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Quantification of community resilience to natural hazards by tracking cell-phone GPS location data☆

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ABSTRACT

Following our ongoing studies on the quantification of urban resilience to natural hazards this paper focuses on quantifying the resilience of local communities which according to reports and satellite radiance data (nighttime light emission) have experienced heavy damage in the wider urban center. Our study focuses on specific heavily damaged communities from the Dallas metroplex and the greater Houston urban area from the February 2021 winter storm. We only distilled cell-phone IDs that their homes are in the identified communities of interest and we trace the path of these IDs on the greater urban center prior, during and after the North American Winter Storm struck. Our study adopts the definition of "engineering" resilience which is encoded in the mean square displacement (MSD) of the citizens of a given community. All computed MSDs of the citizens from these heavily damaged communities show invariably a noticeable suppression during the duration of the storm; yet, immediately after the expiration of the cold storm; all community MSDs from the cities of Dallas and Houston indicate, that in terms of an ensemble average (MSD), each of the communities examined reverted back to the pre-storm response almost immediately; suggesting an inherent "engineering" resilience to the winter storm. Accordingly, this paper confirms our previous findings on the wider urban scale; that even at the community scale the urban fabric of large American cities of medium-to-high population density exhibits a great degree of "engineering" resilience.

1. Introduction

As cities continue to grow, many of them along the coasts of continents that are prone to natural hazards, urban resilience has become a subject of interest in various disciplines [1–17]. The many challenges associated with rapid urban growth, community resilience, and sustainable development are receiving increasing attention; yet, in practice, they have been treated as independent issues [5,18,19].

While the functionality of cities is served with the superposition of a variety of large-scale, complex networks [20–22], including the transportation infrastructure (roads, bus lines, and a subway network when available), water and gas utility networks, the electricity grid, telecommunication networks (telephone and internet) together with overriding social networks [2,23–36] with no apparent common design principles, it appears that cities display a difficult-to-interpret self-organizing behavior that leads to deterministic patterns. In addition to the aforementioned material networks, perhaps the most robust network that serves urban resilience is the living network of the citizens, since cities are essentially the physical manifestation of the daily interaction of its citizens facilitating the generation of creativity, growth, progress and leadership together with economic, intellectual and social wealth [1,2,8,11,15,18,24–26,29–31,37–50].

In an effort to express mathematically this emergent, self-organizing behavior in association with the need to develop a quantitative, science-based understanding of the dynamics and response of cities when subjected to natural hazards, Makris et al. [34,51] envisioned a city to be a matrix where people (cellphone users) are driven by the city's economy and other personal and societal driving incentives while using the collection of its infrastructure networks similarly as thermally driven Brownian particles move within a complex viscoelastic material [52–61].

Mobile phones carried by the citizens of a large city offer rich data on human mobility patterns, and we showed that ensemble averages of cellphone GPS location data [mean-square displacement = (MSD) of cell-phone users from their homes] reveal detailed information on the response of cities to natural hazards as well as to sudden evacuation orders. Our past studies [34,51] employ a "single-state equilibrium",

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which is the response history of the mean-square displacement of the citizens of the entire city when it operates under normal conditions, in association with the definitions of engineering resilience [62,63]. Alternative definitions of urban resilience which attempt to capture wider concepts and metrics have been proposed by [15,64–66].

2. The divergent views on community resilience and the limitations/advantages of our analysis framework

The concept of *community resilience* as it has emerged in disaster risk reduction, climate adaptation, and sustainability science is multidimensional and multifaceted leading to a rich discourse [1,15,63,67–69]. One fundamental debate is whether resilience should be understood as an *outcome* or a *process*. From the outcome perspective, resilience is defined as the *state* or *capacity* of a system to return to equilibrium following a disturbance, often characterized as the ability to "bounce back" to the pre-disturbance regime. This outcome-centric view was coined by Holling [63] as *"Engineering Resilience"*. The work of Bruneau et al. [1] views community resilience as *outcomes* with several components (*Robustness*, *Redundancy*, *Resourcefulness*, *Rapidity*)—that is the ability of communities to mitigate hazards, contain the effect of occurring disasters and carry out recovery activities in ways that minimize social disruption and mitigate the effect of future natural hazards. The multifaceted nature of community resilience (technical, organizational, social and economic dimensions) has also been discussed by Chang and Shinozuka [70]. This engineering-oriented view emphasizes quantifiable system performance and recovery speed.

In contrast, the *process* concept of resilience is understood as an *ongoing, adaptive trajectory* — a community's capacity to reorganize, learn, and transform in the face of shocks — a concept that is rooted in the definition of *"Ecological Resilience"* (Holling, [62]) which emphasizes conditions far from equilibrium where instabilities can flip a system into another regime of behavior which is a different equilibrium state. In this case, resilience is associated with the magnitude of a disturbance (shock) that needs to be absorbed by the system before it changes its structure and stabilizes at a different equilibrium state. Along this line of reasoning, Norris et al. [71] view community resilience as a *process* linking the several of adaptive capacities (such as social capital and economic development) to responses and changes after adverse events. More recent studies (Meerow et al. [15] and references reported therein) offer a wider definition of resilience by including a set of capacities that can be fostered through interventions and policies, which in turn help build and enhance a community's ability to respond and recover from disasters.

At present, the multidimensional and multifaceted nature of community resilience stems from the dynamic interactions of infrastructure, societal and environmental systems. While engineers seek data-driven resilience metrics, social scientists highlight equity, governance, and community competence as equally essential to the concept of engineering resilience. The Social Vulnerability Index (SoVI; Cutter et al. [72]) and the Baseline Resilience Indicators for Communities (BRIC; Cutter et al. [69]), provide baseline snapshots of relative resilience or vulnerability. These indices are useful for benchmarking and comparisons but often oversimplify dynamic processes. Dynamic approaches, on the other hand, seek to capture resilience as a temporal trajectory, emphasizing evolving capacities and recovery pathways. Examples include the National Institute of Standards and Technology's (NIST 2016; [73]) recovery time objectives for infrastructure systems and emerging mobility-based models that quantify community recovery as functional restoration over time. The divergence here lies between resilience as a *fixed measurement* versus resilience as a *time-evolving process*. Infrastructure-focused frameworks, such as the NIST Guide, evaluate resilience primarily through the performance and restoration of buildings, utilities, and transport networks. Conversely, socially-centered approaches, such as those advanced by Cutter et al. [68,69,72], prioritize networks of trust, governance, and equity as the foundation of resilience. These conceptual differences reveal contrasting assumptions about what enables communities to withstand and recover from disasters: the *physical systems* that support human life or the *social systems* that organize collective action. Further conceptual differences emerge when defining resilience versus vulnerability. Some scholars argue resilience is simply the inverse of vulnerability—that is by reducing exposure and sensitivity automatically builds resilience. Others contend the two are distinct yet overlapping concepts: communities can remain vulnerable while simultaneously demonstrating resilient capacities.

Clearly, our quantification of community resilience by monitoring a single metric—that is the mean square displacement (MSD) of the citizens of a given community within an urban center prior and upon a natural hazard strikes is not capable to satisfy all the aforementioned concepts of community resilience. Our framework of analysis serves the concept of *engineering resilience* and our single metric employed—that is the time history of the MSD is an *outcome*. Our MSD metric is incapable to capture issues such as vulnerability reduction, community empowerment or distributive justice which are related to socially-centered interpretations that prioritize governance, trust, and collective efficacy as foundational components of resilience (Cutter et al. [69]). For instance, while nighttime radiance data are employed in this study to corroborate widespread power outages; our analysis does not extend to how households coped with prolonged losses, how vulnerable groups were disproportionately affected, or how recovery processes may have reinforced pre-existing inequalities.

On the other hand, the mean-square displacement (MSD) of the citizens of a community is a system-wide metric that describes with fidelity the physical manifestation of the daily interactions of its citizens through their collective mobility patterns. In this way the concept of "engineering resilience" as defined by Holling [62,63] is served not only with the post-event functionality of the infrastructure networks of a city, but also with the persisting drive of the citizens to resume their daily activities regardless the partial loss of normality in their infrastructure networks. Accordingly, with our framework of analysis a vulnerable community may manifest resilience mainly because of the persisting drive of the citizens to resume their daily activities regardless the heavy damage in their community. By adopting the mean square displacement of the citizens from a community as the metric that quantifies community resilience, the loss recovery triangle happens at a much shorter time-scale during the duration of the natural hazard; rather, during the much longer time scales needed to attain functional recovery of specific infrastructure components [74–76].

