., smoking, caffeine use, etc.) mediate the effect of stress on birth weight. In a review of the literature, Dunkel Schetter and Lobel (2010) concluded that maternal depression and distress are consistently tied to low birth weight (also see Field et al. (2006)).

Looking beyond birth weight and gestation, Currie and Rossin-Slater (2013) report robust impacts of exposure to Texas hurricanes on extended ventilator use or meconium aspiration syndrome (MAS) in newborns. The pathway between stress and ventilator use or MAS is not well studied in the medical literature. Breathing support is often, but not exclusively, used for preterm or smaller newborns with underdeveloped lungs. MAS has several potential causes, not all of them independently linked to maternal stress (e.g., high blood pressure, maternal diabetes, long gestation, long labor, low amniotic fluid index values). Both abnormalities are potentially serious, often tied to comorbidities, and considerably less common than preterm birth or low birth weight, suggesting that hurricane exposure was most detrimental to the least healthy infants. Here, available data on birth measures are limited to gestation and birth weight, but after assessing overall impacts we look for heterogeneous impacts at different degrees of severity for both outcomes. Methodologically, Currie and Rossin-Slater (2013) show that estimates for birth weight and gestation are sensitive to specification, aggregation, and measurement. For our purposes, the primary lesson from their work is the notion that infant outcomes may be endogenous to maternal mobility between the disaster and birth. Sensitivity checks described in Section 5.3 rule out maternal mobility as a major contributing factor to our main results.

2.2. Northridge earthquake

On January 17, 1994, at 4:31 AM, the Northridge earthquake shook the greater Los Angeles area with a moment-magnitude of 6.7. It was felt over approximately 21,400 km^2 in Southern California, Nevada, and Arizona (Dewey et al., 1995). According to the U.S. Geological Survey (USGS), 57 people were killed, more than 9000 were injured, and 20,000 people were left temporarily homeless.[10] At least 90,000 buildings were damaged.

The particular circumstances of the Northridge catastrophe suggest that psychological stress and its physiological consequences were more damaging to the earthquake's survivors than injury, debris, poor nutrition, or inadequate health care. Perhaps 2.7% of the Los Angeles County population was pregnant at the time of the earthquake,[11] and assuming that injuries were distributed uniformly, about 243 of the injured would have been pregnant. Even if every injured and pregnant woman delivered a low birth weight child (a 100% incidence rate that far exceeds the 6% norm), results discussed in Section 4 suggest that injury would explain just 62% of the conditional rise in low birth weight. In spite of large economic losses, little of the structural damage threatened lives. Most insurance claims in the Los Angeles area were for residential damage (Roth and Van, 1997; Comerio, 1998). In addition to federal aid for home repair, there were programs for mental health counseling, job training, and unemployment assistance (Bolin and Stanford, 1998).[12] Importantly, these relief programs began immediately: traffic volumes steadily increased as work and daily life resumed in the week following the earthquake (U.S. Department of Transportation, 2002), train and bus transit lines saw little to no interruption, utilities were restored quickly,[13] and most temporary shelters were closed within a month (EQE International, 1994). Several hospitals were evacuated or shut down in the short run (Cheevers and Abrahmson, 1994), though as we show in Section 5.3 this appears to have had no effect on the likelihood of a hospital birth among affected mothers. Holding access to hospitals constant, it is possible that an altered composition of labor and delivery providers could affect our results through the measurement of birth weight and gestation

[9] See Hobel and Culhane (2003), Hobel et al. (2008), and Dunkel Schetter (2011), among others, for further discussion.

[10] Durkin (1995) counts 72 fatalities and up to 11,800 injuries as direct or immediate indirect consequences of the earthquake. Heart attacks account for much of the difference between the official count of 57 deaths and Durkin's higher figure. Kloner et al. (1997) also report an elevated frequency of heart attacks in the Northridge aftermath.

[11] In 1990, 23.5% of the Los Angeles County population were women of childbearing age (15–44), and national pregnancy rates at the time measured 115.8 women per 1000 of childbearing age.

[12] Homeowners whose dwellings sustained less than $10,000 in damages (as determined by FEMA inspectors) were eligible for grants from the agency's Minimum Home Repair Program. Victims who could not qualify for other federal assistance programs or who had unmet needs after receiving federal assistance could receive aid through the joint OES-FEMA Individual and Family Grant Program.

[13] Eight hours after the earthquake, nearly half of the customers in the Los Angeles Department of Public Works had their power restored. Eleven hours after the earthquake, Southern California Edison had power restored to all but 150,000 homes and businesses. Four days later, power was reconnected to all houses but 7500 in the San Fernando Valley. At the start of the fifth day, all but 10,000 houses had their water service restored (Kandel, 2014)

Table 1
Related research on disasters and birth weight.

Study	Event	Geography	Result
Mansour and Rees (2012)	Fatalities from al-Aqsa Intifada	Palestine (West Bank)	P(LBW) increased 0.001–0.0027 per fatality (3–10% marginal effect)
Camacho (2008)	Landmine explosions in city	Columbia	Birth weight decreased 9 g if in 1st and 2nd trimester
Torche (2011)	Earthquake (Tarapaca)	Chile	P(LBW) increased by 0.017
Bozzoli and Quintana-Domeque (2014)	Macroeconomic crisis	Argentina	Birth weight decreased 30 g
Currie and Rossin-Slater (2013)	Hurricane/tropical storm	United States	P(LBW) increased.016, in specification closest to ours
Burlando (2014)	Blackouts	Zanzibar (Tanzania)	Birth weight decreased 60–70 g
Simeonova (2011)	Natural disasters, varying	United States	Birth weight decreased up to 18 g (floods most harmful)
Kim, Carruthers, and Harris (this study)	Northridge Earthquake	United States	Birthweight decreased 9–11 g P(LBW) increased.002–.005
Brown (2013)	*In utero* during 9/11 not in NY/DC	United States	P(LBW) increased by 0.002
Black et al. (2007)	Loss of (grand)parent	United States	Birth weight decreased 15 g
Carlson (2015)	News of future layoff event	United States	Birth weight decreased 15–20 g P(LBW) increased.0021–.0092

in vital statistics data (Barreca et al., 2010). In specification checks discussed in Section 5.1 we show that inferences are not affected by the exclusion of infants with round birth weights.

Hurricanes are also thought to elicit maternal stress (Dunkel Schetter and Glynn, 2010; Currie and Rossin-Slater, 2013), though by nature they entail one empirical and one conceptual challenge for studies of *in utero* stress on newborn health. Hurricanes are anticipated with enough time, plausibly, to elicit endogenous avoidance, and when they entail flooding they tend to severely alter the landscape, disrupt public services, and endanger the basic needs of pregnant women.[14]

Northridge's impact on daily life and health care was short-lived, but contemporary accounts and psychiatric research suggest that the earthquake had more lasting effects on mental well being. Stress in this setting includes immediate stress from the earthquake and its powerful aftershocks, persistent anxieties from living and working in damaged structures, anticipation of future disasters, and changes in the emotional health of communities. In a psychiatric study of 130 Northridge survivors three months after the earthquake, McMillen et al. (2000) report that 61% met two out of three criteria defining post-traumatic stress disorder. In the months following the Northridge earthquake, the Los Angeles area received at least $35.1 million for earthquake-related mental health counseling (Jordan, 1994). Stress was sufficiently severe and widespread that over 241,000 children received crisis counseling in a FEMA-funded program from January 17 through November, 1994 (Goldman, 1995). On-campus counseling centers and outreach programs were opened and operated by California State University, Northridge (Becker, 1994; Byrnes, 1994b). The non-profit Valley Trauma Center opened its doors for disaster counseling for months after the earthquake (Byrnes, 1994a). Studies of the Northridge aftermath found that earthquake-induced stress affected immune systems and cardiovascular health (Solomon et al., 1997; DeSantis, 1995). One year after Northridge, crisis centers in the Los Angeles area were reportedly flooded with calls from people who were triggered by prominent news coverage of an earthquake in Kobe, Japan (Markman, 1995). Earthquake-induced PTSD is not unique to Northridge. See Goenjian et al. (1994), Lai et al. (2004), and Başoğlu et al. (2004) for evidence of elevated rates of PTSD among earthquake survivors in, respectively, Armenia, Taiwan, and Turkey. In the context of the Northridge earthquake, other physical stresses (i.e., dehydration) were minimized by the speedy restoration of utilities and the mid-winter Mediterranean climate of Southern California.

