Climate Change and Asphalt Binder Selection: Resilient Roads of the Future

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Abstract

Adapting flexible pavements systems to the impact of climate change is a challenge in Canada. It is well-known that increasing temperatures and more frequent extreme heat events represent risks for the flexible pavements. These vulnerabilities may put additional pressure on Canadian transportation infrastructure and economy, as weather begins to deviate more and more from historic temperatures. Selecting suitable Performance Graded Asphalt Cements (PGAC) for pavement construction heavily depends on temperature conditions at the site. Hence, the goal of this research paper is to evaluate the impact of climate change on PGAC selection for several Canadian cities based on different Representative Concentration Pathway (RCP) scenarios. In this study, projected temperature from ANUSPLIN datasets were used to obtain the necessary climatic parameters defined in the most recent PGAC algorithms. Projections of future changes highlighted the need for climate change adaptation policies and action sets in Canada

Introduction

It is well-recognized that adapting Canadian transportation system to the impact of climate change is a challenging endeavor for policy actors and stakeholders. Climate change phenomenon, commonly known as ‘global warming’, has caused and will continue to cause irreversible temperature rise as well as other environmental anomalies that will affect transportation infrastructure As a result, road pavements will need to be more resilient in in light of changing climate in an attempt to provide more efficient and safer service for road users without additional financial impacts. Climate change impacts have potential to be geographically widespread and modally diverse and would stress transportation systems in ways beyond which they were designed. Canadian cities are being subjected to faster and higher warming intensity than the rest of the world and these temperatures will only increase as larger amounts of fossil fuels are being emitted into the atmosphere each year. The winter season will be subject to the most intense warming across the country [1].

Bituminous materials such as Performance-Graded Asphalt Cements (PGACs) are heavily utilized in flexible pavements as the aggregate binding agent to provide a dense and smooth traveling surface over a relatively long service life. Development of SUperior PERforming asphalt PAVEments (SUPERPAVE) and system and resulting PGAC selection procedure based on pavement climatic exposure levels has made significant improvements to durability of flexible pavements over the years. In many instances, suitable PGAC for specific projects are commonly determined based on historic climatic data using prescribed transfer functions and algorithms embedded in Long-Term Pavement Performance (LTPP) software or Web-based online tool known as *LTPPBind*. Currently, several temperature-related parameters obtained from weather station data or reanalysis datasets such as MERRA-2 are taken into account to calculate high temperature (HT) and low temperature (LT) for PGAC [2]. However, in light of climate change, relying on historical climatic data for PGAC selection may increase the risk of premature failures and service life reduction of pavements due to insufficient resistance to future temperatures of the region.

In a study conducted by Environment Canada in collaboration with University of Waterloo, the potential impact of climate change on PGAC selection was investigated for 17 Canadian cities by considering CGCM2A2x and HadCM3B21 climate scenarios based on LTPPBind version 2.1 transfer functions. It was concluded that CGCM2A2x generally yielded greater increase in minimum temperature and 7-day mean maximum temperature [3]. Another study conducted at the University of Waterloo, evaluated climate change effects on future PG changes across 17 Canadian cities for 2041-70 period relative to 1981-2000 baseline using observational data from Australian National University Splines package (ANUSPLIN) and simulated future data from Coupled Model Intercomparison Project Phase 3 (CMIP3). Relying on LTPPBind version 2.1 formulas, maximum pavement temperature (TP_{max}) was calculated from maximum air temperature (T_{max}). Results showed that under moderate warming, 7 of the 17 selected cities may exhibit the need for increase in PGAC grades. Under the most extreme scenario, 12 cities were found to possibly need upgraded PGACs [4]. Similar study was conducted in Italy focusing on the impact of climate change on PGAC across 71 stations with historic weather data available from 1984-2013 and extrapolated to 2033. Based on the original SHRP formulas, researchers concluded that PG 64-22 was the most common grade both for the past and projected future with a national coverage of 55 and 60 percent, respectively. Due to climate change, it was reported that a significant upgrade in PGAC may be required for some location in Italy. Hence, use of modified PGAC with enhanced overall performance was suggested to be considered in order to meet the projected trends [5]. Another study investigated the correlation between climate change and PGAC selection in Chile. The researchers analyzed 94 stations spanning vastly different regions of Chile and acquired historical weather data from these stations from 1970 until 1999. Applying an advanced predictive algorithm known as MIRCO5-WRF, extrapolated weather data was calculated for a 30-year time span in the future (2030-2059). Employing the future climate predictions, it was found that between 10 and 40 percent of all weather stations may require change in their current HT grades and 5 and 10 percent of station may require change in their current LT grades depending on the RCP scenario through 2030-2059 [6].

The objective of this research is to evaluate the relative impact of climate change on PGAC selection according to the most recent transfer functions and algorithms for several major cities in Canada. This study focused on projected data made available by existing credible climate change models to analyze different future timelines and Representative Concentration Pathway (RCP) scenarios of varying intensity.

Methodology

Four time scenarios were chosen in this study to evaluate the relative effect of climate change on PGAC selection. Table 1 summarizes selected time scenarios along with climatic data sources and Table 2 lists selected cities and corresponding climate stations. In present study, climate data available through online climate portal operated by the Computer Research Institute of Montréal (CRIM) and accessible via www.climatedata.ca was utilized. Displayed datasets including maximum and minimum daily temperatures simulated by second iteration of Bias Correction/Constructed Analogues with Quantile (BCCAQv2) mapping reordering method were used for further calculations. The BCCAQ method amalgamates Bias Correction Climate Analogue (BCCA) method and Quantile Mapping (QMAP) methods and combines quantile-mapping bias correction with a constructed analogues approach using daily large-scale temperature and precipitation fields [7]. To account for varying severities of climate change, different RCP scenarios including 2.6, 4.5 and 8.5 were considered. That is to say, RCP 2.6 represent great reduction and RCP 4.5 exemplifies little reduction in GHG emissions. Finally, as the most severe scenario, RCP 8.5 demonstrates a condition under the impact of 'business as usual' case. For comparison purposes, the authors also considered two additional historical datasets: Environment and Climate Change Canada (ECCC) dataset [8] and National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) climatic dataset as of July 1, 2017. It is worth noting that MERRA-2 data was indirectly retrieved via the existing feature in LTPPBind Online Web-based tool [2].

