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The use of bias-corrected climate model projections for bituminous binder selection for the construction of resilient asphalt roads

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The increased frequency of extreme weather events associated with climate change is a growing concern for road authorities, consultants, contractors and end users. Climate change adaptation is not yet incorporated into South Africa's transport design and planning. Current design methods for asphalt pavements include recently introduced performance-graded (PG) specifications for bitumen. Although the need exists to use future-projected temperature maps in the road industry, the hindrance to this adoption has been extracting the appropriate rising air temperatures from climate model projections. This study focuses on the integration of bias-adjusted historical and projected climate model temperature outputs between 1980 and 2060 to estimate changes in pavement temperatures throughout South Africa to inform a strategy for adaptive material selection. Differences in bitumen selection are observed for the PG 58 and PG 52 maximum temperature grade, and an introduction of PG 70 regions, as derived from climate model data in comparison with the SATS 3208 technical standard. The general trend is a gradual increase in maximum pavement design temperatures, mostly affecting the country's northern and central regions and corresponding road networks. This paper concludes that adjustments are required regarding climate projections for use in bituminous binder selection based on the current specification.

Keywords: climate change, temperature model projections, transport adaptation planning, bituminous binder selection, asphalt pavements

INTRODUCTION

Pavement design and material selection are critical aspects of road construction to ensure safety, durability, and cost-effectiveness. The use of performance-based approaches in pavement design is important in meeting performance-related criteria in service under various traffic loads and environmental conditions (Bredenhann *et al* 2019). Constructing roads that can endure real-world environmental conditions is imperative for South Africa, given the increase in frequency and intensity of extreme weather events. Previous research has shown the importance of understanding the impact of a changing climate on road infrastructure (Mokoena *et al* 2019). This study aims to bridge the gap in providing an implementable solution for selecting bitumen during pavement design.

Climate adaptation policies and programmes have been implemented at various levels of government in South Africa, such as through the National Climate Change Adaptations Strategy (Department of Environmental Affairs 2013 (DEA 2013)) and Climate Action Plans. To date, Climate Action Plans have been commissioned by certain municipalities, such as the City of Tshwane (CoT 2021) and the City of Johannesburg (CoJ 2021). The CoT Action Plan specifically includes the revision of design criteria that incorporate climate change-related risks. Although awareness on climate action has increased in the country, climate adaptation has not yet

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been mainstreamed within road planning, design, and construction documents. This will require specific mandates, such as the revision of technical standards and guidelines, to assist road authorities and engineers to implement adaptation plans for roads. Adaptation actions are diverse and do not always have to be a costly exercise, depending on the climate impact being managed (DoT n.d.). This study aims to contribute to the development of resilient roads through bituminous binder selection considering climate model projected increases in ambient temperatures.

Failing to adapt road systems to a changing climate can result in significant financial consequences. Schweikert *et al* (2015) performed a study aimed at quantifying the consequences of not adapting roads to a changing climate due to global warming. They found that the cost of climate change impact on South Africa's national roads will vary between US$116.8 million (R2.1 billion) and US$228.7 million (R4.2 billion) annually in the 2050 decade if a reactive approach is taken. Proactive policies and actions can mitigate this by 25%, as demonstrated by Schweikert *et al* (2015), who emphasised upgrading road infrastructure in areas where climate impacts are expected to surpass current design and maintenance standards.

Recent developments in South Africa have led to the adoption of a performance-graded (PG) specification based on pavement performance principles (Bredenhann *et al* 2019). By correctly specifying the appropriate binder for a given climate, asphalt pavement failures caused by poor bituminous binder selection can be reduced (O'Connell 2012). The PG specification addresses three different ways that asphalt layers can fail, namely: (i) permanent deformation at high service temperatures, (ii) fatigue cracking at intermediate service temperatures, and (iii) brittle fracture at low service temperatures (O'Connell 2012). The selection of bitumen to achieve a given *in-situ* performance within the asphalt layer is influenced by the temperature and traffic conditions in use, as well as the ageing effects of bituminous binders. Given the financial consequences of reactive climate adaptation and reduced reliability of asphalt pavements designed using historical information, this paper intends to introduce a proactive strategy towards adapting bitumen selection standards for asphalt mixes against the impacts of increasing temperatures.

BACKGROUND

In the strategy of adopting bitumen standards for asphalt mixes, this background provides insight into selecting bitumen based on expected in-service temperatures considering the expected climate in South Africa, the associated distresses, and the cost-effective need to align with climate change projections.

Performance-graded specifications for bitumen in South Africa were implemented in 2019 to characterise bitumen used in asphalt mixes. The move from empirical specifications was based on fundamental engineering properties to provide more accurate predictions of *in-situ* asphalt performance (SABS 2021 – for SATS 3208) where the selection of binders is based on: (i) traffic volumes and speed, (ii) climate (maximum and minimum temperatures), and (iii) binder durability. Given the variable nature of climate, the current specification is based on pavement temperatures at approximately 98% statistical reliability using climatic data from a minimum of 20 years (Bredenhann *et al* 2019).

Denneman *et al* (2007) and O'Connell (2012) have highlighted the importance of road temperatures for use in determining the required performance properties of asphalt and bituminous layers in road pavements.

Mokoena *et al* (2019) investigated the impact of increased air temperatures on minimum and maximum pavement temperatures in South Africa due to global warming under one Representative Concentration Pathway 8.5 (RCP8.5) low-mitigation scenario. The study showed that the effects of climate change will affect the binder selection process. In some areas, pavement temperatures showed an increase of up to 7°C between 1980 and 2060. However, a single model projection presented only one of the realisations of how the climate system would evolve under the scenario and therefore does not depict the uncertainty that comes with climate model projections which should also be considered for climate resilient pavement designs. Mokoena *et al* (2021) highlighted the need to consider weather station, satellite, and bias-corrected model outputs in the development of climate resilient pavement designs for the continent, given the challenge of incomplete temperature data often found from weather stations.

This paper focuses on the temperature criteria as a follow-on investigation done by Mokoena *et al* (2019) and Mokoena *et al* (2021). The aim is to provide a best-practice methodology of incorporating climate change in pavement engineering design methods.

South Africa has seen an increase in heatwave frequency and duration over the past few decades. Mbokodo *et al* (2020) investigated historical temperature records from 1960 to 2015 and found that the frequency of heatwaves has increased by 30% over this period, while the duration of heatwaves has increased by 50%. Furthermore, climate simulations have shown that heatwaves in South Africa are expected to occur more frequently and intensely in the future due to climate change. The duration of the heatwaves is also expected to last longer than current-day heatwaves, particularly in the country's interior, during summer. They also found that areas that are not usually prone to heatwaves will begin to experience the phenomenon in future warmer climates. Designing roads that can withstand the impacts of rising air temperatures can offer climate resilience through appropriate material selection as a possible adaptation strategy.

Several studies have shown that current pavement design methodologies are not always adequate in providing resilient infrastructure, because they assume stable climate conditions which is not valid given the unpredictability of weather patterns resulting from climate change, as well as the increased frequency and severity of extreme weather events (Meagher *et al* 2012; Qioa *et al* 2019; Haslett *et al* 2021). Viola and Celauro (2015) highlighted the need for better-performing materials with the expected rise in air and pavement temperatures. A significant shift across Italy was observed, by one performance grade, towards higher design temperatures attributed to climate change, as well as the introduction of new bitumen grades that were not required for prior periods. This would potentially require binder modification which would have financial implications to the production of the required bitumen and therefore the final cost of the asphalt produced (Viola & Celauro 2015). Fletcher *et al* (2016), Delgadillo *et al* (2018) and Mokoena *et al* (2019) have also demonstrated a change in PG requirements using climate models for Canada, Chile, and South Africa, respectively.

Miao *et al* (2022) and Schuster *et al* (2022) found similar changes in PG temperature spatial distributions for China and Brazil, respectively, through statistical analysis of meteorological data from weather stations in each country. Miao *et al* (2022) revealed that there has been an approximate increase of 21% in the permanent deformation of asphalt pavement from

1992 to 2019. They also showed an approximate decrease by 21% in low-temperature cracking between 1970 and 1997, and has remained almost unchanged since then. Schuster *et al* (2022) evaluated meteorological data for two intervals, namely: (i) 1961 to 1990 and (ii) 1991 to 2020, and observed an increase in performance grade for 14.9% of weather stations. They also concluded that considering a stationary climate can lead to inappropriate binder selection.

Qiao *et al* (2019) conducted a comprehensive Life-Cycle Cost Analysis (LCCA) to determine the economic benefits of upgrading asphalt binders as a climate-adaptive solution. They found that pavements with an upgrade in binder for areas more susceptible to increased temperatures showed better performance. A reduction in the International Roughness Index (IRI) by 1–5% was demonstrated, as well as a 4–14% reduction in rutting. Gudipudi *et al* (2017) also found an increase in fatigue cracking by 2–9% and rutting by 9–40% from a case study in the United States after 20 years, due to the impacts of climate change through mechanistic empirical design simulations. Less maintenance needs and longer service life were also reported for these pavements.

Climate change, and particularly the increase in magnitude and frequency of temperature extremes, can therefore lead to significant challenges for pavement service life, with rutting being the distress most prone to occur (Gudipudi *et al* 2017; Dawson 2014). In turn, the consequences of rutting can be reduced riding quality, water drainage challenges, increase in wear and tear, surface deterioration, and higher maintenance costs.

Almeida and Picado-Santos (2022) proposed two main strategies to adapt roads to climate change challenges. The first focuses on the use of future climate prediction models, while the latter considers various pavement modifications that can assist in reducing a pavement system's vulnerability against high and low temperature risks. Almeida and Picado-Santos (2022) suggest a change in bitumen grade to accommodate future temperatures, but not much guidance is available on by how much to increase or decrease the grade. Although the adverse effects of rising air temperatures on pavements are widely acknowledged, there is limited research to inform the development of practical approaches for selecting materials. Some recommendations to mitigate the impacts of high temperatures include cool pavements, increasing the aggregate skeleton, as well as increasing the asphalt layer thickness. However, some of these strategies may not be feasible for South African conditions, given local constraints on the availability of materials and maintenance practices.

To support engineers and road authorities in providing climate resilient roads, appropriate measures and methods need to be developed and provided because climate information is not easily transferable to pavement design for decision-makers. Some road agencies around the world have taken different approaches to address the issue of incorporating future climate data, and typically focus on incorporating risk and vulnerability assessments into their road infrastructure planning processes. The World Road Association developed an International Climate Change Adaptation Framework (Toplis 2015) which provides information for international road authorities to develop localised frameworks and includes a phase for the development and selection of adaptation strategies based on identified climate risks. On the design of resilient pavements, some road authorities have taken the approach to amend existing systems and guidelines for pavement design and practice as a key intervention to ensure improved resilience of new and upgraded roads (Petkovic *et al* 2019). Similarly, South Africa needs to develop strategies that include locally appropriate guideline documents, and technical standards and systems for the design of resilient pavements.

Considering the effects of climate change on air and pavement temperatures, it is imperative to devise a tailored strategy for South Africa that incorporates projections of extreme pavement temperatures for future conditions. This strategy should inform the design process and the selection of bitumen specifications (Mokoena *et al* 2021). This paper explores an appropriate locally applicable approach to material selection, focusing on the change in specifying bitumen as an adaptative design strategy against global warming by using bias-corrected climate model information to develop future pavement temperature projections.

METHODOLOGY

A series of climate models were used to project daily air temperatures. South African domain extracts of bias-corrected daily climate data covering maximum and minimum temperatures at a horizontal resolution of 0.5 × 0.5° (unit = gridded degrees) were obtained from the Inter-Sectoral Impact Model Intercomparison Project Phase 3b (ISIMIP 3b) (Eyring *et al* 2016) for the historical periods 1980–2000 and 2001–2020, the ongoing period 2021–2040 and the future period 2041–2060. The ISIMIP 3b historical and future projection experiments were available for the pre-industrial (piControl, covering at least 500 years), historical (1850–2014) and the projections (2015–2100) for three Shared Socioeconomic Pathways (SSPs). These include SSP5-8.5 representing a world development scenario predominantly fuelled by fossil (posing high mitigation challenge), SSP3-7.0 representing a world with a development option characterised by rivalry (leading to high challenges to both mitigation and adaptation), and SSP1-2.5 representing a world development scenario favouring sustainability (resulting in low challenges to mitigation and adaptation). Climate model simulation outputs were available for five primary models satisfying ISIMIP 3b simulation protocol (GFDL-ESM4, IPSL-CM6A-LR, MR1-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL) – please see the End Note on page 32 of this paper. According to the ISIMIP protocol, primary models are chosen according to the process representation, structural independence, climate sensitivity, and performance in the historical period, as well as the impact modelling spatial input needs for sectors such as fisheries and marine ecosystems (Lange 2019; Lange 2021). The ISIMIP 3b bias-correction method consists of a trend-preserving method applied at the spatial resolution of the data, and a statistical downscaling method which is applied to increase the spatial resolution of the climate model outputs to match that of the forcing observation data (Lange 2019).

