Spatial and Spatio-temporal Epidemiology 46 (2023) 100590

Contents lists available at ScienceDirect

Spatial and Spatio-temporal Epidemiology

journal homepage: www.elsevier.com/locate/sste

The contribution of physical exertion to heat-related illness and death in the Arizona borderlands

Samuel N. Chambers [a,*], Geoffrey A. Boyce [b], Daniel E. Martínez [c], Coen C.W.G. Bongers [d,e], Ladd Keith [f]

[a] Department of Epidemiology and Biostatistics, Mel and Enid Zuckerman College of Public Health, The University of Arizona, Tucson AZ, USA
[b] School of Geography, University College Dublin, Dublin, Ireland
[c] School of Sociology, College of Social and Behavioral Sciences, The University of Arizona, Tucson AZ, USA
[d] School of Sport and Exercise, HAN University of Applied Sciences, Nijmegen, The Netherlands
[e] Department of Medical BioSciences, Radboud University Medical Center, Nijmegen, The Netherlands
[f] School of Landscape Architecture and Planning, The University of Arizona, Tucson AZ, USA

ARTICLE INFO

Keywords:
Critical GIS
Biometeorology
Thermal physiology
Boundary enforcement
Forensics
Extreme heat

ABSTRACT

Recent studies and reports suggest an increased mortality rate of undocumented border crossers (UBCs) in Arizona is the result of heat extremes and climatic change. Conversely, others have shown that deaths have occurred in cooler environments than in previous years. We hypothesized that human locomotion plays a greater role in heat-related mortality and that such events are not simply the result of exposure. To test our hypothesis, we used a postmortem geographic application of the human heat balance equation for 2,746 UBC deaths between 1990 and 2022 and performed regression and cluster analyses to assess the impacts of ambient temperature and exertion. Results demonstrate exertion having greater explaining power, suggesting that heat-related mortality among UBCs is not simply a function of extreme temperatures, but more so a result of the required physical exertion. Additionally, the power of these variables is not static but changes with place, time, and policy.

1. Introduction

Since 1990 nearly 4000 persons are known to have died in Southern Arizona attempting to enter the United States (U.S.) from México without proper documentation (Martínez et al., 2021; Humane Borders, 2022). Among deceased undocumented border crossers (UBCs) for whom a cause of death was established, 73% died due to environmental exposure, most commonly dehydration and hyperthermia (*ibid.*). Temperatures in this region regularly exceed 43 °C during summer months (May-September) and it is common to experience more than 30 consecutive days of temperatures above 38 °C. Paradoxically, research has found that when the location of UBC mortality and geographic information system (GIS) modeling of environmental conditions are analyzed together and compared across four distinct enforcement eras, over a 30-year period between 1990 and 2020, UBC mortality has trended toward locations where the human body should be more, rather than less, capable of regulating core temperature (T_{core}) (Chambers et al., 2022). This trend is a function of a shift of UBC routes of travel toward higher elevations characterized by lower ambient temperature and greater efficiency at evaporative heat loss by sweating. Thus, despite scholarly and journalistic accounts linking extreme temperature to UBC mortality (Associated Press, 2021; Campbell-Staton et al., 2021; Collier, 2021), ambient air temperature alone is inadequate to explain either the persistence of UBC mortality or an observed increase in the rate of mortality over time (Chambers et al., 2021a; Martínez et al., 2021).

Therefore, to better understand these patterns and inform efforts to ameliorate UBC deaths, there is a need to identify additional variables that can explain observed patterns of UBC mortality in the Southern Arizona desert. As such, our study aimed to test whether exertion or ambient temperatures better explained the observed patterns of UBC mortality in the study area. In this paper, we applied geospatial analysis based on the modeling of the human heat balance to test two such

* Corresponding author.
E-mail address: schambers@arizona.edu (S.N. Chambers).

https://doi.org/10.1016/j.sste.2023.100590
Received 21 February 2023; Received in revised form 11 May 2023; Accepted 31 May 2023
Available online 1 June 2023
1877-5845/

variables via regression analysis: the cumulative volume of physical exertion required for pedestrian travel from the border to any given location where UBC remains have been identified, and average surface temperatures across the same routes of travel. Our analysis finds that the physical exertion associated with UBC mortality has increased substantially over time, which plays a greater role in the increase of T_{core} than ambient temperature alone. As we discuss below, this is important because the conditions contributing to the need for greater physical exertion among UBCs are (1) spatially proximate, and (2) correlated with identifiable policy choices. There are clear policy interventions that could be mobilized to address these patterns of mortality and improve public health outcomes in Southern Arizona. In what follows, we discuss in greater detail related previous research on UBC mortality and cause; examine the policy context within which these patterns of mortality are unfolding; describe the methodology and research findings; and consider the implications of our findings for scholarship and policymaking.

2. "Prevention through deterrence" and UBC mortality in Southern Arizona

A number of scholars have discussed how UBC mortality in the Southern Arizona desert can be understood as a function of "structural violence" (see Nevins, 2005; Slack and Whiteford, 2011; Martínez et al., 2014; De León, 2015; Giordano and Spradley, 2017; Chambers et al., 2022), or what medical anthropologist Farmer (2009) defines as a process of structural or institutional "forces conspiring to promote suffering" (*ibid.*, 26), including avoidable exposure to "illness and premature death" (*ibid.*, 25). In 1994, the U.S. government launched its first-ever coordinated nationwide border enforcement strategy, titled "Prevention Through Deterrence" (PTD). The strategy document associated with the launch of PTD was explicit about its premises and objectives. Arguing that "absolute sealing of the border is unrealistic" (U.S. Immigration and Naturalization Service, 1994; 1), the federal government aimed to concentrate U.S. Border Patrol (USBP) infrastructure and personnel into urban areas along the México / United States border, with the aim of redirecting routes of unauthorised entry into more remote desert areas where the government believed that environmental conditions would be "less suited for crossing and more suited for enforcement" (*ibid.,* 7). Although it was never precisely the federal government's objective to *cause* an increasing in UBC mortality, such deaths were always understood as a likely outcome of PTD. For example, the 1994 Border Patrol Strategic Plan observes that UBCs "crossing through remote, uninhabited expanses … along the border can find themselves in mortal danger" (U.S. Immigration and Naturalization Service, 1994; 6). Evaluating the policy in 1997, the U.S. Government Accountability Office further asserted that "if the strategy [PTD] is successful… deaths may increase (as enforcement in urban areas forces aliens to attempt mountain or desert crossings)" (GAO, 1997; 84).

Over time the U.S. government has continued to expand the practices and infrastructures associated with PTD. In our prior work, we have elaborated a periodization of four successive eras associated with this expansion (Martínez et al., 2021; Chambers et al., 2022). USBP's initial border-wide effort (1990–1999) was supplemented first by a further expansion of enforcement personnel and infrastructure like walls and remote video surveillance systems (RVSSs) in smaller regional urban border areas (2000–2005) (Martínez et al., 2014). Next, USBP adopted a "defense-in-depth" strategy that expanded interior enforcement infrastructure like checkpoints and "virtual fence" integrated fixed towers (IFTs) significantly north of the international boundary, complemented by the imposition of post-apprehension consequences like criminal prosecution for "unlawful entry" and "unlawful re-entry" through programs like Operation Streamline (2006–2013) (Chambers et al., 2021a). Then, additional pre- and post-apprehension initiatives aimed at expanding PTD to target lawful asylum seekers, including the reintroduction of family detention, "metering" practices that slowed and limited individuals' access to asylum, and the "Migrant Protection Protocols," which forced asylum seekers to await their immigration court dates in northern Mexican border cities for indefinite lengths of time (2014–2020).

