



Assessing the impact of climate change on future extreme temperature events in major South African cities

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Abstract

In this era of climate change, extreme weather events are expected to become more intense and frequent. This study analysed the long-term future climate data from the mean of five climate model intercomparison project phase 6 (CMIP6) global climate models (GCMs) to examine the impacts of climate change on extreme temperature in four major South African cities. The bias correction was successfully conducted using the CMhyd software program. The analysis of extreme temperatures was conducted using indices developed by the World Meteorological Organization's Expert Team on Sector-specific Climate Indices (ET-SCI) and calculated using the R-based Climpact2 software. All statistical metrics (mean, R^2 and RMSE) show that bias correction was fairly good, and further analysis and conclusions could also be drawn using the adjusted dataset. The overall result shows that annual trends of all temperature indices analysed in this study are significantly increasing for both scenarios (SSP2-4.5 and SSP5-8.5) except for some lower extreme temperature indices (i.e., number of cool days, cold nights and cold spells). In the historical time scale, however, some indices showed no trend for some stations. The study also found that coastal cities had a slower increase in higher extreme weather indices as compared to inland cities. However, for lower extreme indices (such as number of cool days, cold nights, cool day's temperature and cold spells), the opposite was true. This information is important for policymakers, development agents and disaster prevention workers to make informed decisions about adapting to and mitigating extreme weather events.

1 Introduction

Extreme climate or weather events can be defined as the occurrence of a climate or weather with greater or below than a certain threshold value (Seneviratne et al. 2012). These are usually related to extreme temperature and precipitation. Extreme temperature events are one of the major manifestations of climate change that are greatly influencing all life activities on Earth. More specifically, extreme temperatures affect many aspects of the socio-economic, ecological and environmental conditions including human well-being. Common types of extreme temperature events (ETEs)

include heatwaves, warm spells, cold waves and cold spells. According to the new IPCC report (Trisos et al. 2022), climate change has increased the probability of heat waves and drought on land surfaces across most African countries. These impacts are expected to double on marine ecosystems than the land surface. These events have disastrous impacts on human health and ecosystems, such as increased mortality, morbidity, stress, discomfort, reduced productivity, crop failure, livestock loss, fire risk, water scarcity and quality deterioration. Such weather events are becoming common in South Africa (Van der Walt and Fitchet 2022).

The impact assessment of climate change in South Africa has been studied relatively well in recent years. One of the key impacts of climate change in South Africa is the unprecedented extreme temperature. It is predicted that South Africa will experience more significant warming than the global average, and this could have severe consequences on the environment, economy and society (Engelbrecht et al. 2015; Trisos et al. 2022). Many studies (e.g., Muller et al. 2015; Colyn et al. 2018; Mbokodo et al. 2020; Woyessa and Wilson 2021; Bradshaw et al. 2022; Trisos et al. 2022) found that the increase of heatwaves, cold waves, droughts and

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floods in South Africa could have severe consequences on the economy, especially in the agricultural sector, which is a significant contributor to the country's GDP. A study conducted by the University of Pretoria found that the increase in temperature and the decrease in rainfall could lead to a decline in crop yields, especially in the maize-producing regions (Muller et al. 2015). Another study by Colyn et al. (2018) indicated that the increase in temperature could lead to a decline in plant and animal species, particularly in the fynbos biome, this will have severe consequences for biodiversity conservation and ecotourism. Although research on low temperature extremes is very scarce in South Africa, there is an indication that the impacts of cold waves will decrease with the changing climate (e.g., Grab and Simpson 2000; Van Der Walt and Fitchett 2021).

Temperature rise also affects every stage of the water cycle in several ways, putting pressure on water availability. For example, high temperature leads to greater evaporation rates and plant transpiration, which results in water loss in soil and plants. A Stanford study (Diffenbaugh et al. 2015) showed that drought conditions worsened when higher temperatures coincided with minimal precipitation during the California drought of 2011 to 2017. South Africa also experienced serious droughts in 2016 and 2017 which resulted in severe shortages of water supply in major cities around the country. A study in the central region of South Africa indicates that there will be a reduction of rainfall by about 14% by the mid-century (Woyessa and Wilson 2021). It is expected that the combined effect of reduced rainfall and increase in temperature will exacerbate the existing problem of water security in the region.

In addition to the environmental and economic impacts, climate change could also have severe consequences on society, especially in vulnerable communities. Cambell et al. (2018) and Chersich and Wright (2019) revealed that the health-related impacts of extreme weather and climate events are not studied well. This is particularly the worst in developing countries, including Africa, where societies are more susceptible to ETEs and less capable to coping mechanisms. Kapwata et al. (2022) and Trisos et al. (2022) indicated that the increase in temperature could lead to an increase in heat-related illnesses, especially in urban areas. This could have severe consequences for the health sector and could lead to increased healthcare costs.

In recent years, assessing the impact of future temperature increase under various climate change scenarios in South Africa has become a vital and active area of research. Extreme temperatures can have severe effects on the environment, economy and society, making it crucial to take measures to mitigate these impacts. Implementing policies and strategies to reduce greenhouse gas emissions and adapt to climate change can help minimise its negative effects. Therefore, it is essential to monitor and model extreme

temperature trends and impacts in vulnerable areas of South Africa and implement suitable strategies to address them. One of the most widely used methods is the use of global climate models (GCM) data as these data are quiet efficient to analyse historical and future variations with different spatial and temporal scales (Mahmood and Babel 2014; Das et al. 2018; Das and Umamahesh 2022). GCMs plays fundamental roles in improving the understanding of the climate systems, as well as its impact to the environment and the society as a whole (O'Neill et al. 2014; O'Neill et al. 2016). Particularly, the climate model intercomparison project phase 6 (CMIP6) provides multi-model climate projections with alternate scenarios (O'Neill et al. 2016). Many studies (e.g., Chen et al. 2020, 2021; Thorarinsdottir et al. 2020; Kamruzzaman et al. 2021) show that the performance of CMIP6 models generally have significant improvements than CMIP5 in the simulation of climate extremes as compared to the observed climates.

