Modelling Neighbourhood-Level Heat Vulnerability

Background: Extreme heat is a leading cause of weather-related mortality in Canada, with seniors (>65) facing the highest risk [1]. Current public health strategies rely on city-wide alerts derived from Distributed Lag Non-Linear Models (DLNM) [2]. While DLNMs estimate temperature-mortality associations effectively, they average exposure across entire municipalities, masking spatial variations [3]. Furthermore, static regression models provide only a snapshot of risk, limiting their ability to capture the rate at which health deteriorates during an extreme heat event [4]. This gap limits intervention effectiveness, as resources are distributed based on city-wide averages rather than targeted to high-risk zones where vulnerability is highest [5].

Proposal and Rationale: We propose a dynamical mathematical model to stratify heat risk at the neighbourhood level. The objective is to quantify how local environmental deficits accelerate health deterioration during heatwaves. The hypothesis is that heat stress pathology follows a dynamical transition similar to infectious disease progression, where the rate of physiological decline is determined by local effect modifiers. To test this, we will adapt the classical Susceptible-Infected-Recovered (SIR) framework into a novel Vulnerable-Affected-Hospitalized (VAH) compartmental model. We apply this framework to postulate that by treating heat exposure as a state-transition process, the velocity of health collapse in specific subpopulations can be mathematically predicted. This allows for the identification of temporal windows where preventative support can avert hospitalization.

Methodology: The proposed VAH model redefines the compartments to simulate heat stress progression: Vulnerable (V) represents the at-risk population; Affected (A) represents individuals experiencing heat exhaustion, and Hospitalized (H) represents those requiring medical intervention. The model uses Ordinary Differential Equations (ODEs) to model population flow (dV/dt, dA/dt, dH/dt). The transition rates, specifically the rate of effect β (flow from $V \rightarrow A$) and the rate of hospitalization γ (flow from $A \rightarrow H$) are driven by external environmental forcing (temperature) and parameterized by area-level effect modifiers. We also account for a recovery flow ($A \rightarrow V$) to simulate physiological recovery as temperatures drop. Using Canadian census data, we model β and γ as dependent variables of neighbourhood-specific factors: specifically median income, air conditioning prevalence, and age structure. This formulation allows the model to demonstrate how a specific lack of infrastructure (e.g., low tree canopy) accelerates the flow of a population from Vulnerable to Hospitalized. The model will be validated by calibrating outputs against historical hospitalization records from Toronto.

Significance: The final output will be a computational tool that generates daily neighbourhood-specific risk estimates. By identifying specific city blocks where the transition rate to hospitalization is highest, emergency officials can direct ambulances and cooling centers to the neighbourhoods of greatest need before mortality occurs. Restructuring SIR compartments to capture non-linear dynamics is well-established in epidemiological literature [6-8]; however, this research represents the first application of this dynamical framework to environmental heat stress.

References

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