Climate Scenarios for Saskatchewan

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EXECUTIVE SUMMARY

The most recent assessment undertaken by the Intergovernmental Panel on Climate Change (IPCC) reached a number of conclusions concerning global climate change, two of which stated that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" and that "Most of the observed increases in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations". These observed changes in climate are as a result of a global average surface air temperature increase over the 20th century of about 0.6°C. In contrast to these observed changes, global average surface air temperature is projected to increase between 1.4°C and 5.8°C by 2100, relative to 1990. This report explores how these projected global average climate changes may be manifest in Saskatchewan.

Following recommendations outlined by the IPCC, scenarios of climate change were constructed using the most recent global climate model (GCM) results available. These three-dimensional mathematical models of the Earth-atmosphere system are driven by changes in atmospheric composition through the effect of these changes on the radiation balance of this system. It is not known how atmospheric composition will change in the future, since it is dependent on a number of factors, including population and economic growth and energy use. Thus, GCM experiments are usually undertaken using a number of different greenhouse gas emissions scenarios, spanning a range of possible socio-economic futures. For this study, results were available from GCM experiments undertaken at fourteen different climate modelling centres using three emissions scenarios (B1, A1B and A2). The output from GCMs is still not sufficiently reliable to be used directly as climate input into impacts studies so it is necessary to construct scenarios of climate change. These scenarios were constructed by determining the changes in average climate for the 30-year periods centred on the 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099), relative to the 1961-1990 baseline period.

For this analysis, Saskatchewan was divided into two regions - forest and grassland. Since there are a large number of GCM experiments available, a sub-set of climate change scenarios was selected for use based on changes in annual moisture index for the 2050s. A total of five scenarios was selected to represent the smallest, largest and median changes in annual moisture index. For the forest region, these scenarios were from the Bjerknes Centre for Climate Research, Norway (BCM2 B1), the UK Meteorological Office (HadCM3 A1B) and the National Institute for Environmental Studies, Japan (MIMR B1), respectively, and from the Canadian Centre for Climate Modelling and Analysis (CGCM3_T47_2 A1B), the Geophysical Fluid Dynamics Laboratory, USA (GFCM20 B1) and, again, from the National Institute for Environmental Studies, Japan (MIMR B1), respectively, for the grassland region. For each GCM only mean temperature and precipitation information was available and so climate change scenarios were constructed for these variables.

Given the number of scenarios and variables being considered, this report has by necessity focused on annual results. Although the climate change scenarios were selected on the basis of changes in annual moisture index, i.e., on an index which combines the effect of temperature with that of precipitation, scatter plots of mean temperature change versus precipitation change were also presented. For the forest region, these scatter plots indicate that by the 2080s, annual changes in precipitation are positive in this region for all climate change scenarios considered in this analysis. For the 2020s and 2050s, a small number of scenarios indicate decreased precipitation, but these decreases are very slight – only around 5% in the 2020s and about 2% in the 2050s. Changes in mean annual temperature are positive – between 0 and 3°C in the 2020s, 1 to 5°C in the 2050s and between 2 and 7°C for the 2080s. The seasonal picture for the 2050s indicates that the largest spread in scenario results occurs in winter, with temperature changes between 0 and 7°C and mostly positive precipitation changes (up to 30%). For spring, the picture is similar, although the temperature increases are not quite as large. The summer and fall scatter plots show some scenarios with larger precipitation decreases – as much as 10% in summer and around 5% in the fall.

For the 2050s, the forest region of Saskatchewan is projected to experience increases in annual mean temperature of between 0.5 - 1.0°C (for the scenario based on the smallest change in annual moisture index) and 3.0 - 3.5°C (for the scenario based on the median change in annual moisture index). Changes in annual precipitation are between 0 and +10% for all three scenarios for the 2050s, although the median scenario indicates slightly higher increases (+10 to +20%) along the western and northern boundaries of the forest region.

When compared with the forest region, the grassland region indicates larger decreases in precipitation, with decreases in annual mean precipitation still projected for the 2080s. For the 2020s, temperature increases are between 0.5 and 3.0°C, between 1 and 5°C for the 2050s and between 2 and 6.5°C for the 2080s. Changes in the range of annual mean precipitation are similar for the 2020s and 2050s, between -10% and +25%, compared to between -5% and +35% for the 2080s. On a seasonal basis for the 2050s, scenarios projecting decreases in precipitation occur in all seasons. For summer and fall, about half the scenarios project precipitation decreases and by as much as 20 or 30%. The range of temperature increase is largest in winter and spring (between 1 and 6°C), compared to summer and fall (1 to 4°C).

For the 2050s, the grassland region of Saskatchewan is projected to experience increases in annual mean temperature of between 1.5 - 2.0°C (for the scenario based on the smallest change in annual moisture index) and 2.5 - 3.0°C (for the scenario based on the median change in annual moisture index). For precipitation, changes are similar across all time periods, generally between 0 and +10%. For the 2050s, the scenario based on the largest change in annual moisture index indicates that there are some areas of precipitation decrease (between 0 and -10%) in the south-east portion of the grassland region. The scenario based on the smallest change in annual moisture index indicates general increases in precipitation of between 10 and 20% by the 2050s, although these increases are slightly lower (between 0 and 10%) in the south-east portion of the region.

By combining these climate change scenarios with a high resolution 1961-1990 baseline climatology, it was possible to construct climate scenarios for Saskatchewan for minimum, mean and maximum temperatures and precipitation, as well as for the following derived variables: degree days > 5°C, degree days > 18°C (cooling degree days), degree days < 18°C (heating degree days) and annual moisture index for the 2020s, 2050s and 2080s. Results are presented as maps for the whole province and in more detail for Stony Rapids, Prince Albert, La Ronge, Regina, Saskatoon, North Battleford, Yorkton, Weyburn, Moose Jaw and Swift Current.

For the forest region of Saskatchewan, annual mean temperature increases over time at all three sites (Prince Albert, La Ronge and Stony Rapids). By the 2020s, the projected future climate range for La Ronge (-0.01 to 0.98°C) is as warm as baseline conditions at Prince Albert (0.58°C). For Stony Rapids, it is only by the 2080s that the projected annual mean temperature range (-1.91 to 0.4°C) approaches that of baseline conditions at La Ronge (-0.45°C). Precipitation is projected to increase across all sites and all time periods. Prince Albert (406 mm) and Stony Rapids (391 mm) currently receive less precipitation than La Ronge (494 mm). By the 2080s, Prince Albert is projected to receive between 423 and 456 mm, La Ronge between 514 and 547 mm and Stony Rapids between 419 and 446 mm. There is a general increase in the number of degree days >5°C over time at all sites. This implies a lengthening of the growing season and/or the availability of more heat units for plant growth during the growing season. Increases in the number of cooling degree days (i.e., degree days above a threshold temperature of 18°C) are also projected. Baseline conditions currently indicate no cooling degree days at all three forest sites, but as early as the 2020s the scenario range for Prince Albert is above zero (11-72 degree days) while for La Ronge and Stony Rapids this is not the case until the 2050s. Heating degree days, however, decrease over time at all three sites, indicating a reduction in the need for space heating in the future. The annual moisture index gives an indication of moisture availability for plant growth. This index increases across all time periods for all three forest sites. By the 2080s, the index values are projected to increase by at least 1 degree day/mm at each site. The scenario range for La Ronge (2.96-3.77) and Stony Rapids (2.67-3.86) for this time period encompasses baseline conditions at Prince Albert (3.41).

For the grassland region, annual mean temperature at the seven sites increases over time such that by the 2020s, the annual mean temperature is at least 1°C warmer than baseline conditions at all sites, and for Yorkton 3°C warmer (1.3°C compared with 4.3°C). By the 2080s, the projected annual mean temperature is at least double that of baseline conditions. Increases in annual precipitation totals are projected over time at all seven grassland sites. For degree days > 5°C, increases occur at all sites and all time periods. By the 2080s, the projected scenario range indicates that for most sites, degree day totals will be greater than 2000. Yorkton (1902-2177 degree days) and North Battleford (1877-2293 degree days) are the exception to this with only the higher end of the scenario range being greater than this value during this time period. For cooling degree days (degree days > 18°C) all seven grassland sites exhibit baseline values which are above zero, indicating that there may already be some requirement for air-conditioning in summer. This requirement may increase over time, since the degree day values increase. For example, by the 2080s, the cooling degree day range at Regina (257-376 degree days), Weyburn (276-407 degree days) and Yorkton (169-251 degree days) is projected to be between 3 and 5 times greater than baseline conditions for Regina (69 degree days) and Weyburn (75 degree days), but between 14 and 20 times greater than baseline conditions at Yorkton (12 degree days). In contrast, projections for heating degree days (degree days < 18°C) are for a reduction in degree day totals across all sites. For annual moisture index, increases occur across all sites and all time periods. Yorkton and North Battleford currently exhibit the lowest annual moisture index values (3.4 and 4.2 degree days/mm, respectively). By the 2080s, these values have increased to between 3.9 and 4.7 degree days/mm for Yorkton and to between 4.7 and 5.6 degree days/mm for North Battleford. Moose Jaw and Saskatoon currently exhibit the largest baseline values (both 4.7 degree days/mm). By the 2080s, annual moisture index values are projected to be between 5.3 and 6.4 degree days/mm for Moose Jaw and between 5.2 and 6.2 degree days/mm for Saskatoon.

1: INTRODUCTION

In 2007, the Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report (AR4; IPCC, 2007), in which the following conclusions were reached:

- Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.
    - Eleven of the last twelve years (1995-2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850).
    - Mountain glaciers and snow cover have declined on average in both hemispheres.
- At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.
    - Average arctic temperatures increased at almost twice the global average rate in the past 100 years.
    - Satellite data since 1978 show that annual average arctic sea ice extent has shrunk by 2.7 [2.1 to 3.3]% per decade, with larger decreases in summer of 7.4 [5.0 to 9.8]% per decade.
    - Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic (by up to 3°C). The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15%.
    - Long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia.
    - Mid-latitude westerly winds have strengthened in both hemispheres since the 1960s.
    - More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought.
    - Changes in sea surface temperatures, wind patterns and decreased snowpack and snow cover have also been linked to droughts. The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapour.
    - Widespread changes in extreme temperatures have been observed over the last 50 years. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent.
- Palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 m of sea level rise.
- Most of the observed increases in global average temperatures since the mid-20th century is *very likely*[1] due to the observed increase in anthropogenic greenhouse gas concentrations.

[1] The IPCC used the following terms to indicate the assessed likelihood, using expert judgement, of an outcome or a result: *Virtually certain* > 99% probability of occurrence, *Extremely likely* > 95%, *Very likely* > 90%, *Likely* > 66%, *More likely than not* > 50%, *Unlikely* < 33%, *Very unlikely* < 10%, *Extremely unlikely* < 5%.

This is an advance since the TAR's[2] conclusion that "most of the observed warming over the last 50 years is *likely* to have been due to the increase in greenhouse gas concentrations". Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns. (Figure 1).

- For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES[3] emission scenarios. Even if the concentrations of all greenhouse gases and aerosols

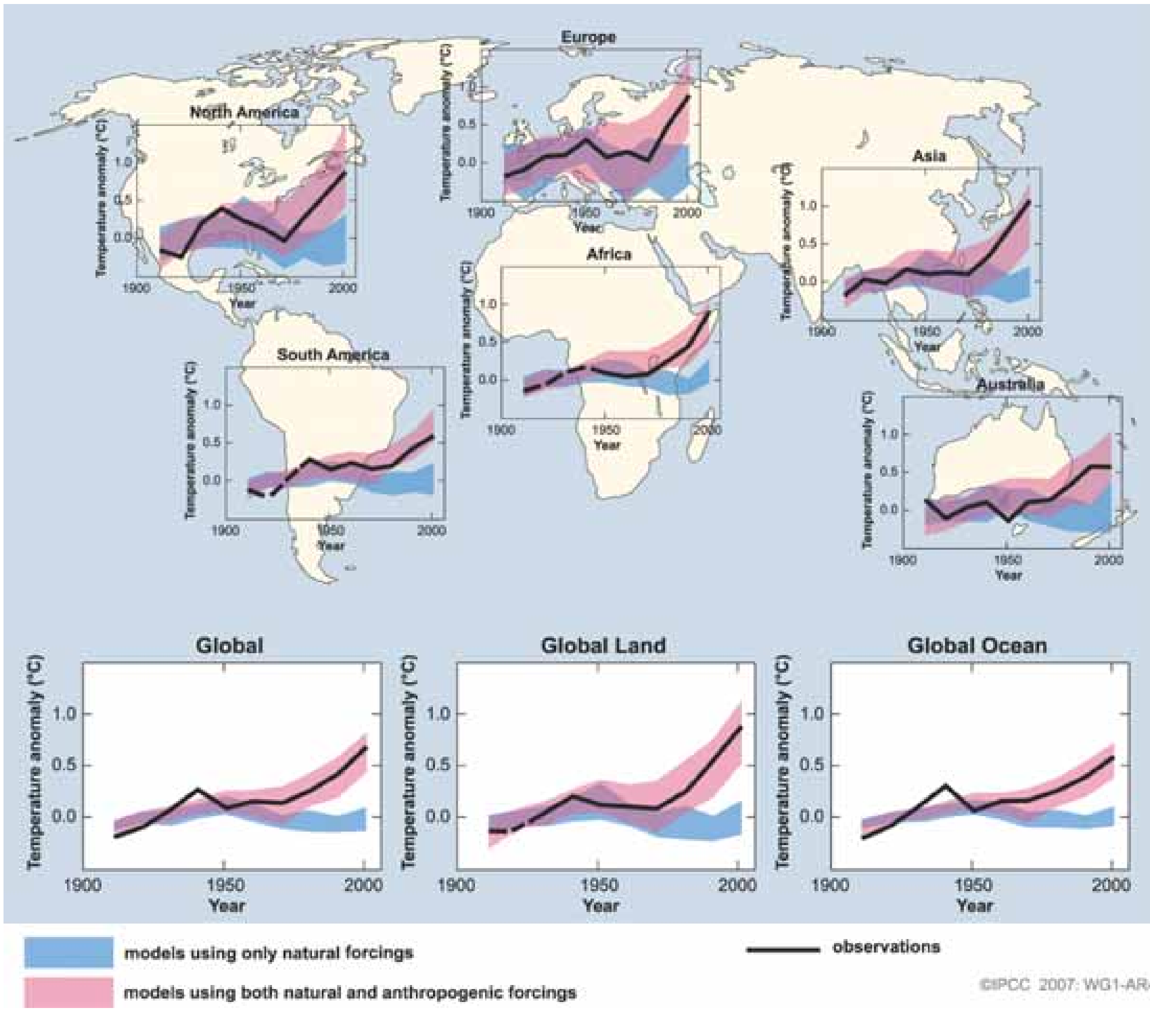

Figure 1: Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901-1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5-95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5-95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. [Source: IPCC (2007)]

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2 The IPCC's Third Assessment Report, published in 2001 (IPCC, 2001).

3 The IPCC Special Report on Emissions Scenarios (Nakicenovic *et al*., 2000).

had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. (Figure 2)

- Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.

Given these conclusions, how may climate evolve in Saskatchewan in response to continued greenhouse gas emissions? This report describes changes in average climate that may occur in Saskatchewan by examining a number of different climate change scenarios. Some background is provided about the construction and selection of climate change scenarios, before these possible future climates are described.

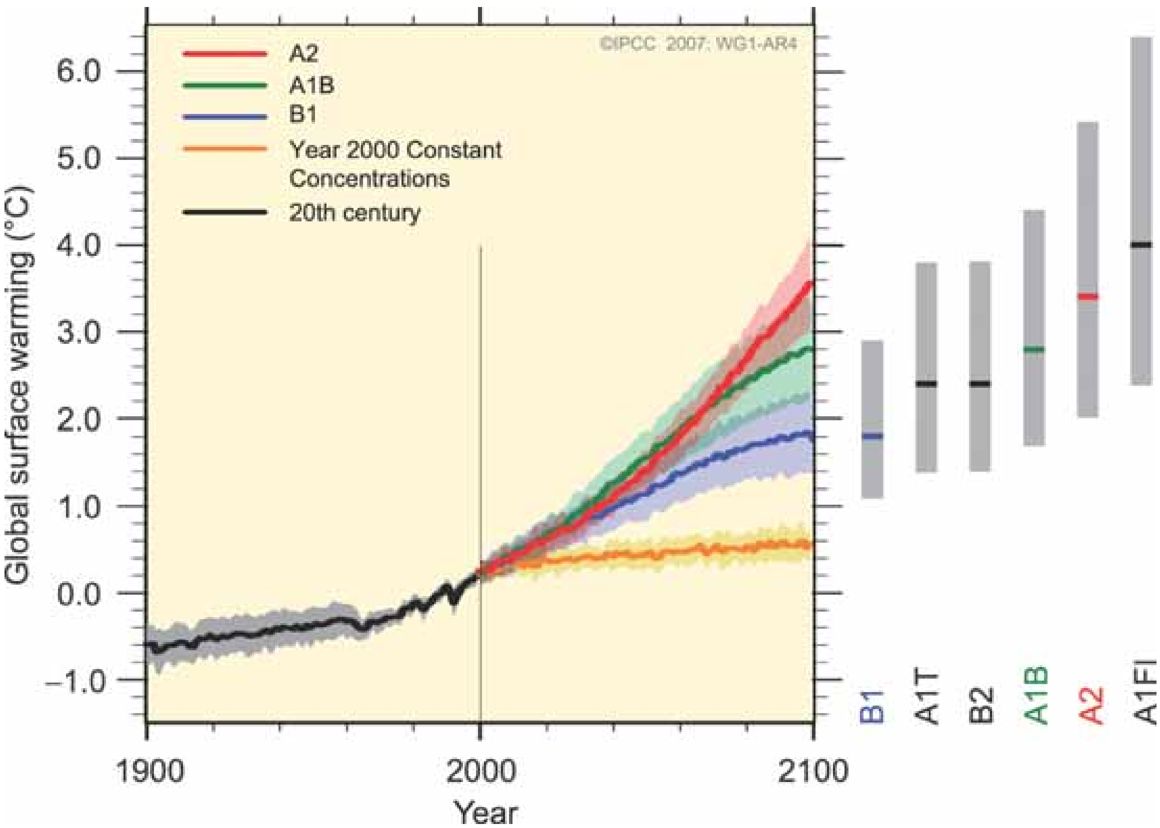


Figure 2: Multi-model averages and assessed ranges for surface warming. Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of the individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. [Source: IPCC (2007)]

2: SCENARIOS

A scenario is defined as a "… coherent, internally consistent, and plausible description of a possible future state of the world" (IPCC, 1994). Given large uncertainties associated with the evolution of future conditions, be they population, economic growth, greenhouse gas emissions or climate to name but a few, the level of confidence associated with a particular future is not yet sufficient to permit a scenario to be referred to as a prediction or a forecast. The roles that scenarios may play in the assessment of climate change impacts are described in the IPCC Third Assessment Report (TAR; IPCC, 2001):

- For the *illustration of climate change*: for example, by depicting the future climate expected in a given region in terms of the present-day climate currently experienced in a familiar neighbouring region.
- For *communication of the potential consequences of climate change*: for example, by specifying a future changed climate to estimate potential future shifts in natural vegetation and identifying species at risk of local extinction. Used in this way, scenarios are awareness-raising devices.
- For *strategic planning*: for example, by quantifying possible future sea-level and climate changes to design effective coastal or river flood defences.
- For *guiding emissions control policy:* for example, by specifying alternative socio-economic and technological options for achieving some pre-specified atmospheric greenhouse gas concentrations.
- For *methodological purposes:* by determining our knowledge (or ignorance) of a system through, for example, the description of altered conditions, the use of a new scenario development technique, or by evaluating the performance of impact models and determining the reasons for any differences in results.
- *To explore the implications of decisions*: by examining the impacts resulting from a particular scenario of future climate and the actions taken to ameliorate particular harmful impacts associated with the scenario.

For this report, the focus is on the illustration of climate change, and in order to do this three types of scenarios must be considered – *emissions* scenarios, *climate change* scenarios and *climate* scenarios.

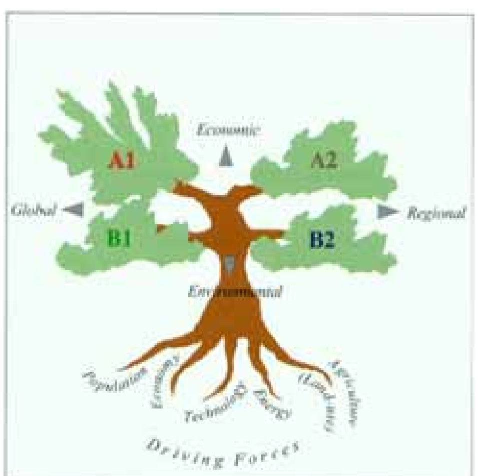


Figure 3: Schematic illustration of the SRES scenarios. The four scenario 'families' are shown, very simplistically, as branches of a two-dimensional tree. In reality, the four scenario families share a space of a much higher dimensionality given the numerous assumptions needed to define any given scenario in a particular modelling approach. The schematic diagram illustrates that the scenarios build on the main driving forces of GHG emissions. Each scenario family is based on a common specification of some of the main driving forces. The A1 storyline branches out into four groups of scenarios to illustrate that alternative development paths are possible within one scenario family. [Source: Nakicenovic *et al*., 2000]

2.1: Emissions Scenarios

Future emissions of greenhouse gases (GHGs) and aerosols into the atmosphere depend very much on factors such as population and economic growth and energy use. For its TAR (IPCC,

2001) the IPCC commissioned a *Special Report on Emissions Scenarios* (SRES; Nakicenovic *et al*., 2000), in which about forty different emissions scenarios were developed. These could be classified into four families, depending on whether or not the scenarios had a global or regional development focus or were driven by environmental rather than economic considerations (Figure 3).

Table 1: Summary descriptions of the six illustrative SRES scenarios.

Emissions Scenario	**Description**
A1FI	A future world of very rapid economic growth and intensive use of fossil fuels
A1T	A future world of very rapid economic growth, and rapid introduction of new and more efficient technology
A1B	A future world of very rapid economic growth, and a mix of technological developments and fossil fuel use
A2	A future world of moderate economic growth, more heterogeneously distributed and with a higher population growth rate than in A1
B1	A convergent world with rapid change in economic structures, 'dematerialisation', introduction of clean technologies, and the lowest rate of population growth
B2	A world in which the emphasis is on local solutions to economic, social and environmental sustainability, intermediate levels of economic development and a lower population growth rate than A2

Of these forty emissions scenarios, six have been chosen as marker scenarios: A1FI, A1B, A1T, A2, B1 and B2, and are described briefly in Table 1. The global-mean temperature changes associated with the SRES emissions scenarios are illustrated in Figure 2 and also in Table 2. The AIFI and B1 emissions scenarios result in the highest and lowest increases in global-mean temperature by the end of the 21st Century, respectively. Emissions of greenhouse gases and aerosols into the atmosphere are the driving force for climate change, since it is the atmospheric concentration of these compounds, produced via both anthropogenic and natural activities, which determines the effect on the energy balance of the Earth-atmosphere-ocean system, and thus on climate. Global climate models (GCMs) are the mechanism through which greenhouse gas and aerosol emissions can be translated into physically-consistent effects on climate.

Table 2: Projected global average surface warming at the end of the 21st century

	Temperature Change (°C at 2090-2099 relative to 1980-1999)	
Case	Best estimate	Likely range
Constant Year 2000 concentrations	0.6	0.3 – 0.9
B1 scenario	1.8	1.1 – 2.9
A1T scenario	2.4	1.4 – 3.8
B2 scenario	2.4	1.4 – 3.8
A1B scenario	2.8	1.7 – 4.4
A2 scenario	3.4	2.0 – 5.4
A1FI scenario	4.0	2.4 – 6.4

2.1.1: Global Climate Models

Global Climate Models (GCMs) are three-dimensional mathematical models which represent the physical processes of, and the known feedbacks between, the atmosphere, ocean, cryosphere and land surface. They can be used for the simulation of past, present, and future climates and have undergone considerable evolution since their first appearance about forty years ago, largely as a result of the substantial advances in computing technology during this time. Most GCMs have a horizontal resolution of between 250 and 600 km, with 10 to 20 vertical layers in the atmosphere and as many as 30 layers in the ocean. This resolution is quite coarse, particularly when considered in comparison with the scales at which most impacts studies are conducted, and means that it is impossible to model directly some of the smaller-scale atmospheric and oceanic processes (e.g., precipitation formation). Such processes have to be averaged over larger scales, or parameterised, i.e., related to other variables that are explicitly modelled.

Warm-start transient response GCMs are the most advanced models of this type and consist of coupled three-dimensional atmosphere-ocean models. The inclusion of oceanic circulation and transfers of heat and moisture from the ocean surface permit the simulation of the time-dependent response of climate to changes in atmospheric composition, and thus provides useful information about the rate as well as the magnitude of climate change. Warm start GCMs simulate the effects of past changes in radiative forcing, i.e., the effect of historical changes in atmospheric composition (typically from the 18th or 19th century) on the radiation balance of the atmosphere. Simulations are then continued into the future using a scenario of future radiative forcing, which is derived from an emissions scenario, such as one described in Section 2.1. The output from GCM experiments provides the basis for the main method of climate change scenario construction.

2.2: CLIMATE CHANGE AND CLIMATE SCENARIOS

Climate change scenarios can be constructed in a number of different ways, but to ensure that they are of most use for impact researchers and policy makers, the following four criteria were put forward to aid scenario selection (Smith and Hulme, 1998):

1. *Consistency at the regional level with global projections*: Scenarios should be consistent with a broad range of global warming projections based on increased concentrations of greenhouse gases.
2. *Physical plausibility*: Changes in climate should be physically plausible, such that changes in different climatic variables are mutually consistent and credible, both spatially and temporally.
3. *Applicability in impact assessments*: Scenarios should describe changes in a sufficient number of climate variables on a spatial and temporal scale that allows for impact assessment.
4. *Representativeness*: Scenarios should be representative of the potential range of future regional climate change in order for a realistic range of possible impacts to be estimated.

Climate change scenarios constructed using GCM output generally conform better with the assumptions listed above than those constructed using other techniques, such as synthetic or analogue approaches. For details of the full range of climate change scenario construction techniques, see Chapter 13 of the IPCC Third Assessment Report (IPCC, 2001).

Table 3: Characteristics of the GCMs available for climate change scenario construction.

Climate Modelling Centre	**Model**	**SRES simulations**	**Resolution**
Bjerknes Centre for Climate Research, Norway (BCCR)	BCM2	A1B, B1	≈1.9°×1.9°
Canadian Centre for Climate Modelling and Analysis (CCCma)	CGCM3_T47*	A1B, A2, B1	≈2.8°×2.8°
	CGCM3_T63	A1B, A2, B1	≈1.9°×1.9°
Centre National de Recherches Meteorologiques, France (CNRM)	CNCM3	A1B, A2	≈1.9°×1.9°
Commonwealth Scientific and Industrial Research Organisation, Australia (CSIRO)	CSMK3	A1B, A2, B1	≈1.9°×1.9°
Geophysical Fluid Dynamics Laboratory, USA (GFDL)	GFCM20	A1B, A2, B1	2.0°×2.5°
Goddard Institute for Space Studies, USA (GISS)	GIAOM	A1B, B1	3°×4°
UK Meteorological Office (UKMO)	HADCM3	A1B, A2, B1	2.5°×3.75°
	HADGEM	A1B, A2	≈1.3°×1.9°
National Institute of Geophysics and Volcanology, Italy (INGV)	INGSXG	A1B	≈1.1°×1.1°
Institute for Numerical Mathematics, Russia (INM)	INCM3	A1B, B1	4°×5°
Meteorological Institute, University of Bonn, Germany (MIUB) Meteorological Research Insitute of KMA, Korea (METRI) Model and Data Group at MPI-M, Germany (M&D)	ECHOG	A1B, A2	≈3.9°×3.9°
Max-Planck Institute for Meteorology, Germany (MPI-M)	MPEH5	A1B, A2, B1	≈1.9°×1.9°
Meteorological Research Institute, Japan (MRI)	MRCGCM	A1B, A2, B1	≈2.8°×2.8°
National Center for Atmospheric Research, USA (NCAR)	NCCCSM	A1B, A2, B1	1.4°×1.4°
	NCPCM	A1B, A2	≈2.8°×2.8°
National Institute for Environmental Studies, Japan (NIES)	MIHR	A1B, B1	≈1.1°×1.1°
	MIMR	A1B, A2, B1	≈2.8°×2.8°
* Five experiments were undertaken with each of the emissions scenarios for this GCM.			

Given the number of GCMs currently available and the fact that new experiments are continually being added, Smith and Hulme (1998) proposed four criteria for selecting GCM outputs suitable for climate change scenario construction from the large sample of experiments available:

1. *Vintage*: Recent model simulations are likely (though by no means certain) to be more reliable than those of an earlier vintage since they are based on recent knowledge and incorporate more processes and feedbacks.
2. *Resolution*: In general, increased spatial resolution of models has led to better representation of climate.

3. *Validation*: Selection of GCMs that simulate the present-day climate most faithfully is preferred, on the premise that these GCMs are more likely (though not guaranteed) to yield a reliable representation of future climate.
4. *Representativeness of results*: Alternative GCMs can display large differences in the estimates of regional climate change, especially for variables such as precipitation. One option is to choose models that show a range of changes in a key variable in the study region.

Parry (2002) describes the criteria used to determine which GCM experiments are made available through the IPCC Data Distribution Centre (DDC; www.ipcc-data.org), the web site established by the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA) to facilitate the provision of GCM output and climate change scenarios to the impacts and adaptation research community. The TGICA provides guidelines and recommendations for the construction and use of scenarios in order to encourage consistency in climate change impacts and adaptation research (IPCC-TGICA, 2007). All GCMs and experiments on the DDC must have met the following criteria:

- be full three-dimensional coupled ocean-atmosphere GCMs,
- be documented in the peer-reviewed literature,
- have performed a multi-century control run[4] (for stability reasons), and
- have participated in the Second Coupled Model Intercomparison Project (CMIP2; http://www-pcmdi.llnl.gov/cmip/cmiphome.html).

In addition, GCMs which have a resolution of at least 3°×3°, which have participated in the Atmospheric Model Intercomparison Project (AMIP; http://www-pcmdi.llnl.gov/amip/) and which consider explicit greenhouse gases (e.g., carbon dioxide, methane, nitrous oxide etc.) are preferred. Table 3 indicates the GCMs and associated SRES experiments that are available from the IPCC DDC and which were available for use in this study.

2.2.1: Construction of climate change scenarios

Although advances in computing technology have enabled large increases in the spatial and temporal resolution of GCMs over the last few years, the conclusion of Mearns *et al*. (1997) that their results are still not sufficiently accurate (in terms of absolute values) at regional scales to be used directly in impacts studies is still valid. Instead, mean differences between the model's representation of current climate (this baseline period is currently 1961-1990) and some time period in the future are calculated (see Figure 4). Thirty-year periods are used to define the baseline and future time periods since averaging over this length of time gives a better indication of the longer-term trend in climate than does a shorter interval. The changes between the future and baseline periods are calculated on a grid-box by grid-box basis and are referred to as *change fields* or *climate change scenarios*. Conventionally, differences (future climate minus baseline climate) are used for temperature variables and ratios (future climate/baseline climate), often expressed in percent terms, are used for other variables such as precipitation and wind speed.

The IPCC TGICA currently recommends that three fixed time horizons in the future, the 2020s (i.e., 2010-2039), the 2050s (2040-2069), and the 2080s (2070-2099), are considered in impacts

[4] A control run is carried out with all GCMs and is an experiment in which the atmospheric composition is set at or near pre-industrial conditions and there are no changes in forcing for the duration of the run. Output from such a simulation provides valuable information about the stability of the model (e.g., if there are errors in the model formulation, it may drift towards an unrealistic climate over time) and the model's representation of natural climate variability.

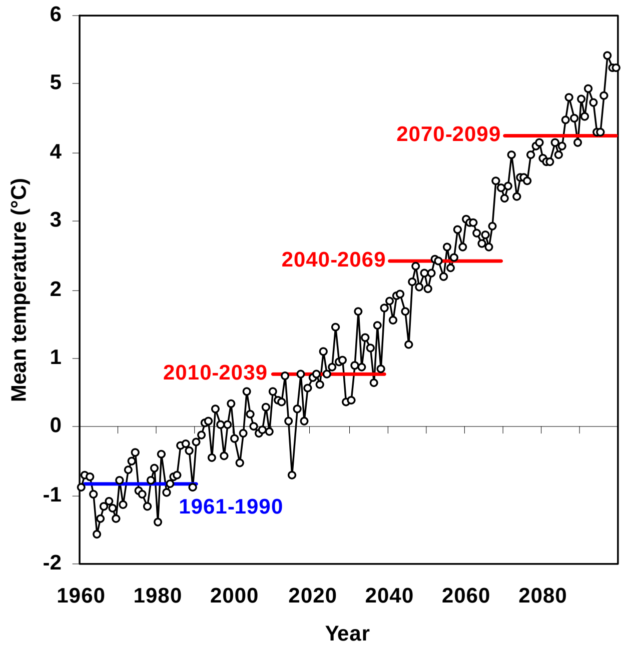


Figure 4: Schematic illustrating the construction of climate change scenarios from GCM output. The graphic shows the time series of mean surface air temperature for the Canadian land area from the CGCM2 simulation forced by the SRES A2 emissions scenario. The blue line indicates the 30-year mean for the 1961-1990 baseline period, whilst the red lines indicate the 30-year mean values for the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099). Scenarios are constructed by calculating the difference, or ratio, between the time means of the future and baseline periods. To create a climate change scenario, this process is carried out for each grid box in the region of interest.

studies. To obtain a *climate scenario*, i.e., a representation of the 'actual' future climate rather than simply the change in climate relative to the baseline period, the climate change scenario is combined with some baseline *observed* climate data set (IPCC-TGICA, 2007). Most climate change scenarios derived from GCM output are generally at monthly or seasonal time scales, and can be combined with observed baseline climate information from daily to seasonal resolution. Since the climate change scenario is combined with observed climate baseline data, the climate scenario will have the same variability as the observed baseline. This may not necessarily be the case in the future, and whilst some simple methods exist for imposing changes in variability on a scenario (generally at site rather than regional scales), the climate variability issue is so complex (consideration to changes in variability must be given over a range spatial and temporal scales) that scenario construction techniques which include climate variability changes have not yet been developed.

For this study, climate change scenarios were constructed according to the IPCC-TGICA guidelines using the GCM output made available on the IPCC DDC for their Fourth Assessment Report (see Table 3). Thus, a total of 56 climate change scenarios were available.

2.2.2: Selecting which climate change scenarios to use

One of the main problems in climate change scenario studies is selecting the number of scenarios to use. The ideal would be to use all available scenarios to build a complete picture of the range of future climate (to the best of our current knowledge), and thus impact response to changes in atmospheric composition. Even though some climate change scenarios may appear to be very similar, non-linearities in impact response can lead to quite different results. However, sufficient resources are seldom available for such studies and in any case the amount of data being dealt with soon becomes overwhelming. On the other hand, use of a single climate change scenario is not recommended for anything other than arbitrary exercises exploring the effect of a change in a particular climate variable on impact response. The IPCC TGICA currently recommends that a number of climate change scenarios are used and that these scenarios should attempt to capture the range of possible future climate in a particular region. One way of selecting these scenarios is to examine changes in particular climate variables over the region of interest and then to select scenarios which span the range of changes. If it is known that the particular impact sector under study is most sensitive to changes in particular climate variables in a certain season, then the changes in these variables in that season can be used to define which climate change scenarios are used.

For many studies, climate change scenarios may be selected based on examination of scatter plots of mean temperature change and precipitation change, thus leading to scenarios which represent cooler and drier, cooler and wetter, warmer and drier, and warmer and wetter conditions when compared to the complete set of scenarios available. For this study, a slightly different approach was used, since we wanted to examine the *combined* effect of temperature with precipitation, since it was felt that this would be a more realistic factor for determining Saskatchewan's vulnerability to climate change than using, in effect, single climate variables . To do this, the annual moisture index[5] was used. This index combines the effect of temperature through the use of degree days above a threshold temperature of 5°C (i.e., a measure of the warmth available during the growing season) with that of annual precipitation. Larger values of the index indicate that moisture availability will be limiting, while smaller values indicate the availability of less heat but of more moisture.

In order to construct scenarios for annual moisture index[6] (AMI), we needed first to calculate the number of degree days (DDs) above a threshold temperature of 5°C (DD5). These are often referred to as growing degree days since they give a general indication of the warmth of the growing season. Calculation of DDs is based on daily mean temperature information. One of the limitations of using GCM information for climate change scenario construction is that one is often constrained by the lack of daily data available from climate change experiments undertaken with these models. Many climate modelling centres archive only a limited amount of daily data simply because they do not have the resources for storing the huge quantities of data that are quickly generated in climate change experiments. So, although there are some daily data available, they are for a limited number of climate change experiments. In order to construct climate change scenarios for DD5, it was therefore necessary to devise a means of determining daily data from the monthly GCM output available.

[5] Annual moisture index (AMI) is degree days > 5°C / mean annual precipitation
[6] Annual moisture index is degree days >5°C/mean annual precipitation.

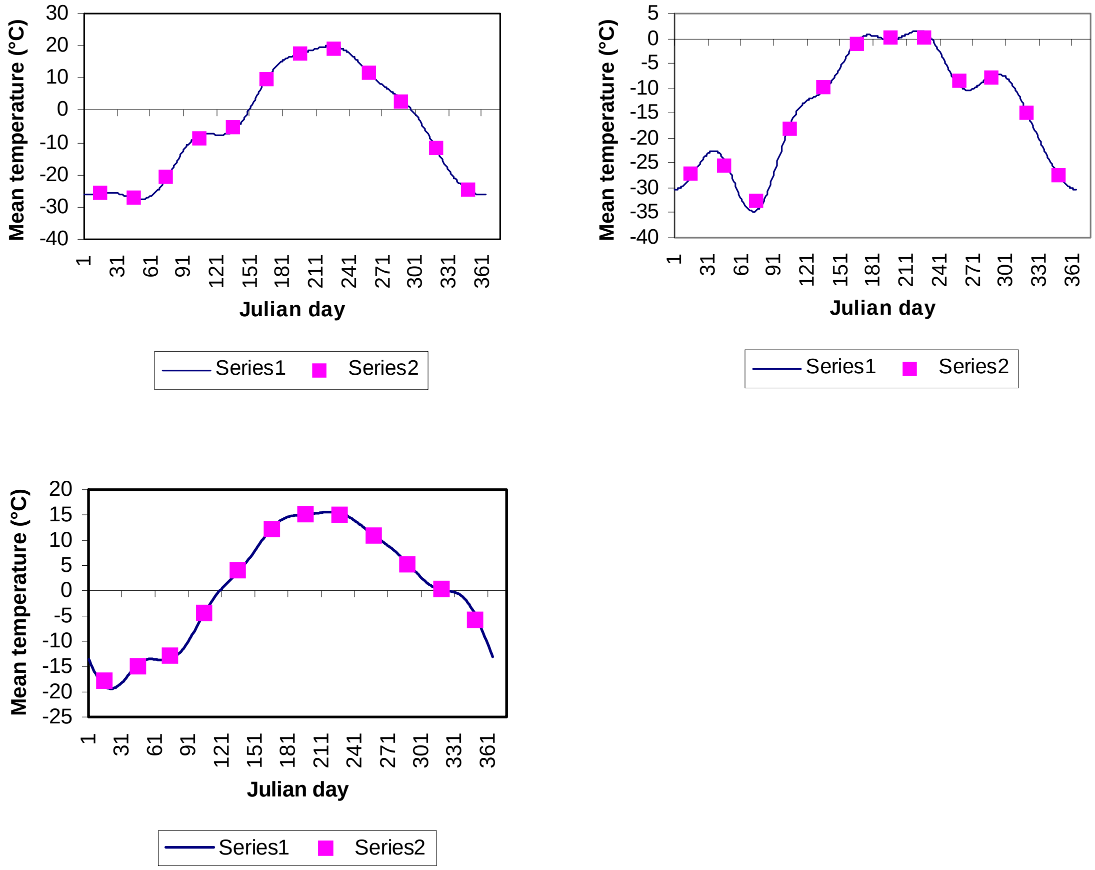


Figure 5: Examples of the harmonic fit algorithm used to derive daily mean temperature from monthly mean temperature values. GCM monthly mean temperatures are indicated by the pink squares (series 2), whilst the daily mean temperature values are shown by the black line (series 1). Each graphic illustrates output from a different grid box for a single year.[Source: Barrow and Yu (2005)]

A relatively simple method was adopted for obtaining daily climatological values from monthly means (Epstein, 1991). This method is based on a harmonic fit and improves upon a simple linear interpolation between monthly means since it allows the daily values to exceed the maximum monthly value and to be less than the minimum monthly value whilst linearly interpolated daily values will always lie within the range of the monthly means.

In this method (Epstein, 1991), the unknown daily climatology can be represented by the sum of harmonic components:

$$y(t) = a_0 + \sum_j \left[a_j \cos\left(\frac{2\pi jt}{12}\right) + b_j \sin\left(\frac{2\pi jt}{12}\right)\right], \text{ j=1,6} \qquad (1)$$

where t is time (months), and

$$a_0 = \sum_T \frac{Y_T}{12}$$

$$a_j = \left[\left(\frac{\pi j}{12}\right) / \sin\left(\frac{\pi j}{12}\right)\right]\sum_T \left[Y_T \cos\left(\frac{2\pi jT}{12}\right) / 6\right] \quad j=1,5$$

$$b_j = \left[\left(\frac{\pi j}{12}\right) / \sin\left(\frac{\pi j}{12}\right)\right]\sum_T \left[Y_T \sin\left(\frac{2\pi jT}{12}\right) / 6\right] \quad j=1,5$$

$$a_6 = \left[\left(\frac{\pi}{2}\right) / \sin\left(\frac{\pi}{2}\right)\right]\sum_T \left[Y_T \cos(\pi T) / 12\right]$$

$$b_6 = 0.0$$

The value of t in Equation (1), for the mth day of month number T is given by $t=(T-0.5)+(m-0.5)/D$, where D is the number of days in month T. Y_T are the climatological monthly mean values.

This approach had been previously tested using monthly mean temperature for a number of individual grid boxes to ensure that this algorithm performed well (Barrow and Yu, 2005; Figure 5). In order to be consistent with how these derived climate variables were calculated for the baseline climate (see Section 3), this algorithm was applied to the 30-year mean values for the four time periods (1961-1990, 2010-2039, 2040-2069 and 2070-2099) and for each grid box in the region of interest. Degree days above a threshold of 5°C were then calculated by summing the difference between the daily mean temperature and the threshold temperature on days when the mean temperature exceeded the threshold temperature. Once the DD5 had been calculated, it was possible to calculate the AMI by dividing the degree day totals by the annual mean precipitation for each time period. In order to construct climate change scenarios for these two variables, the changes between the baseline and future time periods were then expressed in percentage terms.

For climate change scenario selection purposes, Saskatchewan was divided into two regions (see Figure 6): a northern forest region and a southern grassland region. Climate change scenarios were averaged over these two regions and the results examined in order to determine which scenarios to use. Figure 7 shows box-and-whisker plots of the range of annual moisture index (AMI) change (with respect to 1961-1990), in percent, for these two regions. Using the results for the 2050s, the following climate change scenarios were selected for use:

- Forest
    - Largest change in AMI: HadCM3 A1B
    - Smallest change in AMI: BCM2 B1
    - Median change in AMI: MIMR B1
- Grassland
    - Largest change in AMI: GFCM20 B1
    - Smallest change in AMI: CGCM3_T47_2 A1B
    - Median change in AMI: MIMR B1

In this case, the median change scenario selected is the same for the forest and grassland regions, i.e., MIMR B1. Hence, a total of five climate change scenarios were selected for use. For each of these five scenarios, only mean temperature and precipitation information were available.

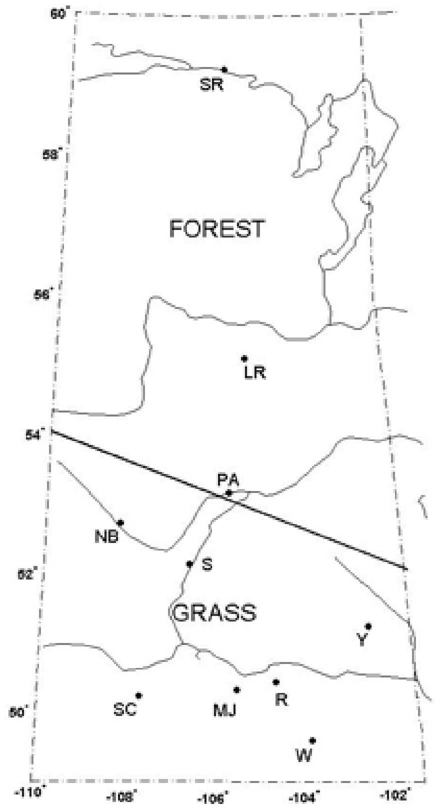
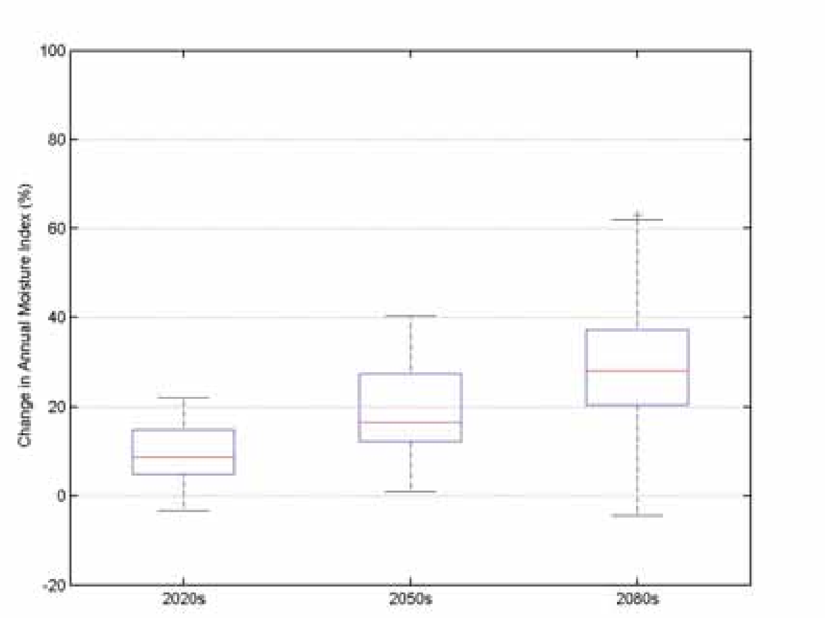


Figure 6: Map of Saskatchewan showing boundary (black line) between forest and grassland regions and major towns: SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

2.2.3: Applying climate change scenarios

The next step in the climate change scenario process is to calculate the climate scenarios, i.e., the representations of 'actual' climate for the 2020s, 2050s and 2080s. Here, the five climate change scenarios selected for use in Section 2.2.2 were combined with the 1961-1990 baseline climatology (see Section 3). This observed baseline climatology is at a resolution of 0.0416667° latitude by 0.0416667° longitude compared with resolutions ranging from 1.9° to 2.8° for the GCM-derived climate change scenarios. Obviously there is a mismatch of spatial scales and so the climate change scenarios were interpolated to 0.5° latitude/longitude resolution using a bilinear two-dimensional interpolation routine available in the MATLAB® software package. This interpolation procedure smoothes the discontinuities between the coarse GCM grid boxes and, given the coarse nature of the climate change scenario data, it was felt that no further value would be added to this data by interpolating to the same resolution as the baseline climatology. Figure 8 illustrates the effect of interpolating coarse-scale data to 0.5° latitude/longitude resolution (Barrow and Yu, 2005). The interpolated climate change scenario information was then applied to the observed baseline climatology. Each 0.5° resolution scenario grid box contains 12 grid boxes for the baseline climatology. Climate scenarios were constructed for the 2020s, 2050s and 2080s by matching the scenario grid boxes with the baseline climatology grid boxes and applying the appropriate scenario changes to the baseline data.

Forest



Grassland

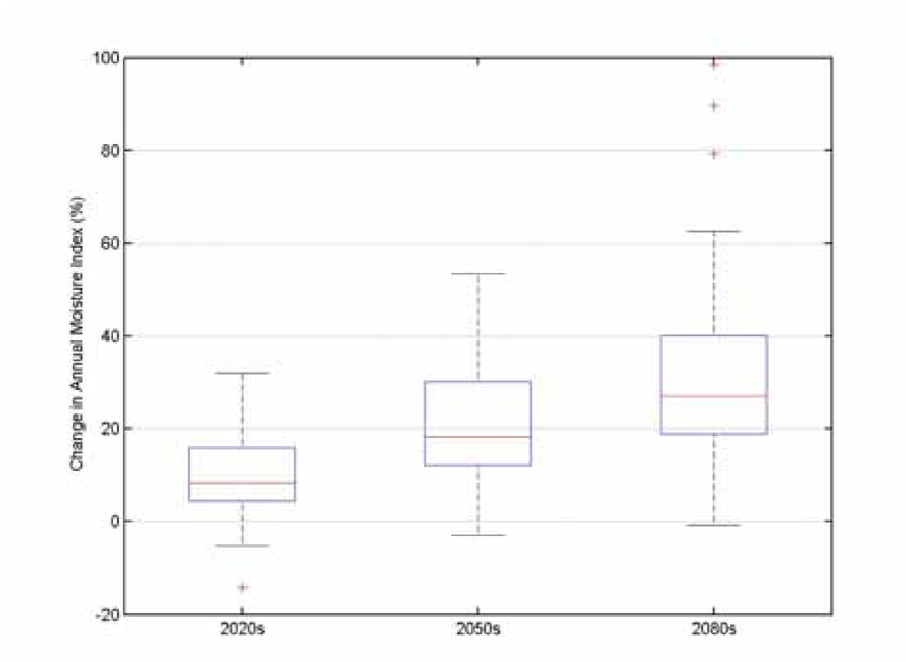


Figure 7: Box-and-whisker plots indicating the range of change in Annual Moisture Index (%), with respect to 1961-1990, the 56 climate change scenarios considered in this study. These statistical plots provide summary information about a data sample, in this case the climate changes over the forest (top) and grassland (bottom) regions. The box (blue) and enclosed line (red) define the upper and lower quartiles, and median value, respectively. The whiskers are the lines extending from each end of the box to show the extent of the rest of the data. If there are outliers in the data, indicated by '+' symbols, then the whisker length is 1.5 × inter-quartile range.