Table 1contains a summary of results from prior work evaluating the effects of harmful events on birth outcomes, spanning large disasters, national crisis, family crisis, and violent conflict. The last three listed studies pertain to events with more potent psychological than physical consequences, and it is telling that their estimated effects tend to be smaller, less variable, and similar in magnitude to our main findings. While the studies summarized in Table 1 differ in their econometric strategies, it is sensible that events yielding widespread physical *and* psychological damage (nearby violence, a 20% decline in economic activity, hurricanes, blackouts, and flooding) result in bigger declines in birth weight. We contribute to this literature by demonstrating that the effect of maternal stress from a short-lived natural disaster is comparable to the effect of more personal loss and economic anxiety.

[14] Maternal dehydration can lead directly to fetal stress, decreased amniotic fluid index values, and therefore abnormal birth outcomes. When Hurricane Ike struck Houston in September 2008, over 4.5 million customers in the greater Houston-Galveston area lost power for three weeks (Electricity Information Administration, 2009). During this time, the daily high temperature averaged 89 degrees Fahrenheit. A rapid needs assessment by the CDC found that 27% of surveyed households required assistance obtaining food, and 11% could not access medical care or prescription medication. As late as September 25, 18% of households reported having no garbage pick up and 7% of households reported not having drinking water (Centers for Disease Control, 2008). In June 2001, Storm Allison carried up to 37 in. of rain in 24 h and resulted in severe residential flooding for over 850,000 residences. One week after the heaviest rainfall, 33% of the surveyed homes in Houston still had floodwaters in their homes with a mean depth of 16 in., 15% did not have power, 15% did not have sewage service, and 6% had no running water (Centers for Disease Control, 2001). June 2001 had an average high temperature of 89 °F.

3. Data and model

3.1. Data

California birth records over the years 1992–1995 are taken from the National Center for Health Statistics (NCHS). Our primary identification strategy proxies for earthquake exposure using mothers' city of residence and the radial distance between that city and the epicenter. An alternate model relies on a "community decimal intensity" (CDI) scale derived from survey responses. In all cases, we know the county of birth and the mother's county of residence. There are two circumstances describing 42% of births where we do not observe mothers' city of residence. When the county of birth differs from the mother's county of residence, we observe her home county but not her city. Second, births in cities with populations fewer than 100,000 are treated as having occurred in an aggregate residual location in the home county. For both cases we have a less accurate idea of where the mother lived when the earthquake struck, but not so inaccurate as to justify omitting these births. When we do not observe mothers' home city, we randomly assign one within her home county. This imputation creates a small degree of measurement error under our preferred specification of proximity, which (given these uncertainties about birth cities) is a simple indicator for birth within about 80 km of the epicenter.[15]

The main analytical sample includes 2,167,895 live births. Primary outcomes of interest are two binary indicators: one for preterm birth, defined as birth before 37 weeks gestation, and another for low birth weight, defined as less than 2500 g. Birth records also provide the infant's gender and a number of variables describing parents and siblings: mother's and father's age and race; mother's education (years of schooling); marital status; mother's count of previous live births still living; total birth order; plurality of the current birth; and mother's number of prenatal care appointments.[16] Additional controls describing mother's city of residence include the Bureau of Labor Statistics annual unemployment rate in the year of birth and annual measures of pollution and air quality drawn from the U.S. Environmental Protection Agency (EPA).[17]

Fig. 1 depicts California cities and their distance from the epicenter, dividing the 62 cities listed in the NCHS data into quartiles. The first quartile consists of "highly affected cities," that is, those that are closest to the epicenter (up to 77.8 km). This region experienced the greatest degree, by far, of shaking and destruction during the earthquake. Compare our definition of highly affected cities with the "shakemap" reproduced in Fig. 2. As a point of reference, Bakersfield is 45 min north of Gorman. In Fig. 1, Gorman would be on the approximate boundary between the "highly affected" group of cities and second-quartile cities.[18] Difference-in-difference analyses to follow compare pre-post differences in birth outcomes of infants born in highly affected cities with pre-post differences among infants born elsewhere in California. One alternative specification defines a continuous earthquake dosage as a function of distance (in kilometers) from the epicenter, and another defines exposure as a binary variable for cities above a particular CDI threshold.

Descriptive statistics of key variables in highly affected and other cities are shown in Table 2. Six percent of newborns are classified as having low birth weight, and 9–10% are born preterm. Newborns in highly affected cities exhibit significantly lower mean birth weight and significantly shorter gestational age, on average. Of course, part of the cross-city difference may be driven by socioeconomic factors that existed before the earthquake. For example, parents in highly affected cities are less educated, on average, and 6.4 percentage points less likely to be married. As shown in Table 3, highly affected cities have substantially poorer air quality. PM-10 readings are 15% higher than in places further from the epicenter, carbon monoxide readings are 34% higher, and ozone readings are 31% higher.

3.2. Methods

We exploit the combination of cross sectional variation in the intensity of the earthquake between cities and intertemporal variation in birth outcomes before and after the earthquake to estimate the causal effect of the earthquake on low birth weight and preterm delivery. Our model is a difference-in-difference estimator:

$$BirthOutcome_{ijmt} = \beta_0 + \beta_1 1994_{ijmt} + \beta_2(1994_{ijmt} * HA_{ijmt}) + \beta_3 X_{ijmt} + HA_{ijmt}\delta_{jm} + M_m + T_t + \theta_j + \epsilon_{ijmt} \quad (1)$$

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15 Orange County is the only county where some cities are within 80 km and some are more than 80 km from the epicenter. See Table S1 in Appendix A for results when the sample excludes imputed Orange County births. Point estimates for low birth weight are slightly larger than they are otherwise, which is consistent with classical measurement error, though these differences may also be driven by treatment effect heterogeneity across Orange County and other affected areas. See Table S2 for results excluding all births with imputed cities of residence. Degrees of freedom are somewhat weaker but results are generally consistent with those reported for all births.

16 Prenatal care may have been affected by the earthquake (a) if mothers compensated for stress or injury with additional prenatal visits or (b) if access to prenatal care was hindered by the earthquake's destruction. We show in Section 5.3 that the former case is more plausible.

17 Air quality controls include the second-highest 24-h recording of particulate matter (PM-10) in the infant's birth year and city of residence, the second-highest 8-h recording of carbon monoxide, and the second-highest 8-h recording of ozone. If data on these pollutants do not exist for a given city, we substitute values for the closest city. When pollutant data for a given city are drawn from more than one EPA monitor, we take the average of all monitors in the city. Graphical evidence suggests that there were no abnormal changes in pollution or air quality levels in the highly affected cities at the time of the earthquake. Graphs of monthly levels of PM10 (particulate matter smaller than 10 μm in diameter), ozone, and carbon monoxide are available in Appendix A, Fig. S1.

18 For an eastern comparison, note that both maps categorize Pasadena as highly affected. Additionally, Pomona (Fig. 1) is due south of Wrightwood (Fig. 2), putting it in the less affected category. Moreno Valley (Fig. 1) is southeast of Wrightwood in Fig. 2.

Fig. 1. California cities by distance from the epicenter.

where *i* is an infant, *j* is the city of residence, and *m,t* is the month and year that infant *i* is born. *BirthOutcome* is an indicator for low birth weight or prematurity in our main results (specifications for continuous measures of birth weight and gestation are also reported), 1994 is an indicator for infants born between January and October of 1994,[19] *HA* is an indicator for whether the city of birth is in the "highly affected" zone (whose seasonality is permitted to differ by δ_{jm}), and *X* is a vector of controls summarized in Tables 2 and 3.[20] Lastly, *M* is a fixed effect for month of the year to control for seasonal shocks, *T* contains fixed effects for birth years 1993, late 1994 (November or December), and 1995, θ is a city fixed effect, and ϵ is the error term. In Eq. (1), β_2 is the difference-in-difference estimate of the effect of the earthquake on birth outcomes.