In our analysis framework, natural hazards such as earthquakes, hurricanes, and winter storms that start and end abruptly are considered as "short-duration" societal stressors and the concept of *engineering resilience* is suitable as shown in this study. For other longer-duration societal stressors such as pandemics, regional wars and economic crises which are stressing cities during larger time scales along which the city may develop mechanisms to readjust, the definition associated with *ecological resilience* is more appropriate, since it emphasizes conditions far from equilibrium where instabilities can flip a system into another regime of behavior—that is, a different equilibrium state. In this case, resilience is associated with the magnitude of a disturbance (shock) that needs to be absorbed by the system before it changes its structure and stabilizes at a different equilibrium state.

3. Problem statement

Our past, system-wide studies for the entire urban center [34,51] examined: (1) the recorded mean-square displacement from three large US cities (Houston, Miami, and Jacksonville) when subjected to category 4 and 5 hurricanes (2017 Harvey, 2017 Irma, and 2019 Dorian), and (2) the response of the Dallas and Houston metroplexes that were subjected to the February 2021 North American winter storm; and revealed that the MSD of all the aforementioned cities when subjected

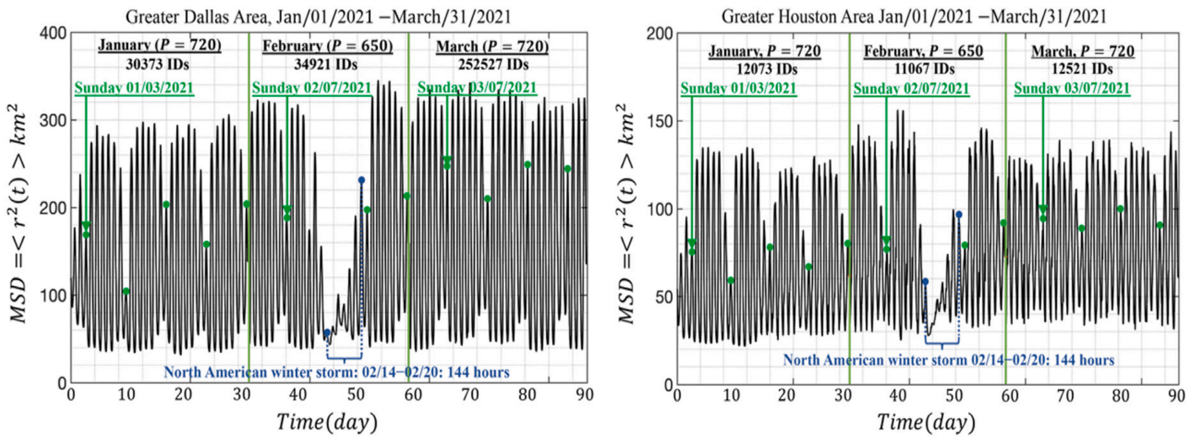

Fig. 1. Time history of the mean-square displacement $\langle r^2(t)\rangle$ (ensemble average) of cellphone IDs in the Dallas metroplex (left) and the city of Houston (right) during *Q1* of 2021. Green dots atop the suppressed spikes indicate Sundays.

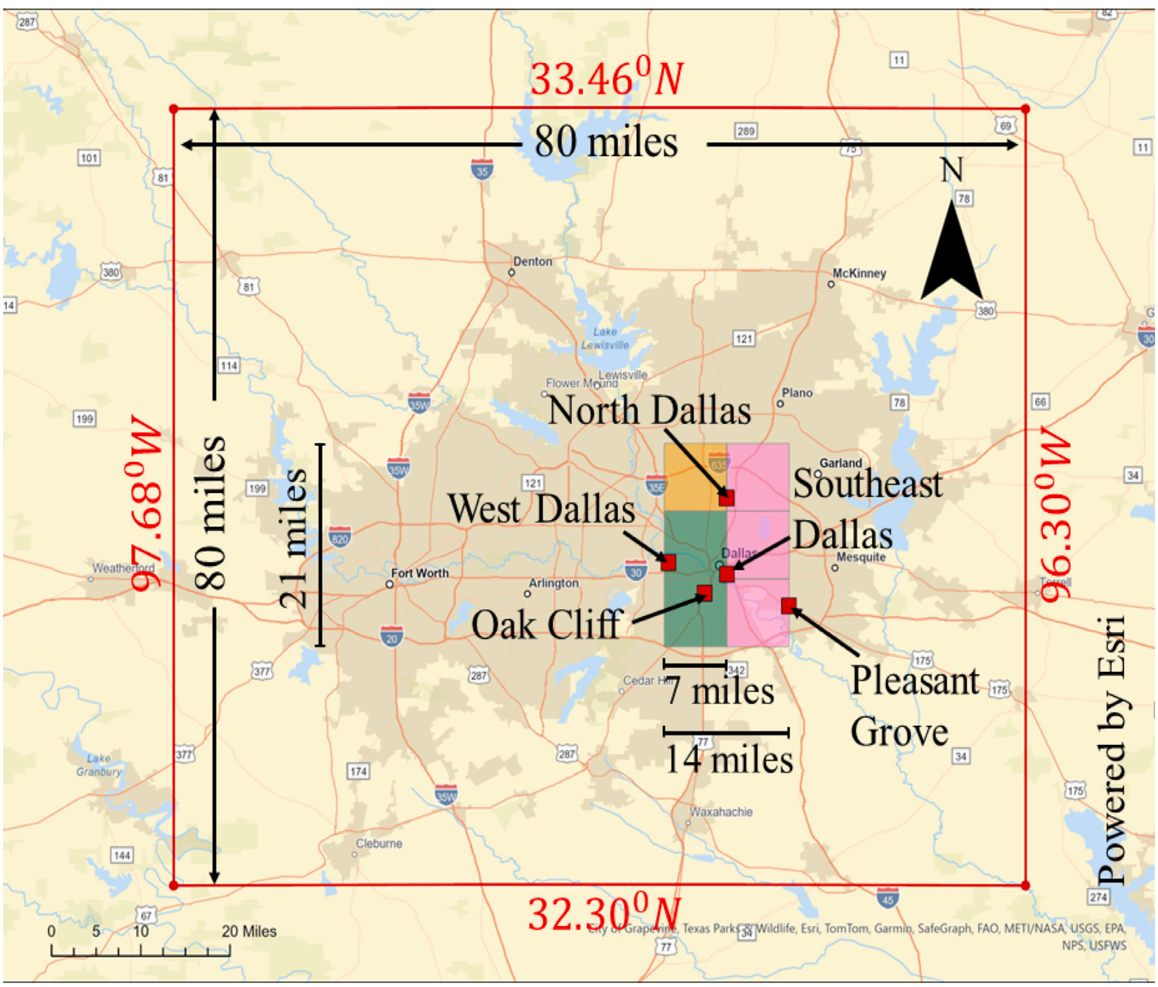

Fig. 2. Polygons that embrace local communities in the city of Dallas which according to reports suffered greater than the average damage during the 2021 North American winter storm [77–82].

to the corresponding violent natural hazard reverts immediately to its pre-event pattern upon the expiration of the duration of the natural hazard. Fig. 1 plots the mean-square displacement MSD = $\langle r^2(t)\rangle$ for the first quarter of 2021 of the city of Dallas (left) and the city of Houston (right).

