Deutsches Ärzteblatt

Heat-related myocardial infarctions under and beyond Paris Agreement goals in Augsburg, Germany

--Manuskript-Entwurf--

Manuskriptnummer:	DAEB-2019-048R1
Vollständiger Titel:	Heat-related myocardial infarctions under and beyond Paris Agreement goals in Augsburg, Germany
Artikeltyp:	Originalarbeit (max.2300 Wörter)
Korrespond. Autor:	Kai Chen, Ph.D. Helmholtz Zentrum Munchen Deutsches Forschungszentrum fur Umwelt und Gesundheit Neuherberg, München GERMANY
Korrespondierender Autor, Zweitinformationen:	
Korrespondierender Autor, Institution:	Helmholtz Zentrum Munchen Deutsches Forschungszentrum fur Umwelt und Gesundheit
Korrespondierender Autor, zweite Institution:	
Erstautor:	Kai Chen, Ph.D.
Erstautor, Zweitinformationen:	
Reihenfolge der Autoren:	Kai Chen, Ph.D.
	Susanne Breitner, Dr. rer. nat.
	Kathrin Wolf, Dr. rer. biol. hum.
	Masna Rai, BSc
	Christa Meisinger, Prof. Dr. med.
	Margit Heier, Dr. med.
	Bernhard Kuch, Prof. Dr. med.
	Annette Peters, Prof. Dr. rer. biol. hum.
	Alexandra Schneider, Dr. rer. biol. hum.
Reihenfolge 'Zweite Informationen' von Autoren:	
Zusammenfassung:	Summary Background: Substantial efforts will be undertaken to limit global warming to 1.5 °C or 2 °C (Paris Agreement goals). Here, we aimed to project future heat-related myocardial infarction (MI) events in Augsburg, Germany, at increases in warming of 1.5 °C, 2 °C and 3 °C. Methods: Using daily time-series of MI cases and temperature projections under three climate scenarios, we projected changes in heat-related MIs at different increases in warming, assuming no future changes in population and adaptation. Results: Under a low emission scenario that limits warming below 2 °C throughout the 21st century, heat-related MI cases will increase by 17 (-1 to 46) per decade at 1.5 °C of warming. Under a high emission scenario, heat-related MI cases will increase by 32 (1 to 83), 54 (1 to 124), and 109 (4 to 313) per decade in warming of 1.5 °C, 2 °C and 3 °C, respectively. Similar results were found under a moderate emission scenario that fails to hold warming below 2 °C. Conclusion: The future burden of heat-related MIs in Augsburg will rise with any increase in warming. Fulfilling the Paris Agreement goals will lead to substantial health

	benefits for MI patients.

Zusammenfassung

Hintergrund: Es werden erhebliche Anstrengungen unternommen, um die globale Erwärmung auf 1,5 ° C oder 2 ° C zu begrenzen (Ziele des Pariser Übereinkommens). Unsere Zielsetzung war, zukünftige hitzebedingte Herzinfarktereignisse (HI) in Augsburg in Bezug auf eine globale Erwärmung um 1,5 ° C, 2 ° C bzw. 3 ° C zu projizieren.

Methoden: Unter Verwendung von täglichen HI-Zeitreihen und Temperaturprojektionen wurden basierend auf drei Klimaszenarien jeweils die Änderungen der hitzebedingten HIs in Bezug auf unterschiedliche Erwärmungslevel projiziert. Dabei wurden mögliche Änderungen der Bevölkerungsstruktur oder eine potentielle Adaptation der Bevölkerung nicht berücksichtigt.

Ergebnisse: In einem emissionsarmen Szenario, das die Erwärmung im gesamten 21. Jahrhundert auf unter 2 ° C begrenzt, werden hitzebedingte HIs bei 1,5 ° C globaler Erwärmung um 17 Fälle (-1 bis 46) pro Jahrzehnt zunehmen. In einem Szenario mit hohen Emissionen steigen die hitzebedingten HI-Fälle bei Erwärmung um 1,5 ° C, 2 ° C bzw. 3 ° C pro Jahrzehnt um 32 (1 bis 83), 54 (1 bis 124) bzw. 109 (4 bis 313) an. Ähnliche Ergebnisse wurden unter einem gemäßigten Emissionsszenario gefunden, bei dem die Erwärmung nicht unter 2 ° C gehalten werden kann.

Fazit: Mit zunehmender globaler Erwärmung steigt die künftige Belastung durch hitzebedingte HI-Fälle in Augsburg. Die Erfüllung der Ziele des Pariser Übereinkommens wird daher zu erheblichen gesundheitlichen Vorteilen für HI-Patienten führen.

Heat-related myocardial infarctions under and beyond Paris Agreement goals in Augsburg, Germany

Kai Chen*, Susanne Breitner, Kathrin Wolf, Masna Rai, Christa Meisinger, Margit Heier, Bernhard Kuch, Annette Peters, and Alexandra Schneider, for the KORA Study Group

Affiliation:

Institute of Epidemiology, Helmholtz Zentrum München–German Research Center for Environmental Health: Dr. Chen, Dr. rer. nat. Breitner, Dr. rer. biol. hum. Wolf, Rai BSc, Dr. med. Heier, Prof. Dr. rer. biol. hum. Peters, and Dr. rer. biol. hum. Schneider

Institute for Medical Information Processing, Biometry and Epidemiology, Ludwig-Maximilians-Universität München: Dr. rer. nat. Breitner and Prof. Dr. rer. biol. hum. Peters

Ludwig-Maximilians-Universität München, Chair of Epidemiology at UNIKA-T: Prof. Dr. med. Meisinger

Independent Research Group Clinical Epidemiology, Helmholtz Zentrum München–German Research Center for Environmental Health: Prof. Dr. med. Meisinger

MONICA/KORA Myocardial Infarction Registry, University Hospital of Augsburg: Prof. Dr. med. Meisinger

KORA Study Centre, University Hospital of Augsburg: Dr. med. Heier

Department of Internal Medicine I - Cardiology, University Hospital of Augsburg: Prof. Dr. med. Kuch

Department of Internal Medicine/Cardiology, Hospital of Nördlingen: Prof. Dr. med. Kuch

German Research Center for Cardiovascular Research (DZHK), Partner-Site Munich: Prof. Dr. rer. biol. hum. Peters

The KORA-Study Group consists of A. Peters (speaker), H. Schulz, L. Schwettmann, R. Leidl, M. Heier, K. Strauch, and their co-workers, who are responsible for the design and conduct of the KORA studies.

