Loss of Resilience in Human Mobility across Severe Tropical Cyclones of Different Magnitudes

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ABSTRACT

Severe tropical cyclones impose threats on highly populated coastal urban areas, thereby, understanding and predicting human movements plays a critical role in evaluating disaster resilience of human society. However, limited research has focused on tropical cyclones and their influence on human mobility resilience. This preliminary study examined the strength and duration of human mobility perturbation across five significant tropical storms and their affected eight urban areas using Twitter data. The results suggest that tropical cyclones can significantly perturb human movements by changing travel frequencies and displacement probability distributions. While the power-law still best described the pattern of human movements, the changes in the radii of gyration were significant and resulted in perturbation and loss of resilience in human mobility. The findings deepen the understanding about human-environment interactions under extreme events, improve our ability to predict human movements using social media data, and help policymakers improve disaster evacuation and response.

Keywords

Disaster resilience, human mobility, social media, tropical cyclones.

INTRODUCTION

Intensifying tropical cyclones severely threaten coastal urban areas where human activities are intensive and complex (Emanuel, 2013; Knutson, et al., 2010; Hao & Wang, 2019; 2020). A tropical storm that reaches maximum sustained winds of 74 miles per hour is classified as a hurricane or typhoon depending on the location (i.e., in the North Atlantic, central North Pacific, and eastern North Pacific, the term hurricane is used; while in the Northwestern Pacific Basin, typhoon is more commonly used). Over the past 100 years, the continental United States has suffered about $10 billion a year in damages (Pielke Jr, et al., 2008). Such damage is expected to increase as a result of the growing concentration of people and properties in the coastal areas. Hurricane Sandy (2012) caused at least 43 deaths and up to $50 billion in economic loss in New York City, making it the most expensive natural disaster in 2012 (Ferris et al., 2013). Typhoon Haiyan (2013) destroyed Tacloban, a city with a population of more than 220,000 people (BBC, 2013). Typhoon Rammasun, a category four typhoon in 2014, caused over 150 fatalities in multiple countries (Khanh, 2014). The Philippines alone suffered 106 fatalities and 1,250 injuries (Council, 2014). The loss of life, immense human suffering, and severe economic loss from these events call for innovative research and technologies to improve disaster evacuation, response, and relief (Gao & Wang 2021).

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One such innovation is studying human mobility using large quantities of empirical data collected from voluntarily reported geolocations from social networking platforms, e.g. Twitter or mobile device apps. Such studies could potentially improve the understanding and prediction of human locations and routes during the occurrences of disasters. Thus, they can help guide the development of disaster response strategies (Pan et al., 2007; Schneider et al., 2011). Without a deep understanding of human mobility during disasters, response plans may be ineffective. Researchers have reported the diversity of individual and household decision-making during the occurrence of natural disasters (Dash and Gladwin, 2007; Dow and Cutter, 1998; Lindell et al., 2005). In Hurricane Sandy's case, while 71 percent of people living in evacuation areas were aware of a mandatory order to move, more than 50 percent of them stayed nonetheless. Unfortunately, most of the fatalities occurred in the mandatory evacuation zones (CDC, 2013). Even people who evacuated were not entirely safe: the data from FEMA showed that the flooding areas were much larger than the evacuation areas, putting people who stayed in the assumed safe areas in severe threat (Rosenzweig and Solecki, 2014). Similar situations happened during the attack of Typhoon Haiyan. While people were ordered to seek shelter in the City of Tacloban, many people moved to concrete buildings instead of seeking higher ground. Many of these buildings were flooded and collapsed and claimed people's lives (Teves and Bodeen, 2013). These tragedies demonstrate that understanding human movements during the occurrence of disasters, rather than assuming people's responses and movements, is crucial to developing effective disaster response strategies and long-term resilient urban planning.

BACKGROUND

Existing research has discovered patterns in human mobility. Two parameters are used to measure human mobility: the exponent β of a power-law probability distribution, which governs human mobility (Brockmann et al., 2006; Cheng et al., 2011; Gonzalez et al., 2008), and the radius of gyration r_g, which captures the size of an individual's activity space (Gonzalez, et al., 2008). Researchers have studied currency circulation data and mobile phone data and confirmed that human movements follow a power-law distribution, with β values ranging from 1.59 to 1.88 (Brockmann, et al., 2006; Cheng, et al., 2011; Gonzalez, et al., 2008). The universal distribution means that human movements can generally be described by the Lévy flight model, which is typically found in animals' movement patterns (Ramos-Fernandez, et al., 2004). Research has also shown that individual movement trajectories exhibited similar shapes after being rescaled by the radius of gyration (Gonzalez, et al., 2008). It has also been discovered that human mobility shows uneven frequencies of visitations (2010).

