

**Main Manuscript for**

Disruption to Test Scores after Hurricanes in the United States

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**This PDF file includes:**

Main Text

Figures 1 to 5

Table 1

**Abstract**

Quantifying how hurricanes disrupt educational attainment is essential to evaluating the burden of climate-related disasters. Here, we examine the association between hurricane-force tropical cyclones and educational attainment among elementary- and middle school-age students in all affected areas in the United States during 2008/2009–2017/2018. Education was based on county-level average standardized test scores in Math and reading/language arts (RLA). Hurricane-force tropical cyclone exposure was defined for counties that experienced a sustained maximal wind speed ≥64 knots. We estimated the association between hurricane-force tropical cyclone exposure and long-term test score disruption using a Bayesian formulation of a difference-in-differences model, accounting for time-varying covariates at the county and grade-cohort level. For hurricane-exposed counties compared with the rest of the state, there were worse test scores in Texas (β -0.12; 95% Credible Interval (CrI) -0.20, -0.04; posterior probability of positive association = XX%) and North Carolina (β -0.15; 95% CrI -0.26, -0.04; probability = XX%), and better test scores in Florida (β 0.19; 95% CrI 0.11, 0.27; probability = XX%). Grade-cohorts and counties with more racial/ethnic minority, low socioeconomic status, and English language learner students tended to have lower test scores (e.g., β -0.57, -0.63, -0.51; probability = XX% for low SES students in RLA), while those with greater shares of Asian and special education students and college educated adults tended to have higher scores (e.g., β 2.85; 95% CrI 1.95, 3.75; probability = XX% for Asian students in Math). Disaster preparedness must maximize resilience to climate-related stressors’ impacts on academic achievement.

**Significance Statement**

Children are vulnerable to the impacts of climate-related disasters, particularly as it pertains to their educational attainment. This paper is the first to comprehensively assess the disruptive effects of hurricanes on educational outcomes among elementary- and middle school-aged students in all affected U.S. counties over a ten-year timeframe. We found that hurricane-force tropical cyclones had differing impacts on standardized test score trajectories across states and that certain sociodemographic groups were at greater risk in educational lapses. These results indicate that child disaster resilience largely depends on state-specific education policies in disaster contexts.

**Main Text**

**Introduction**

Tropical cyclones such as hurricanes and tropical storms are intense circular storms that originate over warm tropical oceans and are characterized by low atmospheric pressure and high windspeeds. They draw energy from the sea surface and maintain strength as long as they remain over warm water (1). Tropical cyclones are very active in the United States; the 2020 Atlantic hurricane season was the most active on record (2), and 2021 was the third time that the storm naming system had ever been exhausted (3). Tropical cyclones will continue to pose a threat to the United States as they make longer landfall and peak closer to land (4, 5). Once tropical cyclones make landfall, they can be extremely disruptive and very destructive. From 1900 to 2017, hurricanes inflicted $2 trillion in damages, equating to $17 billion annually (6).

While there is evidence that tropical cyclones are associated with deaths (7, 8) and hospitalization (9) from many major causes, less is known about their societal burden on medium and long-term mental and behavioral health (10). Children and adolescents, particularly susceptible to climate-related disasters (11), will experience more frequent and severe tropical cyclones in their lifetimes than previous generations due to the effects of climate change (12). Disasters that destroy school buildings and displace students and teachers may cause children to miss school, have poorer academic performance and delayed progress, or fail to complete their education altogether (13). Hurricane Katrina in 2005, for example, displaced 348,000 students across Louisiana, Mississippi, and Alabama (14), and destroyed nearly 80 percent of New Orleans’s public school buildings (15).

