Climate disaster effects on acute health care: a case study and model of the 2021 heatwave in British Columbia, Canada

Dylan G Clark, Kevin E Liang, Ivy Cheng, James D Ford, Kira Gossack-Keenan

Summary

Background Acute health-care systems are a final layer of protection against growing climate impacts on population health. Climate disasters over the past decade have resulted in surges of patients seeking emergency care when preventive measures fall short. We aimed to understand how acute health-care delivery and access is vulnerable to climate disasters.

Methods We built a discrete event simulation model to replicate acute health-care system dynamics during Canada's deadliest climate disaster—the 2021 heatwave. We used public data and government reports to estimate resource capacity per capita and interconnected trajectories to define the movement of patients between resources. In an intervention scenario, we evaluated the efficacy of a package of three interventions in the emergency department and prehospital settings (upstaffing before the disaster, mass casualty procedures, and outpatient cooling beds). Across a 29-day period, we measured six key performance indicators (KPIs) to compare statistical changes in waiting times between baseline and intervention models (physician initial assessment waiting time; waiting time for emergency department bed among most acute patients; waiting time for emergency department bed among least acute patients; ambulance response time; boarding time; and total time in the emergency department). Using Monte Carlo methods, we ran both baseline and intervention models 100 times.

Findings We validated baseline model outputs against real-world data, with no statistically significant differences in all KPI medians. The baseline model showed significant negative effects on five of the six KPIs during the heatwave compared with the preheatwave period. Under the intervention model, four KPIs had significant improvements during the heatwave compared with the preheatwave period while the other two KPIs did not significantly change. Notably, emergency department waiting times decreased by over 35% with the interventions.

Interpretation The model replicated real-world patterns and was a valid representation of system dynamics. Our findings showed that even a small surge in patients can be detrimental to health-care access and delivery. The model also suggests that health-care delays during climate disasters can be avoidable with proactive planning.

Funding The Government of British Columbia.

Lancet Planet Health 2025; 9: e356–63

See **Comment** page e350

Pacific Institute for Climate Solutions, University of Victoria, Victoria, BC, Canada (D G Clark MSc); **Primary Care Clinics, Vancouver Coastal Health, Vancouver, BC, Canada** (K E Liang MD); **Division of Emergency Medicine, Department of Medicine, University of Toronto, Toronto, ON, Canada** (I Cheng PhD); **Department of Emergency Medicine, Sunnybrook Health Sciences Centre, Toronto, ON, Canada** (I Cheng); **Priestley Centre for Climate Futures, University of Leeds, Leeds, UK** (Prof J D Ford PhD); **Department of Emergency Medicine, Vancouver General Hospital, Vancouver, BC, Canada** (K Gossack-Keenan MD)

Correspondence to: Dylan G Clark, Pacific Institute for Climate Solutions, University of Victoria, Victoria, BC V8W 2Y2, Canada **dylanclark@uvic.ca**

Introduction

Climate hazards threaten the safety of health-care providers, disrupt utility networks, and damage health facilities precisely when demands for health care surge.[1–3] Although upstream adaptations (eg, addressing social determinants of health) are foundational to climate resilience, there is also a need to ensure acute health-care systems are able to deliver care when preventive measures fall short.[4,5] Indeed, the rapid increase in climate threats to health, high uncertainty around cascading impacts, and slow deployment of transformative adaptations mean that climate impacts on acute health are likely to increase in the short term unless disaster preparedness is also scaled up.[3,6,7]

Despite the growing pressures climate change is placing on acute health-care systems, there is insufficient evidence of intervention effectiveness. This gap in evidence is due in part to challenges of both measuring disaster impacts on health-care delivery and safely testing the efficacy of interventions.[6] This study aimed to address that gap by exploring how simulation modelling can improve preparedness for climate disasters across acute health-care systems. Our objectives were to validate use of simulation models for climate disaster planning in health systems, measure the potential impacts of a large disaster on health-care access, and evaluate the efficacy of select interventions in reducing health system impacts during a large disaster.

Methods

Study design and case study setting

We used a discrete event simulation (DES) model for this study. DES models are well established tools for health system performance evaluation and planning.[8,9] The models are ideal for analysing bottlenecks and patient flow dynamics and testing health system interventions. Although DES models have been used to

Research in context

Evidence before this study

Climate hazards associated with acute illness and injuries are projected to increase in both size and frequency around the world. Acute health-care services—emergency departments, inpatient wards, and prehospital emergency medical services—can experience dramatic increases in patient volume during extreme heat events, hurricanes, and wildfires. However, there is insufficient evidence about risk factors of acute health-care systems becoming overwhelmed during climate disasters. Further, there is insufficient evidence of interventions to reduce vulnerability. To contextualise this study and identify previous similar work, we searched PubMed, Scopus, and Google Scholar to identify original research articles published from Jan 1, 2010, to Sept, 30, 2024, that analysed impacts of climate change on acute health-care systems. The search terms used were: "climat*" AND ("hospital" OR "patient" OR "healthcare" OR "health-care") AND ("bottleneck" OR "delay" OR "mass casualty"). We found only five studies that explicitly analysed the impacts of climate change on acute health-care systems. Three of the identified studies were qualitative case studies and the other two were retrospective reviews of quantitative data. None of these studies included modelling or quantitative analysis of interventions.