Human movement at the city scale also shows common patterns. Periodic modulations dominate human movements in urban scales (Cho et al., 2011; Liang et al., 2012). Urban dwellers are found to exhibit similar movement patterns across 31 cities (Noulas et al., 2012), and they naturally choose the most efficient configurations if a trip involves multiple stops (Schneider et al., 2013). Researchers from urban science also investigated the relationship between human mobility and socioeconomic status with mobile phone data and found that the relationship was influenced by the spatial arrangement of housing, employment opportunities, and human activities (Wang et al., 2018; Xu et al., 2018). Another study demonstrates the usefulness of WiFi access data in analyzing human mobility patterns and behaviors in heterogeneous urban environments (Traunmueller et al., 2018). Explicitly or implicitly, these studies assumed people were in steady states, i.e., their movements were not disturbed by changes in the external environment. However, studies have demonstrated that external changes, such as exacerbation of weather conditions, natural disasters, and man-made extreme events, can significantly perturb human movements (Bengtsson et al., 2011; Brum-Bastos et al., 2018; Horanont et al., 2013). Unfortunately, limited research has focused on human mobility perturbations or attempted to discover mobility patterns related to human mobility perturbation.

This study attempts to reveal a fundamental pattern in human mobility perturbation: the loss of resilience. Resilience in human mobility refers to the ability of human movements to absorb shocks, maintain the fundamental attributes, and return to equilibrium in steady states (Cutter, et al., 2008). Research has shown that assessment and leverage of resilience are critical to reducing the vulnerability of human societies and communities when facing disasters (Burby et al., 2000; Godschalk, 2003). Humans exhibit diverse coping mechanisms and behavioral adaptions when facing natural hazards and changes in weather conditions (Bagrow et al., 2011; Bengtsson, et al., 2011; Horanont, et al., 2013). These findings led to the discovery of inherent resilience in human mobility (Wang and Taylor, 2014b; Wang et al., 2017). It was found that the power-law governed urban human mobility in New York City during the striking of Hurricane Sandy, and both the shifting distances of the centers of movements and the radii of gyrations of movements correlated to the steady-state values. Although the discovery of human mobility resilience is of critical importance, little evidence is available to validate that resilience can withstand stronger tropical cyclones. We need to understand and evaluate its limits to improve human mobility resilience.

METHODOLOGY

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This study examines how human mobility resilience is impacted during and after the landfall of tropical cyclones. We investigated the most significant hurricanes in 2013 and 2014 tropical cyclone seasons and human mobility in their influenced urban areas.

Hypotheses Development

Based on existing literature, we developed three hypotheses to test human mobility under the influence of tropical cyclones. Pondering on the question of how hurricanes influence human mobility perturbation, we developed our first hypothesis:

Hypothesis 1: Hurricanes of distinct wind speed in different areas cause perturbations on human mobility following similar temporal patterns.

If human mobility perturbations show different patterns, what are the causes of the changes? To answer this question, we examined two parameters to quantify such perturbations. As previously mentioned, two parameters were used to capture the fundamental patterns in human mobility: the scaling parameter, β, and the radius of gyration, r_g. Therefore, we developed our second and third hypotheses as follows:

Hypothesis 2: The loss of resilience of human mobility comes from a fundamental deviation from power-law.

Hypothesis 3: The loss of resilience in human mobility comes from the aggregate effects of individuals changing their radii of gyrations.

Data Collection

Empirical data of human mobility were collected using Twitter, which is a large-scale social networking platform. Twitter data has been used to study critical issues in civil and urban engineering and its geo-locating function provides an open and viable venue to study human mobility (Hawelka, et al., 2014; Sutton, 2009; Wang and Taylor, 2014a). Twitter data has also demonstrated its usefulness in disaster management for different purposes (Huang et al., 2017). We collected human mobility data by continuously streaming global geo-tagged tweets. Each geo-tagged tweet contains a geographical coordinate as well as other information, such as tweet ID, user ID, username, the content of the message, etc. The accuracy of the geographical coordinate is up to 10 meters. Python was used to design a data collection system that streams geo-tagged tweets in real time. The data collection effort started in October 2012, and the system has since been running continuously. Each day during the study period about 9.5 million geo-tagged tweets are collected into the database worldwide. For more information about the data collection, see (Wang and Taylor 2016).

