



Heatwave adaptation conditioned by everyday life: Analysing interacting changes to daily activities during Pacific Northwest summers

Shiv G. Yücel^{ID}*, Tim Schwanen

Transport Studies Unit, School of Geography and the Environment, University of Oxford, United Kingdom

ARTICLE INFO

Dataset link: <https://zenodo.org/records/14039954>, https://github.com/shivyucel/heatwaves_pnw_code

Keywords:

Heatwaves
Adaptation
Human mobility
Cooling
Activity change
Spatial analysis

ABSTRACT

As heatwaves increase in intensity, frequency, and duration, there is an urgent need for adaptation to limit their adverse effects on health, well-being, and livelihoods. Heat exposure and adaptive responses during heatwaves are tightly linked to mobility behaviours – the subject of a rapidly growing body of literature. However, knowledge of the processes which shape and constrain opportunities to seek cooling remains limited, as academic research has yet to examine how people alter the various activities of everyday life in response to heatwaves. Addressing this gap, the current paper models these interdependent activity changes simultaneously, shedding light on behavioural adaptations during heatwaves and the underlying structures which condition them. Combining Google Community Mobility Reports, ERA5 climate re-analysis, and socio-economic data across the Pacific Northwest region of North America, the analysis uses a multi-variate multi-level model to examine how anchor (home, work, transit), essential (grocery/pharmacy), and discretionary (retail/recreation, parks) activity change *together* during summer heatwaves. Focusing on a climatically diverse region and modelling heatwaves as distinct multi-day events, these interdependent responses are explored with the climatic, temporal, and contextual features of heatwaves. Four main conclusions about behavioural adaptation to heatwaves are drawn: (1) A region's typical climate impacts workplace rigidity and adaptations to non-work activities during heatwaves; (2) Absolute and relative intensities have distinct yet comparably large impacts on behavioural responses; (3) Adaptation evolves over time, both between and within heatwaves; (4) Urban form and socio-economic disparities influence activity trade-offs during heatwaves. By contextualizing heatwaves within people's everyday lives, this study highlights the diverse, dynamic, and yet constrained processes by which adaptation occurs.

1. Introduction

Heatwaves prey on existing social and material inequalities, which largely distinguish the 'cool' from the 'damned' (Puley, 2022; Goodell, 2023). These inequalities manifest in people's mobility behaviours during heatwaves – a complex, understudied process which shapes exposure to extreme heat. As extreme heat is estimated to cause 489,000 excess deaths globally every year (Zhao et al., 2021) and as heatwaves increase in intensity, frequency, and duration with human-induced climate change (Perkins-Kirkpatrick and Lewis, 2020), literature on extreme heat mobilities has been rapidly growing (Derakhshan et al., 2023; Stechemesser and Wenz, 2023; Ly et al., 2023; Gu et al., 2024; Tian et al., 2024; Zou et al., 2023; Fan et al., 2023; Kumakura et al., 2024; Linsenmeier, 2024). Many of these analyses leverage large-scale mobility data, such as those generated by cell-phones, which passively collect geo-referenced data over sustained periods of time through the devices people carry with them. These data sources have proven

invaluable for retroactively studying behavioural responses to disasters (Hatchett et al., 2021). They can also be linked with places-of-interest (POIs) to infer people's participation in day-to-day activities and how they are adapted during extreme weather events. Existing research has yet to examine how people alter the various activities of everyday life in response to heatwaves, which is critical to understanding the constrained processes by which people adapt while navigating daily life and its obligations (Oppermann et al., 2018; Teebken et al., 2023).

To address this gap, the present study examines the various activity changes that occur during heatwaves and that shape and constrain opportunities to seek cool environments in space and time. Grounded in concepts from time-geography (Hägerstrand, 1970; Ellegård, 2018), an activity participation framework is employed which considers the diverse roles of different activities and their competing nature given the limited time in a day. Specifically, the analysis uses cell-phone

* Correspondence to: Transport Studies Unit, Oxford University Centre for the Environment, South Parks Road, Oxford, OX1 3QY, United Kingdom.
E-mail address: shiv.yucel@ouce.ox.ac.uk (S.G. Yücel).

mobility data to simultaneously model how people's everyday activities (home, work, transit, grocery/pharmacy, retail/recreation, parks) are altered together during summer heatwaves across the Pacific Northwest region of North America (British Columbia, Washington, Oregon, California). These interdependent relationships are explored with the climatic, temporal, and contextual factors of heatwaves over a large and climatically diverse geographic area. By contextualizing heatwaves alongside the constraints of everyday life, this study highlights the diversity of adaptive responses to heatwaves, as well as the structures of everyday life which condition them.

The Pacific Northwest region has suffered from unprecedented heatwaves in recent years, such as the infamous 2021 heatwave which killed over 800 people in a single week (White et al., 2023; Heeter et al., 2023). In addition to high exposure, the region's vulnerability is shaped by diverse climatic and social factors which influence its residents' sensitivity and adaptive capacity to heatwaves (Adger, 2006). The Pacific Northwest has wide climatic variation, broadly getting hotter and drier southward towards California (Dye et al., 2020) and eastward from the coast to inland regions (Mass, 2021). These diverse climates influence the prevalence of air conditioning — as cooler regions had historically less need — while also impacting people's physiological acclimatization to heat (Arnold et al., 2022). These variations are evident across provinces/states, as BC has the lowest air conditioning ownership of all provinces in Canada (32%), while Washington (53%), Oregon (76%), and California (72%) are all in the bottom U.S. 10 states but exhibit varying degrees of ownership (Quick and Tjepkema, 2023; U.S. Energy Information Administration, 2020). In addition to these climatic differences across regions, there are a range of socio-economic features within each state/province which shape its vulnerability. For example, each province/state contains large metropolitan regions and dense urban areas which are subject to urban heat island effects, and has stark inequalities in people's capacity to adapt to extreme heat that are partially structured along lines of income, race and age (Kearl and Vogel, 2023; White et al., 2023; Henderson et al., 2022). By analysing the Pacific Northwest, this study aims to explore how these diverse climatic and social factors shape how people adapt their everyday lives to heatwaves.

The study period covers three summers after the start of the COVID-19 pandemic (2020, 2021, 2022), including periods both during and after the restrictive mobility policies implemented by governments to limit the spread of disease. Ly et al. (2023), who focus on extreme heat in the San Francisco Bay Area from 2020 to 2021, find that even during stringent stay-at-home measures, extreme heat led to a range of mobility behaviour changes. The current paper accounts for the influence of varying COVID-19 restrictions, which differ across jurisdictions and years (Ding et al., 2020; Bollyky et al., 2023), through a matched-pair algorithm that aims to isolate heat-related activity differences in each county. In addition, year-level fixed effects are included that account for annual differences in how people responded given the changing environmental and policy factors.

The remainder of this section first introduces heatwaves as social disasters and discusses the role of cooling centres as places of refuge. Next, it summarizes existing efforts to characterize heatwave adaptation using large-scale mobility data. Then, the time-geographic approach is explained along with its relevance to heatwave adaptation, highlighting the importance of considering heatwave adaptation as the result of an activity scheduling process. Finally, the analytical framework of this study is presented, which operationalizes time-geographic concepts to study heatwave adaptation alongside the constraints of daily life.

1.1. Heatwaves and protective behaviours

Extreme heat manifests as a disaster during a 'heatwave', commonly defined as consecutive days of extreme temperatures that surpass regional norms (Perkins and Alexander, 2013). These events have

been found to disproportionately harm marginalized groups such as low-income individuals, Hispanic and Black populations, and the elderly (Osberghaus and Abeling, 2022; Lin et al., 2009; Hoffman et al., 2020; Hsu et al., 2021; Arnold et al., 2022; Gronlund, 2014). Despite their high mortality rates, heatwave deaths are largely preventable, the most protective factor being working air conditioning in the home, followed by spending time in a cool space outside the home (Bouchama et al., 2007; Semenza et al., 1996; Kovats and Hajat, 2008; Ostro et al., 2010; Jay et al., 2021). Simply increasing household air conditioning is a response with numerous issues, including affordability and its high energy usage, which creates a negative feedback loop as it contributes to the climatic change which further increases the speed of air conditioning adoption (Lundgren-Kownacki et al., 2018). As a result, understanding opportunities and challenges for seeking cool environments is a pressing topic to improve resilience to heatwaves, and the form of adaptation focused on in this study.

While the effects of heatwaves on human health are impacted by immediate climatic conditions, they are mediated through the geographic and socio-economic context of a region and its residents. The general availability of residential air conditioning in a city is dependent on a region's typical climate (Joe et al., 2016). This leaves typically temperate regions such as the Pacific Northwest, especially its more northern areas, highly vulnerable relative to hotter areas of North America with greater air conditioning prevalence. Socio-economic inequalities also impact heat vulnerability, as lower-income, Hispanic, and Black individuals face greater occupational heat exposure while having lower air-conditioning ownership rates at home or forgoing its use due to the cost of electricity (Hesketh et al., 2020; Harlan et al., 2006; Hayden et al., 2017; Rosenthal et al., 2014; Guardaro et al., 2022; O'Neill, 2005; Romitti et al., 2022). This compounds the risks faced by these marginalized groups, who disproportionately live in hot, dense urban areas subject to urban heat island effects (Hsu et al., 2021; Hoffman et al., 2020). Elderly populations are also highly at-risk during heatwaves, facing greater chronic disease burdens and having reduced abilities to thermoregulate, while also lacking critical networks of social support during disasters (Klinenberg, 1997; Kafety et al., 2020).

When individuals are unable to cool within the home during heatwaves, they are recommended to seek refuge to cool locations outside the home. These include 'informal' cooling facilities, such as indoor retail and recreation spaces, parks, and swimming pools with regular schedules and resources (Palecki and Kunkel, 2001; Widernyski et al., 2017). Governments also prepare 'formal' cooling centres in community centres, libraries, or new infrastructure to provide air-conditioned environments (Bedi et al., 2022; Widernyski et al., 2017). Social and psychological factors shape the usage of cooling facilities, including a lack of perceived risk among vulnerable populations, a stigmatization of government cooling locations, and inadequate behavioural adjustments during early heatwaves (Sampson et al., 2013; Wolf et al., 2010; Anderson and Bell, 2011). An important barrier to the use of cooling facilities, whether formal or informal, is people's ability to reach them (Bradford et al., 2015; Aminipouri et al., 2016; Quick et al., 2022; Li et al., 2024; Eisenman et al., 2016; Fraser et al., 2017). This issue of accessibility is heightened for those most urgently in need, including older individuals who are less mobile and may lack social support, as well as lower-income individuals who cannot afford to seek cooling given monetary or work constraints (Bedi et al., 2022).

1.2. Heatwave mobility analyses

As people's behavioural adaptations — such as spending more time at home or visiting cooling centres — are associated with changes in mobility, a rapidly growing body of literature is analysing high volume mobility data to understand how people adapt to heatwaves. The first branch of literature has analysed changes in overall activity levels as a function of heat, while the second has quantified adaptation-specific

mobilities to potential cooling locations, analysing how their usage changes during heatwaves.

In the activity level analyses, data sources range from subway turnstile data in New York City (Stechemesser and Wenz, 2023) to cell-phone mobility data in Los Angeles County, Houston, Tokyo, across China, and globally (Ly et al., 2023; Gu et al., 2024; Tian et al., 2024; Kumakura et al., 2024; Zou et al., 2023; Fan et al., 2023; Linsenmeier, 2024). While all studies focus on activity levels during periods of extreme heat, they use varied approaches and explore diverse questions. Gu et al. (2024) distinguish flows between neighbourhoods, finding reductions in short-distance travel during heatwaves and unchanging long-distance travel. Other examples include Tian et al. (2024), Fan et al. (2023), and Kumakura et al. (2024), who explore changes in activity timing within a day, and Linsenmeier (2024) who examines how a region's mean climate influences its relationship between temperature and park activity at a global scale. Overall, these studies find a range of changes to activity levels during periods of extreme heat, which are influenced by various climatic, land-use, and socio-economic factors.

In an adaptation-specific mobility study, Derakhshan et al. (2023) use cell-phone mobility data to compare spatial patterns of smartphone locations between heat and control days during the summer of 2017 in Los Angeles County. They observe that 90% of visits to pre-defined cooling resources were to informal locations (e.g. shopping centres), greater usage among individuals from lower-income and older neighbourhoods, longer use of cooling centres (1.1–1.7 times longer) during heatwave days, and a positive relationship between visitation and proximity to the nearest transit stop. This research sheds light on adaptive mobilities during heatwaves as they unfold in space and time, how urban form shapes them, and how they intersect with vulnerable population characteristics.

1.3. Heatwave adaptation conditioned by everyday life

The section below will begin by introducing the process of activity scheduling – grounded in concepts from travel behaviour and time-geography literature – as an approach to understand how adaptive responses during heatwaves are conditioned by everyday life. Subsequently, the analytical framework of this study will be introduced, exploring the interdependence of activities across the climatic, temporal, and contextual features of heatwaves.

1.3.1. Activity schedules and space–time constraints

The sequence of activities and trips individuals participate in on a given day, known as the daily activity pattern, is the result of a complex process of activity *scheduling*. This process, which ultimately shapes the structure of everyday life, can be understood through Hägerstrand's (1970) time-geographic framework. The basic conditions of this framework include, but are not limited to, the premises that people are indivisible and time is limited. As a result, the activities and trips individuals can undertake in a given day are in competition with each other and subject to various constraints in space and time. These constraints can be categorized as capability, coupling, and authority constraints. Capability constraints are physiological, instrumental, or cognitive in nature, including the need for food and sleep, being able to travel with the means at one's disposal, and having knowledge of one's environment. Coupling constraints reflect that some activities require co-occurrence with other people and/or materials, determining whether and when individuals must visit the workplace, for example. Authority constraints are institutional, such as laws, rules, and norms which determine times that certain activities can and cannot be performed.

Different types of activities are associated with different sets of constraints, though their exact nature and stringency will differ from individual to individual (interpersonally) and between situations for a particular individual (intrapersonally) (Schwanen et al., 2008b; Shen

et al., 2015; Zhang et al., 2024). Using an example of paid work activities, individuals able to work remotely face lower coupling constraints to the workplace compared to those who must work in-person. This point emphasizes that although traditional links between activities and constraints have weakened with the rise of digital technologies (Couclelis, 2009; Schwanen et al., 2008a), many still remain. Intrapersonally, paid work constraints may shift due to a variety of situations, including ordinary circumstances such as paid leave during an illness, or during extreme circumstances such as an unforeseen heatwave, as some workplaces close or opening hours are reduced or shifted (Tetzlaff et al., 2023).

In everyday life, the scheduling and rescheduling of some activity types tends to be easier or less costly than for others. This creates a scheduling hierarchy, with some activities more flexible than others based on individuals' commitment and their space and time fixity (Cullen and Godson, 1975). Much literature assumes that paid work is at, or close to, the top of that hierarchy (Hägerstrand, 1970; Cullen and Godson, 1975; Kwan, 1999; Schwanen et al., 2008b). Also considered high in the hierarchy are certain activities at home, for sleep, personal care and caring for others. Transit usage, often necessary to conduct trips for those without vehicles in auto-centric societies, is similarly important in this scheduling hierarchy. These three activities (home, work, transit), defined here as 'anchor' activities, represent rigid points in space and time which individuals arrange other, more flexible activities around (Cullen and Godson, 1975; Kwan, 2013). The next rung in the hierarchy are 'essential' activities, such as grocery and pharmacy visits, which are necessary for household maintenance (Wen and Koppelman, 2000), but more flexible in the daily and weekly schedules of individuals. Finally, 'discretionary' activities such as retail, recreation, and park activity are the most flexible and the last to be scheduled, despite taking on important cooling roles during heatwaves (Widernyski et al., 2017; Derakhshan et al., 2023; Barnett-Itzhaki et al., 2023; Kabisch et al., 2021).