To investigate effects by trimester, we modify Eq. (1) as follows:

$$\begin{aligned} BirthOutcome_{ijmt} = \quad & \alpha_0 + \alpha_1 1st_{ijmt} + \alpha_2 2nd_{ijmt} + \alpha_3 3rd_{ijmt} + \alpha_4(1st_{ijmt} * HA_{ijmt}) + \alpha_5(2nd_{ijmt} * HA_{ijmt}) \\ & + \alpha_6(3rd_{ijmt} * HA_{ijmt}) + \alpha_7 X_{ijmt} + HA_{ijmt}\delta_{jm} + M_m + T_t + \theta_j + \epsilon_{ijmt} \end{aligned} \tag{2}$$

where 1*st* is an indicator for infants who experienced the earthquake during their first trimester *in utero* (and were conceived between October 1993 and January 17th, 1994) 2*nd* is an indicator for infants who were in their second trimester when the earthquake struck (conceived between September and July 1993), and 3*rd* is an indicator for infants conceived between June and January 1993, thereby experiencing the earthquake in their third trimester.[21] The rest of the variables are defined as in Eq. (1). In both specifications, the reference group is the set of infants who are born before or conceived after the Northridge earthquake.

[19] Births between January 1 and January 16 are included in this indicator as we are not able to observe the precise day of birth.

[20] In addition to these controls, we also include an indicator for whether an infant is missing data on the father's age, which affects 6–8% of births. Where missing, father's age is imputed as the mean value by city, birth year, and mother's age.

[21] Additionally, 3*rd* applies to a small number of infants who were conceived between January and March 1993 and born in 1994.

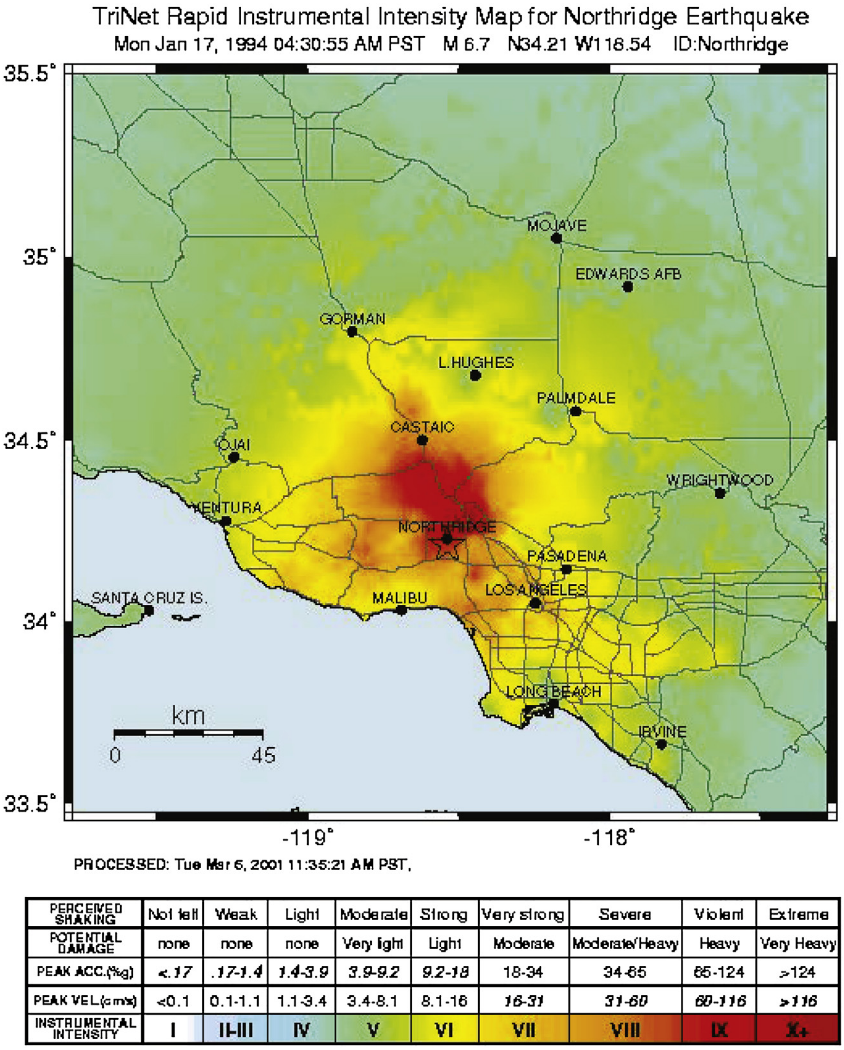

Fig. 2. Northridge earthquake intensity. *Source*: California Integrated Seismic Network.

4. Results

Table 4 shows the results of estimating Eq. (1). Panel A contains results from the full sample. Panel B contains results when the sample is restricted to mothers more susceptible to high levels of stress: single first-time mothers. If the earthquake affects birth outcomes through maternal stress (and not other channels, e.g., physical stress on the mother and fetus), we would expect the effects of the earthquake to be strongest in the group more susceptible to stress. In each column, we report the results for the coefficient on the interaction 1994 * *HA*. All specifications include covariates summarized in Table 2, month fixed effects, year fixed effects, and month-by-*HA* effects. We cluster robust standard errors by county of birth, allowing for the possibility that birth outcomes are correlated within public health service areas.[22]

In each panel of Table 4, columns (1)–(3) display results for low birth weight outcomes. Here, low birth weight (LBW) is an indicator for whether an infant weighs 2499 g or less at birth. We also separately model the probability that an infant is born "Very LBW," defined as birth weight less than 1500 g, or "Mild LBW" defined as birth weight between 1500 and 2499 g.

In Panel A, the coefficient on the interaction term in column (1) is 0.0020 and statistically significant. This implies that infants born in cities within 77.8 km of the epicenter were 0.20 percentage points more likely to be born weighing less than 2500 g. Based on the mean percent of low birth weight in highly affected cities before the earthquake (5.9%), this effect is equivalent to a 3.4% increase in the probability of low birth weight, or about 393 additional LBW infants.[23] Columns (2)

[22] Results are robust to clustering standard errors at the mother's city of residence.

[23] There were 194,434 births in the 77.8-km vicinity of Northridge over the January–October 1993 period; 0.2% of this sum is 393.

Table 2
Summary statistics of California births, 1992–1995.

	(1) Highly affected cities	(2) Other cities	(3) Difference, (1)–(2)
Birth weight (g)	3351.576	3371.113	−19.537***
	(575.245)	(583.065)	(0.799)
Birth weight under 2500 g (%)	6.014	5.967	0.047
	(23.775)	(23.687)	(0.033)
Gestation (weeks)	39.038	39.115	−0.077***
	(2.490)	(2.502)	(0.003)
Gestation under 37 weeks (%)	9.692	9.422	0.270***
	(29.213)	(29.585)	(0.040)
Age of mother (years)	27.103	27.029	0.074***
	(6.117)	(6.132)	(0.008)
Nonwhite, non-black mother (%)	9.674	11.839	−2.165***
	(29.560)	(32.307)	(0.043)
Black mother (%)	8.213	7.256	0.957***
	(27.456)	(25.941)	(0.037)
Education of mother (years)	11.301	11.890	−0.589***
	(3.675)	(3.509)	(0.005)
Married mother (%)	62.013	68.403	−6.390***
	(48.535)	(46.490)	(0.065)
Number of live births now living	1.126	1.127	−0.001
	(1.308)	(1.335)	(0.002)
Age of father (years)	29.654	29.531	0.123***
	(6.882)	(6.888)	(0.009)
Imputed age of father (%)	7.632	5.886	1.746***
	(26.551)	(23.537)	(0.034)
Nonwhite, non-black father (%)	11.775	14.035	−2.260***
	(32.231)	(34.735)	(0.046)
Black father (%)	8.776	8.588	0.187***
	(28.294)	(28.019)	(0.039)
Number of prenatal visits	11.264	11.277	−0.013**
	(4.226)	(4.119)	(0.006)
Male newborn (%)	51.138	51.203	−0.066
	(49.987)	(49.986)	(0.069)
Plurality	1.023	1.024	−0.001
	(0.156)	(0.160)	(2.2E−04)
Total birth order	2.367	2.391	−0.024***
	(1.533)	(1.582)	(0.002)
Births	904,998	1,262,897	

Note: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 3
Summary statistics of California cities, 1992–1995.