The human movement data were retrieved for all the typhoons over 2012 to 2014. After filtering out the ones without sufficient data entries, high-resolution human mobility data collected from eight areas under the influences of five typhoons were used for this study. These cases are (1) Tokyo, Japan (Typhoon Wipha, 2013), (2) Tacloban, Philippines (Typhoon Haiyan, 2013), (3) Cebu, Philippines (Typhoon Haiyan, 2013), (4) Antipolo, Philippines (Typhoon Rammasun, 2014), (5) Manila, Philippines (Typhoon Rammasun, 2014), (6) Okinawa, Japan (Typhoon Halong, 2014), (7) Nakagami, Japan (Typhoon Phanfone, 2014), (8) Calasiao, Philippines (Typhoon Kalmaegi, 2014). The methodology of data collection and analysis are described in the following sub-sections. To test if the occurrences of human mobility perturbation were caused by the attacks of the cyclones, we compared the human movements in different days. We assumed the day each typhoon made landfall was Day 0, and then we retrieved displacement data on that day. Displacement data were also retrieved from the 15 days before the landfall (-) and the 17 days after the landfall (+). Each day was assumed to start at 3 am local time since most of the Twitter activities start to emerge then. We assumed the perturbation state (D_p) is the 24-hour period over which a hurricane made landfall. The steady state (D_s) is normal days that are at least one week before or after the landfall of the typhoons. In total, we collected 1,688,319 geo-tagged tweets from 123,938 individuals in the eight cases.

Data Analysis

We conducted several analyses on the data. First, we analyzed the perturbation strength for each case by examining the changes in the distributions of displacements. We calculated the probability distributions for both D_p and D_s, and let $d_E = [d_E^{(1)}, d_E^{(2)},..., d_E^{(dmax)}]$ be Euclidean distance between the two distributions. Therefore, d_E demonstrates the perturbation strength between human mobility in a perturbation state and a steady state in each case.

Then we calculated the displacements of human movements in each case. A displacement d is the distance between two consecutive coordinates of the same individual. The Haversine formula was used to calculate the distances

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(Robusto, 1957):

$$d = 2r \times \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos\phi_1 \cos\phi_2 \sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right)}\right)$$

where r is the earth radius, which approximately equals to 6,367,000 meters, ϕ is the latitude, and φ is the longitude.

For each case, the displacement data for each 24-hour period were fitted to the truncated power-law distribution. A truncated power-law is represented as:

$$P(\Delta r) \propto \Delta r^{-\beta} e^{-\lambda \Delta r}$$

where Δr is the displacement, β is the exponent parameter, λ is the exponential cutoff value. Due to the heavy tails of the empirical data, we applied the procedure of logarithmic binning to reduce the noise of the empirical data (Newman, 2005; Yan et al., 2013). The procedure follows the introduction from Milojević's study (Milojević, 2010). For each B, the binned value y_B equals to average numbers of displacements d inside the B:

$$y_B = \frac{\sum d}{B_{max} - B_{min}}$$

where B_{max} is the upper limit of B and B_{min} is the lower limit of B. The logarithmic binning was started from $d = 9$ with each bin (B) size equal to 0.05, i.e. $\log(B_{max}) - \log(B_{min}) = 0.05$. We also conducted a Kolmogorov-Smirnov (KS) test and Maximum Likelihood Estimation (MLE) to compare truncated power-law distribution to both exponential distribution and lognormal distribution.

To calculate the value of the radius of gyration, we first calculated the center of mass of human movements using the following equation (Gonzalez, et al., 2008):

$$\vec{r}_{CM} = \frac{1}{n(t)} \sum_{i=1}^{n(t)} \vec{r}_i$$

where n(t) was the number of locations an individual visited in the 24 hours, $\vec{r}_i$ was the coordinate. Then the following formula was used to calculate the radius of gyration:

$$r_g = \sqrt{\frac{1}{n(t)} \sum_{i=1}^{n(t)} \left[2r \times \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_{CM}}{2}\right) + \cos\phi_1 \cos\phi_2 \sin^2\left(\frac{\varphi_2 - \varphi_{CM}}{2}\right)}\right)\right]^2}$$

where the symbols are the same as indicated above.