1.3.2. Heatwave adaptation through an activity participation lens

As heatwaves occur alongside everyday life, people's participation in cooling activities is contingent on the activity scheduling process, competing with other activities of varying flexibility and constrained in space and time. As a result, adaptive responses may not always be possible – seeking cooling may place incompatible claims on the limited time and mobility resources of an individual who must juggle employment and/or domestic responsibilities, for example (Kwan, 1999; Schwanen, 2006). Formal disaster guidance is often ignored, augmented, or adapted to suit people's own needs and priorities (Steele et al., 2023). This means that a more complete understanding of cooling access requires uncovering which activities continue, which can be replaced, and how they constrain each other during heatwaves. Evidence for these substitutive mechanisms exists from an analysis of time use survey data from 2003–2006, which found changes in time allocation to indoor leisure, outdoor leisure, and labour as a function of high temperatures (Graff Zivin and Neidell, 2014).

Considering different activities' flexibility, leaving the home to engage in anchor activities, such as work, has different implications for heat vulnerability than going to a park or retail centre for refuge from extreme heat. The former typically implies a rigid point in an individual's activity schedule that shapes non-work heat relief opportunities in space and time. The latter more likely conveys an ability to engage in potentially cooling activities around (or substituting) existing anchor activities, involving adaptive capacity in the form of schedule flexibility. It is important to note that the same activity category may be protective for some but life-threatening for others, such as those who have air conditioning at home and work compared to those who do not. While more detailed activity data could unveil specific changes to activity schedules and their structure, this paper analyses changes in activity participation which result from this scheduling process,

beginning to shed light on the various interdependent processes which shape adaptation.

The importance of distinguishing activity types is evident from the activity level analyses introduced in Section 1.2. Four of the studies assess the impact of socio-economic inequalities on activity levels during extreme temperatures, discussing that disadvantaged individuals may be especially vulnerable based on their activity changes, despite differing findings. Stechemesser and Wenz (2023), Ly et al. (2023), and Tian et al. (2024) find that individuals in lower-income regions are *less able* to reduce mobility during periods of extreme heat – the latter during both day and night – discussing potential factors such as increased work and personal obligations, the use of public transport to escape local heat conditions, and generally lower adaptive capacity. In contrast, Gu et al. (2024) find that extreme temperatures disproportionately *inhibit* the activity of disadvantaged social groups, contextualizing their results by citing a lack of travel options and less disposable income. These studies may reflect contextually relevant mechanisms, but a greater understanding of vulnerability requires uncovering which different kinds of activities are undertaken and how they constrain each other on a given day. While some activity-level analyses distinguish activity categories (Linsenmeier, 2024; Fan et al., 2023; Kumakura et al., 2024), their scope has mainly been limited to discretionary activities such as parks and retail, or broader land use zones, and interdependent relationships with other day-to-day activities have not been considered.

Adaptation-specific analyses, such as Derakhshan et al.'s (2023) disaggregated analysis on cooling centre usage during heatwaves, focus on specific, adaptive behaviours during heatwaves. Focusing on one single adaptive behaviour is limited because this disregards the multiple ways in which a given adaptation is enabled and constrained by (changes to) other activities undertaken on a given day. Unveiling how activity schedule constraints impact cooling is especially important in the context of heatwaves, as a study in Boston found that when individuals could choose where they spent their time, which equals a situation of weak space–time constraints, outdoor temperatures had little relationship to their individual heat exposure (Kuras et al., 2015).

1.3.3. Analytical framework

This study analyses interacting changes to people's daily activities during heatwaves. These changes are conceptualized as the outcome of the activity scheduling process, whereby time is limited and activities vary in flexibility. Specifically, the analysis uncovers how anchor (home, work, transit), essential (grocery/pharmacy), and discretionary (retail/recreation, parks) activity change *together* during heatwaves, co-occurring and competing with each other on a given day. Grounded in prior literature on heatwaves and associated vulnerabilities, this study explores how adaptive responses are shaped by the climatic, temporal, contextual features of heatwaves.

Climatically, the absolute temperature unveils how heatwave intensity, in a traditional sense, impacts adaptive responses during heatwaves. This factor is considered because prior mobility analyses have identified a range of activity changes during extreme temperatures (Stechemesser and Wenz, 2023; Ly et al., 2023; Gu et al., 2024; Tian et al., 2024) and specific usages of indoor cooling facilities (Derakhshan et al., 2023). In addition to absolute temperature, a heatwave's impact on heat stress is *relative* to a region's norm (Guirguis et al., 2018) – hence the often context-specific definitions of heatwave temperatures (Perkins and Alexander, 2013). This issue of relative intensity is also pertinent on shorter-term scales, as rapid increases in temperature that did not coincide with time to acclimatize resulted in greater emergency-department visits in the US, Pakistan, and various other countries (Van Der Linden et al., 2019). This phenomenon, referred to here as 'short-term' acclimatization, is explored by including a relative intensity variable, capturing how temperature *increases* between a closely matched heatwave and control day influence adaptation.

Various temporal features of heatwaves are considered, and these can be differentiated according to time scale. At the seasonal level, the year is considered to capture changing COVID-19 policies and climatic conditions across years, shown to influence activity level changes during extreme heat (Ly et al., 2023). At the heatwave level, early seasonal heatwaves are considered separately to discern how maladaptive behaviours may contribute to their greater mortality rates relative to later heatwaves (Lee et al., 2014; Anderson and Bell, 2011; Liss et al., 2017), and potentially capture the impacts of shifting institutional constraints as people take early summer vacations. By identifying heatwaves as distinct, multi-day events, two novel contributions are made regarding the dynamic, temporal nature of heatwave adaptation. First, the role of heatwave *length* on adaptive responses is explored, as periods of prolonged heat are associated with greater mortality rates (Anderson and Bell, 2011). Subsequently, a *stage* variable is included, which explores how adaptive responses evolve as distinct heatwaves progress through time, from their first to last day. Additionally, a weekend/weekday distinction within heatwaves is made, because most people face fewer rigid obligations and space–time constraints during weekend days and may hence adapt to heatwaves differently than on weekdays (Stechemesser and Wenz, 2023; Ly et al., 2023; Kumakura et al., 2024).

Contextual factors include the distinction between provinces/states across a climatically diverse latitude range, ranging from British Columbia, the most temperate, down to California. Inland and coastal regions are also compared, as coastal regions are typically more temperate, less air-conditioned, and have been found to face high health-risks due to heatwaves (Fraser et al., 2017; Joe et al., 2016; Guirguis et al., 2018). A region's typical climate influences its preparedness to manage extreme heat through physiological, behavioural, or infrastructural differences (Anderson and Bell, 2011) – the latter including low air conditioning or heat-resistant building materials where there was historically little need. These regional factors capture important elements of 'long-term' acclimatization. Through the inclusion of population density, urban form is explored as a contextual factor, which is important given the impact of urban heat island effects on mortality rates (Campbell et al., 2018; Hsu et al., 2021; Aram et al., 2020). Finally, socio-economic vulnerabilities which impact heatwave vulnerability are included, such as the role of income, race, and age in the competing activity changes undertaken during heatwaves (Hoffman et al., 2020; Hsu et al., 2021; Arnold et al., 2022; Gronlund et al., 2018). A summary of the analytical framework of this study is presented in Fig. 1.

2. Methods

2.1. Data

2.1.1. Mobility data

The mobility data used in this analysis is from Google Community Mobility Reports, a public data set released by Google during the COVID-19 pandemic to monitor mobility changes in response to COVID-19.¹ Compared to a pre-COVID-19 baseline (Jan 3–Feb 6, 2020), the data measures the county-level² percent changes in (1) time spent in one's residence, and total visitation to (2) one's workplace, (3) transit, (4) grocery/pharmacy, (5) retail/recreation/recreation, and (6) parks. The activity types provided by Google are broad, high-level categorizations which contain many location types within them. The examples provided in each mobility report document are shown in Table 1,³

¹ <https://www.google.com/covid19/mobility/>

² County-equivalent level in BC (administrative regions), referred to as counties for simplicity.

³ Example report for California in October 2022 https://www.gstatic.com/covid19/mobility/2022-10-15_US_California_Mobility_Report_en.pdf.

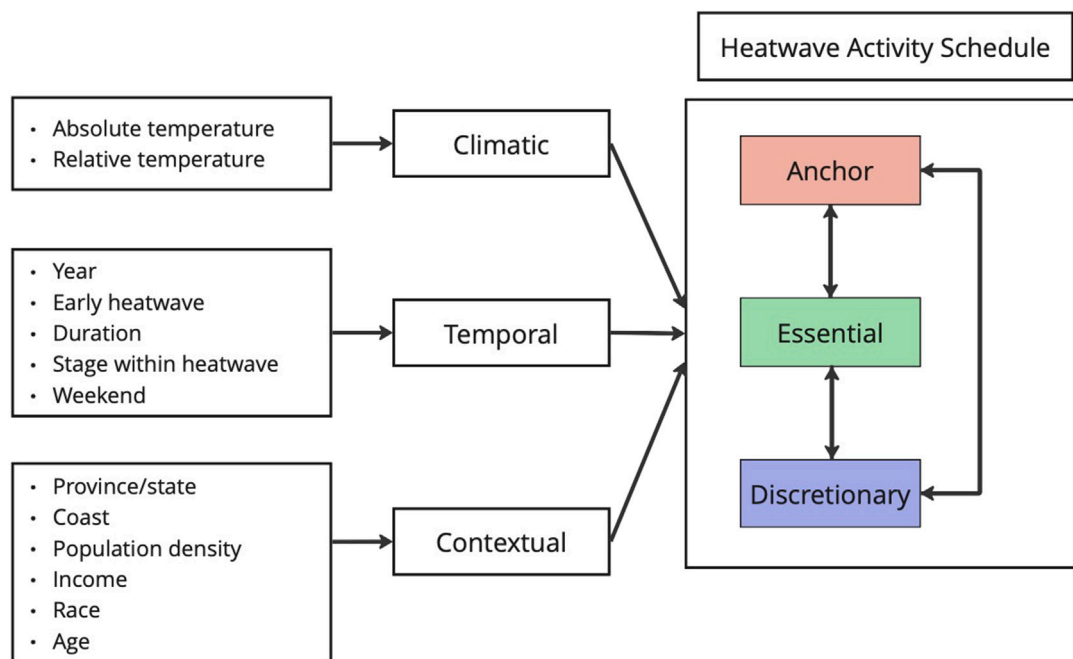


Fig. 1. Analytical framework of this study, focusing on interdependent activity changes among anchor, essential, and discretionary activities during heatwaves.

Table 1

Google community mobility reports activity details.

Activity	Units of % change	Examples in reports
Residential	Time spent (hours)	People's places of residence
Workplaces	Visitor numbers	People's places of work
Transit	Visitor numbers	Public transport hubs such as subway, bus, and train stations
Grocery/pharmacy	Visitor numbers	Grocery markets, food warehouses, farmers markets, speciality food shops, drug stores, pharmacies
Retail/recreation	Visitor numbers	Restaurants, cafes, shopping centres, theme parks, museums, libraries, movie theatres
Parks	Visitor numbers	Public gardens, national parks, public beaches, marinas, dog parks, plazas

although less obvious locations are included as well, such as taxi-stands and seaports under 'transit'. Over the course of the 5-week baseline period, the average level of activity on each day of the week was generated and used to create the relative percent change of each day from March 2020 to October 2022. The six activity types in the Google Community Mobility Reports data are presented in Fig. 2, conceptually clustered based on their roles in the activity schedules of individuals.

Traditionally, activity pattern analyses required data sources such as travel diaries (Kwan, 1998; Schwanen et al., 2008b), in which respondents log all of their daily travel over a period of time. These data sources, while rich, suffer from low compliance, recall bias, and sampling bias, posing practical barriers to their use, and limiting their scale (Kang et al., 2018). The rise of mobile phone-based data sources, whether GPS or call detail record-based, have enabled large-scale activity pattern analyses. Through their large sample sizes and 'always-on' nature (Salganik, 2019), they have enabled retroactive studies to explore responses during past disasters, such as COVID-19-related mobility dynamics in the United States and Brazil (Chang et al., 2020; Peixoto et al., 2020) and cyclone-related migration patterns in Bangladesh (Lu et al., 2016).

The data is generated using aggregated, anonymized data of Google users with Location History on, with missing data where sample sizes

(not provided) were too small to 'confidently and anonymously estimate the change from the baseline',⁴ defined with a 100-user minimum threshold (Aktay et al., 2020). This data set has been used extensively to understand how various types of activity changed as a result of the pandemic and mobility-restricting policy responses (Liu et al., 2021; Ilin et al., 2021; Elarde et al., 2021; Cot et al., 2021; Kamińska and Kazak, 2024), and was used in Linsenmeier's (2024) study on global variations in preferred temperatures for park activity. While raw Google Location History data is not a replacement for individual-level activity schedule diaries (Cools et al., 2021), the data set used in this study has been benchmarked against census and high-volume mobility data, shown to be effective for regional changes in mobility (Gibbs et al., 2023; Finazzi, 2020; Sganzerla Martinez and Kelvin, 2023).

The data that Google released has key limitations – it is pre-aggregated to large spatial units (i.e. counties in US context), and temporal units (i.e. days) – it cannot be used to represent sequences of activities and trips, and – with the exception of time at home – does not provide information on how much time was spent at particular

⁴ <https://support.google.com/covid19-mobility/answer/9824897?hl=en&sjid=7759654188027116565-EU>

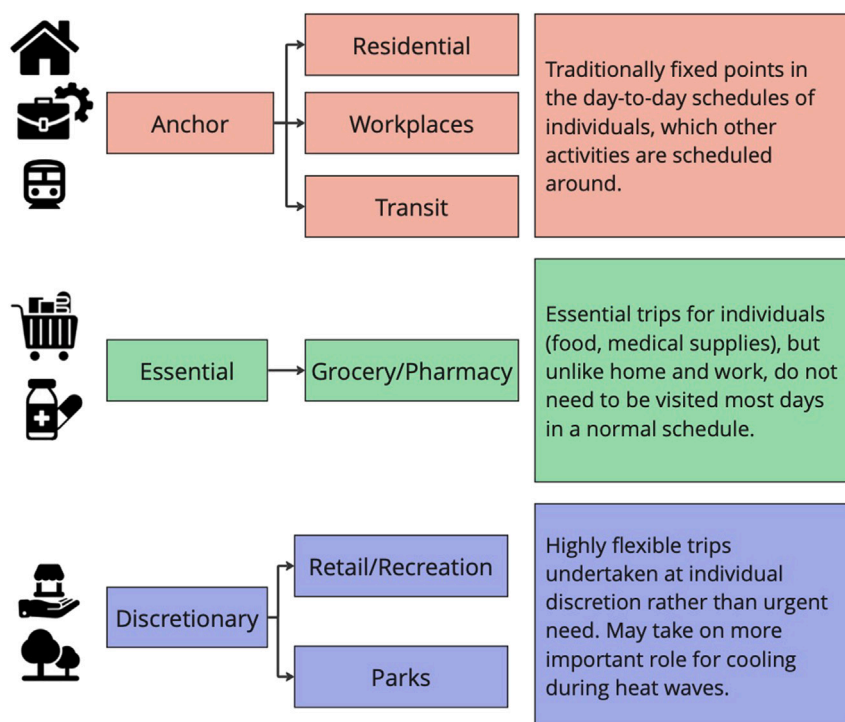


Fig. 2. Conceptual groupings of activity variables.

Table 2
Strengths and weaknesses of Google Community Mobility reports.

Strengths	Weaknesses
Harmonizes activity and location data	Pre-aggregated spatio-temporal data
Diverse range of labelled activity types	Lacks indoor/outdoor distinction
Covers vast spatio-temporal range	Activity inferred from location
High smartphone penetration rate	Sampling bias and digital divide

activity location types. The data therefore offers a rudimentary understanding of activity participation. The activity-type groupings also do not indicate whether workplaces are indoors or outdoors – the former may be protective – or whether people visit others’ residences. The aggregated nature of the data also entails the risk of ecological fallacy, while sampling bias still remains a concern (though less so than with travel and time use diary studies).