This study differs from the one conducted by Mokoena *et al* (2019) in that it utilises nine climate models to create an ensemble, whereas the previous study employed a single CCAM as a preliminary assessment to enhance the comprehension of the potential risks and impacts of air temperature elevation on performance-graded bitumen selection. A climate model ensemble refers to a collection of selected climate models (ensemble members) used in the analysis to obtain more representative projections instead of relying on the projections from a single climate model. Moreover, the previous analysis was carried out under the low-mitigation RCP 8.5 scenario, as one of the scenarios recommended by the Intergovernmental Panel on

Climate Change (IPCC) Fifth Assessment Reports. The current study utilises the SSP5-8.5 scenario by the IPCC's Sixth Assessment Report (AR6) as the latest low-mitigation scenario, and thereby considers a broader range of greenhouse gas (GHG), land-use and air pollutant futures compared to AR5 (IPCC 2021). In this study, the SSP5-8.5 scenario is representative of the upper bound of future temperatures. The use of this scenario allows an evaluation of the possible climate impacts when the climate system has not responded to global mitigation efforts. The scenario is likely to paint a close-to-realistic picture for the short-term (2020–2040), subject to the uncertainty in the inertia of the climate system in response to current mitigation efforts.

Due to the underestimated maximum air temperatures produced during the preliminary study conducted by Mokoena *et al* (2019), a climate model ensemble consisting of nine members was employed for this study to establish the uncertainty associated with the use of climate models.

An improvement in the bias correction was also used for this study which removes systematic errors through adjustment of the daily variability around the monthly mean values methods (Haerter *et al* 2011; Lange 2021). Through the method, daily variability of the temperature data is simply adjusted to reproduce the variability of the observed data. This resulted in reduced errors for the maximum temperature simulations when compared to measured air temperatures.

Subsequently, the minimum and maximum temperature datasets for the 10th, 50th and 90th ensemble percentile over a 20-year climatological period were converted to pavement temperatures, at a 97.5% confidence level, using the Council for Scientific and Industrial Research's (CSIR) ThermalPADS software which is based on the empirically derived Viljoen equations (Viljoen 2001). A similar approach was followed by Mokoena *et al* (2019) where pavement temperature data was processed with ArcGIS software using the Kriging interpolation technique. However, the climate data for this study was produced at a lower spatial resolution of approximately 55 km due to the extensive climate dataset to produce the nine-model climate ensemble.

Three intervals were analysed for this study and included the following:

i. Baseline period from 1980 to 2000 (Period A)
ii. Near-future period from 2020 to 2040 (Period B)
iii. Future period from 2040 to 2060 (Period C).

The baseline period is based on the historical datasets, thus representing a 'stagnant climate'. Intervals (ii) and (iii) assist in understanding future climate impacts and road pavement needs as per projected temperature trends.

RESULTS

Air temperature validation

An important initial step in using climate model data is validating their outputs with observed datasets to ensure the accuracy, reliability, and applicability of the models for decision-making purposes. For this study, validation was performed by comparing the 97.5th percentile value of air temperatures from each climate model at sixteen reference weather stations in South Africa for the baseline period from 1980 to 2000. The median error for each model is shown in Table 1 for maximum and minimum air temperatures, respectively. The error (difference) between climate model projections and weather station observations is shown in Table 1. Positive values indicate where the specific climate model underestimates temperatures, and conversely a negative value represents an overestimation of weather station air temperature values.

The climate model data showed good agreement with the weather station data where, in general, less discrepancy was obtained for maximum air temperatures than for minimum air temperatures. The median error between the weather station and climate model data was calculated as –0.52°C and –2.2°C for the 97.5th percentile seven-day maximum and one-day minimum temperature, respectively, across all nine ensemble members. When considering the maximum air temperature between 1980 and 2000, the climate model that best simulates both maximum and minimum air temperatures is the CANESM5 model.

Pavement temperature validation

Following the air temperature validation procedure, pavement temperatures were then calculated at the same reference points to determine the median error between weather-station-determined pavement temperatures and climate-model-derived pavement temperatures. The error between the two datasets for each climate model is reported in Table 2 for each model.

The median error for maximum temperatures was calculated as 0.37°C, while for minimum temperatures the median error was 1.02°C. Given that the difference between two performance grades is 6°C, the calculated error is minor, thus providing a basis for using the climate model ensemble to project future pavement temperatures depending on the climate scenario that is considered.

Table 1 Climate model median error for 97.5th percentile seven-day maximum air temperature and minimum air temperature

Ensemble member	Maximum air temperature error* (°C)	Minimum air temperature error* (°C)
CANESM5	0.01	0.14
CNRM	–0.52	–3.30
EC-EARTH3	–1.08	–2.16
GFDL-ESM4	0.22	-1.33
IPSL-CM6A	–0.86	–2.64
MPI-ESM1	–0.32	–2.35
MRI-ESM2	–1.06	–2.32
UKESM1	–0.82	–1.93
MIROC6	–0.45	–2.20
Median	**–0.52**	**–2.20**

*(weather station temperature) – (climate model temperature)

Climate model ensemble analysis

Given the relatively low errors, the climate model ensemble was subsequently used to determine its suitability for material selection procedures. This evaluation was based on calculated pavement temperatures computed at 10th, 50th and 90th percentiles of the climate model ensemble. Generally, the climate model ensemble is used to identify a lower boundary for the maximum

Table 2 Climate model-derived pavement temperature error

Ensemble member	Maximum pavement temperature error* (°C)	Minimum pavement temperature error* (°C)
CANESM5	0.05	–0.12
CNRM	0.35	2.94
EC-EARTH3	0.67	1.92
GFDL-ESM4	–0.25	–0.12
IPSL-CM6A	0.73	–3.25
MPI-ESM1	0.34	2.09
MRI-ESM2	0.41	2.07
UKESM1	0.64	1.72
MIROC6	0.37	1.96
Median	**0.37**	**1.02**

*(climate model temperature) – (weather station temperature)

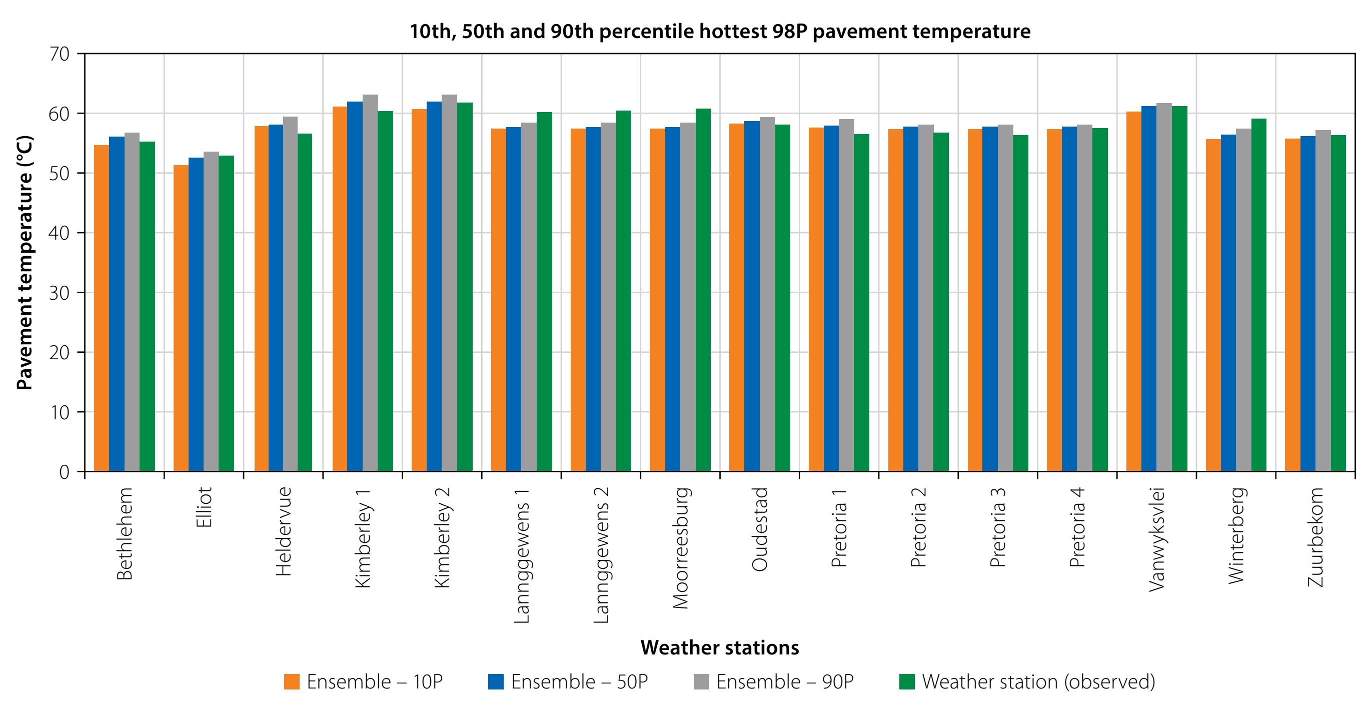


Figure 1 97.5th percentile seven-day maximum pavement temperatures from weather station data and climate model ensemble data

range of uncertainty in climate projections (Stainforth *et al* 2007). Therefore, this factor takes into consideration the diversity among the climate models utilised in the ensemble.

The resulting maximum and minimum pavement temperatures, as per the Viljoen (2001) algorithms, are presented in Figures 1 and 2, respectively, in comparison to calculated pavement temperatures from weather station data. The mean errors between climate-model-derived and weather-station-derived maximum and minimum pavement temperatures at the different percentiles are shown in Tables 3 and 4 on page 22.

The maximum pavement temperatures computed at the 50th percentile had the lowest associated error when compared to pavement temperatures calculated from historical weather station data (see Table 3).