Generally, research related to extreme weather events, particularly temperature extremes, is very scarce in South Africa. The few available researches either focus on historical timescales or do not analyse temperature extremes thoroughly. Thus, the current study was designed to analyse the trends and intensities of heat and cold waves using extreme temperature indices in four major South African cities. Particularly, this study was conducted to analyse (1) the variability of temperature extremes during daytime, (2) extremes during the nighttime temperatures, and (3) variability of warm and cold spells for historical (1950–2014) and two CMIP6 climate change scenarios (2015–2100).

2 Material and methods

2.1 Description of the study area

This study is conducted in four major cities in South Africa, namely, Bloemfontein, Cape Town, Durban and Pretoria, which are major cities of Free State, Western Cape, Kwa-Zulu-Natal, and Gauteng provinces, respectively (as shown in Fig. 1). These are some of the highly populated cities in South Africa where the impacts of climate change are crucial for their sustainable development. Bloemfontein and Pretoria are located in the interior regions while Cape Town and Durban are located in the coastal areas of South Africa. The long-term (1981–2010) climate data and station information for data collected for bias correction for the four cities are given in Table 2.

2.2 Climate model data

The Coupled Model Inter-comparison Project Phase 6 (CMIP6) is the latest climate model output from the World

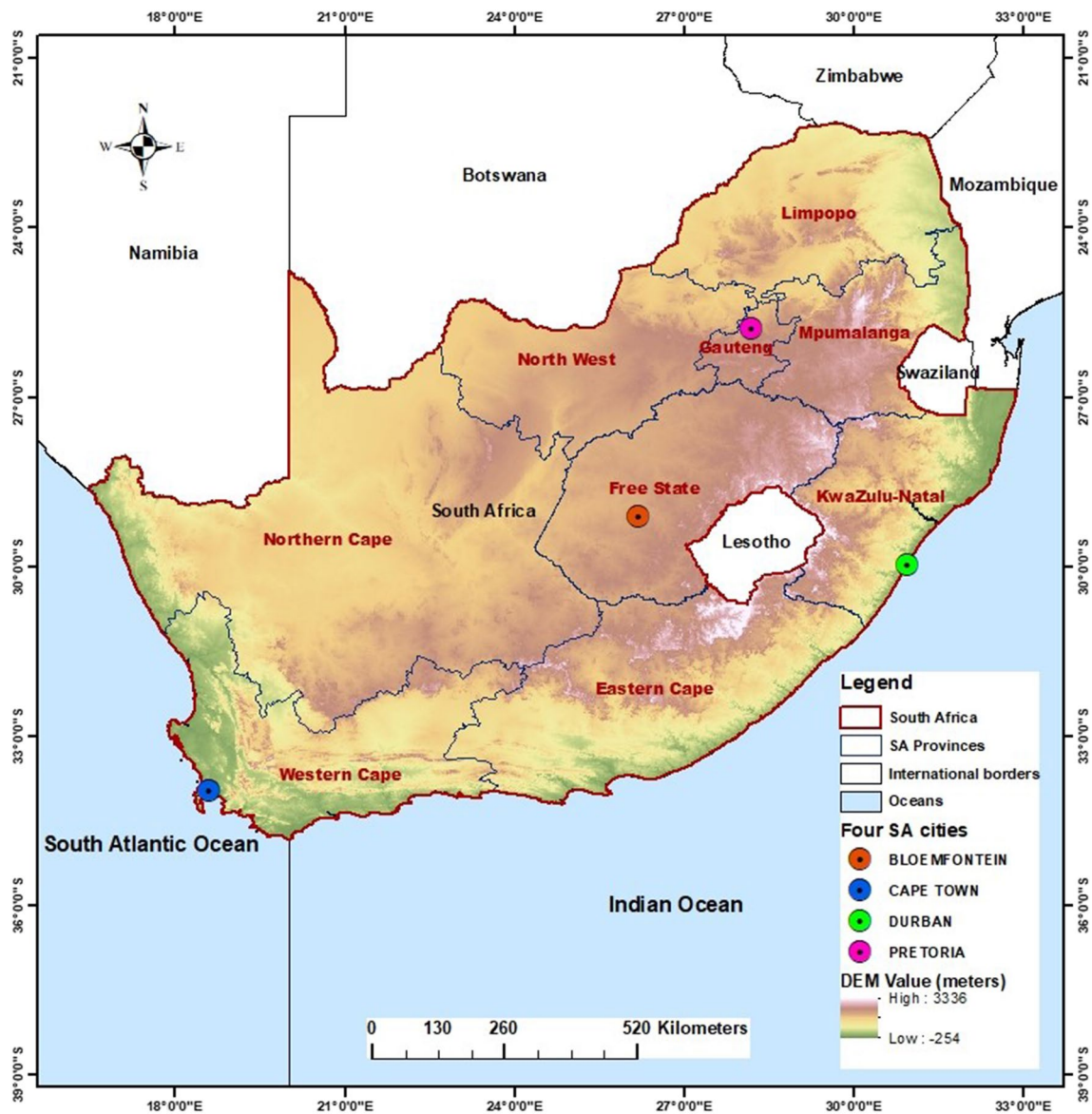


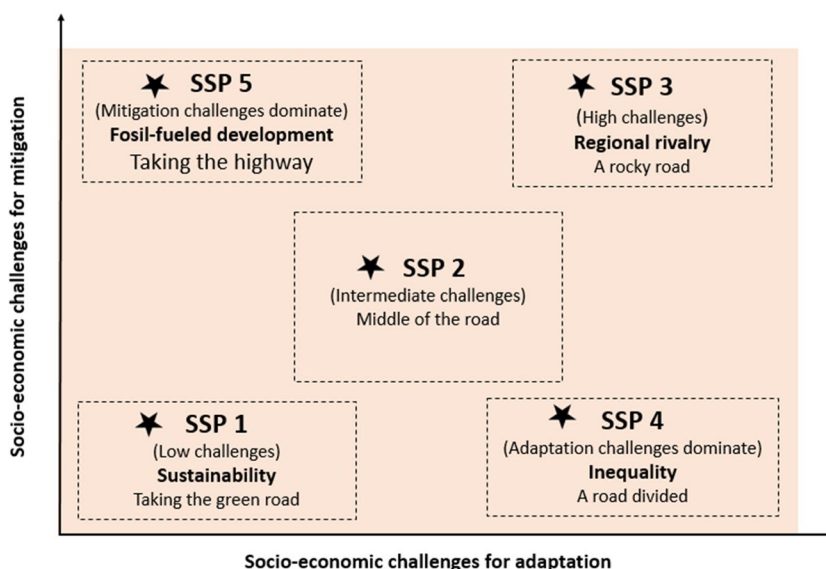
Fig. 1 Location of the study areas of four major cities, viz., Bloemfontein, Pretoria, Western Cape, and Durban in South Africa