Several studies, most of which examined the aftermath of Hurricanes Katrina and Rita, have identified the adverse effects of major hurricanes on student educational outcomes such as academic achievement, negative behaviors, and school attendance (16–20). Despite this research, no study to date has comprehensively assessed the impact of hurricanes on educational attainment over multiple years of study across the entire United States. Here, we examine the association between hurricane-force tropical cyclones and educational attainment among elementary- and middle school-age students in all affected counties of the United States. Our objectives are to (1) estimate the association between hurricane-force tropical cyclone exposure and long-term disruption to Math and Reading/Language Arts (RLA) test scores in U.S. counties using a Bayesian formulation of a difference-in-differences model, and (2) to evaluate how these effects vary by U.S. state.

**Results**

*Summary Statistics*

There were no discernable differences in average standardized test score distributions between 2009 and 2018 (e.g., the median average Math score for fifth-grade cohorts was 4.80 in 2009 and 4.79 in 2018) (Table 1). However, the median average proportions of grade cohort students receiving free lunch increased from 40.5% in 2009 to 49.0% in 2018, as did the average percentage of grade cohort students considered economically disadvantaged (2009 median = 51.0%; 2018 median = 57.2%). In addition, the average median percentage of grade-cohort students identifying as Hispanic increased over twofold from 3.0% in 2009 to 6.5% in 2018 (Table 1). At the county level, the median average proportion of adult residents with a college degree increased from 15.8% in 2009 to 18.1% in 2018 (Table 1). 74 counties were exposed to hurricane-force tropical cyclones over the course of the study period (Figure 1).

*Association of Covariates with Test Scores*

We observed several notable associations between grade-cohort and county-level sociodemographic characteristics and average standardized test scores (Figures 2 and 3). Grade cohorts with greater proportions of racial/ethnic minority students tended to perform worse than average grade cohorts in both Math and Reading/Language Arts. A hypothetical grade cohort that was 100% American Indian/Alaska Native students would have performed at least one grade level below average in Math (β -1.17; 95% Credible Interval (CrI) -1.99, -0.35; posterior probability of positive association = XX%) and RLA (β -1.70; 95% CrI -2.41, -0.99; probability = XX%). A 100% Hispanic grade cohort would have performed nearly one grade level below average in Math (β -0.97; 95% CrI -1.13, -0.80; probability = XX%) and over one grade level below average in RLA (β -1.60; 95% CrI -1.74, -1.46; probability = XX%). A 100% Black grade cohort would have performed over two grade levels below average in both Math (β -2.02; 95% CrI -2.19, 1.85; probability = XX%) and RLA (β -2.24; 95% CrI -2.39, -2.10; probability = XX%). On the other hand, a 100% Asian grade cohort would have performed nearly three grade levels better than the national average cohort in both Math (β 2.85; 95% CrI 1.95, 3.75; probability = XX%) and RLA (β 2.72; 95% CrI 1.97, 3.48; probability = XX%). A grade cohort in which 100% students received free lunch would have performed 0.28 grade levels below average in math (95% CrI -0.35, -0.21; probability = XX%), though would have performed 0.09 grade levels above average in RLA (95% CrI 0.03, 0.15; probability = XX%). A grade cohort with 100% economically disadvantaged students would have performed over half a grade level below the national average cohort in only RLA (β -0.57, -0.63, -0.51; probability = XX%) (Figures 2 and 3, Supplemental Table).

At the county level, counties with higher poverty levels tended to perform worse in math (β -0.83; 95% CrI -1.11, -0.54; probability = XX%). Those with greater shares of English language learners tended to perform better than average in Math (β 0.60; 95% CrI 0.13, 1.07; probability = XX%), but worse in RLA (β -1.07; 95% CrI -1.45, -0.68; probability = XX%). Counties with higher rates of college-educated adult residents tended to perform better than average in both Math (β 2.05; 95% CrI 1.72, 2.39; probability = XX%) and RLA (β 1.74; 95% CrI 1.46, 2.01; probability = XX%). In addition, counties with greater shared of urban schools (β 0.20; 95% CrI 0.07, 0.33; probability = XX%) and special education students (β 0.87; 95% CrI 0.59, 1.16; probability = XX%) tended to perform better than average in RLA (Figures 2 and 3, Supplemental Table).