A general agreement in trend was observed for the calculated seven-day maximum pavement temperatures as shown in Figure 1, where on average the model ensemble median was determined as the most comparable to the weather station data with an average error of 0.15°C. Given that calculated pavement temperatures using the Viljoen algorithms (Viljoen 2001) carry their own error between 1.72°C and –2.05°C depending on the location (Denneman *et al* 2007), a 90th percentile consideration may also be warranted as the conservative approach. Due to the overestimation of minimum air temperatures from the climate models, the minimum pavement temperatures calculated at the 10th percentile

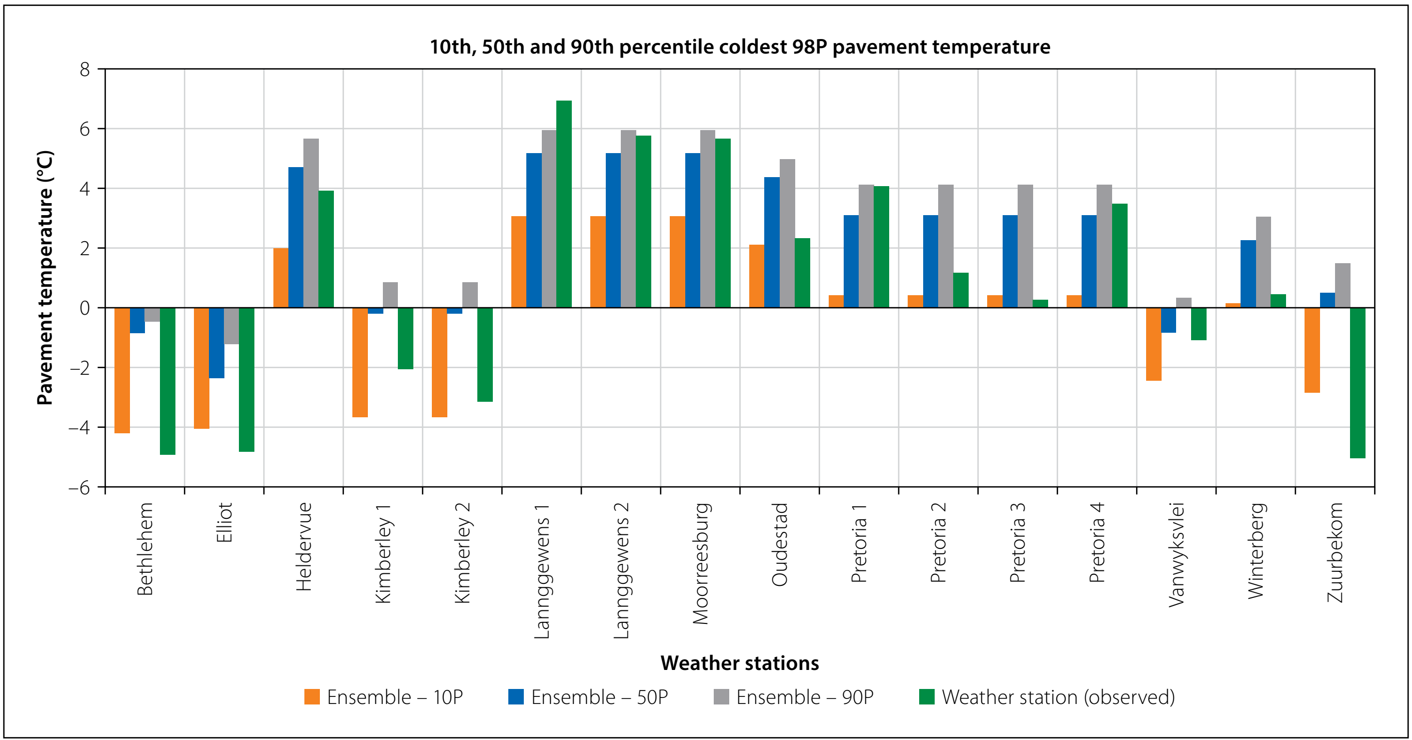


Figure 2 97.5th percentile minimum pavement temperatures from weather station data and climate model ensemble data

Table 3 Errors (°C) related to maximum pavement temperatures determined at different percentiles

Weather station	10P*	50P*	90P*
Bethlehem	–0.57	0.88	1.51
Elliot	–1.58	–0.31	0.70
Heldervue	1.27	1.51	2.84
Kimberley 1	0.77	1.67	2.78
Kimberley 2	–1.13	0.19	1.30
Langgewens 1	–2.76	–2.54	–1.73
Langgewens 2	–3.04	–2.82	–2.01
Moorreesburg	–3.32	–3.10	–2.29
Oudestad	0.17	0.58	1.30
Pretoria 1	1.11	1.50	2.53
Pretoria 2	0.60	1.02	1.31
Pretoria 3	1.05	1.47	1.76
Pretoria 4	–0.08	0.34	0.63
Vanwyksvlei	–0.93	0.02	0.51
Winterberg	–3.43	–2.76	–1.71
Zuurbekom	–0.54	–0.10	0.90
Average	**–0.77**	**–0.15**	**0.64**

*(climate model temperature) – (weather station temperature)

Table 4 Errors (°C) related to minimum pavement temperatures determined at different percentiles

Weather station	10P*	50P*	90P*
Bethlehem	0.72	4.06	4.45
Elliot	0.77	2.46	3.60
Heldervue	–1.92	0.80	1.75
Kimberley 1	–1.61	1.85	2.90
Kimberley 2	–0.52	2.94	3.99
Langgewens 1	–3.86	–1.75	–0.99
Langgewens 2	–2.69	–0.58	0.18
Moorreesburg	–2.59	–0.48	0.28
Oudestad	–0.23	2.04	2.64
Pretoria 1	–3.65	–0.97	0.05
Pretoria 2	–0.75	1.93	2.95
Pretoria 3	0.15	2.83	3.85
Pretoria 4	–3.06	–0.38	0.64
Vanwyksvlei	–1.36	0.25	1.40
Winterberg	–0.31	1.80	2.60
Zuurbekom	2.20	5.53	6.52
Average	**–1.17**	**1.40**	**2.30**

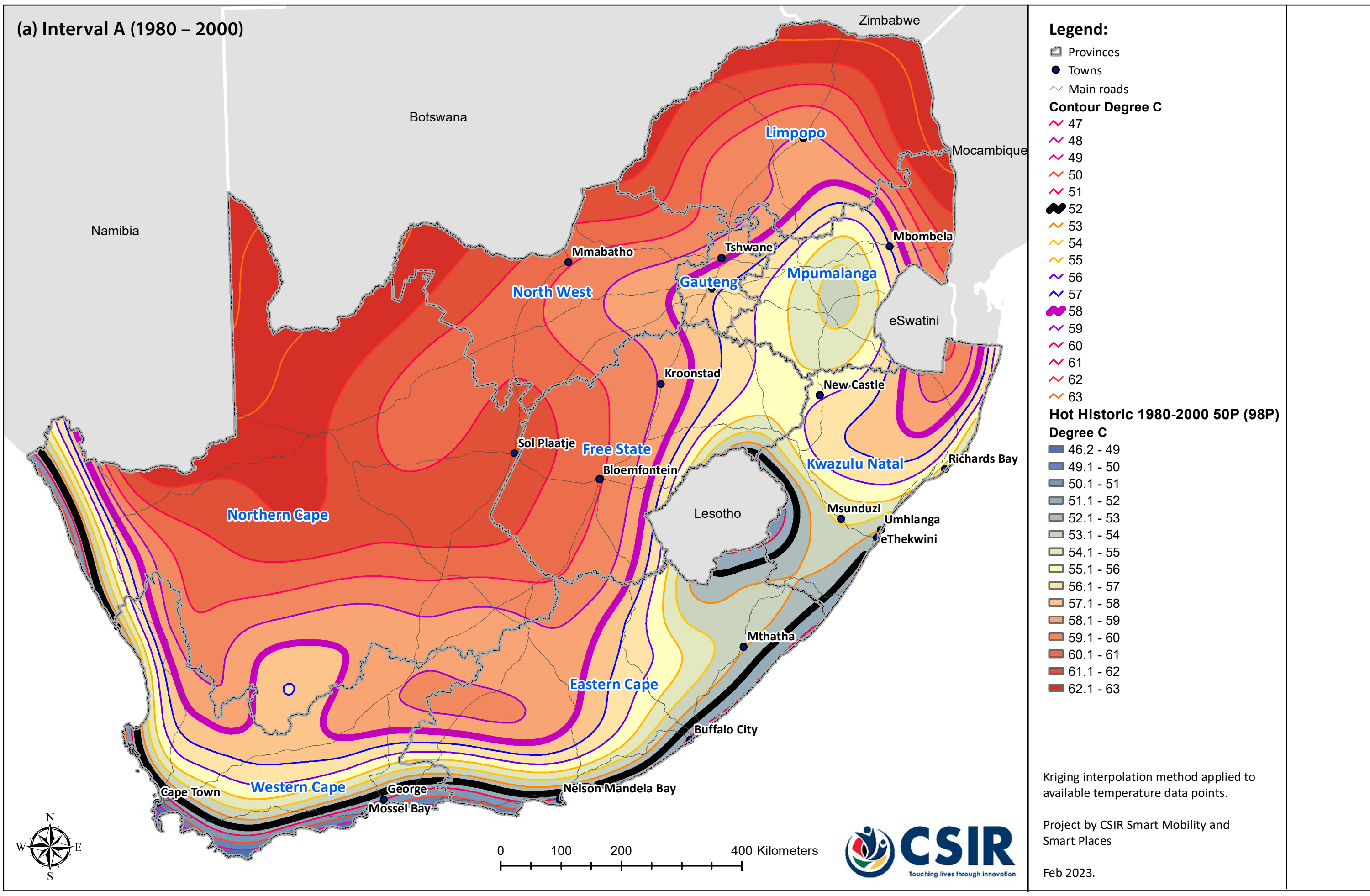
*(climate model temperature) – (weather station temperature)

provided the closest estimations. It is important to note that while these climate projections provide the closest estimates to weather station data, they still provide less conservative pavement temperatures for resilient design considering future climates, particularly where the climate projections provide an underestimation of pavement temperatures represented by negative values.

Climate change influence on PG selection

For South African conditions, the PG selection is typically governed by maximum pavement temperature conditions with an 80°C difference in temperature grade, which is the prescribed difference between the maximum and minimum pavement temperature (SABS 2021 – for SATS 3208). Typically, minimum temperatures are well within the 80°C range from the maximum pavement temperatures, and so the focus of discussion in this paper is on maximum pavement temperatures.

Figure 3 shows the progression of maximum pavement temperatures from the baseline interval (1980–2000) to interval C (2040–2060) at the 50th percentile. This is similar to the PG zones identified in



Kriging interpolation method applied to available temperature data points.

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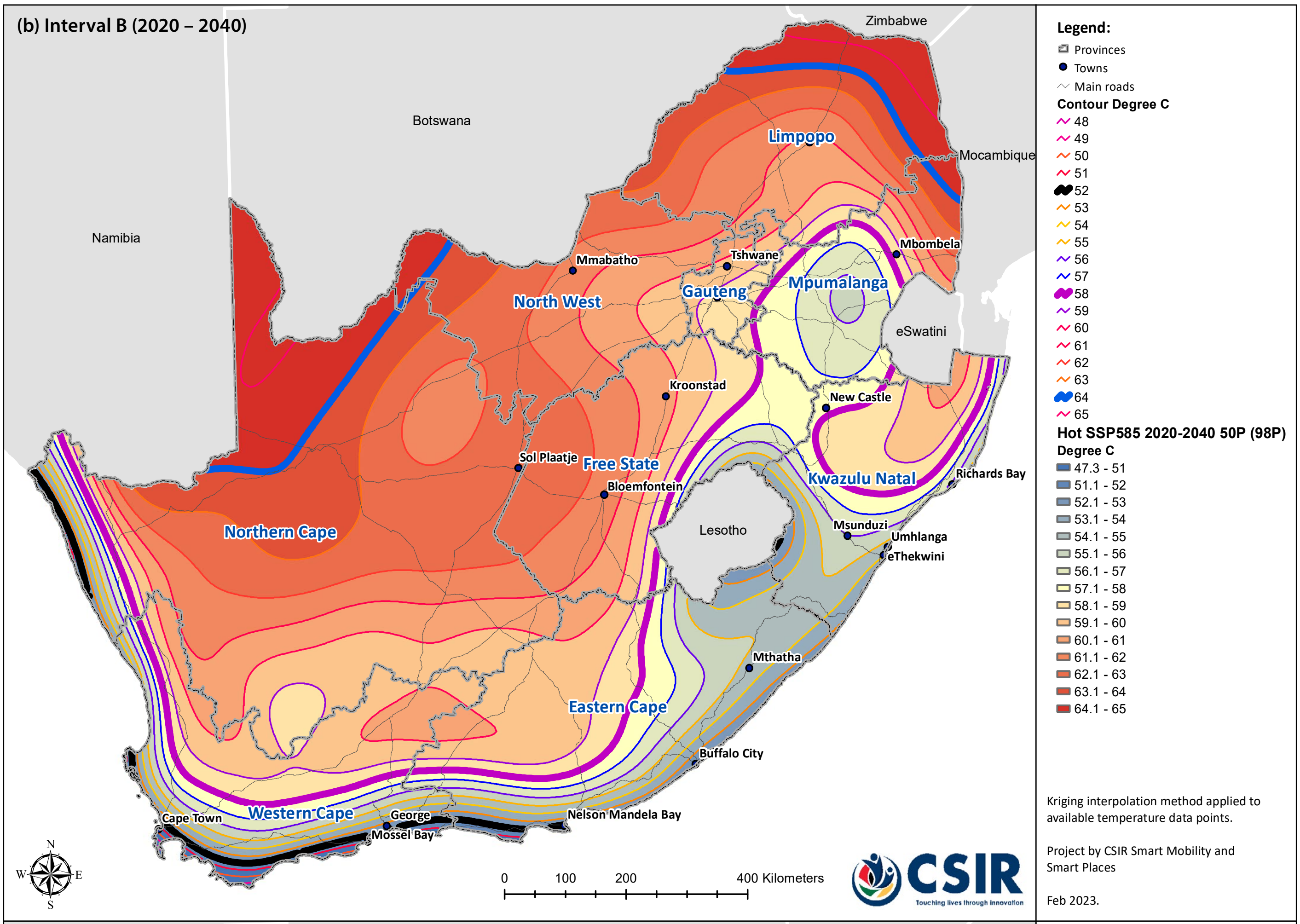
Figure 3 Seven-day maximum pavement temperature (50th percentile climate model) progression from (a) 1980 – 2000, (b) 2020 – 2040, (c) 2040 – 2060


(b) Interval B (2020 – 2040)

Kriging interpolation method applied to available temperature data points.