Added value of this study

To our knowledge, this is the first study to use simulation modelling as a tool to assess climate impacts on health-care delivery and access. Our results show that without proactive planning, even a small surge in patients during a climate event can be detrimental. Further, we present a validated and open-source tool to support health system planning, cost–benefit analyses, and postdisaster analysis.

Implications of all the available evidence

Climate change is rapidly shifting the nature of many hazards, including extreme heat, the deadliest natural hazard globally. In the case of extreme heat preparedness, our study suggests that proactive upstaffing, implementation of plans for emergency department decanting, and use of mass casualty protocols can reduce acute health-care delays and probably save lives. Although climate hazards are increasing in frequency and magnitude, a rise in climate disasters and mortality is not inevitable.

assess health system impacts of earthquakes, mass shootings, and the COVID-19 pandemic,[10–12] they have not been used to analyse climate disaster impacts to our knowledge. This study did not require ethics approval; no patient or survey data were used in the analysis.

We used the 2021 British Columbia extreme heat event (ie, heatwave)—Canada's deadliest climate disaster—as a case study.[13,14] Our modelling experiment focused on an 8-day period from June 25 to July 2, 2021. During this time period, temperatures across the province were between 15°C and 20°C higher than seasonal historic means, and night-time temperatures rarely fell lower than 20°C. The Canadian national temperature record was broken 3 days in a row, reaching an all-time high of 49·6°C. The heat anomalies were at least 150 times more likely due to anthropogenic climate change.[15] Although the severity of the heatwave varied across the province, all five million residents were placed under a heat advisory—indicating risk of heat illness and death.[14]

See Online for appendix

Demands on acute health-care systems increased substantially during the 2021 heatwave (figure 1). Across British Columbia, hospital admissions increased by 6%.[16] The largest increases in demand were associated with the highest acuity patients; Canada Triage and Acuity Scale (CTAS) 1 patients (1 being the highest acuity, 5 being the lowest acuity) increased by 151·9% across Metro Vancouver (population of 2·6 million).[16,17] Subsequently, some of British Columbia's hospitals had all-time records for daily emergency department visits. Similar increases in emergency department visits and health-care demands were observed in Seattle, WA, USA (200 km south), although the state's mortality rate was about half that of British Columbia's.[18]

Increased heat morbidity and mortality over the 8-day extreme heat event led to widespread delays in acute health-care access across British Columbia and the Pacific Northwest. Government reports indicate that waiting times for ambulances in British Columbia nearly doubled for the most acute patients; waiting times for low acuity calls exceeded 20 h in some parts of the province.[14,19]

Model development

We used an iterative process to design, verify, and validate the model and experiment results. This process consisted of four key stages: (1) conceptualising the health system; (2) translating the concept into code; (3) running a baseline model to simulate the disaster; and (4) running a model with hypothetical interventions to reduce care delays.[9,20,21] We describe each of these steps in accordance with the standardised guideline STRESS (appendix pp 2–8).[22]

We focused on the areas of the acute health-care system most affected by climate disasters: prehospital care, emergency departments, intensive care units (ICUs), and medical hospital wards. After identifying these areas, we developed a conceptual patient flow diagram that depicted how patients move through the health system and the required resources (both physical and human resources) at each stage of care (appendix p 2).[21,23] Patient flow mapping was done with coauthor physicians who work in each of these care settings and was informed by other Canadian DES models.[8,24,25]

We identified 16 relevant resources across the acute health-care system to model (figure 2). We used public data and government reports to estimate resource capacity per capita (appendix p 5). Generally, we assumed the number of available resources did not change throughout the day, with the exception of a decrease in available ambulances between 2000 h and 0800 h by 25% (appendix p 4). We also allowed for up to a 15% increase in emergency department beds and 10% increase in non-ICU hospital beds when queuing times became excessive, which reflects the real-world use of hallway beds and so-called normal operation at more than 100% capacity in many hospitals. In the intervention scenario, we increased the number of select resources to reflect proactive upstaffing in the emergency department and prehospital settings (appendix p 8).

We used interconnected trajectories to define the movement of patients between resources (figure 2). Trajectories represented distinct sets of decision trees and resource assignments and were constant across all baseline runs. In the intervention scenario we altered criteria for resuscitation attempts and emergency department decanting.

We designed patient generators that randomly created patients across Poisson distributions of arrival times. We estimated patient volumes related to heat and not related to heat using public data (appendix pp 6–7). Generators were designed to assign properties to each patient, such as triage score and whether they would die. These properties were also randomly assigned based on predefined Poisson distributions.

We used three techniques to validate the model: internal validation, sensitivity analysis, and quantitative validation of indicators.[20] Internal validation was done by the three physician coauthors who work in various sectors of the health system.[9] Sensitivity analyses were based on data from Monte Carlo runs and a range of input parameters used to reflect patient volumes across the five health regions. Finally, we quantitatively validated the model by comparing modelled throughput statistics with real-world values (appendix pp 9–10).[21] We based health system capacity and patient volumes on a service area of 100 000 people. A per-capita approach allowed for generalisation across the region and transferability to other countries.

In the baseline runs we sought to replicate real-world conditions without any interventions. We simulated the health system dynamics leading up to (14-day period), during (8-day period), and directly after (7-day period) the 2021 heatwave. We used Monte Carlo runs to capture uncertainty; 20 runs for each of the five health regions in British Columbia, resulting in 2100 days of preheatwave and postheatwave data and 800 days of heatwave data for a total of 2900 modelled baseline days. Baseline runs did not include any system interventions.