Research has established how each of the preceding enforcement periods resulted in routes of travel shifting toward increasingly remote areas, where more rugged, mountainous conditions and distance from paved roads and settlements provide UBCs with a greater degree of protection from the USBP's apparatuses of surveillance and enforcement (Andreas, 2001; Rubio-Goldsmith et al., 2006; Martínez et al., 2013, 2014; Boyce, 2016; Slack et al., 2016; Soto, 2018; Boyce et al., 2019; Chambers et al., 2021a; Martínez et al., 2021). In addition, a number of studies have also shown how migrants elongate their routes of travel in order to circumnavigate interior enforcement infrastructures like integrated fixed towers and checkpoints (BLM, 2005; Soto, 2018; Chambers et al., 2020; Boyce and Chambers, 2021). As a result of these changes, thousands of UBCs have perished and thousands more disappeared while undertaking the cross-border journey (on the issue of disappearance, see Coalicion de Derechos Humanos and No More Deaths, 2016; Chambers et al., 2021b). In fact, since these policy initiatives began to take effect in the late 1990s, not only has the annual number of UBC deaths in Southern Arizona remained consistently high, but the *rate* of mortality (calculated by dividing the number of UBC deaths by USBP apprehensions and standardized to 100,000) increased steadily, from 43 deaths per 100,000 apprehensions in 2002 to 316 deaths per 100,000 apprehensions in 2020 (Martínez et al., 2021).

It is common for journalists and government officials to cite the extreme temperatures that characterize Arizona's desert borderlands (particularly during summer months that extend from May – September) as the principal cause of these deadly outcomes (Associated Press, 2021; Collier, 2021; U.S. Customs and Border Protection, 2021a; 20201b). Our research has shown, however, that when we examine the location of UBC mortality across the four periods associated with PTD, a consecutively greater proportion of UBCs have perished in locations with greater shade cover and lower ambient temperature, where the body should be better capable of regulating T_{core} (Chambers et al., 2022). This is consistent with past analysis showing UBCs as having stable T_{core} at the time of entry to the U.S., but following multi-day pedestrian journeys through the desert being hospitalized for trauma, rhabdomyolysis, dehydration, acute kidney injury, and encephalopathy—all illnesses that can increase with exertion alone or exertion coupled with heat (Wong et al., 2015; McVane et al., 2019). In discussing previous research findings, researchers suggested a need to consider factors other than ambient temperature to explain observed patterns of UBC mortality, such as changes in the overall physical exertion required to arrive on foot from the México / U.S. border to the locations where UBCs are known to have died (Chambers et al., 2022). This is because 1) physical exertion is directly related to metabolic heat production and heat related illness (Nelson et al., 2011; Adams et al., 2020), and 2) under PTD, border enforcement policy has explicitly aimed to increase the difficulty and distance of pedestrian travel necessary to successfully enter the United States (U.S. Immigration and Naturalization Service, 1994). In what follows, we apply geospatial modeling to test this relationship, in order to better understand how and why UBCs succumb to heat-related illnesses.

3. Data and methods

3.1. Dependent variables

Following Chambers et al., 2022, our analyses draw on UBC data from the Pima County Office of the Medical Examiner (PCOME), which

Table 1
The formulations and process used to calculate the rate of change in core temperature (ΔT_{core}), with accompanying descriptions. Greater details for cost distancing can be found in Chambers, McMahan, and Bongers (2020). Detailed explanations of the physiological processes, mechanisms, and mathematics of the human heat balance, on which this is based, are explained by Ravanelli et al. (2019).

Formulas	Descriptions
$C + R = (T_{skin} - T_{operative}) / 0.155 + (1 / ((Hr \times Hc) \times 1.31)) \times BSA$	Convection (C) and Radiation (R) are a function of skin temperature (T_{skin}), operative temperature ($T_{operative}$), radiative heat transfer (Hr), convective heat transfer (Hc), and body surface area (BSA).
$Hr = ((1258.286) \times (273.2 + ((T_{skin} + T_{rad})/2)) \times 3)$	Hr is a function of T_{skin} and radiant temperature (T_{rad}).
$Hc = 8.3 \times AF \times 0.6$	Hc is a function of airflow (AF in m/s).
Estimated $T_{skin} = 30.0 + (0.138 \times T_{amb}) + (0.254 \times Pa) - (0.57 \times AF) + (1.28 \times 1.28 \times 0.001 \times (M / BSA)) - 0.553$	T_{skin} is a function of ambient temperature (T_{amb}), water vapor pressure (Pa), AF, Hr, M, and BSA.
$Pa = \exp(18.956 - (4030.18 / (T_{amb} + 235)) / 10) \times (RH / 100)$	Pa is a function of Hr and T_{amb}
$T_{operative} = ((Hr \times T_{rad}) + (Hc \times T_{amb})) / (Hr + Hc)$	$T_{operative}$ is a function of Hr, Hc T_{rad}, and T_{amb}.
$C_{res} + E_{res} = (0.0014 \times M) \times (34 - T_{amb}) + (0.0173 \times (5.87 - Pa))$	C_{res} and E_{res} are functions of T_{amb}, M, and Pa
$E_{max} = (\omega h_e(P_{sk,sat} - P_a))/(R_{e,cl} + 1/(h_e \times f_{cl})$	E_{max} is a function of maximum skin wetness (ωmax), saturated water vapor pressure ($P_{sk,sat}$) at skin temperature, Pa, evaporative heat transfer resistance of clothing (*Re*,cl), clothing area factor (fcl) and an evaporative heat transfer coefficient.
$P_{sk,sat} = Pa / (RH/100)$	$P_{sk,sat}$ is a function of Pa and relative humidity (RH)
$E_{vap} = 136.95 \times (AF^{0.6})$	E_{vap} is a function of AF
$VO_{2\ up} = (WS \times 0.2) + (WS \times G \times 0.9) + 3.5$	Uphill or level oxygen consumption ($VO_{2\ up}$) is a function of walking speed (WS) (Crabtree et al., 2021) and terrain Grade (G) (Glass 2007).
$VO_{2\ down} = 6.8192 + (WS \times 0.1313) + (1.2367 \times G)$	Downhill oxygen consumption ($VO_{2\ down}$) is a function of WS and G (Roberge, Wagner, and Skemp 1997).
$M = VO_2 \times 341$	M is a function of VO_2 (in mL)
$W = 9.81 \times Wt \times WS \times G$	W is a function of body weight (Wt), WS, and G
$S = M - W + C \pm R - (C_{res} + E_{res}) - E_{max}$	Body heat storage (S) is a function of a function of M, Wk, C, R, C_{res}, E_{res}, and E_{max}
$\Delta T_{core} = (S \times WS \times BSA) / (Wt \times 3.47)$	The change in core temperature (ΔT_{core}) is a function of S, BSA, and Wt.

is located in Tucson, Arizona (also see Anderson et al., 2008; Martinez et al., 2021). PCOME investigated 3755 UBCs whose postmortem remains were recovered in the Border Patrol's Tucson Sector between 1990 and 2022.[1] For reasons further discussed below, our analytic sample consists of 2744 UBCs examined by PCOME. In order to compare the effects of two independent variables: exertion (measured by VO_2, i.e., oxygen consumption) and ambient temperature (T_{amb}) on the risk of UBC death by heat exposure, we relied on the human heat balance equation. Human heat balance is measured in heat stored (S) and is a function of metabolic heat (M), external work (Wk), radiation (R) and convection (C), evaporative heat loss (E), and respiratory heat exchange by convection (C_{res}) and evaporation (E_{res}) (Ravanelli et al., 2019; Winslow et al., 1936) and is calculated in watts by the formula (S) = M – Wk ± K ± C ± R – (Cres + Eres) – E. In our case, we translated this rate to degrees Celsius per meter walked (ΔT_{core}), as described by Chambers et al. (2020) (Table 1), using Landsat-8 satellite imagery (Rajeshwari and Mani 2014; Ermida et al., 2020) and a digital elevation model (USGS 2017) for each individual record of recovered human remains (RHR) of UBCs in the study area. Improvements were made with the addition of spatially continuous high-resolution humidity (Huntington et al. 2017) and airflow data (Badger and Jørgensen 2011), and corrections made for anisotropic uphill and downhill energy expenditure which was already tested against the locations of RHR in the region (Chambers and Miranker, 2022). As in prior texts, clothing and load specifics were based on typical UBC demographics and activity (De León, 2012; Soto 2018; Chambers et al., 2020). Our analysis encompassed a study area of 76,671 square kilometers in the region, the maximum extent of all known RHR locations for UBC deaths by exposure or undetermined causes in Arizona (Fig. 1). Deaths by heat exposure are defined as those mortalities resulting from hyperthermia or when the core body temperature exceeds 38.3 °C (100.9°F), as determined by the medical examiner (Lougee, Hess, and Winston 2018).