RESULTS AND DISCUSSION

By analyzing the perturbation strengths (d_E), we discovered that human mobility experienced different magnitudes of perturbations in different cases. We collected wind speed data from reports and weather station records. The results between d_E and the wind speeds are shown in Fig. 1.

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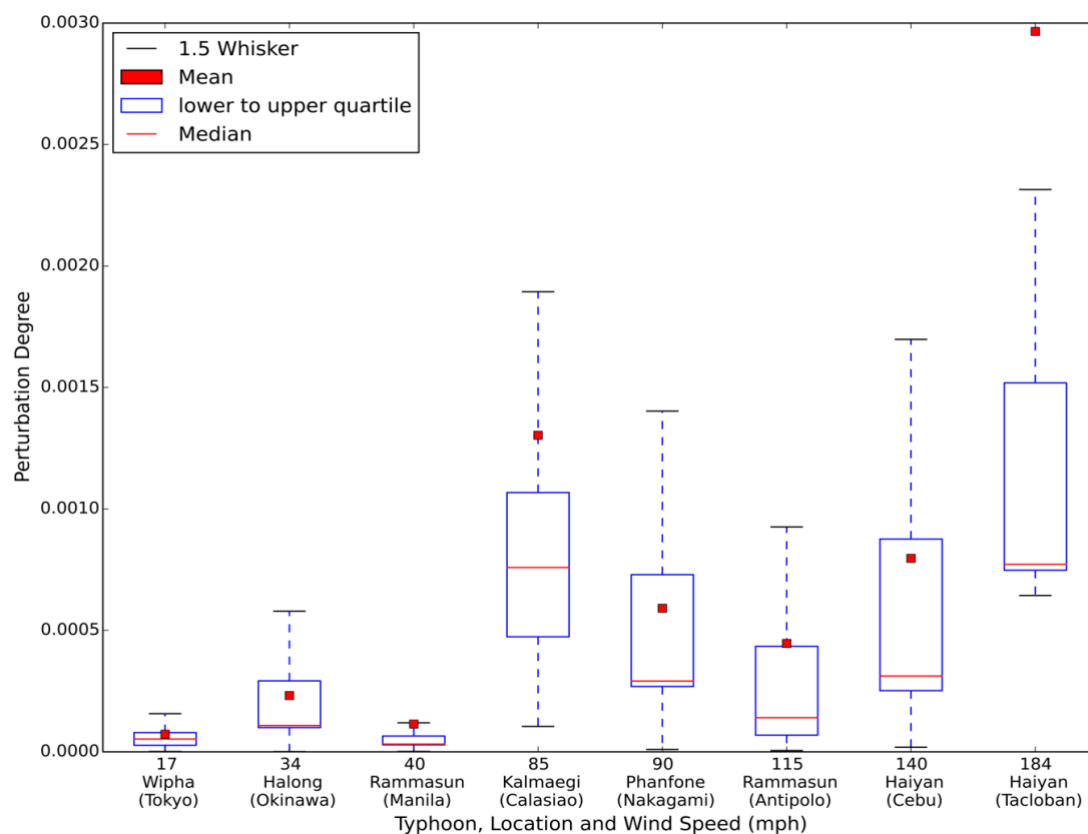
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Figure 1. Wind Speed and Perturbation Degree

We observe that more powerful typhoons characterized by higher wind speed are likely to cause stronger human mobility perturbations. This finding is critical yet not surprising. Higher wind speeds are associated with tropical cyclones of a stronger power, causing more precipitation, gusts, power outages, transportation failures, and even occurrences of other natural hazards, such as storm surge, floods, and landslides. The correlation supports the common assumption that all of these consequences can cause stronger perturbation in human mobility. The correlation also shows that although the occurrences of typhoons influence human mobility, determining the magnitudes of perturbation is a complex task and can be influenced by multiple causes. Such complexity deserves further study.