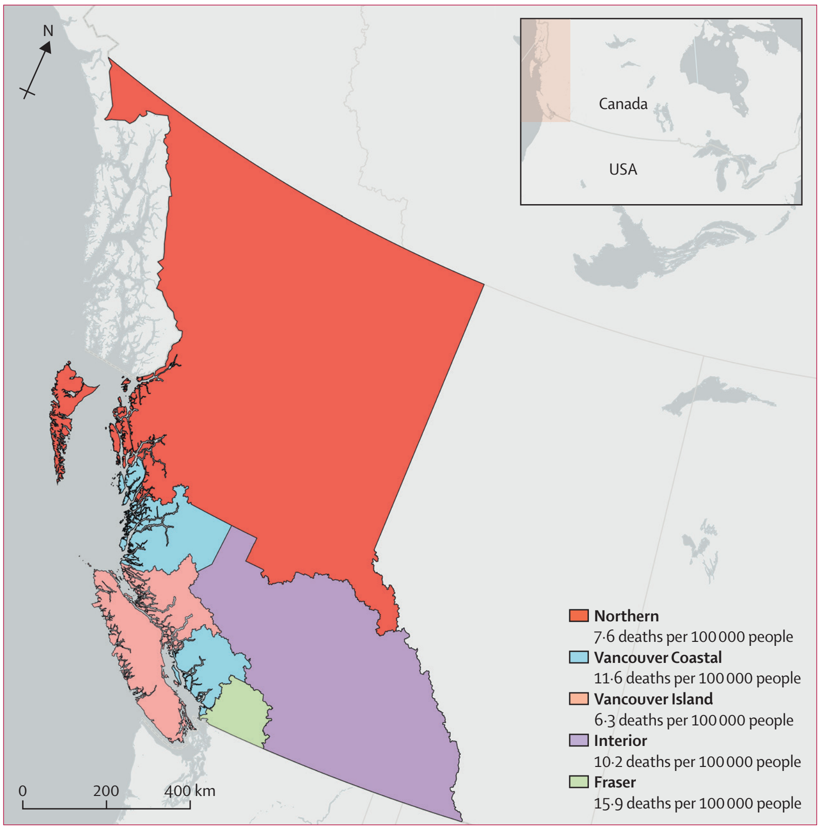


Figure 1: **2021 heatwave mortality across British Columbia, Canada**

We used R Cran language for the model. Specifically, we used RStudio with the packages simmer and simmer. plot.[26] Each component of the code is detailed in the appendix (pp 2–8). All code is available on GitHub

For the **code** see https://github.com/dylangclark/SimulationModel

Evaluation of heatwave impacts

We used key performance indicators (KPIs) to analyse the precision of the model and to determine the effects of the 2021 heatwave in the modelling environment. We selected six KPIs commonly used across Canadian health systems to measure acute health-care delivery: physician initial assessment waiting time; waiting time for emergency department bed among most acute patients; waiting time for emergency department bed among least acute patients; ambulance response time; boarding time; and total time in the emergency department.

Because of the long-tailed distributions in both the real-world and modelling results, we analysed median values and 90th percentile cutoffs (a standard practice in health system evaluation). To analyse changes between the preheatwave, heatwave, and postheatwave periods, we used a paired Wilcoxon signed rank test.[27]

Evaluation of intervention effectiveness

We selected a package of three interventions implemented simultaneously for the study: upstaffing before the