Original GCM resolution **Interpolated to 0.5° latitude/longitude**

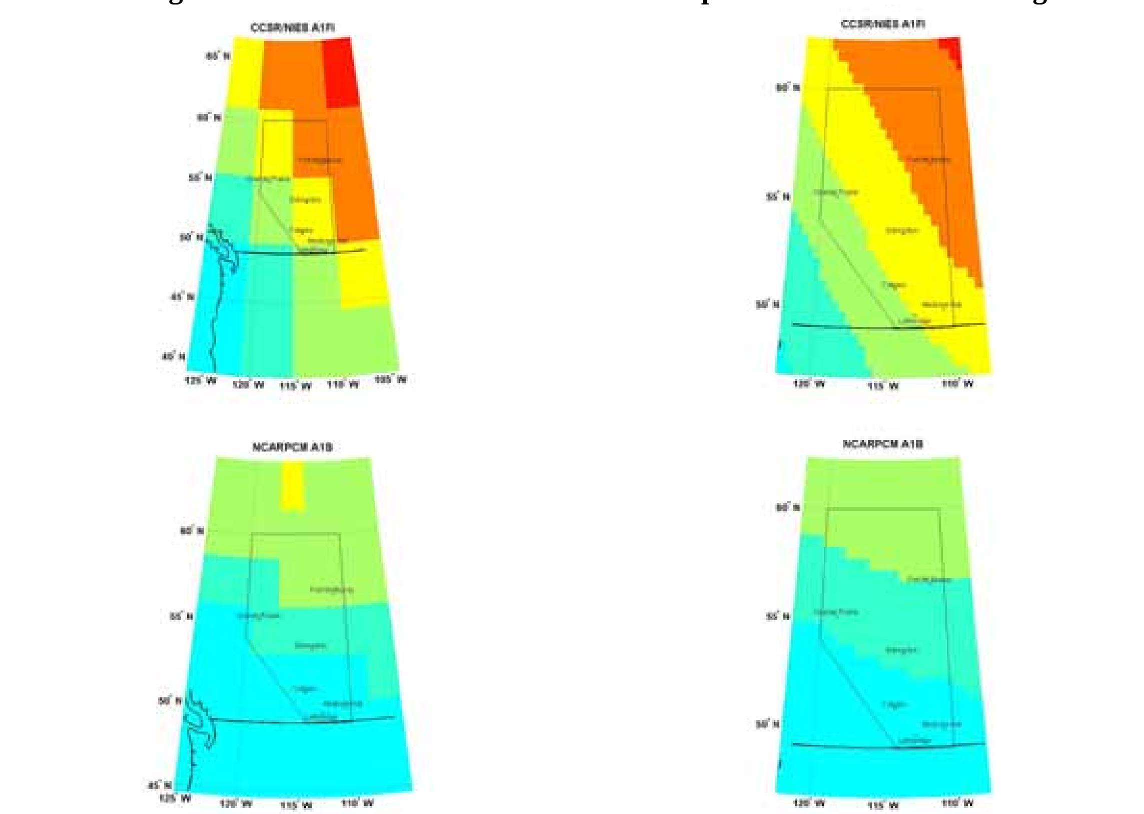


Figure 8: Examples of interpolating coarse-scale climate change scenario information to 0.5° latitude/longitude resolution, using a bilinear 2D interpolation procedure. Changes in mean temperature for the 2050s for two climate change scenarios, CCSRNIES A1FI and NCARPCM A1B, are shown. [Source: Barrow and Yu (2005)]

Since the only climate variables available for the selected scenarios were mean temperature and precipitation, climate scenarios for maximum and minimum temperature were derived by applying mean temperature change scenarios to the baseline maximum and minimum temperature climatologies, respectively. Climate scenarios for annual moisture index and degree days above 5°C (DD5), degree days above 18°C (CDD) and degree days below 18°C (HDD), were calculated by applying the appropriate changes in mean temperature and precipitation to the baseline climate and then recalculating these values, as described in Section 2.2.2, for each of the future time periods. Cooling (CDD; DDs > 18°C) and heating (HDD; DDs < 18°C) degree days are used by the energy industry to give an indication of the amount of energy that may be required for air-conditioning in summer and space heating in winter, respectively. Note that the methodology described in Section 2.2.2 for calculating daily climatological values from monthly means tends to lead to an underestimation of the number of cooling degree days. This is because the more 'extreme' days which will add greatly to cooling degree day totals are not captured well by this methodology.

2.2.4: Climate Change Scenarios for Saskatchewan

This section describes climate change scenarios for Saskatchewan constructed according to the methodology described above. Climate change scenarios are described for the forest and grassland regions. Maps for annual changes only are contained in the main text, while maps for seasonal changes for the 2050s are included in Appendix A.

2.2.4.1: Forest

Scatter plots of mean temperature change versus precipitation change are given for annual conditions for the 2020s, 2050s and 2080s in Figure 9, and by season for the 2050s in Figure 10. The annual scatter plots show that by the 2080s, projected changes in precipitation are positive in this region for all climate change scenarios considered in this analysis. For the 2020s and 2050s, a small number of scenarios indicate decreased precipitation, but these decreases are very slight – only around 5% in the 2020s and about 2% in the 2050s. Changes in mean annual temperature are positive – between 0 and 3°C in the 2020s, 1 to 5°C in the 2050s and between 2 and 7°C for the 2080s. The seasonal picture for the 2050s (Figure 10) indicates that the largest spread in scenario

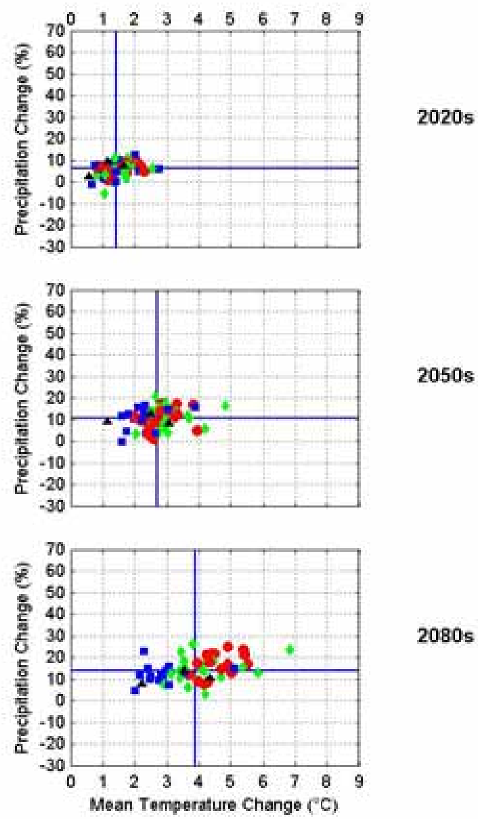


Figure 9: Scatter plots indicating annual changes in mean temperature (°C) and precipitation (%) for the forest region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

results occurs in winter, with temperature changes between 0 and 7°C and mostly positive precipitation changes (up to 30%). For spring, the picture is similar, although the temperature increases are not quite as large. The summer and fall scatter plots show some scenarios with larger precipitation decreases – as much as 10% in summer and around 5% in the fall.

Given the number of scenarios being considered, the points on the plot are divided by emissions scenario only. Black triangles indicate the three scenarios selected on the basis of maximum, minimum and median change in annual moisture index. It is apparent that these three scenarios do not necessarily occupy the 'extreme' corners of the scatter plot, i.e., they do not necessarily represent cooler and drier, or cooler and wetter, or warmer and drier, or warmer and wetter conditions when compared with the complete suite of scenarios.

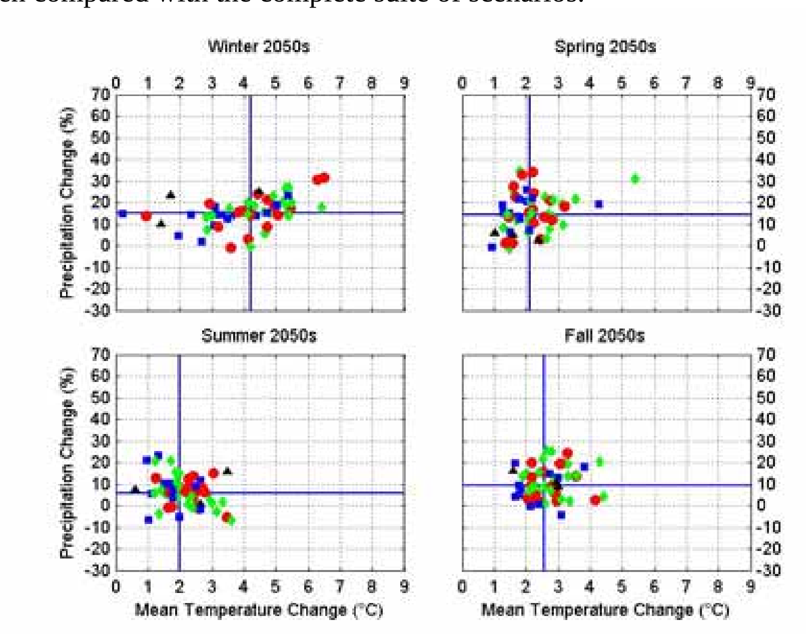


Figure 10: Scatter plots indicating seasonal changes in mean temperature (°C) and precipitation (%) for the forest region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

2.2.4.1a: Mean temperature changes

Changes in annual mean temperature are illustrated in Figures 11-13 for the 2020s, 2050s and 2080s. For the 2020s (Figure 11), the BCM2 B1 (smallest AMI change) scenario indicates an increase in mean temperature of between 0.0 and 0.5°C. The HadCM3 A1B (largest AMI change) scenario indicates changes between 1.0 and 1.5°C, while for the MIMR (median AMI change) scenario increase in the eastern half of the forest region are larger (between 1.5 and 2.0°C) than in the western half of this region (1.0 to 1.5°C). For the 2050s (Figure 12), the smallest AMI change scenario indicates increases of between 0.5 and 1.0°C over most of the forested region compared to between 2.0 and 2.5°C for the largest AMI change scenario. The median AMI change scenario again indicates the largest increases in annual mean temperature of between 3.0 and 3.5°C, although there is a western region of slightly lower temperature increases (between 2.5 and 3.0°C). By the 2080s (Figure 13), annual mean temperatures are shown to be at least 2°C warmer (smallest AMI change scenario) than the baseline, and as much as 4.0 to 4.5°C warmer (median AMI change scenario).

2.2.4.1b: Precipitation changes

Changes in precipitation are illustrated in Figures 14-16 for the 2020s, 2050s and 2080s. Changes are similar for all three scenarios for the 2020s (Figure 14), with increases between 0 and 10%. A similar picture exists for the 2050s (Figure 15), although the median AMI change scenario indicates slightly higher increases along the west and north boundaries of the forest region (10 to 20%). By the 2080s (Figure 16), the median AMI change scenario indicates increases of between 10 and 20% over most of the forest region, while changes are between 0 and +10% for the small and large AMI change scenarios.

Smallest change in AMI
BCM2 B1

Largest change in AMI
HadCM3 A1B

Median change
MIMR B1

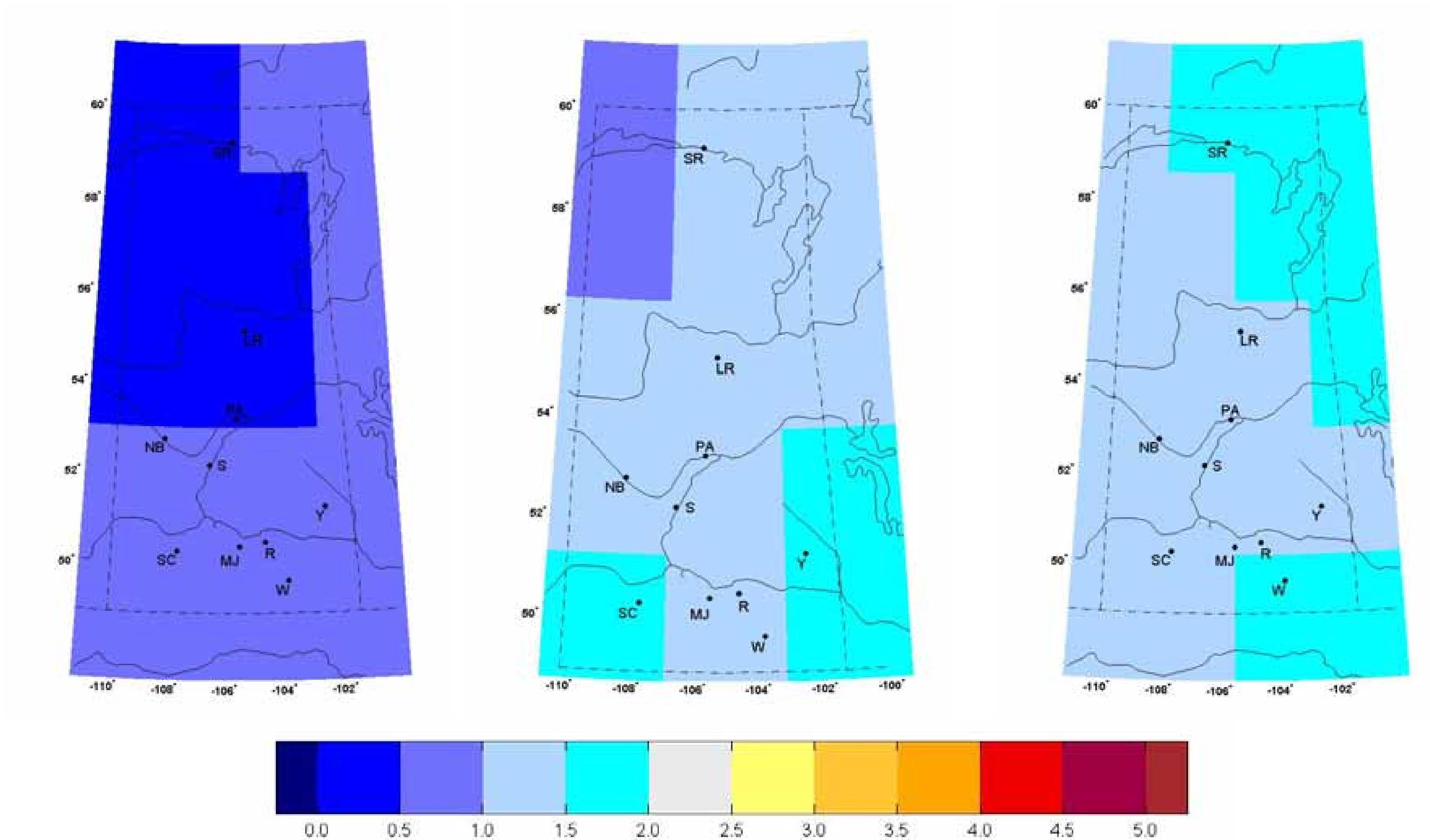


Figure 11: Annual mean temperature change (°C) for the 2020s with respect to 1961-1990 for the forest region of Saskatchewan.

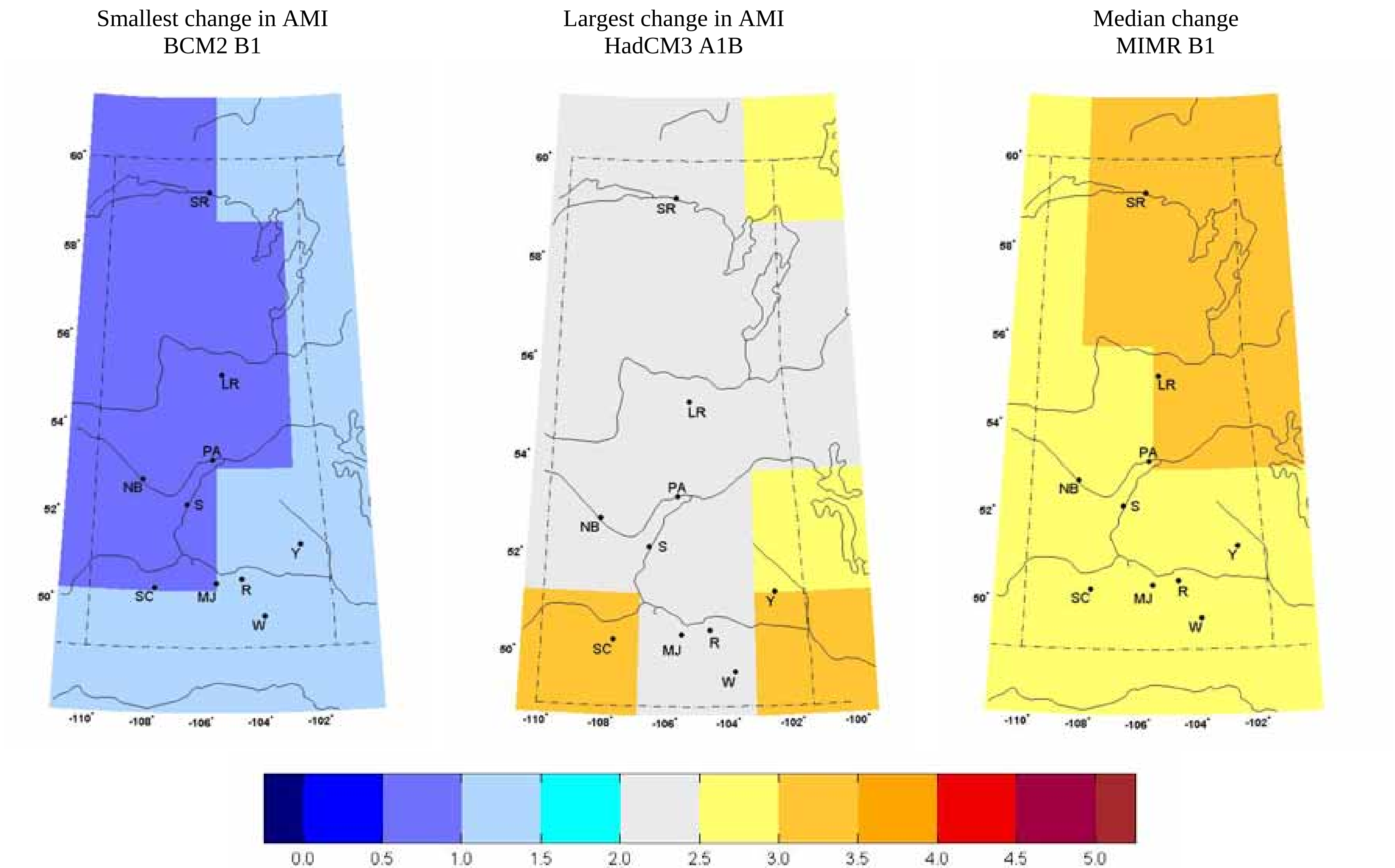


Figure 12: Annual mean temperature change (°C) for the 2050s with respect to 1961-1990 for the forest region of Saskatchewan.

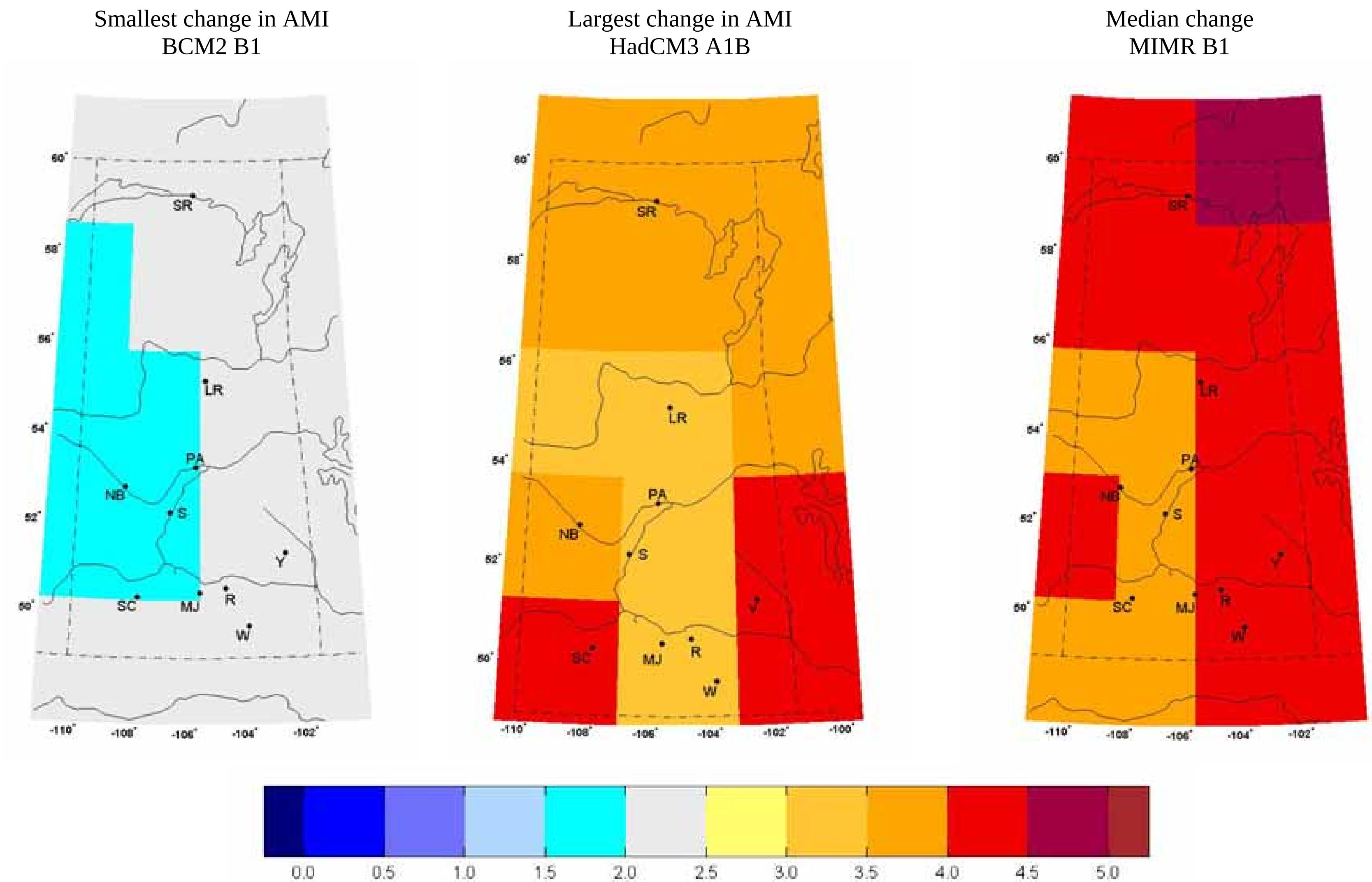


Figure 13 :Annual mean temperature change (°C) for the 2080s with respect to 1961-1990 for the forest region of Saskatchewan.

Smallest change in AMI
BCM2 B1

Largest change in AMI
HadCM3 A1B

Median change
MIMR B1

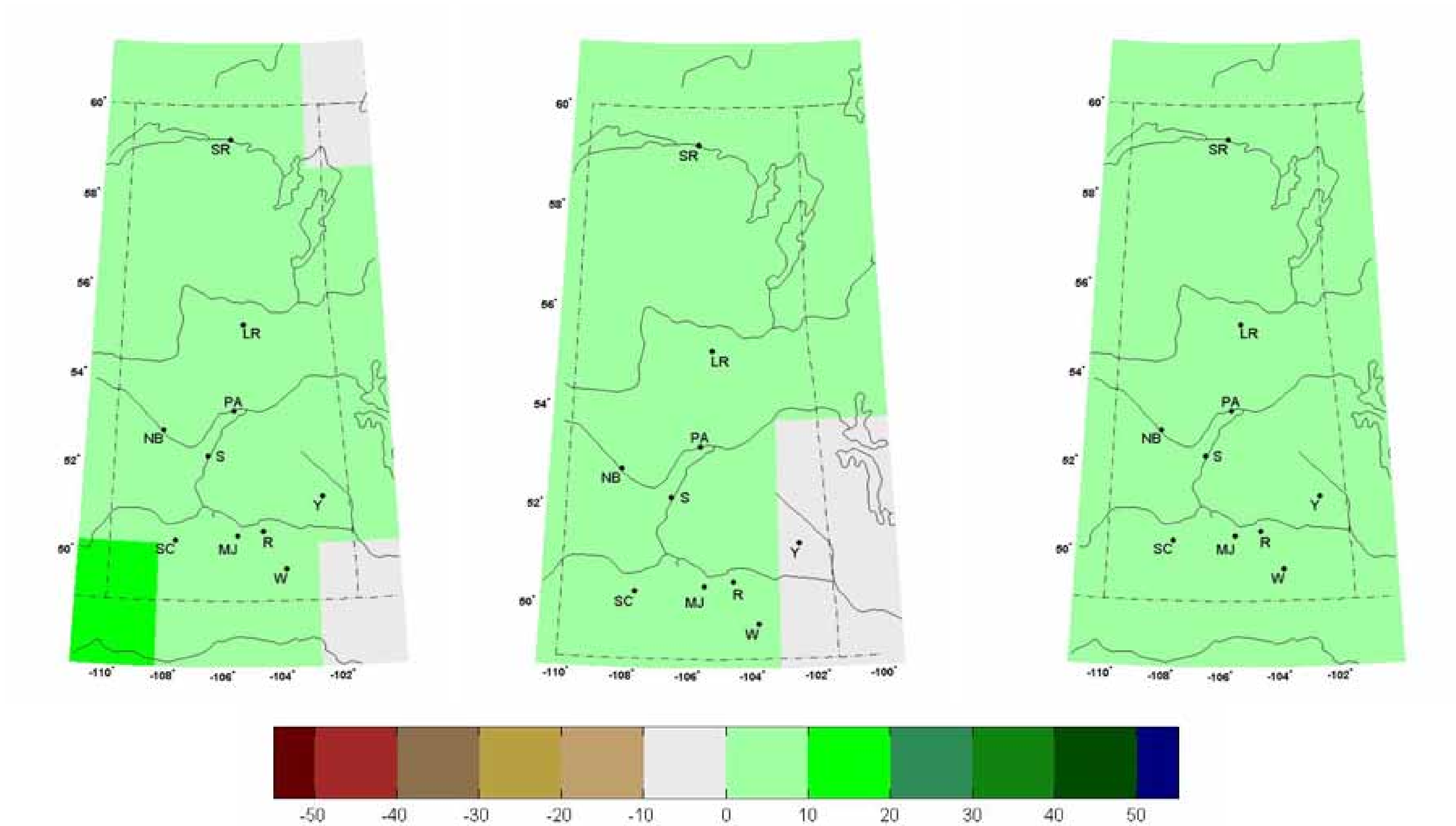


Figure 14 : Annual precipitation change (%) for the 2020s with respect to 1961-1990 for the forest region of Saskatchewan.

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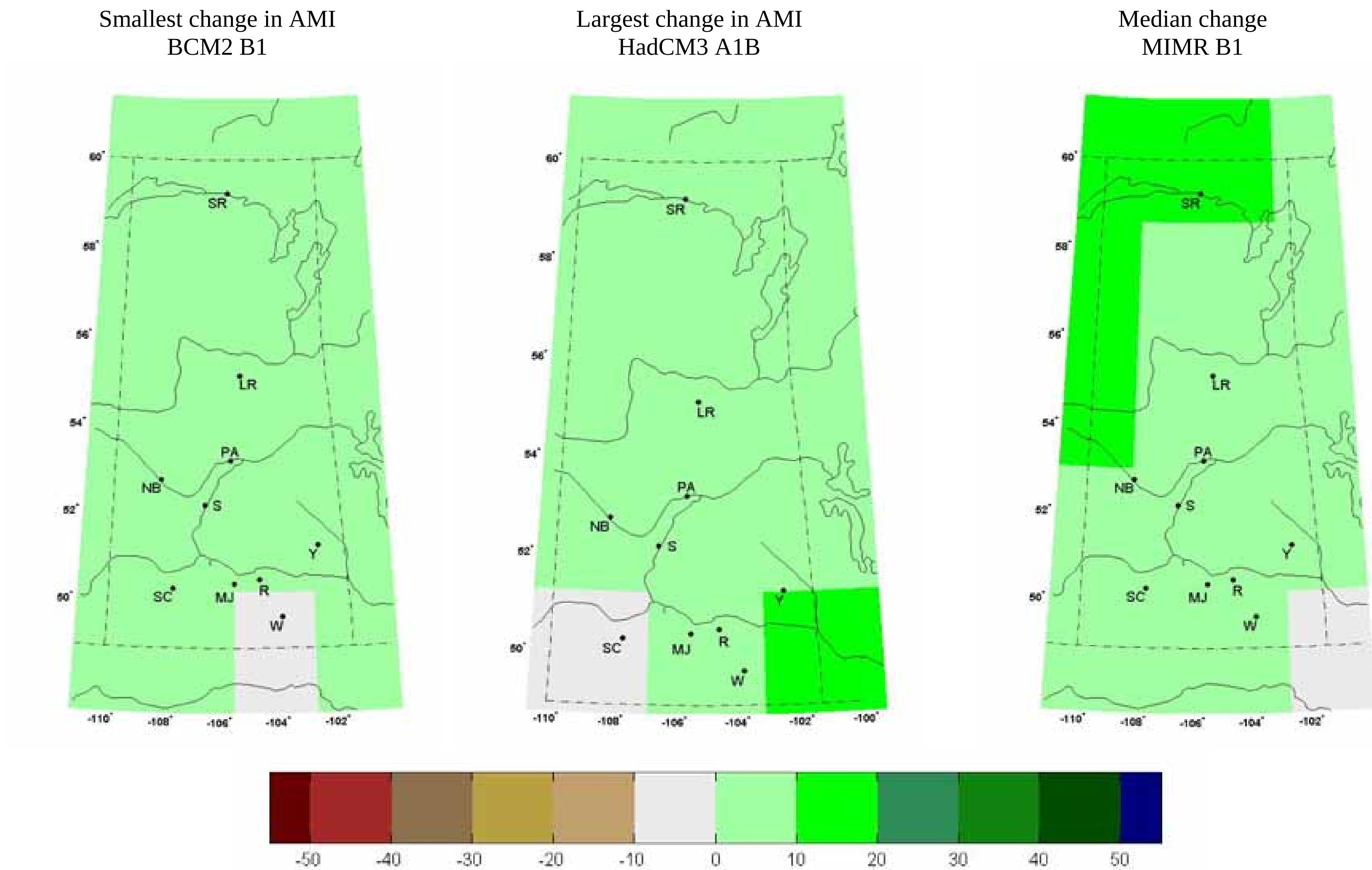

Figure 15: Annual precipitation change (%) for the 2050s with respect to 1961-1990 for the forest region of Saskatchewan.

Smallest change in AMI
BCM2 B1

Largest change in AMI
HadCM3 A1B

Median change
MIMR B1

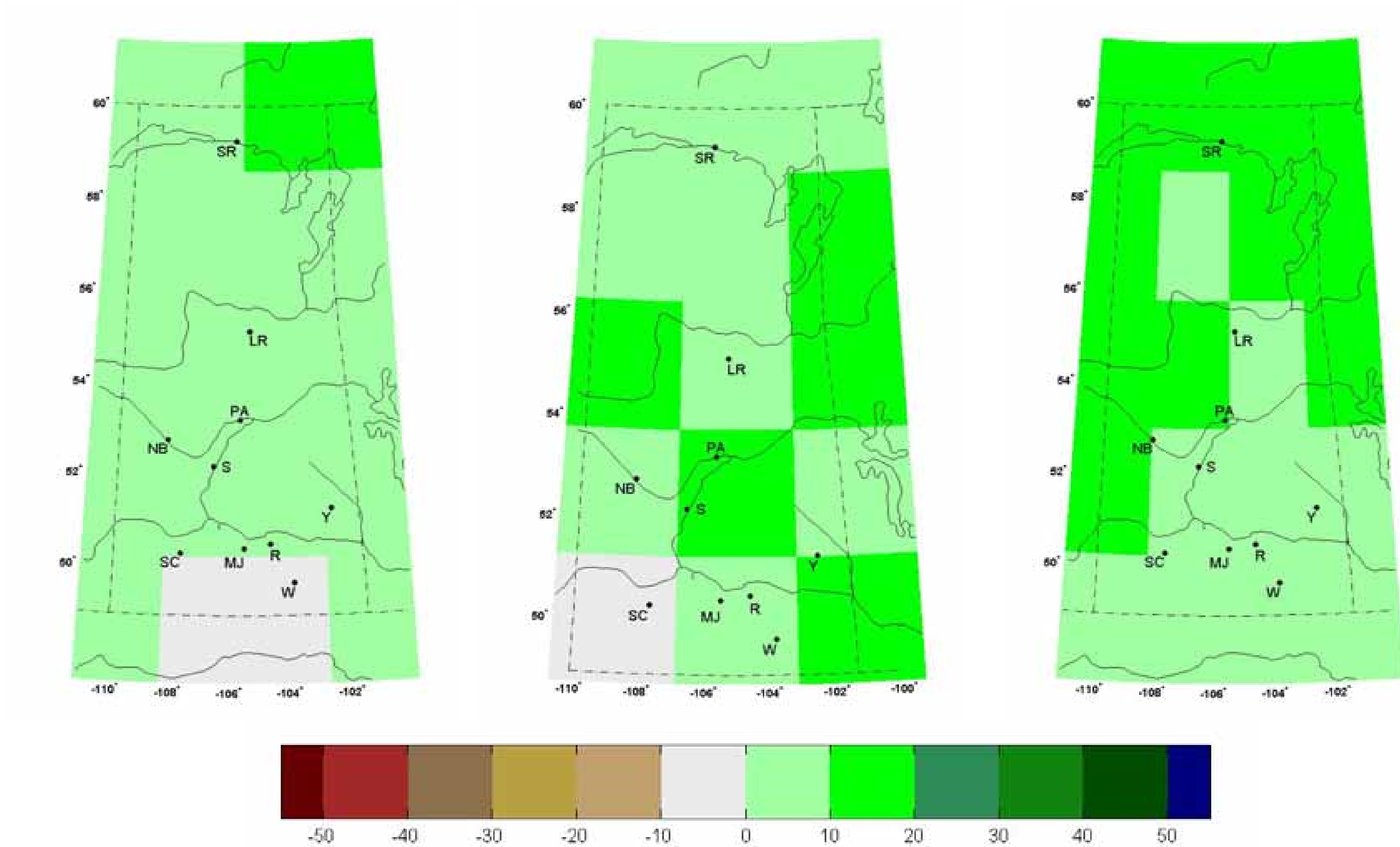

Figure 16: Annual precipitation change (%) for the 2080s with respect to 1961-1990 for the forest region of Saskatchewan.

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2.2.4.2: Grassland

Scatter plots of mean temperature change versus precipitation change are given for annual conditions for the 2020s, 2050s and 2080s in Figure 17, and by season for the 2050s in Figure 18. When compared with the forest region, it is apparent that larger decreases in precipitation are indicated for the grassland region and that decreases in annual mean precipitation are still projected for the 2080s (Figure 17). For the 2020s, temperature increases are between 0.5 and 3.0°C, between 1 and 5°C for the 2050s and between 2 and 6.5°C for the 2080s. Changes in the range of annual mean precipitation are similar for the 2020s and 2050s, between -10% and +25%, compared to between -5% and +35% for the 2080s. On a seasonal basis for the 2050s (Figure 18), it is apparent that scenarios projecting decreases in precipitation occur in all seasons. For summer and fall, about half the scenarios project precipitation decreases and by as much as 20 or 30%. The range of temperature increase is largest in winter and spring (between 1 and 6°C), compared to summer and fall (1 to 4°C).

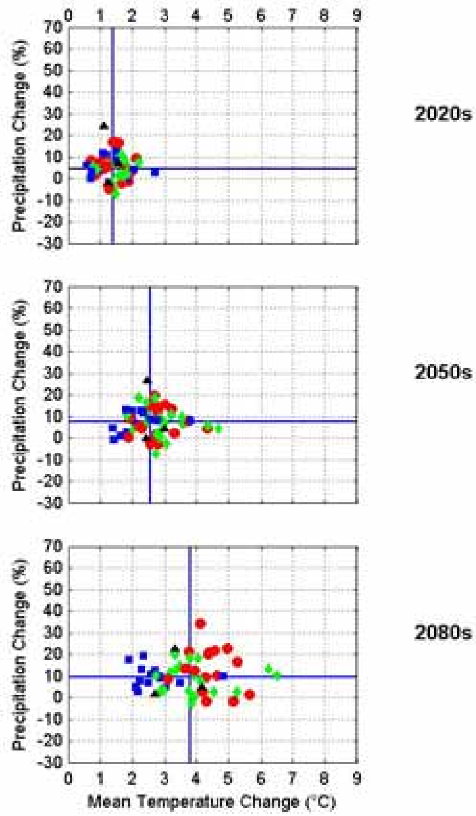

Figure 17: Scatter plots indicating annual changes in mean temperature (°C) and precipitation (%) for the grassland region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

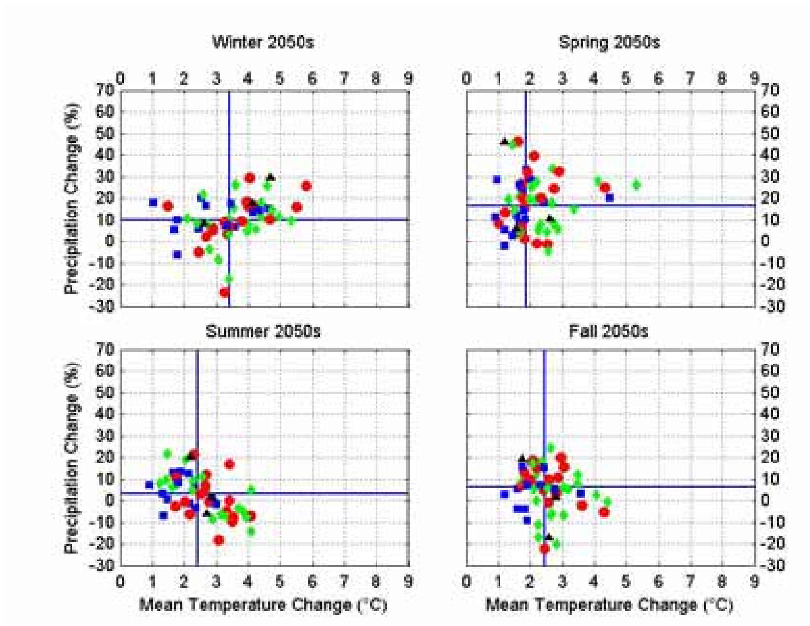

Figure 18: Scatter plots indicating seasonal changes in mean temperature (°C) and precipitation (%) for the grassland region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

2.2.4.2a: Mean temperature change

Changes in annual mean temperature are illustrated in Figures 19-21 for the 2020s, 2050s and 2080s. For the 2020s (Figure 19), both the smallest and largest change in AMI scenarios indicate increases of between 1.0 and 1.5°C, although the largest change scenario indicates a region of slightly lower temperature increase (0.5 to 1.0°C) close to the US border. A similar picture exists for the median change in AMI scenario, although in this case the south-east corner of the grassland region indicates slightly higher temperature increases of between 1.5 and 2.0°C. For the 2050s (Figure 20), increases in annual mean temperature are between 1.5 to 2.0°C for the smallest change in AMI scenario, between 2.0 and 2.5°C for the largest change in AMI scenario and between 2.5 and 3.0°C for the median change in AMI scenario. By the 2080s (Figure 21), the median change in AMI scenario indicates increases of between 3.5 and 4.0°C in the western part of the grassland region and between 4.0 and 4.5°C in the eastern half of this region. The other two scenarios indicate increases in annual mean temperature of between 2.0 and 2.5°C, although there are some areas of slightly lower temperature increase (1.5 to 2.0°C) in the north of the region for the smallest change scenario and some areas of slightly higher temperature increase (2.5 to 3.0°C) in the north-east corner of this region for the largest change scenario.

2.2.4.2b: Precipitation changes

Changes in precipitation for the 2020s, 2050s and 2080s are illustrated in Figures 22-24. Changes in precipitation are similar across all time periods, generally between 0 and 10%. For the 2020s (Figure 22), the largest change in AMI scenario indicates some areas of slight precipitation decrease (0 to -10%) along the boundary of this region with Manitoba, while the smallest change in AMI scenario indicates some areas of larger precipitation increase (10 to 20%) in the west of the grassland region. For the 2050s (Figure 23), the largest change scenario again indicates some areas of precipitation decrease (0 to -10%) in the south-east of the grassland region. The smallest change scenario indicates general increases in precipitation of between 10 and 20%, although for the south-east corner of the region, including Moose Jaw, Regina, Weyburn and Yorkton, increases are slightly lower (0 to 10%). For the 2080s (Figure 24), the smallest change scenario indicates increases of between 10 and 20% over most of the grassland region, whilst the two other scenarios show slightly lower increases of between 0 and 10%.

Smallest change in AMI
CGCM3_T47_2 A1B

Largest change in AMI
GFCM20 B1

Median change
MIMR B1

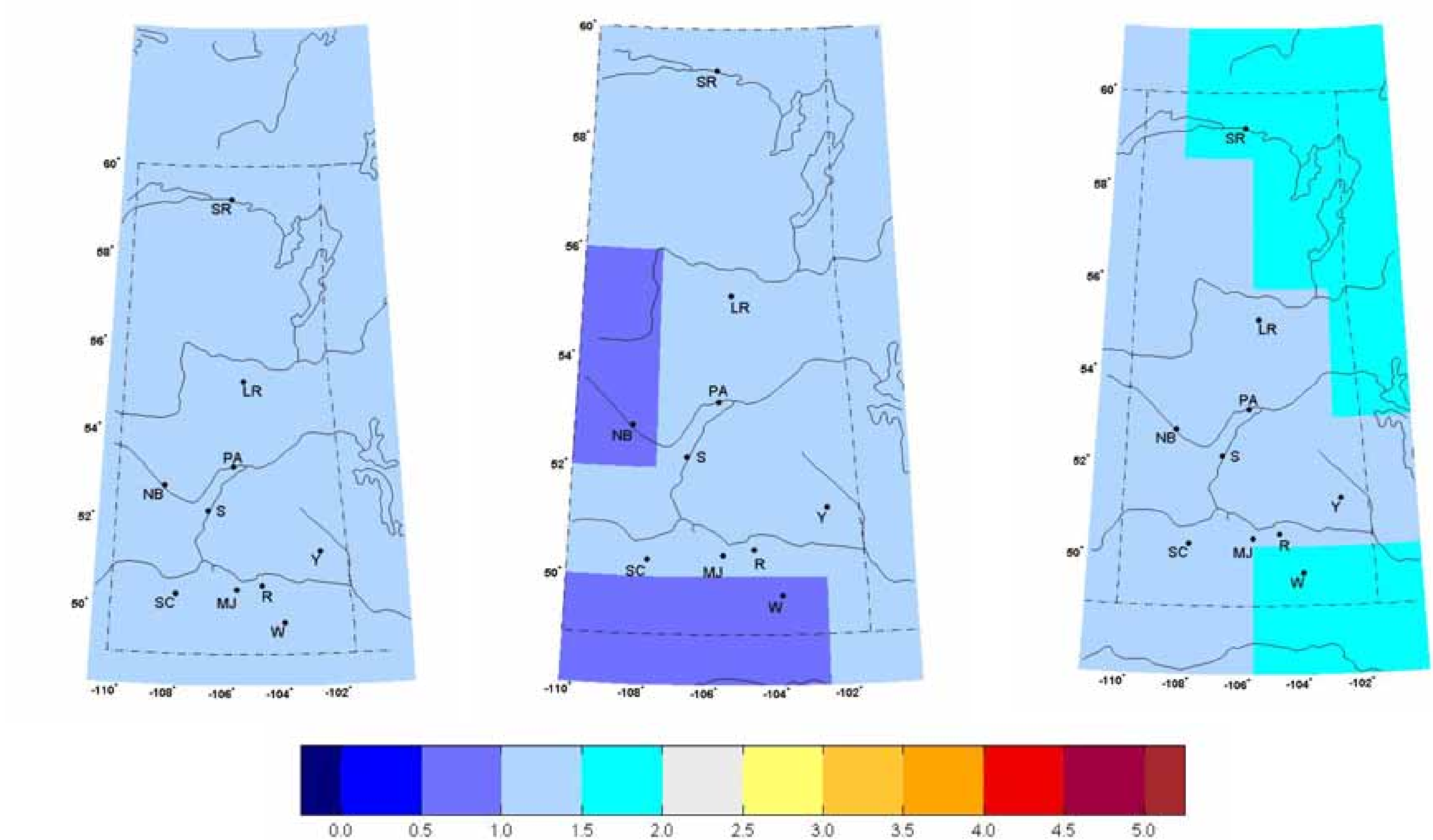

Figure 19: Annual mean temperature change (°C) for the 2020s with respect to 1961-1990 for the grassland region of Saskatchewan.

Smallest change in AMI
CGCM3_T47_2 A1B

Largest change in AMI
GFCM20 B1

Median change
MIMR B1

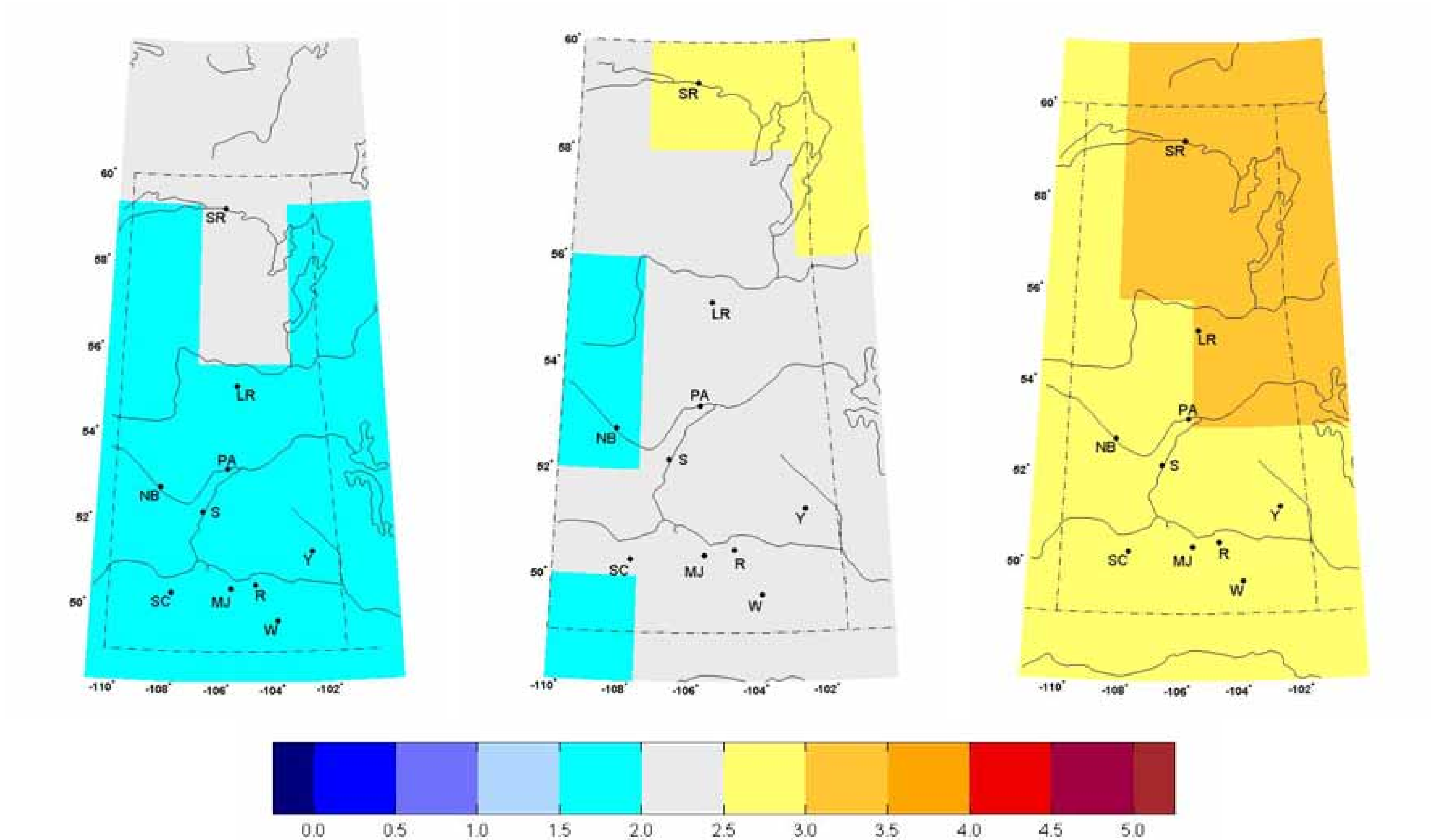

Figure 20: Annual mean temperature change (°C) for the 2050s with respect to 1961-1990 for the grassland region of Saskatchewan.

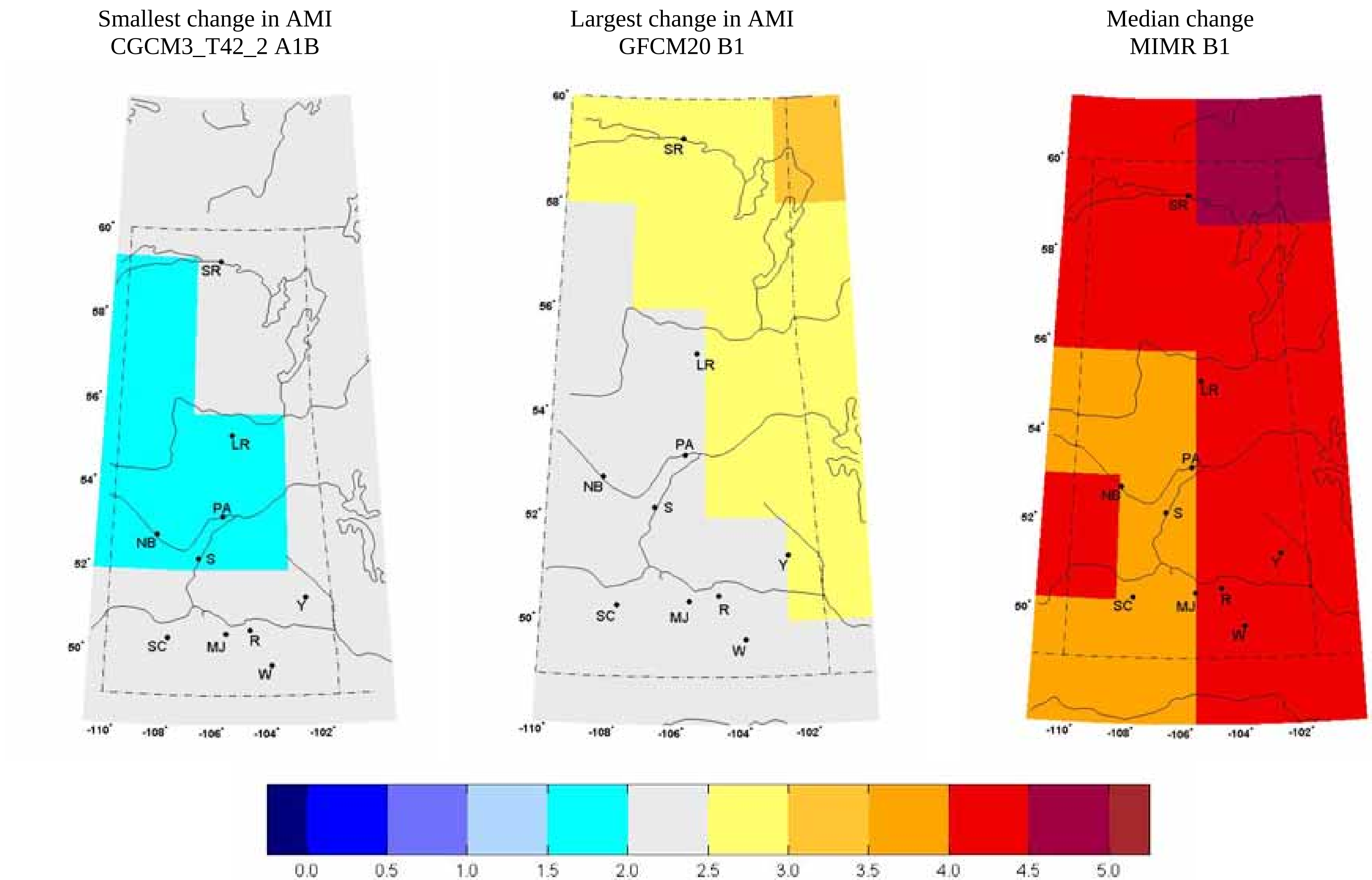

Figure 21: Annual mean temperature change (°C) for the 2080s with respect to 1961-1990 for the grassland region of Saskatchewan.