All HT and LT grades were manually calculated in spreadsheet format using Microsoft Office Excel® according to the latest transfer functions shown in Table 3. Spreadsheet was used rather than LTPPBind Online because of the reported issues in the literature [9] and author's observations which will be explained in some detail later. During HT calculations, a target rut depth of 12.5 mm, which is typical for primary roads, was assumed. Besides, average yearly Degree-Days (DD) air temperature over 10°C were computed following the definition as a running summation of daily highs greater than 10℃ during April 1st until September 30th of each year [10]. For purposes of this research paper, standard loading (less than 3 million ESAL) and fast traffic speed (>70 km/h) was assumed; hence grade bumping required for heavy traffic loading and/or slow speed was not intended. Also, depth-temperature correction was not applied during the analysis and all HT values were determined at asphalt layer surface. It should be emphasized that present study aims to evaluate the relative, rather than the absolute, effect of climate change on PGAC selection.

Analysis and Results

Obviously, ambient air temperature has an immediate effect on the pavement performing temperature during its service life. The overall ambient air temperature trend for selected cities, characterized by the Mean Annual Air Temperature (MAAT), is shown in Figure 1. It is clear that the amount of warming will continue to rise in future. MAAT trends suggested that the amount of warming will likely vary depending on different RCP scenarios. Projected warming in Canada is attributed to a combination of factors such as lower surface albedo due to reductions in snow and ice as well as increased heat transport from southern latitudes [1]. As shown in Figure 1, differences in warming patterns and magnitudes are even greater under more sever GHG emission scenarios.

As previously mentioned, average yearly Degree-Days air temperature over 10°C, referred hereafter as DD, is a key parameter to determine the High Temperature (HT) when using the existing rutting damage model. Use of the DD parameter replaced the traditional average 7-day high temperature method in 2005 to accommodate the southern US climate with mainly warm temperatures throughout the year. Figure 2 displays the DD parameter for baseline and projected scenarios from climate change simulation model as well as observations from ECCC and MERRA-2 databases. Generally, it was found that selected sites are anticipated to experience higher DD particularly under more severe RCP scenarios and further into the future. These results corroborate with another studies conducted in Chile, concluding that climate change would in fact affect the DD and therefore HT calculations [6]. Also, comparison between the calculated DD from ECCC database and the retrieved DD from LTPPBind Online for MERRA-2 database did not show a good agreement, as can be seen in Figure 2. In fact, it was noticed that the DD values from MERRA-2 were relatively lower than those of the ECCC.

Similarly, Figure 3 shows the Mean Annual Minimum Air Temperatures (MAMAT) for all considered cases. As described earlier, the LTPP model incorporates MAMATs and translates them into a minimum pavement temperature. As can be seen in Figure 3, increases are projected for all cities through short, medium and long-term extrapolation periods. RCP scenarios play an important role in the intensity of warming experienced by all cities as more severe scenarios, i.e. RCP 8.5 provides the most severe MAMAT warming averages. These observed trends are in line with findings in by other researchers [5, 6], showing low temperature increases along future time periods and RCP scenarios. In addition, it was noticed that historical MAMATs from MERRA-2 database were significantly lower than those of the ECCC.

For MERRA-2 database, HT and LT were calculated for each city using both spreadsheet and LTPPBind Online as shown in Table 4. Nonetheless, it was found that manual spreadsheet calculations did not accurately match with those of the LTPPBind Online, particularly for HT. This is also in agreement with the findings of other researchers when using LTPPBind Online. Therefore, only manual calculation using spreadsheet was opted for the rest of the analysis, as can be seen in Table 4. As expected, HT results based on ECCC database were relatively higher than those of the MERRA-2 in several examined cities. In comparison to ECCC results, more conservative LTs were obtained using MERRA-2 database during historical cycle. PGAC changes became increasingly evident and substantial in further future and under more sever RCP scenarios.

Table 5 schematically shows the projected shifts in most-suitable PGACs across 16 cities under RCP 8.5 and different analysis cycles. In long-term future, PGAC 64-22, 64-28 and 64-34 are anticipated to become suitable for more cities given aforementioned traffic ESAL and speed assumptions. Estimated upgrades were not equal for all cities, while a few cities can possibly experience up to two grade bumps under considered scenarios. It is worthwhile to note that exposure to the effects of extreme heat events due to climate change is not directly taken in to account in the current PGAC selection methodology. These extreme event may have notable impacts on the service life of the pavements, if not considered properly. Hence, evaluating the probability or intensity of extreme heat events and the associated effects on PGAC selection are crucial.

Conclusion

In summary, 16 Canadian cities were studied in this paper to evaluate the relative impact of climate change on proper PGAC for asphalt paving. Focusing on short, medium and long-term future, relative changes in high and low performing temperature were estimated under RCP 2.6, 4.5 and 8.5 based on most recent LTPP algorithms. Results of this study showed that some of the examined cities may undergo significant PGAC upgrades in future depending on the RCP scenario. In addition, analysis of MERRA-2 and weather station databases showed relatively significant discrepancies with respect to PGAC climate variables for several cities.

Acknowledgements

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TABELS

Table 1: Selected Time Cycles and Climate Data

Scenario	Sources of climate data
Baseline (2000-2019)	ECCC, MERRA-2 and BCCAQv2
Short-Term Future (2020-2039)	BCCAQv2 RCP 2.6, 4.5 & 8.5
Medium-Term Future (2040-2059)	
Long-Term Future (2060-2079)	

