A City Under Heat: Assessing urban heat island impacts on mortality risk from non-communicable diseases in metropolitan zones of Mexico, 2003-2019

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Abstract

Urban heat island (UHI) has been recognized as a serious health threat in urban cities worldwide, which can contribute to thermal discomfort, and a range of morbidity and mortality outcomes. Using mortality records for five International Classification of Diseases chapters (4, 5, 6, 9, and 10) from 2003–2019 across metropolitan regions in Mexico, and summer and winter daytime/nighttime UHI intensity, we assessed the association between UHI intensity and non-communicable disease mortality, stratified by climatic zone, sex, and age group. Results show that UHI intensity varied across climatic contexts, reaching up to 6 °C in temperate regions, where the strongest associations with mortality were also detected. Nighttime UHI during summer emerged as a critical driver of risk, with significant associations observed even at 1 °C increments. Vulnerability extended beyond the elderly, with consistent associations among children, adolescents, and women of reproductive age, highlighting overlooked groups at risk. These findings reveal that UHI effects are heterogeneous across seasons, regions, and demographics, and underscore the urgency of integrating UHI mitigation into climate adaptation and public health strategies to prevent the amplification of health inequities under future warming.

1. Introduction

Global trends of population migration from rural to urban areas have been a continuous phenomenon that accelerated with the onset of the industrial age in the eighteenth century [1–3]. The tipping point between rural-urban demographic balance was reached in 2008, when the global urban population outnumbered the rural one and is projected to be more than 70% of the global population by 2050 [1,4,5]. This urban development —the replacement of natural land surfaces with urban materials such as buildings, roads, using materials like concrete, and asphalt— has caused Urban heat island effect (UHI), which means that temperature in the urban centres is noted to be higher than the surrounding rural or natural areas [1,6,7]. As the world urbanizes at an unprecedented rate, understanding the impacts of UHI on public health becomes critically important.

The UHI has become a widely observed phenomenon in cities around the globe, significantly impacting the health and well-being of urban populations [7–9]. The most immediate health consequence of UHI is the exposure to elevated temperatures, which can exacerbate pre-existing chronic conditions, including cardiovascular, cerebrovascular, and respiratory disorders, as well as increase the risk of heat exhaustion and heat stroke [8,10]. Mortality rates from these conditions rise during periods of extreme heat, particularly among elderly populations [10–13]. Thus, the heating of urban environments has been recognized as a serious health threat in major cities worldwide.

Increased urbanization, an aging population across many regions, and climate change are likely to escalate the health risks associated with UHI, particularly due to increased heat exposure [3,7,10,13,14]. Studies indicate that urban populations face greater health risks compared to their rural or suburban counterparts in hot climate zones, with the most vulnerable social groups disproportionately affected [11,15–18]. However, most existing mortality studies examine intra-city excess mortality specifically during heat wave events [11,12], and tend to focus on the summer months [9,16,17,19]. Furthermore, such research is scarce in temperate zones, especially in developing countries. Growing concerns regarding the intensification of extreme weather events and climate change should amplify interest in this critical topic.

In Mexico, urbanization is a defining demographic trend, with over 70% of the population residing in urban areas and a significant portion concentrated in large metropolitan zones [20–22]. The country is home to a diverse range of climatic zones, from arid deserts to humid tropics [23], presenting a unique and complex scenario for studying the health impacts of UHI. Despite its high degree of urbanization and a significant burden of non-communicable diseases (NCD) [24,25], research on the relationship between UHI and mortality in Mexico is limited [26].

This study assessed the impact of UHI intensity on mortality for NCD's in metropolitan zones of Mexico, which concentrate the country's main urban regions. These areas are distributed across three main climatic zones: arid, temperate, and tropical. We aimed to quantify the mortality risk attributable to seasonal (summer and winter) and temporal (day and night) UHI intensity from 2003 to 2019. The findings from this research aim to enhance our understanding of intra-urban variations in heat-related mortality risk and to aid in the development of city-specific heat action plans.

2. Methods

2.1 Study area

Our study comprises 74 metropolitan zones of Mexico, officially defined and recognized by government institutions such as the Ministry of Agrarian, Territorial and Urban Development (SEDATU), the National Population Council (CONAPO), and the National Institute of Statistics and Geography (INEGI) [20]. These areas are of vital importance to the country, as they concentrate approximately 65% of the national population and are the main centres of economic and social activity [27].

The selection of these 74 zones is based not only on their demographic size and socioeconomic relevance but also on their geographical and climatic diversity. The metropolitan zones are distributed throughout the national territory, allowing for the analysis of the UHI phenomenon across a variety of environments, including, Arid climate zones: Areas characterized by low annual precipitation, high evapotranspiration, and large diurnal temperature ranges. These zones typically include desert and semi-desert environments and are predominant in the northern part of the country (e.g., Monterrey, Mexicali). Temperate climatic zones: Areas with moderate climatic conditions, noticeable seasonal temperature variation, and distinct wet and dry periods. These zones are characteristic of the central region and the highlands (e.g., Valley of Mexico, Guadalajara). Tropical climate zones: Warm and humid areas with high annual precipitation and relatively small annual temperature fluctuations. They are located on the Pacific and Gulf of Mexico slopes (e.g., Mérida, Puerto Vallarta) [23](Fig. 1). This broad geographical and climatic coverage allows us to provide a comprehensive understanding of the UHI's impact on mortality risk from NCD’s in different contexts, which is crucial for developing public health strategies adapted to local conditions.

Fig. 1 Geographical distribution of the metropolitan areas of Mexico by climate zone. Source: Created by the authors based on administrative boundary data from INEGI and CONAPO and climate classification from [23].

2.2 Mortality Data

Mortality data were obtained from the open-data portal of the Ministry of Health of Mexico (http://www.dgis.salud.gob.mx/contenidos/basesdedatos/da_defunciones_gobmx.html, accessed on 17 November 2024) for the period 2003–2019. We selected records where cause of death was classified within five chapters of the International Classification of Diseases, 10th Revision (ICD-10) [28]: Chapter 4 (Endocrine, Nutritional, and Metabolic Diseases), Chapter 5 (Mental, Behavioral, and Neurodevelopmental disorders), Chapter

6 (Diseases of the Nervous System), Chapter 9 (Diseases of the Circulatory System), and Chapter 10 (Diseases of the Respiratory System). Data were filtered to include only deaths where the place of occurrence coincided with the individual's place of residence, ensuring all cases belonged to residents within our study area. Additionally, the data were further filtered to include only deaths from urban areas that occurred during the summer (June-July, August) and winter (December-January-February) seasons.

2.3 Urban Heat Island data

The Urban Heat Island intensity for the 74 metropolitan areas was calculated using UHI data from the public digital repository available at https://yceo.users.earthengine.app/view/uhimap. This repository is a visualization and analysis tool developed on the Google Earth Engine (GEE) platform, which provides UHI intensity data (°C), defined as the difference between urban and surrounding rural Land Surfer Temperature (LST). The LST data used has a spatial resolution of 1 km² and is derived from satellite images captured during both the day and night, allowing for an analysis of diurnal and nocturnal variations of the phenomenon [29]. This methodological approach ensures a robust and consistent dataset for the study period (2003–2019), enabling a detailed evaluation of UHI's temporal and spatial patterns across Mexico's metropolitan areas. For our study we used four sets of UHI intensity: summer daytime (SDUHI), summer nighttime (SNUHI), winter daytime (WDUHI), and winter nighttime (WNUHI). To assign UHI values to municipalities within each metropolitan area, we extracted raster values for each municipality and calculated the mean UHI intensity experienced in that municipality (e.g., 1°C, 2°C, etc.). This procedure allows us to determine the UHI intensity to which the population was exposed and to assess the association between UHI and mortality for specific disease chapters.

2.4 Health impact assessment

To evaluate impact of UHI on public health we implemented a Bayesian framework to build models of the form: $P(C_i|X_k)$, which represents the probability of belonging to Class C_i (independent variable) conditioned on the factors X_k (dependent variable). In this context, C_i denotes deaths from a given non-communicable disease, *i*, (e.g., cardiovascular, respiratory), while X_k refers to the presence of a risk factor, *k*, (e.g., 1°C of UHI intensity). To quantify the relationship between the mortality and UHI intensity, we first calculated:

$$P(C_i|X_k) = \frac{N_{C_i X_k}}{N_{X_k}}$$

where $N_{C_i X_k}$ is the number of deaths occurring under a given UHI intensity X_k, and N_{X_k} is the total population exposed to that intensity. To assess the statistical significance of the mortality–UHI association [i.e. $P(C_i|X_k)$] we applied the statistical diagnostic, epsilon (ε):

$$\varepsilon(C_i|X_k) = \frac{N_k(P(C_i|X_k) - P(C_i))}{(N_k P(C_i)(1-P(C_i)))^{1/2}},$$

which corresponds to a binomial test measuring the statistical dependence of C_i on X_k relative to the null hypothesis, $P(C_i)$. Under the null hypothesis, mortality is assumed to be independent of UHI exposure:

$$P(C_i) = \frac{N_{C_i}}{N}$$

where N_{C_i} represents the number of deaths in class, C_i, and N is the total population of the study region. When the binomial distribution can be approximated by a normal distribution, values of $|\varepsilon| > 2$ were considered significant, corresponding to a 95% confidence interval ($p < 0.05$), indicating that $P(C_i|X_k)$ significantly differs from the null hypothesis, i.e. $P(C_i|X_k) \approx P(C_i)$, for more details see [30,31].

In our study, Classes were defined as deaths by ICD chapters, *i*, (4,5,6,9, and 10) estimated both for the total population and stratified by sex and age group, *j*, i.e. C_{ij} (e.g., $C_{(chapter\ 4)(poptot)}$,

$C_{(chapter\ 9)(men\ 65+)}$). The risk factor X_{klm} corresponds to each 1°C increment of UHI intensity by season, *l*, and time of day, *m,* (daytime or nighttime), e.g., $X_{1°,SD}$. Epsilon values were calculated separately for climatic zone, where N corresponded to the total population inhabiting in arid, temperate, and tropical regions (N_{arid}, $N_{temperate}$, $N_{tropical}$). Because ε increases with the strength of deviation from the null expectation, statistically significant positive values (|ε| > 2) were interpreted as evidence of a non-random association between UHI intensity and mortality for the corresponding disease group [31]. In this context, ε can be regarded both as a statistical diagnostic and as a measure of association strength (i.e., an effect size), indicating how strongly mortality risk under specific UHI exposure levels departs from the null hypothesis of independence.

Results

Mortality data

A total of 1,204,545 deaths were recorded across 74 metropolitan areas of Mexico during the study period from 2003 to 2019, The distribution was seasonally uneven, with 517,285 deaths (43%) occurring in the summer and 687,260 (53%) in the winter. Upon categorization according to the ICD-10 chapters, we observed that: Chapter 9 (Diseases of the Circulatory System) had the highest number of deaths, with 559,763 cases, followed by Chapter 4 (Endocrine, Nutritional, and Metabolic Diseases) with 397,897 deaths. Chapter 5 (Mental, Behavioral, and Neurodevelopmental Disorders) recorded the lowest number of deaths at 15,352. A key finding was that the total number of deaths consistently peaked during the winter season for all disease chapters and across all climatic regions included in the study. Detailed data on deaths by disease and their distribution across climate zones are presented in Table 1.

