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RESEARCH

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low-and middle-income countries [1, 2]. NCDs burden has become an important global health problem, resulting in global health inequalities across the world. However, NCDs are largely preventable, and after the 2011 UN High-Level Meeting on non-communicable diseases, Member States of the WHO adopted "The reduction by a third of premature non-communicable disease mortality by 2030" as the target of Sustainable Development Goals (SDGs) [3]. Therefore, it is necessary to explore the risk factors for NCDs and develop targeted strategies to prevent NCDs and reduce the disease burden.

In recent decades, global climate change has intensified, and the fluctuation range of ambient temperature has increased significantly [4]. The World Meteorological Organization (WMO) reported in the State of the Global Climate 2023 that 2023 was the warmest year since the 174-year observational record. The global average near-surface temperature was 1.45 ± 0.12 °C above the pre-industrial average, with severe heatwaves occurring around the world [5]. Extreme weather and climate events pose a threat to the natural environment and social economy, and health problems caused by extreme heat are of increasing concern [6–9]. Sub-

Table 1 (continued)

Characteristics	1990				2019				EAPC (1990–2019)	
	Deaths cases No. (95% UI)	ASMR per 100,000 No. (95% UI)	DALYs No. (95% UI)	ASDR per 100,000 No. (95% UI)	Deaths cases No. (95% UI)	ASMR per 100,000 No. (95% UI)	DALYs No. (95% UI)	ASDR per 100,000 No. (95% UI)	ASMR No. (95% CI)	ASDR No. (95% CI)
Central Europe	30.49 (-5.08–116.23)	0.02 (0–0.09)	562.61 (-93.82–2148.8)	0.4 (-0.06–1.51)	121.43 (8.84–411.62)	0.06 (0–0.19)	1772.86 (113.55–5888.1)	0.83 (0.05–2.74)	1.49 (-1.34–4.4)	1.09 (-1.76–4.03)
Central Latin America	-103.85 (-3245.77–721.22)	-0.19 (-4.45–0.97)	-1076.22 (-73889.46–17819.88)	-1.73 (-85.08–19.43)	3096.1 (1163.19–4869.12)	1.35 (0.49–2.14)	65504.31 (21092.03–106376.98)	27.5 (8.87–44.81)	7.75 (5.16–10.41)	8.19 (5.91–10.51)
Central Sub-Saharan Africa	-9.67 (-800.44–242.19)	-0.11 (-4.26–1.27)	-16.2 (-23055.31–7296.8)	-1.17 (-89.47–27.15)	404.25 (32.64–861.18)	0.87 (0.01–1.94)	11352.87 (1654.29–23031.49)	18.88 (1.69–40.07)	15.04 (8.46–22.02)	9.95 (6.46–13.55)
East Asia	3811.38 (440.29–9103.91)	0.62 (0.06–1.5)	77938.03 (10216.29–178641.91)	9.99 (1.24–23.42)	11041.17 (5526.79–18962.17)	0.66 (0.33–1.11)	185548.95 (91883–322592.31)	9.78 (4.89–16.88)	0.46 (-0.52–1.45)	0.15 (-0.8–1.12)
Eastern Europe	40.04 (-53.07–216.33)	0.02 (-0.02–0.09)	494.67 (-1652.36–3607.41)	0.19 (-0.62–1.36)	680.83 (77.63–1923.14)	0.2 (0.02–0.55)	11204.23 (1265.48–31659.06)	3.26 (0.37–9.22)	6.83 (3.75–10)	7.52 (4.11–11.04)
Eastern Sub-Saharan Africa	-655.89 (-4469.02–1483.37)	-0.94 (-6.56–2.31)	-18714.36 (-127516.56–39308.15)	-21.3 (-148.53–50.5)	1498.84 (-1845.88–4066.61)	1.01 (-1.38–2.94)	41279.1 (-43771.77–107987.23)	22.26 (-25.75–59.53)	28.31 (18.14–39.36)	24.8 (14.59–35.91)
High-income Asia Pacific	299.08 (-210.77–665.62)	0.17 (-0.09–0.38)	5344.56 (-7010.02–12216.8)	2.78 (-3.37–6.35)	696.29 (188.3–1247.11)	0.13 (0.03–0.22)	9397.7 (2246.83–16859.33)	2.14 (0.5–3.82)	0.11 (-2.1–2.38)	0.21 (-1.86–2.31)
High-income North America	1092.03 (481.36–1952.34)	0.3 (0.13–0.53)	18939.73 (8587.07–32902.29)	5.45 (2.46–9.39)	1668.86 (822.67–2675.32)	0.25 (0.12–0.39)	27286.29 (14071.59–43175.92)	4.51 (2.27–7.07)	-0.04 (-1.04–0.97)	0 (-1–1.02)
North Africa and Middle East	5803.37 (-1572.85–10991.12)	3.86 (-1.01–7.33)	158255.39 (-30567.53–294826.62)	80.72 (-21.35–151.98)	17759.09 (8210.4–27892.81)	4.69 (2.13–7.37)	424307.11 (196441.56–674806.5)	94.22 (43.86–151.06)	0.64 (0.4–0.88)	0.5 (0.27–0.72)
Oceania	-3.86 (-234.62–58.04)	-0.18 (-8.72–2.25)	-103.45 (-6556.69–1673.83)	-3.51 (-202.61–50.43)	83.32 (-44.48–206.5)	1.33 (-0.66–3.33)	2421.02 (-1292.71–5969.85)	30.17 (-16.35–74.51)	7.46 (5.77–9.17)	7.13 (5.51–8.77)
South Asia	10184.97 (-62929.14–36661.31)	2.48 (-14.37–8.69)	257139.8 (-1691957.21–922995.18)	45.93 (-281.9–162.96)	86829.72 (41322.47–134872)	7.1 (3.27–11.21)	1994153.47 (957424.62–3046336.07)	141.22 (68.05–218.26)	2.61 (2.07–3.16)	2.78 (2.23–3.33)
Southeast Asia	-456.48 (-21695.31–7001.09)	-0.21 (-9.61–3.19)	-13845.61 (-605584.3–179732.69)	-4.45 (-203.21–65.51)	16511.32 (3898.88–28003.77)	3.13 (0.58–5.28)	377975.21 (64790.14–644543.87)	61.89 (10.08–105)	8.7 (6.46–10.98)	8.27 (6.11–10.47)

