Disruption to Test Scores after Hurricanes in the United States

Gabriella Y. Meltzer[1*], G. Brooke Anderson[2], Xicheng Xie[3], Joan A. Casey[4,5], Joel Schwartz[6], Michelle L. Bell[7], Yoshira Ornelas Van Horne[5], Jared Fox[8], Marianthi-Anna Kioumourtzoglou[5], Robbie M. Parks[5]

[1]Department of Obstetrics and Gynecology, Columbia University Irving Medical Center, New York, New York, USA

[2]Department of Environmental & Radiological Health Sciences, Colorado State University, Fort Collins, Colorado, USA

[3]Department of Biostatistics and Informatics, Feinberg School of Medicine, Northwestern University, Chicago, Illinois, USA

[4]Department of Environmental and Occupational Health Sciences, University of Washington School of Public Health, Seattle, Washington, USA

[5]Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, New York, New York, USA

[6]Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, Massachusetts, USA

[7]Department of Environmental Health, Yale University School of the Environment, New Haven, Connecticut, USA

[8]Fox EduConsulting, Chevy Chase, Maryland, USA

* Correspondence to: gm3085@cumc.columbia.edu

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 the 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 hierarchical linear 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 better test scores in Florida in math (β = 0.14; 95% CrI: 0.02, 0.26; PP[β>0] = 99.0%) and RLA (β = 0.11; 95% CrI: 0.02, 0.22; PP[β>0] = 99.2%), and worse math scores in North Carolina (β = -0.16; 95% CrI: -0.29, -0.03; PP[β<0] = 99.4%). Grade cohorts with more racialized and minoritized (e.g., Black, Hispanic, Indigenous) and socioeconomically disadvantaged students tended to have lower test scores, while grade cohorts with greater shares of students racialized as Asian and counties with more 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.

Keywords: tropical cyclones, hurricanes, educational attainment, standardized test scores

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 (Zehnder, 2023). Hurricanes are very active in the United States; the 2020 Atlantic hurricane season was the most active on record (Blackwell, 2020), and 2021 was the third time that the storm naming system was exhausted (Harvey, 2021). 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 (Chavas and Chen, 2020; Wang and Toumi, 2021). 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 (Weinkle et al., 2018).

While there is evidence that hurricanes are associated with deaths (Parks et al., 2023, 2022) and hospitalizations (Parks et al., 2021) from many major causes, less is known about their societal burden on medium and long-term mental and behavioral health, including educational attainment (Grineski et al., 2024; Parks and Guinto, 2022). Children and adolescents, who are particularly susceptible to climate-related disasters (Peek et al., 2018), will experience more frequent and severe hurricanes in their lifetimes than previous generations due to climate change (Thiery et al., 2021). 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 (Peek, 2008). Hurricane Katrina in 2005, for example, displaced 348,000 students across Louisiana, Mississippi, and Alabama (Picou and Marshall, 2007) and destroyed nearly 80 percent of New Orleans's public school buildings (Klein, 2015). The strongest tropical

cyclones (hurricane-force winds) have had long-lasting deleterious impacts on education systems in highly impacted communities throughout the United States (Davis et al., 2021).

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 (Holmes, 2002; Lai et al., 2019; Scott et al., 2014; Ward et al., 2008; Weems et al., 2013). 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, which also have varying capabilities in disaster preparedness, response, and recovery. 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.

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 (Boehner, 2002). We retrieved average test score data aggregated at the county level from the Stanford Education Data Archive (SEDA), which were available for academic years 2008-2009 to 2017-2018 (Reardon et al., 2022). 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 (Sharp, 2019). 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 (Reardon et al., 2022).

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. (Anderson, 2017; Anderson et al., 2020; Anderson and Eddelbuettel, 2017). 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, after which it was considered exposed for the entire study period. 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. We lagged hurricane exposure to measure whether standardized test scores based on exams administered in March to May of a given academic year were associated with storms that took place during the previous hurricane season of May to September.

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 (Reardon et al., 2022). A grade cohort is considered all the students in a specific grade level 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 hierarchical linear model (the formulation of which has been previously referred to as a generalized difference-in-differences approach (Lu et al., 2021)) 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 (Donald and Lang, 2007; McElreath, 2016). Bayesian inference is advantageous in that it allows for the full distributional estimation of the parameters of interest, as well as borrowing of information across neighboring (e.g., county) units (Gelman et al., 2015; Parks et al., 2022). 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. The model met all necessary assumptions and was based on those in other

studies examining the effects of environmental exposures on standardized test scores (Lu et al., 2021; Wen and Burke, 2022). The model was the following:

$$\text{Score}_{itg} = \alpha_0 + (\beta + b_s)\text{Hurricane}_{it} + \sum \beta \text{Covariates}_{itg} + \text{Cohort}_{ig} + \text{Year}_t + \varepsilon_{itg}$$

where i was the county, t was the year, and g was the grade. Score_{itg} was the average standardized test score for grade g students in state s, in county i, in year t. Hurricane_{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. We used random effects for the hurricane term by state 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 all random effects to have a prior of the form $N(0, \sigma)$. We assigned priors on random effects (i.e., b_s) to have $\sigma \sim$ $\log\text{Gamma}(\theta,\delta)$ priors with shape θ and rate $\delta = 0.001$. We based our reported positive and negative associations on point estimates with two-sided 95% credible intervals. We obtained posterior probabilities that parameter estimates were clear of the null 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 0 represented the probability that an effect estimate was greater than 0 (Gelman et al., 2015).

