Novel Statistical–Simulation Approach to Promote Health Informed Heat Mitigation Strategies

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Summary

The impact of applying urban heat mitigation strategies was monitored on outdoor thermal comfort and community health records. A novel approach was followed by integrating microclimate simulations and statistical modeling to predict environmental and health responses promoting an efficient method to develop urban policies and plans. The application included increasing urban greenery and albedo within a neighborhood in the York Region, Ontario, Canada. The results ensured the heat mitigation benefits to outdoor thermal comfort during extreme heat conditions. The proposed approach was able to forecast the impact on community health related to all-cause mortalities.

1. Introduction

Climate change, Urban Heat Island (UHI), and heat wave events lead to excessive heat stress for urban microclimates and increase heat-related mortality[1]. Meanwhile, the consequences of the UHI and the frequency and duration of the heat waves around the world are becoming more evident[2]. The characteristics of heat waves are defined regionally according to the local climatic conditions. According to Health Canada reports for Southern Ontario (Greater Toronto Area, GTA), a heatwave occurs when the daytime maximum temperature exceeds 31˚C and the night-time minimum temperature exceeds 20˚C for at least 2 consecutive days. Health Canada also reports a heat wave if the local outdoor heat stress index (temperature-humidity index, *humidex*) reaches 40 or more for at least 2 consecutive days. In the last 20 years, 60 heat warnings and 37 extended heat warnings were issued for the GTA region[3]. Simultaneously, severe health impacts were argued due to the expected increase in heat wave intensity in the future[4]. The Canadian Environment Health Atlas (CEHA) and the Toronto Public Health Department estimated that 120 people die in the GTA annually because of high temperatures. The predictions

[1] Lee et al., "Acclimatization across Space and Time in the Effects of Temperature on Mortality"; Jandaghian and Akbari, "The Effects of Increasing Surface Reflectivity on Heat-Related Mortality in Greater Montreal Area, Canada,".
[2] U. Berardi, "A Cross-Country Comparison of the Building Energy Consumptions and Their Trends"; M. Santamouris, "Recent Progress on Urban Overheating and Heat Island Research"; Paravantis et al., "Mortality Associated with High Ambient Temperatures, Heatwaves, and the Urban Heat Island in Athens, Greece".
[3] "Heat Warning Statistics Archive" City of Toronto.
[4] Fischer and Schär, "Consistent Geographical Patterns of Changes in High-Impact European Heatwaves"

indicate that heat-related mortality will be doubled by 2050[5]. Significant correlations were reported between heat-related mortalities and extreme heat events[6]. Some researchers in North America reported strong causality for daily mortality due to exposure to excessive heat[7]. Also, several studies reported the short-term impact of heat exposure on health records[8]. Rainham and Smoyer-Tomic[9] confirmed a significant association between elderly mortality and extremely hot conditions in the City of Toronto. Berko et al.[10] reported that around 31% of the weather-related mortalities in various US regions were related to exposure to excessive heat. Some studies reported significant correlations between heat waves and the average daily records of all-cause mortalities[11]. Tsekeri et al.[12] confirmed the impact of heat on daily and one-day lagged mortality records. Paravantis et al.[13] proved that the short-term (0 to 1-day lag) effect of heat events on elderly mortality was greater than investigated long-term impacts (up to 12 days).

Furthermore, upgrading the green infrastructure and urban surface albedo was proved to influence the outdoor environmental parameters[14]. The cooling effect of intensifying the greenery cover is associated with blocking solar radiation and the evapotranspiration of vegetation coverage. While increasing the albedo is related to increasing the urban surface reflectivity to solar radiation. Most of the previous applications aimed to promote urban cooling and improve the urban microclimate thermal conditions. However, some studies detected the warming effect of the increased urban greenery cover due to the increased humidity content of the ambient air[15]. Accordingly, further investigations on monitoring and predicting the effect of intensifying the urban greenery cover on urban health and comfort were required.