We studied the displacements before, during, and after landfall of the tropical cyclones. We scaled the numbers of displacements by dividing each day's value by the average value from Day -14 to Day -7. The scaling allowed us to compare the magnitudes of perturbations from different cases directly. The analytical results revealed three distinct perturbation patterns. First, in the cases of Tokyo, Okinawa, and Manila (Fig. 2 grey lines), the numbers of displacements in the perturbation states changed by less than 20% compared to the steady states. The magnitudes of perturbation reduced quickly and returned to the average values within days. Most of the fluctuations were rather mild, within 20 percent. Second, in the cases of Cebu, Antipolo, Calasiao, and Nakagami (Fig. 2 blue lines), the changes were much stronger, up to 60% compared to the average values in the perturbation states. The numbers of displacements kept shifting around the average without reducing the perturbation magnitudes even after two weeks. Last, in the case of Tacloban (Fig. 2 red lines), the number of movements reduced dramatically after the landfall of Typhoon Haiyan. The value remained on a very low level and showed no signs of resuming after two weeks. The severe perturbations are mainly attributed to the devastating storm surge, which destroyed many buildings, vehicles, and trees. The flooding also extended for 1 km inland on the east coast of the city, causing large-scale infrastructure destruction and loss of lives.
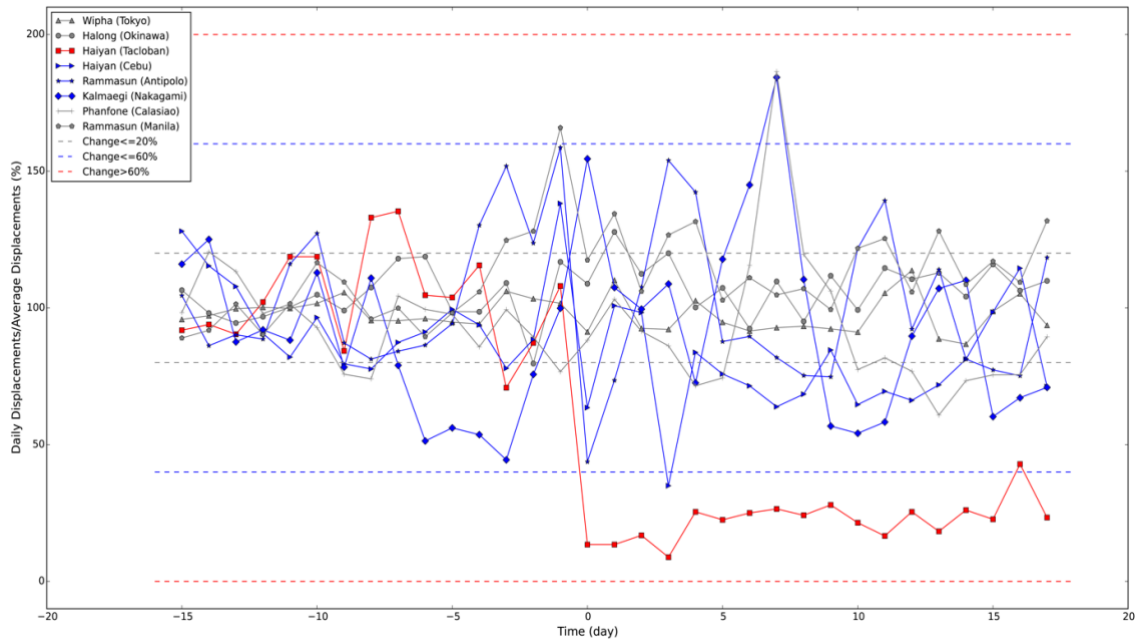
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Figure 2. Changes of Total Displacements