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 (Rue et al., 2009).

Sensitivity analysis

We conducted sensitivity analyses with a model including random intercepts by state, and also restricted 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 to account for the potentially cumulative effects of repeated hurricane exposures over the study period. We also conducted sensitivity analyses examining potential moderating effects by grade level; grade cohort-level proportion of students racialized as Black, Hispanic, and Indigenous and socioeconomically disadvantaged students; and county-level poverty rates and proportion of special education students. None of the sensitivity analyses produced results different from those in the main model.

Results

Summary Statistics

Between 2009 and 2018, national average standardized math scores increased in younger grade cohorts and decreased in older ones, while RLA scores remained relatively stable (Table 1). Some states consistently outperformed others throughout the study period. For example, the median average RLA score in 2018 for eighth-grade cohorts in South Carolina was 7.05 compared to 8.49 in New Jersey (Table S1). The median national 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 socioeconomically 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 nationally, the median average proportion of adult residents with a college degree increased from 15.8% in 2009 to 18.1% in 2018 (Table 1).

Table 1. Educational and demographic characteristics variables in states exposed to hurricanes in the United States in 2009 and 2018.

		Grade	2009 percentiles					2018 percentiles				
			5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
Grade-specific standardized test scores	Mean Standardized Math Score	3	1.24	2.23	2.82	3.28	3.98	1.73	2.54	3.08	3.57	4.29
		4	2.28	3.20	3.74	4.21	4.87	2.24	3.23	3.92	4.45	5.24
		5	3.12	4.20	4.78	5.20	5.97	2.95	4.04	4.72	5.25	6.14
		6	4.25	5.26	5.77	6.34	7.16	3.83	4.94	5.66	6.26	7.36
		7	5.08	6.17	6.84	7.33	8.22	4.47	5.80	6.49	7.20	8.25
		8	6.15	7.28	7.88	8.45	9.48	5.30	6.61	7.39	8.20	9.30
	Mean Standardized RLA Score	3	0.96	2.08	2.72	3.37	4.37	1.00	2.06	2.70	3.43	4.30
		4	2.04	2.94	3.49	4.11	5.02	1.90	2.99	3.63	4.35	5.16
		5	2.93	3.94	4.54	5.02	5.95	2.87	3.76	4.44	5.13	6.07
		6	4.06	5.00	5.52	6.05	6.89	3.84	4.77	5.35	6.10	6.99
		7	4.90	5.83	6.40	6.88	7.73	4.89	5.77	6.40	6.98	7.91
		8	5.92	6.87	7.39	7.90	8.68	5.98	6.84	7.36	7.95	8.84
Grade cohort level variables	Percent American Indian/Alaska Native		0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.02
	Percent Asian		0.00	0.00	0.01	0.01	0.05	0.00	0.00	0.01	0.02	0.06
	Percent Hispanic		0.01	0.04	0.14	0.33	0.77	0.02	0.10	0.24	0.44	0.83
	Percent Black		0.00	0.04	0.14	0.31	0.67	0.00	0.02	0.10	0.26	0.61
	Percent Free Lunch		0.21	0.37	0.45	0.55	0.72	0.26	0.46	0.55	0.68	0.97
	Percent Economically Disadvantaged		0.30	0.48	0.57	0.67	0.84	0.34	0.52	0.61	0.72	0.86
County level variables	Percent English Language Learners		0.00	0.01	0.04	0.08	0.17	0.00	0.02	0.05	0.09	0.17
	Percent Urban Schools		0.00	0.00	0.00	0.00	0.58	0.00	0.00	0.00	0.00	0.58
	Percent with College Degree		0.09	0.12	0.16	0.21	0.34	0.10	0.14	0.18	0.24	0.40
	Percent Living in Poverty		0.09	0.13	0.17	0.20	0.27	0.09	0.13	0.16	0.20	0.26
	Percent Single-Mother Households		0.11	0.15	0.18	0.22	0.27	0.12	0.15	0.18	0.22	0.29
	Percent Special Education		0.08	0.11	0.12	0.14	0.18	0.08	0.10	0.12	0.14	0.18

There were 74 counties exposed to hurricane-force tropical cyclones over the course of the study period (Figure 1).