Table 2: Selected site locations for PGAC study

Location	Station ID# (ECCC & BCCAQv2)	Assigned Coordinates (MERRA-2)	
		LATITUDE	LONGITUDE
Calgary (CAL)	3031093	51.1215°N	114.0076°W
Charlottetown (CHAR)	8300301	46.2904°N	63.1224°W
Edmonton (EDM)	3012209	53.3054°N	113.5774°W
Fredericton (FRED)	8101500	45.8747°N	66.5305°W
Halifax (HFX)	8202250	44.8836°N	63.5094°W
Kelowna (KEL)	1123970	49.9569°N	119.3787°W
Montreal (MON)	7025250	45.4657°N	73.7455°W
Ottawa (OTT)	6106000	45.3192°N	75.6692°W
Prince George (PRG)	1096450	53.8838°N	122.6732°W
Regina (REG)	4016560	50.4321°N	104.6639°W
St. John's (STJ)	8403506	47.6212°N	52.7424°W
Thunder Bay (THB)	6048261	48.3743°N	89.3195°W
Toronto (TOR)	6158733	43.6777°N	79.6248°W
Vancouver (VAN)	1108447	49.1967°N	123.1815°W
Victoria (VIC)	1018620	48.6481°N	123.4287°W
Winnipeg (WIN)	5023222	49.9098°N	97.2365°W

Table 3: Summary of high and low PG equations and required input parameters

HIGH PG

Variables

High temperature PG damage	$PG_{H,d}$
Yearly PG coefficient of variation, percent	$CVPG$
Relative PG value	$PG_{H,rel}$
Average Yearly Degree-Days Air Temp. Over 10°C, x1000°C	DD
Rutting Depth (mm)	RD
Latitude	Lat
Reliability constant @98% reliability: Z=2.055	Z

Equations

1) $$PG_{H,d} = 48.2 + 14DD - 0.96DD^2 - 2RD$$

2) $$CVPG = 0.000034(Lat - 20)^2 RD^2$$

3) $$PG_{H,rel} = PG_{H,d} + (Z)(PG_{H,d})\frac{CVPG}{1000}$$

LOW PG

Variables

Lowest yearly pavement temperature	$T_{L,pav}$
Lowest yearly air temperature	$T_{L,air}$
Latitude	Lat
Depth into HMA surface (0 for surface temperature)	H
Reliability constant @98% reliability: Z=2.055	Z
Standard deviation of lowest yearly air temperature across 20 years	$\sigma^2_{T,air}$

Equations

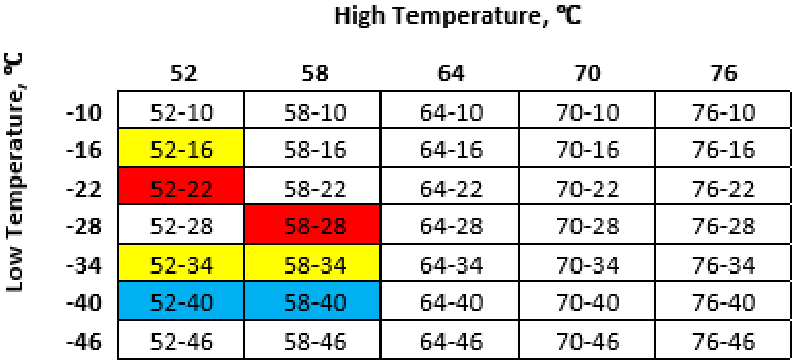
4) $$T_{L,pav} = -1.56 + 0.72T_{L,air} - 0.004Lat^2 + 6.26\log(H + 25) - Z(4.4 + 0.52\sigma^2_{T,air})^{0.5}$$