Table 1. Total deaths recorded for the five NCD chapters by Metropolitan zone (2003–2019),

		Chapter 4		Chapter 5		Chapter 6		Chapter 9		Chapter 10	
Metropolitan zone	**Climatic zone**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Aguascalientes	Arid	2130	3051	171	198	290	401	2857	3966	1089	2089

Celaya	Arid	2063	2829	72	109	144	204	2142	2834	623	1120
Chihuahua	Arid	2266	3180	128	152	372	513	5163	7171	1177	2521
Ciudad Victoria	Arid	903	1179	21	19	87	128	1409	1736	326	559
Culiacan	Arid	1588	1789	67	59	247	263	3155	3701	830	1306
Delicias	Arid	471	675	21	36	78	95	780	1035	268	506
Durango	Arid	1227	1726	41	65	173	202	2524	3446	654	1237
Ensenada	Arid	941	1369	34	37	131	204	2156	2721	509	965
Guaymas	Arid	509	670	24	27	61	63	845	1019	167	360
Hermosillo	Arid	1622	2092	67	79	359	485	3714	4908	1196	2312
Hidalgo del Parral	Arid	265	462	12	9	40	57	737	1141	166	345
Juarez	Arid	4245	6260	218	268	483	673	5927	8243	1279	3029
La Laguna	Arid	3275	4714	90	114	380	478	4529	6220	1110	2154
La Paz	Arid	647	697	35	46	100	110	1159	1380	280	410
Mexicali	Arid	2339	3344	148	158	309	505	4230	5404	1394	2505
Monclova-Frontera	Arid	909	1330	19	27	103	122	1655	2449	202	512
Monterrey	Arid	7521	10679	332	380	1308	1536	16040	20852	3842	6842
Nogales	Arid	387	621	15	28	44	71	660	973	178	332
Nuevo Laredo	Arid	1116	1581	25	14	87	126	1825	2373	492	829
Piedras Negras	Arid	495	735	6	13	48	58	1135	1440	120	285
Queretaro	Arid	2255	3066	131	130	268	321	3402	4465	903	1626
Reynosa	Arid	1953	2627	45	50	176	207	2728	3437	625	1039
Rioverde	Arid	201	320	8	10	28	28	405	569	89	169
Saltillo	Arid	2084	3296	57	84	234	346	3298	4875	757	1681
San Luis Potosi	Arid	2400	3420	159	244	353	498	3313	4775	1160	2301
Tehuacan	Arid	810	1030	24	41	75	94	823	981	332	595
Tijuana	Arid	3586	5010	127	173	498	679	6289	8149	1699	2966
Tula	Arid	432	558	11	18	29	42	446	603	117	243
Zacatecas-Guadalupe	Arid	552	809	32	51	74	113	706	1003	267	547
Guadalajara	Temperate	9954	13243	517	626	1196	1464	14147	17616	5601	8793
Guanajuato	Temperate	363	504	24	26	37	44	463	613	149	321
La Piedad-Penjamo	Temperate	592	865	24	29	47	43	731	943	228	393
Leon	Temperate	4874	6653	251	306	450	589	5138	6670	1981	3548
Morelia	Temperate	2114	2723	120	141	261	293	2713	3261	925	1400
Moroleon-Uriangato	Temperate	277	431	12	14	34	47	537	672	146	234
Ocotlan	Temperate	324	390	22	24	38	40	511	583	206	321
Pachuca	Temperate	1018	1358	42	50	97	134	1355	1907	378	646
Puebla-Tlaxcala	Temperate	9022	11664	313	374	705	974	9473	11793	2879	5015

San Francisco del Rincon	Temperate	332	457	9	11	22	36	274	386	128	215
Teziutlan	Temperate	298	401	22	20	19	31	318	504	94	230
Tianguistenco	Temperate	493	653	12	15	16	19	385	524	121	260
Tlaxcala-Apizaco	Temperate	1093	1382	58	69	63	119	1155	1497	341	632
Toluca	Temperate	4520	5851	121	155	306	417	4859	6368	1711	3124
Tulancingo	Temperate	483	540	8	15	27	38	620	858	148	264
Valle de Mexico	Temperate	49344	65677	1691	2152	3858	5176	68472	88876	19153	33310
Xalapa	Temperate	2049	2701	129	165	250	264	2566	3297	770	1242
Zamora	Temperate	891	1071	34	42	73	62	1075	1275	274	420
Acapulco	Tropical	3118	2779	62	59	254	214	3425	3008	1037	970
Acayucan	Tropical	307	325	7	9	15	22	348	358	96	106
Campeche	Tropical	809	865	43	47	66	90	1240	1325	392	377
Cancun	Tropical	1220	1229	101	95	171	135	1356	1415	599	586
Chetumal	Tropical	500	632	12	23	46	41	626	655	263	256
Chilpancingo	Tropical	574	624	37	31	40	56	693	680	157	215
Coatzacoalcos	Tropical	1243	1300	47	37	124	106	1410	1487	425	509
Colima-Villa de Alvarez	Tropical	768	794	39	35	109	112	1147	1207	332	365
Cordoba	Tropical	954	1172	41	49	79	90	1193	1384	334	510
Cuautla	Tropical	966	1129	36	51	79	79	1101	1240	321	469
Cuernavaca	Tropical	2289	2614	137	115	241	305	2984	3399	929	1221
Matamoros	Tropical	1412	1780	18	21	115	125	2022	2609	386	701
Mazatlan	Tropical	1438	1630	44	43	180	198	2022	2293	484	684
Merida	Tropical	2709	2806	193	156	422	451	5979	6276	1931	2006
Minatitlan	Tropical	936	1047	40	41	76	76	1286	1415	328	384
Oaxaca	Tropical	1361	1663	130	127	158	182	1650	1920	538	793
Orizaba	Tropical	1355	1703	57	49	101	125	1568	2104	483	704
Poza Rica	Tropical	1490	1804	43	46	123	102	1907	2359	486	709
Puerto Vallarta	Tropical	572	611	24	38	93	84	1157	1279	370	467
Tampico	Tropical	1757	2185	40	66	258	256	3335	3764	771	1082
Tapachula	Tropical	867	843	31	22	87	102	904	909	467	471
Tecoman	Tropical	473	394	14	11	38	35	579	525	168	169
Tehuantepec	Tropical	762	699	28	19	58	41	588	524	166	154
Tepic	Tropical	842	1017	31	42	146	163	1553	1754	489	656
Tuxtla Gutierrez	Tropical	2081	2103	64	61	199	192	2095	2236	823	997
Veracruz	Tropical	2989	3130	115	105	323	321	3935	4064	1263	1333
Villahermosa	Tropical	2071	2240	54	44	183	205	2444	2671	777	805
TOTAL		**173,096**	**224,801**	**7,037**	**8,315**	**17,862**	**22,320**	**247,391**	**312,372**	**718,99**	**119,452**

Chapter 4: Endocrine, Nutritional, and Metabolic Diseases; Chapter 5: Mental, Behavioral, and Neurodevelopmental Disorders; Chapter 6: Diseases of the Nervous System; Chapter 9: Diseases of the Circulatory System; Chapter 10: Diseases of the Respiratory System.

To assess mortality differences between summer ($Deaths_s$) and winter ($Deaths_w$) across climate zones, we calculated the percentage change (Δ Deaths % = ($Deaths_w - Deaths_s$) × 100) for each metropolitan zone. Fig. 2 shows these differences across Arid, Temperate, and Tropical regions for five chapters of non-communicable diseases. Overall, tropical regions exhibited the lowest percentage differences for all disease chapters, with several metropolitan zones even displaying negative values (i.e., higher mortality in summer) for mental and behavioural disorders and nervous system diseases. Across all climate zones, respiratory diseases presented the highest positive differences during winter compared to summer, particularly in Arid regions where median increases exceeded 80%. Circulatory and nervous system diseases also showed positive differences across all zones, though of lower magnitude than respiratory diseases. Mental and behavioural disorders revealed mixed patterns, with some negative differences, especially in Tropical zones. Endocrine, nutritional, and metabolic diseases displayed moderate positive differences in Arid and Temperate zones, while values remained close to zero in Tropical regions.

Fig. 2. Percentage change (Δ%) in deaths across climatic zones by disease chapter. The boxplots represent the distribution of percentage differences in deaths between seasons for each climatic zone. Horizontal dashed line indicates no change (Δ = 0%). Colours represent each ICD-10 disease chapters.

Seasonal analysis of UHI-related mortality

UHI intensity varied across climatic zones and periods. In arid regions, SDUHI ranged from 1 to 4 °C, SNUHI from 1 to 2 °C, WDUHI from 1 to 2 °C, and WNUHI from 1 to 3 °C. In temperate regions, SDUHI ranged from 1 to 6 °C, SNUHI from 1 to 4 °C, WDUHI from 1 to 2 °C, and

WNUHI from 1 to 6 °C. In tropical regions, SDUHI ranged from 1 to 4 °C, SNUHI from 1 to 4 °C, WDUHI from 1 to 2 °C, and WNUHI from 1 to 2 °C. Overall, temperate regions exhibited the highest UHI intensity, reaching up to 6 °C during summer daytime and winter nighttime.

Furthermore, UHI intensity is not uniform across municipalities within a given metropolitan region. Due to this spatial heterogeneity, mortality risk was assessed for each incremental increase in UHI (e.g., 1 °C, 2 °C, etc.). This approach allows the detection of potential dose–response patterns, where higher UHI intensities may lead to progressively greater mortality risks. Results are first presented for the total population and subsequently stratified by sex and age.

Figure 3 illustrates the association between summer daytime UHI (SDUHI) intensity and mortality. Strong and consistent associations were observed for Chapter 4 (Endocrine, Nutritional, and Metabolic Diseases), Chapter 9 (Diseases of the Circulatory System), and Chapter 10 (Diseases of the Respiratory System) in temperate regions. For these chapters, epsilon (ε) values exceeded the significance threshold ($\varepsilon \geq 2.0$) starting at 2 °C in most years, indicating that SDUHI contributes substantially to mortality from these causes. In arid and tropical regions, significant ε values (>2) for Chapters 9 and 10 generally appeared at 3 °C, while associations for Chapter 4 were more variable across years. In contrast, Chapters 5 (Mental, Behavioral, and Neurodevelopmental Disorders) and 6 (Diseases of the Nervous System) exhibited the weakest associations across all climatic zones, with ε values consistently below the threshold.

Fig. 3 Heatmap showing significant associations ($\varepsilon \geq 2$) between mortality from selected non-communicable disease chapters and SDUHI intensity across metropolitan municipalities. Associations were estimated by climatic zones (arid, temperate, tropical) for the period 2003–2019. Mortality risk was evaluated at incremental UHI intensities (1 °C, 2 °C, etc).

When evaluating summer nocturnal UHI (SNUHI), similar patterns were found in temperate regions, with strong associations for Chapters 4, 9, and 10. However, at night, significant associations appeared at lower increments—starting at 1 °C. This finding suggests that even small increases in nocturnal thermal stress may exacerbate mortality risks for these chapters. In tropical regions, positive associations were observed from 1 °C for the same chapters, while in arid regions, significant associations emerged at 2 °C, mirroring the daytime pattern. Notably, in temperate regions, strong associations with SNUHI (ε ≥ 2) were also identified for Chapters 5 and 6 throughout most of the study period (Figure 4), highlighting the potential vulnerability of mental and nervous system disorders to nocturnal heat exposure.

Fig. 4 Heatmap showing significant associations (ε ≥ 2) between mortality from selected non-communicable disease chapters and SNUHI intensity across metropolitan municipalities. Associations were estimated by climatic zones (arid, temperate, tropical) for the period 2003–2019. Mortality risk was evaluated at incremental UHI intensities (1 °C, 2 °C, etc).

During winter, temperate regions again showed positive associations between UHI and mortality for nearly all disease chapters in both daytime and nighttime conditions. Significant associations were observed from 1 °C, although for winter daytime UHI (WDUHI), strong associations predominantly appeared after 2013 (Figure 5). In contrast, winter nocturnal UHI (WNUHI) exhibited consistently strong associations (ϵ > 2), in some cases reaching very high values, across almost the entire study period (Figure 6). In tropical and arid regions, similar positive associations were detected from 1 °C, though with greater year-to-year variability during the daytime. At nighttime, however, associations persisted throughout most of the study period (Fig. 6), reinforcing the relevance of nocturnal thermal stress during winter months.