The data set also has a number of strengths which can be leveraged to meet the goals of this study. It distinguishes key destinations in activity schedules by harmonizing rich activity and location metadata from Google Location History. The range of activity types captured in the data are highly suitable for examining the interdependent relationships between activities during heatwaves, remaining relevant for cooling access even without detailed information on activity participation. Additionally, the daily-level mobility changes, which cover a vast spatio-temporal range, make possible a large-scale analysis of heatwave responses across a climatically diverse region and numerous summers. Finally, while sampling bias remains a limitation to note, there is very high penetration of smartphone ownership in Canada (84%) and the United States (85%) (Perrin, 2021; Statistics Canada, 2023b; Oliver et al., 2015). A summary of strengths and weaknesses of the data set are presented in Table 2.

2.1.2. Temperature data

The temperature data used in this analysis is the ERA5 climate re-analysis data set created by the European Union’s Earth Observation Programme (Copernicus).⁵ Accessed through Google Earth Engine, this

data set provides global modelled estimates of hourly 2 m air temperature at 11 km² grid cells. The estimates are resampled using nearest neighbours to a 5 km² resolution when needed to fit into smaller counties. Climate re-analysis data sets combine past observations with models to generate consistent time series data, a valuable feature for comparative, international studies. Compared to land surface temperature, 2 m air temperature better reflects human heat stress (Venter et al., 2021). Hourly temperature data from each county across the Pacific Northwest are collected from May 1 to September 31 from 2016–2022. The four years of historical temperature data (2016–2019) are added to the period of interest (2020–2022) to help identify heatwaves against norms. This amount of historical data is comparable to Nori-Sarma et al. (2022), who used three years of historical temperature data to identify greater emergency department visits during the June 2021 heatwaves in Portland, OR and Seattle, WA.

2.1.3. Socio-economic data

County-level data on population density, income, age, and race in Washington, Oregon, and California are collected from the 2020 American Community Survey (U. S. Census Bureau, 2020). The same socio-economic variables are collected for BC at the administrative region-level from the 2021 Canadian Census (Statistics Canada, 2023a).

2.2. Identification of heatwave and control days, linking activity change data

2.2.1. Heatwaves

For each county, a heatwave is identified as a period of at least two consecutive days where the average of its maximum grid cell temperatures exceeds the 90th percentile from the 2016–2022 period between

⁵ <https://climate.copernicus.eu/climate-reanalysis>

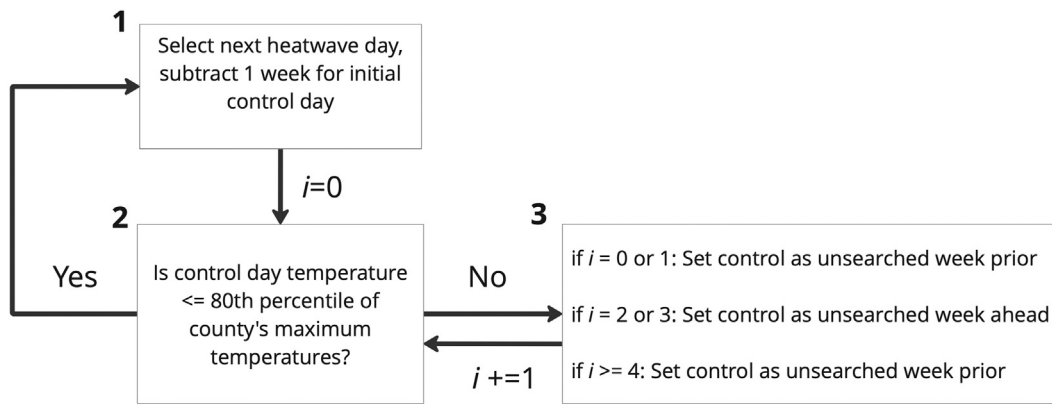


Fig. 3. Control day selection algorithm.

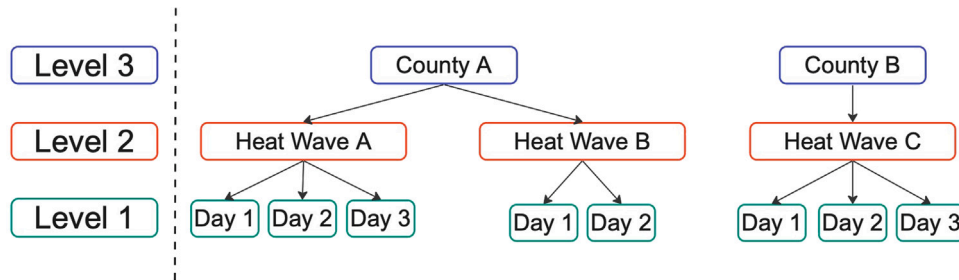


Fig. 4. Hierarchical data structure of days within heatwaves, and heatwaves within counties.

May 1 to September 31, re-configuring code from [Hobday et al. \(2016\)](#). A robustness check which defines heatwaves using only the highest recorded value in the entire county (not an average maximum) produced comparable results. The average maximum provides a more conservative, regional estimate of heatwaves that is less susceptible to outlier influence.

In a review of heatwave definitions, [Perkins and Alexander \(2013\)](#) discuss that relative severity measures, which they define using 90th percentile temperature thresholds, are more suitable for health-related research due to the importance of adaptive capacity on excess mortality and morbidity. Both 90th and 95th percentile thresholds were tested to identify heatwaves, producing consistent climatic and temporal relationships in the model output, however variations were observed among the socio-economic-related activity changes. From a conceptual standpoint, the 90th percentile was deemed most suitable for the equity-related aims of this study. Mild heatwaves, which may only pose an inconvenience to resilient populations, are likely to disproportionately harm heat-vulnerable subgroups who face more exposure in their day-to-day lives ([Guardaro et al., 2022](#)). A 90th percentile threshold captures the impacts of both mild and severe heatwaves – all of which are relatively extreme to their context – capturing a more complete range of responses. Regarding heatwave lengths, studies typically define minimum thresholds as between two and four days. This study chooses a two-day threshold as the most inclusive minimum, linked to various heat-related impacts on death and hospitalization rates in the review of [Arsad et al. \(2022\)](#).

2.2.2. Control days

The Google Community Mobility Reports data captures daily percent changes relative to a pre-COVID-19 baseline for each county and each specific day of the week. For example, the percent change in visitation to retail/recreation in Los Angeles County on a Monday is calculated relative to the average of all Mondays in Los Angeles County from the baseline period. Due to risks of evolving virus or policy conditions over the course of a summer, each heatwave day is assigned

its own closest control day to minimize the unaccounted influence of within-season changes and annual magnitude differences. To classify a control day for a given heatwave day, it must be on the same day of the week, and it must not be on the cusp of being classified as a heatwave (control day temperature is maximum 80th percentile for a county). The algorithm first searches the two weeks prior to the heatwave day, then the two weeks after the heatwave day, then iteratively searches weeks backwards until the criteria is met ([Fig. 3](#)). To allow adequate room to search backwards in May for a control day, the algorithm only considers heatwaves beginning from June 1 onwards, resulting in 63% of pairs being 7 days apart, 26% being 14 days apart, and 11% being at least 21 days apart.

2.2.3. Creation and interpretation of the ‘activity change’ variable

The heatwave and control day activity levels are subtracted from each other, outputting the ‘heat-control activity difference’ for each of the 6 activity types. Days that fall on public holidays are removed due to potentially confounding impacts, as well as extreme outliers greater than 4 standard deviations from the mean of each activity change variable. The ‘heat-control activity difference’ can be interpreted as the percentage change in the level of activity standardized to the county’s baseline.

2.3. Model building

2.3.1. Multi-variate multi-level model

The heat-control day observations are nested within heatwaves, which are nested within counties, shown in [Fig. 4](#). A three-level multi-level model is implemented to account for this, which in its simplest form extends the traditional ordinary least squares (OLS) regression model to allow each heatwave and county to have its own intercept based on group-specific error terms. The three-level model is written as:

$$Y_{ijk} = \beta_{0ijk} + \beta_1 X_{ijk} + e_{0ijk} \quad (1)$$

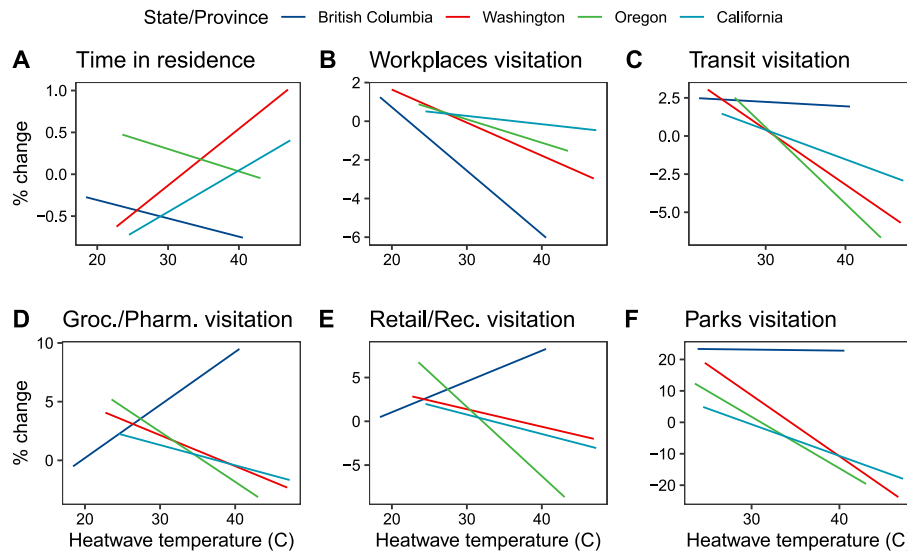


Fig. 5. Descriptive plot of heatwave day temperatures against the heat-control mobility difference for all 6 dependent variables, emphasizing state/province-level heterogeneity and the need to include an interaction term between temperature and state/province.

where Y_{ijk} represents the change in activity (to one of the six location types) for day i in heatwave j in county k . The X_{ijk} represents an explanatory variable at the day level and β_1 is the estimated regression coefficient for X_{ijk} . Within each grouping level, the error terms (random effects), are assumed to follow a normal distribution, where the usual error term e_{0ijk} captures the random variation across days with a mean of 0, shown by $E(e_{0ijk}) = 0$, and a variance estimated by the model, expressed as $\text{var}(e_{0ijk}) = \sigma_{e_0}^2$ (Bell et al., 2019). The intercept structure β_{0ijk} contains a fixed mean γ_0 , in addition to heatwave-specific error terms given by u_{0jk} , and county-level error terms given by v_k . Decomposing the β_{0ijk} can therefore be written as:

$$\beta_{0ijk} = \gamma_0 + u_{0jk} + v_k \quad (2)$$

This random intercept model is used in the analysis, allowing each heatwave and county to have its own random variation around the fixed γ_0 intercept. By parameterizing random effects as part of a distribution, the analysis can explore group level (heatwave and county) characteristics that explain deviations from the average intercept, which is of substantive interest to our research question.

The dependent variables in this analysis represent percent changes in time spent at home or visitation to workplace, transit, grocery/pharmacy, retail/recreation, and parks. A multi-variate multi-level model is implemented, simultaneously modelling all responses together, controlling for their inter-relatedness while assessing their relationships with the independent variables. This enables direct comparisons and contrasts across changes in activity types (Snijders and Bosker, 2011; Schwanen et al., 2004; Mohan et al., 2011; Davies et al., 2021).

A level is added below the day from Fig. 4, where i now represents percent changes in each the following: (1) time in residence, and visitation to (2) workplaces, (3) transit (4) grocery/pharmacy, (5) retail/recreation, (6) parks. The j level now represents the day, the k level represents heatwaves, and the new l level represents the county. The equation, abbreviated to only show two of the six dependent variables, is now given by

$$Y_{ijkl} = \beta_{01} Z_{1ijkl} + \dots + \beta_{06} Z_{6ijkl} + \beta_{11} Z_{1ijkl} X_{jkl} + \dots + \beta_{16} Z_{6ijkl} X_{jkl} + e_{01jkl} Z_{1ijkl} + \dots + e_{06jkl} Z_{6ijkl} \quad (3)$$

where $Z_{1ijkl} = 1$ for the change in residential time, $Z_{2ijkl} = 1$ for the change in workplace visitation, and the same is applied for the other

four dependent variables. The β_0 , β_1 , and e_0 have the same meaning as the single response multi-level model, now simultaneously modelling the six response variables together. The model is estimated using the R2MLwiN software (Zhang et al., 2016).

The first section of the results uses an intercept-only (empty) model, serving two purposes: (1) it explains how much each hierarchical level (day, heatwave, county) contributes to the total variance in each activity change response variable, and (2) it provides covariance terms to explore the interdependence between the various activity types at each level. Subsequently, the full model is produced, populated by the variables presented below.

2.4. Independent variables

Based on the analytical framework of Section 1.3.3, this analysis considers both absolute and *relative* temperature, the latter defined as the temperature *increase* between the heatwave and control day. To account for varying relationships of the dependent variables with absolute temperature across states/provinces (Fig. 5), an interaction term of the dependent variables with absolute temperature across states/provinces is added to the model. The interaction terms are presented with all other covariates in Table 3.

A county's mean temperature in January 2020 is also included, as the temperature of a region when the baseline Google mobility data was collected would influence baseline mobility magnitudes, which would subsequently impact the percentage change values. For example, in a region with cold temperatures, baseline mobility levels to parks may be low, lowering the denominator in Google's raw percentage change calculation, amplifying (positively or negatively) the percentage change. This is interacted with slopes for each state, due to the impacts that regionally different climates may have in this relationship.

The temporal variables include fixed effects for 2021 and 2022, compared to 2020 as a reference year. Dummies are added if a heatwave overlaps with June – capturing early seasonal heatwaves – and if it is longer than 5 days. The stage variable measures how far, in percentage terms, a day is within a heatwave – capturing how activities evolve from the first to the final day. A variable is also added if a heatwave day falls on a weekend.

County-level contextual variables include the province/state variable (interacted with temperature), a coastal dummy, income, and proportions of non-white and age 65+ populations. For the socio-economic indicators, all counties are decile ranked within their state to

Table 3
Categorization and description of independent variables.

Var. Name	Level	Description	Min.	Mean	Max.
Climatic					
Abs. temp * state	Day	Heatwave temp. and state interaction term (C)	18.41	33.39	47.25
Temp. diff.	Day	Difference b/w heatwave and control day temp. (C)	1.18	8.30	26.19
Winter temp : state	County	Mean winter temp. during Google baseline period (C)	-16.39	3.67	14.46
Temporal					
Year = 2021	Heatwave	Fixed effects for 2021	0	0.38	1
Year = 2022	Heatwave	Fixed effects for 2022	0	0.36	1
June heatwave	Heatwave	Dummy if June heatwave	0	0.14	1
Heatwave dur.	Heatwave	Dummy if heatwave >= 5 days	0	0.23	1
Stage	Day	How far into a heatwave the observation day is (%)	0.08	0.64	1.00
Weekend	Day	Dummy if day on weekend	0	0.28	1
Contextual					
Coastal	County	Dummy if county on coast	0	0.30	1
Pop. dens.	County	Decile rank of pop. dens. within state/province	1	5.77	10
Income	County	Decile rank of income within state/province	1	5.61	10
Non-white	County	Decile rank of non-white pop. proportion within state/province	1	5.57	10
Over 65	County	Decile rank of over 65 pop. proportion within state/province	1	5.33	10

Table 4
Heatwave days and temperature summary statistics across states/provinces.

State	Heatwave days (n)	Mean (C)	Std. (C)	Min. (C)	Max. (C)
British Columbia	1081	27.6	3.4	18.4	40.1
Washington	1468	33.0	4.9	20.0	46.9
Oregon	1337	33.5	3.1	23.5	44.4
California	2200	36.5	4.1	24.5	47.3

Table 5
Heatwave events and duration (days) summary statistics across states/provinces.