**Figure 1.** Counties exposed to hurricane-force tropical cyclones during 2009-2018.
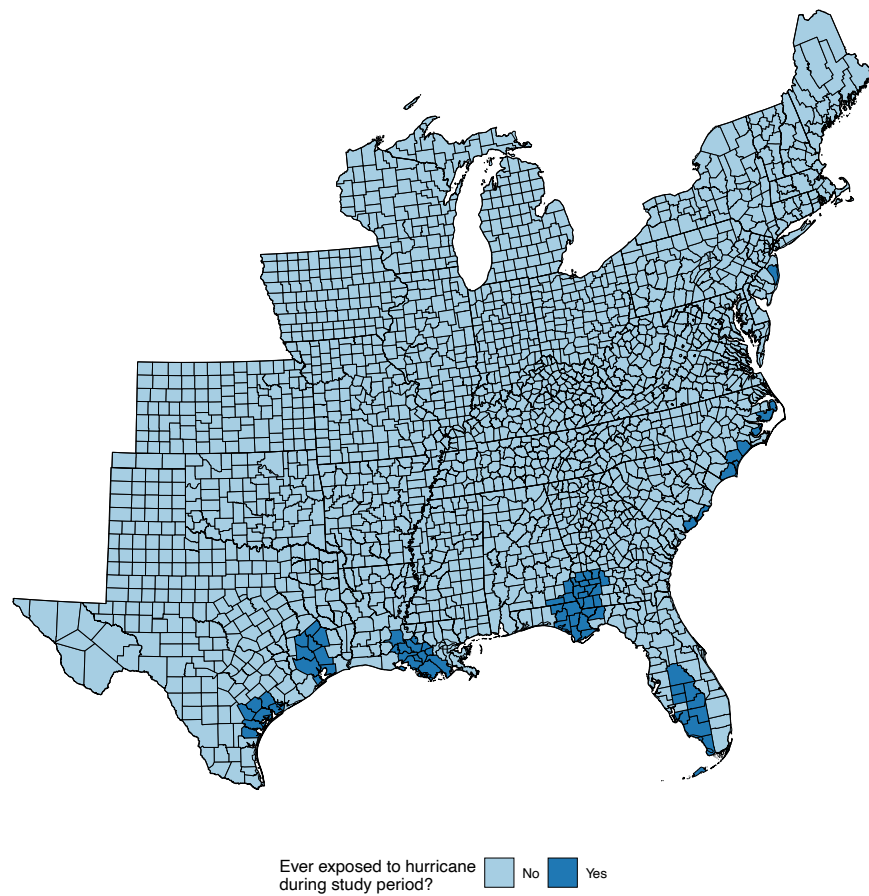
In the figure above, counties highlighted in dark blue are those that were exposed to hurricane-force tropical cyclones over the course of the study period.

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 = -0.04; 95% CrI: -0.11, 0.03; PP[β<0] = 85%). State-specific results showed that counties in North Carolina exposed to hurricane-force tropical cyclones performed worse in math than non-exposed counties (β = -0.16; 95% CrI: -0.29, -0.03; PP[β<0] = 99.4%) (Figure 2, Table S2). In contrast, counties in Florida

exposed to hurricane-force tropical cyclones performed better in math than non-exposed

counties (β = 0.14; 95% CrI: 0.02, 0.26; PP[β>0] = 99.0%) (Figure 2, Table S2).

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.
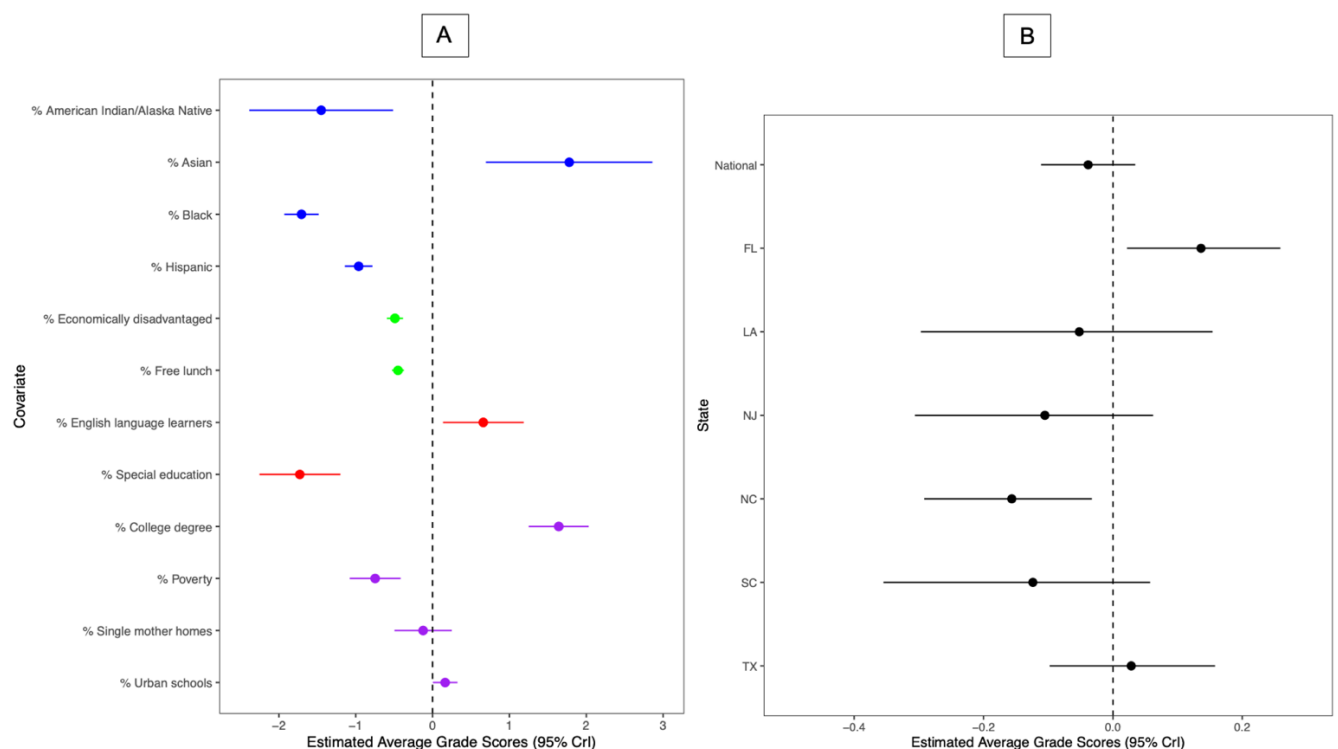
Association of Hurricanes with Reading/Language Arts Scores