Smallest change in AMI
CGCM3_T47_2 A1B

Largest change in AMI
GFCM20 B1

Median change
MIMR B1

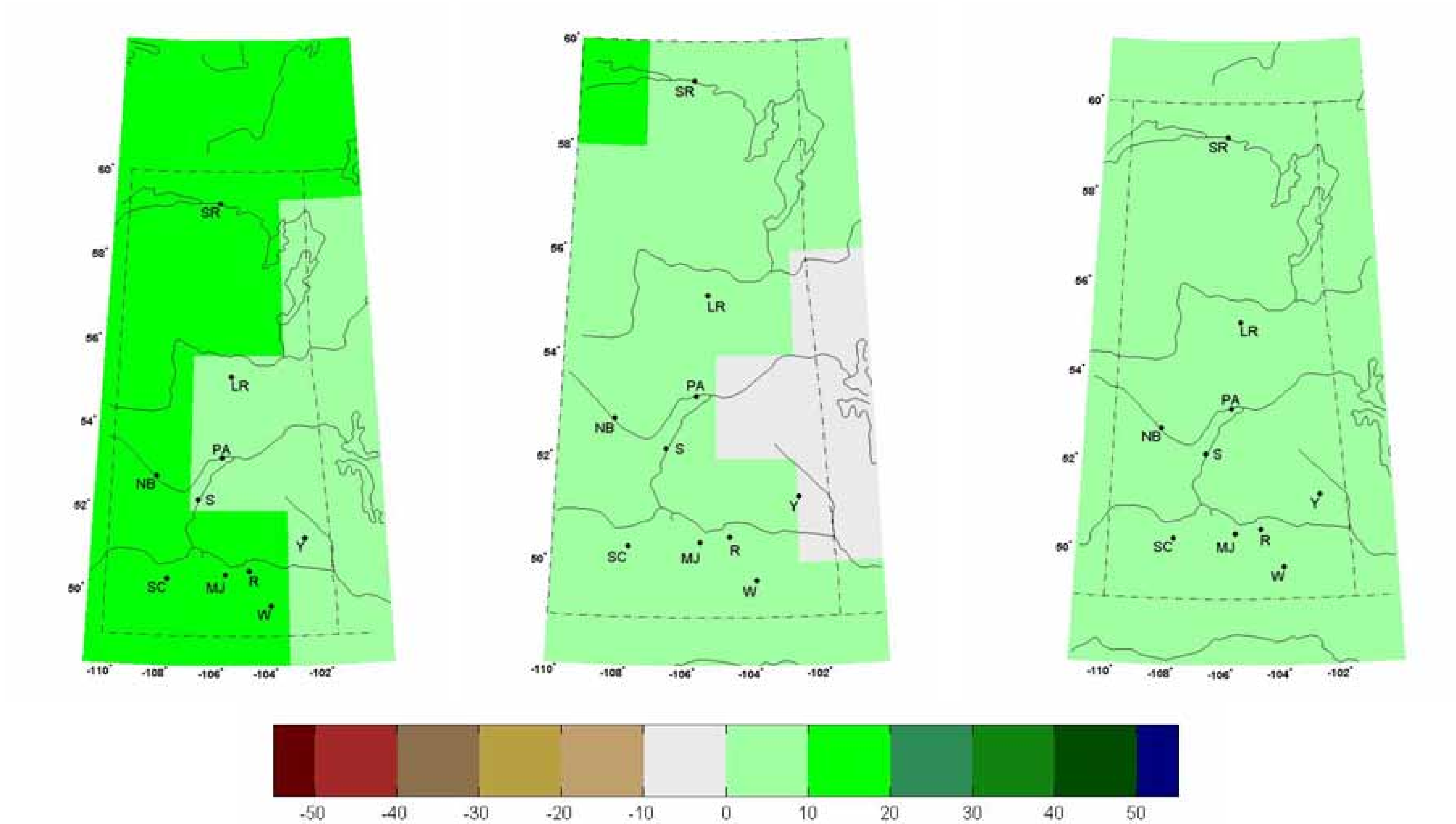

Figure 22: Annual precipitation change (%) for the 2020s with respect to 1961-1990 for the grassland region of Saskatchewan.

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Smallest change in AMI
CGCM3_T47_2 A1B

Largest change in AMI
GFCM20 B1

Median change
MIMR B1

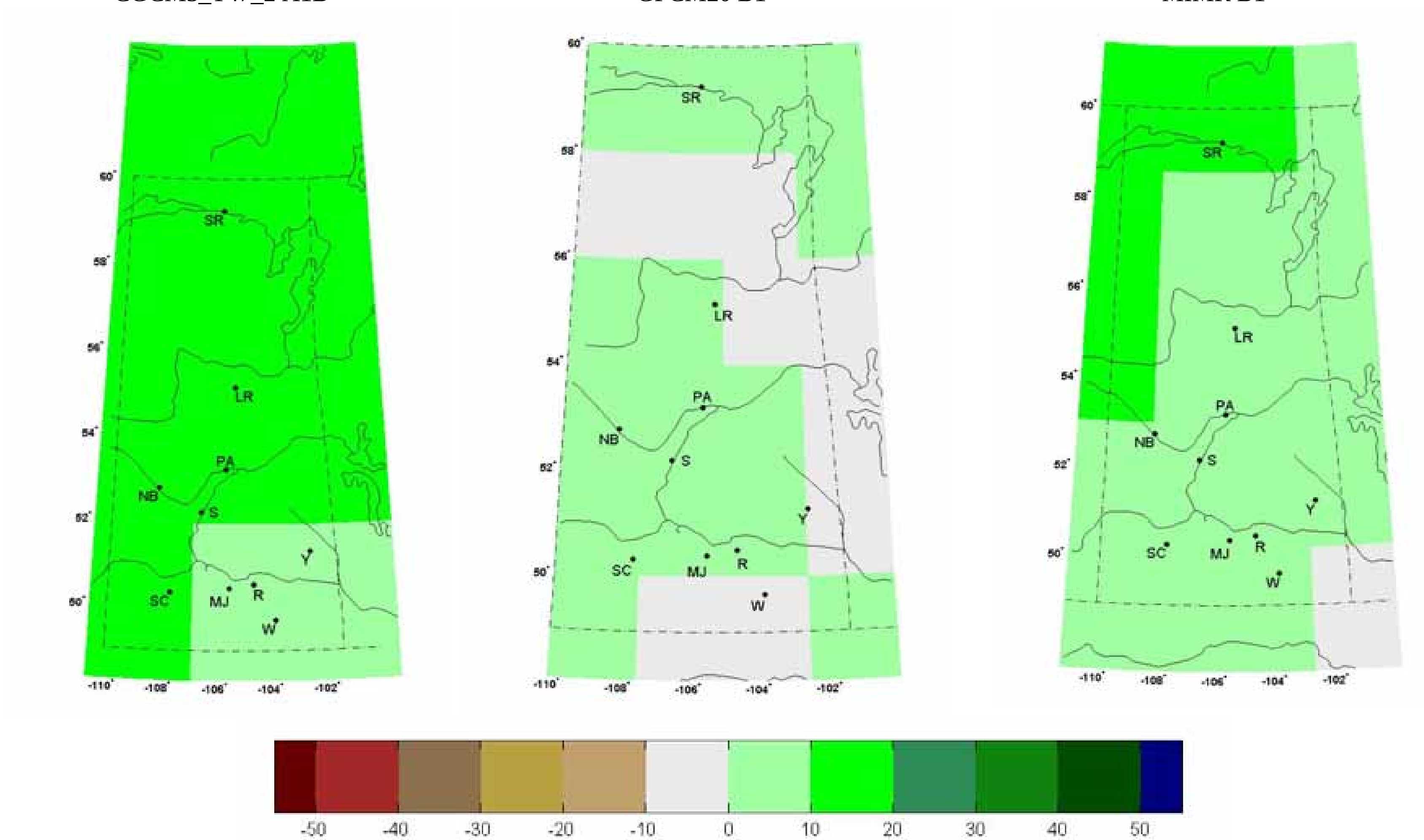


Figure 23: Annual precipitation change (%) for the 2050s with respect to 1961-1990 for the grassland region of Saskatchewan.

Smallest change in AMI
CGCM3_T47_2 A1B

Largest change in AMI
GFCM20 B1

Median change
MIMR B1

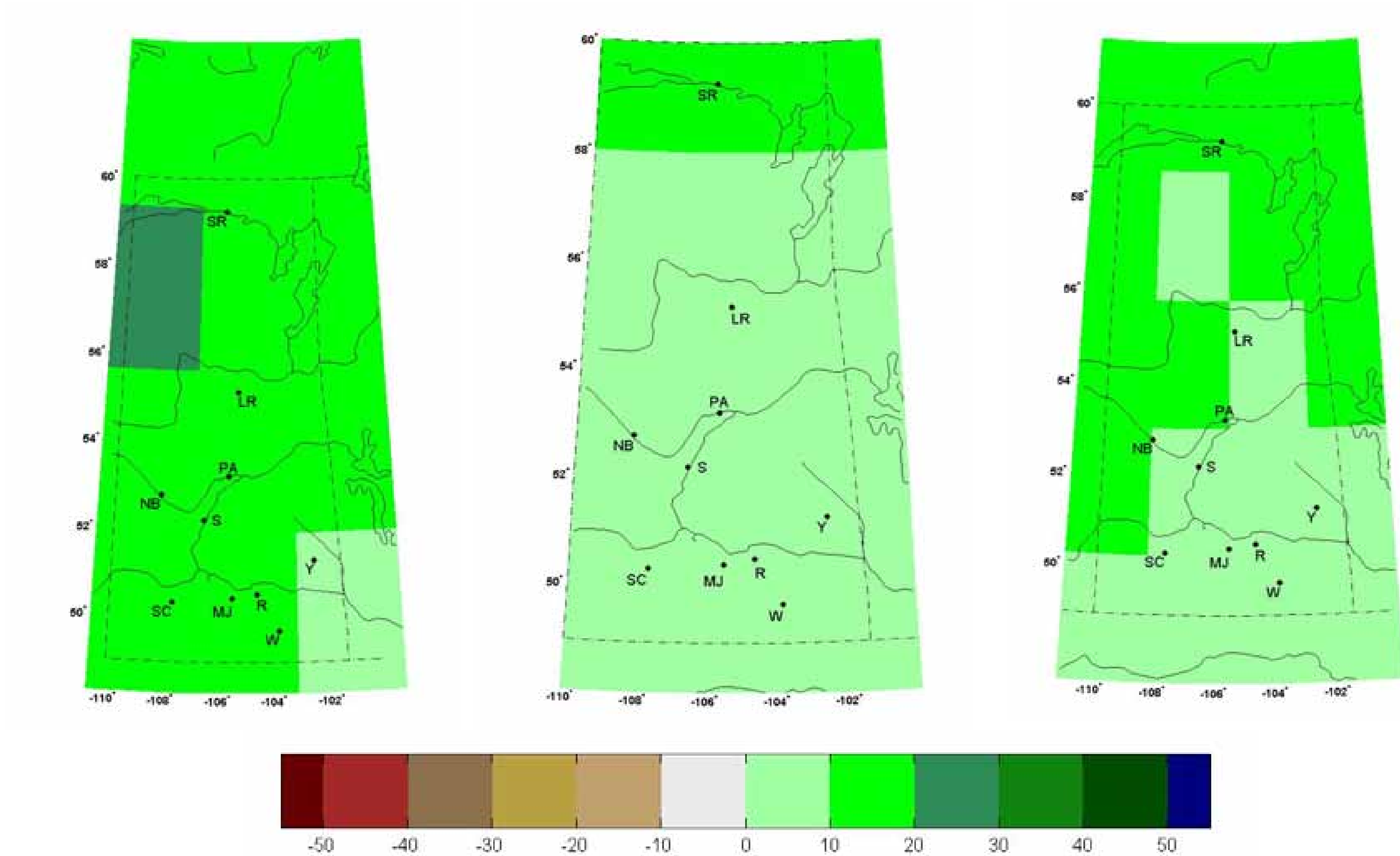


Figure 24: Annual precipitation change (%) for the 2080s with respect to 1961-1990 for the grassland region of Saskatchewan.

3: 1961-1990 BASELINE CLIMATOLOGY

There are a number of observed baseline climatologies available containing information for Western Canada, including Saskatchewan. In all cases, observed station data have been used to create gridded fields of observed climate. The interpolation techniques used to create the gridded information range from the simple (inverse distance weighting of nearest neighbours) to the more sophisticated statistical techniques, such as ANUSPLIN (thin plate smoothing splines on geographic location and elevation). Milewska *et al*. (2005) undertook a comparison of four sets of geo-referenced grids of 1961-1990 climate normals, or thirty-year averages, of monthly maximum and minimum temperatures and total precipitation. These four sets of grids were derived by (i) inverse distance weighting (IDW); (ii) a SQUARE-GRID technique based on a multivariate regression model; (iii) the ANUSPLIN model based on thin plate smoothing splines, and (iv) Parameter-elevation Regression on Independent Slopes Model (PRISM). Intercomparison of point and average values, as well as verification of temperature with upper air soundings and precipitation with streamflow measurements, showed that all grids, except SQUARE-GRID for precipitation, produced very good results in the Prairie ecozone. In most cases, temperatures agreed within 1°C and precipitation within several percent. PRISM, developed by Chris Daly of Oregon State University (Daly *et al*., 1994; OSU, 2004), was verified to model the Arctic inversion correctly and performed best in winter in northern Saskatchewan, Manitoba and Alberta and, along with ANUSPLIN, was recommended for the mountains of south-eastern British Columbia and south-western Alberta. Both of these models also produced precipitation values which were remarkably close to water balance estimates of precipitation computed from streamflow gauge measurements (Milewska *et al*., 2005). However, since the PRISM model performed best for temperature in northern Saskatchewan, it was decided to use this gridded climatology to represent 1961-1990 baseline conditions for the province.

Figures 25 to 28 indicate seasonal mean temperature[7], precipitation and minimum and maximum temperatures for 1961-1990 conditions for Saskatchewan. Maps for baseline mean temperature show a general gradient of decreasing temperature from the south-west of the province to the north-east in all seasons (Figure 25). In winter, the coldest mean temperatures, less than -25°C, occur in the north-eastern-most corner of the province. Mean temperatures in Stony Rapids are between -20°C and -25°C, La Ronge, Prince Albert , Yorkton and North Battleford are between -20°C and -15°C, while for the rest of the province mean temperatures in winter are between -10°C and -15°C, with the exception of the far south-west corner where they are between -5°C and -10°C. In spring, mean temperatures are between 0°C and 5°C from the south to north of La Ronge, between 0°C and -5°C for Stony Rapids and between -5°C and -10°C in the north-east corner. A similar pattern exists in summer, where most of the province to north of La Ronge exhibits mean temperatures between 15°C and 20°C, while the remainder of the province including Stony Rapids is slightly cooler at 10°C to 15°C. In fall, mean temperatures are between 0°C and 5°C to north of La Ronge and then between 0°C and -5°C thereafter.

[7] Mean temperature was derived by dividing the sum of maximum and minimum temperature by two.

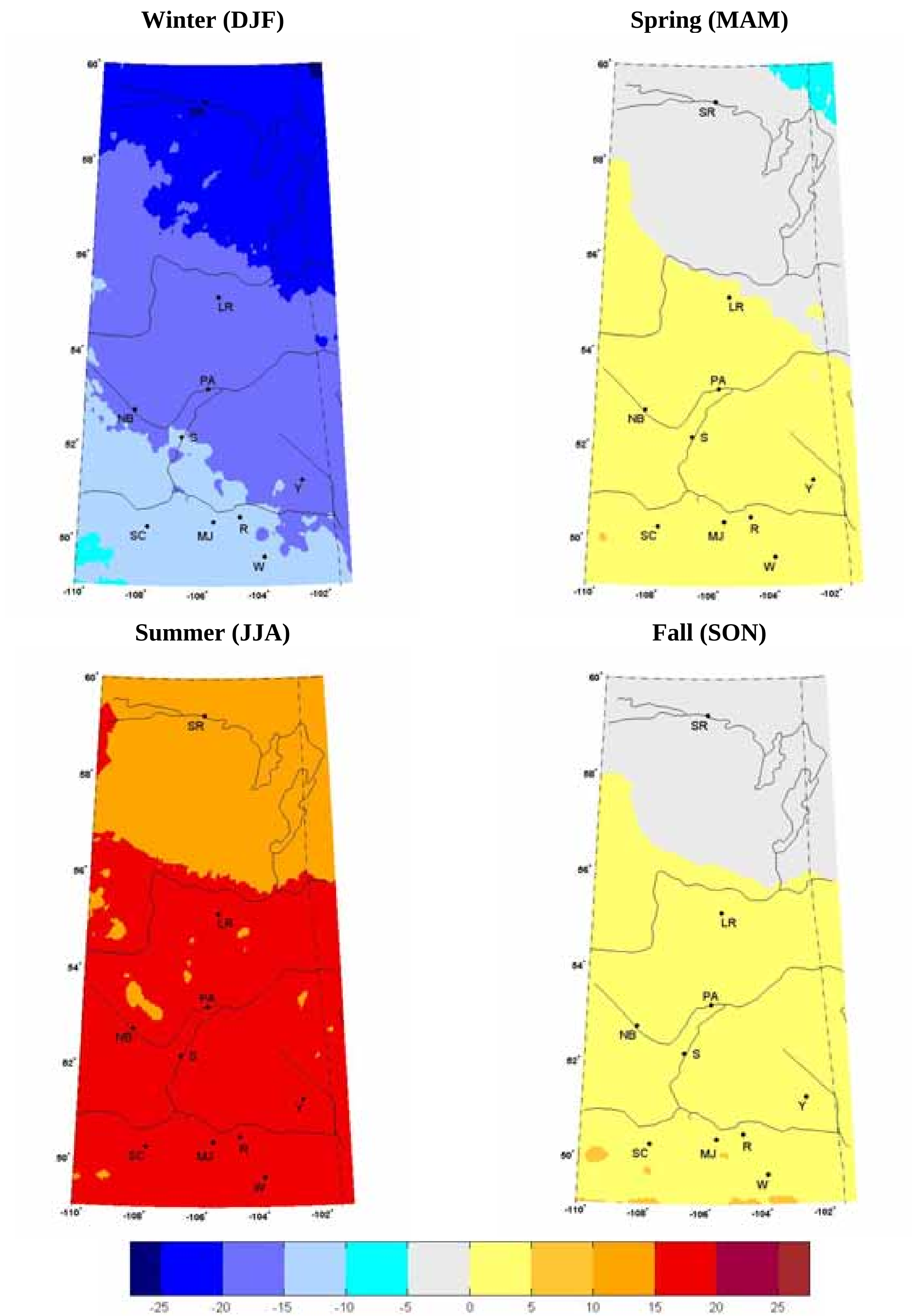


Figure 25: 1961-1990 seasonal mean temperature (°C) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

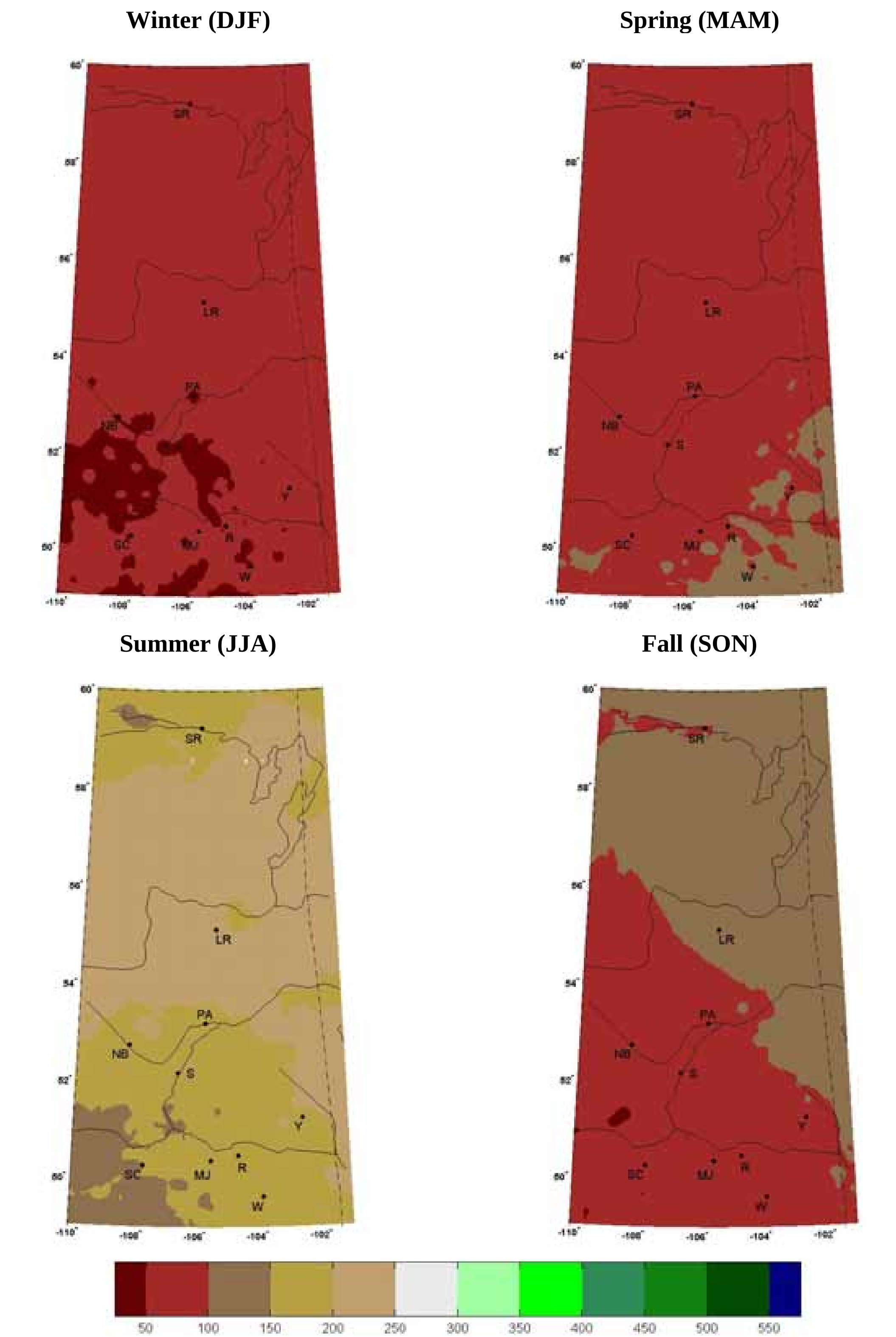


Figure 26: PRISM 1961-1990 seasonal precipitation totals (mm) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

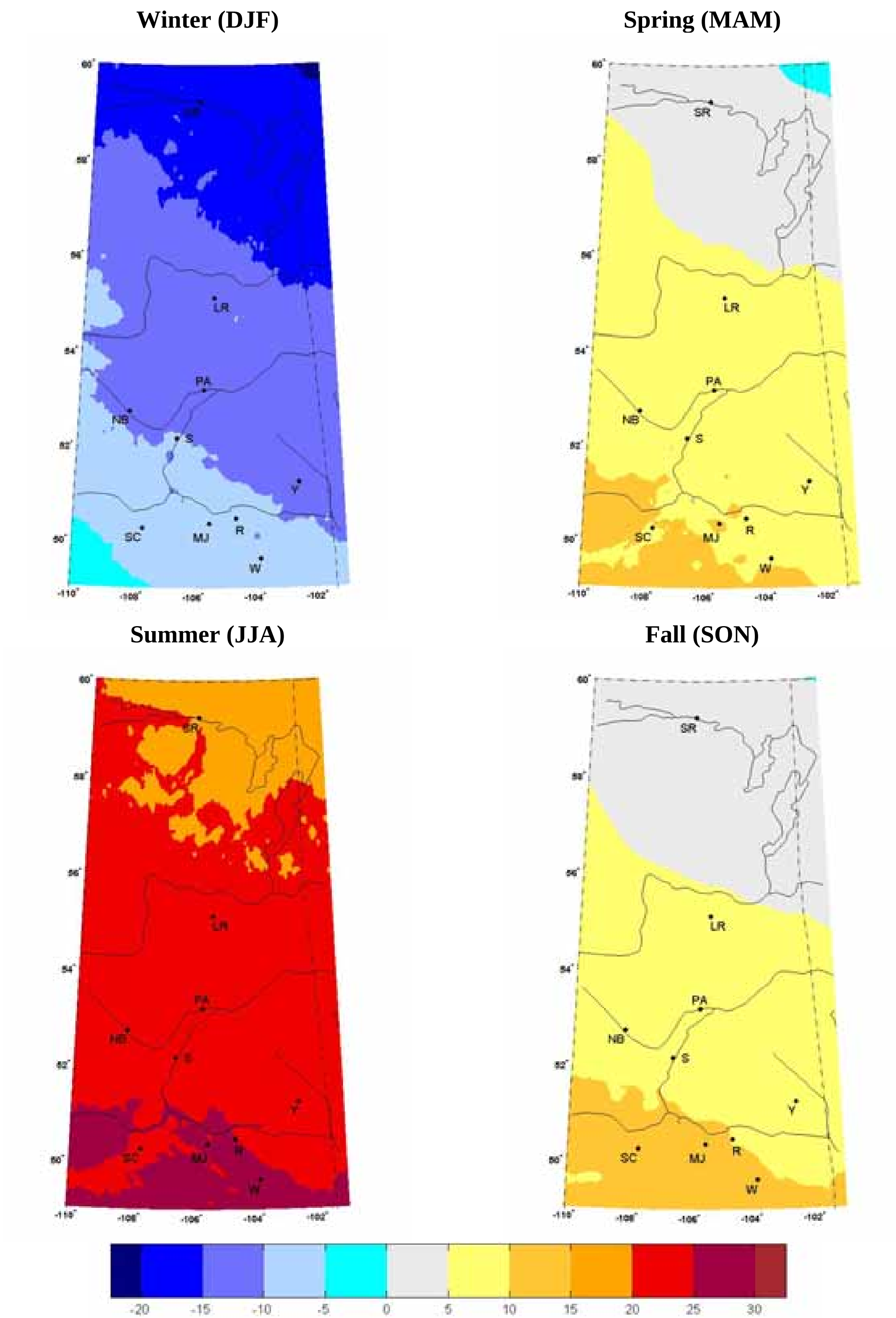


Figure 27: PRISM 1961-1990 seasonal mean maximum temperature (°C) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

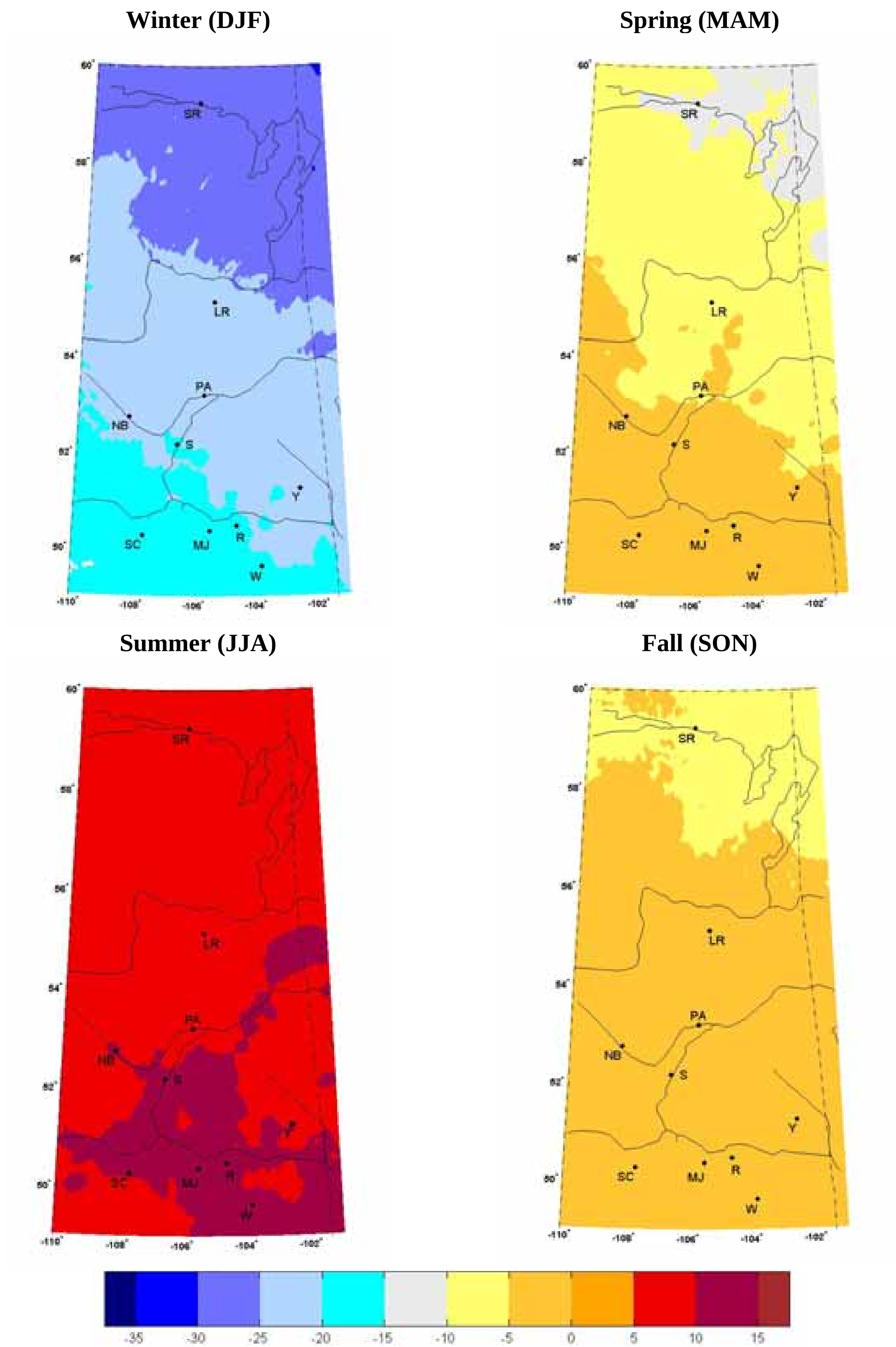


Figure 28: PRISM 1961-1990 seasonal mean minimum temperature (°C) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

Examination of seasonal precipitation patterns (Figure 26) indicates that the largest precipitation totals occur in summer. The south-west corner of the province receives least precipitation, on average, between 100 – 150 mm. Precipitation totals increase towards the north-east: between 150 and 200 mm up to and including Prince Albert, between 200 and 250 mm in a band including La Ronge and then a slightly drier region in the north-west of between 150 and 200 mm, including Stony Rapids. For winter and spring patterns of precipitation are similar, with most of the province receiving between 50 and 100 mm. In spring, the south-east corner of the province is slightly wetter with totals between 100 and 150 mm. In fall, the south-west half of the province is slightly drier than the north-east, with precipitation totals between 50 and 100 mm compared to 100 to 150 mm, respectively.

Figure 27 indicates that 1961-1990 mean maximum temperatures show a similar pattern to those of mean temperature (Figure 9). In winter, warmest temperatures occur in the south-west (-5°C to 0°C) and decline in a north-easterly direction to between -15°C and -20°C. South of Saskatoon, mean maximum temperatures are generally between -5°C and -10°C, between -15°C and -10°C in a broad central band including Prince Albert, North Battleford, La Ronge and Yorkton, and between -20°C and -15°C in the Stony Rapids region. In spring, mean maximum temperatures are between 10°C and 15°C in the south-west, between 5°C and 10°C in a broad central band including Regina, Saskatoon, North Battleford, Yorkton, Prince Albert and La Ronge. For Stony Rapids, mean maximum temperatures in spring are between 0°C and 5°C. In summer, warmest temperatures, between 25°C and 30°C, occur in the south part of the province, including Moose Jaw and Regina. Central areas, to north of La Ronge, experience mean maximum temperatures between 20°C and 25°C, whilst in northern areas, including Stony Rapids, values are between 15°C and 20°C. A similar pattern, but cooler temperatures, exists in the fall. In the south of the province, including Swift Current, Moose Jay and Weyburn, mean maximum temperatures are between 10°C and 15°C. A broad central band including Regina to north of La Ronge, experiences temperatures between 5°C and 10°C, while for Stony Rapids fall maximum temperatures are between 0°C and 5°C.

Seasonal mean minimum temperatures are illustrated in Figure 28. Again, patterns are similar to those of mean and maximum temperatures. In winter, warmest minimum temperatures are experienced in the south-west (between -20°C and -15°C), and coldest minimum temperatures are in the north-east (between -25°C and -30°C). In spring, warmest temperatures are in the south, between 0°C and -5°C,between -5°C and -10°C in central areas and between -10°C and -15°C in the north, including Stony Rapids. In summer, mean minimum temperatures are generally between 5°C and 10°C, although some areas of between 10°C and 15°C occur in the southern half of the province. For most of the province, minimum temperatures are generally between 0°C and -5°C in the fall, although in the far north, including Stony Rapids, temperatures are between -5°C and -10°C.

Annual maps for mean temperature, mean precipitation totals, mean maximum temperature and mean minimum temperature are shown in Figures 29-32, respectively. All temperature maps indicate the south-west to north-east gradient of decreasing temperature. For annual mean temperature (Figure 29), values are between 0°C and 5°C to just south of La Ronge, and between 0°C and -5°C for most of the rest of the province. For annual mean maximum temperature, the south-west corner of the province experiences values between 10°C and 15°C, central areas to north of La Ronge are between 5°C and 10°C, and northern areas including Stony Rapids are between 0°C and 5°C (Figure 31). Mean minimum temperatures (Figure 32) in the southern half of the province are between 0°C and -5°C and between -5°C and -10°C in the north. For precipitation (Figure 30), areas with largest precipitation totals (between 500 and 550 mm) are found in the north-eastern half of the province, particularly close to the border with Manitoba. The south-west part of the province exhibits lowest precipitation totals (300 – 350 mm), although the effect of topography can be seen with higher precipitation totals in higher elevation areas such as the Cypress Hills, south-west of Swift Current. The area around Stony Rapids in the north of the province experiences similar precipitation totals (350 – 400 mm) to Saskatoon, North Battleford, Moose Jaw, Regina and Swift Current, which is slightly lower than most of the northern part of the province (between 450 and 500 mm).

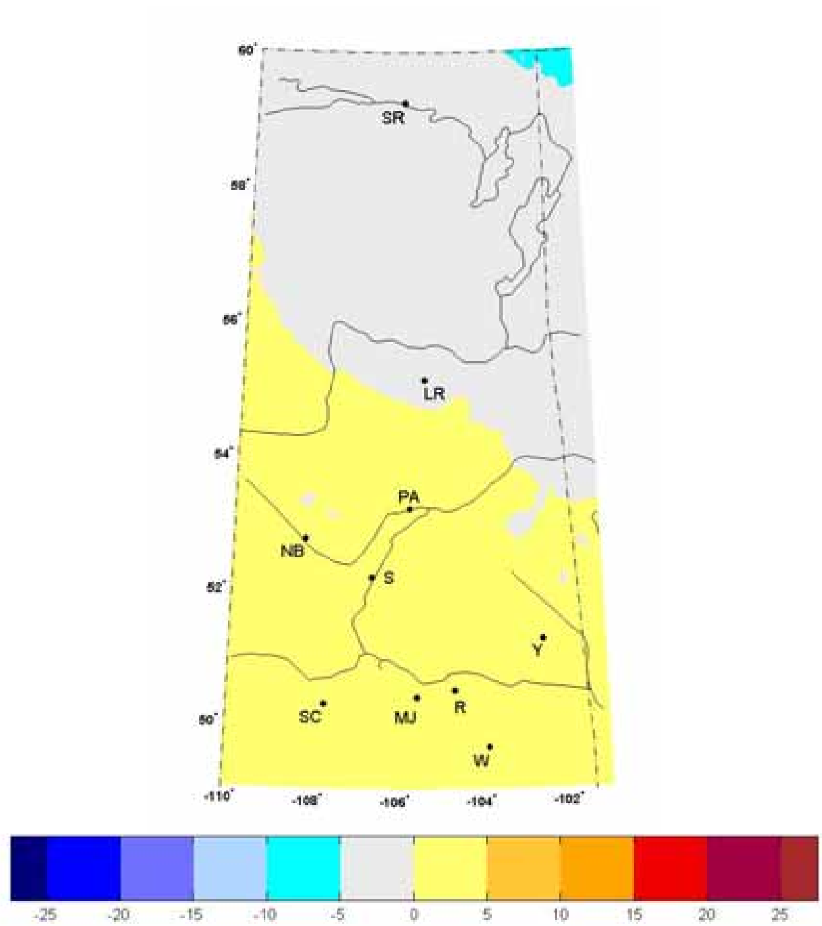


Figure 29: 1961-1990 annual mean temperature (°C) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

The derived variables, degree days > 5°C threshold temperature, cooling degree days (> 18°C), heating degree days (<18°C) and annual moisture index were calculated as described in Section 2.2.2. Figures 33-36 illustrate the annual values for these variable. For growing degree days (DD5; Figure 33), totals decrease from between 1500 to 1750 to just north of Saskatoon, to between 1250 and 1500 in a central band including Prince Albert, to between 750 and 1000 in the north-east part of the province, including La Ronge. For cooling degree days the totals are very low, indicating that for the baseline climate air conditioning requirements are low (Figure 34). For the southern third of the province totals are between 0 and 100, while from Prince Albert north no cooling degree days are accrued. Heating degree day values (Figure 35) increase northwards, from between 5150 and 5700 in the south to between 7900 and 8450 in the north-eastern part of the province. Annual moisture index values (Figure 36) are generally between 4 and 5, although there are some areas as high as 5 and 6 in the south. In the northern half of the province, values are generally between 2 and 3, decreasing to between 1 and 2 in the north-east corner of the province.

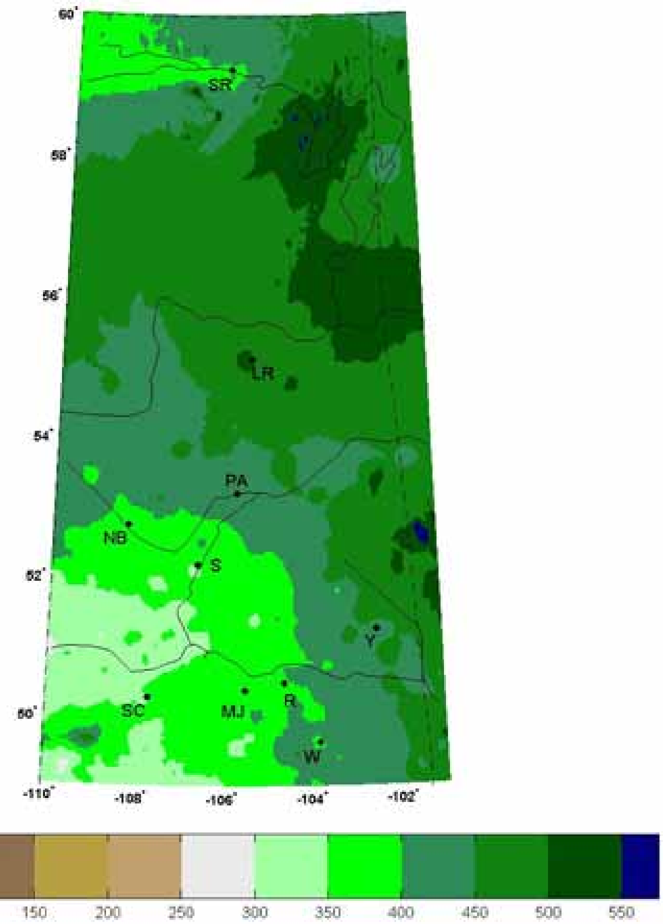


Figure 30: PRISM 1961-1990 annual precipitation totals (mm) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

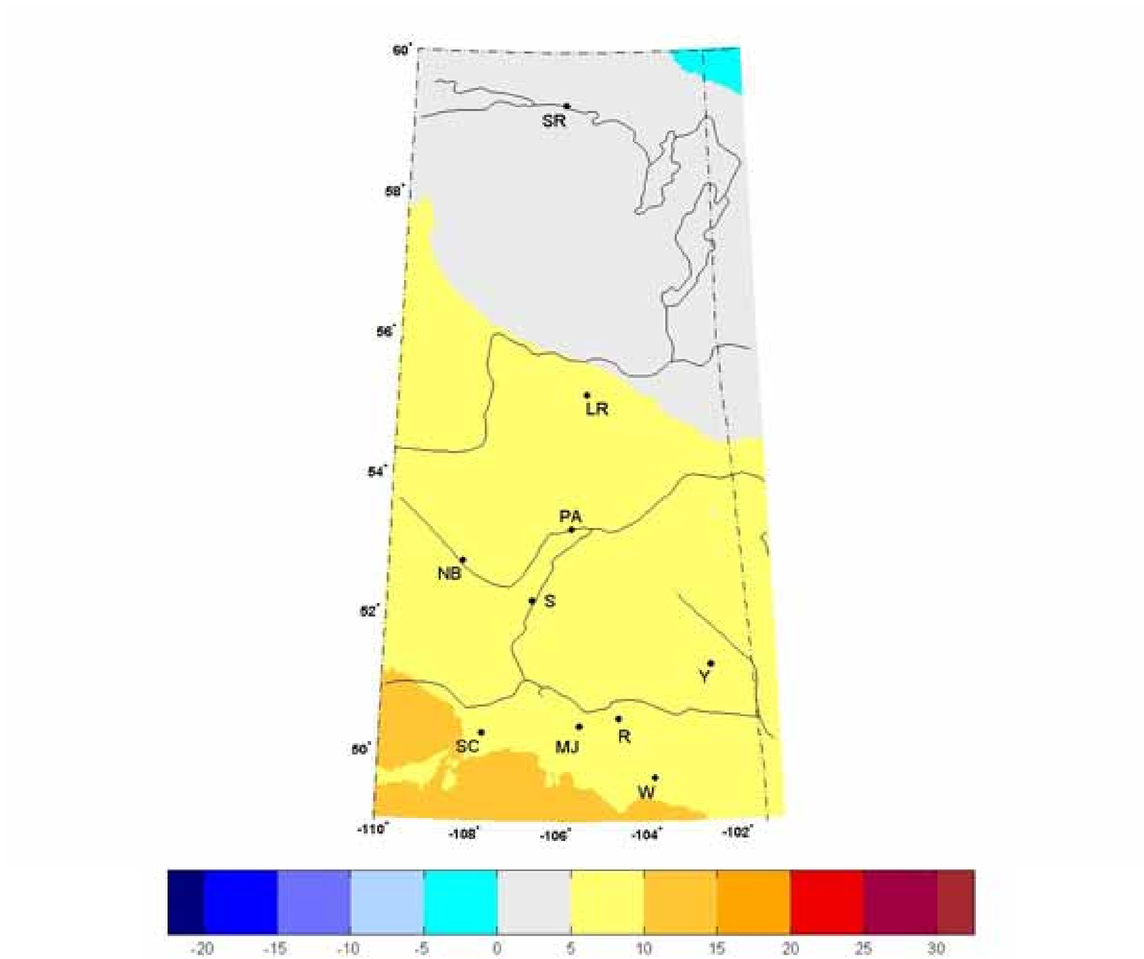


Figure 31: PRISM 1961-1990 annual mean maximum temperature (°C) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

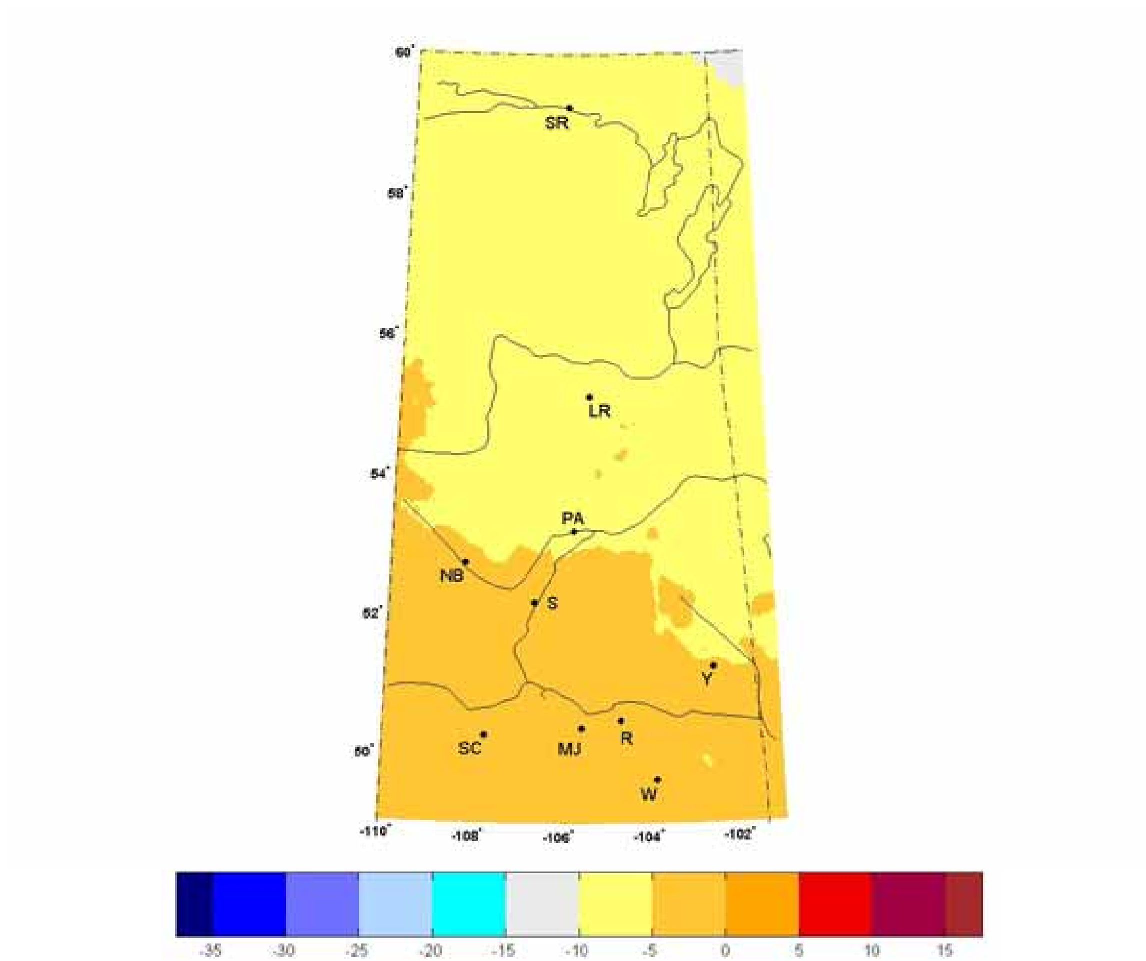


Figure 32: PRISM 1961-1990 annual mean minimum temperature (°C) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

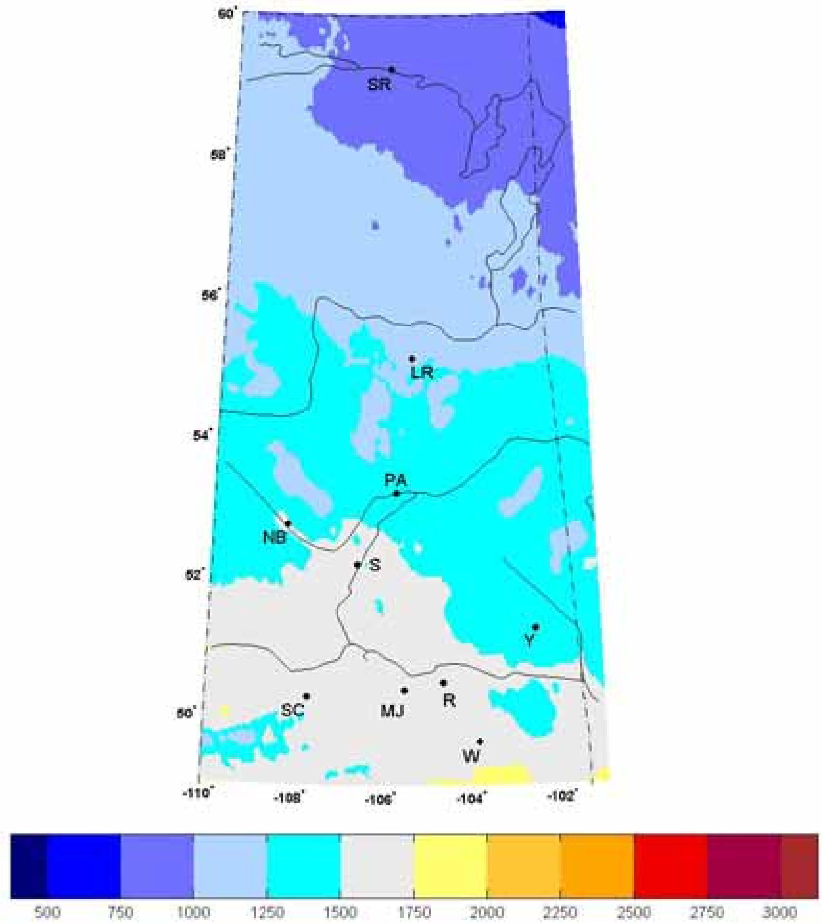


Figure 33: 1961-1990 degree days > 5°C for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

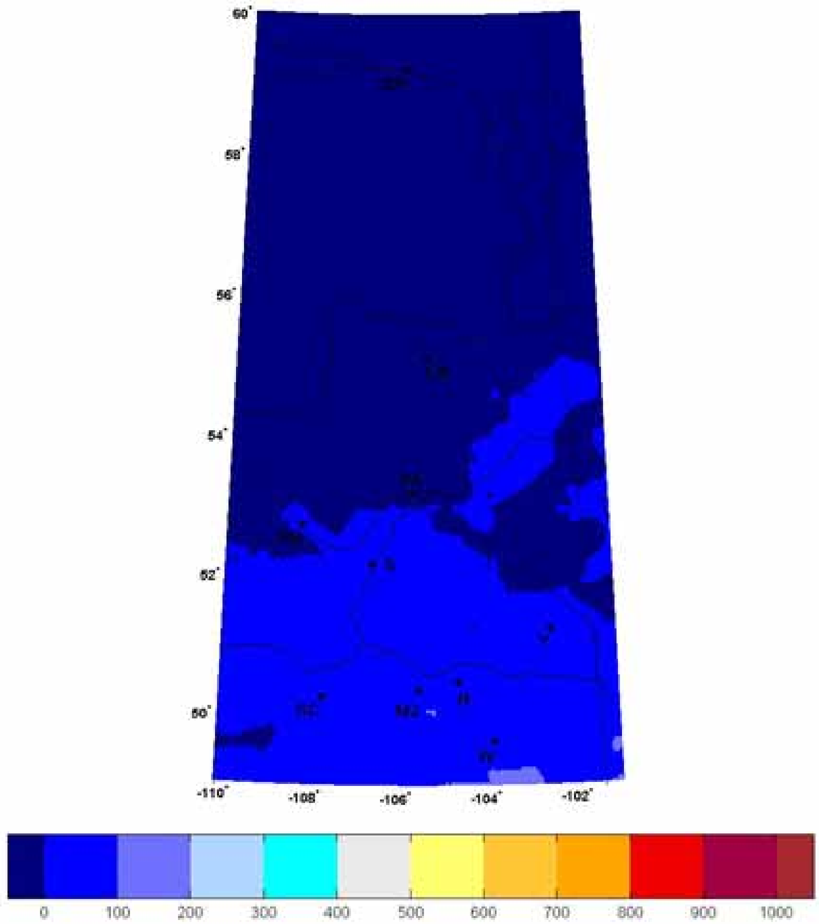


Figure 34: 1961-1990 degree days > 18°C (cooling degree days) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

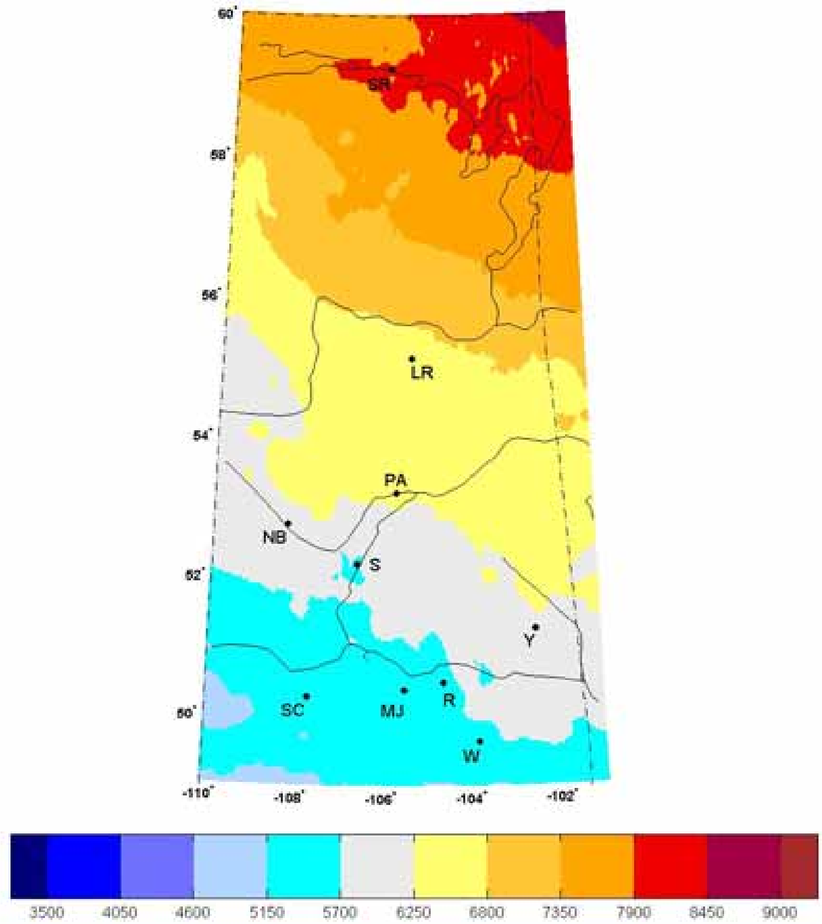


Figure 35: 1961-1990 degree days < 18°C (heating degree days) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

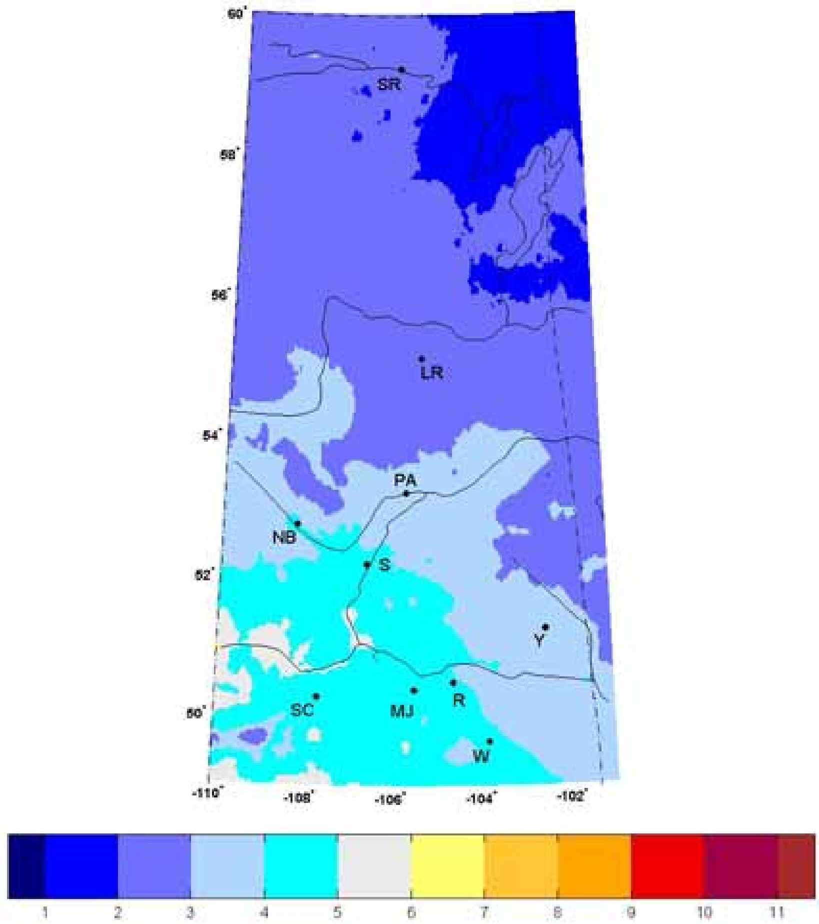


Figure 36: 1961-1990 annual moisture index for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

4: CLIMATE SCENARIOS FOR SASKATCHEWAN

As mentioned earlier, Saskatchewan was considered in two parts for this analysis – a northern forest region and a southern grassland region. Results are described separately for these two regions. Maps showing the provincial patterns of future mean, minimum and maximum temperatures, precipitation, degree days and annual moisture index for the 2050s are provided, but the discussion focuses on the following sites in each region: forest – Stony Rapids, La Ronge and Prince Albert; grassland – North Battleford, Saskatoon, Yorkton, Regina, Weyburn, Swift Current and Moose Jaw.

