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Resilience of human mobility under the influence of typhoons

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Abstract

Climate change has intensified tropical cyclones, resulting in several recent catastrophic hurricanes and typhoons. Such disasters impose threats on populous coastal urban areas, and therefore, understanding and predicting human movements plays a critical role in evaluating vulnerability and resilience of human society and developing plans for disaster evacuation, response and relief. Despite its critical role, limited research has focused on tropical cyclones and their influence on human mobility. Here, we studied how severe tropical storms could influence human mobility patterns in coastal urban populations using individuals' movement data collected from Twitter. We selected 5 significant tropical storms and examined their influences on 8 urban areas. We analyzed the human movement data before, during, and after each event, comparing the perturbed movement data to movement data from steady states. We also used different statistical analysis approaches to quantify the strength and duration of human mobility perturbation. The results suggest that tropical cyclones can significantly perturb human movements, and human mobility experienced different magnitudes in different cases. We also found that power-law still governed human movements in spite of the perturbations. The findings from this study will deepen our understanding about the interaction between urban dwellers and civil infrastructure, improve our ability to predict human movements during natural disasters, and help policymakers to improve disaster evacuation, response and relief plans.

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Keywords: disasters; evacuation; mobility; resilience; Twitter; typhoons

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1. Introduction

Intensifying tropical cyclones severely threaten coastal urban areas where human mobility dynamics are active and complex [1-3]. 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 [4]. Typhoon Haiyan (2013) destroyed Tacloban, a city with a population of more than 220,000 people [5]. Typhoon Rammasun, a category 4 typhoon in 2014, caused over 150 fatalities in multiple countries [6]. The Philippines alone suffered 106 fatalities and 1,250 injuries [7]. The loss of life, the immense human suffering and severe economic loss from these events call for innovative research and technologies to improve disaster evacuation, response and relief.

One recent innovative approach to studying human mobility is using large-scale empirical data. These studies are of critical importance because they can potentially improve the understanding and prediction of human locations and routes during the occurrences of natural disasters. Thus, they can help guide the development of disaster response strategies [8, 9]. Without deep understanding on human mobility during disasters, the effectiveness of disaster response plans is difficult to judge. 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 evacuation areas [10]. Even people that evacuated were not entirely safe. Data from FEMA shows that the flooding areas were 15 percent larger than the evacuation areas, making people who stayed in the assumed safe areas in severe danger [11]. Similar situations happened during the attack of Typhoon Haiyan. While people were ordered to seek shelters in the City of Tacloban, many people moved to concrete buildings instead of higher ground. Many of these buildings collapsed in the storm surge and claimed lives [12]. These tragedies demonstrate that understanding human mobility perturbation during the occurrence of natural disasters, rather than assuming people's responses and movements, may hold the key to saving lives.

2. Background

Existing research has discovered generic and urban human mobility patterns. Two parameters are used to measure generic human mobility: the exponent value β of a power-law probability distribution which governs human mobility [13-16], and the radius of gyration r_g to capture individual human movements [14]. It has been shown that human mobility shows uneven frequencies of visitations [17]. Periodic modulations dominate human movements in urban scales [18, 19]. Urban dwellers exhibited similar movement patterns across 31 cities [20], and they naturally choose the most efficient configurations if a trip involves multiple locations [21]. Explicitly or implicitly, these studies assumed people were in steady states, i.e. their movements were not disturbed by the changes of external environments. However, studies have demonstrated that external changes, such as weather conditions, disasters, emergencies, etc., can significantly perturb human movements [22-24]. Unfortunately, limited research has focused on human mobility perturbations or attempted to discover recurring patterns related to human mobility perturbation.

This study attempts to reveal a fundamental pattern in human mobility perturbation: resilience. Resilience in human mobility means the ability of human movements to absorb shocks, maintain the fundamental attributes, and return to the equilibrium in steady states following natural disasters [25]. Research has shown that assessment and leverage of resilience is critical to reduce vulnerability when human societies and communities are facing disasters. Humans exhibit different coping mechanisms and behavioral adaptions when facing natural disasters and changing weather conditions [22, 23, 26]. Research has shown that 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 (Δd_{CM}) and the radii of gyrations of movements (r_g) were correlated to the values in the steady state [10]. Although the discovery of human mobility resilience is of critical importance, little evidence is available to validate that the resilience can withstand stronger tropical cyclones [27]. We need to understand and evaluate its limits to improve human mobility resilience.