Climate Research Program (WCRP). CMIP6 climate projections are developed with the incorporation of two major components, i.e., the level of climatic forcing and alternative trajectories of socio-economic pathways (SSPs) (van Vuuren and Carter 2014; O'Neill et al. 2016). The level of climate forcing is represented by the representative concentration pathways (RCPs) in the former Coupled Model Inter-comparison Project Phase 5 (CMIP5), whereas SSPs represent the future socio-economic trajectories in the new CMIP6 dataset. The SSPs in CMIP6 define the challenges of the socio-economic settings for adaptation and mitigation (Fig. 2). For example, SSP2 refers to the intermediate challenges for both adaptation and mitigation of climate change whereas SSP5 is when the mitigation challenge dominates.

The naming convention for the CMIP6 data is also derived from these two components. Naming starts with the position of the socio-economic trajectories (SSPs), and then, the level of climate forcing follows. Further description of the CMIP6 dataset is well explained in van Vuuren and Carter (2014), O'Neill et al. (2016), and the CMIP website (<https://wcrp-cmip.org/cmip-phase-6-cmip6/>).

The CMIP6 data is downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) data distribution centre, which is the Copernicus Climate Change Service (C3S), Climate Data Store (C3S 2022). Five GCMs (general circulation models; Table 1) of maximum and minimum air temperature with daily time-step were downloaded. The data includes historical (1950–2014) and future

Fig. 2 Shared socioeconomic pathways (SSPs) mapped in the challenges to mitigation vs adaptation space (modified after O'Neill et al. 2014)



projections (2015–2100) consisting of two scenarios, viz., SSP2-4.5 and SSP5-8.5.

2.3 Bias correction method

As the downloaded GCM data from ECMWF is not bias-corrected, bias correction was considered as one of the crucial tasks to improve the quality of the data. For this purpose, station data of Tmax and Tmin were collected

from meteorological stations (Table 2) found closer to the four cities. The CMhyd software program (Rathjens et al. 2016) was used to do the bias correction. The “distribution mapping” method was used to adjust the predicted climate data to minimise bias and better predict the presence of extreme temperature events in the four cities. The goodness of the bias correction was evaluated by the comparison of station data with the GCM (with similar time bounds) only. The statistical metrics used

Table 1 Description of the five Coupled Model Inter-comparison Project (CMIP6) GCMs used in this study

No	Model	Country	Running Institution
1	ACCESS-CM2	Australia	Commonwealth Scientific and Industrial Research Organization (CSIRO) and ARC-CSS (Australian Research Council Centre of Excellence for Climate System Science)
2	AWI-CM-1-1-MR	Germany	Alfred Wegener Institute
3	EC-Earth3-Veg-LR	Europe	EC-Earth consortium (30 institutes in Europe)
4	MIROC6	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, The University of Tokyo, National Institute for Environmental Studies and RIKEN Center for Computational Science
5	MIROC-ES2L	Japan	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies

Table 2 List of meteorological stations and their long-term climate (1981–2010) in the study area (the four cities)

Station	Lat	Long	Altitude	Long-term climate			Time period of data used for bias correction
				Tmax	Tmin	PRC	
Bloemfontein	−29.11	26.19	1422	26	7.8	569	1951–2012
Cape town	−33.97	18.61	45	22.2	11.7	456	1966–2018
Durban	−29.97	30.95	12	25.6	14.7	1021	1973–2018
Pretoria	−25.77	28.21	1443	25.6	10.3	687	1961–2018

(South African Weather Service (SAWS), 2022)

are also explained in Sect. 2.5 (Statistical analysis) of this study.

2.4 Extreme temperature assessment

The assessment of extreme temperatures (e.g., heat and cold waves) was analysed by using the indices developed by the World Meteorological Organization, Expert Team on Sector-specific Climate Indices (ET-SCI). As described in Alexander and Herold (2016), twelve indices were selected for this study (Table 3). The Climact2 software, which was developed by the ET-SCI team of experts, was used to check the quality of the data before the main analysis was conducted. The Climact2 software is an R-based statistical tool which is freely downloadable from the official ClimPACT2 Github website (<https://github.com/ARCCSS-extremes/climact2/>, accessed on January 7, 2023). The Climact2 software was also used to calculate trends of selected temperature indices (Table 3) relevant to this study. TX90P and TX10P represent hot days and cool days, respectively. Similarly, TN90P and TN10P indicate how warm or cool is the night, respectively, and so on. Description for the indices used in this study is given in Table 3.

2.5 Statistical analysis

The bias correction was conducted by CMhyd software using the “distribution mapping” method. After bias correction, the average dataset of the five GCMs was calculated. Hence, this study is based on the average value (an ensemble) of the five models after bias correction. In addition to the graphical presentation of the empirical cumulative distribution

function curves (ECDFs), t-tests, coefficient of determination (R^2), and the root mean square error (RMSE) were used to assess the bias-correction procedure. The trend of each index was plotted by using Stata software (StataCorp 2019). The significance of trends is also indicated (at $P \leq 0.05$).