Figure 5: Heatmap showing significant associations (ε ≥ 2) between mortality from selected non-communicable disease chapters and WDUHI intensity across metropolitan

municipalities. Associations were estimated by climatic zones (arid, temperate, tropical) for the period 2003–2019. Mortality risk was evaluated at incremental UHI intensities (1 °C, 2 °C, etc).

Figure 6 Heatmap showing significant associations (ε ≥ 2) between mortality from selected non-communicable disease chapters and WNUHI intensity across metropolitan municipalities. Associations were estimated by climatic zones (arid, temperate, tropical) for the period 2003–2019. Mortality risk was evaluated at incremental UHI intensities (1 °C, 2 °C, etc).

By stratifying the population by sex and age, we identified groups potentially more vulnerable to UHI exposure. We also averaged epsilon values ($\bar{\varepsilon}$) across the 2003–2019 period.

In arid regions, significant associations were observed between Chapter 4 diseases and UHI intensity among men aged 5–54 years and women aged 0–34 years for both SDUHI and SNUHI. Only women aged 25–34 showed significant associations with WDUHI. For Chapter 5, associations were found among men aged 15–24 and 45–54 with SDUHI and SNUHI, and among men aged 35–54 with WNUHI. In women, associations were identified across age groups 5–64 years for SDUHI and SNUHI, while only those aged 55–64 showed associations with WDUHI. Mortality from Chapter 9 causes was associated with SDUHI and SNUHI among young women (0–14 years) and middle-aged men (35–44). For Chapter 10 (respiratory diseases), associations were found among men aged 5–54 and 65+, and women aged 0–43 years with SDUHI and SNUHI (Table 2).

Table 2. Average effect size ($\bar{\varepsilon}$) per 1°C increase in UHI intensity, by season (summer/winter) and time of day (daytime/nighttime) in arid regions (2003-2019). Significant associations ($\bar{\varepsilon}$ > 2) are highlighted in bold and colored red.

		$\bar{\varepsilon}$ (SDUHI)				$\bar{\varepsilon}$ (SNUHI)		$\bar{\varepsilon}$ (WDUHI)		$\bar{\varepsilon}$ (WNUHI)		
		1°C	2°C	3°C	4°C	1°C	2°C	1°C	2°C	1°C	2°C	3°C
Chapter 4 - Endocrine, Nutritional and Metabolic Diseases												
Men	0-04	0.27	0.75	1.23		0.10	1.23	0.57		0.01	0.40	
	5-14	0.71	1.26	**3.64**		0.29	**2.36**	0.78		0.25	0.33	

	15-24	0.44	0.73	1.00		-0.06	1.63	0.17		0.41	-0.21	
	25-34	-0.03	0.31	1.25	**2.83**	0.10	0.66	0.10	1.10	0.21	0.07	
	35-44	-0.10	0.75	0.72	0.74	0.47	0.65	0.11	0.39	0.39	0.25	-0.32
	45-54	0.04	1.16	0.62	**2.44**	0.33	0.75	0.34	-1.33	1.10	-0.44	-1.62
	55-64	0.01	0.95	0.41	0.52	0.64	0.14	0.14	-1.38	1.11	-0.45	-1.68
	65+	-0.38	1.15	0.58	0.14	0.68	0.37	0.58	-1.00	1.67	-0.84	-1.96
Women	0-04	0.20	1.02	**2.57**		0.12	1.53	0.32		-0.10	0.20	
	5-14	1.06	1.48	**2.16**		0.15	**2.63**	0.88		0.32	0.63	
	15-24	0.41	1.32	**2.17**		0.21	1.56	0.30		0.28	-0.02	
	25-34	0.05	0.22	1.21	**2.69**	0.23	0.55	0.08	**2.22**	0.30	-0.01	0.90
	35-44	0.43	-0.28	0.45	1.21	0.04	0.63	-0.10	1.38	0.53	-0.13	-0.13
	45-54	-0.02	0.44	0.28	-0.06	0.54	-0.20	0.06	-0.08	1.02	-0.44	-0.50
	55-64	-0.27	0.59	0.51	0.72	0.47	-0.49	-0.23	-0.91	1.56	-1.02	-0.92
	65+	-0.35	0.70	0.43	1.23	0.85	-0.75	-0.05	-1.03	1.67	-1.04	-2.29
Chapter 5 - Mental, Behavioral and Neurodevelopmental disorders												
Men	0-04					0.30		1.88		0.52	1.53	
	5-14	1.24				0.48				0.51		
	15-24	1.15	1.20	**3.50**		0.16	**4.09**	0.80		0.27	0.84	
	25-34	0.23	0.63	1.13		-0.12	1.49	0.06		-0.38	0.54	
	35-44	0.40	0.69	0.76		-0.23	1.63	-0.47		0.02	0.08	**3.63**
	45-54	0.24	0.52	0.57	**5.46**	-0.08	1.14	-0.63		0.12	0.22	
	55-64	-0.06	0.98	0.41	1.81	-0.11	1.30	-0.18	0.34	0.25	0.09	
	65+	-0.01	0.49	-0.02		0.36	0.18	-0.24	0.34	-0.28	0.75	-0.20
Women	0-04	1.15				0.35					1.31	
	5-14	1.75	**2.17**			0.46	**4.51**	1.59		0.40	1.65	
	15-24	0.78				0.49		1.38		0.35	0.70	
	25-34		1.18	**2.62**		0.22	**3.56**	1.26		0.57	0.81	
	35-44	0.90	**2.01**	1.86		0.00	**2.75**	1.25		0.34	1.07	
	45-54	0.80	1.55			0.37		0.83		0.51	1.21	
	55-64	1.07	1.87	**1.99**		0.09	**3.34**	1.11	**3.89**	0.20	0.40	
	65+	-0.07	-0.02	-0.23	0.67	0.48	0.17	0.18	0.03	-0.24	0.83	-0.09
Chapter 6 - Diseases of the Nervous System												
Men	0-04	-0.46	1.07	**2.07**		0.15	1.51	-0.17	1.65	-0.04	0.47	
	5-14	0.56	0.40	1.20		0.01	1.32	0.02		0.10	0.07	
	15-24	0.17	0.45	1.15	**2.62**	0.07	0.79	0.12	0.60	0.05	-0.06	1.64
	25-34	-0.45	0.45	0.77		0.14	0.51	0.14	**2.67**	0.06	-0.07	
	35-44	0.07	0.16	0.74		0.03	0.99	0.06	1.68	0.14	0.19	1.08
	45-54	0.36	0.21	0.49	**2.10**	0.20	1.01	0.26	0.30	-0.11	0.40	0.45
	55-64	-0.07	0.36	0.44	1.55	-0.06	0.47	0.12	0.57	0.23	-0.34	
	65+	-0.51	-0.31	-0.12	0.50	0.18	-0.12	0.07	-0.40	-0.14	0.19	-0.16
Women	0-04	0.20	0.70	0.95		-0.08	1.93	0.61	**2.19**	0.07	0.32	

	5-14	0.16	0.58			0.14	0.59	0.04		0.20	0.28	
	15-24	-0.01	1.01	**2.02**		0.21	1.35	0.29		0.12	0.01	
	25-34	-0.18	0.54	1.96		0.12	1.34	0.47	**3.05**	-0.08	0.03	
	35-44	-0.02	0.40	1.05		0.09	0.54	0.61	1.49	-0.02	0.43	
	45-54	-0.04	0.46	0.71		0.29	1.06	0.27	0.54	0.10	0.17	
	55-64	-0.43	0.26	0.02	**3.51**	-0.06	0.09	-0.05	0.76	0.19	-0.17	1.09
	65+	-0.32	-0.32	0.41		0.28	-0.01	0.83	0.02	-0.31	0.49	0.59
Chapter 9 - Diseases of the Circulatory System												
Men	0-04	0.06	1.20	0.91		0.12	1.41	0.53		0.04	0.28	
	5-14	0.00	1.11	1.58		0.32	1.41	0.99		0.13	0.59	
	15-24	0.00	0.82	0.96		0.38	0.22	0.67	0.71	-0.11	0.33	0.25
	25-34	-0.24	1.18	0.91	0.91	0.00	0.61	0.80	-0.11	0.30	-0.11	-0.07
	35-44	-0.24	1.22	0.79	**3.72**	0.01	0.93	1.27	-0.57	-0.15	0.19	-1.07
	45-54	-0.47	1.20	1.10	-0.41	-0.45	1.90	1.29	-0.33	0.65	-0.63	-1.16
	55-64	-0.81	1.41	0.33	-0.36	-0.54	1.08	1.32	-0.97	0.73	-1.13	-0.51
	65+	-0.81	0.23	1.11	-0.40	-0.49	0.23	0.62	-1.67	0.07	-0.98	-1.76
Women	0-04	0.06	1.46	**3.10**		0.15	1.77	0.38		0.00	0.41	
	5-14	0.51	1.15	**2.98**		0.30	**2.62**	0.53		0.21	0.51	
	15-24	0.12	0.41	1.19		0.02	0.96	0.42	1.78	-0.07	0.64	
	25-34	0.05	0.58	0.75		0.35	0.18	-0.07	0.69	0.17	0.14	0.14
	35-44	-0.46	0.63	1.02	0.83	0.17	0.27	0.45	0.63	0.37	-0.07	-0.38
	45-54	-0.33	0.50	0.63	-0.12	0.27	0.32	0.26	-0.95	0.44	-0.59	1.36
	55-64	-0.29	-0.03	0.35	-0.49	-0.04	0.00	-0.16	-1.75	0.46	-0.61	-1.27
	65+	-0.63	0.16	0.13	-0.52	-0.48	-0.19	-0.51	-1.78	0.20	-1.38	-2.23
Chapter 10 - Diseases of Respiratory System												
Men	0-04	-0.09	0.72	1.38		-0.01	0.55	0.70	-0.28	0.38	-0.37	1.47
	5-14	0.31	1.20	1.63		0.17	**2.24**	0.55		-0.05	0.44	1.76
	15-24	0.11	1.69	1.10		-0.37	**2.78**	0.77		0.14	-0.02	0.74
	25-34	-0.77	1.76	**2.68**		-0.52	**3.27**	1.41	1.97	0.54	-0.07	0.55
	35-44	-0.65	**2.30**	**3.33**	1.19	-1.05	**5.54**	1.55	0.56	0.38	0.27	1.36
	45-54	-0.26	1.92	1.97	0.61	-0.78	**4.04**	1.49	-0.10	0.36	-0.21	-0.13
	55-64	-0.21	1.13	0.63	1.63	-0.04	1.44	0.59	0.22	0.50	-0.68	-0.30
	65+	-0.03	0.11	0.94	**2.46**	0.51	-0.26	0.17	-1.64	-0.10	0.37	-0.97
Women	0-04	0.53	1.12	1.15	**2.81**	0.33	0.60	0.32	0.66	0.35	-0.18	
	5-14	0.85	1.14	**2.20**		0.33	1.75	0.70		-0.15	0.64	
	15-24	0.03	1.70	1.45		-0.12	**2.11**	0.57	1.66	-0.15	0.51	
	25-34	-0.12	1.28	0.93		0.22	**1.99**	0.36		0.22	0.11	
	35-44	-0.15	0.89	1.09		-0.35	1.64	1.04	0.88	-0.07	0.23	0.91
	45-54	-0.24	0.54	0.65		0.18	0.76	0.49	0.56	0.36	-0.18	-0.18
	55-64	-0.15	0.54	1.20	0.69	0.23	0.45	-0.02	-1.02	-0.03	0.00	1.45
	65+	0.63	0.09	0.23	0.36	0.88	-0.39	-0.29	-1.12	-0.58	0.89	-1.75

In temperate regions, Chapter 4 mortality showed significant associations across all UHI conditions for older adults (men and women 55–64 and 65+), while younger groups (men and women 4–25) were more affected by daytime UHI in both summer and winter. For Chapter 5, associations were identified among women <65 years and men <45 years across all UHI conditions. Mortality from Chapter 6 showed associations in men <35 years and women <45 years, although only at higher UHI intensities in all seasons. For Chapter 9, significant associations were observed across age groups, affecting both older adults (>54 years) and children/adolescents (<15 years), in all UHI conditions. Finally, Chapter 10 mortality showed associations among young (5–14) and older (65+) men, and among women aged 15–34 and 65+, again across all UHI exposures (Table 3).