*** Corresponding author.** Tel: +49 89 3187-3697, Fax: +49 89 3187-3380, Email: kai.chen@helmholtz-muenchen.de; kai.chen@yale.edu

Number of words in the main text: 2299 (excluding summary, references, legends, and acknowledgement)

Number of words in the summary: 195

Number of references: 28

Number of figures and tables: 4

Summary

Background: Substantial efforts will be undertaken to limit global warming to 1.5 °C or 2 °C (Paris Agreement goals). Here, we aimed to project future heat-related myocardial infarction (MI) events in Augsburg, Germany, at increases in warming of 1.5 °C, 2 °C and 3 °C.

Methods: Using daily time-series of MI cases and temperature projections under three climate scenarios, we projected changes in heat-related MIs at different increases in warming, assuming no future changes in population and adaptation.

Results: Under a low emission scenario that limits warming below 2 °C throughout the 21st century, heat-related MI cases will increase by 17 (-1 to 46) per decade at 1.5 °C of warming. Under a high emission scenario, heat-related MI cases will increase by 32 (1 to 83), 54 (1 to 124), and 109 (4 to 313) per decade in warming of 1.5 °C, 2 °C and 3 °C, respectively. Similar results were found under a moderate emission scenario that fails to hold warming below 2 °C.

Conclusion: The future burden of heat-related MIs in Augsburg will rise with any increase in warming. Fulfilling the Paris Agreement goals will lead to substantial health benefits for MI patients.

Keywords: Climate change, Paris Agreement, Heat, Myocardial infarction, Projection

Zusammenfassung

<u>Hintergrund:</u> Es werden erhebliche Anstrengungen unternommen, um die globale Erwärmung auf 1,5 ° C oder 2 ° C zu begrenzen (Ziele des Pariser Übereinkommens). Unsere Zielsetzung war, zukünftige hitzebedingte Herzinfarktereignisse (HI) in Augsburg in Bezug auf eine globale Erwärmung um 1,5 ° C, 2 ° C bzw. 3 ° C zu projizieren.

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Introduction

Climate change is the biggest global health threat and tackling it could be the greatest global health opportunity of the 21st century (1). To reduce the health risks of climate change, the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement in 2015, which aims at holding global warming to well below 2 °C above pre-industrial levels and pursuing efforts to limit it to 1.5 °C (2). However, little is known about the difference in health impacts between the 1.5 °C and 2 °C warming targets (3, 4). Although emerging evidence from regional, national, and global studies show a potential increase in temperature-related mortality under climate change (5-9), nearly all these studies focused on a certain future period but not on a specific warming target (3). Thus, it remains unclear whether limiting global warming to 1.5 °C instead of 2 °C will avoid temperature-related health impacts (3, 10).

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) provided a Special Report on the impacts of global warming of 1.5 °C (SR15) and concluded with a very high confidence that heat-related health impact will be greater at 2 °C than at 1.5 °C of global warming (11). However, most of the previous projection studies have been focusing on mortality rather than morbidity (12), leading to limited evidence of climate change impacts on heat-related morbidity. Our recent study found that heat exposure is a potential trigger of MI events (13). Plausible pathophysiological mechanism is shown in *Box 1*. Here, we aimed to project future heat-related myocardial infarction (MI) events in Augsburg, Germany, at warming of degrees consistent with the Paris Agreement goals (1.5 °C and 2 °C) and higher (3 °C). This information can help the health professionals and policy makers to better understand the potential health threat of climate change.

Methods

Study population

We collected data from the population-based Cooperative Health Research in the Region of Augsburg (KORA) MI registry. The study area includes the city of Augsburg and the two adjacent counties (Augsburg and Aichach-Friedberg). We used all recorded cases of MI and coronary deaths among residents aged 25 to 74 (about 400,000 inhabitants) from January 1, 2001, to December 31, 2014. We further analyzed subtypes of MI events including ST-segment elevation MI (STEMI) and non-ST segment elevation MI (NSTEMI) events. Details of this registry are given in the *eMethods*. This study was approved by the ethics committee of

Bavarian Chamber of Physicians and performed in accordance with the Declaration of Helsinki.

Temperature projections

We obtained daily mean temperatures during 2010-2099 from four global climate models under the Inter-Sectoral Impact Model Intercomparison Project Phase 2b (ISIMIP2b) (14). We used three climate change scenarios under the Representative Concentration Pathway (RCP) 2.6, RCP4.5, and RCP8.5, corresponding to low, moderate, and high warming and emission scenarios, respectively (*Box 2*). We applied the method described in Ebi et al. (2018) (3) to determine the period when 1.5 °C, 2 °C, and 3 °C of warming above pre-industrial levels will be reached, using the decade 2010-2019 as a baseline (*eMethods*).

