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ORIGINAL PAPER

The effects of Hurricane Dorian on spatial reactions and mobility

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Abstract
This study sheds new light on how a hurricane affects spatial reactions and mobility across the US states based on Twitter data, whereas prior studies have only focused on the damaged region. First, this study finds that spatial reactions are differentiated by periods. For example, New York shows the second-highest reactions in the pre-hurricane weeks, North Carolina reveals the second-highest reactions in the hurricane weeks, and Texas exhibits the second-highest reactions in the post-hurricane weeks. This study also highlights that a hurricane plays a significant role in spatial displacements of the case study regions (Florida, North Carolina, and New York). To be specific, displacements in the hurricane weeks are 24 times higher than those in the pre-hurricane weeks. Lastly, this study finds that displacements within 5 km significantly increase, whereas those over 50 km significantly decrease in the hurricane weeks.

Keywords Hurricane · Natural disaster · Spatial reaction · Spatial mobility · Tweets

1 Introduction

Natural disasters have exerted serious damages to human environments and property. For instance, according to the National Oceanic and Atmospheric Administration (NOAA), the USA has sustained natural disasters where the cumulative damage cost exceeded $1.75 trillion between 1980 and 2019 (NOAA 2020a).

Among the natural disasters, hurricanes dominate the distribution of damage in the USA. Hurricanes have caused the most damage ($919.7 billion), the highest average even cost ($21.9 billion per event), and 55.1% of the total losses for natural disasters. The cumulative cost of Hurricane events in 2017 is $306.2 billion, breaking the previous cost record of $214.8 billion in 2005 (Climate.gov 2019).

In this vein, it is an important issue how hurricanes play an important role in spatial reactions and mobility (this study defines spatial reactions as behaviors across regions and mobility as movements of people in response to natural disasters) (see, e.g., Qi 2014; Wang and Taylor 2014, 2016). However, to the best of my knowledge, there is no research

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exploring the effect of a hurricane on spatial reactions and mobility across the US states (see, e.g., Congleton 2006; Elsner and Jagger 2006; Pielke and Landsea 1998; Pielke et al. 2008).

Prior studies have explored the effects of other natural disasters, such as droughts and floods, on spatial reactions or environments. For instance, Kim et al. (2019) show the relationship between droughts and public reactions across the US states by employing Google Trends data and principal component analysis between 2004 and 2017. Schlef et al. (2019) highlight that the association between large flood events and atmospheric circulation patterns across the USA based on self-organizing maps (SOMs) and a type of artificial neural network.

Therefore, this study sheds new light on the relationship between a hurricane and spatial reactions and mobility across the US states. This study explores how Hurricane Dorian, which is considered the worst natural disaster in the USA, exerts a significant impact on them by analyzing tweets data across the US states in 2019.

2 Literature review

Many scholars have focused on natural disasters since they cause widespread human, social, economic, and environmental loss. During the past two decades, they have killed millions of people and resulted in significant economic damages (Watson et al. 2007). To be specific, 7000 natural disasters killed two million people, affected five billion people, and damaged $1 trillion between 1980 and 2004 (Strömberg 2007).

Among natural disasters, hurricanes are the most powerful natural disasters. For example, Congleton (2006) finds that the damages of Katrina are in excess of $200 billion, which is one of the most economically costly hurricanes in the USA. Pielke and Landsea (1998) show that the average annual impact of hurricane damages is about $4.8 billion in the USA. Pielke et al. (2008) report that the average annual damage is about $ 10 billion between 1900 and 2005 in the USA.

Most prior studies have explored the relationship between hurricanes and environmental impacts. Boose et al. (2004) investigate that how hurricane wind plays a pivotal role in a disturbance process for forest landscapes by examining 85 hurricanes since European settlement in 1508. McNulty (2002) reports that a single hurricane can convert 10% of the total annual carbon storage for the USA. Chapman et al. (2008) find that Hurricane Katrina influences the structure and composition of coastal forests by analyzing Louisiana's Pearl River basin based on study years among, 1989, 1998, 2005, and 2006.

On the other hand, some authors have explored how hurricanes affect human responses (see, e.g., Canales et al. 2019; Feria-Domínguez et al. 2017; Goldberg et al. 2020; Shao et al. 2017; Sovacool et al. 2020; Yum 2020). For instance, Elliott and Pais (2006) show that low-income black homeowners from New Orleans need a wide array of responses, such as evacuation timing and emotional support, the most by analyzing survey data collected from over 1200 Hurricane Katrina survivors. Wang and Taylor (2014) find that human mobility in New York City follows truncated power-law distributions during and after Hurricane Sandy in 2012. Qi (2014) shows that tropical storms significantly affect human mobility by changing displacements and travel frequencies.

Feria-Domínguez et al. (2017) report the existence of a significant cumulative abnormal market reaction of the main property and casualty insurance companies listed in the New York Stock Exchange in response to five hurricanes in the USA. Goldberg et al. (2020)

show that people who evacuated in the past substantially tend to do so in the future when they have high confidence in their past behavior based on the Meta-Cognitive Model. Shao et al. (2017) report that republicans are less apt not to believe hurricanes are becoming stronger than Democrats and Independents based on original survey data.

Next, Twitter is rising a new tool to understand how natural disasters play an important role in spatial reactions and mobility since it provides a geotagging option, which allows scholars to track the information of spatial reactions and mobility (see, e.g., Ashktorab et al. 2014; Jurdak et al. 2015; Takahashi et al. 2015; Truong et al. 2014; Wang and Taylor 2016; Wang and Zhuang 2017; Wang et al. 2019). For instance, Jurdak et al. (2015) argue that Twitter is a very useful tool for predicting and tracking human mobility based on more than six million geotagged tweets in Australia. Wang and Taylor (2016) show that natural disasters exert an impact on human mobility by exploring 15 cases across five natural disasters based on 3,673,626 geotagged tweets.