Table 1 (continued)

Characteristics	1990				2019				EAPC (1990–2019)	
	Deaths cases No. (95% UI)	ASMR per 100,000 No. (95% UI)	DALYs No. (95% UI)	ASDR per 100,000 No. (95% UI)	Deaths cases No. (95% UI)	ASMR per 100,000 No. (95% UI)	DALYs No. (95% UI)	ASDR per 100,000 No. (95% UI)	ASMR No. (95% CI)	ASDR No. (95% CI)
Southern Latin America	93.76 (-72.84–254.95)	0.22 (-0.18–0.59)	2007.63 (-1127.45–5317.55)	4.36 (-2.65–11.65)	156.8 (40.2–293.09)	0.18 (0.05–0.34)	2836.53 (798.44–5196.76)	3.45 (1–6.3)	1.78 (0.32–3.27)	1.25 (-0.1–2.62)
Southern Sub-Saharan Africa	-105.75 (-504.65–44.48)	-0.45 (-2.12–0.17)	-2532.51 (-11888.2–975.67)	-8.64 (-41.6–3.45)	88.28 (-262.83–308.15)	0.16 (-0.59–0.62)	2123.61 (-5302.32–6965.7)	3.66 (-9.62–12.39)	19.04 (-41.52–142.32)	12.07 (-29.66–78.55)
Tropical Latin America	-1311.95 (-7310.58–882.81)	-1.75 (-9.69–1.15)	-30539.14 (-170458.04–21540.74)	-33.06 (-184.05–22.76)	516.63 (-3951.61–2751.79)	0.22 (-1.72–1.23)	10459.43 (-84441.85–53695.1)	4.4 (-35.04–22.68)	17.24 (-3.2–42)	22.8 (-1.11–52.5)
Western Europe	156.5 (-27.37–341.71)	0.03 (0–0.06)	2559.94 (-718.19–5564.27)	0.45 (-0.12–0.97)	445.52 (178.29–834.14)	0.04 (0.02–0.08)	5560.24 (2206.29–10489.87)	0.58 (0.24–1.09)	1.19 (-0.57–2.97)	0.64 (-1.06–2.38)
Western Sub-Saharan Africa	382.71 (-18544.99–6935.45)	0.35 (-26.17–9.2)	11813.85 (-443384.68–186673.66)	10.1 (-491.21–187.02)	6831.9 (-12417.47–16316.53)	4.34 (-7.93–10.46)	171528.46 (-322558.91–417655.4)	84.42 (-151.28–202.91)	10.79 (8.65–12.96)	10.8 (7.94–13.74)