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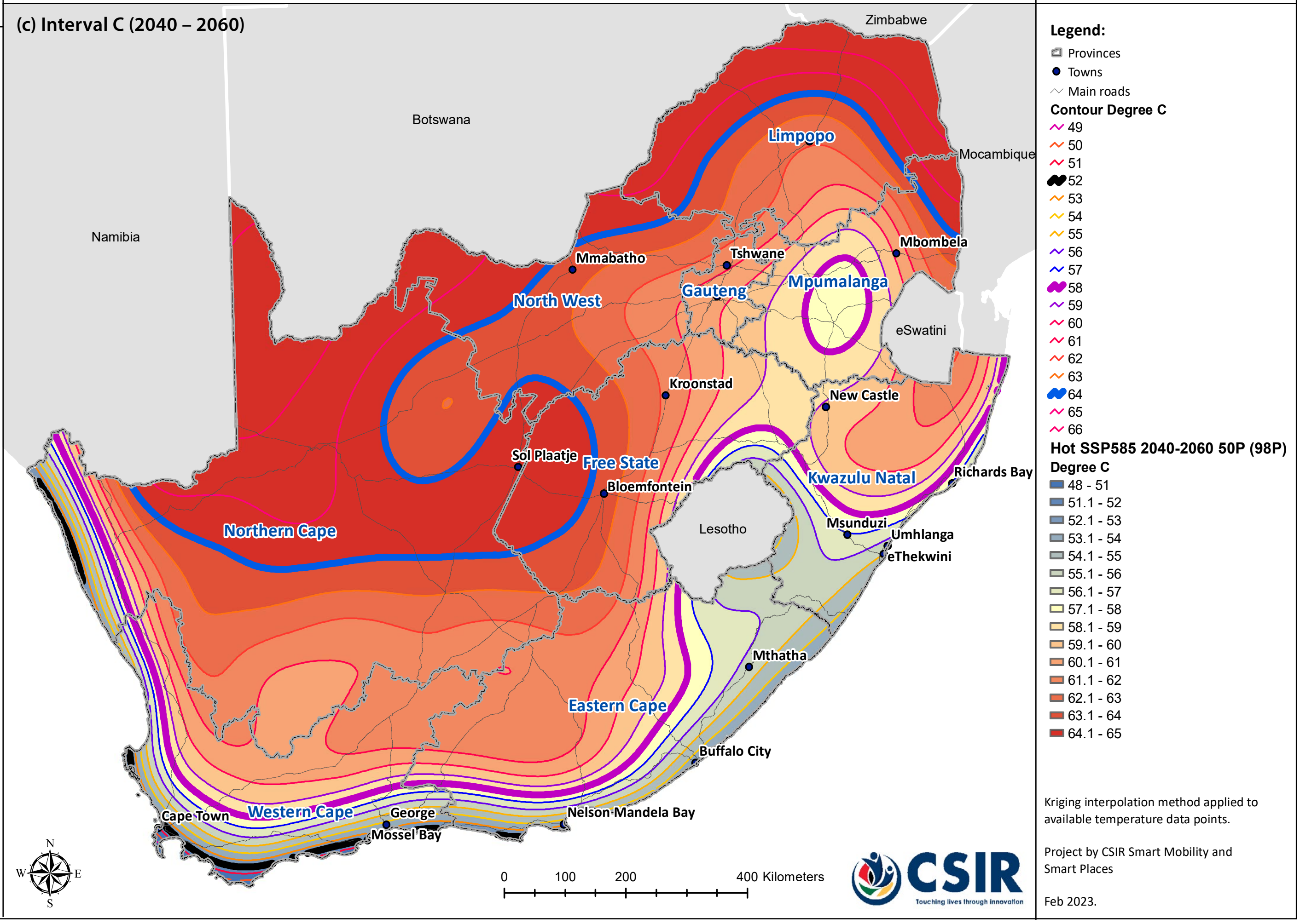
(c) Interval C (2040 – 2060)

Kriging interpolation method applied to available temperature data points.

Project by CSIR Smart Mobility and Smart Places

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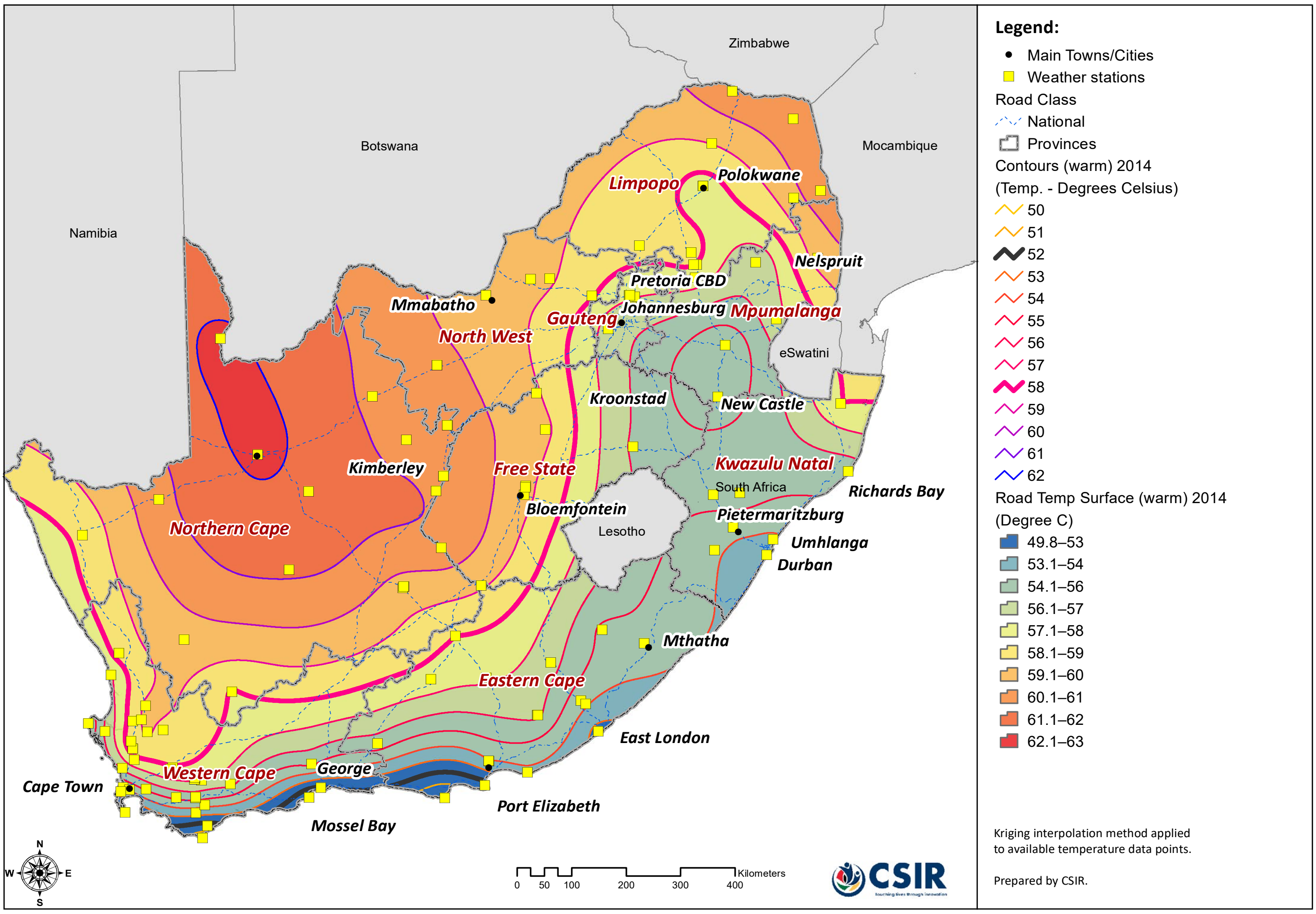


Figure 4 Maximum temperature at 97.5% confidence level for seven-day annual average at a depth of 20 mm below the road surface (SABS 2021 – for SATS 3208)

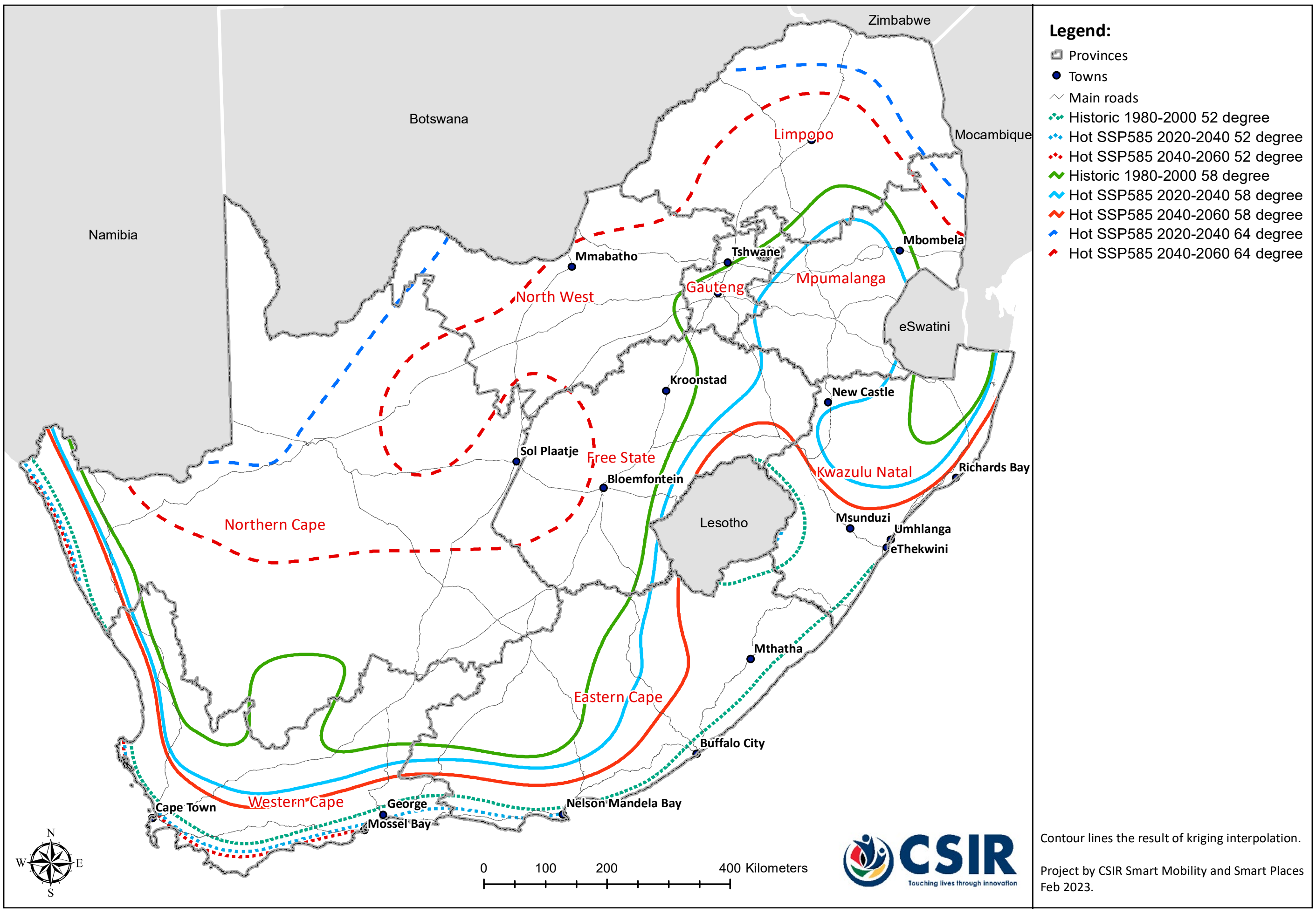
SATS 3208 (SABS 2021) and referenced in the Southern African Bitumen Association Manual 35 (Sabita 2019) as shown in Figure 4 where the northern half of Gauteng is classified as a PG 64 zone and the southern part of Gauteng falls under the PG 58 classification. There is no PG 70 zone observed during the baseline period, but an introduction of the PG 70 zone is observed during interval B (2020–2040) in the most northern part of the country (particularly in the Northern Cape, Limpopo, sections of the Orange Free State and North-West), and progressively moves towards the central parts of the country by interval C.