This paper aims to define the impact of integrating urban greenery and albedo enhancements on urban thermal behavior and community health responses. It also investigates the correlation between outdoor thermal comfort and mortality records. The analysis was designed to evaluate the behavior of integrated urban heat mitigation

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5 Pengelly et al., "Anatomy of Heat Waves and Mortality in Toronto"

6 Azhar et al., "Heat-Related Mortality in India"; Tsekeri, Kolokotsa, and Santamouris, "On the Association of Ambient Temperature and Elderly Mortality in a Mediterranean Island - Crete".

7 Berko et al., "Deaths Attributed to Heat, Cold, and Other Weather Events in the United States, 2006-2010"; Harlan et al., "Heat-Related Deaths in Hot Cities"

8 Basu, Dominici, and Samet, "Temperature and Mortality among the Elderly in the United States"; D'Ippoliti et al., "The Impact of Heat Waves on Mortality in 9 European Cities"; Hajat et al., "Impact of High Temperatures on Mortality".

9 Rainham and Smoyer-Tomic, "The Role of Air Pollution in the Relationship between a Heat Stress Index and Human Mortality in Toronto"

10 Berko et al., "Deaths Attributed to Heat, Cold, and Other Weather Events in the United States, 2006-2010"

11 Azhar et al., "Heat-Related Mortality in India"; Harlan et al., "Heat-Related Deaths in Hot Cities."

12 Tsekeri, Kolokotsa, and Santamouris, "On the Association of Ambient Temperature and Elderly Mortality in a Mediterranean Island - Crete."

13 Paravantis et al., "Mortality Associated with High Ambient Temperatures, Heatwaves, and the Urban Heat Island in Athens, Greece," *Sustainability* 9, no. 4 (2017): 1–22.

14 Berardi, Jandaghian, and Graham, "Effects of Greenery Enhancements for the Resilience to Heat Waves"; Jandaghian and Berardi, "Analysis of the Cooling Effects of Higher Albedo Surfaces during Heat Waves Coupling the Weather Research and Forecasting Model with Building Energy Models" .

15 Santamouris and Osmond, "Increasing Green Infrastructure in Cities"; Wang, Berardi, and Akbari, "Comparing the Effects of Urban Heat Island Mitigation Strategies for Toronto, Canada".

strategies on a neighborhood scale. This research aims to provide stakeholders and policymakers with a novel method to develop urban upgrading plans that consider community health and comfort.

2. Methodology

This paper presents a novel integrated framework by combining the statistical approach with the microclimate simulations to investigate the impact of promoting urban heat mitigation strategies on the urban microclimate and heat-related community health responses. The proposed heat mitigation strategies include increasing the urban greenery cover and surface albedo. Microclimate simulations were developed using a validated version of the Urban Weather Generator (UWG)[16] to predict outdoor heat stress. Then, a statistical approach was developed by integrating data on meteorological measures with population health records to determine the impact of the changes in ambient conditions on community health. This approach monitors the data behavior in a certain temporal and spatial domain to predict the anticipated health response.
The meteorological measures and health records were monitored during a heat event in the York Region as a representation of a typical micro-urban typology in the GTA, Ontario, Canada. The statistical model deployed a log-linear regression using a Poisson probability distribution over a historical dataset using records of daily all-cause mortality counts and meteorological parameters. Thus, the proposed statistical approach delivers an evidence-based correlation to predict the community health responses based on the local environmental measures. The findings can be utilized by stakeholders and policymakers to develop local and regional policies to improve the urban microclimate for the inhabitants.