Health impact assessment

We estimated the number and fraction of MI cases attributable to heat exposure under different degrees of warming based on the assumption of no future changes in population and adaptation, using a recently developed approach (15). Briefly, we applied the previously estimated exposure-response functions between daily mean temperature and daily MI events (*eFigure 1*) (13), the temperature projections, and baseline MI cases to calculate the daily attributable number of MI events. The baseline MI cases were calculated as the average observed number of cases for each day of the year during 2001-2014. Finally, we computed the future changes as the differences between the future decades reaching different degrees of warming and the baseline period for each RCP. We used Monte Carlo simulations to estimate empirical confidence interval (eCI) to address the uncertainty in exposure-response functions and the variability across global climate models. Key elements in the assessment are provided in eBox. Details of the health impact assessment can be found in the *eMethods*.

Results

Figure 1 shows the 10-year moving average global-mean-temperature projections from the average of four global climate models under three RCP scenarios relative to pre-industrial levels. Global-mean-temperature under RCP4.5 and RCP8.5 exceeds 3 °C relative to pre-industrial levels by the end of the 21st century, whereas it remains below 2 °C under RCP2.6. In general, warming of 1.5 °C and 2 °C will be reached around 2030 and 2040, respectively (*Table 1*). Warming of 3 °C will be reached around 2070 under RCP4.5, whereas under RCP8.5 it will be reached 20 years earlier.

Over 2001-2014, there were on average 967 coronary events per year, among which 235 were STEMI and 331 were NSTEMI. Relative to the baseline period, heat-related MIs will increase under all warming scenarios and all RCPs (*Table 2*). When meeting the Paris Agreement target of limiting warming to 1.5 °C, heat-related MI cases per decade in Augsburg will increase by 17 (95% eCI: -1 to 46), 28 (0 to 94), and 32 (1 to 83) under RCP2.6, RCP4.5, and RCP8.5, respectively. Compared to 1.5 °C of warming, 2 °C of warming generally yields larger increases in heat-related MIs, with a significant increase of 51 (3 to 108) for RCP4.5 and 54 (1 to 124) for RCP8.5. When beyond the Paris Agreement target at 3 °C of warming, heat-related MIs are projected to increase by 106 (3 to 287) for RCP4.5 and 109 (4 to 313) for RCP8.5, which correspond to about 1.1% increase in the heat-attributable burden of MI cases.

Figure 2 summarizes the changes in heat-related MIs under different warming scenarios for total and subtypes of MI. With regard to the change of attributable cases, total, STEMI, and NSTEMI events are generally projected to increase with increasing warming degrees. Most of the increased heat-related MIs are NSTEMI events, with the increase ranging from 12 (2 to 27) in 1.5 °C of warming under RCP2.6 to 70 (11 to 171) in 3 °C of warming.

Discussion

Our analyses show that any increase in global warming is projected to increase heat-related MIs in Augsburg, Germany. Holding warming at 1.5 °C instead of 2 °C or 3 °C will avoid a substantial number of heat-related MIs. Under RCP2.6, warming will be limited below 2 °C by 2100 and result in a smaller increase of heat-related MIs. On the contrary, warming by 2100 will be higher than 3 °C under RCP4.5 and RCP8.5, leading to a considerable increasing burden of MIs.

Very few studies have directly estimated the regional health impacts of stabilizing climate warming at 1.5 °C instead of 2 °C (3). Our finding of increasing heat-related impacts for warming at 2 °C than at 1.5 °C is consistent with the conclusion of the IPCC SR15 report (11) and the findings of two recent studies covering European cities (10, 16). We also found a large reduction in heat-related total MIs in Augsburg between 2 °C and 3 °C under both the moderate emission scenario RCP4.5 and the high emission scenario RCP8.5. This suggests that the emission reduction trajectories towards the Paris Agreement goals can avoid heat-related impacts on MI burden.

Among the climate scenarios, RCP2.6 meets the Paris Agreement target of keeping warming well below 2 °C (*Figure 1 and Table 1*), which is in line with a previous review (3). When limiting warming to 1.5 °C under RCP2.6, heat-related MIs are projected to account for 0.2%

(0% to 0.5%) of total MI burden. In comparison, heat-related MIs under RCP4.5 and RCP8.5 will be 2 times larger (0.5%-0.6%) under 2 °C of warming and 5 times larger (1.1%) under 3 °C of warming (*Table 2*). Similarly, a previous study also estimated a much smaller increase in heat-related mortality over the 21st century under RCP2.6 compared to RCP4.5 and RCP8.5 in central and southern European cities (5).

According to the Federal Statistical Office, 135,218 MI events occurred in patients aged between 25 and 74 in Germany in 2015 (including both acute MI patients and cardiac arrest deaths) (17). If our projected changes in attributable fractions in the Augsburg region could be applied to the whole of Germany, a back-of-envelope calculation shows that holding warming at 1.5 °C under RCP2.6 relative to a 3 °C of warming following the high emission pathway RCP8.5 would prevent 1,217 MI cases each year. This number is likely to be underestimated as we only considered patients aged below 75 whereas the elderly have been demonstrated to be more vulnerable to heat-related mortality and morbidity (18, 19). Our findings suggest that ambitious greenhouse gas emission reductions are required to achieve the Paris Agreement targets and to prevent adverse temperature-related health impacts.

Implications for healthcare professionals

Healthcare professionals have vital roles in accelerating progress to tackle climate change, as they are trained to educate patients about health threats, may be trusted more than environmentalists, and can better communicate the health risks posed by climate change and inform public policy to reduce greenhouse gases emissions (1, 20). With the ability to effectively advocate against the health threats of climate change, healthcare professionals should take a lead in fighting climate change (21). To encourage general practitioners and other health professionals to lead on tackling climate change, it is important to understand how climate change can impact health outcomes (22). This study suggests that any additional degrees of warming can result in increasing heat-related MI cases, calling on healthcare professionals to inform public and policymakers about potential health threats of climate change and benefits of taking climate actions to protect health.