Wang and Zhuang (2017) highlight that news agent users generate a larger number of total impressions and tweet more frequently than governmental organizations (GO) and nongovernmental organizations (NGO) users during Hurricane Sandy. Wang et al. (2019) find that socially vulnerable communities are digitally left behind in pre-disaster social responses, whereas physically vulnerable communities show more intense disaster responses to Hurricane Sandy. Takahashi et al. (2015) exhibit that different stakeholders used Twitter mostly in coordinating relief efforts, for the dissemination of second-hand information, and in memorializing those affected during Typhoon Haiyan in the Philippines.

3 Research method

This study explores Hurricane Dorian by collecting tweets data in the Twitter Application Programming Interface (API) in 2019. Hurricane Dorian was the most intense storm, a category 5 hurricane with winds of 200 mph, on record to strike the Bahamas and is considered the worst natural disaster in the US history (see Fig. 1). According to the NOAA,

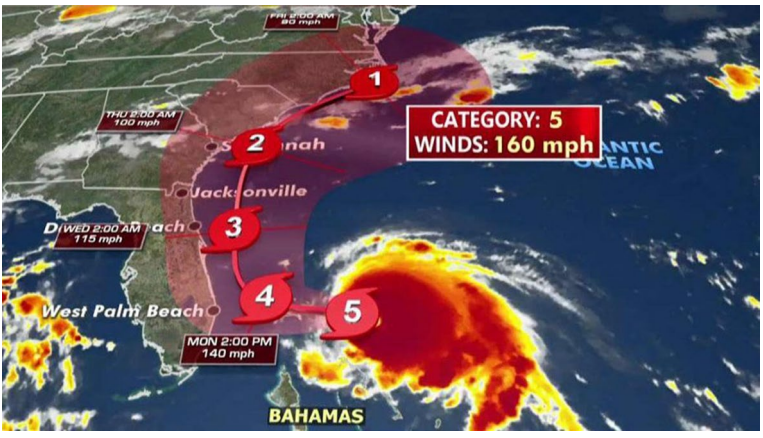


Fig. 1 Hurricane Dorian. *Source*: https://www.foxnews.com/us/hurricane-dorian-bahamas-warning-florida-carolinas

the estimated total damages of Dorian in the USA to be in excess of 1.2 billion (NOAA 2020b).

This study employs Twitter to explore the impacts of Dorian on spatial reactions and mobility. Twitter is a real-time microblogging platform for users who post and interact with messages known as tweets. According to official Twitter statistics, as of 2018, 326 million people are active on Twitter, and 67 million in the USA. Twitter allows user to use a Twitter Application Programming Interface (API), which is an interface program between a client and a server to build the client's software. Twitter Official API offers three tiers of search APIs: standard, premium, and enterprise. However, this study develops its own application since Twitter Official API has a limitation of time constraints; that is, it does not provide access to the past seven days of Twitter data for standard service or 30 days of Twitter data for premium and enterprise service. Because of the limitation, this study creates a new app called "Twitgis" in Twitter developers to collect older tweets more than 30 days by coding a program written in the R language. R is a language and environment for statistical computing and graphics supported by the R Foundation for Statistical Computing. The R language is one of the most popular programming languages among statisticians and data miners for developing statistical software and data analysis. This study uses RStudio, which is an integrated development environment (IDE) for R.

This study selects three keywords ("Dorian," "Hurricane," and "Storm") to analyze the relationship between the hurricane and spatial reactions and mobility. By employing Twitgis in RStudio, this study collects about 2 million (1,973,790) tweets between 08-11-2019 and 09-21-2019 (six weeks). The period consists of two pre-hurricane weeks, two hurricane weeks, and two post-hurricane weeks. This study sets some selection criteria for big data analyses as follows: First, the text in tweets should be written in English. Second, the tweets should have at least one keyword (Dorian, Hurricane, and Storm) in the text. Third, the tweets should be uploaded in the USA. Fourth, the tweets should have geotagged information (or bounding box coordinates) to calculate the human reactions and mobility. After filtering the data, this study utilizes 62,682 samples, which are about 3% of raw data (see Table 1).

4 Spatial reactions to Hurricane Dorian

Figure 2 shows the number of three keywords according to six weeks. The keyword Hurricane shows the highest number of tweets (26,941), followed by Storm (21,473) and Dorian (14,268). The keywords sharply increase from August 25, which is the starting point of the hurricane weeks. The keywords show the highest peak on August 29, and this is because Dorian became a hurricane north of the Greater Antilles on August 28. The second-highest peak is on September 1, which Dorian became a Category 5 hurricane with one-minute sustained winds of 185 mph and a minimum central pressure of 910 millibars.

Table 1 Data samples

	Raw data	Data filtered
Dorian	427,223	14,268
Hurricane	812,010	26,941
Storm	734,557	21,473
Total	1,973,790	62,682

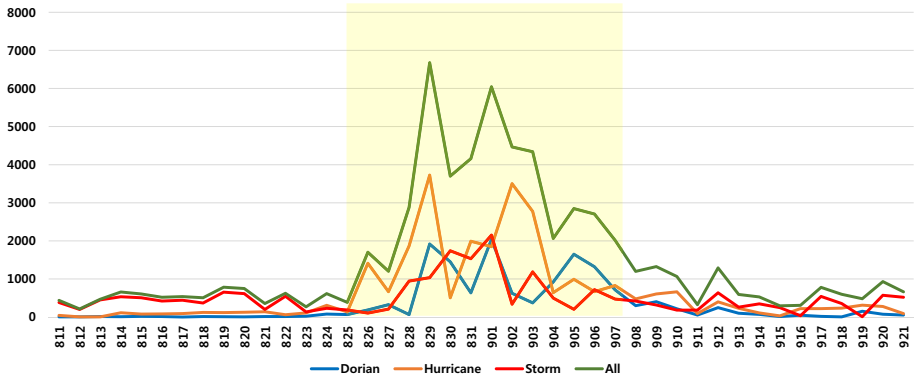


Fig. 2 Number of keywords for six weeks

Figure 3 shows the spatial patterns of three keywords (Dorian, Hurricane, and Storm) in the pre-hurricane weeks, hurricane weeks, and post-hurricane weeks. They show similar spatial patterns during the periods and a sharp increase in the hurricane weeks. During the hurricane weeks, the locations of tweets are heavily concentrated in the coastal areas of the Southeastern USA, such as Florida, North Carolina, and New York.