	(1) Highly affected cities	(2) Other cities	(3) Difference, (1)–(2)
Unemployment rate	8.460	9.356	−0.897*
	(0.753)	(3.890)	(0.506)
PM-10 ($\mu g/m^3$)	91.867	79.735	12.132***
	(26.518)	(29.402)	(4.304)
Carbon monoxide (ppm)	7.182	5.358	1.824***
	(2.453)	(2.389)	(0.361)
Ozone (ppm)	0.119	0.091	0.028***
	(0.024)	(0.032)	(0.005)
City-years	60	171	
Cities	15	45	

Note: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

and (3) show that increases in the probability of low birth weight are driven by mild LBW rather than more severe LBW. For comparison, the estimated effect of the earthquake on the probability of low birth weight is approximately 11% of the estimated effect of maternal smoking (Abrevaya, 2006).

Panel B of Table 4 shows that the estimated effect of the earthquake on low birth weight is over twice as large for single first-time mothers, who are assumed to be more susceptible to stress. Among these mothers, the earthquake led to a 0.54 percentage point increase in the probability of a low birth weight infant, equivalent to an additional 155 LBW infants in

Table 4
Eq. (1) results – the effect of the earthquake on birth outcomes.

	(1) LBW	(2) Very LBW	(3) Mild LBW	(4) Prematurity	(5) Extreme prematurity	(6) Mild prematurity
Panel A (full sample)						
1994*Highly affected city	0.00202**	0.000652**	0.00137*	0.000625	−0.0000229	0.000648
	(0.000761)	(0.000301)	(0.000717)	(0.000994)	(0.000170)	(0.000984)
N	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895
R^2	0.104	0.032	0.075	0.058	0.017	0.048
Panel B (single and first-time mothers, singleton births)						
1994*Highly affected city	0.00538**	−0.000182	0.00556***	0.00358	−0.00183***	0.00540**
	(0.00198)	(0.000980)	(0.00180)	(0.00261)	(0.000560)	(0.00237)
N	294,332	294,332	294,332	294,332	294,332	294,332
R^2	0.019	0.015	0.010	0.023	0.011	0.017

Note: Standard errors in parentheses. Standard errors are clustered by county of residence. "Very LBW" refers to infants born under 1500 g. "Mild LBW" refers to infants 1500–2499 g. "Extreme prematurity" describes gestation under 28 weeks. "Mild prematurity" is gestation at 28–36 weeks.
$^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.

this population, or approximately 21% of the effect of smoking on the probability of low birth weight. Consistent with the broader sample of births, these impacts are concentrated among milder LBW newborns.

The column (4) specification estimates the linear probability of birth before 37 weeks' gestation, and columns (5) and (6) contain results for extreme prematurity (births less than 28 weeks) and mild prematurity (between 28 and 37 weeks), respectively. In the full sample specification (Panel A), we do not detect a significant preterm birth gap between highly affected cities and more removed cities along any of these margins. In the restricted sample of single, first-time mothers, however, we find that a decline in extreme prematurity of 0.18 percentage points offsets a 0.54 percentage point rise in milder prematurity, such that the net effect of proximity on preterm birth is statistically insignificant. It is possible that the earthquake led to fewer infants carried to the point of a live but extremely premature birth.

Our characterization of cities as "highly affected" is fairly accurate but arbitrary. Fig. 2 shows that while there are marked discontinuities in the impact of the earthquake, the strength of tremors lessens with distance from the epicenter. With this in mind, Table 5 reports results from a version of Eq. (1) in which the binary indicator of proximity within 77.8 km ($HA = \mathbf{1}(distance \leq 77.8\,\text{km})$) is replaced with a continuous measure of proximity equal to $1/distance$, where *distance* is equal to kilometers from the epicenter.[24]

Point estimates in Table 5 can be interpreted, approximately, as the conditional gap in birth outcomes between a city 1 km from the epicenter ($1/distance = 1$) and the city farthest from the earthquake (884 km, such that $1/distance \approx 0.001$). For the full sample, we find this gap to be quite large: 7.9 percentage points with respect to low birth weight. Echoing results from the binary measure of proximity, column (2) of Table 5 results suggest a significant but much larger impact on very low birth weight. For the high-stress subsample in Panel B, the estimated impact on low birth weight is implausibly large at 20–22 percentage points. Large point estimates in Table 5 and visual evidence from Fig. 2 support $HA = \mathbf{1}(distance \leq 77.8\,\text{km})$ as the preferred specification. Nevertheless, results in Table 5 demonstrate that inferences from a binary proximity measure are robust in sign and significance to more continuous measures of exposure to the Northridge earthquake.

Table 5
Eq. (1) results – linear proximity to the earthquake and birth outcomes.

	(1) LBW	(2) Very LBW	(3) Mild LBW	(4) Prematurity	(5) Extreme prematurity	(6) Mild prematurity
Panel A (full sample)						
1994*Inverse KM	0.0790**	0.0485***	0.0305	0.0388	0.0112*	0.0276
	(0.0292)	(0.00939)	(0.0277)	(0.0348)	(0.00627)	(0.0371)
N	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895
R^2	0.104	0.032	0.075	0.058	0.017	0.048
Panel B (single and first-time mothers, singleton births)						
1994*Inverse KM	0.224***	0.0280	0.196***	0.302***	−0.0276	0.329***
	(0.0549)	(0.0405)	(0.0515)	(0.0785)	(0.0239)	(0.0774)
N	294,332	294,332	294,332	294,332	294,332	294,332
R^2	0.019	0.015	0.010	0.023	0.011	0.017

Note: Standard errors in parentheses. Standard errors are clustered by county of residence. "Very LBW" refers to infants born under 1500 g. "Mild LBW" refers to infants 1500–2499 g. "Extreme prematurity" describes gestation under 28 weeks. "Mild prematurity" is gestation at 28–36 weeks.
$^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.

Table 6
Eq. (1) results – CDI and birth outcomes.

	(1) LBW	(2) Very LBW	(3) Mild LBW	(4) Prematurity	(5) Extreme prematurity	(6) Mild prematurity
Panel A (full sample)						
CDI≥4	0.00273***	0.000759	0.00197***	0.00367***	0.000210	0.00346**
	(0.000740)	(0.000556)	(0.000718)	(0.00131)	(0.000258)	(0.00130)
N	1,269,963	1,269,963	1,269,963	1,269,963	1,269,963	1,269,963
R^2	0.104	0.033	0.074	0.058	0.017	0.048
Panel B (single and first-time mothers, singleton births)						
CDI≥4	0.00796***	0.000831	0.00713***	0.0102***	−0.00108	0.0113***
	(0.00192)	(0.00125)	(0.00208)	(0.00229)	(0.00102)	(0.00196)
N	179,043	179,043	179,043	179,043	179,043	179,043
R^2	0.021	0.016	0.011	0.023	0.012	0.017

Note: Standard errors in parentheses. Standard errors are clustered by county of residence. "Very LBW" refers to infants born under 1500 g. "Mild LBW" refers to infants 1500–2499 g. "Extreme prematurity" describes gestation under 28 weeks. "Mild prematurity" is gestation at 28–36 weeks.
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 6 reports results from a third exposure measure that is less arbitrary than our 77.8 km radius and more grounded in perceptions of shaking and damage. The community decimal intensity (CDI) scale aggregates telephone survey responses from people who experienced an earthquake. The measure, widely used today, was developed by Dengler and Dewey (1998) following the Northridge earthquake using survey data from about 6000 affected adults. Examples of survey questions include "Did you feel it?"; "Was it difficult to stand or walk?"; "Was there damage to the building?" Responses are quantified, weighted (with more weight given to recollections of moving furniture or structural damage), and aggregated by community. The range is 1–7 for cities in the Northridge vicinity. Dengler and Dewey (1998) and others show that spatial CDI distributions are smoother than moment magnitude readings, and for our purposes, CDI responses may better reflect variation in the stress of experiencing an earthquake.

One drawback of using city-level CDI data over the simple kilometer radius is that we introduce additional measurement error when birth cities are imputed. Another drawback is that CDI variation is lumpy.[25] Accordingly, we limit the sample to unimputed birth cities and define a binary indicator of high CDI for cities rating 4 or higher on the 7-point scale. Four-fifths of births in the 77.8-km radius were in high CDI cities, and no births in high CDI cities were outside the 77.8-km radius.