3. Methodology

This study examines how human mobility resilience is impacted during the attacks of tropical cyclones. The examination was based on high-resolution empirical human mobility data collected from 8 areas under the influences of 5 Typhoons. 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). Twitter, a large-scale social networking platform, has been used to study key issues in civil and urban engineering [28-31], and its geo-locating function provides an open and viable venue to study human mobility. We collected human mobility data by continuously streaming global geo-tagged tweets. After a typhoon occurred, we retrieved the 24-hour human mobility data from the impacted areas as well as 15-day data before the landing of the typhoon and 17-day data after the landing of the typhoon.. To test if the occurrences of human mobility perturbation may have been caused by the attacks of typhoons, we compared the human movements in different days. We assumed the day each typhoon made landfall was day 0, and 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 3am in the morning local time. We assume the perturbation state (D_p) is the 24-hour period during which a typhoon made landfall. The steady state (D_s) refers to days that are at least one week before or after the landfall of the typhoons.

3.1 Data Collection

Empirical data of human mobility were collected using Twitter. Python was used to design a data collection system that streams geo-tagged tweets in real time. Each geo-tagged tweet contains a geographical coordinate as well as other information, such as tweet ID, user ID, user name, content of the message, etc. The accuracy of the geographical coordinate is up to 10 meters. The data collection effort started in October, 2012 and the system has since been running continuously. Each day about 9.5 million geo-tagged tweets are collected into the database worldwide. For more information about the data collection, see [32, 33].

After the 2013 and 2014 tropical cyclone seasons, the most significant tropical cyclones were retrieved and the areas they influenced were investigated. Then tweets from these areas were retrieved. After filtering out the cyclones without sufficient data entries, 8 cases were obtained for analysis. These cases include 1,688,319 tweets from a total of 123,938 individuals.

3.2 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. First, we calculated the probability distributions for both $\mathbf{D}_p$ and $\mathbf{D}_s$, and let $\boldsymbol{d}_E = [d_E^{(1)}, d_E^{(2)}, \ldots, d_E^{(dmax)}]$ be Euclidean distances between the two distributions. Therefore, $\boldsymbol{d}_E$ 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 [34]:

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

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:

$$P(\Delta r) \propto \Delta r^{-\beta} e^{-\lambda \Delta r} \tag{2}$$

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 [35, 36]. The procedure follows the approach from Milojević's study [37]. For each B, the binned value y_B equals to average numbers of displacements d inside the B:

$$y_B = \frac{\sum d}{B_{\max} - B_{\min}} \tag{3}$$

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 radius of gyration, we first calculated the center of mass of human movements using the following equation [14]:

$$\vec{r}_{CM} = \frac{1}{n(t)} \sum_{i=1}^{n(t)} \vec{r}_i \tag{4}$$

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

$$r_g = \sqrt{\frac{1}{n(t)} \sum_{i=1}^{n(t)} \left[2r \times \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_{CM}}{2}\right) + \cos\phi_1 \cos\phi_2 \sin^2\left(\frac{\varphi_2 - \varphi_{CM}}{2}\right)} \right) \right]^2} \tag{5}$$

where the symbols are the same as indicated above.

4. Results and Discussion

By analyzing the perturbation strengths, we discovered that human mobility experienced different magnitudes of perturbations in different cases. We collected wind speed data from reports and weather station records, and conducted a Pearson test between the strength of human mobility perturbation and wind speed. The results showed that the median values of $\boldsymbol{d_E}$ were weakly correlated with wind speeds (r = 0.69, p<0.1) (Figure 1). The statistical results show that although human mobility is influenced by the occurrences of typhoons, the magnitudes of perturbation can be influenced by multiple causes. The complexity deserves further study.