5) $$\sigma^2_{T,air} = variance^2$$

Table 4: Calculated PGAC grades under different scenarios for selected sites

Climate Data City	**ECCC 2000-2019**	**MERRA-2 (LTPPBind Online)**	**MERRA-2 (Manual)**	**BCCAQv2 2000-2019**	**BCCAQv2 RCP 2.6 2020-2039**	**BCCAQv2 RCP 2.6 2040-2059**	**BCCAQv2 RCP 2.6 2060-2079**	**BCCAQv2 RCP 4.5 2020-2039**	**BCCAQv2 RCP 4.5 2040-2059**	**BCCAQv2 RCP 4.5 2060-2079**	**BCCAQv2 RCP 8.5 2020-2039**	**BCCAQv2 RCP 8.5 2040-2059**	**BCCAQv2 RCP 8.5 2060-2079**
CAL	48.5-31.1 **(52-34)**	47.8-39.2 **(52-40)**	48.3-39.1 **(52-40)**	49.6-33.6 **(52-34)**	51.5-31.1 **(52-34)**	51.7-31.4 **(52-34)**	51.3-31.0 **(52-34)**	52.1-30.0 **(58-34)**	54.1-28.9 **(58-34)**	56.5-27.4 **(58-28)**	51.1-30.5 **(52-34)**	55.3-28.2 **(58-34)**	58.6-27.1 **(64-28)**
CHAR	45.0-23.1 **(52-28)**	38.2-27.0 **(52-28)**	38.4-27.0 **(52-28)**	47.2-23.2 **(52-28)**	46.7-24.1 **(52-28)**	49.2-20.3 **(52-22)**	50.3-20.7 **(52-22)**	49.7-20.1 **(52-22)**	50.9-19.7 **(52-22)**	53.0-17.9 **(58-22)**	48.4-21.1 **(52-22)**	51.2-19.3 **(52-22)**	55.0-17.0 **(58-22)**
EDM	49.3-33.1 **(52-34)**	46.5-45.2 **(52-46)**	47.0-45.1 **(52-46)**	50.0-37.8 **(52-40)**	51.9-35.9 **(52-40)**	52.2-36.4 **(58-40)**	51.8-34.6 **(52-40)**	52.7-34.7 **(58-40)**	54.6-31.7 **(58-34)**	56.8-30.2 **(58-34)**	52.1-34.5 **(58-40)**	56.1-34.5 **(58-40)**	59.3-30.3 **(64-34)**
FRED	49.9-27.3 **(52-28)**	45.9-38.0 **(52-40)**	46.3-38.1 **(52-40)**	51.3-26.8 **(52-28)**	51.5-27.0 **(52-28)**	53.0-24.8 **(58-28)**	53.3-27.1 **(58-28)**	53.5-25.1 **(58-28)**	55.2-24.3 **(58-28)**	56.5-23.9 **(58-28)**	52.6-26.6 **(58-28)**	55.8-23.1 **(58-28)**	58.9-21.6 **(64-22)**
HFX	47.6-21.3 **(52-22)**	46.2-24.2 **(52-28)**	46.5-24.1 **(52-28)**	48.0-21.5 **(52-22)**	47.8-21.6 **(52-22)**	49.9-19.3 **(52-22)**	50.4-19.8 **(52-22)**	50.0-19.8 **(52-22)**	51.8-18.5 **(52-22)**	52.9-18.0 **(58-22)**	49.1-21.1 **(52-22)**	52.4-18.8 **(58-22)**	55.2-15.9 **(58-16)**
KEL	55.2-26.3 **(58-28)**	47.9-36.7 **(52-40)**	48.4-36.7 **(52-40)**	56.0-27.9 **(58-28)**	56.7-26.2 **(58-28)**	57.5-26.3 **(58-28)**	57.6-24.3 **(58-28)**	58.1-23.5 **(64-28)**	60.0-21.2 **(64-22)**	62.3-22.5 **(64-28)**	57.5-24.6 **(58-28)**	61.8-22.5 **(64-28)**	64.6 -21.9 **(70-22)**
MON	52.3-25.1 **(58-28)**	50.1-40.9 **(52-46)**	50.5-41.0 **(52-46)**	52.8-25.3 **(58-28)**	53.4-26.9 **(58-28)**	54.4-25.5 **(58-28)**	54.6-25.3 **(58-28)**	55.3-25.1 **(58-28)**	56.7-23.6 **(58-28)**	58.7-22.4 **(64-28)**	54.1-25.6 **(58-28)**	57.1-23.6 **(58-28)**	60.6-21.1 **(64-22)**
OTT	52.8-26.4 **(58-28)**	49.3-42.9 **(52-46)**	49.6-42.8 **(52-46)**	52.8-29.9 **(58-34)**	53.6-27.4 **(58-28)**	54.6-26.5 **(58-28)**	54.9-26.7 **(58-28)**	55.3-26.2 **(58-28)**	56.7-25.3 **(58-28)**	58.8-23.3 **(64-28)**	54.4-26.8 **(58-28)**	57.1-24.1 **(58-28)**	60.8-22.2 **(64-28)**
PRG	47.7-34.8 **(52-40)**	43.1-43.9 **(52-46)**	43.6-43.9 **(52-46)**	50.2-39.2 **(52-40)**	50.7-37.1 **(52-40)**	52.2-38.1 **(58-40)**	51.6-36.3 **(52-40)**	51.7-35.2 **(52-40)**	53.4-33.5 **(58-34)**	55.8-32.6 **(58-34)**	52.0-36.6 **(52-40)**	56.2-34.2 **(58-40)**	59.5-31.0 **(64-34)**
REG	51.9-35.4 **(52-40)**	52.1-45.0 **(58-46)**	52.6-44.9 **(58-46)**	53.1-34.8 **(58-40)**	55.0-33.1 **(58-34)**	55.4-32.5 **(58-34)**	54.9-32.6 **(58-34)**	55.4-32.1 **(58-34)**	57.2-30.2 **(58-34)**	59.4-28.6 **(64-34)**	54.4-32.7 **(58-34)**	58.2-30.0 **(64-34)**	61.4-28.5 (64-34)
STJ	41.4-18.5 **(52-22)**	27.8-20.7 **(52-22)**	28.0-20.7 **(52-22)**	42.8-19.3 **(52-22)**	40.7-18.4 **(52-22)**	44.5-16.5 **(52-22)**	41.2-17.7 **(52-22)**	41.8-17.2 **(52-22)**	43.8-15.8 **(52-16)**	45.3-15.1 **(52-16)**	42.7-17.5 **(52-22)**	43.6-16.4 **(52-22)**	48.1-13.3 **(52-16)**
THB	47.9-33.2 **(52-34)**	44.5-39.4 **(52-40)**	45.0-39.4 **(52-40)**	47.6-32.5 **(52-34)**	49.1-32.8 **(52-34)**	49.7-30.8 **(52-34)**	49.8-31.5 **(52-34)**	50.2-31.2 **(52-34)**	51.6-29.5 **(52-34)**	53.1-27.8 **(58-28)**	49.6-31.8 **(52-34)**	52.0-29.8 **(58-34)**	55.2-26.0 **(58-28)**
TOR	53.1-22.4 **(58-28)**	44.9-22.8 **(52-28)**	45.2-22.7 **(52-28)**	53.3-22.3 **(58-28)**	54.3-22.6 **(58-28)**	55.1-21.6 **(58-22)**	55.4-22.6 **(58-28)**	56.1-20.6 **(58-22)**	57.4-19.5 **(58-22)**	59.6-18.5 **(64-22)**	54.7-23.2 **(58-28)**	57.1-20.6 **(58-22)**	60.8-16.2 **(64-22)**
VAN	47.5-14.4 **(52-16)**	44.4-18.1 **(52-22)**	44.9-18.1 **(52-22)**	50.6-15.6 **(52-16)**	51.7-13.2 **(52-16)**	52.8-15.1 **(58-16)**	53.1-13.5 **(58-16)**	52.3-11.7 **(58-16)**	54.8-10.5 **(58-16)**	56.7-11.2 **(58-16)**	52.0-12.5 **(52-16)**	56.9-10.6 **(58-16)**	59.8-9.7 **(64-10)**
VIC	48.2-12.6 **(52-16)**	43.7-16.9 **(52-22)**	44.2-16.8 **(52-22)**	49.7-14.0 **(52-16)**	50.8-11.2 **(52-16)**	52.0-12.9 **(52-16)**	52.2-11.6 **(58-16)**	51.2-10.5 **(52-16)**	53.9-9.4 **(58-10)**	55.6-10.0 **(58-10)**	50.9-11.0 **(52-16)**	55.6-8.8 **(58-10)**	58.3-8.1 **(64-10)**
WIN	51.9-35.0 **(52-40)**	51.6-42.1 **(52-46)**	52.2-42.1 **(58-46)**	52.4-35.2 **(58-40)**	54.5-33.0 **(58-34)**	55.3-32.8 **(58-34)**	54.8-32.4 **(58-34)**	55.4-30.8 **(58-34)**	57.1-28.6 **(58-34)**	59.1-26.5 **(64-28)**	54.6-33.7 **(58-34)**	57.3-30.9 **(58-34)**	60.5-27.7 **(64-28)**