State	Heatwaves (n)	Mean (d.)	Std. (d.)	Min. (d.)	Max. (d.)
British Columbia	294	3.9	2.0	2.0	9.0
Washington	441	3.6	1.9	2.0	11.0
Oregon	439	3.6	1.8	2.0	10.0
California	712	3.6	2.0	2.0	11.0

Table 6
Summary statistics for all 6 heatwave activity change variables (%).

Activity	Heatwave days (n)	Mean (%)	Std. (%)	Min. (%)	Max. (%)
Residential	4884	-0.1	1.5	-6.0	6.0
Workplaces	5944	-0.5	3.6	-18.0	16.0
Transit	3391	-0.7	8.5	-41.0	41.0
Groc./Pharm.	4482	1.3	6.3	-27.0	30.0
Retail/Rec.	5226	0.4	6.7	-30.0	31.0
Parks	2818	-1.6	26.8	-119.0	122.0

eliminate collinearity with the state variable, as well as to account for the differing currencies between British Columbia and the U.S. states. A variance inflation factor test indicated low multicollinearity among all independent variables in the model. The full vector of independent variables, X_{jkl} in Eq. (3) above, is expanded as follows:

$$\begin{aligned}
 X_{jkl} = & AbsTemp_{jkl} * State_{jkl} + TempDiff_{jkl} + Year_{jkl} + \\
 & HeatwaveDur_{jkl} + Stage_{jkl} + Weekend_{jkl} + Popdens_{jkl} + \\
 & Income_{jkl} + NonWhite_{jkl} + Over65_{jkl} + Coast_{jkl} + \\
 & WinterTemp_{jkl} : State_{jkl}
 \end{aligned} \quad (4)$$

3. Results

3.1. Descriptive statistics

3.1.1. Heatwave intensity and duration

Average heatwave day temperatures rise across states/provinces moving from North to South, but all heatwaves have average lengths of around 4 days everywhere (Tables 4–5). In British Columbia, the mean heatwave day temperature is 28C, followed by 33C in Washington,

34C in Oregon, and 37C in California, with state-level distributions plotted in Fig. 6. The differing numbers of heatwave days (Table 4), grouped within heatwaves (Table 5), are largely driven by the number of counties in each state. After removing missing values and outliers to create the data set, British Columbia has 24 counties, Washington has 36, Oregon has 34, and California has 56. The geographic distribution of average heatwave temperatures is shown in Fig. 7, where 12/162 counties are omitted due to insufficient mobility data.

3.1.2. Heatwave - control day activity differences

The distributions of raw activity change values (Table 6, Fig. 8) are influenced both by sample size and the nature of the activity being measured. The lower variance of residential activity is due to the nature of the Google data, measuring the change in ‘time in residence’ – a far more constrained range than the aggregate visitation used to calculate all other variables. After time in residence, workplace changes have the largest sample size and lowest variance, present in 5944/6086 heatwave-control day pairs, whereas changes in parks have the least number of observations (2818) and the highest variance. The disproportionately high standard deviation of parks – over 3 times

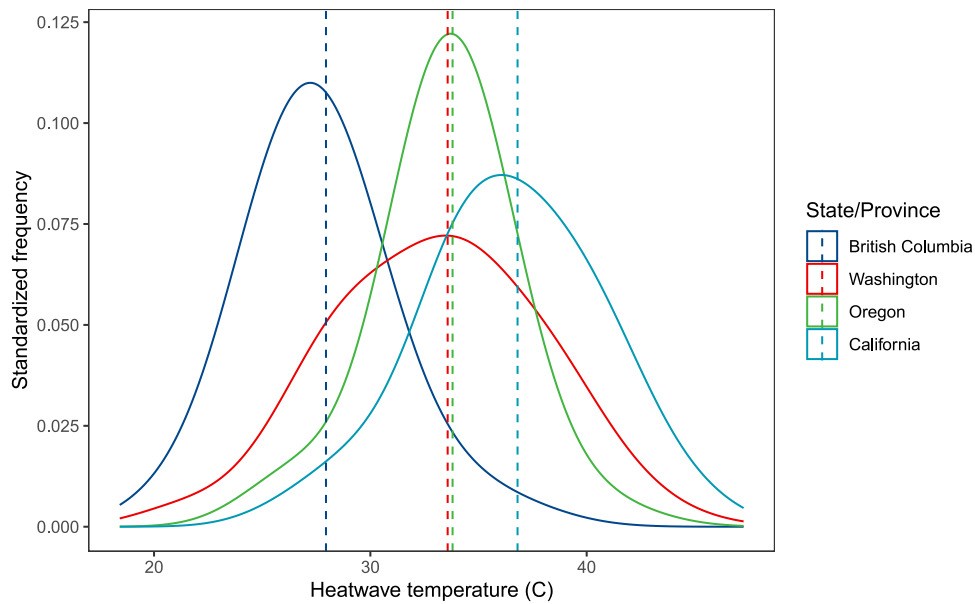


Fig. 6. Distribution of heatwave day temperatures across states/provinces.

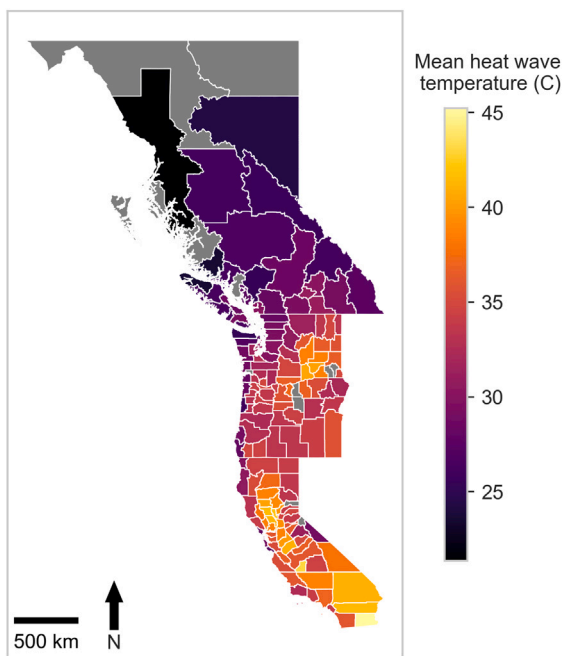


Fig. 7. Geographic distribution of average heatwave temperatures across the Pacific Northwest.

higher than transit, the next highest variance – suggests that by nature park activity is highly variable in addition to its lower sample size.

Across 2020, 2021, and 2022, despite vastly different overall mobility levels due to lockdown restrictions (Liu et al., 2021), the heatwave-specific activity changes have comparable distributions (Fig. 9). These annual distributions justify the inclusion of all years in the same model, where heterogeneity due to climatic or COVID-19 factors can be explored with annual fixed effects, such as the varying changes in time in residence during heatwaves across 2020, 2021 and 2022.

3.2. The (co)variance of heatwave responses

3.2.1. Impact of factors varying at day, heatwave, and county-level

Based on the results of the intercept-only model, factors that vary at each hierarchical level of the model (day, heatwave, county) have distinct impacts on the heatwave activity change response variables (Table 7). Across all outcome variables, factors that vary at the day level (Level 1), such as temperature, explain roughly 50% or more of the variation in the observed heatwave activity changes. Anchor variables (residential, workplace, transit), have the highest percentages of total variance explained at the day level, and the least variation explained by time-invariant county-level differences. Heatwave-level factors are the most influential to the variance in grocery/pharmacy visitation (39.0%) compared to all other responses. For discretionary activities, the explained variance in park visitation is more influenced by time-invariant, county-level factors (33.4%), whereas retail/recreation's distribution of variance skews more towards the day and heatwave levels. These findings support the use of a multi-level model, as all variables have 30+% percent of their variation explained at higher groupings, which are explored in the full model.

3.2.2. The interdependence of heatwave activity adaptation

Observing the covariances⁶ from the intercept-only model, strong patterns of co-occurrence and competition emerge among the activity change variables (Table 8). The relationships differ substantially across the three analytical levels, further supporting the use of multi-level modelling. Between-state differences in these relationships likely exist, contributing to the state-level differences explored in the full model.

Visitation to the workplace has competing, substitutional effects with both home and non-home activity types during heatwaves. Decreasing changes in workplace activity lead to positive changes in time at home (Level 1) and visitation to grocery/pharmacy (Level 2/3), retail/recreation (Level 1) and parks (Level 3). Additionally, changes in workplace activity exhibit substitutional effects with transit usage (Level 2), likely due to transit's strong co-occurrence with grocery/pharmacy

⁶ Covariances are converted to correlations for interpretability using the formula: $corr_{x,y} = \frac{Cov(x,y)}{\sqrt{Var(x)+Var(y)}}$.

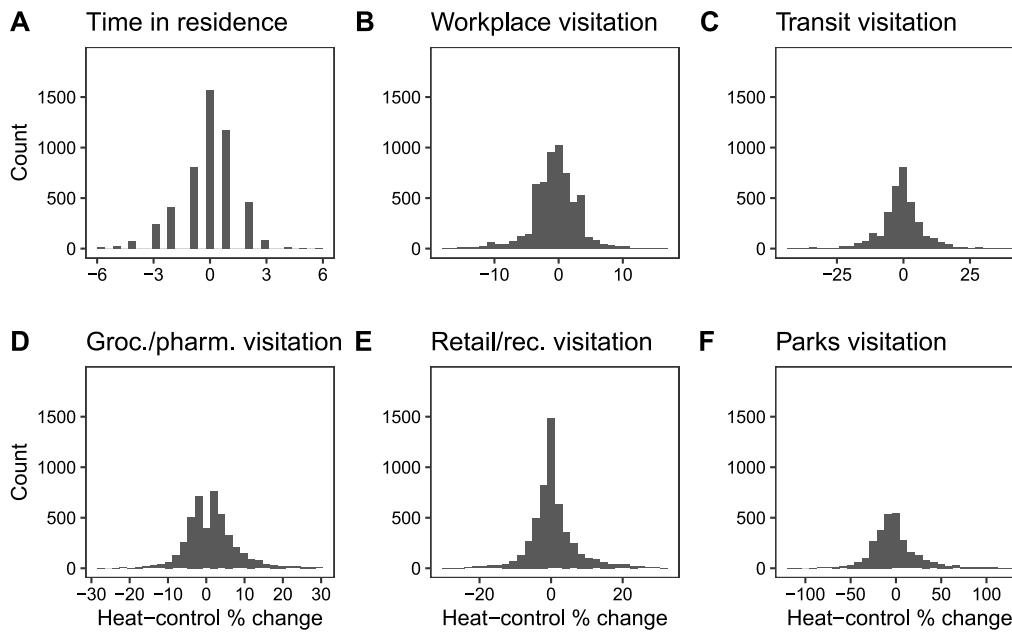


Fig. 8. Distribution of all heatwave activity change variables.

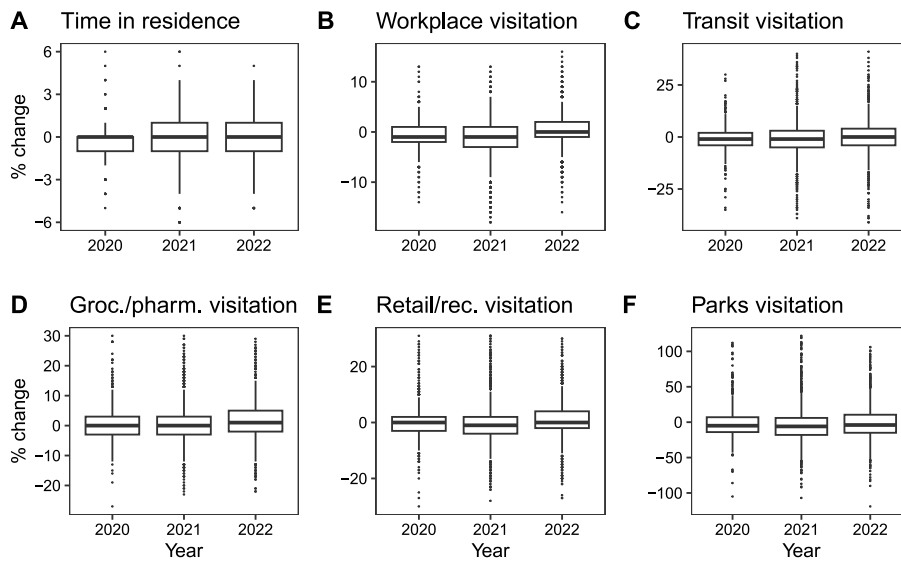


Fig. 9. Boxplot of average heatwave activity changes across years.

Table 7
Intercept-only model, explained variance at each hierarchical level.

Outcome	Level 1 (days)	Level 2 (heatwave)	Level 3 (county)
Residential	66.0%	27.6%	6.4%
Workplaces	69.5%	26.8%	3.7%
Transit	66.1%	24.1%	9.8%
Grocery/Pharm.	48.4%	39.0%	12.7%
Retail/rec/	49.4%	33.9%	16.7%
Parks	49.6%	17.0%	33.4%

(Level 1/2/3), retail/recreation (Level 1/2/3), and park (Level 1/3) visitation in the data.

Time spent at home competes with all activity types on at least one hierarchical level, exhibiting negative relationships with changes

in workplace (Level 1), transit (Level 1/3), grocery/pharmacy (Level 1/2/3) and park (Level 1/3) visitation during heatwaves. Changes in time in residence and workplace visitation also exhibit a *positive* covariance at Level 2, suggesting that some factors which vary at the

Table 8

Correlation matrix of intercept-only model. Depicts the relationships between dependent variables at each hierarchical level (day, heatwave, county).

	Residential	Workplaces	Transit	Grocery/pharm.	Retail/rec.	Parks
Residential	1					
	1					
	1					
Workplaces	0.16	1				
	0.15*	1				
	-0.05*	1				
Transit	-0.68*	-0.14	1			
	0.05	-0.18*	1			
	-0.16*	0.04	1			
Grocery/pharm.	-0.70*	-0.22	0.78*	1		
	-0.21*	-0.18*	0.37*	1		
	-0.28*	-0.09*	0.33*	1		
Retail/rec.	-0.72*	-0.23	0.78*	0.91*	1	
	-0.21*	-0.09	0.35*	0.77*	1	
	-0.28*	-0.11*	0.39*	0.66*	1	
Parks	-0.70*	-0.59*	0.73*	0.86*	0.87*	1
	-0.17*	-0.26*	0.24*	0.55*	0.53*	1
	-0.32*	0.02	0.32*	0.53*	0.56*	1
County						
Heat-wave						
Day						

*p<0.05

heatwave-level correspond to simultaneous decreases or increases in anchor activities.

At each level of the model, changes in grocery/pharmacy, retail/recreation, and park visitation appear to co-occur during heatwaves. These relationships are the strongest county, heatwave, and day-level relationships of the entire model.

3.3. Full multi-variate multi-level model

3.3.1. Model interpretation

In the final model (Table 9), California is used as a reference category, and 33C is the mean value at which the state-level fixed effects are calculated. To plot the state-level fixed effects in Fig. 10, all variables except heatwave day temperature are held constant at the mean across the Pacific Northwest. This includes a global average for the winter temperature predictor (4C), to neutralize biases due to varying temperatures in the baseline period of the Google Mobility data set. Only the statistically significant shifts will be discussed, unless otherwise specified.

3.4. Climatic variables

A North–South pattern emerges in changes to workplace visitation during heatwaves, with greater rigidity moving South across states/provinces. The most drastic shifts downwards are observed in the more temperate British Columbia ($p<0.001$), followed by Washington ($p<0.001$), Oregon ($p<0.001$), then California (Fig. 10B). A similar North–South pattern emerges when observing the relationship between workplace visitation and heatwave day temperature, the steepest negative slope in British Columbia ($p<0.001$), followed by Washington ($p<0.001$), then Oregon and California with more mild negative slopes ($p<0.05$).

The dynamics of non-work adaptation vary across regions. In Oregon, Washington, and California, a dominant pattern is a decrease in essential and discretionary activity as heatwave day temperatures rise. In Washington and California, these changes are met with increased time in residence as temperatures rise.⁷ Oregon, however, exhibits a more negative relationship with time spent in residence ($p<0.001$)

⁷ Note that California's mean heatwave temperature is 36C, where its time in residence estimate crosses the 0-axis.

and decreasing visitation to all other activity types – especially retail ($p<0.05$). This may be the result of greater time spent in non-home facilities for those who continued to visit them, a mechanism omitted in the 'visitation' metric but found in prior research (Derakhshan et al., 2023). This is a topic for further research.