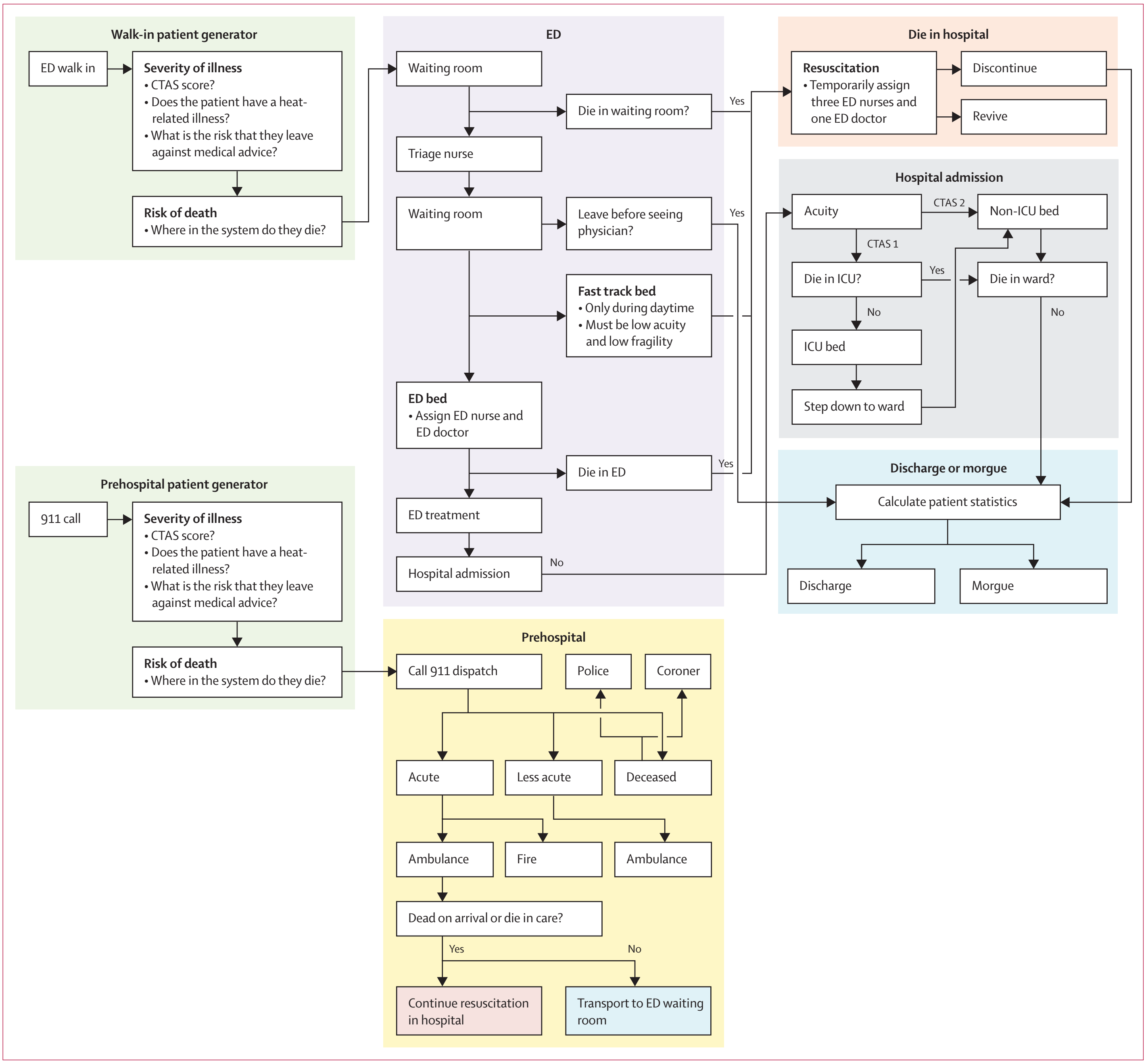


Figure 2: **Patient flows and resources that were the foundation for the simulation model**
Patient flows and criteria are indicated with arrows. A full list of all resources included in the model and their specific capacity is in the appendix (p 4). CTAS=Canada Triage and Acuity Scale. ED=emergency department. ICU=intensive care unit.

disaster; mass casualty procedures; and establishing community-based cooling beds (appendix p 8). These interventions were all previously qualitatively discussed in other heat-response studies and in postdisaster analyses; however, none were widely implemented in the real-world 2021 heatwave.[12,14] To evaluate efficacy of the intervention scenario, we modified the baseline model parameters to reflect the intervention assumptions, then ran an additional 2900 days of the model. Finally, we analysed statistical changes in KPIs between the baseline model ensemble and the intervention model ensemble.

Role of the funding source

The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The model produced a total 762 001 patients across all the Monte Carlo runs (381 043 for the baseline scenario and 380 958 during the intervention). Over the 29-day simulation period there were an average of 131·4 emergency department visits per 100 000 patients per day. The mean incidence of daily emergency department visits was 129·5 per 100 000 patients preheatwave and postheatwave and 136·4 daily visits per 100 000 patients during the heatwave (figure 3). The mean incidence of simulated daily hospitalisations was 21·4 per 100 000 preheatwave and postheatwave and 23·2 during the heatwave. The mean mortality incidence was 1·8 deaths per day per 100 000 patients during the preheatwave and postheatwave, which increased to 2·9 per 100 000 during the heatwave.

Median real-world throughput times were between the first and third quartiles of the model results for all KPIs (appendix pp 9–10). We also observed alignment between the modelled data distributions and real-world data. Although there were few real-world observations of waiting times during the 2021 heatwave, the model did resemble all available data.

The simulated increase in patients during the heatwave resulted in significant delays across five of the six KPIs (table). The largest change in delays happened at the entry stages of the system (eg, ambulance response time and waiting time for an emergency department bed). The number of CTAS 4 patients who waited more than an hour for an ambulance increased from 0·2% preheatwave to 2·8% during the heatwave. Additionally, the median wait for a physician initial assessment was 70 min during the preheatwave period and increased by 13 min during the heatwave (appendix pp 11–12). Delays further into a patient's care (eg, boarding time and ICU length of stay) were either insignificant or decreased slightly (table). To capture these long-tailed changes, we looked at delays among the 90th percentile of runs (figure 4). The physician initial assessment 90th percentile across all baseline runs was 319 min preheatwave and increased by 72 min during the heatwave. Similarly, the 90th percentile waiting time for an emergency department bed among the least acute patients increased from 354 min to 446 min.

In the prehospital setting, the 90th percentile wait for an ambulance increased by 0·4 min (table), while the 99th percentile waiting times increased from 22 min to 257 min (increase of 3 h 54 min). There were no statistically significant changes to the KPIs during the postheatwave period compared with the preheatwave period across both medians and 90th percentiles.