*Association of Hurricanes with Math Scores*

There was no association in the national model between hurricane-force tropical cyclone exposure and standardized Math test scores (β 0.00; 95% CrI -0.05, 0.05; probability = XX%). State-specific results showed that counties exposed to hurricane-force tropical cyclones performed worse in Math than non-exposed counties in North Carolina (β -0.15; 95% CrI -0.26, -0.04; probability = XX%). On the other hand, counties exposed to hurricane-force tropical cyclones performed better in Math than non-exposed counties in Florida (β 0.19; 95% CrI 0.11, 0.27; probability = XX%) (Figure 2, Supplemental Table).

*Association of Hurricanes with Reading/Language Arts Scores*

There was no association in the national model between hurricane-force tropical cyclone exposure and RLA scores (β 0.00; 95% CrI -0.04, 0.04; probability = XX%). State-specific results did show, however, that counties in Texas exposed to hurricane-force tropical cyclones performed worse in RLA than unexposed (β -0.12; 95% CrI -0.20, -0.04; probability = XX%) (Figure 3, Supplemental Table).

**Discussion**

In this comprehensive analysis of the association between hurricane-force tropical cyclones and educational attainment in the United States, we found that although hurricane-force tropical cyclones were not associated with standardized test performance in math or reading/language arts on the national level, we observed associations for certain states. Accounting for both grade cohort- and county-level time varying characteristics, we found that hurricane-force tropical cyclones were associated with higher math scores in Florida and lower math and reading/language arts scores in North Carolina and Texas, respectively.

There are several factors that may negatively influence a child’s educational vulnerability during and following hurricanes. These include the destruction of school buildings and loss of vital records; displacement of students and teachers leading to delayed enrollment and multiple school changes; family separation and financial instability; unwelcoming and unsupportive new school environments following relocation; poor academic performance pre-disaster; the loss of a parent in the disaster; and increased work demands to compensate for lost income and assets (13, 21). All of these stressors could also compromise cognitive functioning and subsequent academic achievement (22).

There is evidence from the literature pointing to the negative consequences of hurricanes on child education. Scott et al. found that fourth to eighth grade New Orleans students exposed to the disaster exhibited more aggressive behavior, and in turn, had worse academic achievement (16). In this same cohort of students, Weems et al. found that students exposed to the hurricane had greater posttraumatic stress, which predicted test anxiety, which was negatively associated with academic achievement (17). Ward et al. found that Mississippi students displaced by Katrina had both lower academic performance and were more likely to engage in negative behaviors, patterns that persisted two years following the storm (18). On the school level, Holmes found that if the 1999-2000 storms in North Carolina had not occurred, twenty more schools throughout the state would have met their academic standards (19). Lai et al. (2019) studied public schools affected by 2008 Hurricane Ike and found that attendance and rates of economically disadvantaged students were significant risk factors for worse academic recovery trajectories (20).

The null and positive results we observed may reflect state-level education policies that are implemented in the post-disaster context that influence their schools’ and students’ vulnerability or resilience. For example, Florida, a state that is prone to hurricanes, has policies in place such as make-up instructional days for schools, as well as resources available to support special education students (23, 24). States such as Texas and North Carolina, on the other hand, may not have had the infrastructure in place to effectively withstand the deleterious effects of storms on their students’ academic achievement (25, 26). It is also possible that states where we observed positive relationships between tropical cyclones and test scores received large influxes of federal disaster relief funding (27). Another possibility is that test scores only reflected the performance of more privileged students who were less impacted by the storm. Those students who were more vulnerable, such as racial/ethnic minorities or those living in poverty, may be more likely to have been exposed to storm-related stressors and/or been displaced, not have been enrolled in or attended school, and therefore not have taken standardized tests (14, 21, 28, 29). It is also possible that displaced students were relocated to communities whose schools had better performance than their original schools, which may have mitigated negative achievement effects (30).