We also analyzed the daily numbers of displacements (Ni) in six ranges of distance for each case. The six ranges were: (1) 1-100m, (2) 100-500m, (3) 500m-1km, (4) 1-5km, (5) 5-10km, and (6) over 10km. The numbers of displacements at different ranges of distances experienced noticeable, although diverse, perturbations (Fig. 3). Similarly, the results displayed three different patterns as well. First, when the strength of perturbation was relatively low, i.e. in the cases of Tokyo, Okinawa, and Manila, there was a clear trend that people increased their short-distance travels and reduced their long-distance travels. However, when tropical cyclones were attacking an urban area with strong winds, the changes started to become more chaotic. This second pattern could be observed in the cases of Cebu, Antipolo, Calasiao, and Nakagami. Changes happened at all distances and there were no clear, distinguishable patterns, although it was observed that the magnitudes of changes increased with the growth of d_E. The third pattern was observed in the case of Tacloban, where displacements at all levels decreased dramatically, and long-distance travel disappeared entirely.
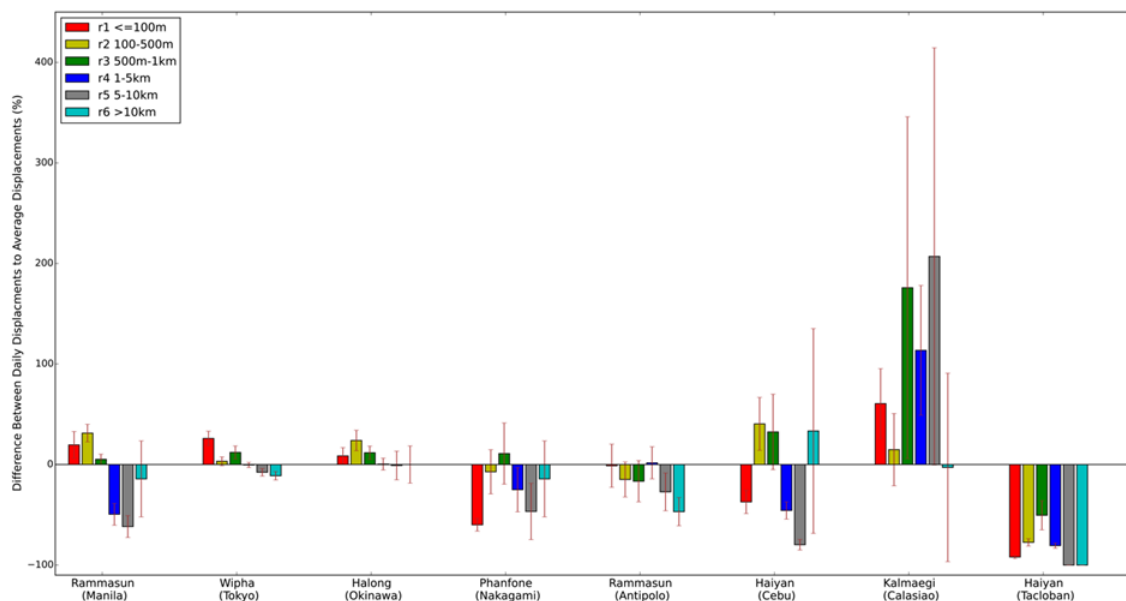
Figure 3. Changes in Displacements at Different Ranges

The results of the analysis on displacements demonstrated that stronger perturbations show entirely different

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patterns. Therefore, we found support for Hypothesis 1. The examination of Hypothesis 1 has identified the fundamental attributes to the impact of typhoons on the resilience in human mobility: the magnitude of typhoons (i.e. wind speed) and the perturbation patterns. The different patterns also suggested a key finding: Human mobility possesses inherent resilience, but resilience has its limitations. When a typhoon is extremely powerful, such as Typhoon Haiyan, the resilience can collapse.

To understand the cause of the collapse (Hypothesis 2), we first analyzed human mobility data for every 24 hours from all of the cases. We fitted each dataset into the truncated power-law distribution (Fig. 4). The results were surprising; although having different values of scaling-invariances, almost all of the data from different cases followed truncated power-law distributions. The power-law dominates human mobility patterns, even during most of the days in Tacloban during the attack of Typhoon Haiyan. Therefore, we rejected Hypothesis 2.

Although Hypothesis 2 is rejected, the analysis result implies an important discovery. While previous research has demonstrated that human mobility follows similar patterns across multiple big cities around the world (Noulas, et al., 2012), our finding further establishes that human mobility follows power-law distribution in perturbation states even when typhoons impact it with different strengths.
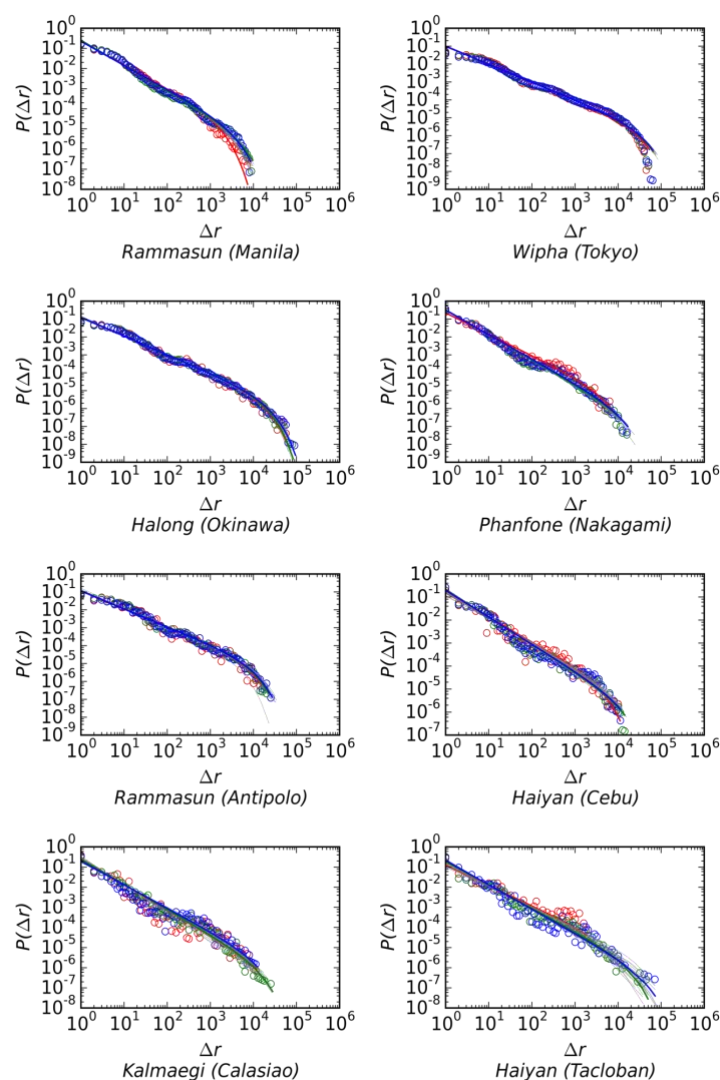