Figure 4 illustrates the proportion of tweets in the pre-hurricane weeks, hurricane weeks, and post-hurricane weeks. In the pre-hurricane weeks, Florida, California, and Texas have a high proportion of tweets. In the hurricane weeks, the proportion is heavily concentrated in Florida. In the post-hurricane weeks, the Northeast region shows a higher proportion than that in the pre-hurricane weeks and hurricane weeks.

Table 2 shows the proportion of tweets data according to US states. Florida ranks first in all periods and shows an extreme gradient. Florida has a share of 9.1 in the pre-hurricane weeks, 35.3 in the hurricane weeks, and 14.4 in post-hurricane weeks. In the hurricane weeks, the proportion of tweets in Florida increases by about four times, meaning that residents in Florida react significantly to the hurricane. This result is reasonable since Florida is the most damaged state by Hurricane Dorian. In contrast, the other ranks are fluctuated by the periods. For instance, New York ranks second with a share of 7.9, followed by Texas (7.9), California (6.4), and North Carolina (5.1) in the pre-hurricane weeks. North Carolina places second (6.1), ahead of Texas (5.2), California (5.1), and South Carolina (5.0) in the hurricane weeks. Texas takes second (10.4), followed by California (7.8), New York (6.6), and North Carolina (6.6) in the post-hurricane weeks. The results show that the most dangerous state (Florida) consistently exhibits the highest reactions, whereas the other states reveal different reactions according to the pre-hurricane, hurricane, and post-hurricane weeks.

Figure 5 shows that states show the different spatial reactions among the pre-hurricane, hurricane, and post-hurricane weeks. For example, Florida shows the highest reactions in the hurricane weeks, followed by the post-hurricane weeks and the pre-hurricane weeks. In contrast, New York demonstrates the highest reactions in the pre-hurricane weeks and the lowest reactions in the hurricane weeks. North Carolina exhibits the highest reactions in the post-hurricane weeks, followed by the hurricane weeks and the pre-hurricane weeks.