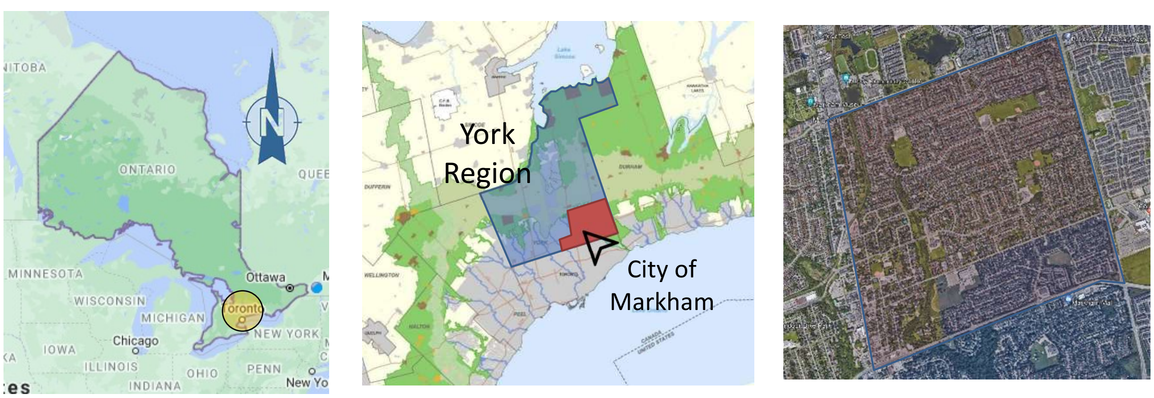

Figure 1 – Province of Ontario (left), York region in the context of the Ontario Greenbelt (Center), and the residential neighborhood in the city of Markham used in the simulation (right).

The proposed application was conducted in a residential neighborhood in the York Region that represents typical residential neighborhoods in the GTA. Specifically, the simulation was conducted over a residential neighborhood with an area of 4.19 km^2 in the city of Markham, as shown in Figure 1. While this study is concerned with the community responses during heat events, an extended weather scenario of 2 weeks (from June 18 to July 2) covering an extreme heat event was utilized as a simulation period. This scenario was developed by Environment and Climate Change Canada

[16] Dardir and Berardi, "Development of Microclimate Modeling for Enhancing Neighborhood Thermal Performance through Urban Greenery Cover".

(ECCC) as an expected weather scenario for southern Ontario in 2030. The meteorology forecast includes days with a maximum ambient temperature of 39 °C and an average ambient temperature of 27.7 °C. It also predicts the humidex with a maximum value of 54 and an average value of 33.9. Accordingly, the study monitored the humidex to represent the environmental changes. The outdoor heat stress index is a better representation than the ambient temperature of human responses toward heat behavior in the urban environment.

The statistical approach intends to build a historical dataset for the studied community. The dataset contains health data and weather parameters for the York Region for 17 years (from 2003 to 2019). The daily records of health and weather data were obtained from Statistics Canada and Environment Canada, respectively. This study focuses only on warm and hot seasons, which extend from May to September each year. The weather data were obtained from the Toronto Buttonville Airport weather station (43.86N -79.37W), which is located 10 km away from the study location. The health records were retrieved from the Research Data Centers (RDCs) using the Statistics Canada microdata of the Canadian Vital Statistics - Death Database (CVSD) for mortality counts. The dataset was built on a daily temporal scale for the humidex and the all-cause mortality considering the lagged impact of heat events on the health responses. The developed method utilized a correlational statistical approach by conducting a log-linear regression analysis among variables following a Poisson distribution. The daily counts for mortalities were included in the dataset as one observation daily. In total, 24,145 mortalities (cases) in 2600 days (observations) were included in the dataset. The descriptive statistics of the dataset revealed an average daily all-cause mortalities of 9.28 with a standard deviation of 3.45. It also showed an average daily humidex of 21.1 with a 95% percentile of 31.8. Figure 2a shows the progression of all-cause mortalities over the years of investigation. The increase in daily mortalities in the last years is mainly associated with the population increase in York Region by 50% in 20 years (from 2002 to 2021). However, the mortalities during hot seasons recorded an elevated increase of 69% in a shorter period. Referring to the relationship to the hot conditions, Figure 2b shows the evolution of mortalities regarding the humidex value.