Figure 4. Human Mobility Distributions

To investigate Hypothesis 3, we calculated the values of the radius of gyration (r_g) before (-), during (0), and after (+) the landings of typhoons for each 72 hours. We only included the active users, each of whom reported at least five locations in the 72-hour periods. Each individual's r_g was calculated (Fig. 5). Comparing data in each set, we found that the changes in r_g of human movements aligned with the patterns we found in the displacement analysis.

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With increasing perturbation degrees, the magnitudes of changes in r_g increased. The values of r_g eventually declined when the perturbation was extremely strong, this was demonstrated in Tacloban as r_g experienced a significant reduction due to the destructive power unleashed by Typhoon Haiyan. Therefore, we found support for Hypothesis 3.
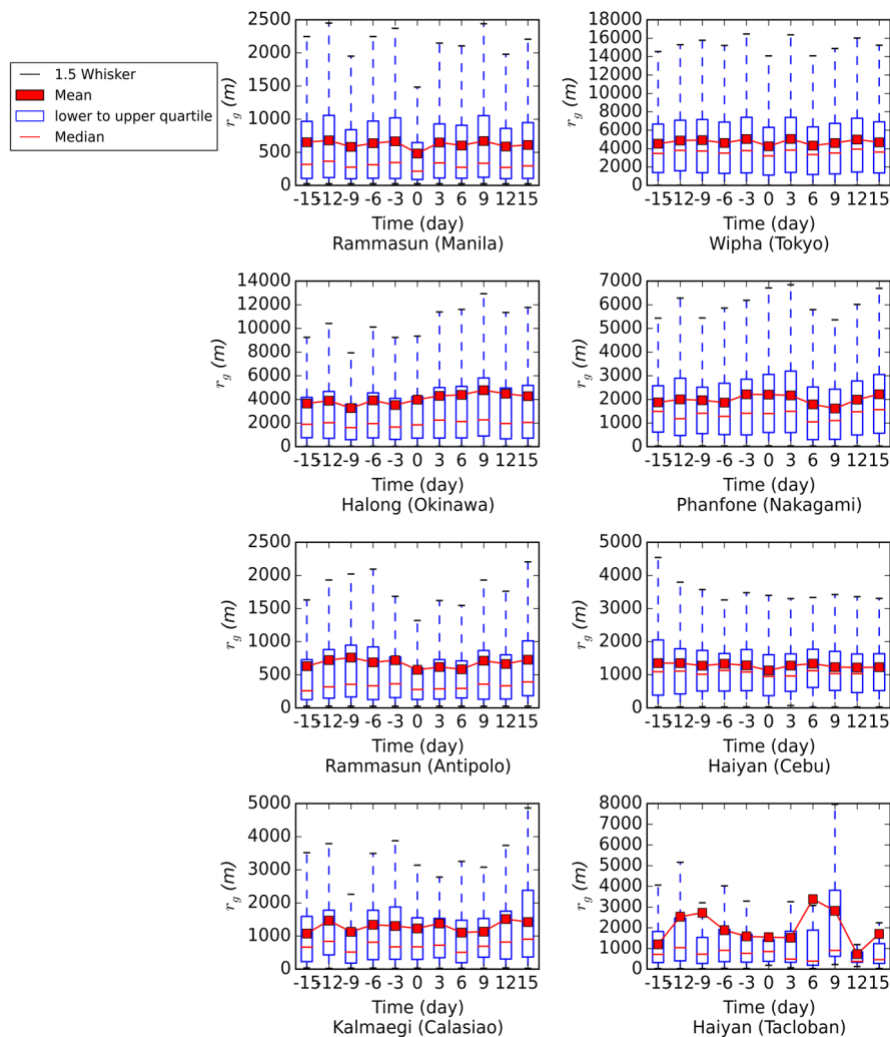