Table 3. Average effect size ($\bar{\varepsilon}$) per 1°C increase in UHI intensity, by season (summer/winter) and time of day (daytime/nighttime) in temperate regions (2003-2019). Significant associations ($\bar{\varepsilon}$ > 2) are highlighted in bold and colored red.

		$\bar{\varepsilon}$ (SDUHI)						$\bar{\varepsilon}$ (SNUHI)				$\bar{\varepsilon}$ (WDUHI)			$\bar{\varepsilon}$ (WNUHI)					
		1°C	2°C	3°C	4°C	5°C	6°C	1°C	2°C	3°C	4°C	1°C	2°C	3°C	1°C	2°C	3°C	4°C	5°C	6°C
Chapter 4 - Endocrine, Nutritional and Metabolic Diseases																				
Men	0-04	0.5	0.2	0.7	1.0	0.2		0.1	0.9	0.2		-0.22	-0.14	1.72	0.27	0.35	0.95	-0.11	0.12	-0.02
	5_14	0.5	0.7	0.5	1.7			0.5	0.7	1.3		0.15	1.08	**3.33**	0.32	0.85	1.05	1.02	1.23	
	15-24	0.1	0.5	0.6	1.1	0.7	**2.1**	0.2	0.6	1.1		0.01	0.37	1.71	0.32	0.12	0.52	0.70	0.85	0.90
	25-34	-0.1	0.0	0.8	0.6	1.0	-0.2	0.3	0.4	0.3	1.9	0.32	0.46	1.85	0.01	-0.27	0.38	0.57	-0.12	-0.09
	35-44	0.0	-0.1	1.3	0.3	0.6	-0.7	0.6	0.8	0.1	-0.5	0.22	0.36	0.03	-0.18	0.11	1.12	0.84	0.28	0.36
	45-54	-0.2	0.8	1.6	0.5	-0.1	-0.2	0.7	1.4	0.6	1.1	0.70	0.18	0.17	0.12	-0.24	1.10	1.28	-0.15	0.50
	55-64	-0.4	0.6	**2.2**	0.1	0.3	-1.3	1.0	1.2	-0.4	-0.4	1.55	-0.03	0.72	0.63	0.17	0.90	0.53	-0.92	0.18
	65+	0.1	1.5	**2.3**	-0.1	0.1	-1.5	**2.8**	0.6	-1.2	-1.2	**2.38**	-0.45	1.44	**2.41**	0.16	0.36	-0.21	-1.41	-1.38
Women	0-04	0.4	0.0	0.6	0.9			0.4	0.2	0.5		-0.37	1.11	1.57	0.19	0.36	0.46	0.37	0.46	
	5_14	0.6	0.8	0.7				0.3	0.5			0.67	0.91	**2.61**	0.59	0.81	0.50	0.53	1.77	
	15-24	0.2	0.2	0.4	1.2	1.9	**2.0**	0.4	0.4	1.0		0.41	1.16	**2.10**	0.50	-0.11	0.72	0.47	1.60	1.27
	25-34	0.3	0.1	0.8	0.6	0.8	0.0	0.7	0.1	0.4	0.7	0.57	0.42	1.55	0.33	-0.29	0.25	0.56	0.13	0.45
	35-44	-0.1	0.5	0.4	0.7	0.1	-1.3	0.4	0.9	0.0	0.2	0.93	0.62	0.89	0.20	-0.48	1.10	0.27	-0.20	-0.15
	45-54	0.1	0.3	1.3	0.2	-0.1	0.7	0.9	0.7	-0.1	-0.5	0.98	-0.11	0.35	0.41	0.28	1.40	0.15	-0.99	-0.13
	55-64	0.2	0.7	**2.1**	-0.1	-0.8	-1.6	1.7	0.3	-0.8	-1.1	1.57	0.25	0.64	1.46	0.20	1.49	-0.50	-1.86	-1.46
	65+	1.2	1.7	2.0	-0.6	-0.7	-1.7	**3.2**	0.0	-1.9	-1.7	**2.37**	-0.29	1.81	**3.47**	0.73	0.75	-1.85	-2.98	-2.93

Chapter 5 - Mental, Behavioral and Neurodevelopmental disorders																				
Men	0-04	0.8	1.6		**9.0**			0.6	1.8				**2.88**		1.36	1.19	**2.11**	1.40		
	5_14	1.0	0.6	1.4				0.7	1.8			1.16			1.79	1.58	1.33			
	15-24	0.4	1.4	0.6	1.2	**2.2**	**4.1**	0.6	0.8	**2.0**		0.47	1.91	**4.64**	0.69	0.92	0.86	1.07	1.36	
	25-34	0.0	0.1	0.2	1.2	1.5		0.0	0.2	1.0		0.38	**2.40**	**2.78**	0.18	0.12	0.39	0.45	0.76	
	35-44	-0.5	-0.1	0.5	0.8	0.8	1.4	0.3	0.1	0.7	0.8	0.80	-0.30	**2.08**	0.60	0.11	0.42	0.08	-0.02	0.52
	45-54	-0.1	0.1	0.1	0.4	1.1	1.6	0.7	-0.1	0.3	0.4	0.58	1.71	1.80	0.26	-0.01	-0.02	0.29	0.13	0.71
	55-64	0.7	-0.1	-0.2	0.9	1.2	1.1	0.7	-0.5	0.3	-0.3	0.31	1.12	1.07	0.20	0.14	-0.24	-0.06	-0.01	0.35
	65+	0.2	0.1	0.3	0.6	0.3	-0.7	0.9	-0.5	-0.5	0.2	0.74	0.93	1.58	1.17	0.22	-0.53	-0.75	-0.72	-0.32
Women	0-04			**2.3**					1.5			1.02			1.03	**2.28**	1.89			
	5_14	1.5			**3.6**					**4.1**		1.39			1.37	1.62			**2.81**	
	15-24	1.1	1.0	1.4	**2.4**			1.0	1.4			0.65	**7.19**		1.07	1.36	1.64	1.73		
	25-34	1.5	1.1	1.3	**3.9**			0.8	1.9	**6.8**		1.46	**2.48**	**8.23**	1.05	1.08	1.62	1.09	**2.07**	
	35-44	1.1	0.5	**2.2**	**3.2**	1.6	**4.1**	0.6	1.1	**3.0**		0.54		**4.06**	1.10	0.79	1.52	0.82	**2.46**	
	45-54	1.4	0.7	0.9	**2.1**	**4.3**		0.6	0.9	1.3		0.62		**7.77**	0.50	0.11	0.83	1.11	1.28	
	55-64	0.9	0.6	1.1	1.2	**2.4**	1.0	0.7	0.8	1.6		0.58	1.95	**3.30**	0.53	0.56	1.04	0.81	1.27	
	65+	0.0	0.4	-0.3	-0.3	0.3	-0.4	1.0	-0.6	-0.3	-0.6	0.81	0.80	0.62	0.95	0.28	-0.48	-0.24	-0.36	-0.02
Chapter 6 - Diseases of the Nervous System																				
Men	0-04	-0.1	0.1	0.9	1.5	**2.0**		0.8	-0.1	0.9	**3.1**	-0.20	1.22	1.33	0.11	0.91	0.50	-0.36	0.42	0.41
	5_14	0.3	0.1	0.2	0.8	0.9		0.2	0.2	0.6	**2.0**	0.28	0.32	**3.17**	0.36	0.10	0.38	0.28	0.72	1.50
	15-24	-0.1	0.2	0.4	0.4	0.9	**3.0**	0.1	0.1	0.9	0.6	0.35	0.84	1.04	-0.21	0.65	0.30	0.28	0.12	0.35
	25-34	0.2	0.1	0.2	1.0	0.1		0.6	-0.2	0.1	0.3	0.10	0.61	**2.04**	0.16	0.01	0.35	-0.01	0.11	0.06
	35-44	-0.1	0.0	0.4	0.9	0.8		0.9	0.2	0.5	0.1	0.42	0.88	0.83	-0.03	0.20	0.41	0.45	0.11	1.09
	45-54	0.0	0.2	0.1	0.9	1.4	1.2	0.8	-0.2	0.1	-0.1	0.33	1.02	1.51	-0.18	0.22	0.18	0.19	0.70	0.40
	55-64	0.0	0.4	0.3	0.6	0.9	0.7	0.9	-0.1	0.0	0.3	0.33	0.81	1.69	0.36	0.19	-0.12	0.18	0.55	0.24
	65+	0.1	0.6	0.4	-0.1	0.1	-0.7	1.5	-0.4	-0.5	0.2	0.48	0.12	1.31	0.83	0.54	-0.71	-0.25	-0.25	0.78
Women	0-04	0.1	0.5	0.4	1.8	**2.3**	1.1	0.7	0.2	1.1	0.3	0.04	1.36	1.99	0.41	0.52	0.10	0.25	0.56	1.83
	5_14	0.2	0.6	0.4	1.5	1.9	1.0	0.6	0.6	0.7	1.8	0.32	1.40	1.67	0.25	0.39	0.45	0.05	0.63	**2.55**
	15-24	0.1	0.1	0.8	1.0	**2.2**		0.5	0.2	0.9	0.7	0.02	1.31	**3.09**	0.27	0.07	0.32	0.13	0.75	**2.06**
	25-34	0.5	0.3	0.4	0.7	0.5		0.7	-0.1	0.8		0.32	0.27	**2.78**	-0.15	0.27	0.84	0.57	0.14	**2.98**
	35-44	-0.2	0.5	0.7	0.7	1.4	0.4	0.3	0.2	0.6		0.45	0.68	1.58	0.45	0.06	0.17	0.25	0.06	
	45-54	-0.4	0.5	0.3	0.5	1.0	0.7	0.9	0.1	0.2	1.2	0.46	-0.02	**2.60**	0.29	-0.06	0.41	0.01	0.11	0.78
	55-64	-0.4	0.5	0.9	0.6	0.7	0.9	0.7	0.2	0.5	0.0	0.33	0.96	1.43	0.50	0.41	-0.05	-0.01	0.32	0.50
	65+	0.0	0.2	0.4	0.0	-0.1	-0.4	1.6	-0.7	-0.1	-1.0	0.09	0.35	1.49	0.98	0.37	-0.60	-0.53	-0.02	0.97
Chapter 9 - Diseases of the Circulatory System																				
Men	0-04	-0.2	0.4	0.5	0.8	1.4		0.9	0.4	0.9		0.08	1.02	1.90	0.06	0.15	0.59	0.38	1.51	
	5_14	0.4	0.7	1.2	1.1			0.5	1.1	1.3		0.54	0.70	**3.24**	0.60	1.11	0.25	1.07	1.78	**4.20**
	15-24	-0.2	0.1	0.8	0.0	0.1	0.8	0.4	0.3	0.6	-0.1	0.51	0.52	0.97	0.31	0.52	0.15	-0.27	0.50	0.40
	25-34	0.0	0.8	0.5	0.0	0.4	0.9	0.8	0.2	0.2	-0.1	0.37	0.46	0.73	0.61	-0.07	0.08	0.22	-0.12	0.95
	35-44	-0.6	0.2	1.0	0.3	0.0	0.2	0.8	0.6	0.4	-0.7	0.60	0.39	0.72	0.21	0.17	0.38	0.39	0.84	0.30
	45-54	-0.6	1.2	1.1	0.0	-0.4	0.8	1.0	1.1	0.5	-0.1	0.46	0.69	0.51	0.28	0.13	0.38	0.64	0.78	1.79
	55-64	-0.7	1.2	**2.1**	-0.2	-0.3	-1.6	1.5	1.3	0.2	-0.6	0.66	-0.43	0.91	0.05	0.32	0.68	0.70	1.16	1.95
	65+	-0.6	1.9	**2.3**	-0.4	-0.2	-1.1	**2.5**	**2.0**	-0.4	-0.6	0.05	-0.34	1.10	0.63	0.52	0.19	0.90	1.71	**2.89**