Using an anisotropic cost distance function (Wood and Schmidtlein, 2012; Field et al., 2022), with the border as a starting point and ΔT_{core} as a cost surface, we calculated the total estimated increase in core temperature for each individual location of RHR. To minimize the heteroscedasticity of cost distances and (Szabó et al., 2012) allow for the identification of clusters, we used flow accumulation and direction (Frachetti et al., 2017) to calculate total walking distance and used this to normalize all values for statistical and spatial comparison. Using polynomial regression analyses (Mohamed and Srinavin, 2002; Schweiker and Wagner, 2015), we tested to what degree T_{amb} and VO_2, as independent variables, impacted ΔT_{core} as the dependent variable for each RHR location. To account for the distinct nonlinear relationships (Kanosue et al., 2010; James et al., 2015), we used quadratic regression for VO_2, and for T_{amb}, we used cubic regression. We used this to compare whether exertion or ambient temperature played a larger role in increasing T_{core}, and how this varied by policy era. We performed these analyses for five consecutive time periods based on policy changes as described in Table 2. Because we are interested in assessing the relationships between border enforcement measures, physical exertion, and environmental conditions, we purposefully limited our analysis to UBC remains classified as having died due to heat exposure or those with an undetermined cause of death.[2] We, for instance, excluded motor vehicle accident deaths, homicides, suicides, drownings, and other

[1] As discussed in Martínez et al. (2021), PCOME is a comprehensive provider of medical-legal death investigation for Cochise, Graham, La Paz, Pima and Santa Cruz counties in Southern Arizona, and it further provides investigatory services as-needed for Apache, Gila, Greenlee, Navajo and Pinal counties. PCOME's records are therefore comprehensive for UBC RHRs (and suspected UBC RHRs) across the study area. There are, of course, issues of jurisdiction, infrastructure and terrain that shape and limit where human remains are likely to be encountered in the first place. For example, law enforcement, tribal officials, hunters, ranchers, recreational hikers and humanitarian actors tend to concentrate their activities in lower elevation areas closer to established roads; while areas like the Barry Goldwater U.S. Air Force Range impose extreme restrictions on civilian access, only occasionally permitting volunteer search-and-rescue organizations to enter (and always accompanied by Air Force personnel). On the one hand, these issues introduce selection bias on the RHR data collected and published by PCOME. On the other hand, the factors introducing this selection bias remained essentially consistent throughout the study period.

[2] As Martínez et al. 2021 note, given the remote locations where US authorities typically recover UBC remains for which a cause of death is "undetermined," it is probable that a large proportion of such individuals perished due to exposure to the elements, especially if there are no visible signs of trauma on the remains. We performed a secondary analyses, removing undetermined cases, but the resulting coefficients and patterns were similar to those found in the full analyses. For these reasons, we include these cases in our reports.

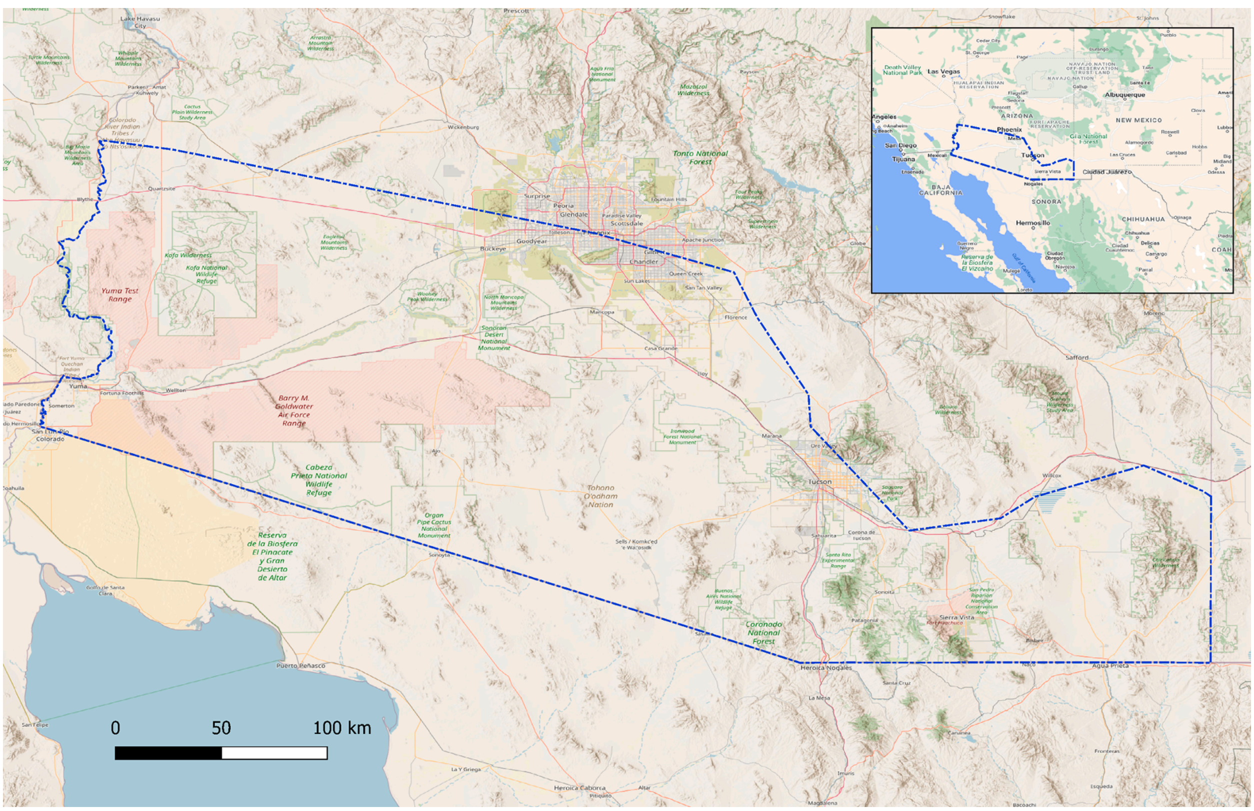

Fig. 1. Map covering study area, outlined in blue, encompassing the Southern Arizona landscape and the maximum northern extent of known RHR locations for UBC deaths by exposure or undetermined causes from FY 1990 to 2022.

Table 2
Description of Policy Eras, Southwestern Border Patrol Apprehensions, Tucson Sector Apprehensions, and PCOME Recovered UBC Remains (FY 1990–2022) Adapted from Martinez et al. (2021). Sources: US Customs and Border Protection; Pima County Office of the Medical Examiner.