3 Results

3.1 Bias correction metrics

The bias corrections of the CMIP6 dataset for the four selected cities were successfully implemented as shown in Fig. 3 by the empirical cumulative distribution function (ECDF). Visual observation of the graphs reveals that there is a fairly good fit between the observed and adjusted (bias-corrected) values in all four cities for both the time series mean monthly maximum and minimum temperatures. Tmin is significantly overestimated except in Durban where it is significantly underestimated. This is more pronounced to the lower end of Tmin values, as clearly indicated in Fig. 3, panel b. The dataset for Pretoria has improved significantly. Tmax’s bias correction is inconsistent with some parts being underestimated and others overestimated. For example, around 50% of the lower-end data for Bloemfontein is overestimated, while it is underestimated for Pretoria. Overall, Tmin’s bias correction is more significant than that of Tmax.

Table 4 also presents basic statistical performance indicators for the bias corrections of both maximum and minimum temperatures. The coefficient of determination (R^2) exceeded 0.75 for both maximum and minimum temperatures, whereas the root mean square error (RMSE) was below 3.19. The long-term mean values of adjusted Tmax and Tmin is also

Table 3 ET-SCI extreme temperature indices used in this study

Index	Definition	Units	Description
TX90P	Annual number of days when TX > 90th percentile	%	Annual number of hot days
TX10P	Annual number of days when TX < 10th percentile	%	Annual number of cool days
TN90P	Annual number of days when TN > 90th percentile	%	Annual number of warm nights
TN10P	Annual number of days when TN < 10th percentile	%	Annual number of cold nights
TXx	Annual maximum value of TX	°C	Annual daytime hottest temperature
TNx	Annual maximum value of TN	°C	Annual nighttime warmest temperature
TXn	Annual minimum value of TX	°C	Annual daytime coolest temperature
TNn	Annual minimum value of TN	°C	Annual nighttime coldest temperature
WSDI	Annual number of days with at least six consecutive days when TX > 90th percentile	days	Annual longest (6 consecutive days) hot spell
WSDI3	Annual number of days with at least three consecutive days when TX > 90th percentile	days	Annual longest (3 consecutive days) hot spell
CSDI	Annual number of days with at least six consecutive days when TN < 10th percentile	days	Annual longest (6 consecutive days) cold spell
CSDI3	Annual number of days with at least three consecutive days when TN < 10th percentile	days	Annual longest (3 consecutive days) cold spell

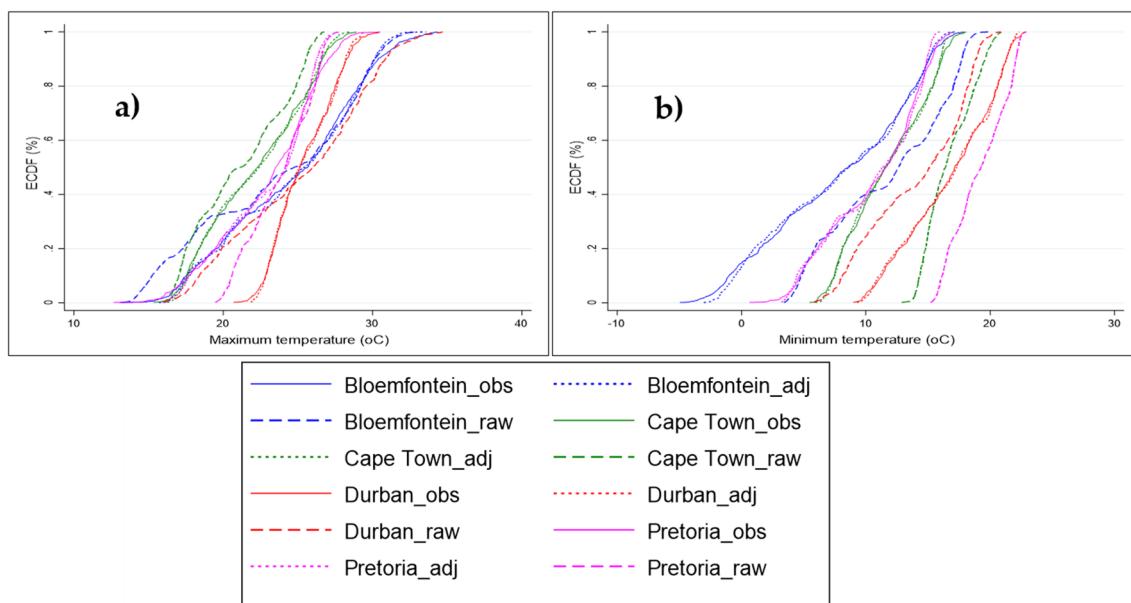


Fig. 3 Graphical representation of the empirical cumulative distribution function (ECDF) for station data, bias-corrected, and raw data for **a)** Tmax and **b)** Tmin

Table 4 Basic statistics for the evaluation of bias correction for monthly data of max and min temperature for the four cities

Parameters	Tmax			Tmin		
	Mean	R ²	RMSE	Mean	R ²	RMSE
BloemfonteinObs	24.6	-	-	7.88	-	-
BloemfonteinAdj	24.61	0.85	1.82	7.88	0.93	1.65
Bloemfontein_Raw	23.62	0.84	2.23	11.8	0.91	1.34
Cape Town_Obs	22.15	-	-	11.71	-	-
Cape Town_Adj	22.17	0.88	1.18	11.7	0.88	1.14
Cape Town_Raw	21.19	0.79	1.09	16.7	0.62	1.22
Durban_Obs	25.39	-	-	16.75	-	-
Durban_Adj	25.38	0.75	1.15	16.73	0.81	1.66
Durban_Raw	25.2	0.35	3.19	14.12	0.76	2.05
Pretoria_Obs	22.96	-	-	10.6	-	-
Pretoria_Adj	22.93	0.75	1.6	10.57	0.75	1.93
Pretoria_Raw	23.8	0.63	1.35	19.19	0.66	1.29

closer to the observed values. All these results indicate that the bias correction process is fairly good, and further analysis and conclusions could also be drawn using the adjusted dataset.

