

**Main Manuscript for**

Disruption to Test Scores after Hurricanes in the United States

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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 students in all affected areas in the United States during 2008/2009–2017/2018 school years. Educational performance was based on county-level average standardized test scores in math and reading/language arts (RLA). Hurricane-force tropical cyclone exposed counties were those that experienced a sustained maximal wind speed ≥64 knots. We estimated the association between hurricane-force tropical cyclone exposure and long-term test scores using a Bayesian 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 (PP) of negative association = 99.9%) and North Carolina (β = -0.15; 95% CrI: -0.26, -0.04; PP[β<0] = 99.5%) and better scores in Florida (β = 0.19; 95% CrI: 0.11, 0.27; PP[β>0] = 99.9%). Grade cohorts and counties with more people racialized and minoritized (e.g., Black, Hispanic, Indigenous), socioeconomically disempowered and English language learner students tended to have lower test scores, while those with greater shares of students racialized as Asian and enrolled in special education programs and college-educated adults tended to have higher scores regardless of hurricane exposure. Disaster preparedness must maximize resilience to climate-related stressors’ impacts on academic achievement, especially for vulnerable populations.

**Significance Statement**

Children are vulnerable to the impacts of climate-related disasters, including as it pertains to their educational performance. 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 United States 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 for educational lapses. These results indicate that child post-disaster recovery likely 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). Hurricanes 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 was exhausted (3). Hurricanes will continue to pose a threat to the United States as they make longer landfall and peak closer to land than in previous years (4, 5). Once Hurricanes 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 in the United States (6).

While there is evidence that hurricanes are associated with deaths (7, 8) and hospitalizations (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, who are particularly susceptible to climate-related disasters (11), will experience more frequent and severe hurricanes in their lifetimes than previous generations due to climate change (12). Hurricanes 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). The strongest tropical cyclones (hurricane-force winds) have had long-lasting deleterious impacts on education systems in highly impacted communities throughout the United States (16).

Several studies, most of which examined the aftermath of Hurricanes Katrina and Rita, have identified the adverse effects of individual major hurricanes on student educational outcomes such as academic achievement, negative behaviors, and school attendance (17–21). 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 or assessed differences across climatically and politically differing states. Here, we examined 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 were to (1) estimate the association between hurricane-force tropical cyclone exposure and long-term effects on math and reading/language arts (RLA) test scores in United States counties and (2) to evaluate how these effects vary by 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 racialized 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). There were 74 counties exposed to hurricane-force tropical cyclones over the course of the study period (Figure 1).

*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; PP[β>0] = 50%). 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; PP[β<0] = 99.5%) (Figure 2, Supplemental Table). In contrast, 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; PP[β>0] = 99.9%).

*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; PP[β>0] = 50%). State-specific results showed that counties in Texas exposed to hurricane-force tropical cyclones performed worse in RLA than unexposed counties (β = -0.12; 95% CrI: -0.20, -0.04; PP[β<0] = 99.9%) (Figure 3, Supplemental Table).

racialized and minoritized (e.g., Black, Hispanic, Indigenous)grade cohorts with greater proportions of students racialized as tended to performGs with greater shares of students receiving tended to perform worse but betterGsmore socioeconomically disempoweredtended to perform worse thangrade

**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 long-term 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, 22). All of these stressors could also compromise cognitive functioning and subsequent academic achievement (23).

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 Hurricane Katrina exhibited more aggressive behavior, and in turn, had worse academic achievement (17). 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 (18). 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 (19). 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 (20). 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 (21).

For many states, we observed null associations between hurricane exposure and educational test scores, and in a few states, exposure appeared to increase test scores. These results 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 (24, 25).

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 (26, 27). It is also possible that states where we observed positive or null relationships between hurricanes and test scores received large influxes of federal disaster relief funding (28). Another possibility is that test scores only reflected the performance of more privileged students who were less impacted by the hurricane; more vulnerable students, 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, 22, 29, 30). 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 (31).

Our findings consistently demonstrated the educational vulnerability of racially and socioeconomically marginalized groups, regardless of hurricane 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 (32, 33). These disparities stem in large part 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” (34). In contrast, grade cohorts with greater shares of Asian students tended to perform better overall, which scholars attribute to unique cultural attributes (35–37). 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 programs. As a result, they are more readily able to identify students most at-risk or in greatest need post-hurricane and provide them with necessary resources and teacher attention. Counties with greater shares of English language learner students may have had worse reading/language arts scores due to language barriers (38). 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, potentially salient covariates on the grade cohort and county levels were not available in the SEDA dataset, including student gender composition; rates of public, private, and charter schools; or variables pertaining to school performance or funding. Third, the county was the smallest spatial unit available to capture hurricane 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 hurricane exposure and grade cohort composition. Lastly, our difference-in-difference approach does not account for the cumulative effects of repeated hurricane exposure over the ten-year study period that may have compounding, adverse effects on students’ educational success and school communities’ disaster recovery (39).

This study shows that the educational associations of hurricanes 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 (40). We retrieved average test score data aggregated at the county level from the Stanford Education Data Archive (SEDA), which were available for academic years from 2008-2009 to 2017-2018 (41). We only included states if they contained at least one county that experienced at least one hurricane 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 United States students (42). 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 United States, over time, and across grades (41).

*Exposure*

We obtained data on tropical cyclone wind exposure in the United States with full space and time coverage over the study period of 2008 to 2018 from publicly available datasets generated by Anderson et al. (43–45). We used daily estimates of maximum wind sustained speed by county to classify whether a county had been exposed to a hurricane in a given year. We defined hurricane exposure by peak sustained winds in a county’s population center associated with a hurricane at the point of closest approach having reached or exceeded 64 knots or 74 miles per hour.

*Covariates*

We retrieved time-varying, annual covariates at both the grade cohort and county level from SEDA that we considered to be potential confounders and/or effect modifiers of the association between hurricane exposure and standardized test performance (41). A grade cohort is considered students in a specific grade in a given county. 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-differences approach with two-way fixed and random effects model to assess the association between hurricane-force tropical cyclone exposure and average annual standardized test scores at the county level (46, 47). 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 met all necessary assumptions and was based on those in other studies examining the effects of environmental exposures on standardized test scores (48, 49), The model was the following:

Score*itgs* = βsHurricane*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*itgs* was the average standardized test score for grade *g* students in state *s*, in county *i*, in year *t*. Hurricane*its* was whether a hurricane-force tropical cyclone occurred in a given state *s*, 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, the interaction between state *s* and treatment of hurricane exposure were random 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. We assigned random effects to have logGamma(θ,δ) priors with shape θ and rate δ = 0.001. We based our reported positive and negative associations on point estimates with two-sided 95% credible intervals that excluded the null. We obtained comparative analyses of effect estimates through a formal comparative analysis of 1,000 draws from the posterior marginal distribution of each effect estimate. The proportion of draws that was greater than the other set of draws represented the probability that one effect estimate was greater than its comparator (50).

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

*Sensitivity analysis*

We conducted sensitivity analyses restricting models 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 over the study period. We also conducted an analysis using lagged exposure effects. We also conducted sensitivity analyses examining potential moderating effects by proportion of grade cohort-level proportion of Black, Hispanic, and Indigenous and socioeconomically disempowered students, as well as county-level proportion of special education students. 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.** Counties exposed to hurricane-force tropical cyclones during 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.