FY	Policy Era	Description of Policy Era	Southwestern Apprehensions/ Encounters	Tucson Sector Apprehensions/ Encounters	Tucson Apprehensions as% of Total USBP Apps	PCOME Recovered UBC Remains
1990	Initial Funnel Effect (1990–1999)	Launch of PTD and Operations Hold the Line (1993, El Paso) and Gatekeeper (1994, San Diego). Pre-concentration of border enforcement efforts in southern Arizona; although Operation Safeguard (Arizona) launched in FY 1995, and expanded in 1997, resources did not materialize until 1999; Tucson Sector apprehensions steadily increased; UBC recovered remains remained low.	1049,321	53,061	5%	8
1991			1077,876	59,728	6%	7
1992			1145,574	71,036	6%	5
1993			1212,886	92,639	8%	11
1994			979,101	139,473	14%	11
1995			1271,390	227,529	18%	8
1996			1507,020	305,348	20%	13
1997			1368,707	272,397	20%	21
1998			1516,680	387,406	26%	17
1999			1537,000	470,449	31%	19
2000	Secondary Funnel Effect (2000–2005)	Undocumented migration displaced into southern Arizona; relatively steady volume of Tucson Sector apprehensions; 35%-plus of all border-wide apprehensions occurred in USBP Tucson Sector; Recovered UBC remains nearly tripled. Walls and RVSS concentrate in urban areas like Nogales and Douglas, AZ. Migration and UBC mortality shift toward more remote desert areas.	1643,679	616,346	37%	70
2001			1235,718	449,675	36%	76
2002			929,809	333,648	36%	143
2003			905,065	347,363	38%	146
2004			1139,282	491,771	43%	167
2005			1171,369	439,079	37%	199
2006	Tertiary Funnel Effect (2006–2013)	Steady decrease in border-wide and Tucson Sector apprehensions; ~30%-plus of all apprehensions still occurred in Tucson Sector, though the proportion dropped across time. At least 160 recovered UBC remains recorded each year. "Defense in Depth" strategy launched with internal checkpoints and IFTs deployed significantly north of the borderline. Operation Streamline and other "post-apprehension consequences" introduced.	1071,972	392,074	37%	167
2007			858,638	378,239	44%	207
2008			705,005	317,696	45%	160
2009			540,865	241,673	45%	182
2010			447,731	212,202	47%	221
2011			327,577	123,285	38%	174
2012			356,873	120,000	34%	168
2013			414,397	120,939	29%	177
2014	Localized Funnel Effect (2014–2019)	Decreased proportion of border-wide apprehensions in the Tucson Sector. Proportion of Central American apprehensions increased. Pre-and post-apprehension deterrence measures launched to target lawful asylum-seekers as well as UBCs. One-year USBP recidivism rates steadily declined during this era, with a mean of 11% across the six fiscal years.	479,371	87,915	18%	119
2015			331,333	63,397	19%	135
2016			408,870	64,891	16%	138
2017			303,916	38,657	13%	134
2018			396,579	52,172	13%	118
2019			851,508	63,490	7%	124
2020	Title 42 Era (2020–2022)	U.S. government used COVID-19 emergency to suspend access to asylum for most categories of asylum-seekers. USBP began tracking "encounters," which include both Title 8 Apprehensions and Title 42 Expulsions. USBP encounters, recovered UBC remains, and recidivism rates all increased.	400,651	66,076	16%	206
2021			1659,206	191,232	12%	225
2022			2206,436	251,984	11%	179

non-exposure related deaths, as doing so would bias our results. Two records were removed due to local errors in the model input. In sum, our analytic sample consists of 2744 cases, which represent approximately 88% of all UBC deaths investigated by the PCOME from 1990 to 2022. Lastly, to verify our regression analysis results and to compare and identify the spatial association and identify geographic clusters of high and low T_{amb}, VO_2, and ΔT_{core} values, we performed a Getis-Ord Gi* hotspot analysis (Getis and Ord 1992) for each variable by the minimum distance between RHR locations by era.

3.2. Focal independent variable

As noted above, prior research has examined how undocumented migration and migrant deaths in Southern Arizona have varied across four distinct enforcement eras since 1990 (Martinez et al., 2013, 2021; Chambers et al., 2022). We expand upon the work of Chambers et al. (2022) and Martinez et al. (2021) by extending and slightly revising the enforcement eras these scholars examined (see Table 2). Whereas prior studies have categorized 2020 as part of the "Localized Funnel Effect" era, we identify 2020 as actually representing the beginning of a new fifth era of border enforcement in Southern Arizona. These five distinct policy eras, which are described in Table 2, constitute our focal independent variable.

We contend that the border enforcement landscape changed drastically in the early months of 2020. On March 20, 2020, the Trump Administration reinstituted Title 42 of the U.S. public health code, which "permits the Director of the CDC to 'prohibit…the introduction' into the United States of individuals when the director believes that 'there is serious danger of the introduction of [a communicable] disease into the United States" (American Immigration Council, 2022). Though the Trump administration cited justification for re-implementing Title 42 was a desire to prevent the spread of COVID-19 as a pretext for re-implementing Title 42, it is documented that the underlying intent has been to disrupt immigrants' access to the U.S. asylum system (American Immigration Council, 2022). Under Title 42, most border-crossers encountered by U.S. officials, whether they are undocumented immigrants trying to avoid detection or asylum seekers attempting to initiate the asylum process, are swiftly processed and returned to México without the opportunity to conduct a credible fear interview. Because of the reinstatement of Title 42, USBP now tracks what they call "encounters," which include Title 8 Apprehensions as well as Title 42 Expulsions (see Table 2).

The USBP has tracked the border-wide one-year recidivism rate for decades, which represents the proportion of undocumented border crosser re-encountered by the agency within one year (for a discussion of the limitations of the government's methodology for tracking this issue, see TRAC 2022). One consequence of Title 42 has been a pronounced increase in this rate, which can be understood as a defining feature of the Title 42 era (2020–2022). Despite dropping from roughly 16% in 2013 to 7% by 2019, recidivism rates increased nearly four-fold the following year to 26%, and once again increased to 27% in 2021 (U.S. Customs and Border Protection, 2023). Though the one-year USBP recidivism rate for 2022 is not yet publicly available, it likely remains near 2020–2021 rates. Ultimately, recidivism is an important factor to consider because multiple crossing attempts, particularly at quick intervals, are likely to increase individuals' risk of exposure, exhaustion, physical depletion, and death.

4. Results

Our regression analysis showed a notable positive relationship between both T_{amb} and ΔT_{core} (Fig. 2) and VO_2 and ΔT_{core} (Fig. 3), with all p-values for each policy era being highly statistically significant ($p < 0.001$). This was expected as each is part of the heat balance equation but R^2 values show that VO_2 has been a better or equal predictor for ΔT_{core}. This is consistent with prior non-geographic physiological studies showing human locomotion can significantly increase the risk to develop excessive hyperthermia, in extreme heat but also in temperature-controlled environments (Brotherhood 2008; Sawka et al., 2001). Still, R^2 values vary by policy era. Whereas T_{amb} explains 39% of the observed variation in RHR initially, it rises to 68% in the Localized Funnel Effect era, but drops during Title 42. VO_2 had a consistently greater than 50% determining power across all eras and greater than 60% in the three most recent policy eras. Although near equal in importance to T_{amb} in the Localized Era, it remained strong in Title 42.

These variations and relationships are also recognizable geographically (Fig. 4). Although varying by time and location, generally, the greatest ΔT_{core} values correspond to the greater VO_2 and T_{amb} values, especially for those RHR locations near the center of the Arizona/Sonora boundary, land which is part of the Tohono O'odham Nation. Although T_{amb} is high in the western part of the study area near Cabeza Prieta NWR and the Goldwater Air Force Range, this does not always correspond to those RHR locations with high ΔT_{core} values but rather higher VO_2. This corresponds to UBC taking routes running adjacent to or on the sides of mountain ranges. Likewise, in the eastern part of the study area, locations with lower relative T_{amb} can have higher ΔT_{core} and VO_2 values. This corresponds to higher elevations in the Madrean Sky Islands region and Coronado National Forest where the Sonoran Desert transitions to woodlands, forests, and the cooler Chihuahuan desert.

In-depth cluster analysis further validates these findings. Overall, there are spatial similarities of VO_2 and ΔT_{core} in all eras but the prevalence and clustering of low VO_2 values, as evident in the Getis-Ord Gi* hotspot analysis of the Initial and Secondary Funnel Effects, correspond to the lower R^2 values for that variable in our regression analysis (Fig. 5). Similarly, the clusters of hotspots and coldspots are most similar for T_{amb} and ΔT_{core} during the Tertiary Funnel Effect, when the R^2 value rises for T_{amb} after its drop during the Secondary Funnel Effect. Durting the Localized Funnel Effect, when the R^2 values were most similar, VO_2 hotspots show a strong relationship to and are most similar to those of ΔT_{core} in the center and east of the study area, whereas T_{amb} hotspots are most similar and prevalent in the west. The especial similarity of ΔT_{core} and VO_2 hotspots during Title 42 corresponds to the relative maintaining of its importance and the simultaneous drop in T_{amb}'s R^2 in our regression analysis.