Table 6 specification of Eq. (1) is therefore a logical test of whether infants meeting our broad, radial measure of proximity to the earthquake were more affected in areas where citizens reported more shaking. We find this to be the case, with the incidence of LBW rising 0.27 percentage points in the full sample and 0.79 percentage points in the high-stress restricted subsample. These point estimates are 35–48% larger than analogous estimates using radial proximity, and as before, appear to be driven by mild LBW.[26] The CDI measure also points to higher rates of mild preterm birth, by 0.35–1.1 percentage points, respectively, across the full and restricted samples. Table 6 results support the causal inferences we make from simpler proximity measures, but at the cost of omitting 42% of infants who were born in smaller towns and cities. We maintain radial proximity as our preferred measure of earthquake exposure, emphasizing that this broader treatment may understate the effect of experiencing the earthquake *in utero* on newborn health.

Turning to results by trimester in Table 7, we find effects of the earthquake on low birth weight to be strongest in the first and third trimesters in the full sample. A mother living in cities designated as "highly affected" who experienced the earthquake in her first (third) trimester was 0.33 (0.42) percentage points more likely to have an LBW infant. An important new insight in Table 7 is the marginally significant effect on severe LBW for full-sample infants experiencing the earthquake in their third trimester (one sixth of one percentage point). Echoing some of our earlier findings, none of the Panel A point estimates for prematurity are statistically significant at conventional levels.

It is perhaps not surprising that the earthquake had larger effects on birth weight when it coincided with the first or third trimester. The first trimester is the most important period for fetal development and establishes the trajectory for weight gain over the balance of the pregnancy (Mook-Kanamori et al., 2010). The third trimester, however, is when the majority of fetal weight gain actually occurs. Low birth weight and Intrauterine Growth Restriction have been linked to several risk factors, including maternal hypertension (Mamelle et al., 2001), which is in turn plausibly linked to stress.

That being said, findings in Table 7 Panel B indicate that mothers who were more susceptible to stress were more affected if they were in their second or third trimester on January 17th, 1994. The incidence of mild LBW was significantly more likely regardless of trimester for the stress-susceptible group.

[24] Results are qualitatively robust to alternative functional forms, e.g., exponential or piece-wise.
[25] Among January–October 1994 births in the 77.8-km radius, 93% were born in (unimputed) cities that rated 3 or 4 on the CDI scale, and more intense ratings were rare.
[26] Table 6 point estimates are also larger in magnitude than estimated effects of radial proximity among the subsample of births in non-imputed cities. See Table S2 in Appendix.

Table 7
Eq. (2) results – the effect of the earthquake on birth outcomes, by trimester.

	(1) LBW	(2) Very LBW	(3) Mild LBW	(4) Prematurity	(5) Extreme prematurity	(6) Mild prematurity
Panel A (full sample)						
Earthquake during 1st trimester	−0.0113***	−0.00514***	−0.00619***	−0.0124**	−0.00202**	−0.0104**
	(0.00348)	(0.00158)	(0.00206)	(0.00513)	(0.000833)	(0.00446)
Earthquake during 2nd trimester	−0.0131***	−0.00598***	−0.00710***	−0.0141**	−0.00276***	−0.0114**
	(0.00393)	(0.00185)	(0.00225)	(0.00571)	(0.000984)	(0.00487)
Earthquake during 3rd trimester	−0.0316***	−0.0140***	−0.0176***	−0.0585***	−0.00841***	−0.0501***
	(0.00401)	(0.00196)	(0.00219)	(0.00563)	(0.00103)	(0.00466)
1st trimester*Highly affected	0.00325*	0.00128	0.00197	0.00381	0.000451	0.00336
	(0.00161)	(0.000855)	(0.00126)	(0.00263)	(0.000574)	(0.00229)
2nd trimester*Highly affected	0.00249	0.000507	0.00198	0.00136	−0.000182	0.00154
	(0.00225)	(0.000997)	(0.00149)	(0.00290)	(0.000537)	(0.00255)
3rd trimester*Highly affected	0.00418**	0.00163*	0.00255**	0.00182	0.000154	0.00167
	(0.00166)	(0.000885)	(0.00119)	(0.00332)	(0.000718)	(0.00267)
N	2,136,038	2,136,038	2,136,038	2,136,038	2,136,038	2,136,038
R^2	0.104	0.033	0.075	0.061	0.017	0.050
Panel B (single and first-time mothers, singleton births)						
Earthquake during 1st trimester	−0.0130**	−0.00550**	−0.00753**	−0.0186**	−0.00182	−0.0168***
	(0.00526)	(0.00251)	(0.00330)	(0.00714)	(0.00152)	(0.00604)
Earthquake during 2nd trimester	−0.0194***	−0.00834***	−0.0111**	−0.0209**	−0.00302*	−0.0179**
	(0.00598)	(0.00283)	(0.00412)	(0.00807)	(0.00165)	(0.00700)
Earthquake during 3rd trimester	−0.0399***	−0.0166***	−0.0233***	−0.0720***	−0.0112***	−0.0608***
	(0.00622)	(0.00295)	(0.00377)	(0.00783)	(0.00158)	(0.00664)
1st trimester*Highly affected	0.00428	−0.000876	0.00516*	0.00466	−0.00251**	0.00717**
	(0.00333)	(0.00144)	(0.00263)	(0.00379)	(0.000975)	(0.00328)
2nd trimester*Highly affected	0.00875*	0.00110	0.00765*	0.00636	−0.00175	0.00811*
	(0.00451)	(0.00193)	(0.00378)	(0.00435)	(0.00132)	(0.00412)
3rd trimester*Highly affected	0.00723**	0.00139	0.00584**	0.00348	0.000301	0.00318
	(0.00336)	(0.00163)	(0.00220)	(0.00370)	(0.000939)	(0.00337)
N	289,928	289,928	289,928	289,928	289,928	289,928
R^2	0.020	0.015	0.010	0.026	0.012	0.019

Note: Standard errors in parentheses. Standard errors are clustered by county of residence. "Very LBW" refers to infants born under 1500 g. "Mild LBW" refers to infants 1500–2499 g. "Extreme prematurity" describes gestation under 28 weeks. "Mild prematurity" is gestation at 28–36 weeks.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

5. Robustness checks

5.1. Changes in specification

Table 8 reports on our tests of the sensitivity of results to specification changes, with specifications for LBW on the left (columns 1a to 5a) and specifications for prematurity on the right (columns 1b to 5b). Baseline point estimates are repeated in columns (1a) and (1b).

The column (2a) and (2b) model redefines low birth weight or prematurity as a weak inequality condition rather than a strict inequality condition, i.e., birth weights ≤2500 g, rather than <2500 g, are categorized as low birth weight and gestation ≤37 weeks is defined as preterm. The magnitude of the estimated effect on LBW in Panels A and B are almost identical with baseline results. Including 37-week gestations with preterm births dramatically increases the estimated effect of the earthquake, increasing the differential from an imprecise zero to 0.3 percentage points in the full sample and 0.5 percentage points in the restricted sample. This, along with evidence of a higher rate of mild preterm birth under some specifications (see Tables 4–6), indicates that the earthquake had a small effect on gestation, most noticeable at the 37-week medical definition of early term gestation.

Specifications reported in column (3a) and (3b) omit newborns whose birth weight was measured in round multiples of 100 g. Barreca et al. (2010) note that less healthy newborns and newborns of lower socioeconomic status are overrepresented at round birth weights, in part because hospitals serving these populations are less likely to have precise neonatal scales. The earthquake may have shifted the composition of births across hospitals in a way that inadvertently increased the recorded rate of LBW. Comparing columns (1a/1b) with (3a/3b) does not suggest that this possibility had bearing on our results. Point estimates for LBW are within one standard error of the baseline, and inferences do not change for preterm birth. Unreported analyses find no change in the likelihood of having a round birth weight in cities most affected by the earthquake.

Column (4a) and (4b) report results from a specification where dependent variables are continuous measures of birth weight and gestational age rather than binary designations of LBW or preterm birth. Results in these specifications are consistent with those from Table 4. For the full sample, the earthquake reduced birth weight by 9.8 g and reduced gestation by 0.026 weeks. Focusing on mothers more susceptible to stress, we estimate that the earthquake reduced birth weight by 11.4 g and reduced gestation by 0.047 weeks.