61.36) in 2019 and the EAPC was 3.68 (95% CI: 3.16, 4.21)

Asia (7.1, 95% UI: 3.27–11.21), followed by North Africa and Middle East (4.69, 95%UI: 2.13–7.37), while Western Europe had the lowest ASMR (0.04, 95%UI: 0.02–0.08) (Table 1). South Asia also had the highest ASDR (141.22,95% UI: 68.05–218.26) and Western Europe also had the lowest (0.58, 95% UI: 0.24–1.09) among 21 GBD regions in 2019 (Table 1). From 1990 to 2019, the ASMR and ASDR among 21 GBD regions around the world, except in Australasia and high-income North America, showed an increasing trend, especially in Eastern Sub-Saharan Africa, which has the fastest rise, with EAPC of 28.31 (95% CI: 18.14–39.36) for ASMR and 24.8 (95% CI: 14.59–35.91) for ASDR (Table 1). ASMR and ASDR declined slightly in Australia with an EAPC of -2.08 (95% CI:-2.51–1.65) for ASMR and -2.43 (95% CI:-2.88–1.98) for ASDR, as did ASMR in High-income North America (Table 1). In 2019, among the 204 countries and territories in the world, Oman had the highest ASMR of NCDs due to high temperature in 2019 (27.79, 95%UI: 11.02–40.77), followed by Qatar (26.78, 95%UI: 10.99- 43.43) and United Arab Emirates (26.32, 95%UI: 12.78–39.51) (Table S1; Fig. 1). e top of three countries with the highest ASDR were United Arab Emirates (483.64, 95%UI: 231.83–739.71), Oman (453.03, 95%UI: 190.67–668.63) and Mali (373.46, 95%UI: 202.09–551.94) (Table 1