There was no association in the national model between hurricane-force tropical cyclone

exposure and RLA scores (β = 0.00; 95% CrI: -0.06, 0.07; PP[β>0] = 55.5%). State-specific

results showed that counties in Florida exposed to hurricane-force tropical cyclones

performed better in RLA than unexposed counties (β = 0.11; 95% CrI: 0.02, -0.04; PP[β<0] =

99.9%) (Figure 3, Table S2).

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.
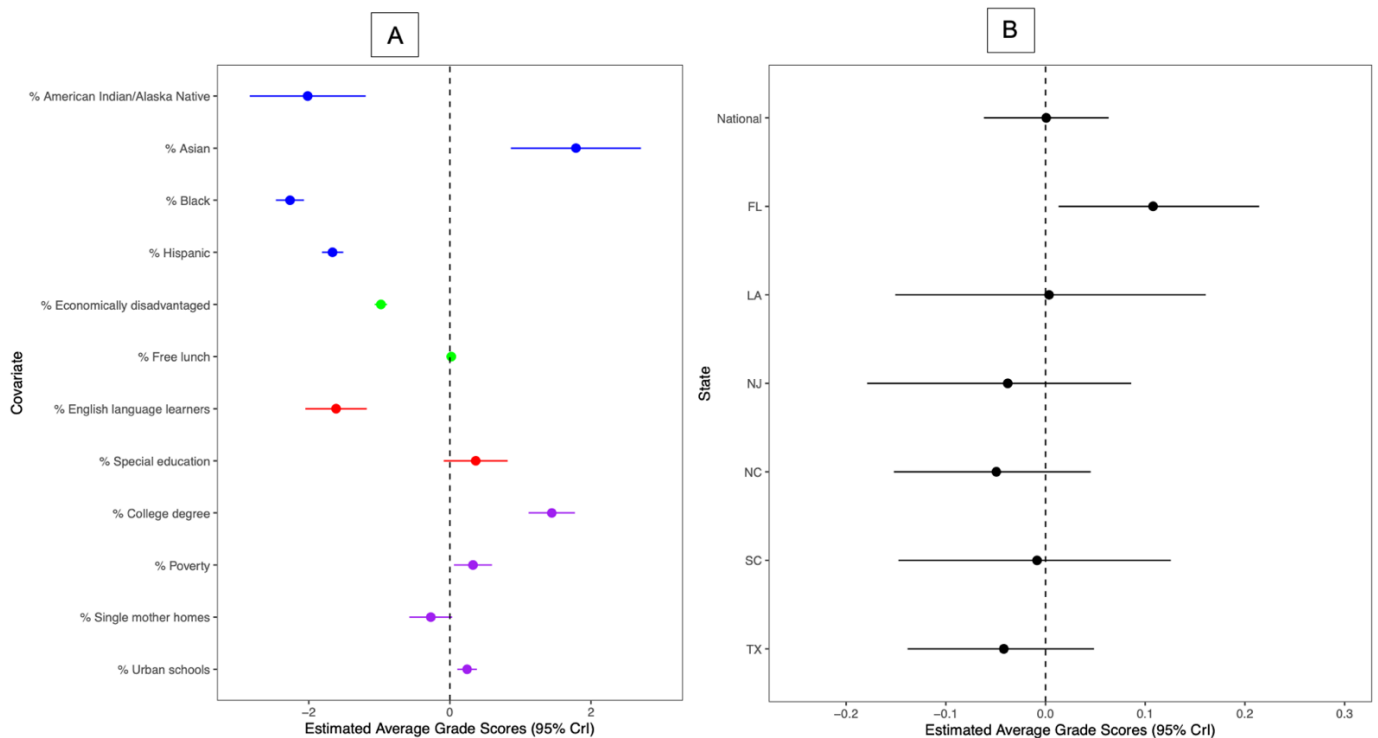
Association of Covariates with Test Scores

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 racialized and minoritized students (e.g., Black, Hispanic, Indigenous) tended to perform worse than average grade cohorts in both math and RLA. In contrast, those with greater proportions of students racialized as Asian tended to perform better than the national average cohort in both math and RLA. Grade cohorts with greater shares of students receiving free lunch tended to perform worse in math, but better in RLA. Grade cohorts with more socioeconomically disadvantaged students tended to perform

worse than the national average grade cohort in only RLA (Figures 2 and 3, Supplemental Table).