Fig. 1 reveals that while the MSDs for the Dallas and Houston greater urban areas exhibit a stable daily and weekly periodicity, they exhibit a noticeable suppression during the duration of the North American winter storm. What is remarkable in Fig. 1 is that immediately after the expiration of the cold winter storm (sometime by Saturday, February 20, 2021) [89,90], both the city of Dallas and Houston resume normal activity with the MSD of its citizens to revert back to its normal oscillation pattern as recorded prior to the storm. This invariant, systematic ability of large American cities, following a natural hazard,

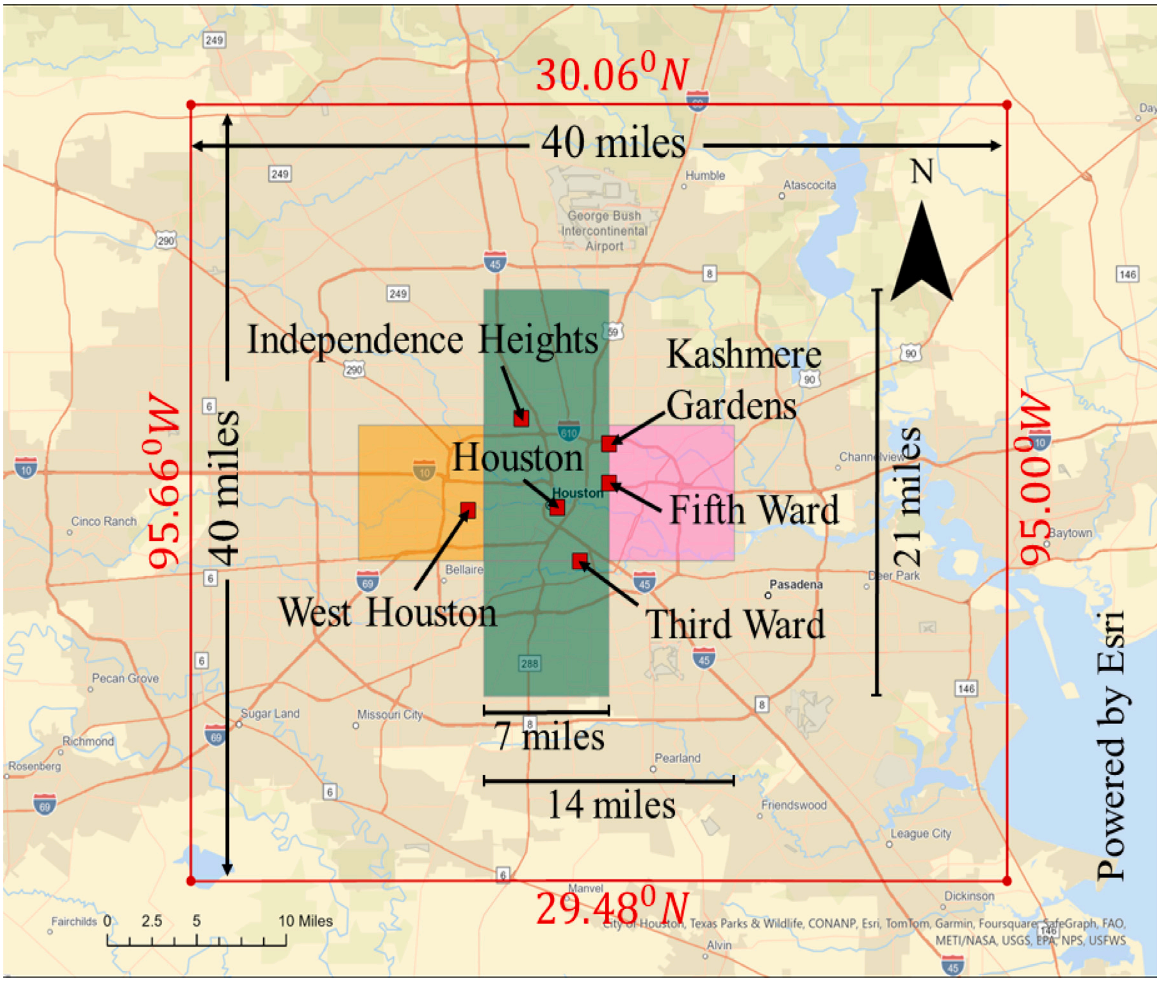

Fig. 3. Polygons that embrace local communities in the city of Houston which according to reports suffered greater than the average damage during the 2021 North American winter storm [80,83–88].

to revert immediately to their initial steady-state behavior and resume their normal, pre-event activities suggests that large American cities, at the system-wide scale, exhibit a higher degree of inherent resilience to natural hazards (see also [34]). While large urban areas may exhibit the aforementioned high degree of inherent resilience at the system-wide scale; some local communities within the large urban center may suffer heavier than the average damage which will challenge their local resilience and prolong their recovery times.

In this study, we identify from published reports and nighttime light emission data local communities in the cities of Dallas and Houston that suffered heavy damage from the 2021 winter storm; and extract their corresponding mean-square displacement (MSD) after distilling cell-phone users for which their home is within these communities of interest. As an example, Figs. 2 and 3 show polygons of communities/neighborhoods within the Dallas metroplex (Fig. 2) and the greater Houston area (Fig. 3) which reported heavy damage during the 2021 North American winter storm [77–88]. The recorded MSDs presented in this study reveals valuable information on the recovery time of these local communities suggesting that the living network of the citizens of a city is a very robust network that servers urban resilience.

4. The february 2021 north American winter storm

The North American winter storm happened during the 3rd week of February 2021 and ended sometime towards the end of that week before Sunday, February 21, 2021 [89,90]. Over 4 million people lost power due to the storm which resulted in a state-wide crisis in Texas causing major damage to the Texas power grid [91]. The communities shown in Fig. 2 that suffered higher-than-the-average damage are North and Southeast Dallas, West Dallas, Oak cliff and Pleasant Grove [77–82].

In particular, North Dallas was hard hit by the winter storm facing significant power outages and communication disruptions that led to failures. Additionally, challenges in communication avenues between public officials and electricity providers (e.g. ONCOR Electric Delivery) were reported by news and the media. The need to prioritize during the cold storm critical infrastructures such as hospitals further complicated and affected the power distribution and decision-making processes, taking into consideration that the area north of Interstate 30 had 75% more feeders (primary power distribution lines) than the southern service area and the majority of critical infrastructure was also located above Interstate 30 [77].

Similarly, the winter storm that hit Oak Cliff in February 2021 had an unexpected effect [78,79]. There was severe weather with extreme cold, heavy snowfall and prolonged power outages that resulted in a detrimental way to the community. Taking into consideration the increased demand on the electric grid, the Electric Reliability Council of Texas (ERCOT) initiated rolling power outages in the early hours on February 15. In Oak Cliff, more than 17,000 houses experienced outages that were lasting far longer than the expected duration, leaving people without heat in dangerously low temperatures [78]. In addition, these prolonged outages affected not only residential properties but also restricted infrastructure maintenance and emergency response activities. Ice accumulation on power lines and fallen trees