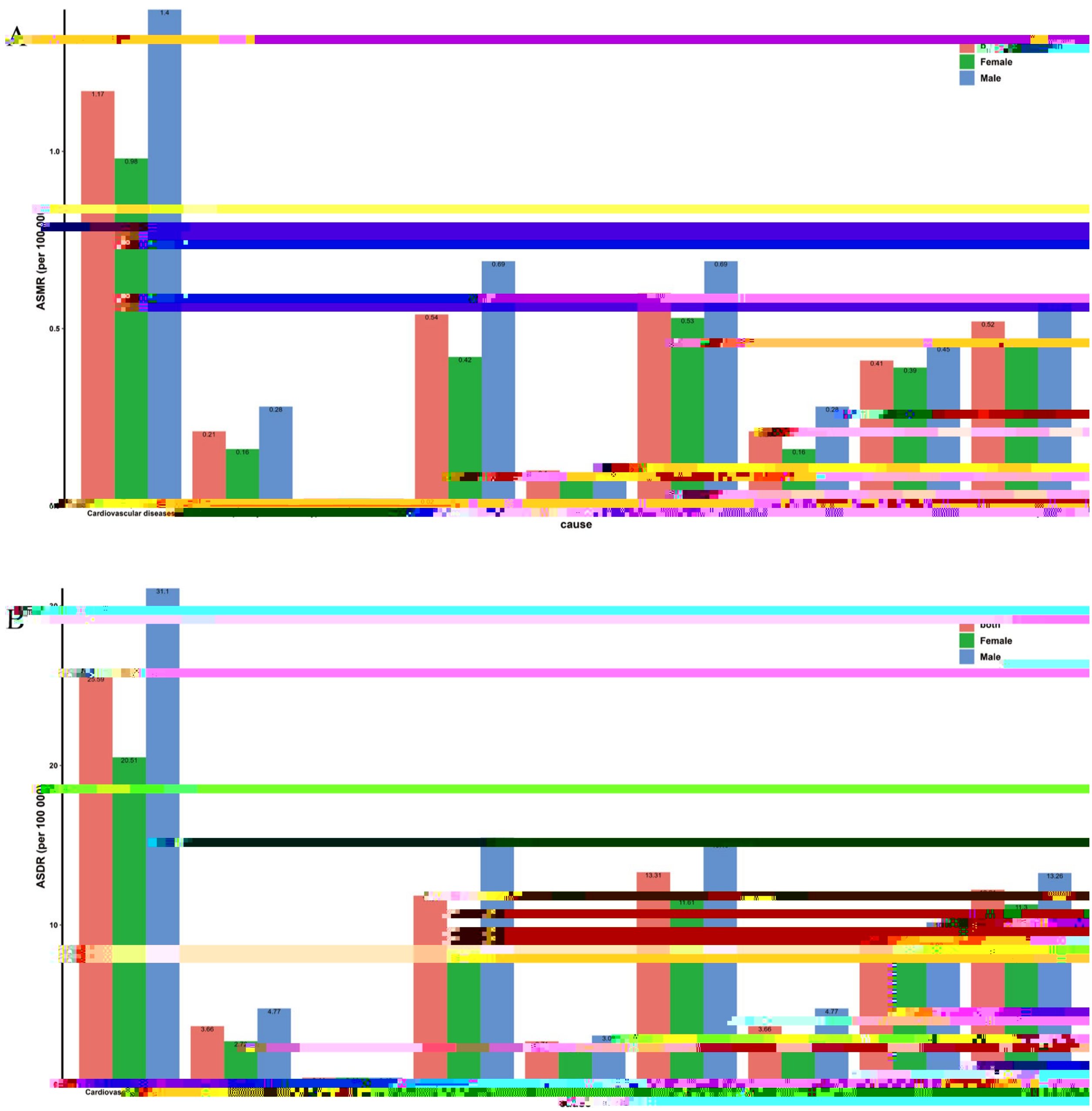

Fig. 2 Global ASMR (**A**) and ASDR (**B**) of cause-specific NCDs attributable to high temperature by sex, 2019. ASMR, age-standardized mortality rate; ASDR, age-standardized DALY rate; NCDs, non-communicable diseases

1990 to 2019. Overall, the trends of the curves fitted to SDI and ASMR and the curves fitted to SDI and ASDR were essentially consistent, with nonlinear correlations. Significant correlations were found between the SDI and both ASMR ($r = -0.17$, $P < 0.001$) and ASDR ($r = -0.20$, $P < 0.001$) (Fig. 4). ASMR and ASDR showed an increasing trend until the SDI value was about 0.4, then ASMR and ASDR peak at the SDI value near 0.4, and leveled off after the SDI value was about 0.7. The maximum values of both ASMR and ASDR were in the low-middle SDI regions, while the minimum values were all found in the high SDI regions (Fig. 4). Among the different GBD regions, except for Australasia and High-income North America, ASMR showed an upward trend. ASDR also increased in all regions apart from Australasia. South Asia had the greatest changes in both ASMR and ASDR, while the changes

Table 2 ASMR and ASDR of cause-specific NCDs attributable to high temperature in 1990 and 2019 and the temporal trends from 1990 to 2019