Adaptive mechanisms in British Columbia are distinct from all other states, as heatwaves lead to decreasing time at home and greater visitation to spaces for essential and discretionary activities. This is evidenced through the negative intercept and slope for time in residence ($p<0.001$), which – coupled decreases in workplace visitation – correspond to the most positive intercepts for grocery/pharmacy ($p<0.001$), retail/recreation ($p<0.001$), and park activity ($p<0.01$). Additionally, increasing slopes with temperature emerge for grocery/pharmacy ($p<0.001$) and retail/recreation ($p<0.001$), the only region where this is seen.

Transit activity, despite being conceptualized as an anchor point in everyday activity schedules, appears to be used to engage in out-of-home non-work activities during heatwaves, as supported by the covariance analysis. This is best exemplified in British Columbia, which has the lowest workplace visitation across the four states/provinces, but a transit intercept shift that is 3.9% higher than California ($p<0.05$), shifting upwards with the increase in non-home activity (Fig. 10C). This mechanism is supported by prior literature finding a positive relationship between proximity to transit services and cooling centre usage during heatwaves (Derakhshan et al., 2023). This reliance on transit to reach out-of-home locations during heatwaves may also be influenced by a substitution away from active travel modes during periods of extreme heat. Park visitation is the only activity with a decreasing relationship with heatwave temperature in every state/province, consistent with the prior literature on activity levels in park/green spaces (Kumakura et al., 2024).

Greater relative heatwave intensities stimulate out-of-home non-work activity (Fig. 11). Controlling for the absolute temperature of the heatwave day, greater increases in temperature between heatwave and control days lead to relative decreases in time at home ($p<0.05$) and workplace visitation ($p<0.001$) for greater visitation to transit ($p<0.001$), grocery/pharmacy ($p<0.001$), retail/recreation ($p<0.01$), and parks ($p<0.001$). The impact of temperature increases on adaptive responses is particularly strong for parks (2.2% per degree Celsius), with a greater magnitude than any of the state-level relationships with absolute temperature.

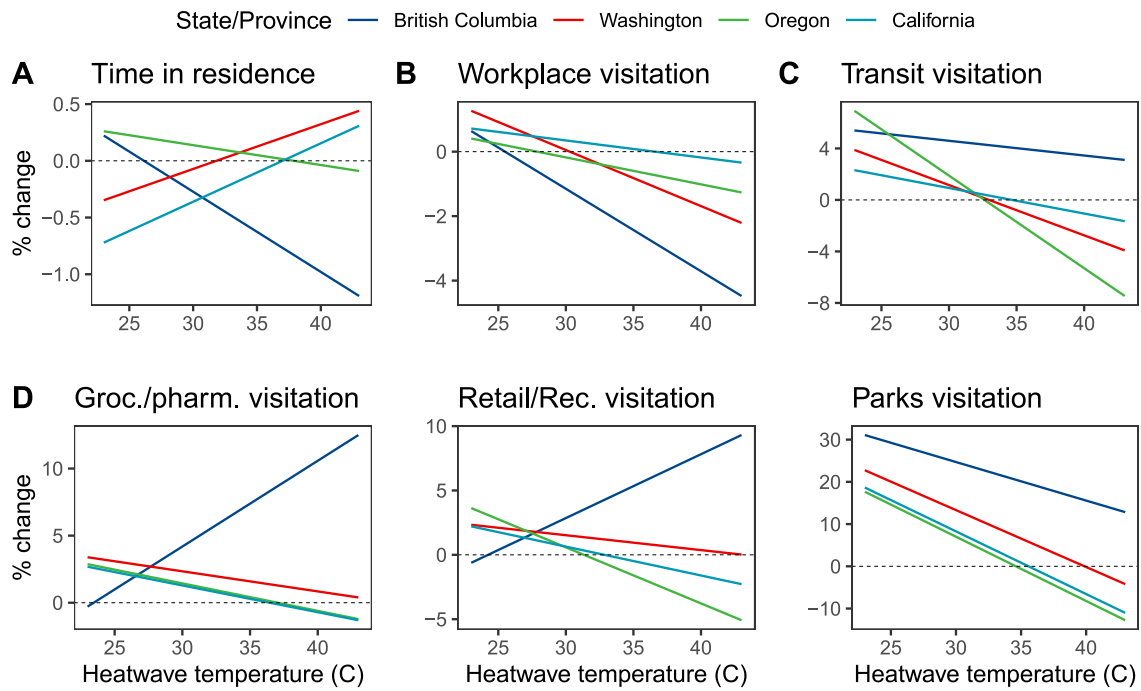


Fig. 10. Average percent changes in activity across all four states/provinces, and relationships with heatwave temperature (C).

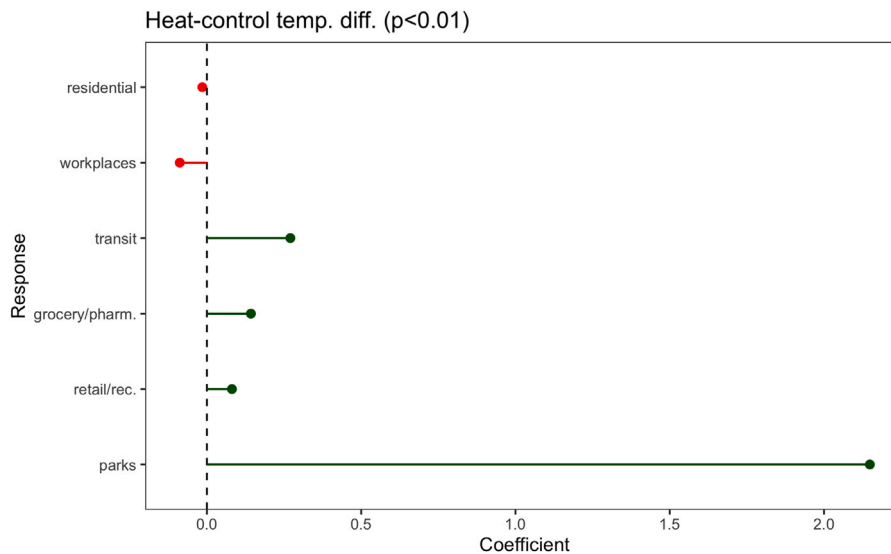


Fig. 11. Coefficients from full multi-variate multi-level for temperature difference between heatwave and control day.

The winter temperature-state interaction term successfully controls for bias from the winter period when the Google activity was recorded, through mechanisms explained in Section 2.4. This is particularly important in BC, the state with the coldest winters on average, as statistically significant relationships are found across 4/6 dependent variables.

3.5. Temporal variables

During 2021 heatwaves, compared to those in 2020, the coefficients suggest greater time spent in residence ($p < 0.001$), substituting grocery/pharmacy ($p < 0.01$), retail ($p < 0.01$), and especially park visitation ($p < 0.001$) during heatwaves (Fig. 12A). These greater substitutions of out-of-home activities in 2021 were potentially due to the unprecedented heatwaves along with historic wildfires and air pollution in the

Pacific Northwest in 2021 (White et al., 2023; Parisien et al., 2023). This may have led to a greater propensity to decrease activity outside the home, in line with the US Environmental Protection Agency recommendations during wildfires (EPA, 2018). In 2022, compared to 2020, there was greater workplace visitation during heatwaves ($p < 0.001$), as COVID-19 stay-at-home restrictions had been lifted and workplaces re-opened (Fig. 12B).

During June heatwaves, there are greater substitutions of home and work activities to visit discretionary locations. The coefficients suggest less time spent at home ($p < 0.001$) and lower workplace visitation ($p < 0.001$), but greater changes in retail ($p < 0.001$) and park visitation ($p < 0.05$) relative to later heatwaves (Fig. 12C).

During longer heatwaves, workplace obligations and outdoor activity are reduced more compared to shorter heatwaves. This is evidenced by negative coefficients for workplace ($p < 0.1$), park ($p < 0.001$), and transit ($p < 0.01$) visitation (Fig. 12D). While these changes occur, more

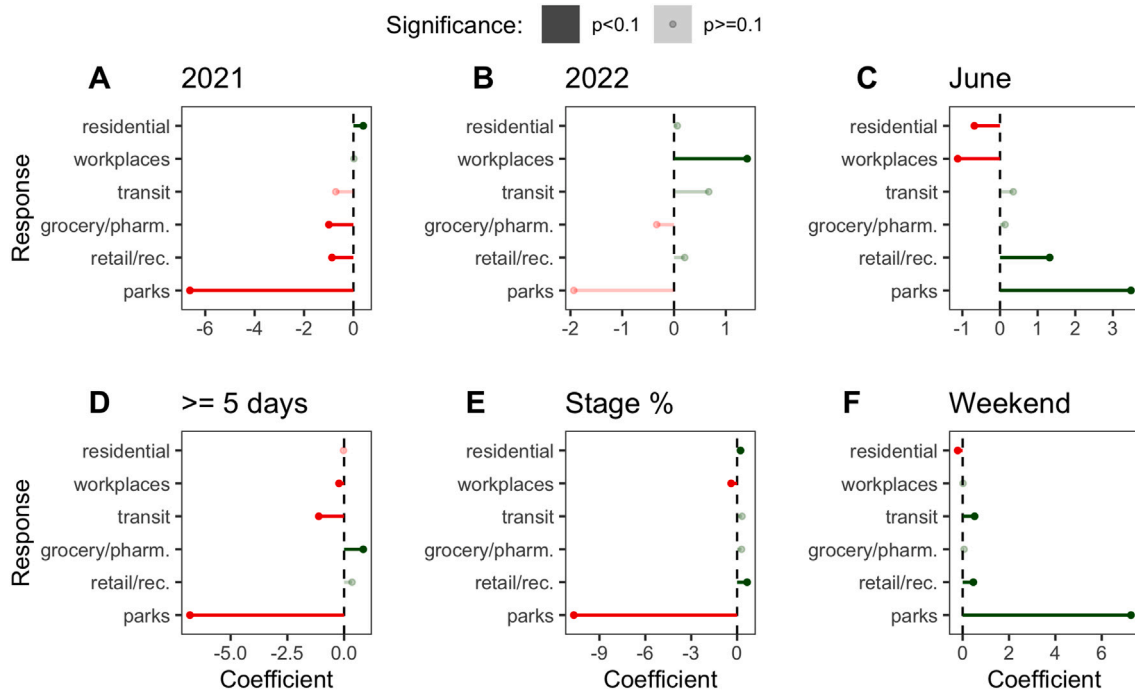


Fig. 12. Coefficients from full multi-variate multi-level model for temporal variables.

grocery/pharmacy activity is observed ($p < 0.01$) during heatwaves of 5 days or longer. Unlike home and work, these essential locations do not need to be visited every day, although eventually all households must make trips to groceries and pharmacies. This upwards jump in visitation during heatwaves of 5 days or more suggests a postponement of essential trips during shorter heatwaves, which are eventually visited during prolonged episodes.

As distinct heatwaves progress, captured through the ‘stage’ variable, workplace and park visitation are substituted for greater indoor activity. From the first to the final day of a heatwave, the drop in workplace visitation ($p < 0.01$) may be the result of it being overcome as a rigid anchor point in individuals’ activity schedules (Fig. 12E). Concurrently, changes in park visitation decrease by 10.7% ($p < 0.001$) from the first to the final day of a heatwave, coupled with increasing changes in time spent at home ($p < 0.001$) and retail/recreation visitation ($p < 0.01$).

On weekends, greater activity schedule flexibility may permit greater discretionary activity during heatwaves. Greater substitutions of time in residence ($p < 0.001$) by transit ($p < 0.1$), retail/recreation ($p < 0.01$) and park ($p < 0.001$) visitation are observed compared to weekdays (Fig. 12F).

3.6. County-level contextual factors

In typically temperate, coastal regions, there are greater substitutions of home and workplace obligations by non-work activities outside the home. The coefficients suggest less time at home ($p < 0.001$) and lower workplace visitation ($p < 0.5$), and more visitation to grocery/pharmacy ($p < 0.001$), retail/recreation ($p < 0.01$) and park ($p < 0.001$) spaces. These activities outside the home also correspond to greater transit usage ($p < 0.05$) in coastal areas (Fig. 13A).

In more population dense counties, subject to greater urban heat island effects, heatwave responses involve less visitation to non-work activities outside the home. This is evidenced by the greater reductions of grocery/pharmacy ($p < 0.01$), retail/recreation ($p < 0.1$), and park ($p < 0.01$) visitation as population density increases (Fig. 13B).

Socio-economic conditions also shape adaptive responses to heatwaves, with implications for various activity types. In counties with

greater shares of non-white people, adaptive responses to heatwaves involve greater time at home ($p < 0.05$), substituting grocery/pharmacy ($p < 0.05$) and transit visitation ($p < 0.1$) (Fig. 13C). In lower-income counties, changes in park visitation are more positive during heatwaves ($p < 0.05$), potentially used as out-of-home cooling options during heatwaves (Fig. 13D). In counties with more older people, more time is spent at home during heatwaves ($p < 0.001$) at the expense of grocery/pharmacy ($p < 0.05$), park ($p < 0.1$), and transit activity ($p < 0.05$) (Fig. 13E).

4. Discussion

4.1. Regional context influences heatwave activity participation

The extents to which workplace visitation is reduced during heatwaves, and how non-work activities are adapted, vary across regions. In more temperate regions across the Pacific Northwest, particularly in British Columbia and coastal regions, the results suggest greater substitutions of workplace obligations and time in residence by visits to out-of-home, potentially cooling locations. In typically hotter regions, workplace visitation is less elastic, and activity participation is adapted by reducing out-of-home non-work activities.

Moving South across states/provinces, there appears to be a greater ‘business as usual’ approach to workplace obligations during heatwaves. Following a North–South pattern, BC has the most temperate climate and most elastic workplace visitation during heatwaves, followed by Washington, then Oregon and California. In a review of occupational impacts of the 2021 heatwaves in British Columbia, the most commonly cited direct impact was work stoppage or cancellation – in both indoor and outdoor sectors (Tetzlaff et al., 2023). In contrast, in Washington, Oregon, and California, protective occupational measures primarily involve cool-down breaks, shade, and education/training (Schmidt, 2022). In addition to differences in protective policy, typically hotter, acclimatized regions may have greater air conditioning prevalence in indoor workplaces, contributing less to exposure and being potentially protective, particularly for higher-income workers (Guardaro et al., 2022).

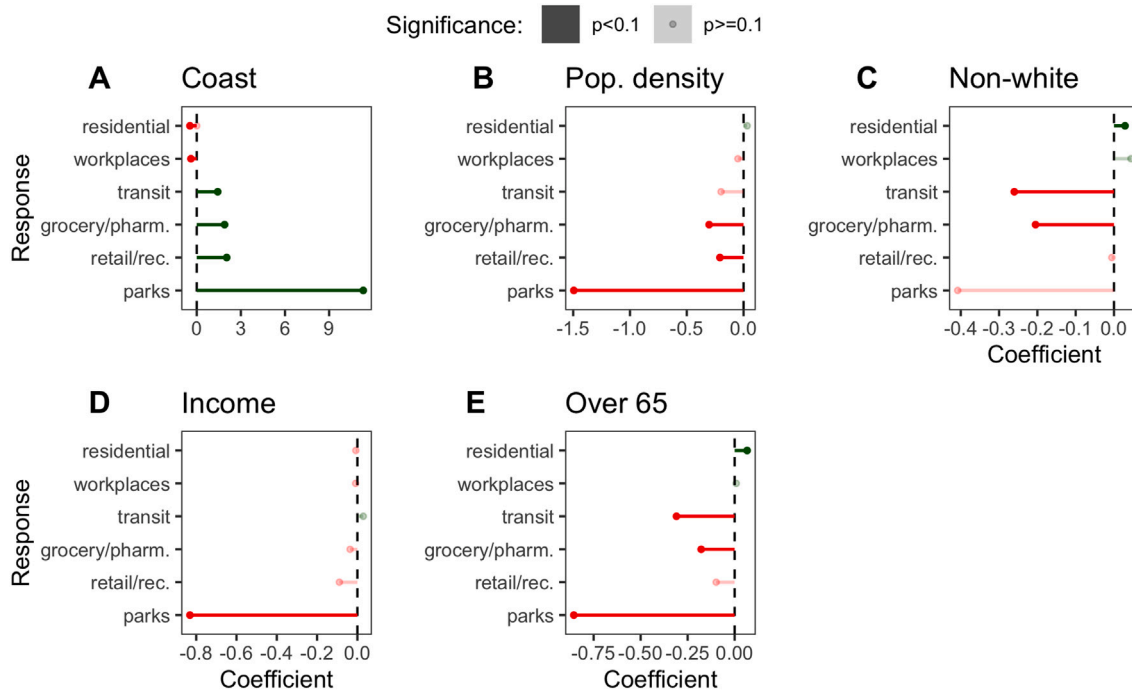


Fig. 13. Coefficients from full multi-variate multi-level model for contextual variables.