The highest volume of heat-related patients was in the Fraser Health region, where there was a mean increase of 11·7 patients arrivals and 2·2 deaths per 100 000 patients per day (figure 3). The lowest increase in patients and deaths during the heatwave was in the Vancouver Island Health region with an increase of 3·6 patients and 0·6 deaths per 100 000 patients (appendix pp 10–11). These differences were a direct result of model inputs. Causes of the variation in regional morbidity and mortality has been discussed in other work.[14,16,17]

The median physician initial assessment wait increased by 20% during the heatwave period in the Fraser Health

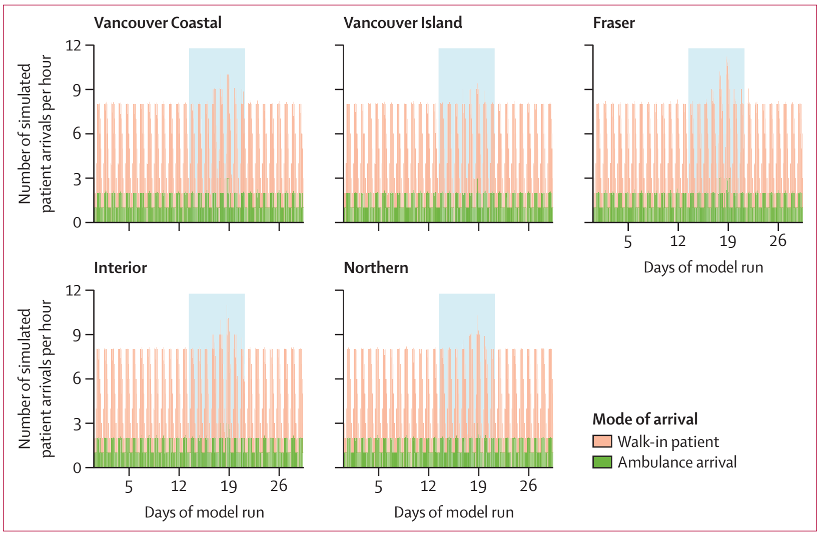


Figure 3: **Modelled number of patient arrivals per hour by health authority with identified mode of arrival**
The light blue area represents the heatwave period in the model. The largest increase in patient volume was in the Fraser Health region, while the smallest increase was in the Vancouver Island Health region. The circadian pattern of patient arrivals is visible with the large daily peaks and valleys.

	Indicator description	Median change during heatwave (95% CI); p value	90th percentile change during heatwave (95% CI); p value
Physician initial assessment waiting time	Time from patient triage to being seen by a physician	Increase of 12·7 min (10·8 to 14·6); p<0·0001	Increase of 72·1 min (58·4 to 86·3); p<0·0001
Waiting time for emergency department bed among most acute	Time from waiting room arrival to being moved to an emergency department bed among CTAS 1 and CTAS 2 patients	Increase of 1·2 min (0·9 to 1·4); p<0·0001	Increase of 9·7 min (7·7 to 11·9); p<0·0001
Waiting time for emergency department bed among least acute	Time from waiting room arrival to being moved to an emergency department bed among CTAS 4 and CTAS 5 patients	Increase of 2·8 min (2·1 to 3·4); p<0·0001	Increase of 92·2 min (76·8 to 108·0); p<0·0001
Ambulance response time	Time between 911 call and ambulance arrival to scene	Increase of 0·2 min (0·1 to 0·3); p=0·0001	Increase of 0·4 min (0·2 to 0·5); p<0·0001
Boarding time	Time from hospital admission decision to physically being moved to hospital ward	Decrease of 15·1 min (–25·9 to –4·5); p=0·0052	No significant change (–31·0 to 8·5)
Total time in emergency department	Time from getting an emergency department bed to being discharged or moved to a hospital bed	Increase of 4·0 min (2·4 to 5·5); p<0·0001	Increase of 24·7 min (12·6 to 36·9); p=0·0002

We analysed the magnitude and significance of change between the preheatwave and heatwave periods using a paired Wilcoxon signed rank test. CTAS=Canada Triage and Acuity Scale.

Table: **Six key performance indicators measuring changes across time periods**

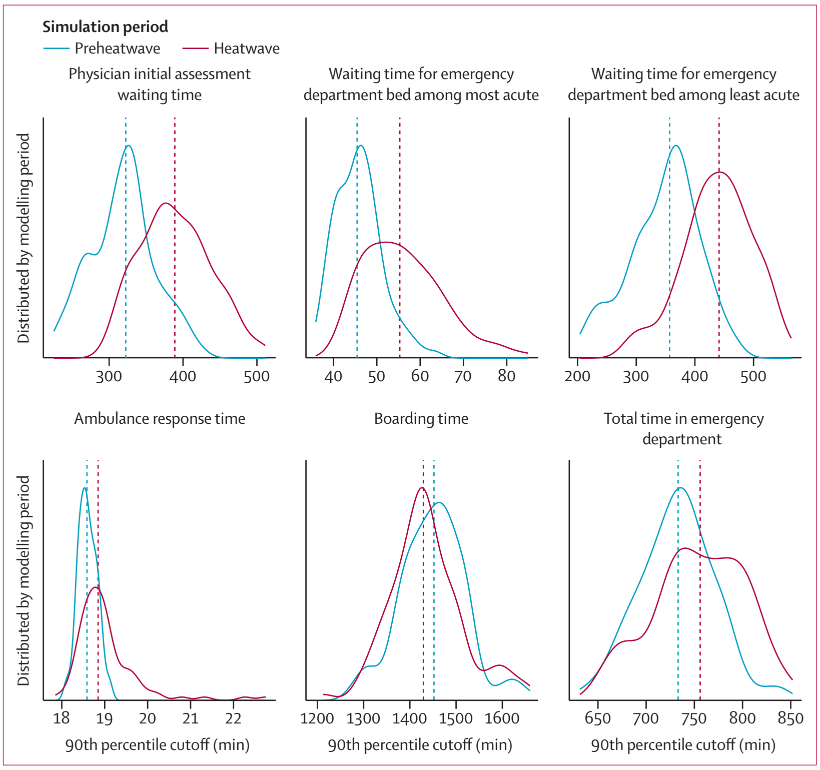


Figure 4: **Distribution of modelled 90th percentile waiting times**
These graphs depict changes in the distribution of 90th percentile cutoffs across all the Monte Carlo runs (n=100) for each key performance indicator. The dashed line reflects the median 90th percentile cutoff of all runs during the preheatwave and heatwave periods. Except for boarding time, there were statistically significant changes in the distribution of all KPIs between the preheatwave and heatwave periods. Some indicators, such as ambulance response time, had a long-tailed distribution across the model runs during the heatwave.