The sea surface temperatures, as driven by the coastal upwelling, contribute to the lowering of air temperatures, compared to the adjacent interior regions, and therefore the associated cooler pavement temperatures as observed for coastal regions, particularly across the KwaZulu-Natal and Eastern Cape border. Lakhraj-Govender and Grab (2018) investigated temperature trends for coastal and adjacent higher-lying interior regions of KwaZulu-Natal. They found that, while there is no trend in annual maximum temperatures for interior regions, there is a significant increasing trend along the coast. However, annual minimum temperatures show significant warming at all stations, with interior regions experiencing double the warming rate (Engelbrecht *et al* 2015). The spatial resolution used in this study is 0.5° gridded degree, which is approximately 55 km and may not appropriately capture the distribution across some meso- and micro-climates, particularly in coastal regions. It is therefore advisable to model pavement temperatures at a finer resolution to enhance the precision of pavement temperatures at local scales.

Figure 5 shows the progression of the 50th percentile isotherms, as the climate model ensemble for maximum pavement temperatures, over the three investigated periods between 1980 and 2060, starting with the reference period 1980–2000 and for the future periods 2020–2040 and 2040–2060, for maximum asphalt pavement temperatures in South Africa. Figure 5 shows the progression of seven-day maximum road temperatures at 20 mm depth for each 20-year interval with the historic weather station data lines similar to SATS 3208 (SABS 2021).

The model ensemble median portrays a realistic spatial pattern of the 58°C road temperature isotherm, and this is also close to the 2014 observation-based pattern. The model projections for the respective future periods are characterised by major spatial shifts to the 58°C road temperature isotherm, as well as the emergence of temperature isotherm thresholds that did not exist during the 1980–2000 baseline period. The warming in the pavement temperatures is consistent with the pattern of projected warming in ambient temperatures over South Africa under climate change (DEA 2013).

Evaluating the change in pavement temperatures from the baseline interval (1980–2000) assists in estimating the impact of climate change on asphalt road temperatures at selected locations across the country. The difference from the baseline period at each percentile is presented for maximum pavement temperatures in Table 5. The results show that positive shifts are expected in maximum temperatures throughout the country, while



Contour lines the result of kriging interpolation.

Project by CSIR Smart Mobility and Smart Places
Feb 2023.

Figure 5 Maximum pavement temperature progression from baseline interval A to C

negative temperature shifts, indicating temperatures that are cooler than the long-term average, were not observed at any of the percentiles under the SSP5-85 scenario.

The observed maximum pavement temperature shifts are between 0.9°C and 4.4°C, depending on the location in the country and the computed climate ensemble percentile. This translates to certain inner parts of the country experiencing an increase in performance grade for maximum temperatures during interval B (2020–2040) in comparison to the maximum pavement temperature map in SATS 3208 (SABS 2021) as presented in Table 6.

The current PG zones for South Africa are established at a 97.5% confidence level based on historical pavement temperatures (SABS 2021 – for SATS 3208). Although certain locations do not experience a change in PG class with climate change, as shown in Table 6, they will have a reduced confidence level, thereby increasing the uncertainty of asphalt pavement performance. Therefore, the risk of failure of asphalt pavements in these areas can be expected to increase because of the high probability of selecting unsuitable bitumen based on historical climate data. This is

Table 5 Maximum pavement temperature shifts from baseline period

Location	Temperature shift (°C) from A to B			Temperature shift (°C) from A to C		
	10P	50P	90P	10P	50P	90P
Johannesburg	1.6	1.5	1.8	2.5	3.1	4.1
Pretoria	0.9	1.4	1.7	1.9	3.2	3.9
Kimberley	1.5	1.1	0.6	2.7	3.1	2.8
Upington	1.8	1.6	0.8	2.4	3.1	2.3
Musina	0.6	2.2	2.6	2.2	3.6	4.0
Louis Trichardt	0.9	1.9	2.1	1.9	3.5	4.0
Mbombela	1.1	1.5	2.2	2.1	3.3	4.4
Bloemfontein	0.9	1.3	1.7	2.6	3.2	4.0
Cape Town	3.5	1.7	1.8	4.3	1.9	2.1
Durban	1.5	1.6	1.9	2.4	2.6	3.1
Pietermaritzburg	1.9	2.2	1.5	2.2	3.2	3.8

Table 6 Change in maximum temperature grade compared to baseline period

Location	PG change from interval A to B			PG change from interval A to C		
	10P	50P	90P	10P	50P	90P
Cape Town						
Durban						+1
Bloemfontein						+1
Pietermaritzburg						+1
Kimberley			+1		+1	
Upington	+1	+1	+1			
Johannesburg			+1	+1	+1	
Pretoria	+1	+1				
Mbombela		+1				
Louis Trichardt			+1		+1	
Musina		+1		+1		

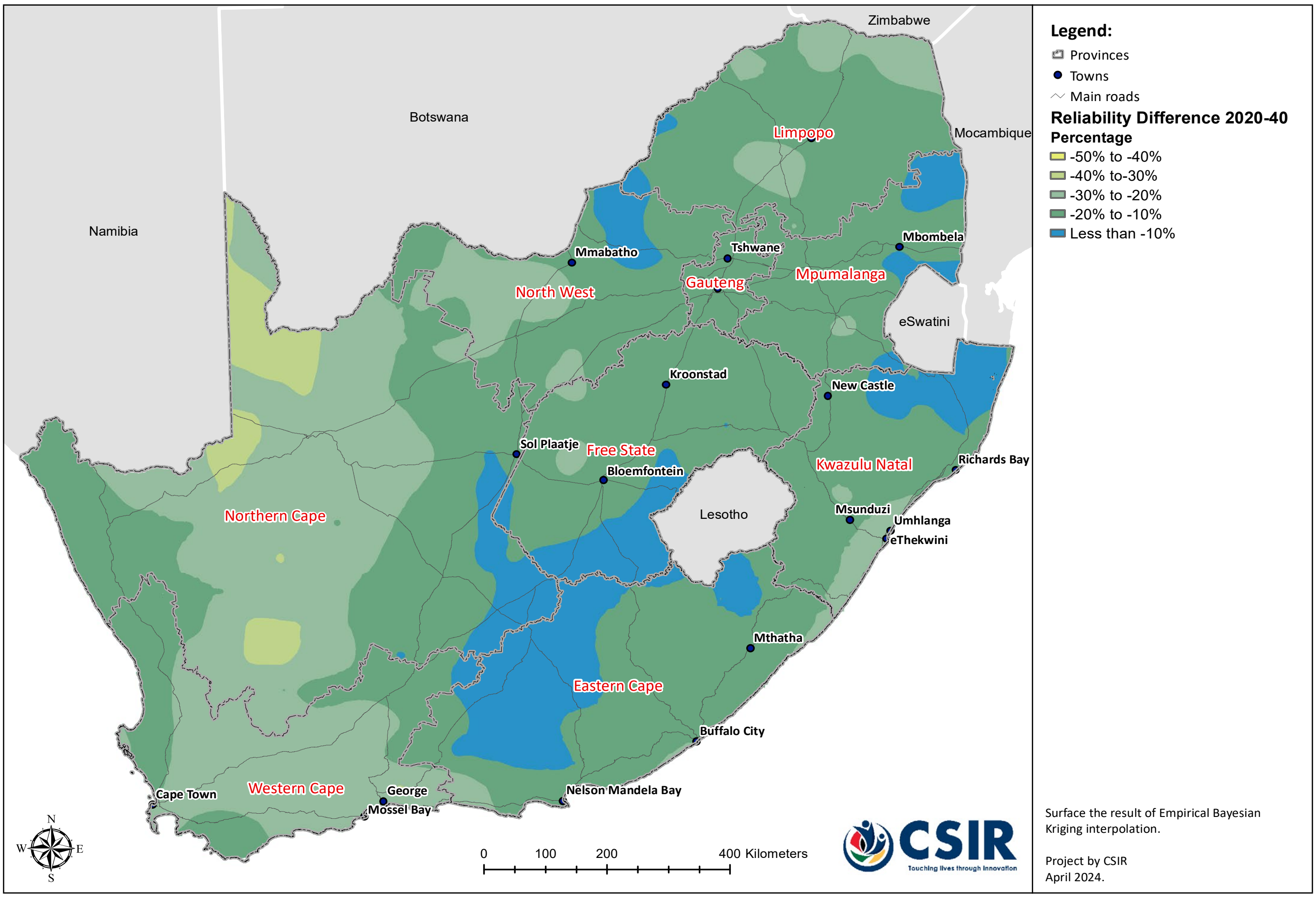


Figure 6 Change in maximum pavement temperature reliability (%) from baseline interval A to B

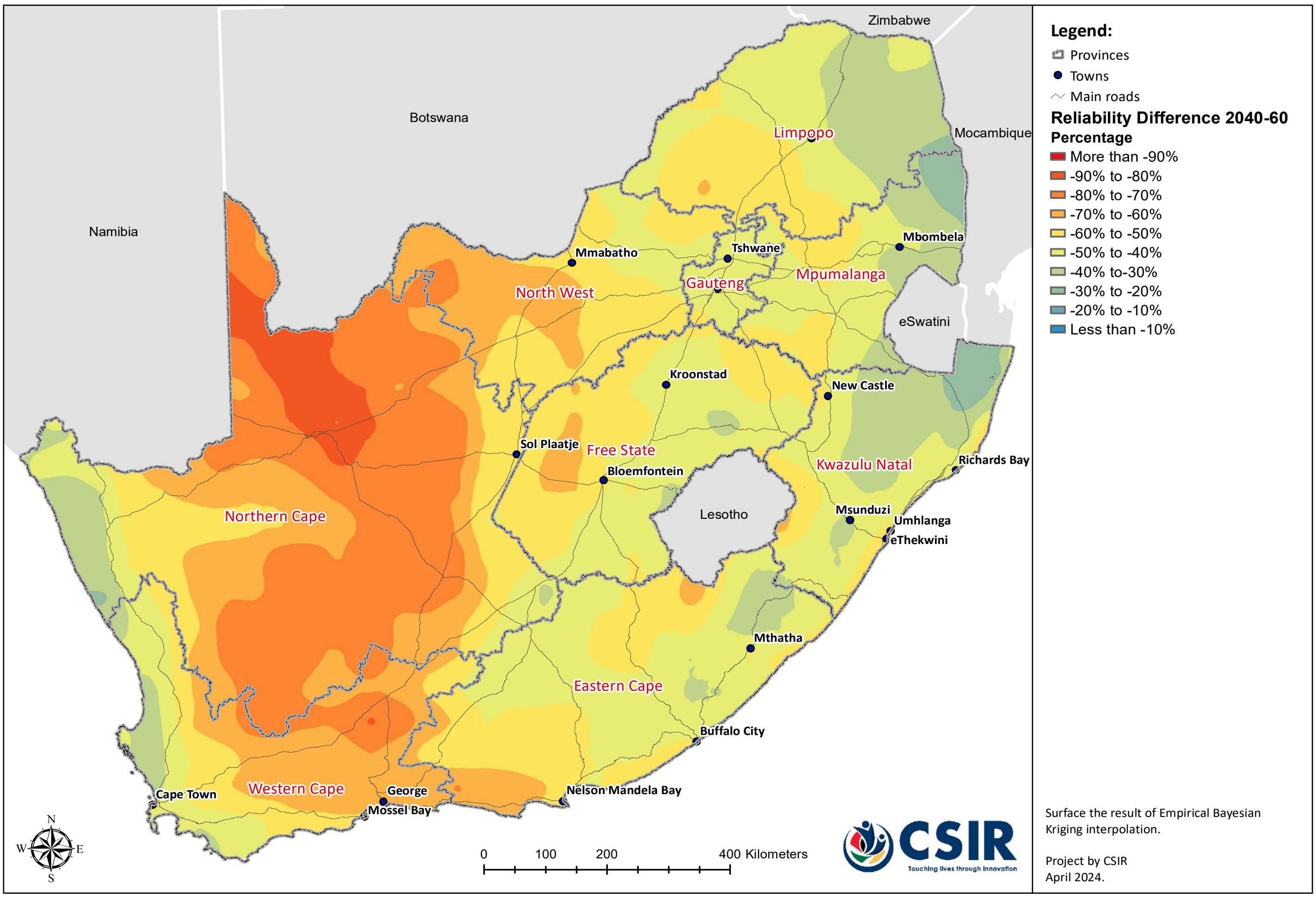


Figure 7 Change in maximum pavement temperature reliability (%) from baseline interval A to C