3.2 Extremes in daytime temperature

The extreme daytime temperature values which are evaluated by TX90P, TX10P, TXx, and TXn are shown in Fig. 4. The magnitude of the slopes of the linear trends of extreme temperature indices is also given in Table 5. The time series plots indicate that hot days are increasing significantly irrespective of locations and scenarios. Comparing the slopes

(Table 5), the trends of hot days will increase by an average of 1.7 and 2.9 times that of the historical for SSP2-4.5 and SSP5-8.5, respectively. Similarly, the trends of the annual daily hottest temperature (TXx) increased by 1.2- and 2.7-fold than that of the historical trends for SSP2-4.5 and SSP5-8.5, respectively. Generally, it is also indicated that the trends of TX90P and TXx are higher in inland cities (Bloemfontein and Pretoria) compared to the coastal cities (Cape Town and Durban).

The time series graphs indicate that cooler daytime temperatures (TXn) are rising significantly for both SSP2-4.5 and SSP5-8.5 scenarios compared to historical data, with the latter scenario showing a greater increase. The annual

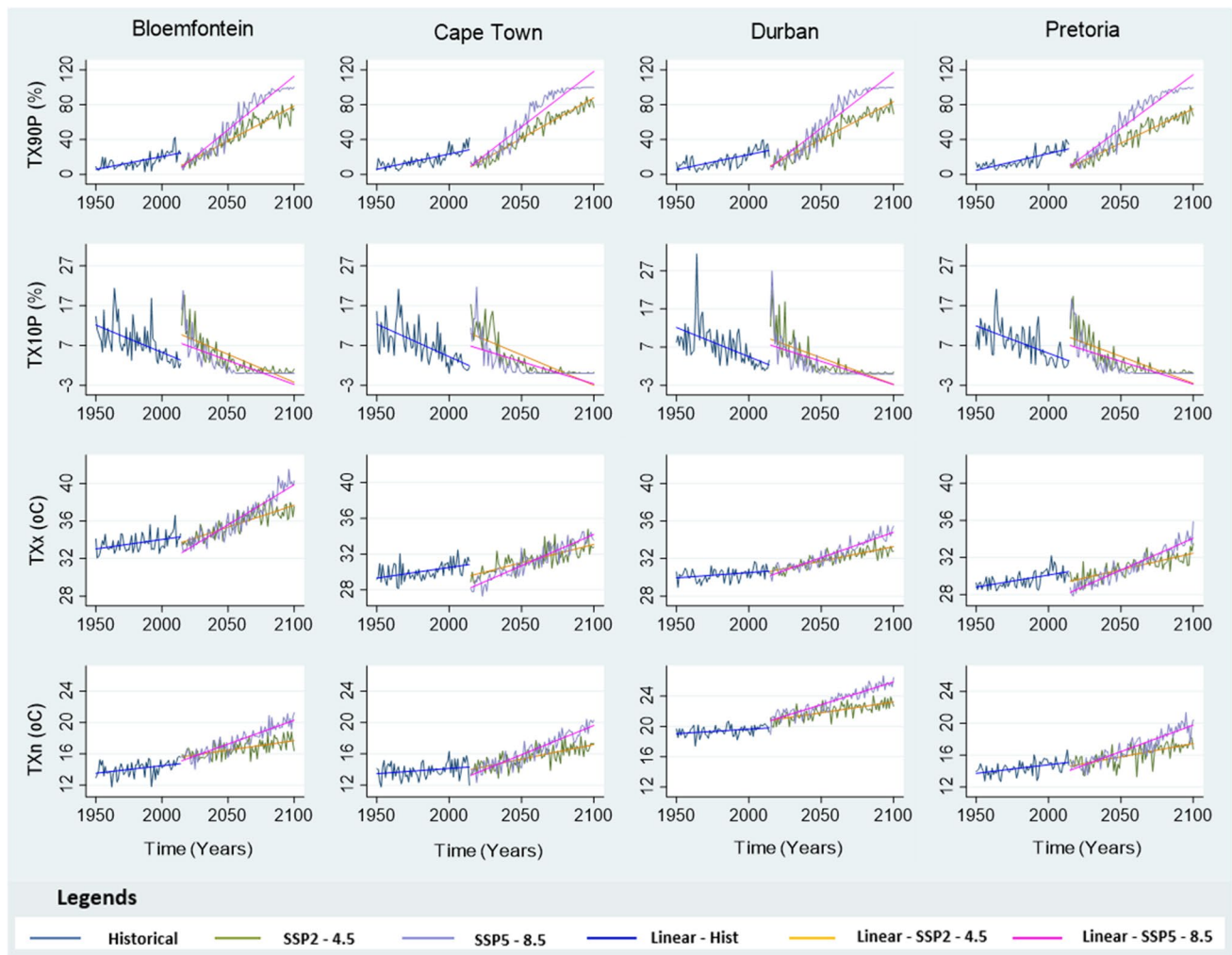


Fig. 4 Daytime extreme temperatures: Rows show indices and columns show the station names

number of cool days (TX10P) is decreasing significantly for all the historical, SSP2-4.5 and SSP5-8.5 scenarios. Coastal cities have a higher decreasing trend than the inland cities for TX10P. On average, coastal cities show 40 and 70% decreasing trend with respect to the historical, whereas, for inland cities, it was 23 and 58% for SSP2-4.5 and SSP5-8.5 scenarios, respectively. Similarly, the increase in slopes by coastal cities for TXn is almost doubles that of inland ones.

3.3 Extremes in nighttime temperature

Figure 5 shows the time series plots for nighttime temperature indices. Irrespective of location and climate scenarios, there is a general warming trend in the number of warm nights (TN90P), the warmest nighttime temperature (TNx) and the coldest nighttime temperature (TNn) on an annual scale. As indicated in Table 5, there are no significant trends in TNn and TNx in the historical time scale. However, for

the intermediate challenge (SSP2-4.5) and high emission scenarios (SSP5-8.5), TN90P increases at least 2.1 and 4.6 times more than the historical trends, respectively. The increase in TN90P trends is slightly higher in coastal cities compared to inland cities. For both climate change scenarios, the linear trends for TNn and TNx have at least doubled compared to the historical time.