Our findings consistently demonstrated the educational vulnerability of racially and socioeconomically marginalized groups, regardless of tropical cyclone exposure. Grade cohorts with greater shares of Black, American Indian/Alaska Native, Hispanic, and economically disadvantaged students performed more poorly on standardized testing in both math and reading/language arts. This comports with previous findings that these groups are at a systematic disadvantage in terms of standardized testing and overall educational attainment (31, 32). These disparities stem from school segregation and “policies associated with school funding, resource allocations, and tracking [that] leave minority students with fewer and lower-quality books, curriculum materials, laboratories, and computers; significantly larger class sizes; less qualified and experienced teachers; and less access to high-quality curriculum” (33). On the other hand, grade cohorts with greater shares of Asian students tended to perform better overall, which scholars attribute to exerting greater academic effort (34). Interestingly, counties with greater shares of special education students tended to perform better on standardized testing, which may be indicative of the fact that they have more resources available to invest in diagnostic assessment and individual education plans. Counties with greater shares of English language learner students may have had worse reading/language arts scores due to language barriers (35). County-level socioeconomic status based on those living in poverty and residents with a college degree also tended to be strongly associated with academic performance.

This study has several limitations. First, standardized testing is not a complete representation of students’ academic success and potential as opposed to a more holistic measure such as grade point average. However, unlike grade point average, which is weighted differently across schools, test scores are easily accessible and comparable across school districts, counties, subjects, and time. Second, the county was the smallest spatial unit available to capture tropical cyclone exposure and relevant covariates. Given the large size of counties and the many diverse schools within each of them, future analyses should consider using a more granular spatial unit of analysis such as a school district to have greater variance and better capture actual tropical cyclone exposure and grade cohort composition. Third, our difference-in-difference approach does not account for the cumulative effects of repeated tropical cyclone exposure over the ten-year study period that may have compounding, adverse effects on students’ educational success and school communities’ disaster recovery (36).

This study shows that the educational effects of tropical cyclones are not only highly variable by state, but that disparities in academic performance persist across racial/ethnic and sociodemographic lines, placing already disadvantaged students in positions of greater vulnerability to the effects of climate-related disasters. To increase children’s educational resilience to the effects of tropical cyclones, policymakers should address both disaster-related educational procedures and policies, as well as underlying sociodemographic educational disparities.

**Materials and Methods**

*Outcomes*

We ascertained educational attainment based on annual standardized test scores in Math and reading/language arts (RLA) administered in the spring to public school third to eighth grade students across 2,420 counties in the contiguous United States as mandated by the No Child Left Behind Act of 2001 (37). We retrieved average test score data aggregated at the county level from the Stanford Education Data Archive (SEDA), which were available for academic years during 2008-2009 to 2017-2018 (38). We only included states if they contained at least one county that experienced at least one tropical cyclone during our study period. SEDA data adjusted for interstate differences in academic proficiency using the National Assessment of Educational Progress (NAEP), an annual exam administered at the same time on the same academic content to a representative sample of US students (39). The SEDA test scores are centered at the grade level and scaled such that a score of 4, for example, is equal to the average national NAEP score across four cohorts of students in fourth grade in the spring of 2009, 2011, 2013, and 2015. According to SEDA documentation, “1 unit in this metric is equal to the average per-grade increase in scores between fourth and eighth grade for those same cohorts, assuming usual grade promotion.” This allows scores to be comparable across the entire US, over time, and across grades (38).

*Exposure*

We obtained data on tropical cyclone wind exposure in the US with full space and time coverage over the study period of 2008 to 2018 from publicly available datasets generated by Anderson et al. (40–42). We used daily estimates of maximum wind sustained speed by county to classify exposures on an annual basis. We defined hurricane exposure by peak sustained winds in a county’s population center associated with a tropical cyclone at the point of closest approach having reached or exceeded 64 knots or 74 miles per hour.