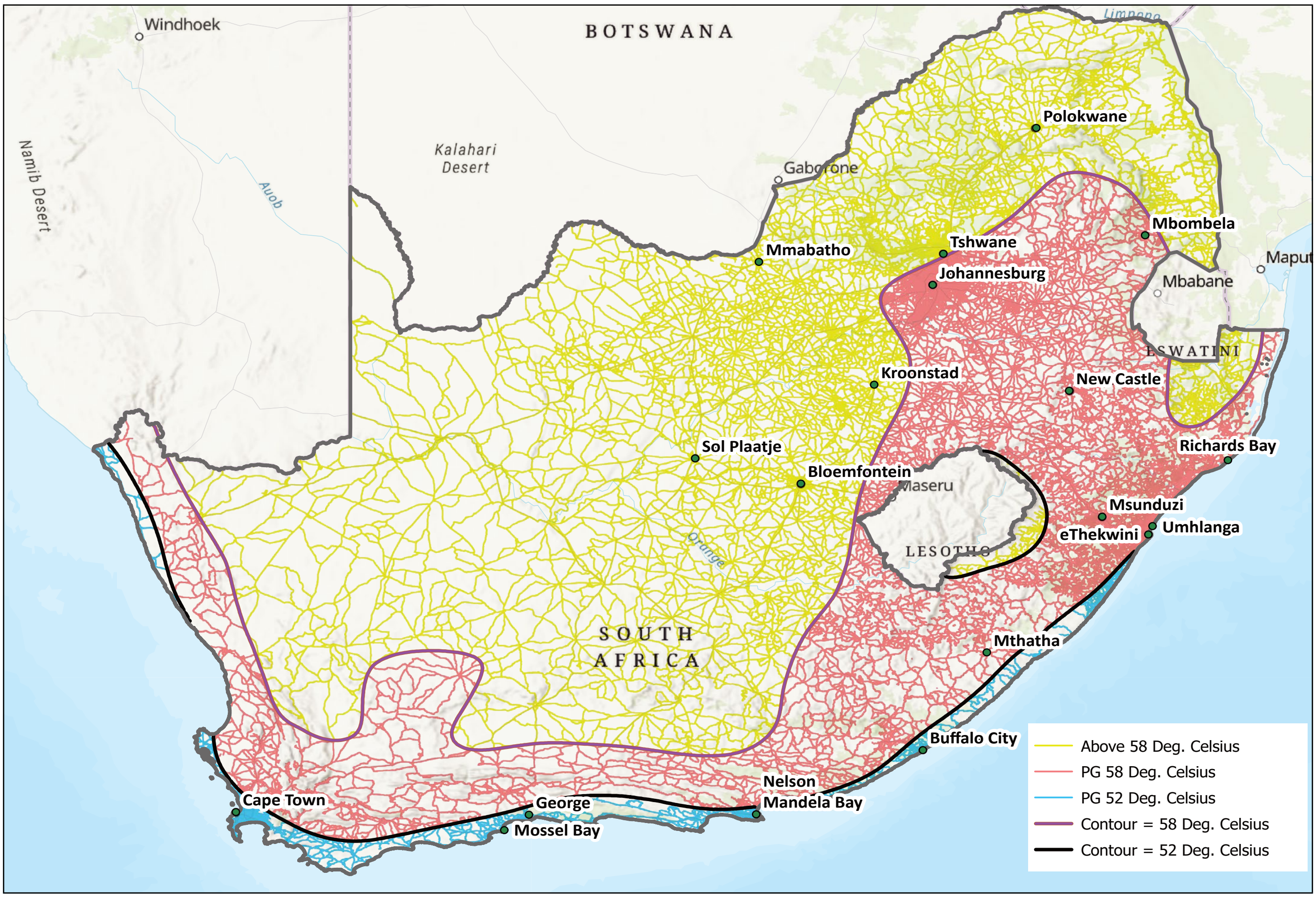


Figure 8 Road network within each maximum PG zone (baseline period 1980–2000)

illustrated in Figure 6 which shows the decrease in confidence levels for pavement temperatures across South Africa between 2020 and 2040. It can be observed that, when climate change is not taken into consideration, most of the country can expect between a 10% and 20% decrease in confidence levels, whereas a change in binder grade may not be required in certain regions. The decrease in confidence levels will be more pronounced beyond 2040, as can be seen in Figure 7 where, on average, asphalt pavement temperatures will undergo a decrease in confidence level by approximately 57%. This is expected to decrease by more than 70% in the Northern Cape, and in parts of the Western Cape and the North-West Province.

Climate change influence on PG selection for road authorities

To provide decision-makers with quantitative evidence by determining the implications of climate change on asphalt road surfaces in South Africa, the MapIt™ road database in ArcGIS™ was used to estimate the network length within each PG zone for the calculated maximum pavement temperatures. This was performed at the climate model ensemble's 50th percentile value for each point across the national grid. Four road categories from the database were used to assess the change in road network length embedded in the software. Although the database does not contain the complete road network, it does provide a reasonable estimate to quantify the percentage change which can be related to the progression of PG requirements between 1980 and 2000 (shown in Figure 8), between 2020 and 2040 (shown in Figure 9) and up to 2060 (shown in Figure 10). The four road categories used include (i) national roads, (ii) provincial roads, (iii) secondary roads and (iv) residential roads. However, it should be noted that most of these roads are gravel or surfaced with seals, except for the primary road network and certain roads within metropolitan districts. Nonetheless, the illustrated network has been provided to guide selection for future asphalt road construction.

South Africa's road network is estimated at 750 000 km, hence Tables 7 to 9 highlight discrepancies in the comprehensiveness of the MapIt™ database. However, a trend in binder classification change and the resulting financial consequences in future periods can still be established with the available dataset from the baseline period.

Based on historical temperatures and the road database used in this study, about 40% of South Africa's road network currently falls within the PG 64 zone for maximum pavement temperatures, and about 48% falls within the PG 58 zone, as illustrated in Figure 8 and Table 7. When considering the subsequent 20 years for interval B (2020–2040), which is representative of current climate, the PG 64 zone increases to approximately 60% of the road network. This indicates a 44% increase in coverage for this binder grade as shown in Table 8. It can also be seen that the PG 58 and PG 52 requirements decrease by approximately 34% and 50% respectively for the period between 2020 and 2040.

Table 7 Baseline road network within each maximum PG zone (1980–2000)

Road Category	PG 64	PG 58	PG 52
National	7 206	7 370	1 361
Provincial	34 858	35 008	5 199
Secondary	62 364	45 020	4 365
Residential	34 287	70 390	20 701
Total	**138 715**	**157 787**	**31 627**

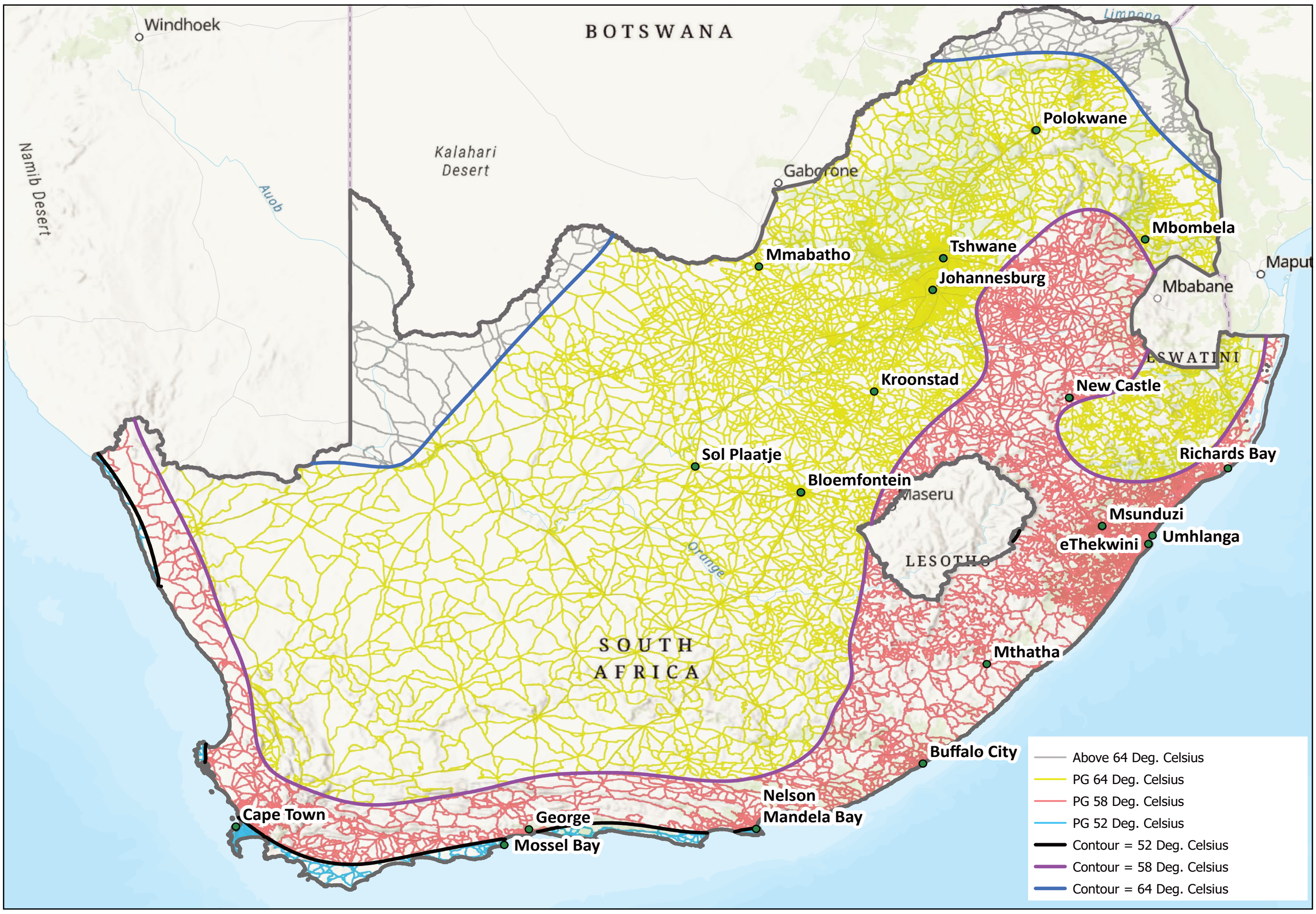


Figure 9 Road network within each maximum PG zone (2020–2040)

Furthermore, during this interval, it can be seen from Table 8 that about 8 700 km fall within a PG 70 maximum pavement temperature zone, which represent approximately 2.5% of the road network.

During interval C (2040–2060), the PG 70 zone increases slightly to represent approximately 10% of the country's road network and the PG 64 zone remains dominant, increasing by about 49% compared to the baseline period. From Table 9, significant differences in bitumen selection are observed for the PG 58 and PG 52 maximum temperature criteria and an introduction of PG 70 zones as derived from climate model data and in comparison with the SATS 3208 (SABS 2021) technical standard.

The change in road network for each PG zone has been presented at the 50th percentile of the ensemble. Considering that current design temperatures are based on a higher confidence level of 97.5% to ensure the selected binder will be suitable for expected maximum pavement temperatures, it should be noted that extreme events could exceed this confidence level, therefore conservative choices may be more appropriate in such scenarios. The 90th percentile climate ensemble value may also be considered to ensure climate resilience by improving the reliability within a given temperature grade so that future extreme events can be absorbed.