Women	0-04	0.2	0.3	1.1	1.8		1.6	0.3	0.6	1.2		0.89	1.64	**3.26**	0.38	0.45	0.92	0.51	**2.01**	1.85
	5_14	0.7	0.7	1.0	1.8	**4.4**		0.3	1.1	**2.1**		0.28	0.72	**3.86**	0.32	1.26	1.05	1.04	1.55	
	15-24	-0.1	0.1	0.9	0.6	0.8		0.2	0.5	0.5	1.4	0.54	1.25	1.46	0.44	0.11	0.40	-0.02	0.89	
	25-34	-0.1	0.7	0.7	0.1	0.7		0.9	0.3	0.0	0.5	0.13	1.65	1.84	0.30	0.20	0.39	0.17	0.07	0.70
	35-44	-0.3	0.1	1.0	-0.1	0.5	0.0	0.6	0.3	0.0	-0.2	0.72	0.36	0.53	0.65	0.14	0.05	0.38	-0.12	0.10
	45-54	-0.2	0.3	1.2	-0.2	-0.4	0.1	0.8	0.9	0.0	0.1	0.59	0.07	0.23	0.27	-0.12	0.58	0.41	0.33	0.08
	55-64	-0.5	0.9	1.7	0.0	-0.6	-1.0	1.4	1.0	-0.6	0.0	0.96	0.11	0.24	0.47	0.18	0.88	0.12	0.17	0.45
	65+	-0.9	**2.4**	**2.2**	-1.4	-1.5	-1.9	**2.4**	1.9	-0.4	-0.8	-0.56	-0.86	0.72	0.16	0.55	0.49	0.75	**2.19**	**4.33**
Chapter 10 - Diseases of Respiratory System																				
Men	0-04	-0.4	0.5	0.2	-0.1	0.0	-0.1	0.3	0.4	-0.1	0.9	-1.25	-0.30	0.28	-0.14	0.54	1.64	0.20	-0.43	-1.12
	5_14	0.6	0.8	0.7	**2.6**	**2.8**		0.2	0.6	1.5		0.29	**2.61**	**2.56**	0.76	0.35	0.63	0.58	0.09	
	15-24	0.1	0.0	0.4	1.1	0.6		0.3	0.6	0.4	1.4	0.57	0.02	1.85	0.29	0.30	0.17	0.17	0.65	1.81
	25-34	-0.2	0.2	0.5	1.0	1.0	0.5	0.4	0.5	0.6	-0.4	0.20	0.58	1.17	0.11	0.09	0.53	0.08	0.35	0.23
	35-44	-0.2	0.2	0.8	0.8	0.5	1.3	0.8	0.3	0.4	0.9	0.50	-0.08	0.53	-0.23	-0.12	0.55	0.70	0.25	-0.11
	45-54	-0.5	0.1	1.2	0.0	0.7	-0.3	0.8	0.4	0.3	0.3	0.72	1.00	0.28	0.03	0.29	0.24	0.51	-0.04	0.30
	55-64	-0.6	0.9	1.1	-0.3	-0.6	1.3	1.4	0.1	-0.1	0.2	0.70	-0.12	0.04	0.72	0.24	0.44	-0.21	-0.35	1.19
	65+	-0.3	1.5	1.7	-0.8	-0.5	-1.2	**3.2**	0.0	-1.0	-0.7	**2.40**	-0.45	0.68	**2.12**	0.11	0.04	-0.82	-0.21	-0.15
Women	0-04	-0.5	0.1	0.7	0.5	0.0		0.3	0.3	-0.3	0.1	-1.37	0.09	0.30	0.00	0.56	1.13	-0.11	-0.39	-0.01
	5-14	0.7	1.1	0.8				0.3	1.2	0.7		-0.01	0.44	**2.91**	0.35	0.31	0.98	0.84	0.74	**4.60**
	15-24	0.0	0.5	0.8	1.3			0.5	0.4	**2.8**		0.59	0.27	**2.25**	0.46	0.44	0.18	0.26	1.32	**2.20**
	25-34	-0.2	0.2	1.3	1.5	**2.6**	0.9	0.8	0.6	1.0		0.42	1.40	**2.70**	0.18	0.71	0.55	0.18	0.70	
	35-44	0.3	0.3	0.5	0.5	1.0	0.3	0.6	0.1	0.6	1.0	0.57	1.12	1.62	0.17	0.24	0.12	0.09	0.84	1.45
	45-54	-0.7	1.2	0.6	0.4	0.3	0.0	0.4	0.7	0.2	0.2	0.87	0.33	0.56	0.37	-0.03	0.34	0.22	0.19	0.33
	55-64	0.0	0.6	1.3	0.0	0.2	-0.2	1.0	0.9	-0.3	0.0	0.73	0.31	0.28	0.45	-0.20	0.55	-0.13	0.12	0.91
	65+	-0.3	1.5	1.7	-1.1	-0.6	-2.2	**3.4**	-0.5	-0.9	-1.6	**2.69**	0.08	0.51	**2.45**	-0.03	0.02	-1.10	-0.91	0.93

In tropical regions, most significant associations were found with SDUHI and SNUHI. For Chapter 4, associations were detected in men aged 5–14 and women aged 5–14 and 25–35. For Chapter 5, affected groups included men aged 15–64 and women aged 15–24, 35–44, and 65+. For Chapter 6, associations were observed among men <15 years and women aged 15–24 and 55–64. For Chapter 9, associations occurred among men aged 5–14, 35–44, and 65+, and women aged 0–4, 15–24, and 65+. For Chapter 10, significant associations were restricted to women aged 0–4 and 65+. In winter, associations were scarce; only women aged 45–54 showed significant associations between Chapter 5 mortality and UHI intensity (Table 4).

Table 4. Average effect size ($\bar{\varepsilon}$) per 1°C increase in UHI intensity, by season (summer/winter) and time of day (daytime/nighttime) in tropical regions (2003-2019). Significant associations ($\bar{\varepsilon}$ > 2) are highlighted in bold and colored red.

		$\bar{\varepsilon}$ (SDUHI)				$\bar{\varepsilon}$ (SNUHI)		$\bar{\varepsilon}$ (WDUHI)		$\bar{\varepsilon}$ (WNUHI)	
		1°C	2°C	3°C	4°C	1°C	2°C	1°C	2°C	1°C	2°C
Chapter 4 - Endocrine, Nutritional and Metabolic Diseases											
Men	0-04	0.52	0.30	1.23		0.31		-0.12	0.73	0.01	0.87
	5_14	0.44	0.38	1.44		0.59	**4.60**	0.73	1.54	0.51	
	15-24	0.61	0.55	0.63		0.24		0.00	0.65	0.10	3.39
	25-34	-0.08	0.47	0.42	0.34	-0.30	1.44	0.06	0.33	-0.07	-0.23
	35-44	0.30	0.06	-0.05	-0.59	0.14	0.55	0.09	0.17	0.21	0.27
	45-54	-0.14	0.45	-0.11	1.80	-0.12	-0.23	-0.08	0.45	-0.13	-0.37
	55-64	0.41	0.07	-0.27	-2.19	-0.26	-0.54	0.29	-0.04	-0.25	-0.40
	65+	0.14	0.11	0.19	-1.10	-0.19	-0.85	-0.08	0.42	0.00	-0.39
Women	0-04	0.22	0.18	0.90		0.42		0.15	0.22	0.36	1.06
	5_14	0.80	1.10	**2.78**		0.59		0.61	1.43	0.41	2.36
	15-24	0.35	0.16	1.01		0.26		0.16	0.61	0.07	2.10
	25-34	-0.17	0.14	0.52		0.00	**2.57**	0.01	0.58	0.37	1.64
	35-44	0.06	0.23	-0.05	0.32	-0.20	0.92	0.24	0.07	-0.30	0.57
	45-54	0.25	0.41	-0.70	-0.21	-0.38	0.22	0.10	0.37	-0.34	-0.43
	55-64	0.46	0.33	-0.21	-1.27	-0.55	-0.66	0.09	0.57	-0.68	-0.22
	65+	0.35	0.36	-0.51	0.05	-0.42	-1.29	0.23	0.37	-0.03	-0.41
Chapter 5 - Mental, Behavioral and Neurodevelopmental disorders											
Men	0-04							0.42		0.98	
	5_14	1.08						0.89		0.62	
	15-24	0.23	0.55	0.33		0.22	**3.18**	0.75	1.80	0.61	
	25-34	0.22	0.23	1.20		0.10	**3.96**	0.26	1.63	0.33	2.51
	35-44	0.17	-0.06	0.38	1.52	0.02	**2.92**	-0.02	0.75	0.37	1.23
	45-54	0.10	-0.06	0.38	0.81	0.64		0.07	0.09	0.32	1.16
	55-64	0.00	-0.14	1.09	1.01	0.46	**2.30**	-0.02	0.97	0.28	0.24
	65+	-0.15	0.15	0.38	-0.53	0.08	0.85	-0.03	0.36	0.16	0.58
Women	0-04							0.79		1.04	
	5_14	0.98						0.65			
	15-24		0.75	**2.89**		1.05		0.47		1.09	1.37
	25-34	1.11	0.83	1.49		0.80		0.71		0.76	
	35-44		0.92	**2.51**		0.97		0.47		0.72	
	45-54	0.55	0.98	1.07		0.34		0.16	**2.09**	1.34	3.38
	55-64	0.59	0.75			0.34		0.49		0.64	2.75
	65+	-0.16	-0.03	0.64	**2.50**	0.45	0.57	-0.41	0.66	0.06	1.25
Chapter 6 - Diseases of the Nervous System											

