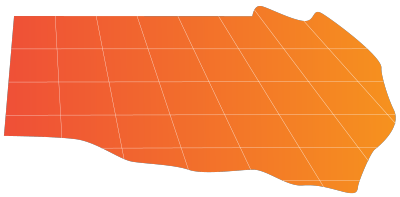

NARCliM

NSW | ACT Regional Climate Modelling project

NARCliM Technical Note 4
Issued: December 4, 2014

NARCliM Climatological Atlas

Roman Olson, Jason P. Evans, Daniel Argüeso and Alejandro Di Luca

Climate Change Research Centre,
University of New South Wales,
Kensington, NSW, Australia, 2052

Citation:
Olson, R., J. P. Evans, D. Argüeso and A. Di Luca, 2014: *NARCliM Climatological Atlas*. NARCliM Technical Note 4, 423 pp, NARCliM Consortium, Sydney, Australia

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Acknowledgements

Support for this work was provided by the NSW Office of Environment and Heritage through the NSW/ACT Regional Climate Modelling (NARCliM) Project, and by the Australian Research Council through the Future Fellowship FT110100576. This work was was made possible through the Merit Allocation Scheme award from the NCI National Facility at the Australian National University.

We wish to thank the OEH personnel, and Yvonne Scorgie and Ian MacAdam in particular, for inputs into the design of the atlas. We are thankful to the administration of Climate Change Research Centre at the University of New South Wales for the logistical support.

We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multimodel data set. Support of this data set is provided by the Office of Science, U.S. Department of Energy. We thank the scientists at NCAR Mesoscale and Microscale Meteorology Division for maintaining the Weather Research and Forecasting Model. We would like to acknowledge the scientists involved in generating AWAP observational datasets that are utilized in this atlas.

Chapter 1

Introduction

This atlas presents seasonal and annual means, mean biases, and projected future changes for the State of New South Wales, and Australian Capital Territory, for temperature and precipitation. These results are the outcome of the NARCliM (New South Wales / Australian Capital Territory Regional Climate Modelling) project [9, 23]. We include results from simulations performed using Regional Climate Models (RCMs), the Global Climate Models (GCMs) used to drive the RCMs, and an observational gridded dataset (AWAP). The atlas is organized as follows: chapter 1 introduces the atlas and the NARCliM project, chapter 2 presents climatologies from observations, chapters 3 shows GCM and RCM climatologies from the reanalysis period (years 1950–2009), and chapters 4 through 9 contain results for the present (1990–2009), near future (2020–2039), and far future periods (2060–2079). For the present, in addition to climatologies, we show biases in the RCMs and the GCMs. For each of the future periods we present both the climatologies and the future changes. Each of chapters 4 through 9 includes results for driving GCMs, the original RCM output, and the bias-corrected RCM output (*i.e.* corrected for model biases compared to observations).

1.1 NARCliM Project Description

The NARCliM project is designed to create regional scale climate projections for use in climate change impacts and adaptation studies, and ultimately to inform climate change policy making [9, and others]. Details on NARCliM can be found at http://www.ccrc.unsw.edu.au/NARCliM/. NARCliM is a unique project because its design has used a bottom-up approach, heavily involving end user input. This was intended to facilitate useability of model outputs by the end users (*e.g.* adaptation community). Other benefits of early end-user involvement are an improved understanding by the end users of the climate modelling process and its limitations.

The key idea behind the project is downscaling several GCMs (previously available climate projections on a global scale, but with a poor representation of regional features) to South-East Australia. GCMs are large computer programs that solve complex equations governing weather and climate processes. They output climate variables (*e.g.* temperature, windspeed, humidity) for points on a grid. The downscaling is performed using Weather Research and Forecasting (WRF) RCM [25]. The RCM takes the large-scale atmospheric state simulated by GCMs as an input, and produces climate on regional and local scales as output. Unlike a GCM, an RCM is limited

to a region of the Earth, however it includes many more processes relevant for local and regional scales, including a much better representation of topography. The advantage of this method is that it explicitly models these important local and regional-scale processes.

Due to computing and data storage limitations, the project is limited to a 12-member GCM / RCM ensemble. This has been created by choosing four GCMs and downscaling each of these with three different RCMs (three versions of WRF using different parameterizations of sub-grid atmospheric physics). All RCM simulations were performed at 10 km resolution over NSW/ACT. This high-resolution domain was embedded within a 50 km resolution domain that covers the CORDEX-AustralAsia region (Figure 1.1). Choosing this larger domain ensures that future work that focuses on Coupled Model Intercomparison Project phase 5 (CMIP5) results can take advantage of simulations performed for the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative. CORDEX is an international effort sponsored by the World Climate Research Programme. The inner domain is shown in Figure 1.2. It is chosen with a particular focus on simulations of the east-coast climate as this relatively narrow coastal strip, east of the mountains: contains almost half the population of Australia; displays a unique climate response to oceanic modes compared to further inland [22]; is generally poorly modelled by GCMs [27] but is well modelled at 10 km resolution [10]; and is strongly influenced by East-Coast Lows which are often small, rapidly developing storm systems [26]. This atlas focuses on the results for the inner domain.

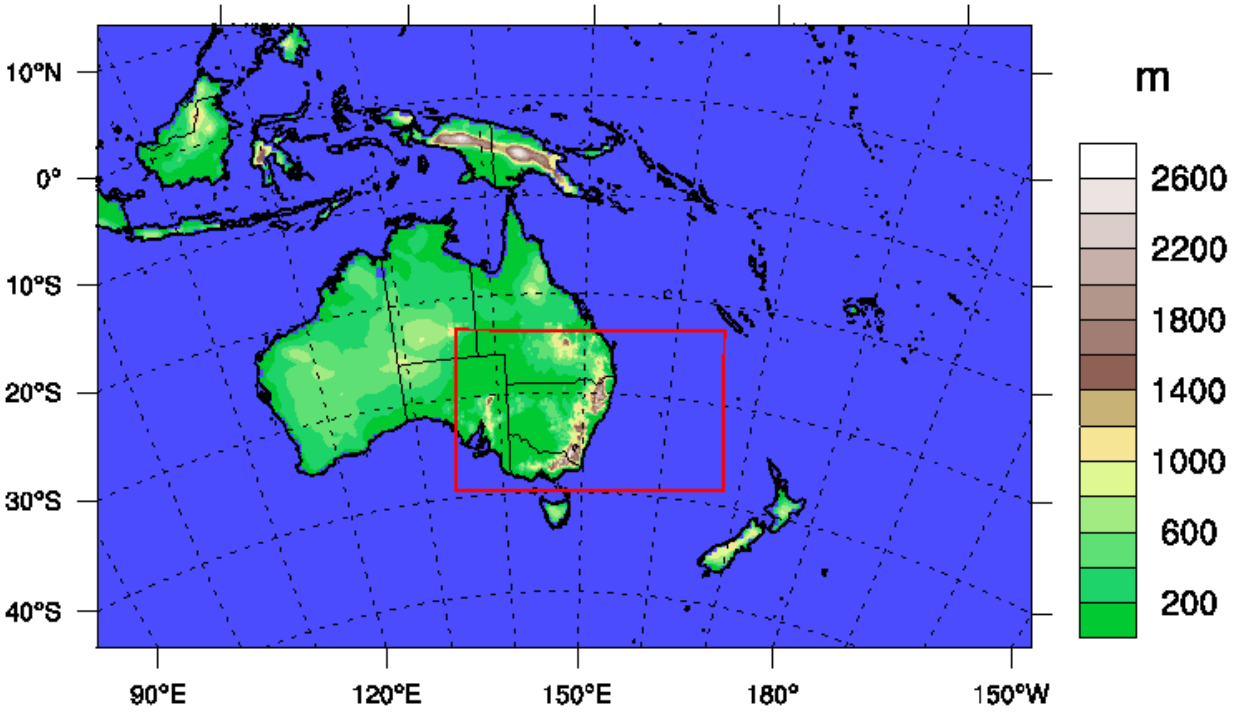

Figure 1.1: Map of NARCliM domains 1 and 2

Like previous regional climate projection projects, NARCliM has two main phases. In phase one, three RCMs are used to downscale the NCEP/NCAR reanalysis [19] from 1950 to 2009. The reanalysis is a numerical ”reproduction” of global climate and weather patterns over years 1950-2009, and is constructed by combining weather observations, and climate models. This particular reanalysis was chosen due to its relatively long-term coverage allowing to perform a 60-year long historical simulation. Southeast Australia has experienced strong decadal variability in precipitation over the second half of the 20th century with particularly wet decades in the 1950s and 1970s. These reanalysis-driven simulations provide a strong test of the RCMs ability to simulate both these very wet periods and the recent dry period known as the Millennium Drought [28]. This phase provides an estimate of the RCM quality including any systematic RCM biases.

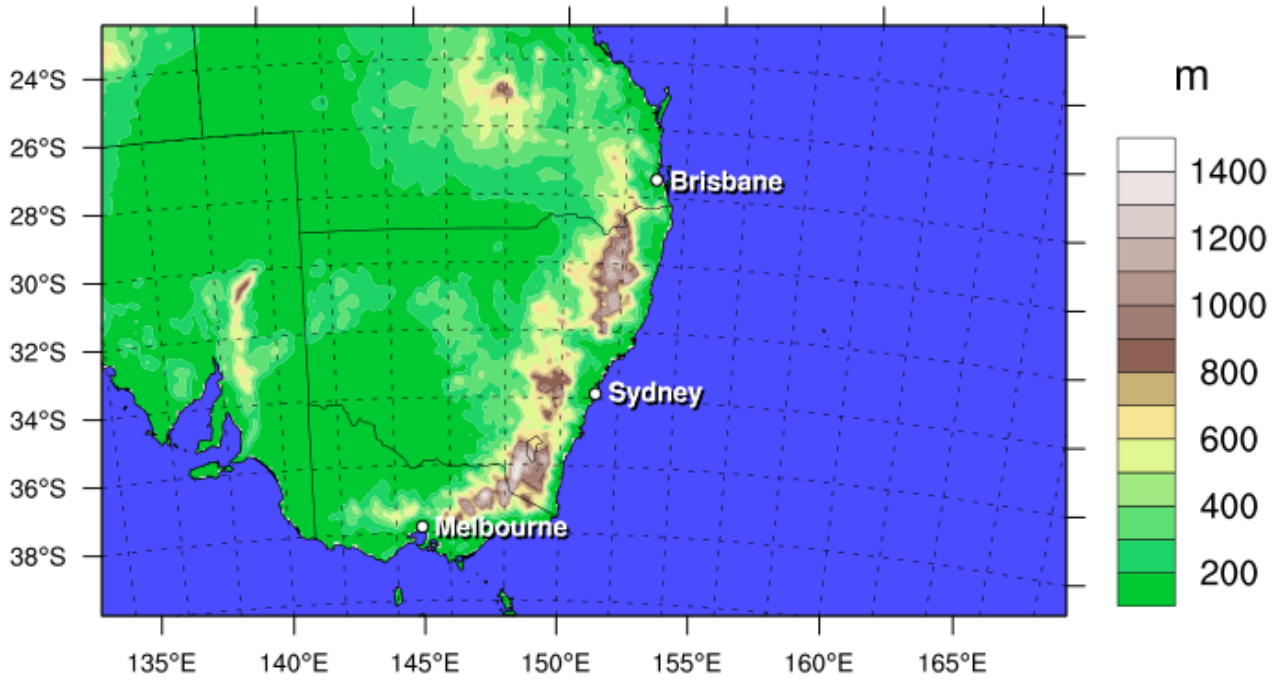

Figure 1.2: Map of NARCliM domain 2

In phase two, the three RCMs are used to downscale four GCMs in three 20-year time slices (1990-2009, “present”; 2020-2039, “near future”; 2060-2079, “far future”). For future projections the SRES A2 emission scenario [12] is used. This scenario assumed an overall relatively high growth rate of atmospheric greenhouse gas emissions. A careful choice of both RCMs and GCMs is required for this small ensemble to adequately sample the model uncertainty. The methodology used to make these decisions is described in the reports [8, 7]. The GCMs chosen are the MIROC3.2, ECHAM5, CCCMA3.1 and CSIRO-MK3.0. The chosen RCMs, and the parametrizations used therein are given in Table 1.1 below. These are versions of the WRF model for different parametrizations of planetary boundary layer, surface layer, cumulus physics, microphysics, and radiation.

NARCliM Ensemble Member	Planetary Boundary Layer Physics / Surface Layer Physics	Cumulus Physics	Microphysics	Shortwave and Longwave Radiation Physics
R1	MYJ / Eta similarity	KF	WDM 5 class	Dudhia / RRTM
R2	MYJ / Eta similarity	BMJ	WDM 5 class	Dudhia / RRTM
R3	YSU / MM5 similarity	KF	WDM 5 class	CAM / CAM

Table 1.1: The three RCMs selected from a 30 model ensemble. MYJ / Eta similarity: Mellor-Yamada-Janjic Planetary Boundary Layer (PBL) scheme [13] with Eta similarity surface layer; YSU / MM5 similarity: Yonsei University PBL scheme [11] with the MM5 similarity theory surface layer [24, 5, 29]; KF: Kain-Fritsch cumulus scheme [17, 18, 16]; BMJ: Betts-Miller-Janjic cumulus scheme [2, 1, 13, 14]; WDM5: WRF Double Moment 5-class microphysics scheme [20]; Dudhia: Dudhia shortwave radiation scheme [4], RRTM: Rapid Radiative Transfer Model longwave radiation scheme [21]; CAM: NCAR Community Atmosphere Model version 3.0 shortwave and longwave radiation schemes [3].

The atlas contains both the original RCM output, and the bias-corrected RCM output (*i. e.,* RCM output corrected for biases between the models and observations). During the bias-correction procedure, we first compare distributions of daily model output and observations for all seasons. Then, we apply the correction factors (independent of season) to RCM output to make the distributions of daily RCM output match daily observations. For present, near-future, and far-future periods, we use Australian Water Availability Project (AWAP) observations [15] for period 1990-2009 to calculate corrections. These observations are discussed and plotted in Chapter 2. For reanalysis runs, we use AWAP data for climatological period 1961-1990 to calculate the corrections. Note that we do not perform bias-correction for modeled daily mean RCM temperature, since directly comparable observations exist neither in the AWAP dataset, nor in any other national data. Modeled daily mean temperature is an average over model output at hourly resolution. Thus, simply averaging the daily maximum and daily minimum AWAP observations to obtain daily mean temperature does not result in a directly comparable metric. Hence, the bias-corrected plots exclude daily mean temperature. The in-depth description of the bias-correction methodology, and the guidance on when to use the bias-corrected vs. the original output is given in report [6].

Chapter 2

AWAP Observed Climatologies

Here we present observed temperature and precipitation climatologies from the AWAP project, produced by the Bureau of Meteorology [15]. This dataset is directly compared to RCM and GCM output in later chapters. AWAP is a daily dataset at 5 km by 5 km spatial resolution. The dataset is generated by interpolating surface station measurements of precipitation, maximum and minimum temperature and vapour pressure. AWAP data starts in 1900 for precipitation, 1910 for temperature, 1970 for vapour pressure, and extends up to the present - it is constantly updated with the most recent observations. During most of the period of NARCliM reanalysis runs (1950-2009), AWAP gridded dataset includes information from $\sim$ 6000 to 7000 rainfall stations and $\sim$ 300 to 800 temperature stations. A substantially smaller number of temperature stations ($\sim$ 100) were used for the first few years (1950-1956).

The gridding of the *in situ* daily observations was generated using an anomaly-based approach to take advantage of their smoother spatial distribution and they were then converted to absolute values by adding (or multiplying in the case of precipitation) a climatological analysis. More details on the analysis method used to interpolate station data onto the AWAP grid can be found in Jones et al (2009) [15].

Observational gridded datasets are the most appropriate kind of data to compare to regional climate models. Such gridded data generally constitute area-averaged estimations, making them directly comparable to model output. Before plotting, we interpolate the AWAP observations onto the NARCliM domain 2 grid using a simple inverse distance weighting method. We approximate seasonal and annual mean near-surface air temperature by an average of AWAP's seasonal means of daily maximum and daily minimum air temperatures.

We present AWAP data for two periods: reanalysis period (years 1950–2009), and present day (years 1990–2009). Reanalysis period AWAP observations can be directly compared to reanalysis RCM output, while present-day AWAP data - to present day RCM output.

2.1 Reanalysis Period (1950-2009) AWAP Observations

This subsection contains reanalysis period (1950-2009) seasonal and annual climatologies for AWAP observations of temperature and precipitation. These observations are directly comparable to output from reanalysis RCM runs presented in Chapter 3.

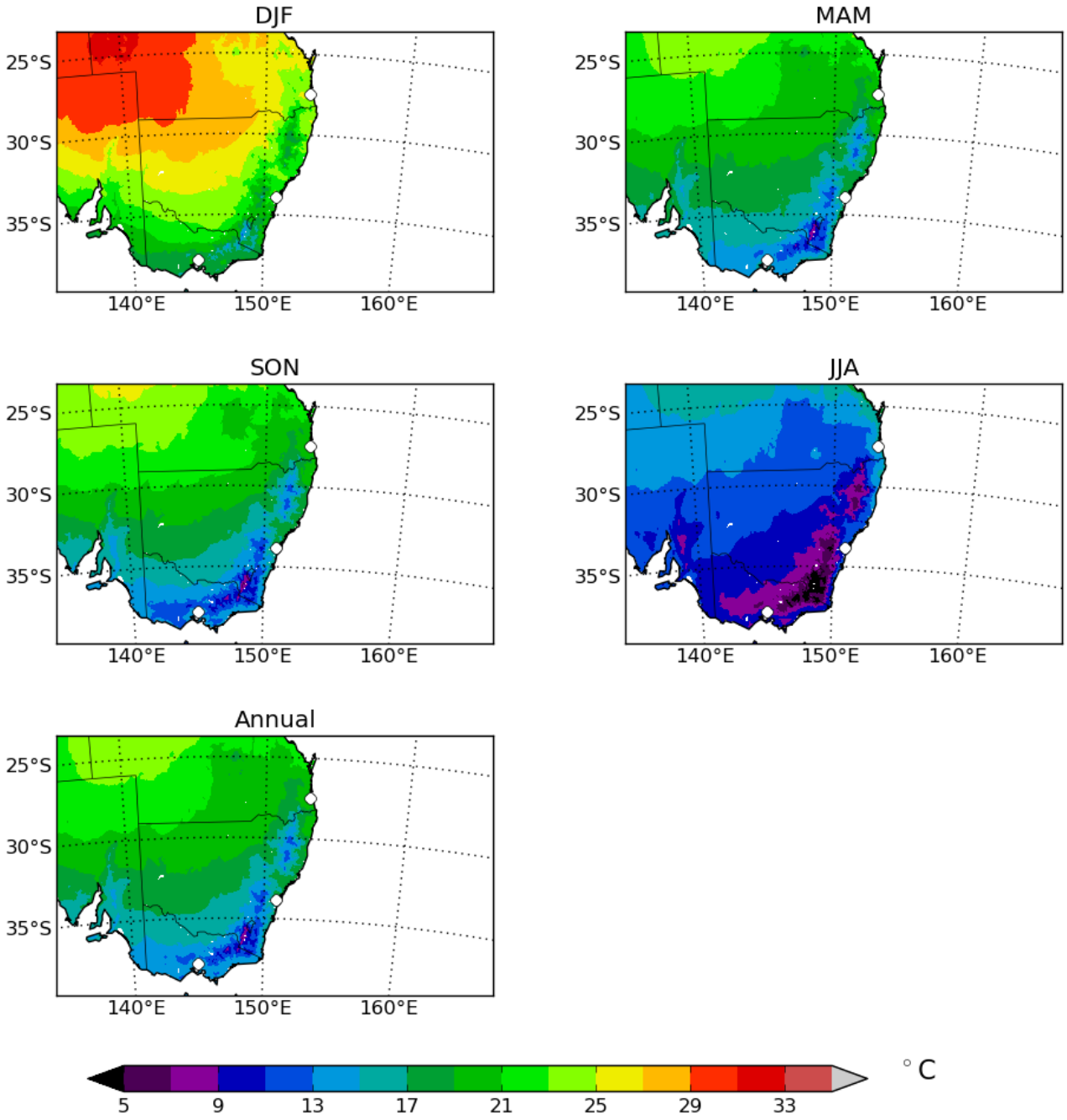

Figure 2.1: Seasonal and annual means of AWAP near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

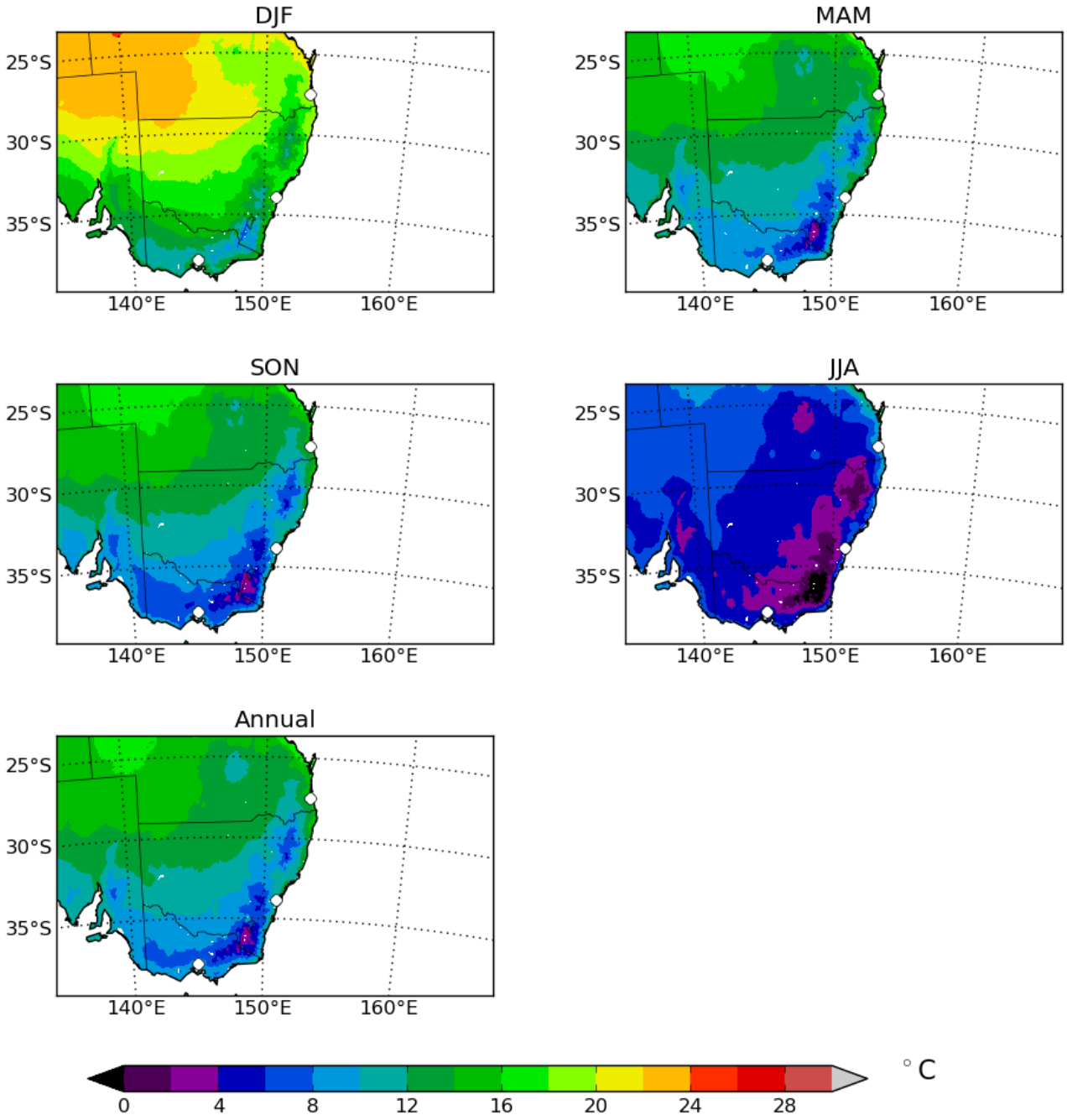

Figure 2.2: Seasonal and annual means of AWAP daily minimum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

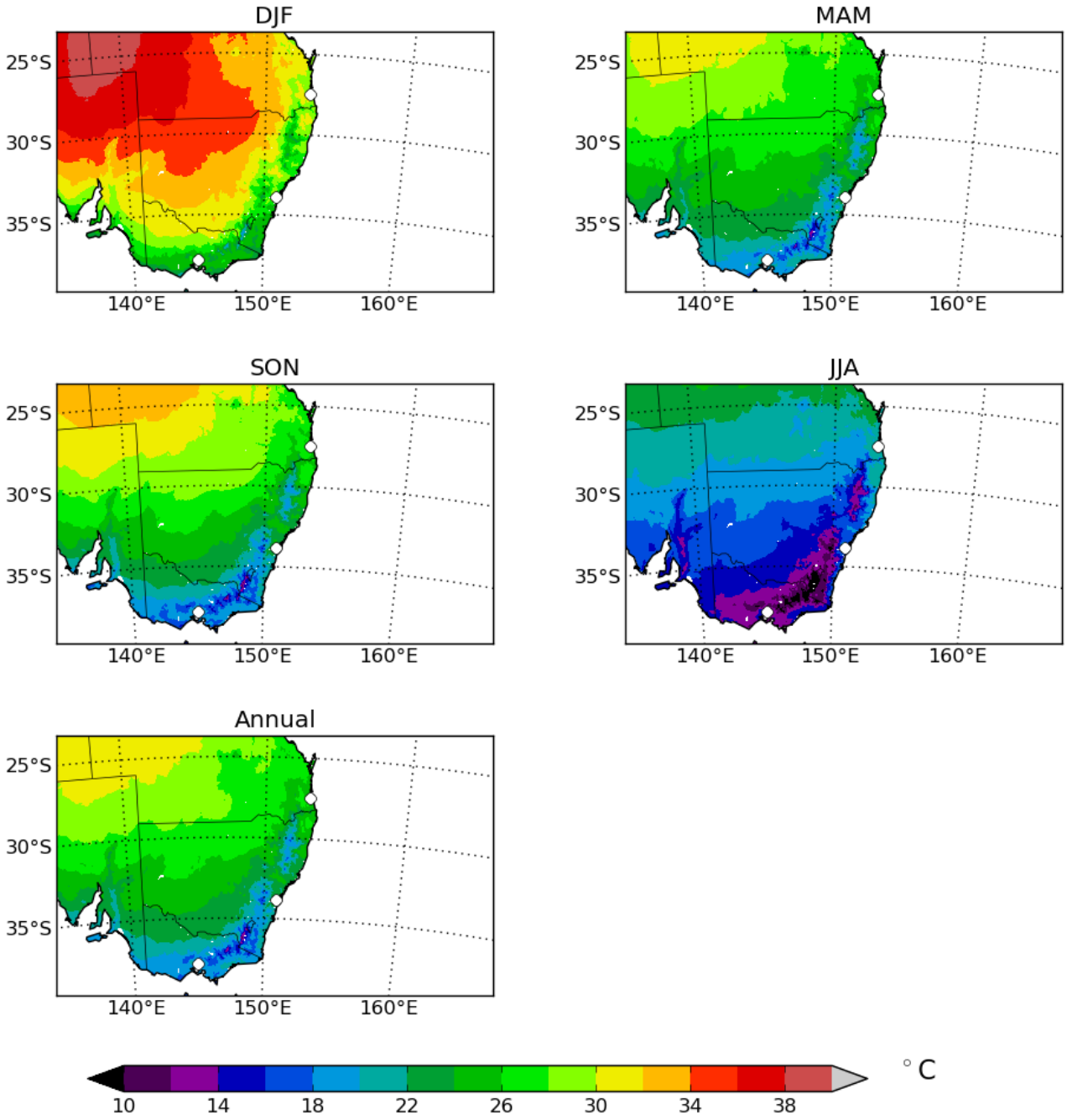

Figure 2.3: Seasonal and annual means of AWAP daily maximum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

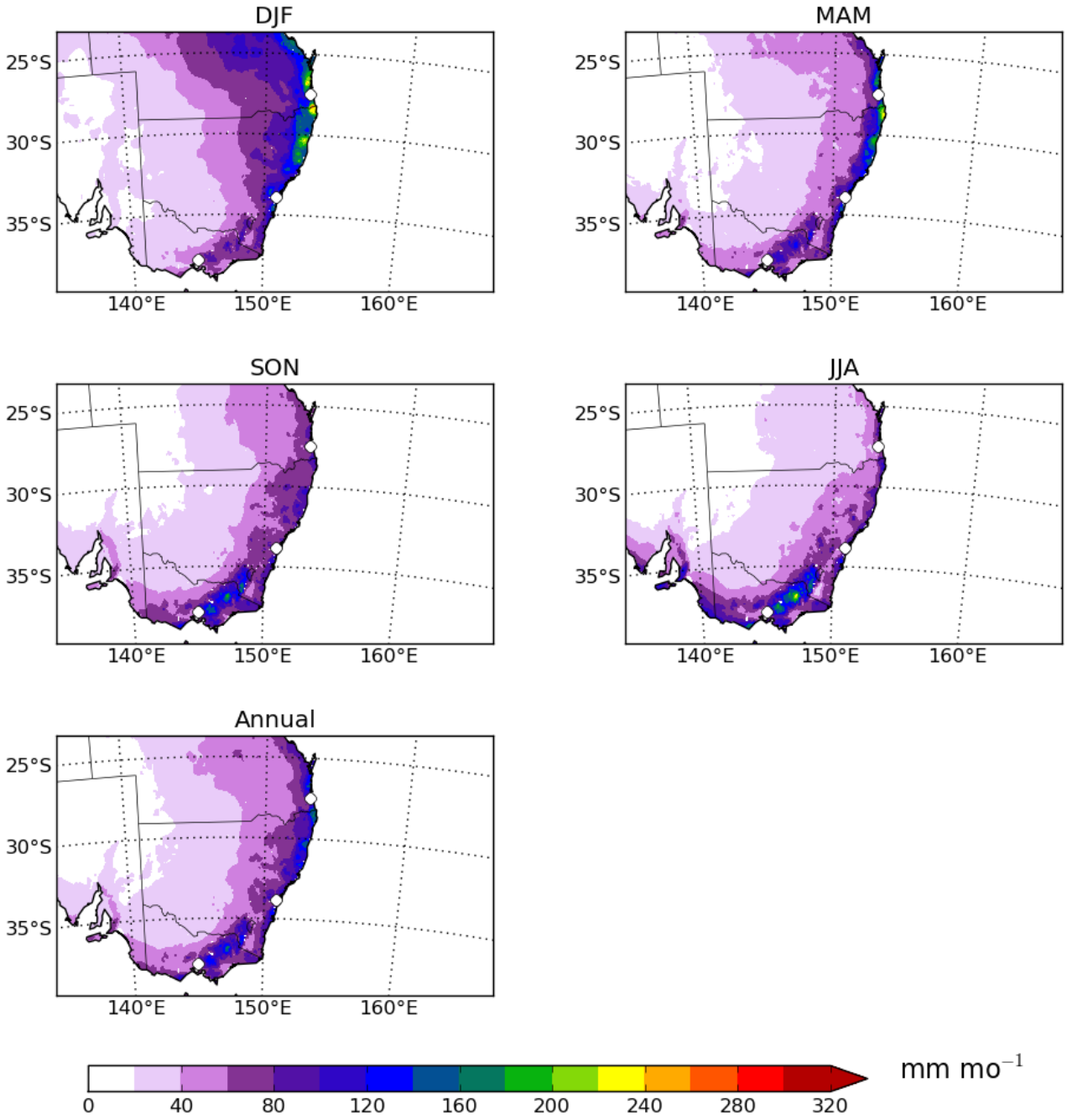

Figure 2.4: Seasonal and annual means of AWAP precipitation for years 1950-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

2.2 Present-Day (1990-2009) AWAP Observations

This subsection contains present-day (1990-2009) seasonal and annual climatologies for AWAP observations of temperature and precipitation. These observations are directly comparable to the output from present-day runs presented in Chapter 4. These observations are also used to perform bias-correction of present, near-future and far-future RCM output.

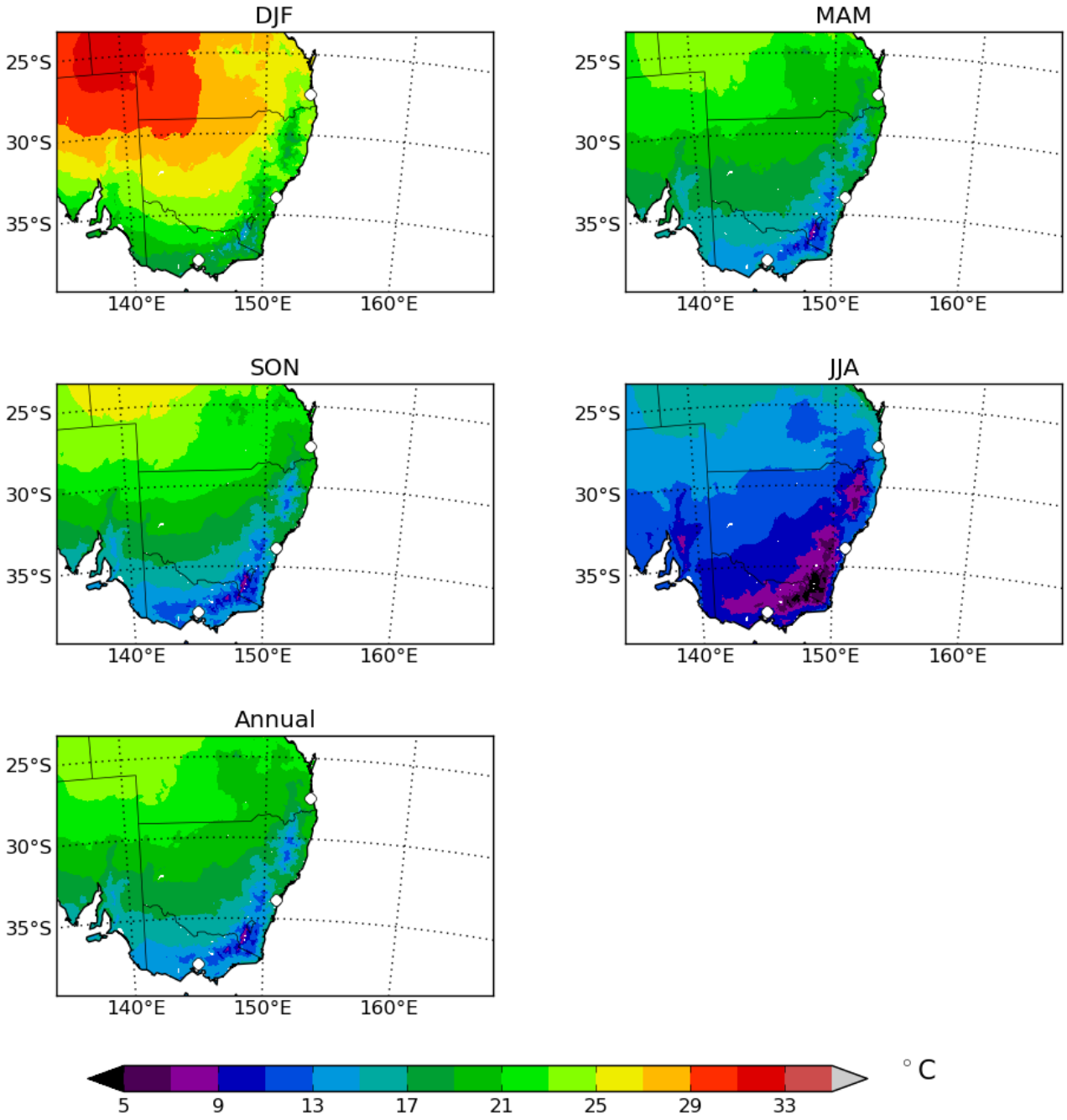

Figure 2.5: Seasonal and annual means of AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

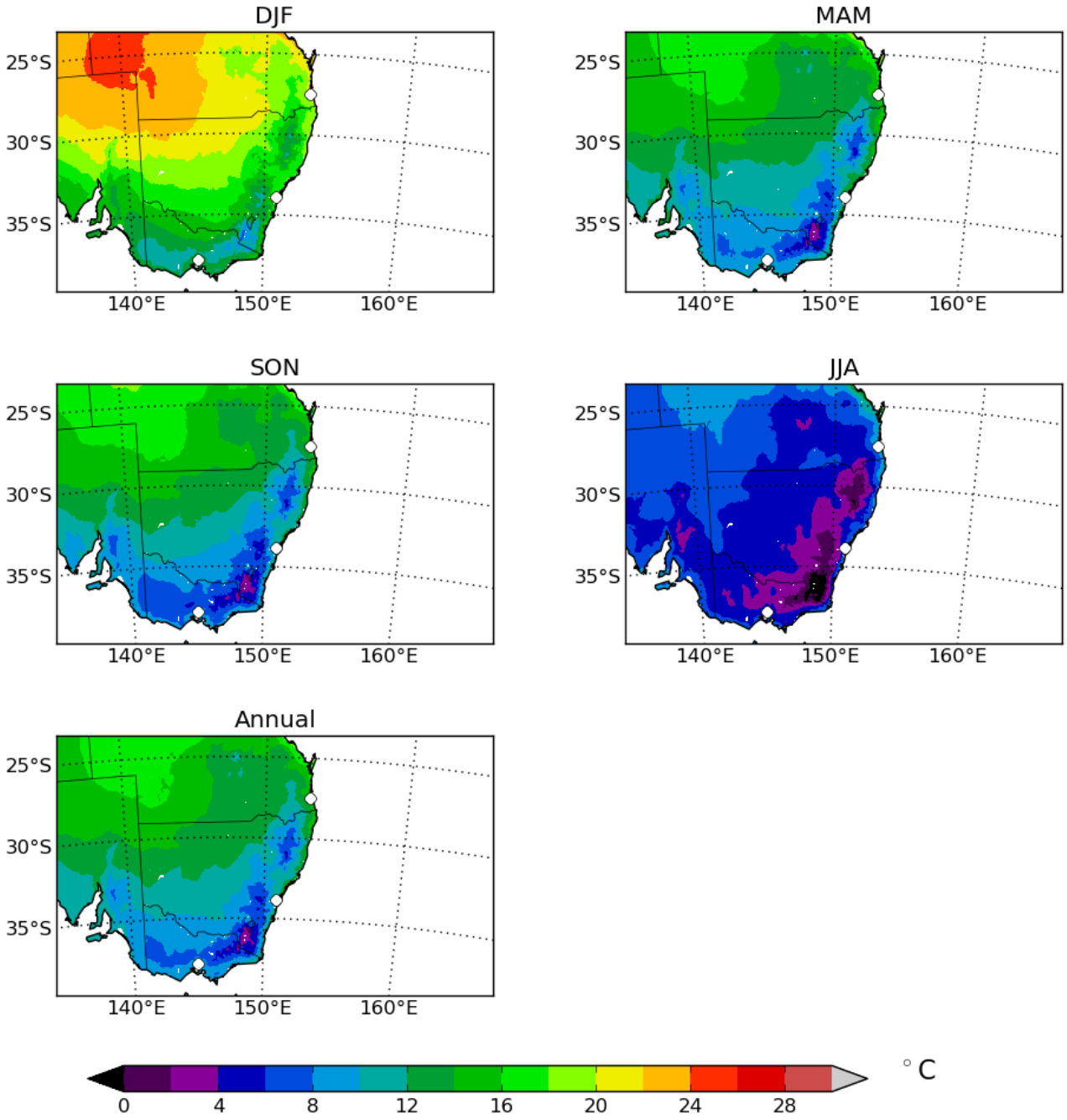

Figure 2.6: Seasonal and annual means of AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

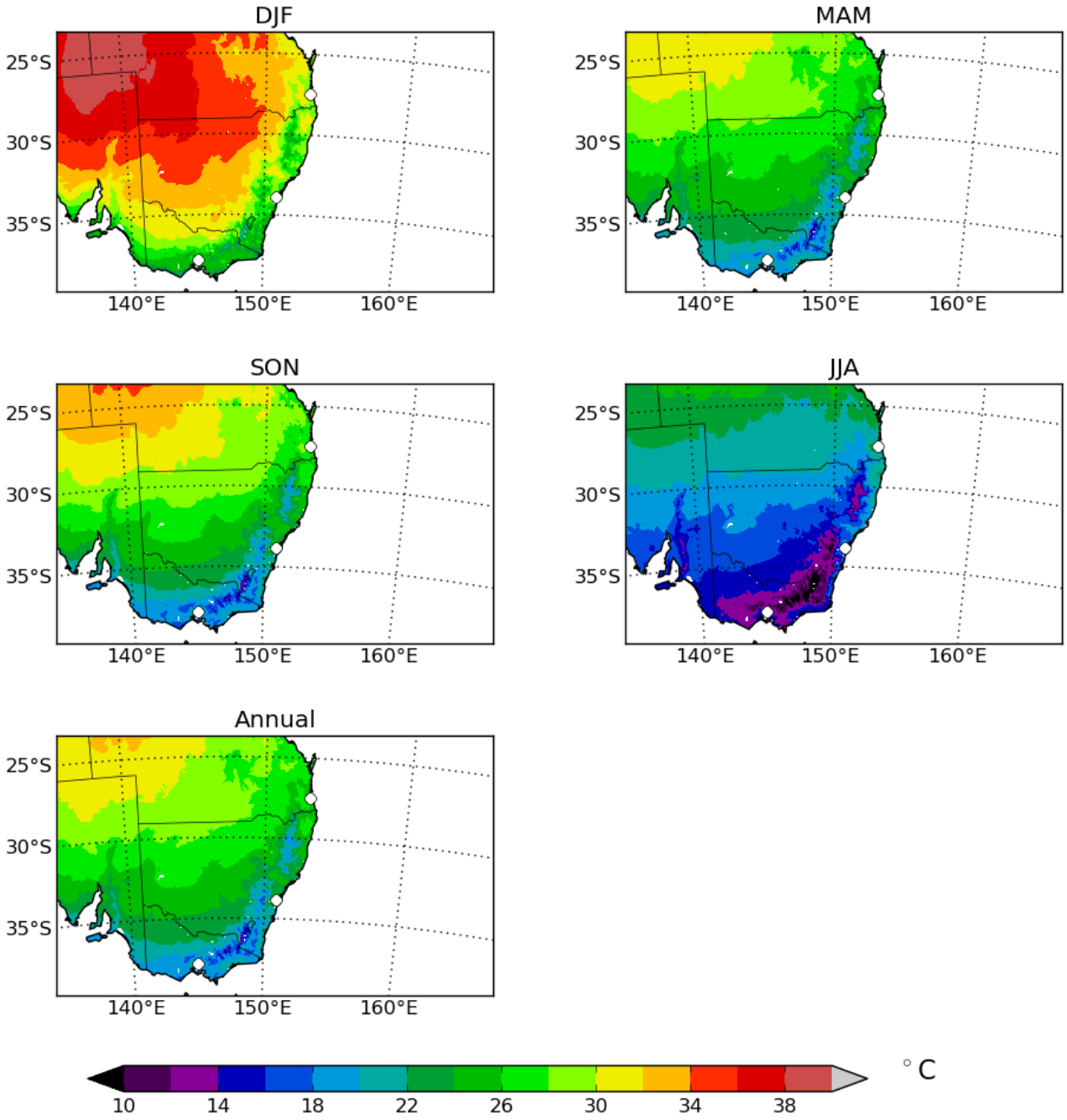

Figure 2.7: Seasonal and annual means of AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

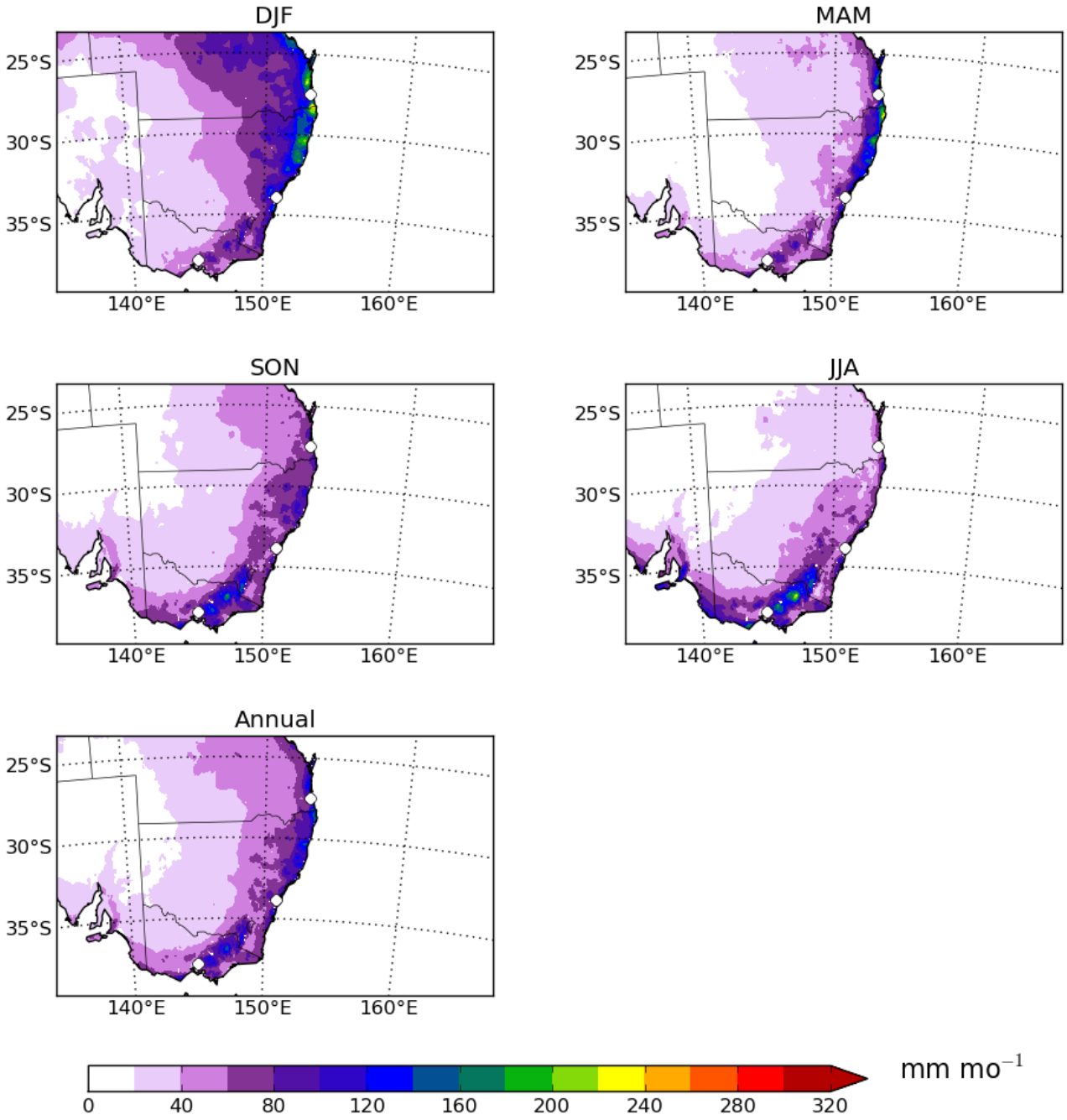

Figure 2.8: Seasonal and annual means of AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 3

Reanalysis Period (1950-2009) Model Climatologies

Here we present results from the NARCliM simulations driven by reanalysis data. Reanalyses are the most complete and closest-to-reality available 3-D description of the atmosphere at any given time. They are estimates of the historical states of the atmospheric system, including regional and large-scale atmospheric features on a three-dimensional grid. They are produced using a combination of a global model and climate observations from sources such as station measurements, satellites and radiosondes. The methodology to derive a reanalysis product for a given period, including the global climate model, and the procedure for blending this climate model with the observations (known as ”data assimilation scheme”), is consistent through the entire period. This makes reanalysis appropriate for long-term studies. Reanalyses are thus regarded as ”perfect boundary conditions” to drive a RCM, and the comparison of a reanalyses-driven RCM simulation with observations allows the isolation of errors coming from the RCM itself. It should be noted however that the amount (and type) of data available for assimilation into the reanalysis changes with time. Hence the quality of the reanalysis improves in more recent decades due largely to improvements in the available satellite data.

The NCEP/NCAR Reanalysis Project 1 (NNRP) [19] was selected to provide boundary conditions for the NARCliM reanalysis runs. The choice of NNRP was mainly based on its remarkable length, which spans over 60 years from 1948 to the present and therefore allows for the representation of modes of inter-decadal variability known to be important for the Australian climate. It also provides a snapshot of the atmosphere every 6 hours (00, 06, 12 and 18 UTC), which is an adequate frequency to capture the diurnal cycle. NNRP uses the T62 NCEP global spectral model (equivalent to a horizontal grid spacing of $\sim$ 210km) with 28 sigma vertical levels and uses a three-dimensional variational data assimilation scheme consisting of a spectral statistical interpolation system.

Subsequent sections present climatological seasonal and annual means for near-surface air temperature and precipitation from the reanalysis runs. We first show original RCM output, and then bias-corrected RCM output. The bias-corrected RCM output is the RCM output corrected for climatology period (1961-1990) biases between the models and the observations.

3.1 1950-2009 Regional Model Output

This subsection contains climatologies for reanalysis period (1950-2009) for near-surface air temperature, daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the original RCM output. We note that these RCM runs were driven by NNRP reanalysis [19]; as opposed to present, near-future, and far-future runs, which were all driven by GCM output. Thus, these runs aim to capture the actual observed course of internal climate variability and weather patterns. The results are presented as seasonal and annual mean climatologies for each model and variable.

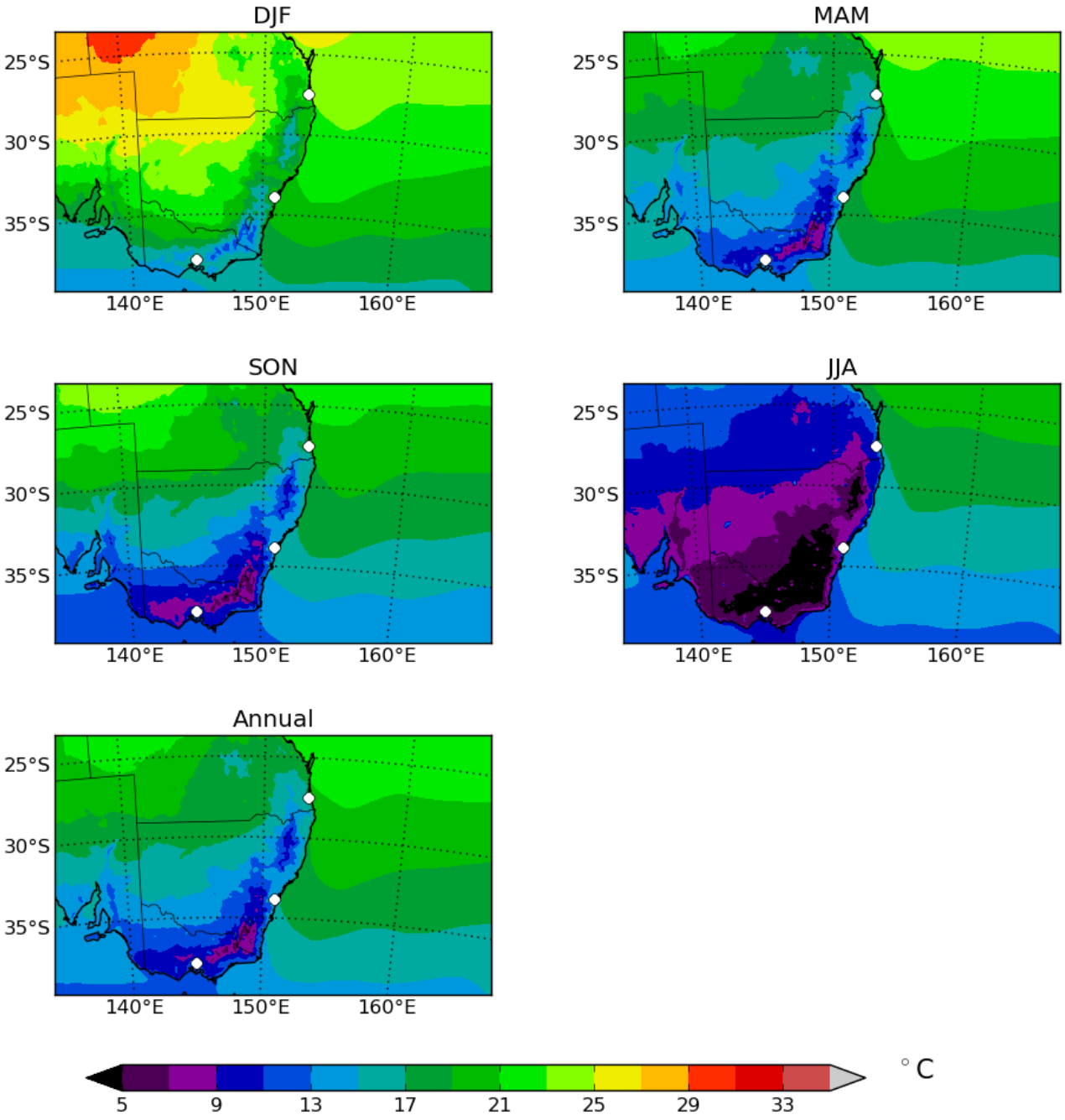

Figure 3.1: Seasonal and annual means of NNRP R1 near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

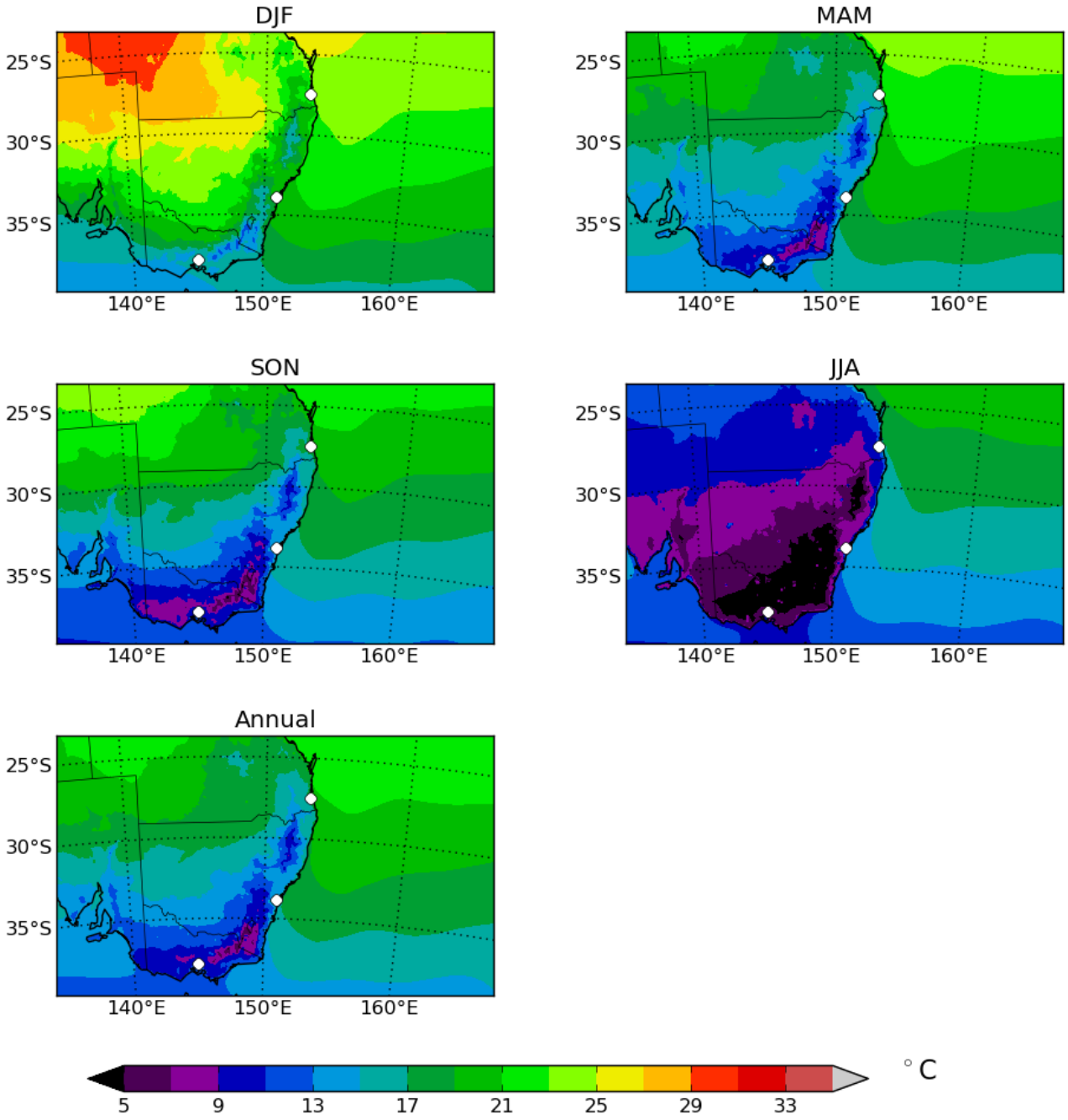

Figure 3.2: Seasonal and annual means of NNRP R2 near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

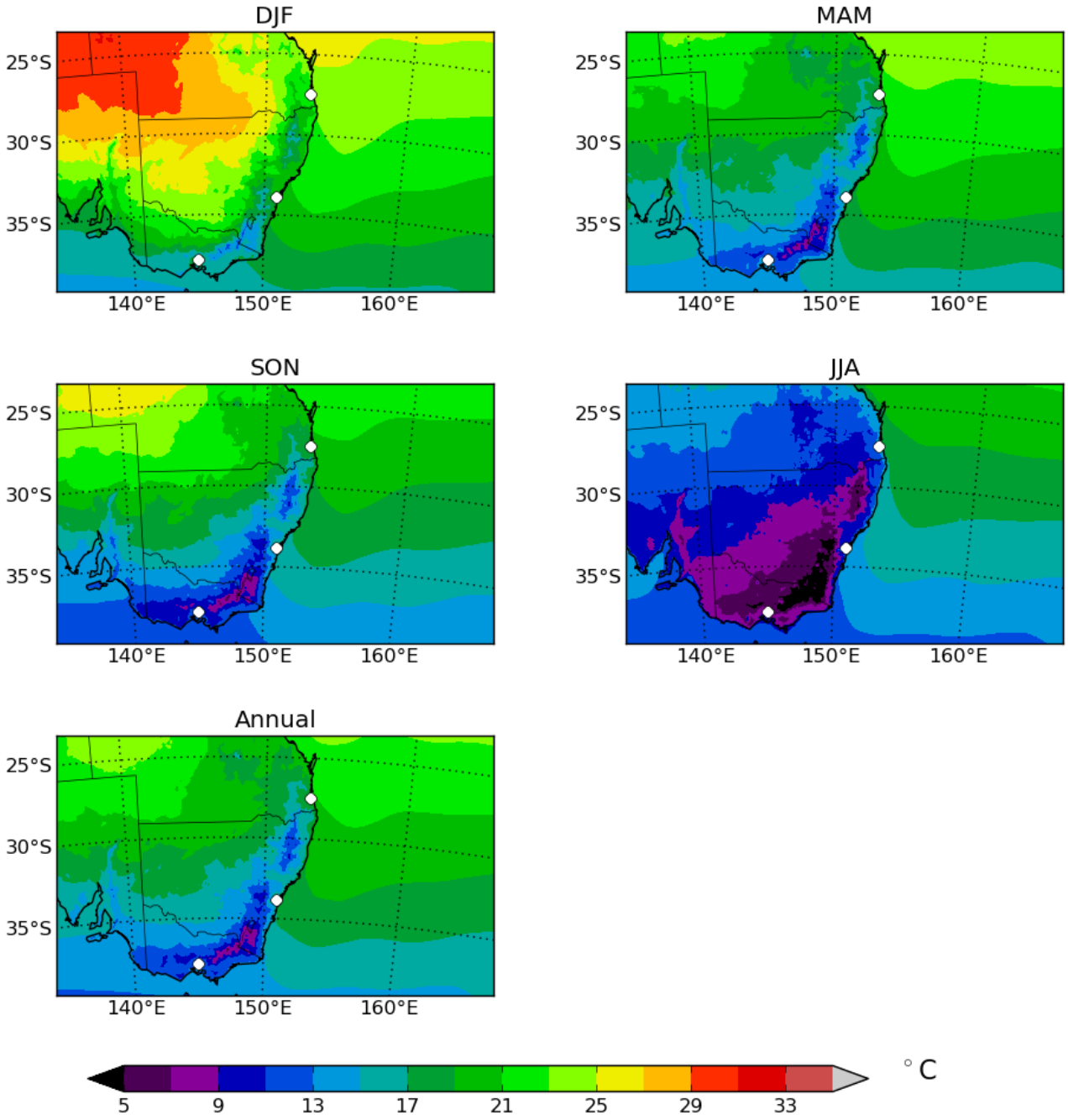

Figure 3.3: Seasonal and annual means of NNRP R3 near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