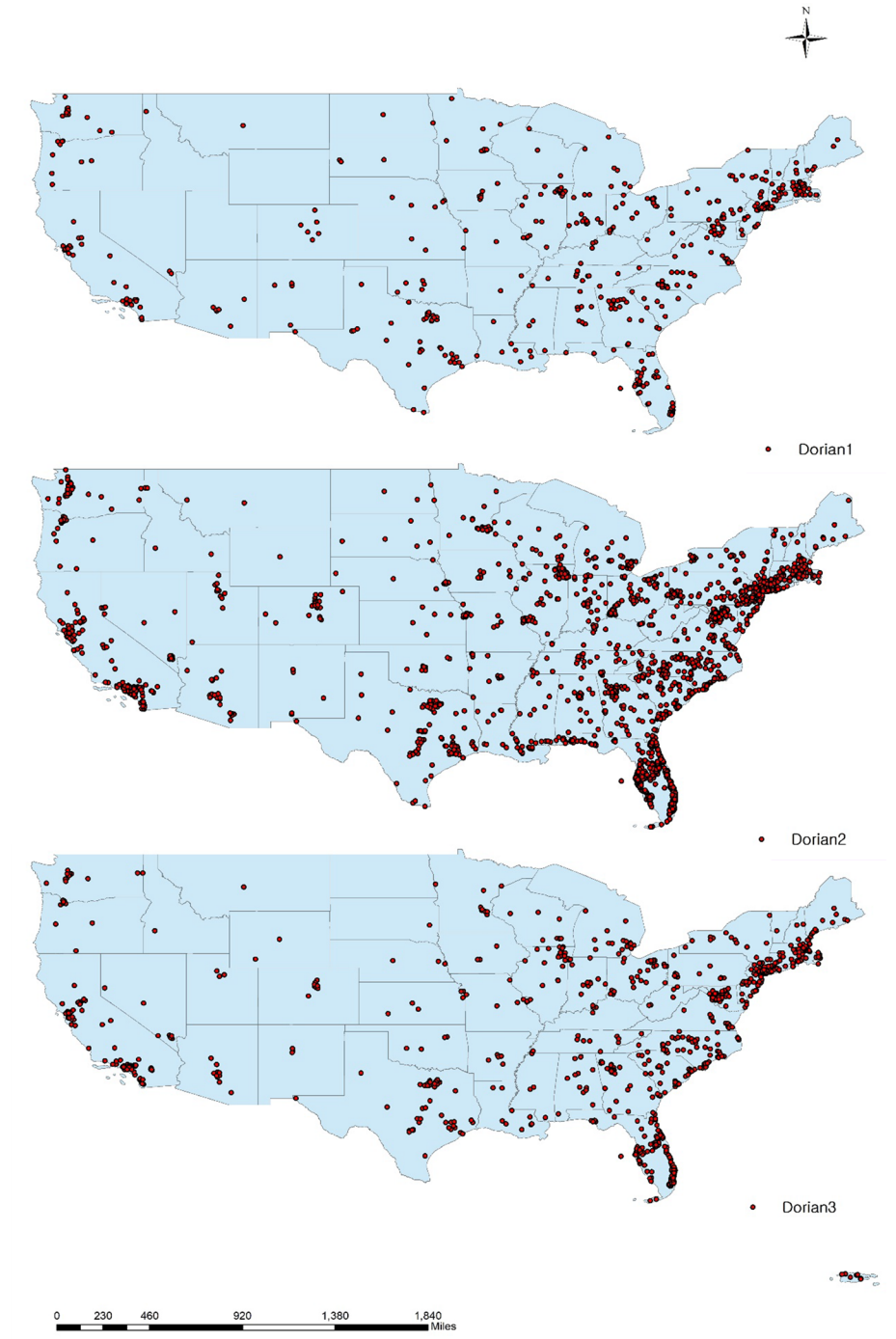
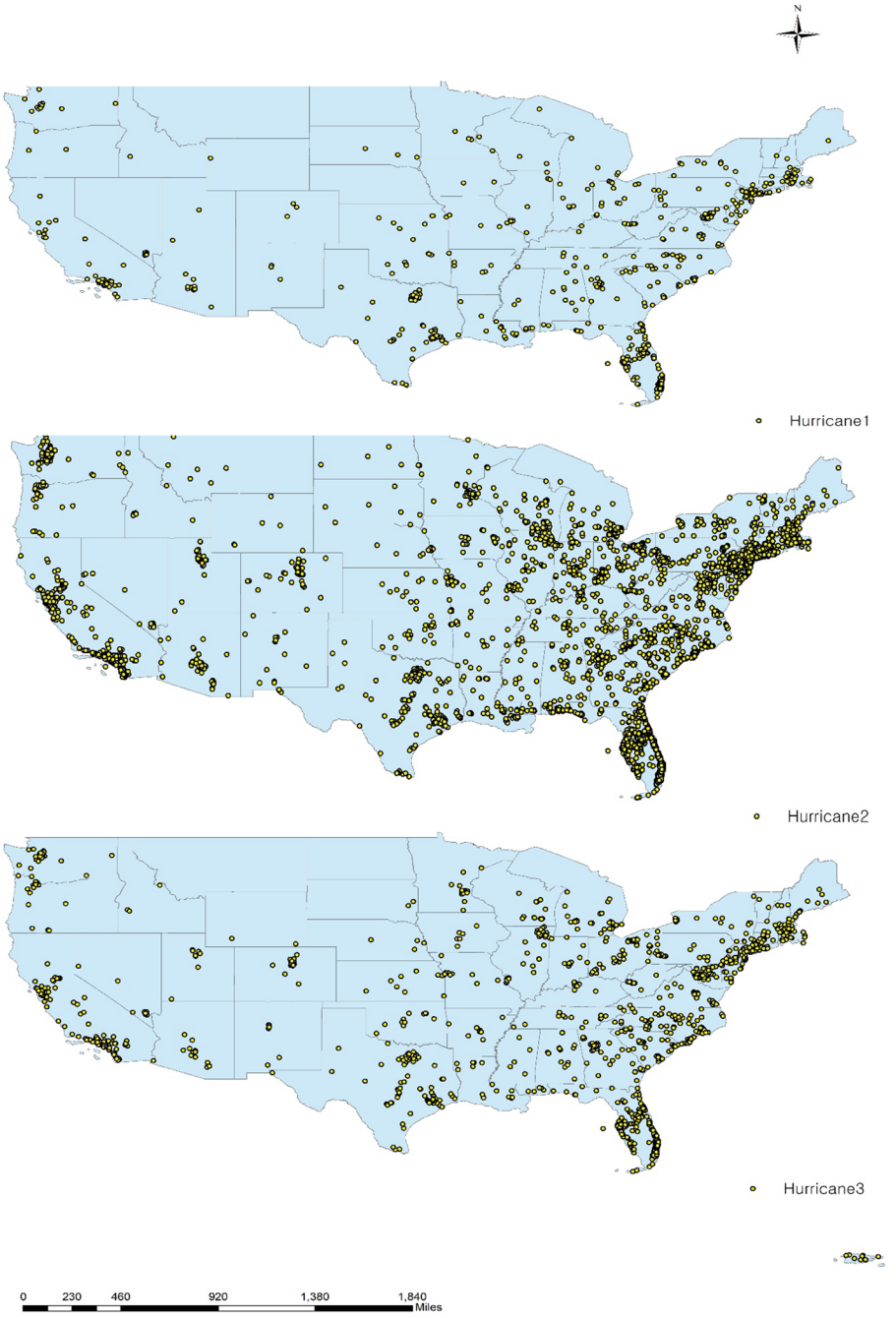