4.1: FOREST

Figures 37-44 show maps of the annual values for the 2050s for mean temperature, precipitation mean maximum and minimum temperatures, degree days > 5°C, degree days > 18°C (cooling degree days), degree days < 18°C (heating degree days) and annual moisture index for the forest region of Saskatchewan. Similar maps for the 2020s and 2080s are contained in Appendix B.

Figures 45-52 illustrate the range of scenario results for the different climate variables for Prince Albert, La Ronge and Stony Rapids for the 1961-1990 baseline period, the 2020s, 2050s and 2080s. This range is derived from the three selected scenarios and indicates simply the minimum and maximum values of this group. Where the scenario range increases over time – some of this increase will be due to climate change and some is due to increasing uncertainty in factors such as emissions scenarios and the climate models themselves. This type of plot allows for easy comparison across the sites.

4.1.1: Temperature

Figure 45 illustrates the range of scenario results for annual mean temperature for Prince Albert, La Ronge and Stony Rapids for the 1961-1990 baseline period, the 2020s, 2050s and 2080s. Mean annual temperature increases over time at all sites. By the 2020s, the projected future climate range for La Ronge (-0.01 to 0.98°C) is as warm as baseline conditions at Prince Albert (0.58°C). For Stony Rapids, it is only by the 2080s that the projected annual mean temperature range (-1.91 to 0.4°C) approaches that of baseline conditions at La Ronge (-0.45°C), and by this time period annual mean temperature at Stony Rapids may be above 0°C. Figures 47 and 48 show a very similar picture for annual mean maximum and minimum temperatures, respectively.

4.1.2: Precipitation

Figure 46 illustrates the range of scenarios results for the three forest sites for annual precipitation totals. Precipitation is projected to increase across all sites and all time periods. Prince Albert (406 mm) and Stony Rapids (391 mm) currently receive less precipitation than La Ronge (494 mm) and this pattern is projected to continue in the future. By the 2080s, Prince Albert is projected to receive between 423 and 456 mm, La Ronge between 514 and 547 mm and Stony Rapids between 419 and 446 mm. There is no overlap between baseline conditions and the future range of projected precipitation at any of the sites and for any of the three future time periods.

4.1.3: Degree days

Degree days are a temperature-based index and can be used with any relevant threshold temperature. Here, three threshold temperatures are considered: above 5°C, above 18°C and below 18°C. A threshold temperature of 5°C is widely recognised as indicative of general plant growth. Figure 49 indicates that there is a general increase in this index over time at all sites. This implies a lengthening of the growing season and/or the availability of more heat units for plant growth during the growing season. By the 2020s, the scenario range for La Ronge (1351-1468 degree days) overlaps with baseline conditions at Prince Albert (1382 degree days), while at Stony Rapids the scenario range for the 2050s (1010-1376 degree days) encompasses baseline conditions at La Ronge (1239 degree days). The higher end of the scenario range for this time period at Stony Rapids is almost equal to baseline conditions at Prince Albert (1382 degree days). By the 2080s the scenario range at Stony Rapids (1136-1622 degree days) encompasses baseline conditions at Prince Albert (1382 degree days) and La Ronge (1239 degree days).

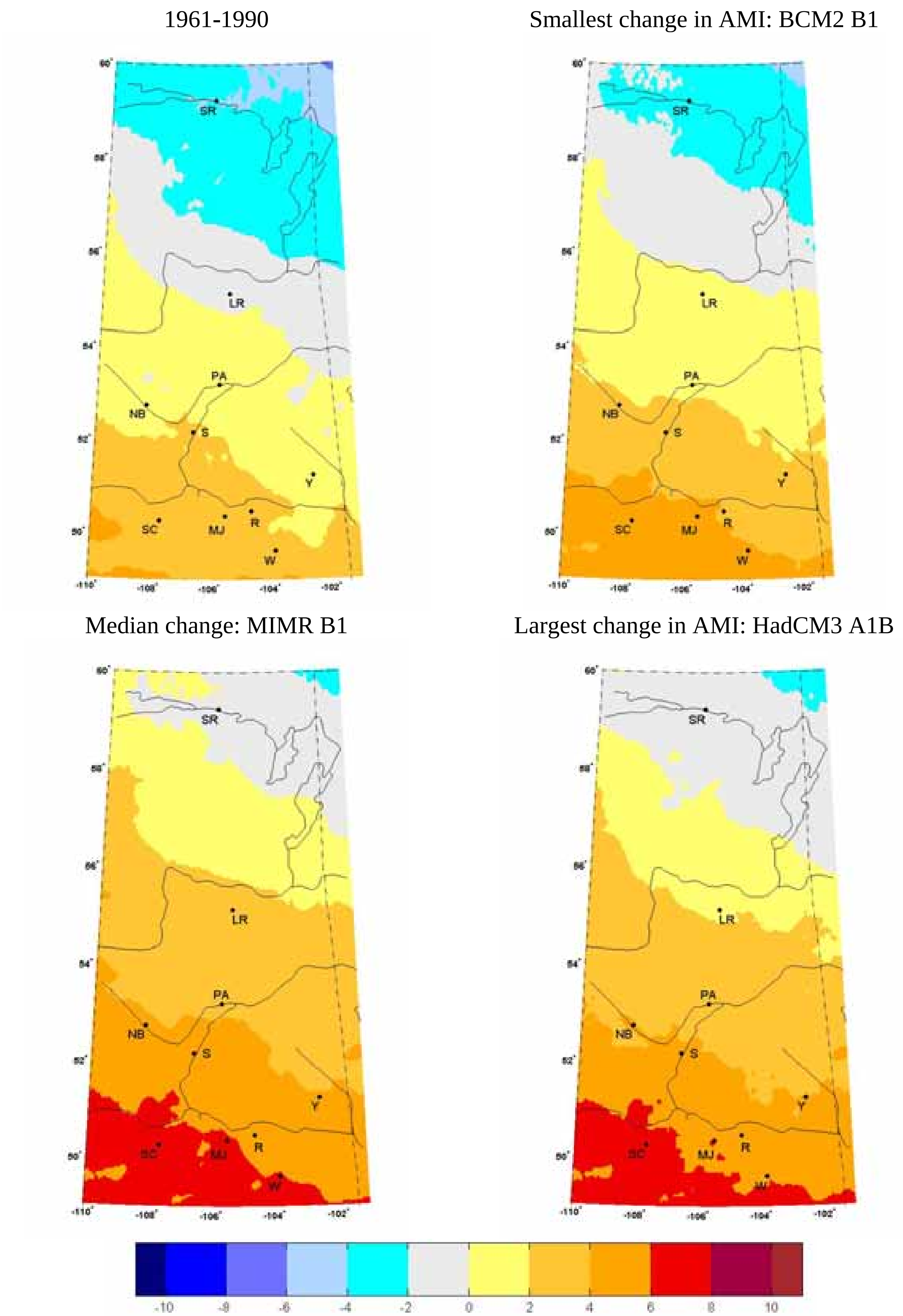


Figure 37: Annual mean temperature (°C) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

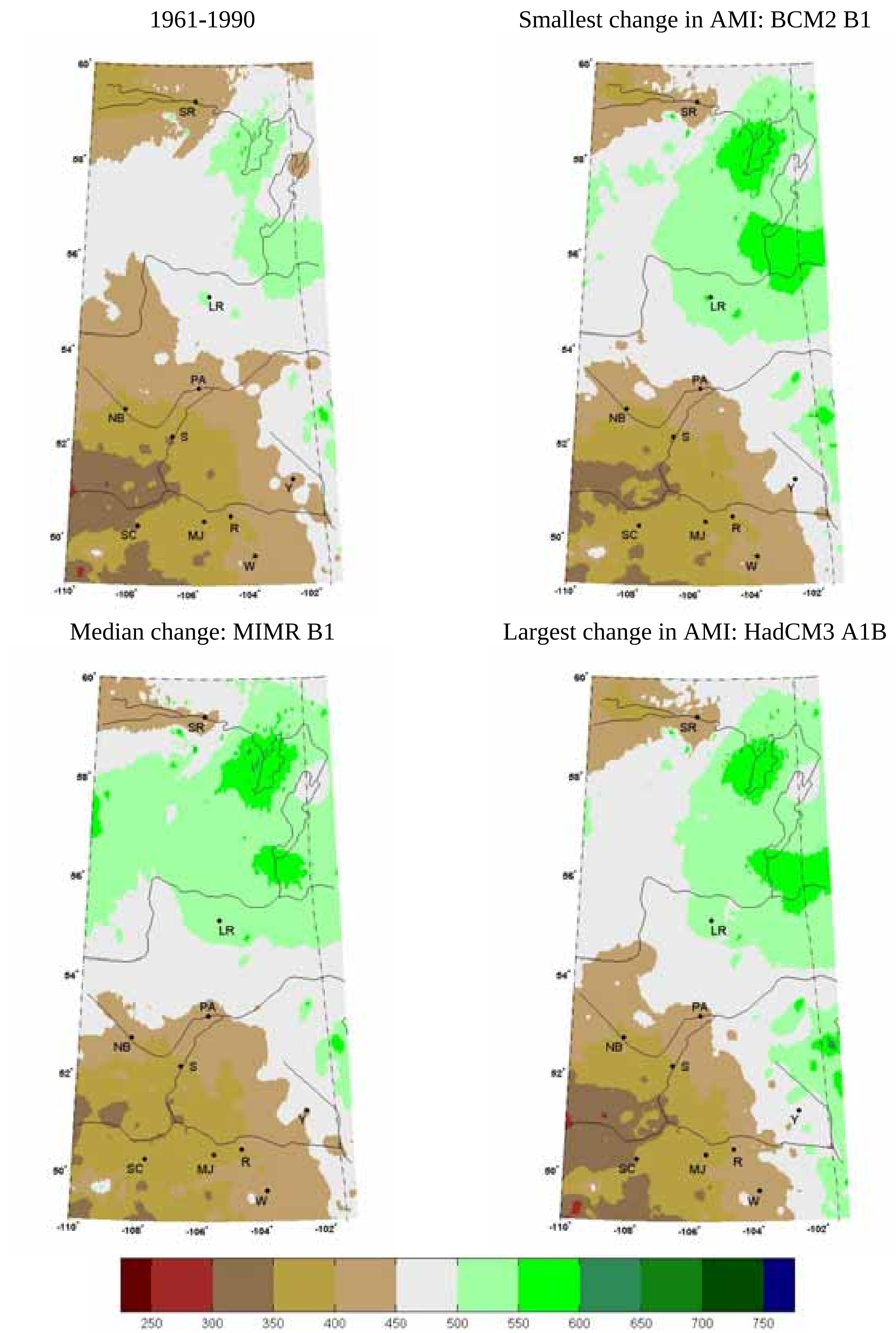


Figure 38: Annual precipitation (mm) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

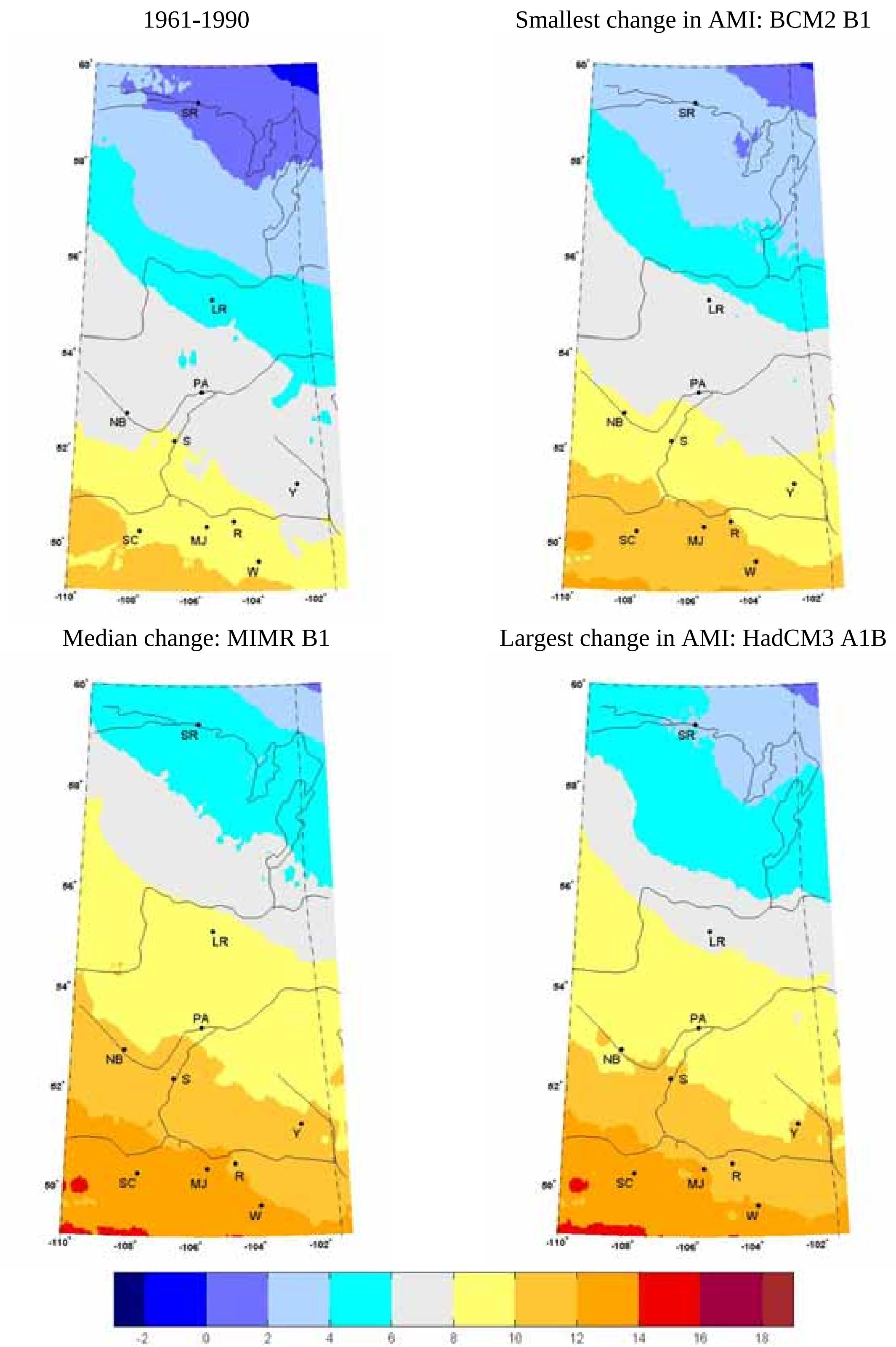


Figure 39: Mean maximum temperature (°C) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

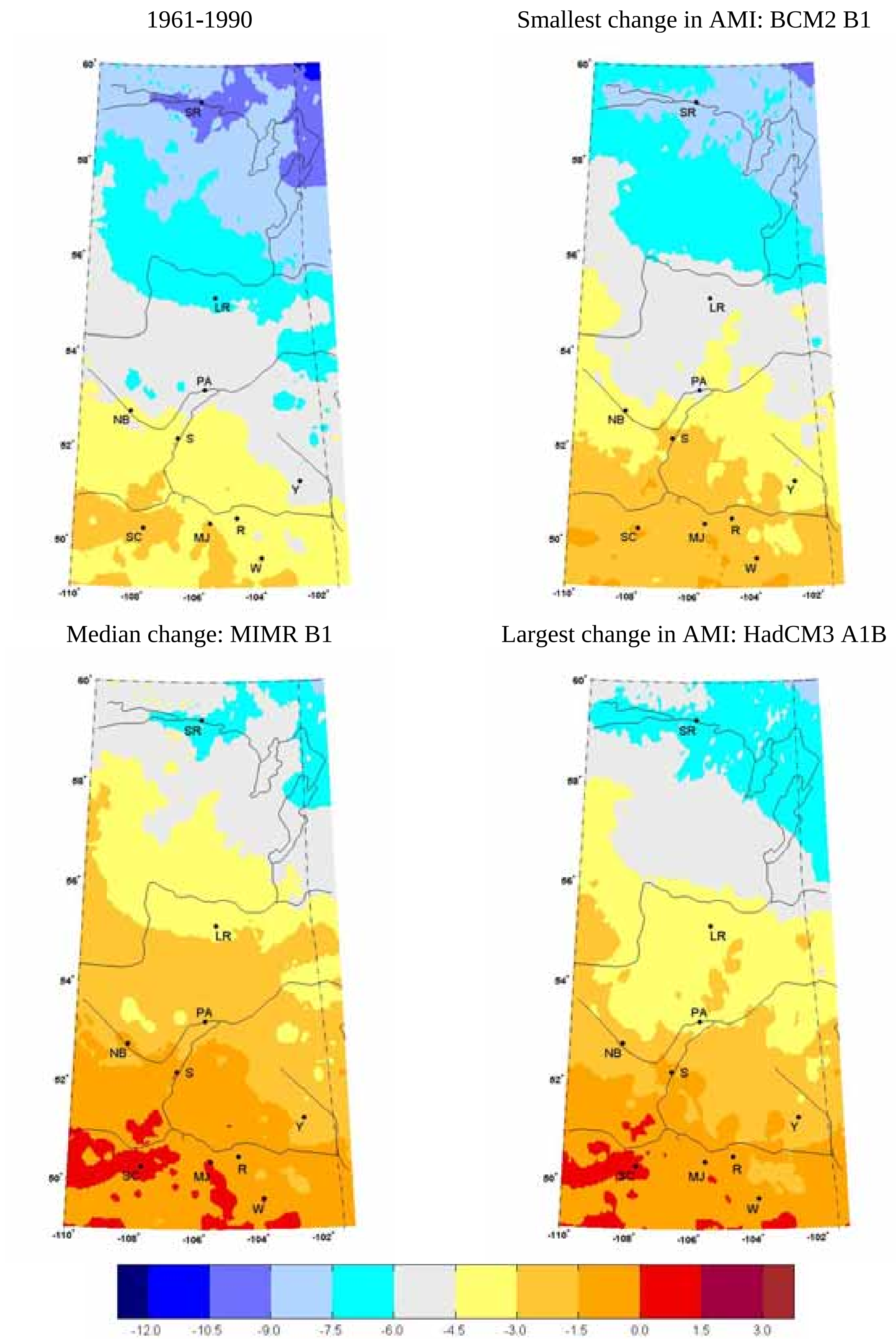


Figure 40: Mean minimum temperature (°C) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

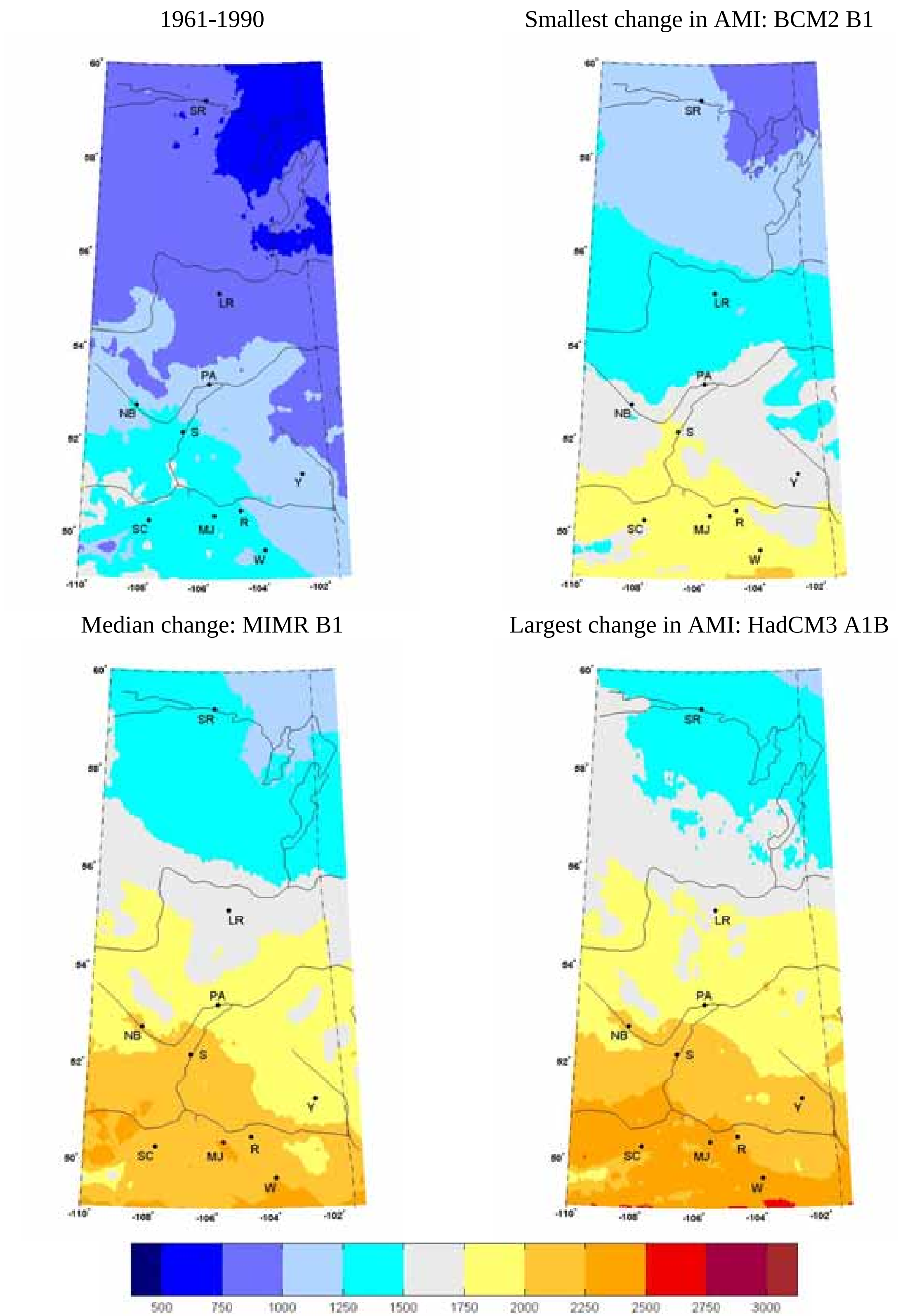


Figure 41: Degree days >5°C for the 2050s, selected based on AMI change over forest region of Saskatchewan.

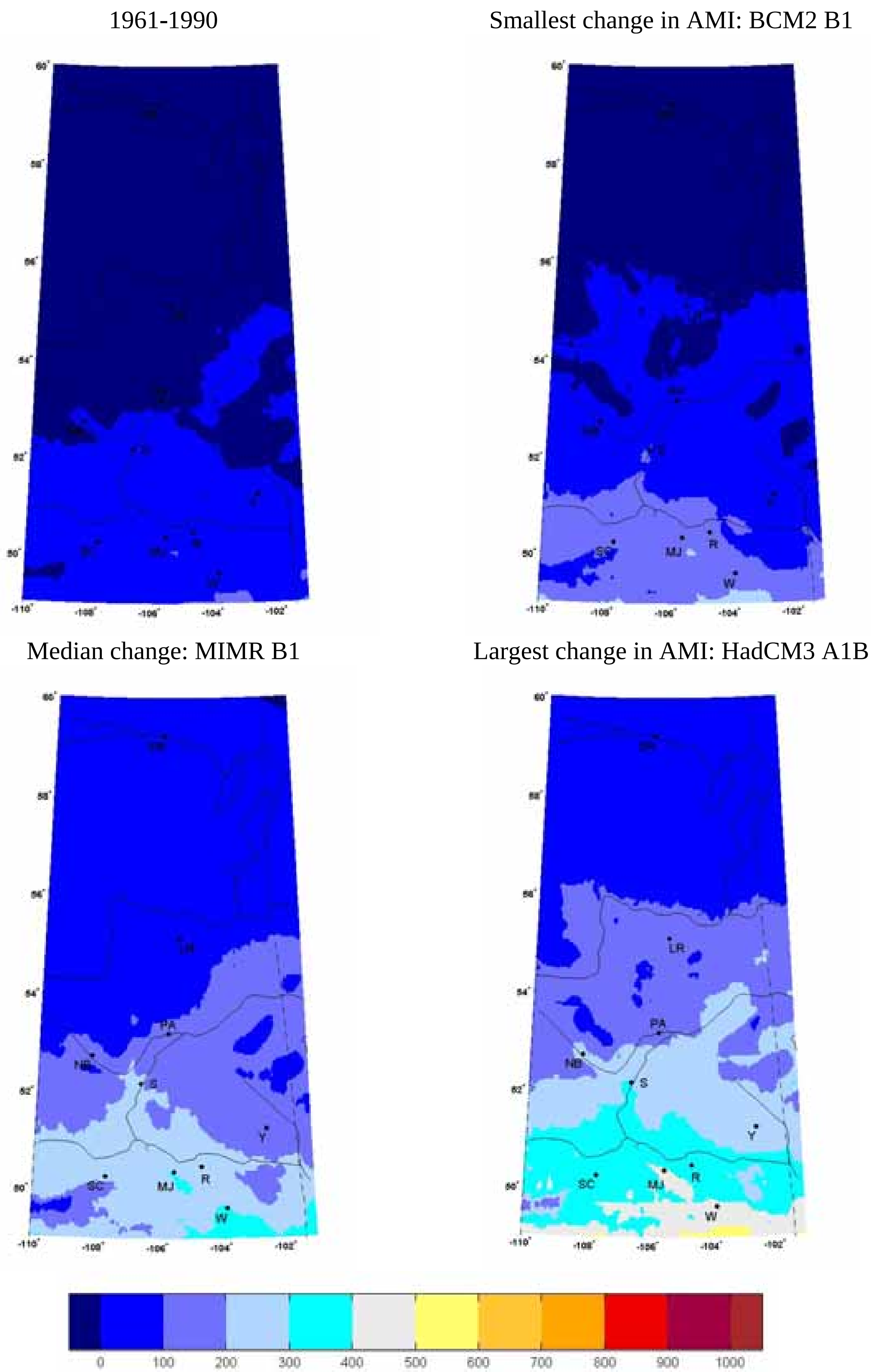


Figure 42: Degree days >18°C (cooling degree days) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

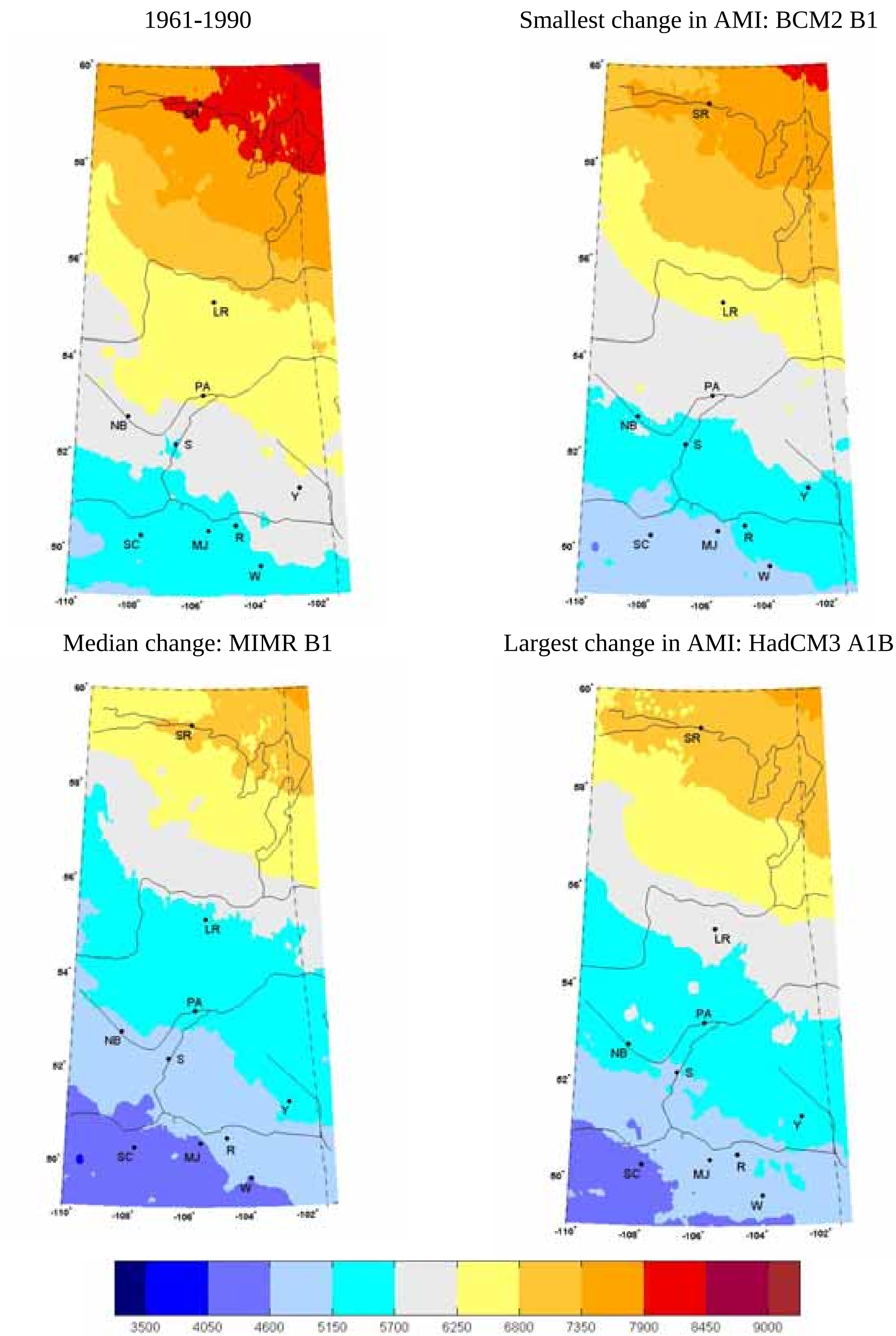


Figure 43: Degree days <18°C (heating degree days) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

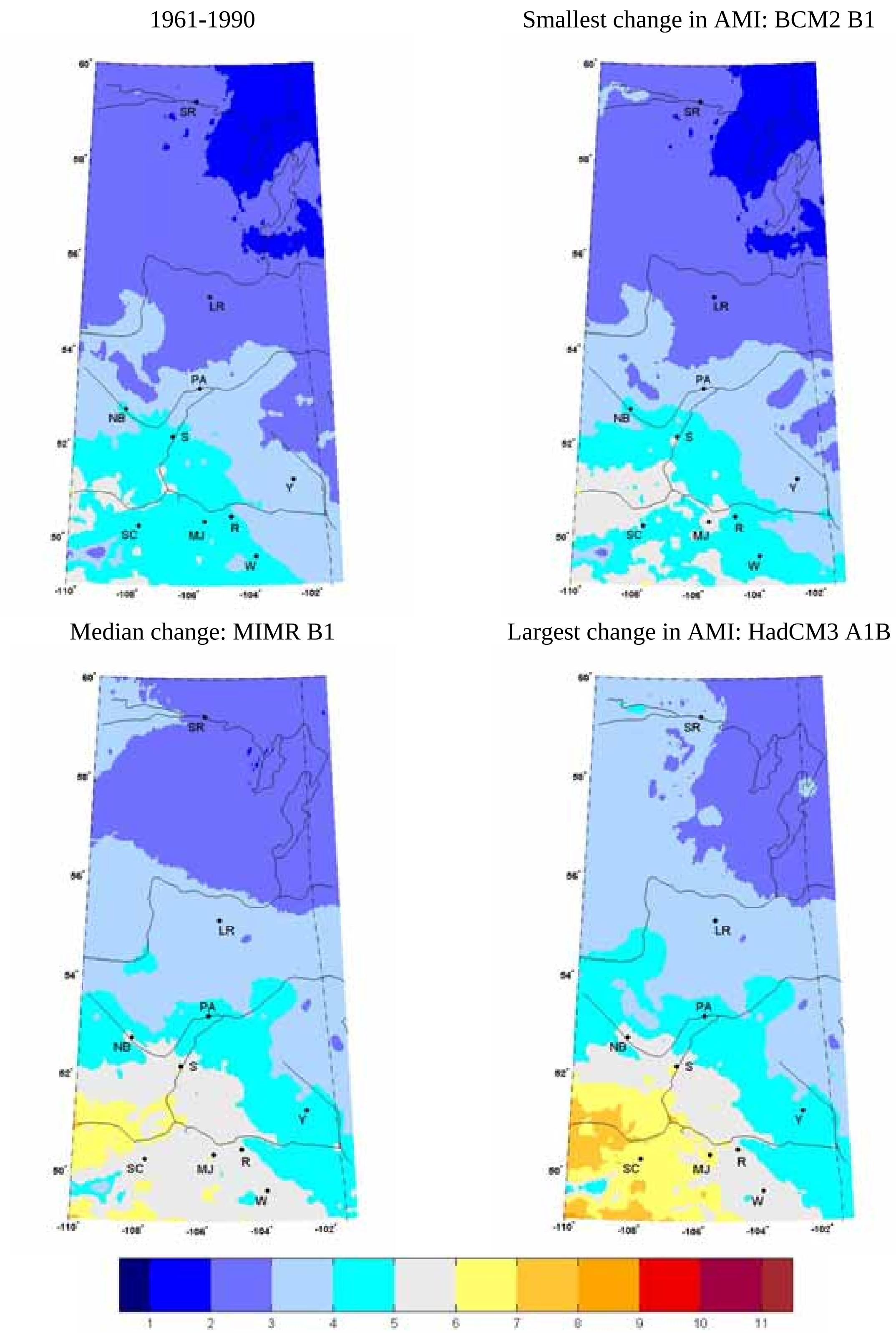


Figure 44: Annual moisture index for the 2050s, selected based on AMI change over forest region of Saskatchewan.

Figure 50 shows the results for the three forest sites for degree days > 18°C, i.e., cooling degree days. This threshold temperature is used as an indication of the requirement for air conditioning in summer. Baseline conditions at all sites indicate that, on average, no cooling degree days are currently counted. Increases occur at all sites – as early as the 2020s, the scenario range for Prince Albert is above zero (11-72 degree days). This is not the case until the 2050s for La Ronge (0.9-132 degree days), while for Stony Rapids, cooling degree days occur beginning in the 2050s (0-35 degree days).

Figure 51 illustrates the results for degree days < 18°C, i.e., heating degree days. This threshold temperature is used to indicate when space heating is required. In this case, the value of this index decreases over time at all sites, indicating a reduction in the need for space heating. By the 2020s, the scenario range at La Ronge (6177-6515 degree days) overlaps with baseline conditions at Prince Albert (6328 degree days), while for Stony Rapids, the 2080s scenario range (6433-7240 degree days) overlaps with baseline conditions at La Ronge (6703 degree days).

4.1.4: Annual moisture index

Annual moisture index, defined as the ratio of annual degree days total above a threshold temperature of 5°C to annual total precipitation, combines temperature and precipitation information into an index which can be used to give an indication of moisture availability for plant growth. Increases (decreases) in this index indicate either increases (decreases) in the degree day total, or decreases (increases) in annual precipitation. Figure 52 indicates that the annual moisture index increases across all time periods for all three forest sites. By the 2080s, the index values are projected to increase by at least 1 degree day/mm at each site. The scenario range for La Ronge (2.96-3.77) and Stony Rapids (2.67-3.86) for this time period encompasses baseline conditions at Prince Albert (3.41). Given that the scenario ranges for degree days > 5°C and for precipitation indicate increases over time, this implies that the increases in annual moisture index

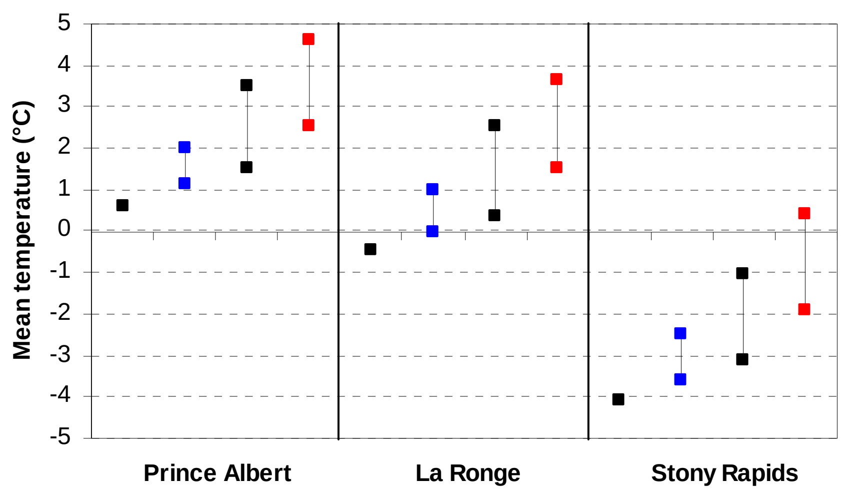


Figure 45: Annual mean temperature (°C) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

are driven by the degree day increases, rather than the precipitation increases.

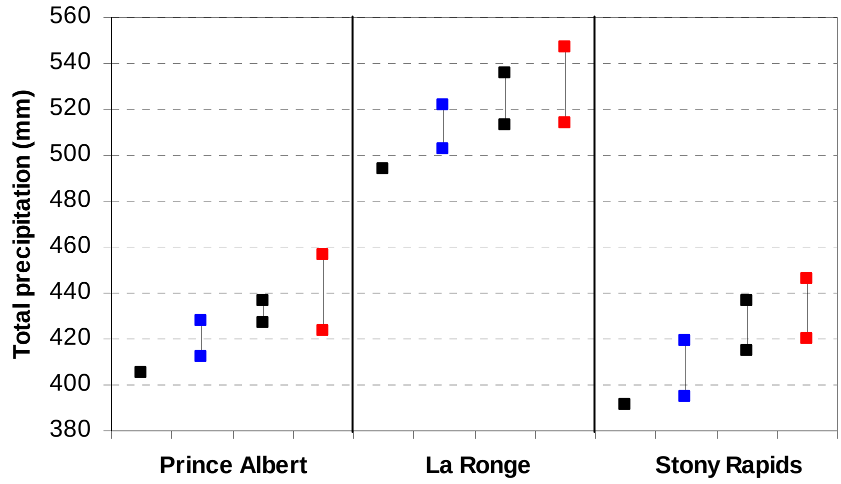


Figure 46: Annual precipitation total (mm) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

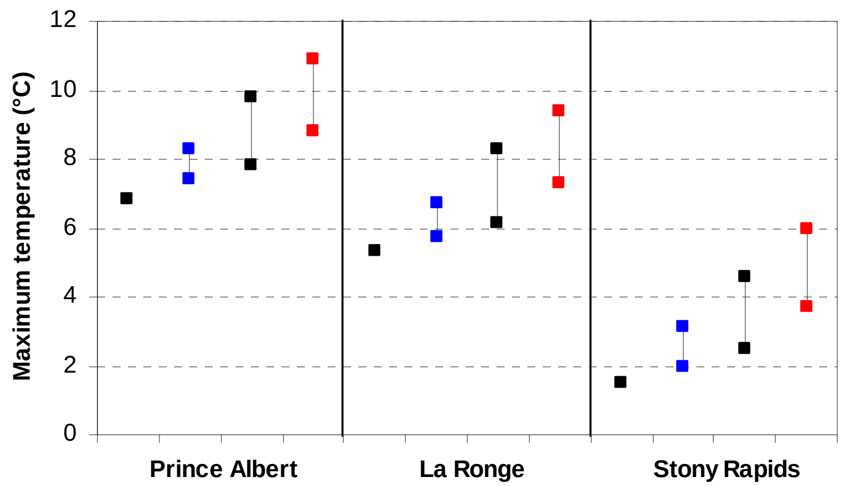


Figure 47: Annual mean maximum temperature (°C) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

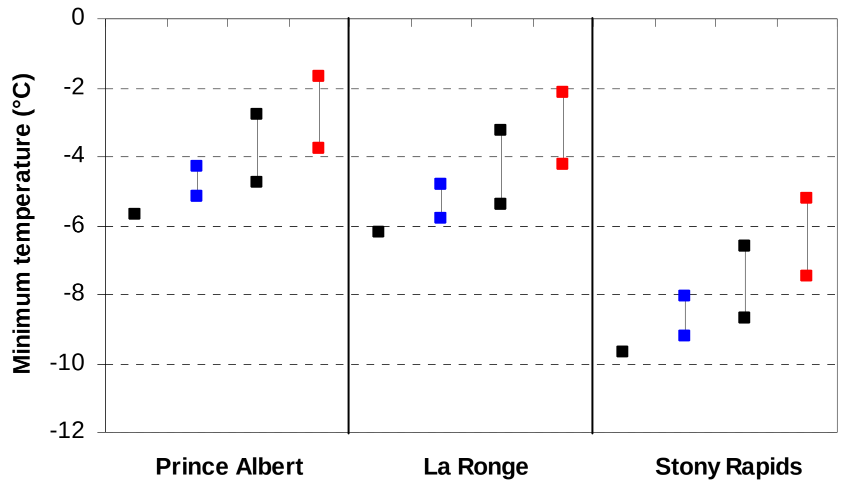


Figure 48: Annual mean minimum temperature (°C) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

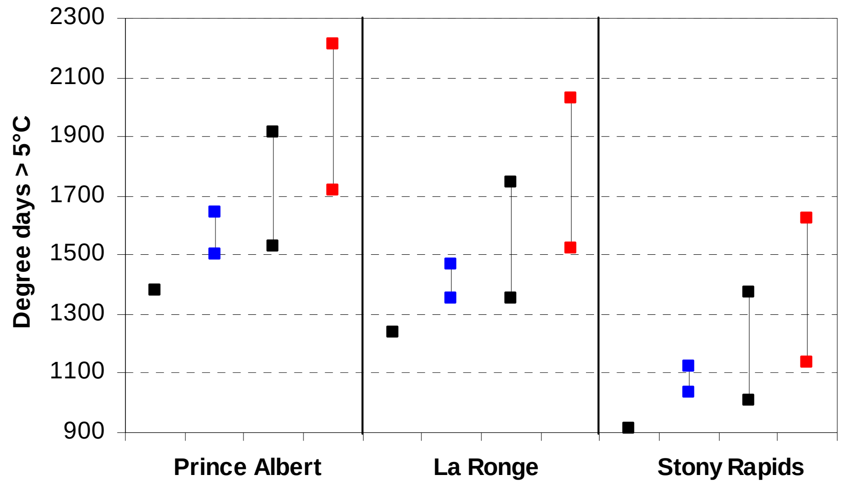


Figure 49: Degree days > 5°C for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

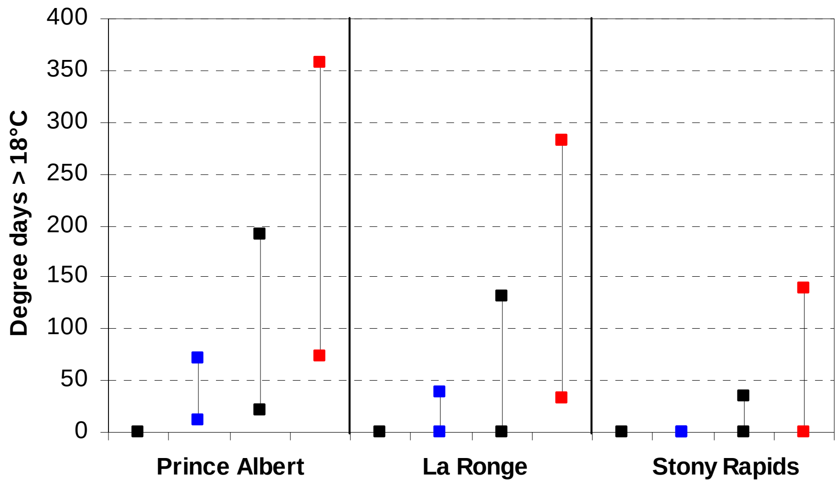


Figure 50: Degree days > 18°C (cooling degree days) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

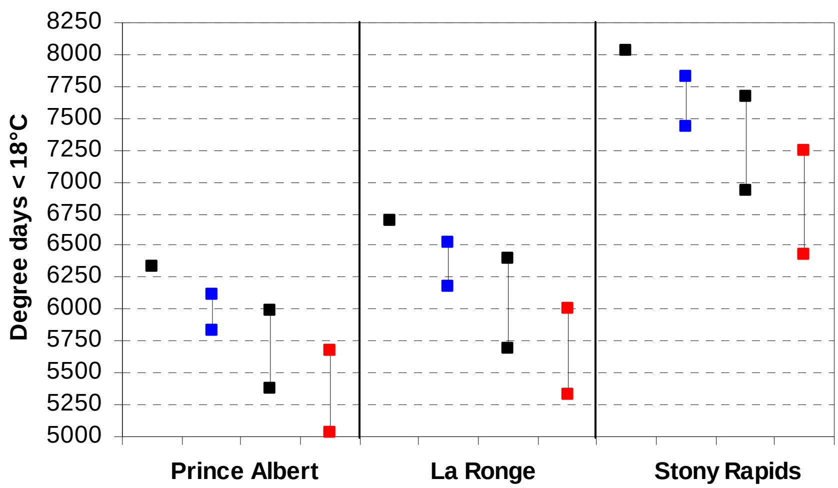


Figure 51: Degree days < 18°C (heating degree days) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

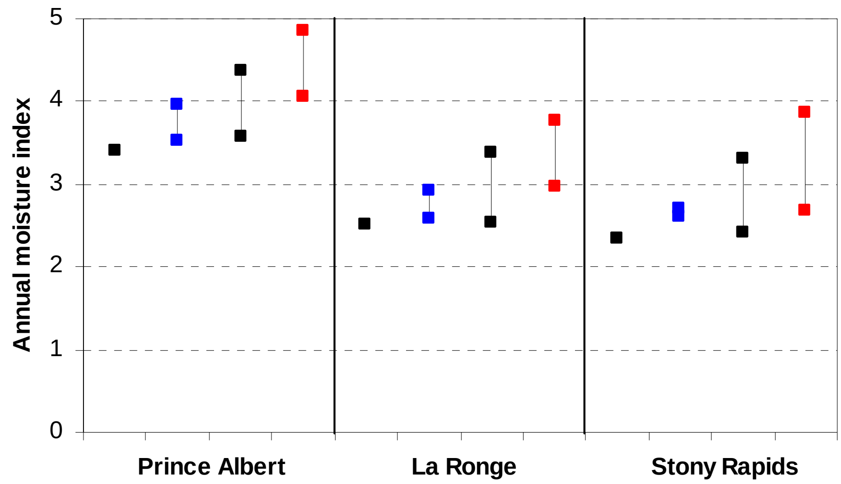


Figure 52:Annual moisture index for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

4.2: GRASSLAND

Figures 53-60 show maps of the annual values for the 2050s for mean temperature, precipitation mean maximum and minimum temperatures, degree days > 5°C, degree days > 18°C (cooling degree days), degree days < 18°C (heating degree days) and annual moisture index for the grassland region of Saskatchewan. Similar maps for the 2020s and 2080s are contained in Appendix B. Figures 61-68 illustrate the range of scenario results for the different climate variables for Regina, Saskatoon, North Battleford, Yorkton, Weyburn, Moose Jaw and Swift Current for the 1961-1990 baseline period, the 2020s, 2050s and 2080s. As mentioned earlier, this range is derived from the three selected scenarios and indicates simply the minimum and maximum values of this group.