At the county level, counties with higher poverty levels tended to perform worse in math. Those with greater shares of English language learners tended to perform better than average in math, but worse in RLA. Counties with higher rates of college-educated adult residents tended to perform better than average in both math and RLA. In addition, counties with greater shares of urban schools and special education students tended to perform better than average in RLA (Figures 2 and 3, Table S2).

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 RLA 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 and RLA scores in Florida and lower math scores in North Carolina.

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; prolonged school closure; 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 (Jahan et al., 2022; Peek, 2008; Peek and Richardson, 2010). All of these stressors could also compromise cognitive functioning and subsequent academic achievement (Pfefferbaum et al., 2016).

There is evidence from the literature pointing to the negative consequences of hurricanes and other disasters 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 (Scott et al., 2014). 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 (Weems et al., 2013). 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 (Ward et al., 2008). 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 (Holmes, 2002). 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 (Lai et al., 2019). Although counties in Louisiana were exposed to hurricane-force tropical winds during our study period, we did not observe any significant effects of hurricane exposure on standardized test scores in that state.

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 (Anderson, 2022;

Solochek, 2023). States such as 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 (The Innovation Project, 2019; Mack, 2018). Whereas states

like Florida, where storms are more frequent, appear to have more easily accessible

guidelines and an emphasis on returning students to school as quickly as possible, North

Carolina's return-to-school guidelines are less publicly accessible, and its schools seem

slower to reopen post-disaster (Fuller and Davis, 2021). 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 (U.S. Department of Education). Another

possibility is that in these states, test scores only reflected the performance of more privileged

students who were less impacted by the hurricane; more vulnerable, racially minoritized or

socioeconomically disadvantaged students 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 (Bolin and Kurtz, 2018; Fussell et al., 2010;

Peek and Richardson, 2010; Picou and Marshall, 2007). It is also possible that displaced

students were relocated to schools with more resources and funding than their original ones,

which may have mitigated potential negative effects on academic achievement (Pane et al.,

2008). As a result, we suggest that education policymakers facilitate the entry of displaced

students into new school settings and provide supporting guidelines for affected schools like

those readily available in Florida. There is a large body of literature pointing to voluntary

migration in the aftermath of natural disasters, influenced by social, economic, and cultural

factors (Chumky et al., 2022; Hauer et al., 2020; Sheldon and Zhan, 2022). Our results may

therefore be partially explained by the fact that post-disaster migration would have changed

the sociodemographic composition of families in a hurricane-impacted county, thus indirectly affecting its students' educational outcomes.

Our findings consistently demonstrated the educational vulnerability of racially and socioeconomically marginalized groups, regardless of hurricane exposure. Grade cohorts with greater shares of students racialized as Black, American Indian/Alaska Native, Hispanic, and who were socioeconomically disadvantaged 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 (Gordon and Cui, 2018; White et al., 2016) and further speaks to the need for post-storm resources to be targeted in this direction. In contrast, grade cohorts with greater shares of students racialized as Asian tended to perform better overall, which scholars attribute to unique cultural attributes (Hsin and Xie, 2014; Li and Xie, 2020; Liu and Xie, 2016). Counties with greater shares of special education students tended to perform better on standardized testing, which may be indicative of the fact that the individual education programs (IEPs) required for this unique cohort may help schools identify and support this particularly vulnerable population. Indeed, the designation of a child with an IEP can be leveraged by schools to identify and prioritize students most at-risk post-hurricane and help to ensure they receive necessary supports. Counties with greater shares of English language learner students may have had worse reading/language arts scores due to language barriers (Bailey, 2007). 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 or teacher-observed qualitative measures. However, unlike grade point average, which is weighted differently across schools, standardized 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 Stanford Education Data Archive dataset, including grade cohort gender composition; county 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, test scores, and relevant covariates. Given the large size of counties and the many diverse schools and likely differential hurricane impacts within each of them, future analyses should consider using a more granular spatial unit of analysis such as a census tract or school district to have greater variance and better capture actual hurricane exposure and grade cohort composition. Fourth, if students had been displaced by hurricanes, their test scores would have been reflected in their new, rather than original, counties of residence and/or schooling. Fifth, our metric of hurricane exposure was solely based on wind speed, whereas hurricane impacts could perhaps have been more comprehensively captured by accounting for the extent of rainfall and/or structural damage. Lastly, we made two major assumptions in our analysis. We first assumed that the effect of hurricanes on test scores remained the same across time even when several years of recovery may have passed. We also assumed that hurricanes are rare events, but that certain states and counties are more frequently exposed to hurricanes than others. We only partially accounted for this by including random effects by state in a sensitivity analysis. Under the current trajectory of climate change, the rarity of hurricanes may not hold as they become more powerful and frequent. Greater intensity and potential regularity of hurricanes therefore warrants further investigation.