Fig. 3 Tweets in pre-hurricane weeks, hurricane weeks, and post-hurricane weeks



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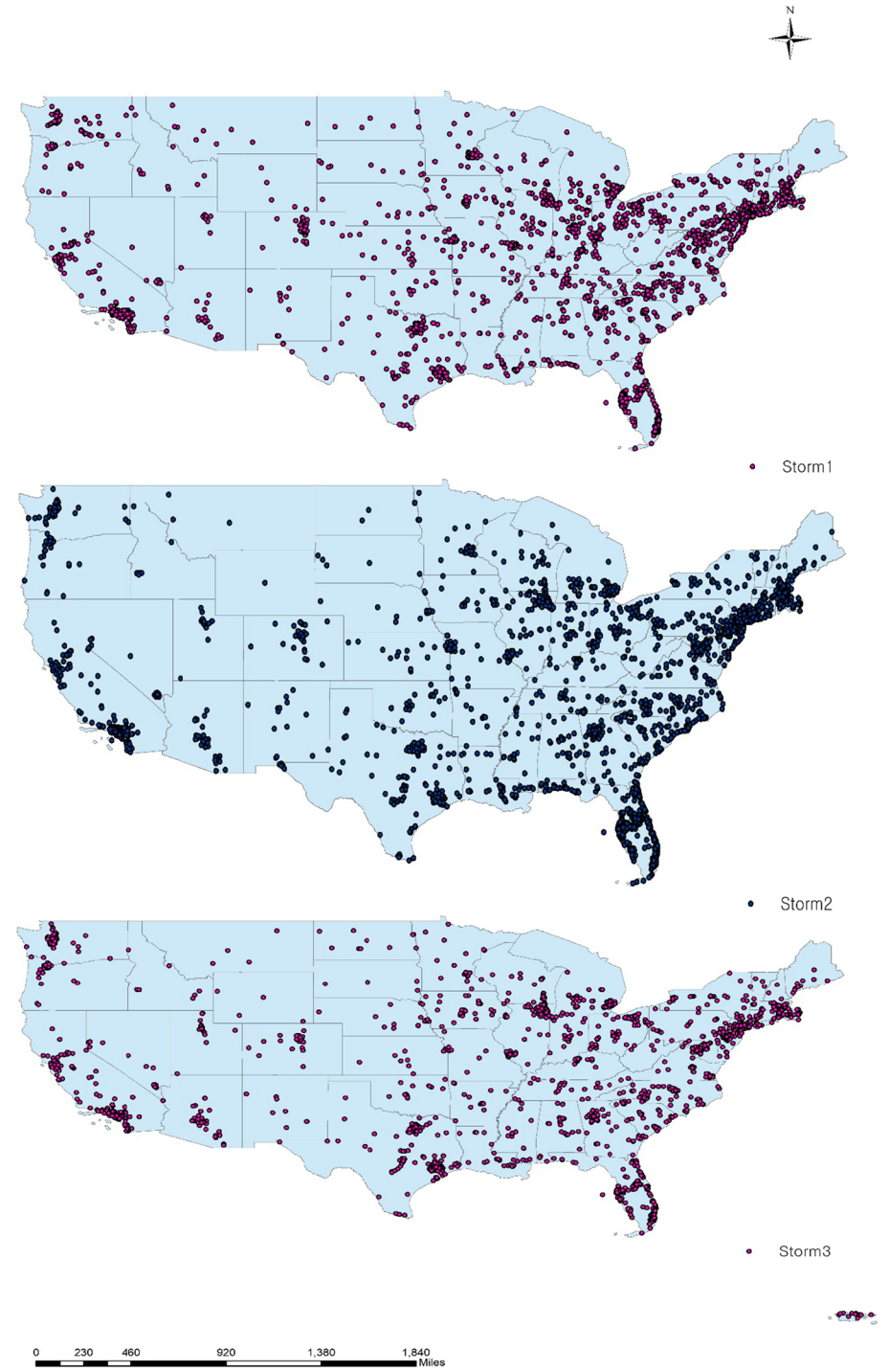

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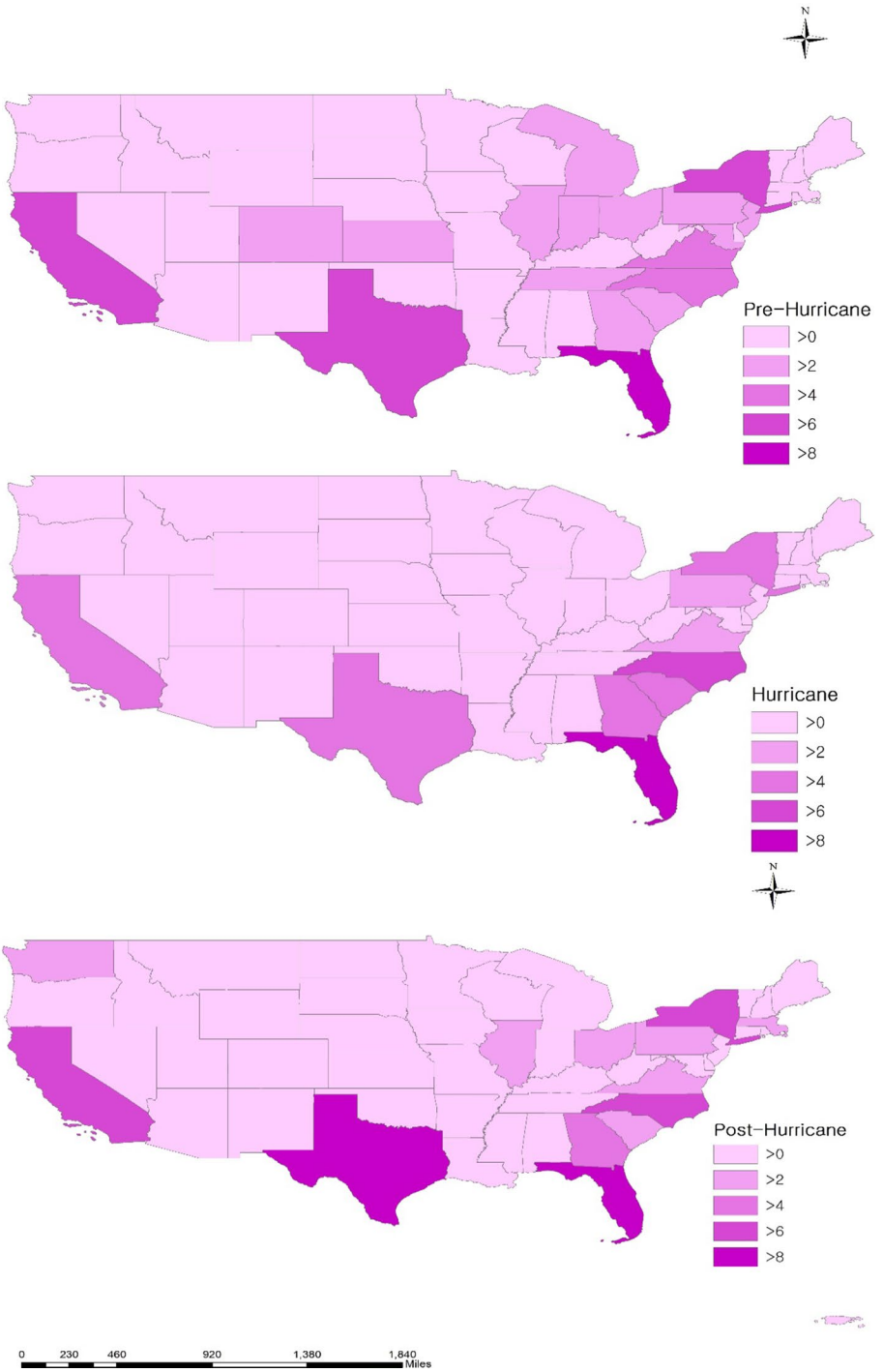