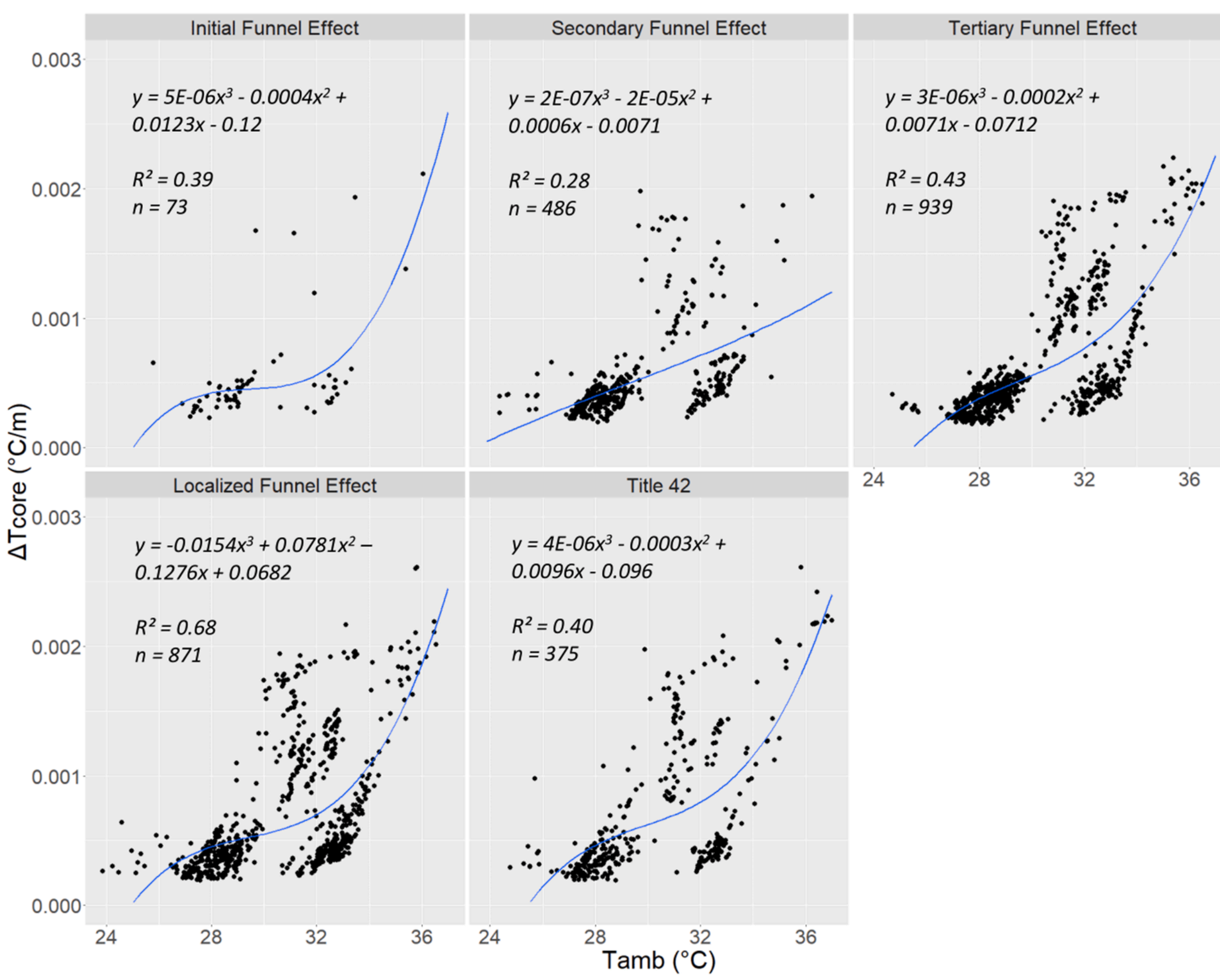

Fig. 2. Scatterplots representing the sensitivity of change in core temperature (ΔT_{core}) to ambient temperature ($T_{amb,}$), over time, for all known locations of individual undocumented border crosser mortalities in the study area.

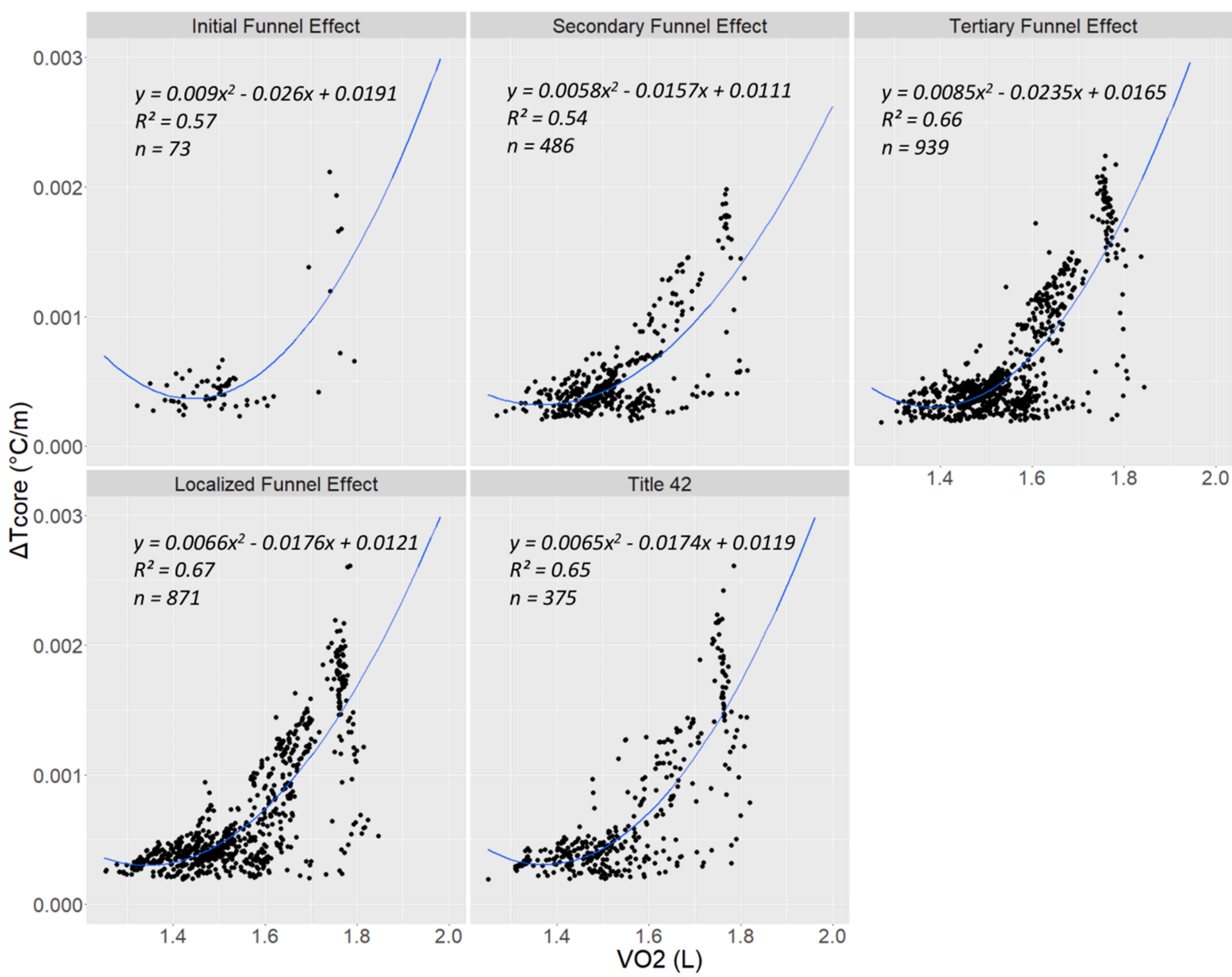

Fig. 3. Scatterplots representing the sensitivity of change in core temperature (ΔT_{core}) to physical exertion measured by oxygen consumption (VO_2), over time, for all known locations of individual undocumented border crosser mortalities in the study area.