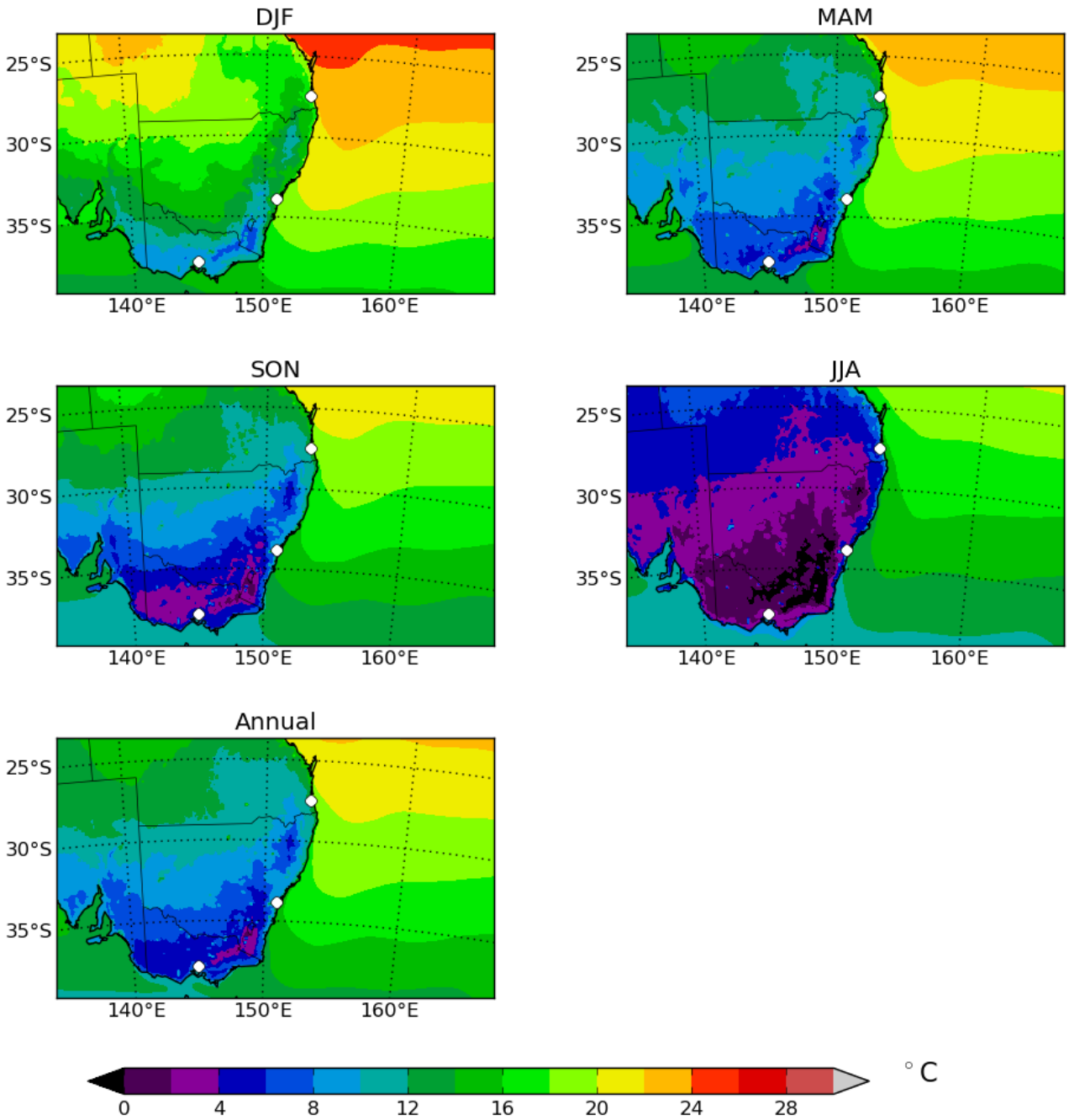

Figure 3.4: Seasonal and annual means of NNRP R1 daily minimum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

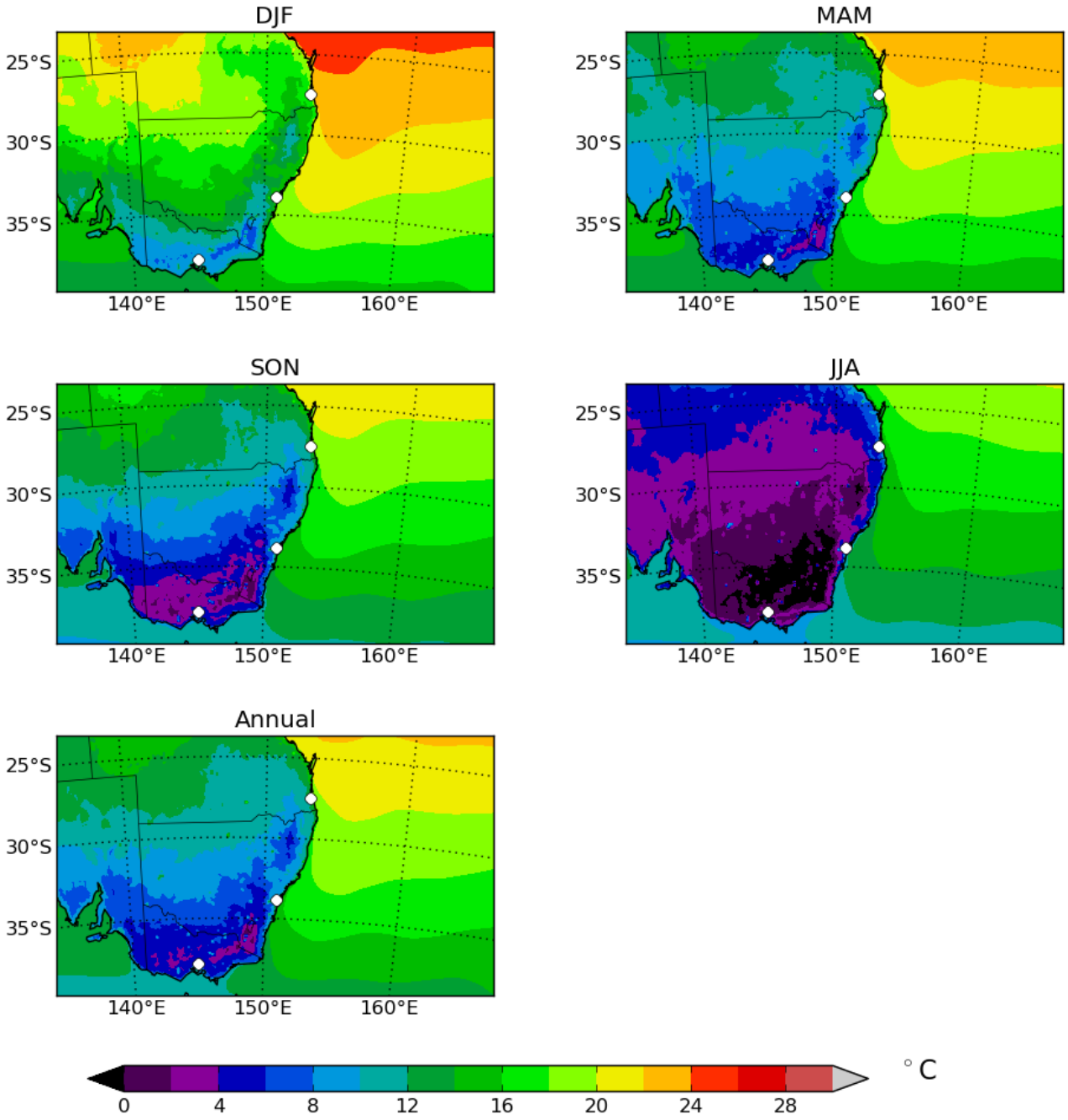

Figure 3.5: Seasonal and annual means of NNRP R2 daily minimum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

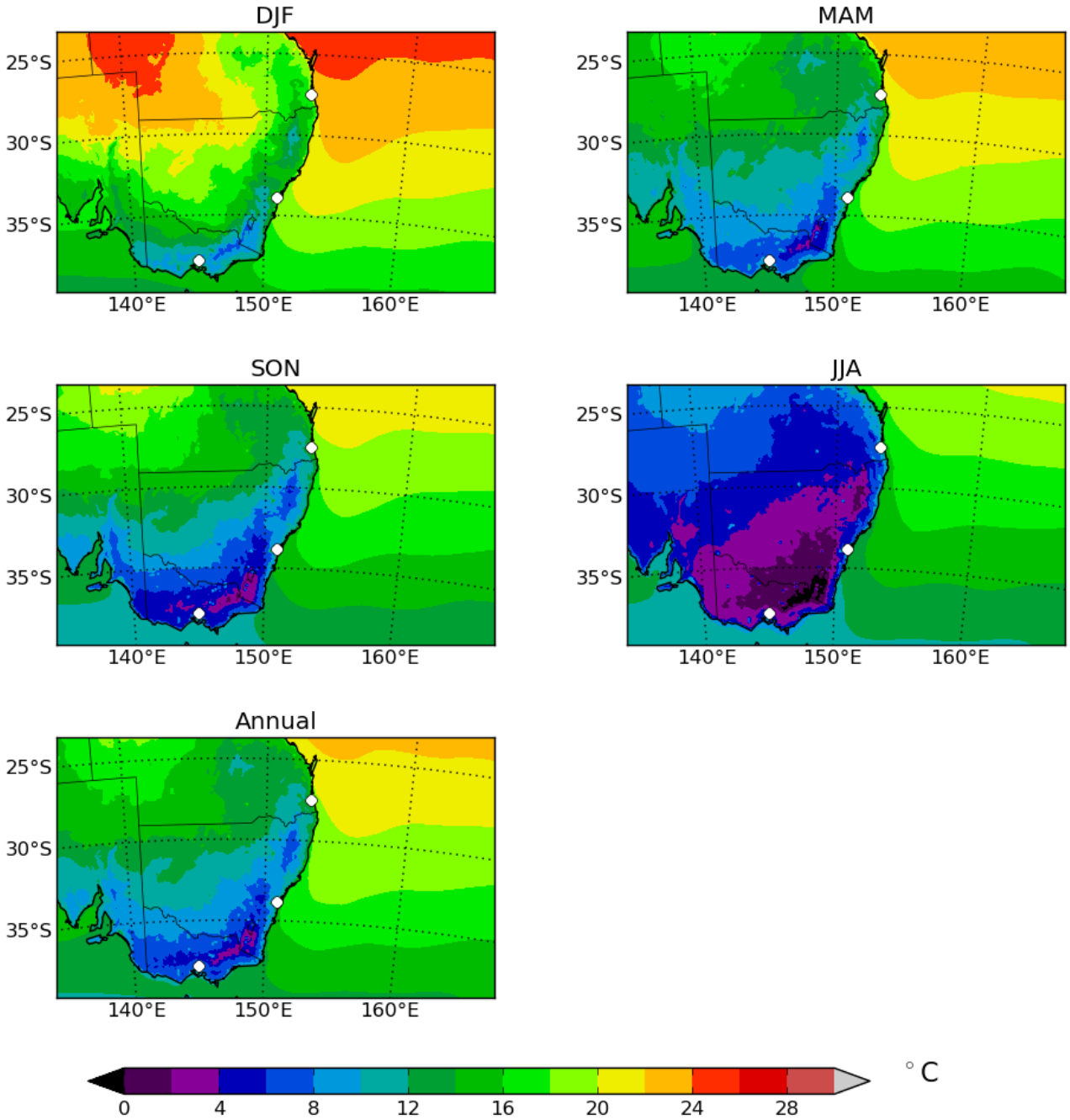

Figure 3.6: Seasonal and annual means of NNRP R3 daily minimum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

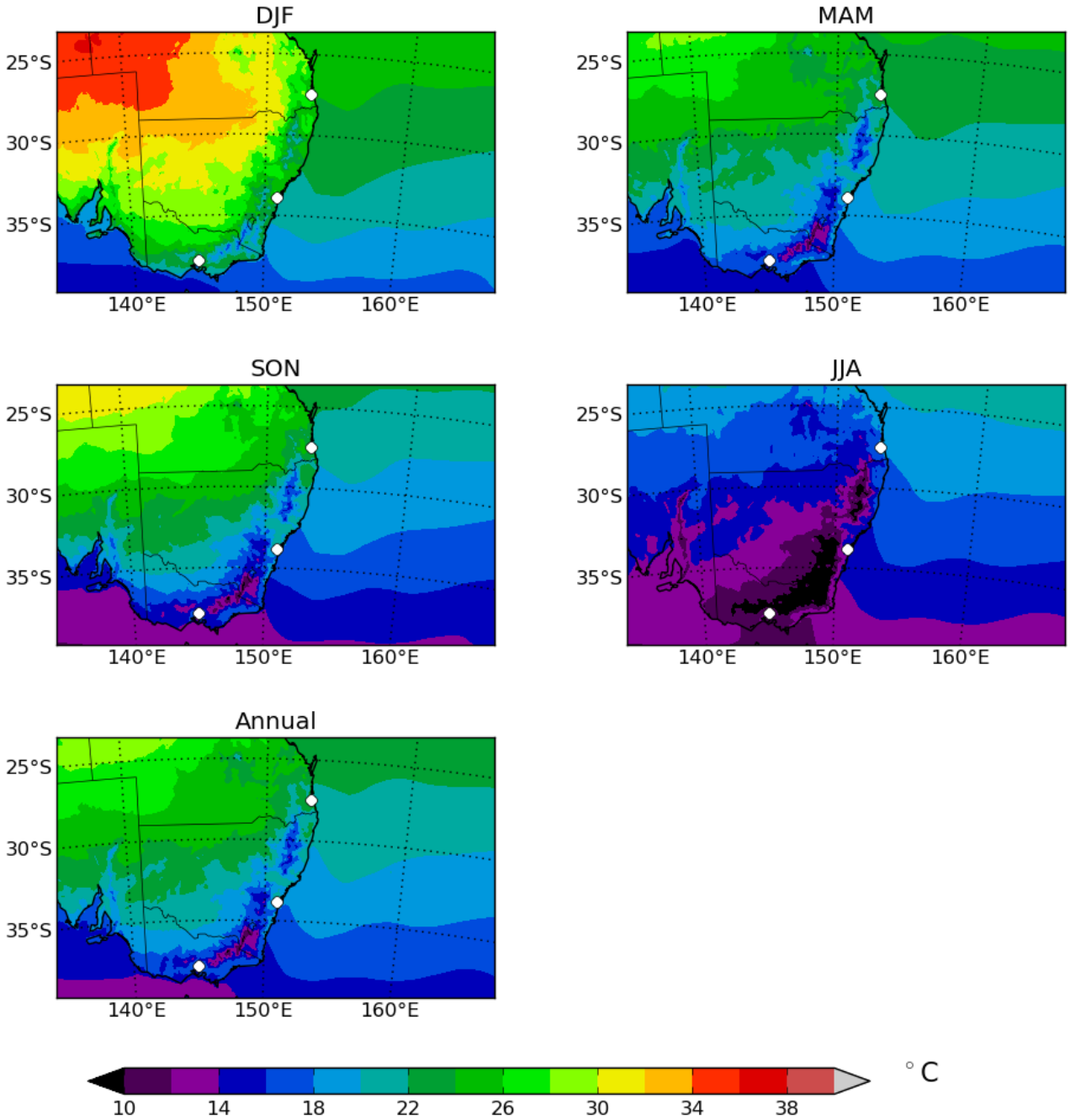

Figure 3.7: Seasonal and annual means of NNRP R1 daily maximum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

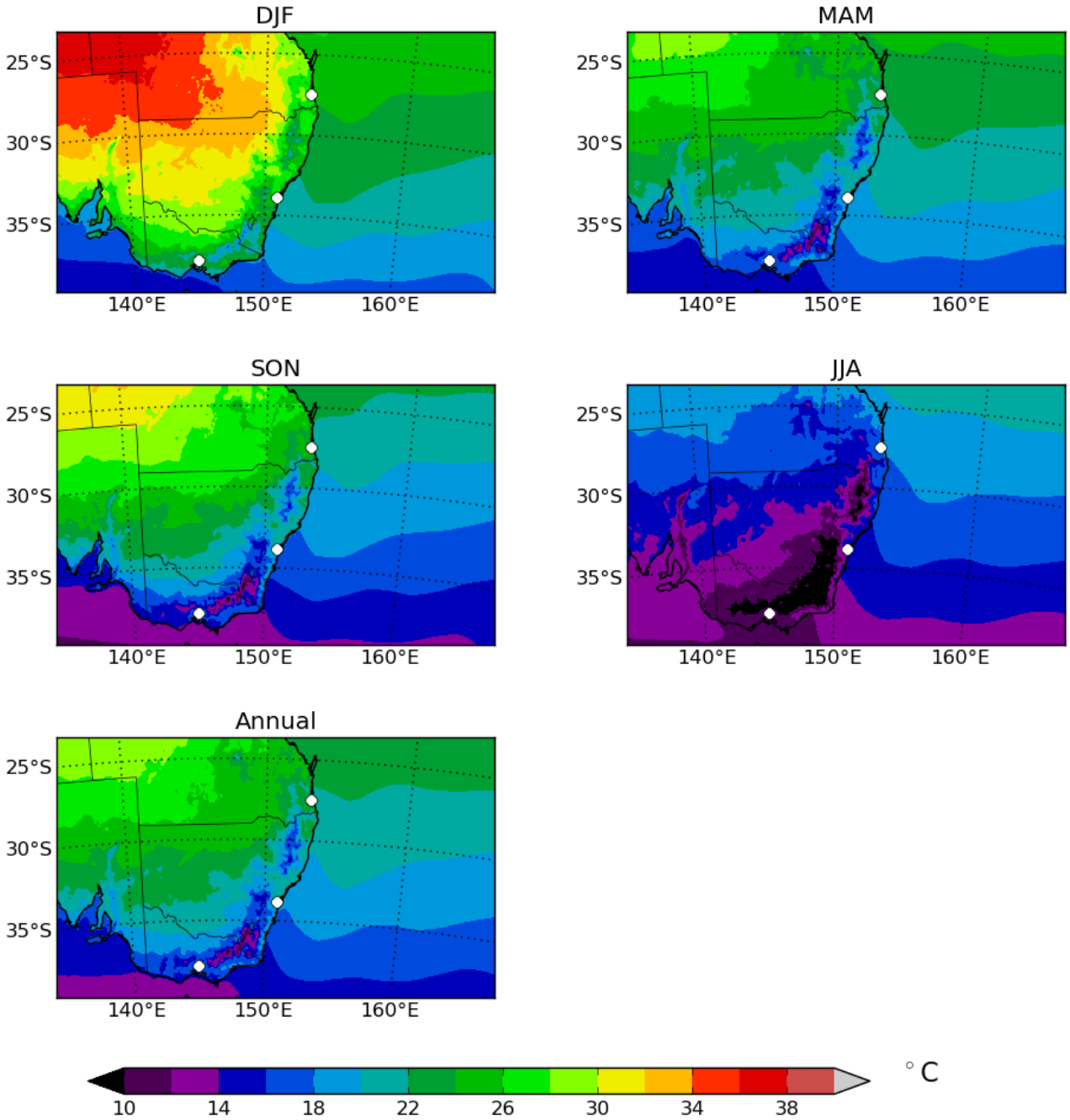

Figure 3.8: Seasonal and annual means of NNRP R2 daily maximum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

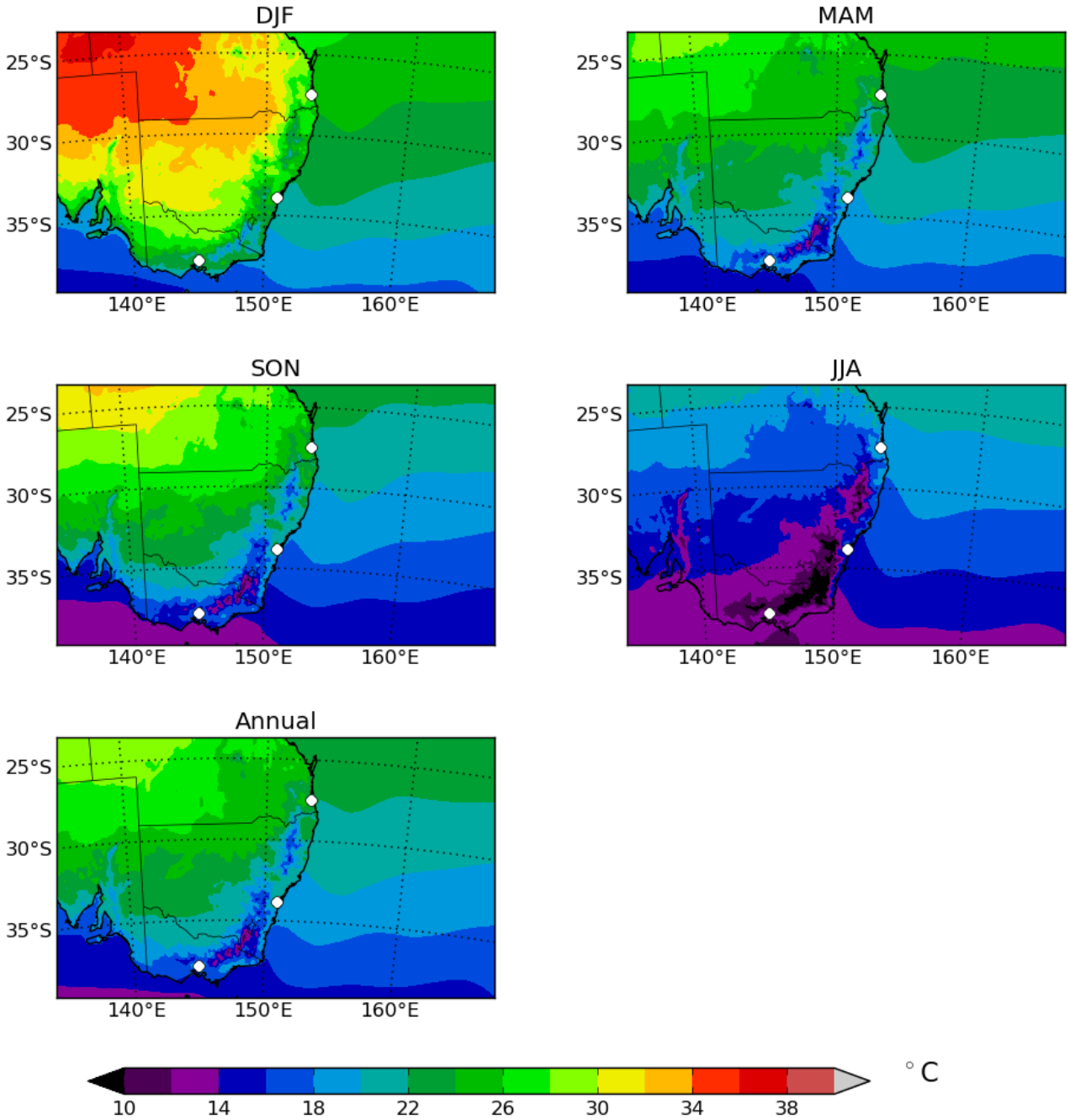

Figure 3.9: Seasonal and annual means of NNRP R3 daily maximum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

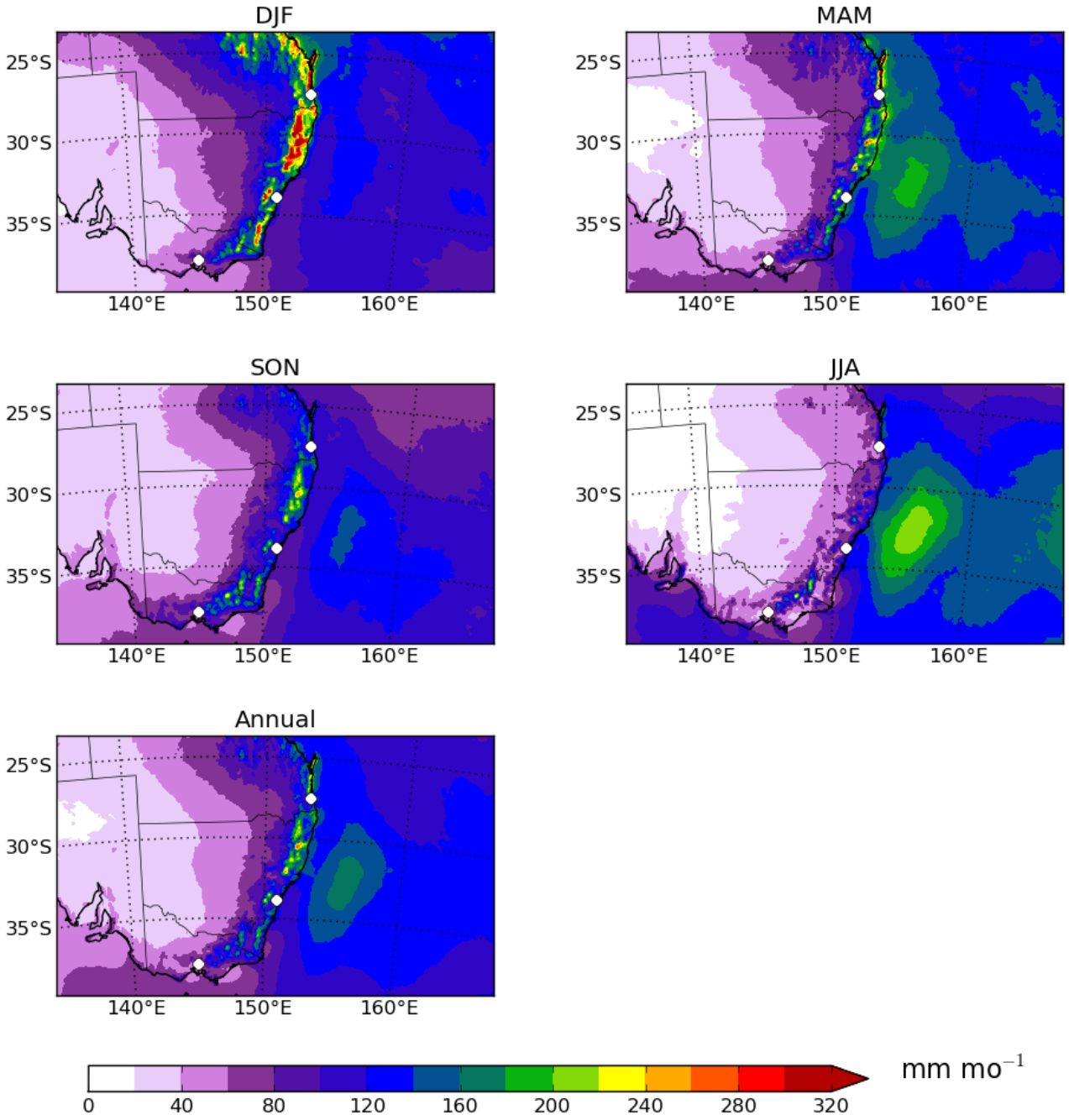

Figure 3.10: Seasonal and annual means of NNRP R1 precipitation for years 1950-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

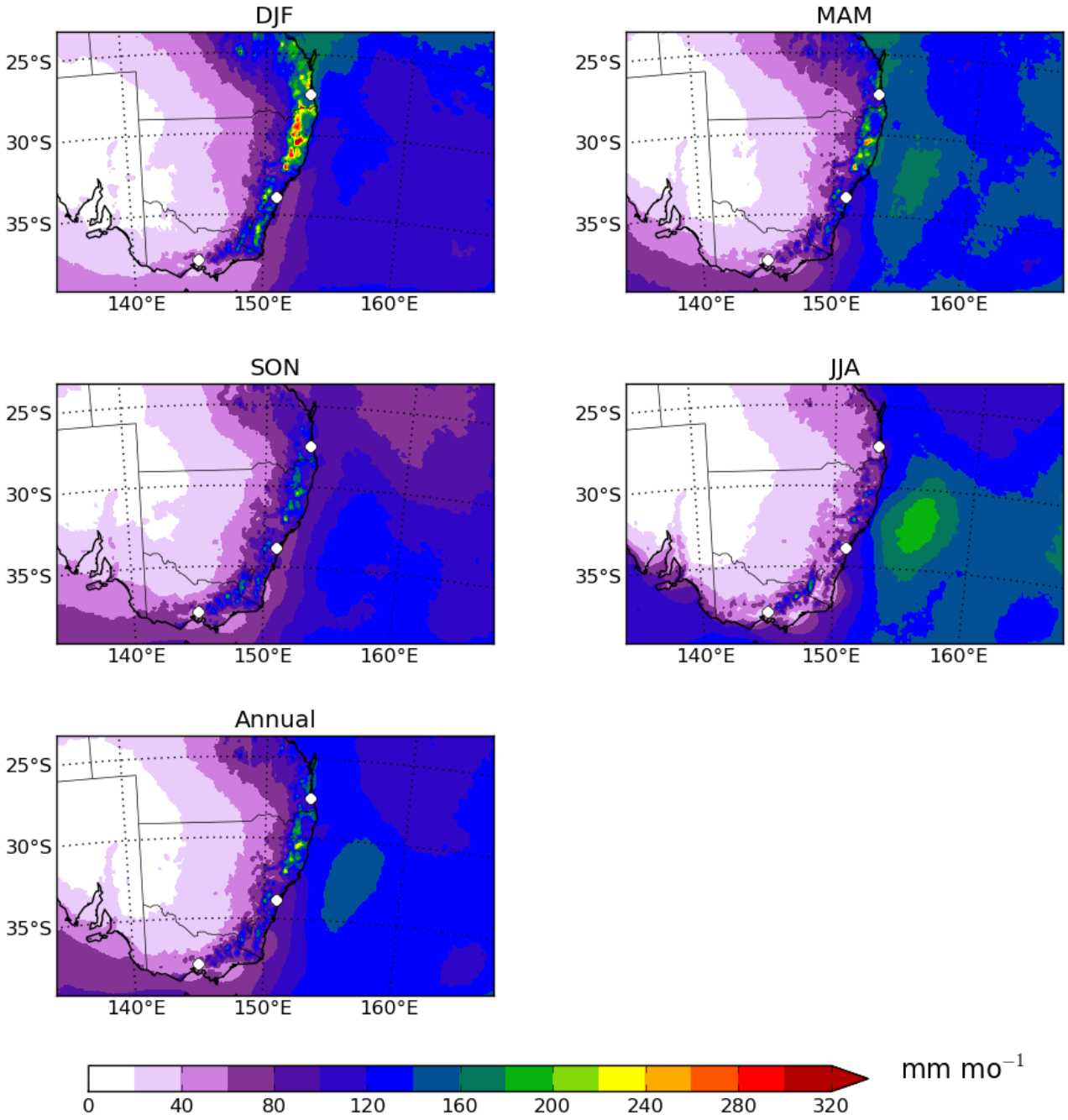

Figure 3.11: Seasonal and annual means of NNRP R2 precipitation for years 1950-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

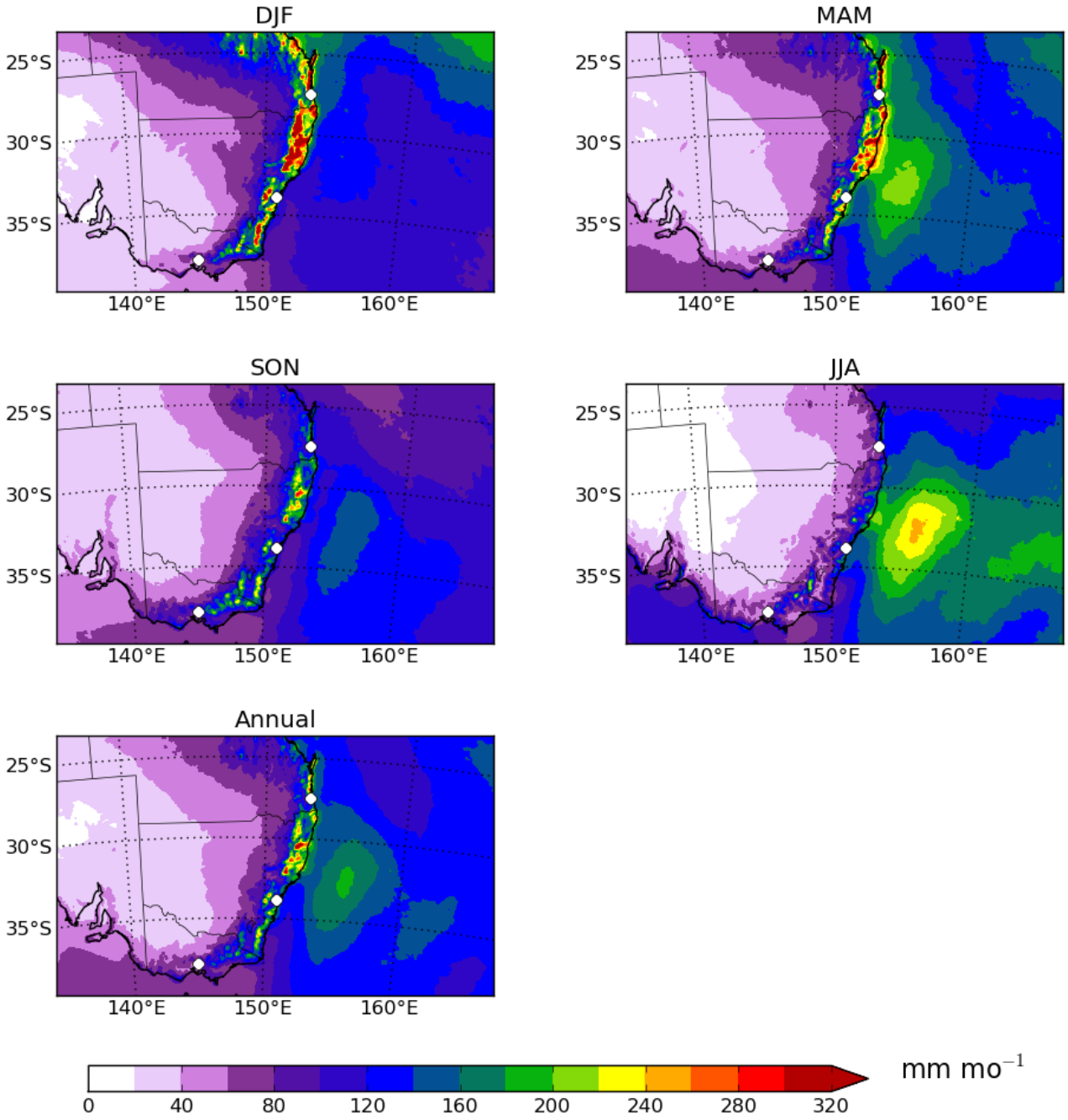

Figure 3.12: Seasonal and annual means of NNRP R3 precipitation for years 1950-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

3.2 1950-2009 Bias-Corrected Regional Model Output

This subsection contains climatologies for reanalysis period (1950-2009) for daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the bias-corrected RCM output (*i.e.* RCM output that has been corrected for the biases between the models and the observations of climate for years 1961-1990 using the methods described here [6]). The corrections are calculated by comparing distributions of daily model output and observations for all seasons. Thus, the corrections are independent of the season. We note that these RCM runs were driven by NNRP reanalysis [19]; as opposed to present, near-future, and far-future runs, which were all driven by GCM output. Thus, these runs aim to capture the actual observed course of internal climate variability and weather patterns. The results are presented as seasonal and annual mean climatologies for each model and variable.

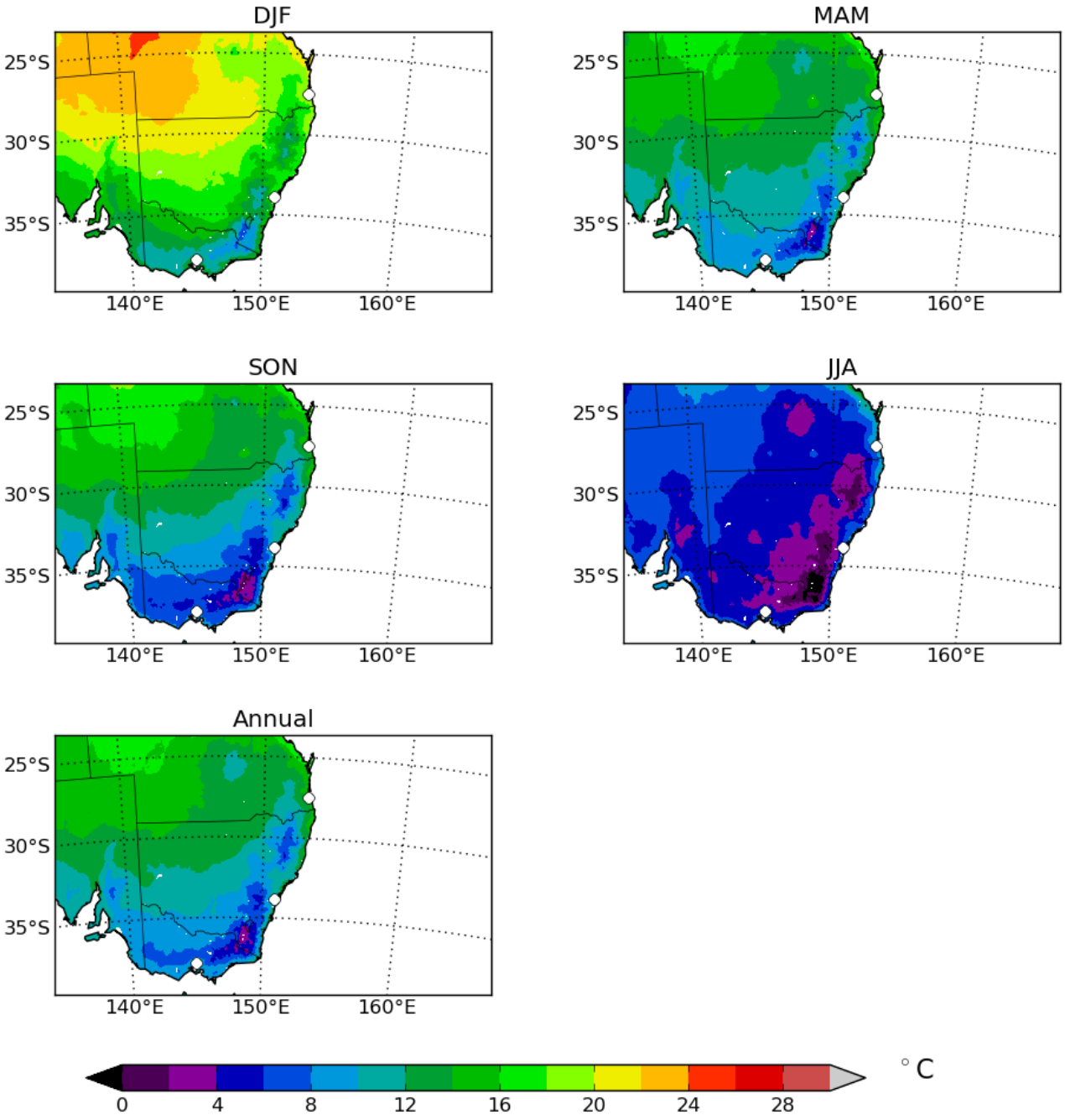

Figure 3.13: Seasonal and annual means of NNRP R1 bias-corrected daily minimum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

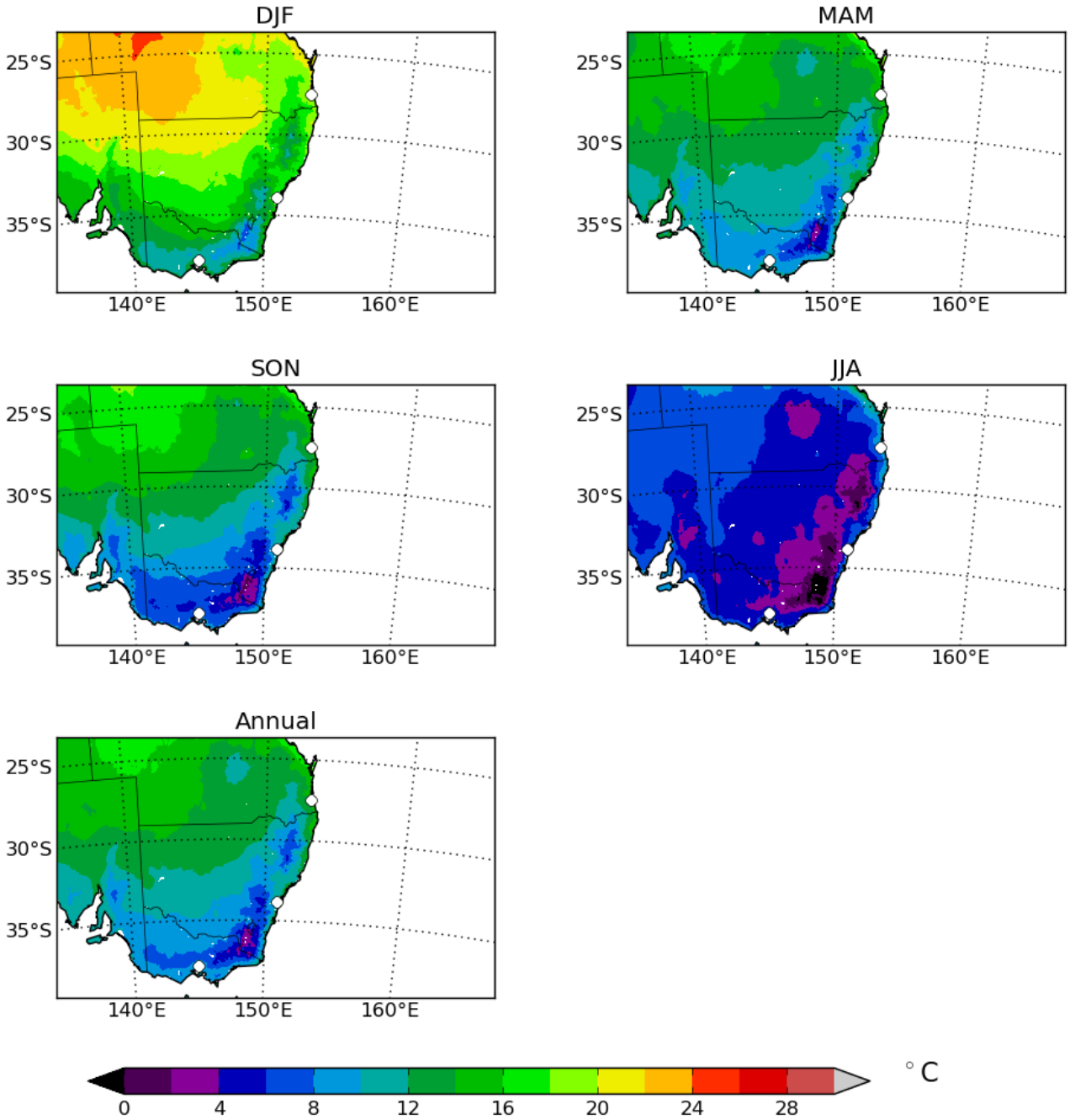

Figure 3.14: Seasonal and annual means of NNRP R2 bias-corrected daily minimum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

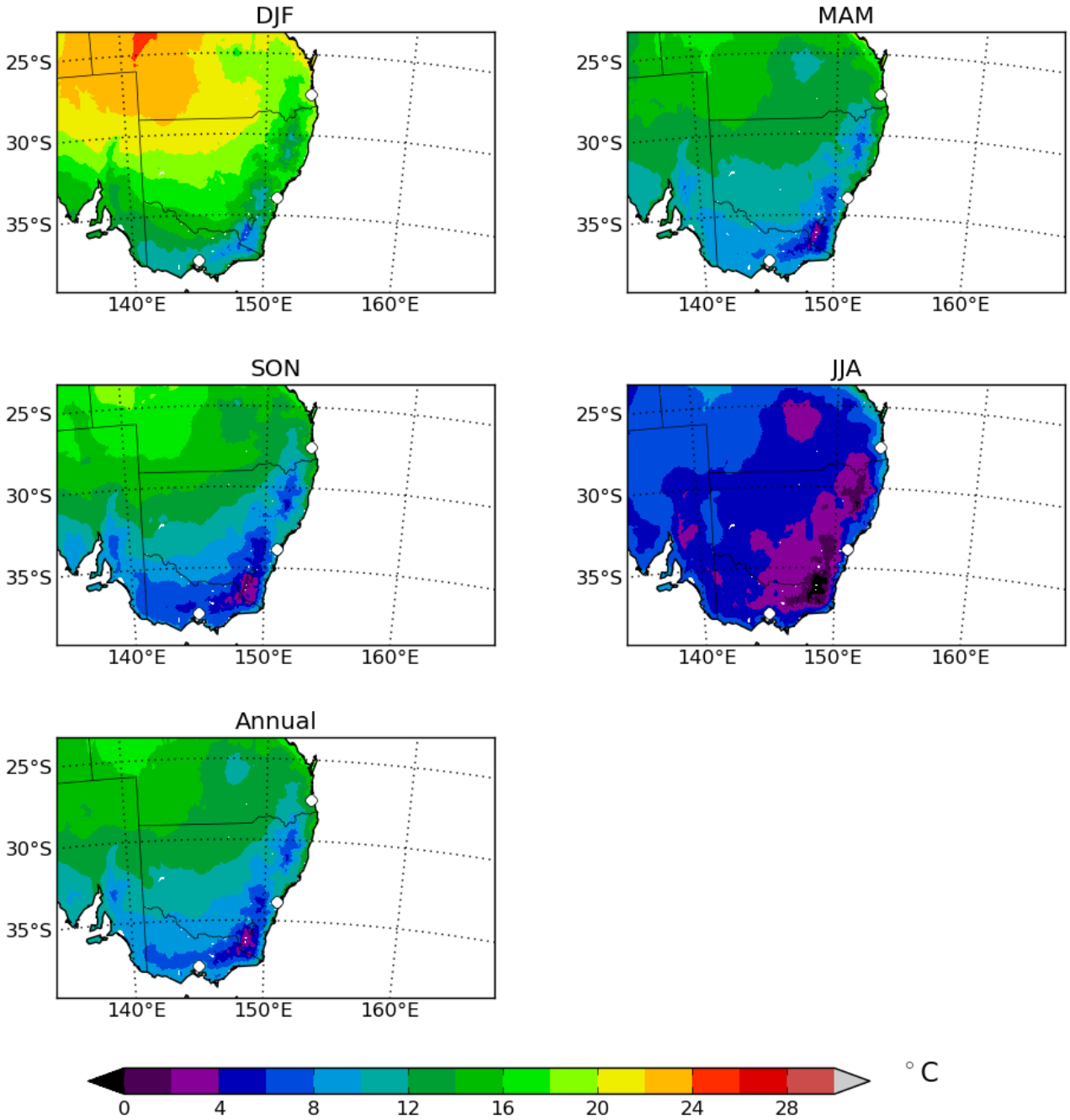

Figure 3.15: Seasonal and annual means of NNRP R3 bias-corrected daily minimum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

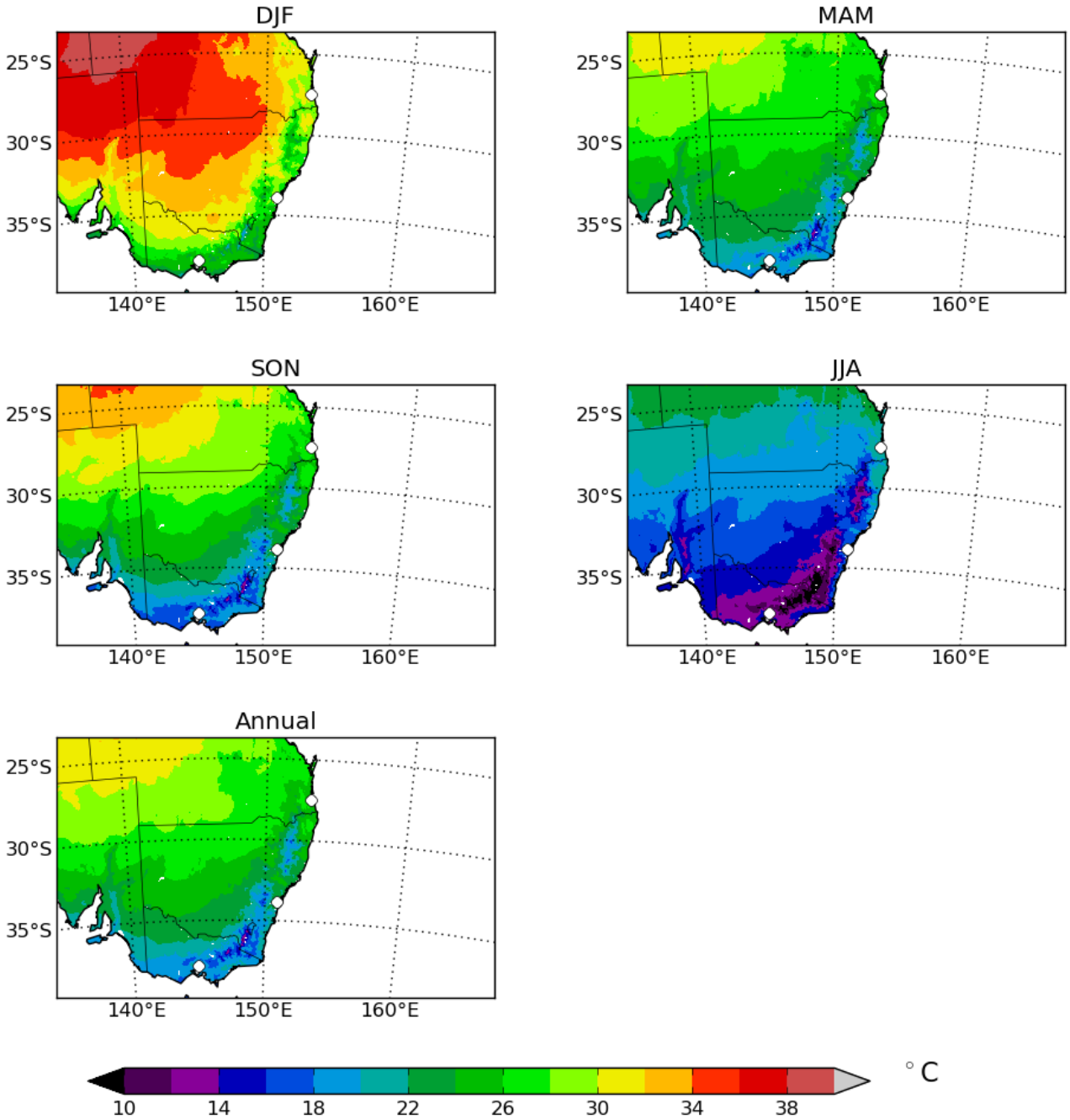

Figure 3.16: Seasonal and annual means of NNRP R1 bias-corrected daily maximum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

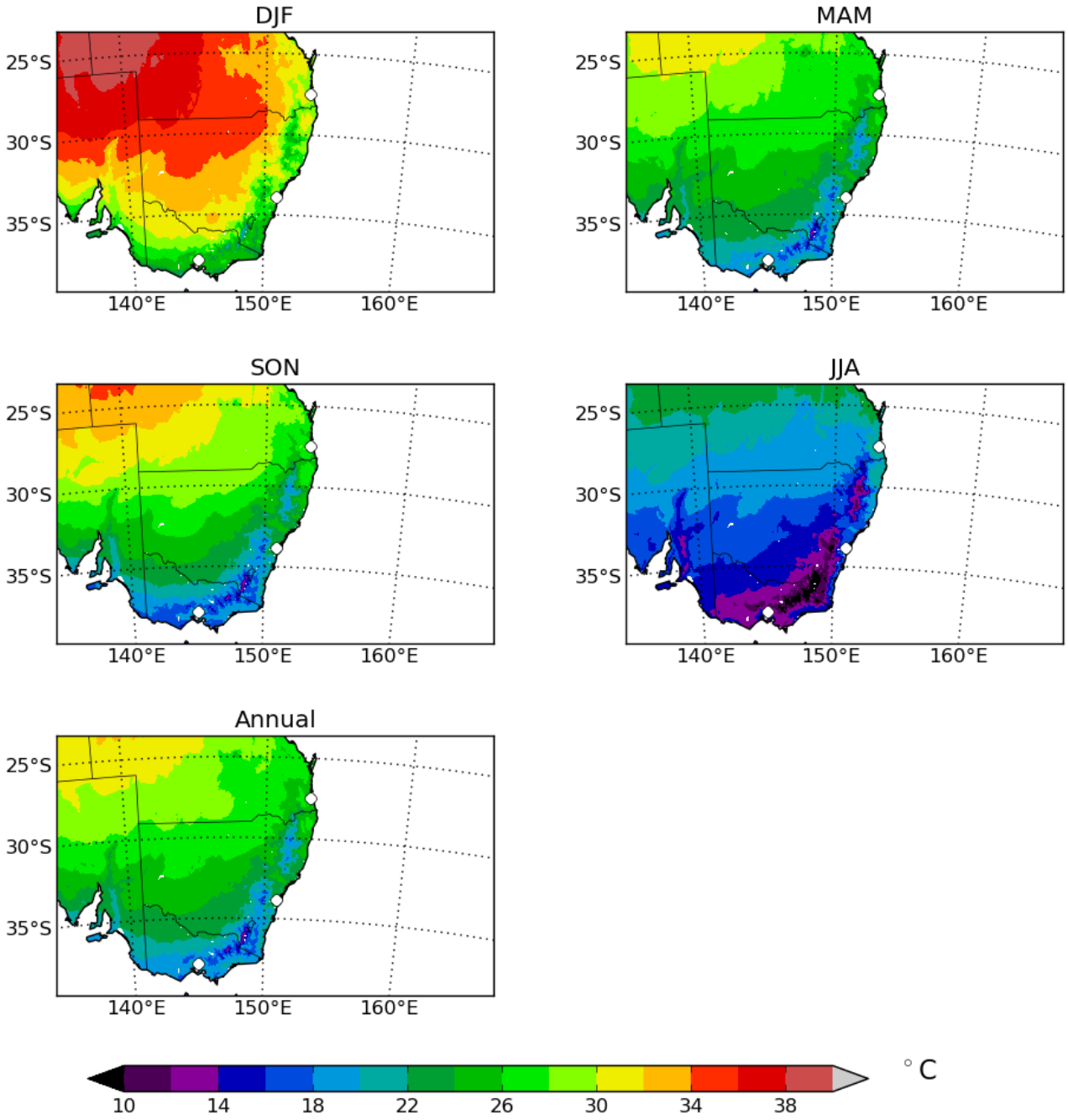

Figure 3.17: Seasonal and annual means of NNRP R2 bias-corrected daily maximum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

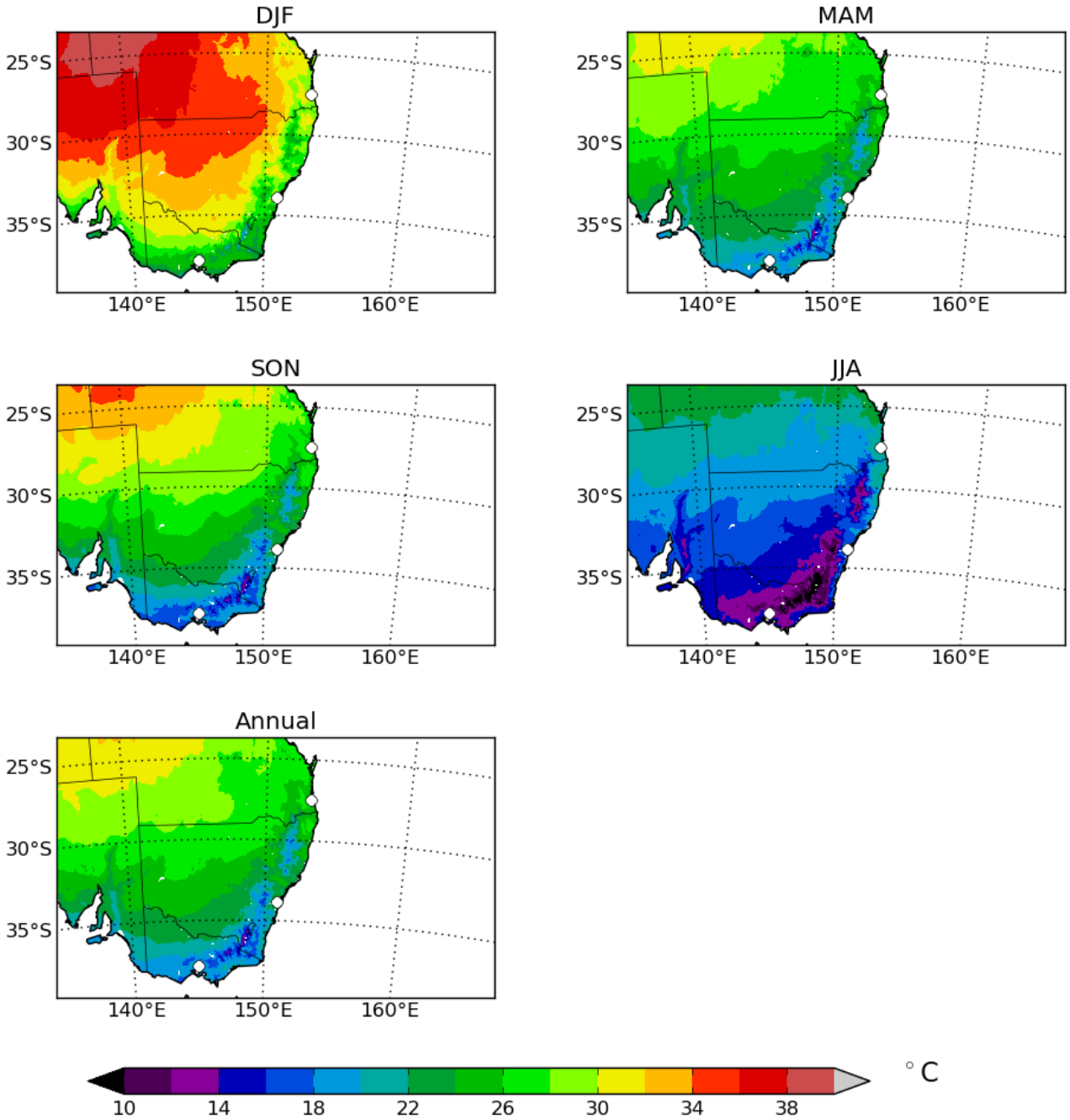

Figure 3.18: Seasonal and annual means of NNRP R3 bias-corrected daily maximum near-surface air temperature for years 1950-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

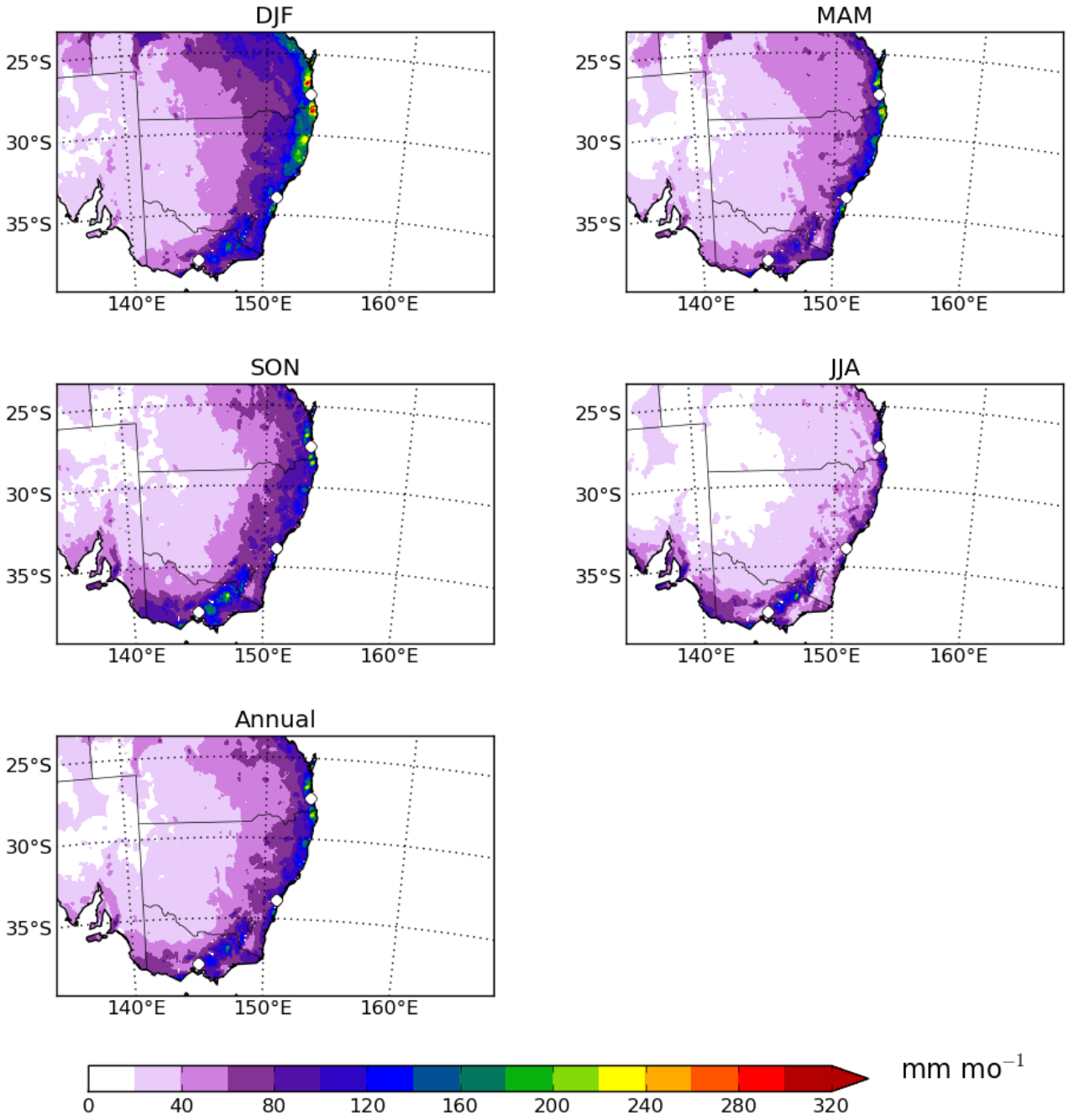

Figure 3.19: Seasonal and annual means of NNRP R1 bias-corrected precipitation for years 1950-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

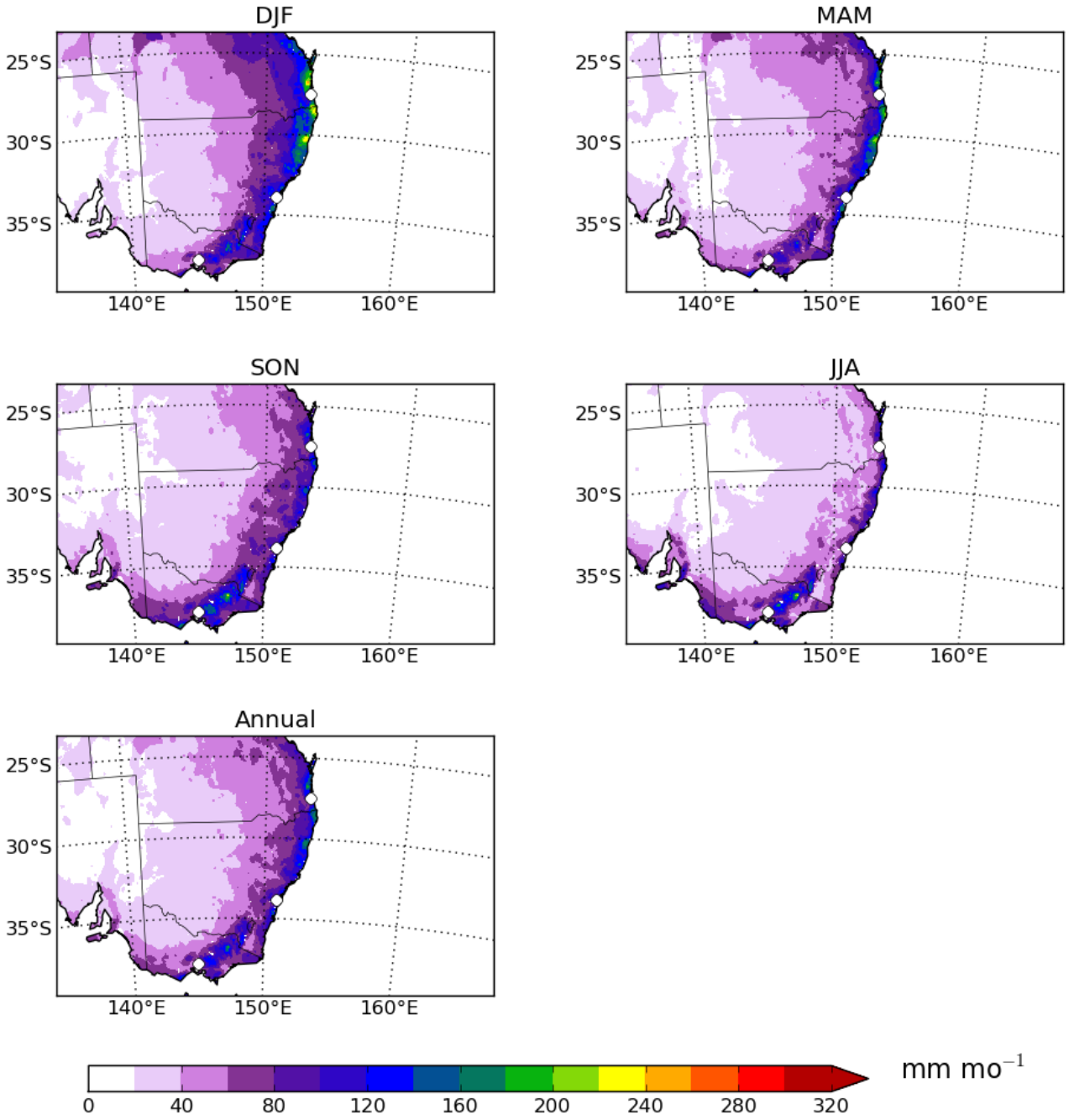

Figure 3.20: Seasonal and annual means of NNRP R2 bias-corrected precipitation for years 1950-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

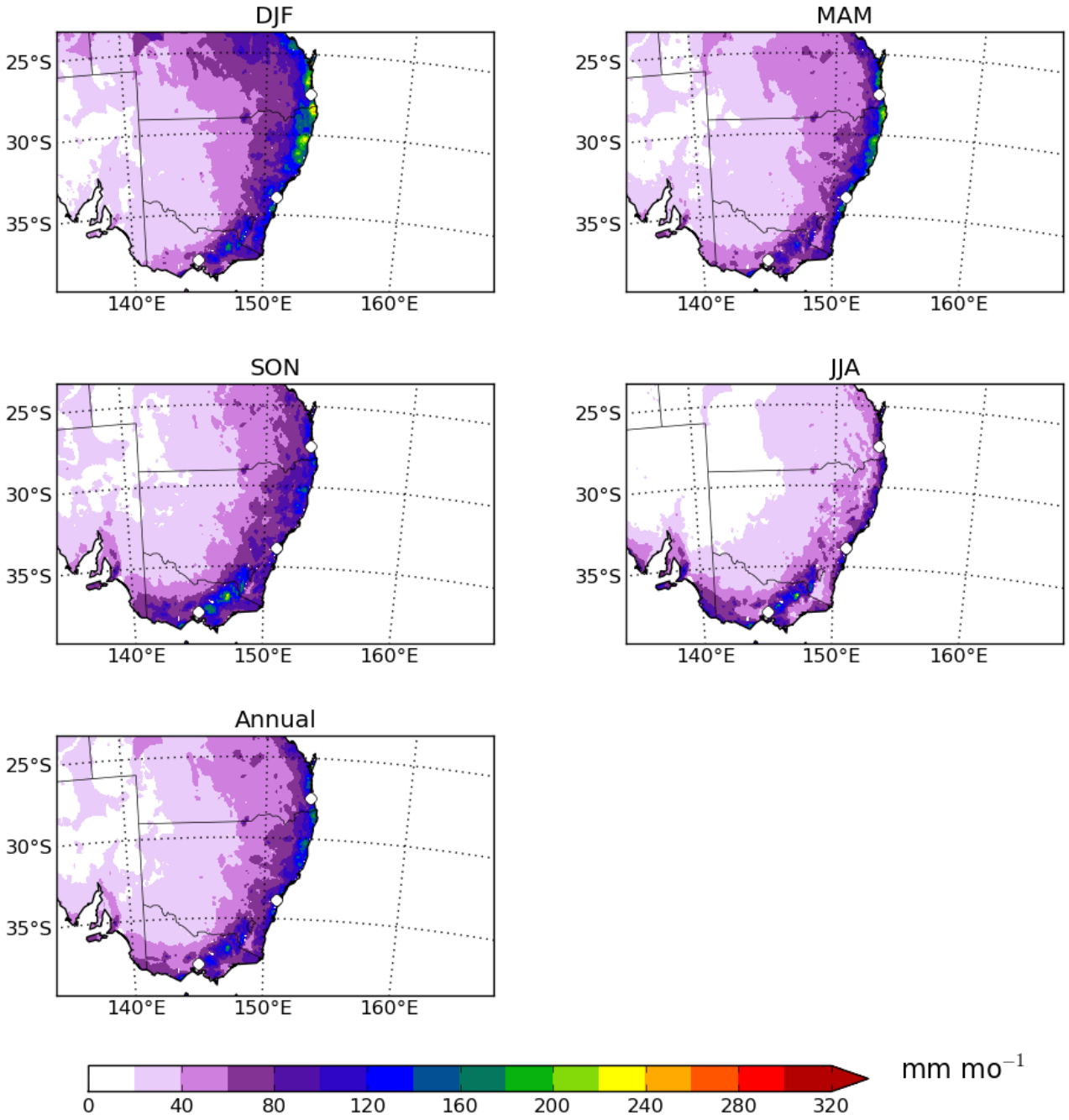

Figure 3.21: Seasonal and annual means of NNRP R3 bias-corrected precipitation for years 1950-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 4

Present Day (1990-2009) Model Climatologies

This chapter contains the climatological seasonal and annual means for present-day near-surface air temperature and precipitation. We first show the results for the GCMs used to drive the RCMs, then for original RCM output, and finally for bias-corrected RCM output. The bias-corrected RCM output is the RCM output corrected for biases between the models and the observations using the methods described here [6].