*Covariates*

We retrieved time-varying covariates at both the grade cohort and county level from SEDA and the American Community Survey and the Common Core of Data (38). At the grade cohort level, covariates included the percentage of students who identified as Black, Hispanic, Asian, and American Indian/Alaska Native; the percentage of students who received free lunch; and the percentage of students who were considered economically disadvantaged. At the county level, covariates included the percentage of students in urban locale schools; percentage of English language learner students; percentage of special education students; percentage of adult county residents with a college degree; percentage of county residents living in poverty; and percentage of households headed by single mothers.

*Statistical analysis*

We developed a Bayesian formulation of a state-specific generalized difference-in-difference with two-way fixed effects model to assess the association between hurricane-force tropical cyclone exposure and average annual standardized test scores at the county level. If a given county had been exposed to a hurricane-force tropical cyclone in a particular year, we treated all associated grade cohorts as exposed for the remainder of the study period. A cohort is considered students in a specific grade in a given county. The model, based on those in other studies examining the effects of environmental exposures on standardized test scores (43, 44), was the following:

Score*itgs* = βsCyclone*its* + ∑βCovariates*itg* + Cohort*ig* + Year*t* + ε*itg*

where *i* was the county, *s* was the state, *t* was the year, and *g* was the grade. Score*itg* was the average standardized test score for grade *g* students in county *i* in year *t*. Cyclone*it* was whether a hurricane-force tropical cyclone occurred in a given year *t* and county *i*. Covariates*itg* were covariates for grade *g* students in *i* county in a given year *t*. Cohort*ig* and Year*t* were cohort and year fixed effects, and ε*itg* was the random error.

We used weakly informative priors so that parameter estimation would be driven by the data. All β terms were assigned N(0,1000) priors. Random effects were assigned logGamma(θ,δ) priors with shape θ and rate δ = 0.001.

We conducted statistical analysis in R version 4.3.1, and all models were fitted using integrated nested Laplace approximation (INLA) executed by the R-INLA software.

*Sensitivity analysis*

We conducted sensitivity analyses where we restricted the model to counties whose student enrollment was greater than the 5th and lower than the 95th percentiles, as well as counties that only experienced one hurricane or tropical cyclone over the study period. We also conducted an analysis using lagged exposure effects. None of the sensitivity analyses produced meaningfully different results from the main model.

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**Figures and Tables**

**A map of the united states

Description automatically generated**

**Figure 1.** County-level Hurricane-Force Tropical Cyclone Exposure, 2009-2018



B

A

**Figure 2. A)** Estimated Association Between Grade-Cohort and County Sociodemographic Factors and 2009-2018 Average Standardized Math Grade Scores [Blue = grade-cohort race/ethnicity, Green = grade-cohort socioeconomic status, Red = county student body, Purple = county sociodemographics]; **B)** Estimated Association Between Hurricane-Force Tropical Cyclone Exposure and 2009-2018 Average Standardized Math Grade Scores

Dots indicate point estimates; whiskers, 95% credible intervals.



B

A

**Figure 3. A)** Estimated Association Between Grade-Cohort and County Sociodemographic Factors and 2009-2018 Average Standardized RLA Grade Scores [Blue = grade-cohort race/ethnicity, Green = grade-cohort socioeconomic status, Red = county student body, Purple = county sociodemographics]; **B)** Estimated Association Between Hurricane-Force Tropical Cyclone Exposure and 2009-2018 Average Standardized RLA Grade Scores