Fig. 4 Proportion of tweets in six weeks

Table 2 Proportion of tweets in top 20

	Pre-hurricane weeks	Hurricane weeks	Post-hurricane weeks
1	Florida (9.1)	Florida (35.3)	Florida (14.4)
2	New York (7.9)	North Carolina (6.1)	Texas (10.4)
3	Texas (7.9)	Texas (5.2)	California (7.8)
4	California (6.4)	California (5.1)	New York (6.6)
5	North Carolina (5.1)	South Carolina (5.0)	North Carolina (6.6)
6	Virginia (4.1)	Georgia (4.6)	Georgia (4.3)
7	Pennsylvania (3.7)	New York (4.4)	Virginia (3.9)
8	Georgia (3.7)	Virginia (3.2)	South Carolina (3.8)
9	Ohio (3.5)	Pennsylvania (2.4)	Illinois (2.7)
10	Indiana (3.2)	Ohio (1.9)	Pennsylvania (2.6)
11	Illinois (3.2)	Illinois (1.8)	Ohio (2.4)
12	New Jersey (2.5)	New Jersey (1.7)	Washington (2.4)
13	Tennessee (2.3)	Massachusetts (1.6)	Massachusetts (2.3)
14	Colorado (2.2)	Alabama (1.3)	New Jersey (1.8)
15	Kansas (2.1)	Louisiana (1.3)	Michigan (1.8)
16	South Carolina (2.1)	Tennessee (1.3)	Alabama (1.7)
17	Michigan (2.0)	Maryland (1.2)	Maryland (1.7)
18	Maryland (2.0)	Michigan (1.1)	Arizona (1.7)
19	Massachusetts (2.0)	Arizona (1.1)	Tennessee (1.4)
20	Washington (1.7)	Washington (1.0)	Louisiana (1.3)

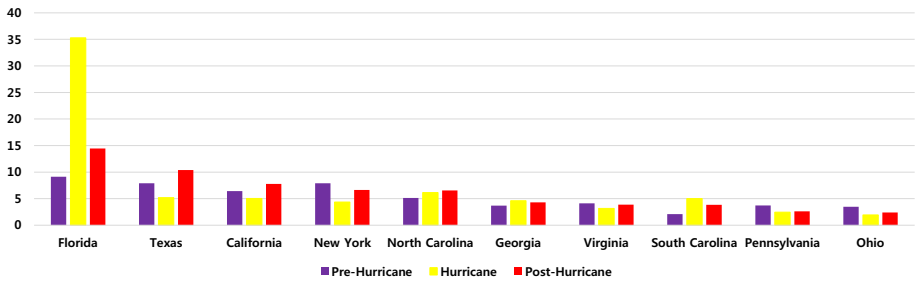

Fig. 5 Proportion of tweets among periods in top 10 states

5 Displacements according to Hurricane Dorian

This study selects three study areas based on (1) geographical locations, (2) the impacts of the hurricane, and (3) the proportion of tweets since Hurricane Dorian mainly hits the Southeastern USA: Florida (the Southeastern region, the strong impact, and the highest proportion); North Carolina (the Southeastern region, the medium impact, and the fifth-highest proportion); and New York (the North-eastern region, the weak impact, and the fourth-highest proportion). The boundaries of three study areas are as follows: Florida (latitude: 24.523096 to 31.000888, and Longitude: −87.634938 to −80.031362), North Carolina (latitude: 33.842316 to 36.588117, and Longitude:

−84.321869 to −75.460621), and New York (latitude: 40.496103 to 45.01585, and longitude: −79.762152 to −71.856214).

This study employs the Haversine formula to explore how Hurricane Dorian affects displacements of individuals in different regions. Displacements are defined as the distance between two consecutive geolocations of people calculated by the Haversine formula. This study employs the Haversine formula since our Earth is nearly spherical that has latitudes and longitudes. The formula calculates the great circle distance between two points on a sphere using their latitudes and longitudes measured along the surface (see, e.g., Chopde and Nichat 2013; Robusto 1957; Wang and Taylor 2016). The Haversine formula can be expressed as follows:

$$d = 2r \times \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\emptyset_2 - \emptyset_1}{2}\right) + \cos\emptyset_1\emptyset_2 \sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right)}\right) \quad (1)$$

where d is displacements, r is the earth radius (6371 km), $\varnothing_1$ and $\varnothing_2$ are the latitudes of origin and destination of individuals, and φ_1 and φ_1 are the longitudes of origin and destination of individuals for a trip in a day. This study calculates displacements of individuals for all trips and puts them into the pre-hurricane week, the hurricane week, and post-hurricane week categories. This study divides distance categories into six groups as follows: within 5 km, 5–10 km, 10–25 km, 25–50 km, 50–100 km, and over 100 km.

This study finds that displacements in the hurricane weeks significantly increase, compared with the pre-hurricane weeks and post-hurricane weeks. For instance, the number of displacements in the hurricane weeks is 1661, which is about 24 times higher than those in the pre-hurricane weeks (70). This is attributable to the fact that people move to a safer place in the hurricane weeks. In particular, Florida shows 1410 displacements, which is 52 times higher than those in the pre-hurricane weeks (27). North Carolina and New York show a similar result from Florida, but relatively lower displacements. Displacements in North Carolina in the hurricane weeks are 150, which is about 11 times higher than the pre-hurricane weeks (14), and those in New York in the same period are 101, which is about 3.5 times higher than the pre-hurricane weeks (29) (see Table 3).