4.1 1990-2009 Driving GCMs

This subsection contains climatologies for present-day near-surface air temperature and precipitation from each of the GCMs used to provide boundary conditions to the RCMs. The plots are ordered first by GCM, and then by variable.

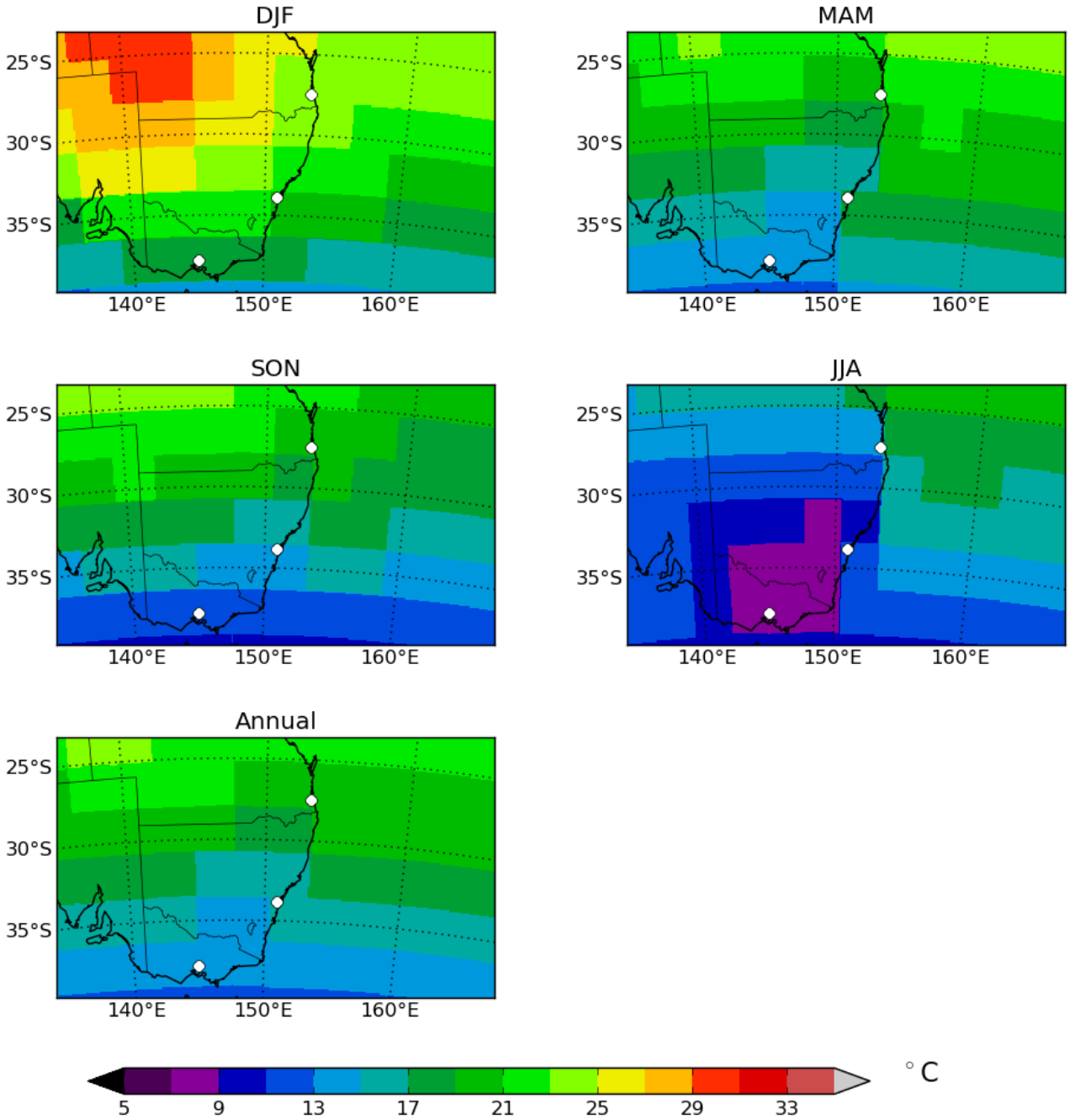

Figure 4.1: Seasonal and annual means of MIROC3.2 near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

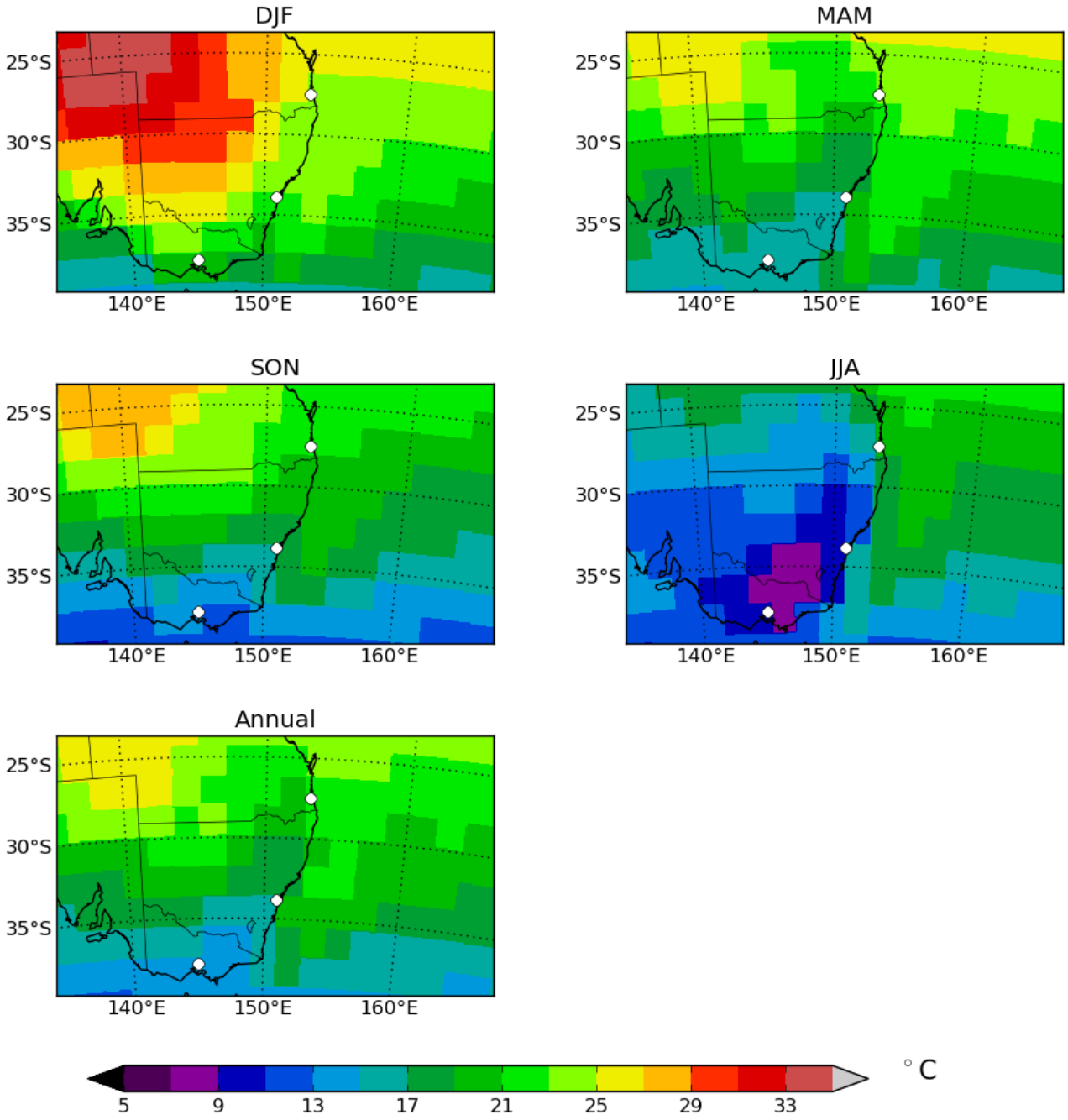

Figure 4.2: Seasonal and annual means of ECHAM5 near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

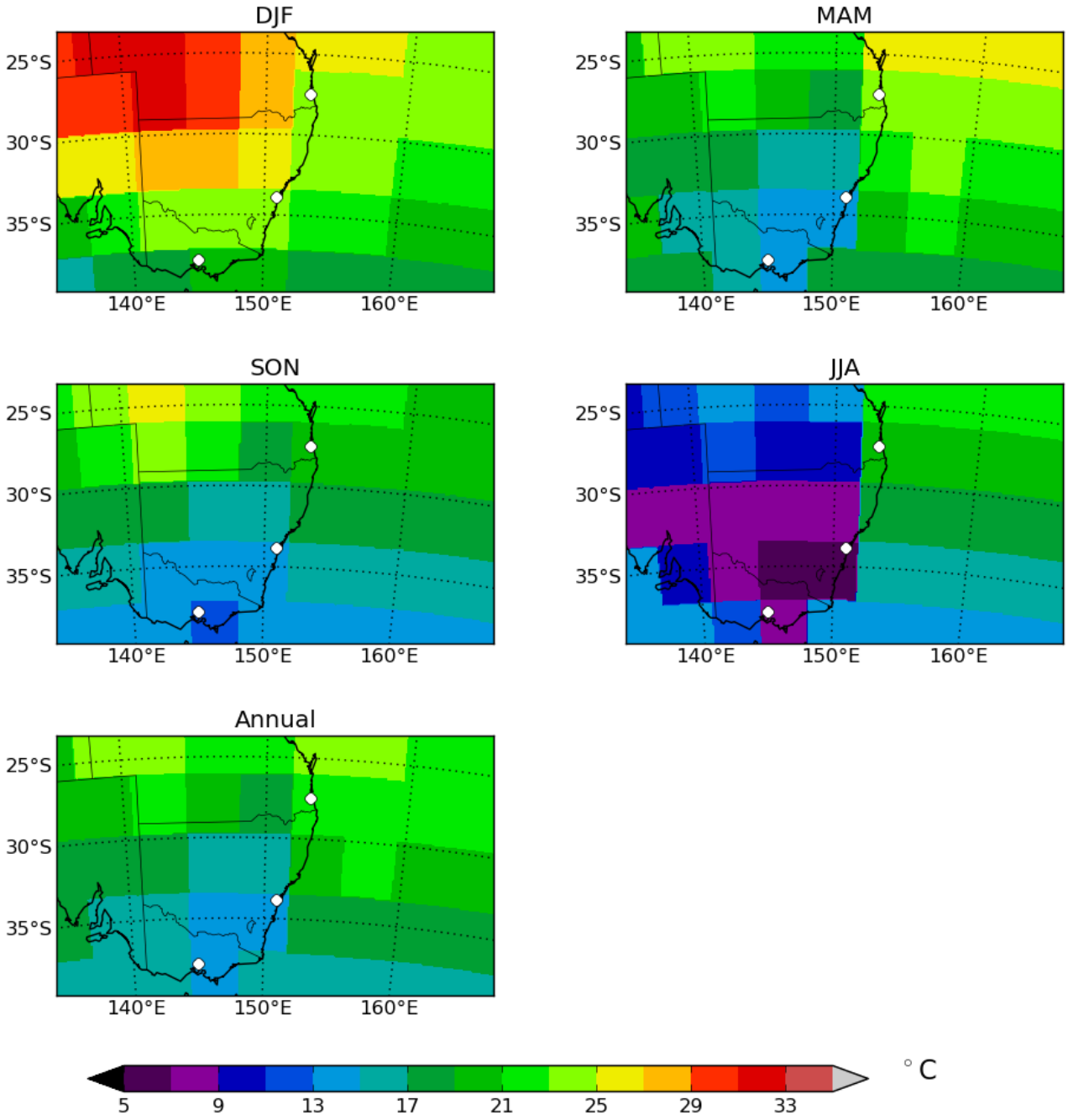

Figure 4.3: Seasonal and annual means of CCCMA3.1 near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

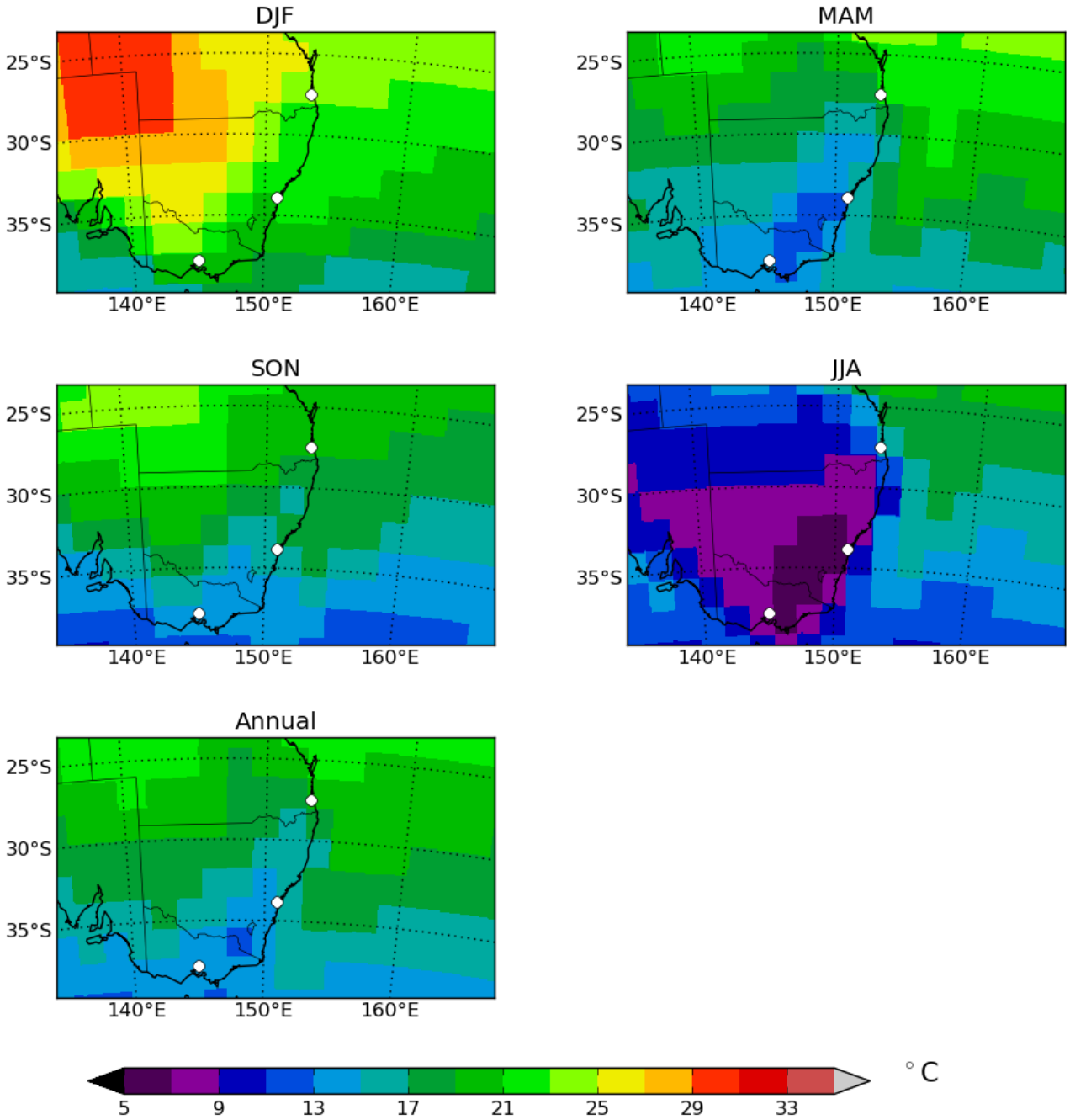

Figure 4.4: Seasonal and annual means of CSIRO-MK3.0 near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

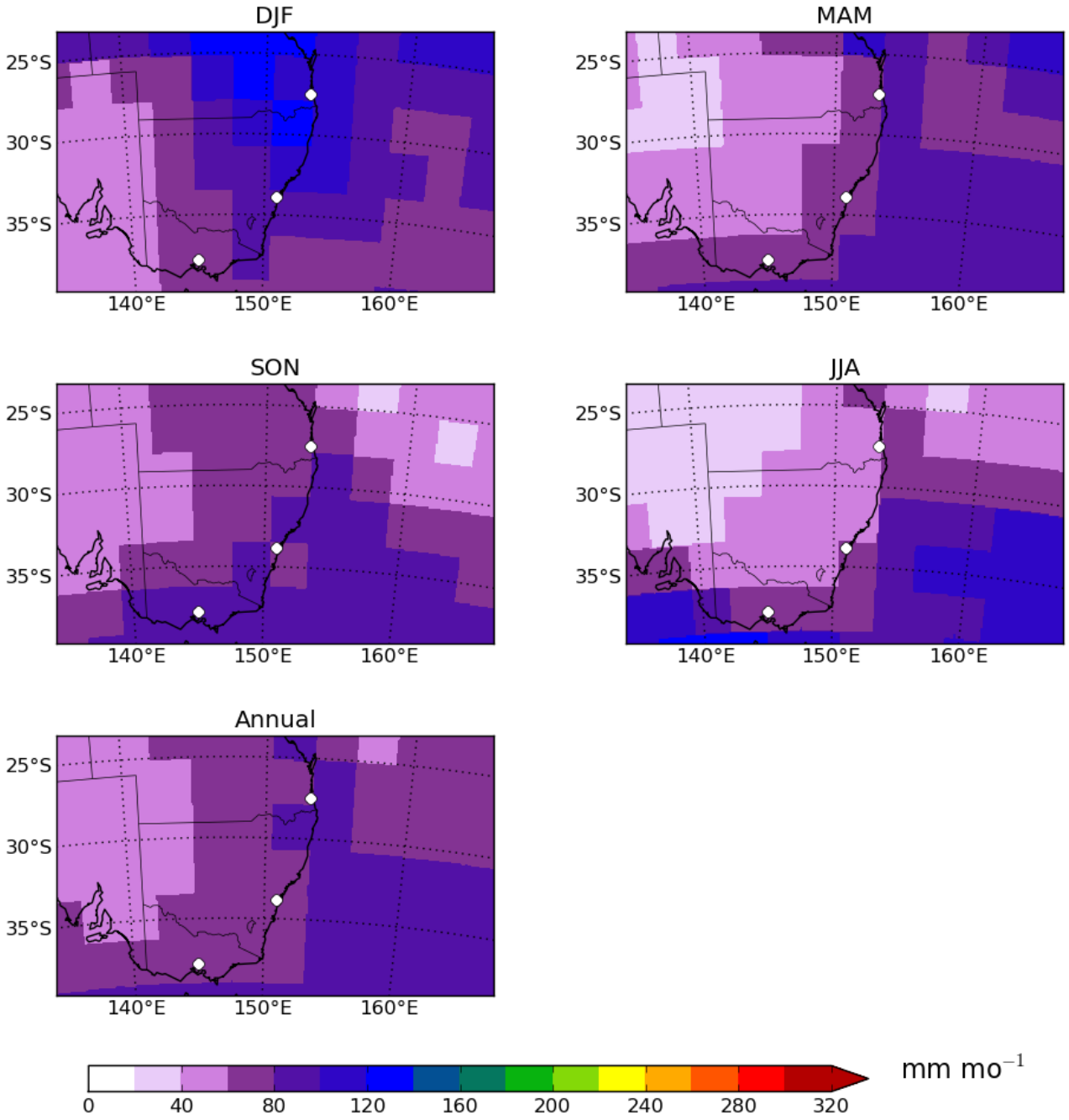

Figure 4.5: Seasonal and annual means of MIROC3.2 precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

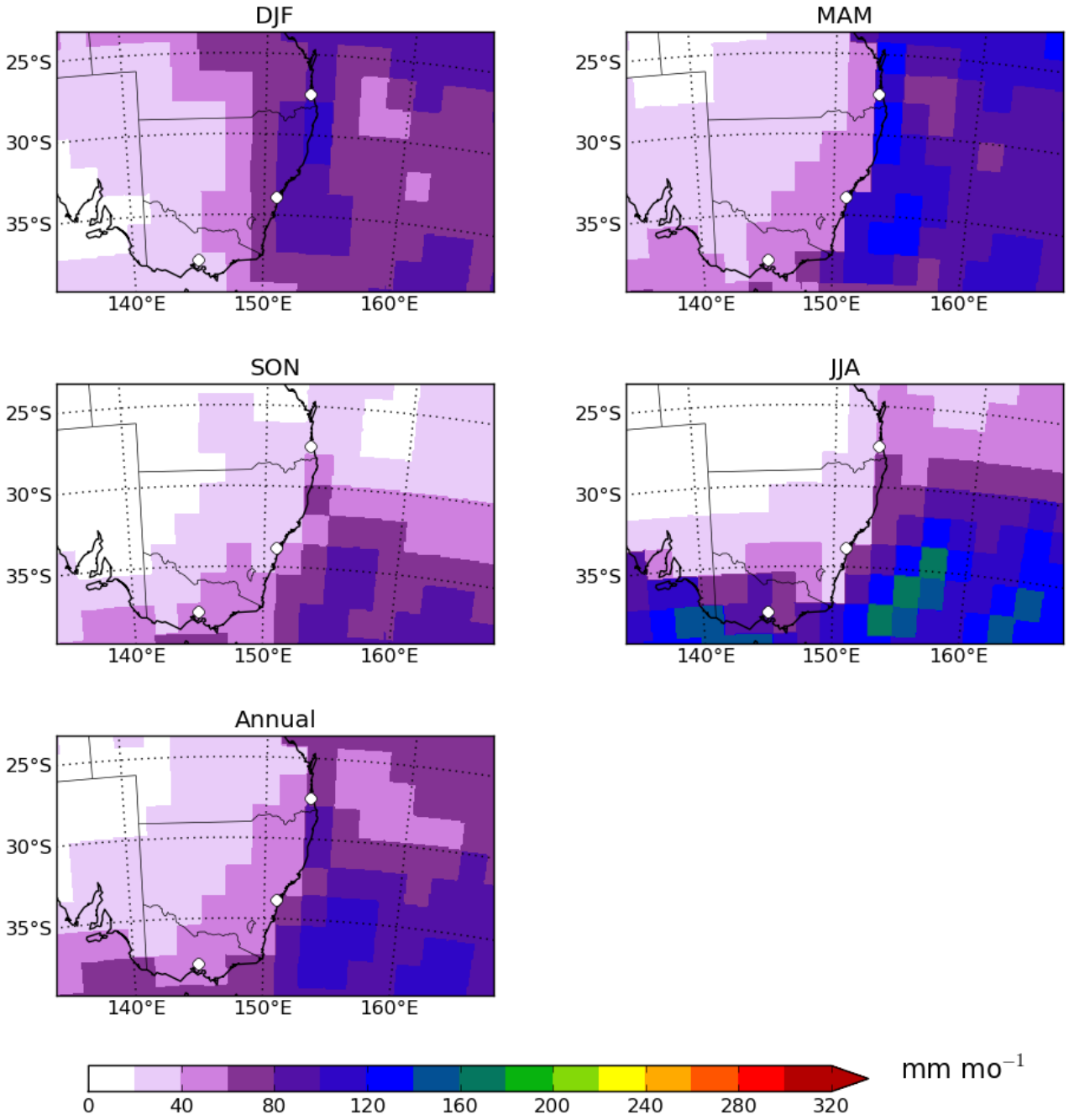

Figure 4.6: Seasonal and annual means of ECHAM5 precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

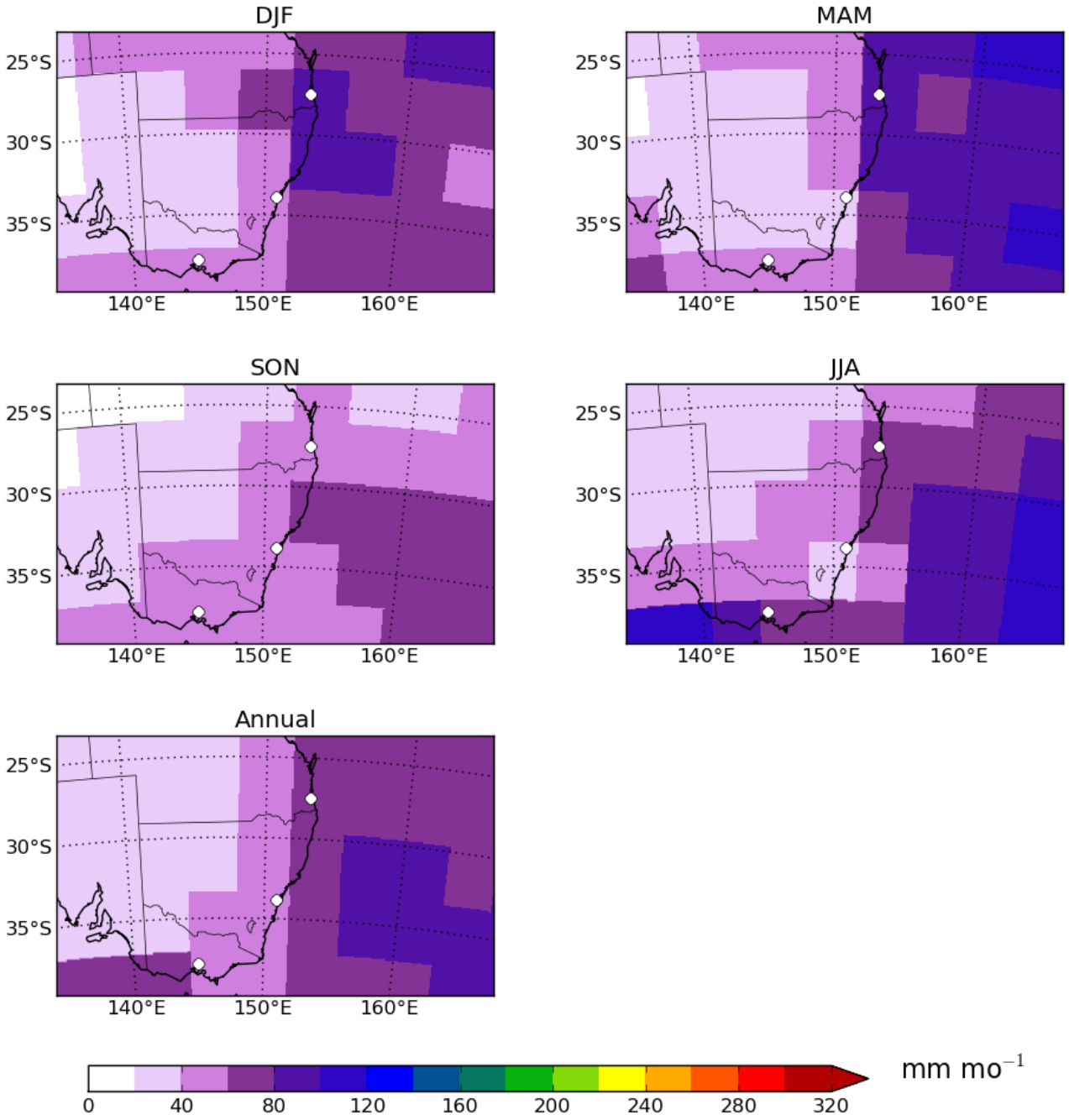

Figure 4.7: Seasonal and annual means of CCCMA3.1 precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

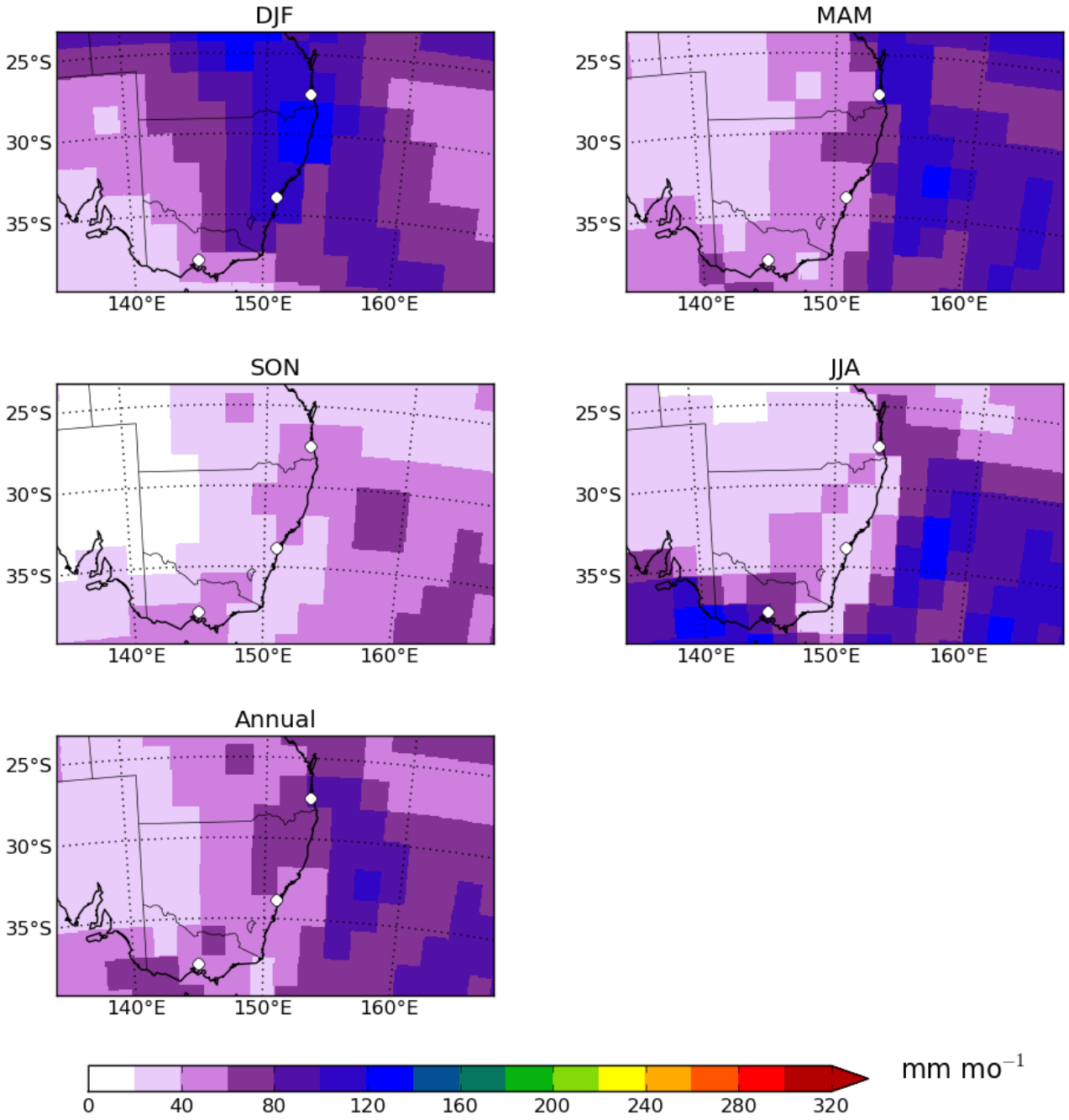

Figure 4.8: Seasonal and annual means of CSIRO-MK3.0 precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

4.2 1990-2009 Regional Model Output

This subsection contains climatologies for present-day near-surface air temperature, daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the original RCM output. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average modeled climatologies, whereas the individual-model plots show the level of uncertainty in modeled climate.

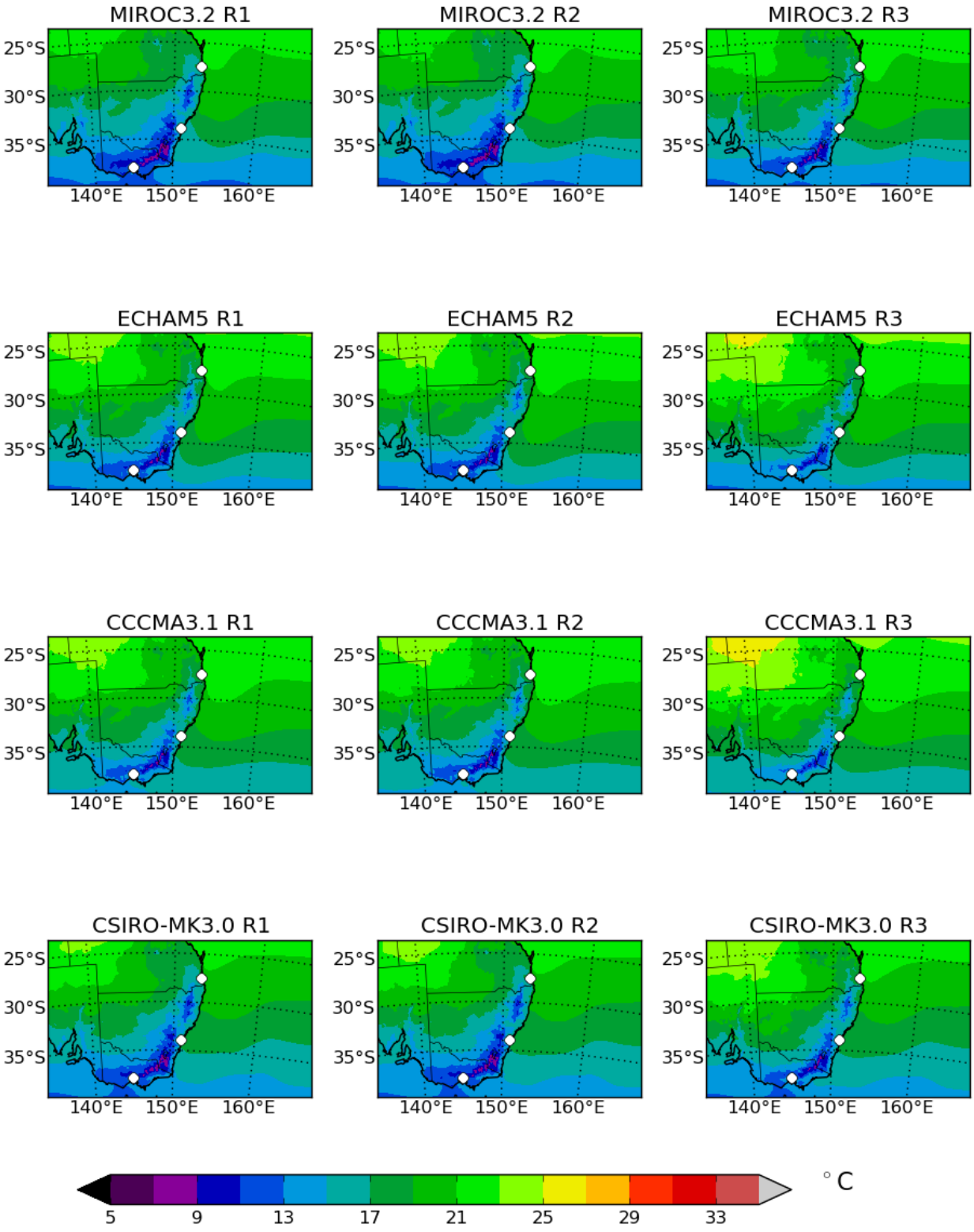

Figure 4.9: Annual mean of near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

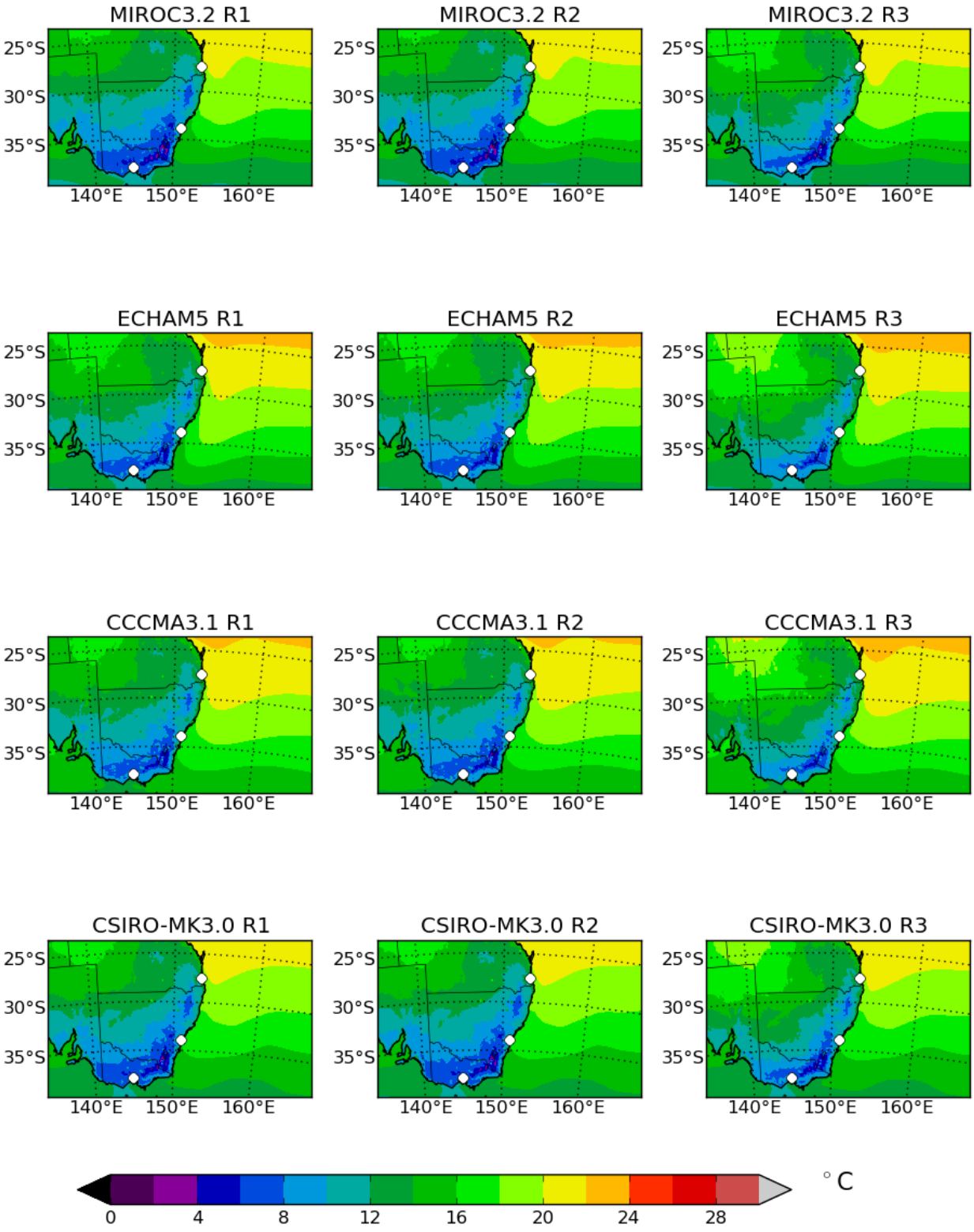

Figure 4.10: Annual mean of daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

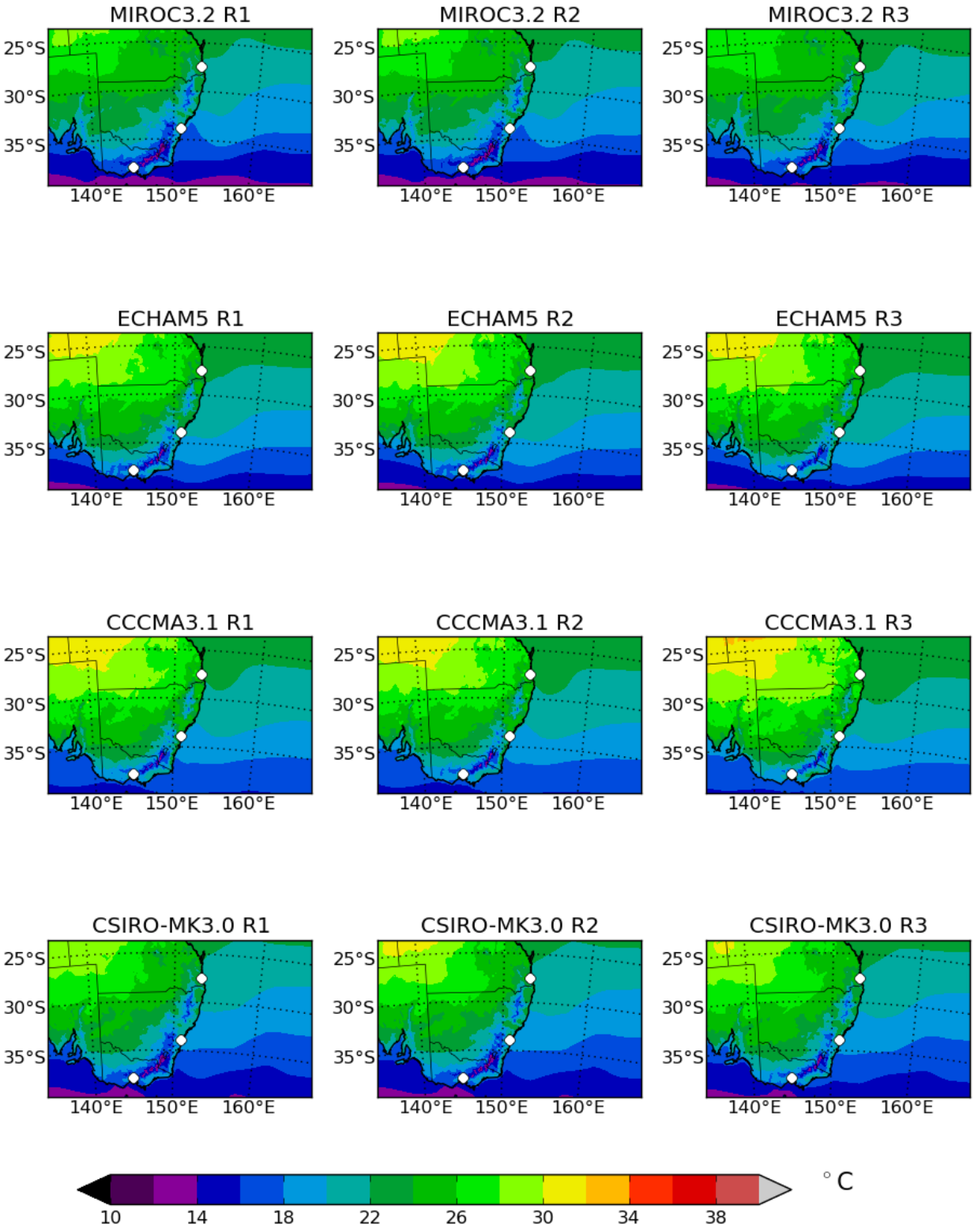

Figure 4.11: Annual mean of daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

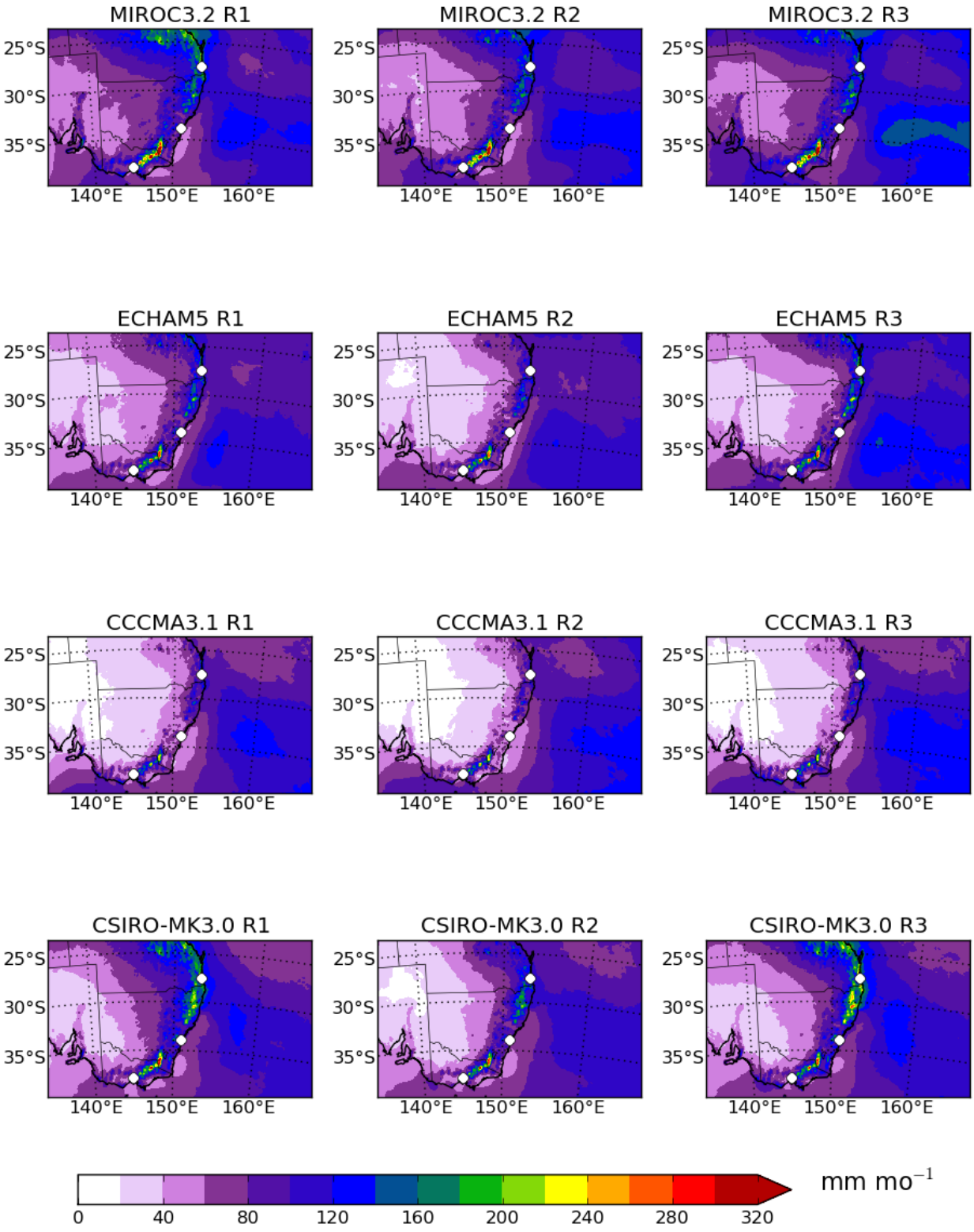

Figure 4.12: Annual mean of precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

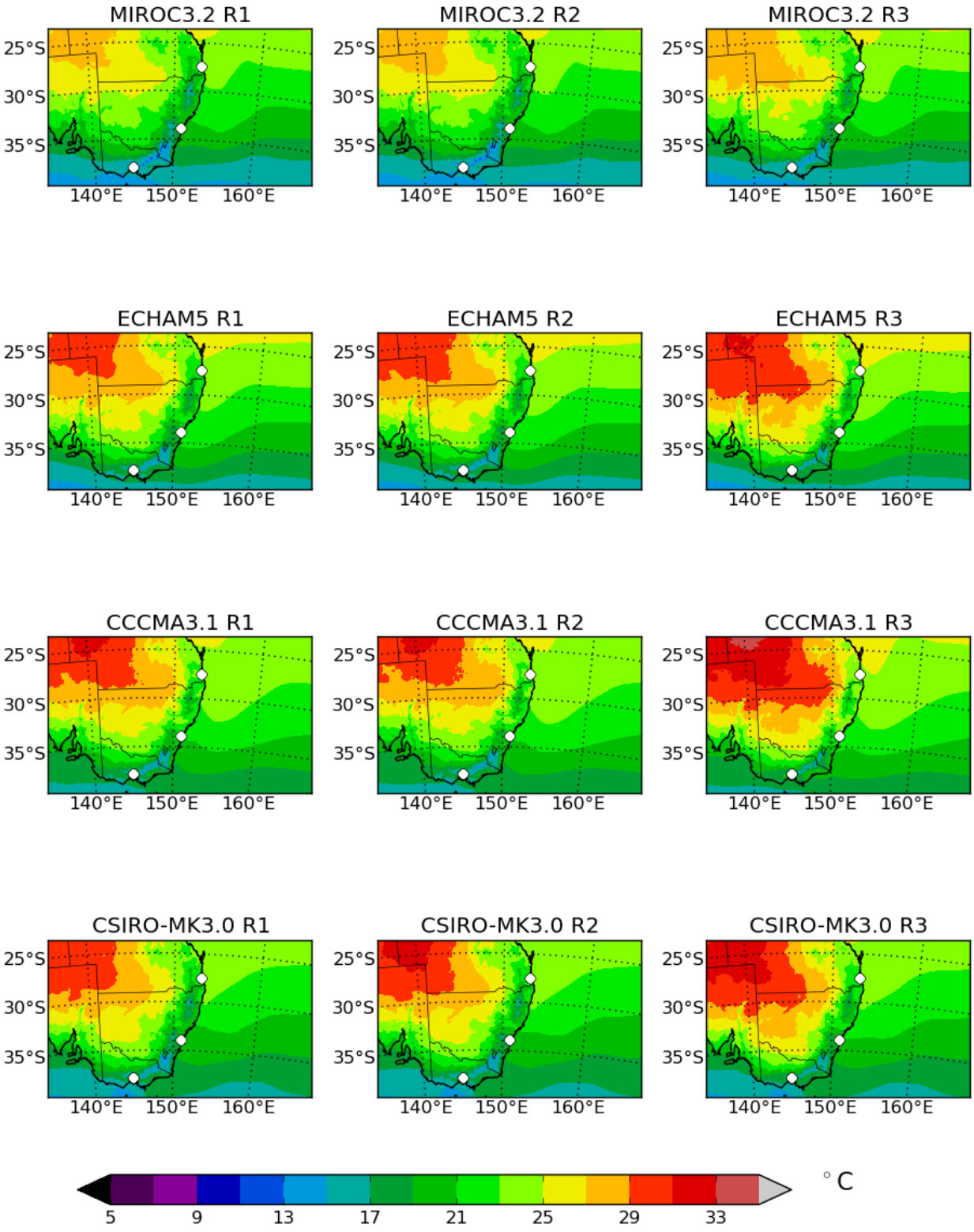

Figure 4.13: DJF mean of near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