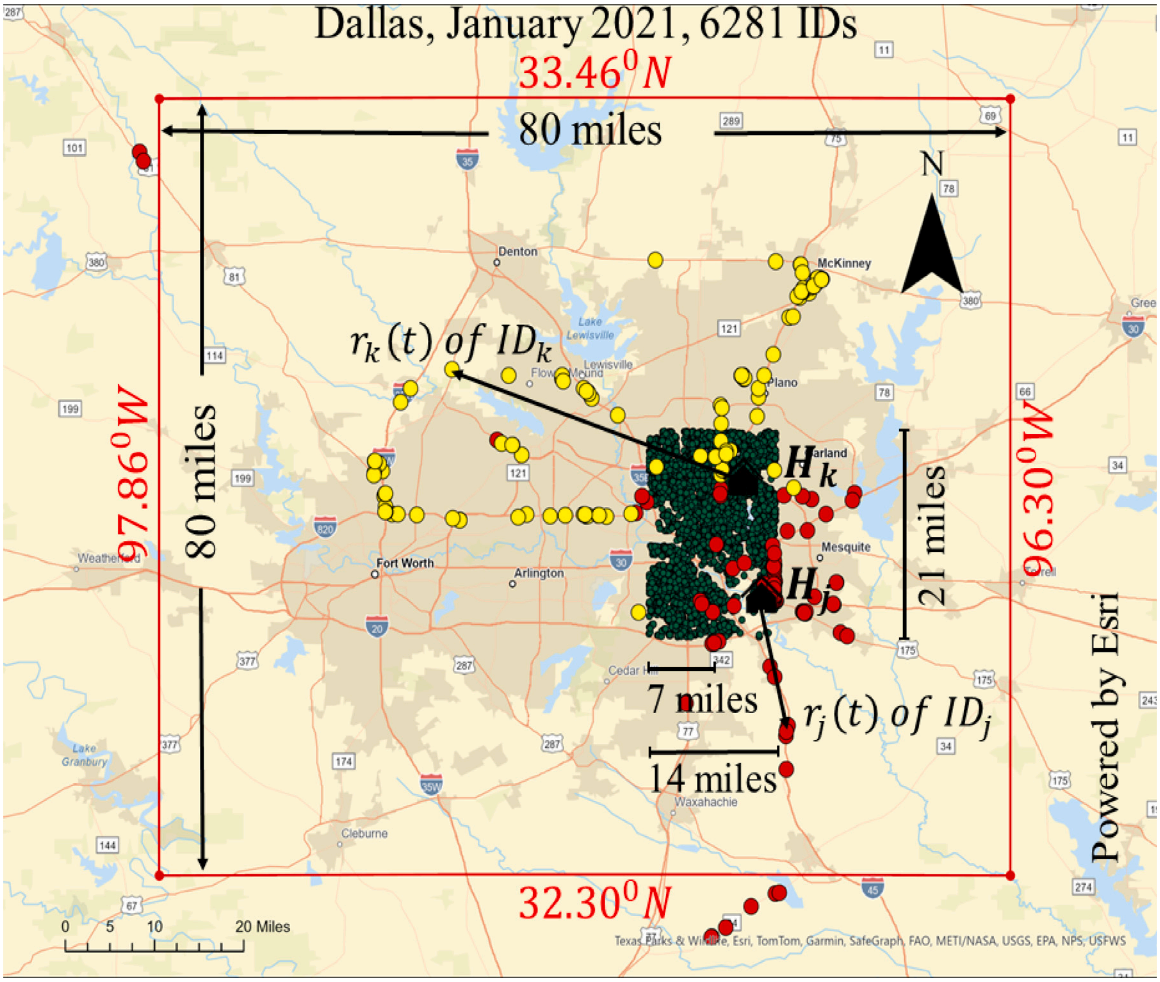

Fig. 4. GPS locations of the homes of anonymous cell-phone users (IDs) in the polygons of interest shown in Fig. 2 (green dots). Red and yellow dots show the GPS location traces of two distinct IDs (j and k) during the month of January 2021.

resulted in additional power outages. Highways and road conditions became dangerous because of the freezing conditions and snow precipitation, that affected negatively mobility transits and emergency response efforts [78,79].

During the North American winter storm of 2021, the Pleasant Grove community in Dallas faced significant difficulties [80]. The Pleasant Grove society as a whole which can be identified by a mixture of affluent and common modest dwellings, suffered from severe cold and multiple states power outages, leaving inhabitants in darkness and with restricted access to essential services. Numerous issues were made worse due to the older homes, many of which lacked proper insulation and the weaking aging infrastructure. The lack of reliable income from unprivileged social groups made difficult to cover basic necessities such as large utility bills and food expenses, accentuating an existing problematic situation. Access to transportation became a significant issue due to icy conditions. The prioritization of electricity by the providers to critical facilities and areas with hospitals left the community at a disadvantage. Furthermore, the residents of Pleasant Grove experienced an absence in communication, information and support during the storm [80].

Moreover, the north American winter storm which occurred in mid-February 2021 severely impacted West Dallas, especially in the 75212-zip code, where three-fourths of homes experienced power outages at some point. Additionally, the inconsistent power supply, combined with burst pipes caused extensive water damage in several apartment-complexes overseen by the Dallas House Authority (DHA) [81].

Going to Southeast Dallas' zip code 75217 and Fair Park, nearly one thousand (1000) customers experienced significant power outages together with an increased volume of emergency calls (e.g. fires, water shut-offs, etc.). Pipe breaks and burst pipes caused by freezing temperatures led to more substantial water damage throughout the community. Several historic buildings were affected and experienced substantial damage including the Hall of State, which recently underwent a 14 million renovation. The Tower building and Cotton Bowl were also suffered by water damage. The aftermath of the winter storm in Southeast Dallas area brought to the surface long term challenges related to home repairs, potential flooding, mold and toxic water. The storm caused significant damage to homes in the community leading to displacement for many residents [80,82].

In view of this heavy reported damage we have distilled cell-phone users from the three distinct rectangles showing in Fig. 2. The smaller orange rectangle includes mostly cell-phone IDs from North Dallas, the medium-size, green rectangle includes mostly cell-phone IDs from West Dallas and Oak Cliff; whereas, the large pink rectangle includes cell-phone IDs from Pleasant Grove and some IDs from North and Southeast Dallas.

Similarly to the city of Dallas, the city of Houston also faced significant challenges during the 2021 winter storm, with several communities experiencing severe disruptions. The communities shown in Fig. 3 that suffered higher-than-the-average damage are Independence Heights, Fifth and Third Ward, Kashmere Gardens, downtown Houston and West Houston [80,83–88].

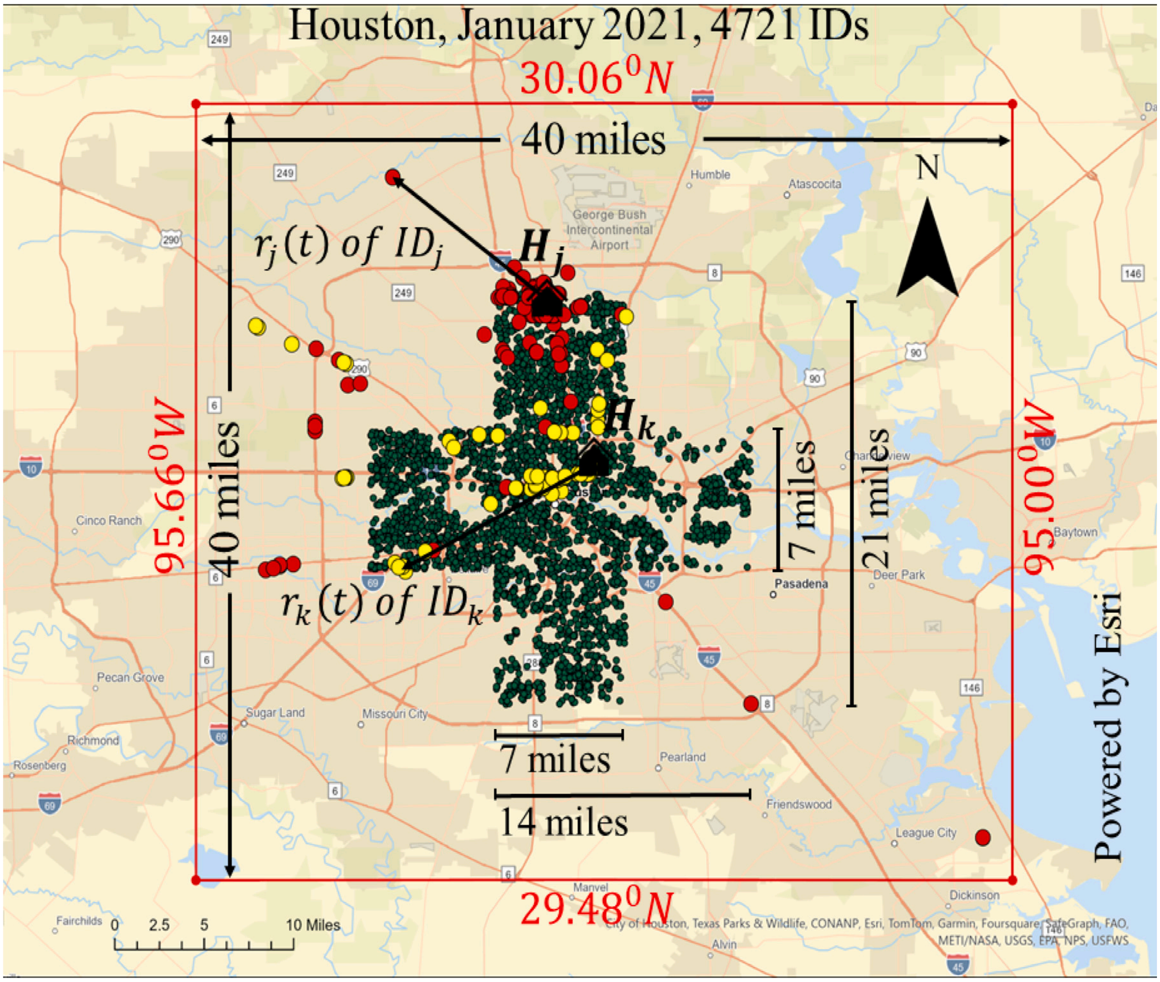

Fig. 5. GPS location of the homes of anonymous cell-phone users (IDs) in the polygon of interest shown in Fig. 3 (green dots). Red and yellow dots show the GPS location traces of two distinct IDs (*j* and *k*) during the month of January 2021.