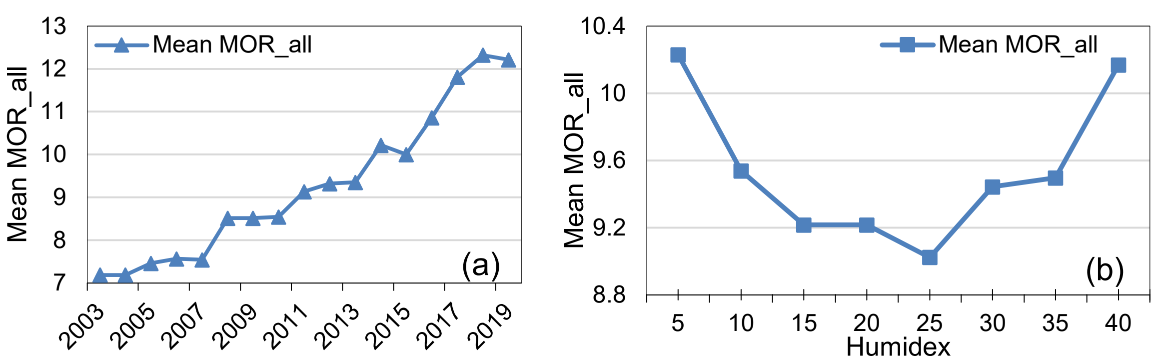

Figure 2 – Average daily all-cause mortalities in association with (a) time and (b) humidex

It is noticed that higher mortalities are associated with higher humidex values during extreme heat conditions (humidex ~ 40). However, with low humidex values, the mortalities reported another peak which refers to other possible effects of environmental changes that could impact the mortality rates. Other environmental risks like flooding and storms that can be associated with low humidex values could contribute to high mortality rates.

3. Microclimate Simulations

The simulation approach was developed utilizing an updated version of the open-source code of UWG[17] to assess the combined effect of increasing the urban greenery cover and the urban albedo on the outdoor heat index. Detailed descriptions of the updated model components, theoretical approaches, and model validation procedures are published in Dardir and Berardi[18]. The updated version promotes better prediction of the evaporative cooling effect, more realistic shading behavior, further adaptability to urban surface variety, redefining the latent component of the air node, and defining new urban components. The UWG model was used to assess the heat mitigation scenarios associated with the urban green infrastructure and surfaces albedo. The simulation considers the reference performance (the existing condition) and the maximum performance (maximum allowable tree canopy, vegetation cover, and albedo). The maximum possible increase in greenery cover was provided by York Region based on land budget analyses, while the current and enhanced albedo values were proposed based on previous studies[19]. The associated values of reference and maximum allowable parameters and associated humidex values are shown in Table 1.

Table 1 – Simulation values and humidex for reference and maximum allowable parameters

Parameter	Greenery Cover		Albedo	Total Heat Mitigation
	Vegetation cover	Tree canopy		
Reference value	30%	44%	20%	
Average humidex	*31.8*			
Maximum allowable value	55%	57%	60%	
Average humidex	*29.9*		*31.9*	*29.7*

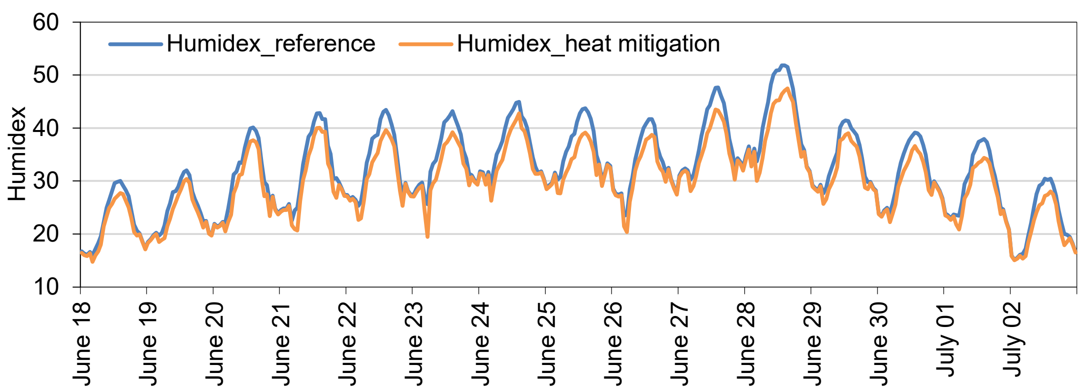

Figure 3 – Difference in humidex behavior when applying the heat mitigation scenario

The average humidex value was calculated for all various applications. For the reference case, the average humidex recorded 31.8 with a maximum value of 51.9 during the heat wave peak. Enriching the urban greenery cover to the allowable limit reduced the average humidex to 29.9 while increasing the albedo only did not achieve a reduction in

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[17] Bueno et al., "The Urban Weather Generator".