Table 8
Robustness and specification tests.

	Low birth weight					Prematurity				
	(1a) Baseline	(2a) Birth weight ≤2500 g	(3a) Round weights omitted	(4a) Birth weight (continuous)	(5a) City FE excluded	(1b) Baseline	(2b) Gestation ≤37 weeks	(3b) Round weights omitted	(4b) Gestation (continuous)	(5b) City FE excluded
Panel A (full sample)										
1994*Highly affected	0.00202**	0.00205**	0.00175**	−9.837***	0.00229**	0.000625	0.00335**	0.000180	−0.0258***	−0.000408
	(0.000761)	(0.000754)	(0.000748)	(2.231)	(0.000901)	(0.000994)	(0.00127)	(0.00103)	(0.00845)	(0.00132)
N	2,167,895	2,167,895	2,077,740	2,167,579	2,167,895	2,167,895	2,167,895	2,077,740	2,092,896	2,167,895
R^2	0.104	0.104	0.104	0.123	0.103	0.058	0.054	0.058	0.070	0.058
Panel B (single and first-time mothers, singleton births)										
1994*Highly affected	0.00538**	0.00558***	0.00566***	−11.39**	0.00580***	0.00358	0.00523***	0.00356	−0.0471**	0.00301
	(0.00198)	(0.00196)	(0.00200)	(5.530)	(0.00199)	(0.00261)	(0.00133)	(0.00253)	(0.0194)	(0.00300)
N	294,332	294,332	281,658	294,296	294,332	294,332	294,332	281,658	284,090	294,332
R^2	0.019	0.020	0.019	0.049	0.019	0.023	0.022	0.023	0.040	0.022

Note: Standard errors in parentheses. Standard errors are clustered by resident county.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 9
Alternative sample windows.

	Low birth weight					Prematurity				
	(1a) Baseline	(2a) 1991–1995	(3a) 1992–1994	(4a) 1991–1994	(5a) 1991–1993	(1b) Baseline	(2b) 1991–1995	(3b) 1992–1994	(4b) 1991–1994	(5b) 1991–1993
Panel A (full sample)										
1994*Highly affected	0.00202** (0.000761)	0.00248*** (0.000893)	0.00326** (0.00123)	0.00346*** (0.00123)		0.000625 (0.000994)	0.00123 (0.000970)	0.00218* (0.00116)	0.00258** (0.00107)	
1993*Highly affected					−0.0000129 (0.00158)					0.00170 (0.00231)
N	2,167,895	2,740,817	1,653,188	2,226,110	1,113,006	2,167,895	2,740,817	1,653,188	2,226,110	1,113,006
R^2	0.104	0.103	0.102	0.102	0.102	0.058	0.057	0.058	0.057	0.057
Panel B (single and first-time mothers, singleton births)										
1994*Highly affected	0.00538** (0.00198)	0.00628*** (0.00195)	0.00519** (0.00240)	0.00614** (0.00229)		0.00358 (0.00261)	0.00422 (0.00270)	0.00389 (0.00333)	0.00466 (0.00312)	
1993*Highly affected					−0.00629 (0.00408)					−0.00332 (0.00555)
N	294,332	371,983	228,613	306,264	152,461	294,332	371,983	228,613	306,264	152,461
R^2	0.019	0.020	0.021	0.021	0.021	0.023	0.023	0.024	0.024	0.024

Note: Standard errors in parentheses. Standard errors are clustered by resident county.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 10
Eq. (1) results with city injury and structural damage rates included as additional controls.

	(1) LBW	(2) Very LBW	(3) Mild LBW	(4) Prematurity	(5) Extreme prematurity	(6) Mild prematurity
Panel A (radial proximity indicator)						
1994*Highly affected	0.000926* (0.000514)	−0.000437 (0.000583)	0.00136 (0.000845)	−0.00121 (0.00314)	−0.000432 (0.000603)	−0.000783 (0.00256)
N	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895
R^2	0.104	0.032	0.075	0.058	0.017	0.048
Panel B (high CDI indicator)						
CDI ≥ 4	0.00586*** (0.00129)	−0.00134 (0.00145)	0.00721*** (0.00186)	0.00824* (0.00480)	−0.000628* (0.000335)	0.00886* (0.00463)
N	1,269,963	1,269,963	1,269,963	1,269,963	1,269,963	1,269,963
R^2	0.104	0.033	0.074	0.058	0.017	0.048

Note: Standard errors in parentheses. Standard errors are clustered by county of residence. "Very LBW" refers to infants born under 1500 g. "Mild LBW" refers to infants 1500–2499 g. "Extreme prematurity" describes gestation under 28 weeks. "Mild prematurity" is gestation at 28–36 weeks.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Specifications reported in columns (5a) and (5b) estimate Eq. (1) without fixed effects for city of residence. Results are not substantially different from baseline findings repeated in column (1a/1b).

Further sensitivity tests are included in Table 9, where we deviate from the baseline sample window of 1992–1995. As above, full sample results are displayed in Panel A, and Panel B results pertain to the restricted sample of single, first-time mothers. Baseline results are repeated in columns (1a) and (1b). Columns (2a) and (2b) expand the analytical sample to birth years 1991–1995, columns (3a) and (3b) contract the sample to 1992–1994, and columns (4a) and (4b) list results for a 1991–1994 sample. Looking across columns 1–4, we show that results from the baseline 1992–1995 sample are conservative with respect to low birth weight and preterm outcomes. Excluding 1995 births increases the magnitude and precision with which we estimate prematurity in the full sample.

Columns (5a) and (5b) of Table 9 contain results for a falsification test, where we limit the sample to 1992–1993 births and control for the interaction 1993 * *HA* in place of the causal difference-in-difference estimate. This is an indirect test of our identifying assumption that affected cities would have followed the same trajectory of birth outcomes as less affected cities in the absence of the Northridge earthquake, which would be questionable if highly affected cities exhibited different rates of low birth weight or prematurity in 1993, before the earthquake. As we see in columns (5a) and (5b), however, we do not observe a significant change in low birth weight or preterm delivery in 1993.

Next, we explore the extent to which additional controls for injury and structural damage rates could explain the inferred effect of proximity to the Northridge earthquake. In Table 10 we report results from Eq. (1) with the addition of two control variables: city-level injury rates and a structural damage index. Injury data are the number of persons per thousand who were treated and released from area hospitals, as estimated by Durkin (1995). Structural damage indices are computed from the same survey of affected households that yielded the CDI (Dengler and Dewey, 1998). These city-level controls can be thought of as the aggregate likelihood that a mother or her building was physically harmed because of the earthquake.[27] Any remaining effect of proximity is therefore a stronger indication of non-physical, psychological mechanisms connecting Northridge to infant health. We emphasize, however, that variation in aggregate structural and personal harm likely soaks up much of the variation in stress that we seek to quantify. Destruction itself is stressful (Nolen-Hoeksema and Morrow, 1991), even without injury. We view Table 10 model, therefore, as strong test of the residual effect of proximity.

Panel A of Table 10 lists results of Eq. (1) when the *HA* treatment of interest is the radial indicator for cities within 77.8 km of the epicenter. There, we show that LBW rates are 0.09 percentage points higher in more affected areas, with weak statistical significance. This means that 45% of the baseline 0.20 percentage point estimate remains unexplained by spatial variation in injury and structural damage. Echoing earlier findings, the positive point estimate appears to be driven by mild LBW, which exhibits the same percentage point gain as in the baseline Table 4 specification but with a larger standard error. Panel B lists results for the specification of Eq. (1) where CDI greater than 3 is used to indicate highly affected cities. As in Table 6, we limit the sample to non-imputed birth cities. Results for LBW indicate a strong residual effect of high CDI, one that is actually more than twice as large as the corresponding estimate in Table 6. Since the structural damage component was one element of CDI, this attributes an outsized role to recollections of pictures shaking, furniture moving, and so forth.