Characteristics	Death			DALY		
	1990ASMR	**2019ASMR**	**EAPC1 (%)**	**1990 ASDR**	**2019 ASDR**	**EAPC2 (%)**
Non-communicable diseases (NCDs)	0.56 (-2.72–1.84)	1.9 (0.99–2.83)	3.66 (3.14–4.18)	11.87 (-65.96–40.1)	41.45 (21.49–61.36)	3.68 (3.16–4.21)
Cardiovascular diseases	0.37 (-2.27–1.51)	1.17 (0.13–1.98)	3.43 (2.92–3.95)	7.84 (-53.68–33.1)	25.59 (2.07–44.17)	3.43 (2.92–3.95)
Ischemic heart disease	-0.01 (-2.22–0.75)	0.54 (-0.53–1.2)	8.71 (6.92–10.53)	-0.62 (-52.76–16.68)	11.84 (-12.71–26.8)	9.63 (7.45–11.85)
Stroke	0.41 (-0.89–1.63)	0.6 (0.07–1.3)	0.97 (0.63–1.31)	9.23 (-20.44–36.19)	13.31 (1.4–28.97)	0.91 (0.59–1.24)
Hypertensive heart disease	-0.04 (-0.56–0.42)	0.02 (-0.2–0.24)	30.17 (17.97–43.63)	-0.77 (-11.58–8.9)	0.44 (-4.24–4.94)	32.26 (17.82–48.48)
Diabetes and kidney disease	0.15 (-0.82–0.75)	0.52 (0.11–1.06)	3.96 (3.54–4.37)	3.51 (-23.01–21.24)	12.21 (1.51–24.89)	4.02 (3.57–4.46)
Diabetes mellitus	0.16 (-0.47–0.8)	0.41 (0.08–1.04)	3.11 (2.79–3.43)	3.84 (-11.64–19.87)	9.5 (1.75–24.16)	2.96 (2.64–3.28)
Chronic kidney disease (CKD)	-0.01 (-0.74–0.44)	0.1 (-0.28–0.38)	9.73 (7.72–11.79)	-0.32 (-21.66–12.66)	2.71 (-8.07–10.46)	11.21 (8.38–14.12)
Chronic respiratory diseases	0.04 (-1.26–1.02)	0.21 (-0.29–0.85)	4.378 (3.43–5.33)	0.52 (-24.77–19.68)	3.66 (-5.72–15.29)	4.679 (3.59–5.78)
Chronic obstructive pulmonary disease (COPD)	0.04 (-1.26–1.02)	0.21 (-0.29–0.85)	4.38 (3.43–5.33)	0.52 (-24.77–19.68)	3.66 (-5.72–15.29)	4.68 (3.59–5.78)