Men	0-04	0.16	0.26	**2.19**		0.41	**3.65**	0.18	0.19	0.05	-0.26
	5_14	0.49	-0.19	1.54		0.34	**3.05**	-0.02	0.64	0.30	1.70
	15-24	0.00	0.10	0.41	0.36	0.14		0.45	-0.02	0.31	1.60
	25-34	0.12	0.00	0.47	0.64	0.22		0.10	0.08	-0.03	0.76
	35-44	0.31	-0.04	0.69	0.47	0.00		0.10	0.09	0.07	1.55
	45-54	0.29	0.10	0.38		0.32		-0.19	0.40	-0.07	0.83
	55-64	0.40	0.04	0.07	0.72	0.03	1.12	0.26	0.19	0.11	1.00
	65+	-0.12	0.00	0.38	-0.96	0.22	-0.06	0.11	0.27	0.19	0.29
Women	0-04	0.13	0.23	1.11		0.35		0.32	0.67	0.19	0.62
	5_14	0.60	-0.05	1.77		0.45		0.34	0.23	0.48	1.49
	15-24	0.50	-0.16	1.36		0.25	**6.01**	0.07	0.79	-0.24	1.47
	25-34	0.37	0.08	0.95		0.21		0.45	0.29	0.46	
	35-44	0.24	0.35	0.66		0.22		0.14	0.74	0.48	
	45-54	0.14	-0.17	1.25	0.78	0.18	1.66	0.33	0.55	0.05	2.28
	55-64	0.22	-0.03	0.82	0.66	0.01	**4.35**	-0.07	0.59	0.24	0.50
	65+	-0.35	0.23	0.35	-0.18	0.24	-0.09	0.07	0.01	0.39	0.79
Chapter 9 - Diseases of the Circulatory System											
Men	0-04	0.38	0.35	0.48		-0.14		0.34	0.83	0.11	2.75
	5_14	0.85	0.19	**2.74**	**2.08**	0.75		0.38	1.16	0.23	0.91
	15-24	0.26	-0.20	0.57	0.86	0.28	1.09	-0.04	0.50	-0.03	1.10
	25-34	0.09	0.05	0.06	0.57	-0.08	0.55	0.12	-0.29	-0.19	0.73
	35-44	0.46	-0.22	-0.12	**2.31**	0.04	0.18	0.07	0.31	0.41	-0.05
	45-54	0.10	0.21	0.02	0.32	0.37	-0.08	0.23	-0.12	0.69	-0.47
	55-64	0.02	0.01	0.20	1.61	0.37	-0.59	0.44	0.39	0.53	-0.06
	65+	-0.56	0.18	1.14	**5.35**	1.23	-1.72	0.82	0.80	1.44	-0.14
Women	0-04	0.52	0.21	1.63	**2.19**	0.36		0.27	0.52	0.27	
	5_14	0.93	0.32	1.84		0.73		-0.12	1.39	0.47	1.66
	15-24	0.13	0.08	1.23	1.15	0.33	**2.71**	0.18	0.94	0.35	
	25-34	-0.14	0.23	0.66		-0.08		-0.12	0.71	0.15	0.09
	35-44	-0.10	0.02	0.57	-0.47	0.52	0.70	0.19	-0.02	-0.20	0.79
	45-54	-0.01	0.25	-0.19	0.66	0.20	0.49	0.35	-0.26	0.17	-0.09
	55-64	-0.24	0.71	-0.40	-0.68	-0.06	0.00	0.18	0.69	0.10	-0.05
	65+	-0.15	-0.18	1.28	**4.18**	1.50	-1.88	0.87	0.78	1.36	0.38
Chapter 10 - Diseases of Respiratory System											
Men	0-04	-0.02	0.31	0.22	1.53	-0.01		-0.15	0.10	-0.17	0.45
	5_14	0.58	0.59	0.79		0.27		0.28	0.87	0.41	
	15-24	-0.09	0.39	0.65	0.50	0.02		0.33	0.42	0.39	
	25-34	0.31	0.08	0.21		0.02		0.05	0.45	0.07	0.73
	35-44	-0.27	0.39	0.48	0.22	0.28		0.59	-0.24	0.48	1.29
	45-54	-0.46	0.25	0.96	0.65	0.23		0.02	0.48	0.18	0.37
	55-64	-0.42	0.41	0.31	0.07	0.14	0.28	0.07	0.31	0.04	-0.58
	65+	-0.24	-0.05	1.09	0.89	0.43	-1.08	0.24	0.53	0.81	-0.46
Women	0-04	0.08	0.32	0.52	**2.41**	-0.33	**3.3**	-0.25	0.57	0.11	0.08

	5_14	0.66	0.46	1.46		0.72		0.36	0.60	0.55	
	15-24	0.47	0.60	0.24		0.49		-0.04	0.67	0.18	0.80
	25-34	0.10	0.43	0.70		0.26		0.39	0.66	0.23	
	35-44	0.02	-0.10	0.78		0.02	1.98	0.29	0.00	0.06	0.98
	45-54	-0.01	0.16	0.69	-0.03	0.32	1.50	0.01	0.82	-0.18	0.55
	55-64	-0.30	0.39	0.14	0.72	0.11	1.29	0.09	0.30	-0.10	0.22
	65+	-0.38	0.17	0.56	**3.02**	0.46	-0.85	0.33	-0.04	0.48	-0.11

Discussion

Our findings reveal that UHI intensity was not uniform across climatic zones or periods. Temperate regions experienced the strongest effects, reaching up to 6 °C during summer daytime and winter nighttime, suggesting higher heat retention capacity in urban areas under these conditions. In contrast, tropical and arid regions exhibited lower intensities, generally below 4 °C, indicating that background climate and surface characteristics modulate UHI magnitude [32–35]. These spatial and temporal contrasts are particularly relevant for public health, as stronger UHI intensity in temperate metropolitan areas could increase vulnerability to chronic non-communicable diseases. Elevated nighttime temperatures, such as those observed in winter, may reduce physiological recovery and exacerbate cardiovascular and metabolic risks [36,37], while extreme summer daytime heat intensifies thermal stress, contributing to higher mortality during heatwaves events [11,12,38].

Importantly, UHI intensity was not uniform across municipalities within the same metropolitan region. To account for this spatial heterogeneity, we evaluated mortality risk per incremental increase in UHI intensity (e.g., at 1 °C, 2 °C, etc.), capturing the nonlinear relationship between heat exposure and health outcomes. This approach highlights how even small increases in UHI can substantially amplify risks in vulnerable urban areas and provides critical insights for both urban planning and public health preparedness.

The association between UHI intensity and non-communicable disease mortality showed strong heterogeneity across climatic zones. The most consistent associations were observed in temperate regions, particularly for cardiovascular, metabolic, and respiratory diseases (ICD10-chapters 4,9, and 10), likely reflecting the compounded effects of elevated background temperatures, limited adaptation measures [39], and higher levels of urbanization [40]. Conversely, weaker associations in tropical regions may reflect physiological acclimatization [41] or behavioural adaptations [42–44] to persistent heat, although these adaptations may not fully offset underlying vulnerabilities.

Nocturnal UHI during summer emerged as a particularly critical driver of mortality risk. In temperate regions, strong associations appeared at just 1 °C of nighttime UHI, whereas daytime effects required higher thresholds. These findings underscore the importance of nocturnal thermal stress, which can impair recovery, exacerbate chronic conditions, and intensify cumulative heat-related risks. Winter UHI also showed significant associations, especially at night, reinforcing the notion that mortality risks are not limited to extreme daytime heat events.

Our stratified analysis by sex and age revealed that vulnerability to UHI-related mortality extends beyond the elderly [19,45,46]. Children, adolescents, and young adults were also at risk, especially in temperate regions under summer and winter daytime UHI. Circulatory, metabolic, and respiratory mortality displayed a U-shaped pattern, with both the youngest (<15) and the oldest (>54) men and women at risk. For mental disorders (chapter 5) and diseases of the nervous system (Chapter 6), younger male groups (<35) were vulnerable to daytime UHI in both summer and winter. Women showed heightened vulnerability across almost all age groups for mental and behavioral disorders (chapter 5) under both summer and winter UHI.

In arid regions, women exhibited broader age ranges of vulnerability than men. Circulatory (chapter 9) and respiratory diseases (chapter 10) disproportionately affected young women, middle-aged men, and children. Mental and behavioral disorders (chapter 5) showed consistent associations in men <55 and women <65, with stronger effects in summer. Mortality from nutritional and metabolic diseases (chapter 4) affected younger groups (men 5–54, women 0–34), particularly under summer UHI during both day- and nighttime periods.

In tropical regions, respiratory mortality predominantly affected women, a sex-specific difference that aligns with evidence from other tropical settings [47,48]. Associations were concentrated in summer daytime and nighttime UHI, and less evident in winter. Vulnerability was distributed across multiple age groups, but risks were especially pronounced in children (0–14) and older women (65+). Respiratory mortality (chapter 10) was almost exclusively significant among women, suggesting sex-specific pathways. These findings highlight that physiological susceptibility, exposure patterns, and social determinants jointly shape vulnerability profiles [41,45]. Importantly, the evidence that young groups are significantly affected challenges the conventional assumption that heat-related health risks are primarily confined to older populations [46].

Climatic context further modulated these patterns of vulnerability. In temperate regions, where UHI intensity peaked at 6 °C, mortality risks were widespread across diseases and demographic groups. In arid regions, associations were more selective and heterogeneous, but women showed broader susceptibility—possibly reflecting gendered differences in occupational exposure, health care access, or social roles. In tropical regions, UHI intensities were lower, yet significant associations emerged, often among younger age groups and women, pointing to pre-existing vulnerabilities, high baseline temperatures, and limited adaptive capacity. These contrasts highlight that UHI-related health risks cannot be explained by thermal exposure alone but are mediated by socioeconomic inequality, housing conditions, and urban infrastructure.

In summary, our study provides robust evidence that the urban heat island significantly exacerbates mortality risks from multiple non-communicable disease chapters, with marked heterogeneity across climatic zones, seasons, and demographic groups. These findings extend previous research by disentangling UHI-specific effects from broader temperature impacts and by demonstrating critical differences between daytime and nighttime exposure as well as between summer and winter seasons. The identification of vulnerable subpopulations—including children, women of reproductive age, and older adults—underscores the need to address health inequities in the context of climate change.

Given rapid and uncontrolled urbanization in low- and middle-income countries [39,49] and the expected intensification of UHI under global warming [50], our results emphasize that mitigating urban heat should be a key priority for climate adaptation and public health policy [44]. Strategies such as green infrastructure [51], reflective surfaces [12], heat alert systems, and strengthened healthcare preparedness [52] are essential to reduce UHI-related health burdens and prevent the amplification of health inequities in a warming world.