When this conservative approach is considered, the resulting map for maximum pavement temperatures is shown in Figure 11 (on pages 30 and 31), and the following is noted:

- A PG 70 zone for maximum temperatures is observed even during the historical baseline period 1980–2000.
- Most of the country's north, across most of the Northern Cape, North-West, Limpopo, parts of the Free State, and Mpumalanga is contained within the PG 70 zone for maximum temperatures for future periods.

DISCUSSION

In this study, a nine-member climate model ensemble was used to assess maximum

Table 8 Road network (km) within each maximum PG zone (2020–2040) 328 130 and percentage change compared to baseline period

Road category	PG 70		PG 64		PG 58		PG 52	
	km	% change	km	% change	km	% change	km	% change
National	180	–	9 756	35%	5 450	–26%	551	–59%
Provincial	1 946	–	46 715	34%	24 175	–31%	2 229	–57%
Secondary	4 148	–	72 477	16%	33 888	–25%	1 237	–72%
Residential	2 416	–	71 358	108%	39 918	–43%	11 686	–44%
Total	**8 690**	**–**	**200 306**	**44%**	**103 431**	**–34%**	**15 703**	**–50%**

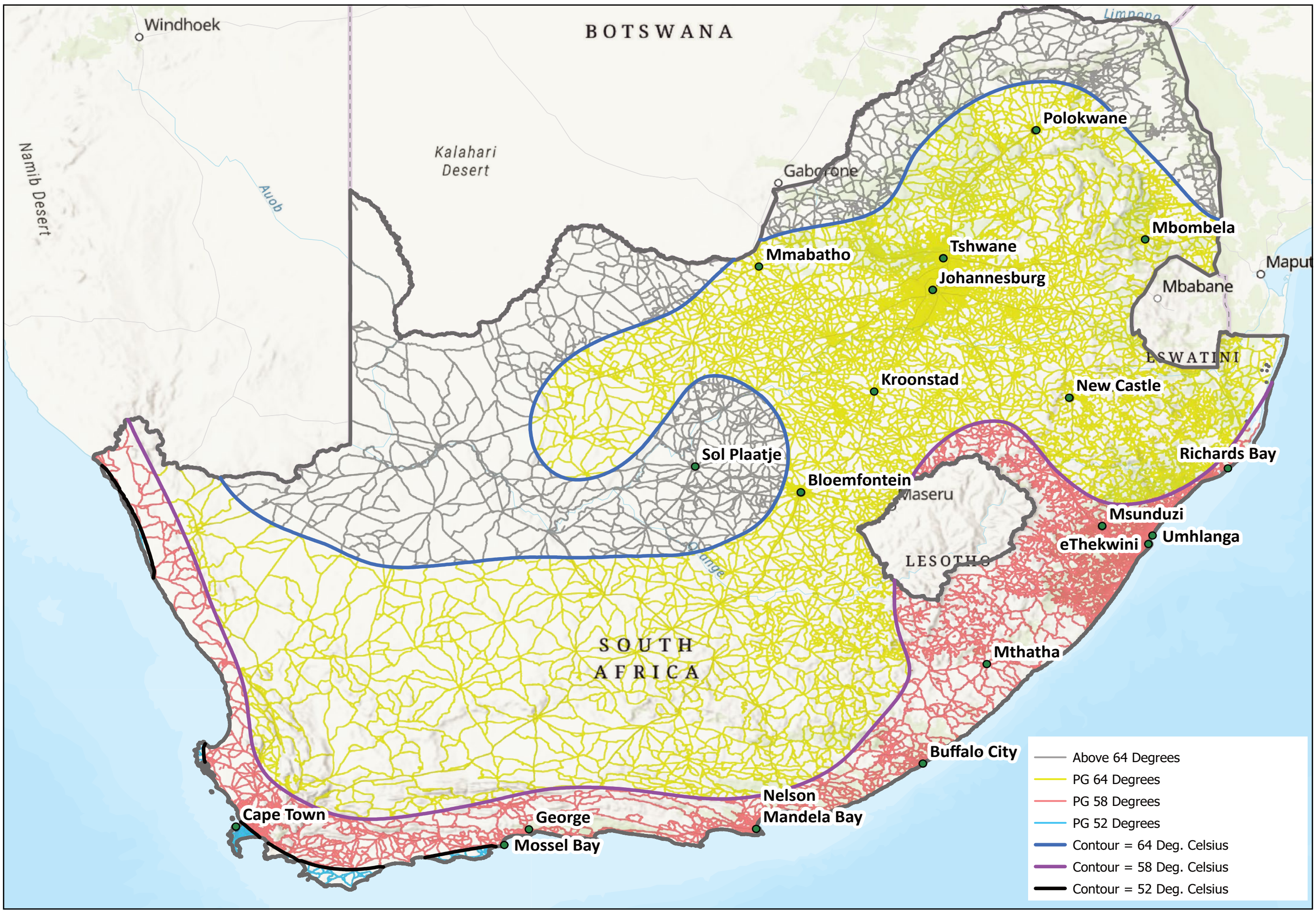


Figure 10 Road network within each maximum PG zone (2040–2060)

asphalt pavement temperatures as a strategy to understand future climatic requirements for selecting performance-graded bitumen in South Africa. Overall, the bias-corrected climate models performed reasonably well in simulating historical daily temperatures, as well as pavement temperatures derived from climate model data in comparison to weather station data. The average error between weather station and climate model data was approximately 1°C for the maximum air temperatures and approximately 2°C for minimum air temperatures. The error was even less (<1°C) when considering the pavement temperature calculated from the two climatic data sources.

The bias-corrected climate model projections show that an increase in performance grade is expected for many locations in South Africa when considering the current time interval (2020–2040) in comparison to the use of historical temperature data. For South Africa, an introduction of PG 70 bitumen is observed for the current 2020–2040 interval in comparison to the baseline interval of 1980–2004.

The need to consider future climate in the selection of PG bitumen is clear. For South Africa, a change in the spatial distribution of PG bitumen has been demonstrated and a need for PG 70 bitumen for approximately 10% of the country's road network when considering the mean results of climate models. This supports the current provision for PG 70–10 grade based on previous road temperature measurements (SABS 2021 – for SATS 3208).

It should also be noted that by their nature, future climate projections also contain inherent sources of uncertainty based on their formulation. Depending on the required projections, the current framework developed can be used with future models that may have reduced uncertainty.

The climate models require future emissions as an input, which depend on human actions. Climate scientists account for this in their projections by considering various potential emission scenarios. Typically, all models show good agreement

Table 9 Road network within each maximum PG zone (2040–2060) and percentage change compared to baseline period

Road category	PG 70		PG 64		PG 58		PG 52	
	km	% change	km	% change	km	% change	km	% change
National	1 881	–	9 918	38%	3 974	–46%	163	–88%
Provincial	9 613	–	47 855	37%	16 475	–53%	1 122	–78%
Secondary	19 639	–	72 542	16%	18 975	–58%	593	–86%
Residential	7 333	–	75 798	121%	35 598	–49%	6 648	-68%
Total	**38 466**	**–**	**206 113**	**49%**	**75 022**	**–52%**	**8 526**	**–73%**

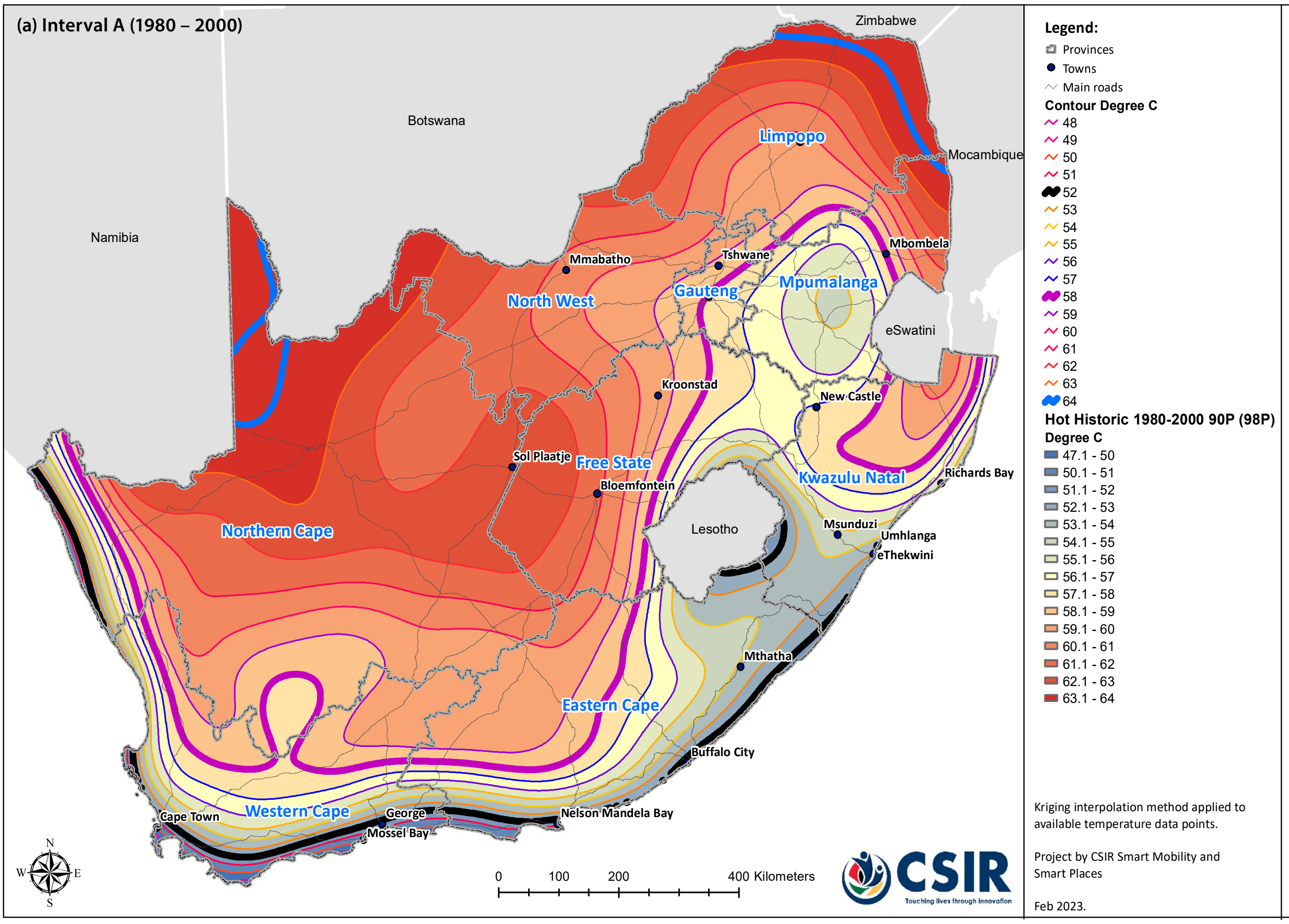


Figure 11 Maximum pavement temperature (90th percentile climate model) progression from (a) Interval A (1980–2000), (b) Interval B (2020–2040), (c) Interval C (2040–2060)

between hindcast data and observations but will deviate with future projections, and those deviations will increase with longer projection times. Therefore, it is important to consider an ensemble of model projections to provide information on a range of plausible future conditions. Furthermore, climate modelling is conducted on a relatively coarse scale and engineering design applications that could benefit from regional downscaling to up to 1 km horizontal resolution or sub-kilometre horizontal resolutions. There are additional uncertainties associated with various downscaling methodologies.