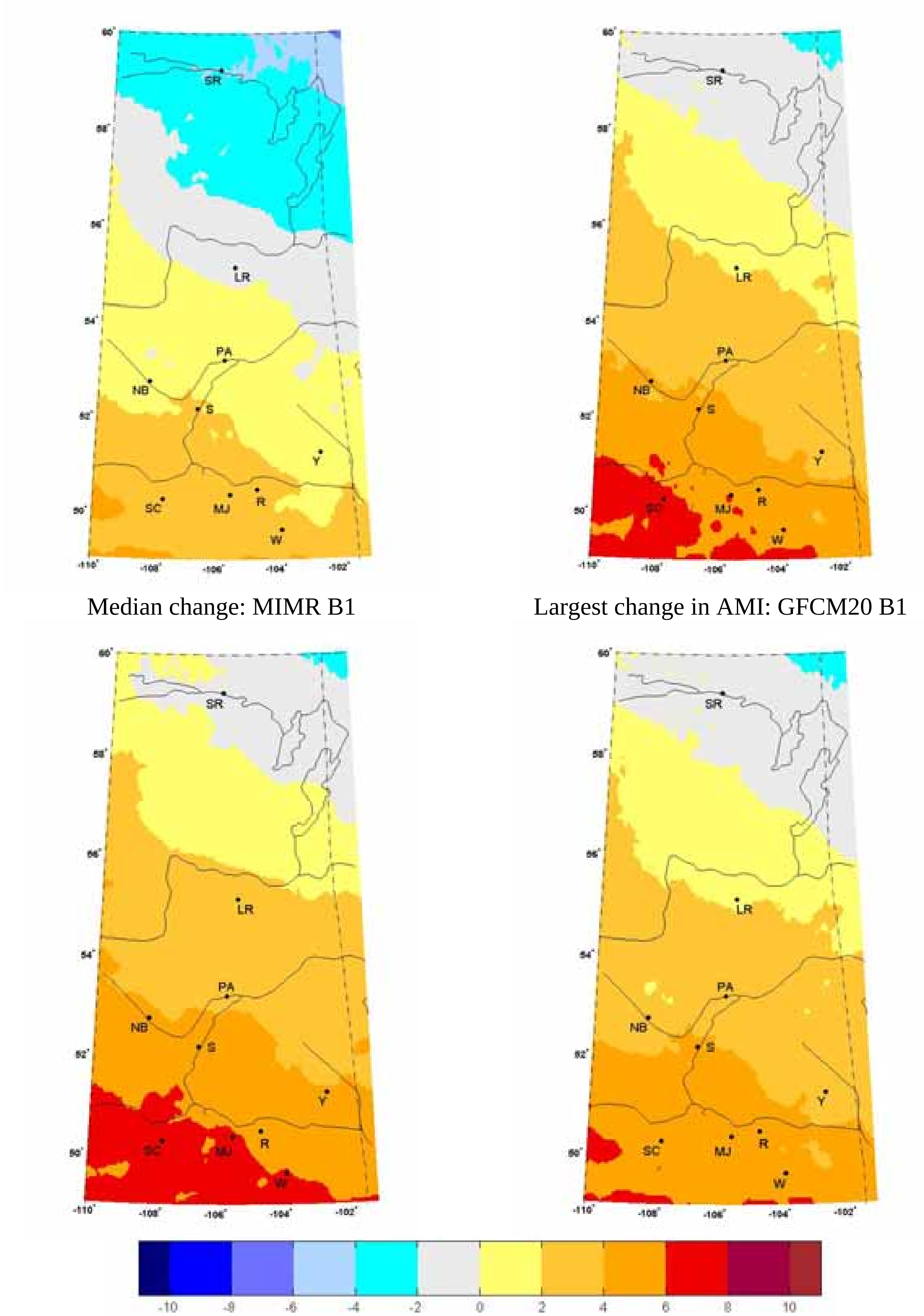
4.2.1: Temperature

Figure 61 illustrates that annual mean temperature at the seven grassland sites increases over time such that by the 2020s, the annual mean temperature is at least 1°C warmer than baseline conditions at all sites, and for Yorkton 3°C warmer (1.3°C compared with 4.3°C). By the 2080s, the projected annual mean temperature is at least double that of baseline conditions. Figures 63 and 64, for annual mean maximum and minimum temperature, respectively, show a very similar picture.

4.2.2: Precipitation

Figure 62 shows the scenario ranges for annual precipitation totals. Although this figure indicates a general increase in precipitation over time at all sites, there is some overlap with baseline conditions at Yorkton and Weyburn for the 2020s and 2050s. By the 2080s, the projected range in annual precipitation for Regina (394-445 mm), Weyburn (412-466 mm) and North Battleford (393-439 mm) encompasses baseline conditions at Yorkton (437 mm).

1961-1990 Smallest change in AMI: CGCM3_T47_2 A1B



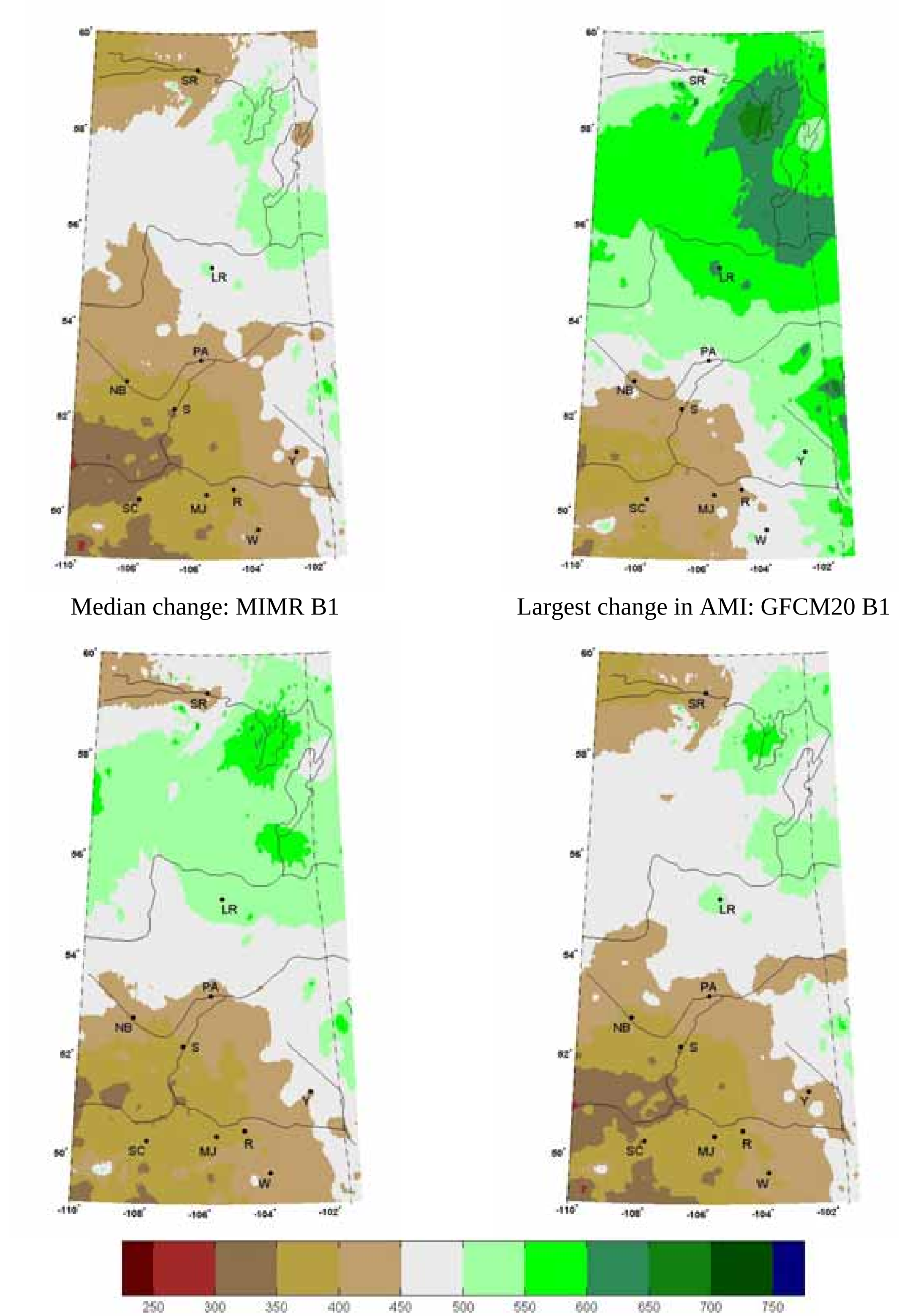
Median change: MIMR B1

Largest change in AMI: GFCM20 B1

Figure 53: Annual mean temperature (°C) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

1961-1990

Smallest change in AMI: CGCM3_T47_2 A1B



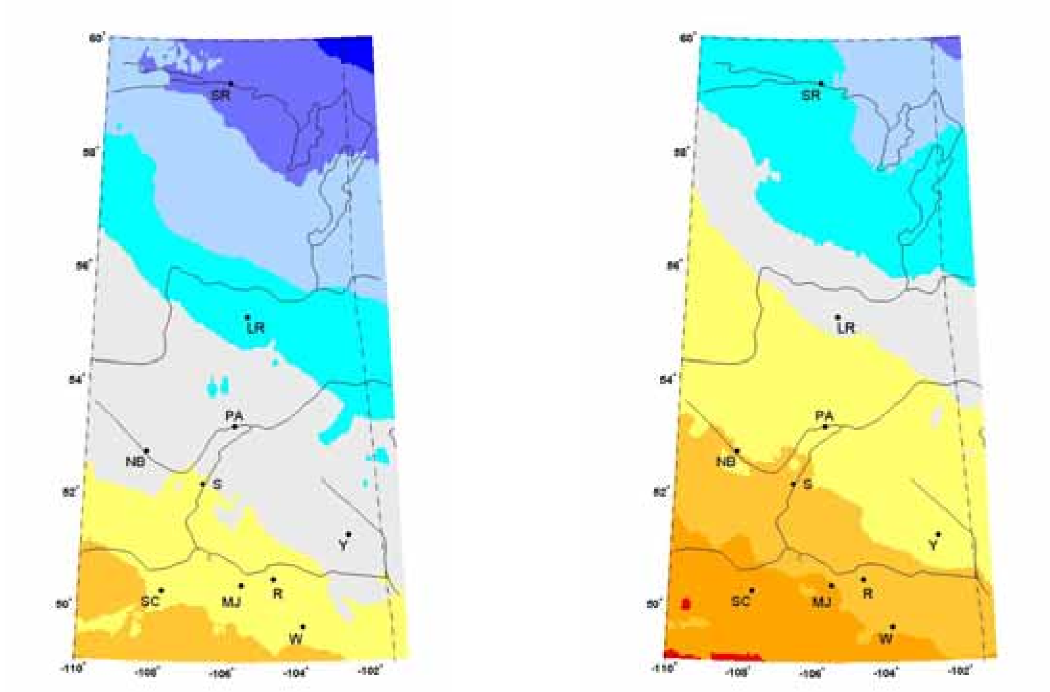
Median change: MIMR B1

Largest change in AMI: GFCM20 B1

Figure 54: Annual precipitation total (mm) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

1961-1990

Smallest change in AMI: CGCM3_T47_2 A1B



Median change: MIMR B1 Largest change in AMI: GFCM20 B1

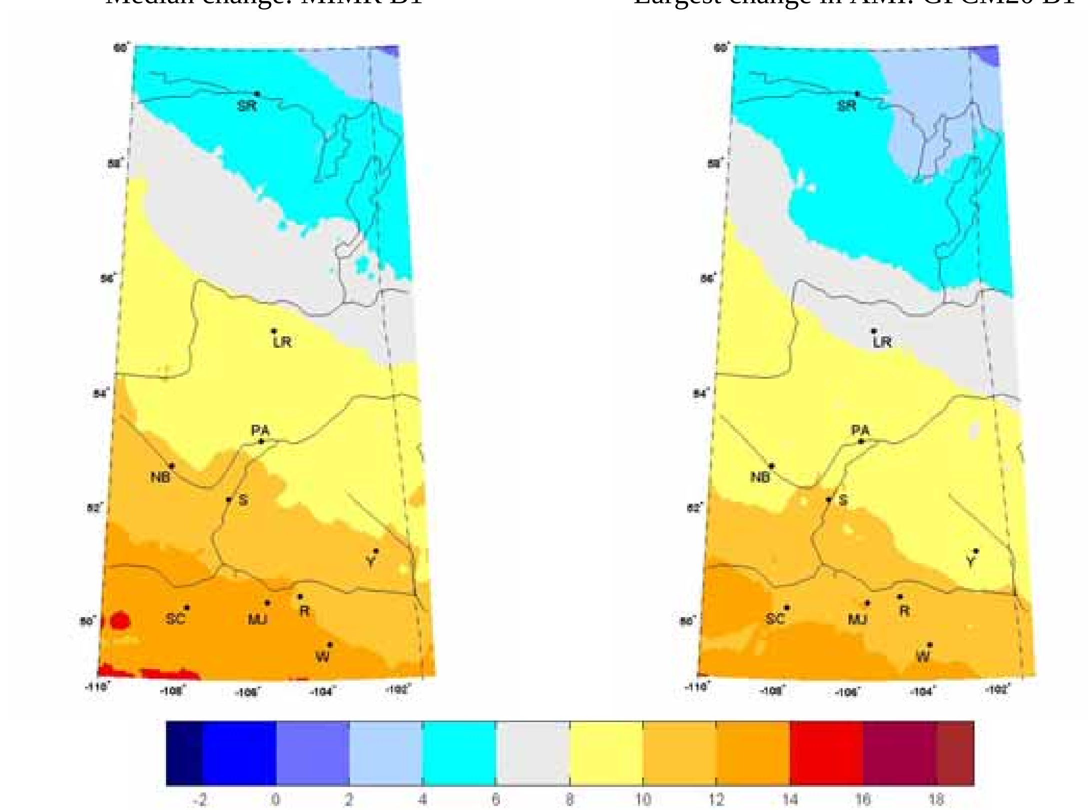


Figure 55: Mean maximum temperature (°C) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

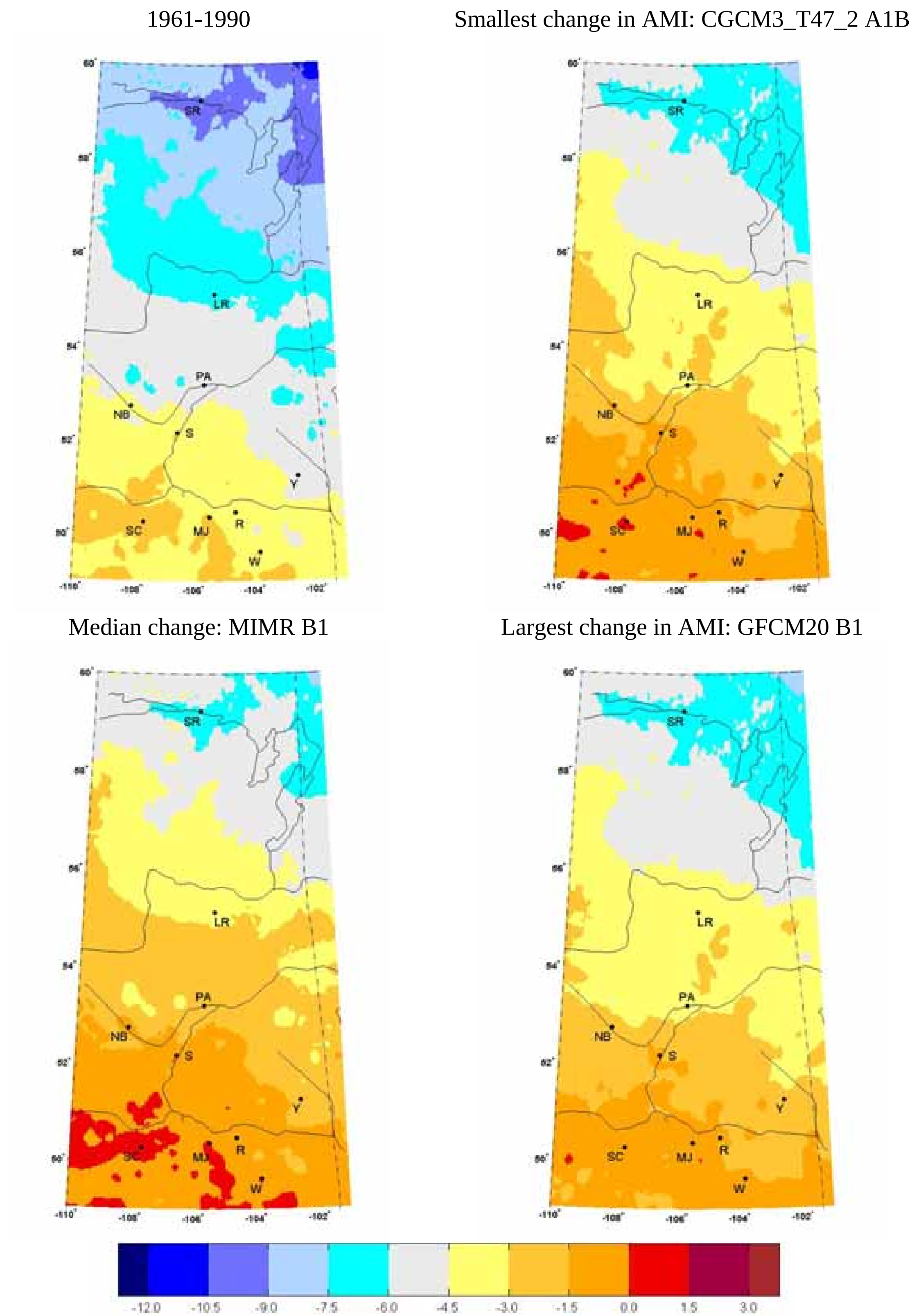


Figure 56: Mean minimum temperature (°C) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

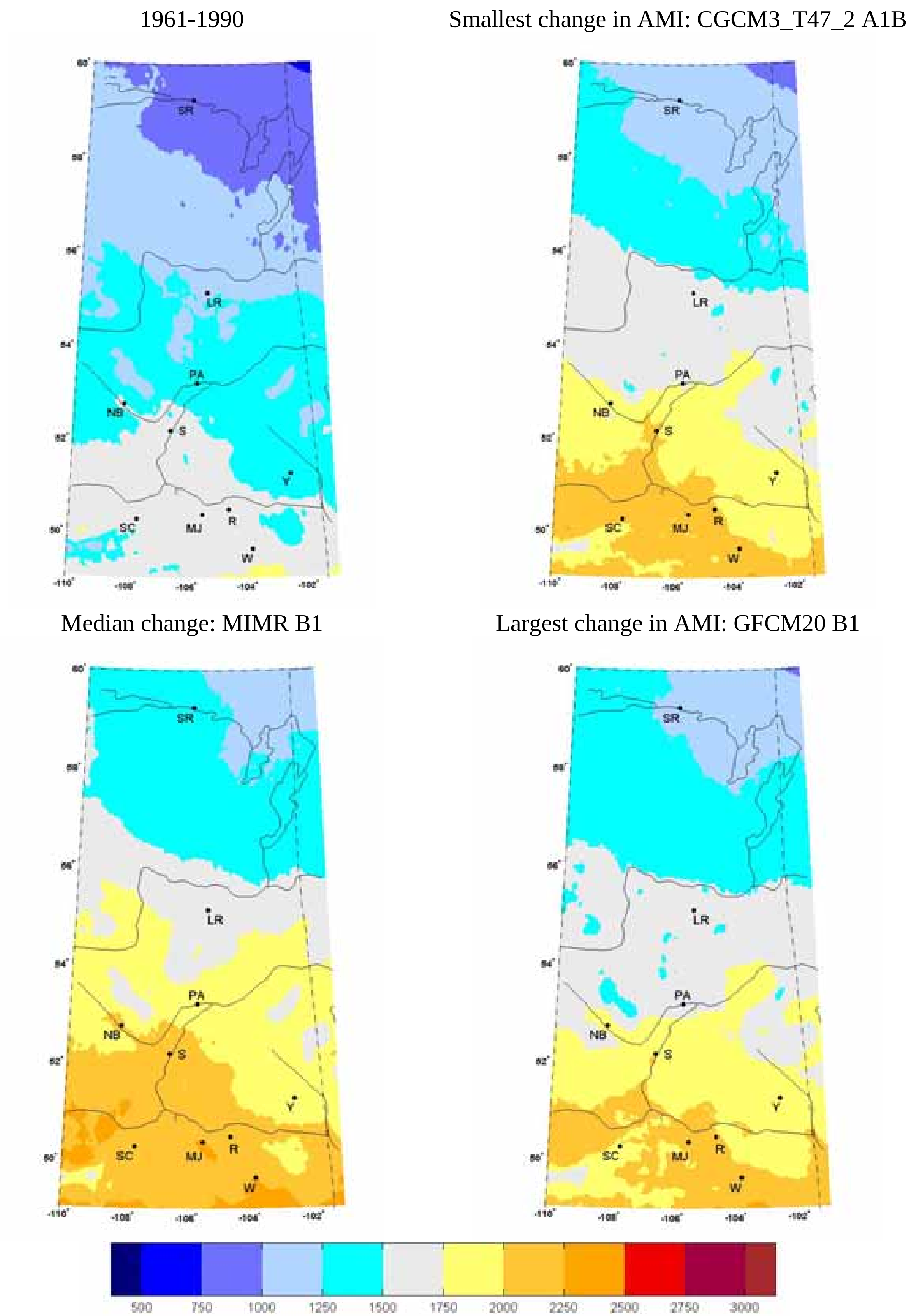


Figure 57: Degree days > 5°C for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

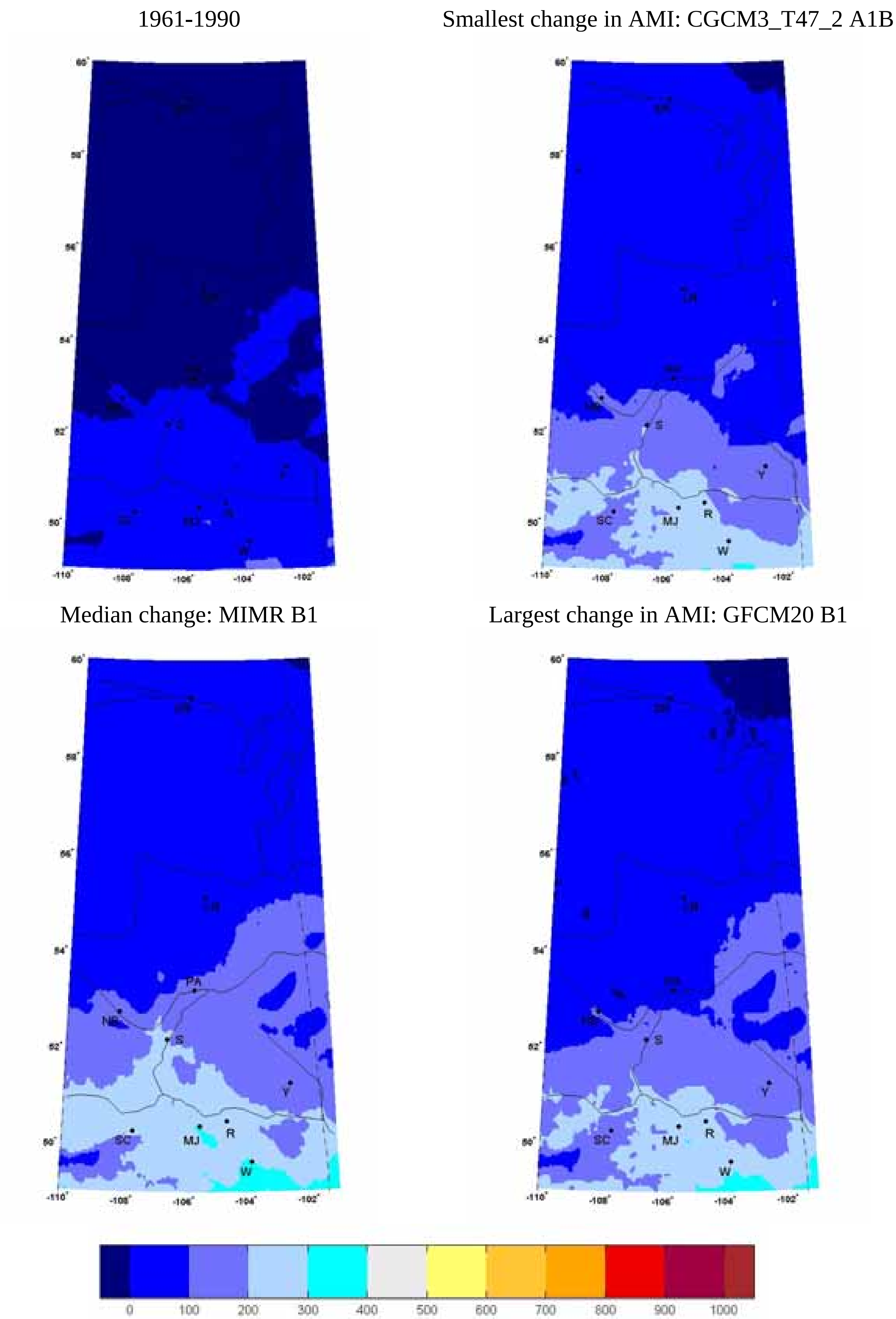


Figure 58: Degree days > 18°C (cooling degree days) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

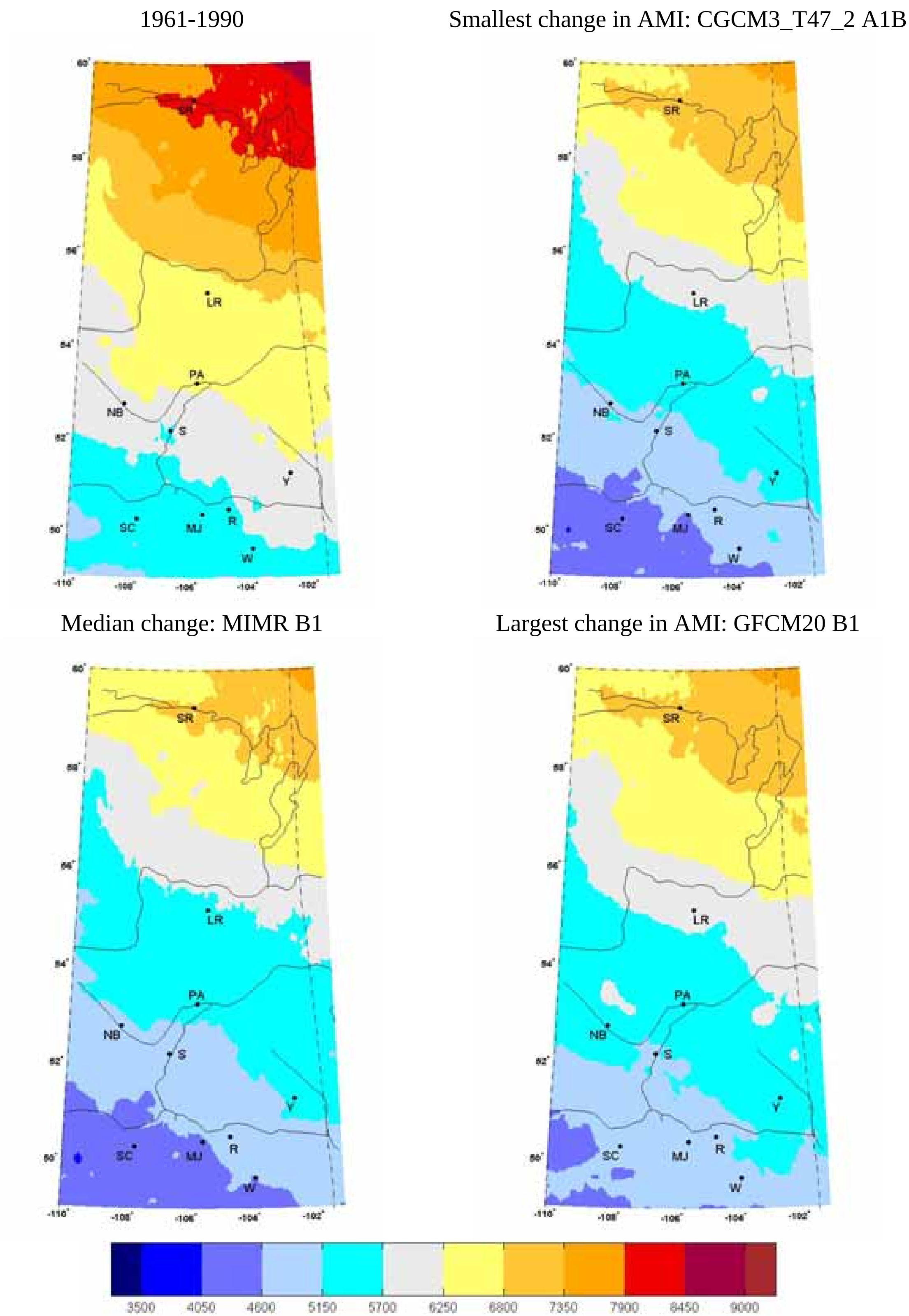


Figure 59: Degree days < 18°C (heating degree days) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

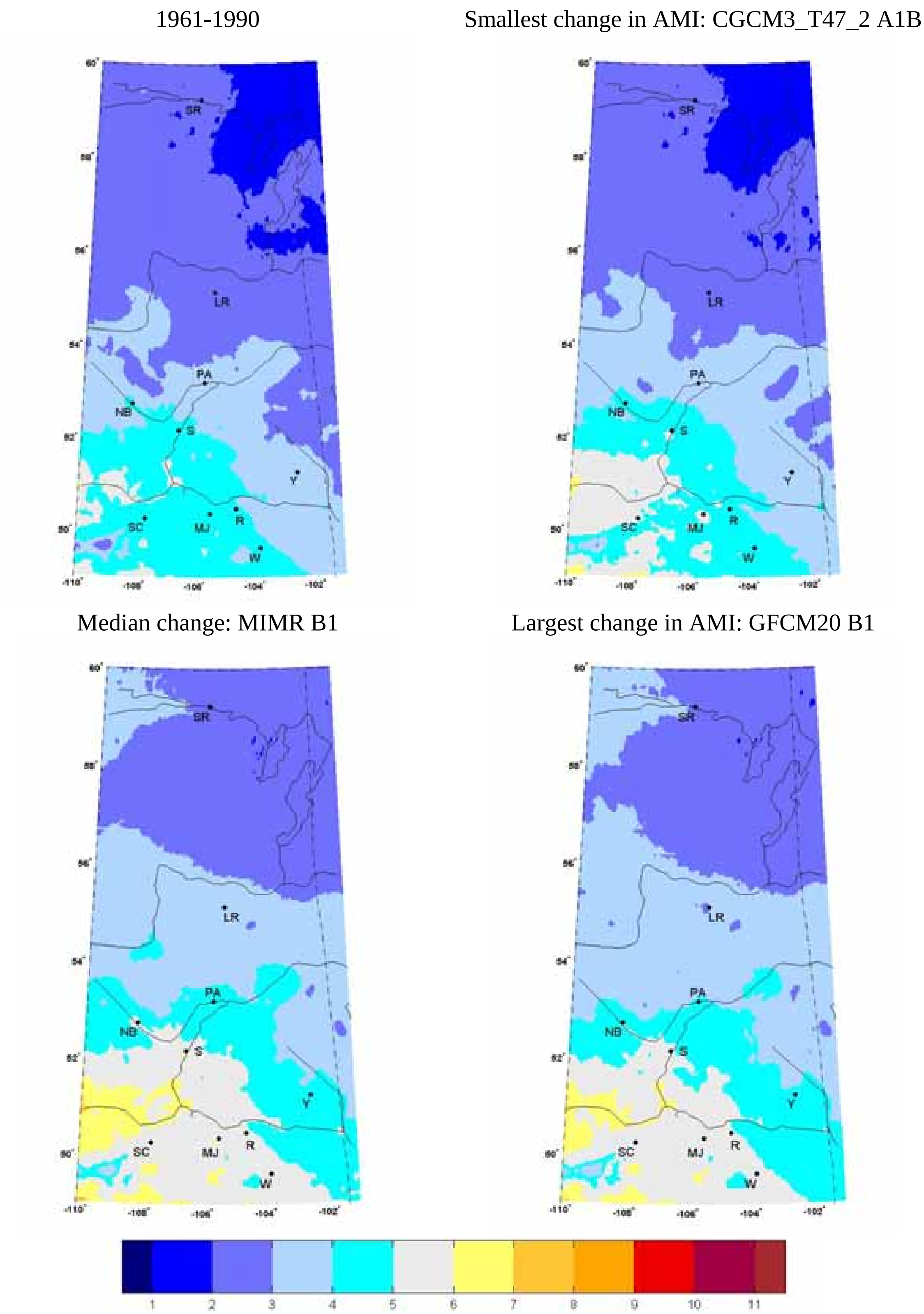


Figure 60: Annual moisture index for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

4.2.3: Degree days

Figure 65 shows the scenario ranges for degree days > 5°C. Baseline values are generally between 1500 and 1700 degree days at all sites, with the exception of Yorkton (1483 degree days). Increases occur in this index value at all sites and all time periods. By the 2080s, the projected scenario range indicates that for most sites, degree day totals will be greater than 2000. Yorkton (1902-2177 degree days) and North Battleford (1877-2293 degree days) are the exception to this with only the higher end of the scenario range being greater than this value during this time period.

The scenario ranges for cooling degree days (degree days > 18°C) are shown in Figure 66. For all seven grassland sites, the baseline values are above zero, indicating that there may already be some requirement for air-conditioning in summer. This requirement may increase over time, since the degree day values increase. For example, by the 2080s, the cooling degree day range at Regina (257-376 degree days), Weyburn (276-407 degree days) and Yorkton (169-251 degree days) is projected to be between 3 and 5 times greater than baseline conditions for Regina (69 degree days) and Weyburn (75 degree days), but between 14 and 20 times greater than baseline conditions at Yorkton (12 degree days).

In contrast to projections for cooling degree days, those for heating degree days (degree days < 18°C) are for a reduction in degree day totals across all sites. Figure 67 illustrates the scenario ranges for this index. Baseline totals are between 5279 degree days for Swift Current and 6060

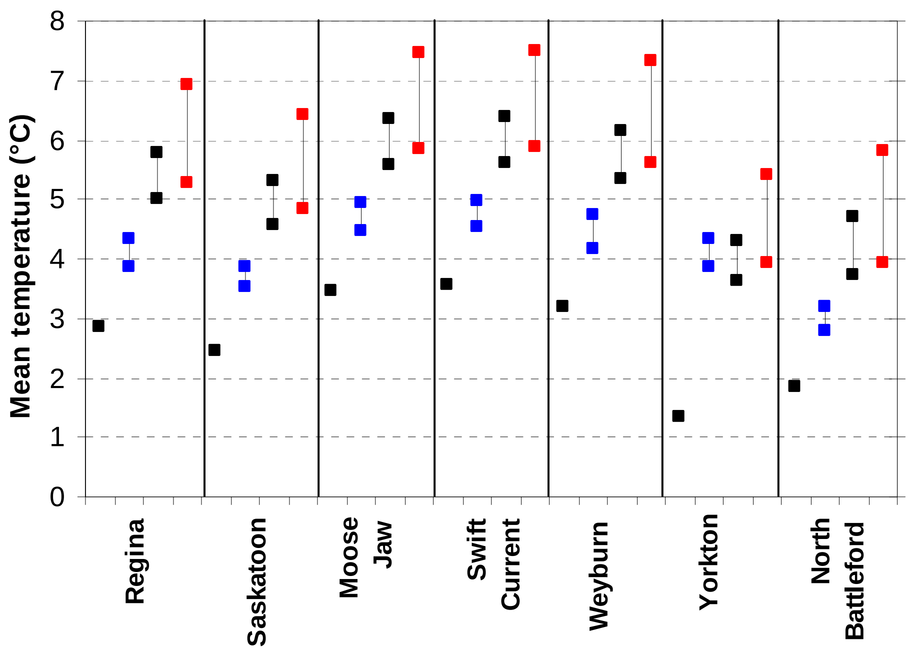


Figure 61: Annual mean temperature (°C) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

degree days for Yorkton. By the 2080s, degree day totals are projected to be between 4806 and 5255 for Yorkton, and between 4100 and 4586 for Swift Current.

4.2.4: Annual moisture index

Figure 68 illustrates the scenario ranges for annual moisture index. Increases in this index occur across all sites and all time periods. Yorkton and North Battleford currently exhibit the lowest annual moisture index values (3.4 and 4.2 degree days/mm, respectively). By the 2080s, these values have increased to between 3.9 and 4.7 degree days/mm for Yorkton and to between 4.7 and 5.6 degree days/mm for North Battleford. In the case of Yorkton, this range encompasses baseline conditions for most of the other grassland sites. Moose Jaw and Saskatoon currently exhibit the largest baseline values (both 4.7 degree days/mm). By the 2080s, annual moisture index values are projected to be between 5.3 and 6.4 degree days/mm for Moose Jaw and between 5.2 and 6.2 degree days/mm for Saskatoon. As is the case for the forest region, it is the increase in degree days > 5°C that appears to be driving the increase in annual moisture index.

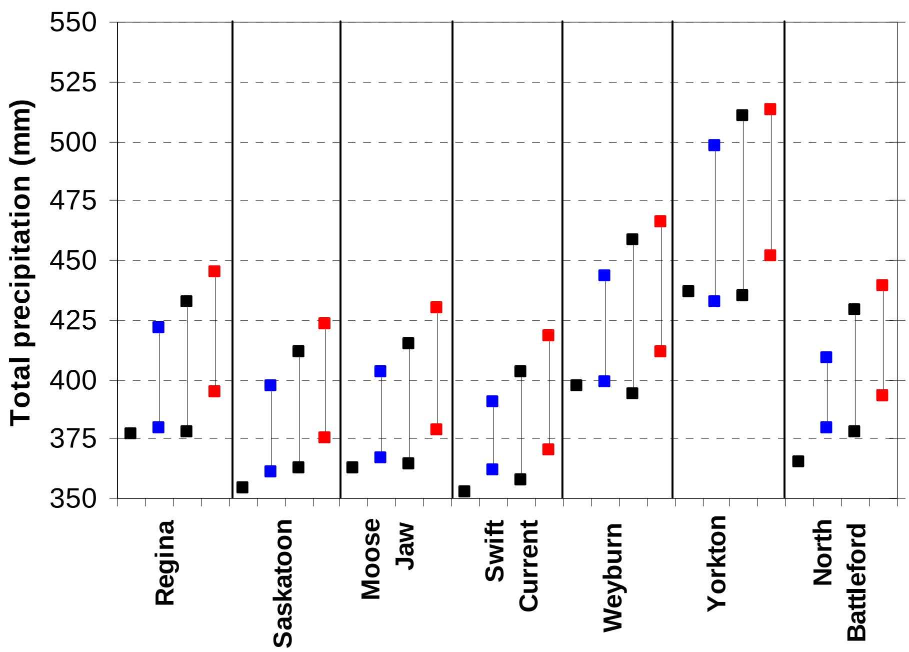


Figure 62: Annual precipitation total (mm) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

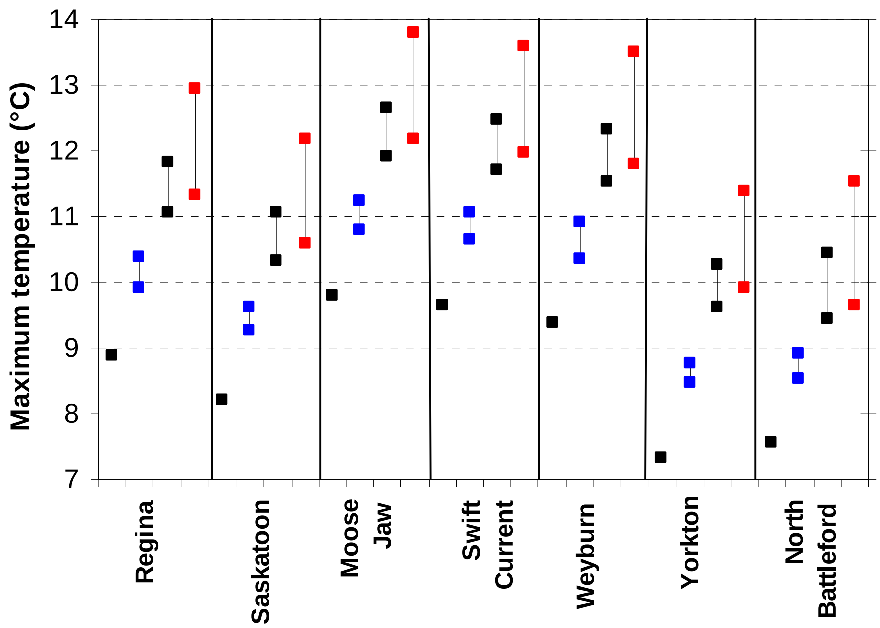


Figure 63: Annual mean maximum temperature (°C) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

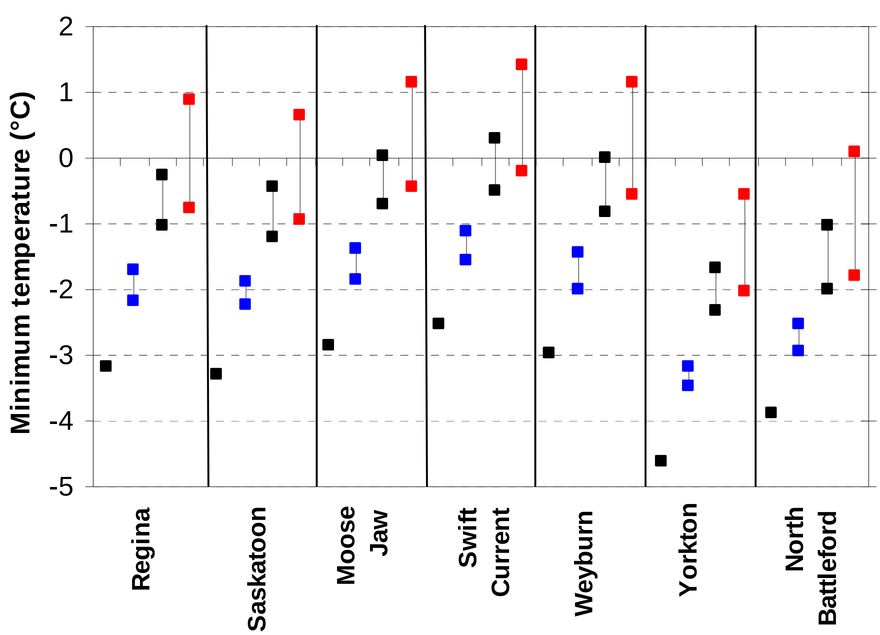


Figure 64: Annual mean minimum temperature (°C) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

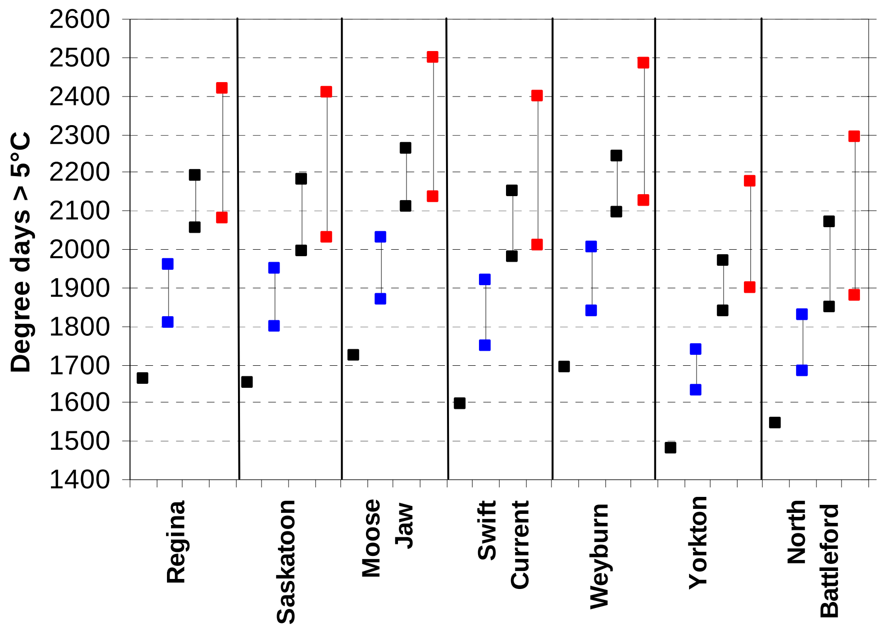


Figure 65: Degree days > 5°C for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

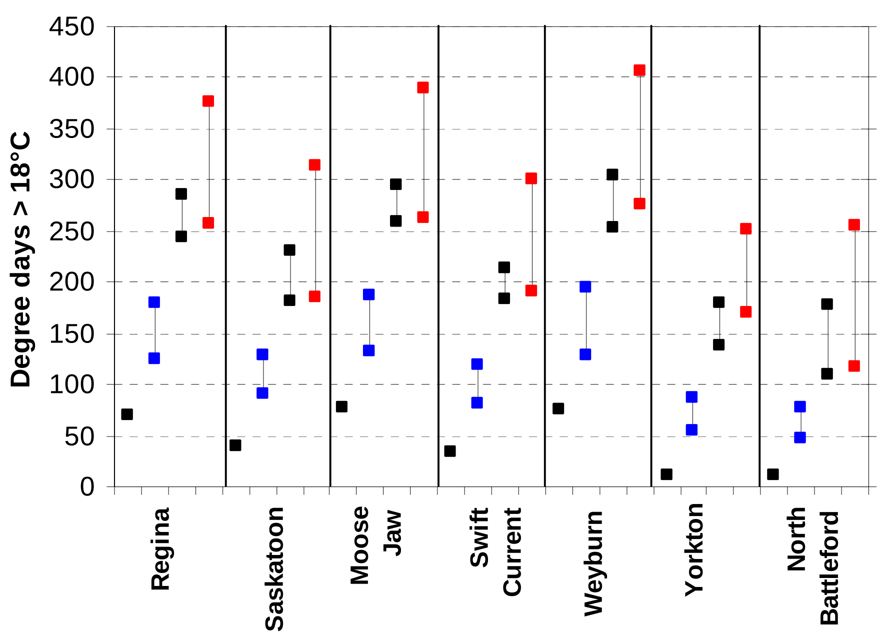


Figure 66: Degree days > 18°C (cooling degree days) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

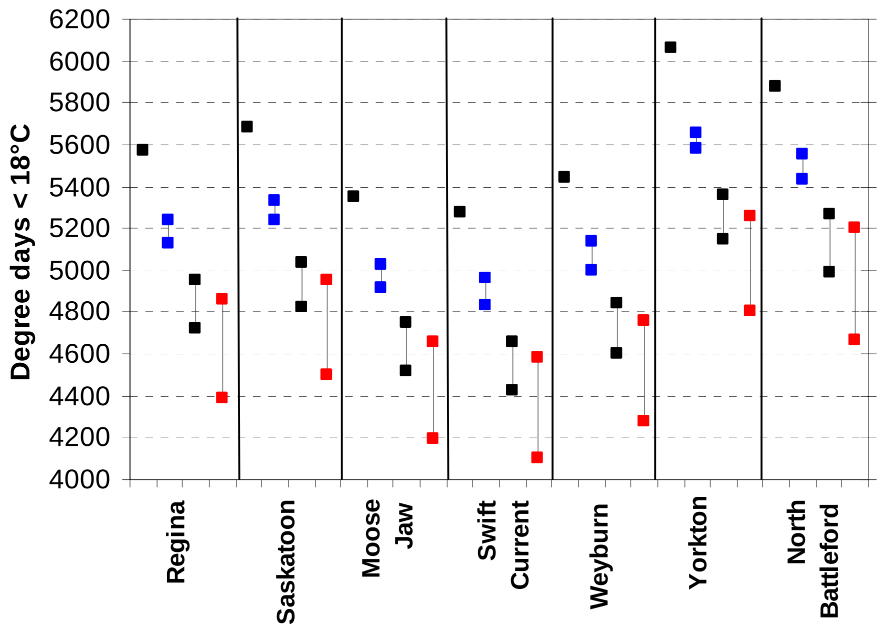


Figure 67: Degree days < 18°C (heating degree days) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

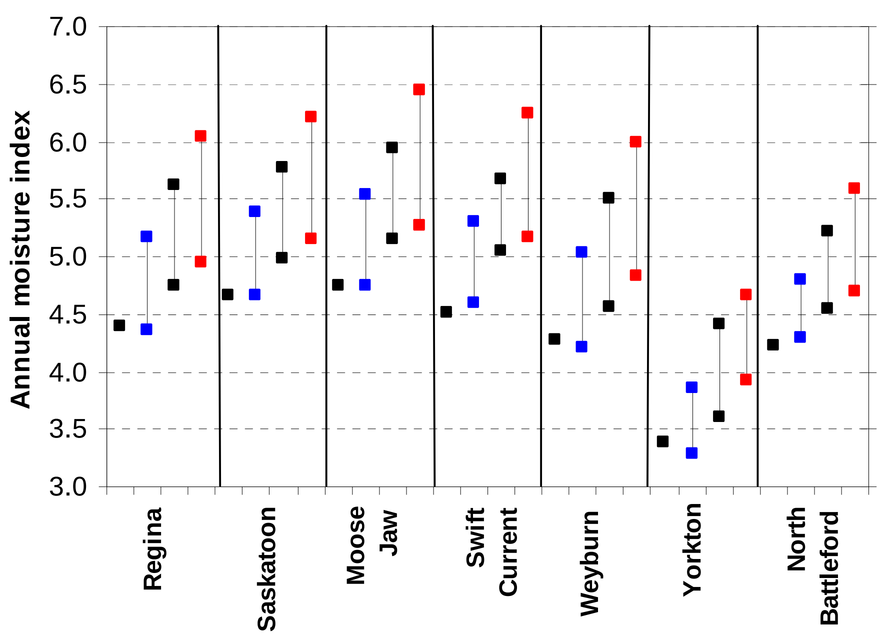


Figure 68: Annual moisture index for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

5: FUTURE RESEARCH DIRECTIONS

This report has described the construction of climate change scenarios for Saskatchewan using global climate model output in accordance with criteria recommended by the IPCC. It is important to conform with these criteria to ensure consistency amongst climate change impacts assessments, thus permitting conclusions to be drawn concerning the likely impacts of future climate change.