Table 9

Summary of full multi-variate multi-level model. California as the reference state, state-level shifts calculated at 33C heatwave.

Percent change in mobility:						
	Residential	Workplaces	Transit	Grocery/pharmacy	Retail/rec.	Parks
Intercept	-0.76***	0.96*	1.37	3.26**	0.47	10.35 .
State-climatic variables						
State = British Columbia (CA ref)	-0.28	-2.11***	3.92*	5.41***	4.38***	18.14**
State = Washington (CA ref)	0.25**	-0.66***	-0.35	1.20*	1.21*	5.45*
State = Oregon (CA ref)	0.29***	-0.62***	-0.60	0.14	-0.69	-1.37
Heatwave temperature (CA)	0.05***	-0.05*	-0.20*	-0.20***	-0.22***	-1.48***
Heatwave temperature BC (CA ref)	-0.12***	-0.20***	0.08	0.84***	0.72***	-0.57
Heatwave temperature WA (CA ref)	-0.01	-0.12***	-0.19	0.05	0.11	0.14
Heatwave temperature OR (CA ref)	-0.07***	-0.03	-0.52	-0.01	-0.21*	-0.03
Heat-control temp difference	-0.02*	-0.09***	0.27***	0.14***	0.08**	2.15***
Winter temperature BC	0.05**	0.13***	0.29 .	-0.09	-0.19	-1.30*
Winter temperature WA	-0.03	-0.04	-0.04	0.47***	0.31*	2.25***
Winter temperature OR	0.01	-0.07	0.28	0.40**	0.34*	-0.40
Temporal variables						
Year = 2021	0.40***	0.02	-0.71	-0.99**	-0.87**	-6.62***
Year = 2022	0.06	1.41***	0.67	-0.33	0.20	-1.94
June heatwave	-0.68***	-1.12***	0.35	0.13	1.32***	3.44*
Heatwave duration >= 5 days	-0.03	-0.22 .	-1.12**	0.84**	0.35	-6.79***
Heatwave day stage (%)	0.22***	-0.39**	0.32	-0.29	0.66**	-10.68***
Weekend = 1	-0.21***	0.02	0.52 .	0.06	0.46**	7.26***
Contextual county-level variables						
Coast = 1	-0.46***	-0.39*	1.43*	1.89***	2.04***	11.32***
Pop-dens decile	0.03	-0.05	-0.20	-0.30**	-0.21 .	-1.49**
Income decile	-0.01	-0.01	0.03	-0.04	-0.09	-0.83*
Non-white decile	0.03*	0.05	-0.26 .	-0.20*	-0.01	-0.40
Over 65 decile	0.07***	0.01	-0.31*	-0.18*	-0.10	-0.85 .

. p<0.1, *p<0.05, **p<0.01, ***p<0.001

When adapting around workplace obligations, the extent to which non-home locations are visited varies by region. In British Columbia, which only has 32% air conditioning ownership compared to Washington (53%), Oregon (76%), and California (72%), heatwaves lead to stark increases in essential and discretionary activities – capturing potential cooling behaviours to non-work locations (Quick and Tjepkema, 2023; U.S. Energy Information Administration, 2020). All other states, which have hotter climates and greater air conditioning

prevalence rates than British Columbia, exhibit decreases in essential and discretionary activity for time at home through their intercepts and/or slopes with temperature (Quick and Tjepkema, 2023; U.S. Energy Information Administration, 2020). Similar mechanisms appear when coastal and inland regions are compared. In coastal counties, which are more temperate, less air conditioned, and face greater health-risks due to heatwaves (Fraser et al., 2017; Joe et al., 2016; Guirguis et al., 2018), there are greater decreases in workplace obligations and

time spent at home to visit potential cooling facilities outside the home, most resembling the relative changes in British Columbia.

The findings of this study highlight that regional factors, such as typical climates and general air conditioning prevalence, influence adaptive behavioural responses to heatwaves. These differences are relevant when linking mobility-based responses to vulnerability. In British Columbia, for example, which has low air conditioning ownership rates and where most heatwave deaths occur at home (B.C. Coroners Service, 2022), the results suggest that staying home may tend to be more maladaptive than doing so in a typically hot, air-conditioned region. For future research using mobility data to understand heatwave adaptation, context-specific adaptive processes should be considered, specifying which activity types are taking place.

4.2. Relative heatwave intensities shape adaptive responses

The relative intensity variable captures how activity changes are influenced by the level of temperature *increase* on a heatwave day. As opposed to long-term, regional factors described above, this captures elements of short-term acclimatization at a day-to-day scale, found to influence the health-risks of heatwaves (Van Der Linden et al., 2019). Similar mechanisms to the regional analysis are observed, as greater temperature differences vis-à-vis a control day lead to greater reductions in time at home and workplace activity for greater out-of-home non-work activities, the same trade-offs as seen in British Columbia and coastal regions. These findings highlight that responses to heatwaves are not only sensitive to longer-term acclimatization at a regional level, through factors such as typical climate and air conditioning ownership, but also short-term acclimatization and experiences with the relative temperature increases of heatwaves. Absolute and relative temperature have distinct yet similarly large effects on behavioural adaptation in the model, justifying the inclusion of both measures in future studies.

4.3. Adaptive responses evolve with temporal factors

By including years during and after COVID-19, and exploring their heterogeneity with fixed effects, this analysis considers how changing climatic and policy conditions influence heatwave adaptation. During the unprecedented heatwaves coupled with wildfires and air pollution in 2021, the results concur with an adherence to wildfire public health recommendations, as grocery/pharmacy, retail, and parks were visited less to spend more time at home, compared to both 2020 and 2022 (White et al., 2023; Parisien et al., 2023; EPA, 2018). The results are in line with Ly et al. (2023), who find greater activity declines on hot days in 2021 compared to 2020. The greater propensity to stay home may have influenced the record-breaking mortality of the 2021 heatwaves, where most deaths occurred in people's homes (B.C. Coroners Service, 2022), suggesting a compounding effect of fires and air quality on heatwave adaptive responses. In 2022, relative to the COVID-19-restricted activity in 2020, there is relatively greater workplace visitation during heatwaves. These results suggest that workplace re-openings may have constrained opportunities to visit other locations during heatwaves, or potentially offered a source of cooling, particularly for those working in air-conditioned offices.

Exploring how activities change together, this analysis sheds light on behaviours which may lead early heatwaves to pose greater mortality risk (Anderson and Bell, 2011; Liss et al., 2017; Lee et al., 2014). During June heatwaves, relative to later ones, greater activity rates appear to be driven by discretionary behaviours, as changes in visitation to retail/recreation and parks increase while time at home and workplace visitation decrease. This may result from an underestimation of the health risks of extreme heat, before messaging and community engagement efforts take effect and individuals adjust their activity accordingly (Bedi et al., 2022; Errett et al., 2023; Randazza et al., 2023; Erens et al., 2021; Lane et al., 2014). These responses may also intersect

with shifting institutional constraints, as early summer vacations may allow people to substitute workplace obligations for other activities.

Activity participation is altered in complex ways during longer heatwaves, presenting bidirectional changes in activities. During longer heatwaves, workplace, park, and transit activity decrease relative to shorter heatwaves. Concurrently, grocery/pharmacy exhibits *greater* visitation, due to potential postponements of essential trips during shorter heatwaves, which may not be feasible during longer heatwaves, when – at some point during the heatwave – people have to visit grocery/pharmacy locations. This postponement mechanism may be of relevance to time-integrative studies of food access (Widener, 2018), highlighting how access may vary during climate disasters. These complex mechanisms are overlooked by considering aggregate increases or decreases in activity levels, as various trade-offs across activity types shape adaptive responses.

The competing activities which constrain adaptation evolve as heatwaves progress. This is shown through the stage variable, where more time is spent at home from the beginning to the end of a heatwave, while changes in workplace and park visitation drop. These results suggest that workplace obligations are more rigid during the early portion of heatwaves, beyond which they are reduced more effectively as activity schedules are adapted. Together with the findings on duration, these temporal results add nuance to prior studies of park usage during heatwaves, suggesting that parks are visited the most during the early periods of shorter heatwaves, beyond which they are substituted for more time at home (Barnett-Itzhaki et al., 2023; Kabisch et al., 2021).

On weekends, when activity schedules are typically more flexible, greater changes in discretionary activity are observed by substituting time at home. Distinguishing which activities are engaged in relatively more, the results of this study build on prior literature finding greater activity elasticity during extreme heat on the weekends (Stechemesser and Wenz, 2023; Ly et al., 2023; Kumakura et al., 2024). These findings also convey that activity schedules during weekdays may permit fewer opportunities to engage in discretionary activity outside the home during heatwaves.

4.4. Urban and socio-economic impacts on adaptation

Simultaneously considering the various activity types that individuals engage in during heatwaves, this analysis reveals how urban form shapes adaptive opportunities to heatwaves. In more population dense counties, which face amplified heatwave risks due to urban heat island effects (Hsu et al., 2021), adaptive responses tend to involve less grocery/pharmacy, retail, and especially park activity compared to population-sparse counties. Densely built environments and a lack of green space in urban areas, which contribute to extreme heat amplification (Aram et al., 2020), may also shape adaptive responses by hindering potential for out-of-home activities during heatwaves.

In non-white counties, the co-occurring negative change in grocery/pharmacy and transit usage, which corresponds to greater time at home, suggests a degree of transit captivity to reach essential services during heatwaves. Racial minority groups, who are disproportionately at risk of heatwaves and more reliant on public transit (Labban et al., 2023), may encounter greater barriers to essential activities during heatwaves.

Greater changes in park usage in lower-income counties highlight the role of green spaces as sources of heat refuge for individuals who may face lower abilities to cool at home. These results build on prior literature which find greater overall activity levels in lower-income neighbourhoods during extreme heat (Stechemesser and Wenz, 2023; Ly et al., 2023; Tian et al., 2024), which are likely related to inequalities in residential heat exposure, precipitating visitation to non-home locations to seek cooling.

By analysing which activities are altered and how they are related, this analysis finds that in counties with older populations, greater time is spent at home by reducing transit, grocery/pharmacy, and park usage

during heatwaves. This supports the findings of [Stechemesser and Wenz \(2023\)](#), who find strong subway mobility reductions among individuals in neighbourhoods with greater proportions of individuals aged 65+ in New York City. The current analysis suggests that the observed reductions are not only due to substitutions of discretionary activity, which may include cooling options, but also visitation to essential locations, both of which may increase the vulnerability of an already at-risk subgroup.

4.5. Limitations and future research

Primary limitations to this study stem from the nature of the Google data, as discussed in Section 2.1.1. The Google Community Mobility Reports data was only produced for March 2020–October 2022. Therefore this study's results are specific to the three summers after the start of the COVID-19 pandemic. Though changes in adaptation are explored across years and mobility restrictions had been lifted by 2022, all three years fall broadly within the epidemic phase. A return to relative normalcy in the ensuing years – such as greater in-office working obligations – may further shape adaptive responses to heatwaves and should be considered when interpreting results. Further, a more detailed analysis would be enabled by more disaggregated data, which would allow for individual-level analyses as opposed to county-level inferences. More detailed activity pattern data could also shed light on trip timing, shown to be important during heatwaves ([Tian et al., 2024](#); [Kumakura et al., 2024](#)), as well as trip chaining, purpose, visits to other people's homes, any inter-county visitation, and whether workplaces are indoors versus outdoors. This latter point is essential, as indoor, air-conditioned workplaces may be protective while outdoor work can be life-threatening during heatwaves. Finally, despite high smartphone ownership rates – estimated at 85% in the US and 84% in Canada – those most vulnerable during heatwaves, including low-income, homeless, and older individuals, are underrepresented ([Perrin, 2021](#); [Guardaro et al., 2022](#); [Fransson et al., 2023](#)).

There are four suggested avenues for future research. The first is to explore adaptive responses in other spatio-temporal contexts, including low and middle-income countries, which are highly vulnerable to heatwaves, are characterized by lower uptake of air conditioning in homes, and have greater proportions of outdoor workers exposed to extreme heat ([De Sario et al., 2023](#); [Mastrucci et al., 2019](#); [Kjellstrom et al., 2009](#); [Marcotullio et al., 2021](#)). The second is to use more granular data, whether cell-phone or traditional travel or time use data, to understand how competing activities influence behavioural adaptation to heatwaves on more dis-aggregated scales, with a particular focus on heat-vulnerable groups such as the low-income individuals, Black and Hispanic people, and the elderly. The third is for research to prioritize the development of public, spatially disaggregated data on air conditioning prevalence ([Romitti et al., 2022](#)). This data is especially lacking for non-metropolitan regions and locations outside the home, such as workplaces. The last is to continue to conceptualize issues of cooling access not only in terms of the cooling behaviour itself, but also through the constraints of everyday life, such as workplace obligations, which constrain adaptive opportunities.

5. Conclusion

This paper examines how the various activities of everyday life are altered during heatwaves, shaping and constraining opportunities to seek cool environments. Through a simultaneous modelling approach that is applied to data across the Pacific Northwest, these interdependent activity changes are linked to climatic, temporal and contextual factors of heatwaves. Using this novel approach, the following main insights are drawn:

- People's adaptive responses to heatwaves vary with regional climate.

- Absolute and *relative* heatwave intensities condition adaptation.
- Adaptation is a dynamic process that evolves over time.
- Urban form and socio-economic disparities shape activity trade-offs during heatwaves.

By contextualizing heatwaves alongside the constraints of everyday life, this study highlights the diverse mechanisms by which behavioural adaptation occurs, as well as the underlying structures which condition it.

CRediT authorship contribution statement

Shiv G. Yücel: Writing – original draft, Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Tim Schwanen:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Funding

SGY is supported by the Canadian Social Sciences and Humanities Research Council (SSHRC) Doctoral Fellowship and the Canadian Centennial Scholarship Fund.

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.

Acknowledgements

The authors are thankful to Xiao Li and Yuan Liang for their thoughtful comments on an earlier draft of the paper.

Data availability

The datasets and code supporting the conclusions of this article are both openly available. Datasets are stored as a Zenodo repository here: <https://zenodo.org/records/14039954>. The code is stored as a GitHub repository (Python/R) here: https://github.com/shivyucel/heatwaves_pnw_code.