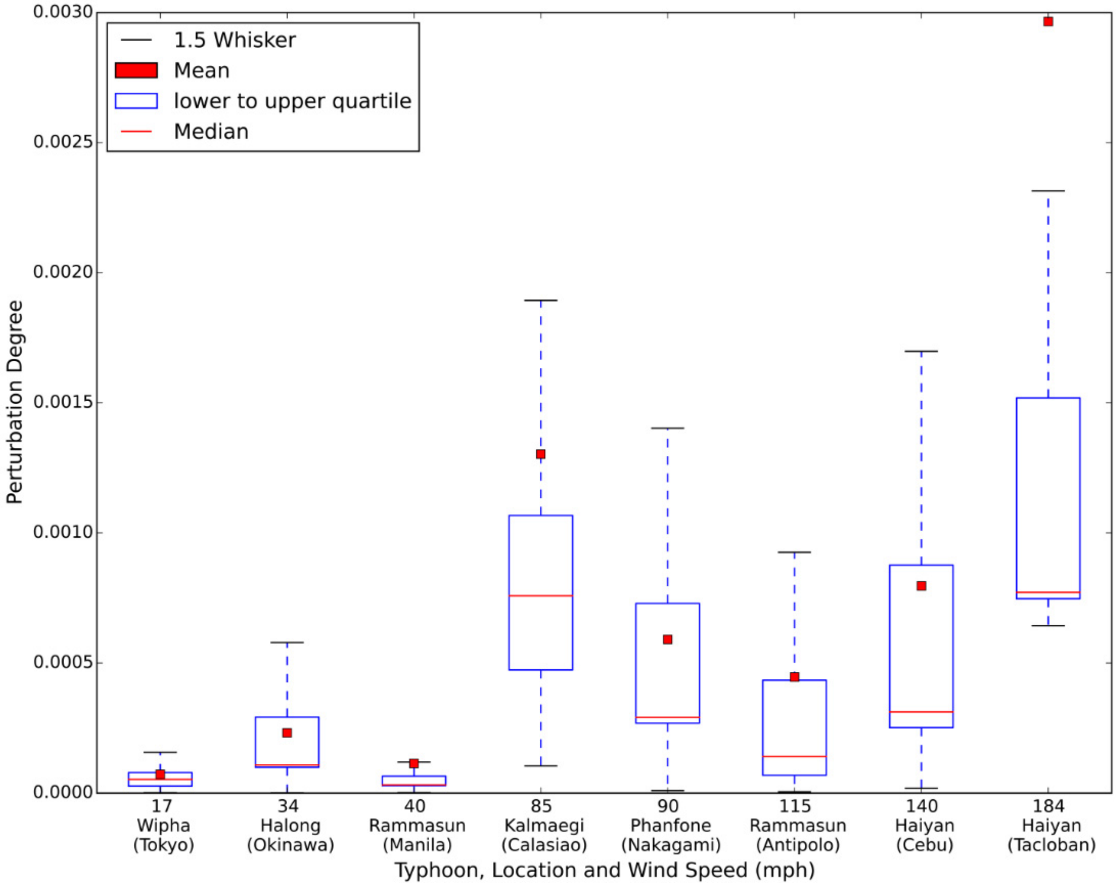

Figure 1. Wind Speed and Perturbation Degree

We fitted the displacement data from each time period to the truncated power-law and conducted the Maximum Likelihood Estimation test. The results from data fitting show that in most cases power-law still governs human mobility even in the cases that the perturbations were extremely strong (Figure 2).

5. Conclusions

Human mobility in urban areas can be influenced by natural and man-made disasters, and coastal cities are especially vulnerable to tropical cyclones. Existing research has reported that the change of natural environment could cause behavioral change and temporary or even permanent human migrations. In this study we collected empirical human movement data using Twitter to discover whether human mobility is resilient or collapsed under the influence of tropical cyclones. The data were analyzed to identify and quantify human mobility perturbation from steady states. Our findings demonstrate that: (1) tropical cyclones can cause human mobility perturbation; (2) the magnitudes of perturbations were diverse but weakly correlated with wind speed; and (3) truncated power-law still governed human mobility despite the different levels of perturbations which indicate that the fundamental patterns in human mobility are resilient.