When this study explores displacements of the whole data based on the distance categories, displacements within 5 km significantly increase, whereas those over 50 km significantly decrease in the hurricane weeks (see Fig. 6). To be specific, displacements within 5 km during the hurricane weeks are 34%, which is quite higher than 26% (pre-hurricane weeks) and 21% (post-hurricane weeks). In contrast, displacements between 50 and 100 km consist of 7%, which is about one half of 14% (pre-hurricane weeks) and 15% (post-hurricane weeks). Also, displacements over 100 km during the hurricane weeks are 27% behind 30% (pre-hurricane weeks) and 30% (post-hurricane weeks).

Table 3 Displacements according to periods

	Pre-hurricane	Hurricane	Post-hurricane
Florida	27	1410	91
North Carolina	14	150	24
New York	29	101	21
All	70	1661	136

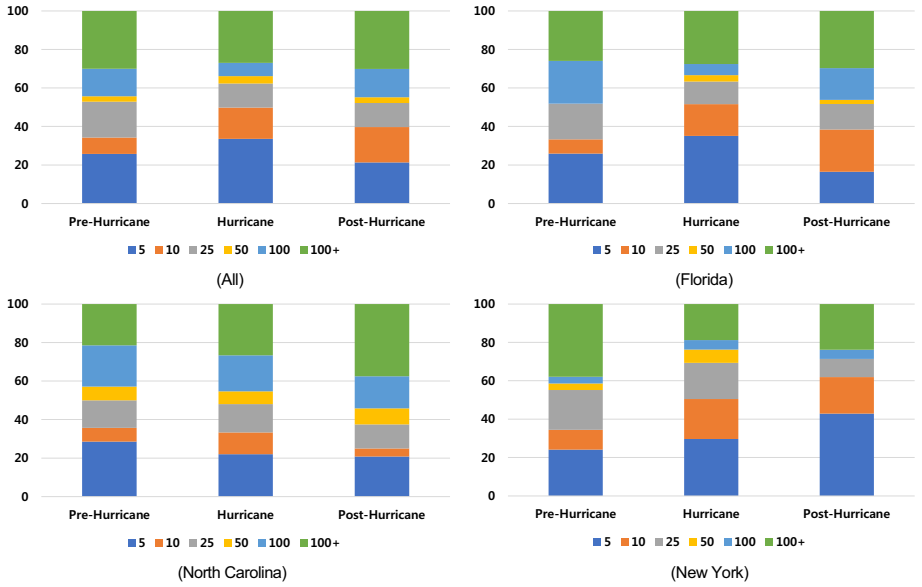

Fig. 6 Displacements according to regions

On the other hand, regions have different displacements among pre-hurricane weeks, hurricane weeks, and post-hurricane weeks. For instance, people in Florida show a higher proportion of displacements within 5 km (35%) in the hurricane weeks than those in pre-hurricane weeks (26%) and post-hurricane weeks (16%). In contrast, they exhibit a lower proportion of displacements between 50 and 100 km (6%) (22%: pre-hurricane weeks and 16%: post-hurricane weeks). People in North Carolina reveal a higher proportion of displacements between 5 and 10 km (11%) in the hurricane weeks (7%: pre-hurricane weeks and 4%: post-hurricane weeks). In contrast, they do not show a lower proportion of displacements for long distance trips in the hurricane weeks, inconsistent with other states. People in New York show a higher proportion of displacements between 5 and 10 km (21%) in the hurricane weeks than 10% (pre-hurricane weeks) and 19% (post-hurricane weeks). In contrast, they show a lower proportion of displacements over 100 km (19%) (38%: pre-hurricane weeks and 24%: post-hurricane weeks).

This study further employs the Chi-square test and Fisher's exact test to check statistical significance for the relationship between spatial mobility and Hurricane Dorian (the Chi-square test for the whole region, Florida, and North Carolina; and the Fisher's exact test for New York). The Chi-square test is a statistical method to determine whether there is a significant relationship between the expected frequencies and observed frequencies in categorical (nominal) variables. The Chi-square value tells us how much difference exists between the observed counts and expected counts if there were no relationships in the sample. The Chi-square formula is as follows:

$$x^2 = \sum \frac{(O-E)^2}{E} \tag{2}$$

where O is the observed value and E indexes the expected value, which is a generalization of the weighted average. After running the Chi-square test, this study finds that there is a significant relationship between spatial mobility and the hurricane period for the whole region. However, when this article employs the test for Florida and North Carolina, only Florida shows a significant association (see Table 4).

On the other hand, the Fisher's exact test is a statistical significance test to find if there are nonrandom associations between two variables. The test could be an alternative method of the Chi-square test when the expected values less than five are more than 20%. This study employs the Fisher's exact test for New York because it violates the condition of the Chi-square test mentioned above. To be specific, New York has 25.0% of expected values less than 5, which is higher than 20% of the criterion of the Chi-square test. The equation is as follows:

$$N = \sum_{i} Ei = \sum_{j} Fj \tag{3}$$

where two variables are X and Y, m and n observed values in the $m \times n$ matrix, aij is the number of observations in which $x = i$ and $y = j$, and Ei and Fj are the sums of the row and column.

$$P = \frac{\left(E_1!E_2!...E_m!\right)\left(F_1!F_2!...F_n!\right)}{N!\prod_{ij} aij!} \tag{4}$$

then calculate the conditional probability of getting the actual matrix based on Eq. 4, which is the multivariate generalization of the hypergeometric probability function. Then calculate all possible matrices of nonnegative integers based on Eq. 4 to find values consistent with Ei and Fj. The Fisher's exact test shows that there is no significant association for New York (see Table 4). The Chi-square test and the Fisher's exact test show that Hurricane Dorian significantly affects the spatial mobility in the study area, but the impacts of displacements are differentiated by the regions.