Strengths and limitations

To the best of our knowledge, this is the first study projecting heat-related MIs under and beyond Paris Agreement goals. Our estimates are based on a validated, complete, and detailed registration of all MI and coronary death cases in Augsburg, in combination with an advanced and established approach to account for uncertainty in exposure-response functions and variability across climate models (5). Our estimates could be interpreted as the changes in heat-related MIs if the current Augsburg population were exposed to future temperatures under global warming of 1.5 °C, 2 °C and 3 °C. Thus, our projections allow isolation of the effects of a changing climate from other factors such as demographic change and population adaptation (5).

Our study has several limitations. First, our projections of the health impacts focus on specific Paris Agreement targets rather than consistent future periods. This approach used different periods for different warming targets (e.g., 2022-2031 for 1.5 °C and 2032-2041 for 2 °C under RCP8.5), which limits our ability to consider impacts of future population changes in size, age structure, lifestyle, and underlying MI rates. As we expect more NSTEMI events but less STEMI events occurring in the future in Augsburg (13), the future changes in total temperature-related MI burden may be underestimated. Moreover, the temperature projections we used have a relatively coarse spatial resolution (~ 50 km). Future studies using higher resolution temperature projections, such as the temperature projections from COSMO-CLM developed by Deutscher Wetterdienst, are warranted to estimate regional health impact of climate change. Furthermore, we did not consider population adaptation to heat (23). However, heat-related vulnerability may further increase in Augsburg (13), resulting in an increased future temperature-related impacts.

Conclusion

The burden of heat-related MIs in Augsburg will increase with any degree increase in global warming, with a smaller burden at 1.5 °C than at 2 °C or 3 °C. Compared with a high emission scenario, limiting global warming at 1.5 °C under a low emission scenario will lead to substantial health benefits for MI patients, suggesting that climate change mitigation policies are needed to fulfill the Paris Agreement goals.

Key messages

- Any increase in global warming will increase heat-related MIs.
- Compared to 2 °C of warming, 1.5 °C of warming reduces about half of all heat-related MIs.
- Under a high emission pathway, heat-related MIs at 3 °C will be 5 times larger than at 1.5 °C under a low emission pathway.
- Failing to meet the Paris Agreement goal will result in a substantial increase in heat-related MIs, especially for NSTEMI events.

Box 1. Potential pathophysiological link between heat exposure and myocardial infarction

Heat exposure may lead to the onset of myocardial infarction through 1) vasodilation and increased surface blood circulation, which may increase cardiac work load and result in hemoconcentration and thrombosis promotion, and 2) releasing interleukins that modulate local and systemic inflammation and result in endothelial dysfunction (24, 25). Potential mechanisms for the heat exposure effects on myocardial infarction are shown in Figure Box1.

Box 2. Climate change scenarios

The Intergovernmental Panel on Climate Change (IPCC) uses Representative Concentration Pathways (RCPs) to describe different 21st century trajectories of greenhouse gases emissions and atmospheric concentrations, air pollution emissions, and land use (26). The numbers in RCPs correspond to different target levels of radiative forcing in 2100. Radiative forcing reflects the effect of greenhouse gases and aerosols on the Earth's energy balance. Three RCPs were used in this study, including a stringent emission mitigation scenario (RCP2.6), one intermediate scenario (RCP4.5), and one scenario with very high greenhouse gases emissions (RCP8.5).

- RCP2.6 aims to limit global warming below 2 °C and requires substantial net negative emissions by 2100, with an average of about 2 Gt/year for CO_2 emissions (27).
- RCP4.5 is a scenario that stabilizes radiative forcing by 2100, with CO_2 emissions peak around 42 Gt/year in 2040 and decline to 2080 before leveling off around 15 Gt/year (28).
- RCP8.5 assumes no additional mitigation efforts to reduce emissions (or the so-called "Business-as-usual" scenario), with an average CO_2 emissions of 73 Gt/year over the 21st century (29).

Relative to 1986-2005, global mean sea level rise in 2081-2100 will likely be 0.40 m, 0.47 m, and 0.63 m under RCP2.6, RCP4.5, and RCP8.5, respectively.

Funding

KC acknowledges support from the Alexander von Humboldt Foundation for the Humboldt Research Fellowship. The KORA research platform was initiated and financed by the Helmholtz Zentrum München, German Research Center for Environmental Health, which is funded by the German Federal Ministry of Education, Science, Research, and Technology and by the State of Bavaria. Since 2000, the MI data collection has been co-financed by the German Federal Ministry of Health and Social Security to provide population-based MI morbidity data for the official German Health Report (see www.gbe-bund.de).

Conflict of interest statement

None.

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Figure Legends

Figure 1. Time-series of 10-year moving average of annual global mean near-surface temperature change relative to pre-industrial levels under different climate scenarios (RCPs). X-axis denotes the start year of a 10-year moving window.

Figure 2. Changes in heat-related MI cases per decade projected for 1.5 °C, 2 °C, and 3 °C of warming by MI types. Red and blue bars represent changes in the heat-related number of STEMI and NSTEMI events in future warming decades relative to 2010-2019 under three climate scenarios (RCP2.6, RCP4.5, and RCP8.5). Black dots and vertical lines denote changes and 95% empirical CIs in the heat-related total number of MI events.

Figure Box 1. Plausible pathophysiological mechanisms liking heat exposure to myocardial infarction.

eFigure 1. Overall lag-cumulative exposure-response functions between air temperature and myocardial infarction with 95% confidence intervals in Augsburg, Germany during 2001-2014. The exposure-response functions were obtained from Chen et al. (2019) (13). The red lines represent heat effect (temperature above 18.4 °C), whereas blue lines represent cold effect (temperature below 18.4 °C).