References

- Adger, W.N., 2006. Vulnerability. *Glob. Environ. Chang.* 16 (3), 268–281.
- Aktay, A., Bavadekar, S., Cossoul, G., Davis, J., Desfontaines, D., Fabrikant, A., Gabrilovich, E., Gadepalli, K., Gipson, B., Guevara, M., Kamath, C., Kansal, M., Lange, A., Mandayam, C., Oplinger, A., Pluntke, C., Roessler, T., Schlosberg, A., Shekel, T., Vispute, S., Vu, M., Wellenius, G., Williams, B., Wilson, R.J., 2020. Google COVID-19 community mobility reports: Anonymization process description (version 1.1). URL [arXiv:2004.04145](https://arxiv.org/abs/2004.04145)[cs].
- Aminipouri, M., Knudby, A., Ho, H.C., 2016. Using multiple disparate data sources to map heat vulnerability: Vancouver case study: Heat vulnerability. *Can. Geogr. / Le Géographe Can.* 60 (3), 356–368.
- Anderson, G.B., Bell, M.L., 2011. Heat waves in the United States: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environ. Health Perspect.* 119 (2), 210–218.
- Aram, F., Solgi, E., Garcia, E.H., Mosavi, A., 2020. Urban heat resilience at the time of global warming: evaluating the impact of the urban parks on outdoor thermal comfort. *Environ. Sci. Eur.* 32 (1), 117.
- Arnold, L., Scheuerell, M.D., Busch Isaksen, T., 2022. Mortality associated with extreme heat in Washington state: The historical and projected public health burden. *Atmosphere* 13 (9), 1392, URL <https://www.mdpi.com/2073-4433/13/9/1392>.
- Arsad, F.S., Hod, R., Ahmad, N., Ismail, R., Mohamed, N., Baharom, M., Osman, Y., Radi, M.F.M., Tangang, F., 2022. The impact of heatwaves on mortality and morbidity and the associated vulnerability factors: A systematic review. *Int. J. Environ. Res. Public Heal.* 19 (23), 16356.
- Barnett-Itzhaki, Z., Sar-Shalom, A., Cohn, L., Chen, L., Steinitz, O., 2023. The effect of heatwaves on the number of visits to national parks and reserves. In: Shrestha, S.L. (Ed.), *PLOS ONE* 18 (8), e0289201.

- B.C. Coroners Service, 2022. Extreme heat and human mortality: A review of heat-related deaths in B.C. in summer 2021. Report to the Chief Coroner of British Columbia.
- Bedi, N.S., Adams, Q.H., Hess, J.J., Wellenius, G.A., 2022. The role of cooling centers in protective vulnerable individuals from extreme heat. *Epidemiology* 33 (5), 611–615.
- Bell, A., Fairbrother, M., Jones, K., 2019. Fixed and random effects models: making an informed choice. *Qual. Quant.* 53 (2), 1051–1074.
- Bollyky, T.J., Castro, E., Aravkin, A.Y., Bhandia, K., Dalos, J., Hulland, E.N., Kiernan, S., Lastuka, A., McHugh, T.A., Ostroff, S.M., Zheng, P., Chaudhry, H.T., Ruggiero, E., Turilli, I., Adolph, C., Amlag, J.O., Bang-Jensen, B., Barber, R.M., Carter, A., Chang, C., Cogen, R.M., Collins, J.K., Dai, X., Dangel, W.J., Dapper, C., Deen, A., Eastus, A., Erickson, M., Fedosseeva, T., Flaxman, A.D., Fullman, N., Giles, J.R., Guo, G., Hay, S.I., He, J., Helak, M., Huntley, B.M., Iannucci, V.C., Kinzel, K.E., LeGrand, K.E., Magistro, B., Mokdad, A.H., Nassereldine, H., Ozten, Y., Pasovic, M., Pigott, D.M., Reiner, R.C., Reinke, G., Schumacher, A.E., Serieux, E., Spurlock, E.E., Troeger, C.E., Vo, A.T., Vos, T., Walcott, R., Yazdani, S., Murray, C.J.L., Dieleman, J.L., 2023. Assessing COVID-19 pandemic policies and behaviours and their economic and educational trade-offs across US states from Jan 1, 2020, to July 31, 2022: an observational analysis. *Lancet* 401 (10385), 1341–1360.
- Bouchama, A., Dehbi, M., Mohamed, G., Matthies, F., Shoukri, M., Menne, B., 2007. Prognostic factors in heat wave related deaths: a meta-analysis. *Arch. Intern. Med.* 167 (20), 2170–2176.
- Bradford, K., Abrahams, L., Hegglin, M., Klima, K., 2015. A heat vulnerability index and adaptation solutions for Pittsburgh, Pennsylvania. *Environ. Sci. Technol.* 49 (19), 11303–11311.
- Campbell, S., Remenyi, T.A., White, C.J., Johnston, F.H., 2018. Heatwave and health impact research: A global review. *Heat & Place* 53, 210–218.
- Chang, S., Pierson, E., Koh, P.W., Gerardin, J., Redbird, B., Grusky, D., Leskovec, J., 2020. Mobility network models of COVID-19 explain inequities and inform reopening. *Nature* 589 (January).
- Cools, D., McCallum, S.C., Rainham, D., Taylor, N., Patterson, Z., 2021. Understanding Google location history as a tool for travel diary data acquisition. *Transp. Res. Rec.: J. Transp. Res. Board* 2675 (5), 238–251.
- Cot, C., Cacciapaglia, G., Sannino, F., 2021. Mining Google and Apple mobility data: temporal anatomy for COVID-19 social distancing. *Sci. Rep.* 11 (1), 4150.
- Couclelis, H., 2009. Rethinking time geography in the information age. *Environ. Plan. A: Econ. Space* 41 (7), 1556–1575.
- Cullen, I., Godson, V., 1975. Urban networks: The structure of activity patterns. *Prog. Plan.* 4, 1–96.
- Davies, M., Moon, G., Lewis, N.M., 2021. Substance use and sexuality: Comparing sexual identity and attraction using a multilevel multivariate model. *Wellbeing, Space Soc.* 2, 100052.
- De Sario, M., de'Donato, F.K., Bonafede, M., Marinaccio, A., Levi, M., Ariani, F., Morabito, M., Michelozzi, P., 2023. Occupational heat stress, heat-related effects and the related social and economic loss: a scoping literature review. *Front. Public Heal.* 11, 1173553.
- Derakhshan, S., Bautista, T.N., Bouwman, M., Huang, L., Lee, L., Tarczynski, J., Wahagheghe, I., Zeng, X., Longcore, T., 2023. Smartphone locations reveal patterns of cooling center use as a heat mitigation strategy. *Appl. Geogr.* 150, 102821.
- Ding, W., Levine, R., Lin, C., Xie, W., 2020. Social Distancing and Social Capital: Why U.S. Counties Respond Differently to COVID-19. Working Paper Series 27393, National Bureau of Economic Research.
- Dye, A.W., Rastogi, B., Clemesha, R.E.S., Kim, J.B., Samelson, R.M., Still, C.J., Williams, A.P., 2020. Spatial patterns and trends of summertime low cloudiness for the Pacific Northwest, 1996–2017. *Geophys. Res. Lett.* 47 (16), e2020GL088121.
- Eisenman, D.P., Wilhalme, H., Tseng, C.-H., Chester, M., English, P., Pincetl, S., Fraser, A., Vangala, S., Dhaliwal, S.K., 2016. Heat death associations with the built environment, social vulnerability and their interactions with rising temperature. *Heat. & Place* 41, 89–99.
- Elarde, J., Kim, J.-S., Kavak, H., Züfle, A., Anderson, T., 2021. Change of human mobility during COVID-19: A united states case study. In: Benenson, I. (Ed.), *PLOS ONE* 16 (11), e0259031.
- Ellegård, K., 2018. Thinking time geography: Concepts, methods and applications. Taylor & Francis.
- EPA, 2018. Wildfires and indoor air quality (IAQ). <https://www.epa.gov/indoor-air-quality-iaq/wildfires-and-indoor-air-quality-iaq>.
- Erens, B., Williams, L., Exley, J., Ettelt, S., Manacorda, T., Hajat, S., Mays, N., 2021. Public attitudes to, and behaviours taken during, hot weather by vulnerable groups: results from a national survey in England. *BMC Public Health* 21 (1), 1631.
- Errett, N.A., Hartwell, C., Randazza, J.M., Nori-Sarma, A., Weinberger, K.R., Spangler, K.R., Sun, Y., Adams, Q.H., Wellenius, G.A., Hess, J.J., 2023. Survey of extreme heat public health preparedness plans and response activities in the most populous jurisdictions in the United States. *BMC Public Health* 23 (1), 811.
- Fan, Y., Wang, J., Obradovich, N., Zheng, S., 2023. Intraday adaptation to extreme temperatures in outdoor activity. *Sci. Rep.* 13 (1), 473.
- Finazzi, F., 2020. The earthquake network project: A platform for earthquake early warning, rapid impact assessment, and search and rescue. *Front. Earth Sci.* 8, 243.
- Fransson, A., Björklund Carlstedt, A., Gustafsson, S., 2023. Older adults' occupations in heat waves: A scoping review. *Scand. J. Occup. Ther.* 30 (7), 1000–1015.
- Fraser, A.M., Chester, M.V., Eisenman, D., Hondula, D.M., Pincetl, S.S., English, P., Bondank, E., 2017. Household accessibility to heat refuges: Residential air conditioning, public cooled space, and walkability. *Environ. Plan. B: Urban Anal. City Sci.* 44 (6), 1036–1055.
- Gibbs, H., Ballantyne, P., Cheshire, J., Singleton, A., Green, M.A., 2023. Harnessing mobility data to capture changing work from home behaviours between censuses. *Geogr. J.* geoj.12555.
- Goodell, J., 2023. The heat will kill you first: Life and death on a scorched planet. Little, Brown.
- Graff Zivin, J., Neidell, M., 2014. Temperature and the allocation of time: Implications for climate change. *J. Labor Econ.* 32 (1), 1–26.
- Gronlund, C.J., 2014. Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. *Curr. Epidemiol. Rep.* 1 (3), 165–173.
- Gronlund, C.J., Sullivan, K.P., Kefelegn, Y., Cameron, L., O'Neill, M.S., 2018. Climate change and temperature extremes: A review of heat- and cold-related morbidity and mortality concerns of municipalities. *Maturitas* 114, 54–59. Publisher: Elsevier.
- Gu, X., Chen, P., Fan, C., 2024. Socio-demographic inequalities in the impacts of extreme temperatures on population mobility. *J. Transp. Geogr.* 114, 103755.
- Guardaro, M., Hondula, D., Ortiz, J., Redman, C., 2022. Adaptive capacity to extreme urban heat: The dynamics of differing narratives. *Clim. Risk Manag.* 35, 100415.
- Guirguis, K., Basu, R., Al-Delaimy, W.K., Benmarhnia, T., Clemesha, R.E.S., Corcos, I., Guzman-Morales, J., Hailey, B., Small, I., Tardy, A., Vashishtha, D., Zivin, J.G., Gershunov, A., 2018. Heat, disparities, and health outcomes in San Diego county's diverse climate zones. *GeoHealth* 2 (7), 212–223.
- Hägerstrand, T., 1970. What about people in the regional sciences? *Pap. Reg. Sci.* 24 (1), 7–24.
- Harlan, S.L., Brazel, A.J., Prasad, L., Stefanow, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. *Soc. Sci. Med.* 63 (11), 2847–2863.
- Hatchett, B.J., Benmarhnia, T., Guirguis, K., VanderMolen, K., Gershunov, A., Kerwin, H., Khlystov, A., Lambrecht, K.M., Samburova, V., 2021. Mobility data to aid assessment of human responses to extreme environmental conditions. *Lancet Planet. Heal.* 5 (10), e665–e667.
- Hayden, M.H., Wilhelmi, O.V., Banerjee, D., Greasby, T., Cavanaugh, J.L., Nepal, V., Boehnert, J., Sain, S., Burghardt, C., Gower, S., 2017. Adaptive capacity to extreme heat: Results from a household survey in Houston, Texas. *Weather. Clim. Soc.* 9 (4), 787–799.
- Heeter, K.J., Harley, G.L., Abatzoglou, J.T., Anchukaitis, K.J., Cook, E.R., Coulthard, B.L., Dye, L.A., Homfeld, I.K., 2023. Unprecedented 21st century heat across the Pacific Northwest of North America. *Npj Clim. Atmospheric Sci.* 6 (1), 5.
- Henderson, S.B., McLean, K.E., Lee, M.J., Kosatsky, T., 2022. Analysis of community deaths during the catastrophic 2021 heat dome: Early evidence to inform the public health response during subsequent events in greater Vancouver, Canada. *Environ. Epidemiol.* 6 (1), e189.
- Hesketh, M., Wuellner, S., Robinson, A., Adams, D., Smith, C., Bonauto, D., 2020. Heat related illness among workers in Washington State: A descriptive study using workers' compensation claims, 2006–2017. *Am. J. Ind. Med.* 63 (4), 300–311.
- Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M., Holbrook, N.J., Moore, P.J., Scannell, H.A., Sen Gupta, A., Wernberg, T., 2016. A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.* 141, 227–238.
- Hoffman, J.S., Shandas, V., Pendleton, N., 2020. The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. *Climate* 8 (1), 12.
- Hsu, A., Sheriff, G., Chakraborty, T., Manya, D., 2021. Disproportionate exposure to urban heat island intensity across major US cities. *Nat. Commun.* 12 (1), 2721.
- Ilin, C., Annan-Phan, S., Tai, X.H., Mehra, S., Hsiang, S., Blumenstock, J.E., 2021. Public mobility data enables COVID-19 forecasting and management at local and global scales. *Sci. Rep.* 11 (1), 13531.
- Jay, O., Capon, A., Berry, P., Broderick, C., De Dear, R., Havenith, G., Honda, Y., Kovats, R.S., Ma, W., Malik, A., Morris, N.B., Nybo, L., Seneviratne, S.I., Vanos, J., Ebi, K.L., 2021. Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *Lancet* 398 (10301), 709–724.
- Joe, L., Hoshiko, S., Dobraca, D., Jackson, R., Smorodinsky, S., Smith, D., Harnly, M., 2016. Mortality during a large-scale heat wave by place, demographic group, internal and external causes of death, and building climate zone. *Int. J. Environ. Res. Public Heal.* 13 (3), 299.
- Kabisch, N., Kraemer, R., Masztalerz, O., Hemmerling, J., Püffel, C., Haase, D., 2021. Impact of summer heat on urban park visitation, perceived health and ecosystem service appreciation. *Urban For. & Urban Green.* 60, 127058.
- Kafeety, A., Henderson, S.B., Lubik, A., Kancir, J., Kosatsky, T., Schwandt, M., 2020. Social connection as a public health adaptation to extreme heat events. *Can. J. Public Heal.* 111 (6), 876–879.
- Kamińska, J.A., Kazak, J.K., 2024. Differences in changes of mobility patterns across the globe—Evidence from a natural experiment. *Trans. GIS tgis.13266*.
- Kang, M., Moudon, A.V., Hurvitz, P.M., Saelens, B.E., 2018. Capturing fine-scale travel behaviors: a comparative analysis between personal activity location measurement system (PALMS) and travel diary. *Int. J. Heal. Geogr.* 17 (1), 40.