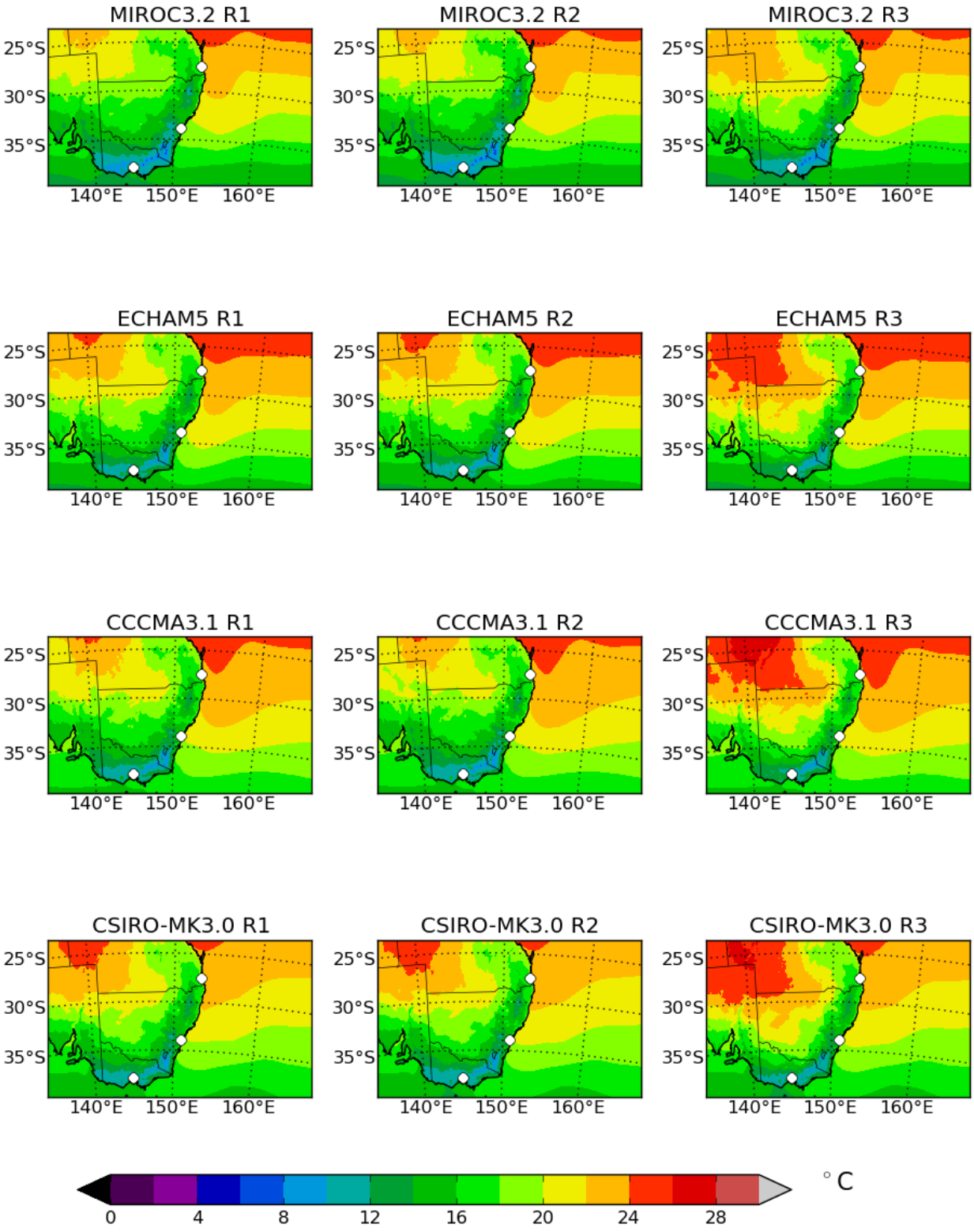

Figure 4.14: DJF mean of daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

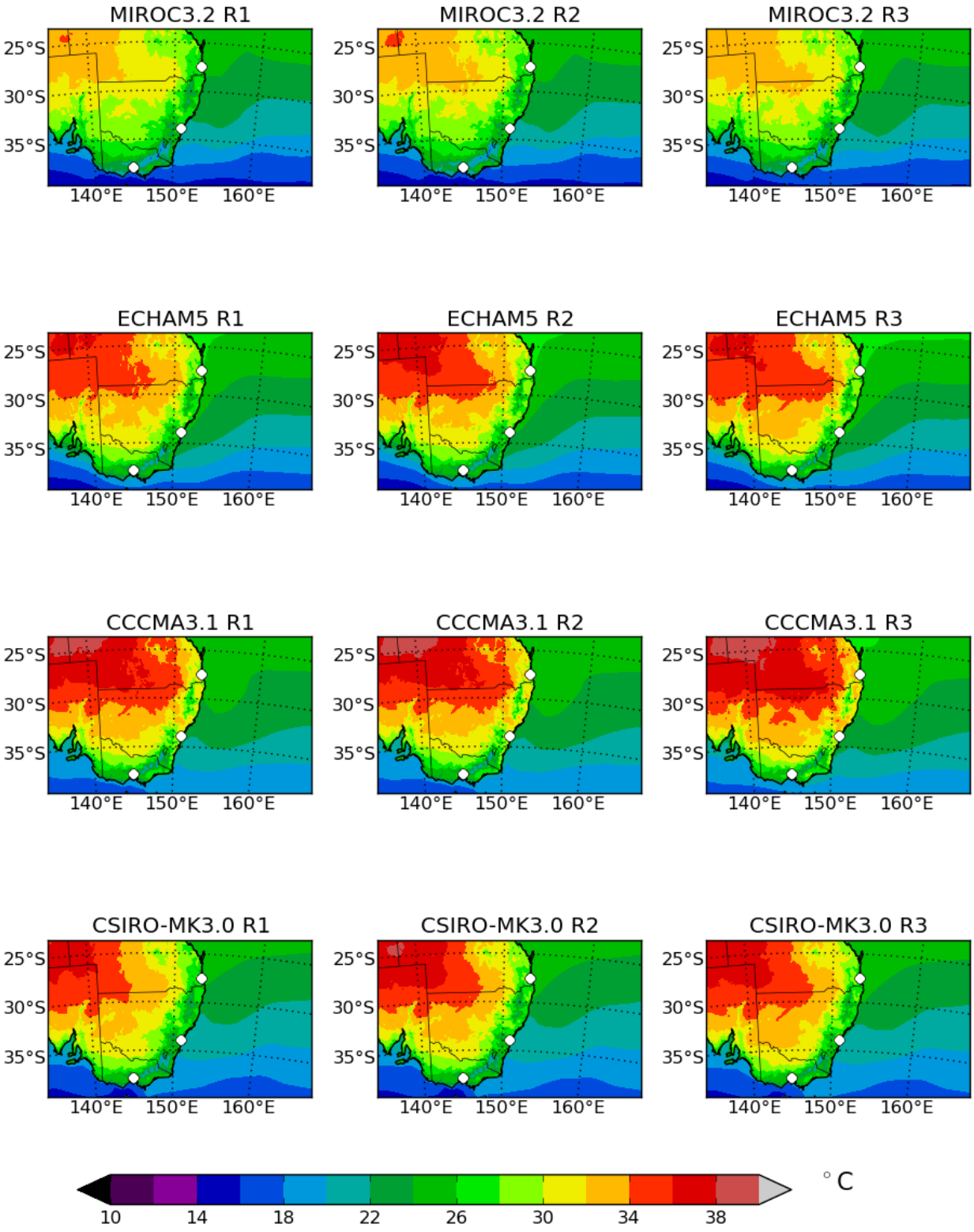

Figure 4.15: DJF mean of daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

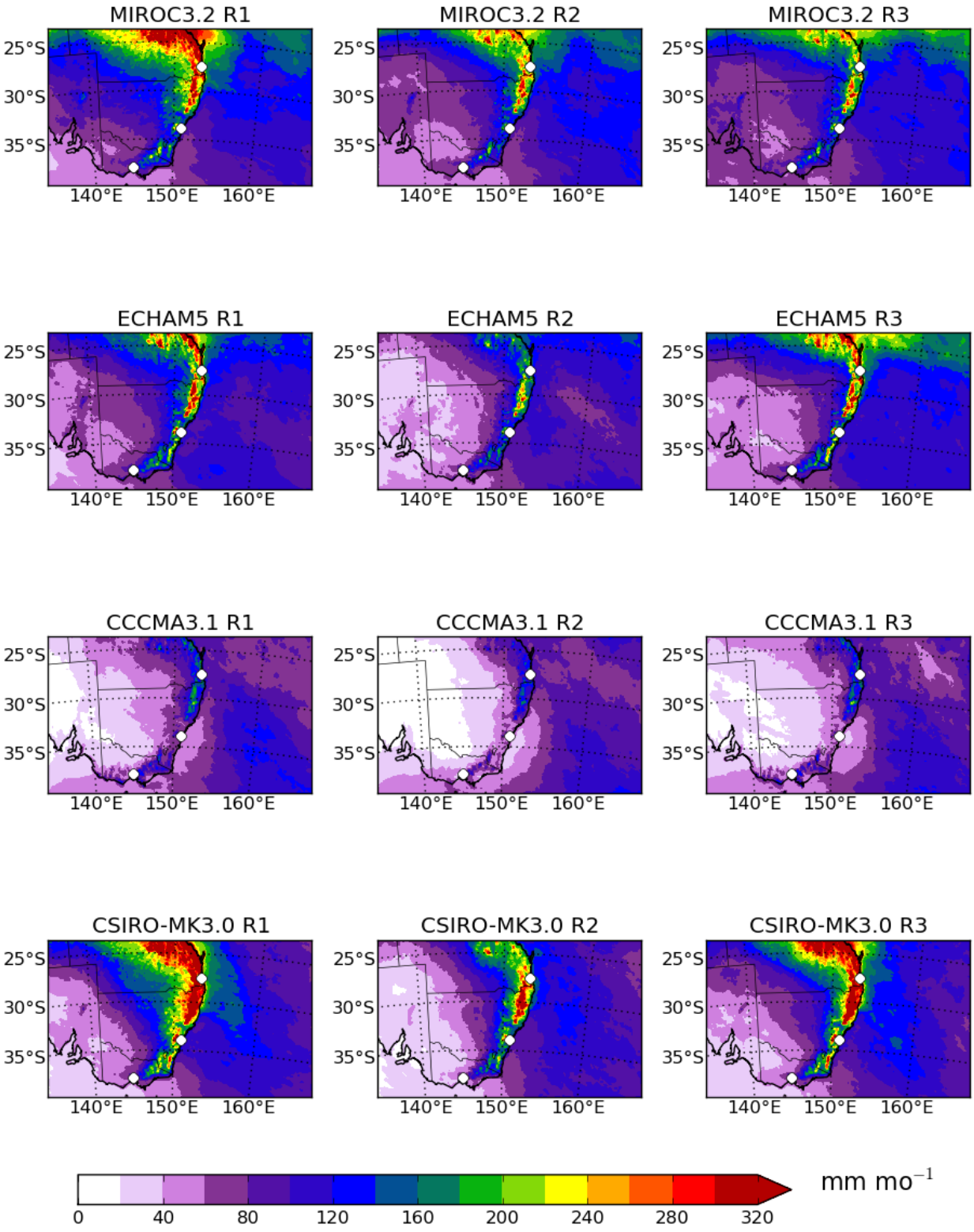

Figure 4.16: DJF mean of precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

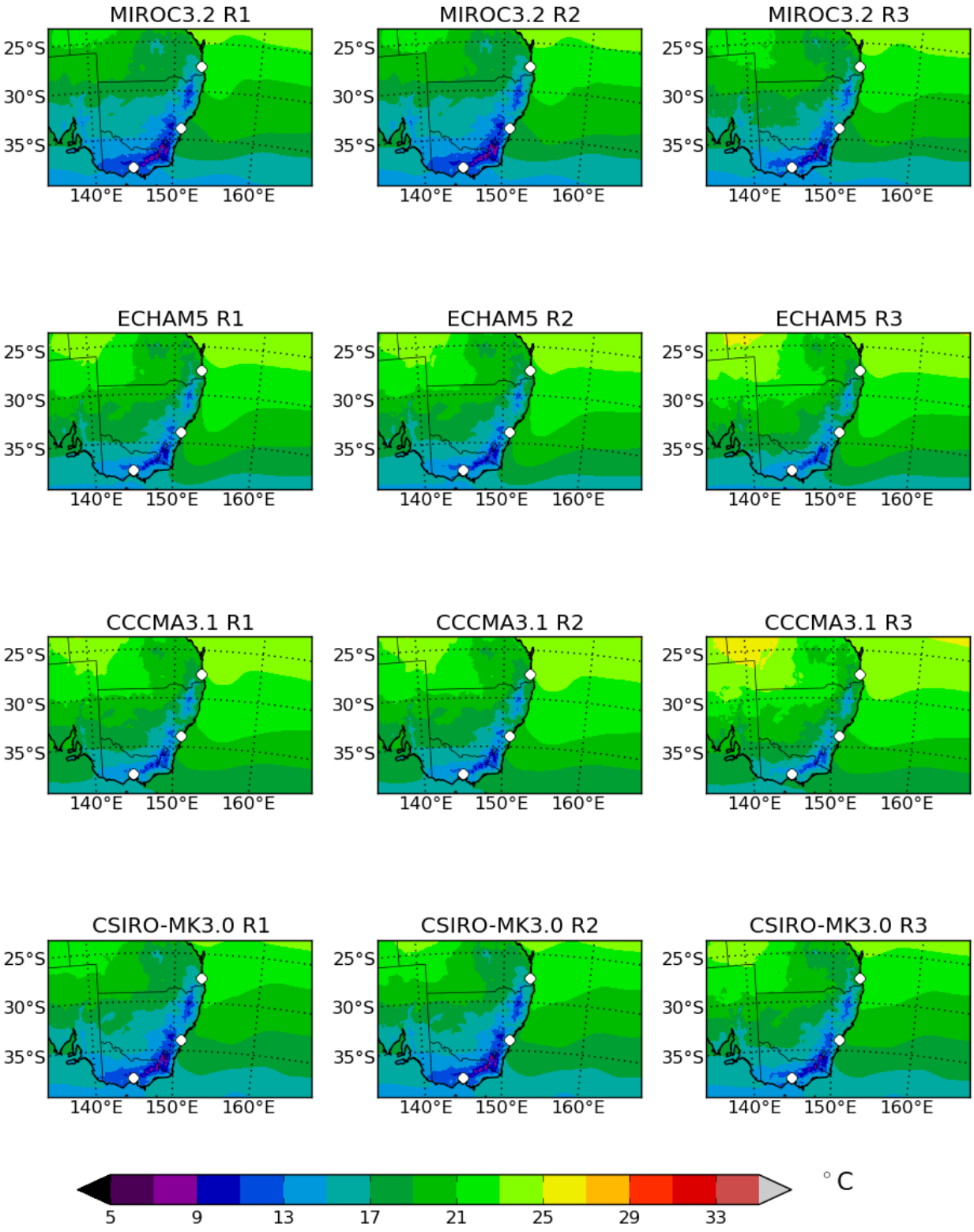

Figure 4.17: MAM mean of near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

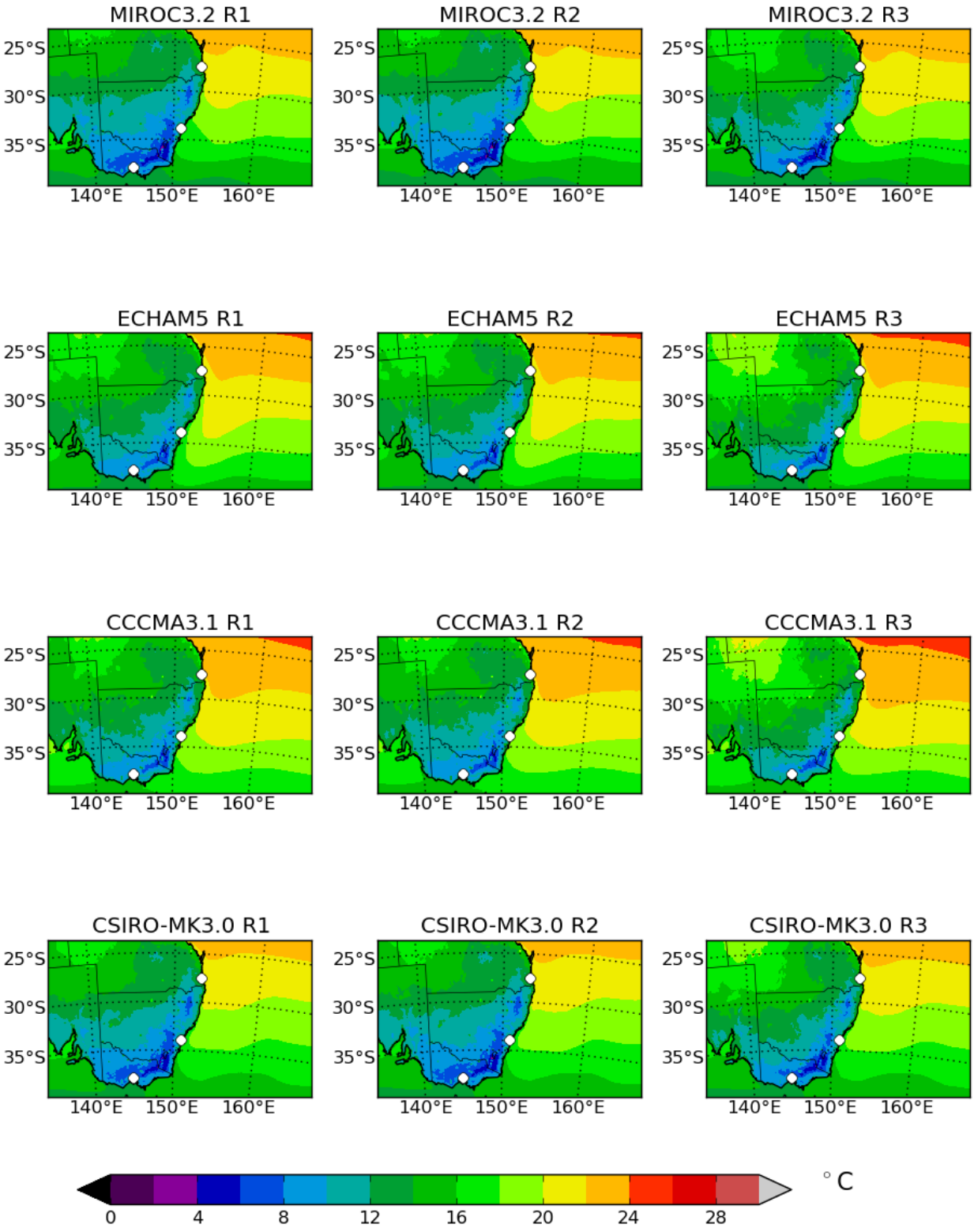

Figure 4.18: MAM mean of daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

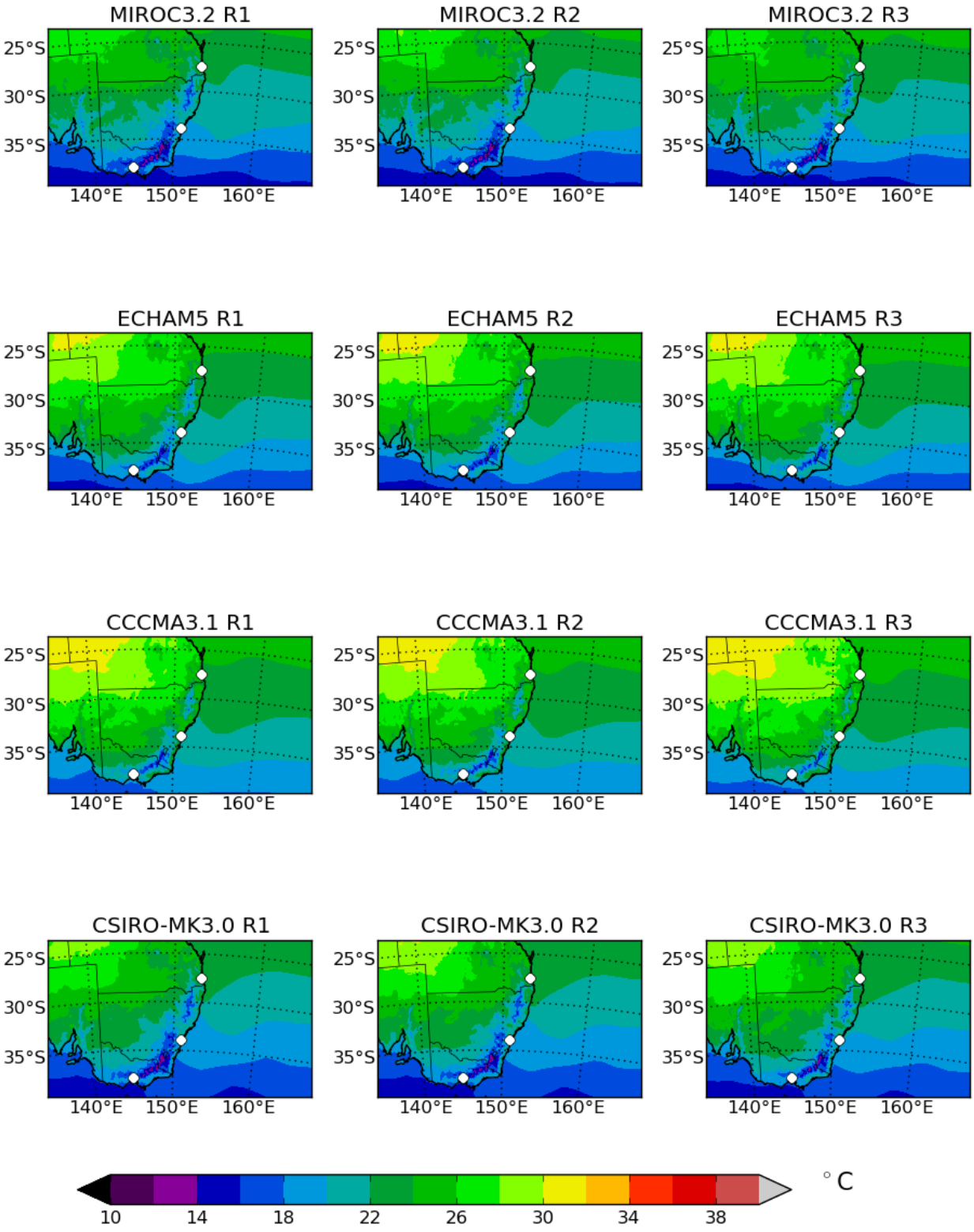

Figure 4.19: MAM mean of daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

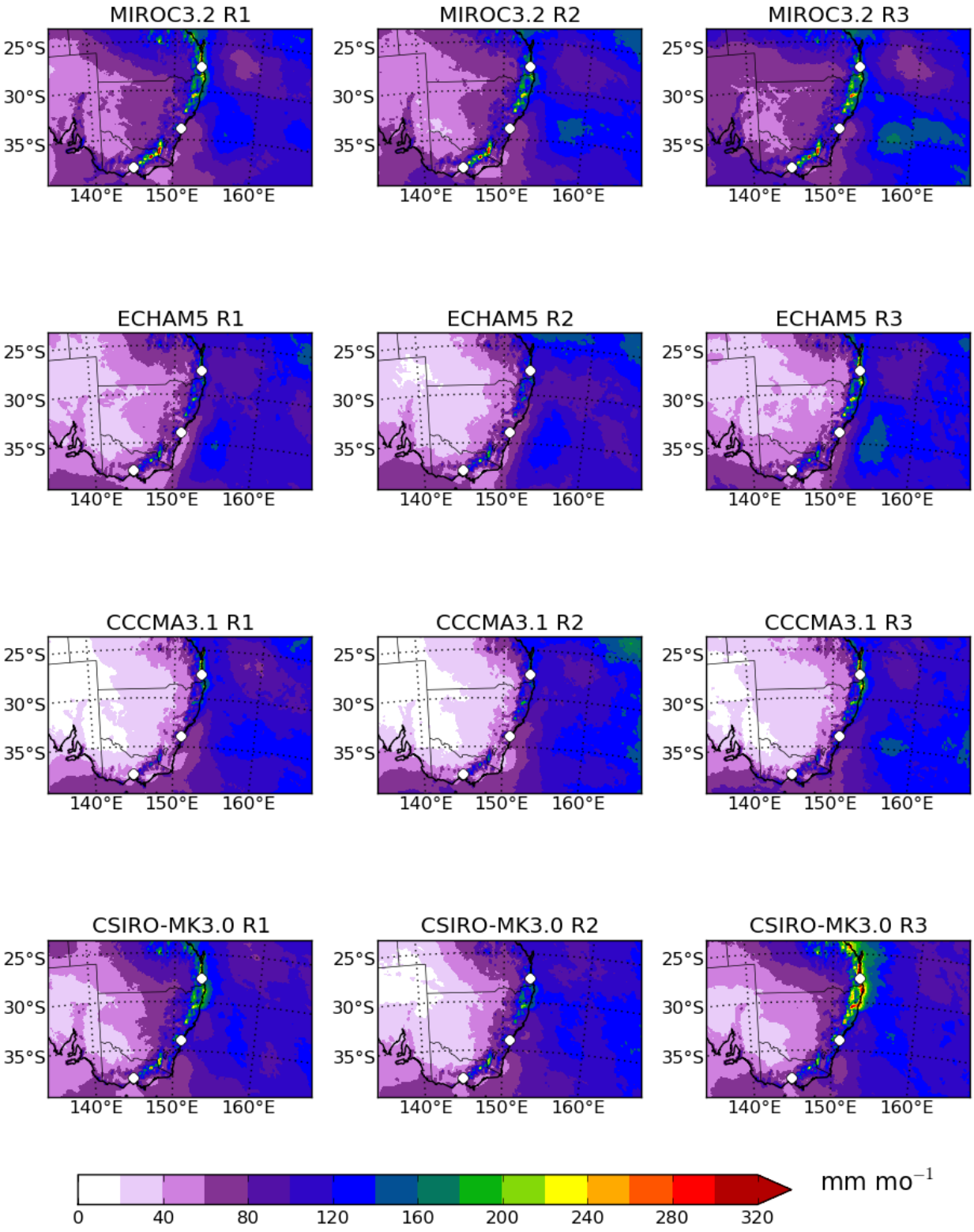

Figure 4.20: MAM mean of precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

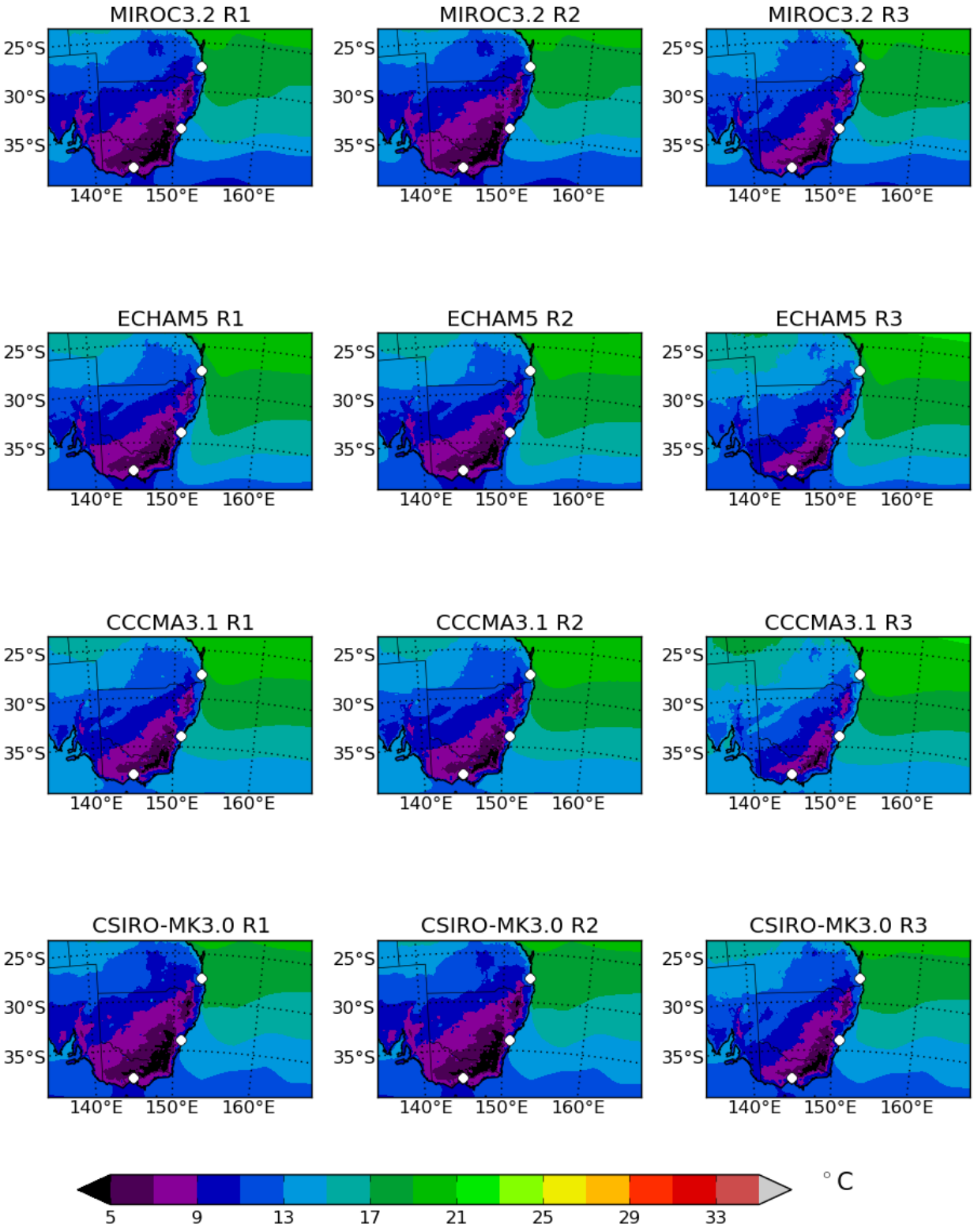

Figure 4.21: JJA mean of near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

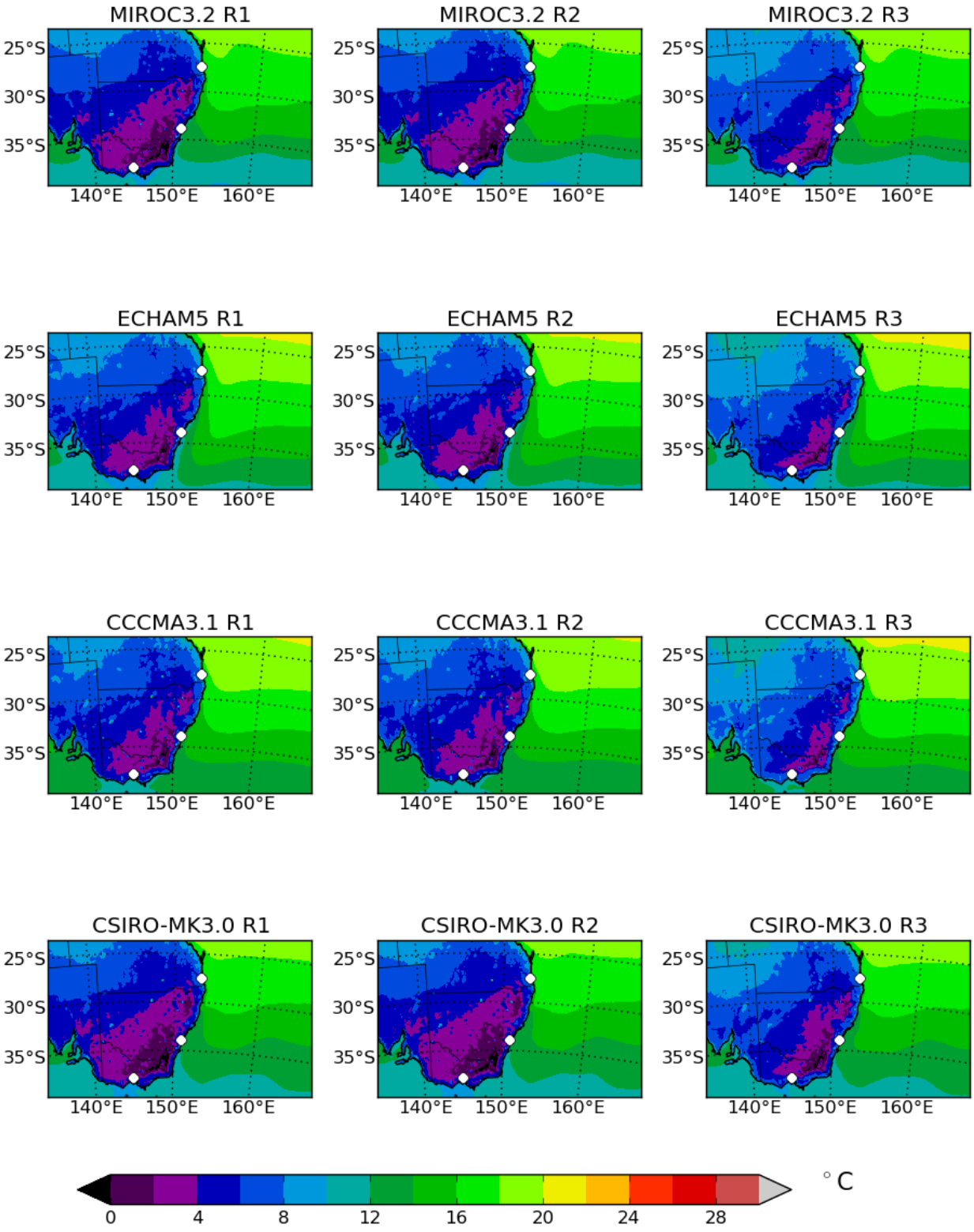

Figure 4.22: JJA mean of daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

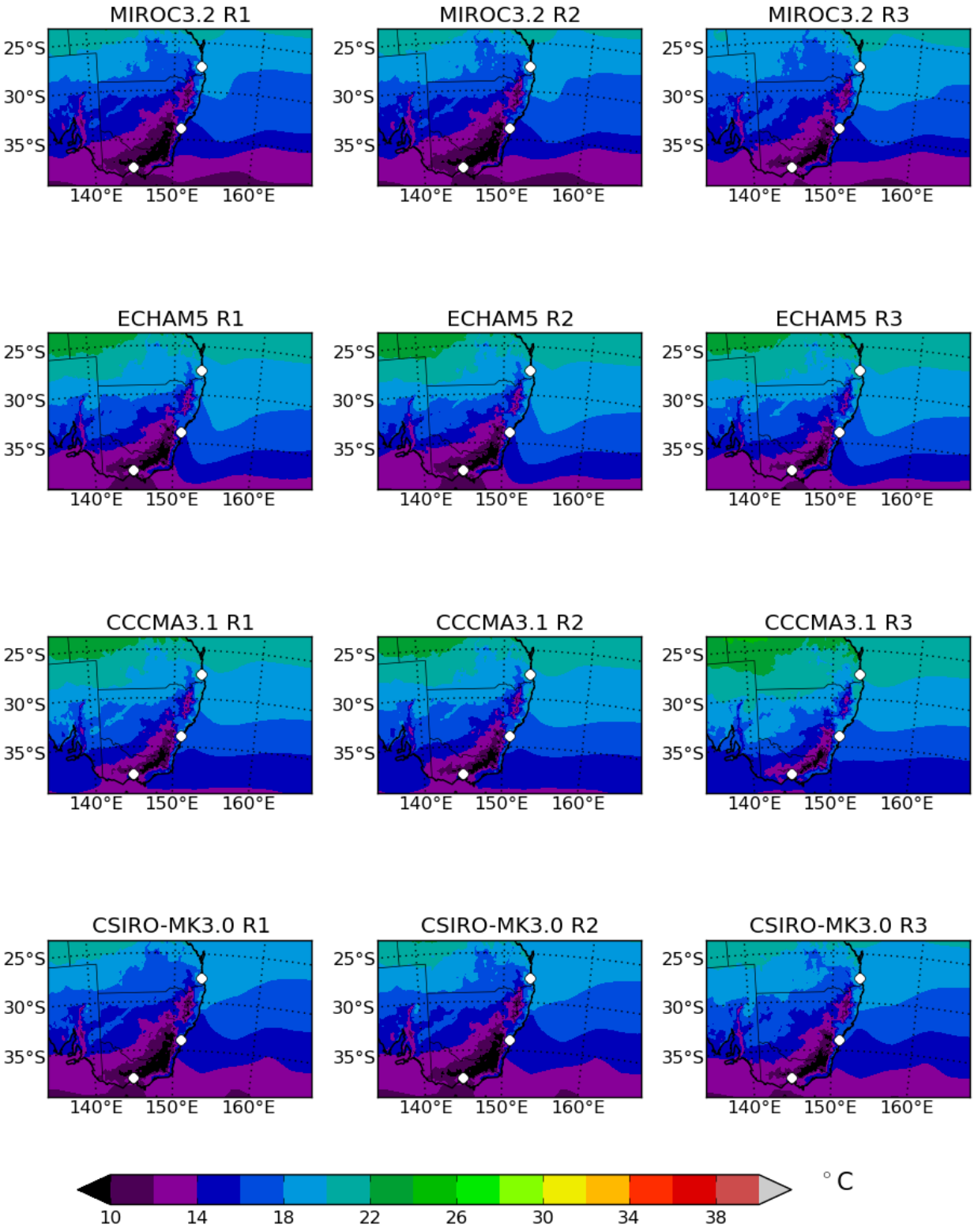

Figure 4.23: JJA mean of daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

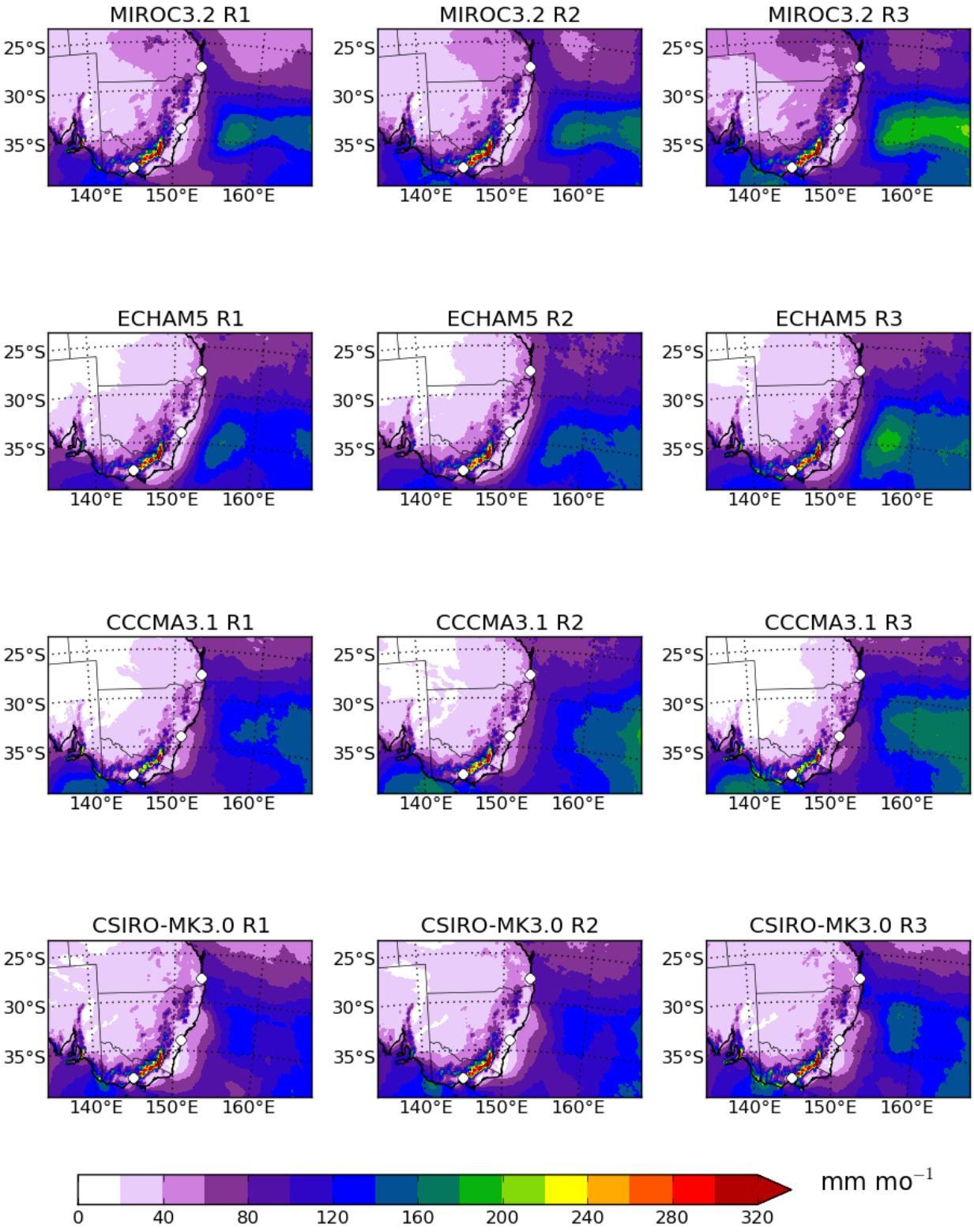

Figure 4.24: JJA mean of precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

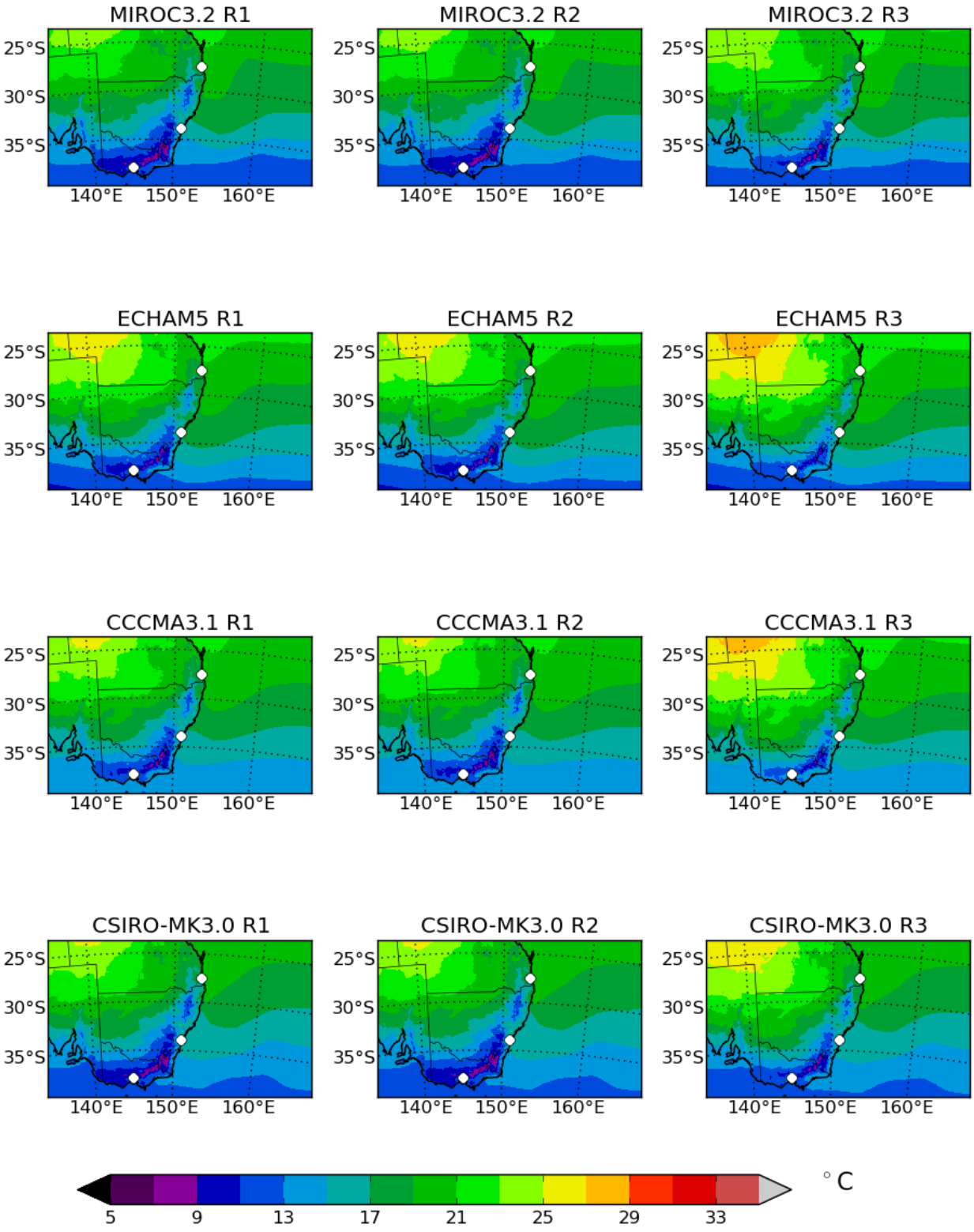

Figure 4.25: SON mean of near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

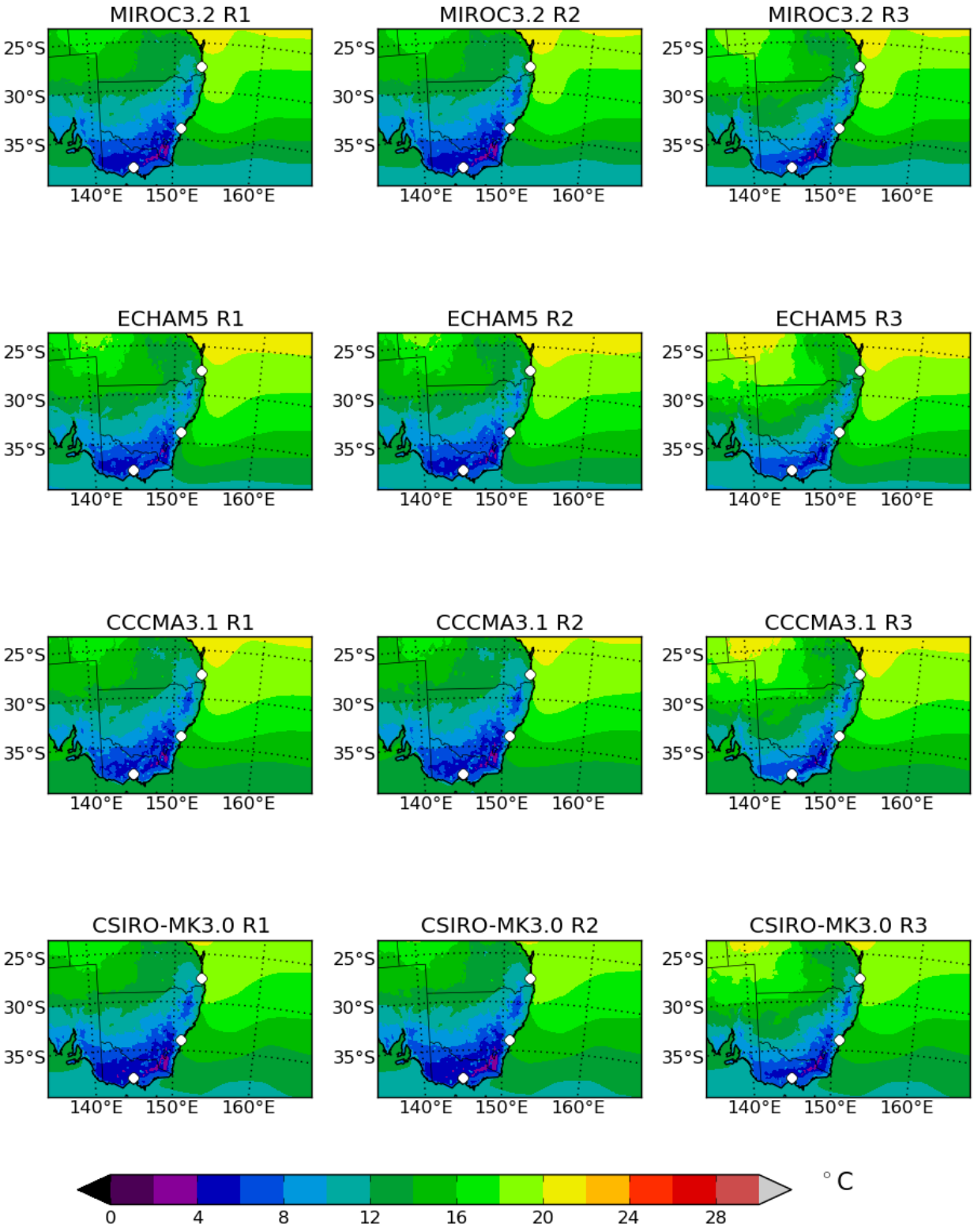

Figure 4.26: SON mean of daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

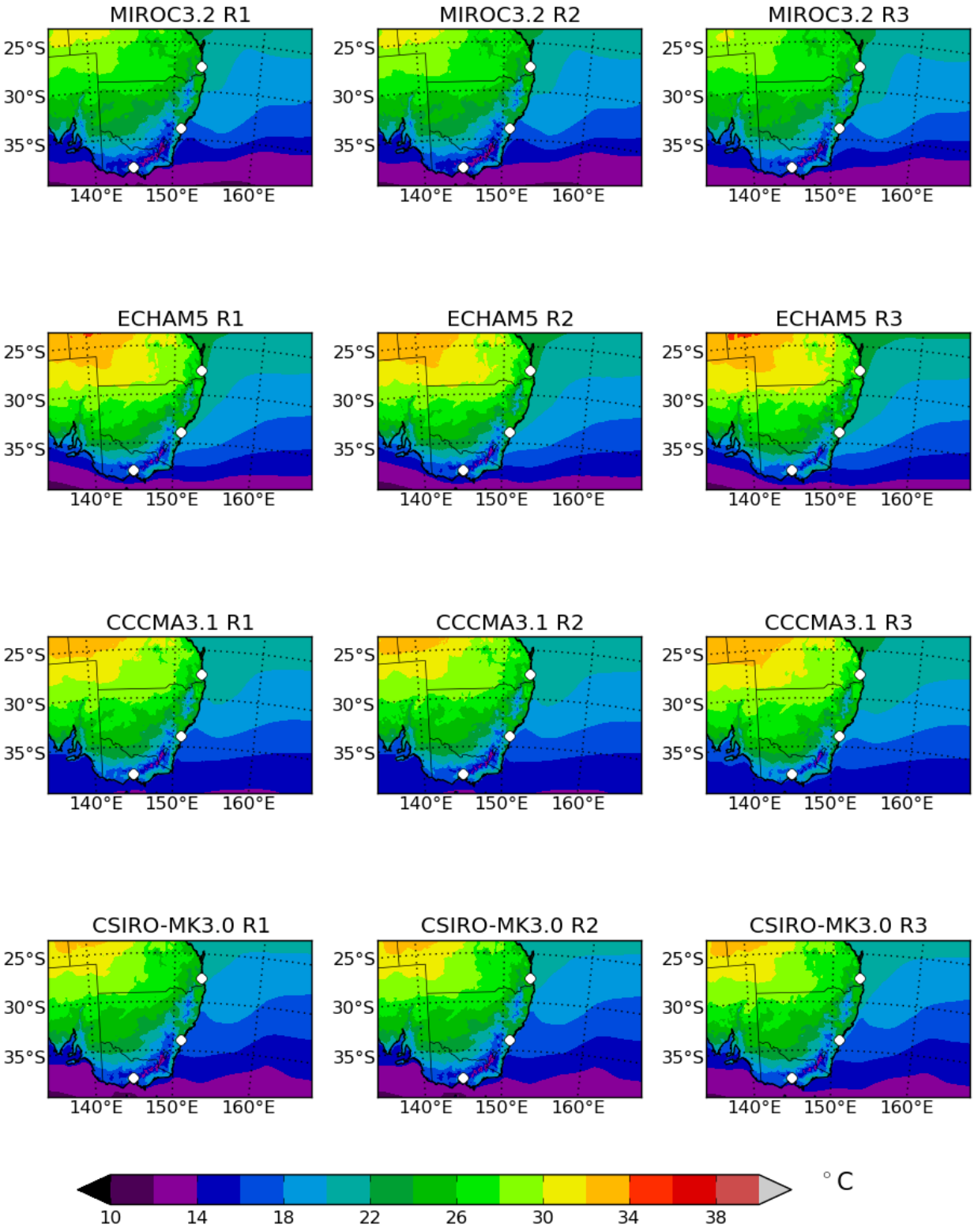

Figure 4.27: SON mean of daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

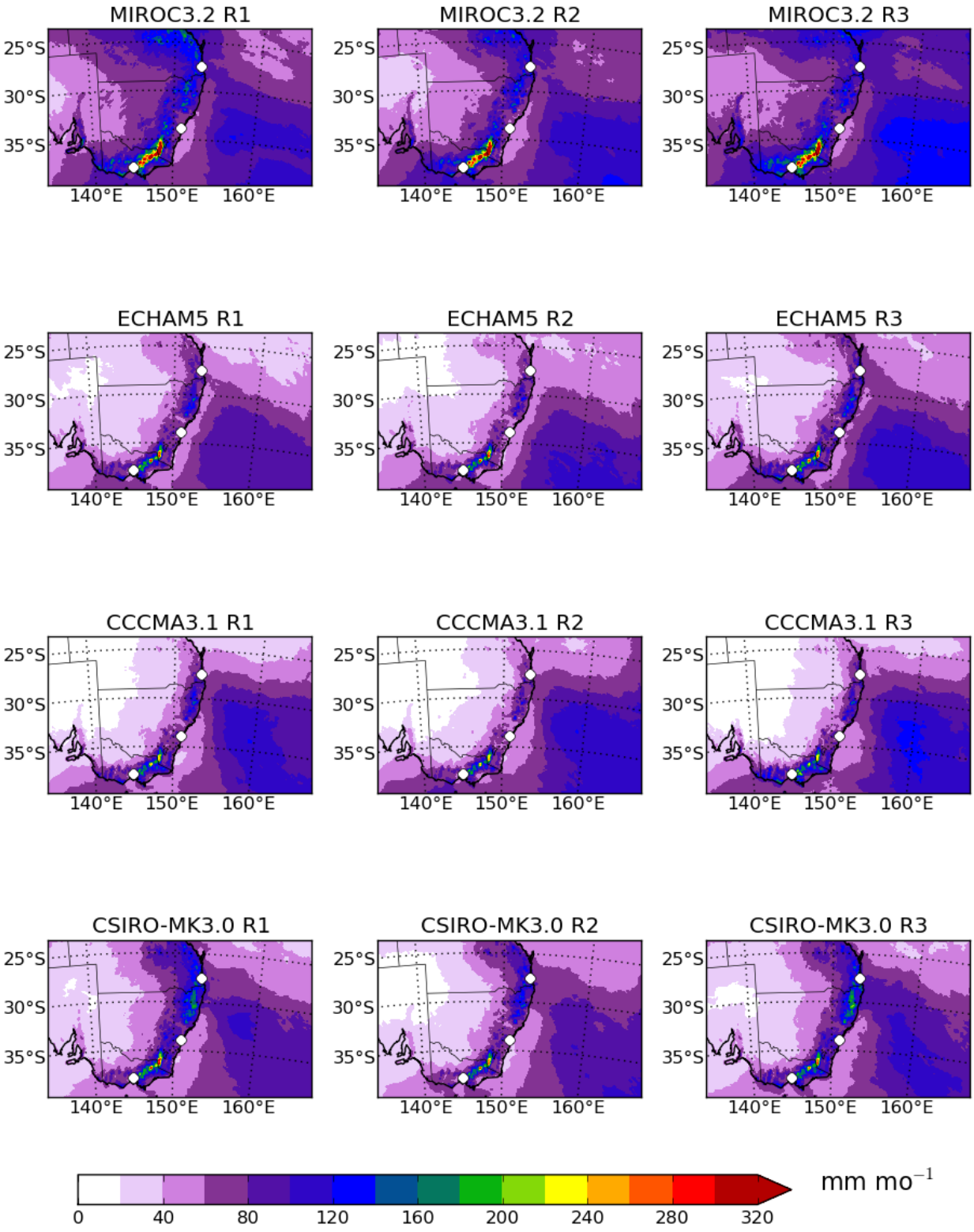

Figure 4.28: SON mean of precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

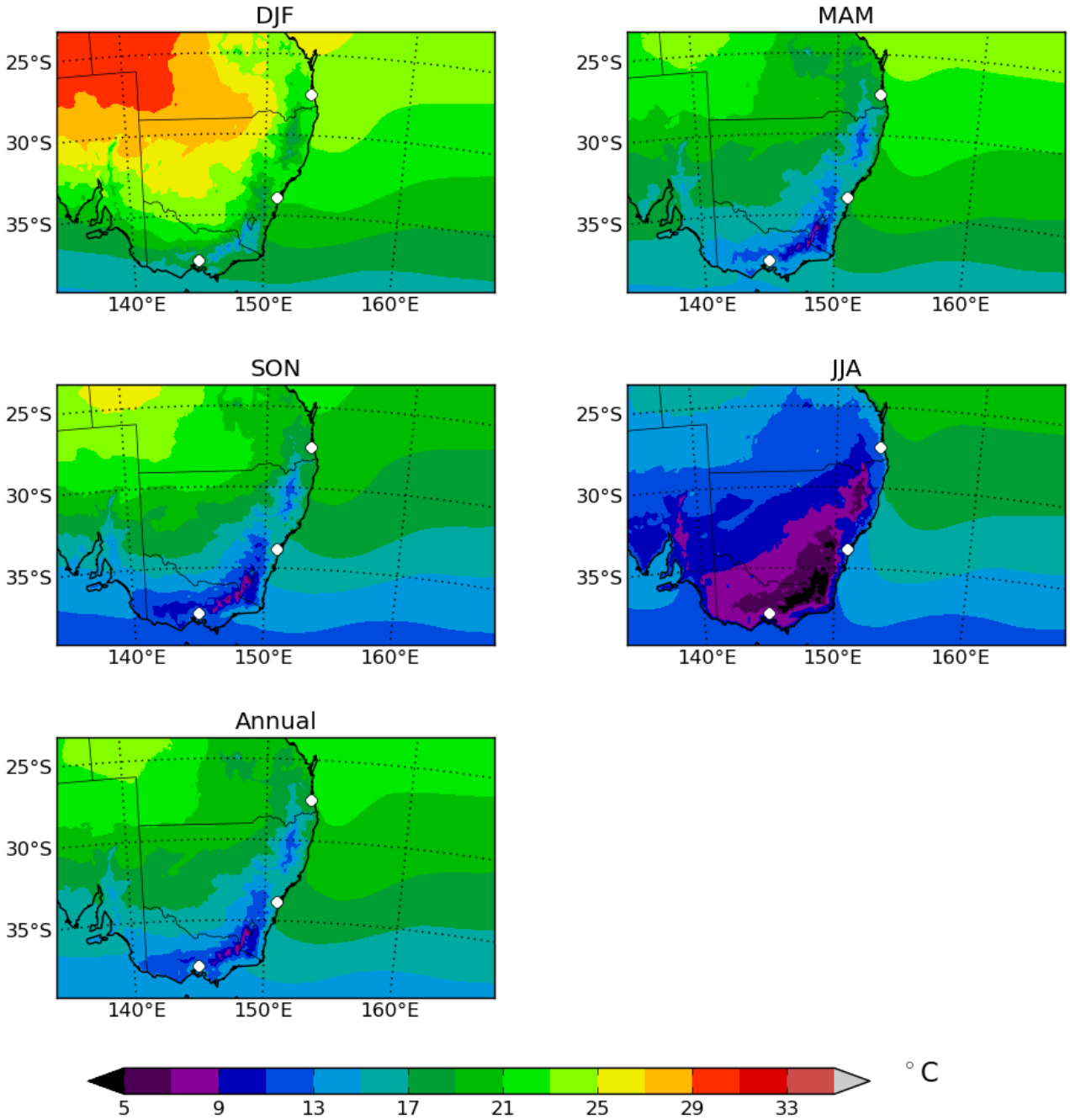

Figure 4.29: Seasonal and annual multimodel means of near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

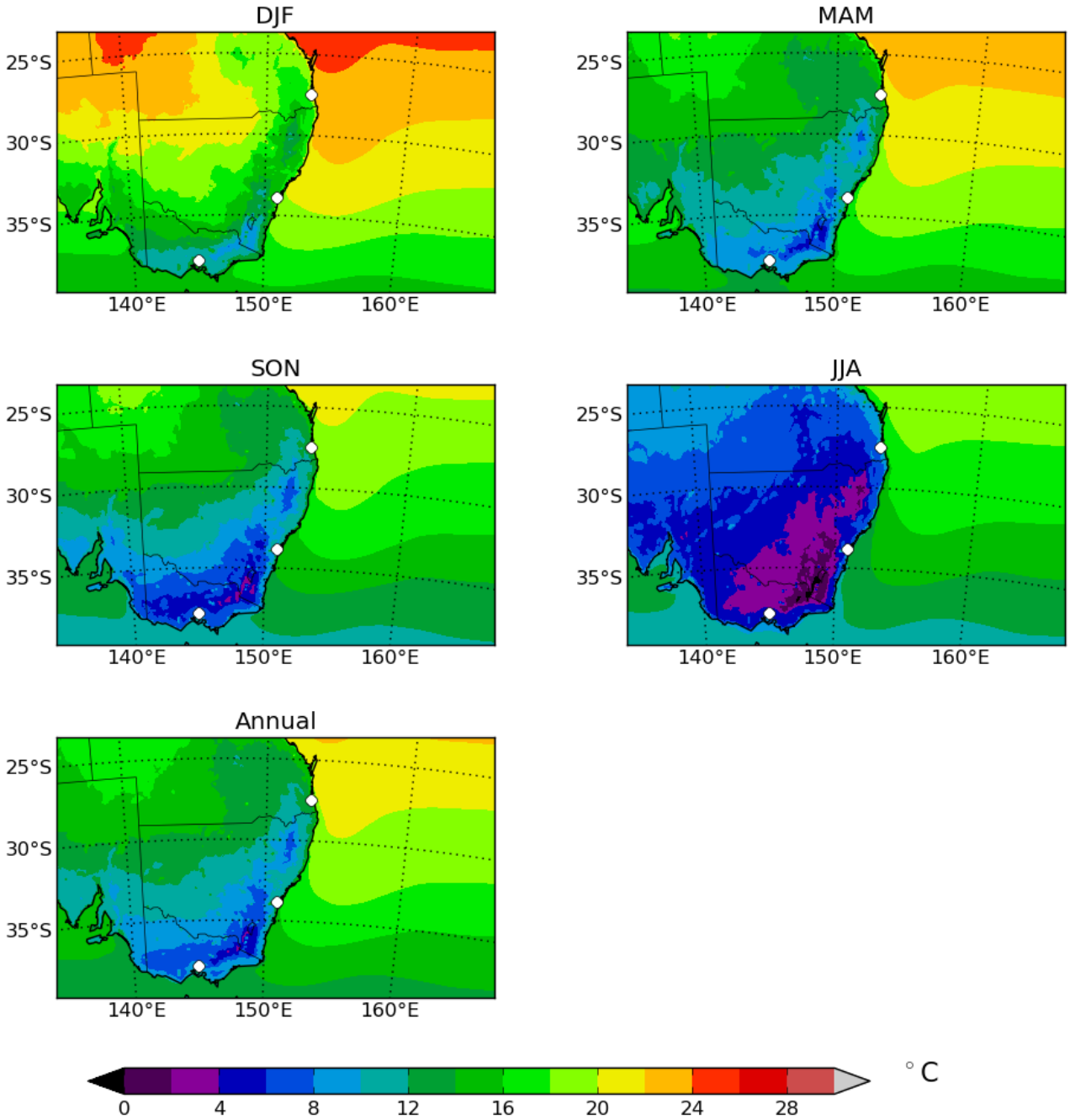

Figure 4.30: Seasonal and annual multimodel means of daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

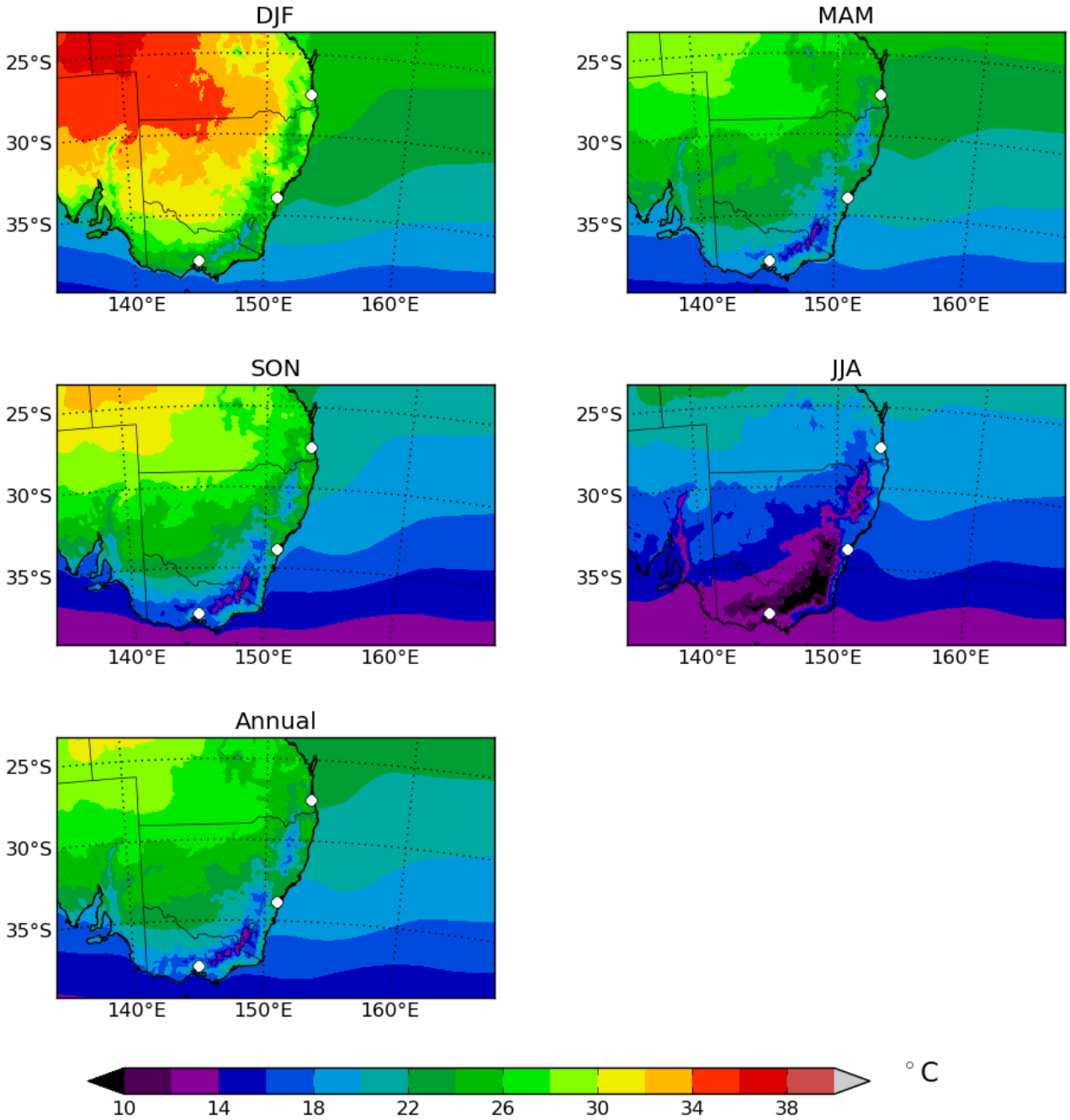

Figure 4.31: Seasonal and annual multimodel means of daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

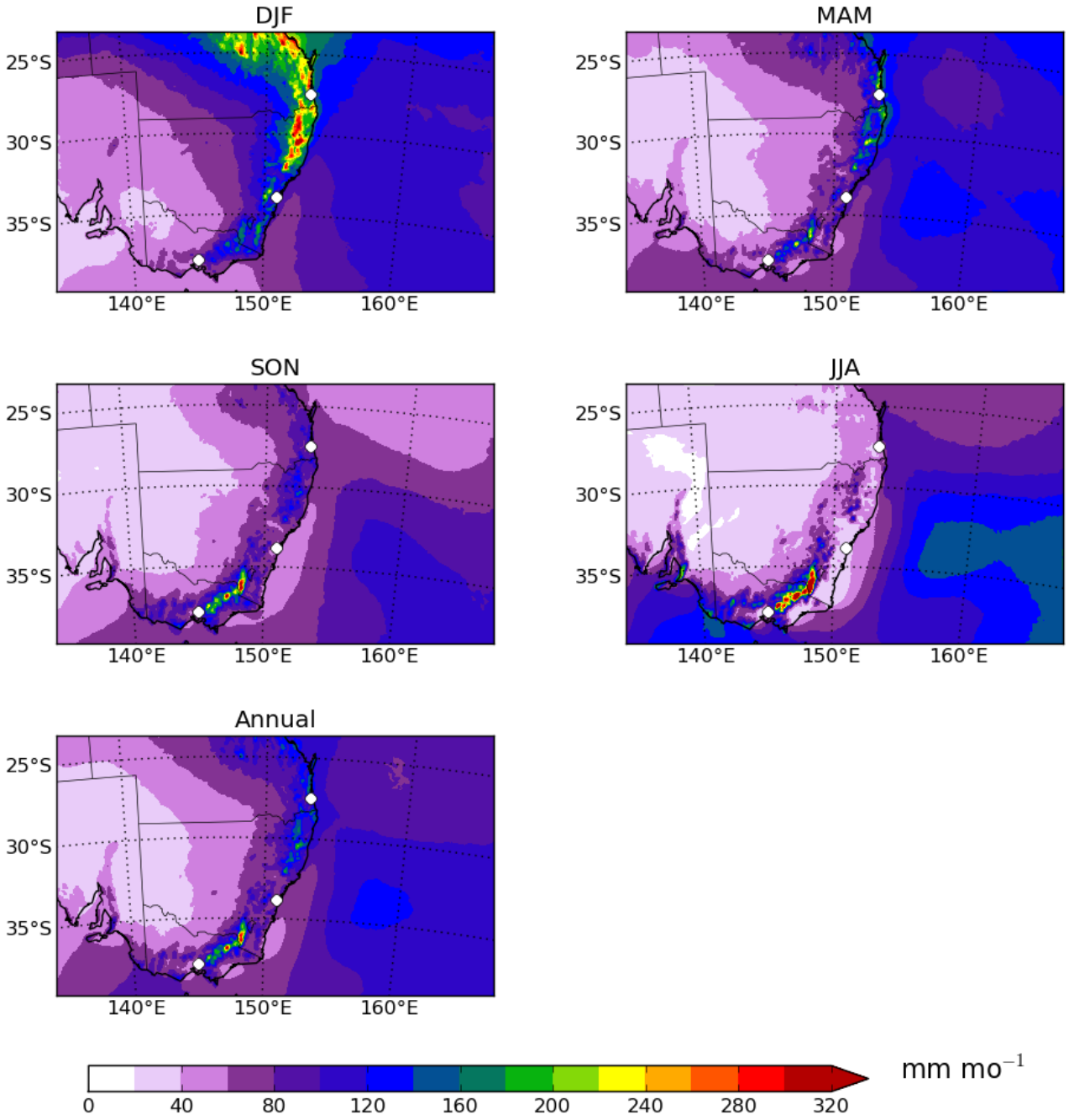

Figure 4.32: Seasonal and annual multimodel means of precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

4.3 1990-2009 Bias-Corrected Regional Model Output

This subsection contains climatologies for present-day daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the bias-corrected RCM output (*i.e.* RCM output that has been corrected for the biases between the models and the observations of climate using the methods described here [6]). The corrections are calculated by comparing distributions of daily model output and observations for all seasons. Thus, the corrections are independent of the season. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average modeled climatologies, whereas the individual-model plots show the level of uncertainty in modeled climate.