Table 5: Predicted change in most-suitable PGAC grades under RCP 8.5 for **(a)** 2020-2039, **(b)** 2040-2059 and **(c)** 2060-2079

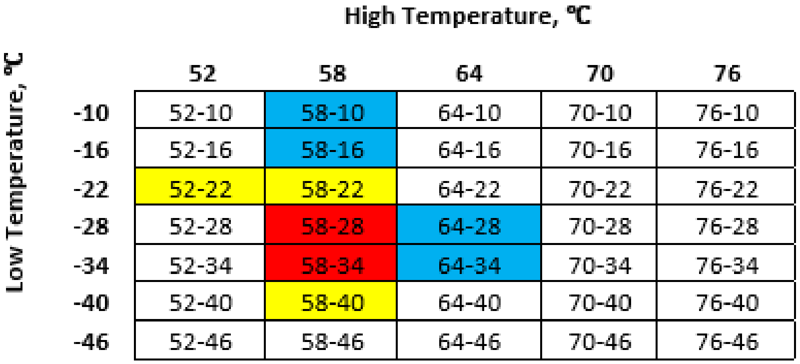


High Temperature, ℃

Low Temperature, ℃

	52	**58**	**64**	**70**	**76**
-10	52-10	58-10	64-10	70-10	76-10
-16	🟨 52-16	58-16	64-16	70-16	76-16
-22	🟥 52-22	58-22	64-22	70-22	76-22
-28	52-28	🟥 58-28	64-28	70-28	76-28
-34	🟨 52-34	🟨 58-34	64-34	70-34	76-34
-40	🟦 52-40	🟦 58-40	64-40	70-40	76-40
-46	52-46	58-46	64-46	70-46	76-46

(a)

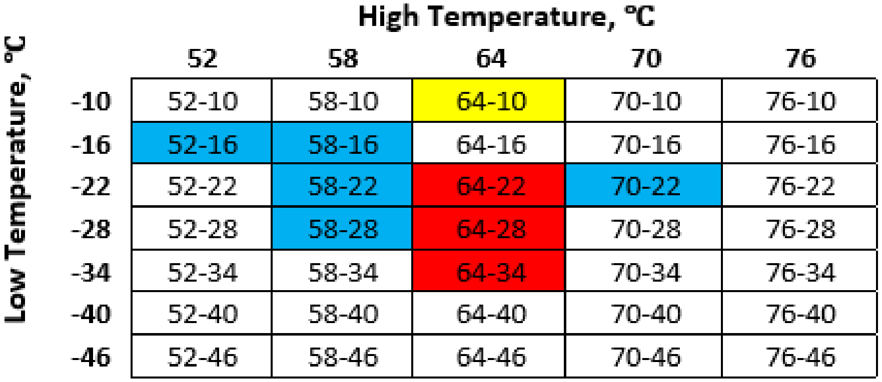


High Temperature, ℃

Low Temperature, ℃

	52	**58**	**64**	**70**	**76**
-10	52-10	🟦 58-10	64-10	70-10	76-10
-16	52-16	🟦 58-16	64-16	70-16	76-16
-22	🟨 52-22	🟨 58-22	64-22	70-22	76-22
-28	52-28	🟥 58-28	🟦 64-28	70-28	76-28
-34	52-34	🟥 58-34	🟦 64-34	70-34	76-34
-40	52-40	🟨 58-40	64-40	70-40	76-40
-46	52-46	58-46	64-46	70-46	76-46

(b)