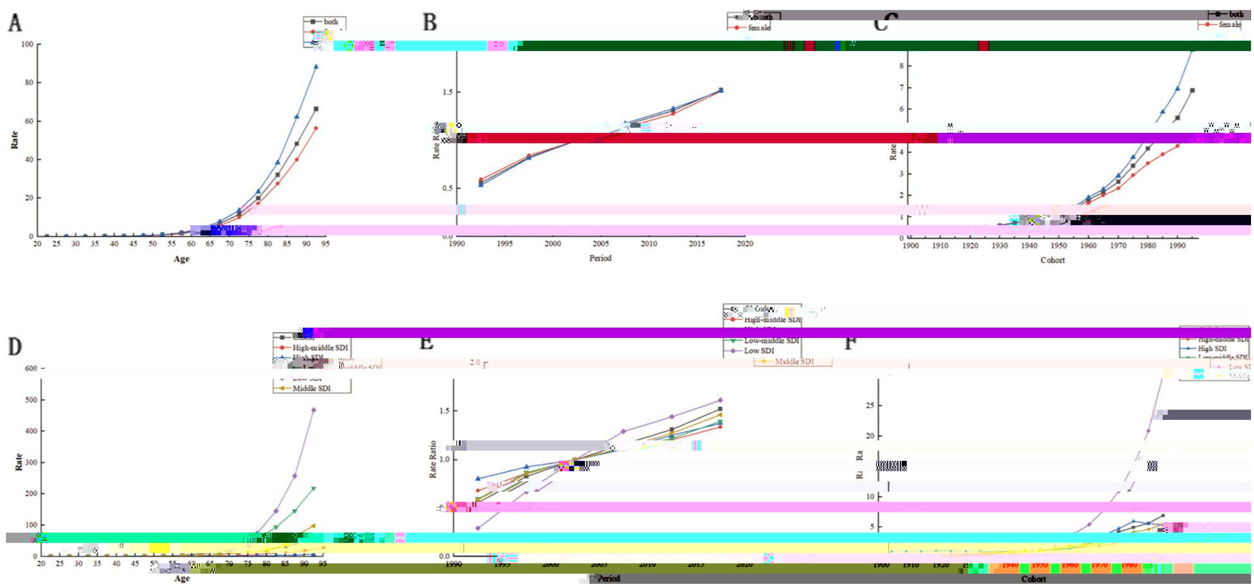

Fig. 3 Age, period, cohort e ects on mortality of cause-specific NCDs attributable to high temperature, globally (**A**-**C**) and in SDI regions (**D**-

of ASMR in High-income Asia Pacific and ASDR in High-income North America were the smallest.

Discussion

is study comprehensively analyzed the burden and temporal trends of NCDs caused by high temperature from 1990 to 2019 at the global, regions and countries levels, compared the di erences in disease burden by sex, validated the relationship between SDI and ASMR, ASDR, and further analyzed the e ects of age, period, and cohort on the mortality rate of high-temperature-related NCDs using APC model. We aimed to highlight the significant burden of NCDs attributable to high temperature globally, inform research priorities for environmental health researchers and provide a reference for public health policy makers in identifying vulnerable populations and areas in need of early prevention.

In recent years, the burden of NCDs caused by global high temperature has been considerable, with ASMR of 1.9% and ASDR of 41.45% in 2019. During the 30-year period 1990 to 2019, furthermore, the global number of deaths of NCDs attributable to high temperature increased by more than 6 times, and the increasing trend in DALY was also evident, which has been reported in

The climate of South Asia and North Africa and Middle East are predominantly tropical, with high temperatures throughout the year. Countries in South Asia, such as India and Pakistan, are suffering from extreme high temperature and heat wave disasters in recent years [33, 34], and extreme high temperature approaching 50 °C have been observed in North Africa on several occasions [35]. Many studies have consistently shown that extreme high temperature affects the increased risk of morbidity, exacerbation and mortality in NCDs, such as COPD [36], diabetes mellitus [17], CKD [37], ischemic heart disease [10], hypertensive heart disease [14] and stroke [38]. In addition, the burden of diseases caused by high temperature may be related to factors such as the level of socioeconomic development [39], the proportion of the elderly [40] and the rate of population growth [35] in regions and countries. Therefore, the rapid increase in the burden of NCDs attributable to high temperature in Eastern Sub-Saharan Africa may be related to its continuous population growth [41]. Oman and Qatar, which are located in the west of Asia, have the highest ASMR among the 204 countries and territories, and the highest ASDR was in United Arab Emirates, followed by Oman. These 3 countries were in the regions with the highest disease burden as mentioned above. However, there are few records on the diseases burden attributable to high temperature in these vulnerable countries and regions [42], let alone studies on high-temperature-related NCDs. We expect more studies will to be reported in these areas, so that we can learn about their climate and demographic dynamics, provide early warning and take effective heat adaptation measures in advance. For example, building shading facilities as needed, and adding emergency access in hospitals for heat-related illnesses when heat waves persist.