[18] Dardir and Berardi, "Development of Microclimate Modeling for Enhancing Neighborhood Thermal Performance through Urban Greenery Cover"

[19] Jandaghian and Berardi, "Analysis of the Cooling Effects of Higher Albedo Surfaces during Heat Waves Coupling the Weather Research and Forecasting Model with Building Energy Models"; Jandaghian and Akbari, "Increasing Urban Albedo to Reduce Heat-Related Mortality in Toronto and Montreal, Canada".

humidex value. However, applying both strategies promoted the reduction in average humidex by 6.6% (from 31.8 to 29.7). It is observed that increasing only albedo did not help the overall thermal performance, but it was useful when integrated with enriching the greenery cover. Figure 3 shows the outdoor thermal behavior when applying both heat mitigation strategies. A better impact of heat mitigation is noticed during the daytime, and the maximum reduction of humidex is noticed during the peak day of the heat wave. During this day, the maximum humidex was reduced by 8.5% (from 51.9 to 47.5). It can be concluded that some single strategies, for example, the albedo, are not efficient when only applied in heat mitigation. But they can be beneficial when integrated with other strategies. Such results can be used by decision-makers to initiate policies to improve urban quality.

4. Statistical Modeling

The proposed statistical approach utilizes the Poisson regression following a log-linear function to model health data (mortality counts). The log-linear regression assumes a Poisson probability distribution for data behavior which deals with non-normal distributions and heteroscedasticity that are mainly expected with health data. This method was applied to predict the impact of humidex on mortalities. The regression analysis was conducted between daily mortality records and daily average humidex during hot and warm seasons for 17 years. The daily average humidex (Hmdx_avr) was added as a continuous independent covariate, and the 'Month' parameter was added as a categorical variable to test the influence of different months in the hot season on health behavior. For the category parameter estimation, the reference month was September and other months were related to it. Table 2 shows the regression analysis of the all-cause mortality (MOR_all) where the dependent variable was the log scale of MOR_all. The Wald Chi-Square and significance tests show the importance of considering the factor of months in the model. Referring to regression coefficients, the increased impact of humidex on mortality was declared in September, May, and June, with a maximum impact in May. An insightful conclusion can be derived that higher values of Humidex in warm seasons (transitional seasons) have higher impacts on mortality rates than in summer seasons. The predictive regression result can be represented by Eq. 1, where $n_{(Month)}$ is the time coefficient based on the month of the event. This equation and other predictive regression outputs are utilized in prediction models to forecast mortality based on outdoor thermal performance. Policymakers can utilize this method for estimating community health responses considering the outdoor conditions.

Table 2 – Regression analysis of all-cause mortality

Parameter	Coeff.	Std. Error	Wald Chi-Square	*p-value*
(Intercept)	2.140	0.0277	6610.992	0.000
Month			30.441	0.000
May	0.087	0.0217		
June	0.018	0.0211		
July	-0.048	0.0224		
August	-0.003	0.0217		
September	0	.		
Hmdx_avr	0.004	0.0012	10.042	0.002

$$\text{Log (MOR\_all)} = 0.004 \text{ Hmdx\_avr} + 2.14 + n_{(Month)} \quad (1)$$

Further analysis of this method is to consider the lagged effect of the humidex value on the mortality parameter. As the mortality could be impacted by delayed effects of heat events, the lag effect of humidex was considered for one week. The lagged study included the whole dataset, with no special focus on extreme events. The 'Month' parameter was maintained as a categorical factor. Table 3 reveals that May maintained the highest impact over time. The Wald Chi-Square test and significance values implied that the highest impact of humidex happens on the same day of occurrence of an event. A further impact was noticed after four days from the event (at lag04), however, it was not as considerable as the same-day impact. The results ensure the direct and short-term impact of heat exposure on all-cause mortality, as implied by previous studies[20].