High Temperature, ℃

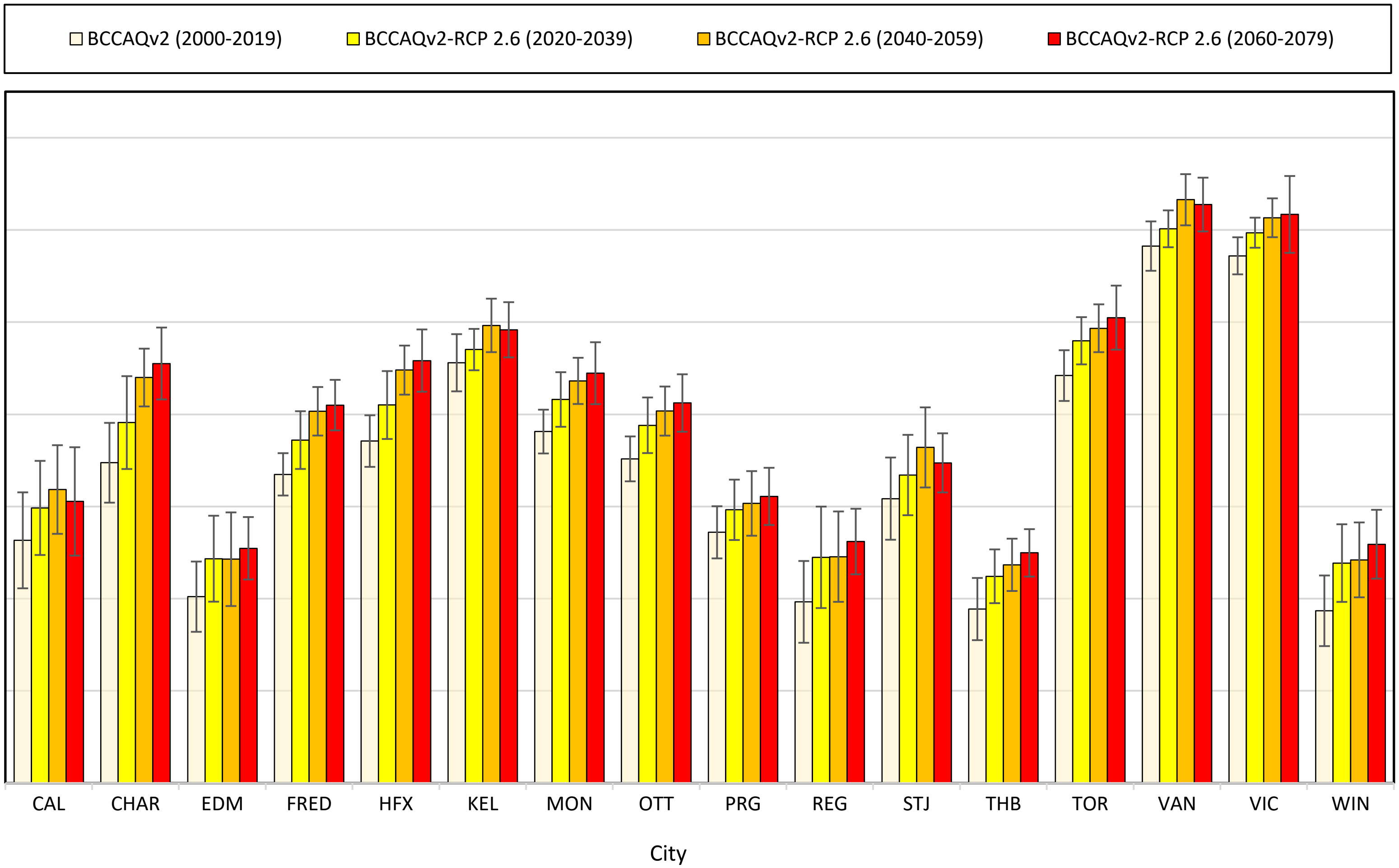
Low Temperature, ℃

	52	**58**	**64**	**70**	**76**
-10	52-10	58-10	🟨 64-10	70-10	76-10
-16	🟦 52-16	🟦 58-16	64-16	70-16	76-16
-22	52-22	🟦 58-22	🟥 64-22	🟦 70-22	76-22
-28	52-28	🟦 58-28	🟥 64-28	70-28	76-28
-34	52-34	58-34	🟥 64-34	70-34	76-34
-40	52-40	58-40	64-40	70-40	76-40
-46	52-46	58-46	64-46	70-46	76-46

🟦 = 1 city
🟨 = 2 cities
🟥 = 3+ cities

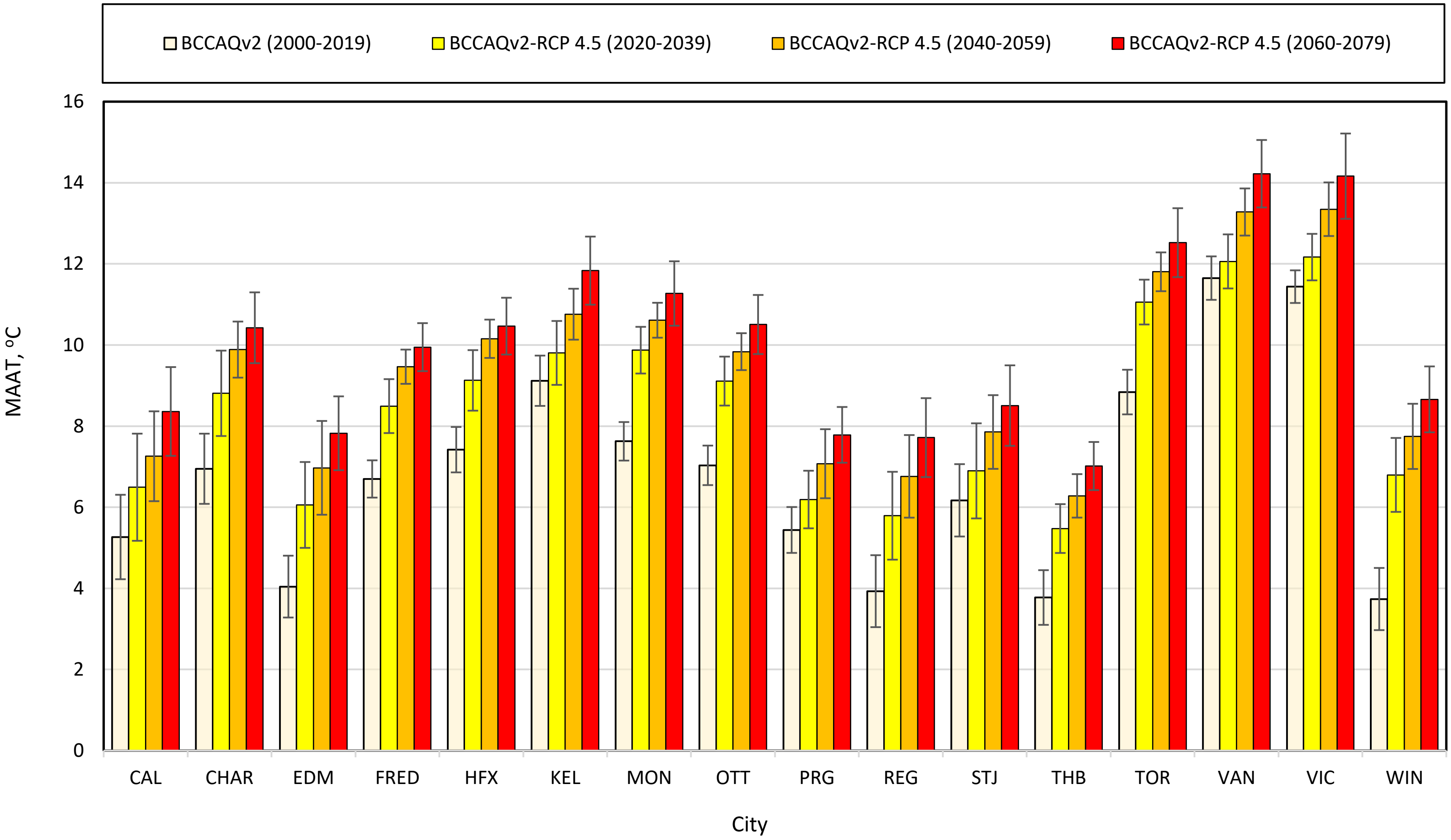
(c)