Conclusion

This study shows that educational outcomes associated with hurricane exposure are not only highly variable by state, but that disparities in academic performance persist across racial/ethnic and sociodemographic lines. To increase children's educational resilience to the effects of hurricanes, policymakers should address both disaster-related educational procedures and policies, as well as underlying sociodemographic educational disparities by focusing on four key aspects of school recovery – emotional, academic, financial, and physical – detailed by the U.S. Government Accountability Office (Nowicki, 2022). This will not only enhance student, but also community resilience to the effects of climate change-driven extreme weather events.

References

Anderson, G.B., 2017. hurricaneexposuredata [WWW Document]. GitHub. URL https://github.com/geanders/hurricaneexposuredata (accessed 1.25.23).

Anderson, G.B., Eddelbuettel, D., 2017. Hosting Data Packages via drat: A Case Study with Hurricane Exposure Data. R J 9, 486–497. https://doi.org/10.32614/rj-2017-026

Anderson, G.B., Ferreri, J., Al, -Hamdan Mohammad, Crosson, W., Schumacher, A., Guikema, S., Quiring, S., Eddelbuettel, D., Yan, M., Peng, R.D., 2020. Assessing United States County-Level Exposure for Research on Tropical Cyclones and Human Health. Environmental Health Perspectives 128, 107009. https://doi.org/10.1289/EHP6976

Anderson, M., 2022. More than 2.5 million Florida students have missed school during Hurricane Ian. NPR.

Bailey, A.L., 2007. The Language Demands of School: Putting Academic English to the Test. Yale University Press.

Blackwell, J., 2020. Record-breaking Atlantic hurricane season draws to an end [WWW Document]. National Oceanic and Atmospheric Administration. URL https://www.noaa.gov/media-release/record-breaking-atlantic-hurricane-season-draws-to-end (accessed 9.26.23).

Boehner, J.A., 2002. H.R.1 - 107th Congress (2001-2002): No Child Left Behind Act of 2001 [WWW Document]. URL http://www.congress.gov/ (accessed 1.23.23).

Bolin, B., Kurtz, L.C., 2018. Race, Class, Ethnicity, and Disaster Vulnerability, in: Rodríguez, H., Donner, W., Trainor, J.E. (Eds.), Handbook of Disaster Research, Handbooks of Sociology and Social Research. Springer International Publishing, Cham, pp. 181–203. https://doi.org/10.1007/978-3-319-63254-4_10

Chavas, D., Chen, J., 2020. Tropical cyclones could last longer after landfall in a warming world. Nature 587, 200–201. https://doi.org/10.1038/d41586-020-03118-2

Chumky, T., Basu, M., Onitsuka, K., Hoshino, S., 2022. The current research landscape of disaster-induced migration: A systematic review and bibliometric analysis. International Journal of Disaster Risk Reduction 74, 102931. https://doi.org/10.1016/j.ijdrr.2022.102931

Davis, C.R., Cannon, S.R., Fuller, S.C., 2021. The storm after the storm: the long-term lingering impacts of hurricanes on schools. Disaster Prevention and Management: An International Journal 30, 264–278. https://doi.org/10.1108/DPM-03-2020-0055

Donald, S.G., Lang, K., 2007. Inference with Difference-in-Differences and Other Panel Data. The Review of Economics and Statistics 89, 221–233. https://doi.org/10.1162/rest.89.2.221

Fuller, S.C., Davis, C.R., 2021. Academic Progress for Students Following a Hurricane. Education Policy Initiative at Carolina, University of North Carolina at Chapel Hill.

Fussell, E., Sastry, N., VanLandingham, M., 2010. Race, socioeconomic status, and return migration to New Orleans after Hurricane Katrina. Popul Environ 31, 20–42. https://doi.org/10.1007/s11111-009-0092-2

Gelman, A., Carlin, J.B., Stern, H.S., Dunson, D.B., Vehtari, A., Rubin, D.B., 2015. Bayesian Data Analysis, 3rd ed. Chapman and Hall/CRC, New York. https://doi.org/10.1201/b16018

Gordon, M.S., Cui, M., 2018. The Intersection of Race and Community Poverty and Its Effects on Adolescents' Academic Achievement. Youth & Society 50, 947–965. https://doi.org/10.1177/0044118X16646590

Grineski, S., Alexander, C., Allain, M.L., Clark, A.S., Collins, T.W., Goodwin, E., Mullen, C.J., Scott, M., Shaker, Y., Ramos, K.D., Renteria, R.A., Rubio, R., 2024.

Environmental Influences on Academic Proficiency. Curr Epidemiol Rep 11, 1–19. https://doi.org/10.1007/s40471-023-00324-0

Harvey, S., 2021. 2021 hurricane season uses up name list for only 3rd time in history [WWW Document]. CW 39 Houston. URL https://widget.airnow.gov/aq-dial-widget-primary-pollutant/?city=Houston&state=TX&country=USA (accessed 9.26.23).

Hauer, M.E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., Wrathall, D., 2020. Sea-level rise and human migration. Nat Rev Earth Environ 1, 28–39. https://doi.org/10.1038/s43017-019-0002-9

Holmes, G.M., 2002. Effect of Extreme Weather Events on Student Test Performance. Natural Hazards Review 3, 82–91. https://doi.org/10.1061/(ASCE)1527-6988(2002)3:3(82)

Hsin, A., Xie, Y., 2014. Explaining Asian Americans' academic advantage over whites. Proceedings of the National Academy of Sciences 111, 8416–8421. https://doi.org/10.1073/pnas.1406402111

Hurricanes Florence and Matthew: Research into the Impact of the Storms on Schools, 2019. . The Innovation Project.