region and 17% in the Interior Health region, while the smallest increases were in the Vancouver Coastal Health and the Northern Health regions. Similarly, ambulance response times increased most in the Fraser Health region (increase of 3%) and the Interior Health region (increase of 1%). The smallest change to ambulance response time was in the Vancouver Island Health and Northern Health regions.

There were significant reductions in system delays under the intervention scenario (figure 5). All KPI median values, except boarding time, showed statistically significant reductions. Boarding time increased by about 15 min during the heatwave compared with the baseline scenario (appendix p 12). In some cases, the intervention scenario resulted in heatwave waiting times dropping below the preheatwave values. Median emergency department waiting times decreased during the heatwave with the intervention compared with the preheatwave period (decrease of 36%), whereas the emergency department waiting times increased by 4% under the baseline scenario. The physician initial assessment wait also decreased during the heatwave with the intervention (decrease of 27%) compared with an increase of 16% under the baseline scenario. This improvement represented an average of 35 patients per 100 000 per day who had a physician initial assessment within 120 min, who otherwise would not have been seen in that timeframe. The modelled interventions resulted in ambulance response times remaining unchanged between the preheatwave and heatwave period compared with the baseline scenario that saw ambulance wait increasing by a median of 15 s and multihour waits for less acute calls. The 99th percentile of ambulance waits during the heatwave dropped from 257 min to 21 min with the intervention.

Discussion

The model was able to replicate real-world patterns across the acute health-care system and was a valid representation of system dynamics. Further, the hundreds of Monte Carlo runs were a useful approach to capturing uncertainty and variable system dynamics.

The model was slightly less sensitive to bottlenecks during the heatwave compared with the limited real-world indicators that were available. For example, ambulance response times were reported to be between 9 min and 13 min for CTAS 1 patients in parts of British Columbia, while the model resulted in a range of 6–13 min. There was also variation between the modelled boarding time and real-world observed boarding time. This difference between the model and the real world could be due to tipping points or system limits that were not captured in the model (eg, ambulances breaking down due to heat or employees calling in sick). Indeed, our model did not reflect infrastructure failures, which inhibited patient care in the real world (CT scanner failures, aeromedical groundings, and ambulance breakdowns).[14] Real-world boarding time increases could have also been impacted by COVID-19 protocol and pre-existing hospital bed shortages, which we did not capture in the model.

Our findings show that even a small surge in patients can be detrimental to acute health-care access. The results suggest that the increase in acuity and mortality among heat-affected patients produced delays in both the prehospital and emergency department settings. This finding is echoed in postdisaster reviews that have highlighted delays in ambulances returning to service due to emergency department backups, insufficient decanting of patients who needed to be cooled, and challenges in resource allocation.[14,19]

The model showed tipping points and thresholds across the system, which could be useful for decision making. For example, we observed the importance of emergency department decanting and clearing waiting room backlogs throughout the night. We also observed that when the ratio of high acuity patients and resuscitations increased even by a small percentage—only 0·6 more high acuity patients per 100 000 people per day during the heatwave—there were large effects across the system.

The model did consistently recover within a few days of a surge; there were no significant changes between the preheatwave and postheatwave KPIs. Although available real-world indicators also showed a swift recovery across British Columbia health systems, a pure modelling approach might miss important qualitative changes such as stress and burnout among health-care personnel, which can have detrimental system impacts after a climate disaster.[28]

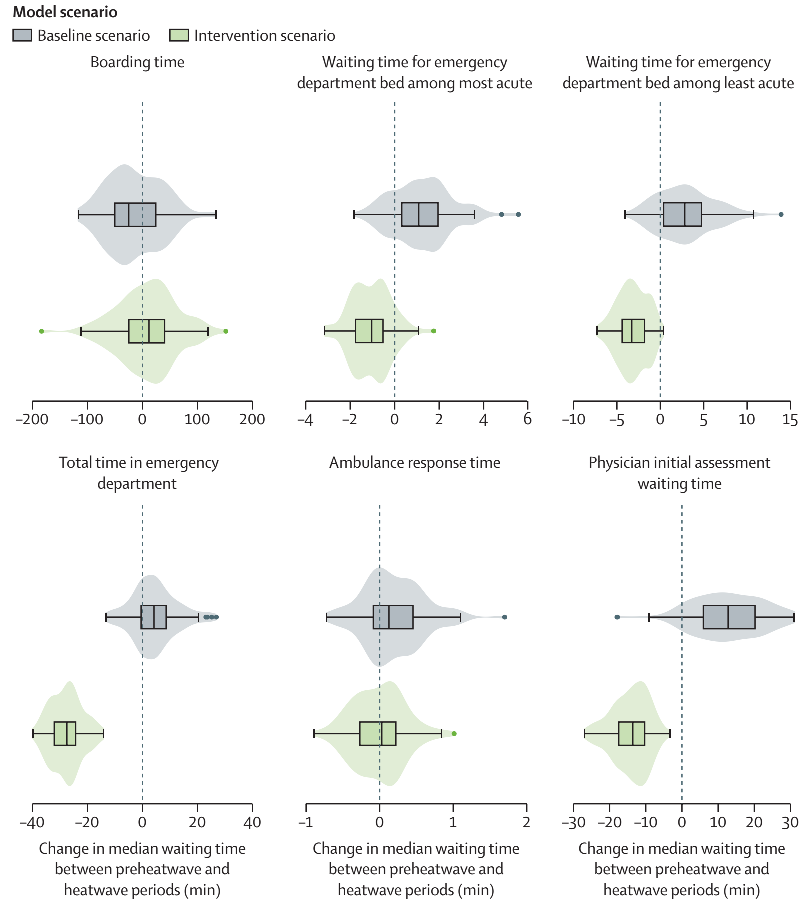
Importantly, the model results suggest that health-care delays and subsequent impacts could be almost entirely avoided if key interventions are deployed leading up to and during a heatwave. We observed that the suite of interventions targeting both patient resource allocation (mass casualty procedures and non-emergency department decanting beds) and available resources (upstaffing) were important. The findings show that simulation modelling can be used to plan for and develop evidence-based health system interventions.