Several vulnerabilities had become noticeable in Houston's downtown area caused by the crucial effects of the North American winter storm 2021. The cold storm brought widespread power outages that put in danger the health of individuals by disrupting and interfering with traffic signals, heating systems and elevators. Many incidents of residential, commercial and business buildings being damaged by burst water pipes, destroyed poor insulations and weak inadequate preparedness were reported. Also, there was a considerable impact disruption to mobility and transportation patterns. The absence of snow removal and de-icing procedures-methods on roads and highways created hazardous and risky situations, for both drivers and pedestrians. The emergency vehicles faced difficulties moving around on icy-slippery roads and for some instances made it almost impossible. Due to the aging infrastructure and limited resources, low income and vulnerable resident populations faced the greatest difficulties, giving emphasis to an already-existing inequality [83].

The aftermath of the North American winter storm 2021 in Houston's Third Ward urban area arose significant challenges revealing the community's infrastructure vulnerabilities. The storm caused extensive damage to pipes and plumbing systems, leaving many houses and apartments without water or with low/minimal water pressure. Lack of supplies also, made repairs more difficult for landlords, something that reflected by the period of time it took place to complete fixes and restorations. Emotional tolls had been at a high rate, with feelings of helplessness, neglect and abandonment being predominant [83,87].

The historically black suburb of Kashmere Gardens in Northeast Houston suffered to a great extent during the winter storm 2021. People's households were left without running water and electricity since power disruptions. Burst pipes and pipelines caused long water shortages. The lack of plumbing supplies and materials, the busy plumbing technicians and the realization that so many homes were already dealing with damage from earlier natural disasters like Hurricane Harvey had made the whole situation worse. Many Houston communities, notably Kashmere Gardens, were still dealing with the aftermath of the ice storm long after the phenomenon had passed. While disadvantaged groups struggled to get necessities such as food, water, and shelter, the storm additionally revealed structural injustices and inequality [84,88].

The impact of the winter storm in Independence Heights, a historically black community of Houston was also devastating. Residents faced disparities in access to generators and hotel rooms. Older homes with poor insulation, leaking roofs and outdated pipes made the community less resilient to extreme weather conditions. Food supply chains broke down during the storm affecting the neighborhoods without grocery stores and pharmacies. Combining the above with structural vulnerabilities drove the community to suffer more. Out-of-the-norm energy bills, lack of insulation and difficulty in accessing essential resources combined with the lack of communication were exacerbating the crisis [80].

The winter storm of 2021 had a significant impact on Houston's Fifth Ward community, exposing social injustices, infrastructure weaknesses, and challenges with disaster response. The prolonged blackout that affected the residents brought out emphasis to how vulnerable the electrical grid is. Moreover: the lack of preparedness and winterization

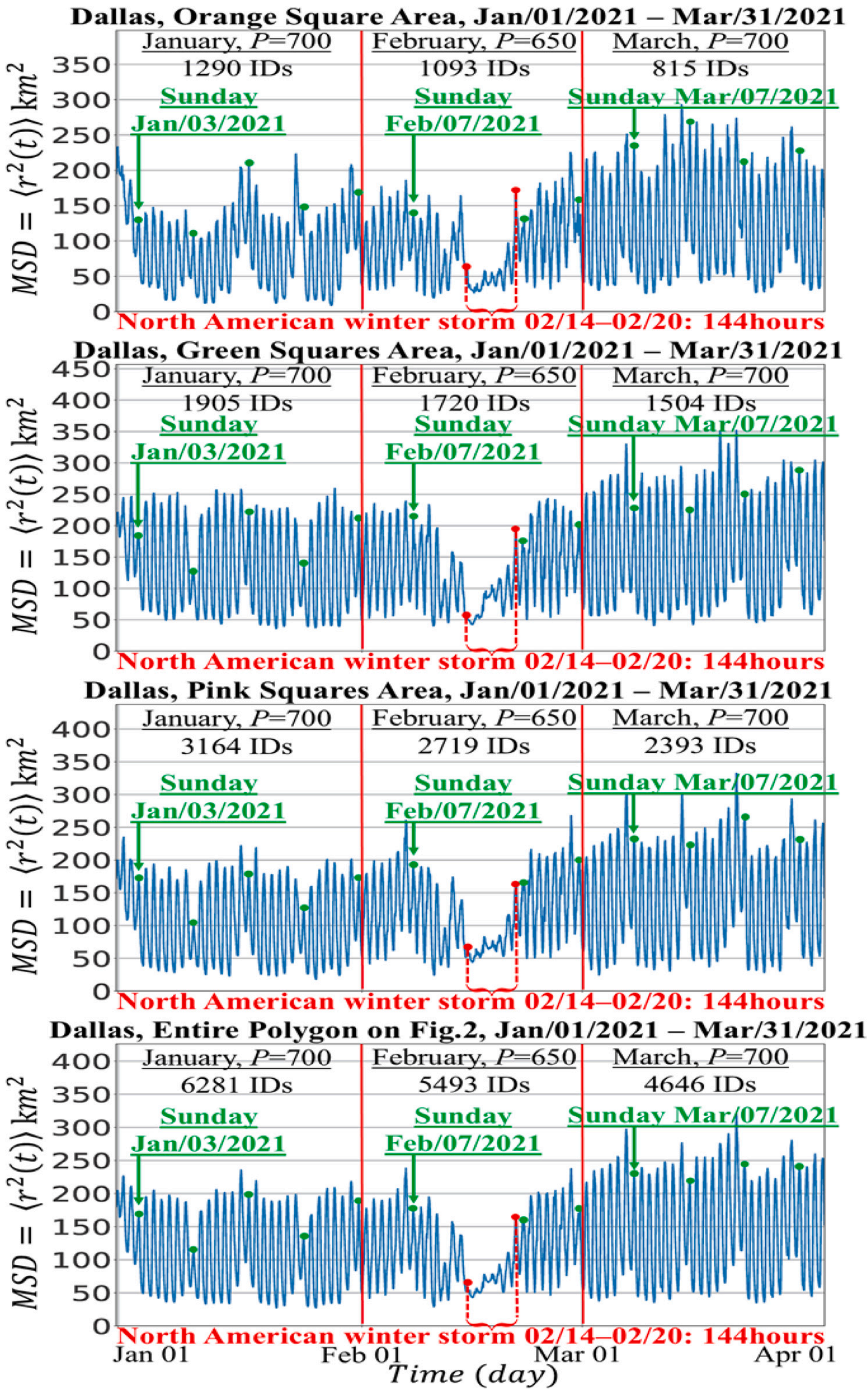

Fig. 6. Time histories of the mean-square displacement $\langle r^2(t) \rangle$ (ensemble average) of cell-phone IDs that their homes belong in the orange rectangle shown in Fig. 2 (top), green rectangle (second from top), pink rectangle (third from top), and in all three rectangles shown in Fig. 2 (bottom).

of the power infrastructure contributed to the widespread outages. The storm disrupted the water supply, leaving residents without access to clean water due to burst pipes and contamination concerns. Icy conditions disrupted transportation access to essential services and contributed to an overall decline in community's performance. Infrastructure strain was obvious with aging infrastructure, burst water pipes due to freezing and ill-equipped infrastructure. Lack of immediate response: despite the lifting of the boil water advisory in some areas of Houston, parts of the Fifth Ward still struggled to regain access to clean water [85,87].