Funding

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Table 1. Decades when 1.5 °C, 2 °C, and 3 °C of global warming are projected to be reached.*

RCP	Decade 1.5 °C reached	Decade 2 °C reached	Decade 3 °C reached
RCP2.6	2026-2035	Not reached	Not reached
RCP4.5	2024-2033	2036-2045	2069-2078
RCP8.5	2022-2031	2032-2041	2047-2056

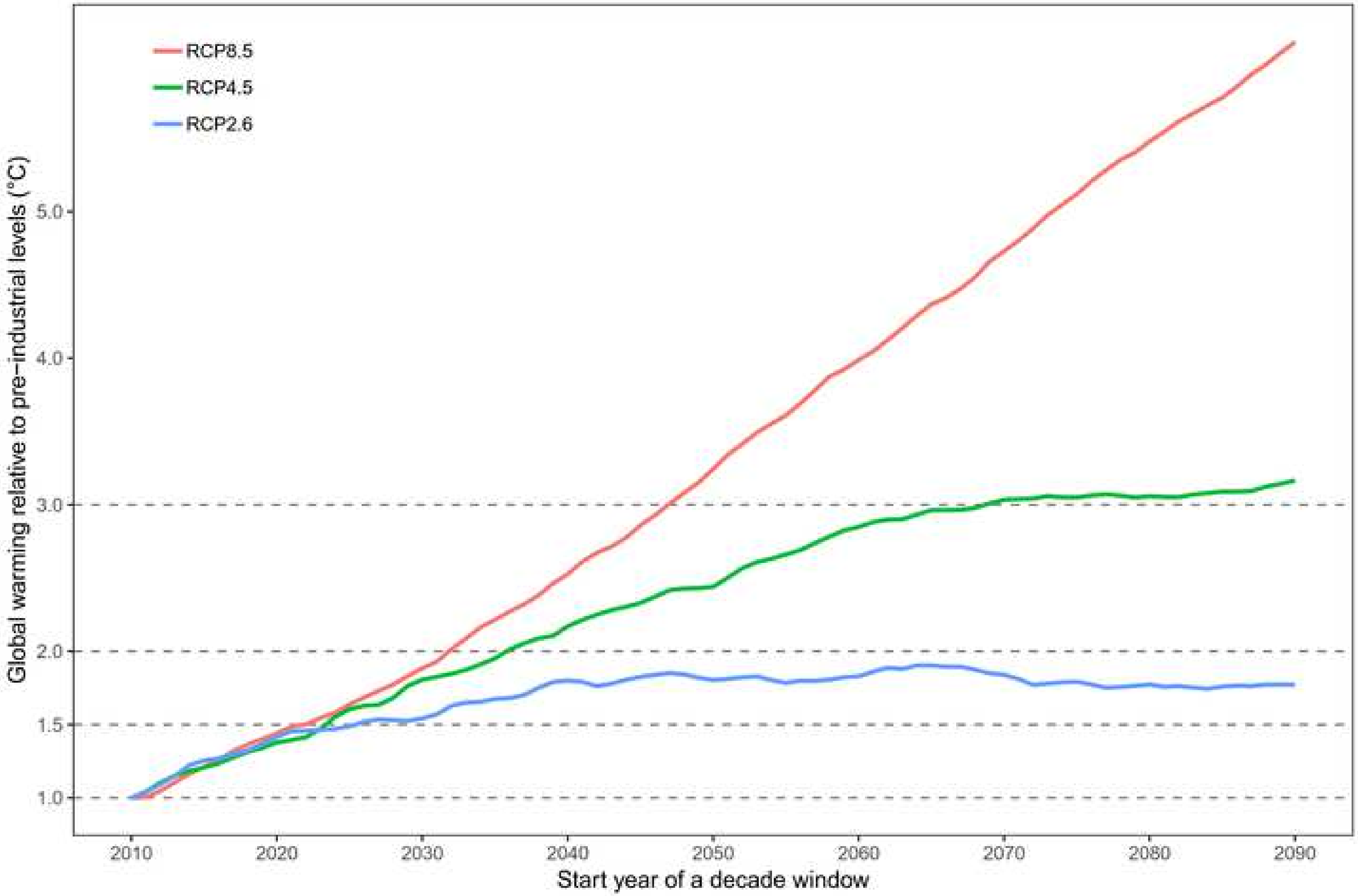
* Based on the average of 4 global climate models, i.e., GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5.