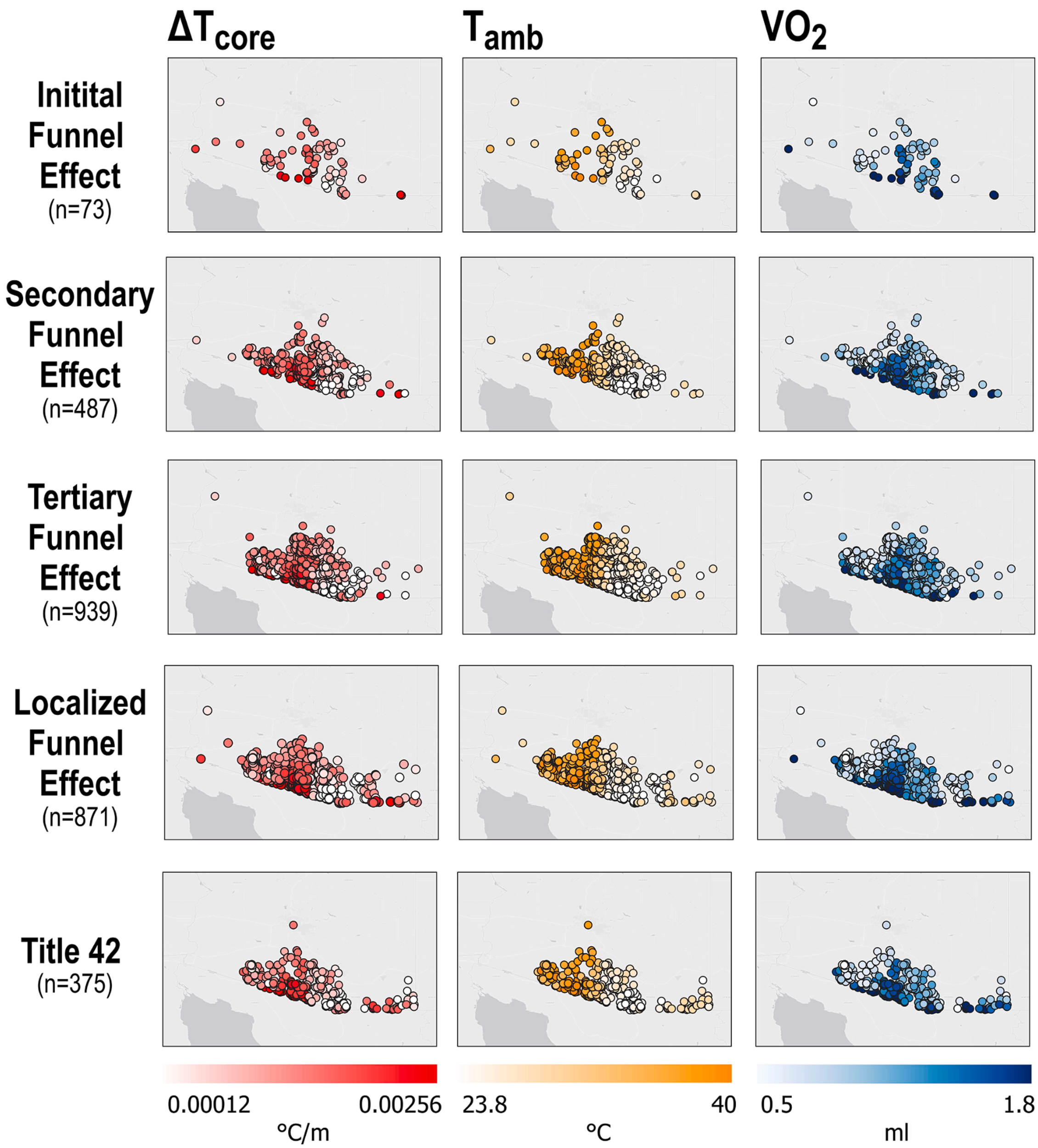

Fig. 4. Maps comparing, by policy era, the mean change in core temperature (ΔT_{core}), ambient temperature (T_{amb}), and physical exertion (VO_2) to reach the known locations of individual undocumented border crosser mortalities.

5. Discussion & conclusion

The aim of this study was to test whether physical exertion or ambient temperatures better explained the observed patterns of UBC mortality in Southern Arizona between 1990 and 2022. Our findings suggest that any account of heat-related illness and mortality among UBCs in the México / U.S. borderlands must attend not just to the impact of the general climatic condition of ambient temperature, but also to patterns of physical exertion and how these affect the body's ability to manage and survive these temperatures. The previous rise and subsequent drop in the importance of ambient temperature in the Title 42 Era, the greater determining power of oxygen uptake across all but one policy era, and this variable accounting for over 50% across all policy eras strengthens our argument. The uneven distribution of values geographically also supports our claim, demonstrating that though UBCs may traverse cooler climates, the simple act of walking can contribute to a significant increase in T_{core}. Although the importance of ambient temperature grew during the Localized Funnel Effect, our analysis shows that during Title 42, not only have crossers taken repeat attempts, but that exertion plays a greater role in their heat-related deaths in these attempts. This runs contrary to the common assumption of media and policymakers that it is solely or primarily heat contributing to the deaths.

Understanding the relationship between ambient temperatures and exertion is important because it suggests that much can be done to alleviate deadly outcomes for UBCs in the U.S.-Mexico borderlands. From a humanitarian and public health perspective, it suggests a need for additional interventions in more remote and difficult-to-access regions of the desert. These include a role for federal agencies and Tribal nations in expanding search and rescue practices and providing clean, safe drinking water across the jurisdictions they manage. Particularly, our study offers a better understanding of death by heat exposure for

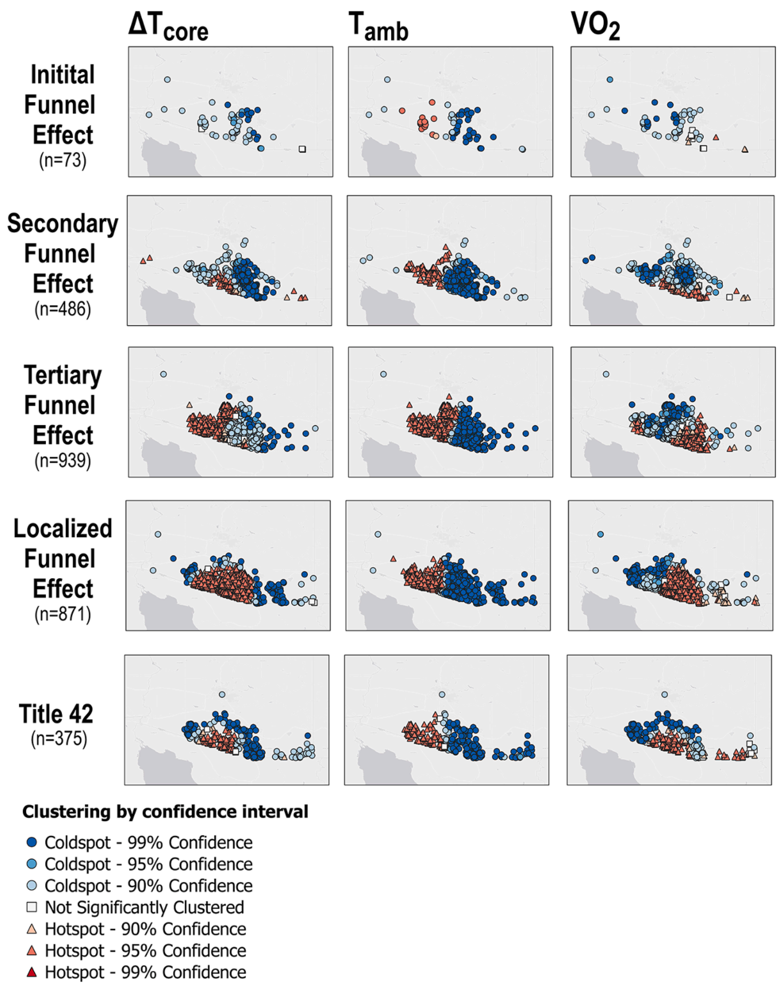

Fig. 5. Maps comparing, by policy era and analyzed RHR locations, the results of our Getis-Ord GI* hotspot analysis for (ΔT_{core}), ambient temperature (T_{amb}), and physical exertion (VO_2) values. Hotspots represent geostatistically significant clustering of high values and coldspots, significant clustering of low values for each variable.