West Houston residents, especially those in apartments complexes like 3030 Elmside, 2901 Elmside and 10550 Valley Forge, came across

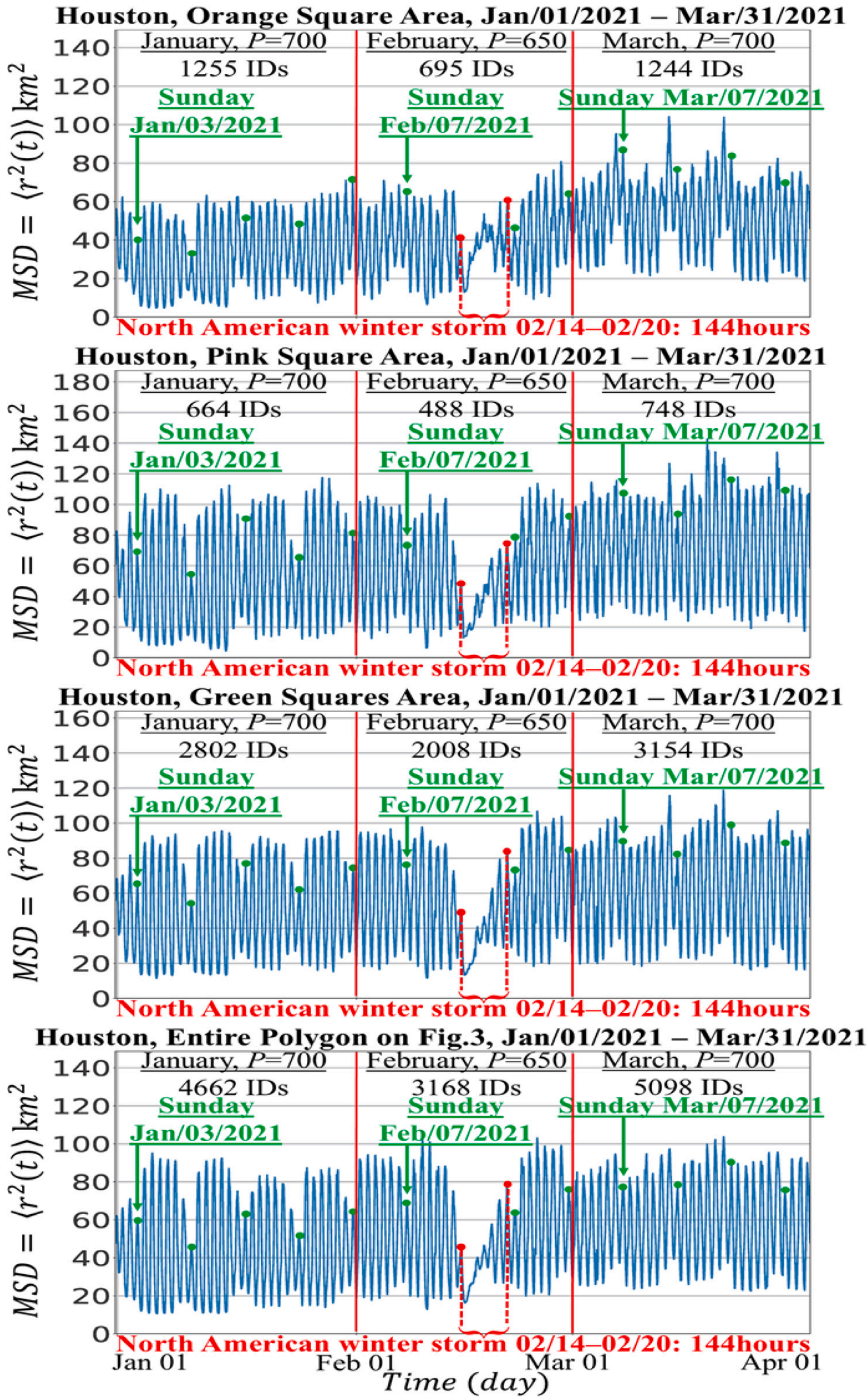

Fig. 7. Time histories of the mean-square displacement $\langle r^2(t)\rangle$ (ensemble average) of cell-phone IDs that their homes belong in the orange rectangle shown in Fig. 3 (top), pink rectangle (second from top), green rectangles (third from top), and in all three rectangles shown in Fig. 3 (bottom).

severe difficulties during the winter storm in 2021. Many apartment buildings experienced prolonged power outages due to the electricity grid breakdown, leaving inhabitants to suffer below-freezing temperatures without electricity or heating. Moreover, beyond the additional losses to the infrastructure, the breakdown of pipes led to serious water shortages that extended for several weeks.. The inhabitants were driven to adopt unusual methods, such as collecting water from commercial containers, in order to fulfill their basic demands. Following the storm, which uncovered West Houston's infrastructure weaknesses along with the need for significant preparation plans to withstand such emergencies like that, authorities and community organizations activated quickly to restore services. Some of the measures put in place included temporary facilities and washing stations [86].

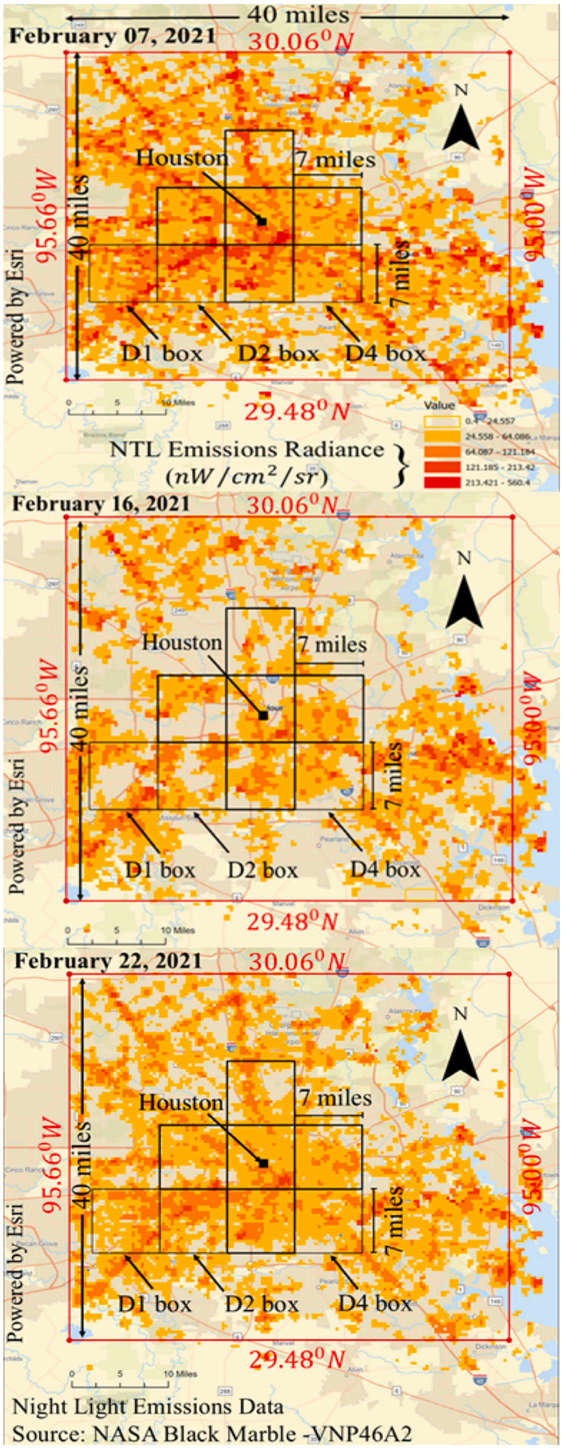

Fig. 8. Nighttime light emission (radiance) data recorded with the National Polar-orbiting Partnership (NPP) satellite prior (top), during (center) and upon (bottom) the 2021 winter storm struck the city of Houston. [92–96].

In view of the heavy damage reported for the aforementioned communities of Houston we have distilled cell-phone IDs from the three distinct rectangles showing in Fig. 3. The orange rectangle includes cell-phone IDs from West Houston, the larger green rectangle includes cell-phone IDs from Independence Heights, downtown Houston and Third Ward; whereas the pink rectangle on the right includes mostly cell-phone IDs from Kashmere Gardens and Fifth Ward.

5. MSD from GPS location data of cell-phone users (IDs)

Fig. 4 shows with green dots the home-locations of 6281 IDs which belong to the polygons of interest shown in Fig. 2 that include the communities West Dallas, Oak Cliff, North and Southeast Dallas and Pleasant Grove which have been distilled so that they exhibit at least 700 appearances at the top of the hour during the month of January 2021 [34,35]. The red dots appearing in Fig. 4 show the GPS location trace of a single ID$_j$ during the month of January 2021, whereas the yellow dots show the GPS location trace of another ID$_k$ during the same period. The distance $r_j(t)$ shown in Fig. 4 is the distance of ID$_j$ from its home H_j at time t. Similarly, the distance $r_k(t)$ is the distance of ID$_k$ from its home H_k at time t. The origin of every ID$_j$ (home H_j) was identified by extracting the most frequent location occupied by ID$_j$ during the time interval from 1:00 AM to 4:00 AM.