In contrast, the annual number of cold nights (TN10P) has a significant decreasing trend for all locations, climate scenarios and time scales. Here, the trend (decreasing) by the intermediate challenge (SSP2-4.5) is greater than the high emission scenario (SSP5-8.5). Compared to historical times, the slopes in coastal cities are higher than those in inland cities.

3.4 Warm spells

All stations show significant increasing trends of warm spell duration for both 3 days (WSDI3) and 6 days (WSDI)

Table 5 The magnitude of the slope of linear trends for all the indices shown in Figs. 4–7

Station	TX90P			TX10P			TXx		
	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5
Bloemfontein	0.28	0.81	1.21	−0.13	−0.11	−0.06	0.02	0.05	0.08
Cape town	0.33	0.93	1.25	−0.16	−0.1	−0.04	0.03	0.04	0.07
Durban	0.37	0.86	1.25	−0.14	−0.08	−0.05	0.01*	0.03	0.05
Pretoria	0.29	0.79	1.2	−0.13	−0.09	−0.05	0.02	0.04	0.07
Station	TXn			TN90P			TN10P		
	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5
Bloemfontein	0.02	0.02	0.06	0.17	0.69	1.12	−0.08	−0.09	−0.08
Cape town	0.01*	0.04	0.08	0.16	0.64	1.15	−0.13	−0.13	−0.08
Durban	0.01*	0.03	0.06	0.24	0.62	1.14	−0.09	−0.1	−0.08
Pretoria	0.01*	0.03	0.07	0.22	0.51	1.08	−0.11	−0.1	−0.1
Station	TNn			TNx			WSDI3		
	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5
Bloemfontein	0.01*	0.03	0.07	0	0.02	0.04	0.83	3.18	4.89
Cape town	0.01*	0.03	0.06	0.01*	0.02	0.03	1.04	3.68	5.1
Durban	0.02	0.02	0.05	0	0.02	0.03	1.13	3.39	5.1
Pretoria	0.01*	0.02	0.04	0.01*	0.01*	0.03	0.96	3.01	4.96
Station	WSDI			CSDI3			CSDI		
	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5	Hist	SSP2-4.5	SSP5-8.5
Bloemfontein	0.25	2.78	5.22	0	0	−0.04	0	0	0
Cape town	0.41	3.47	5.4	−0.1	−0.05	0	0	0	0
Durban	0.48	3.14	5.46	−0.02	−0.07	0	0	0	0
Pretoria	0.27	2.39	5.22	−0.04	0	0	0	0	0

An asterisk sign (*) after a number indicates that the trend values are not statistically significant at $P < 0.05$

thresholds (Fig. 6; Table 5). The slopes of SSP5-8.5 are greater than that of SSP2-4.5 for both WSDI3 and WSDI for all stations. WSDI has a higher increasing trend than WSDI3 for all locations and scenarios. As a result, the slope of the trend for WSDI varies between 5 and 20 times, whereas WSDI3 is only 2 to 5 times the historical time-scale irrespective of location and scenarios. It can also be indicated that the trend of warm spell duration for coastal cities is slower than the inland cities, which is true for both scenarios and indices.

3.5 Cold spells

Although the time series plots in Fig. 7 show decreasing trends, the cold spell duration does not have a significant trend for most of its scenarios and locations. Specifically, CSDI does not have a significant trend irrespective of scenario and location. However, during its historical times, CSDI3 showed a significant decreasing trend except for Bloemfontein. In general, the few trends indicate that short-time cold spells (CSDI3) significantly decreased during the historical time-scale and

may continue to decrease significantly for some coastal cities like Durban and Cape Town for the intermediate challenge (SSP2-4.5). However, the trend lacks consistency for the high-emission scenario (SSP5-8.5).

4 Discussion

This study examines the impact of climate change on extreme temperature trends in four major South African cities. According to literature (for example, Seneviratne et al. 2012; Engelbrecht 2019; Trisos et al. 2022), both maximum and minimum temperatures are projected to rise rapidly. The findings of this study also reveal a consistent influence on extreme temperatures.

The results indicate that all cities are likely to experience a warmer climate in the future. This is true for both historical and climate change scenarios (SSP2-4.5 and SSP5-8.5), although the rate of change differs. Specifically, the rate of increase is higher in the high emission