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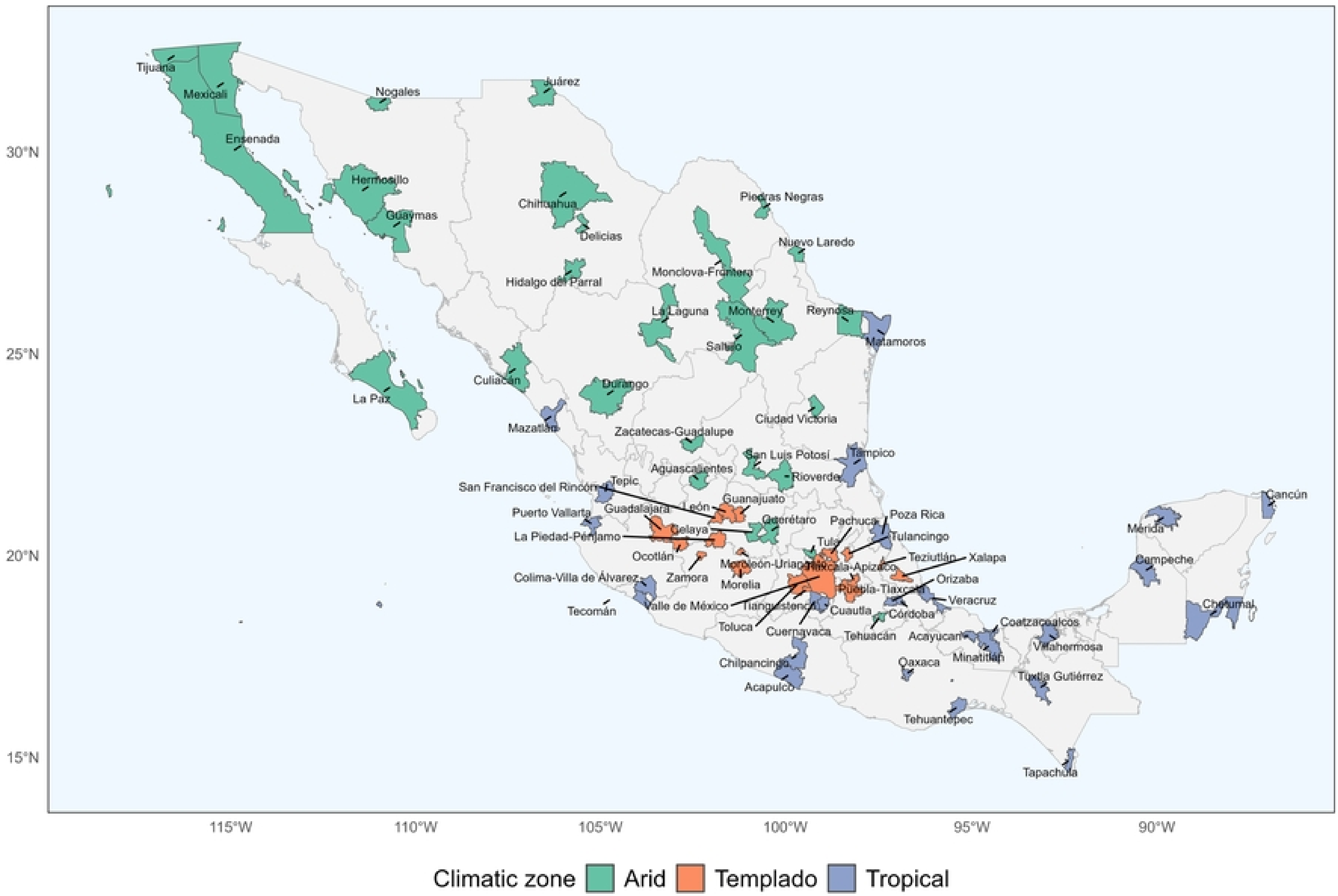
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Nuevo Laredo
Monclova-Frontera
La Laguna
Monterrey
Reynosa
Matamoros
Saltillo
Culiacán
La Paz
Durango
Mazatlán
Ciudad Victoria
Zacatecas-Guadalupe
San Luis Potosí
Tampico
Aguascalientes
Rioverde
Tepic
San Francisco del Rincón
Guanajuato
León
Puerto Vallarta
Guadalajara
Querétaro
Pachuca
Poza Rica
Celaya
La Piedad-Pénjamo
Tulancingo
Tula
Ocotlán
Moroleón-Uriangato
Teziutlán
Xalapa
Tlaxcala-Apizaco
Orizaba
Colima-Villa de Álvarez
Zamora
Morelia
Puebla-Tlaxcala
Veracruz
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Cuautla
Córdoba
Tecomán
Toluca
Cuernavaca
Tehuacán
Acayucan
Coatzacoalcos
Villahermosa
Minatitlán
Chilpancingo
Oaxaca
Tuxtla Gutiérrez
Acapulco
Tehuantepec
Tapachula
Cancún
Mérida
Campeche
Chetumal
30°N
25°N
20°N
15°N
115°W
110°W
105°W
100°W
95°W
90°W
Climatic zone
Arid
Templado
Tropical

Figure 1

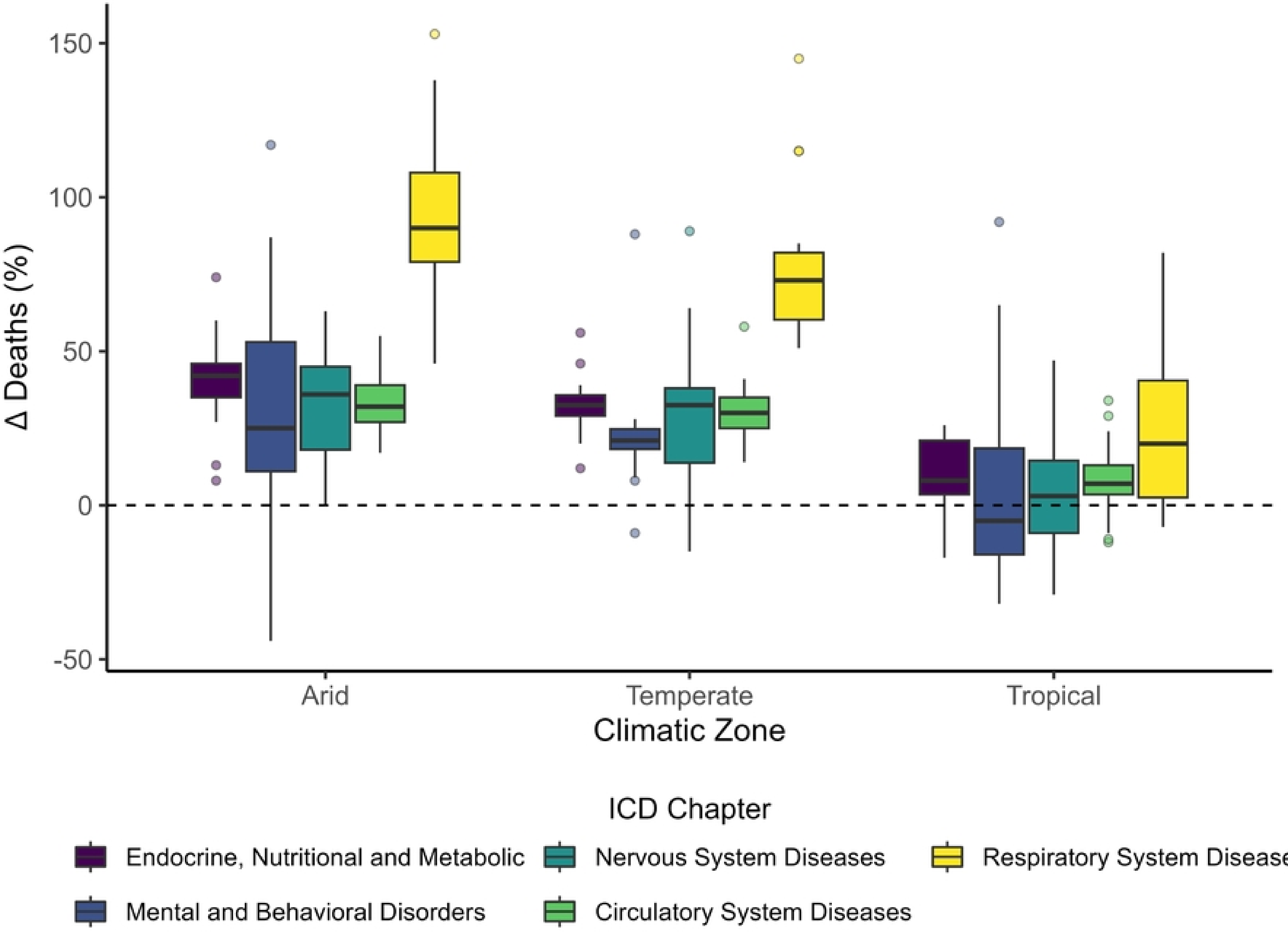

150
100
50
0
-50
Δ Deaths (%)
Arid
Temperate
Tropical
Climatic Zone
ICD Chapter
Endocrine, Nutritional and Metabolic
Nervous System Diseases
Respiratory System Disease
Mental and Behavioral Disorders
Circulatory System Diseases