5.2. Placebo test: moving the epicenter

Main results discussed in Section 4 show that birth weight in close proximity to Northridge noticeably deviated from expectations. It is possible that this was merely due to sampling variation. If several locations deviated from expectations by even greater degrees, that would cast doubt on the earthquake as a primary factor in weaker infant outcomes. We assess this threat to internal validity by estimating a distribution of “treatment effects” across every city in the NCHS birth records and then computing the probability that we observe a point estimate as large as the one associated with the true epicenter. Specifically, for each city further than 30 km from the epicenter, we re-estimate our main specification as if the alternative city was the actual epicenter of the earthquake.[28] We then compare the estimated effect from the true epicenter to the distribution of false estimates arising from this series of placebo tests.

Fig. 3 depicts results. For the full sample, the estimated effect of the earthquake on low birth weight at the true epicenter is greater than all but four placebo estimates (Panel I), one of which was plausibly affected by the earthquake (Glendale). For the high stress subsample, the estimated effect at the true epicenter is higher than all but the Oxnard coefficient (Panel III). Regarding preterm birth, however, Panels II and IV of Fig. 3 show that baseline effect estimates are not exceptional relative to the distribution of falsification tests. This is expected as our initial results in Table 4 indicate the earthquake did not significantly affect the likelihood of preterm birth. Results for the placebo distribution of *t*-statistics (not shown) follow the same pattern.

5.3. Migration and access to care

One concern with our empirical strategy is endogenous migration after the earthquake, i.e., the idea that some expectant mothers moved outside the radius of “highly affected” cities after January 17th, 1994 and before delivery. If the expectant mothers who migrate after the earthquake are not representative of the full sample, then difference-in-difference results may reflect compositional changes in mothers more so than the impact of stress on fetal health and development. Plausibly, mothers from more advantaged backgrounds, who are less likely to deliver a preterm or LBW infant, may be more able and likely to leave their community than disadvantaged, higher-risk mothers. This migration pattern would bias results away from zero, overstating the deleterious effect of the earthquake on newborn outcomes. To investigate this possibility, we regress mothers’ and fathers’ characteristics on other covariates in Eq. (1).

Results are found in Table 11. As in previous tables, Panel A contains results for the full sample and Panel B contains results for our high-stress subsample. The coefficient on the interaction term estimates the post-earthquake change in parental characteristics in highly affected cities, relative to the same difference across other cities. For both the full and high-stress subsample, proximity to Northridge in 1994 does not appear to affect the average level of mothers’ education, mothers’ age, or fathers’ race. Relative to the rest of the full sample, mothers in highly affected cities were 0.1 percentage points less likely to be black (1.5% of the area mean prior to 1994), and in the restricted sample fathers were 0.4 percentage points less likely to be under 25 (0.7% of the restricted sample mean prior to 1994). Both differentials are small and correlated with lower rather than higher rates of LBW and preterm birth, and by conditioning on parental characteristics in Eq. (1), we control for any *ex ante* differences between black and white mothers or between younger and older fathers.

We also assess mothers’ migration by examining changes in the total number of births and the total number of LBW births in each city by month and year, following Simeonova (2011). If results are driven by outmigration of more advantaged

[27] Reported injury rates were too infrequent to explain our findings (refer back to our computations in Section 2.2), but we acknowledge the possibility that unreported injuries played a role. Citywide aggregates should approximate geographic variation in all degrees of injury.

[28] Analytical samples for each false epicenter omit births within 30 km of Northridge. Having already established that proximate cities realized a differential change in birth outcomes, excluding them will give false epicenters a better chance at meeting the treatment effect estimated for the true epicenter. Results are robust to wider or narrower radial exclusions.

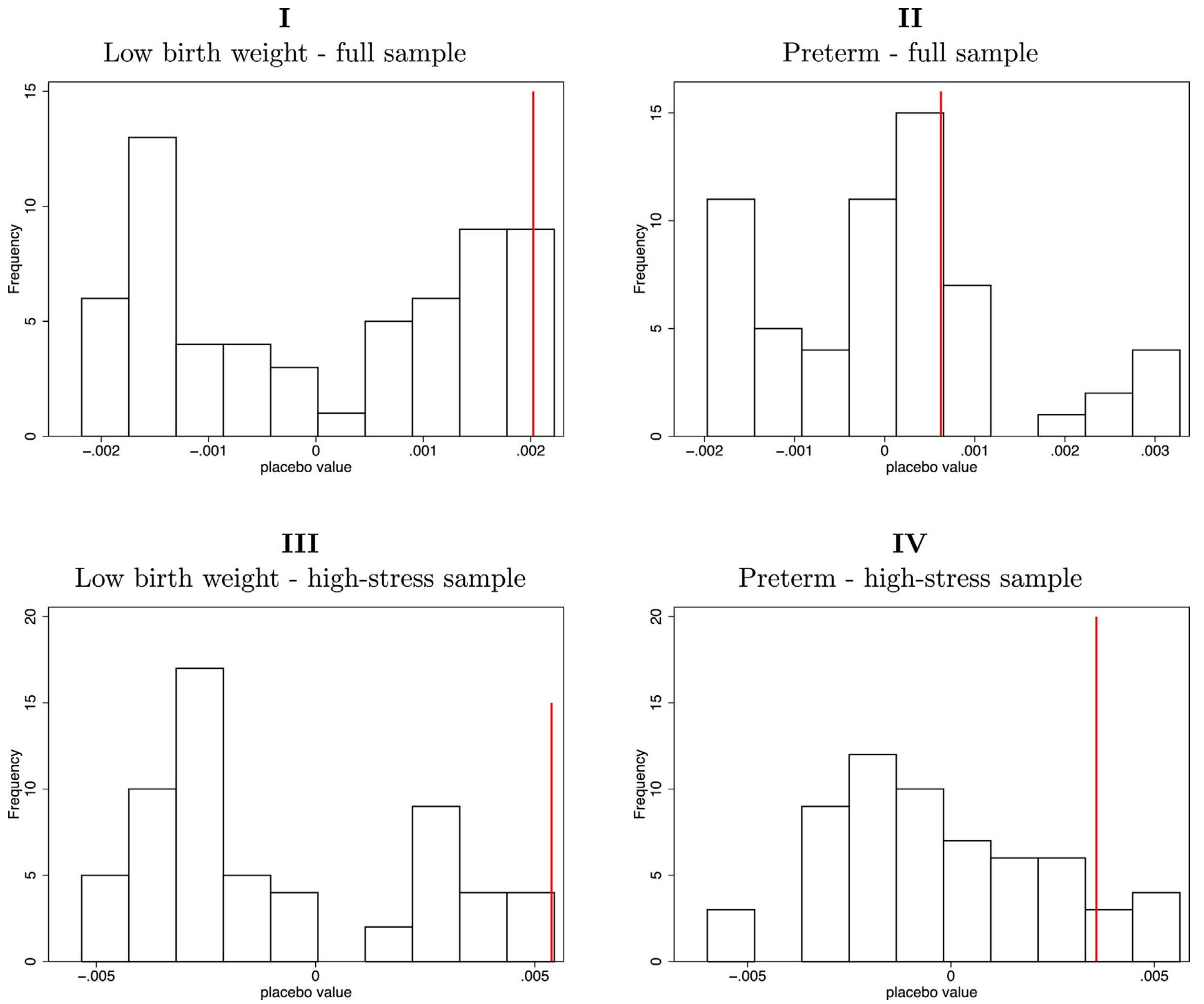

Fig. 3. Placebo permutation tests for the full sample. *Note*: Each figure depicts a distribution of β_2 estimates from Eq. (1) for the given outcome and sample, where the distribution is generated by "moving" the epicenter from Northridge to 60 alternative cities. Solid lines signify the β_2 estimate for the true epicenter, which can also be found in Table 4.

mothers, we might expect to observe a decrease in total 1994 births in highly affected cities but a relative increase in the number of LBW births. We empirically test this notion by aggregating births to a city-month panel and estimating Eq. (3):

$$TotalBirth_{js} = \gamma_0 + \gamma_1 1994_{js} + \gamma_2 HA_{js} + \gamma_3(1994_{js} * HA_{js}) + \gamma_4 X_{js} + M_s + \psi_{js}, \quad (3)$$

where *TotalBirth* is either the total number of births in city *j* during month *s* or total number of low birth weight newborns.[29] If the coefficient γ_3 in Eq. (3) is negative when modeling the total birth count, we should be concerned about endogenous migration. However, as the results in Panel C, column (9) of Table 11 show, we do not detect a significant change in total births. Highly affected cities saw an average of 126.9 fewer births per month in 1994, but the standard error is large and we cannot reject the hypothesis of no change in total births. Additionally, note that the population share of LBW newborns is approximately 0.06. With this in mind, we would about expect 7–8 fewer LBW infants per month, which coincides with the insignificant point estimate reported in column (10). This implies our main findings from microdata are not driven by a disproportionate outflow of healthy infants. Columns (3)–(6) in Panel C examine whether the earthquake affected aggregate births by race and LBW status. None of these difference-in-difference results are statistically significant.