6 Discussion

Many prior studies have highlighted how natural disasters play an important role in human life (see, e.g., Boose et al. 1994; Chapman et al. 2008; Congleton 2006; Elliott and Pais 2006; Elsner and Jagger 2006). However, to the best of my knowledge, there is no research exploring the effect of a hurricane on spatial reactions and mobility across the US states according to different periods. Therefore, this study explores how Hurricane Dorian exerts

Table 4 Chi-square test and Fisher's exact test

	All	FL	NC		NY
Chi-square	996.145	34.330	4.499	Fisher	4.801
DF	1	5	5		
P-value	0.000	0.000	0.480	*P* value	0.444
N	1867	1528	188	N	151

a significant impact on spatial reactions and mobility in the USA before, during, and after the hurricane weeks.

This study finds some important results, which are inconsistent or consistent with prior studies (see, e.g., Ahmouda et al. 2019; Fussell and Lowe 2014; Kromm and Sturgis 2008; Martín et al. 2017; Mitchell et al. 2012; Qi 2014; Wang and Taylor 2016). First, this study finds that human reactions to a hurricane significantly increase during the hurricane weeks. This finding is inconsistent with the finding of Ahmouda et al. (2019). They show that hurricanes (Matthew 2016; Harvey 2017) do not cause significant disturbance in the tweet numbers in any of the study regions (Houston, Texas; Miami-Dade County, Florida; and North and South Carolina) before, during, and after the hurricane period. However, the finding of this article is more reasonable since governments and centers for natural disasters release the information of the hurricane via Twitter, residents upload the damage, location, and magnitude of the hurricane, and people share and retweet the forecast and report of the hurricane during the hurricane weeks. Therefore, human reactions should be higher in the hurricane weeks than in the post-hurricane weeks.

This study suggests that a hurricane plays an important role in displacements, and the finding is consistent with prior studies (Fussell and Lowe 2014; Kromm and Sturgis 2008; Mitchell et al. 2012; Peek and Fothergill 2008; Reich and Wadsworth 2008; Varano et al. 2010; Wadsworth et al. 2009). Moreover, this study shows that Hurricane Dorian plays a significant role in spatial displacements, but the effects are differentiated by regions, which is consistent with the results of Martín et al. (2017). They highlight that 54% of Twitter users show displacements, with observed differences by regions (Southern, Central, and Northern Conglomerate in South Carolina) according to Hurricane Matthew.

This study highlights that Hurricane Dorian increases long trips and decreases short trips, but the hurricane plays a different role in trips according to regions. The finding is consistent with Qi (2014) and Wang and Taylor (2016). The former one shows that people increase their frequency of short trips by 21.7%, whereas they decrease long trips by 65% in New York according to Hurricane Sandy. The latter one highlights that natural disasters significantly affect human movements, but the effect varies across the regions (Japan, Philippines, Chile, the USA, Britain, Germany, and Australia).

7 Conclusions

The USA is severely damaged by natural disasters. Every state is damaged by one or more of serious natural disasters every year, such as hurricanes, winter storms, earthquakes, floods, droughts, landslides, tornadoes, tsunamis, volcanoes, and wildfires. Therefore, it is one of the most important issues for governments and urban planners to understand how they affect spatial reactions and mobility. In this sense, this study sheds new light on the relationship between a hurricane and spatial reactions and mobility across the US states. This study finds some important findings as follows:

- The number of tweets significantly increases during the hurricane weeks, compared with the pre-hurricane weeks and the post hurricane weeks.
- Florida shows the highest proportion of tweets across the pre-hurricane weeks, hurricane weeks, and post-hurricane weeks, but it reveals a sharp gradient.
- The highest reactions of states are differentiated by the pre-hurricane, hurricane, and post-hurricane weeks.

- Hurricane Dorian plays a significant role in spatial displacements.
- People tend to travel short trips and avoid long trips during the hurricane weeks.

This study suggests significant policy implications as follows: First, governments and policymakers should understand the effects of natural disasters from the national perspective. Prior studies have heavily focused on the damaged region to understand the relationship between natural disasters and human reactions (see, e.g., Ahmouda et al. 2019; Han et al. 2019; Martín et al. 2017; Stowe et al. 2018; Wang and Taylor 2016). However, this study finds that other regions as well as the damaged regions show significant spatial reactions in response to natural disasters. Therefore, governments should explore the spatial reactions to citizens across regions to cope with natural disasters effectively and provide relevant news and information for not only the damaged regions, but also other regions.

Second, governments and transportation planners should examine the characteristics of displacements in their regions according to natural disasters since this study finds that displacements are differentiated by regions. For instance, this study shows that people in the strongly damaged region (Florida) show displacements more than those in the weakly damaged regions (North Carolina and New York). There would be many accidents or difficult situations during emergency evacuations in response to natural disasters. Thus, the studies on the characteristics of displacements in their regions would be helpful to guide their citizens to safer trips and movements.

Third, governments and centers for natural disasters should examine the relationship between displacements and socio-demographic variables, such as gender, age, race/ethnicity, and income, according to natural disasters. Studies on the relationship between displacements and natural disasters based on Twitter API cannot consider the socio-demographic variables because Twitter does not provide personal information to protect users' privacy. Scholars would be able to conduct more elaborate research with the statistical variables to understand the displacements and the characteristics of individuals.

Lastly, this study suggests some limitations and directions for future studies. First, this study highlights spatial reactions and mobility for Hurricane Dorian only based on Twitter, and the results might be different from other data samples. Future research should explore the relationship between a hurricane and spatial reactions and mobility based on various data sources. Second, this study only explores the spatial reactions and displacements for a hurricane, whereas other natural disasters, such as winter storms and earthquakes, would play a different role in them. Future articles should examine the spatial reactions and displacements for a multitude of natural disasters. Third, this study did not consider various explanatory variables, such as gender or age, which may significantly affect displacements because of the limitation of Twitter API. Future research should highlight the relationship between displacements and socio-demographic variables.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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