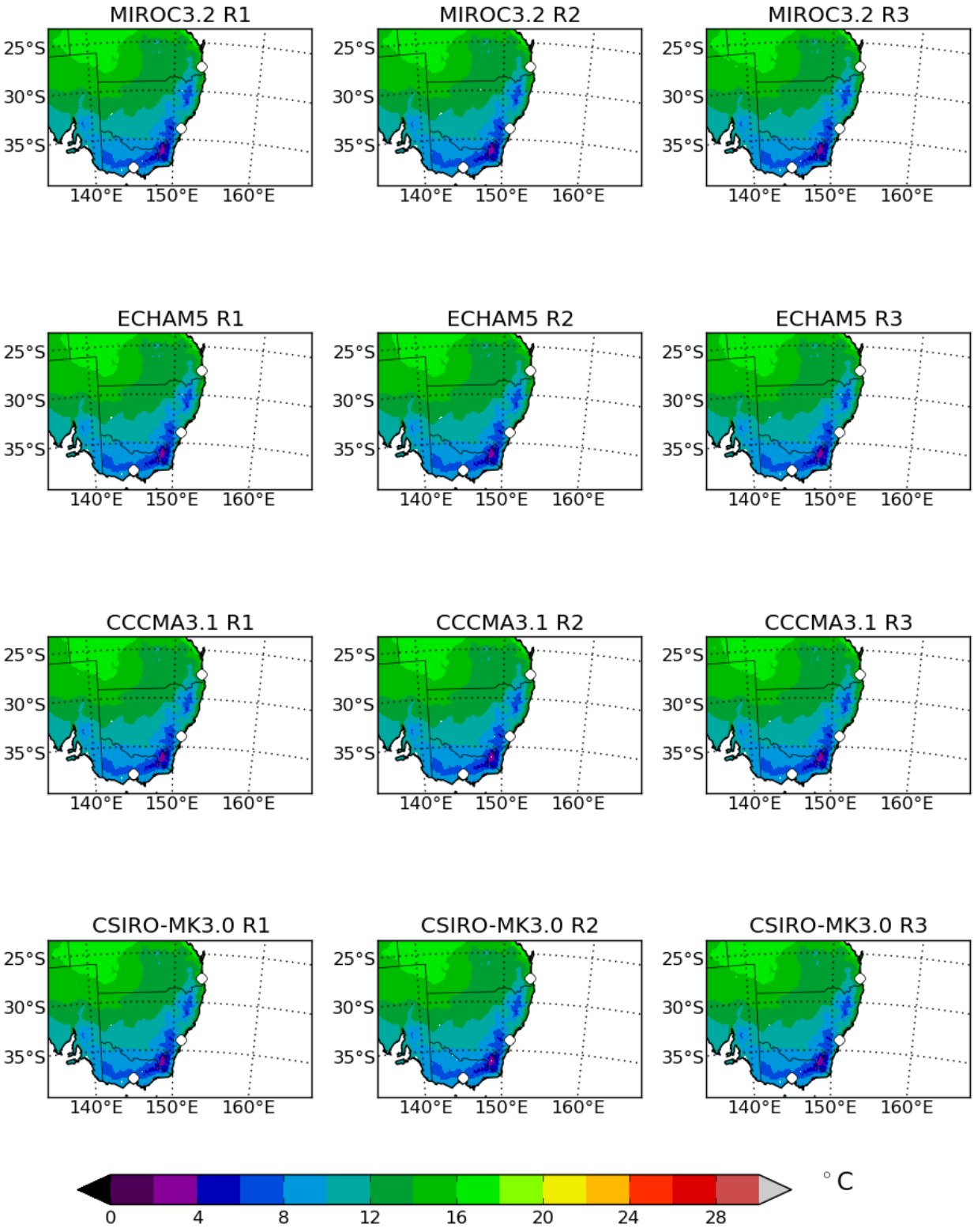

Figure 4.33: Annual mean of bias-corrected daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

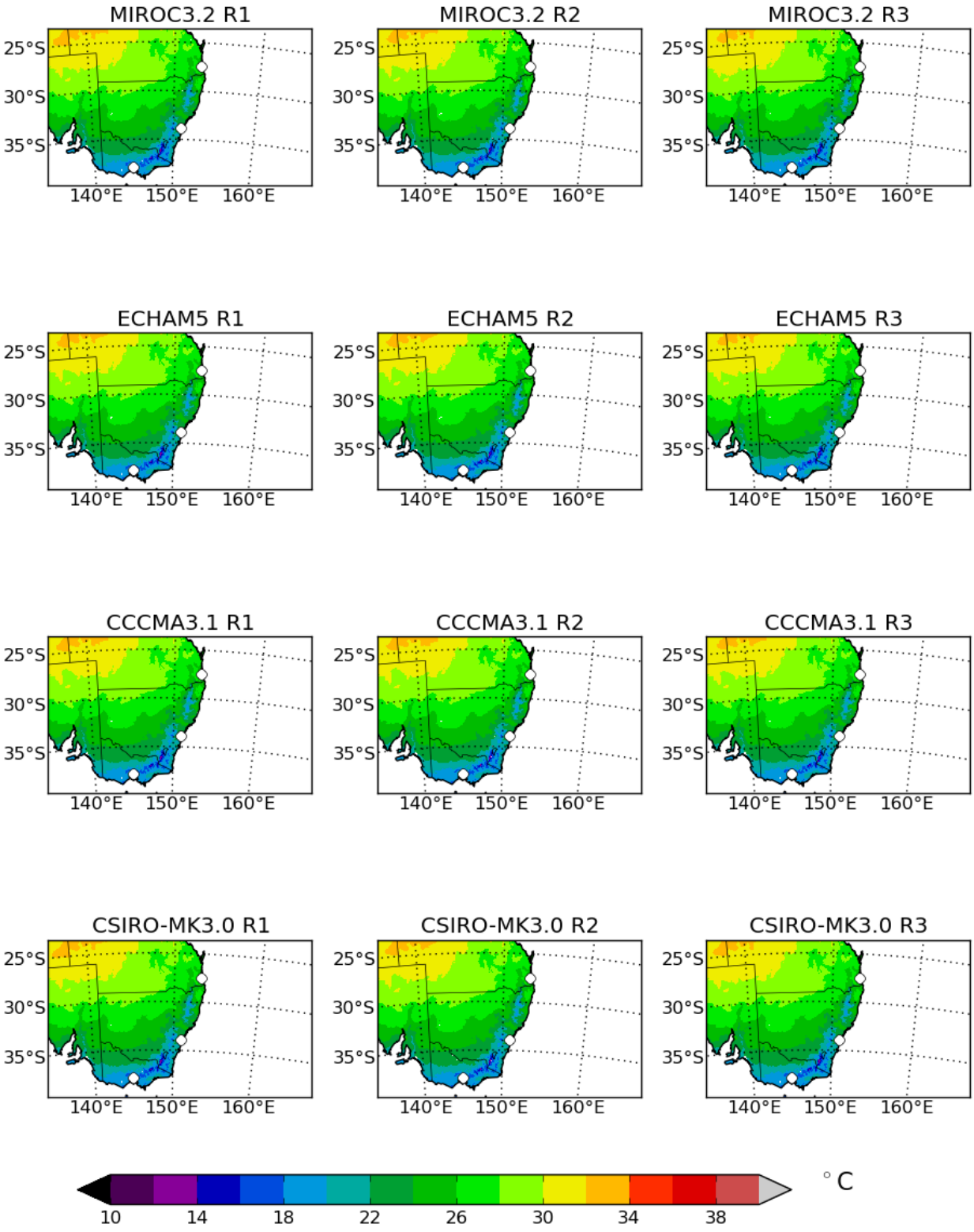

Figure 4.34: Annual mean of bias-corrected daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

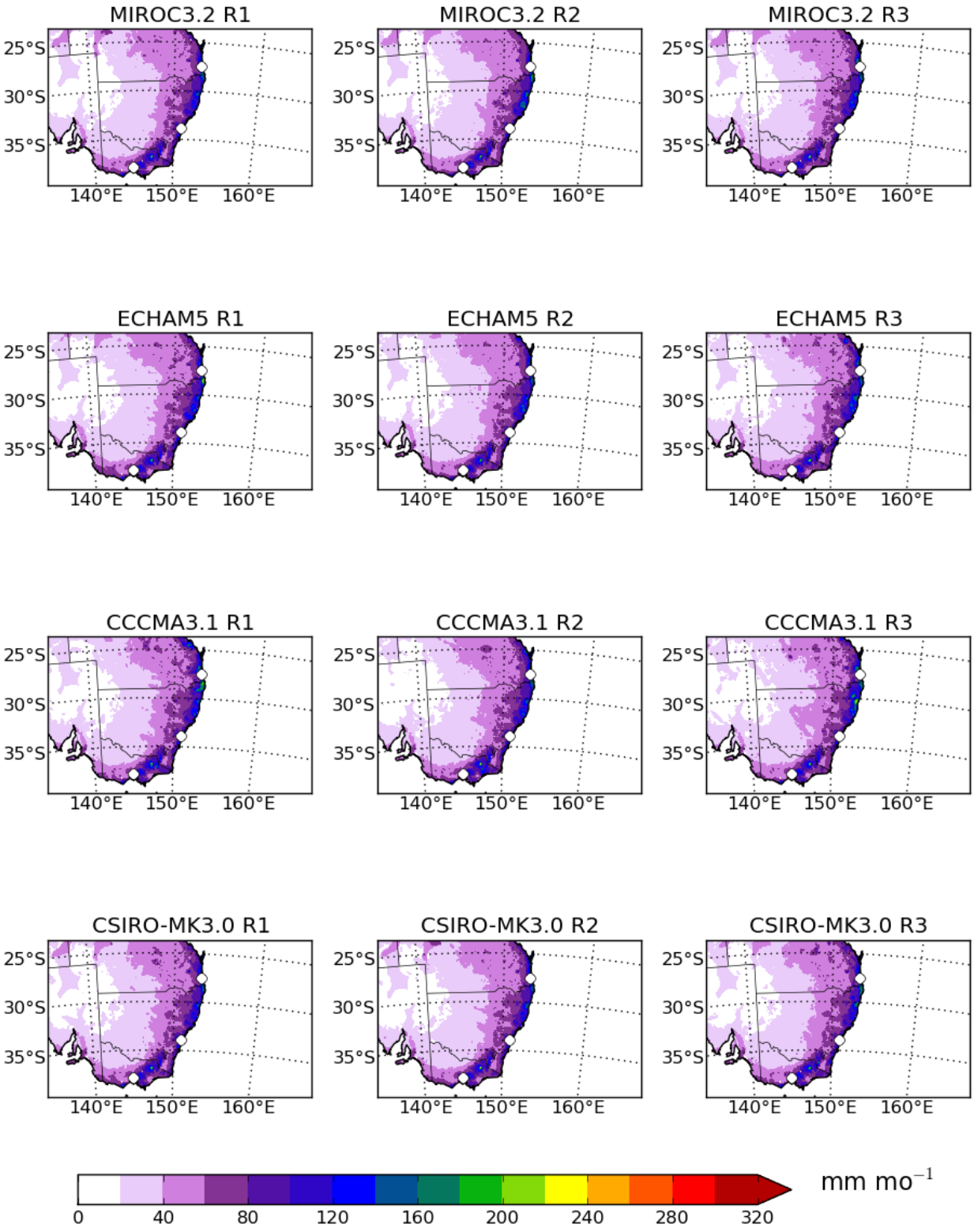

Figure 4.35: Annual mean of bias-corrected precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

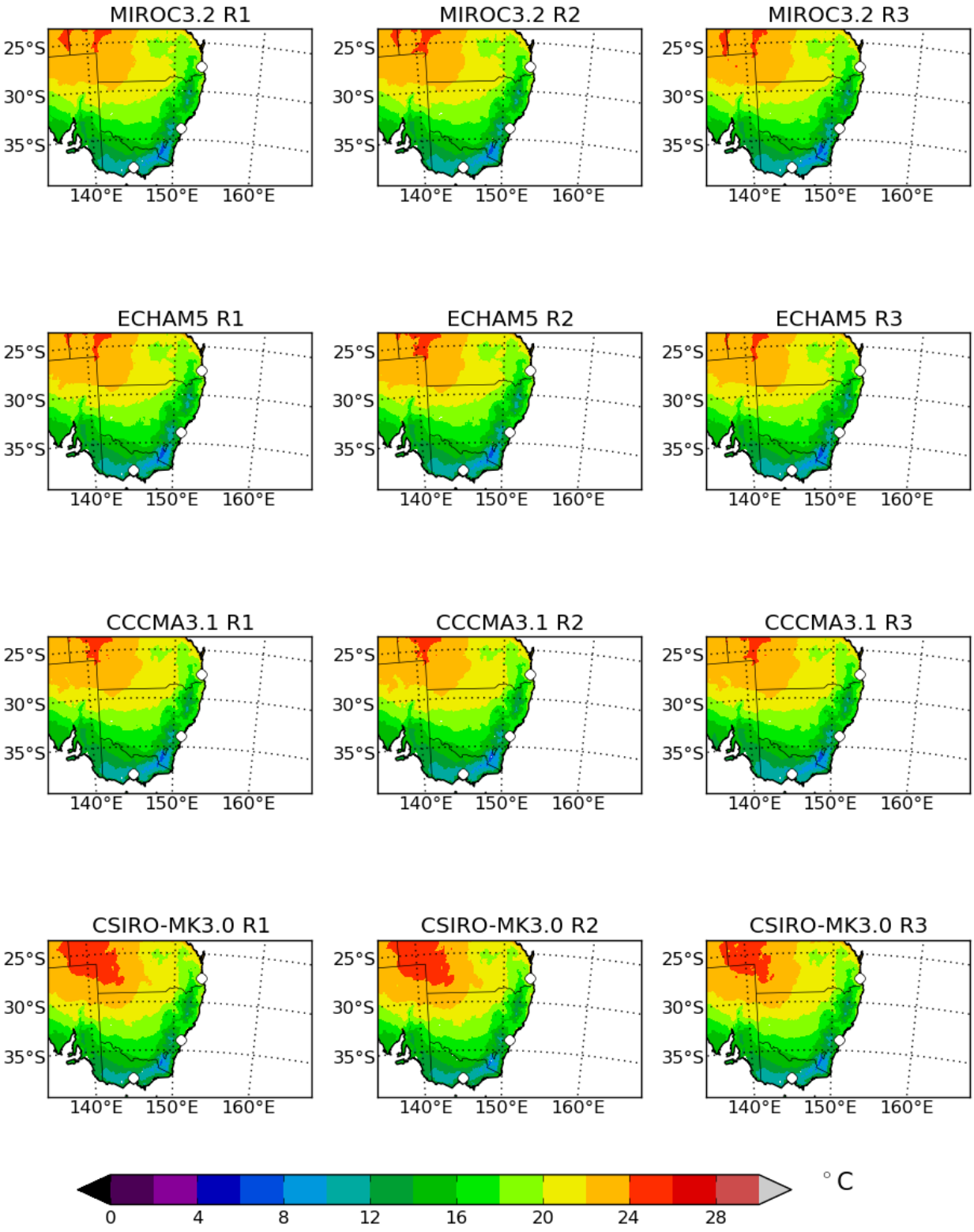

Figure 4.36: DJF mean of bias-corrected daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

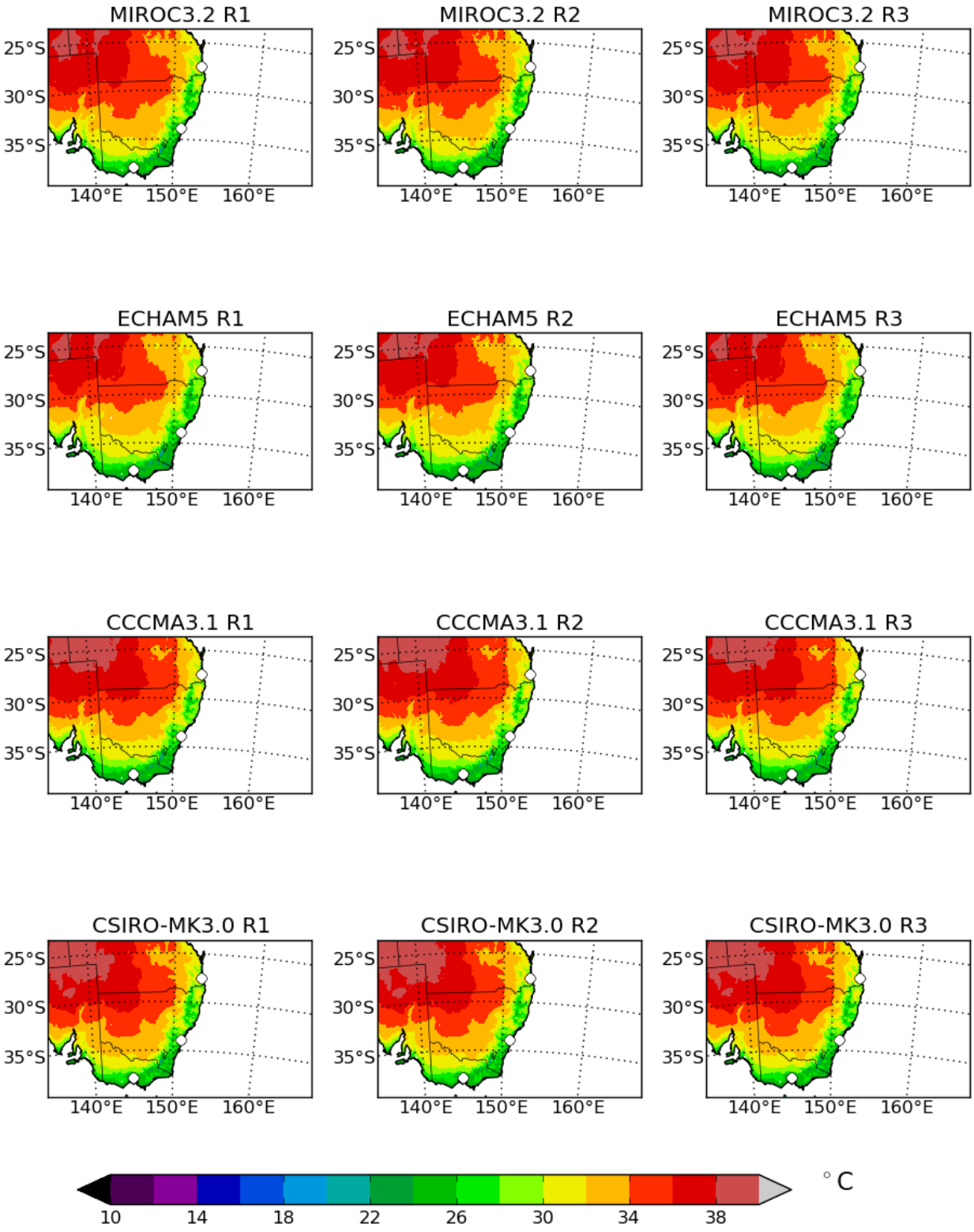

Figure 4.37: DJF mean of bias-corrected daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

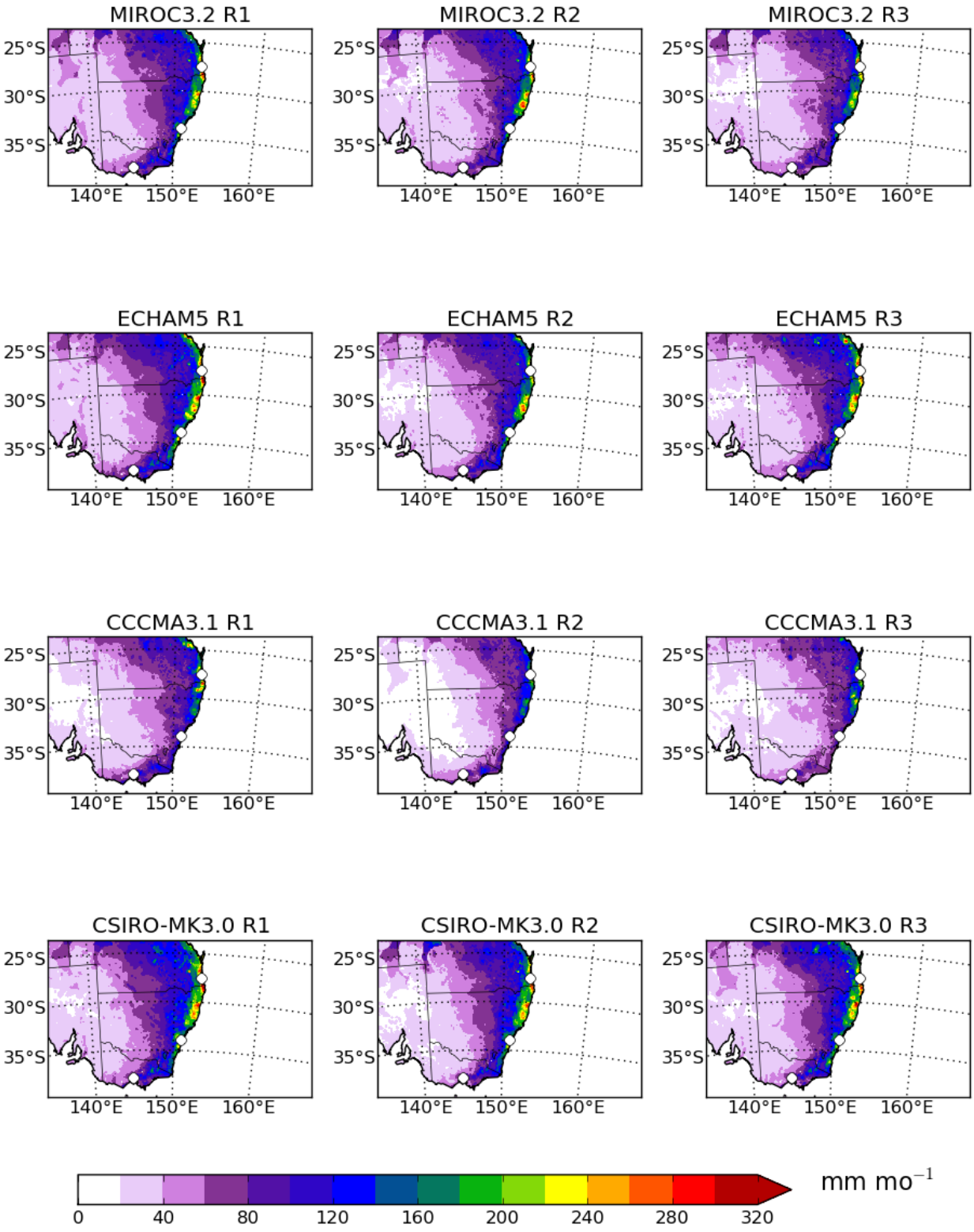

Figure 4.38: DJF mean of bias-corrected precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

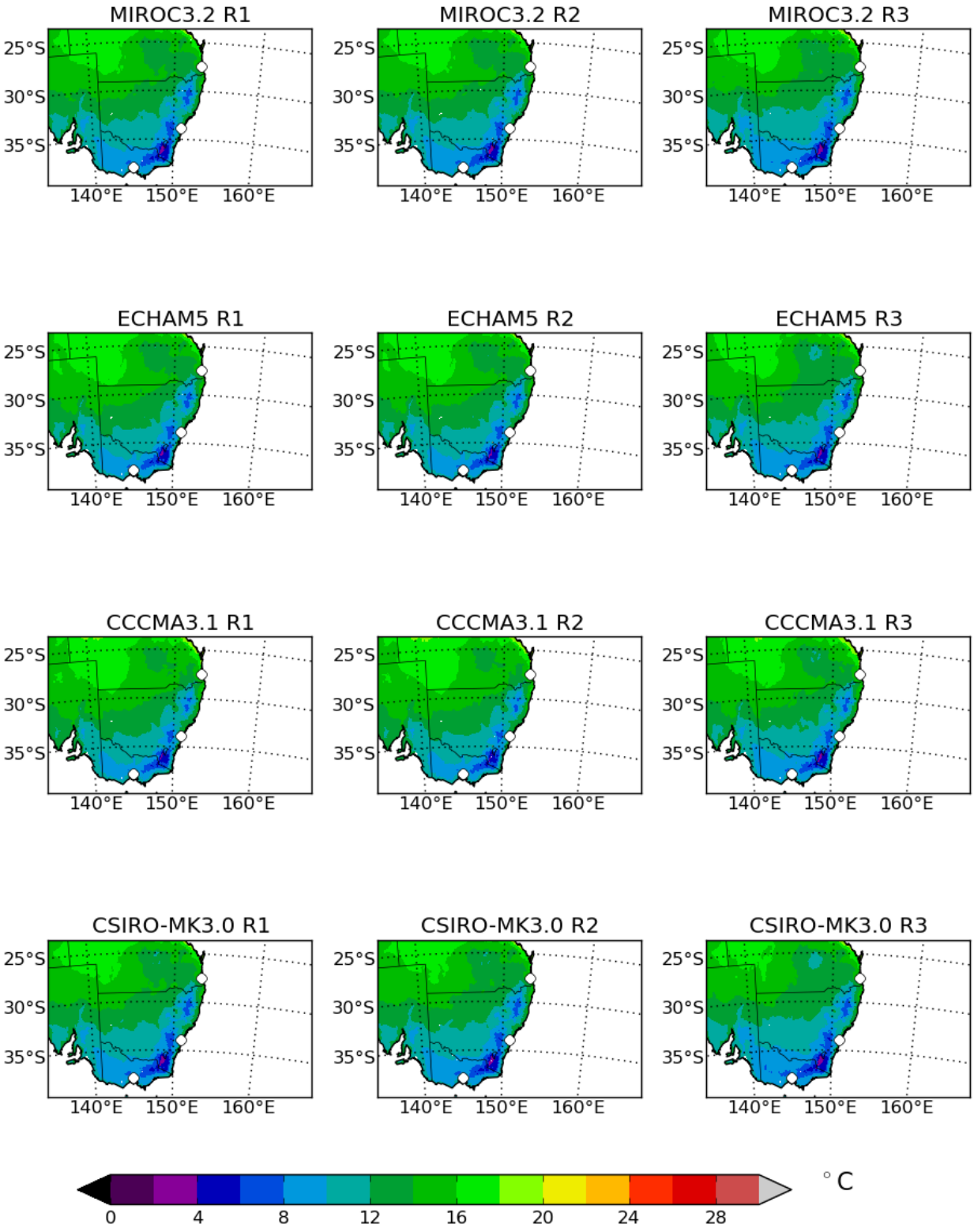

Figure 4.39: MAM mean of bias-corrected daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

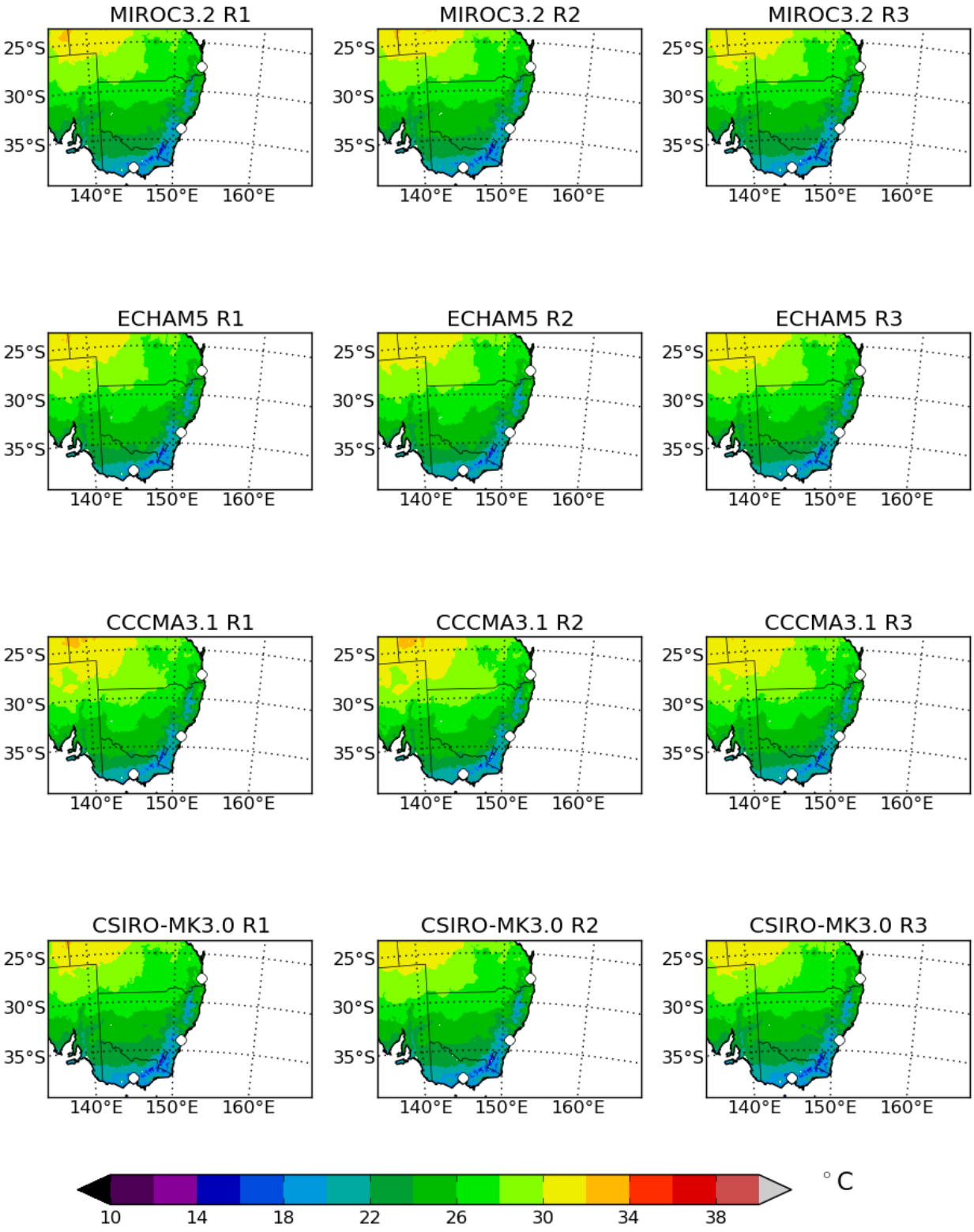

Figure 4.40: MAM mean of bias-corrected daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

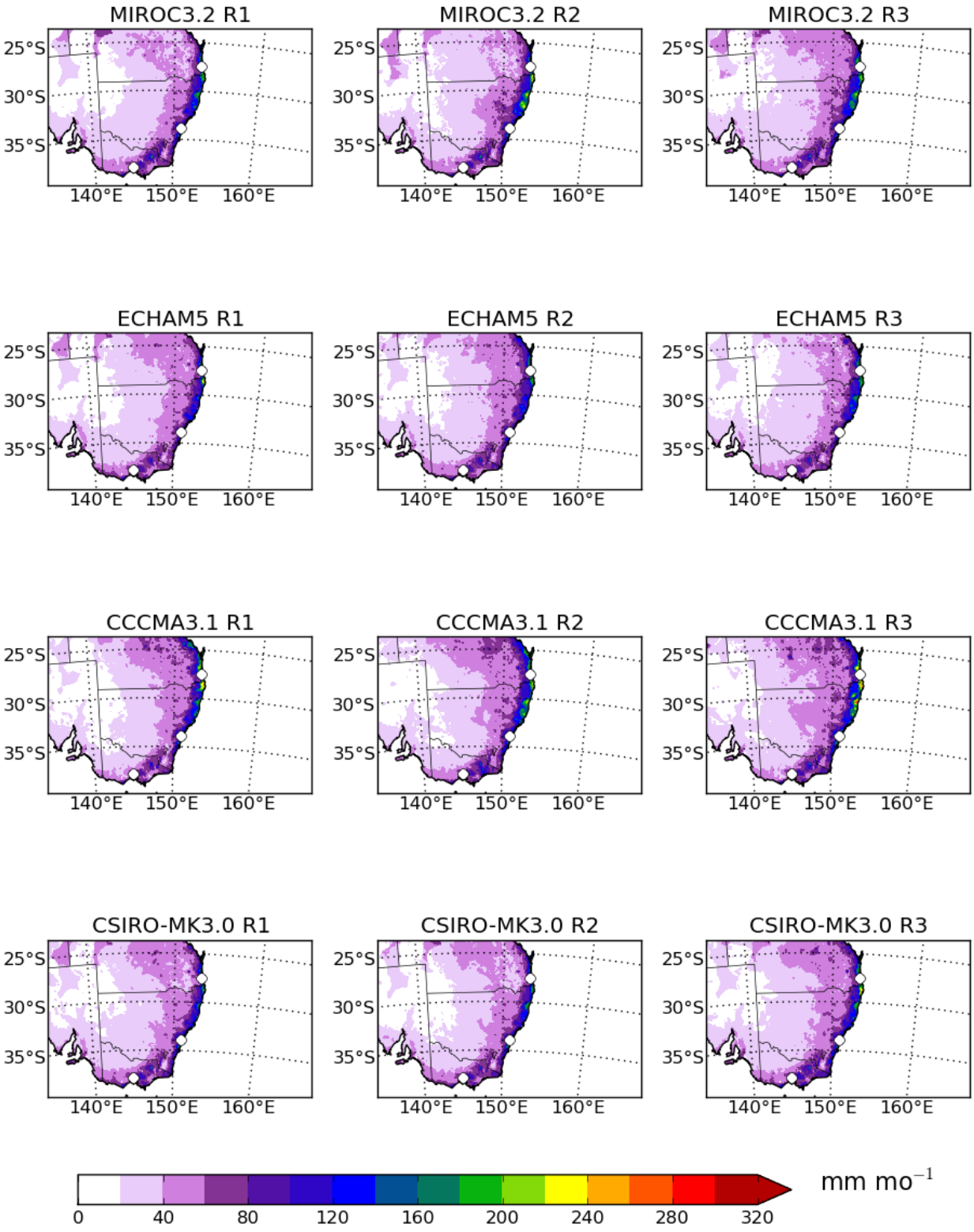

Figure 4.41: MAM mean of bias-corrected precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

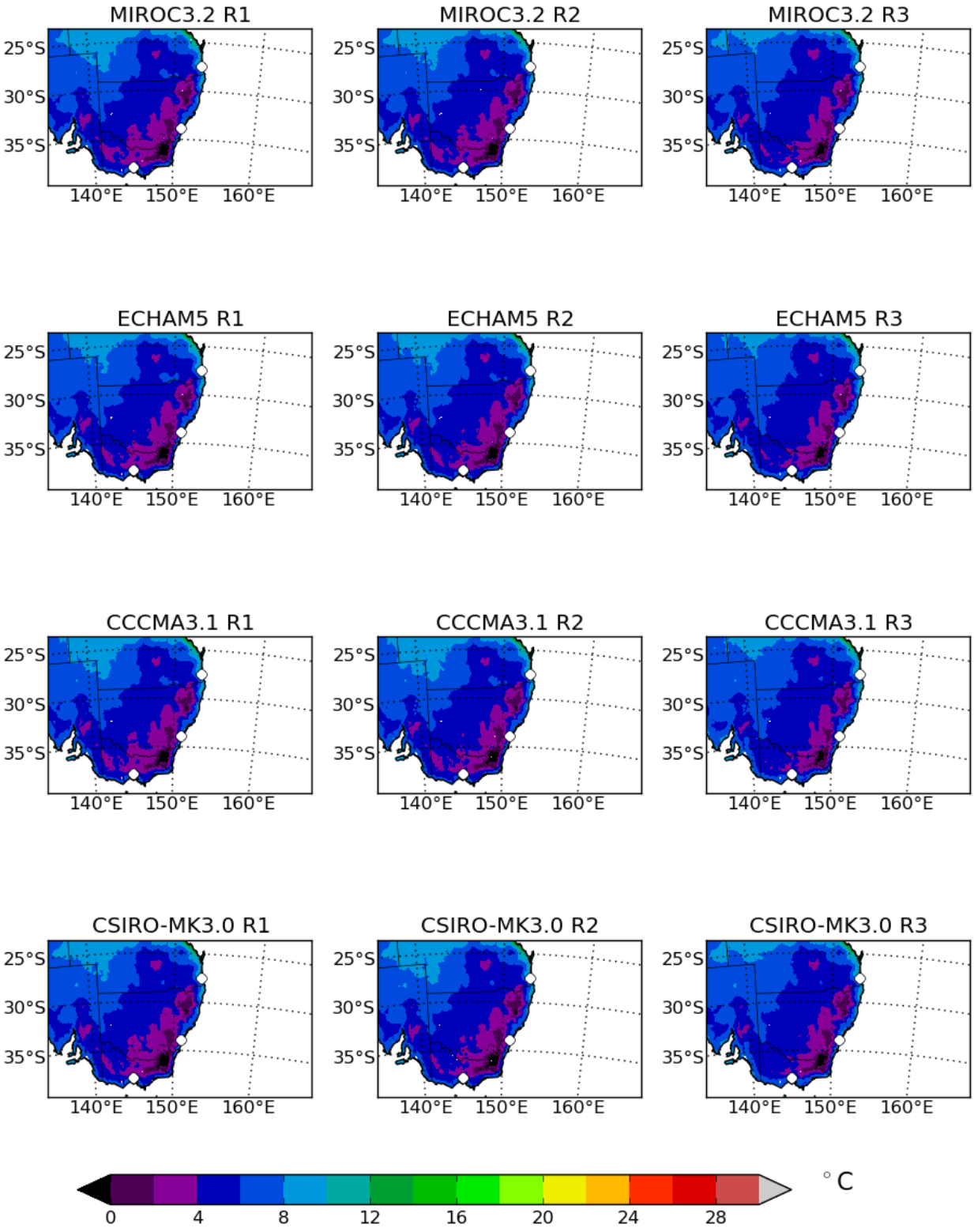

Figure 4.42: JJA mean of bias-corrected daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

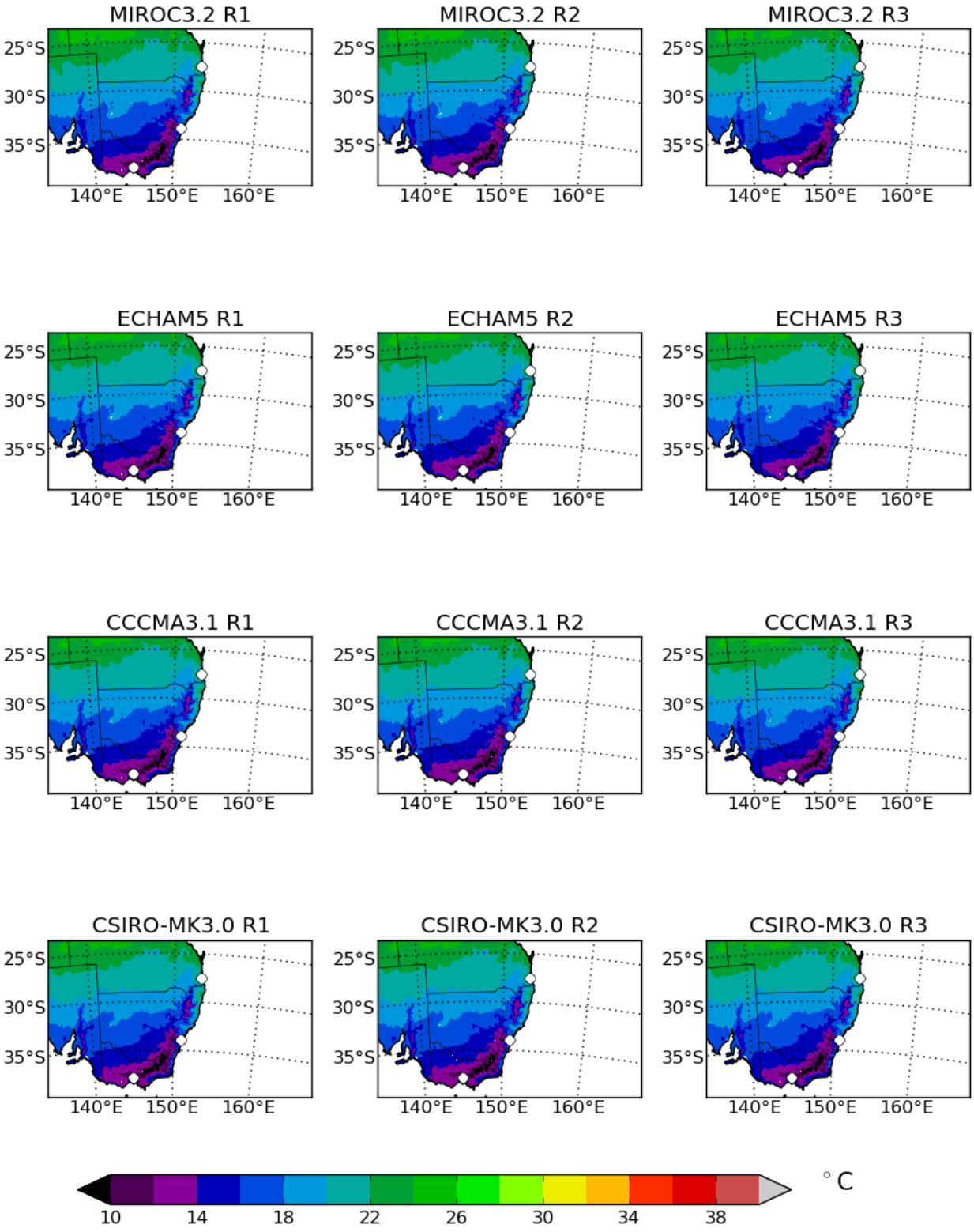

Figure 4.43: JJA mean of bias-corrected daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

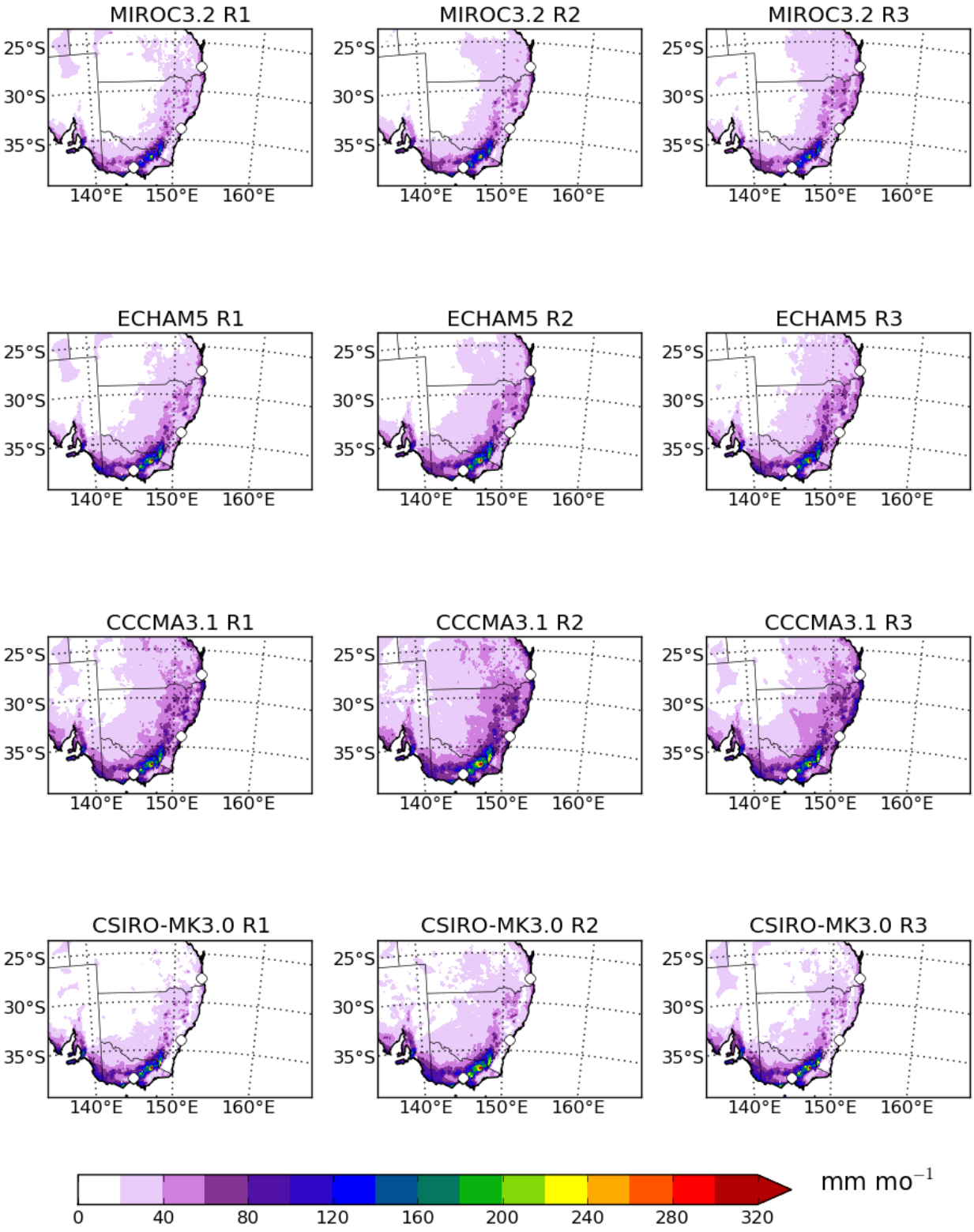

Figure 4.44: JJA mean of bias-corrected precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

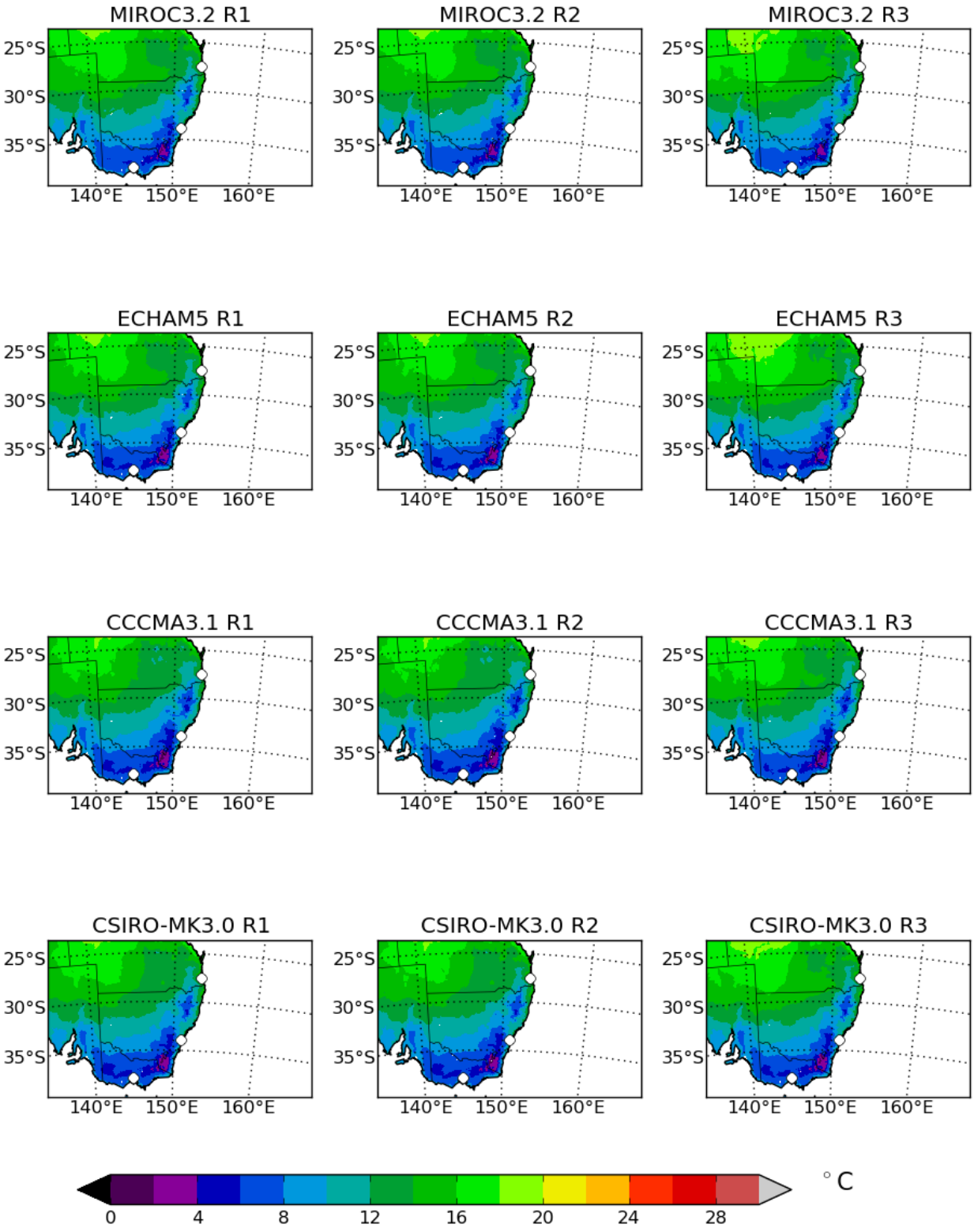

Figure 4.45: SON mean of bias-corrected daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

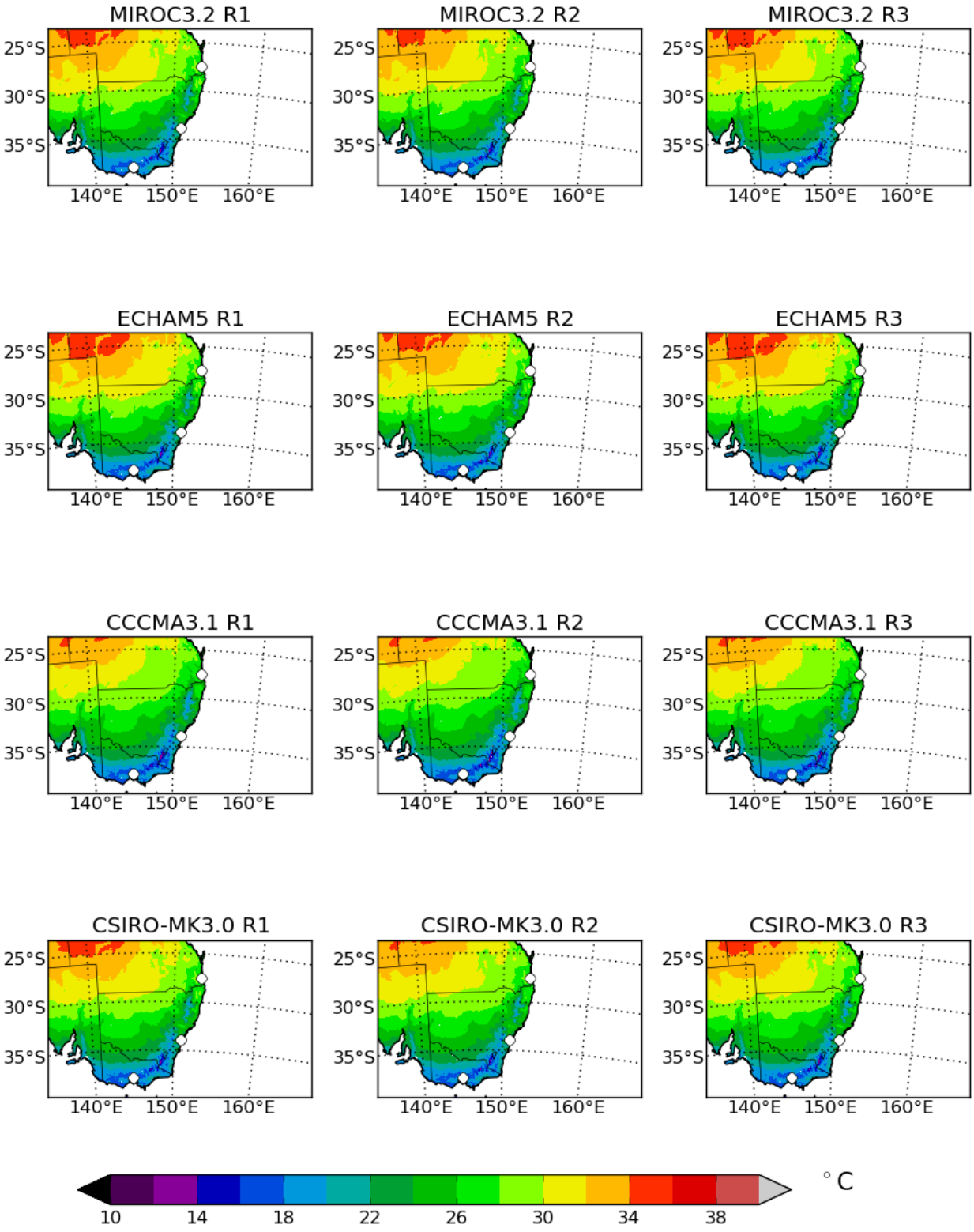

Figure 4.46: SON mean of bias-corrected daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

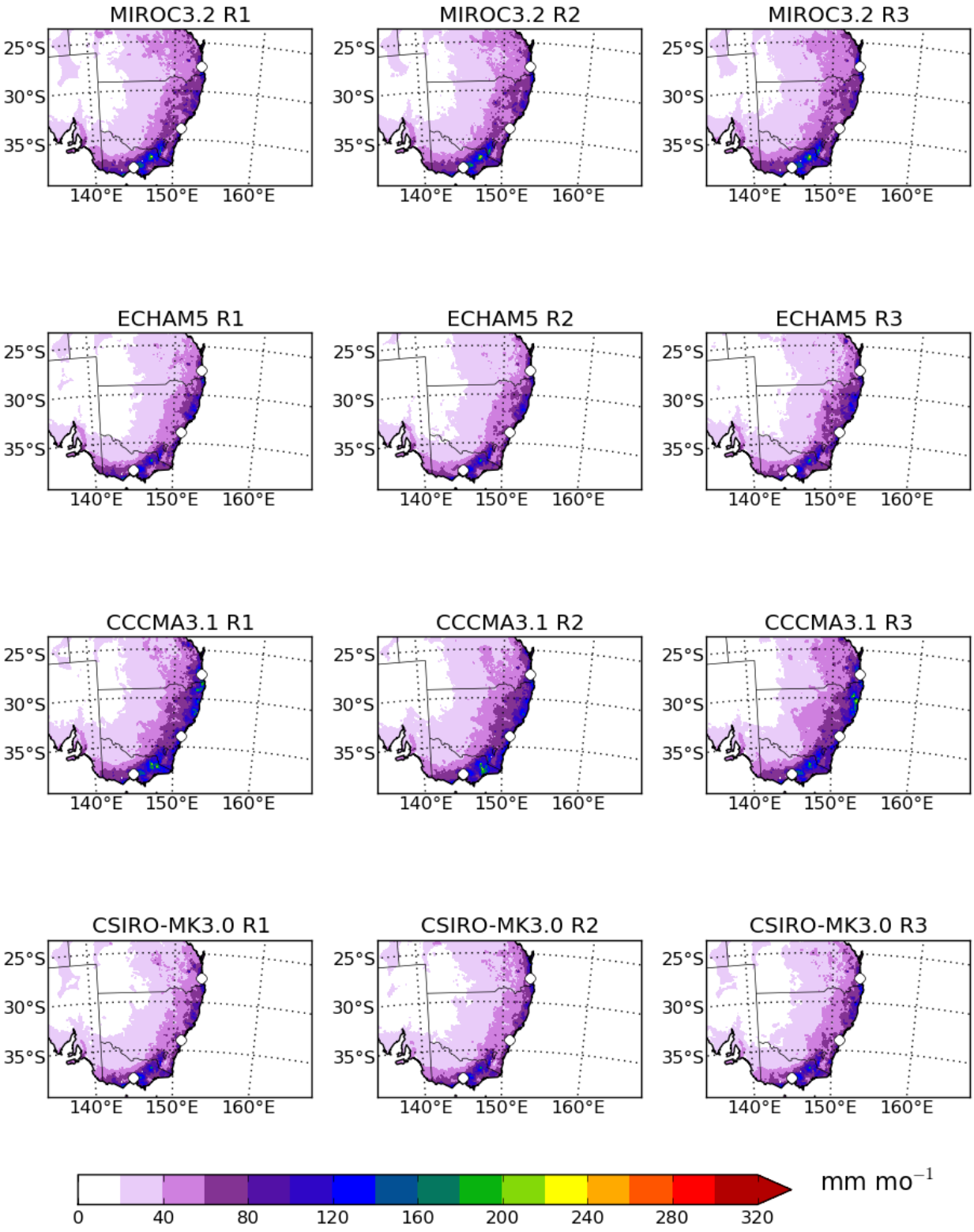

Figure 4.47: SON mean of bias-corrected precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