For the construction of physically-plausible and internally-consistent climate change scenarios for a large region like Saskatchewan, the techniques used within this report really represent the only currently available means of developing regional-scale scenarios. To advance this work, there are a number of options available:

1. To consider an expanded set of derived climate variables, such as mean frost-free period, mean growing season precipitation and summer moisture index.
2. To expand the number of scenarios used, so that the scenario ranges, such as those illustrated in Figure 63, can be expressed in terms of box-and-whisker plots. In this type of statistical plot, the box represents 50% of the scenario results and the whiskers the extreme scenarios. A box-and-whisker plot would give a much better idea of the spread of the scenario results and prevents the range of results being dominated by any one scenario. Use of only three scenarios means that there is insufficient information to construct such a plot.
3. Consideration of all available scenarios, which is not a trivial task, may allow a probabilistic analysis of the results so that information about risk and uncertainty could be included. For example, this may allow us to make a statement such as: “We are 90% confident that future temperature increases by the 2050s will be below 2°C”.
4. To link the scenarios with information about GCM-simulated ‘natural’ climate variability and to express the projected scenario changes in terms of their significance, i.e., whether or not the projected changes are within the range of model-simulated ‘natural’ climate variability.
5. To continue to update the scenarios as global climate model results are released for use.
6. To focus on specific locations. Statistical downscaling of the climate change scenarios is another possible avenue for research. These techniques, in which statistical relationships are developed (where possible) between the coarse-resolution GCM output and individual site information, may add value to the scenarios by identifying the coarse-resolution ‘drivers’ of the local climate conditions. Typical ‘drivers’ are mean sea level pressure, relative or specific humidity and air flow, and more confidence can be placed in these GCM-derived climate variables than in variables such as precipitation. However, there are a number of disadvantages associated with the statistical downscaling approach to scenario construction, and if one of the main objectives of any future scenarios research is to ensure that the range of plausible future climates is considered, then statistical downscaling is not recommended because it is resource-intensive.
7. Inclusion of results from the Canadian Regional Climate Model (CRCM). While only a limited number of climate change experiments have been undertaken with the CRCM, the results could be included with those from GCMs to give an indication of the effect of dynamical downscaling on the future climate of Saskatchewan.
8. To consider GCM performance in simulating current climate when selecting scenarios for use in impacts studies. GCMs can be ranked according to how well they simulate the baseline climate. If this route is followed, then we are assuming that GCMs which perform better at simulating the 1961-1990 climate will also perform better at simulating future climate. However, GCM performance must be assessed at global, continental and regional scales – it is misleading and potentially dangerous to consider a GCM’s performance at regional scales

only. Good performance at simulating regional climate does not mean that the GCM should be ranked highly. In fact, if the GCM performs well at the regional scale but not at the global or continental scales then it is actually performing poorly since it is not simulating the spatial patterns of climate correctly and the fact that it performs well at the regional scale may simply be due to chance. Ranking of GCM performance is not a trivial task and a number of factors need to be considered such as whether we are simply interested in average climate or whether we want to consider variability also. There are a number of observed baseline climatologies available for use in this sort of exercise and these too need to be examined carefully to determine which ones are considered more reliable than others.

The climate change scenarios described within this report represent plausible changes in future average climate. Thus, changes in climate variability are not included and it is these changes in variability which are likely to have the largest effect on the frequency and magnitude of extreme climate events which, in turn, tend to have the largest impact on our environment. Working at the regional scale means that the inclusion of changes in climate variability as well as changes in mean climate is not a trivial task. Statistical techniques (such as stochastic weather generators) exist which allow the perturbation of observed time series by both changes in means and variability in a simple manner. These techniques are best applied at the site scale, so one option would be to focus on specific locations in Saskatchewan, such as the ten sites used in this report.

Another option for consideration is the use of past climate information, i.e., from prior to the beginning of the instrumental record. Where palaeo-climate information exists, this may be used to contextualise GCM-derived climate change scenarios and also to provide valuable information about environmental responses to particular climate conditions or events. Also, a more detailed examination of the instrumental record for sites in Saskatchewan, rather than simply using the 30-year climate normal (average), would provide more information about observed climate variability and thus also help contextualise the climate scenarios.

ACKNOWLEDGEMENTS

All of the global climate model data used for climate change scenario construction, with the exception of the Canadian global climate models CGCM3_T47 and CGCM3_T63, were obtained from the IPCC Data Distribution Centre (www.ipcc-data.org). The Canadian GCM data were obtained from the Canadian Centre for Climate Modelling and Analysis (www.cccma.bc.ec.gc.ca). The observed baseline data (PRISM) for Saskatchewan were obtained from Ron Hopkinson, on behalf of Environment Canada.

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APPENDIX A: SEASONAL CLIMATE CHANGE SCENARIOS FOR THE 2050s

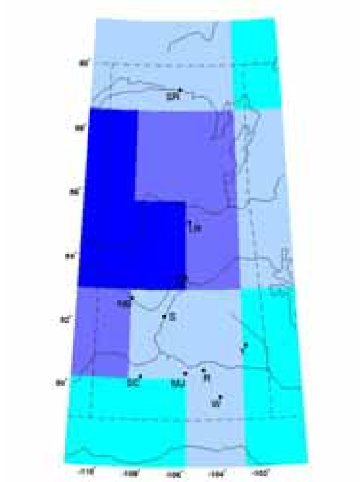
Mean temperature change (°C) for the 2050s
A1: Winter
A2: Spring
A3: Summer
A4: Fall

Precipitation change (%) for the 2050s
A5: Winter
A6: Spring
A7: Summer
A8: Fall

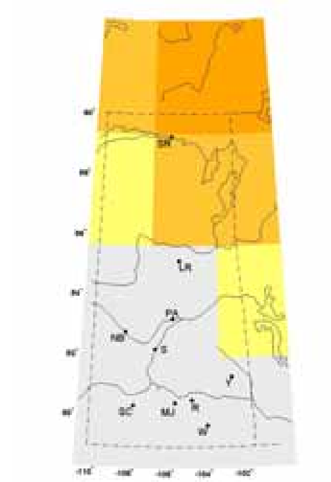
Forest: Largest change HadCM3 A1B

Grass: Largest change GFCM20 B1

Forest: Smallest change BCM2 B1



Grass: Smallest change CGCM3_T47_2 A1B



Median MIMR B1

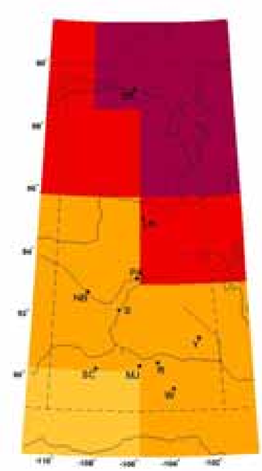
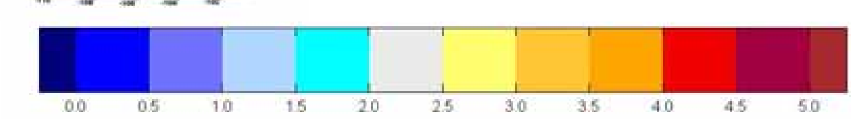
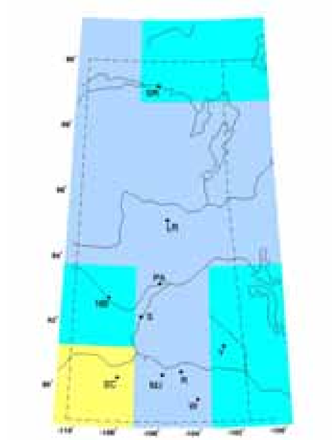


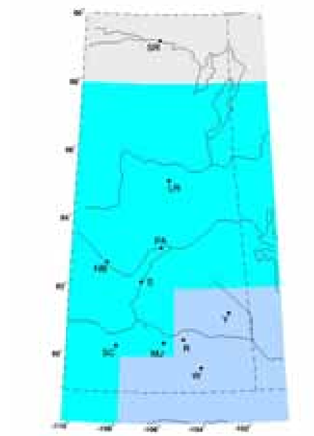
Figure A1: Winter (DJF) mean temperature change (°C) for the 2050s with respect to 1961-1990.



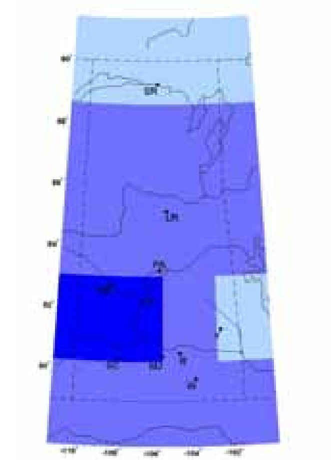
Forest: Largest change HadCM3 A1B



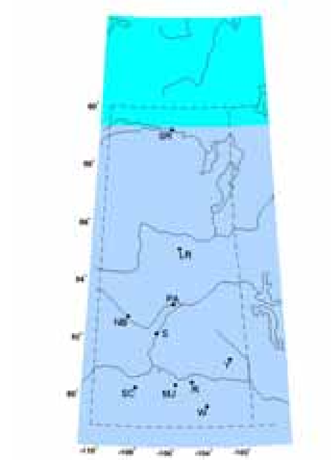
Grass: Largest change GFCM20 B1



Forest: Smallest change BCM2 B1



Grass: Smallest change CGCM3_T47_2 A1B



Median MIMR B1

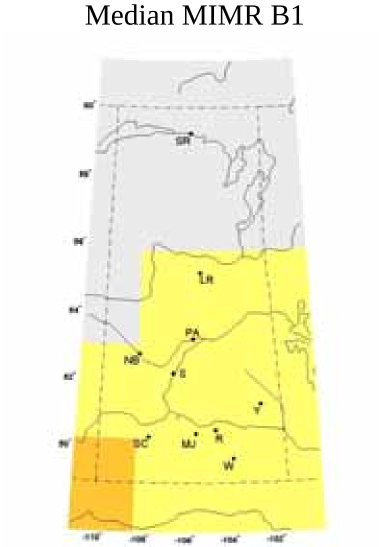
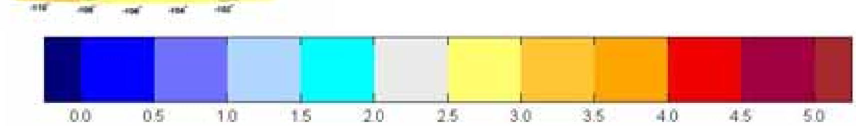
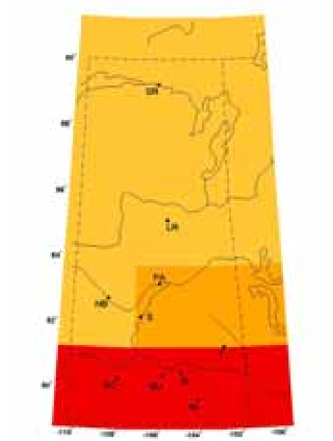


Figure A2: Spring (MAM) mean temperature change (°C) for the 2050s with respect to 1961-1990.

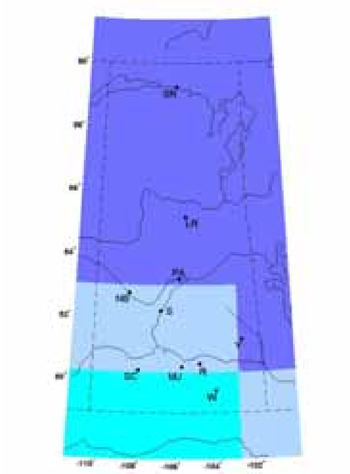


Forest: Largest change HadCM3 A1B



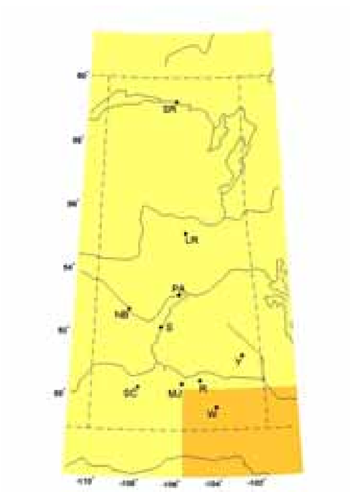
Grass: Largest change GFCM20 B1

Forest: Smallest change BCM2 B1



Grass: Smallest change CGCM3_T47_2 A1B

Median MIMR B1



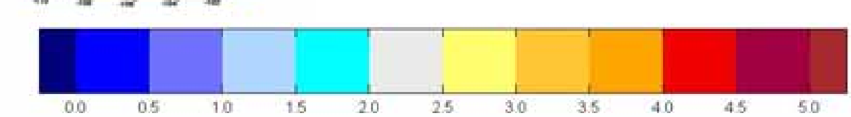
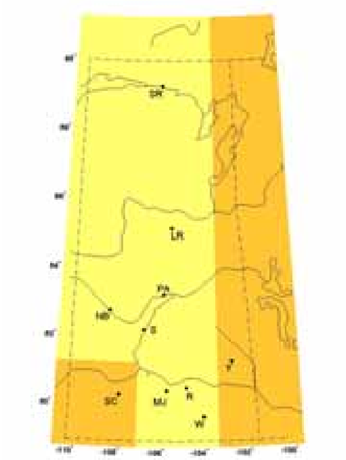


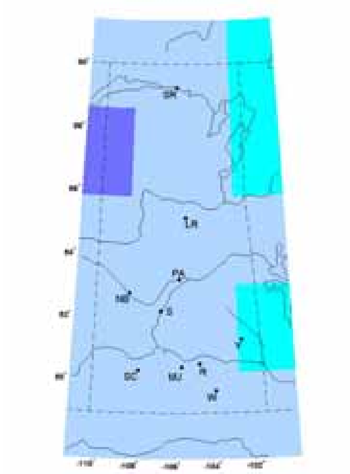
Figure A3: Summer (JJA) mean temperature change (°C) for the 2050s with respect to 1961-1990.

Forest: Largest change HadCM3 A1B

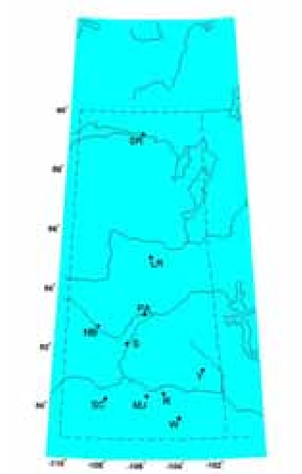


Grass: Largest change GFCM20 B1

Forest: Smallest change BCM2 B1



Grass: Smallest change CGCM3_T47_2 A1B



Median MIMR B1

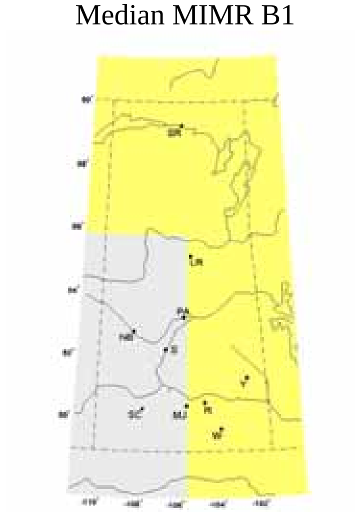
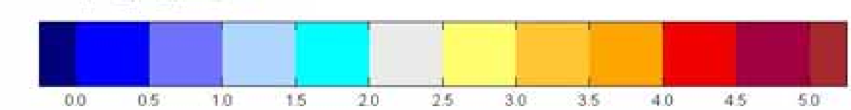
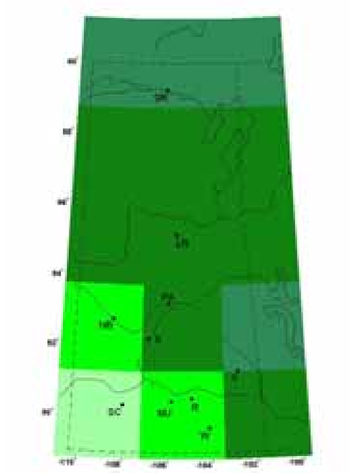


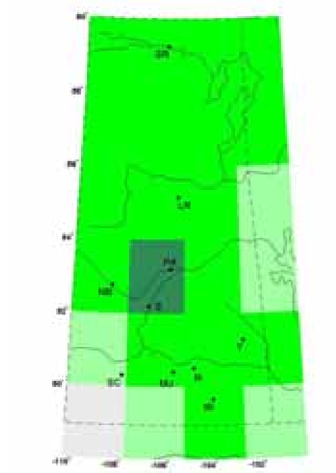
Figure A4: Fall (SON) mean temperature change (°C) for the 2050s with respect to 1961-1990.



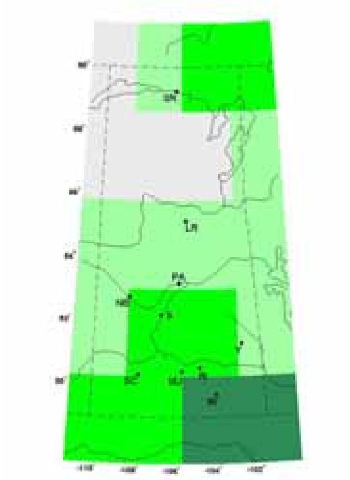
Forest: Largest change HadCM3 A1B



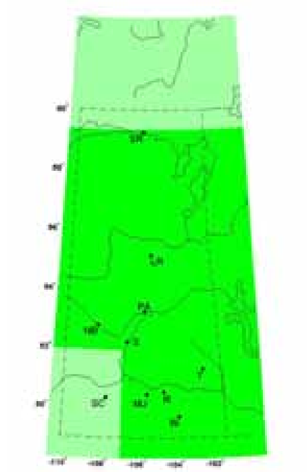
Grass: Largest change GFCM20 B1



Forest: Smallest change BCM2 B1



Grass: Smallest change CGCM3_T47_2 A1B



Median MIMR B1

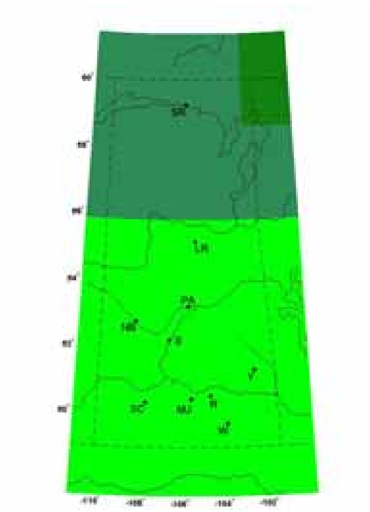
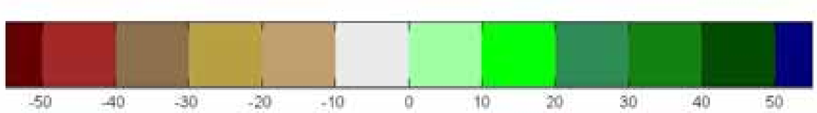
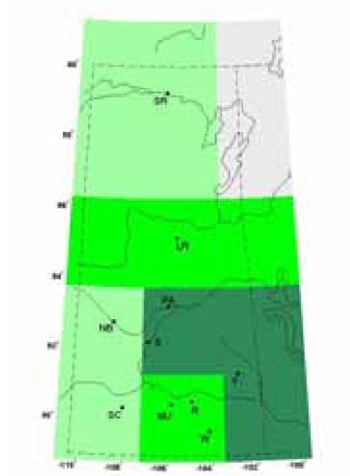


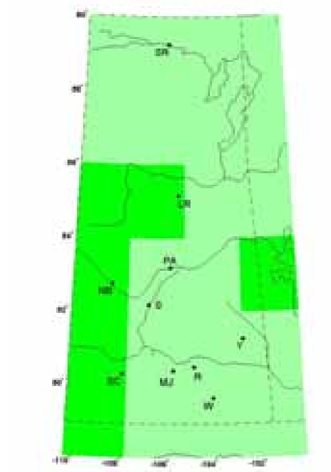
Figure A5: Winter (DJF) precipitation change (%) for the 2050s with respect to 1961-1990.



Forest: Largest change HadCM3 A1B

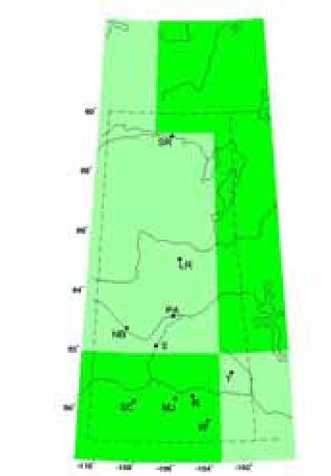


Grass: Largest change GFCM20 B1



Forest: Smallest change BCM2 B1

Grass: Smallest change CGCM3_T47_2 A1B



Median MIMR B1

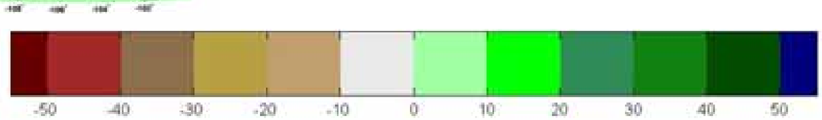


Figure A6: Spring (MAM) precipitation change (%) for the 2050s with respect to 1961-1990.

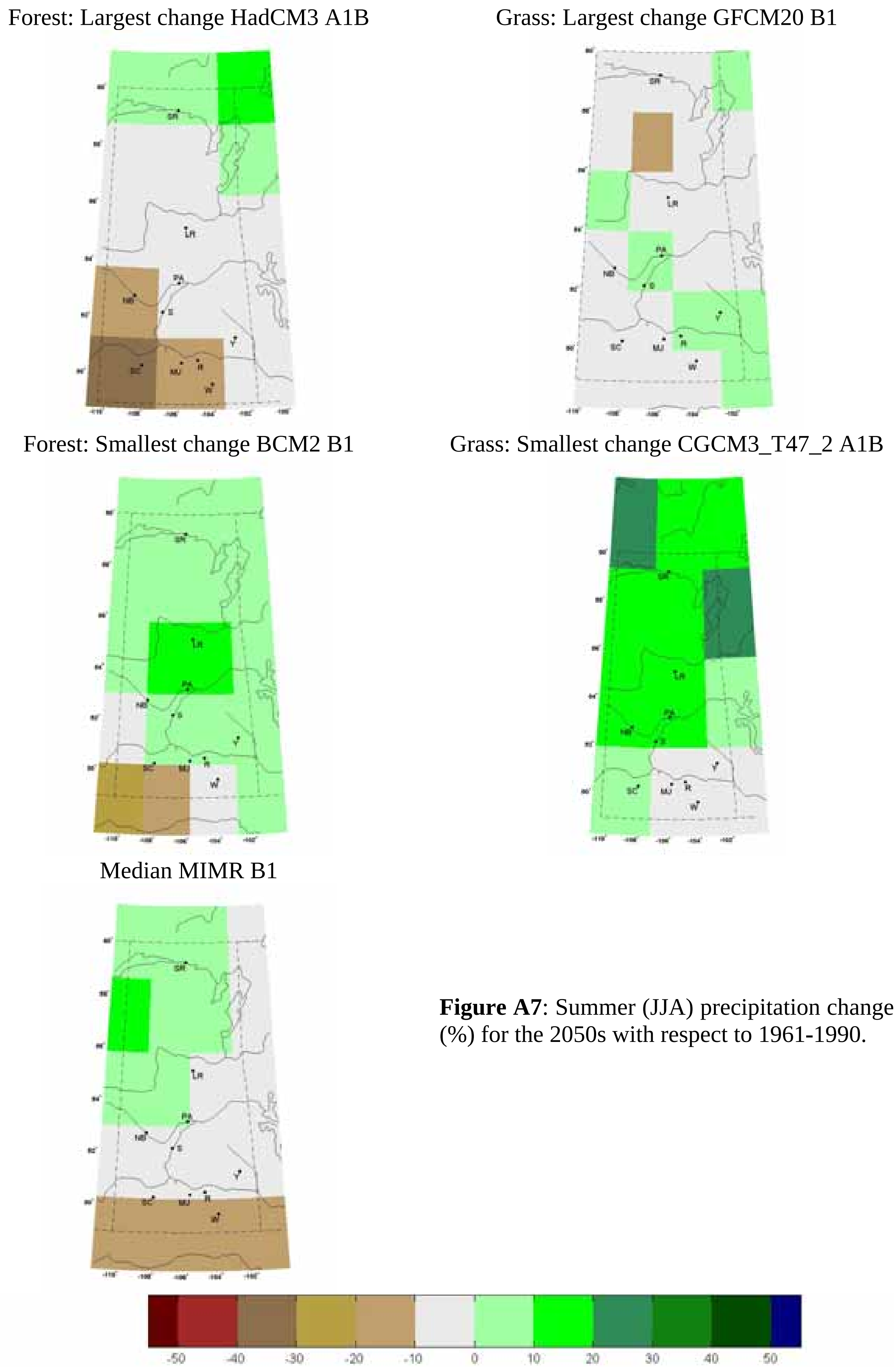
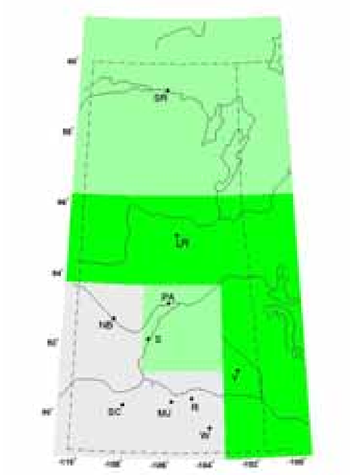
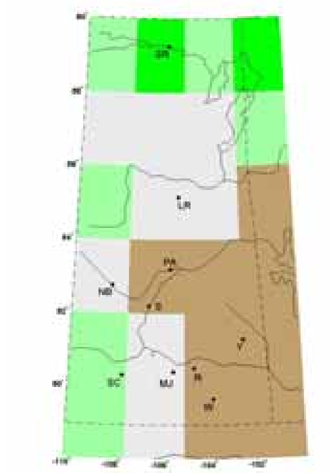


Figure A7: Summer (JJA) precipitation change (%) for the 2050s with respect to 1961-1990.

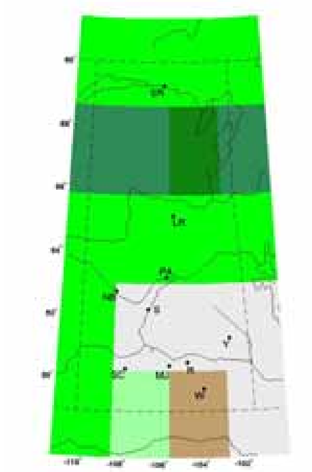
Forest: Largest change HadCM3 A1B



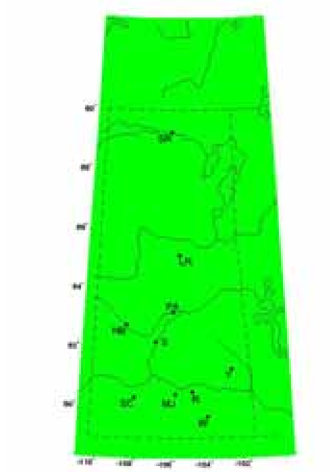
Grass: Largest change GFCM20 B1



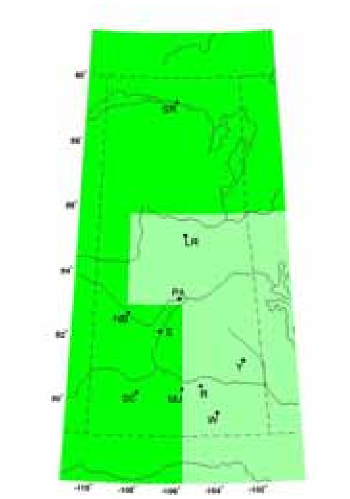
Forest: Smallest change BCM2 B1



Grass: Smallest change CGCM3_T47_2 A1B



Median MIMR B1



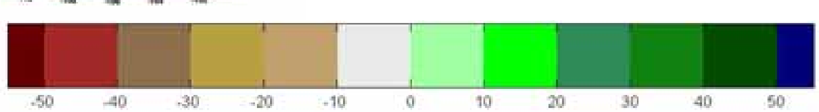


Figure A8: Fall (SON) precipitation change (%) for the 2050s with respect to 1961-1990.

APPENDIX B: ANNUAL CLIMATE SCENARIOS FOR SASKATCHEWAN

This appendix contains maps of annual climate scenarios for mean temperature, precipitation, maximum and minimum temperature, degree days > 5°C, degree days > 18°C (cooling degree days), degree days < 18°C (heating degree days) and annual moisture index for the 2020s and 2080s. Each set of maps consists of four graphics: the 1961-1990 baseline, the smallest change in AMI scenario, the largest change in AMI scenario and the median change in AMI scenario. Maps are presented first for the forest region of Saskatchewan and then for the grassland region.

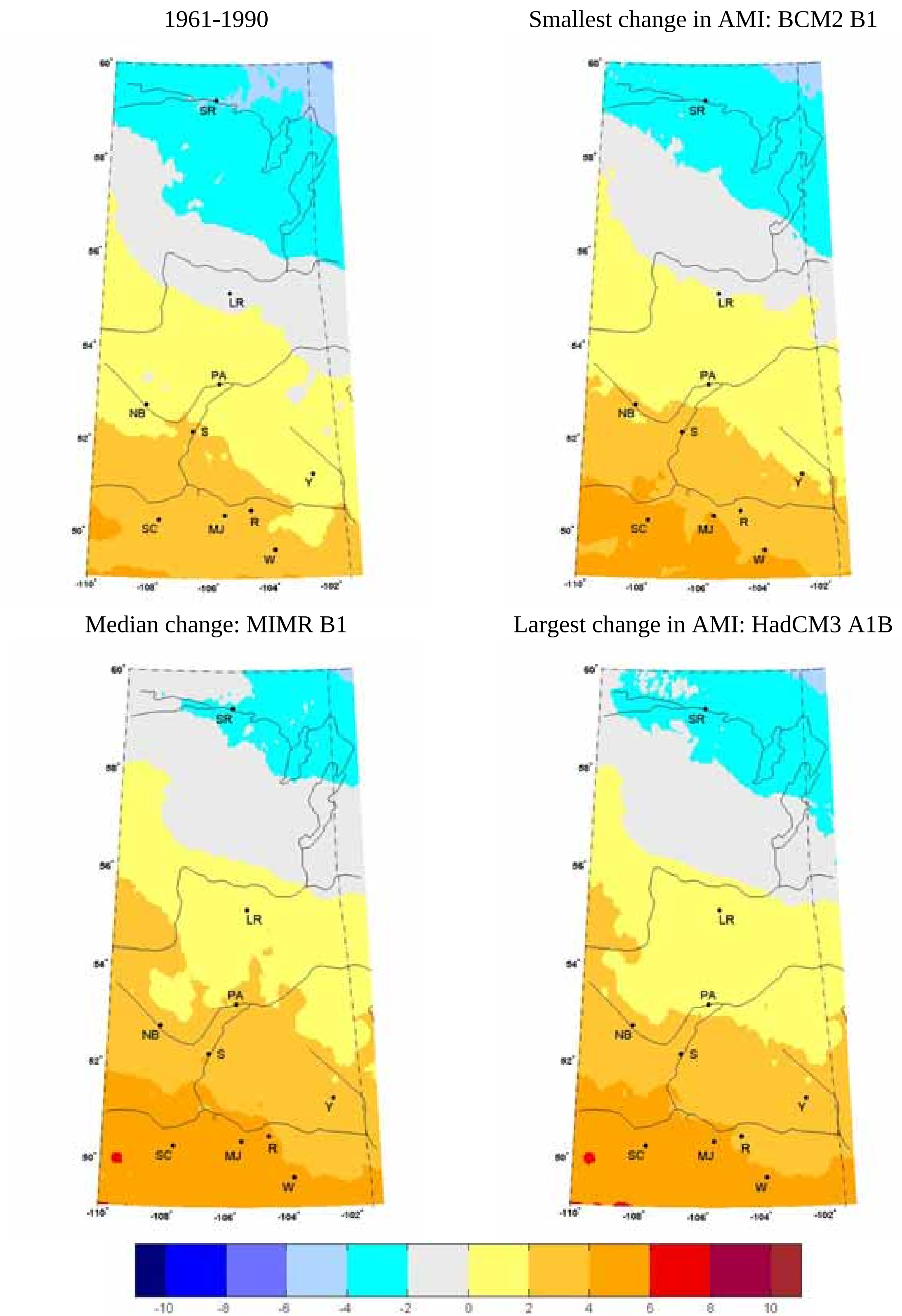


Figure B1: Annual mean temperature (°C) for the 2020s, selected based on AMI change over forest region of Saskatchewan.

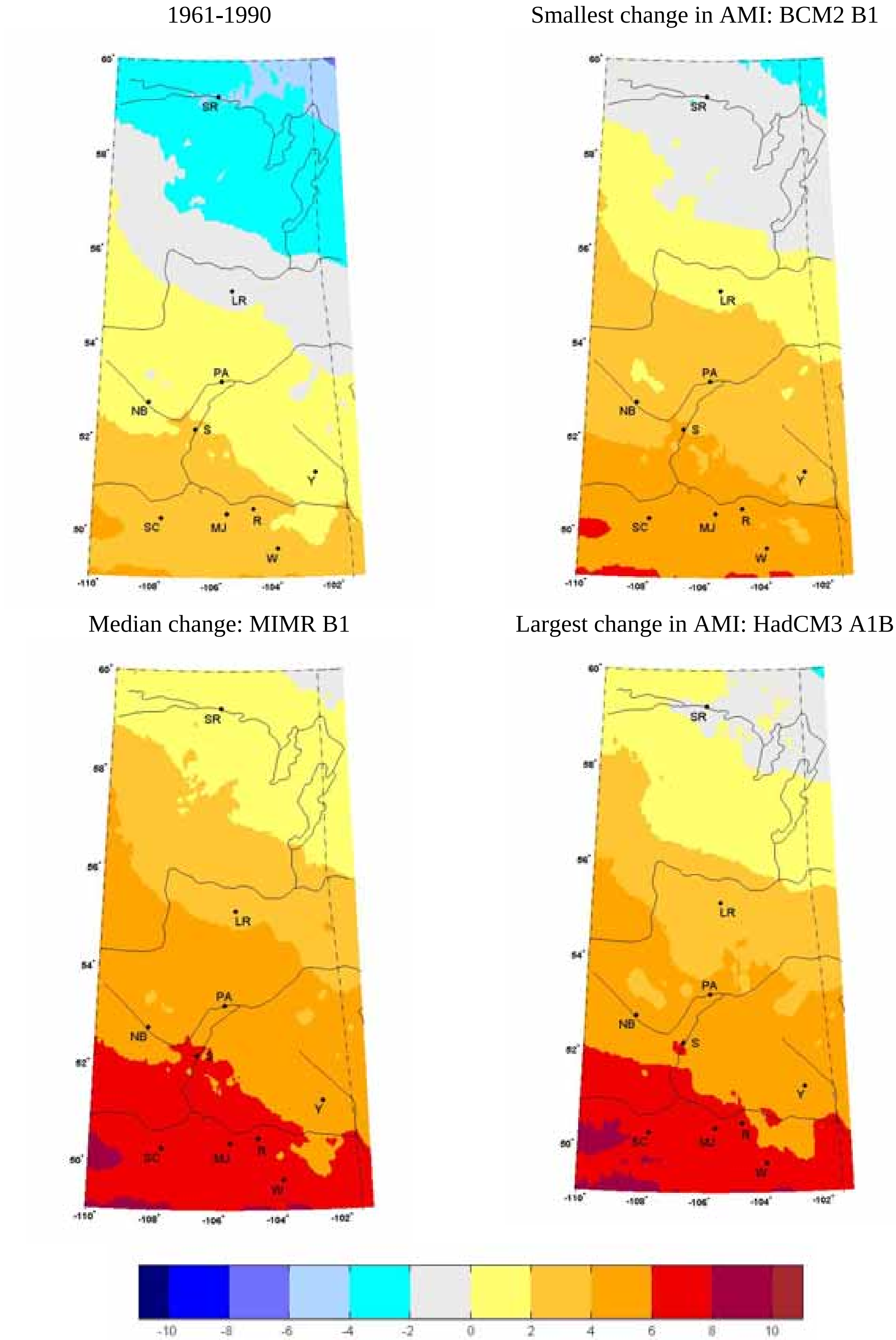


Figure B2: Annual mean temperature (°C) for the 2080s, selected based on AMI change over forest region of Saskatchewan.

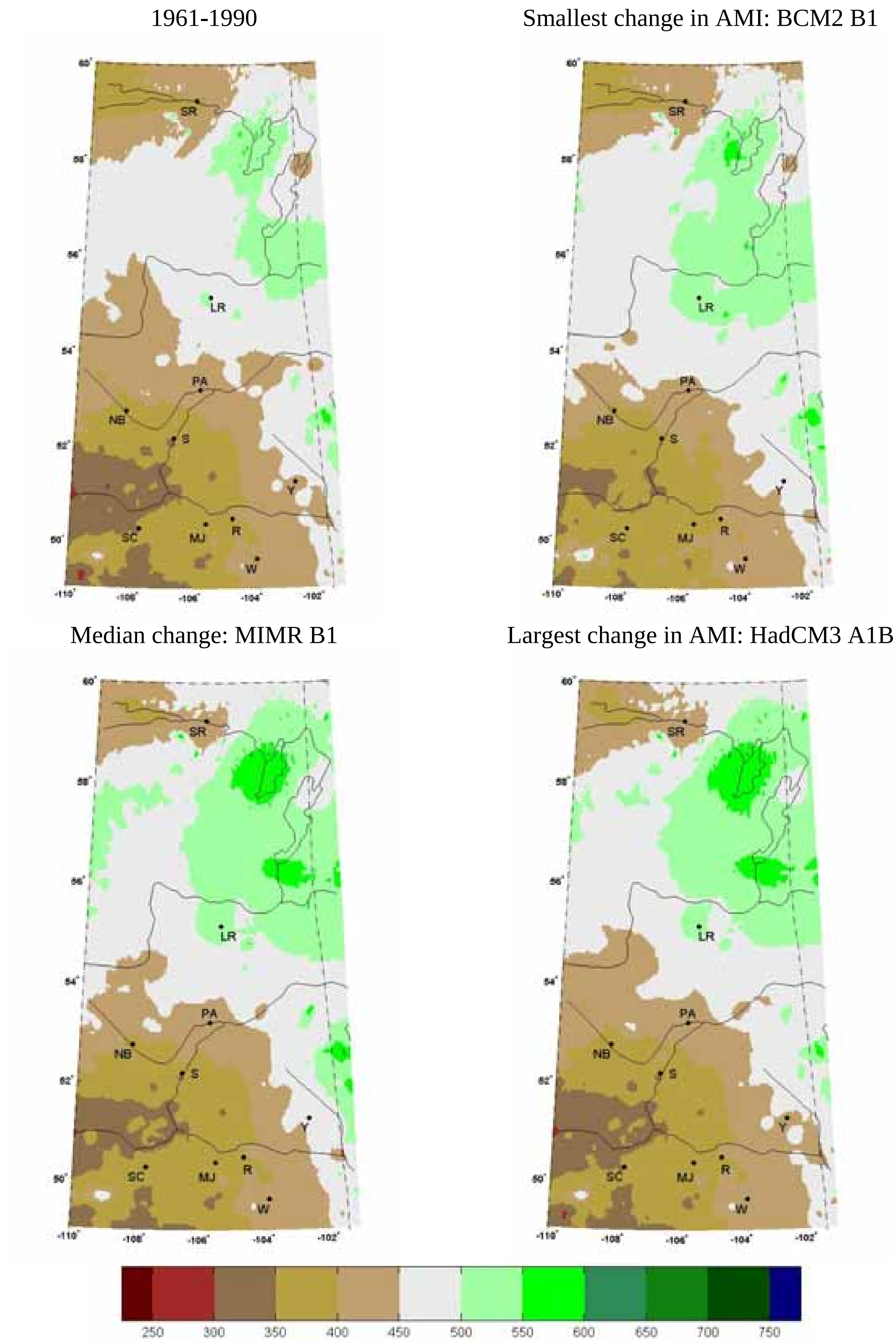


Figure B3: Annual precipitation (mm) for the 2020s, selected based on AMI change over forest region of Saskatchewan.

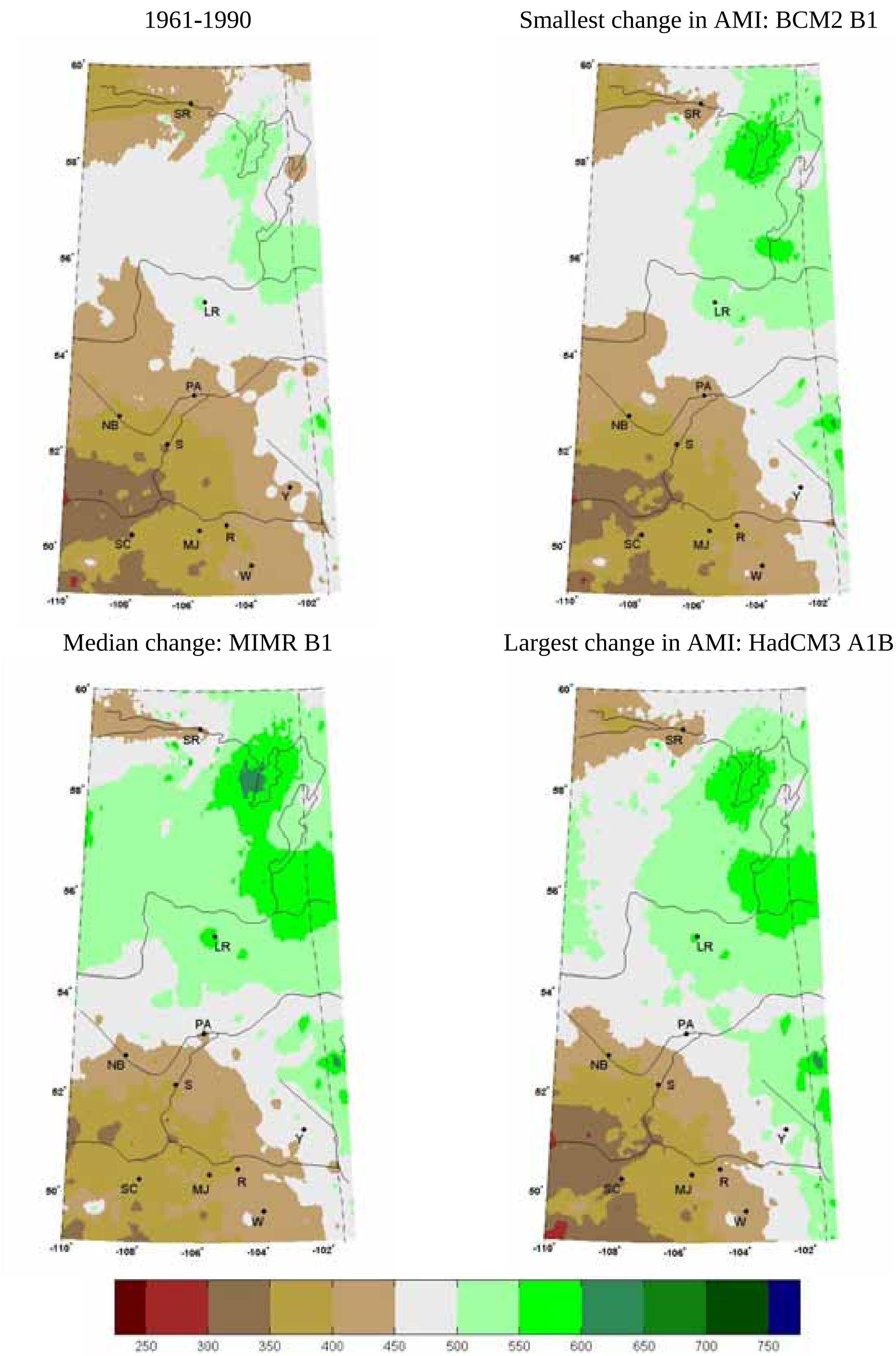


Figure B4: Annual precipitation (mm) for the 2080s, selected based on AMI change over forest region of Saskatchewan.

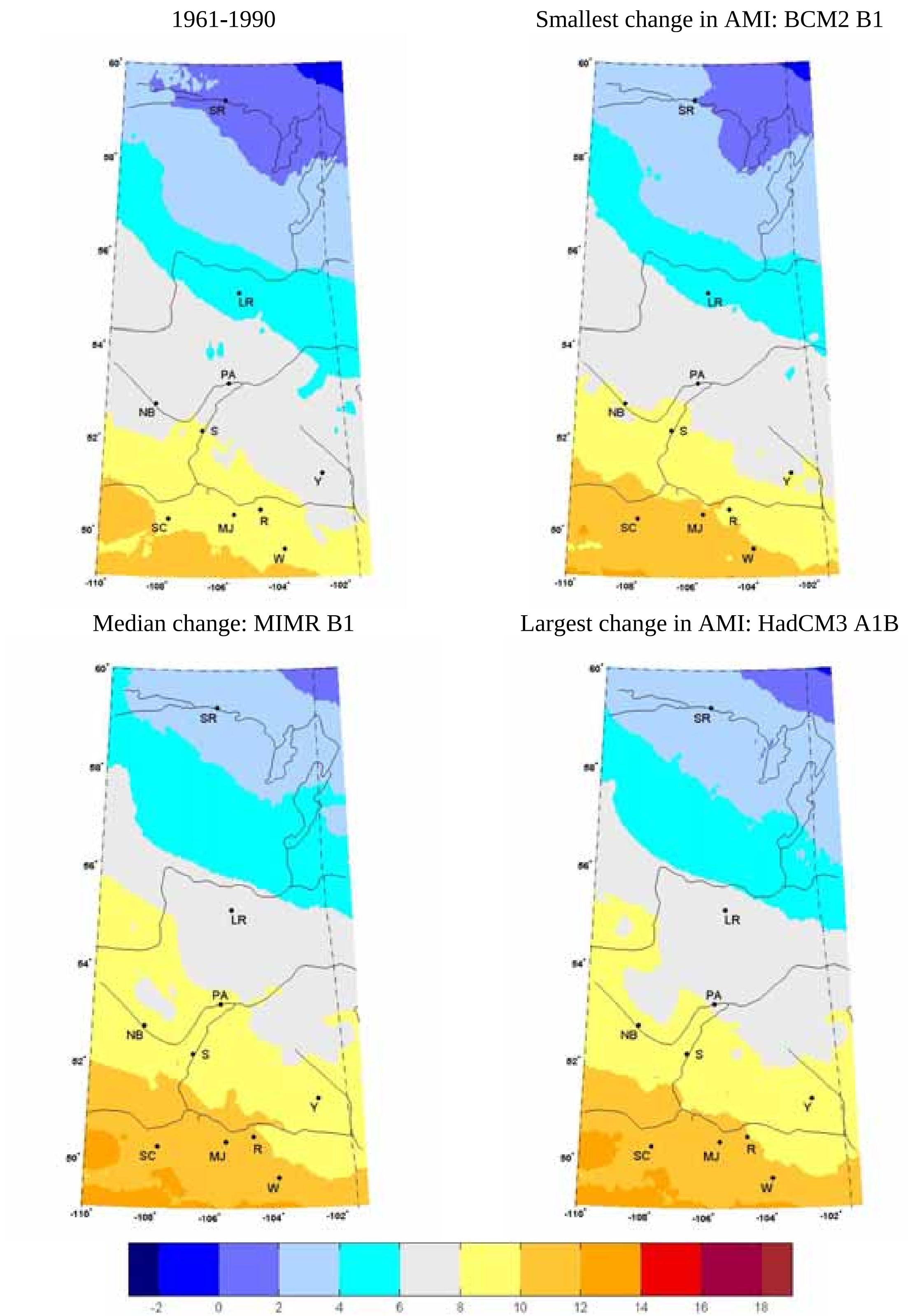


Figure B5: Annual mean maximum temperature (°C) for the 2020s, selected based on AMI change over forest region of Saskatchewan.