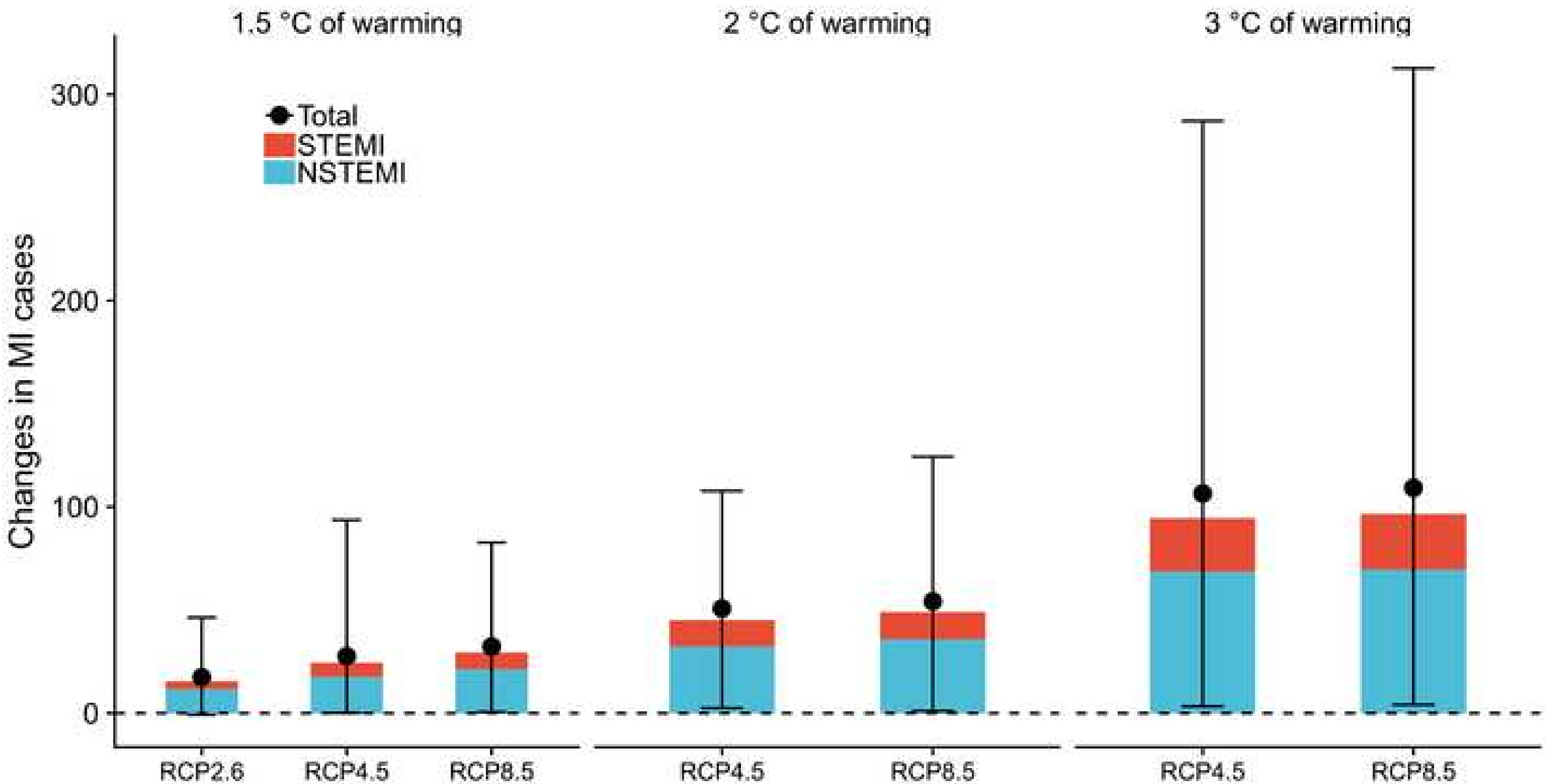
Table 2. Changes in attributable number and fraction (95% eCIs) of heat-related MI cases per decade in Augsburg under 1.5 °C, 2 °C, and 3 °C of global warming.*

Warming	RCP	Attributable number			Attributable fraction (%)		
		Total	STEMI	NSTEMI	Total	STEMI	NSTEMI
1.5 °C	RCP2.6	17 (-1, 46)	4 (-4, 15)	12 (2, 27)	0.2 (0, 0.5)	0.2 (-0.2, 0.6)	0.4 (0, 0.8)
	RCP4.5	28 (0, 94)	7 (-8, 29)	18 (1, 53)	0.3 (0, 1.0)	0.3 (-0.3, 1.2)	0.5 (0, 1.6)
	RCP8.5	32 (1, 83)	8 (-8, 25)	21 (4, 48)	0.3 (0, 0.9)	0.3 (-0.4, 1.1)	0.6 (0.1, 1.5)
2.0 °C	RCP2.6	-	-	-	-	-	-
	RCP4.5	51 (3, 108)	13 (-13, 35)	32 (7, 60)	0.5 (0, 1.1)	0.5 (-0.5, 1.5)	1 (0.2, 1.8)
	RCP8.5	54 (1, 124)	13 (-14, 39)	36 (7, 72)	0.6 (0, 1.3)	0.6 (-0.6, 1.7)	1.1 (0.2, 2.2)
3.0 °C	RCP2.6	-	-	-	-	-	-
	RCP4.5	106 (3, 287)	26 (-25, 89)	69 (14, 163)	1.1 (0, 3.0)	1.1 (-1.1, 3.8)	2.1 (0.4, 4.9)
	RCP8.5	109 (4, 313)	27 (-27, 97)	70 (11, 171)	1.1 (0, 3.2)	1.2 (-1.2, 4.1)	2.1 (0.3, 5.2)

* 95% eCIs were obtained by considering the uncertainty of concentration-response function using 5000 times of Monte Carlo simulations and four global climate models. The decades when 1.5 °C, 2.0 °C, and 3.0 °C of global warming are projected to be reached vary among RCPs, see Table 1.

Figure1


RCP8.5
RCP4.5
RCP2.6
Global warming relative to pre-industrial levels (°C)
5.0
4.0
3.0
2.0
1.5
1.0
2010
2020
2030
2040
2050
2060
2070
2080
2090
Start year of a decade window


1.5 °C of warming
2 °C of warming
3 °C of warming
Total
STEMI
NSTEMI
Changes in MI cases
300
200
100
0
RCP2.6
RCP4.5
RCP8.5
RCP4.5
RCP8.5
RCP4.5
RCP8.5