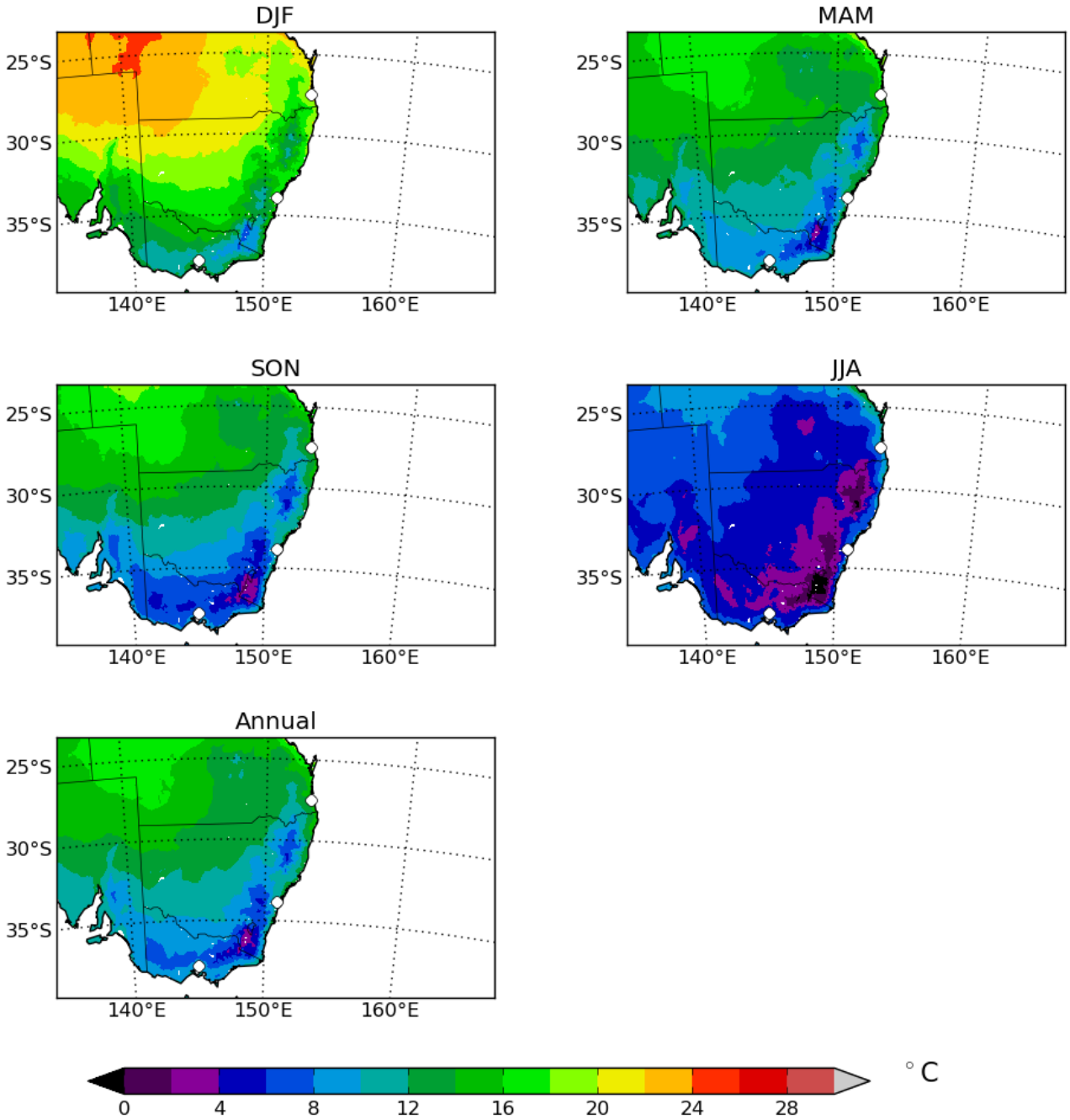

Figure 4.48: Seasonal and annual multimodel means of bias-corrected daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

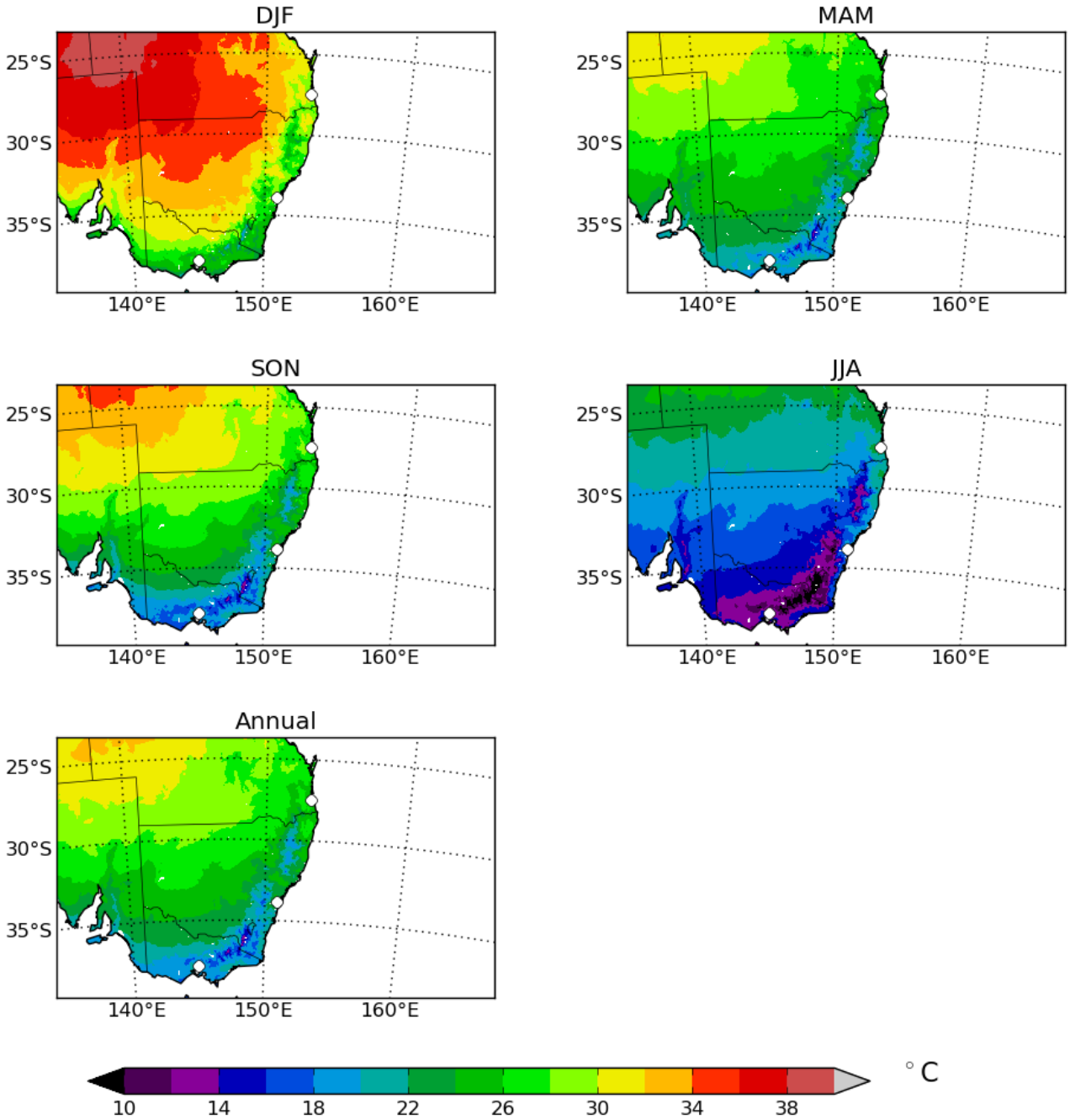

Figure 4.49: Seasonal and annual multimodel means of bias-corrected daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

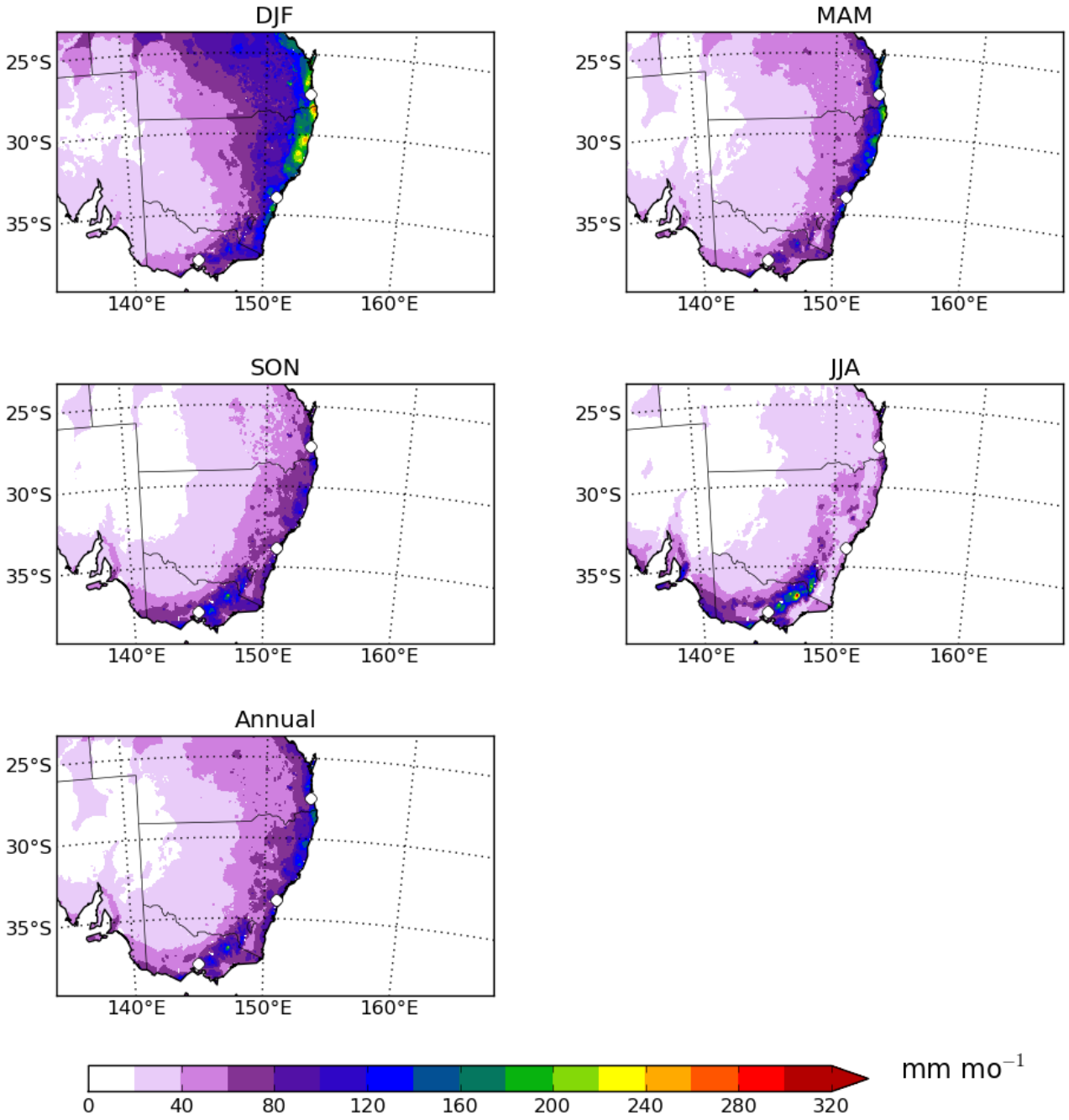

Figure 4.50: Seasonal and annual multimodel means of bias-corrected precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 5

Biases: Present Day Models - Observations

This chapter contains climatological seasonal and annual mean biases (models - observations) for present-day (1990-2009) near-surface air temperature and precipitation. We first show the results for the GCMs used to drive the RCMs, then for original RCM output, and finally for bias-corrected RCM output. The bias-corrected RCM output is the RCM output corrected for biases between the models and the observations using the methods described here [6].

5.1 Biases: 1990-2009 Driving GCMs - Observations

This subsection shows climatological biases for present-day near-surface air temperature and precipitation for each of the GCMs used to provide boundary conditions to the RCMs. The biases are defined as the difference between the GCM output and the AWAP climatology for the period 1990-2009. The plots are ordered first by GCM, and then by variable.

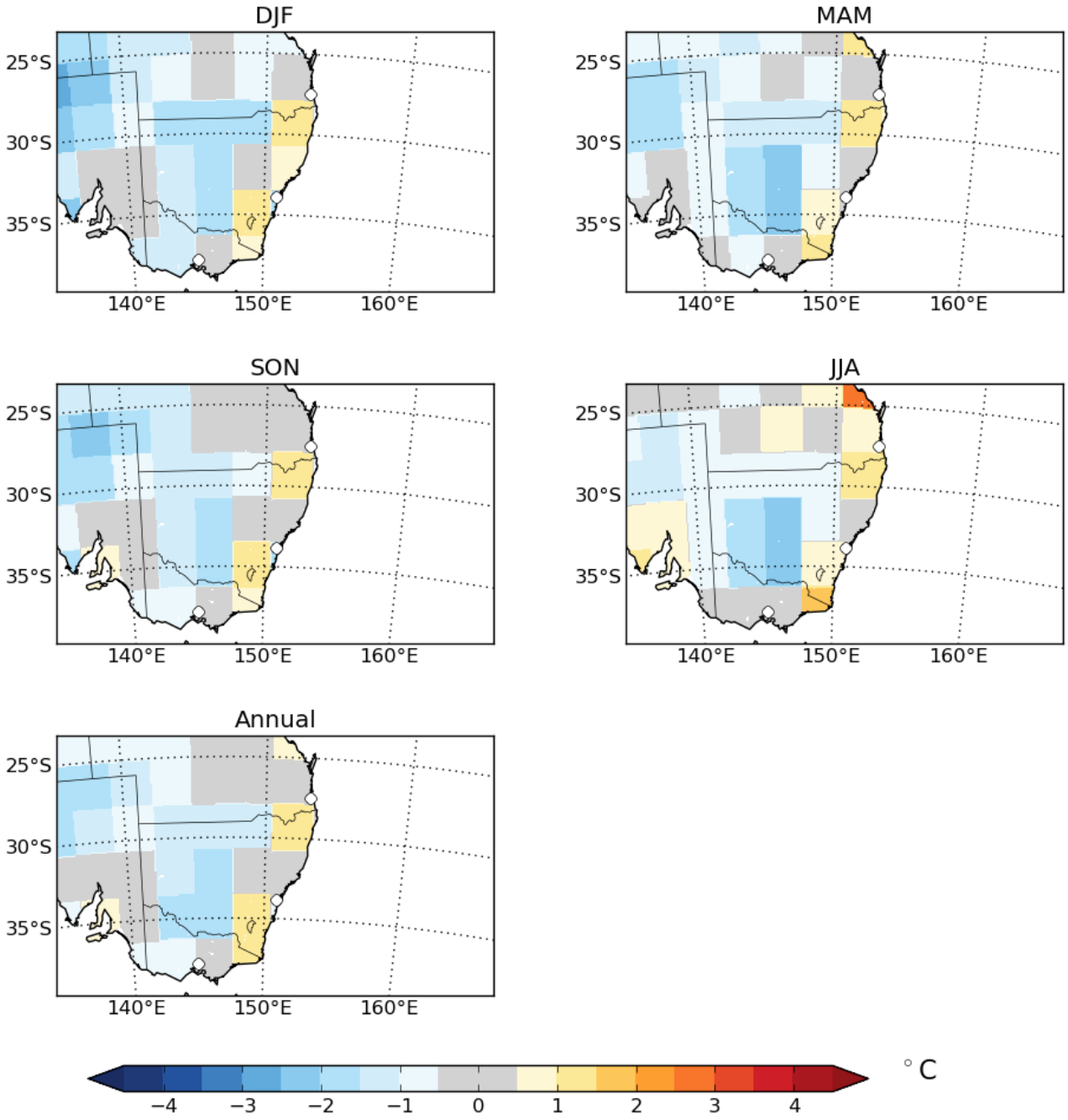

Figure 5.1: Seasonal and annual means of MIROC3.2 - AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

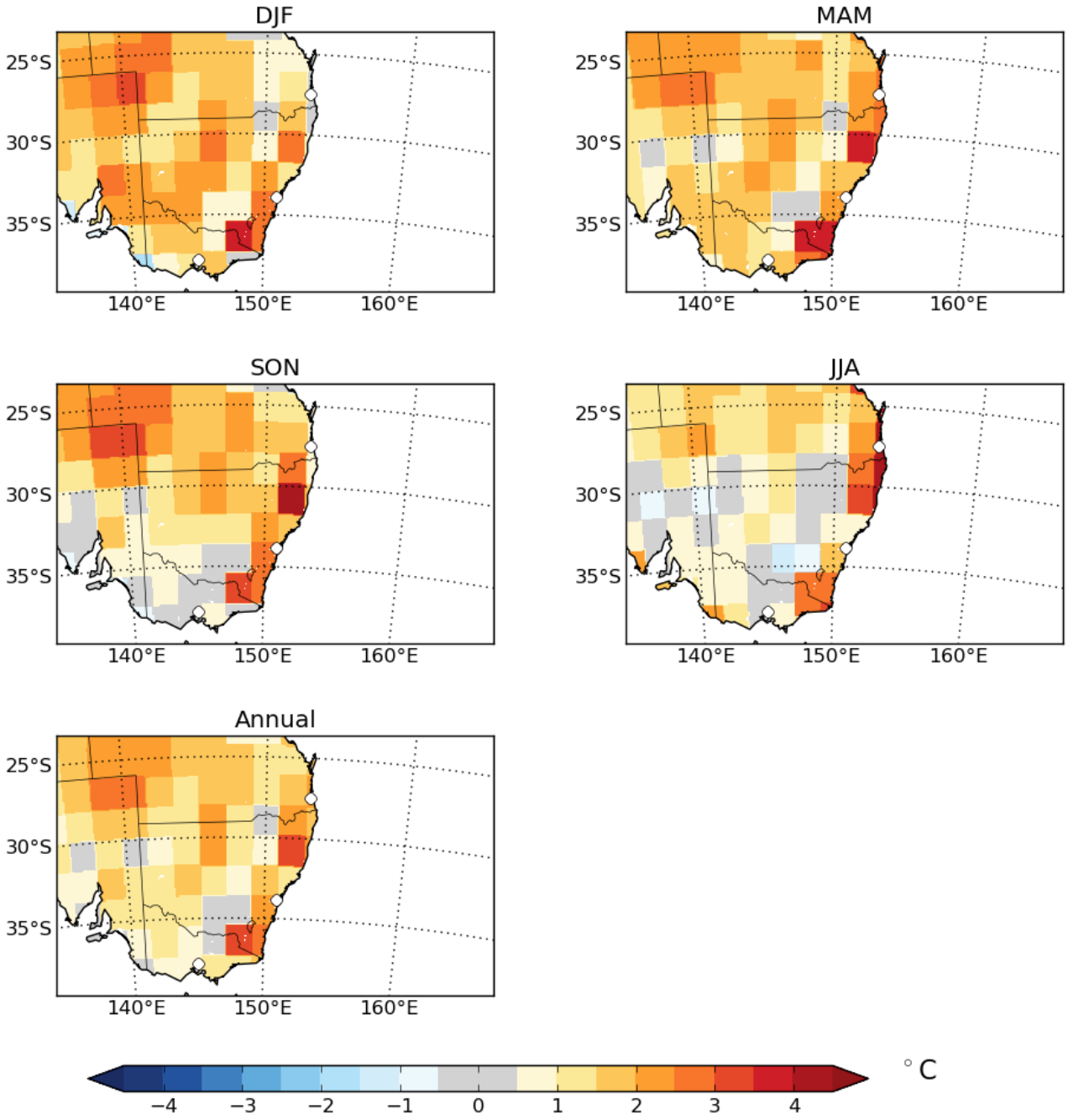

Figure 5.2: Seasonal and annual means of ECHAM5 - AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

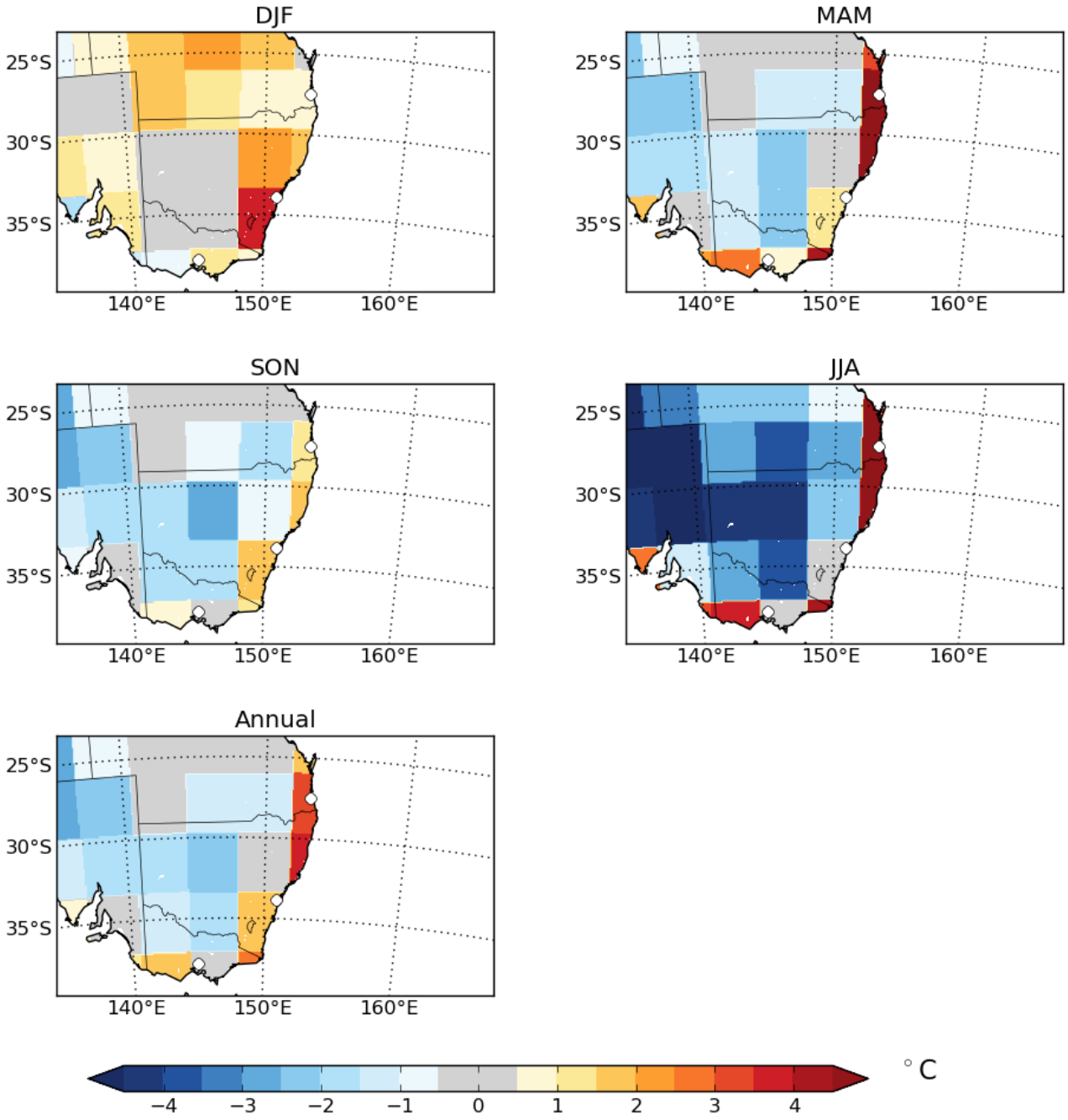

Figure 5.3: Seasonal and annual means of CCCMA3.1 - AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

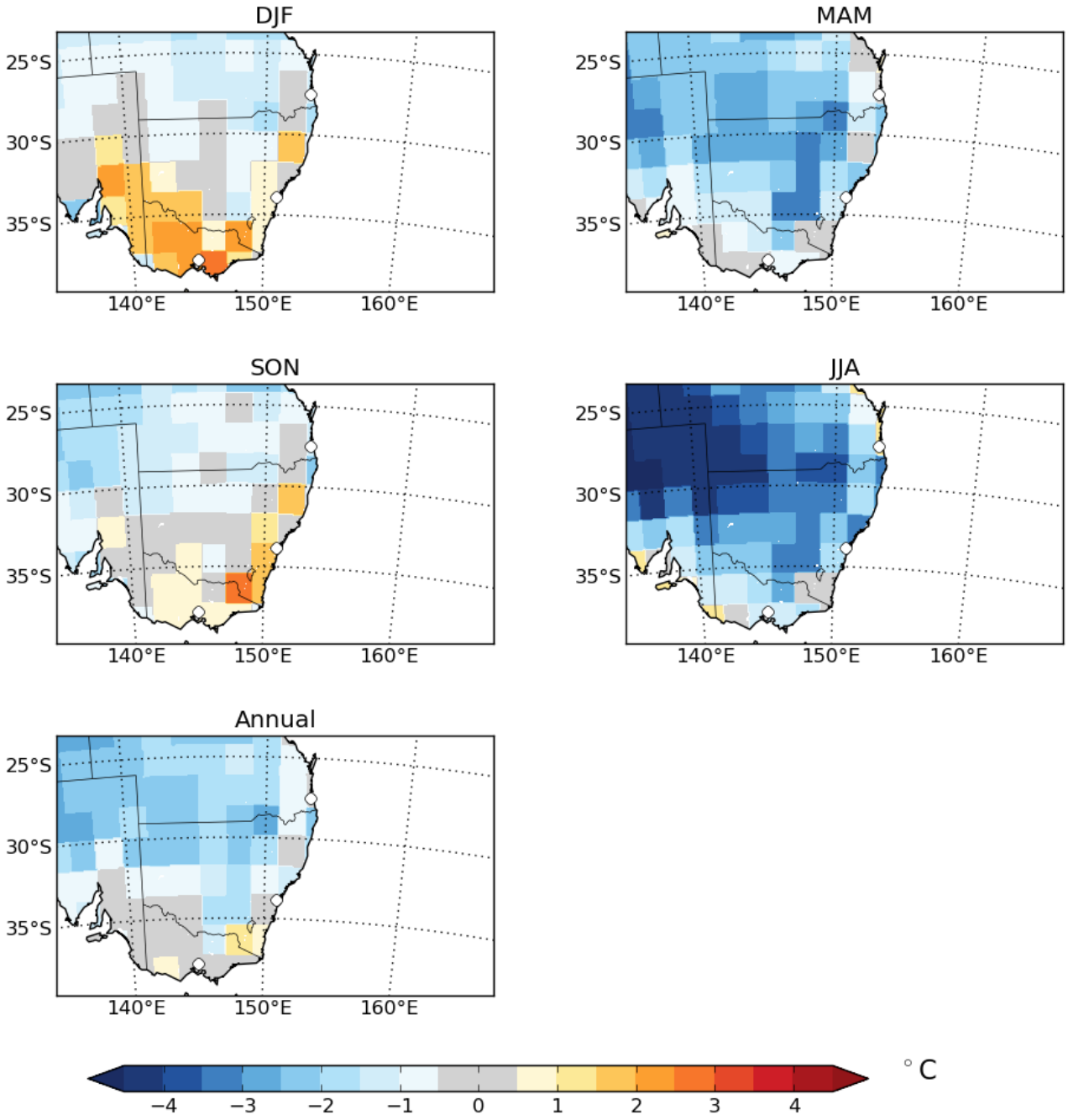

Figure 5.4: Seasonal and annual means of CSIRO-MK3.0 - AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

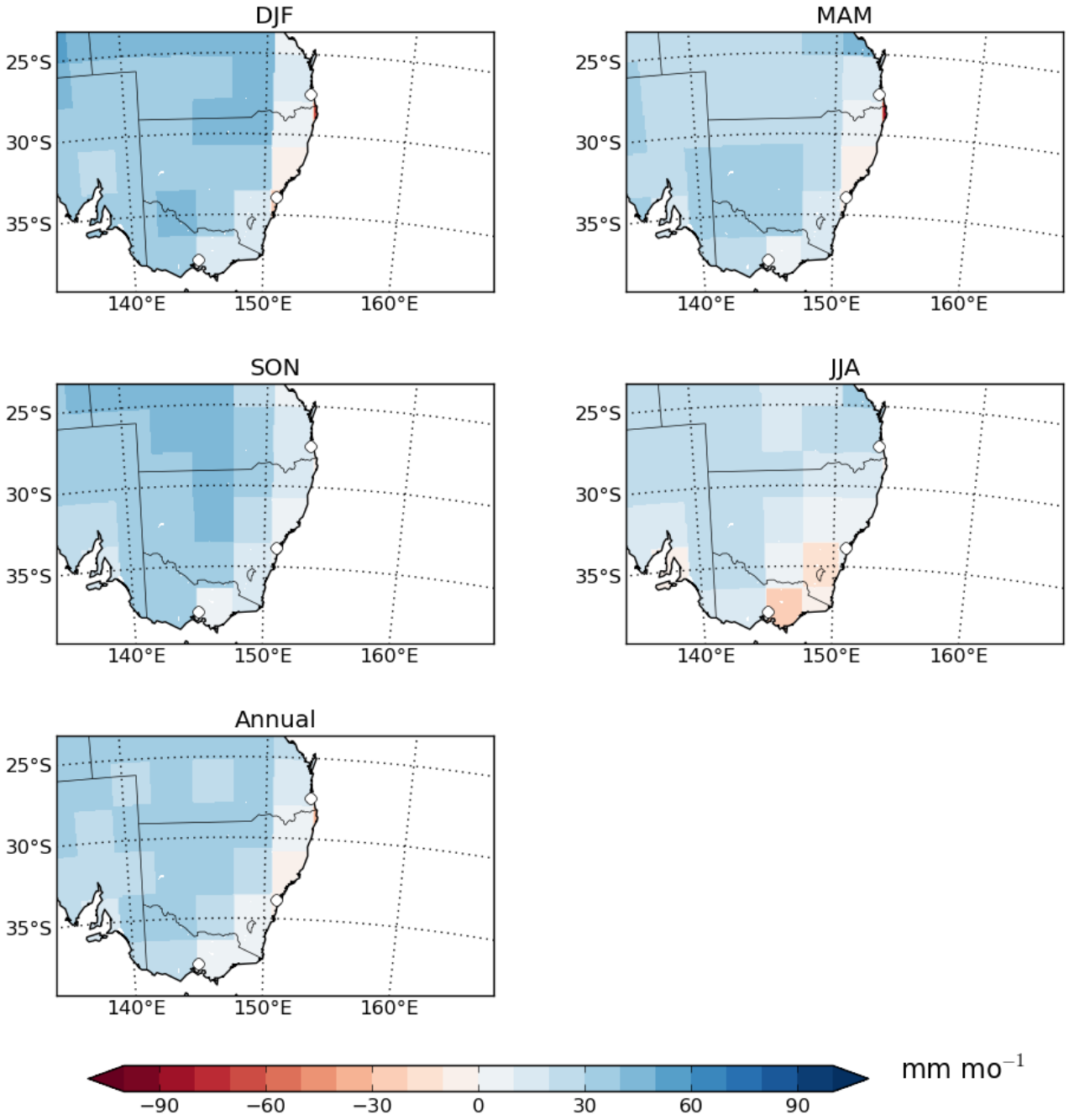

Figure 5.5: Seasonal and annual means of MIROC3.2 - AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

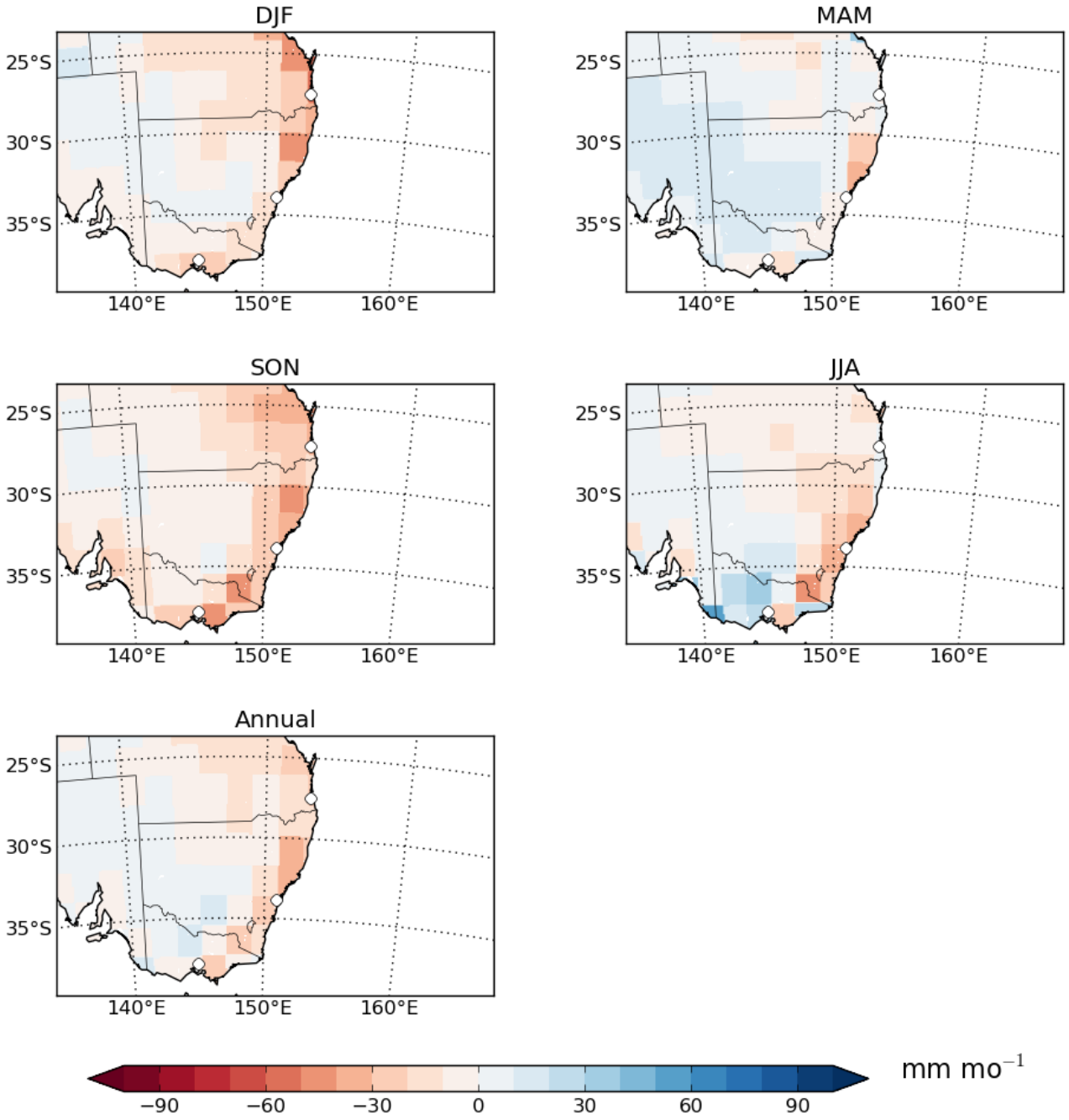

Figure 5.6: Seasonal and annual means of ECHAM5 - AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

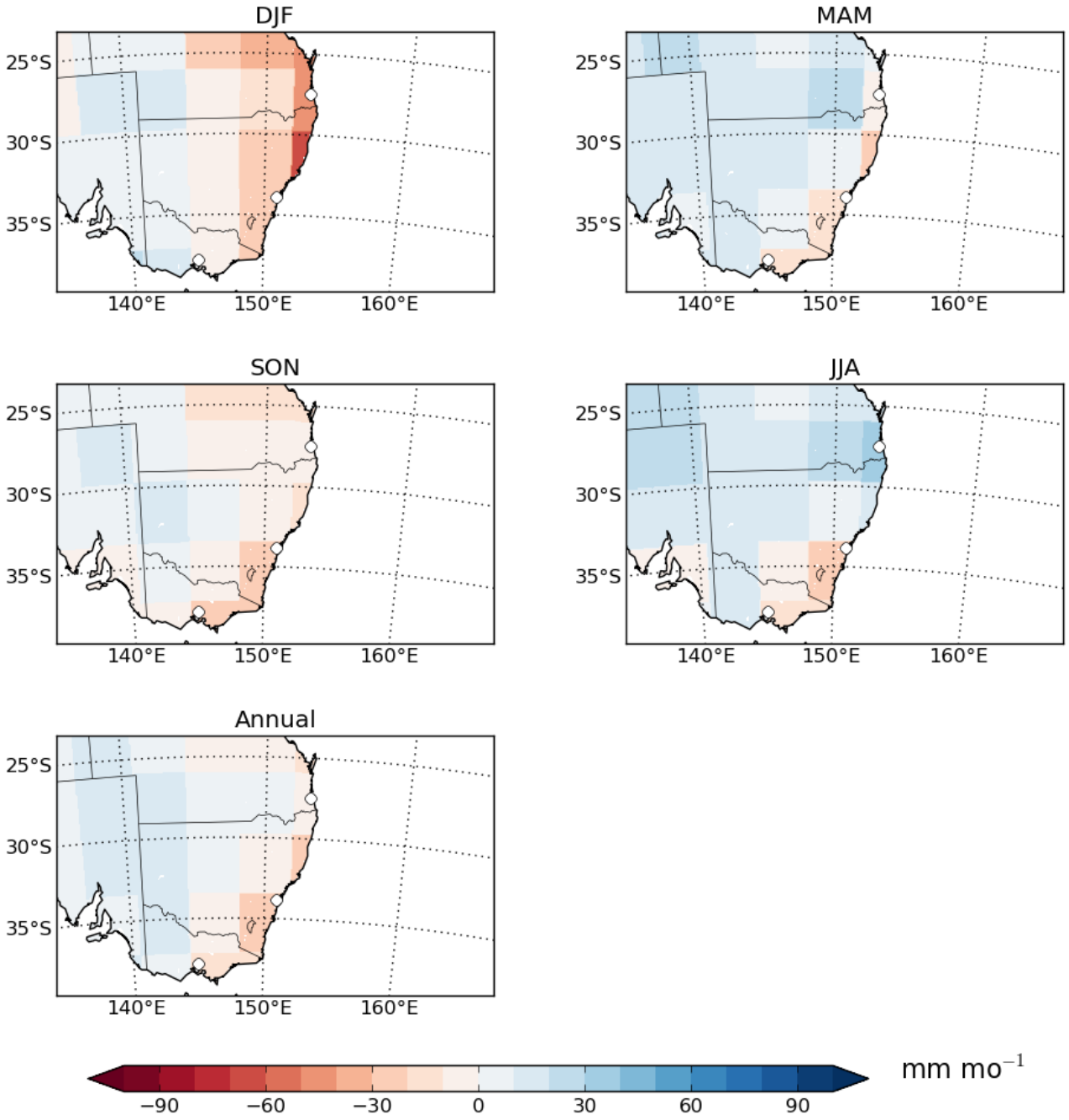

Figure 5.7: Seasonal and annual means of CCCMA3.1 - AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

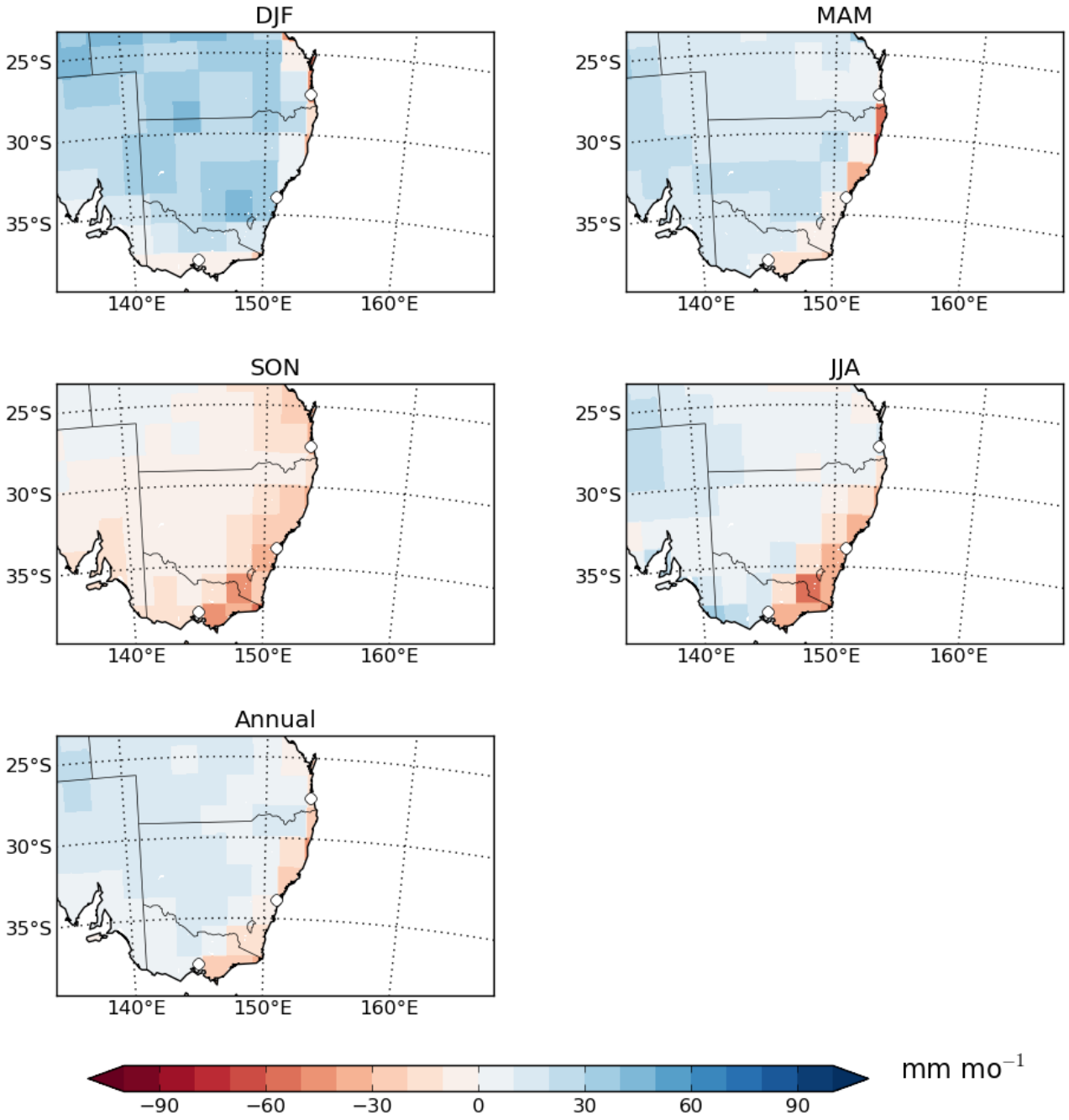

Figure 5.8: Seasonal and annual means of CSIRO-MK3.0 - AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

5.2 Biases: 1990-2009 Regional Model Output - Observations

This subsection contains climatological biases for present-day near-surface air temperature, daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation for the original RCM output. The biases are defined as the difference between model output and AWAP observations for the period 1990-2009. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average model bias, whereas the individual-model plots show the spread of biases between models.

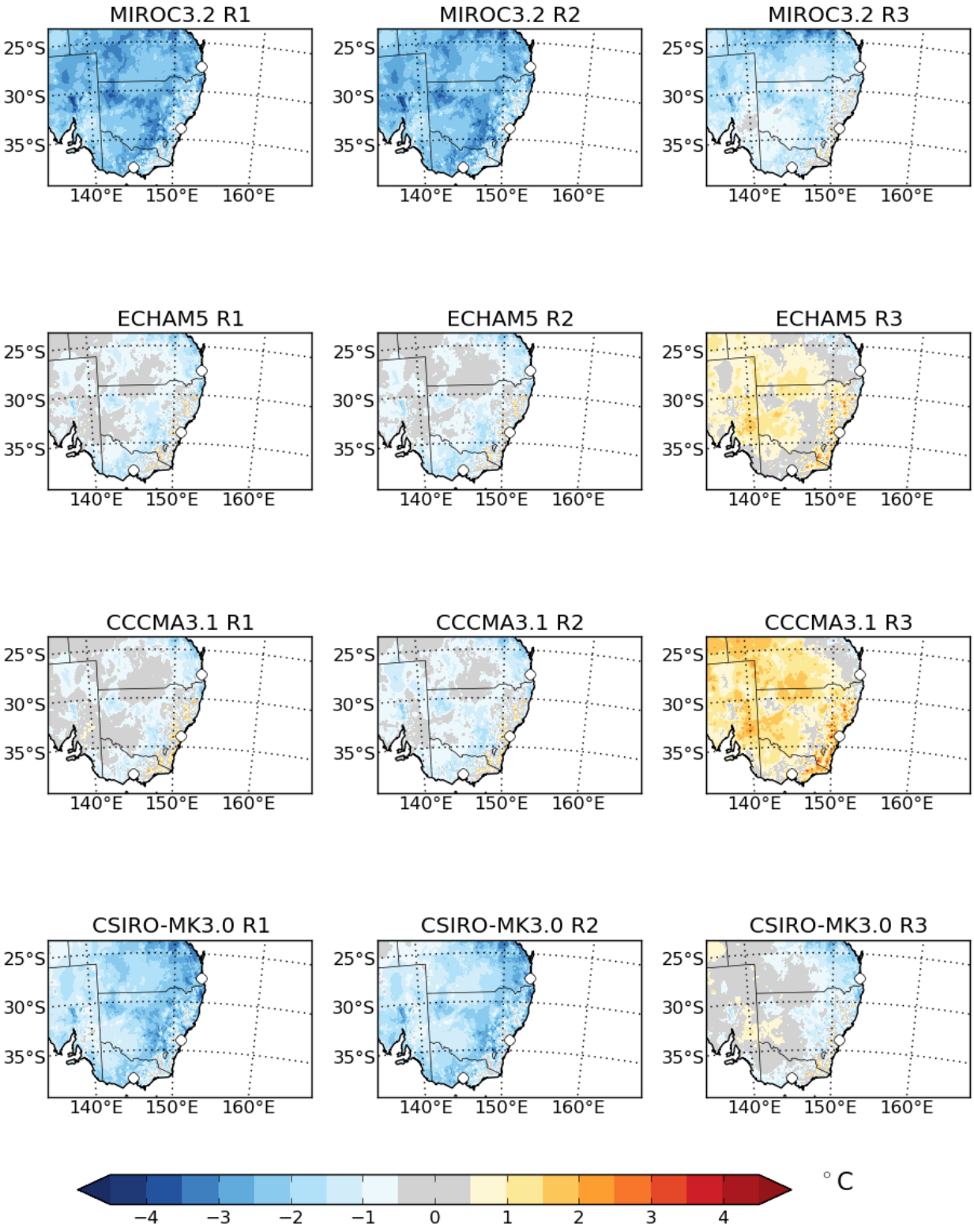

Figure 5.9: Annual mean of WRF minus AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

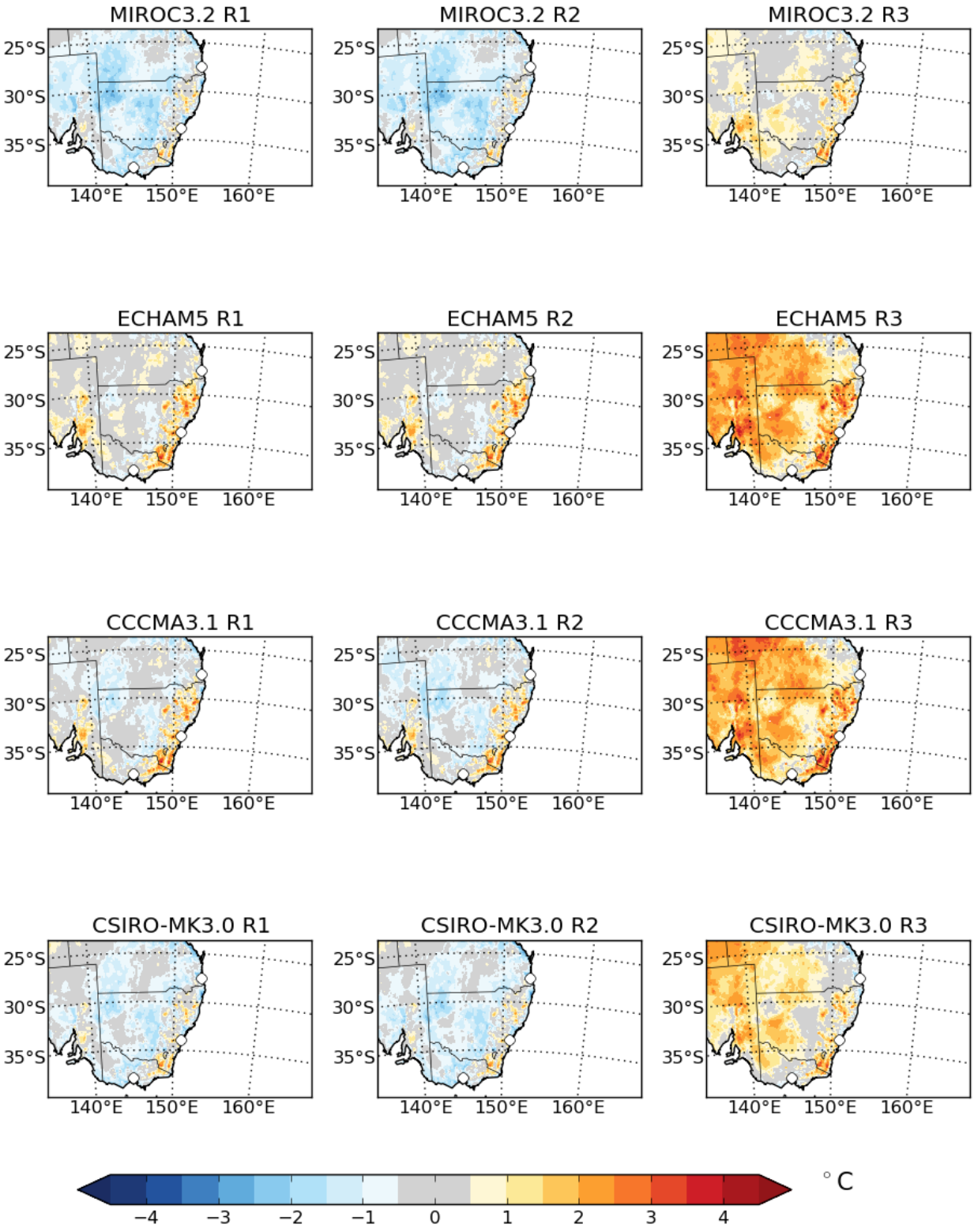

Figure 5.10: Annual mean of WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

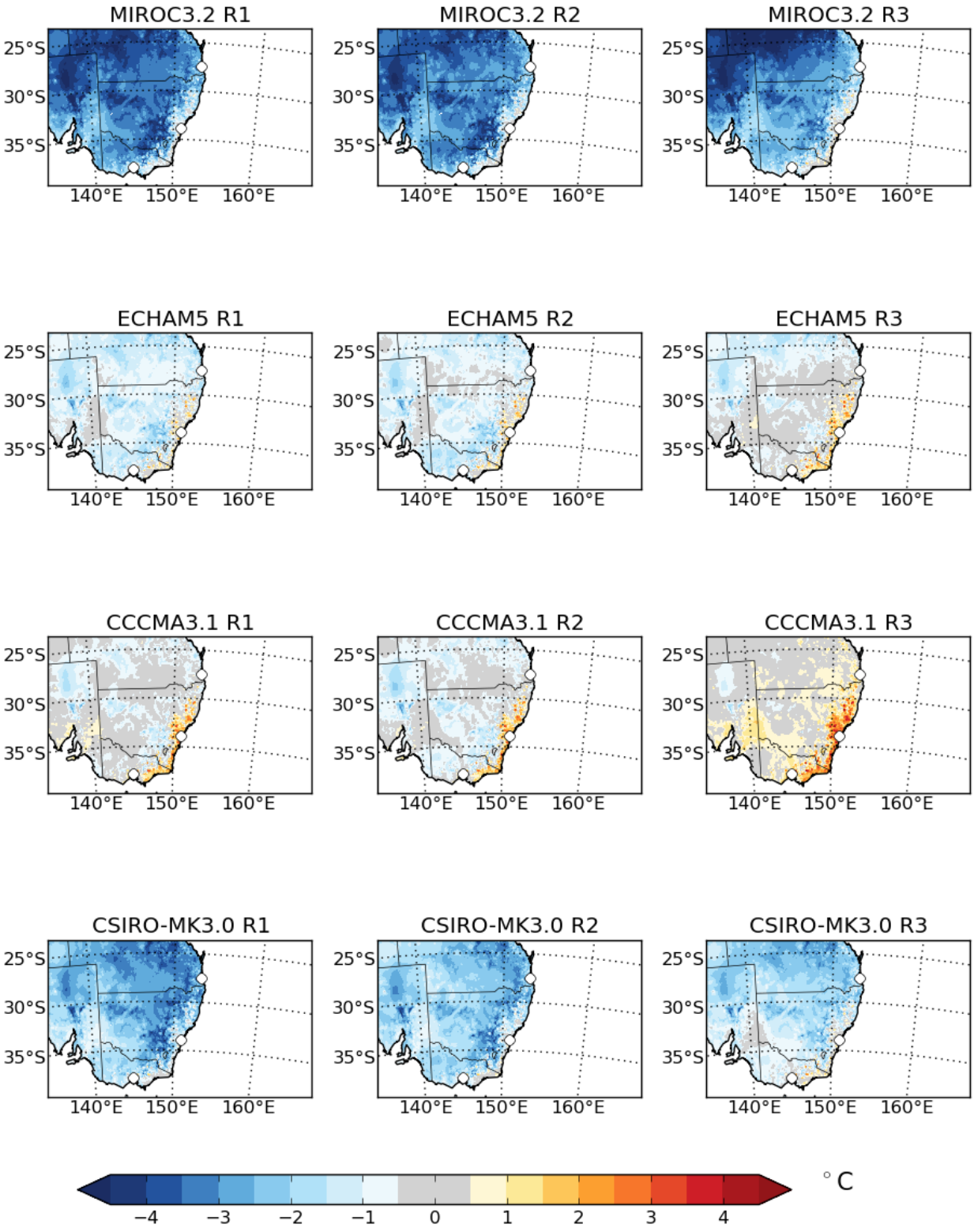

Figure 5.11: Annual mean of WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

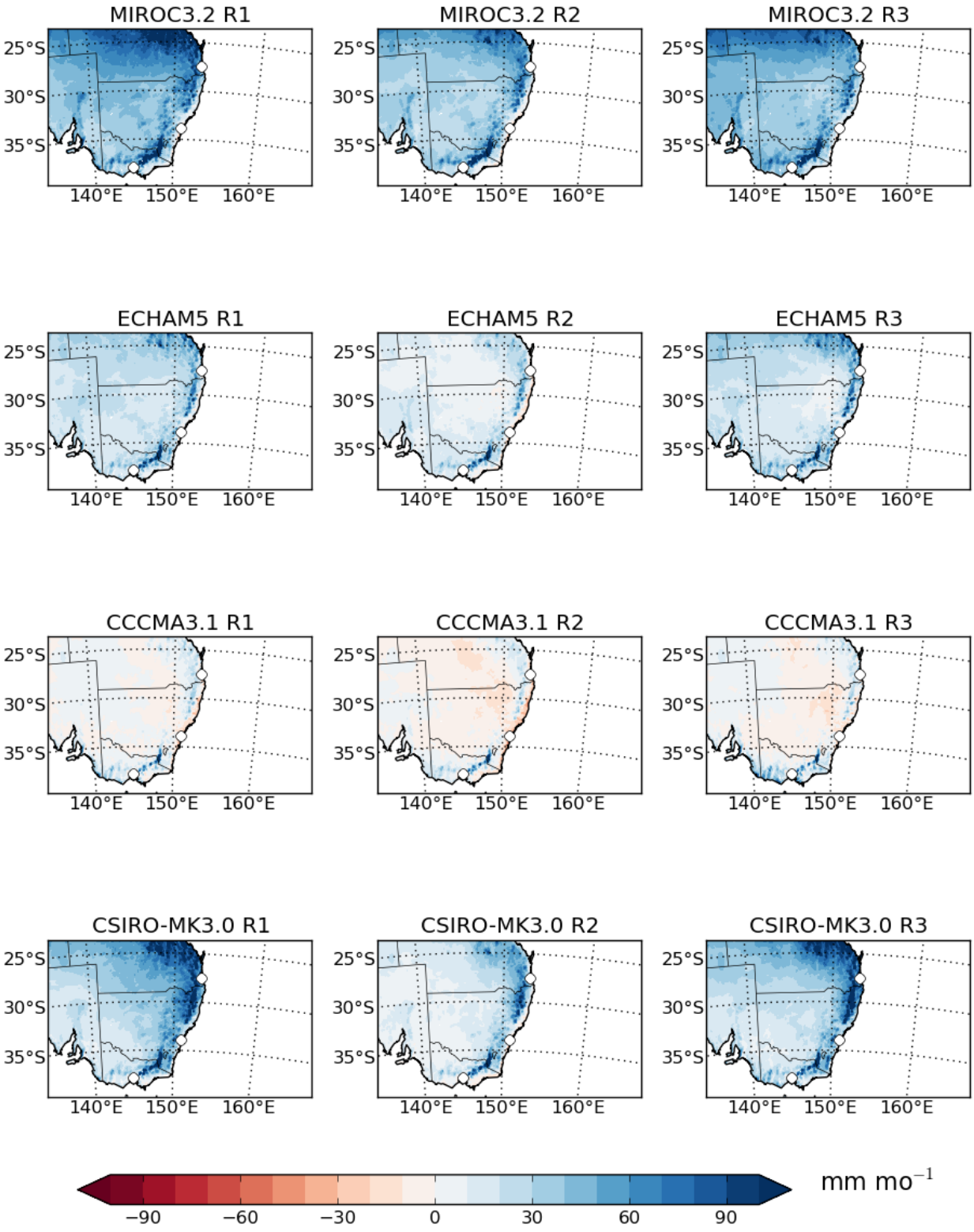

Figure 5.12: Annual mean of WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

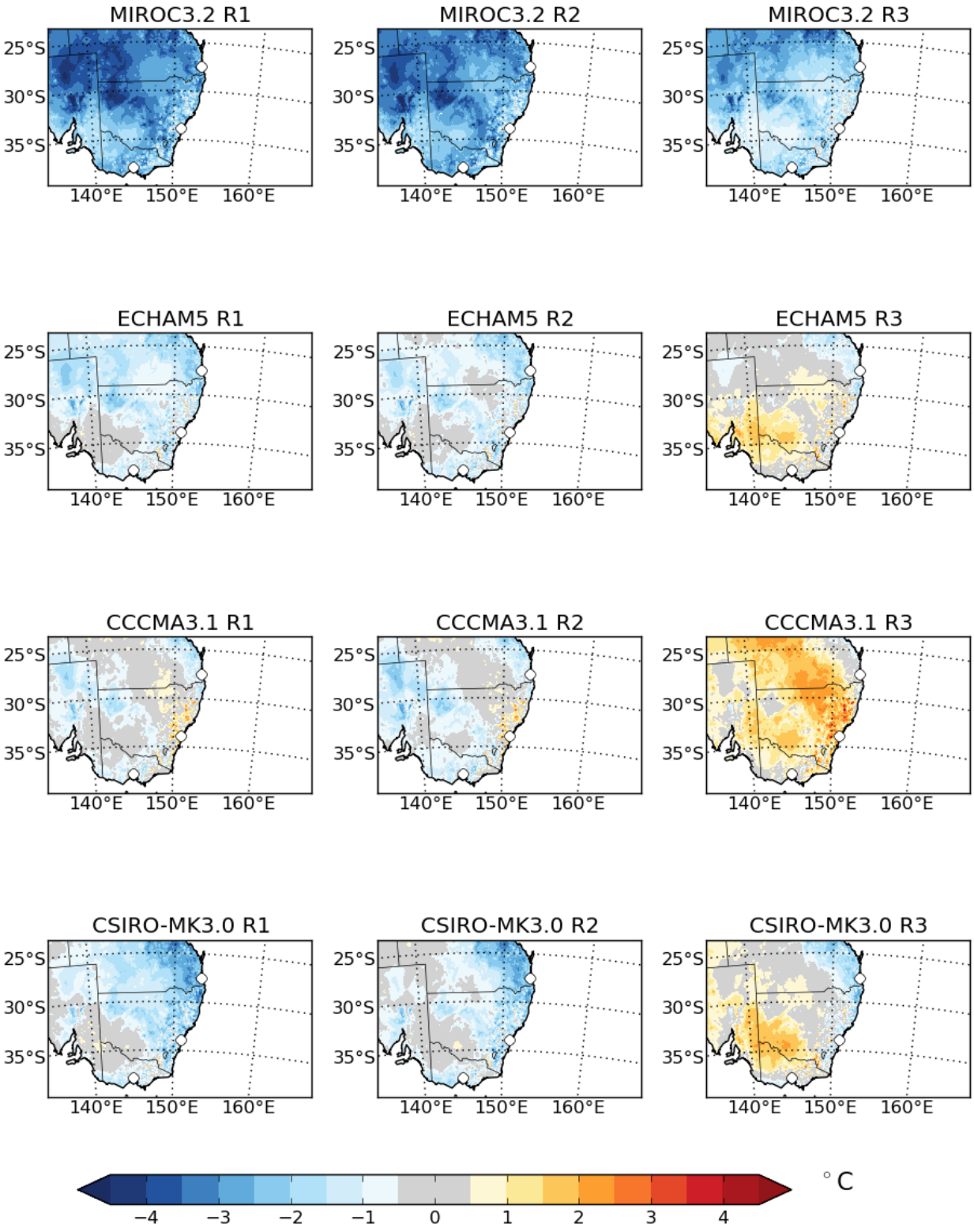

Figure 5.13: DJF mean of WRF minus AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