UBCs and the importance of limiting exertion, a factor that has increased in importance since the Initial Funnel Effect and the establishment of PTD.

Meanwhile, additional work is needed to understand what part of external health factors (e.g., dehydration and comorbidities), may play in the impacts of heat and exertion. Also, our research assumes UBCs take the least costly route possible, but as these individuals are known to avoid detection and interception (a condition necessary for successful unauthorised entry), it is possible exertion plays a larger role than measured here as UBCs circumvent infrastructure likes walls, checkpoints, and surveillance towers (Boyce and Chambers, 2021; Chambers et al., 2021a). In short, our findings may be conservative estimates. Future analyses should examine how these externalities increase T_{core}. In addition, some local factors may impact exertion that are not readily known by the available spatial data. Field measurements could improve the precision of measurements of exertion and ambient and body temperatures.

Our findings have broader implications, as extreme heat is the deadliest U.S. weather-related risk (Hondula et al., 2015). In Arizona alone, nearly 3000 people experience heat-related illnesses each year and heat-related deaths are increasing, reaching a record 552 in 2021 (ADHS, 2021). In the Phoenix metropolitan area, nearly two-thirds of recorded heat-related deaths occurred outdoors (Iverson et al., 2020). The human heat balance model presented within this article could be used to better understand the relationship between ambient temperatures and exertion in other contexts, such as outdoor work or recreation in both urban and rural communities. The human heat balance equation could help better inform the suite of heat mitigation and management strategies (Keith and Meerow, 2022) that decisionmakers, such as urban planners, public health practitioners and emergency managers are pursuing as heat risk increase with climate change and evolving work conditions. Finally, our use of the heat balance equation, regression, and cluster analyses offer a framework for the investigation of UBC mortality outside Arizona, in other U.S. border states but also globally.

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.

Data availability

The data for this study are available upon request from the corresponding author. RHR records are also in the public domain and are available in the Arizona Open GIS Initiative for Deceased Migrants at: https://humaneborders.info/

Acknowledgments

The authors wish to thank Raquel Rubio-Goldsmith, our colleagues at Humane Borders, and our colleagues at the Pima County Office of the Medical Examiner for their many years of collaboration. We also wish to thank Dr. Heidi E. Brown for her help in reviewing the original manuscript.

References

Adams, W.M., Stearns, R.L., Casa, D.J., Adams, W., Jardine, J., 2020. Exertional heat stroke. Exertional Heat Illness. Springer, Cham. https://doi.org/10.1007/978-3-030-27805-2_4.

American Immigration Council, 2022. A Guide to Title 42 Expulsions at the Border. American Immigration Council, Washington, DC. Available at. https://www.americanimmigrationcouncil.org/research/guide-title-42-expulsions-border.

Anderson, Bruce, E., Bruce, O.Parks., 2008. Symposium on Border Crossing Deaths: Introduction. J. Forensic Sci. 53 (1), 6–7.

Andreas, P., 2001. The transformation of migrant smuggling across the US-Mexican Border. Glob. Hum. Smuggling Comp. Perspect. 107–125.

Arizona Department of Health Services (ADHS), 2021. Heat-Caused & Heat-Related Deaths in Arizona by Year (2011-2021). Phoenix [online]Available at: https://www.azdhs.gov/documents/preparedness/epidemiology-disease-control/extremeweather/pubs/heat-related-mortality-year.pdf [Accessed 1 January 2023].

Wong, C., Hsu, W., Carr, G.E., 2015. Spectrum of critical illness in undocumented border crossers. The Arizona–Mexico border experience. Ann. Am. Thorac. Soc. 12 (3), 410–414.

Wood, N.J., Schmidtlein, M.C., 2012. Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest. Nat. Hazards 62 (2), 275–300.

Associated Press. (2021, July 12) More migrant deaths recorded amid record heat along Arizona desert. Available from: https://www.abc15.com/news/region-central-southern-az/more-migrant-deaths-recorded-amid-record-heat-along-arizona-border [Accessed 1st September 2021].

Badger, J., Jørgensen, H.E., 2011. A high resolution global wind atlas-improving estimation of world wind resources. In: Proceedings of the Risø International Energy Conference 2011. Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi, pp. 215–225.

Boyce, G.A., 2016. The rugged border: surveillance, policing and the dynamic materiality of the US/Mexico frontier. Environ. Plan. D Soc. Space 34 (2), 245–262.

Boyce, G.A., Chambers, S.N., Launius, S., 2019. Bodily inertia and the weaponization of the Sonoran desert in US boundary enforcement: a GIS modeling of migration routes through Arizona's Altar Valley. J. Migr. Hum. Secur. 7 (1), 23–35.

Boyce, G.A., Chambers, S.N., 2021. The corral apparatus: counterinsurgency and the architecture of death and deterrence along the Mexico/United States border. Geoforum 120, 1–13.

Brotherhood, J.R., 2008. Heat stress and strain in exercise and sport. J. Sci. Med. Sport 11 (1), 6–19.

Bureau of Land Management (BLM), 2005. Southern Arizona Project to Address Public Land Degradation As a Result of Illegal Immigration, 2004, End-of-the-Year Report. Phoenix: Bureau of Land Management.

Campbell-Staton, S.C., Walker, R.H., Rogers, S.A., De León, J., Landecker, H., Porter, W., et al., 2021. Physiological costs of undocumented human migration across the southern United States border. Science 374 (6574), 1496–1500. https://doi.org/10.1126/science.abh1924. Available from:

Chambers, S.N., Boyce, G.A., Jacobs, W.J., 2021b. Constructing a desert labyrinth: the psychological and emotional geographies of deterrence strategy on the US/Mexico border. Emot. Space Soc. 38, 100764.

Chambers, S.N., Boyce, G.A., Launius, S., Dinsmore, A., 2021a. Mortality, surveillance and the tertiary "funnel effect" on the US-Mexico border: a geospatial modeling of the geography of deterrence. J. Borderl. Stud. 36 (3), 443–468.

Chambers, S.N., Boyce, G., Martínez, D.E., 2022. Climate impact or policy choice? the spatiotemporality of thermoregulation and border crosser mortality in southern Arizona. Geogr. J. https://doi.org/10.1111/geoj.12443.

Chambers, S.N., Miranker, M., 2022. Dehydration rate and a novel model to aid search and relief for undocumented border crossers in the Sonoran Desert. Prof. Geogr. 74 (4), 642–658.

Chambers, S.N., McMahan, B., Bongers, C.C., 2020. Developing a geospatial measure of change in core temperature for migrating persons in the Mexico-US border region. Spat. Spatio Temporal Epidemiol. 35, 100363.

Coalicion de Derechos Humanos, No More Deaths. Disappeared: How the USBorder Enforcement Agencies are Fueling a Missing Persons Crisis. http://www.thedisappearedreport.org/.

Collier, I., 2021. Arizona and Texas see Record Migrant Deaths on Mexico border As Temperatures Top 43C. July 13. Sky News. Available from: https://news.sky.com/story/rizona%2010and%2010texas%2010see%2010record%2010migrant%2010deaths%2010on%2010mexico%2010border%2010as%2010temperatures%2010top%201043c%201012354751 [Accessed 1st September 2021].

Crabtree, S.A., White, D.A., Bradshaw, C.J., Saltré, F., Williams, A.N., Beaman, R.J., Bird, M.I., Ulm, S., 2021. Landscape rules predict optimal superhighways for the first peopling of Sahul. Nat. Hum. Behav. 5 (10), 1303–1313.

U.S. Customs and Border Protection, 2023. CBP Enforcement statistics, U.S. Customs and Border Protection. Available at: https://www.cbp.gov/newsroom/stats/cbp-enforcement-statistics (Accessed: February 6, 2023).

De León, J., 2012. Better to be hot than caught: Excavating the conflicting roles of migrant material culture. Am. Anthropol. 114 (3), 477–495.