Dots indicate point estimates; whiskers, 95% credible intervals.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Grade** | **2009 percentiles** | | | | | **2018 percentiles** | | | | |
| Grade-specific standardized test scores |  |  | 5th | 25th | 50th | 75th | 95th | 5th | 25th | 50th | 75th | 95th |
| Mean Standardized Math Score | 3 | 1.33 | 2.34 | 2.90 | 3.39 | 4.06 | 1.57 | 2.40 | 2.95 | 3.42 | 4.20 |
| 4 | 2.28 | 3.26 | 3.82 | 4.29 | 5.06 | 2.28 | 3.28 | 3.88 | 4.41 | 5.21 |
| 5 | 3.07 | 4.16 | 4.80 | 5.30 | 6.04 | 3.03 | 4.14 | 4.79 | 5.36 | 6.24 |
| 6 | 4.07 | 5.17 | 5.82 | 6.42 | 7.19 | 3.87 | 5.15 | 5.81 | 6.42 | 7.38 |
| 7 | 4.85 | 6.12 | 6.82 | 7.39 | 8.24 | 4.78 | 6.00 | 6.76 | 7.37 | 8.35 |
| 8 | 5.78 | 7.11 | 7.87 | 8.49 | 9.43 | 5.56 | 6.95 | 7.74 | 8.48 | 9.48 |
| Mean Standardized RLA Score | 3 | 1.35 | 2.36 | 2.96 | 3.47 | 4.29 | 1.28 | 2.41 | 3.04 | 3.58 | 4.37 |
| 4 | 2.22 | 3.30 | 3.87 | 4.35 | 5.14 | 2.26 | 3.38 | 3.95 | 4.50 | 5.21 |
| 5 | 3.17 | 4.24 | 4.82 | 5.34 | 6.08 | 3.09 | 4.23 | 4.85 | 5.42 | 6.13 |
| 6 | 4.19 | 5.23 | 5.81 | 6.34 | 7.04 | 4.17 | 5.22 | 5.84 | 6.39 | 7.18 |
| 7 | 5.07 | 6.17 | 6.73 | 7.20 | 7.94 | 5.16 | 6.20 | 6.81 | 7.30 | 8.06 |
| 8 | 6.03 | 7.13 | 7.68 | 8.18 | 8.89 | 6.16 | 7.15 | 7.75 | 8.28 | 9.05 |
| Grade cohort level variables | Percent American Indian/Alaska Native |  | 0.0 | 0.0 | 0.2 | 0.5 | 8.3 | 0.0 | 0.0 | 0.2 | 0.4 | 3.8 |
| Percent Asian |  | 0.0 | 0.0 | 0.6 | 1.4 | 4.5 | 0.0 | 0.2 | 0.6 | 1.3 | 5.0 |
| Percent Hispanic |  | 0.0 | 1.1 | 3.0 | 8.6 | 42.3 | 0.7 | 2.6 | 6.5 | 15.8 | 52.8 |
| Percent Black |  | 0.0 | 1.2 | 4.6 | 20.8 | 64.9 | 0.0 | 1.0 | 3.8 | 19.3 | 62.8 |
| Percent Free Lunch |  | 17.4 | 29.9 | 40.5 | 51.5 | 70.6 | 23.5 | 38.1 | 49.0 | 61.4 | 92.7 |
| Percent Economically Disadvantaged |  | 24.3 | 39.6 | 51.0 | 61.9 | 81.6 | 30.5 | 46.3 | 57.2 | 68.8 | 99.6 |
| County level variables | Percent English Language Learners |  | 0.0 | 0.1 | 1.0 | 3.6 | 11.7 | 0.0 | 0.5 | 1.8 | 5.1 | 13.8 |
| Percent Urban Schools |  | 0.0 | 0.0 | 0.0 | 0.0 | 52.4 | 0.0 | 0.0 | 0.0 | 0.0 | 54.0 |
| Percent with College Degree |  | 9.1 | 12.4 | 15.8 | 21.2 | 34.4 | 10.6 | 14.3 | 18.1 | 23.8 | 38.9 |
| Percent Living in Poverty |  | 7.1 | 11.6 | 15.3 | 19.2 | 26.0 | 8.0 | 12.1 | 15.7 | 19.7 | 26.1 |
| Percent Single-Mother Households |  | 9.9 | 13.3 | 15.9 | 19.5 | 27.3 | 10.3 | 13.6 | 16.5 | 20.2 | 28.3 |
| Percent Special Education |  | 0.0 | 11.0 | 13.7 | 16.1 | 19.8 | 9.1 | 12.2 | 14.3 | 16.7 | 20.7 |

**Table 1.** Educational and demographic characteristics variables in the United States in 2009 and 2018.