Figure 2

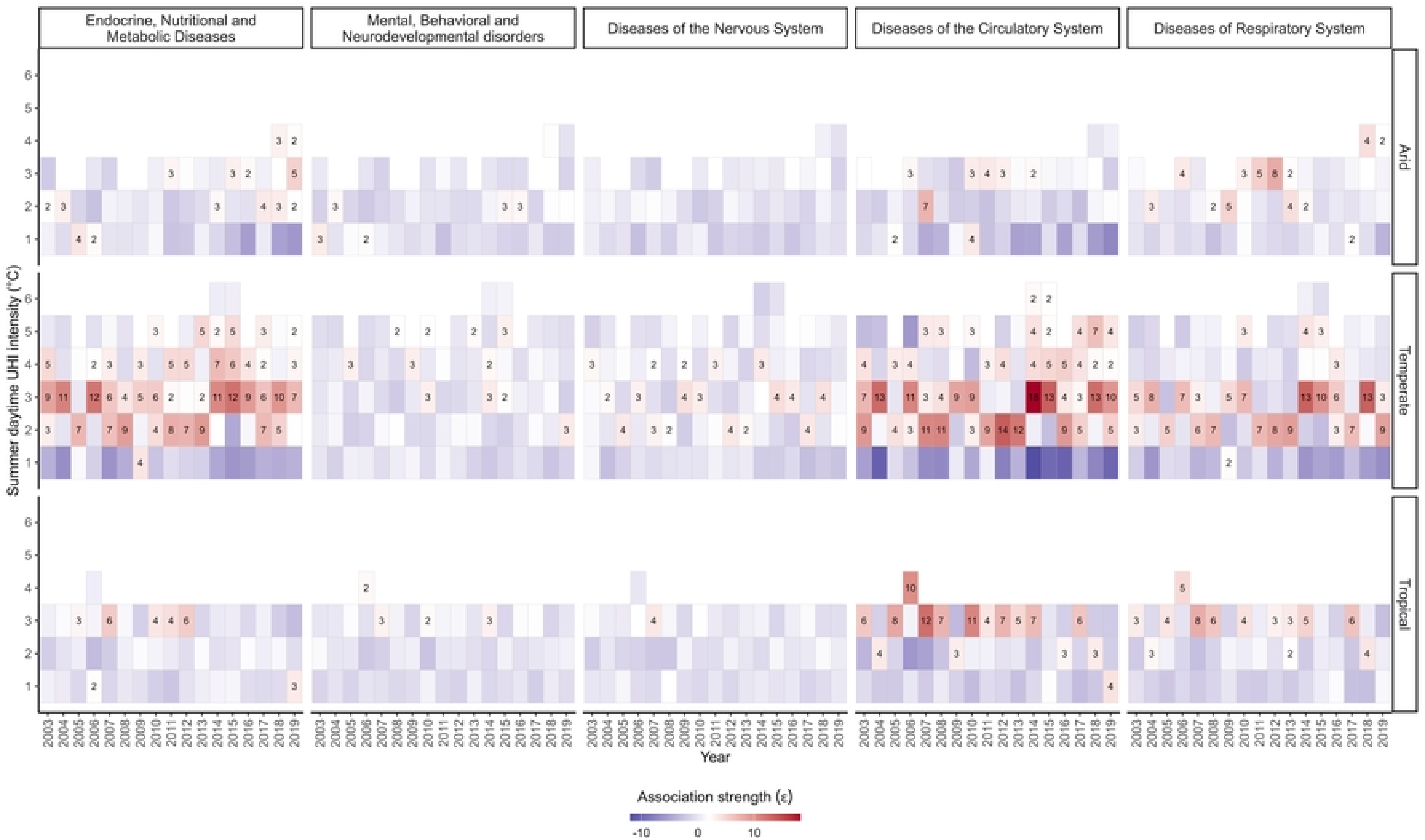
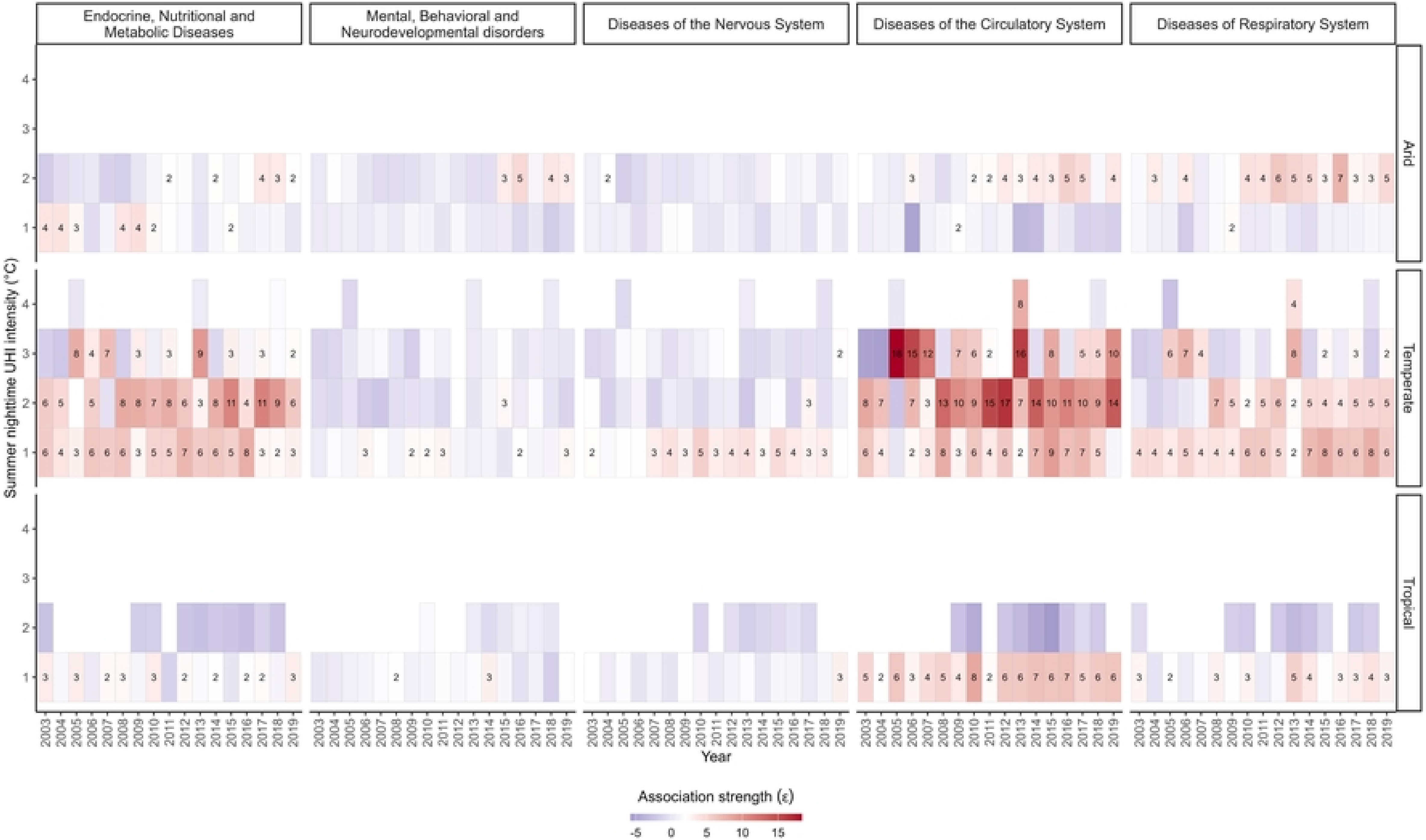
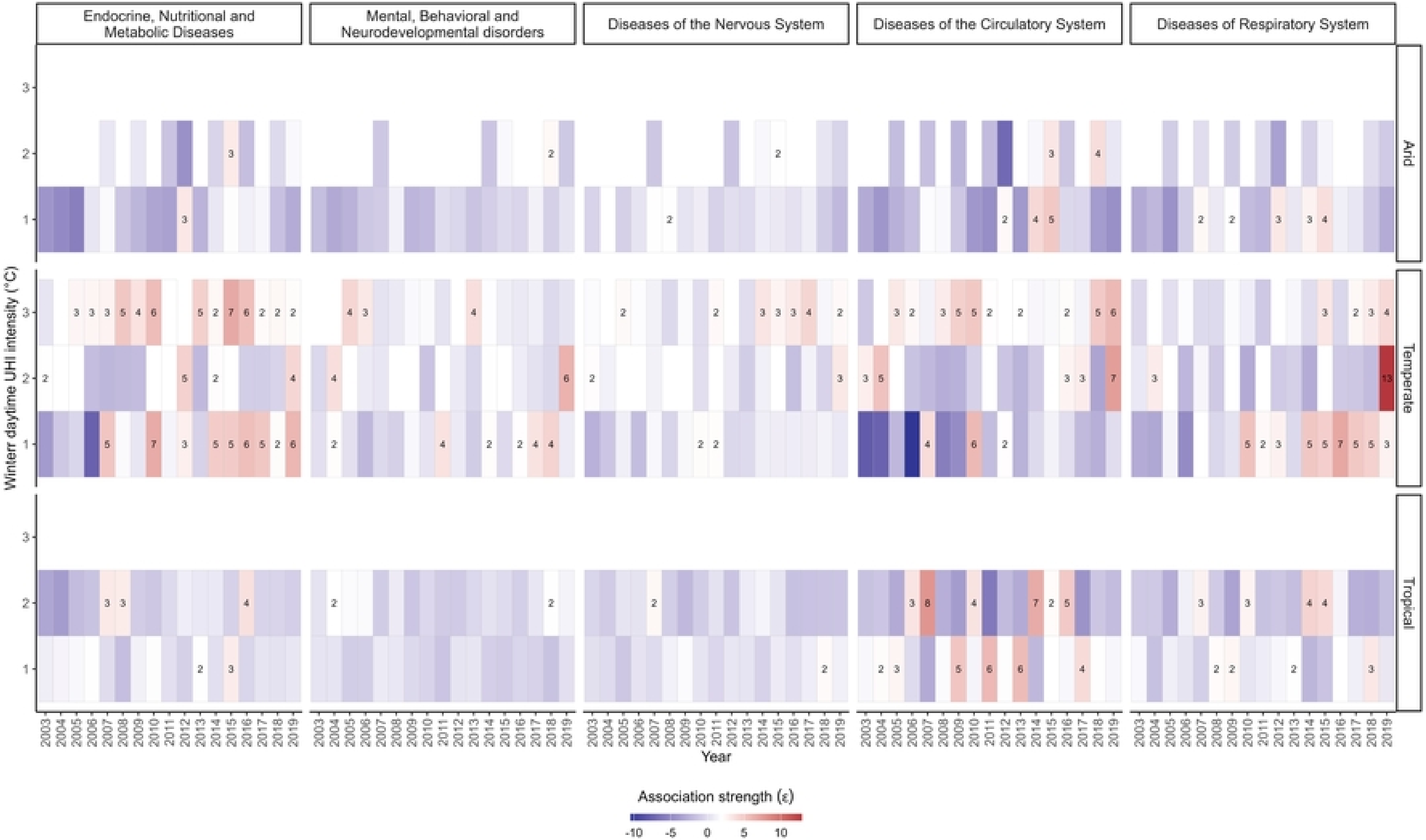

Endocrine, Nutritional and Metabolic Diseases
Mental, Behavioral and Neurodevelopmental disorders
Diseases of the Nervous System
Diseases of the Circulatory System
Diseases of Respiratory System
Arid
Temperate
Tropical
Summer daytime UHI intensity (°C)
Year
Association strength (ε)
-10
0
10

Figure 3



Endocrine, Nutritional and Metabolic Diseases
Mental, Behavioral and Neurodevelopmental disorders
Diseases of the Nervous System
Diseases of the Circulatory System
Diseases of Respiratory System
Arid
Temperate
Tropical
Summer nighttime UHI intensity (°C)
Year
Association strength (ε)
-5
0
5
10
15

Figure 4



Endocrine, Nutritional and Metabolic Diseases
Mental, Behavioral and Neurodevelopmental disorders
Diseases of the Nervous System
Diseases of the Circulatory System
Diseases of Respiratory System
Arid
Temperate
Tropical
Winterr daytime UHI intensity (°C)
Year
Association strength (ε)

Figure 5

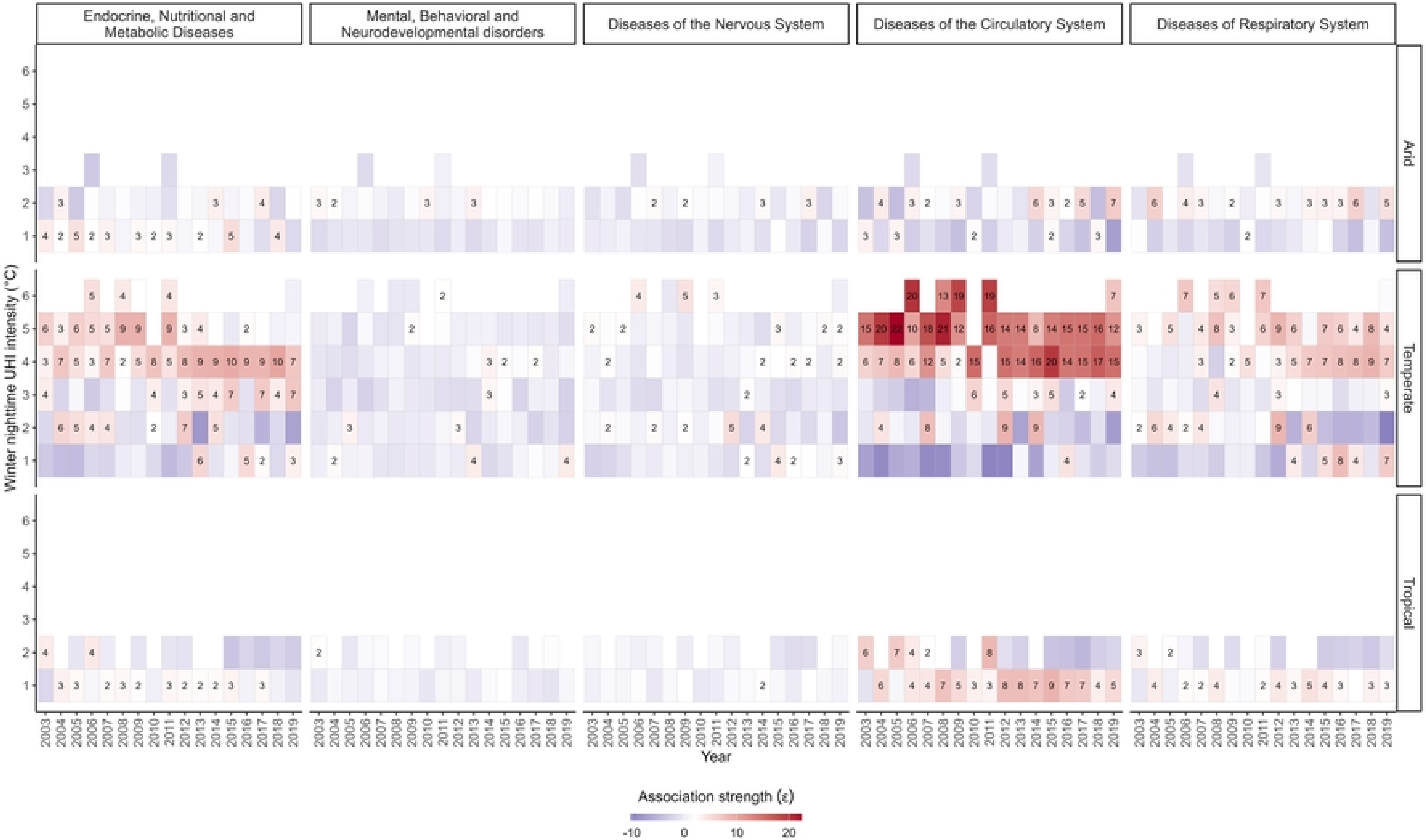

Endocrine, Nutritional and Metabolic Diseases
Mental, Behavioral and Neurodevelopmental disorders
Diseases of the Nervous System
Diseases of the Circulatory System
Diseases of Respiratory System
Arid
Temperate
Tropical
Winter nighttime UHI intensity (°C)
Year
Association strength (ε)

Figure 6