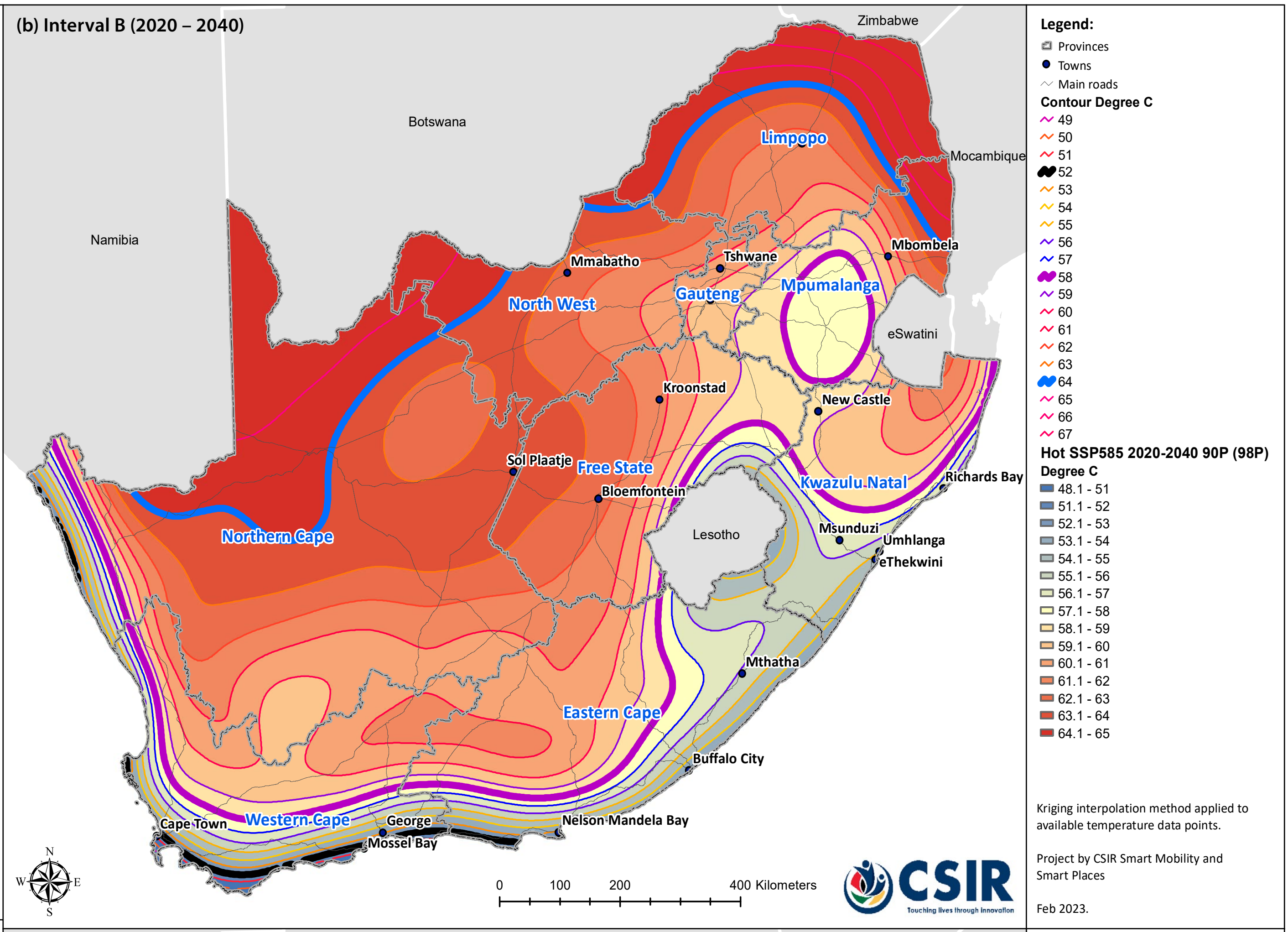
Despite these uncertainties, it is still important for engineers to consider data that is representative of key features of the climate system and its variability when incorporating climate model information in coming up with a design. It is well established that, with climate change, an assumption that the climate could be considered stationary does not necessarily lead to a good representation of future conditions. Climate projections based on an ensemble of models and potential emission scenarios are recommended for consideration in engineering design (Meagher *et al* 2012; Jacobs *et al* 2013; Jacobs *et al* 2014; National Academies of Sciences, Engineering, and Medicine 2014; Mokoena *et al* 2019). To ensure appropriate levels of reliability, model bias-correction is considered key in ensuring that climate model outputs are suitable for local impact modelling applications.

There exist several sources of uncertainty with the selection of an appropriate PG binder for a particular location using future climate projections. The PG system itself has uncertainty in the determination of pavement temperatures. A variety of pavement temperature models that translate air temperatures to pavement temperatures are available, and typically include other weather parameters to those used by Viljoen (2001), such as wind speed and measures to account for solar absorptance. These models all have some empiricism, either directly or through assumptions within analytical or numerical solutions, and therefore have associated uncertainty. Any pavement temperature model must also be calibrated or verified using observations, which have their own uncertainties associated with measurements and limited spatial coverage in many areas. These uncertainties with the PG system exist regardless of the source of temperature data used (historical observations or future projections).

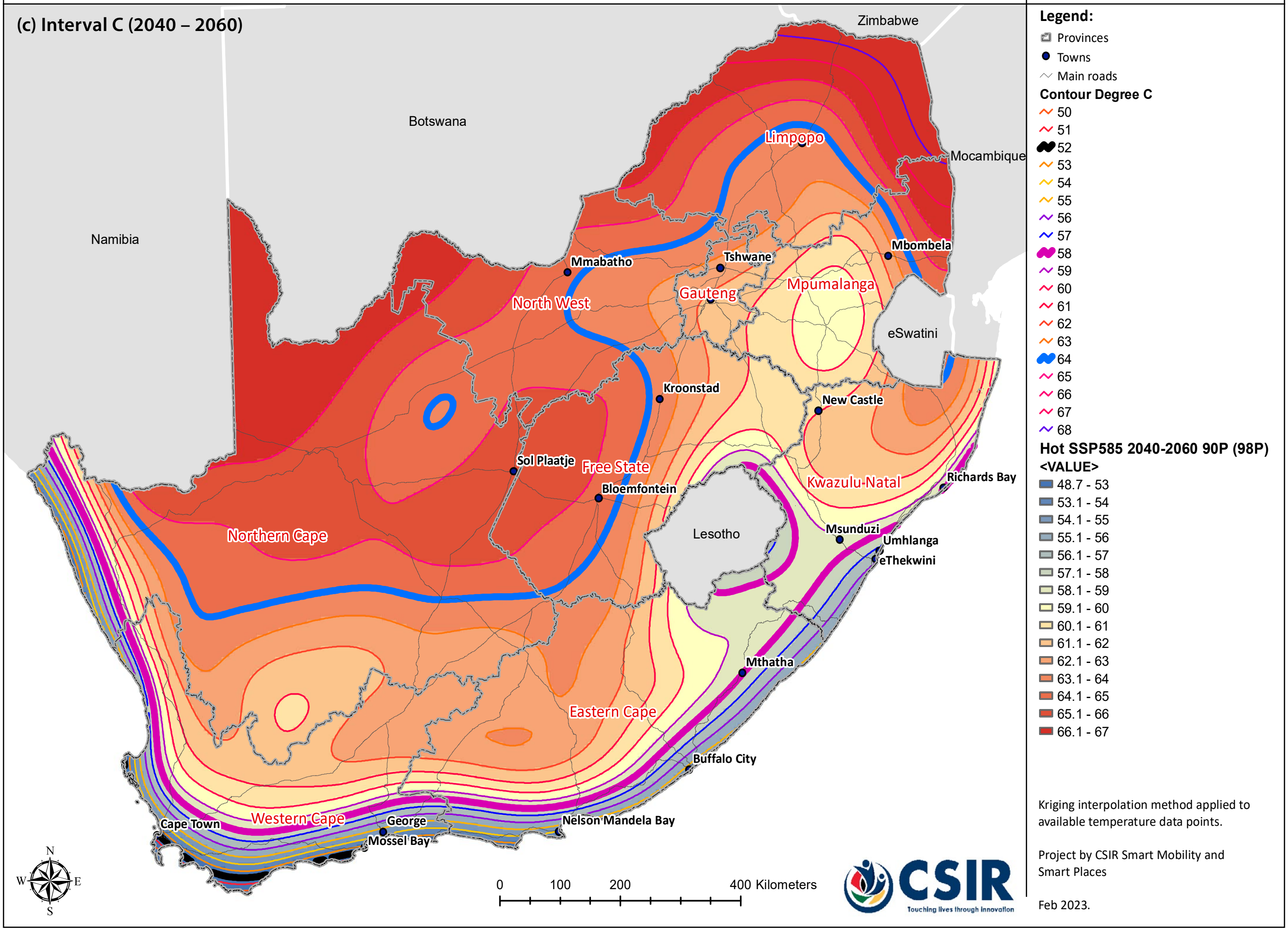
Decision-makers can establish a minimum level of uncertainty beyond which climate change impacts are highly likely to occur. This "non-discountable climate change envelope" represents a level of uncertainty that should be considered as a minimum for planning and decision-making purposes, ensuring that the potential impacts of climate change are not underestimated or discounted (Stainforth *et al* 2007).

Roads are costly to construct and maintain, even without considering damage related to climate events. The need for higher PG binders could increase the initial cost of construction due to the need for stiffer or modified binders. However, there are also costs associated with not adapting to expected climate by using existing binder

(b) Interval B (2020 – 2040)



(c) Interval C (2040 – 2060)



grades and design methodologies. There will be a higher risk that the pavement will not perform as designed over the expected life, which will lead to increased user costs due to rough roads and potentially decreased safety. Road agencies would need to spend more to maintain roads in a safe and reliable operational condition. Therefore engineers need to consider the full life of the pavement when selecting materials through cost-benefit or life-cycle cost analysis. A material with a higher initial cost may very well be the more economical choice when the full pavement life is considered. The lower the reliability of the PG binder for the area, the more likely it is to not meet expected performance over its design life.

The selection of the PG binder to be used ideally should be integrated with the structural design process so that the whole pavement system is designed to withstand expected temperature conditions. In areas with higher uncertainty with respect to future temperatures, the pavement can be designed so that the top layer can be replaced using a different binder during regular maintenance cycles. Also, more cost-effective options such as the use of recycled materials in the various pavement layers can be considered, effectively strategically designing pavements to be flexible for easier adaptation in future as more certainty evolves with expected temperatures.

CONCLUSION

To bridge the gap for climate adaptation of roads in South Africa, this study has demonstrated the integration of bias-corrected historical and projected climate model temperature outputs to estimate changes in pavement temperatures in South Africa. The intention is to inform a strategy for adaptive material selection that can be considered for application in other pavement design procedures, where applicable. This paper has shown that an acceptable level of accuracy can be obtained from climate model-derived pavement temperatures when appropriate bias-correction is employed. The progression of pavement temperatures using climate model information also indicates a change in reliability of currently used binders for South African roads.

The change in bitumen requirements for the South African road network was assessed according to the 50th percentile of a climate model ensemble analysis. The most comparable projections for maximum road temperatures at 20 mm depth were found with the climate model ensemble's 50th percentile values given the lowest errors observed at this percentile and similarity with the maps provided in current design standards. Where a more conservative approach is required, the 90th percentile ensemble values may also be considered.

The general trend is an increase in higher PG grades over time mostly affecting the country's northern and central regions and the corresponding road networks. The PG 70 maximum temperature grade remains the highest needed for the country's roads when considering future periods using climate model temperature projections. The results also show the reduced reliability in the PG bitumen selections over time, even when a change in grade is not necessary.

Current pavement design procedures consider the expected growth in traffic, but are currently based on historical climate information. The findings of this study will need to be incorporated in current guidelines and manuals to prevent financial consequences because of premature failures or increased maintenance needs.

END NOTE

ISIMIP: Inter-Sectoral Impact Model Intercomparison Project; GFDL-ESM4: Geophysical Fluid Dynamics Laboratory-Earth System Model; IPSL-CM6A-LR: Institute Pierre-Simon Laplace coupled model for CMIP6; UKESM1-0-LL: UK Earth System Model for CMIP6; MR1-ESM1-2-HR: Meteorological Research Institute Earth System Model version 1-2, MRI-ESM2-0: Meteorological Research Institute Earth System Model version 2-1.

AUTHOR CONTRIBUTIONS

Conceptualisation	GM, RM
Methodology	RM, GM, MM, JS
Software	JM
Validation	MM
Formal analysis	RM
Investigation	RM
Data curation	JM, RM
Writing (original draft preparation)	RM, GM, JS
Writing (review and editing)	RM, GM, MM, JS
Visualisation	JM
Supervision	GM, MM
Project administration	RM

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