Table 12lists difference-in-difference estimates for two obstetric outcomes that one might expect to have been affected by proximity to Northridge. First, we estimate the impact of the earthquake on the number of prenatal care visits that mothers' report. The main finding in column (1) is that being pregnant in a highly affected area during the earthquake led

[29] The rest of the variables are defined as before, except that their values are monthly averages.

Table 11
Eq. (1) results for parental characteristics and aggregate birth outcomes.

	(1a) Years of education	(2a) Black mother	(3a) Mother age < 25	(4a) Mother age > 40	(5a) Black father	(6a) Father age < 25
Panel A (full sample)						
1994*Highly affected	0.0352	−0.00130**	−0.000642	−0.000357	−0.000136	−0.000447
	(0.0501)	(0.000537)	(0.00156)	(0.000326)	(0.000696)	(0.00176)
N	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895	2,167,895
R^2	0.078	0.050	0.020	0.001	0.044	0.015
	(1b) Years of education	(2b) Black mother	(3b) Mother age < 25	(4b) Mother age > 40	(5b) Black father	(6b) Father age < 25
Panel B (single and first-time mothers, singleton births)						
1994*Highly affected	0.0630	0.000506	−0.00127	0.000112	0.000573	−0.00436*
	(0.0398)	(0.00279)	(0.00245)	(0.000487)	(0.00301)	(0.00255)
N	294,332	294,332	294,332	294,332	294,332	294,332
R^2	0.049	0.075	0.027	0.002	0.064	0.022
	(9) Births	(10) LBW births	(11) white births	(12) white LBW births	(13) black births	(14) black LBW births
Panel C (city-level aggregates)						
1994*Highly affected	−126.9	−7.128	−106.6	−14.80	−5.194	−1.599
	(164.1)	(10.07)	(137.6)	(20.21)	(7.622)	(2.408)
N	3588	3588	3588	3588	3588	3588
R^2	0.286	0.290	0.285	0.363	0.281	0.360

Note: Standard errors in parentheses. Standard errors are clustered by resident county.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 12
Eq. (1) results for health care decisions.

	(1) Number of prenatal visits	(2) Hospital birth
Panel A (full sample)		
1994*Highly affected	0.287***	−0.00369
	(0.0586)	(0.00316)
N	2167,895	2,167,895
R^2	0.125	0.009
Panel B (single and first-time mothers, singleton births)		
1994*Highly affected	−0.00357	−0.00369
	(0.00234)	(0.00316)
N	294,332	2,167,895
R^2	0.007	0.009

Note: Standard errors in parentheses. Standard errors are clustered by resident county.
*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

to a statistically significant but economically small increase in prenatal care visits. Compared to a sample mean of 11.26, the earthquake led to a 2.5% increase in prenatal care visits for the full sample and no distinguishable change in prenatal care for the restricted sample. This is important for two reasons. First, the increase in overall prenatal care after the earthquake in highly affected areas contradicts the notion that reduced access to care is responsible for our main result. Second, but equally important, the increased number of prenatal visits is evidence of at least a small degree of compensating behavior on the part of affected mothers (but not, it would seem, mothers most susceptible to stress). Note that prenatal care is included as a control variable in Eq. (1), meaning that results are net of such compensating behavior.[30]

Another issue related to health care is the likelihood of giving birth in a hospital since several hospital facilities in the affected area were temporarily or permanently closed as a result of the earthquake. Difference-in-difference results for the linear probability of a hospital birth indicate no significant change among mothers overall (column 2a) or among mothers in the stress-susceptible group (column 2b). Almost all of births are recorded as occurring in a hospital in both the full and restricted samples. Main results are virtually unchanged if we include “hospital birth” as an additional control variable (see Table S3 in Appendix A). While we acknowledge the hospital system was disrupted (in places, severely) by the earthquake, results for prenatal care indicate that affected mothers accessed care above and beyond expectations. Finally, low birth

[30] We acknowledge the possibility that damage to some medical facilities and the increased demand for prenatal care may have had an adverse effect on the *quality* of prenatal care after the earthquake. However, we have not found qualitative evidence to support this hypothesis, nor do we have any data to empirically evaluate it.

weight is more reasonable as a precursor to a hospital birth than vice versa. It is possible that accessible hospitals could reduce low birth weight by stopping early labor. If this was driving our results, however, we would also expect the earthquake to have a stronger and more precise effect on prematurity.

Thus, we conclude that endogenous migration and access to health care did not play a substantial role in our main findings. The composition of mothers was relatively unchanged after the earthquake, access to health care had compensating rather than restricting effects, and aggregate changes in births do not support a story of selective outmigration.

6. Conclusion

We provide evidence that maternal stress leads to a higher probability of low birth weight, a small decline in gestation age, but no robust change in the likelihood of preterm birth. We rely on identification from intertemporal and spatial variation in stress caused by the 1994 Northridge earthquake in California. Infants born in highly affected cities were 0.20 percentage points more likely to weigh less than 2500 g at birth. Among single and first-time mothers, presumed to be more susceptible to stress, the effect of the earthquake was 2.6 times larger at 0.54 percentage points. Most specifications indicate that the earthquake led to increases in the probability of mildly low birth weight, rather than very low birth weight. This last observation is consistent with the idea that the earthquake operated mainly through psychological stress. Had we found that the earthquake led to more severe birth weight and gestation changes, we would give more credence to mediating and unobserved factors like access to nutrition, shelter, and water.

When disasters serve as natural quasi-experiments in stress, results must be viewed through the lens of the geographic and institutional context surrounding these events, as well as unique circumstances of the event itself. Earthquakes have idiosyncratic impacts, as do natural disasters more generally. Particularly for pregnant women, a natural disaster may impose immediate physical and psychological stress but may also lead to physical hardship if lifeline services are disrupted or access to nutrition or medical care is limited. A holistic view of the disaster in question is of paramount importance when comparing results discussed here to those of related work.

For example, our estimate of the Northridge earthquake's impact on infant outcomes is easily less than half of that estimated for a 2005 earthquake in Tarapaca, Chile (Torche, 2011). But the destruction caused by the Tarapaca earthquake was much more comprehensive in nature. Rock slides blocked roads to the point where relief materials had to be air-dropped. Power and water were disrupted for several weeks. Following the Northridge earthquake, all utilities were reconnected within four days. While there was extensive damage to freeway overpasses, the infrastructure was sufficient to allow navigation to essential goods and supplies via surface streets.

The effect of the Northridge earthquake on low birth weight, though economically small, is greater than that reported in Currie and Rossin-Slater's (2013) study of severe storms and birth outcomes. The earlier study discerned no precise impact on birth weight or gestation alongside significant impacts on more severe outcomes. Earthquakes and hurricanes differ on several dimensions, and our findings may be reconciled by the duration of disruption, climate, and other contextual factors. Northridge was an unanticipated disaster followed by a quick recovery in terms of transportation, access to food and water, and normal daily activities. Contemporary accounts suggest that stress and mental health were the most lasting consequences of the Northridge earthquake. Our findings are most similar in magnitude to those of Carlson (2015) and Black et al. (2016), who study the effect of other psychological shocks on newborn health.

Results point to the potential value of counselors and other resources specifically focused on helping expectant mothers cope with stress in the wake of a natural disaster. More generally, we provide quasi-experimental evidence that maternal psychological stress does indeed lead to low birth weight, which has been previously linked to adverse outcomes over the life course. Incorporating stress management and behavioral counseling into high-risk pregnancy and maternal fetal medicine practices may yield substantial benefits in averting low birth weight and associated consequences.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jebo.2017.05.014.

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