- Kearl, Z., Vogel, J., 2023. Urban extreme heat, climate change, and saving lives: Lessons from Washington state. *Urban Clim.* 47, 101392.
- Kjellstrom, T., Holmer, I., Lemke, B., 2009. Workplace heat stress, health and productivity – an increasing challenge for low and middle-income countries during climate change. *Glob. Heal. Action* 2 (1), 2047.
- Klinenberg, E., 1997. Heat waves and hot environments. In: *The Public Health Consequences of Disasters*. Oxford University Press, pp. 245–269.
- Kovats, R.S., Hajat, S., 2008. Heat stress and public health: A critical review. *Annu. Rev. Public Health* 29 (1), 41–55.
- Kumakura, E., Ashie, Y., Ueno, T., 2024. Assessing the impact of summer heat on the movement of people in Tokyo based on mobile phone location data. *Build. Environ.* 265, 111952.
- Kuras, E.R., Hondula, D.M., Brown-Saracino, J., 2015. Heterogeneity in individually experienced temperatures (IETs) within an urban neighborhood: insights from a new approach to measuring heat exposure. *Int. J. Biometeorol.* 59 (10), 1363–1372.
- Kwan, M.-P., 1998. Space-time and integral measures of individual accessibility: A comparative analysis using a point-based framework. *Geogr. Anal.* 30 (3), 191–216.
- Kwan, M.-P., 1999. Gender and individual access to urban opportunities: A study using space-time measures. *Prof. Geogr.* 51 (2), 211–227.
- Kwan, M.-P., 2013. Beyond space (as we knew it): Toward temporally integrated geographies of segregation, health, and accessibility: Space-time integration in geography and GIScience. *Ann. Assoc. Am. Geogr.* 103 (5), 1078–1086.
- Labban, M., Chen, C.-R., Frego, N., Nguyen, D.-D., Lipsitz, S.R., Reich, A.J., Rebbeck, T.R., Chouairi, T.K., Kibel, A.S., Iyer, H.S., Trinh, Q.-D., 2023. Disparities in travel-related barriers to accessing health care from the 2017 national household travel survey. *JAMA Netw. Open* 6 (7), e2325291.
- Lane, K., Wheeler, K., Charles-Guzman, K., Ahmed, M., Blum, M., Gregory, K., Graber, N., Clark, N., Matte, T., 2014. Extreme heat awareness and protective behaviors New York City. *J. Urban Heal.* 91 (3), 403–414.
- Lee, M., Nordio, F., Zanobetti, A., Kinney, P., Vautard, R., Schwartz, J., 2014. Acclimatization across space and time in the effects of temperature on mortality: a time-series analysis. *Environ. Heal.* 13 (1), 89.
- Li, C., Su, X., Fan, C., Han, H., 2024. Behavior-encoded models reveal differentiated access to public cooling environment by race and income. *Npj Urban Sustain.* 4 (1), 19.
- Lin, S., Luo, M., Walker, R.J., Liu, X., Hwang, S.-A., Chinery, R., 2009. Extreme high temperatures and hospital admissions for respiratory and cardiovascular diseases. *Epidemiology* 20 (5), 738–746.
- Linsenmeier, M., 2024. Global variation in the preferred temperature for recreational outdoor activity. *J. Environ. Econ. Manag.* 127, 103032.
- Liss, A., Wu, R., Chui, K.K.H., Naumova, E.N., 2017. Heat-related hospitalizations in older adults: An amplified effect of the first seasonal heatwave. *Sci. Rep.* 7 (1), 39581.
- Liu, Y., Wang, Z., Rader, B., Li, B., Wu, C.-H., Whittington, J.D., Zheng, P., Stenseth, N.C., Bjornstad, O.N., Brownstein, J.S., Tian, H., 2021. Associations between changes in population mobility in response to the COVID-19 pandemic and socioeconomic factors at the city level in China and country level worldwide: A retrospective, observational study. *Lancet Digit. Heal.* 3 (6), e349–e359.
- Lu, X., Wrathall, D.J., Sundsoy, P.R., Nadiruzzaman, M., Wetter, E., Iqbal, A., Qureshi, T., Tatem, A., Canright, G., Engø-Monsen, K., Bengtsson, L., 2016. Unveiling hidden migration and mobility patterns in climate stressed regions: A longitudinal study of six million anonymous mobile phone users in Bangladesh. *Glob. Environ. Chang.* 38, 1–7.
- Lundgren-Kownacki, K., Hornyanszky, E.D., Chu, T.A., Olsson, J.A., Becker, P., 2018. Challenges of using air conditioning in an increasingly hot climate. *Int. J. Biometeorol.* 62 (3), 401–412.
- Ly, A., Davenport, F.V., Diffenbaugh, N.S., 2023. Exploring the influence of summer temperature on human mobility during the COVID-19 pandemic in the San Francisco Bay Area. *GeoHealth* 7 (6), e2022GH000772.
- Marcotullio, P.J., Kefler, C., Fekete, B.M., 2021. The future urban heat-wave challenge in Africa: Exploratory analysis. *Glob. Environ. Chang.* 66, 102190.
- Mass, C., 2021. *The weather of the Pacific Northwest*. University of Washington Press.
- Mastrucci, A., Byers, E., Pachauri, S., Rao, N.D., 2019. Improving the SDG energy poverty targets: Residential cooling needs in the global South. *Energy Build.* 186, 405–415.
- Mohan, J., Twigg, L., Taylor, J., 2011. Mind the double gap: Using multivariate multilevel modelling to investigate public perceptions of climate trends. *Br. J. Criminol.* 51 (6), 1035–1053.
- Nori-Sarma, A., Milando, C., Weinberger, K.R., Hess, J.J., Errett, N.A., Wellenius, G.A., 2022. Association between the 2021 heat wave in Portland, Oregon, and Seattle, Washington, and emergency department visits. *JAMA* 328 (23), 2360.
- Oliver, N., Matic, A., Frias-Martinez, E., 2015. Mobile network data for public health: Opportunities and challenges. *Front. Public Heal.* 3.
- O'Neill, M.S., 2005. Disparities by race in heat-related mortality in four US cities: The role of air conditioning prevalence. *J. Urban Heal.: Bull. N. Y. Acad. Med.* 82 (2), 191–197.
- Oppermann, E., Strengers, Y., Maller, C., Rickards, L., Brearley, M., 2018. Beyond threshold approaches to extreme heat: Repositioning adaptation as everyday practice. *Weather. Clim. Soc.* 10 (4), 885–898.
- Osberghaus, D., Abeling, T., 2022. Heat vulnerability and adaptation of low-income households in Germany. *Glob. Environ. Chang.* 72, 102446.
- Ostro, B., Rauch, S., Green, R., Malig, B., Basu, R., 2010. The effects of temperature and use of air conditioning on hospitalization. *Am. J. Epidemiol.* 172 (9), 1053–1061.
- Palecki, M., Kunkel, K., 2001. The nature and impacts of the July 1999 heat wave in the Midwestern United States: Learning from the lessons of 1995. *Bull. Am. Meteorol. Soc.* 82, 1353–1368.
- Parisien, M.-A., Barber, Q.E., Bourbonnais, M.L., Daniels, L.D., Flannigan, M.D., Gray, R.W., Hoffman, K.M., Jain, P., Stephens, S.L., Taylor, S.W., Whitman, E., 2023. Abrupt, climate-induced increase in wildfires in British Columbia since the mid-2000s. *Commun. Earth & Environ.* 4 (1), 309.
- Peixoto, P.S., Marcondes, D., Peixoto, C., Oliva, S.M., 2020. Modeling future spread of infections via mobile geolocation data and population dynamics. An application to COVID-19 in Brazil. *PLoS ONE* 15 (7 July), 1–23.
- Perkins, S.E., Alexander, L.V., 2013. On the measurement of heat waves. *J. Clim.* 26 (13), 4500–4517.
- Perkins-Kirkpatrick, S.E., Lewis, S.C., 2020. Increasing trends in regional heatwaves. *Nat. Commun.* 11 (1), 3357–3357.
- Perrin, A., 2021. *Mobile technology and home broadband 2021*. Pew Research Center: Internet, Science & Tech, <https://www.pewresearch.org/internet/2021/06/03/mobile-technology-and-home-broadband-2021/>.
- Puley, G., 2022. *Extreme heat: Preparing for the heat waves of the future*. Technical report, IFRC | UN OCHA | Red Cross Red Crescent Climate Centre.
- Quick, M., Christidis, T., Olaniyan, T., Newstead, N., Pinault, L., 2022. Exploring the associations between cooling centre accessibility and marginalization in Montreal, Toronto, and Vancouver, Canada. *Can. Geogr. / Le Géographe Can.* cag.12805.
- Quick, M., Tjepkema, M., 2023. The prevalence of household air conditioning in Canada. *Stat. Can. Heal. Rep.* 34 (82).
- Randazza, J.M., Hess, J.J., Bostrom, A., Hartwell, C., Adams, Q.H., Nori-Sarma, A., Spangler, K.R., Sun, Y., Weinberger, K.R., Wellenius, G.A., Errett, N.A., 2023. Planning to reduce the health impacts of extreme heat: A content analysis of heat action plans in local United States jurisdictions. *Am. J. Public Health* 113 (5), 559–567.
- Romitti, Y., Sue Wing, I., Spangler, K.R., Wellenius, G.A., 2022. Inequality in the availability of residential air conditioning across 115 US metropolitan areas. In: Galea, S. (Ed.), *PNAS Nexus* 1 (4), pgac210.
- Rosenthal, J.K., Kinney, P.L., Metzger, K.B., 2014. Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Heal. & Place* 30, 45–60.
- Salganik, M.J., 2019. *Bit by bit: Social research in the digital age*. Princeton University Press.
- Sampson, N.R., Gronlund, C.J., Buxton, M.A., Catalano, L., White-Newsome, J.L., Conlon, K.C., O'Neill, M.S., McCormick, S., Parker, E.A., 2013. Staying cool in a changing climate: Reaching vulnerable populations during heat events. *Glob. Environ. Chang.* 23 (2), 475–484.
- Schmidt, C.W., 2022. Hot pursuit: New efforts to prevent heat-related illness on the job. *Environ. Health Perspect.* 130 (9), 092001.
- Schwanen, T., 2006. On 'arriving on time', but what is 'on time'? *Geoforum* 37 (6), 882–894.
- Schwanen, T., Dieleman, F.M., Dijst, M., 2004. The impact of metropolitan structure on commute behaviour in the Netherlands: A multilevel approach. *Growth Chang.* 35 (3), 304–333.
- Schwanen, T., Dijst, M., Kwan, M.-P., 2008a. ICTs and the decoupling of everyday activities, space and time: Introduction. *Tijdschr. Voor Econ. En Soc. Geogr.* 99 (5), 519–527.
- Schwanen, T., Kwan, M.-P., Ren, F., 2008b. How fixed is fixed? Gendered rigidity of space-time constraints and geographies of everyday activities. *Geoforum* 39 (6), 2109–2121.
- Semenza, J.C., Rubin, C.H., Falter, K.H., Selanikio, J.D., Flanders, W.D., Howe, H.L., Wilhelm, J.L., 1996. Heat-related deaths during the July 1995 heat wave in Chicago. *N. Engl. J. Med.* 335 (2), 84–90. Publisher: Massachusetts Medical Society.
- Sganzerla Martinez, G., Kelvin, D.J., 2023. Convergence in mobility data sets from apple, Google, and Meta. *JMIR Public Heal. Surveill.* 9, e44286.
- Shen, Y., Chai, Y., Kwan, M.-P., 2015. Space-time fixity and flexibility of daily activities and the built environment: A case study of different types of communities in Beijing suburbs. *J. Transp. Geogr.* 47, 90–99.
- Snijders, T.A.B., Bosker, R.J., 2011. *Multilevel analysis: An introduction to basic and advanced multilevel modeling*. SAGE.
- Statistics Canada, 2023a. *2021 Census of Population*. <https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm?Lang=E>.
- Statistics Canada, 2023b. *Telecommunications: Connecting Canadians*.
- Stechemesser, A., Wenz, L., 2023. Inequality in behavioural heat adaptation: an empirical study with mobility data from the transport system in New York City, NY, USA. *Lancet Planet. Heal.* 7 (10), e798–e808.
- Steele, W., Handmer, J., McShane, I., 2023. *Hot Cities: A Transdisciplinary Agenda*. Edward Elgar Publishing.
- Teebken, J., Mitchell, N., Jacob, K., Heimann, T., 2023. Classifying social adaptation practices to heat stress—Learning from autonomous adaptations in two small towns in Germany. *Weather. Clim. Soc.* 15 (1), 95–108.
- Tetzlaff, E.J., Goulet, N., Gorman, M., Ioannou, L.G., Kenny, G.P., 2023. Working under the 2021 heat dome: A content analysis of occupational impacts mentioned in the Canadian media. *Healthcare* 11 (17), 2423, Number: 17 Publisher: Multidisciplinary Digital Publishing Institute.

- Tian, H., Cai, H., Hu, L., Qiang, Y., Zhou, B., Yang, M., Lin, B., 2024. Unveiling community adaptations to extreme heat events using mobile phone location data. *Journal of Environmental Management* 366, 121665.
- U. S. Census Bureau, 2020. American community survey 1-year estimates. <https://www.census.gov/programs-surveys/acs/data.html>.
- U.S. Energy Information Administration, 2020. Residential energy consumption survey. <https://www.eia.gov/consumption/residential/data/2020/index.php?view=consumption>.
- Van Der Linden, N., Longden, T., Richards, J.R., Khursheed, M., Goddijn, W.M.T., Van Veelen, M.J., Khan, U.R., Van Der Linden, M.C., 2019. The use of an 'acclimatisation' heatwave measure to compare temperature-related demand for emergency services in Australia, Botswana, Netherlands, Pakistan, and USA. In: Zou, Y. (Ed.), *PLOS ONE* 14 (3), e0214242.
- Venter, Z.S., Chakraborty, T., Lee, X., 2021. Crowdsourced air temperatures contrast satellite measures of the urban heat island and its mechanisms. *Sci. Adv.* 7 (22), eabb9569.
- Wen, C.-H., Koppelman, F.S., 2000. A conceptual and methodological framework for the generation of activity-travel patterns. *Transportation* 27, 5–23.
- White, R.H., Anderson, S., Booth, J.F., Braich, G., Draeger, C., Fei, C., Harley, C.D.G., Henderson, S.B., Jakob, M., Lau, C.-A., Mareshet Admasu, L., Narinesingh, V., Rodell, C., Roocroft, E., Weinberger, K.R., West, G., 2023. The unprecedented Pacific Northwest heatwave of June 2021. *Nat. Commun.* 14 (1), 727.
- Widener, M.J., 2018. Spatial access to food: Retiring the food desert metaphor. *Physiol. Behav.* 193, 257–260.
- Widernyski, S., Schramm, P., Conlon, Noe, R., Grossman, E., Hawkins, M., Nayak, S., Roach, M., Hiltz, A.S., 2017. The use of cooling centers to prevent heat-related illness: Summary of evidence and strategies for implementation. *Clim. Heal. Tech. Rep. Ser.* <https://www.cdc.gov/climateandhealth/docs/UseOfCoolingCenters.pdf>.
- Wolf, J., Adger, W.N., Lorenzoni, I., Abrahamson, V., Raine, R., 2010. Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities. *Glob. Environ. Chang.* 20 (1), 44–52.
- Zhang, Z., Parker, R.M.A., Charlton, C.M.J., Leckie, G., Browne, W.J., 2016. **R2MLwiN**: A package to run *MLwiN* from within *R*. *J. Stat. Softw.* 72 (10).
- Zhang, X., Wang, X., Li, Y., Tang, Y., 2024. Gendered space-time constraints, daily activities, and social cohesion: Evidence from Fuzhou, China. *Trans. Plan. Urban Res.* 27541223241238382.
- Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A.M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., Pan, S.-C., Íñiguez, C., Ameling, C., De La Cruz Valencia, C., Åström, C., Houthuijs, D., Dung, D.V., Royé, D., Indermitte, E., Lavigne, E., Mayvaneh, F., Acquaotta, F., de'Donato, F., Di Ruscio, F., Sera, F., Carrasco-Escobar, G., Kan, H., Orru, H., Kim, H., Holobaca, I.-H., Kyselý, J., Madureira, J., Schwartz, J., Jaakkola, J.J.K., Katsouyanni, K., Hurtado Diaz, M., Ragetti, M.S., Hashizume, M., Pascal, M., De Sousa Zanotti Stagliorio Coelho, M., Valdés Ortega, N., Rytí, N., Scovronick, N., Michelozzi, P., Matus Correa, P., Goodman, P., Nascimento Saldiva, P.H., Abrutzky, R., Osorio, S., Rao, S., Fratianni, S., Dang, T.N., Colistro, V., Huber, V., Lee, W., Seposo, X., Honda, Y., Guo, Y.L., Bell, M.L., Li, S., 2021. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *Lancet Planet. Heal.* 5 (7), e415–e425, URL <https://linkinghub.elsevier.com/retrieve/pii/S2542519621000814>.
- Zou, Y., Xie, W., Lou, S., Zhang, L., Huang, Y., Xia, D., Yang, X., Feng, C., Li, Y., 2023. How weather impacts the citizens' activity patterns in southern China? Enlightenment from large-scale mobile phone signaling data of Guangzhou. *Urban Clim.* 52, 101700.