FIGURES



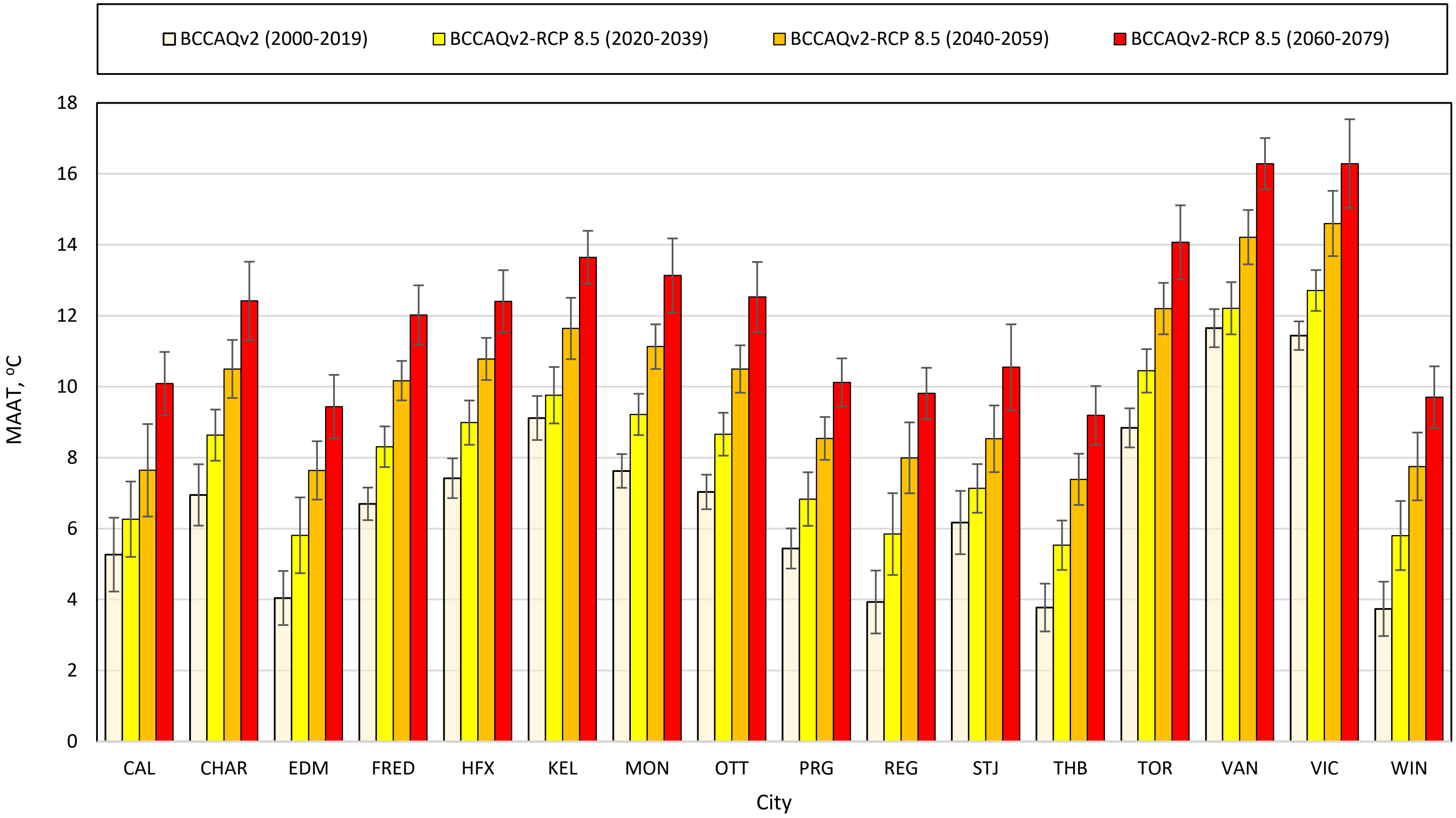
BCCAQv2 (2000-2019)
BCCAQv2-RCP 2.6 (2020-2039)
BCCAQv2-RCP 2.6 (2040-2059)
BCCAQv2-RCP 2.6 (2060-2079)
MAAT, ºC
0
2
4
6
8
10
12
14
CAL
CHAR
EDM
FRED
HFX
KEL
MON
OTT
PRG
REG
STJ
THB
TOR
VAN
VIC
WIN
City

(a)



BCCAQv2 (2000-2019)
BCCAQv2-RCP 4.5 (2020-2039)
BCCAQv2-RCP 4.5 (2040-2059)
BCCAQv2-RCP 4.5 (2060-2079)
MAAT, °C
16
14
12
10
8
6
4
2
0
CAL
CHAR
EDM
FRED
HFX
KEL
MON
OTT
PRG
REG
STJ
THB
TOR
VAN
VIC
WIN
City

(b)



(c)

Figure 1: MAAT for baseline and **(a)** RCP 2.6, **(b)** RCP 4.5, **(c)** RCP 8.5 scenarios