Figure_Box1

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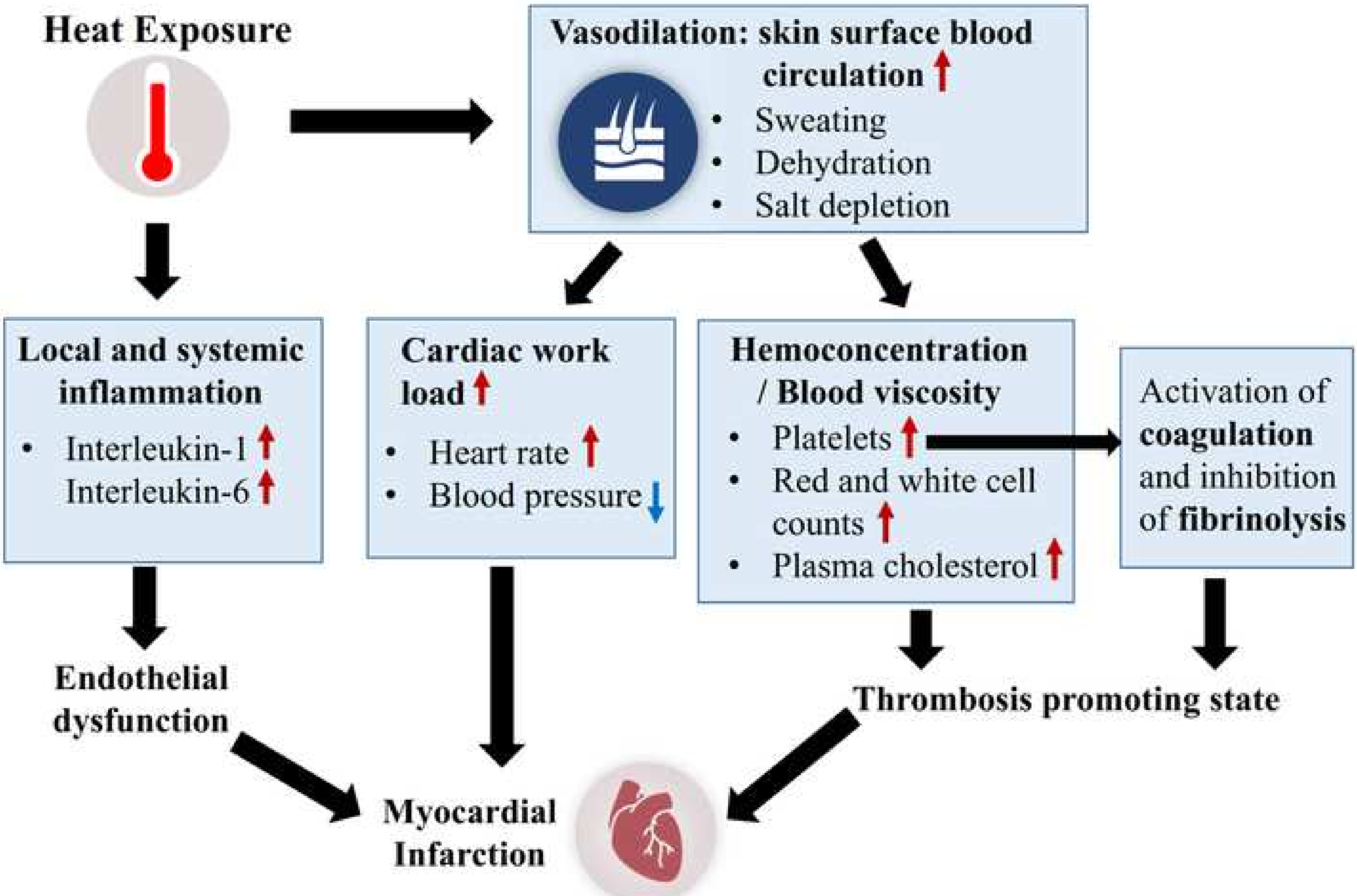

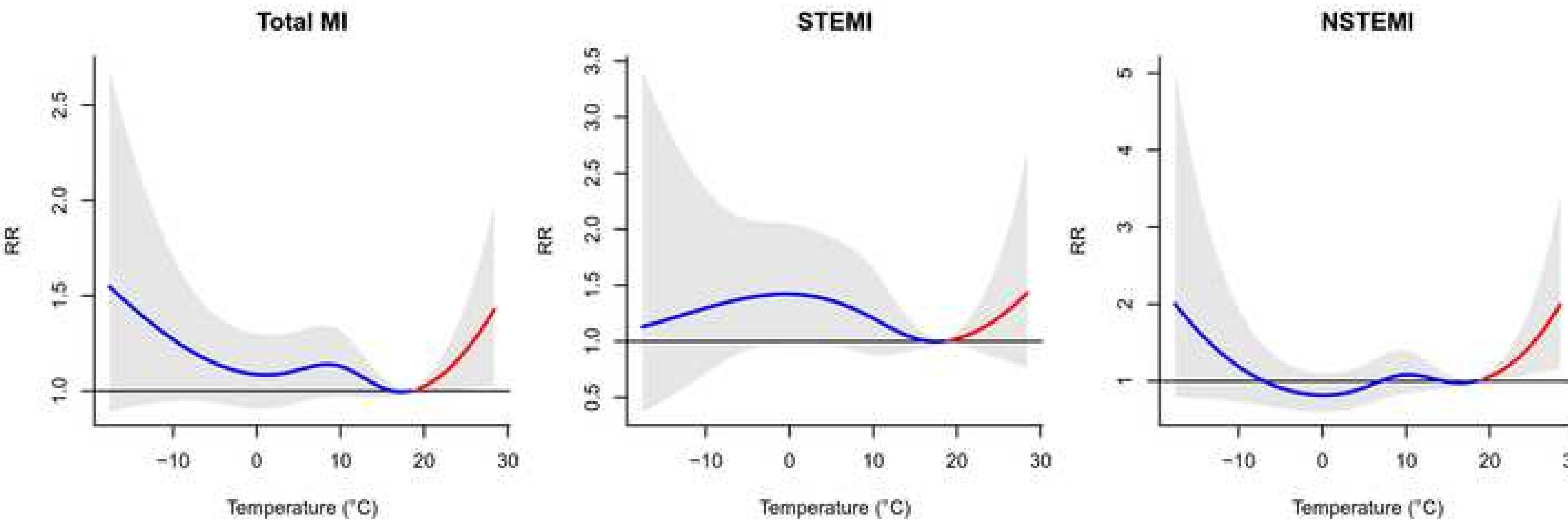
Total MI
STEMI
NSTEMI
RR
1.0
1.5
2.0
2.5
0.5
3.0
3.5
1
2
3
4
5
−10
0
10
20
30
Temperature (°C)