Jahan, F.A., Zviedrite, N., Gao, H., Ahmed, F., Uzicanin, A., 2022. Causes, characteristics, and patterns of prolonged unplanned school closures prior to the COVID-19 pandemic—United States, 2011–2019. PLOS ONE 17, e0272088. https://doi.org/10.1371/journal.pone.0272088

Klein, R., 2015. These Are The Schools That Hurricane Katrina Destroyed. HuffPost Voices. URL https://www.huffpost.com/entry/new-orleans-schools-hurricane-katrina_n_55cba766e4b0f73b20bb9a13 (accessed 9.26.23).

Lai, B.S., Esnard, A.-M., Wyczalkowski, C., Savage, R., Shah, H., 2019. Trajectories of School Recovery After a Natural Disaster: Risk and Protective Factors. Risk, Hazards & Crisis in Public Policy 10, 32–51. https://doi.org/10.1002/rhc3.12158

Li, W., Xie, Y., 2020. The influence of family background on educational expectations: a comparative study. Chinese Sociological Review 52, 269–294. https://doi.org/10.1080/21620555.2020.1738917

Liu, A., Xie, Y., 2016. Why do Asian Americans academically outperform Whites? – The cultural explanation revisited. Social Science Research 58, 210–226. https://doi.org/10.1016/j.ssresearch.2016.03.004

Lu, W., Hackman, D.A., Schwartz, J., 2021. Ambient air pollution associated with lower academic achievement among US children: A nationwide panel study of school districts. Environmental Epidemiology 5, e174. https://doi.org/10.1097/EE9.0000000000000174

Mack, R., 2018. Texas schools affected by Hurricane Harvey say more resources are needed to help students recover. The Texas Tribune.

McElreath, R., 2016. Statistical Rethinking: A Bayesian Course with Examples in R and Stan. Chapman and Hall/CRC, New York. https://doi.org/10.1201/9781315372495

Natural Disaster Resources | U.S. Department of Education [WWW Document], n.d. URL https://www.ed.gov/hurricane-help (accessed 10.2.23).

Nowicki, J.M., 2022. School Districts in Socially Vulnerable Communities Faced Heightened Challenges after Recent Natural Disasters (No. GAO-22-104606), Disaster Recovery. United States Government Accountability Office, Washington, DC.

Pane, J.F., McCaffrey, D.F., Kalra, N., Zhou, A.J., 2008. Effects of Student Displacement in Louisiana During the First Academic Year After the Hurricanes of 2005. Journal of Education for Students Placed at Risk (JESPAR) 13, 168–211. https://doi.org/10.1080/10824660802350169

Parks, R.M., Anderson, G.B., Nethery, R.C., Navas-Acien, A., Dominici, F., Kioumourtzoglou, M.-A., 2021. Tropical cyclone exposure is associated with increased hospitalization rates in older adults. Nat Commun 12, 1545. https://doi.org/10.1038/s41467-021-21777-1

Parks, R.M., Benavides, J., Anderson, G.B., Nethery, R.C., Navas-Acien, A., Dominici, F., Ezzati, M., Kioumourtzoglou, M.-A., 2022. Association of Tropical Cyclones With County-Level Mortality in the US. JAMA 327, 946–955. https://doi.org/10.1001/jama.2022.1682

Parks, R.M., Guinto, R.R., 2022. Invited Perspective: Uncovering the Hidden Burden of Tropical Cyclones on Public Health Locally and Worldwide. Environmental Health Perspectives 130, 111306. https://doi.org/10.1289/EHP12241

Parks, R.M., Kontis, V., Anderson, G.B., Baldwin, J.W., Danaei, G., Toumi, R., Dominici, F., Ezzati, M., Kioumourtzoglou, M.-A., 2023. Short-term excess mortality following tropical cyclones in the United States. Science Advances 9, eadg6633. https://doi.org/10.1126/sciadv.adg6633

Peek, L., 2008. Children and Disasters: Understanding Vulnerability, Developing Capacities, and Promoting Resilience — An Introduction. Children, Youth and Environments 18, 1–29.

Peek, L., Abramson, D.M., Cox, R.S., Fothergill, A., Tobin, J., 2018. Children and Disasters, in: Rodríguez, H., Donner, W., Trainor, J.E. (Eds.), Handbook of Disaster Research, Handbooks of Sociology and Social Research. Springer International Publishing, Cham, pp. 243–262. https://doi.org/10.1007/978-3-319-63254-4_13

Peek, L., Richardson, K., 2010. In Their Own Words: Displaced Children's Educational Recovery Needs After Hurricane Katrina. Disaster Medicine and Public Health Preparedness 4, S63–S70. https://doi.org/10.1001/dmp.2010.10060910

Pfefferbaum, B., Noffsinger, M.A., Jacobs, A.K., Varma, V., 2016. Children's Cognitive Functioning in Disasters and Terrorism. Curr Psychiatry Rep 18, 48. https://doi.org/10.1007/s11920-016-0685-2

Picou, J.S., Marshall, B.K., 2007. Social Impacts of Hurricane Katrina on Displaced K–12 Students and Educational Institutions in Coastal Alabama Counties: Some Preliminary Observations. Sociological Spectrum 27, 767–780. https://doi.org/10.1080/02732170701534267

Reardon, S.F., Fahle, E.M., Ho, A.D., Shear, B.R., Kalogrides, D., Salida, J., 2022. Stanford Education Data Archive (SEDA) [WWW Document]. URL https://purl.stanford.edu/db586ns4974 (accessed 1.23.23).