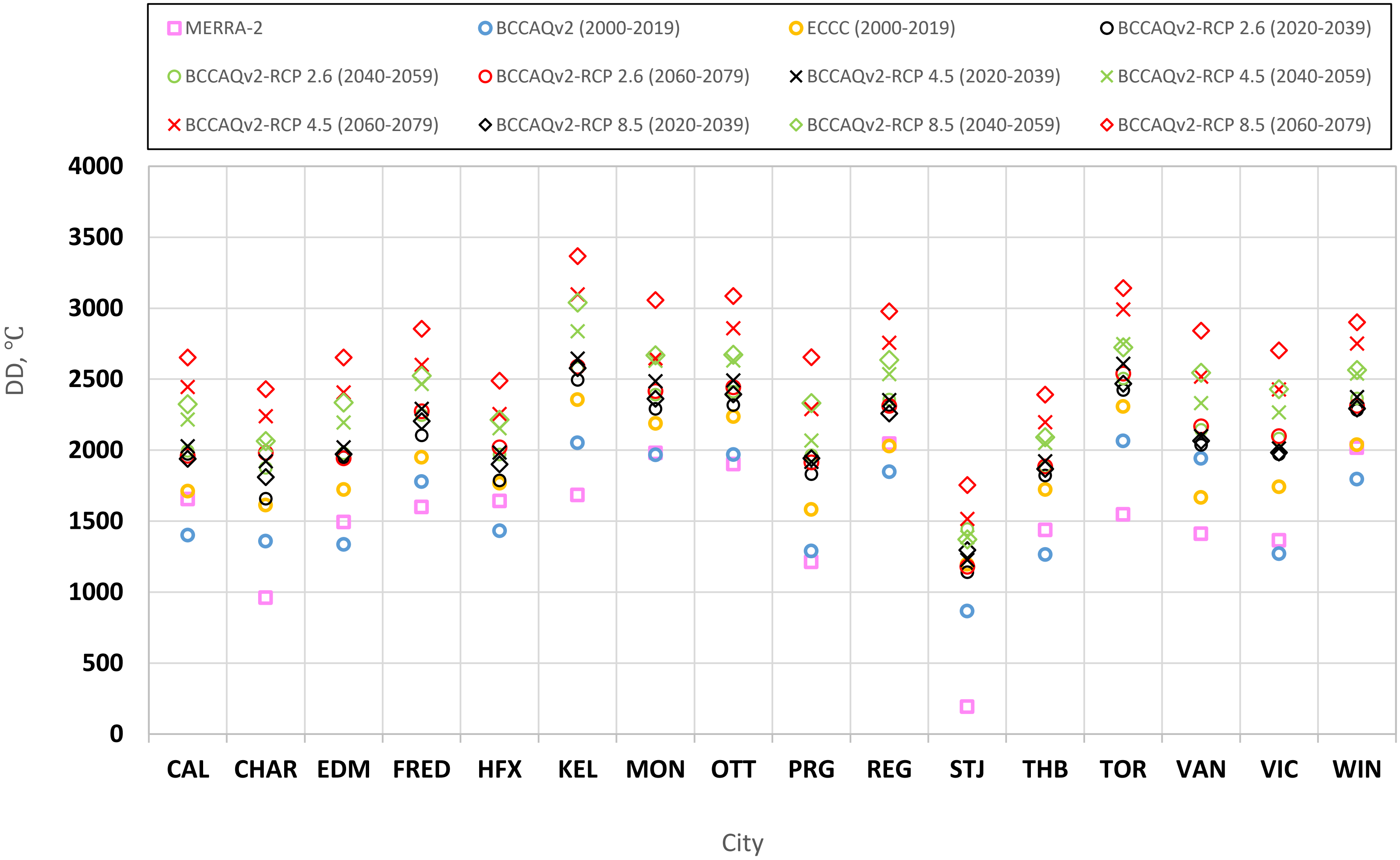


Figure 2: DD for baseline and different RCP scenarios

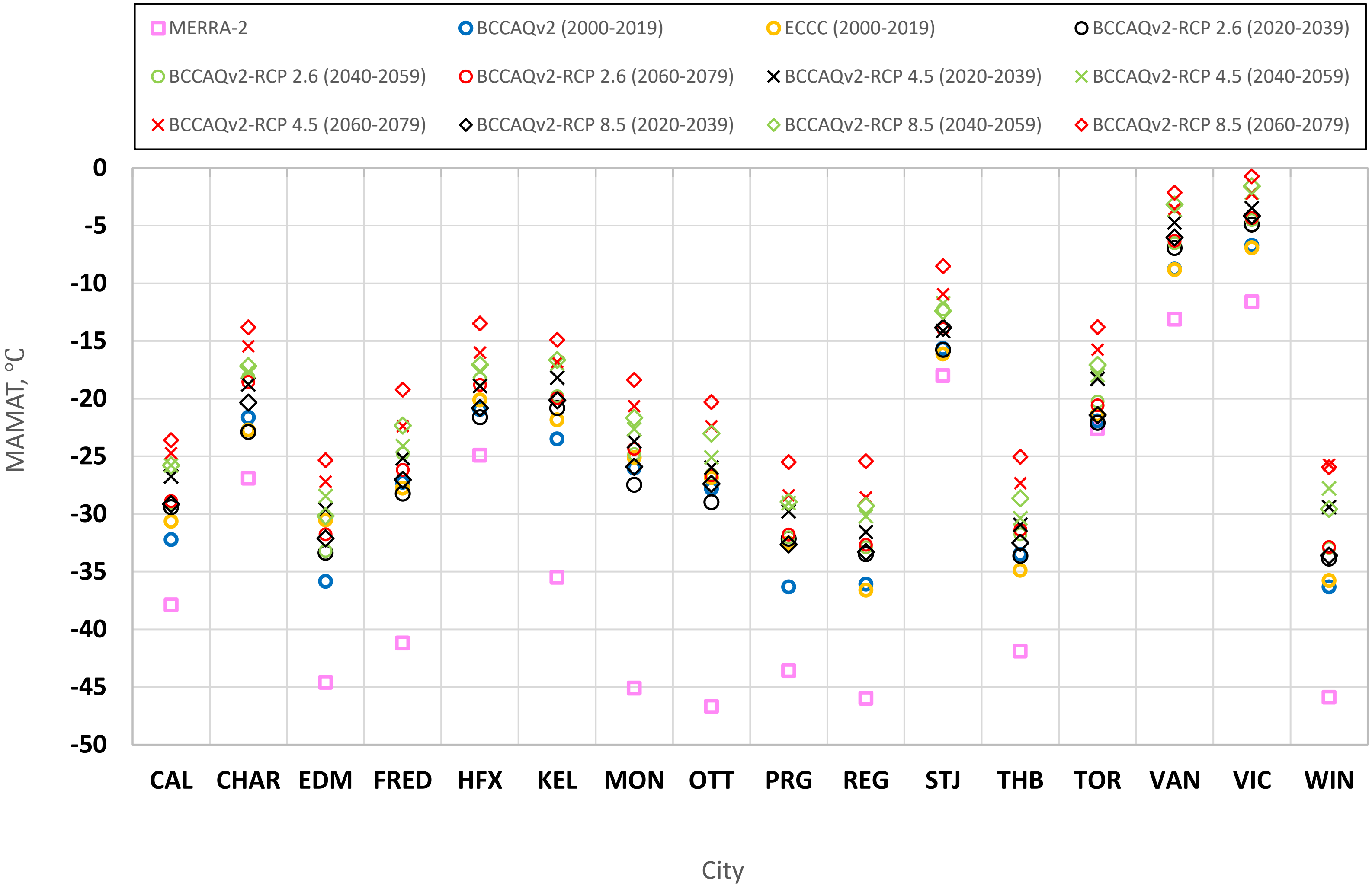


Figure 3: MAMAT for baseline and different RCP scenarios