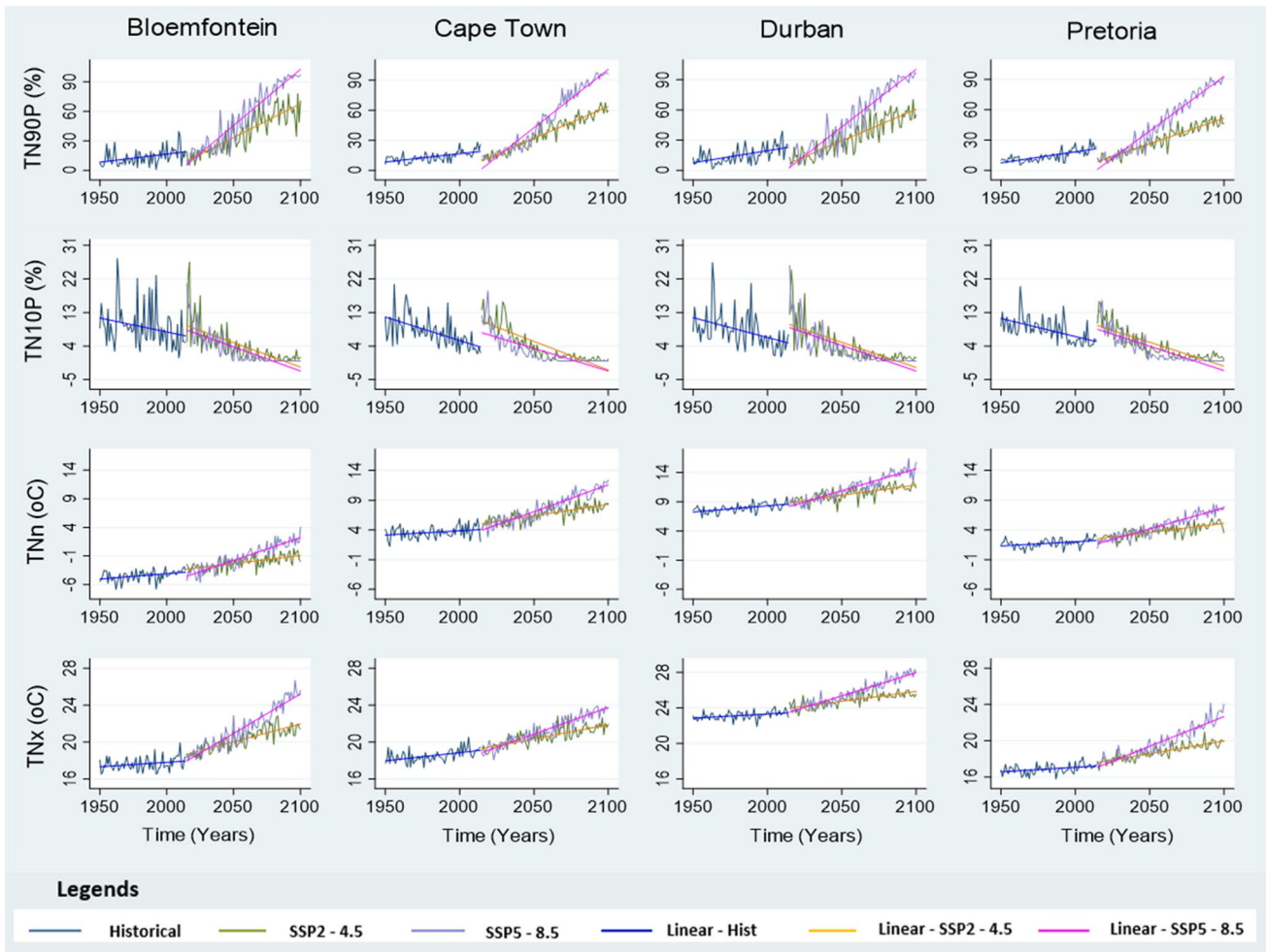


Fig. 5 Nighttime extreme temperature indices: rows show indices and columns show the station names

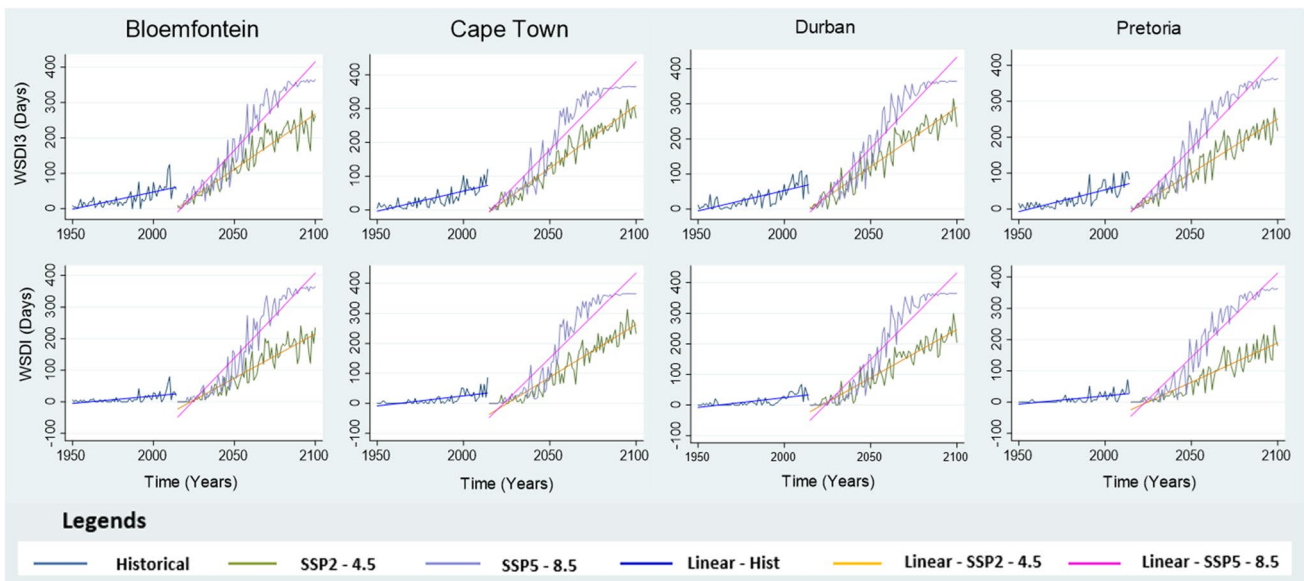


Fig. 6 Extreme temperature indices for warm spells: Rows show indices and columns show the station names