De León, J., 2015. The Land of Open Graves: Living and Dying On the Migrant Trail, 36. Univ of California Press.

Ermida, S.L., Soares, P., Mantas, V., Göttsche, F.M., Trigo, I.F., 2020. Google Earth engine open-source code for land surface temperature estimation from the landsat series. Remote Sens. 12 (9), 1471. https://doi.org/10.3390/rs12091471 (Basel).

Farmer, P., 1996. On suffering and structural violence: a view from below. Daedalus 125 (1), 261–283. Available from: https://www.jstor.org/stable/20027362.

Field, S., Glowacki, D.M., Gettler, L.T., 2022. The importance of energetics in archaeological least cost analysis. J. Archaeol. Method Theory 1–34.

Frachetti, M.D., Smith, C.E., Traub, C.M., Williams, T., 2017. Nomadic ecology shaped the highland geography of Asia's Silk Roads. Nature 543 (7644), 193–198.

Getis, A., Ord, J.K., 1992. The analysis of spatial association by use of distance statistics. Geogr. Anal. 24 (3), 189–206.

Giordano, A., Spradley, M.K., 2017. Migrant deaths at the Arizona-Mexico border: spatial trends of a mass disaster. Forensic Sci. Int. 280, 200–212. https://doi.org/10.1016/j.forsciint.2017.07.031. Available from:

Glass, S.G.,B., 2007. ACSM's Metabolic Calculations Handbook. LippincottHuntington, J. L., Baltimore.

James, C.A., Richardson, A.J., Watt, P.W., Gibson, O.R., Maxwell, N.S., 2015. Physiological responses to incremental exercise in the heat following internal and external precooling. Scand. J. Med. Sci. Sports 25, 190–199.

Kanosue, K., Crawshaw, L.I., Nagashima, K., Yoda, T., 2010. Concepts to utilize in describing thermoregulation and neurophysiological evidence for how the system works. Eur. J. Appl. Physiol. 109, 5–11.

Hondula, D.M., Davis, R.E., Saha, M.V., Wegner, C.R., Veazey, L.M., 2015. Geographic dimensions of heat-related mortality in seven U.S. cities. Environ. Res. 138, 439–452. https://doi.org/10.1016/j.envres.2015.02.033.

Humane, Borders.. Arizona OpenGIS Initiative for Decreased Migrants. https://humaneborders.info/app/map.asp.

Iverson, S.A., Gettel, A., Bezold, C.P., Goodin, K., McKinney, B., Sunenshine, R., Berisha, V., 2020. Heat-associated mortality in a hot climate: Maricopa County, Arizona, 2006-2016. Public Health Rep. 135 (5), 631–639. https://doi.org/10.1177/0033354920938006.

Keith, L., Meerow, S., 2022. Planning For Urban Heat Resilience. Planning Advisory Services (PAS) Report 600. American Planning Association. Available from: http://www.planning.org/publications/report/9245695/ [Accessed 21 January 2023].

D. Martinez, R. Reineke, R. Rubio-Goldsmith, B. Anderson, G. Hess and B. Parks, 2013. A continued humanitarian crisis at the border: undocumented border crosser deaths recorded by the Pima County Office of the medical examiner, 1990-2012. Available at SSRN 2633209.

Martínez, D.E., Reineke, R.C., Rubio-Goldsmith, R., Parks, B.O., 2014. Structural violence and migrant deaths in Southern Arizona: data from the Pima County Office of the medical examiner, 1990–2013. J. Migr. Hum. Secur. 2 (4), 257–286.

Martinez, D.E., Reineke, R.C., Boyce, G.A., Chambers, S.N., Launius, S., Anderson, B.E., Hess, G.L., 2021. Migrant Deaths in Southern Arizona: Recovered Undocumented Border Crosserremains Investigated by the Pima County Office of the Medical Examiner, 1990 –2020. Binational Migration Institute, University of Arizona, Tucson, Arizona. Accessed 28 12 2021. https://sbs.rizona.edu/sites/sbs.arizona.edu/files/BMI%20Report%202021%20ENGLISH_FINAL.pdf.

McVane, B.A., Andreae, M.C., Fernando, D.B., Strayer, R.J., 2019. Exertional rhabdomyolysis in a long-distance migrant. J. Emerg. Med. 56 (5), 551–553.

Mohamed, S., Srinavin, K., 2002. Thermal environment effects on construction workers' productivity. Work Study 51 (6), 297–302. https://doi.org/10.1108/00438020210441849.

Nelson, N.G., Collins, C.L., Comstock, R.D., McKenzie, L.B., 2011. Exertional heat-related injuries treated in emergency departments in the US, 1997–2006. Am. J. Prev. Med. 40 (1), 54–60.

Nevins, J., 2005. A beating worse than death: imagining and contesting violence in the US-Mexico borderlands. AmeriQuests 2 (1).

Rajeshwari, A., Mani, N.D., 2014. Estimation of land surface temperature of dindigul district using landsat 8 data. Int. J. Res. Eng. Technol. 3 (05), 122–126.

Ravanelli, N., Bongers, C.C., Jay, O., 2019. The biophysics of human heat exchange. Heat Stress in Sport and Exercise. Springer, Cham, pp. 29–43.

Robergs, R.A., Wagner, D.R., Skemp, K.M., 1997. Oxygen consumption and energy expenditure of level versus downhill running. J. Sports Med. Phys. Fit. 37 (3), 168–174.

Sawka, M.N., Latzka, W.A., Montain, S.J., Cadarette, B.S., Kolka, M.A., Kraning II, K.K., Gonzalez, R.R., 2001. Physiologic tolerance to uncompensable heat:intermittent exercise, field vs laboratory. Med. Sci. Sports Exerc. 33, 422–430.

Schweiker, M., Wagner, A., 2015. A framework for an adaptive thermal heat balance model (ATHB). Build. Environ. 94, 252–262.

Slack, J., Whiteford, S., 2011. Violence and migration on the Arizona-Sonora border. Hum. Organ 70 (1), 11–21.

Slack, J., Martínez, D.E., Lee, A.E., Whiteford, S., 2016. The geography of border militarization: violence, death and health in Mexico and the United States. J. Lat. Am. Geogr. 7–32.

Soto, G., 2018. Banal materiality and the idea of sovereignty: the migration funnel effect and the policing of the US-Mexico border, 2000–2016. Polit. Geogr. 66, 113–129.

Szabó, S., Novák, T., Elek, Z., 2012. Distance models in ecological network management: a case study of patch connectivity in a grassland network. J. Nat. Conserv. 20 (5), 293–300.

Rubio-Goldsmith, R., McCormick, M., Martinez, D. and Duarte, I., 2006. The'Funnel Effect'& Recovered Bodies of Unauthorized Migrants Processed by the Pima County Office of the Medical Examiner, 1990-2005. *Available at SSRN 3040107*.

Transactional Records Access Clearinghouse. (2022) Most border patrol apprehensions are for repeat crossers, but agency data doesn't yet provide the full picture. https://trac.syr.edu/reports/694/.

U.S. Customs and Border Protection. (2021a, July 1) Summer heath poses increased risk for migrant deaths. Available from: https://www.cbp.gov/newsroom/local-media-release/summer-heat-poses-increased-risk-migrant-deaths [Accessed 1st September 2021].

U.S. Customs and Border Protection, 2021b. Border Patrol Heat Related Dangers. June 20. U.S. Customs and Border Protection. Available from: https://www.cbp.gov/newsroom/local%2010media%2010release/extreme%2010temperatures%2010anticipated%2010weekend [Accessed 1st September 2021].

U.S. Geological Survey (USGS), 2017. 1/3rd Arc-Second Digital Elevation Models (DEMs) - USGS National Map 3DEP Downloadable Data Collection. U.S. Geological Survey.

U.S. Immigration and Naturalization Service, 1994. Border Patrol Strategic Plan: 1994 and Beyond. U.S. Border Patrol, Washington, DC.

Winslow, C.E., Herrington, L.P., Gagge, A.P., 1936. A new method of partitional calorimetry. Am. J. Physiol. Leg. Content 116 (3), 641–655.