Rue, H., Martino, S., Chopin, N., 2009. Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. Journal of the Royal Statistical Society: Series B (Statistical Methodology) 71, 319–392. https://doi.org/10.1111/j.1467-9868.2008.00700.x

Scott, B.G., Lapré, G.E., Marsee, M.A., Weems, C.F., 2014. Aggressive Behavior and Its Associations With Posttraumatic Stress and Academic Achievement Following a Natural Disaster. Journal of Clinical Child & Adolescent Psychology 43, 43–50. https://doi.org/10.1080/15374416.2013.807733

Sharp, H., 2019. An Overview of NAEP (No. NCES 2019-153). National Center for Education Statistics.

Sheldon, T.L., Zhan, C., 2022. The impact of hurricanes and floods on domestic migration. Journal of Environmental Economics and Management 115, 102726. https://doi.org/10.1016/j.jeem.2022.102726

Solochek, J.S., 2023. Florida school districts consider Idalia makeup days. Tampa Bay Times.

Thiery, W., Lange, S., Rogelj, J., Schleussner, C.-F., Gudmundsson, L., Seneviratne, S.I., Andrijevic, M., Frieler, K., Emanuel, K., Geiger, T., Bresch, D.N., Zhao, F., Willner, S.N., Büchner, M., Volkholz, J., Bauer, N., Chang, J., Ciais, P., Dury, M., François, L., Grillakis, M., Gosling, S.N., Hanasaki, N., Hickler, T., Huber, V., Ito, A., Jägermeyr, J., Khabarov, N., Koutroulis, A., Liu, W., Lutz, W., Mengel, M., Müller, C., Ostberg, S., Reyer, C.P.O., Stacke, T., Wada, Y., 2021. Intergenerational inequities in exposure to climate extremes. Science 374, 158–160. https://doi.org/10.1126/science.abi7339

Wang, S., Toumi, R., 2021. Recent migration of tropical cyclones toward coasts. Science 371, 514–517. https://doi.org/10.1126/science.abb9038

Ward, M.E., Shelley, K., Kaase, K., Pane, J.F., 2008. Hurricane Katrina: A Longitudinal Study of the Achievement and Behavior of Displaced Students. Journal of Education for Students Placed at Risk (JESPAR) 13, 297–317. https://doi.org/10.1080/10824660802350391

Weems, C.F., Scott, B.G., Taylor, L.K., Cannon, M.F., Romano, D.M., Perry, A.M., 2013. A theoretical model of continuity in anxiety and links to academic achievement in disaster-exposed school children. Dev Psychopathol 25, 729–737. https://doi.org/10.1017/S0954579413000138

Weinkle, J., Landsea, C., Collins, D., Musulin, R., Crompton, R.P., Klotzbach, P.J., Pielke, R., 2018. Normalized hurricane damage in the continental United States 1900–2017. Nat Sustain 1, 808–813. https://doi.org/10.1038/s41893-018-0165-2

Wen, J., Burke, M., 2022. Lower test scores from wildfire smoke exposure. Nat Sustain 5, 947–955. https://doi.org/10.1038/s41893-022-00956-y

White, G.W., Stepney, C.T., Hatchimonji, D.R., Moceri, D.C., Linsky, A.V., Reyes-Portillo, J.A., Elias, M.J., 2016. The increasing impact of socioeconomics and race on standardized academic test scores across elementary, middle, and high school. American Journal of Orthopsychiatry 86, 10–23. https://doi.org/10.1037/ort0000122

Zehnder, J., 2023. tropical cyclone. Encyclopedia Britannica.

Data availability

The data used in this study were created from the following datasets: Tropical cyclone and hurricane exposure data are available as a package developed by Dr. Anderson via https://github.com/geanders/hurricaneexposure and https://github.com/geanders/hurricaneexposuredata. County-level standardized test score and covariate data from 2008/2009 to 2017/2018 are available via the Stanford Education Data Archive Version 4.1: https://purl.stanford.edu/xv742vh9296.

Code availability

All code for analysis and visualization presented in this manuscript is available at https://github.com/sparklabnyc/tropical_cyclones_educational_attainment_2022.

Author contributions

GYM and RMP established and formulated the study design. GYM, RMP, and GBA acquired, analyzed, and interpreted data. RMP obtained funding. GYM and RMP conducted analysis and prepared results with input from MAK. GYM and RMP wrote the first draft of the paper, and JAC, JS, MLB, GBA, YOVH, JF, and MAK contributed to critical revisions. XX reviewed all statistical code.

Competing Interest

The authors declare no competing interests.