Fig. 5 shows with green dots the home-locations of 4721 IDs which belong to the polygons of interest shown in Fig. 3 that include the communities of Independence Heights, Fifth and Third Ward, Kashmere Gardens, West and Downtown Houston which have been distilled so that they exhibit at least 700 appearances at the top of the hour during the month of January 2021 [34,35]. The red dots appearing in Fig. 5 show the GPS location trace of a single ID$_j$ during the month of January 2021, whereas the yellow dots show the GPS location trace of another ID$_k$ during the same period. The distance $r_j(t)$ shown in Fig. 5 is the distance of ID$_j$ from its home H_j at time t. Similarly, the distance $r_k(t)$ is the distance of ID$_k$ from its home H_k at time t. The origin of every ID$_j$ (home H_j) was identified by extracting the most frequent location occupied by ID$_j$ during the time interval from 1:00 AM to 4:00 AM. While the trace of the locations of each individual cell-phone ID shown in Figs. 4 and 5 is unique and every individual has a distinct purpose for generating the recorded trace, the collection of all traces of the anonymous cell-phone users in a given community is treated in this work as a random (stochastic) process. For each of the communities examined in this work we processed longitude and latitude data (in degrees from the Greenwich meridian and from the equator), [51] at various times for tens of thousands of anonymous cell-phone users (IDs).

Fig. 6 plots the time histories of the mean-square displacement MSD = $\langle r^2(t)\rangle$

$$\langle r^2(t)\rangle = \frac{1}{M}\sum_{j=1}^{M} r_j^2(t) = \frac{1}{M}\sum_{j=1}^{M}(x_j^2(t) + y_j^2(t)), \tag{1}$$

of the IDs that their home is located in each of the three rectangles shown in Fig. 2. The top MSD in Fig. 6 is computed by tracing IDs that their home is only in the orange rectangle which includes IDs mostly from North Dallas. The second MSD from the top is computed by tracing only IDs that their home is in the green rectangle in Fig. 2 which includes IDs mostly from West Dallas and Oak Cliff; whereas, the third MSD from the top is computed by tracing IDs that their home is in the pink rectangle which includes IDs mostly from Southeast Dallas and Pleasant Grove. The bottom MSD in Fig. 6 is computed by tracing IDs that their home belongs in the entire polygon shown in Fig. 2—that is the combined orange, green and pink rectangles.

Fig. 6 reveals that the computed MSDs at the community scale from the Dallas communities shown in Fig. 2 exhibit the same daily and weekly periodicity that emerges from the entire Dallas Metroplex shown in Fig. 1 left. All 4 computed MSDs plotted in Fig. 6 show a noticeable suppression during the duration of the North American winter storm which immediately after the expiration of the cold winter storm [sometime by Saturday], February 20, 2021 [89,90] all four MSDs, indicate that in terms of an ensemble average, each of the communities examined resume normal activity with the MSD of its citizens to revert back to its normal oscillation pattern as recorded before the winter storm. This remarkable, immediate recovery observed in all four MSDs plotted in Fig. 6 suggests that even at the community

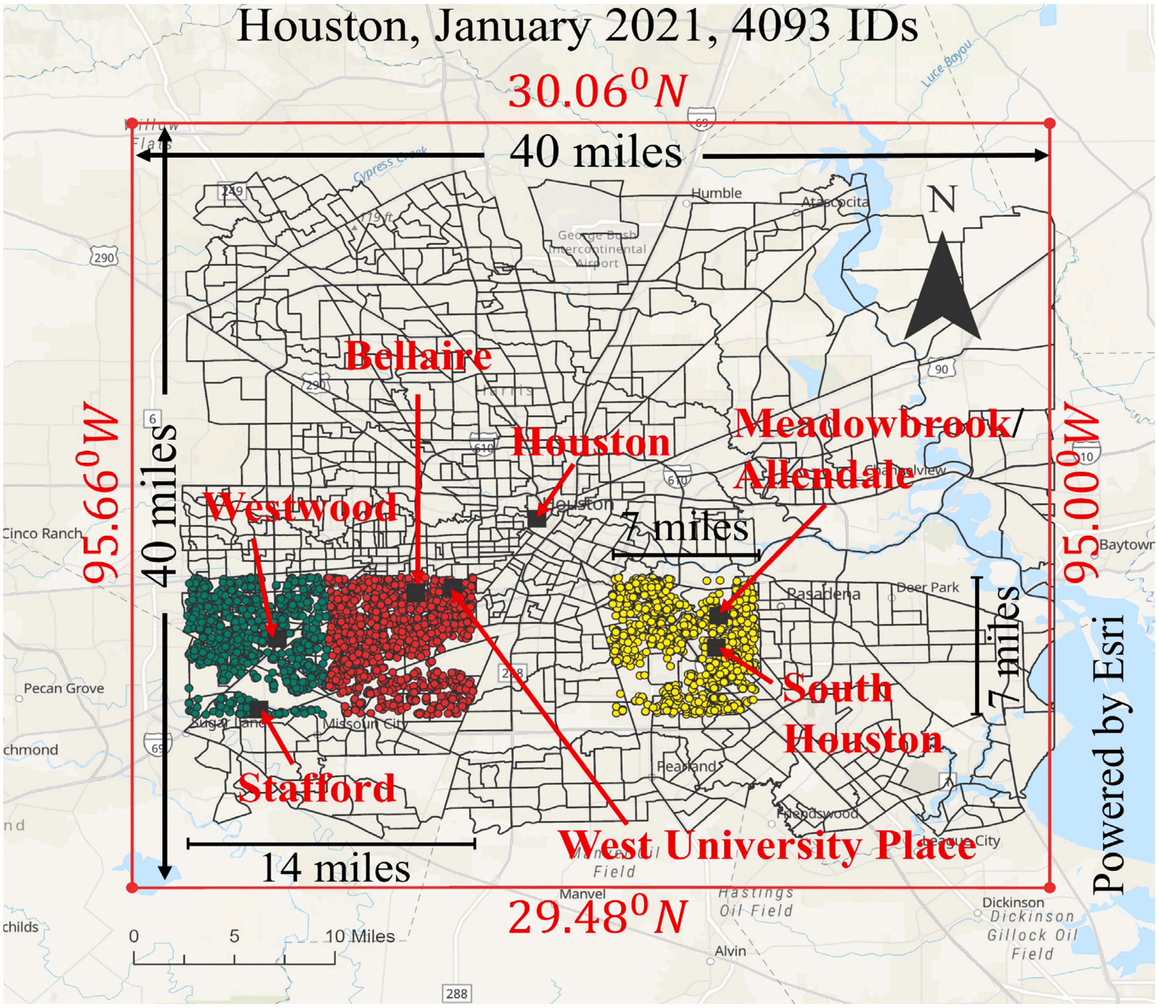

Fig. 9. GPS location of the homes of anonymous cell-phone users (IDs) in the squares D1 (green dots), D2 (red dots), D4 (yellow dots) during the month of January 2021.

scale the urban fabric exhibits a great degree of engineering resilience as defined by Holling [63].

Similarly, Fig. 7 plots the time-histories of the mean-square displacement MSD = $\langle r^2(t)\rangle$ given by Eq. (1) of the IDs whose home is located in each of the three rectangles shown in Fig. 3. The top MSD in Fig. 7 is computed by tracing IDs that their home is only in the orange rectangle which includes IDs mostly from West Houston. The second MSD from the top is computed by tracing IDs that their home is only in the pink rectangle which includes IDs mostly from Kashmere Gardens and Fifth Ward; whereas, the third MSD from the top is computed by tracing IDs that their home is in the green rectangle which includes IDs mostly from Independence Heights and Third Ward. The bottom MSD in Fig. 7 is computed by tracing IDs that their home belongs in the entire polygon shown in Fig. 3—that is the combined orange, green and pink rectangles. Fig. 7 brings forward the same trends of inherent community resilience described when discussed the MSDs shown in Fig. 6.