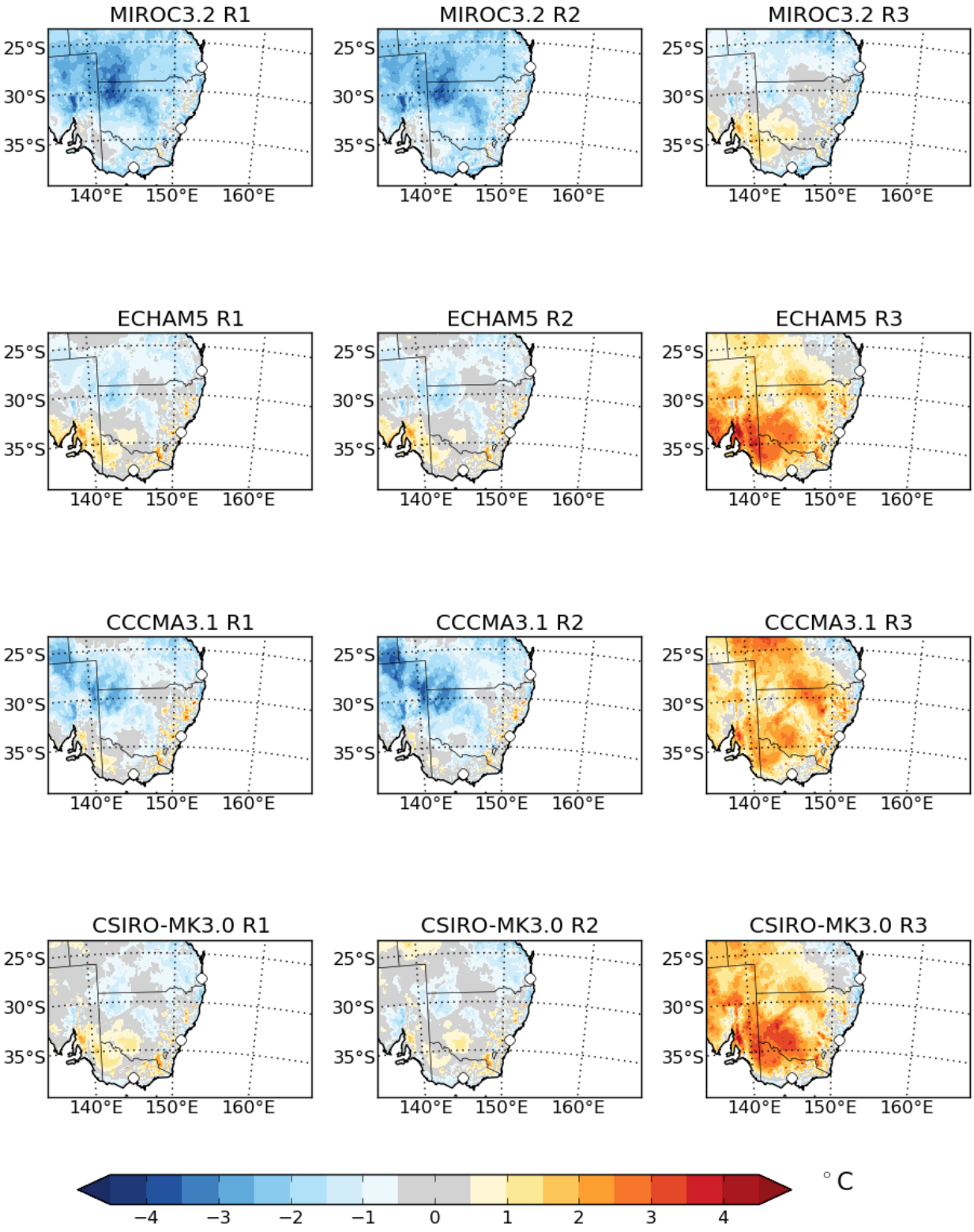

Figure 5.14: DJF mean of WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

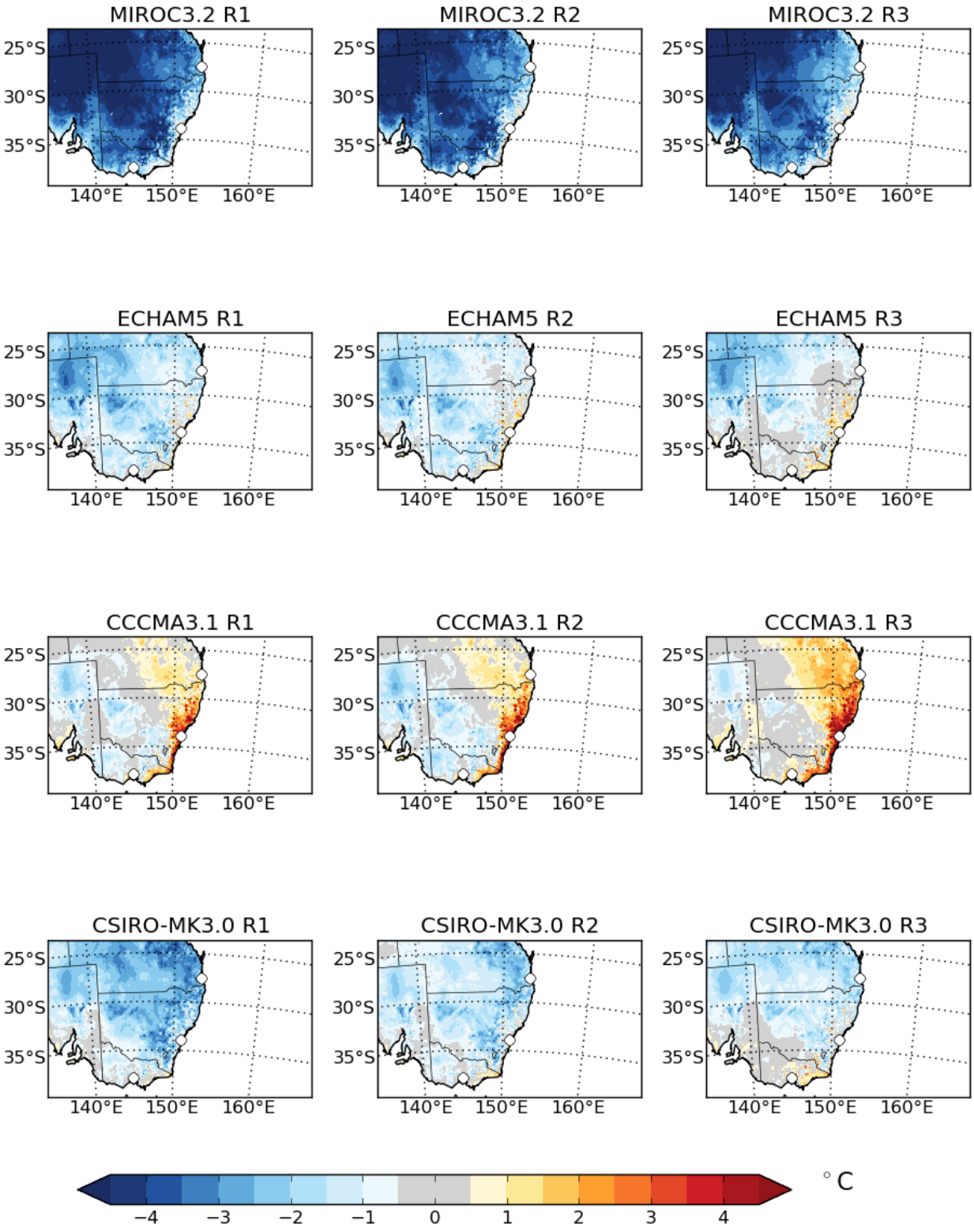

Figure 5.15: DJF mean of WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

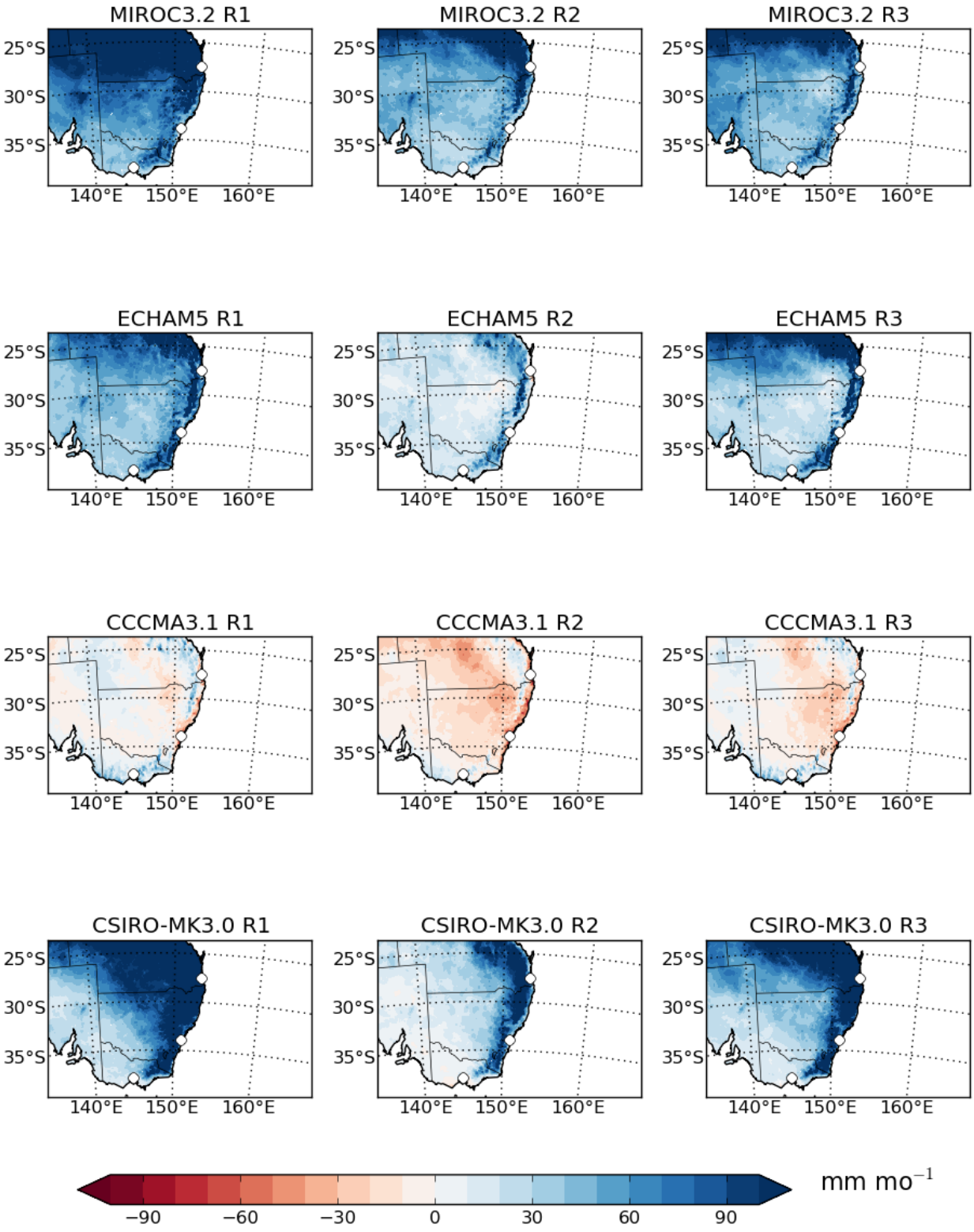

Figure 5.16: DJF mean of WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

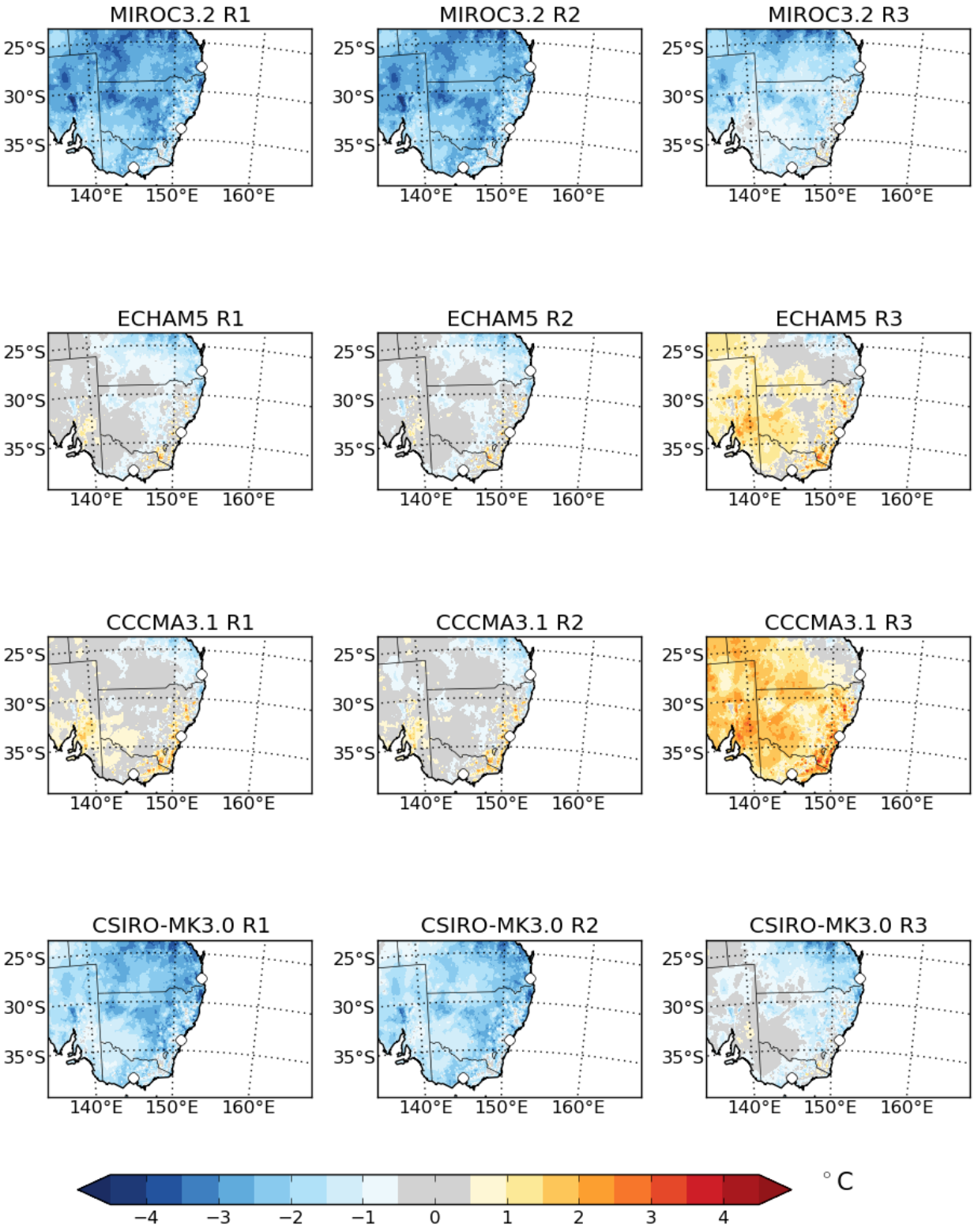

Figure 5.17: MAM mean of WRF minus AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

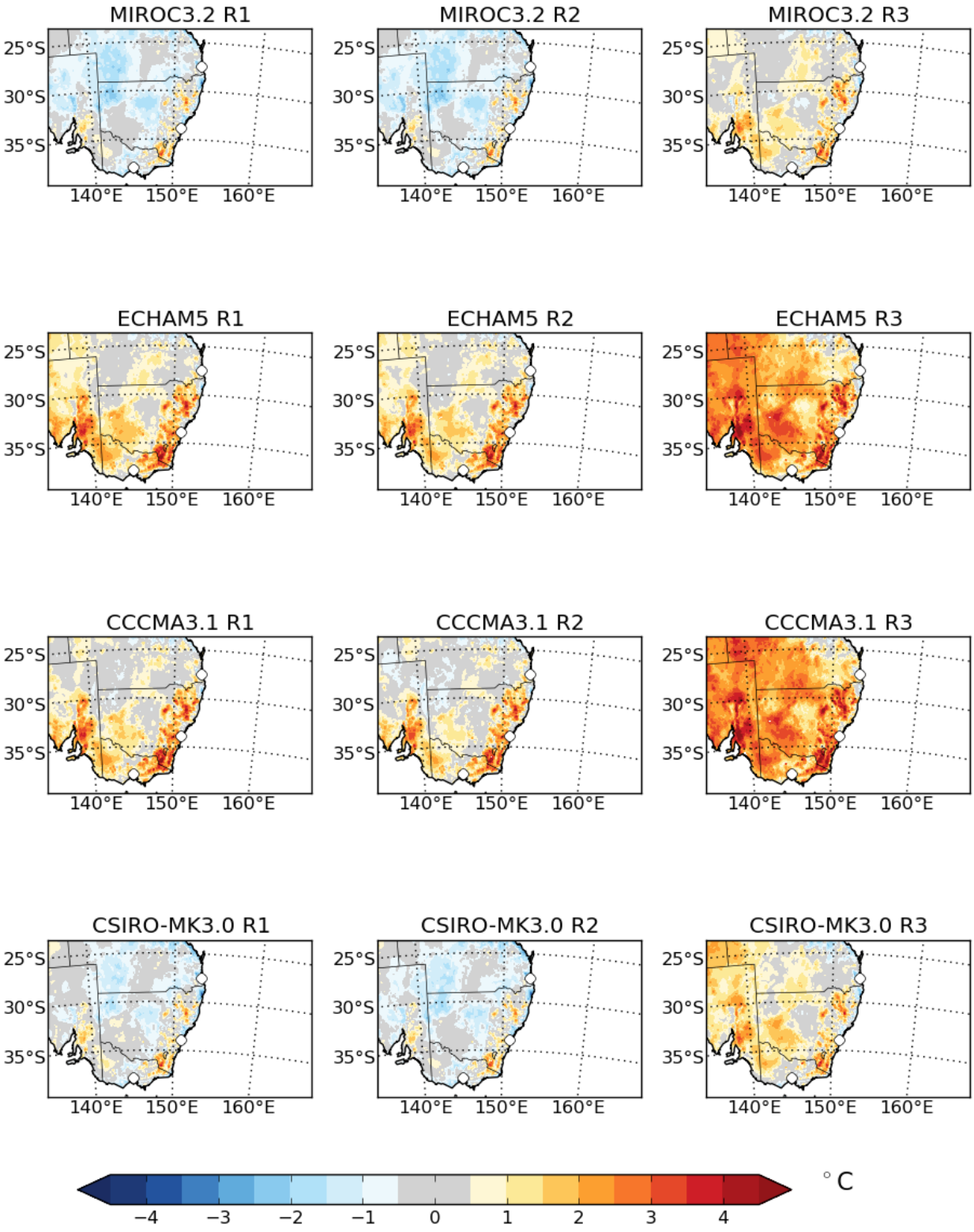

Figure 5.18: MAM mean of WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

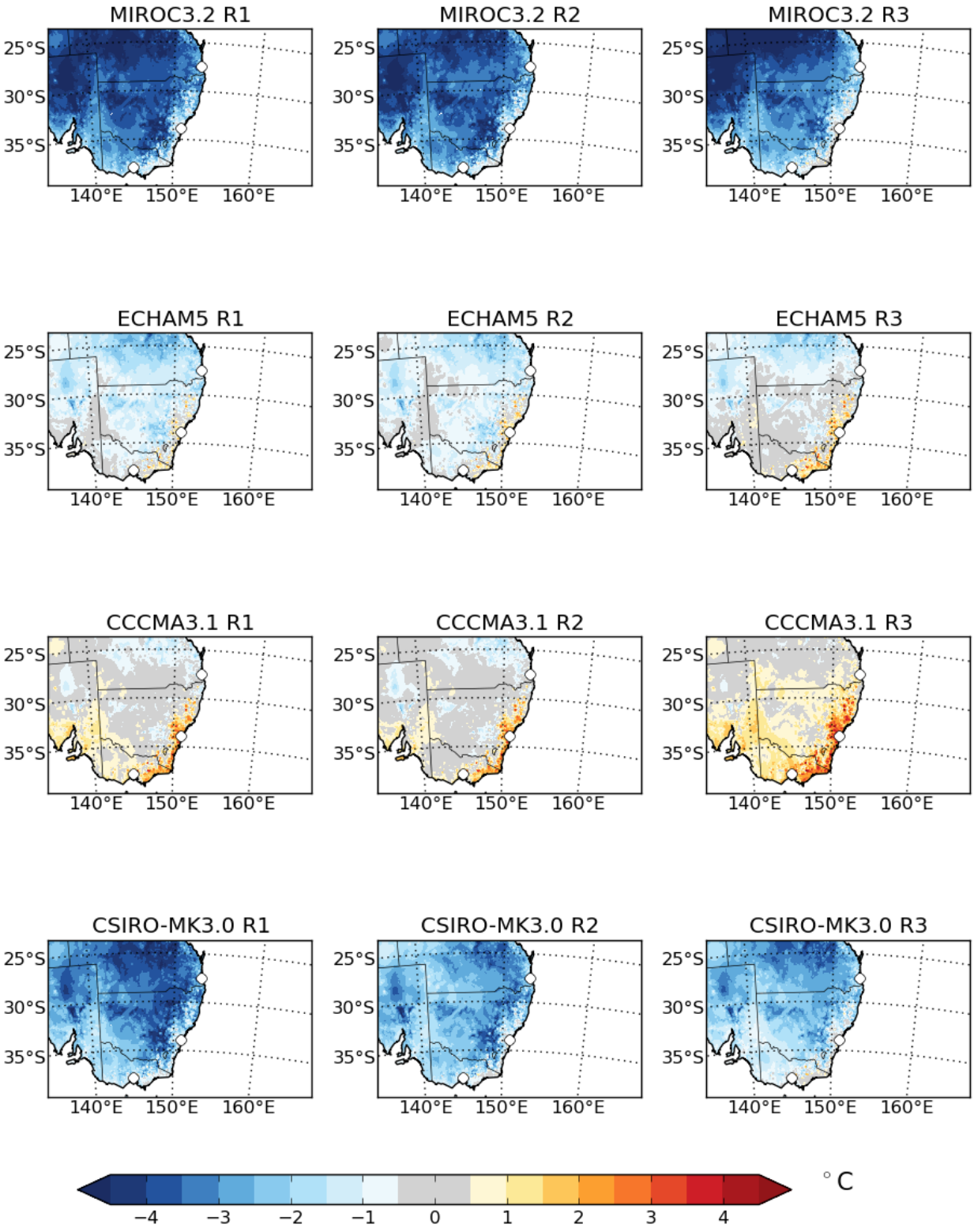

Figure 5.19: MAM mean of WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

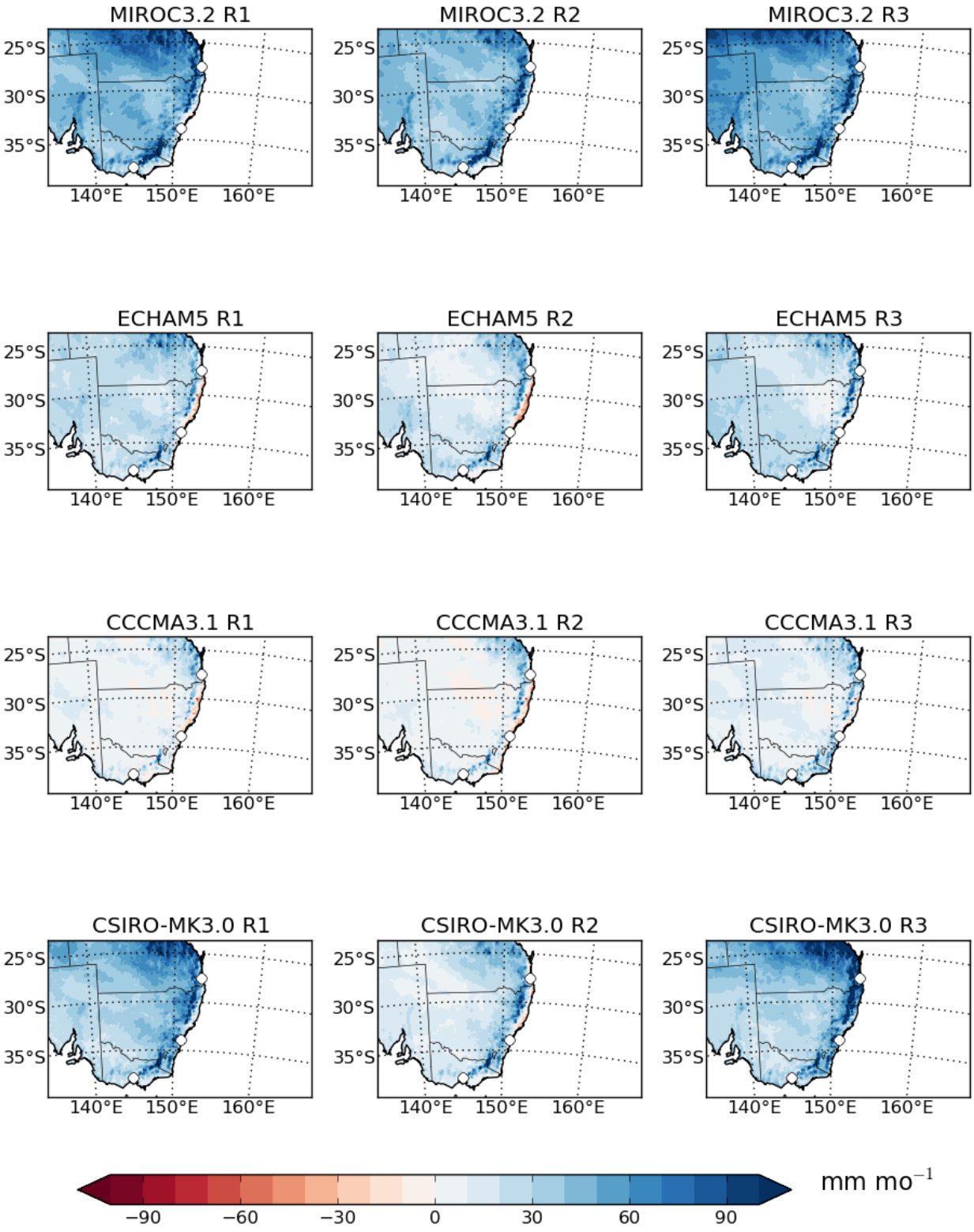

Figure 5.20: MAM mean of WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

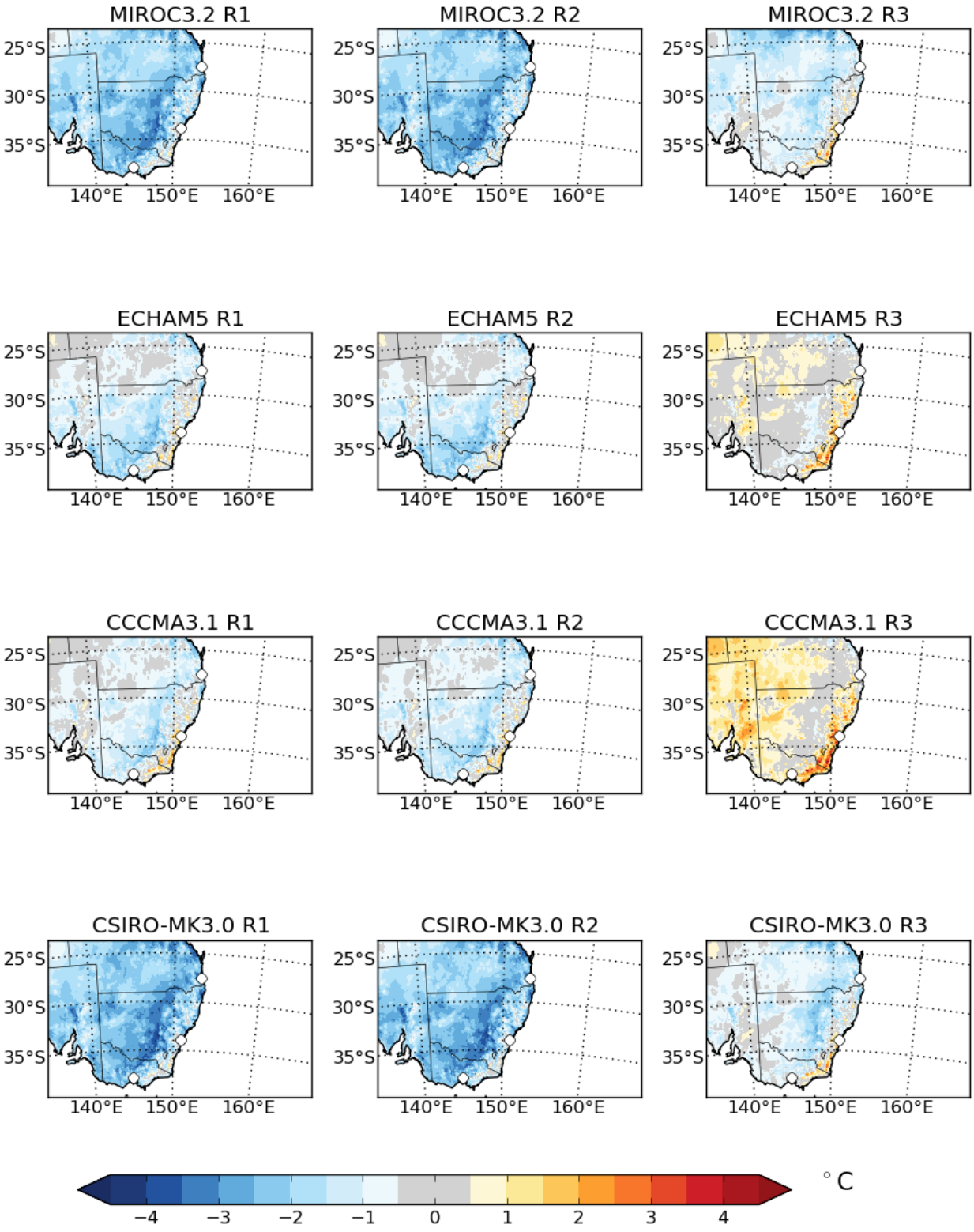

Figure 5.21: JJA mean of WRF minus AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

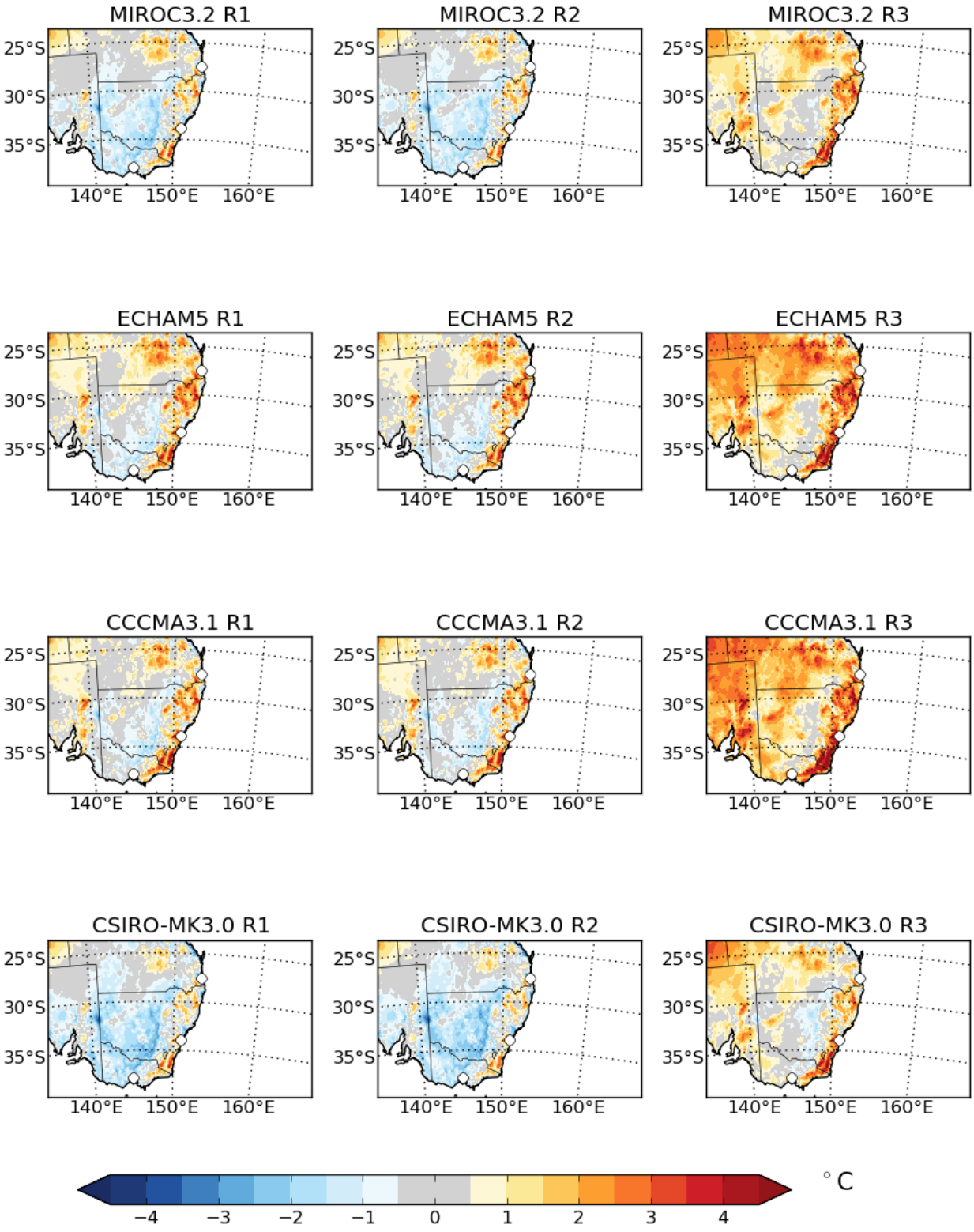

Figure 5.22: JJA mean of WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

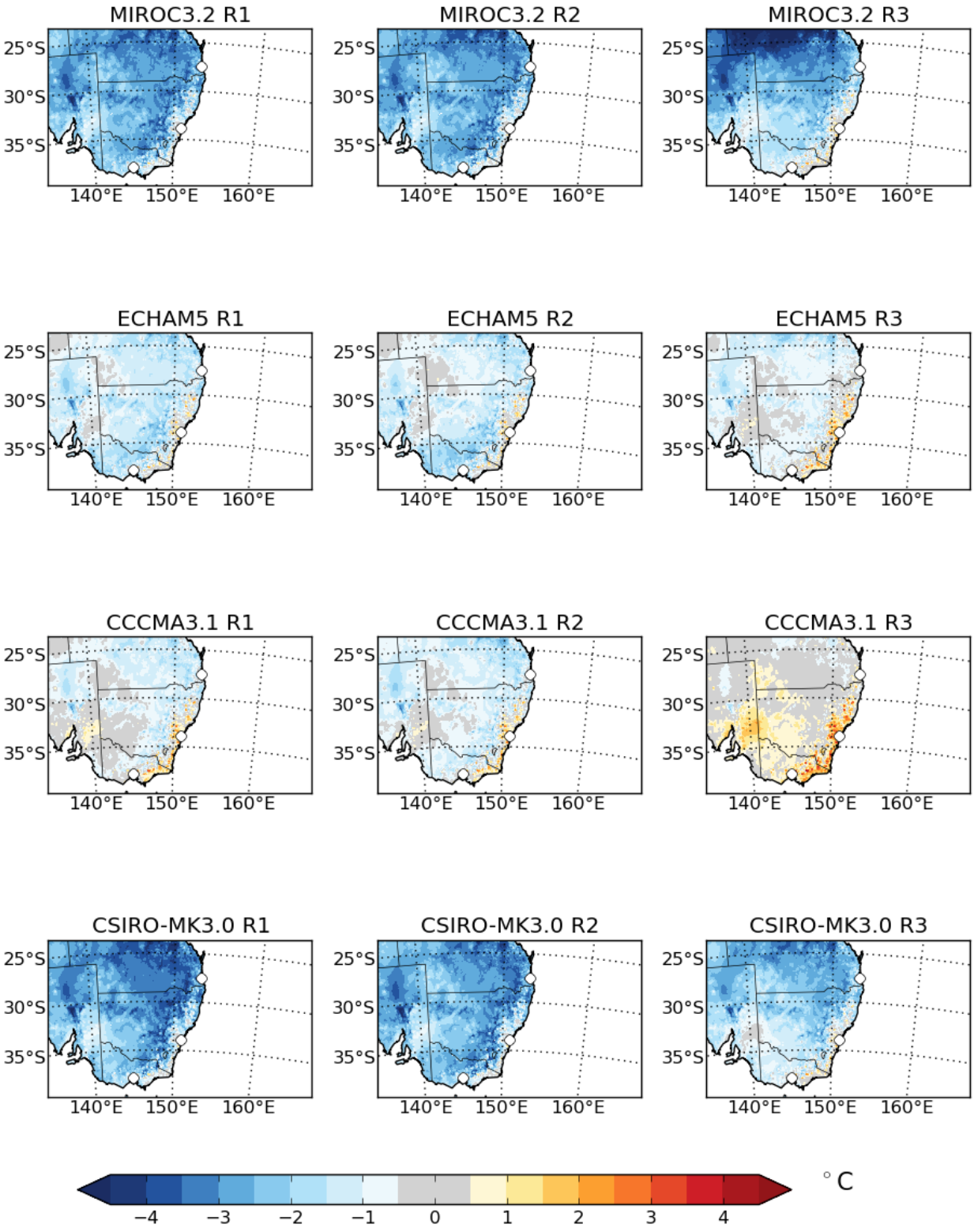

Figure 5.23: JJA mean of WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

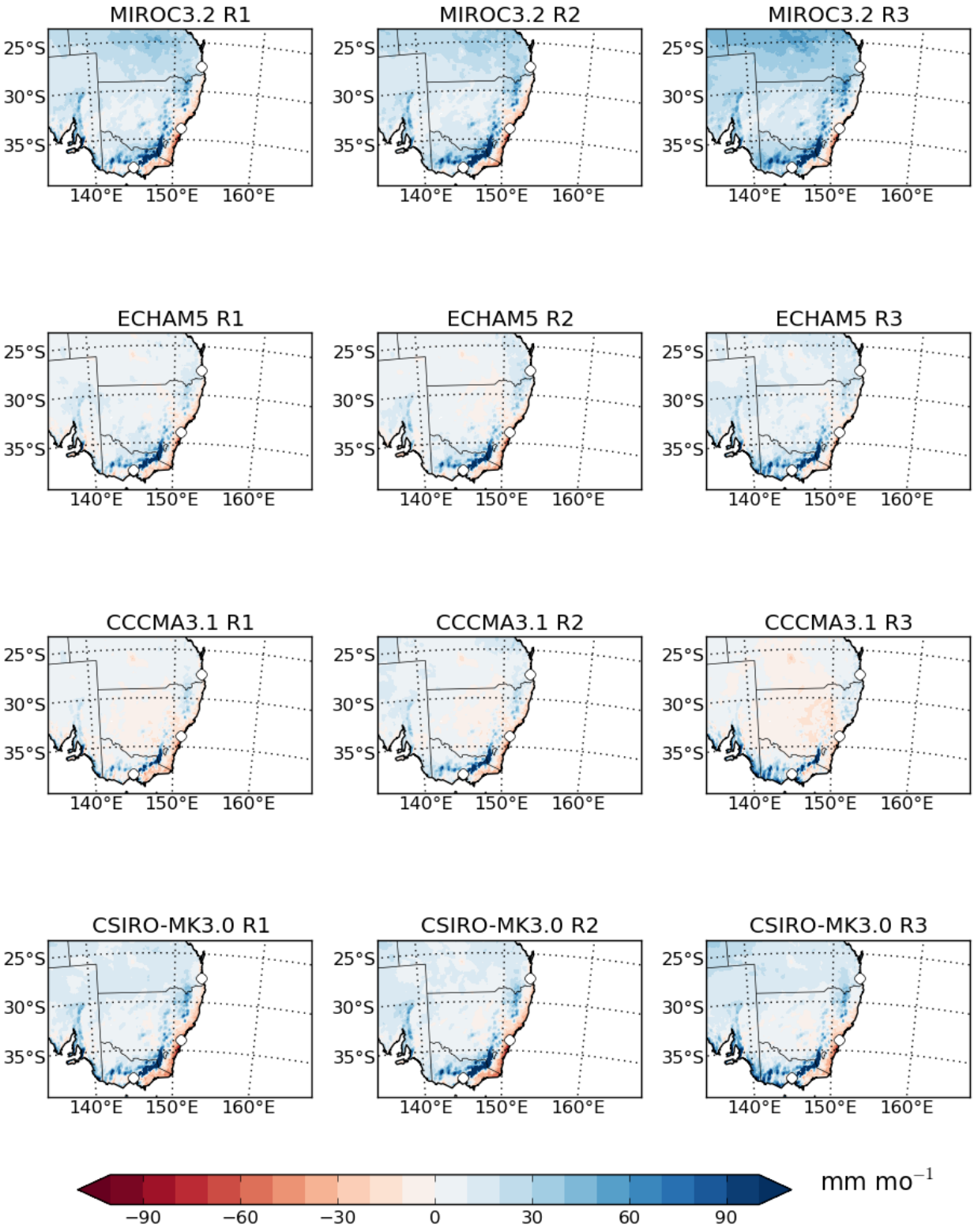

Figure 5.24: JJA mean of WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

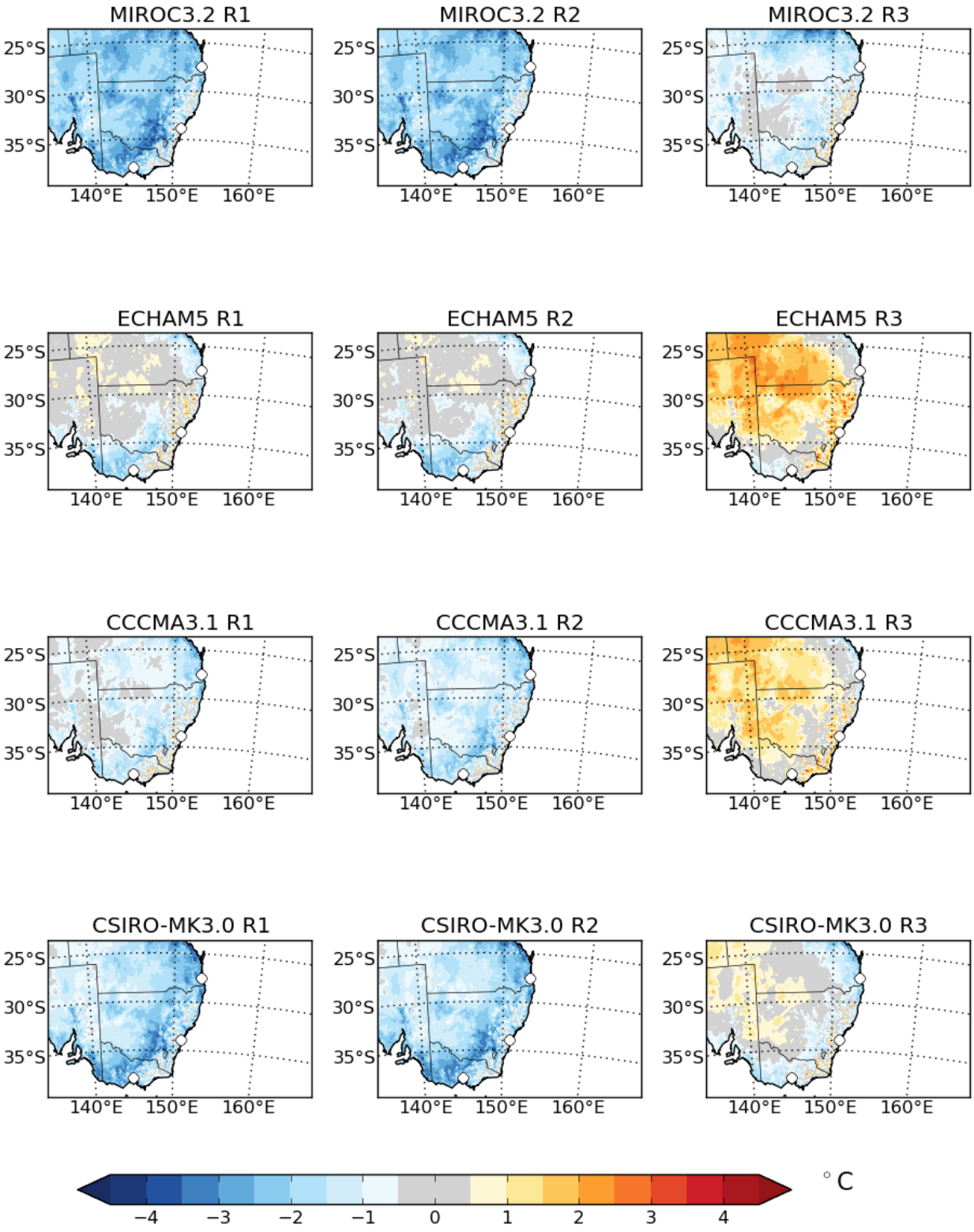

Figure 5.25: SON mean of WRF minus AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

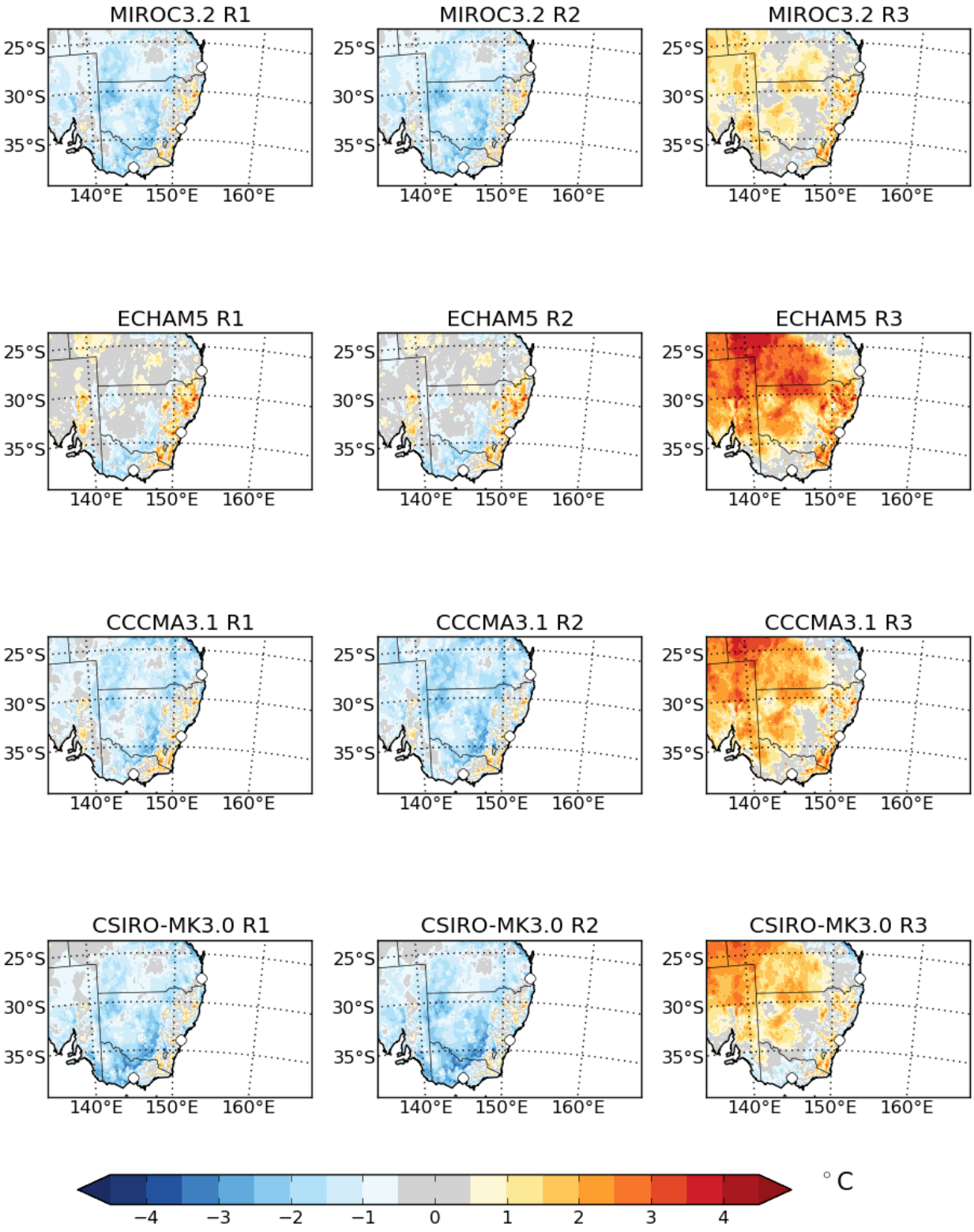

Figure 5.26: SON mean of WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

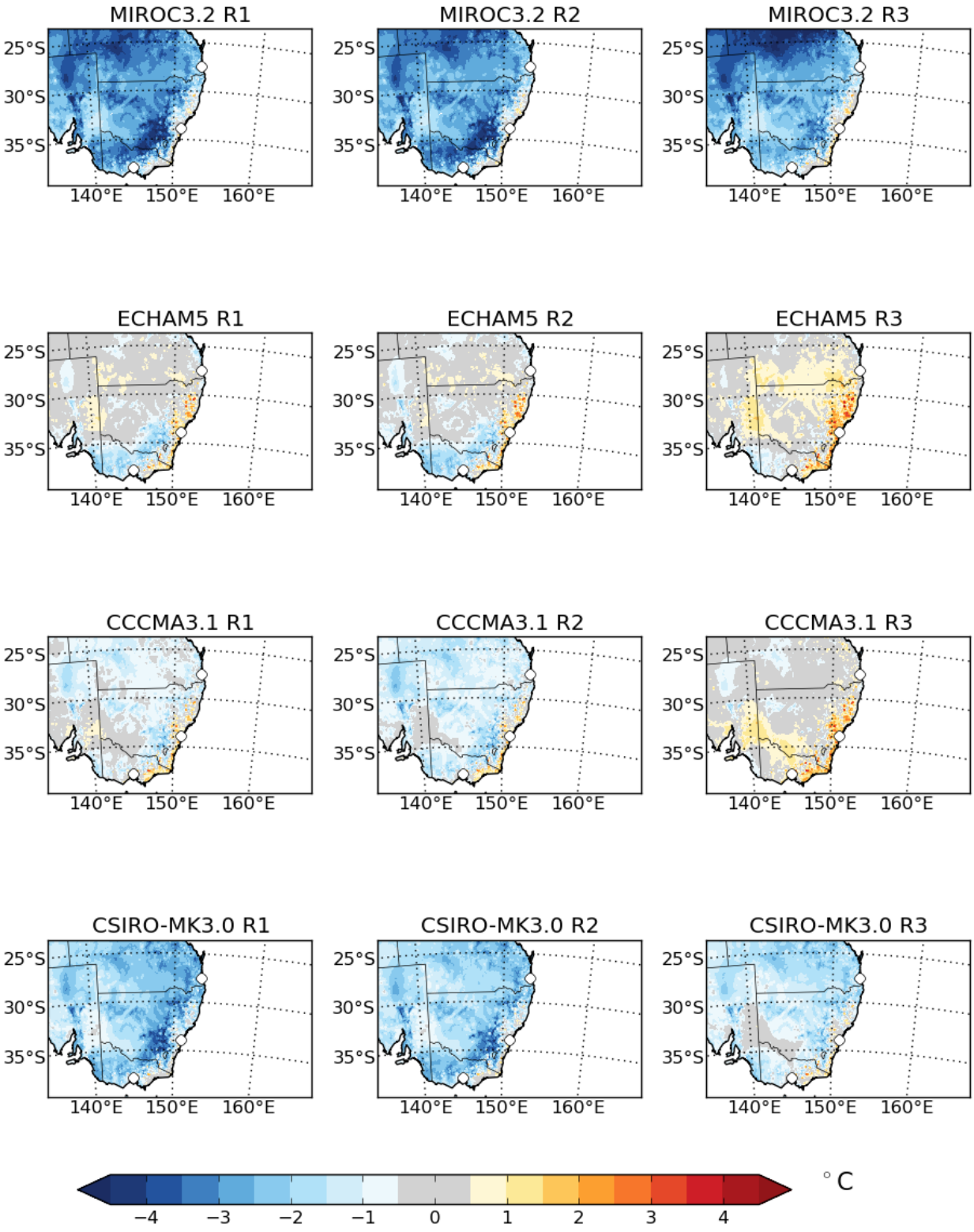

Figure 5.27: SON mean of WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

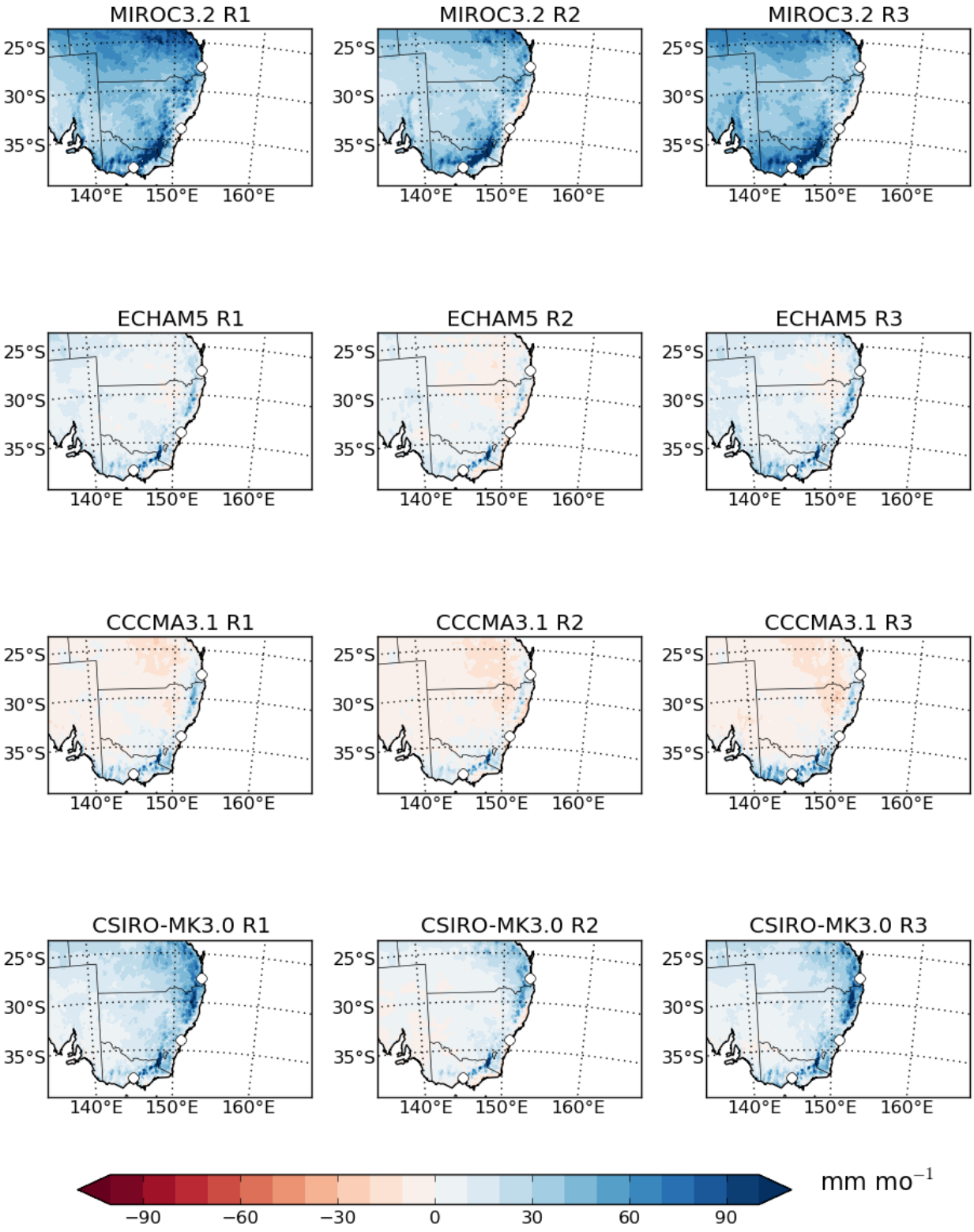

Figure 5.28: SON mean of WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

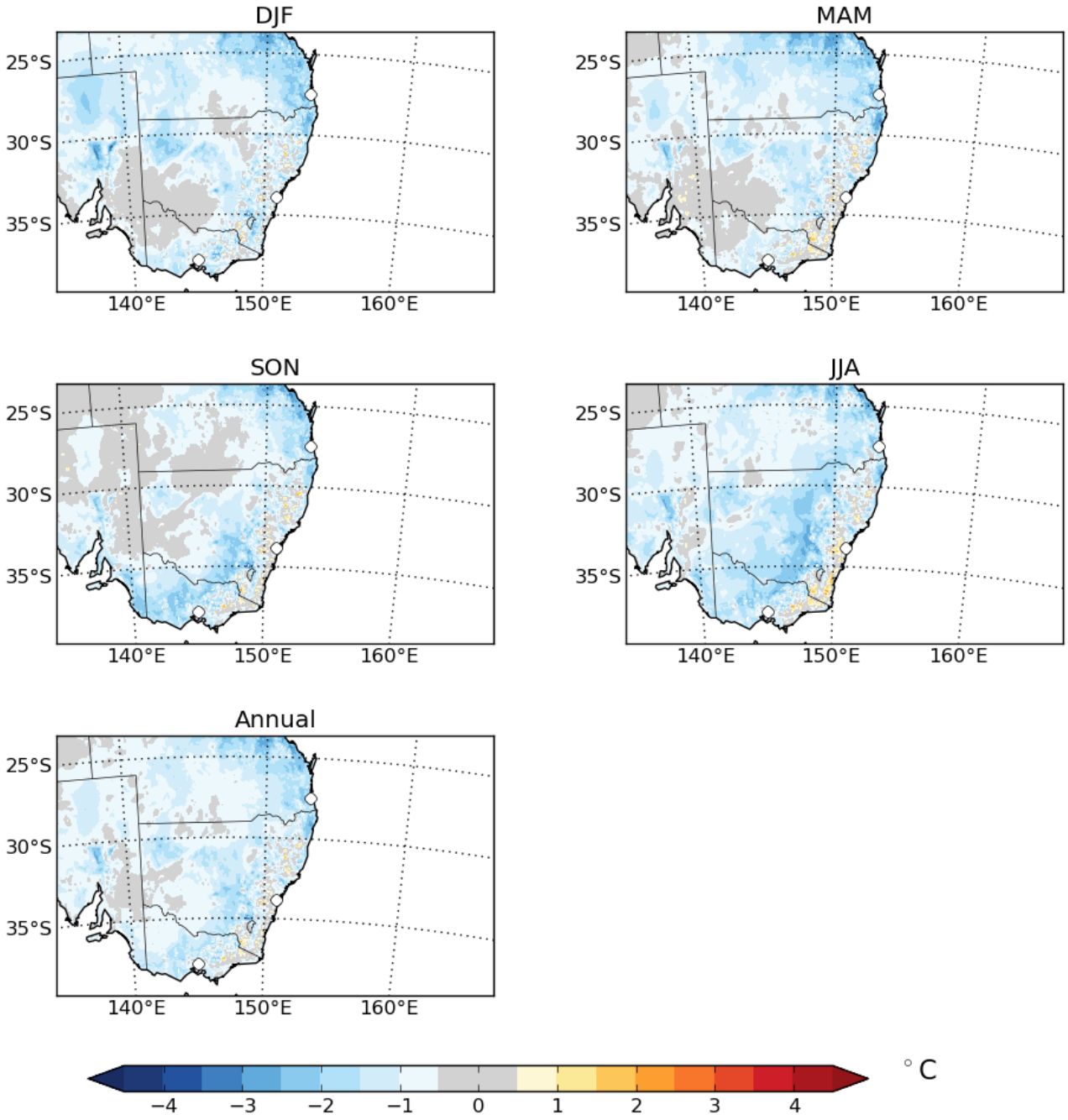

Figure 5.29: Seasonal and annual multimodel means of WRF minus AWAP near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

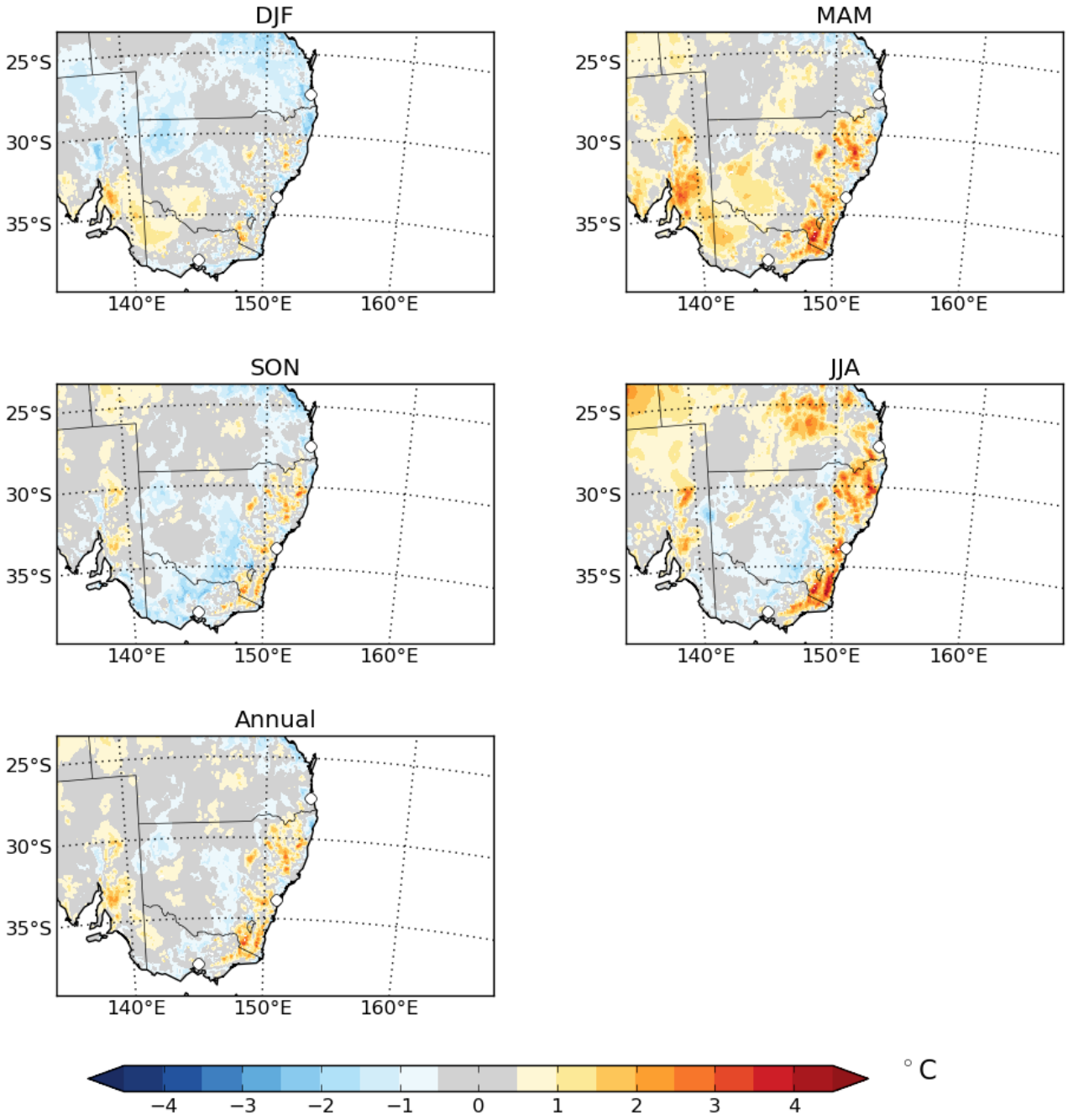

Figure 5.30: Seasonal and annual multimodel means of WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