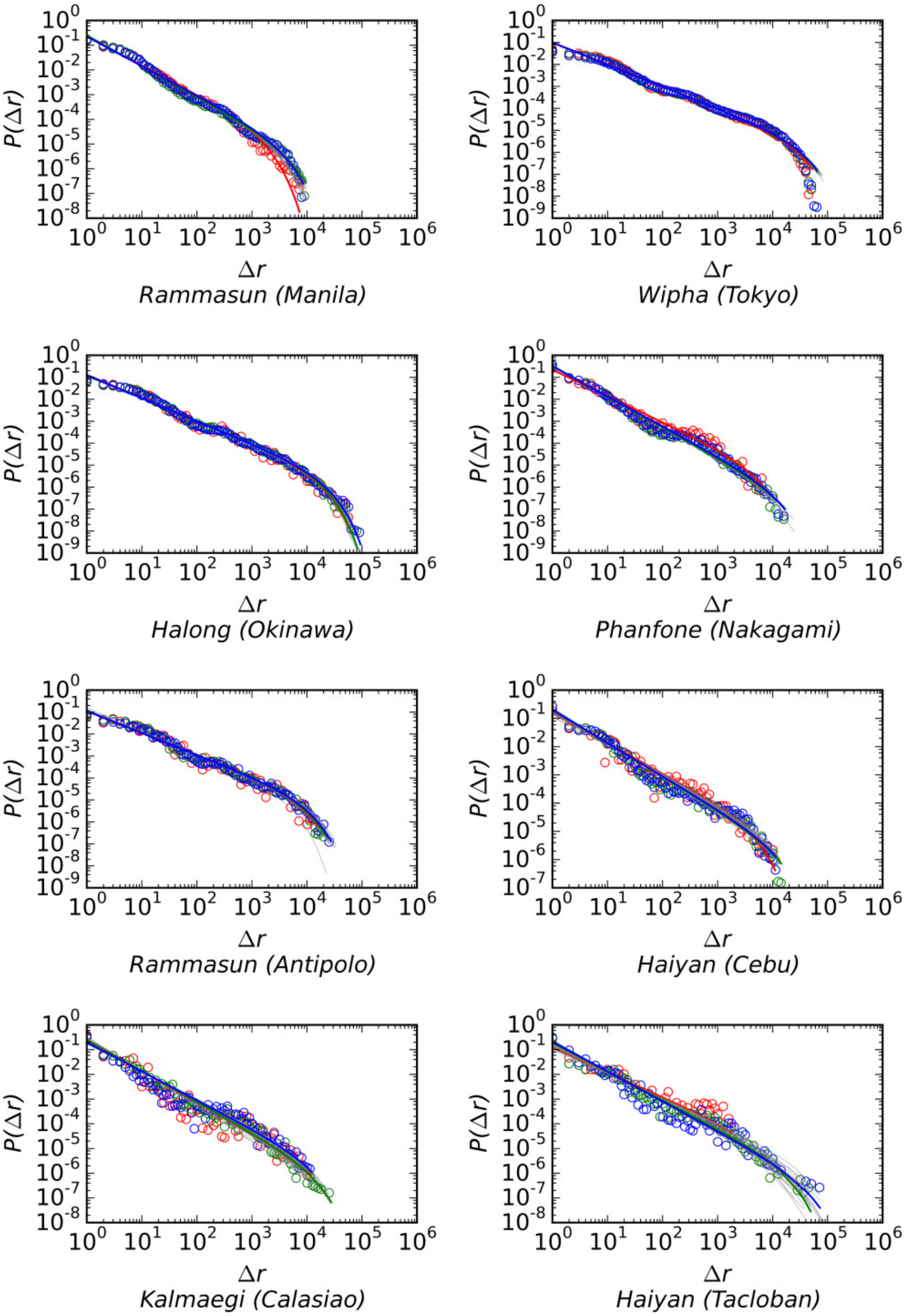

Figure 2. Human Mobility Distributions

While this study is an attempt to explore human mobility perturbation and resilience under the influence of different tropical cyclones, future research can build on the results of this study by examining more tropical cyclones. Also, the cause of perturbations in human mobility are complex. While we demonstrated that the perturbations are not a reflection of the deviation from power-law distribution, more research is needed to discover what the underlying causes are. This will help policy makers and practitioners to better predict human movements and improve disaster evacuation, response, and recovery plans.

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