6. Evidence of the power outages in houston from radiance data collected from NASA

While the severe vulnerabilities reported in Refs. [83–87] for the communities in Houston shown in Fig. 3 go beyond power outages and include burst of water piping and disruption in the transportation system due to lack of snow removal and deicing; night time emission data may offer visual information on the extend of power outages.

Radiance data capture nighttime light emissions and originate from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument aboard the National Polar-orbiting Partnership (NPP) NASA satellite [92–96]. The VIIRS ensures high-quality, cloud-corrected measurements suitable for comparing changes in light emission patterns in cities. The available dataset has a moderate spatial resolution so that each pixel represents 500 m x 500 m (1/4 km^2) on the ground. This resolution appears to be sufficient for identifying general radiance patterns across cities prior, during and upon the natural hazard strikes.

As an example, Fig. 8 shows radiance data (nighttime light emissions) from the greater Houston area prior (Fig. 8 top on February 07, 2021), during (Fig. 8 center on February 16, 2021) and after (Fig. 8 bottom on February 22, 2021) the February 2021 North American Winter Storm. The classification of radiance intensity values is divided into five different levels, as indicated by the legend shown in Fig. 8. These levels represent different intensities of nighttime light emissions, with the first class being considered as the average radiance level over the analyzed period. For our analysis, greater emphasis was placed on the higher radiance levels to identify areas potentially experiencing greater-than-average power outages.

Fig. 8 reveals that during the winter storm large fractions of the polygons shown in Fig. 3 manifest an appreciable suppression in the nighttime light emission — an observation that is in agreement with

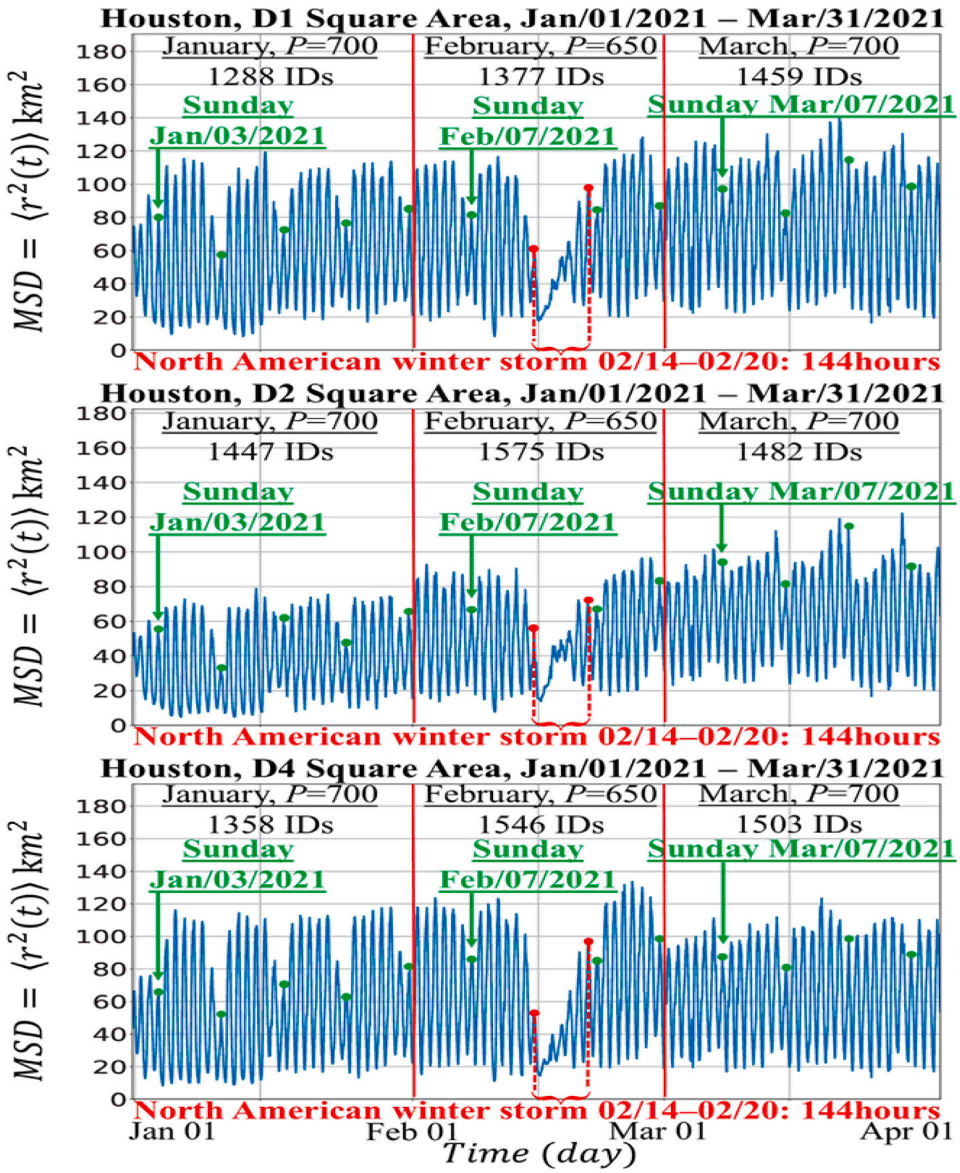

Fig. 10. Time histories of the mean-square displacement $\langle r^2(t)\rangle$ (ensemble average) of cell-phone IDs that their homes belong in the square D1 (green dots) shown in Fig. 9 (top), square D2 (red dots) shown in Fig. 9 (second from the top), square D4 (yellow dots) shown in Fig. 9 (bottom).

the widespread power outages reported in Refs. [83–87]. Nevertheless, there are other areas within the greater Houston area that experience comparable suppression of the night- time light emission (such as the boxes D1 and D2) as the communities within the polygon shown in Fig. 3. On the other hand Fig. 8 reveals that the suppression of the nighttime light emission in box D4 during the February 2021 winter storm is not as drastic. Fig. 9 shows with green dots the home locations of 1288 IDs during January 2021 which belong to the square D1, with red dots the home locations of 1447 IDs during January 2021 which belong to the square D2, and with yellow dots the home locations of 1358 IDs during January 2021 that belong to the square D4.

Fig. 10 plots the time-histories of the mean square displacement MSD = $\langle r^2(t)\rangle$ given by Eq. (1) of the IDs whose home is located in each of the three squares, D1, D2 and D4 shown in Fig. 9. The top MSD in Fig. 10 (top) is computed by tracing IDs that their home is only in square D1 which includes IDs from the Westwood and Stafford communities. The second MSD from the top is computed by tracing IDs that their home is only in square D2 which includes IDs from the West University Place and Bellaire communities, whereas the third MSD from the top is computed by tracing IDs that their home is in square D4 which includes IDs from the South Houston and Meadowbrook/Allendale communities. Similarly to results offered by Fig. 6 and Fig. 7, Fig. 10 reveals invariably the same trends where the MSD of the IDs from these communities reverts back to the pre-event regime immediately after the expiration of the winter storm.

7. Conclusions

This paper, which is part of a wider study on the quantification of urban resilience to natural hazards, focuses on quantifying the resilience of local communities which according to reports have experienced heavy damage. Our study focuses on communities from the Dallas metroplex and the greater Houston urban area which suffered heavy reported damage during the February 2021 winter storm. We only distilled cell-phone IDs that their homes are in the identified communities of interest and we trace the path of these IDs on the greater urban center prior, during and after the North American Winter Storm struck. All computed mean-square displacements (MSD) of the citizens from these communities show invariably a noticeable suppression during the duration of the storm; yet, immediately after the expiration of the cold storm; all community MSDs from the cities of Dallas and Houston indicate that in terms of an ensemble average (MSD), each of the communities examined reverted back to the pre-storm response almost immediately; suggesting an inherent community resilience to the winter storm. Accordingly, this paper confirms our previous findings on the urban scale; that even at the community scale, the urban fabric of large American cities of medium-to-high population density exhibits a great degree of engineering resilience.

CRediT authorship contribution statement

Georgios Chatzikyriakidis: Validation, Software, Investigation, Data curation. **Nicos Makris:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Tue Vu:** Validation, Software, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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