The results showed a negative correlation between SDI and the burden of NCDs attributable to high temperature, suggesting that areas with a high SDI had a lower burden of disease. Some studies indicated that people living in high-temperature environments have a higher heat stress tolerance compared to people living in suitable temperature for long periods of time [43]. However, our findings revealed that regions and countries located in areas with perennially high temperatures instead have the highest disease burden, such as South Asia and North Africa and Middle East, whose SDI values were not high. Therefore, we speculate that thermal adaptation had a limited role in reducing the burden of high-temperature-related NCDs, and factors such as economic and social development of the regions can greatly affect the NCDs burden caused by high temperature, which has been reported in previous studies [39, 44, 45]. Countries and territories with high levels of economic development have better healthcare and prevention systems for NCDs, which can largely reduce the incidence and mortality of high-temperature-related illnesses. In addition, government employees, the proportion of manual laborers, and the number of low-income elderly people were also socio-economic reasons affecting the NCDs burden attributable to high temperature [46]. With regard to cooling strategies, the use of air conditioning is undoubtedly the most widely used method in the world. However, the use of air-conditioning not only weakens people's thermal perception and adaptation functions, but also has the disadvantage of environmental unsustainability. For vulnerable people in economically underdeveloped areas, it is unaffordable to purchase air conditioners and pay for their electricity [47]. More attention and efforts are therefore urgent to reduce the NCDs burden attributable to high temperature in countries that are in hot climate zones and less developed economically [illegible] heat exposure and the incidence of non-communicable diseases among men. Additionally, in order to reduce the damage to health caused by hot work, it is necessary to provide hot-workers with cooling guidance and allowances.

First, the age e ect in the APC model showed that the global mortality rate of NCDs attributable to high temperature increased with age, especially after the age group of 65–69 years. e incidence and mortality of NCDs in the elderly were much higher than that in young people because of organ aging and physiological function decline [55]; And the elderly were more sensitive to high temperature [56]; In addition, a study found that patients su ering from NCDs such as ischemic heart disease, diabetes mellitus, stroke, and hypertension were susceptible to extreme temperature [57], coupled with the increasing proportion of aging population in the world, the elderly were at higher risk of NCDs death due to high temperature. We found that mortality increased most slowly with age in high SDI regions, while those in low SDI regions had the fastest rate in the age group after 70–74 years. In addition to the special characteristics of the elderly in terms of physiological functioning, they are also disadvantaged in terms of access to economic and social resources related to heat adaptation [58]. Unhealthy lifestyle and inadequate health resources may be important contributors to the higher burden among older adults in low SDI regions [59]. Consequently, it is necessary to develop health management plans for older adults in hot weather at the community level, such as comprehensive monitoring of potential health risk factors, assessment of the ability to adapt to high temperatures, health education and NCDs intervention, and the establishment of public cooling places for the elderly [56]. Second, the results indicated that the period e ect of NCDs mortality attributable to high temperature showed an increasing trend year by year globally. e technology of diagnosis and etiological determination of NCDs had become more mature, and the registration and reporting of vital health data had become timely over time, which may also explain the upward trend in period e ect. ird, during the period of 1990 to 2019, the upward trend in cohort e ect suggested that the global death risk of high-temperature-related NCDs increased the further back in the birth year one went.

ere are several limitations in this study. Data bias was inevitable even though GBD 2019 had explicitly corrected the data by using methods such as standardization and improved modelling. First, GBD 2019 did not estimate high-temperature exposure using a method that takes potential synergies between relative risk factors into account. In addition, the patterns of data availability for high temperature exposure measurements were inconsistent across locations and time [18]. Second, the determination of the cause of death is complex, so bias in the attribution of death may occur. Regions with poor medical diagnosis technology are more likely to have data errors. ird, the limited number of specific diseases of NCDs included in GBD 2019 and data from areas with low healthcare accessibility may have led to an underestimation of NCDs detection rates [60]. ese potential data sources and biases may a ect the accuracy of the study results. Fourth, there are a lot of factors a ecting NCDs, however, we only examined the e ect of high temperature due to the limitations of the GBD 2019 data.

erefore, in the future, consideration should be given to using more comprehensive and detailed data to include factor99618(t)-5.9(a Waiuo0 9.8 56.6imit)-6(a)(t pl)-5(a.12)7(tr)-8(ii(,

had

TMREL Theoretical minimum risk exposure level
ASR

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