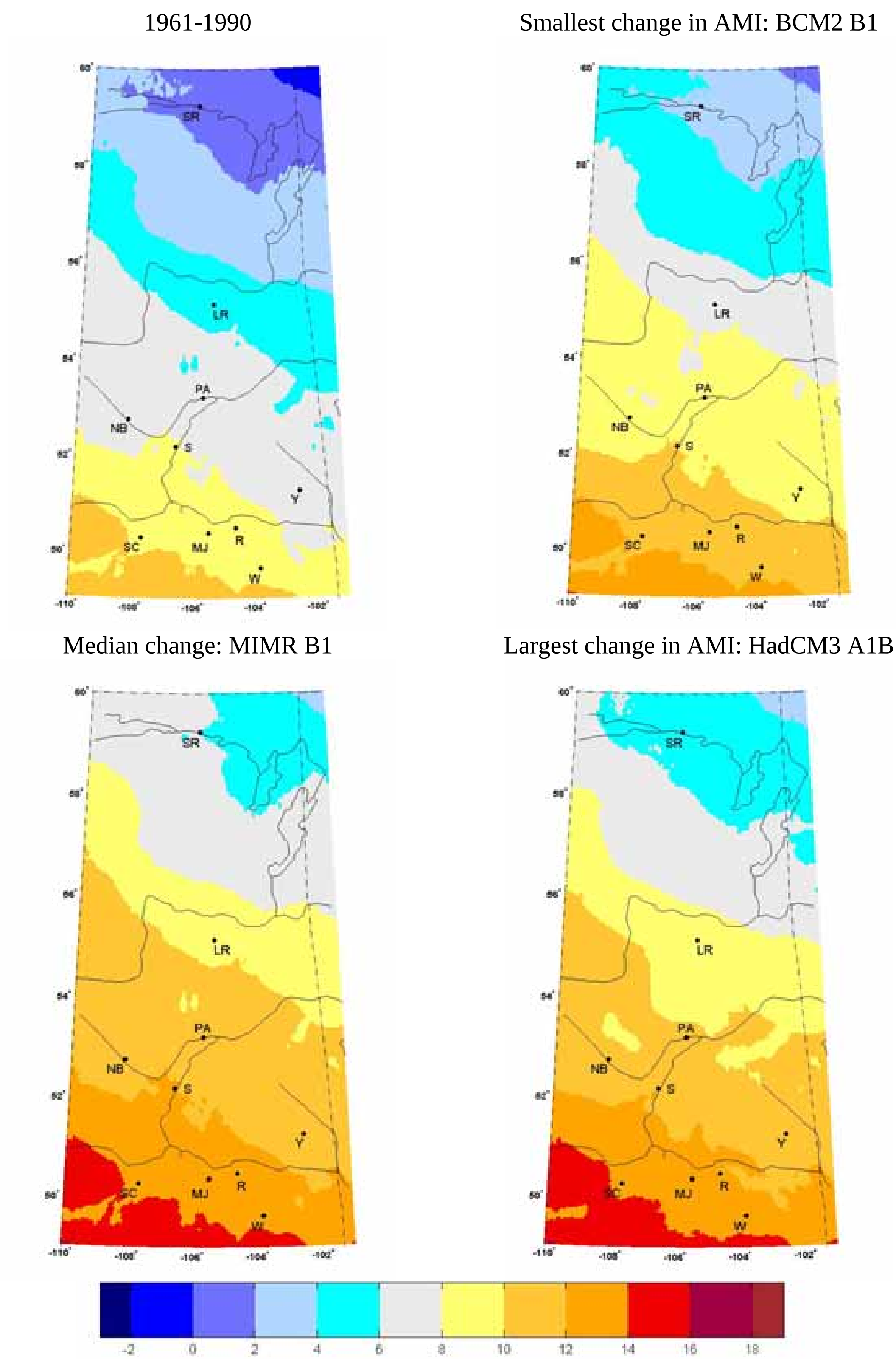


Figure B6: Annual mean maximum temperature (°C) for the 2080s, selected based on AMI change over forest region of Saskatchewan.

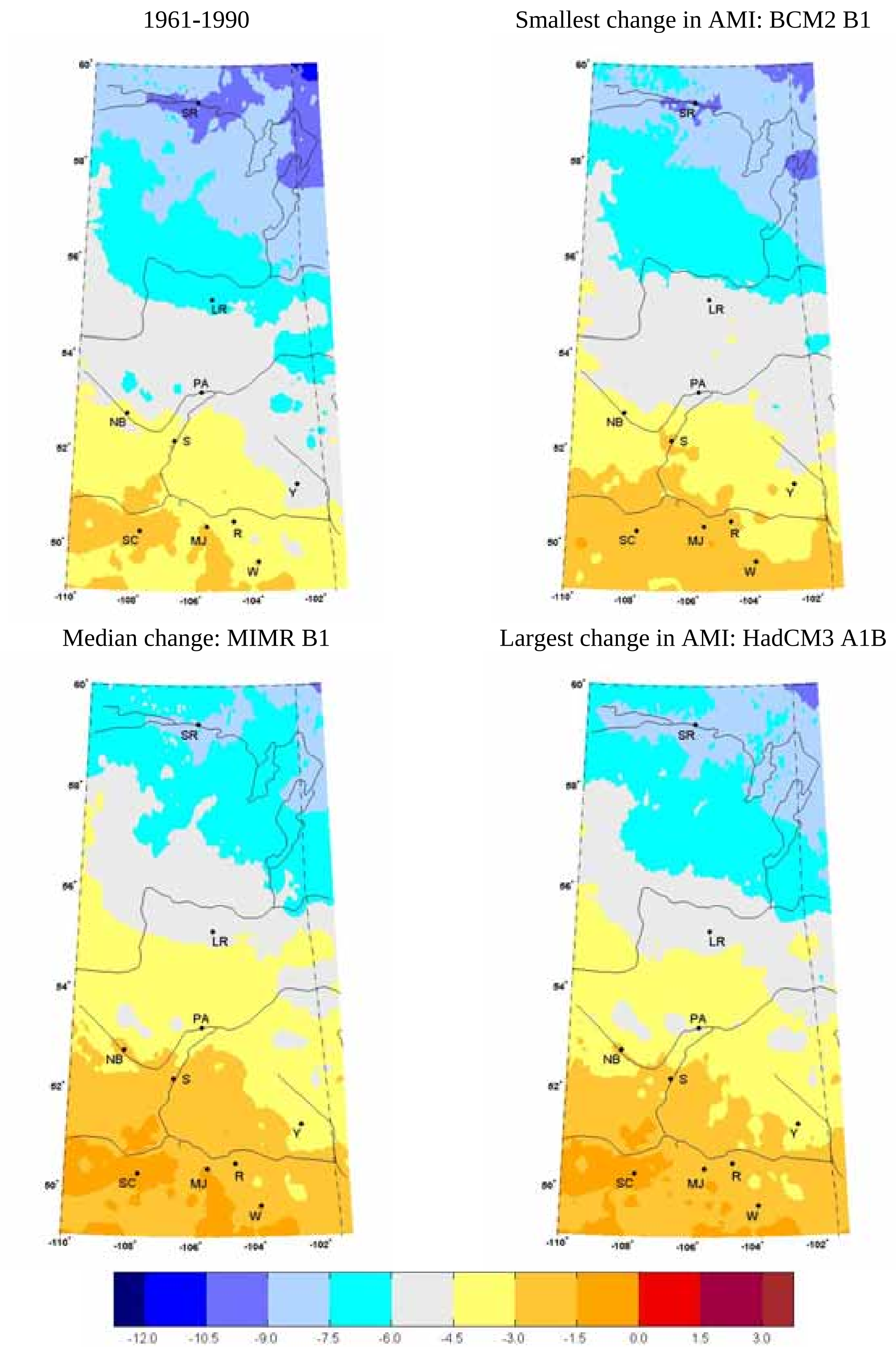


Figure B7: Annual mean minimum temperature (°C) for the 2020s, selected based on AMI change over forest region of Saskatchewan.

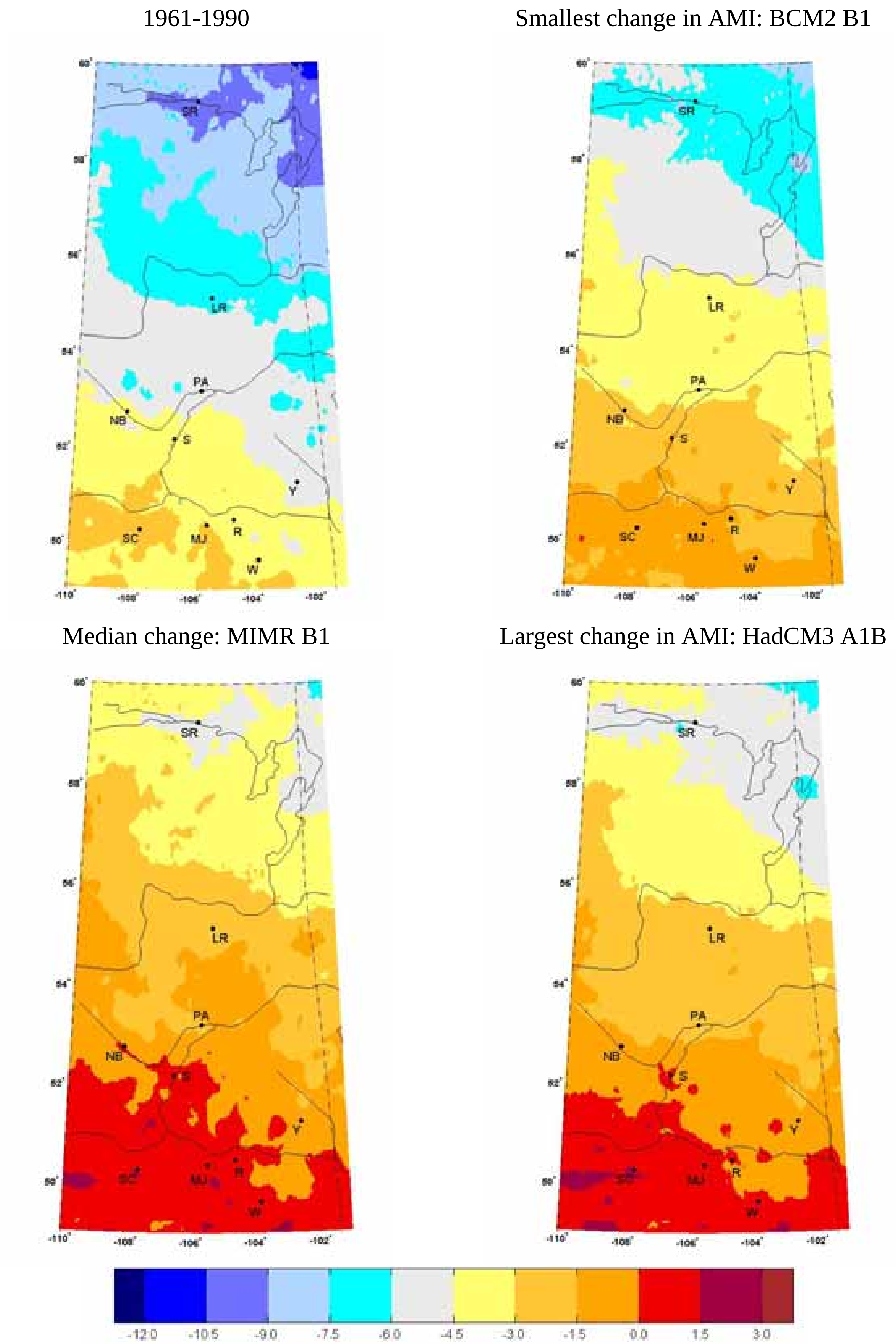


Figure B8: Annual mean minimum temperature (°C) for the 2080s, selected based on AMI change over forest region of Saskatchewan.

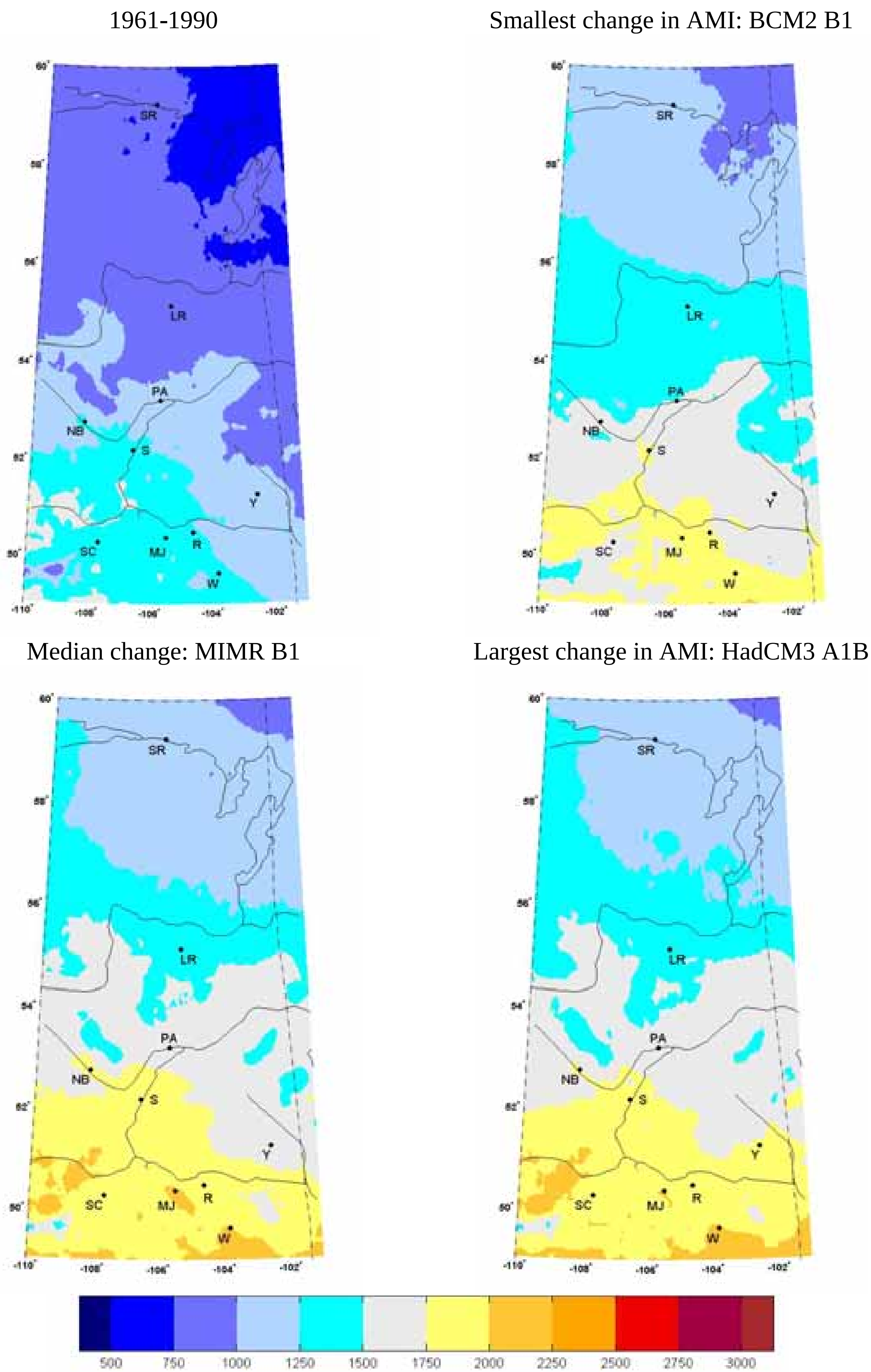


Figure B9: Degree days >5°C for the 2020s, selected based on AMI change over forest region of Saskatchewan.

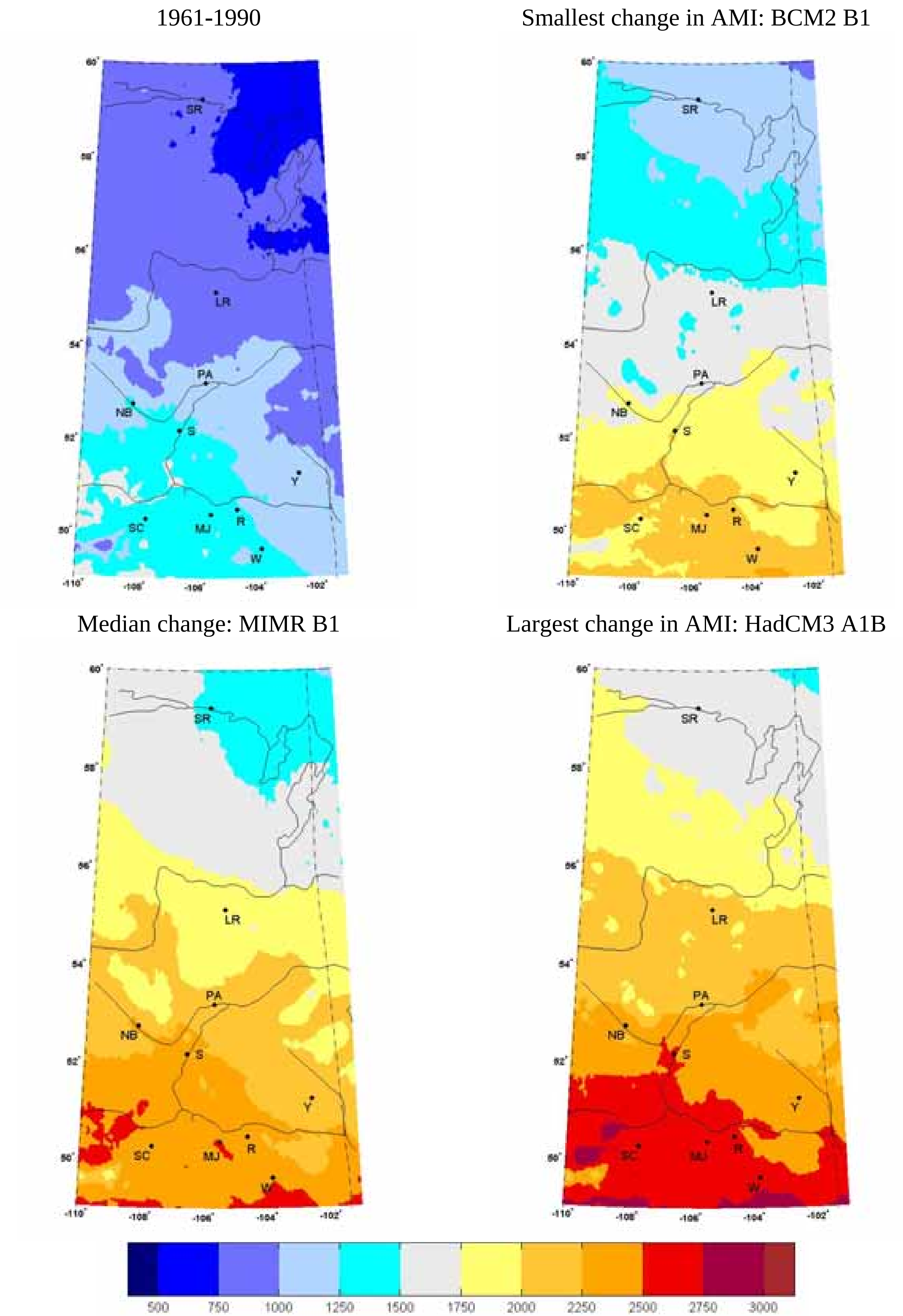


Figure B10: Degree days >5°C for the 2080s, selected based on AMI change over forest region of Saskatchewan.

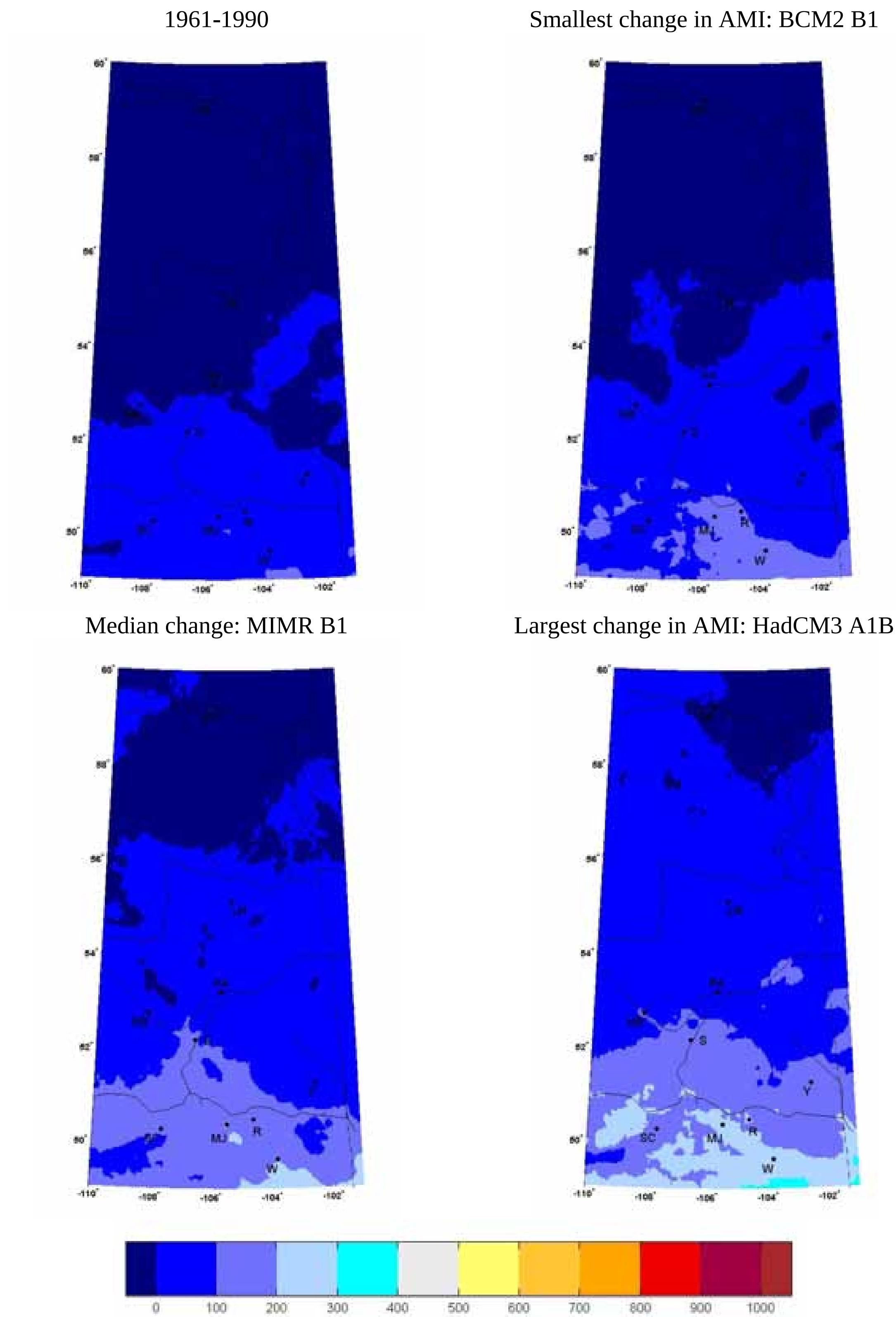


Figure B11: Degree days >18°C (cooling degree days) for the 2020s, selected based on AMI change over forest region of Saskatchewan.

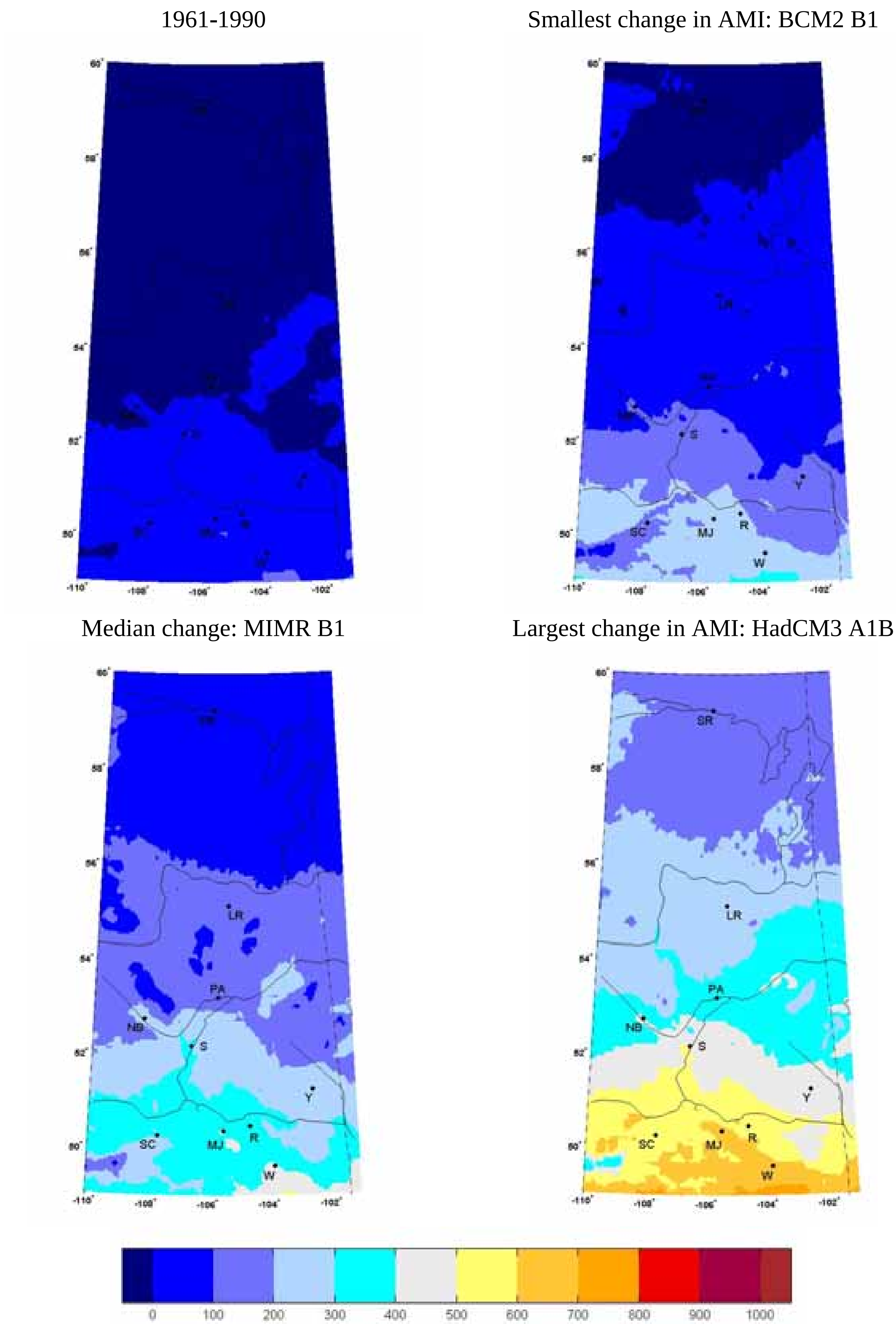


Figure B12: Degree days >18°C (cooling degree days) for the 2080s, selected based on AMI change over forest region of Saskatchewan.

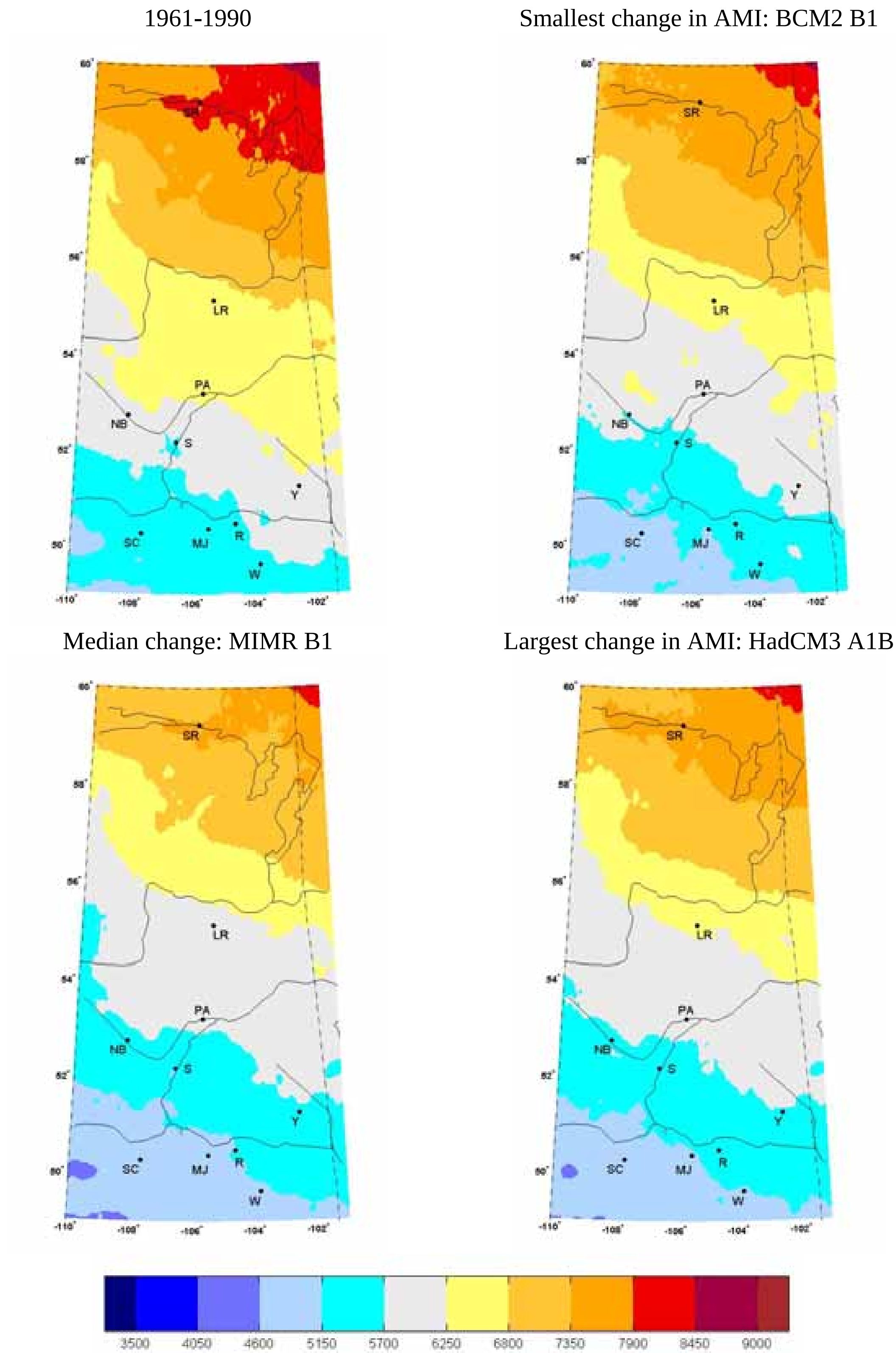


Figure B13: Degree days <18°C (heating degree days) for the 2020s, selected based on AMI change over forest region of Saskatchewan.

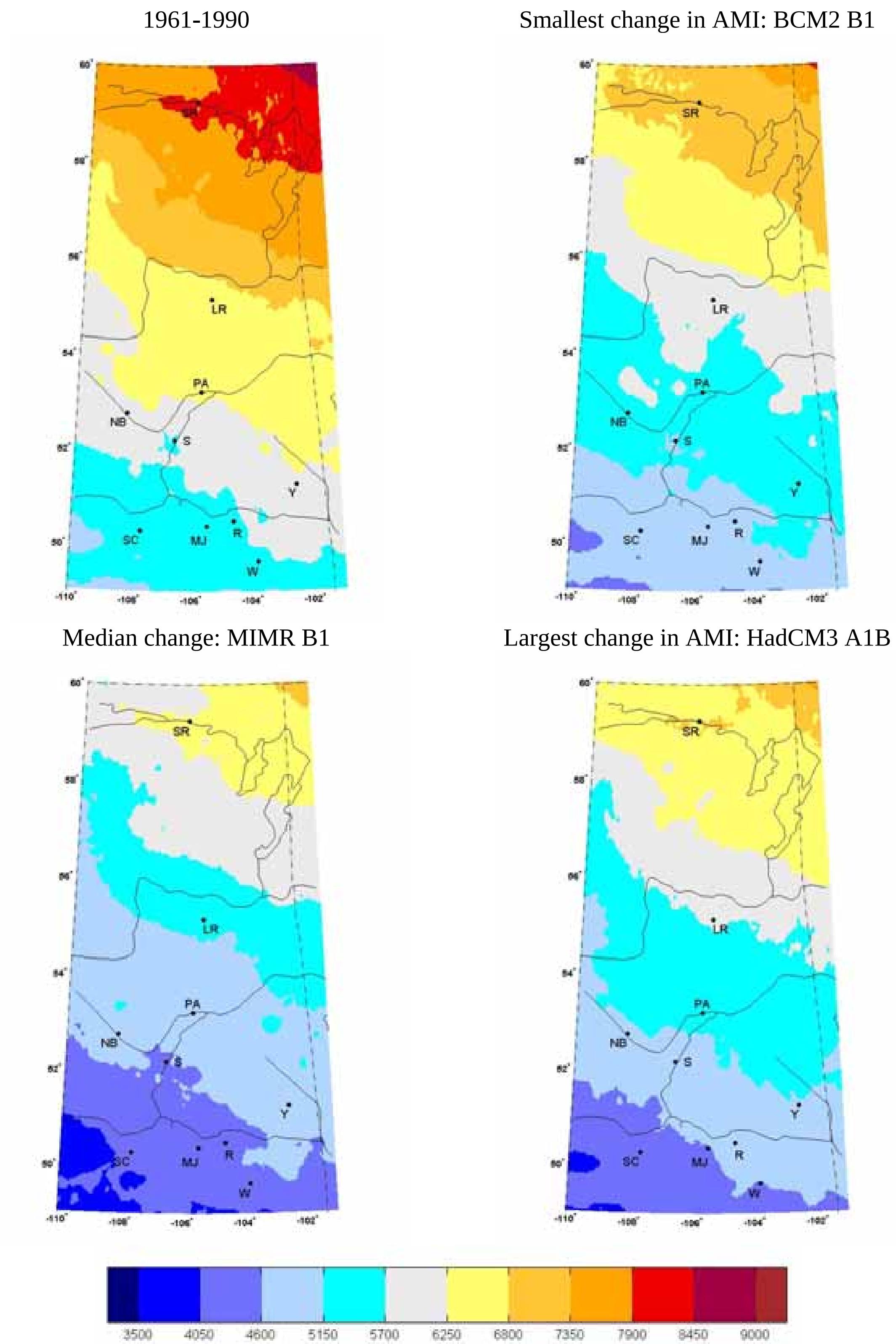
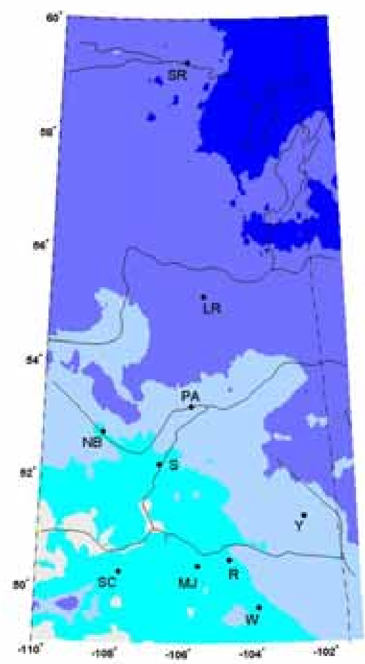
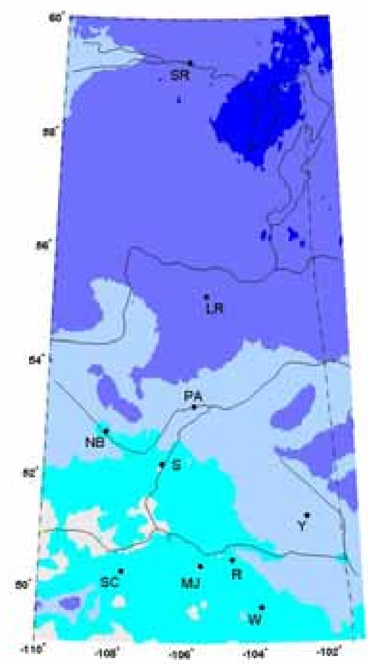


Figure B14: Degree days <18°C (heating degree days) for the 2080s, selected based on AMI change over forest region of Saskatchewan.

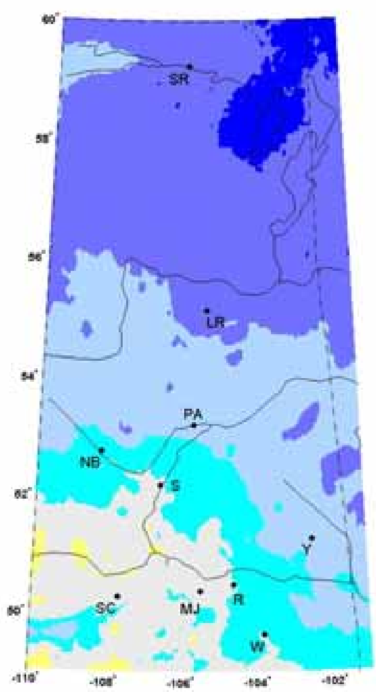
1961-1990



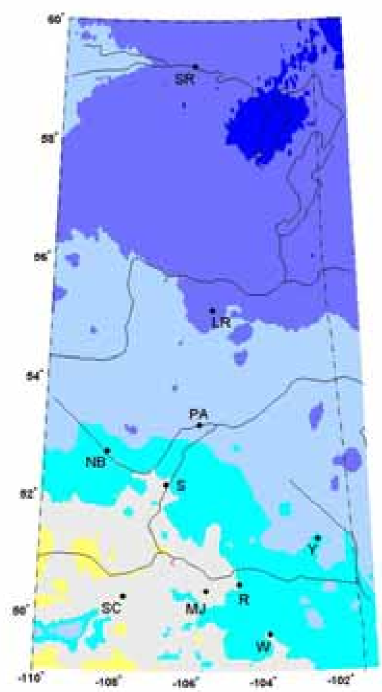
Smallest change in AMI: BCM2 B1



Median change: MIMR B1



Largest change in AMI: HadCM3 A1B



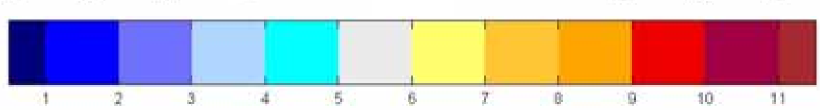


Figure B15: Annual moisture index for the 2020s, selected based on AMI change over forest region of Saskatchewan.

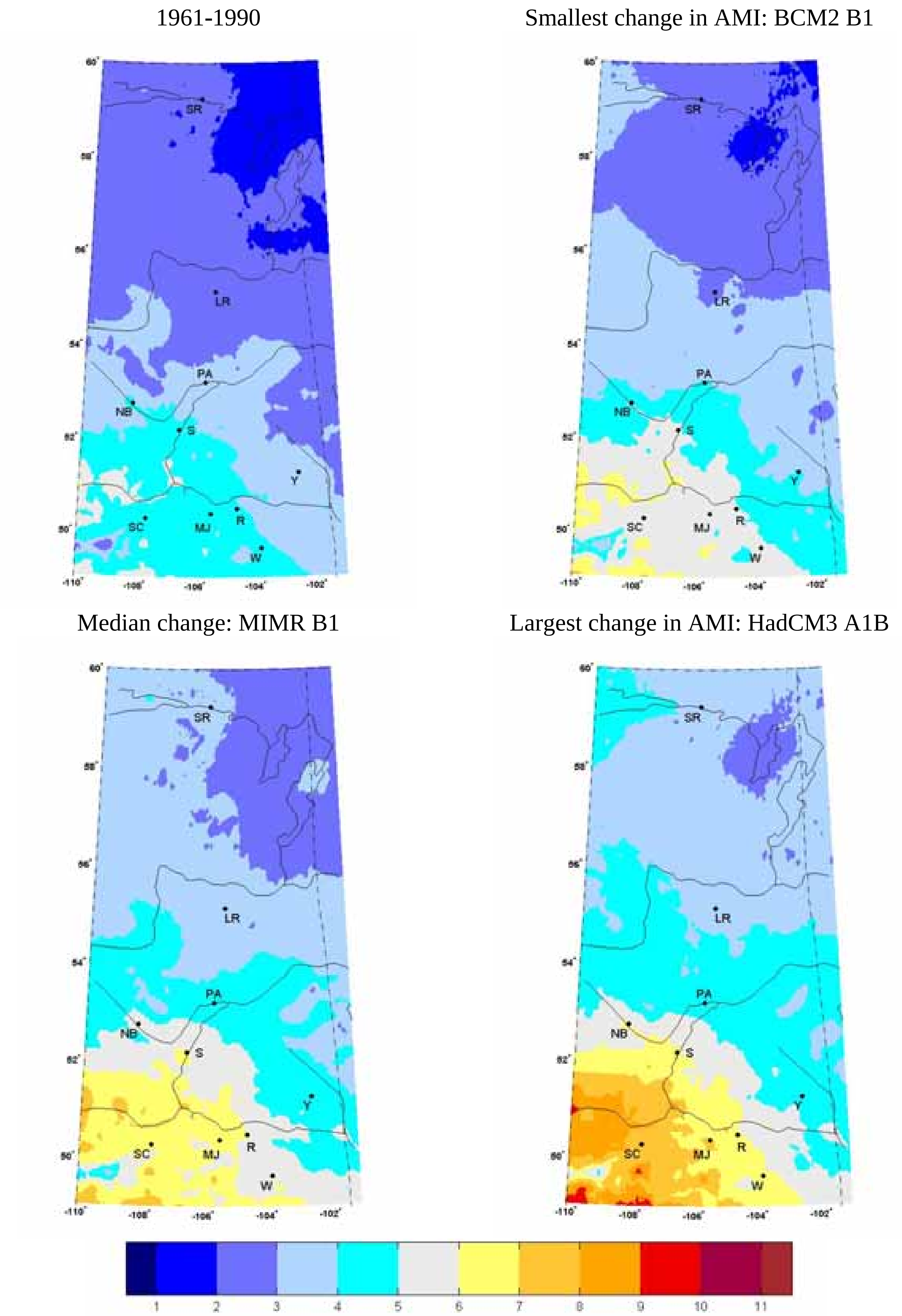


Figure B16: Annual moisture index for the 2080s, selected based on AMI change over forest region of Saskatchewan.

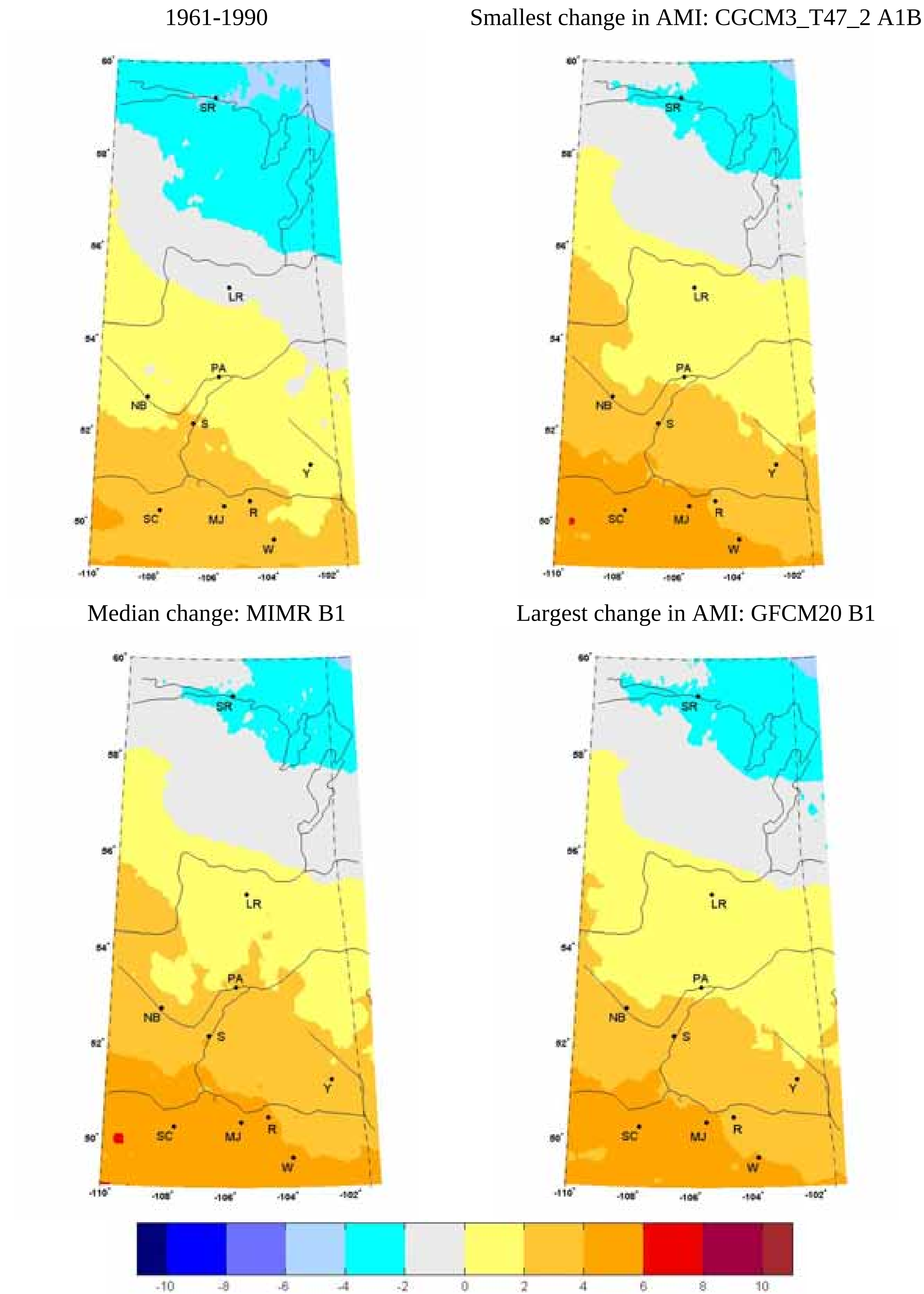


Figure B17: Annual mean temperature (°C) for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

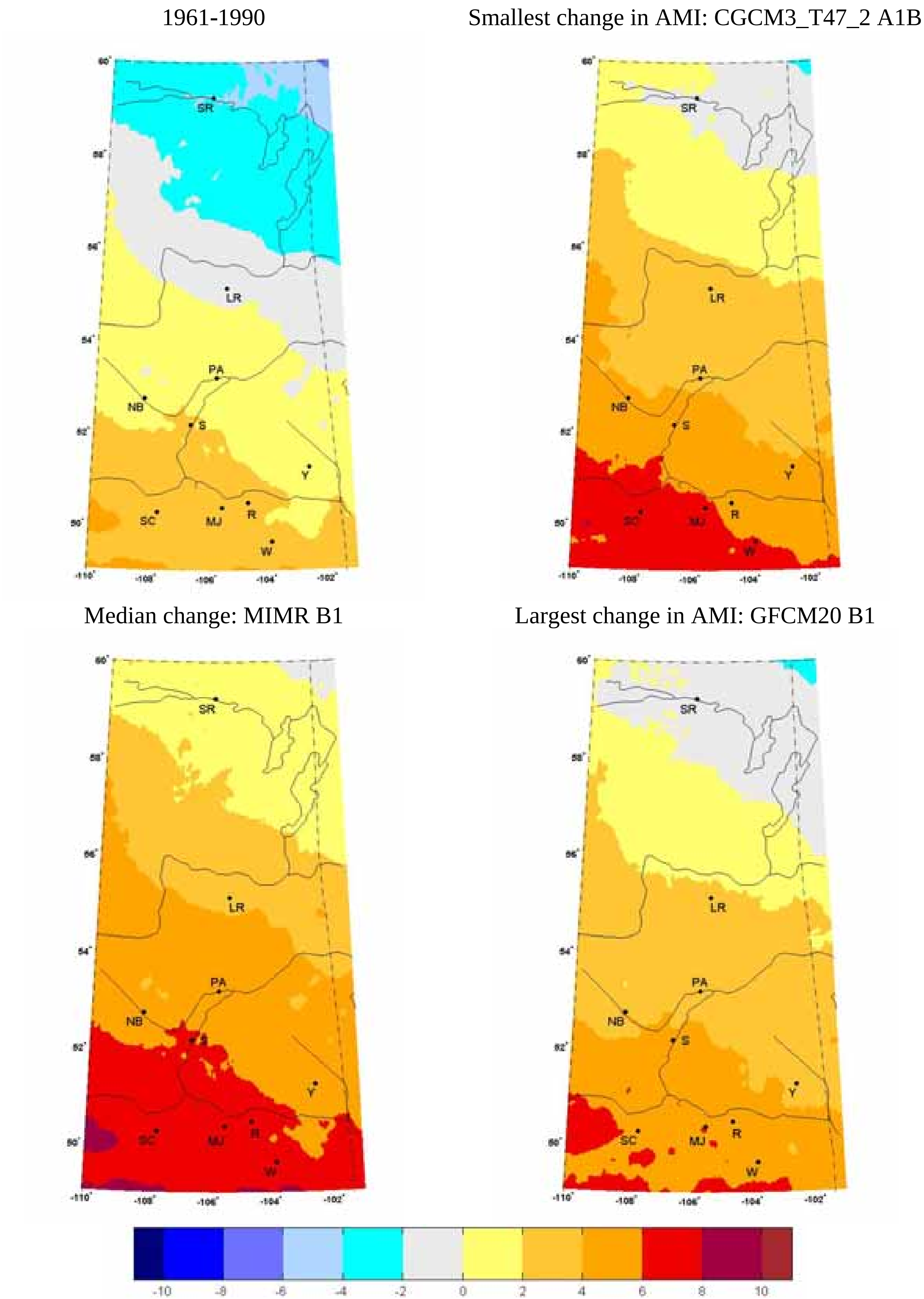


Figure B18: Annual mean temperature (°C) for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

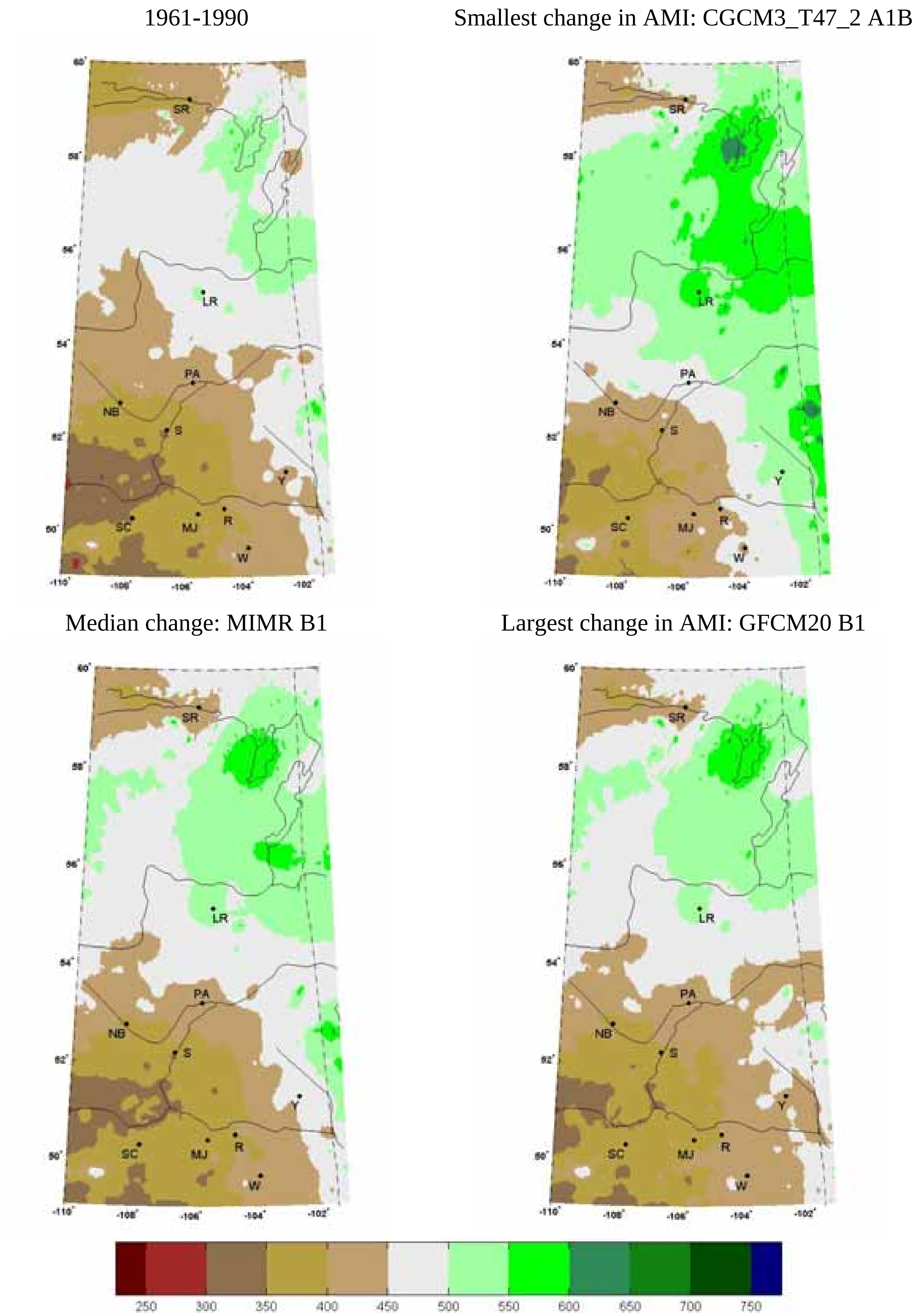


Figure B19: Annual precipitation total (mm) for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