We chose to create a model that generalised health system dynamics at a regional scale. However, across Canada as well as in other countries, rural hospitals are often more resource constrained and might have less cushion to absorb shocks, potentially increasing vulnerability to cascading impacts. These dynamics deserve more research—especially amidst recent temporary closures of emergency departments across rural regions of Canada, the USA, and the UK.[29,30]

One key difference between our model and real-world systems is the narrow boundary of our model. We developed and validated the model for estimating operational dynamics in an acute health-care setting; we did not include other elements of the health system such as posthospital care (eg, rehabilitation, home care) because interactions might have compromised our design goals.

We made several assumptions that might have affected results. We did not explicitly model resources for patient diagnosis and treatment (eg, imaging, laboratories, operating rooms), instead we used a probabilistic function based on the patient CTAS score for a general diagnosis and treatment time. Further, we excluded some institution-specific care trajectories, including designated psychiatric areas, specialist consultations, or inter-facility transports (these dynamics can reduce delays under a Nash equilibrium or similar balancing). We acknowledge these limitations and note that models are not perfect, but some are useful. The validation results show that our novel simulation model can capture health system dynamics during a major climate disaster.

This paper not only shows ways to plan for risks but also shows how vulnerable systems can be if proactive steps are not taken. As the severity and frequency of health threats continue to shift, decision makers must evaluate the potential impacts on the acute health-care system and proactively address vulnerabilities. When day-to-day acute health-care access is constrained, the system is not well positioned to absorb an unanticipated shock, which is particularly relevant due to present emergency department waiting times, overcrowding in hospital wards, and emergency department closures in Canada and across the USA and Europe.[30] Conversely, our modelling suggests that investments that improve baseline acute health-care access could also reduce bottlenecks during a disaster. Additional planning and investment are probably needed to better prepare acute health-care systems for climate disasters. Our open-access and validated simulation model could be a useful tool for decision makers and system managers.



Intervention scenario assumptions

Upstaffing
Increase prehospital, emergency department, and hospital staff just before and during the heatwave

Community-based cooling beds
Establish a location where low acuity emergency department patients can be transferred for ongoing cooling and monitoring

Mass casualty incident protocol (code orange)
When patient needs exceed system capacity, resources are triaged to save the largest number of lives

Figure 5: **Health system delays under the baseline and intervention scenarios**
Interventions are described in greater detail in the appendix (p 8). The distribution of change in median times (ie, median heatwave delay minus median preheatwave delay) across all model runs (n=100) is captured with the shaded area here. The box plot signifies mean and SD for both the scenarios.

Contributors
All authors were involved in the study design and conceptualisation. DGC developed the model code with support from KEL. IC, JDF, and KG-K supported study design and framing. KG-K, KEL, and IC supported model validation. DGC conducted the analysis, led writing, and had final responsibility for the decision to submit for publication. All authors had access to the study data and code and IC and KEL verified the data. All authors have read and approved the final version of the manuscript.

Declaration of interests
DGC and IC received indirect financial support for the research from the Government of British Columbia through the Canadian Climate Institute. All other authors declare no competing interests.

Data sharing
All code used in this study is available on GitHub at https://github.com/dylangclark/SimulationModel. All data used to inform the model parameterisation are available at https://github.com/dylangclark/BC_Heatwave. The simulation model is available for readers to interact with and run on Shiny at https://resilientdata.shinyapps.io/SimulationModel/.

Acknowledgments
We are grateful to the Government of British Columbia for funding the Canadian Climate Institute's analysis of economic costs and impacts of the 2021 heatwave. This paper originated from the project.