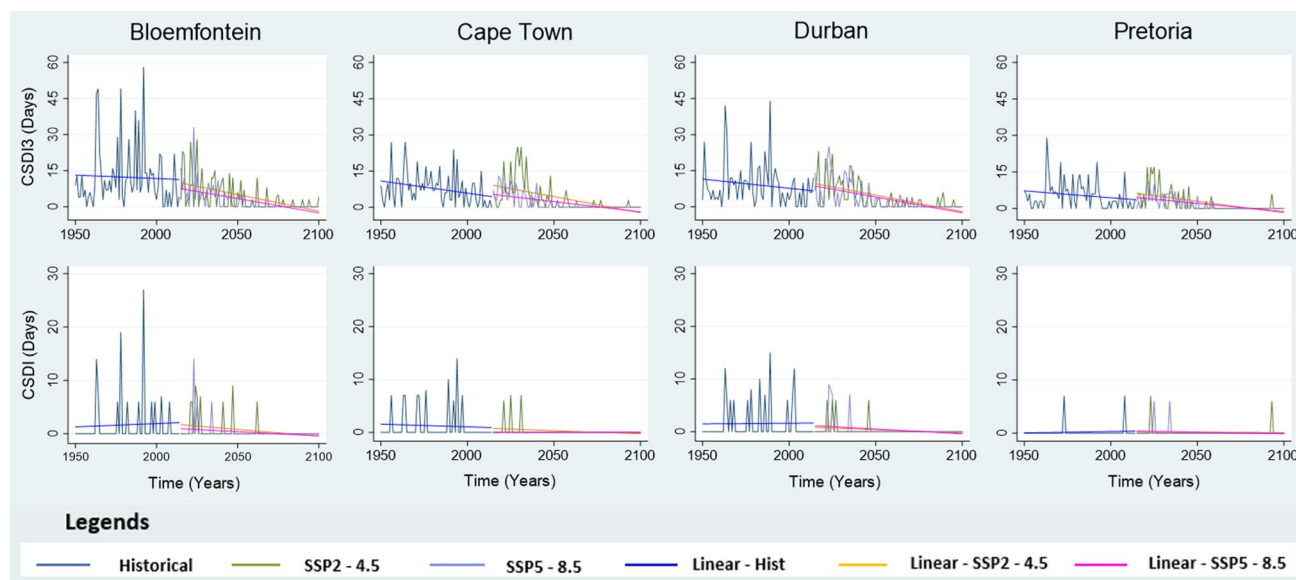


Fig. 7 Extreme temperature indices for cold spells: Rows show indices and columns show the station names

(SSP5-8.5) than in the intermediate challenge (SSP2-4.5). The findings further indicate that the impact of extreme low temperature in these cities is not a major concern as their trends are decreasing or diminishing. On the other hand, the likelihood of extreme high temperatures is increasing, as evidenced by an annual increase in the number of hot days, hottest day temperature and warm spells. The low risk of extreme low temperatures is also indicated by decreasing annual trends for the number of cold nights, temperature of coldest nights and cold spells. Similar results have been reported by Kruger et al. (2019), Engelbrecht (2019), Kapwata et al. (2022), Mbokodo et al. (2020) and Van der Walt and Fitchett (2021).

The other major result from this study is the comparison of inland versus coastal stations. It is clearly indicated that there is a significant difference between inland and coastal cities on the general trends of extreme temperature indices on a changing climate. Hence, the trends of the rising temperature indices (e.g. TX90P, TXx, WSDI) for coastal cities were lower (increasing trend) than the inland cities. Similar trends are reported by Van der Walt and Fitchett (2021). Alternatively, the general trends of lower extreme indices (such as TX10P, TN10P, TXn and CSDI3) for coastal cities was higher (decreasing trend) than the inland cities. In other words, the number of hot days and their temperature is decreasing, while the number of cold days is also decreasing, but their temperature is increasing in coastal than inland areas. This makes coastal areas to have milder and less variable air temperature (lower daily temperature ranges). This results are consistent with the reports of Hardin et al. (2018), Khan et al. (2021), and Kapwata et al. (2022).

The rise in extreme temperatures, such as hot days and nights, will have negative impacts on the socio-economic, environmental and well-being of society in general. According to Seckler and Amerasinghe (2000), South Africa is nearing a state of physical water scarcity. Even if rainfall remains constant, existing water stress will worsen and place more pressure on agricultural and municipal water supplies (Pereira 2017). Numerous studies (Seneviratne et al. 2012; Mbokodo et al. 2020; Scholes and Engelbrecht 2021; Trisos et al. 2022; Kapwata et al. 2022) have also found a significant correlation between human health and extreme temperatures, particularly heatwaves. Myers and Rother (2012) also indicated that the burden of climate-sensitive diseases is expected to increase in South Africa's hotter and drier climate. Additionally, the increase in heatwaves can also affect the general ecology by inducing other ecological hazards such as wildfires (Engelbrecht 2019; Mbokodo et al. 2020).

As it is well explained in the IPCC report (Trisos et al. 2022), the Southern African region is one of the hot-spots of the impacts of climate change. The report further explains that the occurrence of unprecedented extreme temperatures will be the major phenomena for the twenty-first century. Previous studies (Seneviratne et al. 2012; Lakhraj-Govender and Grab 2019; Trisos et al. 2022; Meque et al. 2022) indicate that climate variations, such as heat and cold waves, are the results of global, regional or local drivers. Some of these large-scale drivers of extreme weather events in the African region include the El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM) (Trisos et al. 2022; Meque et al. 2022). Other local variables such soil moisture (Wehrli

et al. 2019; Mbokodo et al. 2023) and vegetation condition (Hao et al. 2020) have also significant impacts on local temperature extremes. This region is particularly susceptible to the effects of climate change due to its geographical location and level of socio-economic development (Scholes and Engelbrecht 2021). However, the presence of milder and less variable temperature in the coastal than the inland stations could be due to the impacts of sea breeze from the nearby oceans in the coastal stations (Hardin et al. 2018; Khan et al. 2021; Kapwata et al. 2022). In addition to the overall rise in temperature caused by climate change, the El Niño Southern Oscillation (ENSO) is suggested as the major driver and primary cause of extreme temperature patterns in Southern Africa (Seneviratne et al. 2012; Lakhraj-Govender and Grab 2019; Brimicombe et al. 2021; Trisos et al. 2022; Meque et al. 2022).

5 Conclusion

This study assessed the impact of climate change on extreme temperature trends in four major South African cities using data from five GCMs. The results showed an increase in hot days, warm nights and warm spells and a decrease in the number of cold nights, cool days and cold spells for both climate change scenarios. Except for historical times, all four cities had similar trends (either increasing or decreasing) for both scenarios. However, coastal cities showed a lower rate of increase in trends for higher extreme indices (e.g., TX90P, TXx, WSDI) than inland cities. The reverse is true for lower extreme indices (such as TX10P, TN10P, TXn and CSDI3). Hence, policymakers, health and disaster prevention workers should focus on higher extreme temperature events than the lower extreme temperatures. Similarly, inland cities should also get more priority than the coastal ones during planning of the management of extreme weather events since coastal cities showed a lower daily temperature ranges than the inland ones. To respond to the effects of extreme climatic conditions, strong inter-sectoral collaboration between government, industry and community is required. Furthermore, multi-, inter- and trans-disciplinary research approach is required to address the multifaceted challenges that the society is facing and for effective adaptation and mitigation planning.

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Data availability The datasets generated during and/or analysed during the current study will be available on request.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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