eBox: Key elements in the climate change impact assessment

- The expose-response curves were obtained from a previous research (3);
- We assume a constant population (size, age structure, and lifestyle);
- We assume a constant incidence for the total number and subtypes of MI;
- The temperature projections for the Augsburg region were obtained from 4 global climate models under 3 different climate change scenarios;
- Projection uncertainty source includes both the uncertainty of exposure-response curves and the variability across 4 climate models

eMethods

Study population

We collected data from the population-based Cooperative Health Research in the Region of Augsburg (KORA) MI registry. The Augsburg region includes the city of Augsburg (with an area of 147 km^2) and the two adjacent rural counties (1,854 km^2). The MONICA/KORA MI registry was founded in 1984 as part of the WHO MONICA (Monitoring Trends and Determinants in Cardiovascular Disease) project and since 1996 has been continued as part of the KORA research program. Since 1984, all cases of MI in eight hospitals in the study area and coronary deaths occurring among residents aged 25 to 74 years old (about 400,000 inhabitants) have been continuously registered in the MONICA/KORA MI registry. Following the MONICA protocol, MI patients who survived at least 24 hours after hospitalization are interviewed about the event, demographic information, co-morbidities, medication, and family history. If a patient survives the 28th day after hospital admission, the MI is identified as nonfatal, otherwise as fatal. Coronary deaths are fatal cases outside the hospital or within the 24-hour after admission to a hospital. All coronary deaths (ICD-9 codes: 410-414) were identified by checking all death certificates through the regional health departments and by information from the last treating physician and/or coroner.

In this study, we used all recorded cases of MI and coronary deaths among residents aged 25 to 74 from January 1, 2001, to December 31, 2014. We further analyzed subtypes of MI events including ST-segment elevation MI (STEMI) and non-ST segment elevation MI (NSTEMI) events. Bundle branch block was not included in this analysis due to its small sample size (38.6 cases/year). More details of this registry can be found elsewhere (1, 2).

Exposure-response functions and baseline MI

We applied estimates of the exposure-response functions (ERFs) between daily mean temperature and daily MI events from our previous work for the period 2001-2014 (3). Briefly, we conducted a time-stratified case-crossover study and used a distributed lag nonlinear model with a maximum lag of 10 days to estimate the ERFs. Temperature and MIs generally showed U-shaped associations, with significant increasing risks for heat [temperatures above the minimum MI temperature (MMIT, as the reference temperature, 18.4 °C)] but non-significant increasing risk for cold (temperatures below the MMIT) (*eFigure 1*). The baseline MI cases were calculated as the average observed number of cases for each day of the year during 2001-2014.

Temperature projections

We obtained daily mean temperature projections during 2010-2099 from the Inter-Sectoral Impact Model Intercomparison Project Phase 2b (ISIMIP2b) (4). We used three climate change scenarios under the Representative Concentration Pathway (RCP) 2.6, RCP4.5, and RCP8.5, corresponding to low, moderate, and high warming and emission scenarios, respectively. We obtained daily temperature simulations at a spatial resolution of 0.5° × 0.5° from all four global climate models (GCMs) included in ISIMIP2b (i.e., GFDL-ESM2M, HadGEM2-ES, IPSL-CM5-IL, and MIROC5). These temperature simulations have been bias-corrected based on the EWEMBI dataset (5). As applied in previous studies (6, 7), we obtained daily temperatures in the baseline and future periods by extracting the temperature projections in one grid cell that covers the geographical center of the Augsburg area.

To determine the period when 1.5 °C, 2 °C, and 3 °C of warming above pre-industrial levels will be reached, we applied the method described in Ebi et al. (2018) (8) in support of the IPCC Special Report on the impacts of global warming of 1.5 °C. We first defined the baseline period as the decade 2010-2019, as its center year 2015 is the first year reaching 1 °C above pre-industrial levels (defined as the average of 1850-1900) (8). We then created a series of 10-year moving average projection windows, starting from 2011-2020 with a one-year step. We thus selected decade windows for each RCP when the GCM-ensemble average of global mean near-surface air temperature reached 0.5 °C, 1 °C, and 2 °C above the 2010-2019 baseline.

Health impact assessment

We estimated the number and fraction of MI cases attributable to heat exposure in baseline and future periods under the assumption of no future changes in population and adaptation, using a recently developed approach (9). Briefly, we applied the previously estimated ERFs (3) and the modeled daily series of temperature and MI to calculate the daily attributable number of MI cases. We then calculated the total attributable number by summing the contributions from all the days of the series and calculated the attributable fraction as the ratio of the total attributable number to the total number of MI cases. Finally, we computed the future changes as the differences between the future periods and the baseline period for each GCM and each RCP.

We computed the GCM-ensemble average total attributable number and fractions of MI cases by combinations of RCPs and future periods corresponding to warmings of 1.5 °C, 2 °C and 3 °C. We used Monte Carlo simulations to estimate empirical confidence interval (eCI) to address the uncertainty in ERF and the variability across GCMs. We obtained eCI from the empirical distribution across 5,000 samples of random parameter sets describing the ERF in the distributed lag nonlinear model and four GCMs, as described in more detail elsewhere (6, 9). Briefly, we quantified the uncertainty in ERF by generating 5,000 samples through Monte Carlo simulations for the estimated coefficients in the distributed lag nonlinear model which estimated the ERF. We then generated results for each of the four GCMs. We obtained the 95% eCI, defined as the 2.5^{th} - 97.5^{th} percentiles of empirical distribution across ERF coefficients samples and GCMs. Thus, the 95% eCI account for both the ERF and GCM sources of uncertainty.

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