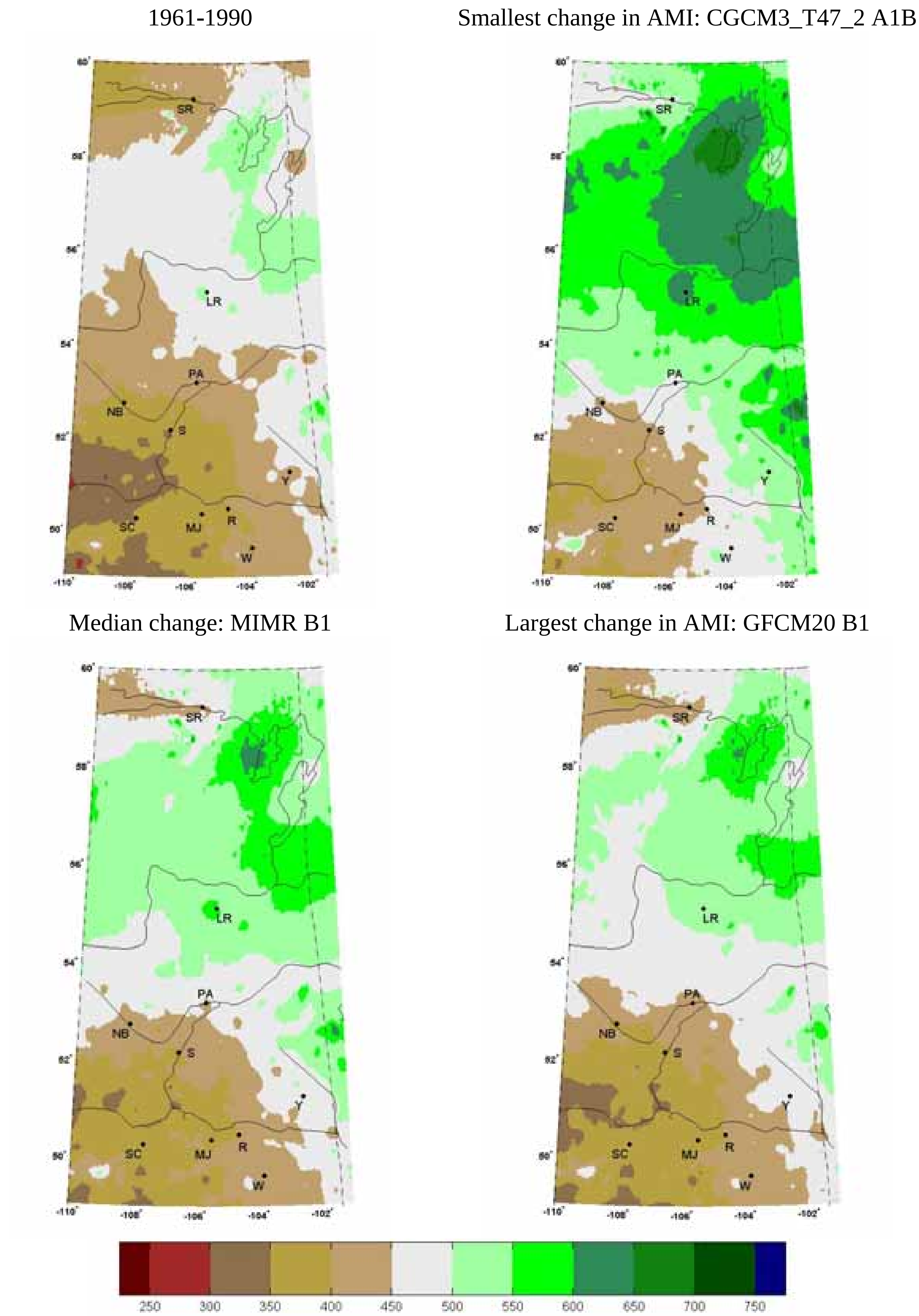


Figure B20: Annual precipitation total (mm) for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

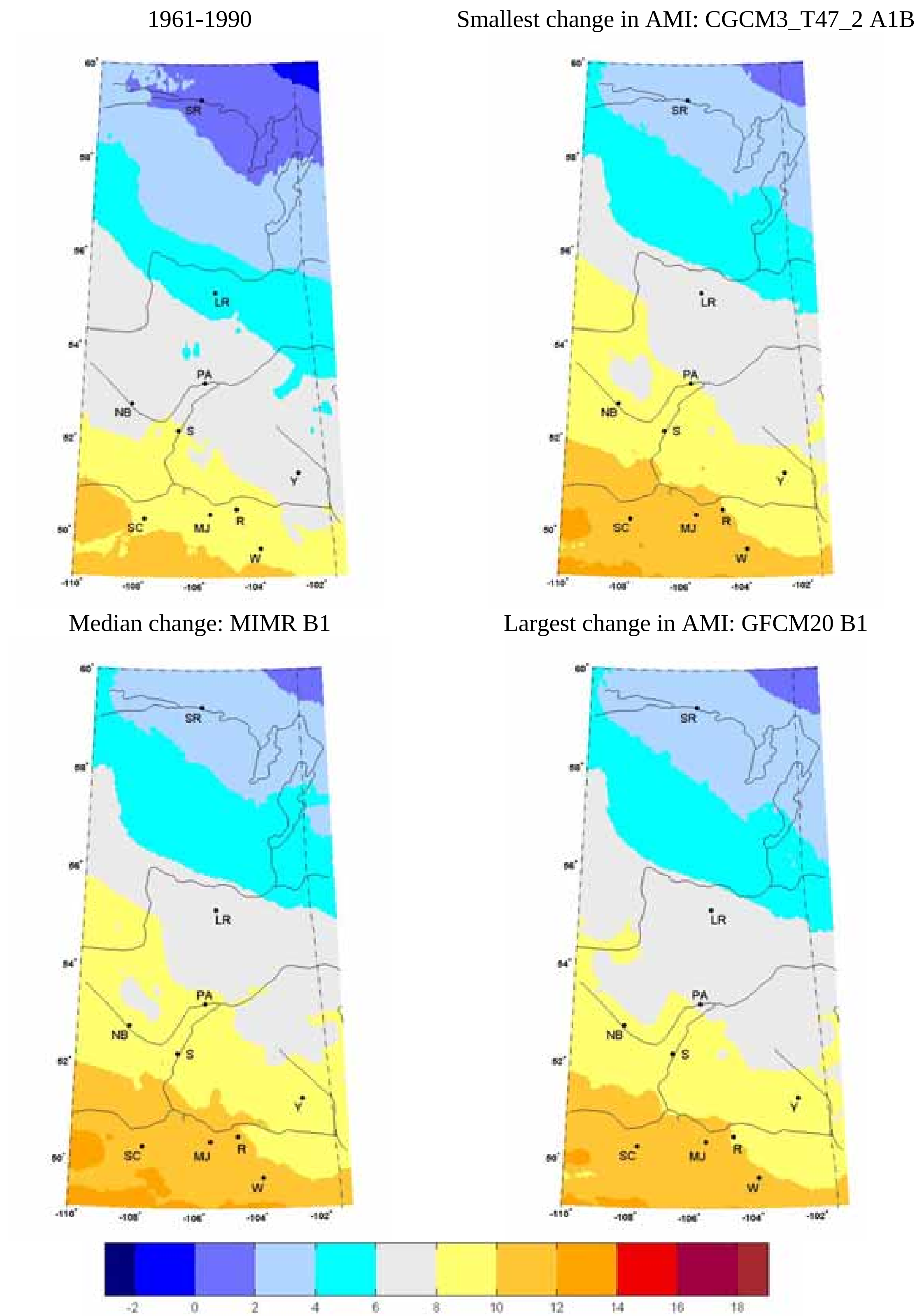


Figure B21: Annual mean maximum temperature (°C) for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

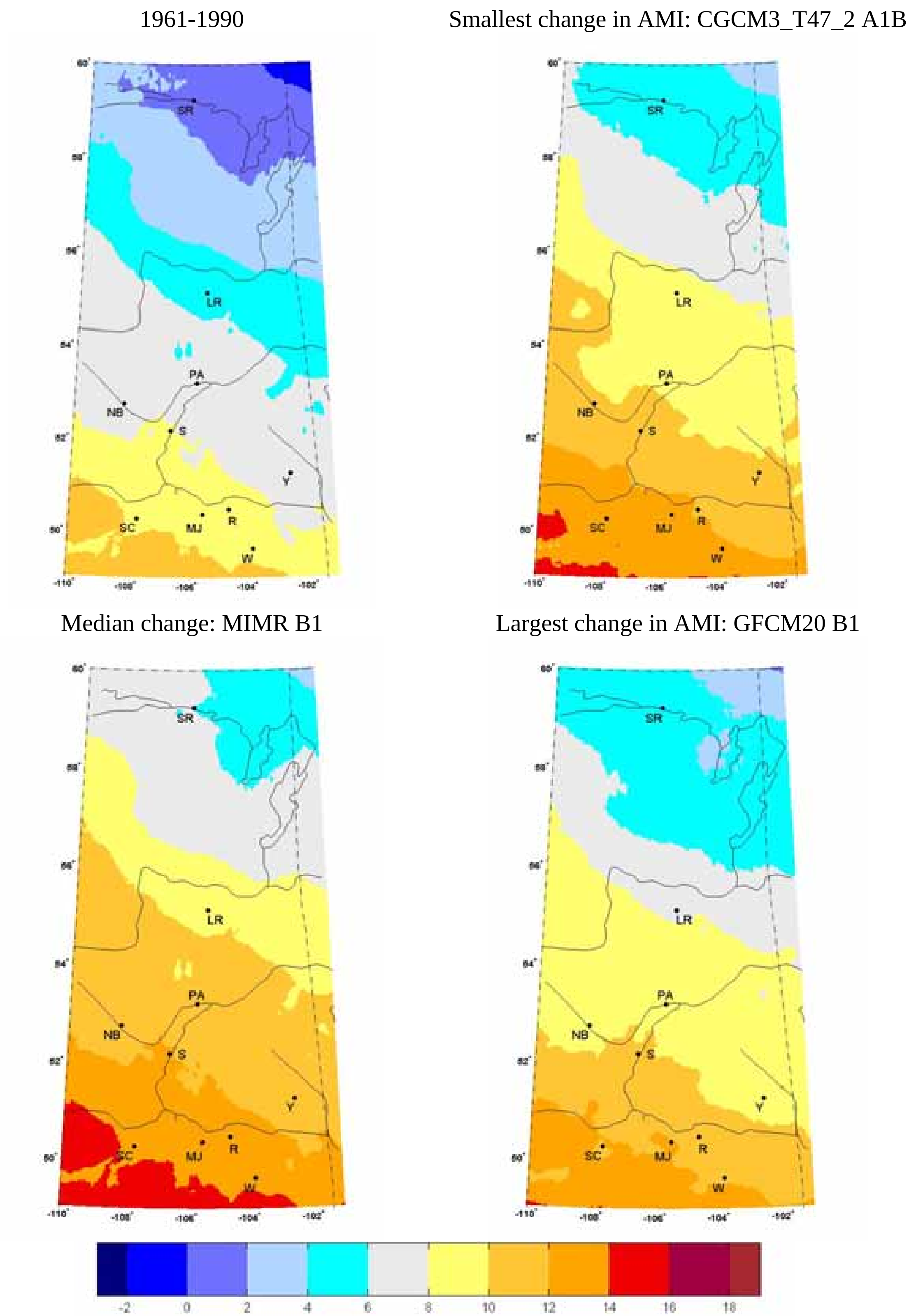


Figure B22: Annual mean maximum temperature (°C) for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

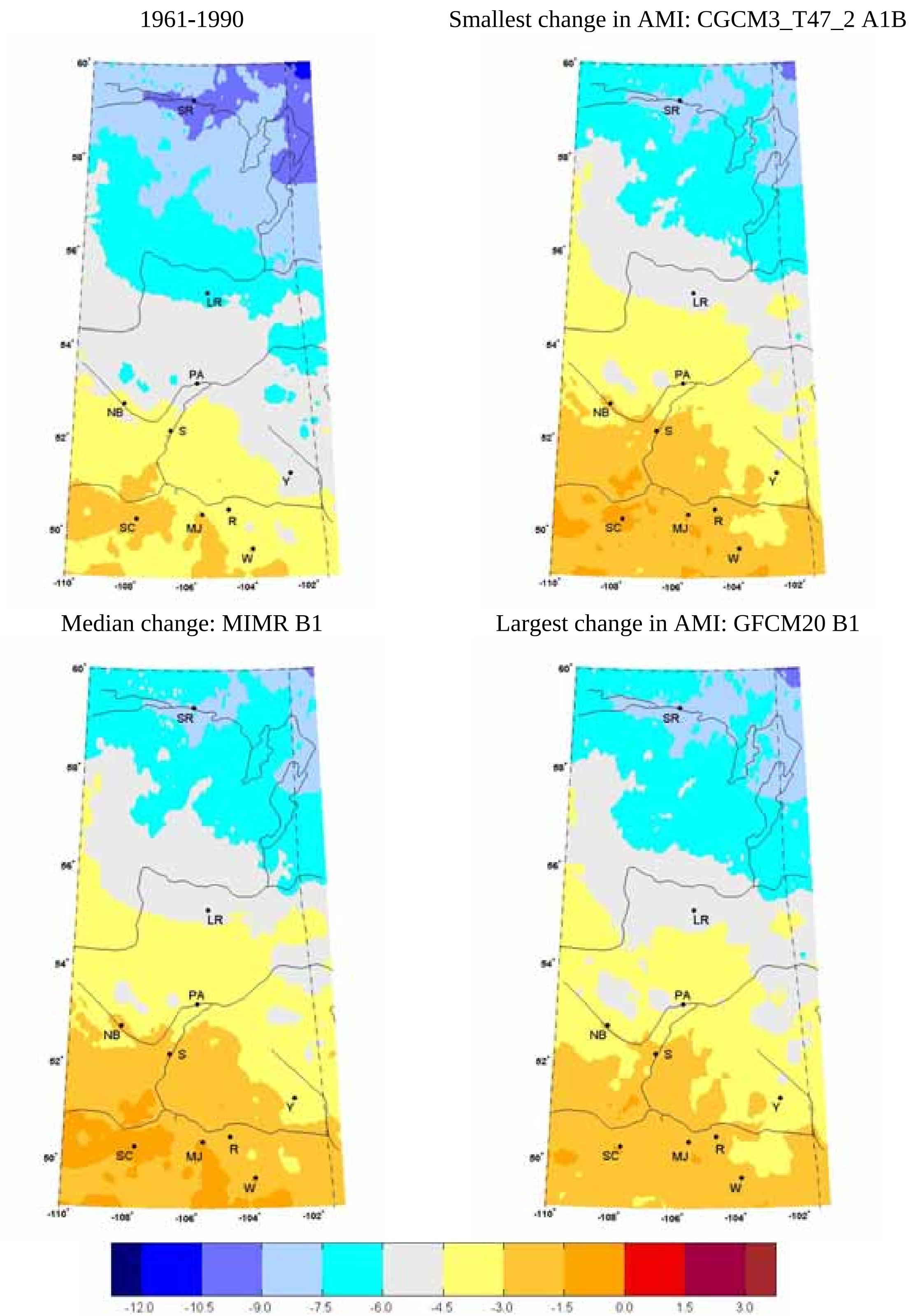


Figure B23: Annual mean minimum temperature (°C) for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

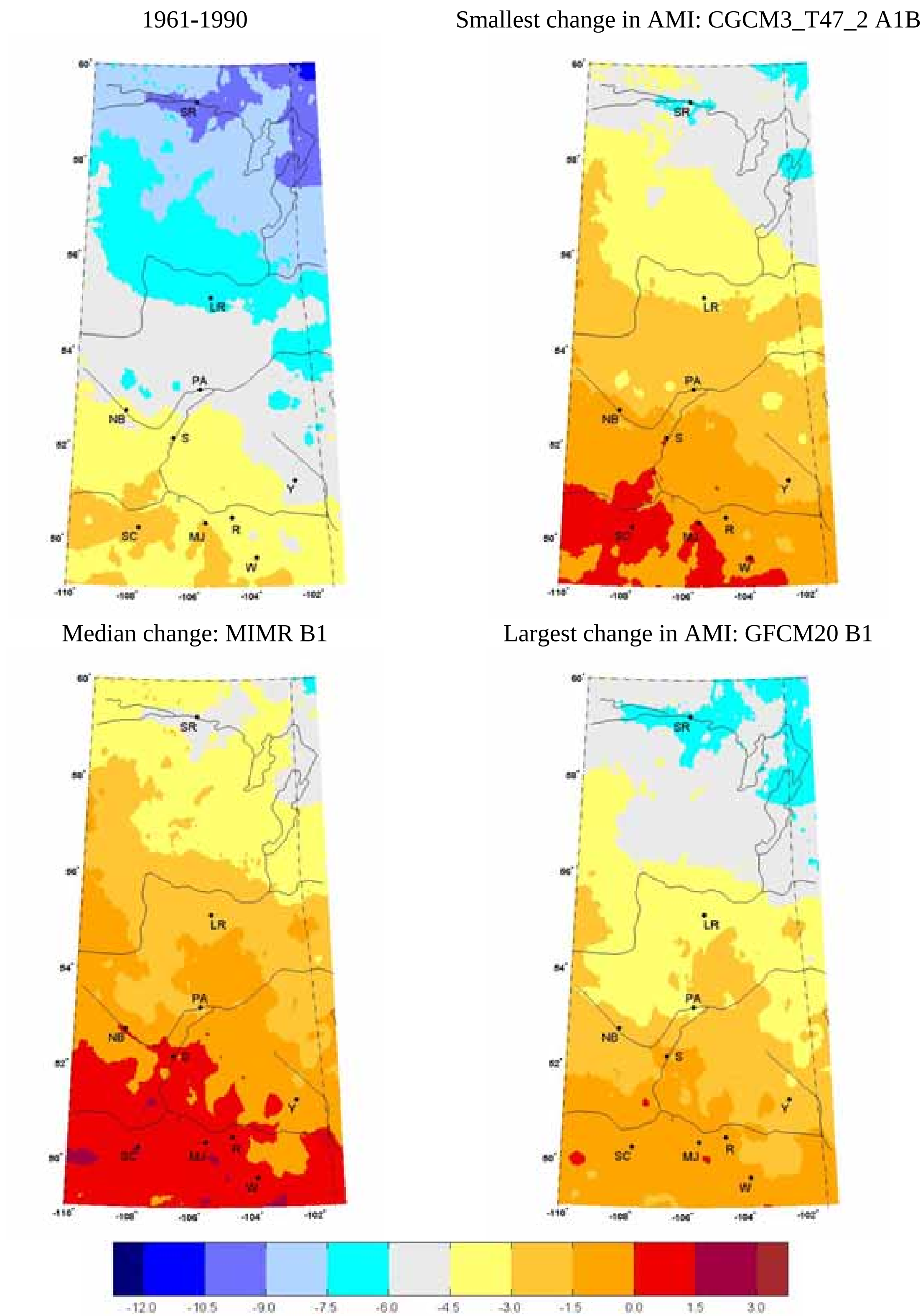


Figure B24: Annual mean minimum temperature (°C) for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

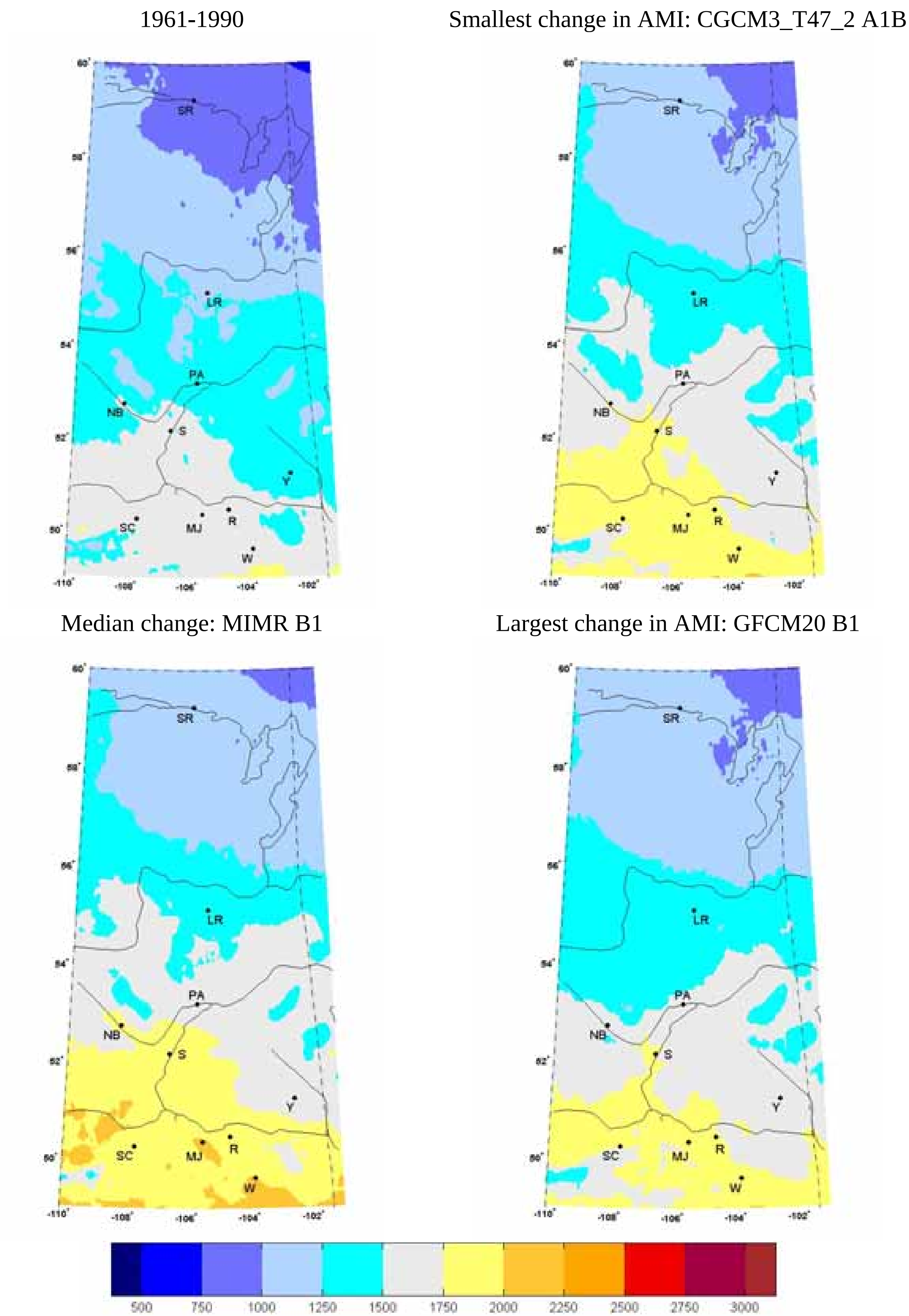


Figure B25: Degree days > 5°C for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

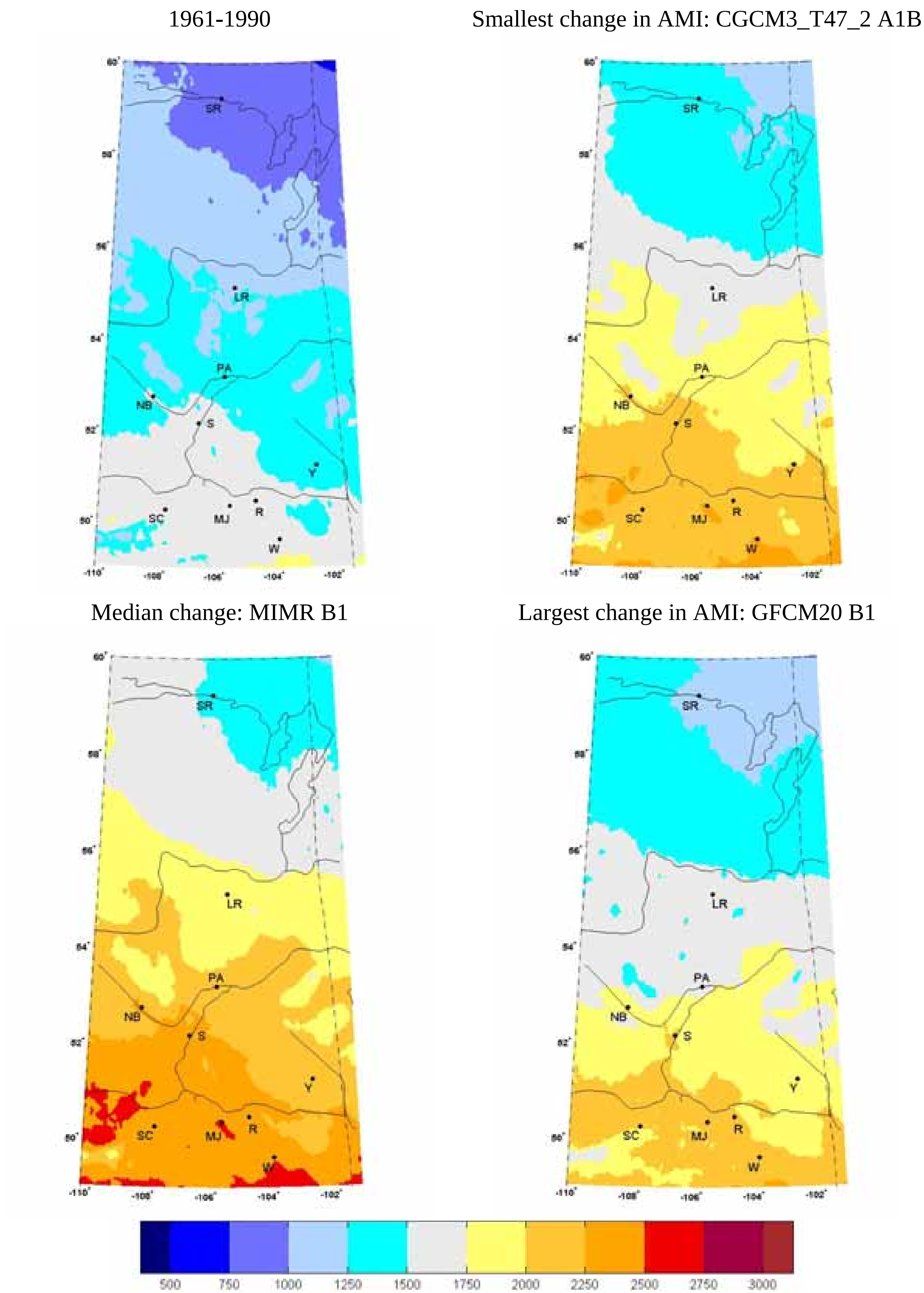


Figure B26: Degree days > 5°C for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

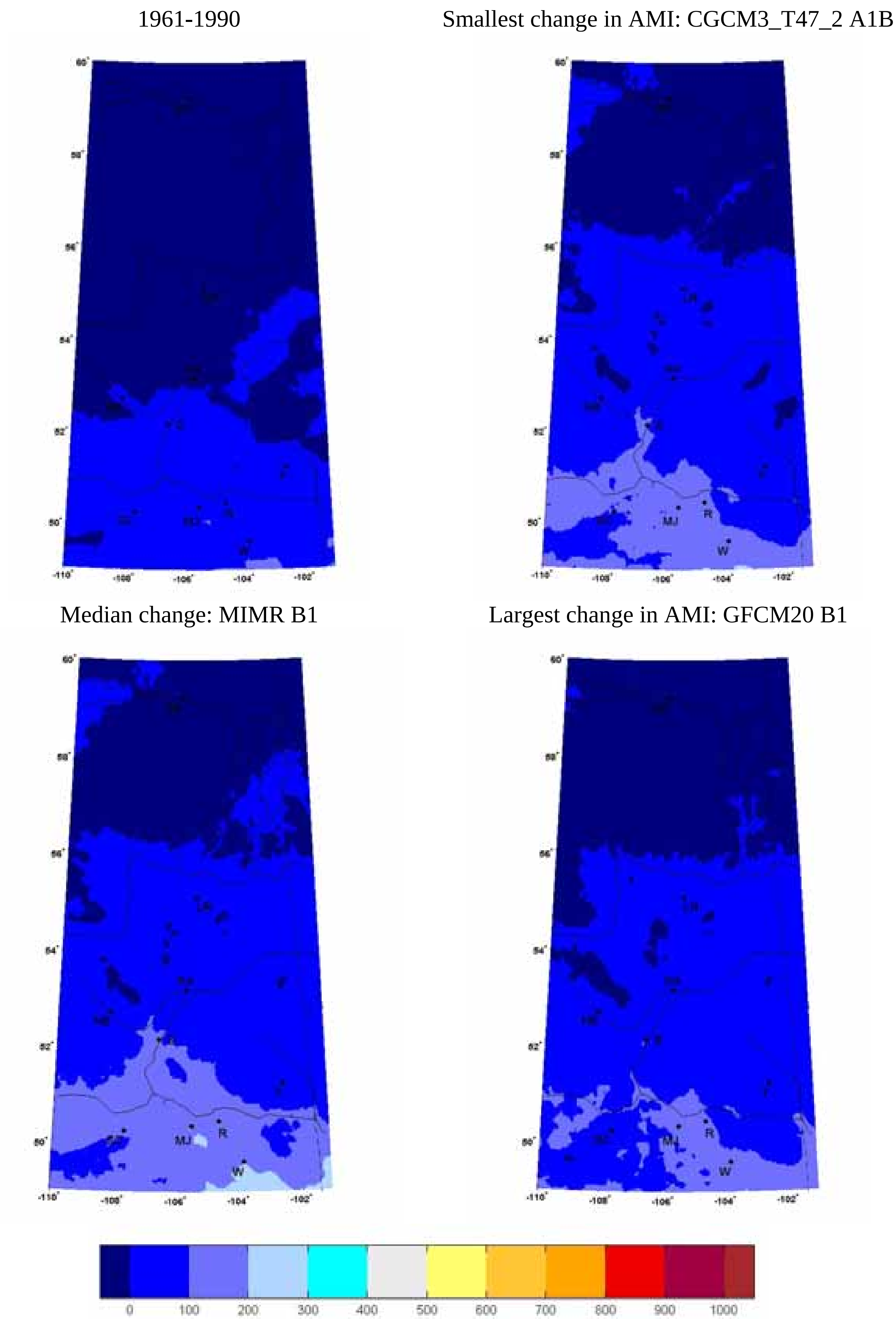


Figure B27: Degree days > 18°C (cooling degree days) for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

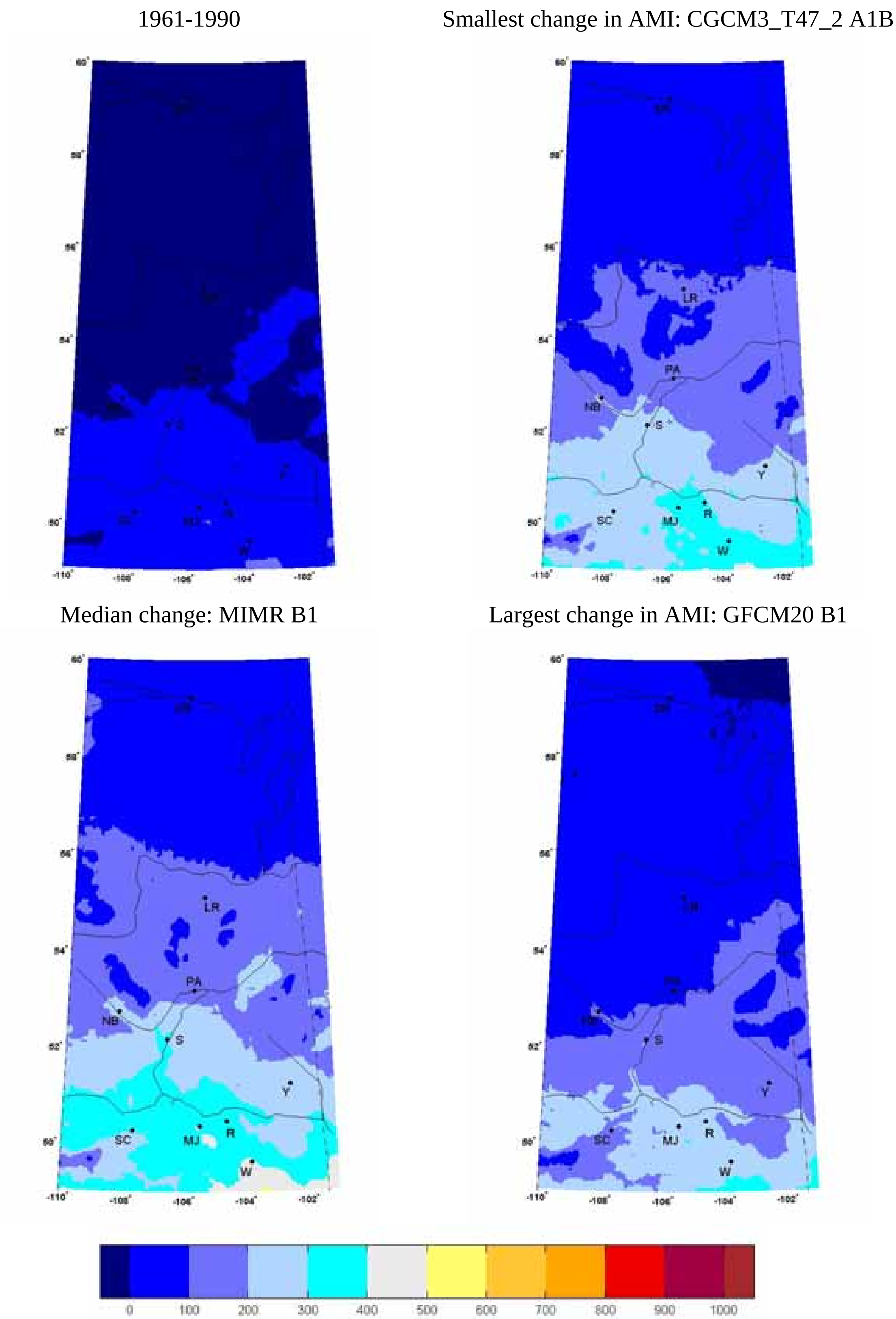


Figure B28: Degree days > 18°C (cooling degree days) for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

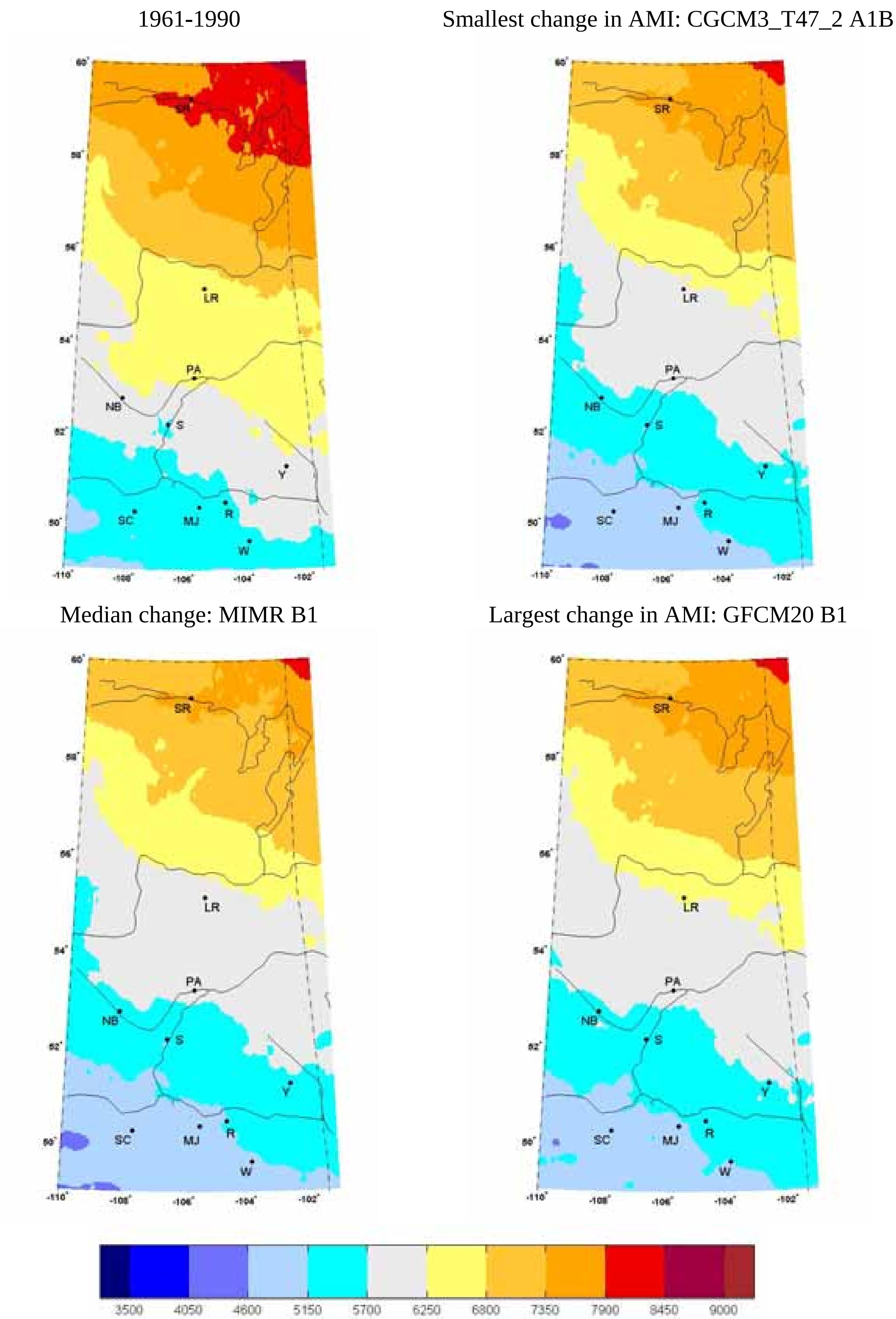


Figure B29: Degree days < 18°C (heating degree days) for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

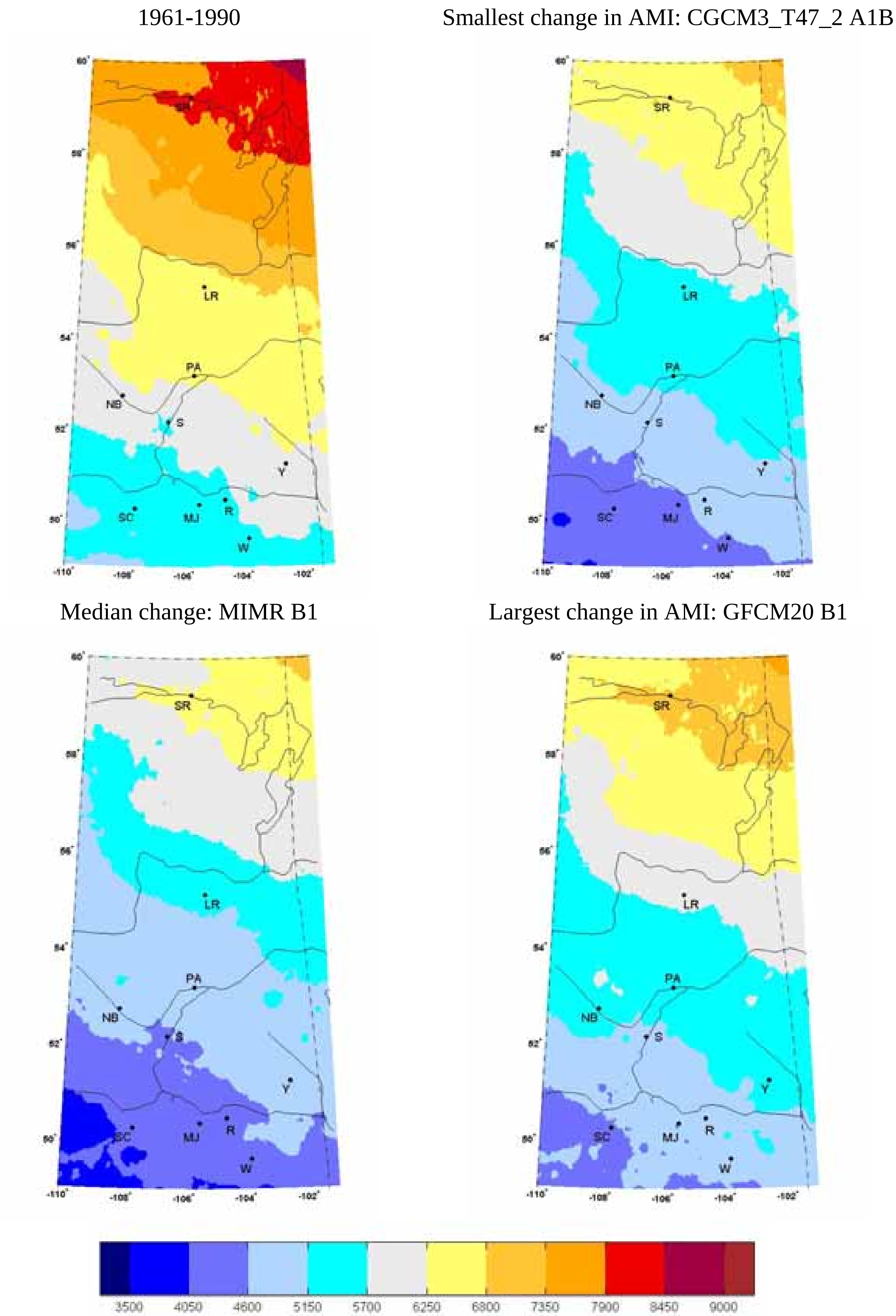


Figure B30: Degree days < 18°C (heating degree days) for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

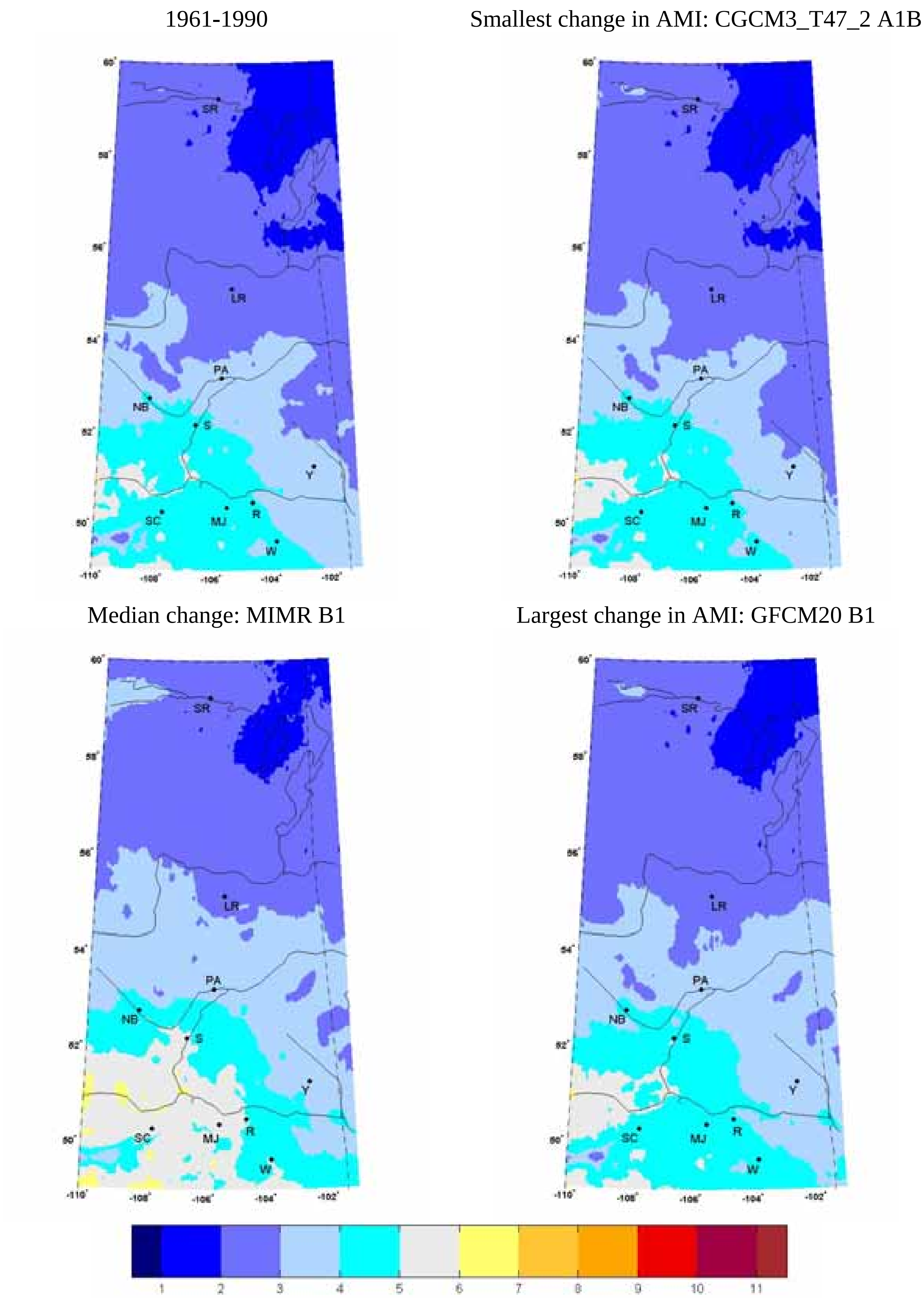


Figure B31: Annual moisture index for the 2020s, selected based on AMI change over grassland region of Saskatchewan.

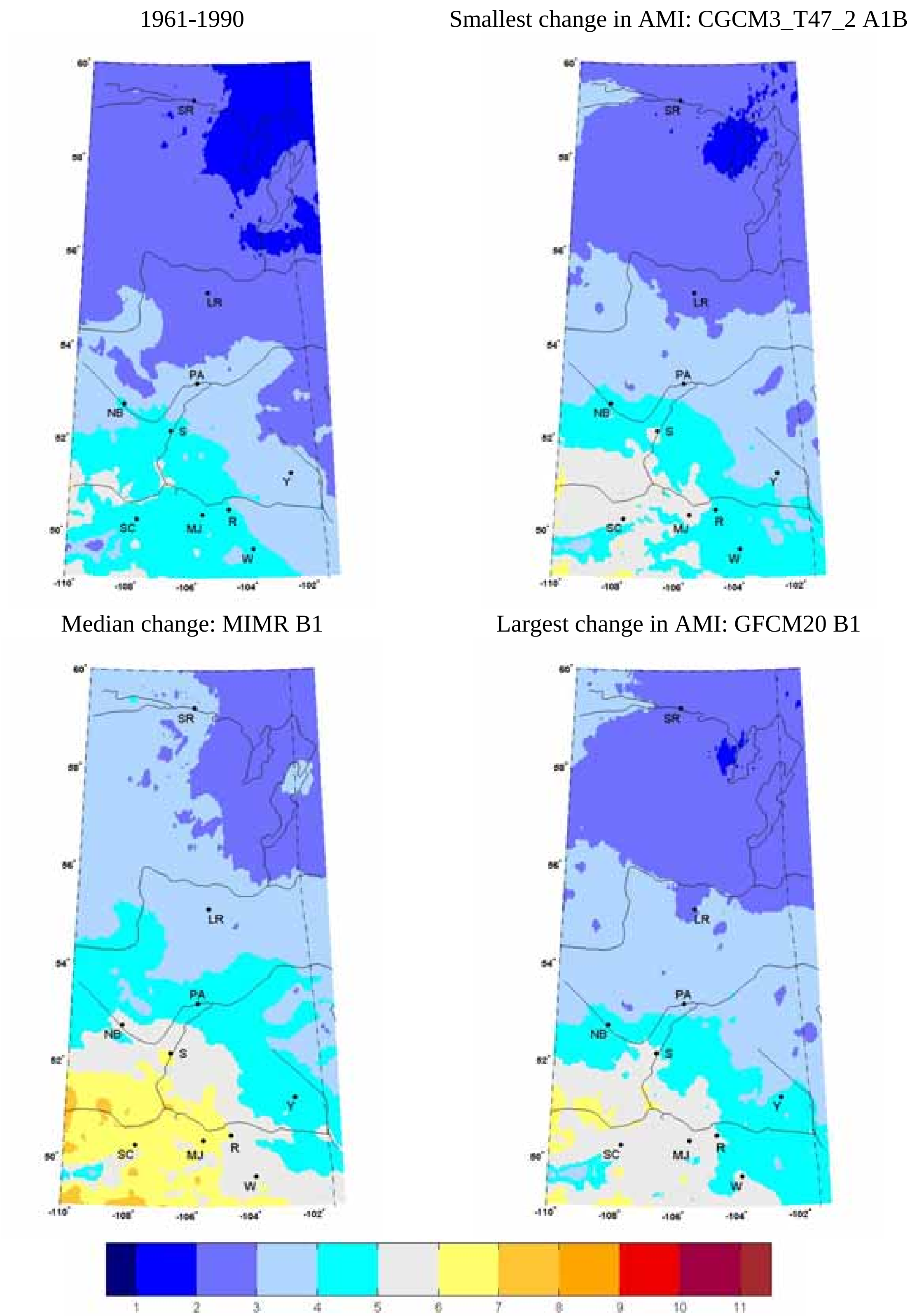


Figure B32: Annual moisture index for the 2080s, selected based on AMI change over grassland region of Saskatchewan.

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