References
1 Corvalan C, Villalobos Prats E, Sena A, et al. Towards climate resilient and environmentally sustainable health care facilities. *Int J Environ Res Public Health* 2020; **17:** 1–18.
2 Ford JD, Zavaleta-Cortijo C, Ainembabazi T, et al. Interactions between climate and COVID-19. *Lancet Planet Health* 2022; **6:** e825–33.
3 Romanello M, Walawender M, Hsu S-C, et al. The 2024 report of the *Lancet* Countdown on health and climate change: facing record-breaking threats from delayed action. *Lancet* 2024; **404:** 1847–96.
4 Ebi KL, Vanos J, Baldwin JW, et al. Extreme weather and climate change: population health and health system implications. *Annu Rev Public Health* 2021; **42:** 293–315.
5 Malik IH, Ford JD, Clark DG, Pearce TD. Climate change, mass casualty incidents, and emergency response in the Arctic. *Environl Res: Infrastruct Sustain* 2024; **4:** 043002.
6 Lawrence J, Blackett P, Cradock-Henry NA. Cascading climate change impacts and implications. *Clim Risk Manage* 2020; **29:** 100234.
7 Berrang-Ford L, Siders AR, Lesnikowski A, et al. A systematic global stocktake of evidence on human adaptation to climate change. *Nat Clim Chang* 2021; **11:** 989–1000.
8 Peng Q, Yang J, Strome T, Weldon E, Chochinov A. Bottleneck detection and reduction using simulation modeling to reduce overcrowding of hospital emergency department. *Journal of Modeling and Optimization* 2020; **12:** 100–09.
9 Rutberg MH, Wenczel S, Devaney J, Goldlust EJ, Day TE. Incorporating discrete event simulation into quality improvement efforts in health care systems. *Am J Med Qual* 2015; **30:** 31–35.
10 Lin YX, Lin CH, Lin CH. A challenge for healthcare system resilience after an earthquake: the crowdedness of a first-aid hospital by non-urgent patients. *PLoS One* 2021; **16:** e0249522.
11 Bovim TR, Gullhav AN, Andersson H, Dale J, Karlsen K. Simulating emergency patient flow during the COVID-19 pandemic. *J Simul* 2022; **00:** 1–15.
12 Armstrong JBP. Preparing your emergency department for disaster: optimizing surge capacity during mass casualty events. *Healthc Manage Forum* 2023; **37:** 86–89.
13 White RH, Anderson S, Booth JF, et al. The unprecedented Pacific Northwest heatwave of June 2021. *Nat Commun* 2023; **14:** 727.
14 Beugin D, Clark D, Miller S, Ness R, Pelai R, Wale J. The case for adapting to extreme heat: costs of the 2021 BC heat wave. Canadian Climate Institute, 2023.
15 Philip SY, Kew SF, Van Oldenborgh GJ, et al. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. *Earth Syst Dyn* 2022; **13:** 1689–1713.
16 Clark DG, Jackson EH, Hohl CM, Liang KE. Extreme heat impacts on acute care: examining emergency department visits and hospital admissions during the 2021 British Columbia heatwave. *J Clim Change Health* 2024; **17:** 100310.
17 Gossack-Keenan K, Yeom DS, Kanu J, et al. Heatstroke presentations to urban hospitals during BC's extreme heat event: lessons for the future. *CJEM* 2024; **26:** 111–18.
18 Wettstein ZS, Hall J, Buck C, Mitchell SH, Hess JJ. Impacts of the 2021 heat dome on emergency department visits, hospitalizations, and health system operations in three hospitals in Seattle, Washington. *J Am Coll Emerg Physicians Open* 2024; **5:** e13098.
19 Health Emergency Management, British Columbia. Heat and smoke plan—Vancouver acute. Oct 5, 2022. https://github.com/dylangclark/BC_Heatwave/blob/main/VCH-2022-F-108.pdf (accessed Nov 1, 2024).
20 Banks J. Handbook of simulation: principles, methodology, advances, applications, and practice. John Wiley & Sons, 1998.
21 Vanbrabant L, Braekers K, Ramaekers K, Van Nieuwenhuyse I. Simulation of emergency department operations: a comprehensive review of KPIs and operational improvements. *Comput Ind Eng* 2019; **131:** 356–81.
22 Monks T, Currie CSM, Onggo BS, Robinson S, Kunc M, Taylor SJE. Strengthening the reporting of empirical simulation studies: introducing the STRESS guidelines. *J Simul* 2019; **13:** 55–67.
23 Debacker M, Van Utterbeeck F, Ullrich C, Dhondt E, Hubloue I. SIMEDIS: a discrete-event simulation model for testing responses to mass casualty incidents. *J Med Syst* 2016; **40:** 273.
24 Baia Medeiros DT. Improving timely access to emergency diagnostic imaging via data analysis and discrete event simulation. Master's Thesis, University of Toronto, 2019, 1–75.
25 Doudareva E, Carter M. Using discrete event simulation to improve performance at two Canadian emergency departments. Proceedings—2021 Winter Simulation Conference; Dec 12–15, 2021.
26 Ucar I, Smeets B, Azcorra A. simmer: discrete-event simulation for R. *J Stat Softw* 2019; **90:** 1–30.
27 Hollander M, Wolfe DA, Chicken E. The two-sample location problem. In: Nonparametric statistical methods. John Wiley & Sons, 2015: 115–50.
28 Tetzlaff EJ, Cassan C, Goulet N, Gorman M, Hogya B, Kenny GP. "Breaking down in tears, soaked in sweat, and sick from the heat": media-based composite narratives of first responders working during the 2021 Heat Dome. *Am J Ind Med* 2024; **67:** 442–52.
29 Goetz C. Rural hospital closures in Kansas, United States: can inpatient tele-consultation services improve care and hospital finances? *Lancet Reg Health Am* 2024; **38:** 100853.
30 Varner C. Emergency departments are in crisis now and for the foreseeable future. *CMAJ* 2023; **195:** E851–52.