Table 3 – Poisson regression of all-cause mortality considering the humidex lag effect

Parameter	Coeff.	Std. Error	Wald Chi-Square	*p-value*
(Intercept)	2.155	0.0391	3034.224	0.000
Month			17.444	0.002
May	0.081	0.0250		
June	0.019	0.0211		
July	-0.044	0.0233		
August	0.001	0.0225		
September	0	.		
Hmdx_avr	0.006	0.0018	11.025	0.001
Hmdx_avr_LAG01	-0.003	0.0025	1.821	0.177
Hmdx_avr_LAG02	0.001	0.0026	.240	0.624
Hmdx_avr_LAG03	-0.003	0.0026	1.627	0.202
Hmdx_avr_LAG04	0.005	0.0026	3.960	0.047
Hmdx_avr_LAG05	-0.004	0.0025	2.725	0.099
Hmdx_avr_LAG06	0.001	0.0019	.572	0.450

5. Health Informed Heat Mitigation Approach

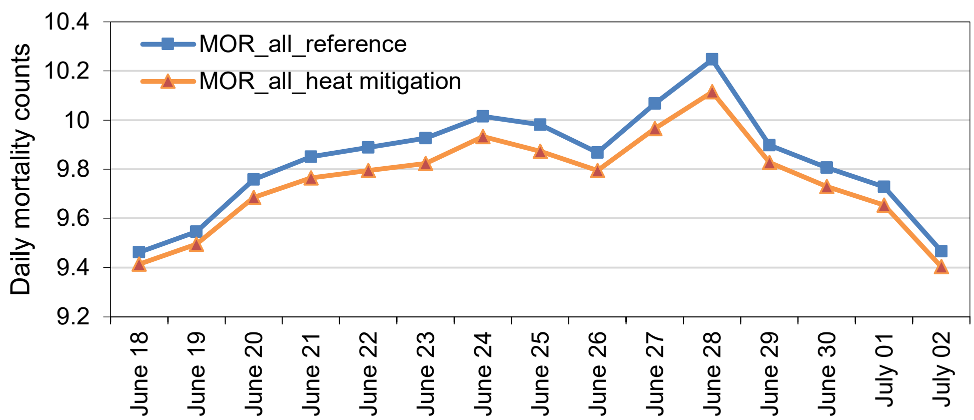

Figure 4 – Forecast for all-cause mortality when applying urban heat mitigation

The relationship between humidex and all-cause mortality in York Region was confirmed by the predictive regression analysis. Eq. 1 was integrated into the simulation model to predict the possible enhancements in mortality rates when applying the heat mitigation scenario applied earlier. The application during the 2 weeks of the expected weather scenario was repeated to forecast the daily mortalities when applying heat mitigation and

[20] Tsekeri, Kolokotsa, and Santamouris, "On the Association of Ambient Temperature and Elderly Mortality in a Mediterranean Island - Crete"; Paravantis et al., "Mortality Associated with High Ambient Temperatures, Heatwaves, and the Urban Heat Island in Athens, Greece."

compare them to the reference case, see Figure 4. The average daily mortality in the whole period was moved from 9.8 in the reference case to 9.7 when heat mitigation was applied. During the peak day of the heat wave, a reduction of 1.4% of daily all-cause mortality rates was achieved, which means that one life can be saved each 8 days of extreme heat events. Referring to the whole period, an average reduction of 0.8% of daily all-cause mortality was reached; this indicates that one life can be saved every 12 days during hot seasons. This approach has strong potential to predict community health records based on urban upgrading policies and actions. Accordingly, this method is of interest to health authorities and planning stakeholders to manage plans and policies.

6. Conclusion

A novel approach was utilized in this paper by integrating microclimate simulations and statistical modeling to predict the environmental and health impacts of integrating urban greenery and albedo enhancements. An application was designed in a residential neighborhood in York Region, Ontario to evaluate the outdoor thermal behavior of integrated urban heat mitigation strategies on a neighborhood scale. The integrated heat mitigation strategies showed promising performance during heat events enhancing the outdoor heat stress. An evidence-based relationship between outdoor heat stress and all-cause mortality was conducted based on Poisson regression analysis. The predictive regression resulted in prediction models that can forecast mortality records based on outdoor thermal performance. This method can be utilized to promote urban upgrading and estimate community health and comfort responses.

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