Figure 5. Changes in the Radius of Gyration

CONCLUSION

A recent white paper released from the National Academies of Sciences, Engineering, and Medicine (Cutter et al. 2019) addresses the lack of longitudinal data and systems for measuring the human dimensions of resilience and encourages the employment of big data in resilience science. Taking advantage of crowdsourced individuals' geolocations collected from social media microblogs posted on Twitter, this research measures human mobility resilience across tropical cyclone cases. Our preliminary analysis of displacements demonstrated three patterns for human mobility while influenced by severe tropical cyclones. While displacements from all cases suffered temporary fluctuations, the three cases with smaller d_E absorbed the perturbations quickly (Pattern 1). However, with the increasing perturbation degree, it became increasingly difficult to absorb the shocks. Human mobility experienced a higher magnitude of fluctuation and required a longer period to return to equilibrium (Pattern 2). In the case of Typhoon Haiyan in Tacloban, human mobility collapsed, and the movements dropped to an extremely low level (Pattern 3).

To understand the perturbation and loss of resilience, we tested two sets of hypotheses. The analysis on the first set allowed us to find those stronger perturbations in human mobility exhibit significantly different patterns from the weaker ones. Low-magnitude perturbation often exhibits mild fluctuations in travel frequencies and distances and returns to its equilibrium in a short period. High-magnitude perturbation, on the other hand, forces human movements to significantly deviate from their balance more erratically, taking a significantly longer time to return

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to equilibrium. While low-magnitude perturbation is linear and shows a clear pattern of oscillation, the high-magnitude perturbation is non-linear, chaotic, and more difficult to predict.

These findings highlight the possibility that human mobility can lose its resilience in extreme conditions. When experiencing mild influences from tropical cyclones, human mobility suffers temporary perturbation but strives to return to its state of equilibrium. However, powerful influences from severe tropical cyclones, or disasters in general, can destroy established resilience in human mobility, forcing individuals to deviate from their routines and adapt to new environments. The process is often more time-consuming, unpredictable, and associated with the collapse of established equilibriums.

Although tropical cyclones can trigger different patterns of human mobility perturbation, we found that a truncated power-law governs human mobility universally, even when influenced by extremely powerful natural disasters, such as Typhoon Haiyan. While this finding confirms that the power-law is the fundamental pattern in human mobility (Brockmann, et al., 2006; Gonzalez, et al., 2008), it also suggests that perturbation and the collapse of human mobility are not caused by the deviation from power-law. The scaling parameter β is an insensitive factor and cannot be used to capture these phenomena in human movements.

Instead, the perturbation and loss of resilience of human mobility are more likely to be the results of individuals changing their radii of gyrations. We found that the radius of gyration is not only a key parameter to describe the fundamental patterns on the individual level (Gonzalez, et al., 2008), but also a critical factor to capture and analyze perturbations in aggregated human mobility. This links human mobility perturbation from the micro-level to the macro-level, enabling more accurate location and travel predictions during the occurrence of natural disasters to minimize loss of life and human suffering. With more detailed spatial data of urban environments and local communities' socioeconomic and mitigation planning data, the research findings can also inform human-infrastructure interactions and resilient urban planning. Our future work will include more cases of severe tropical cyclones to achieve generalizable findings. We will consider the impact of disaster mitigation strategies (Berke et al. 2012), early warnings (Gao & Wang 2021), and spatial arrangement of facilities (Xu et al. 2020) in further investigations on human mobility resilience, while also ensuring vulnerable populations are well-represented in the analysis (Samuels and Taylor, 2020) and taking into consideration social media activity drop-offs (Samuels, et al., 2020). Future studies can also explore human-centered resilience measurement by integrating finer-scale damages derived from multi-modal social media data (Hao & Wang 2020; Wang et al. 2020) across severe tropical cyclones.

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