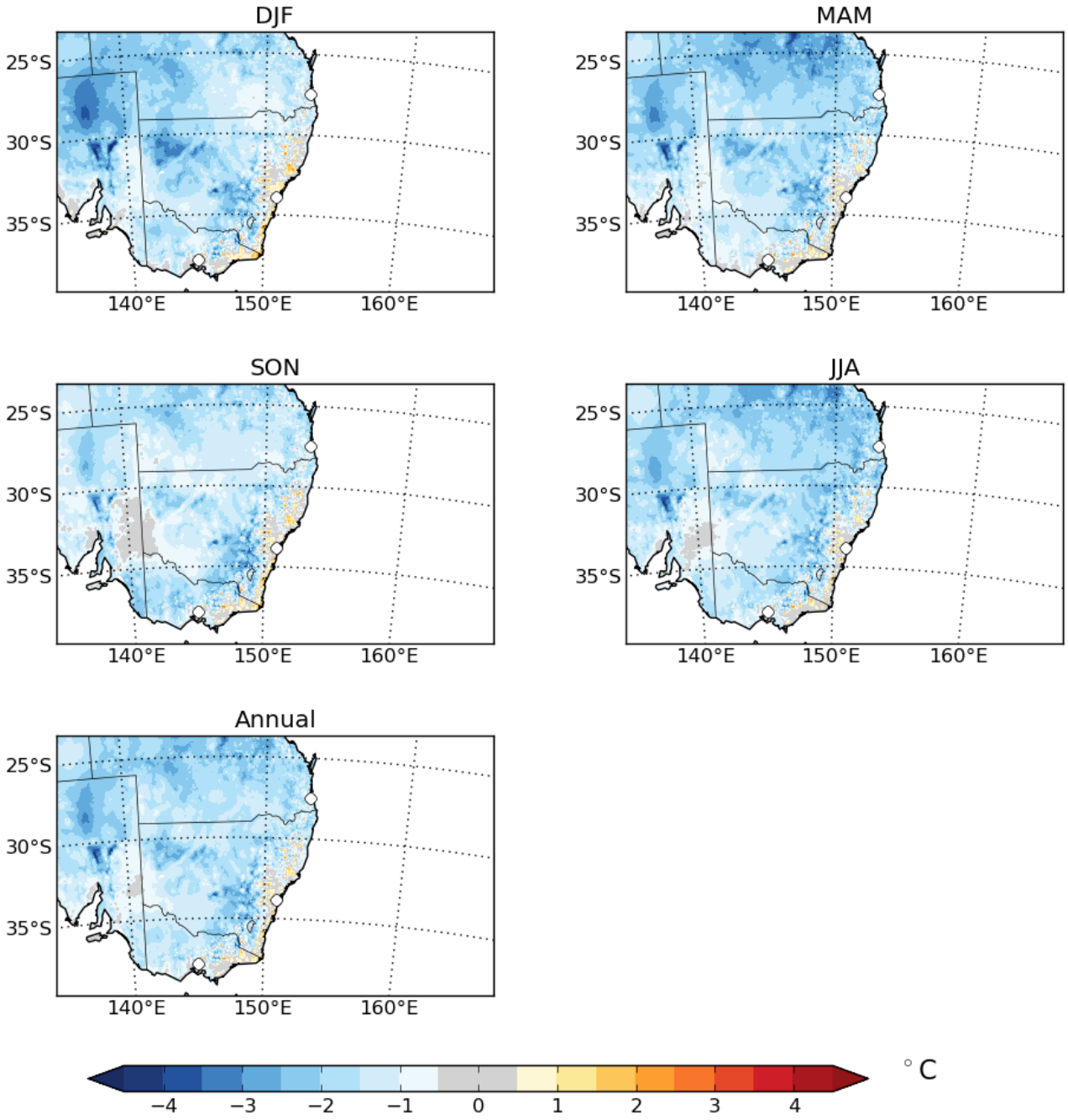

Figure 5.31: Seasonal and annual multimodel means of WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

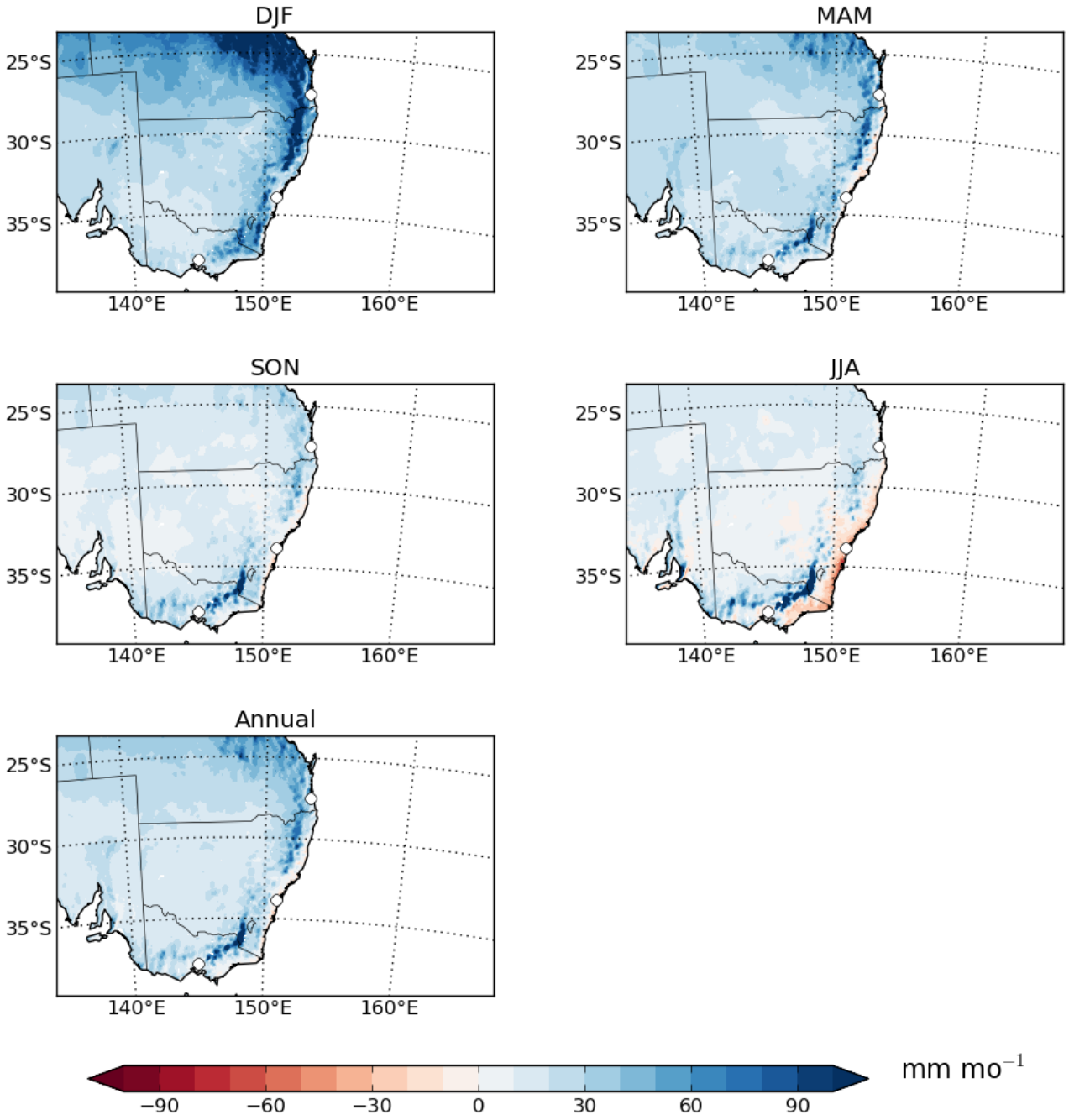

Figure 5.32: Seasonal and annual multimodel means of WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

5.3 Biases: 1990-2009 Bias-Corrected Regional Model Output - Observations

This subsection contains climatological biases for present-day daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation for the bias-corrected RCM output (*i.e.* RCM output that has been already corrected for the biases between the models and the observations using the methods described here [6]). The corrections are calculated by comparing distributions of daily model output and observations for all seasons. Thus, the corrections are independent of the season. The biases are defined as the difference between model output and AWAP observations for the period 1990-2009. Since here the model output has been already bias-corrected, the residual biases are very small. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average model bias, whereas the individual-model plots show the spread of biases between models.

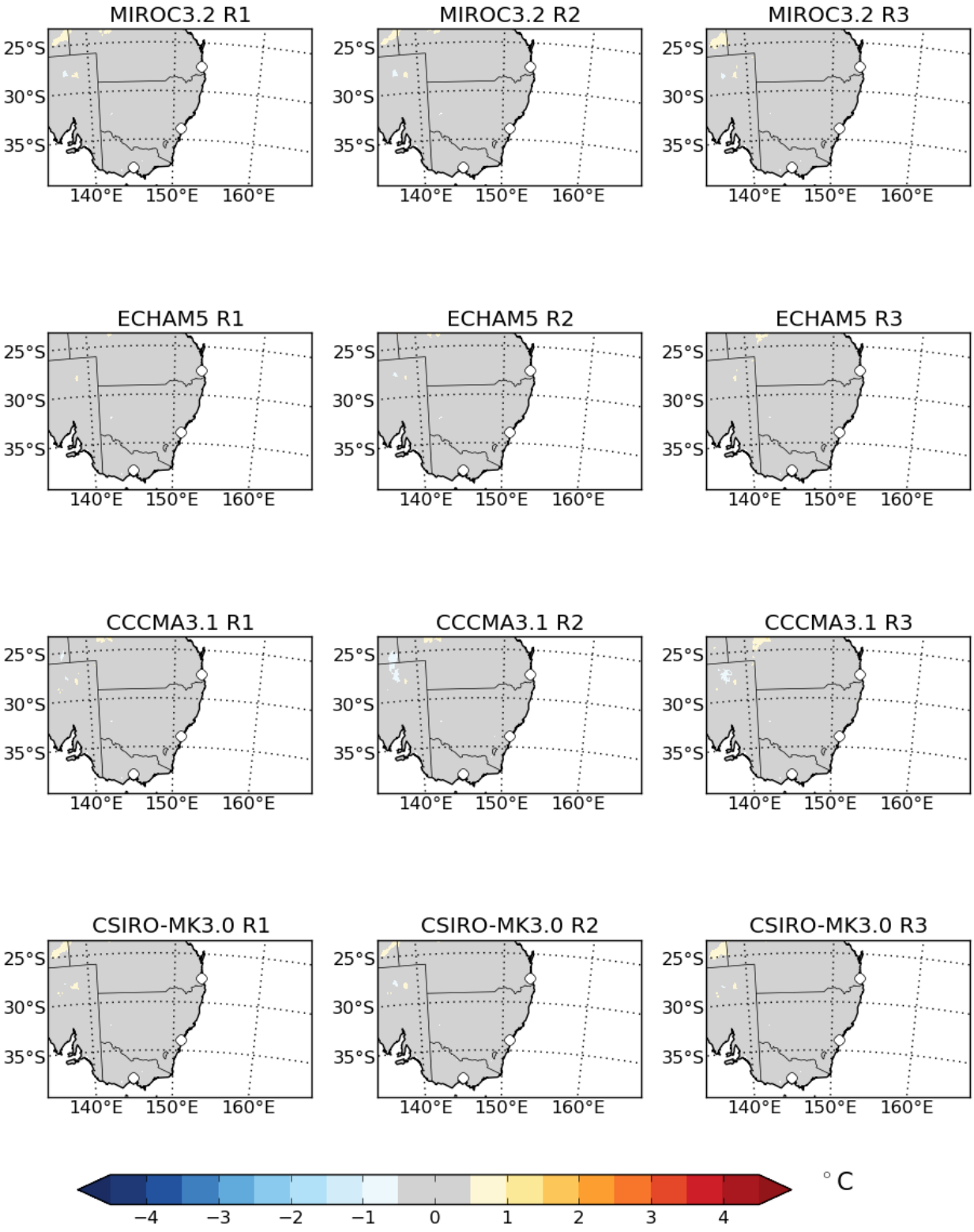

Figure 5.33: Annual mean of bias-corrected WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

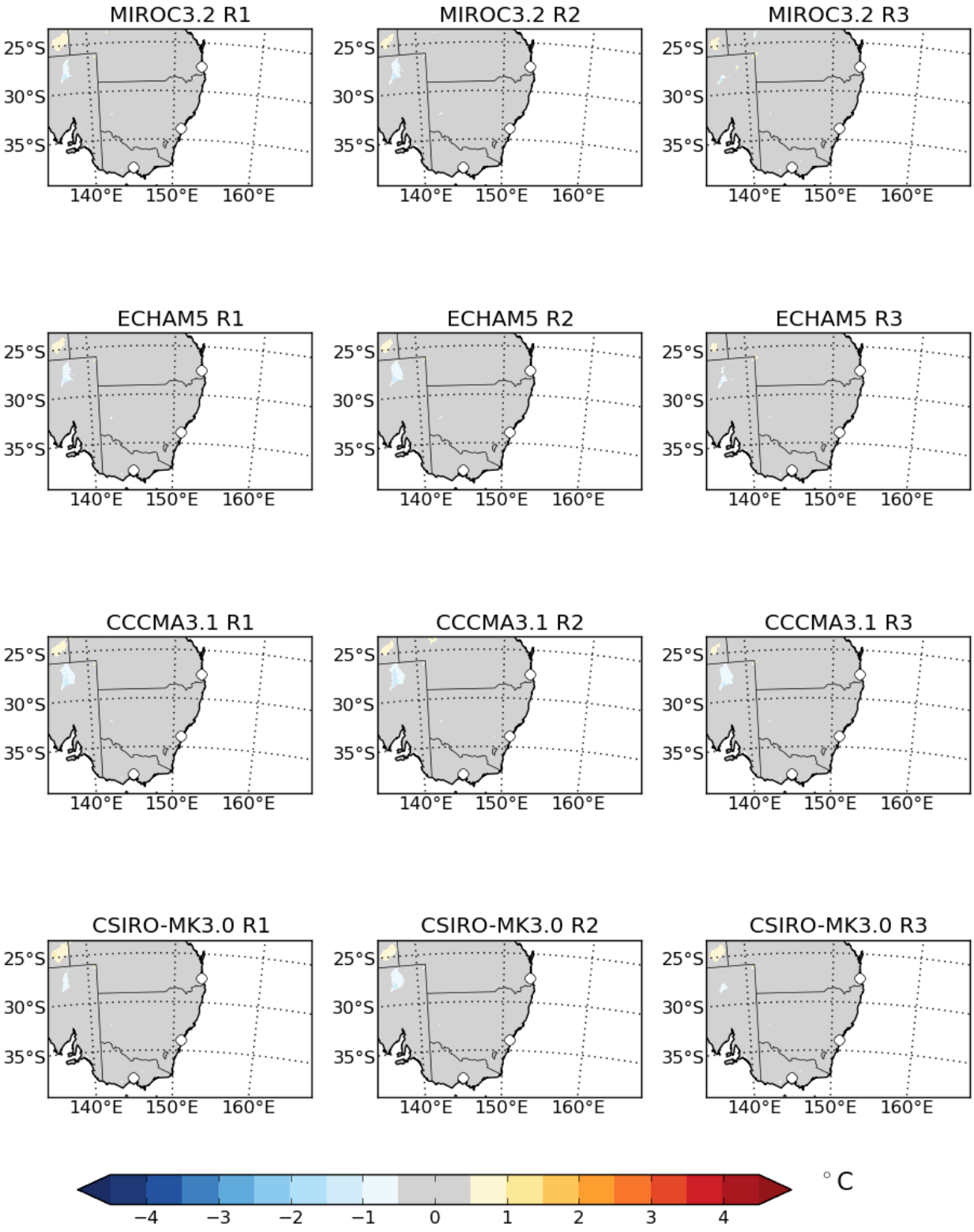

Figure 5.34: Annual mean of bias-corrected WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

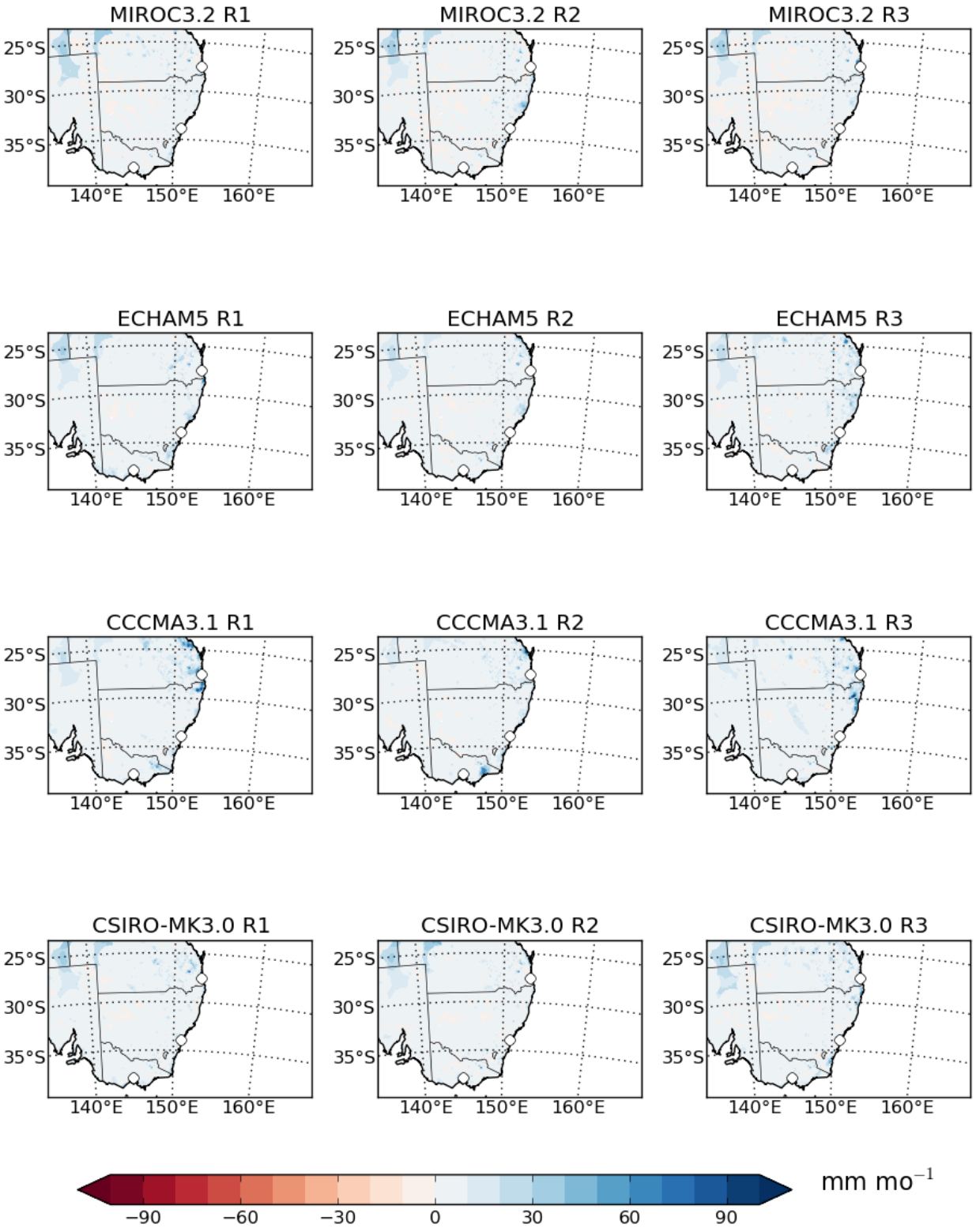

Figure 5.35: Annual mean of bias-corrected WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

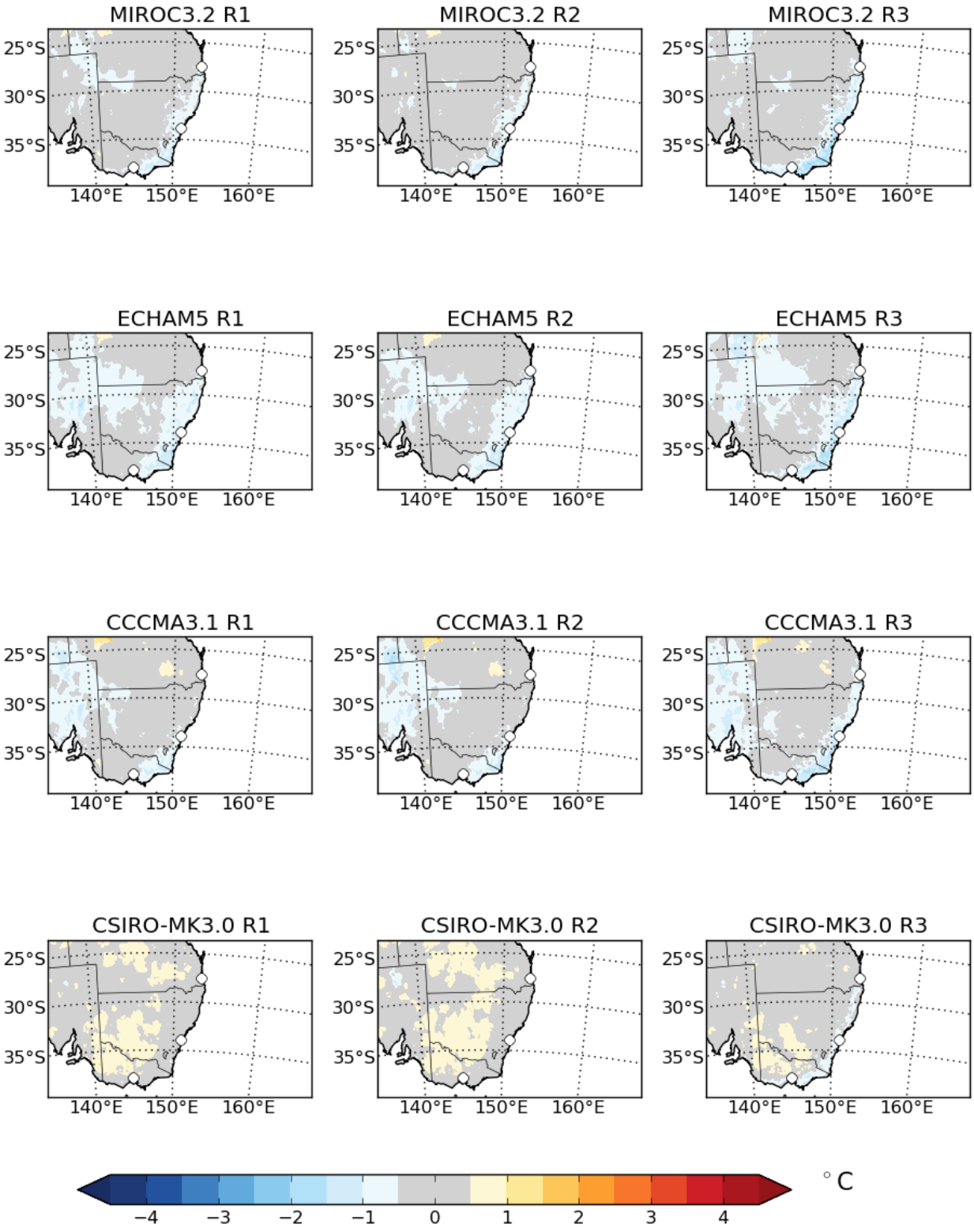

Figure 5.36: DJF mean of bias-corrected WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

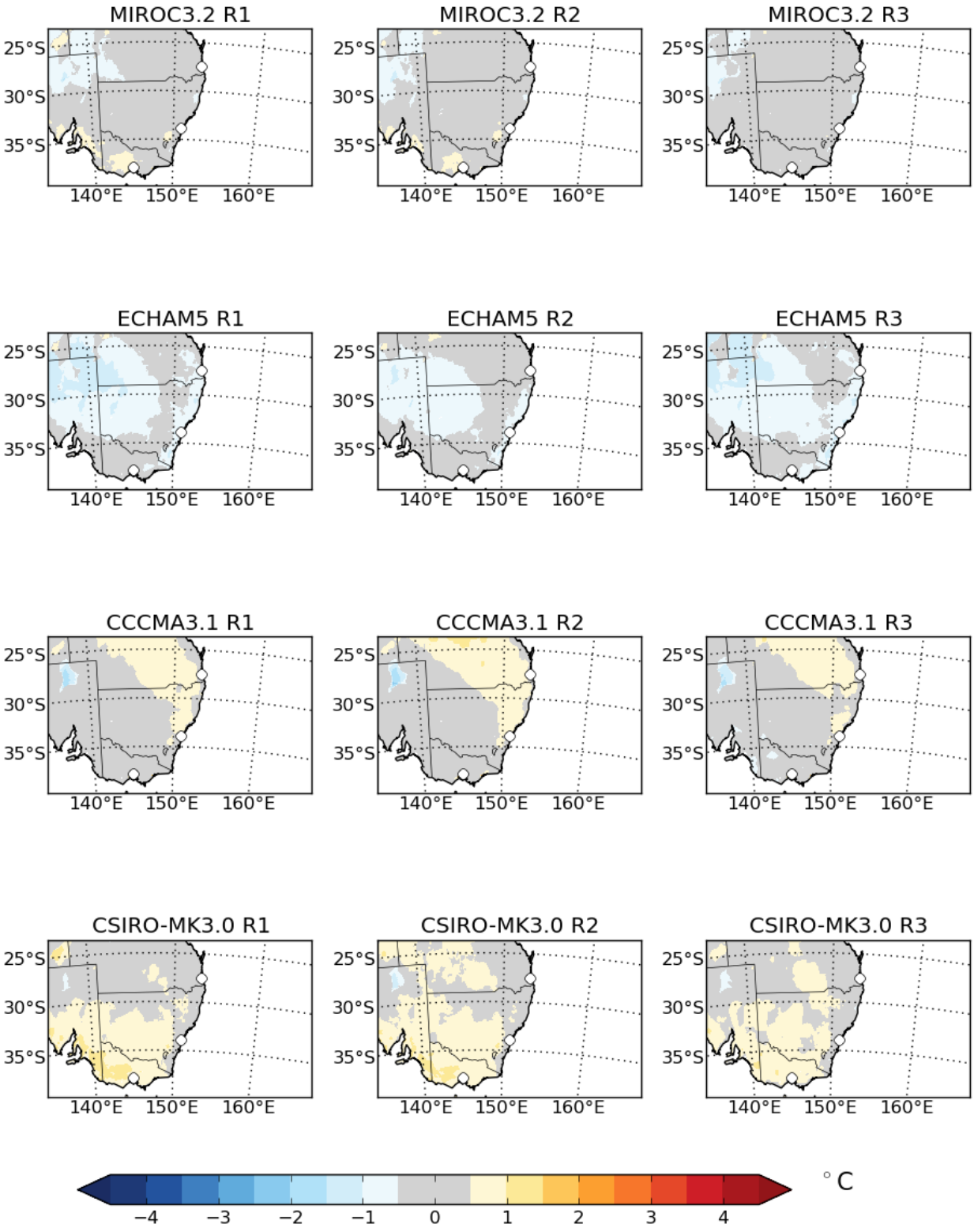

Figure 5.37: DJF mean of bias-corrected WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

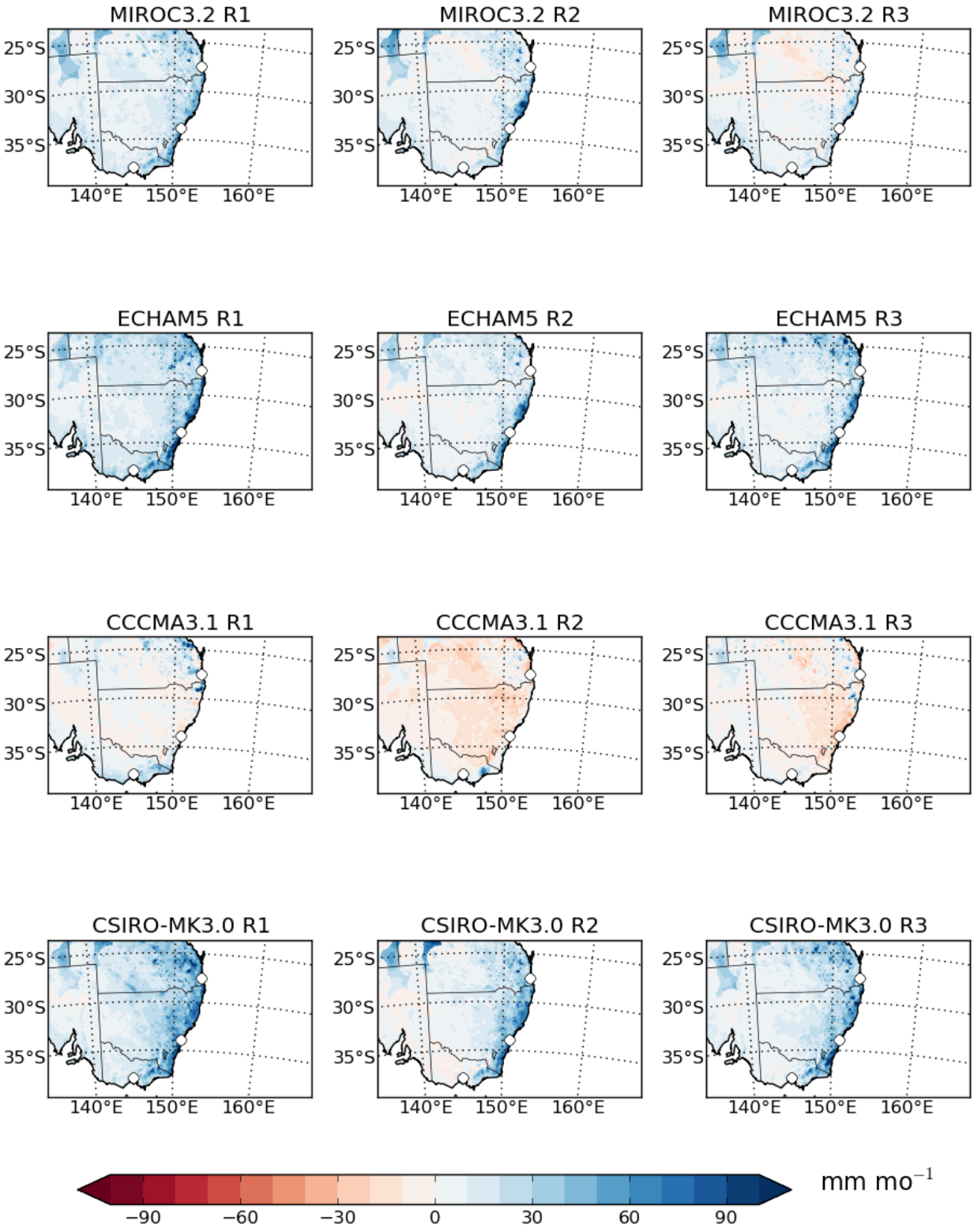

Figure 5.38: DJF mean of bias-corrected WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

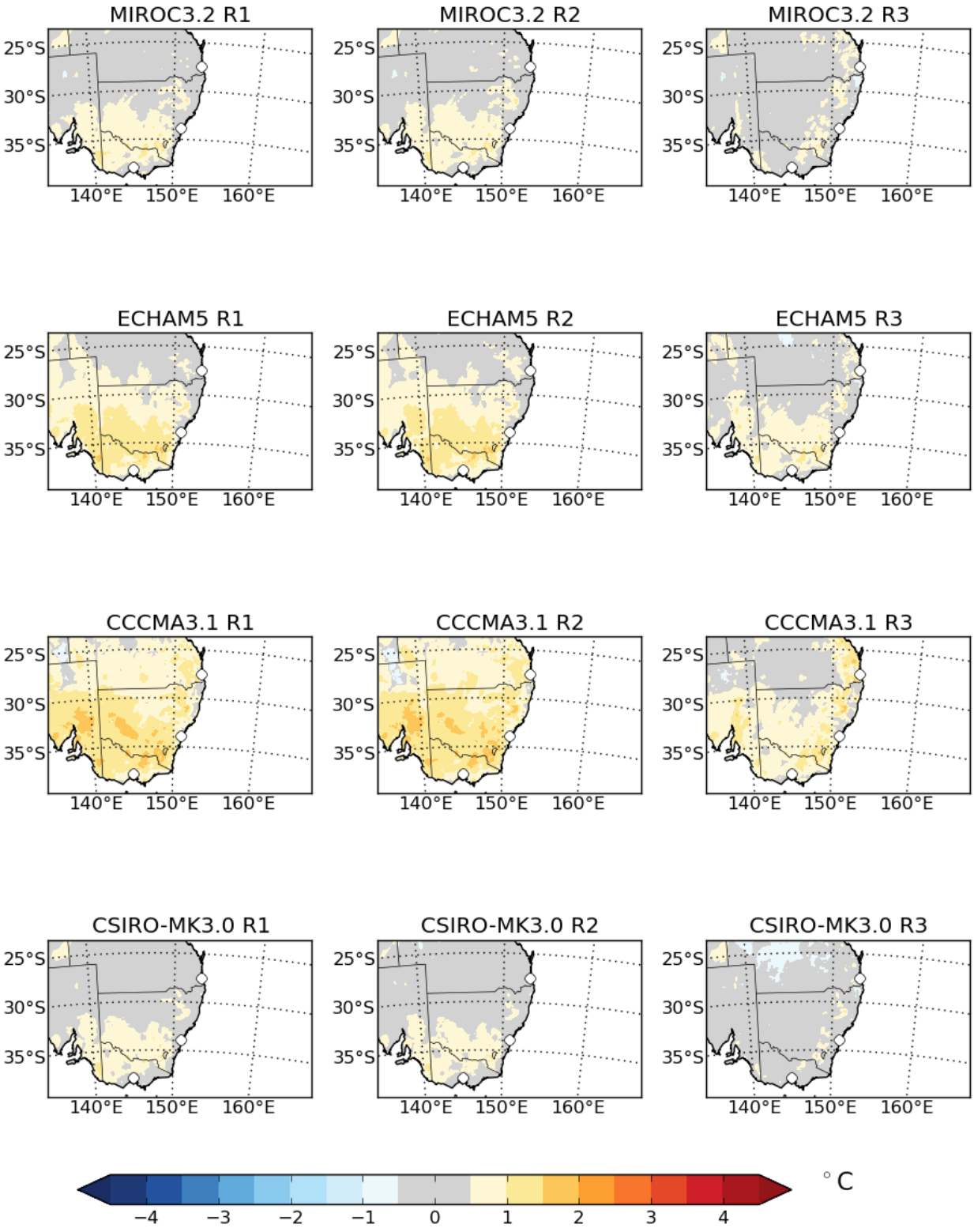

Figure 5.39: MAM mean of bias-corrected WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

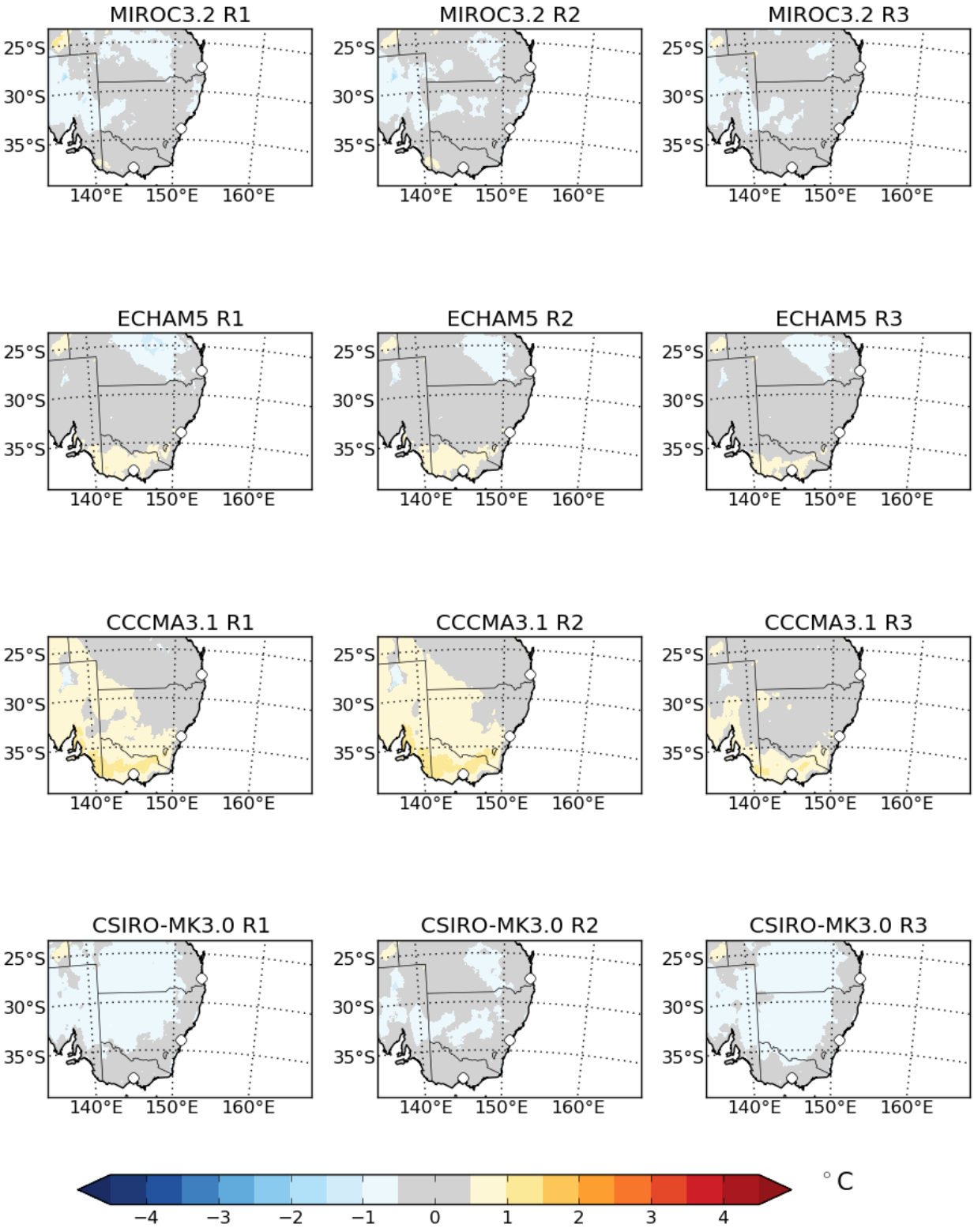

Figure 5.40: MAM mean of bias-corrected WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

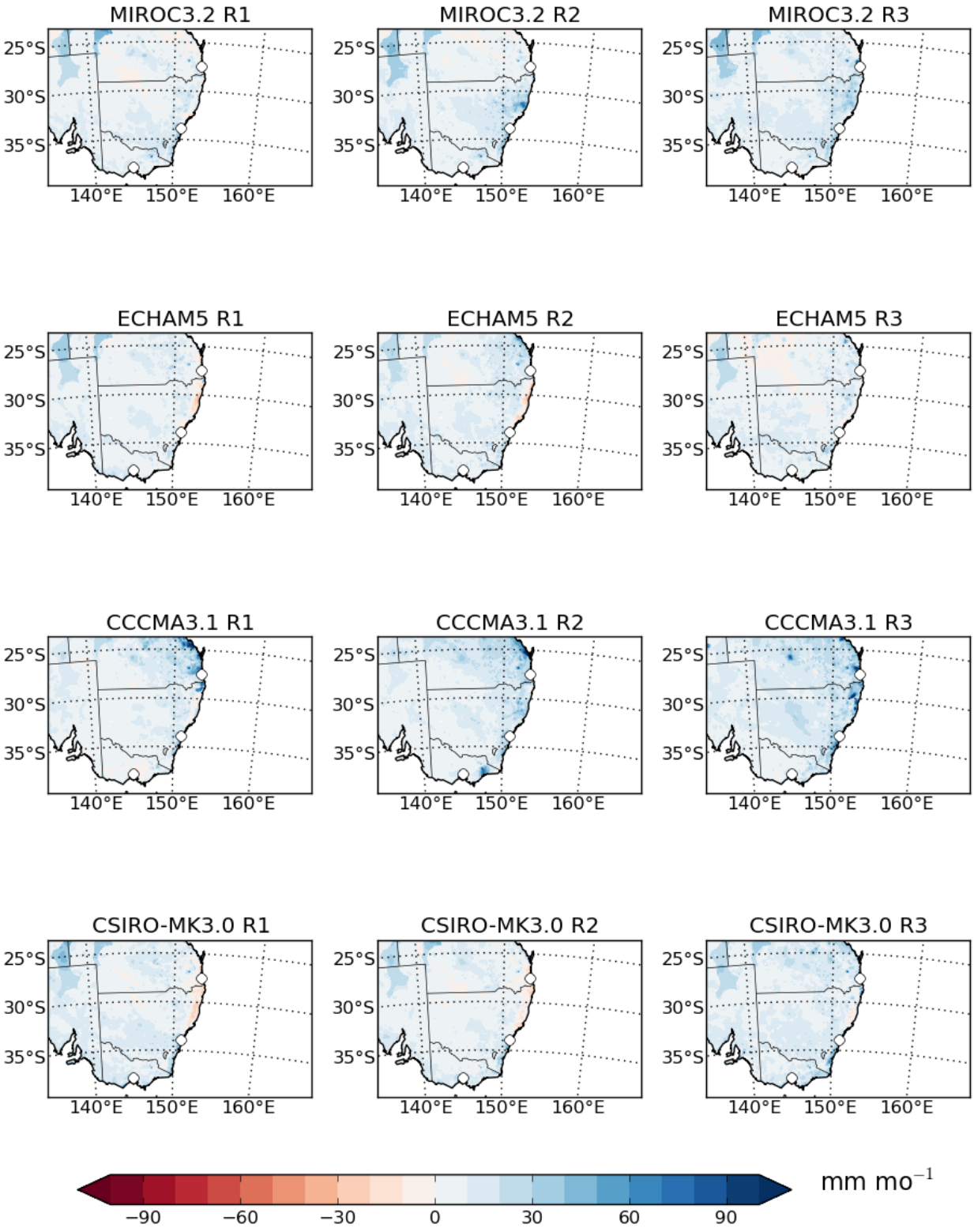

Figure 5.41: MAM mean of bias-corrected WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

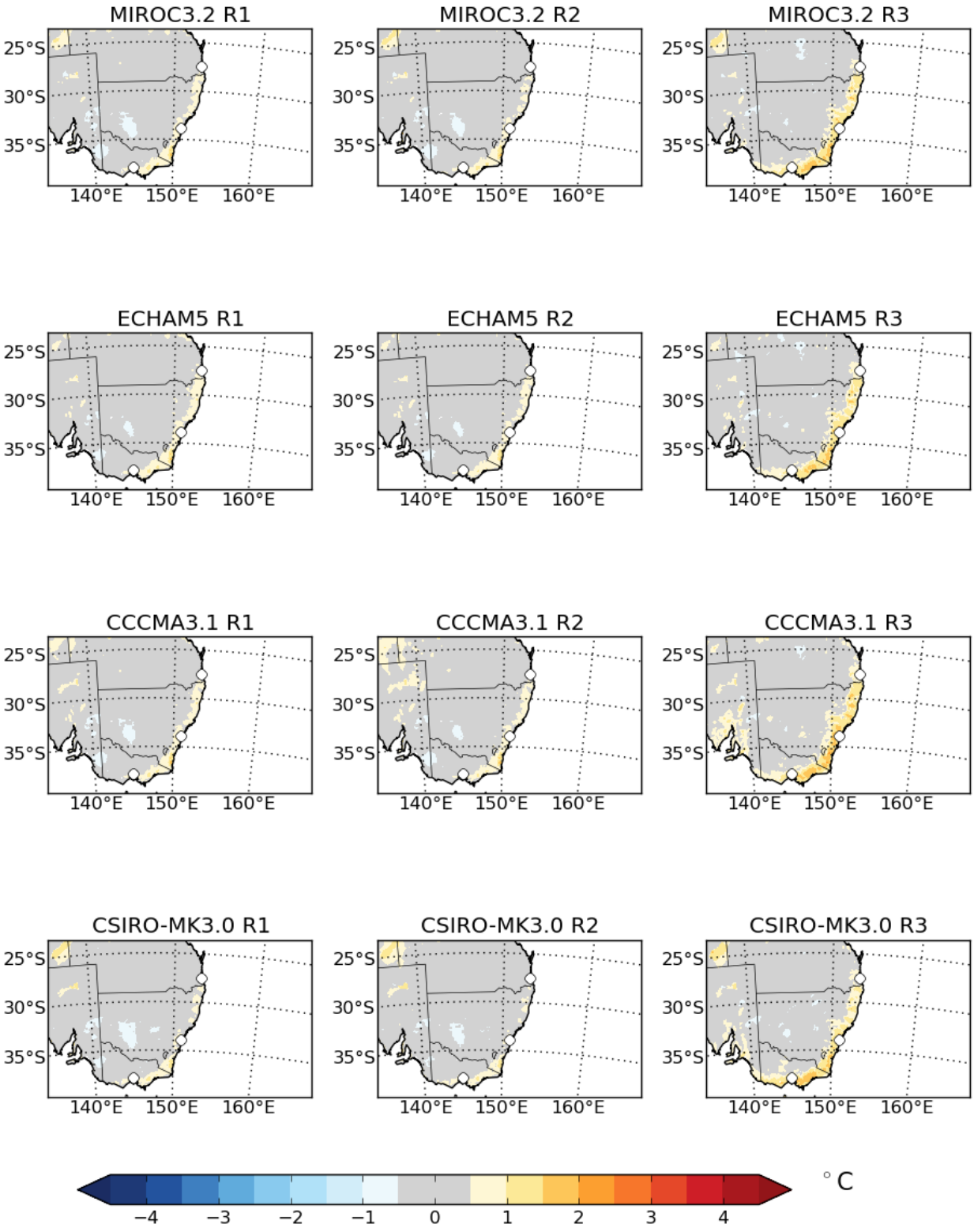

Figure 5.42: JJA mean of bias-corrected WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

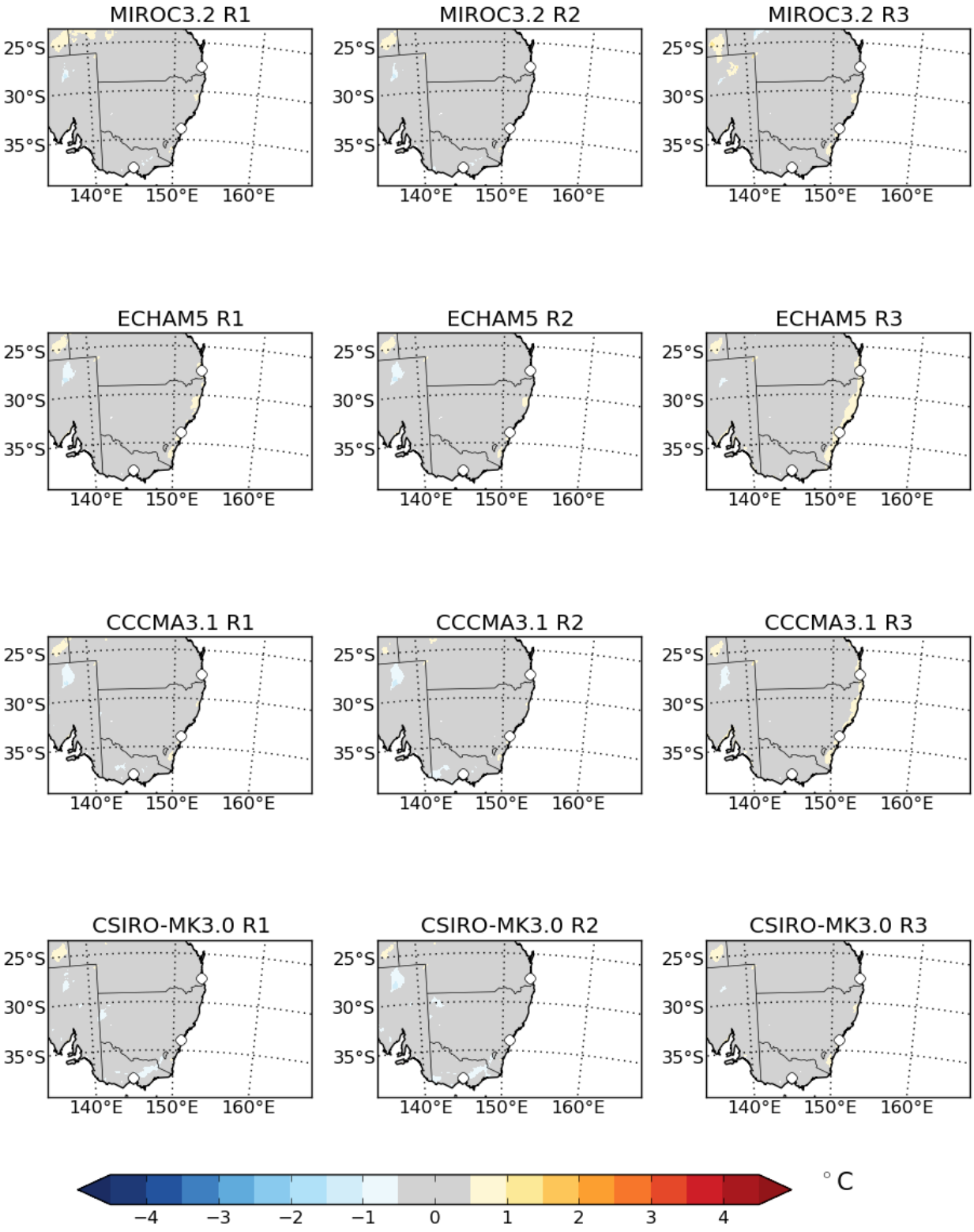

Figure 5.43: JJA mean of bias-corrected WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

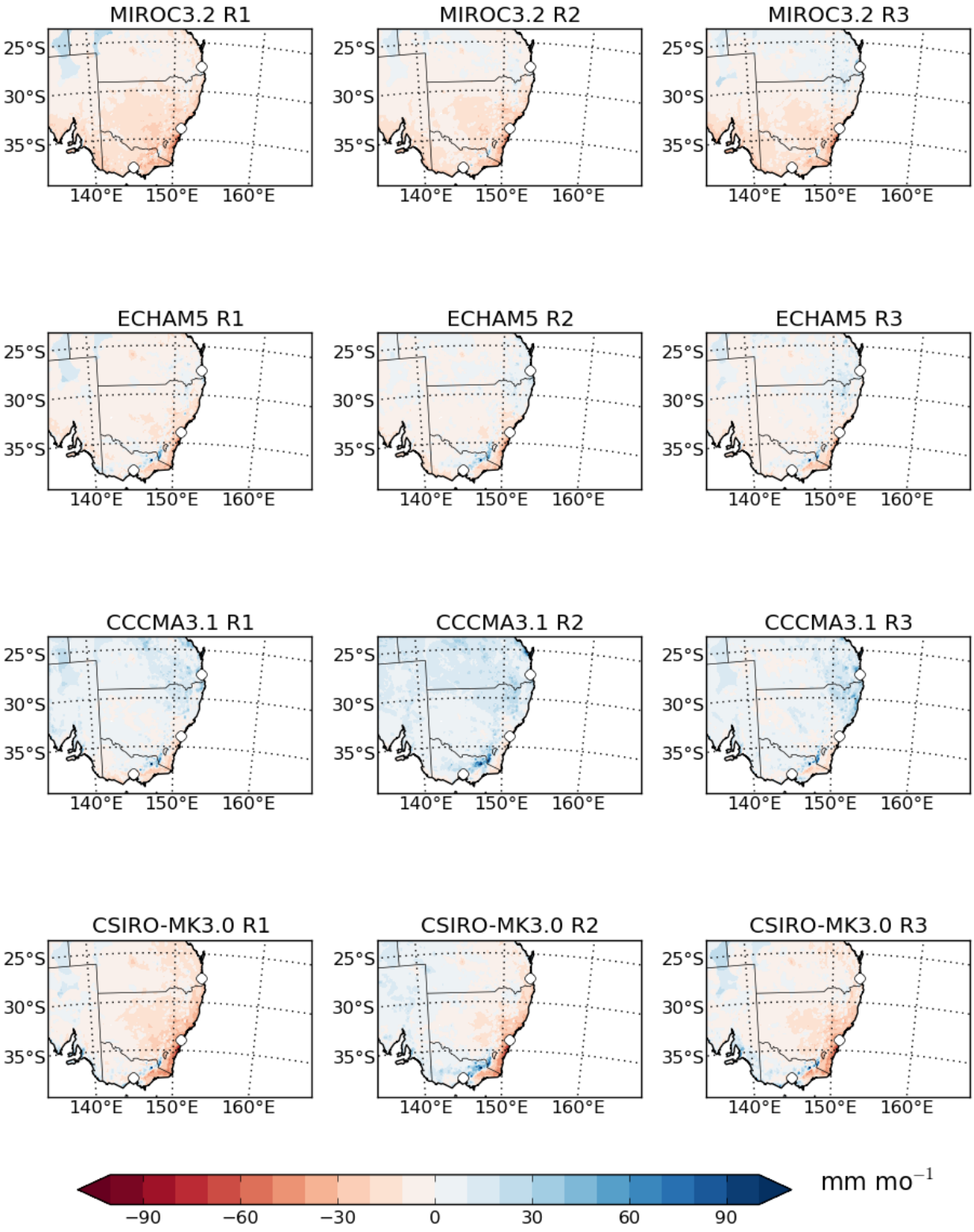

Figure 5.44: JJA mean of bias-corrected WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

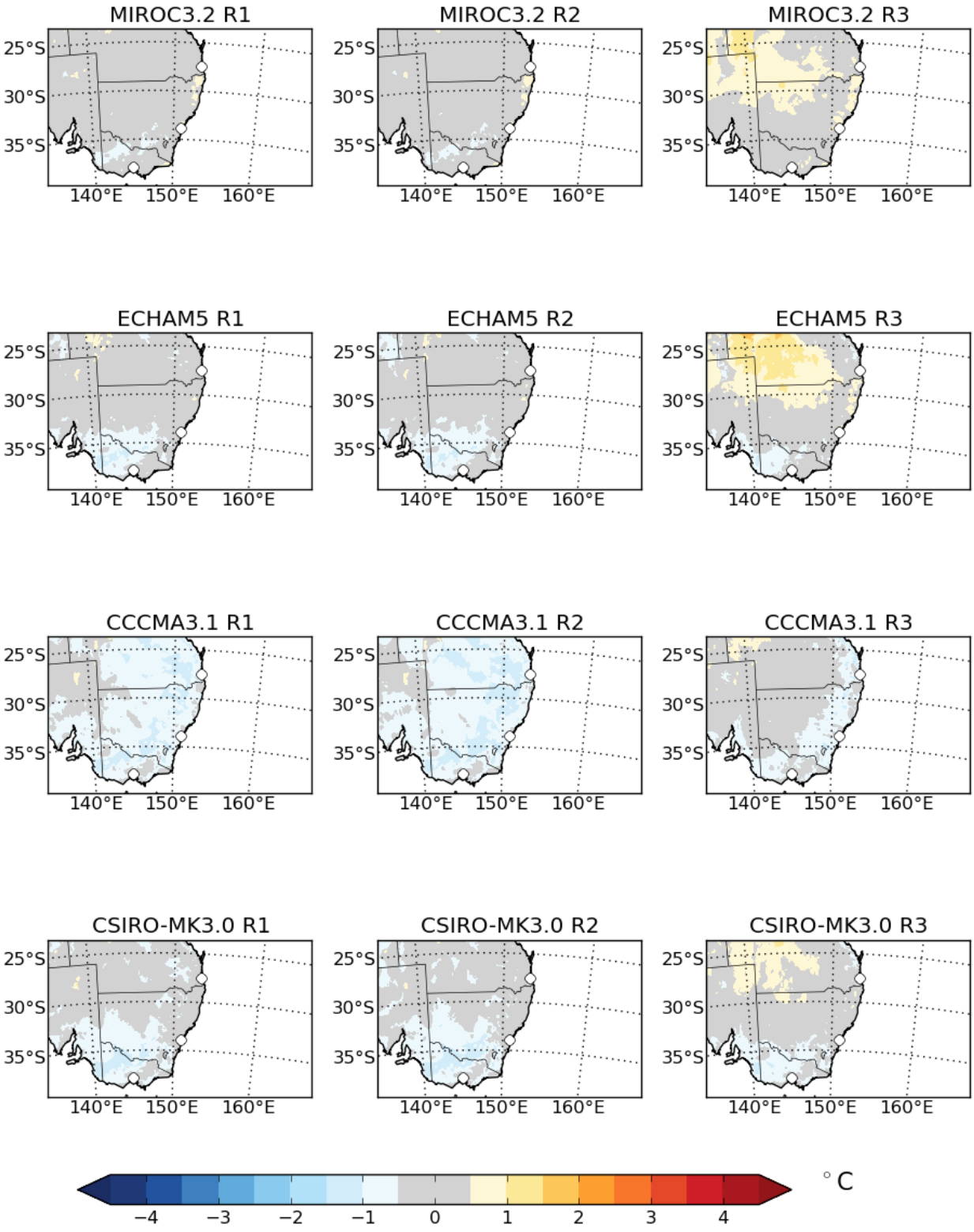

Figure 5.45: SON mean of bias-corrected WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

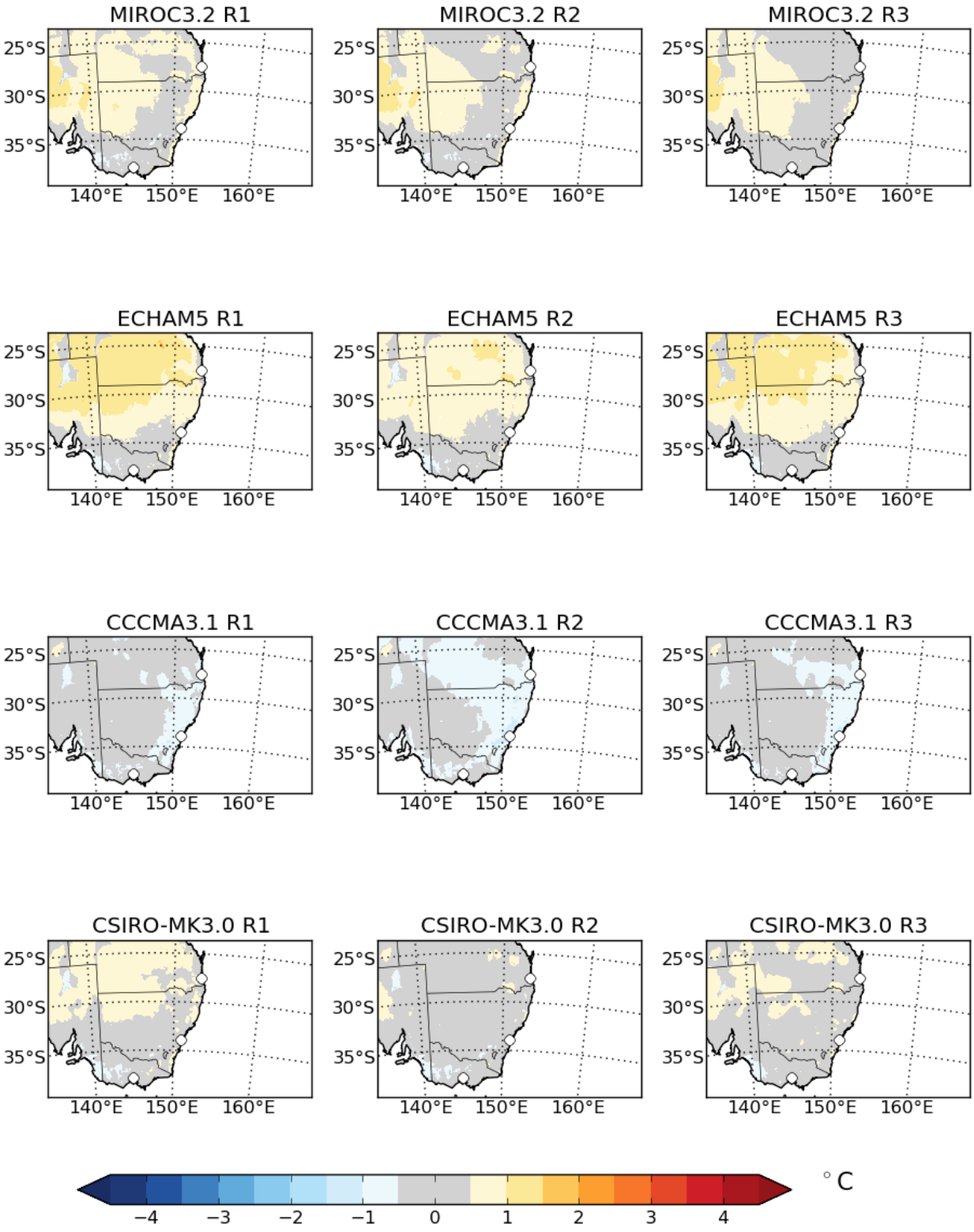

Figure 5.46: SON mean of bias-corrected WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

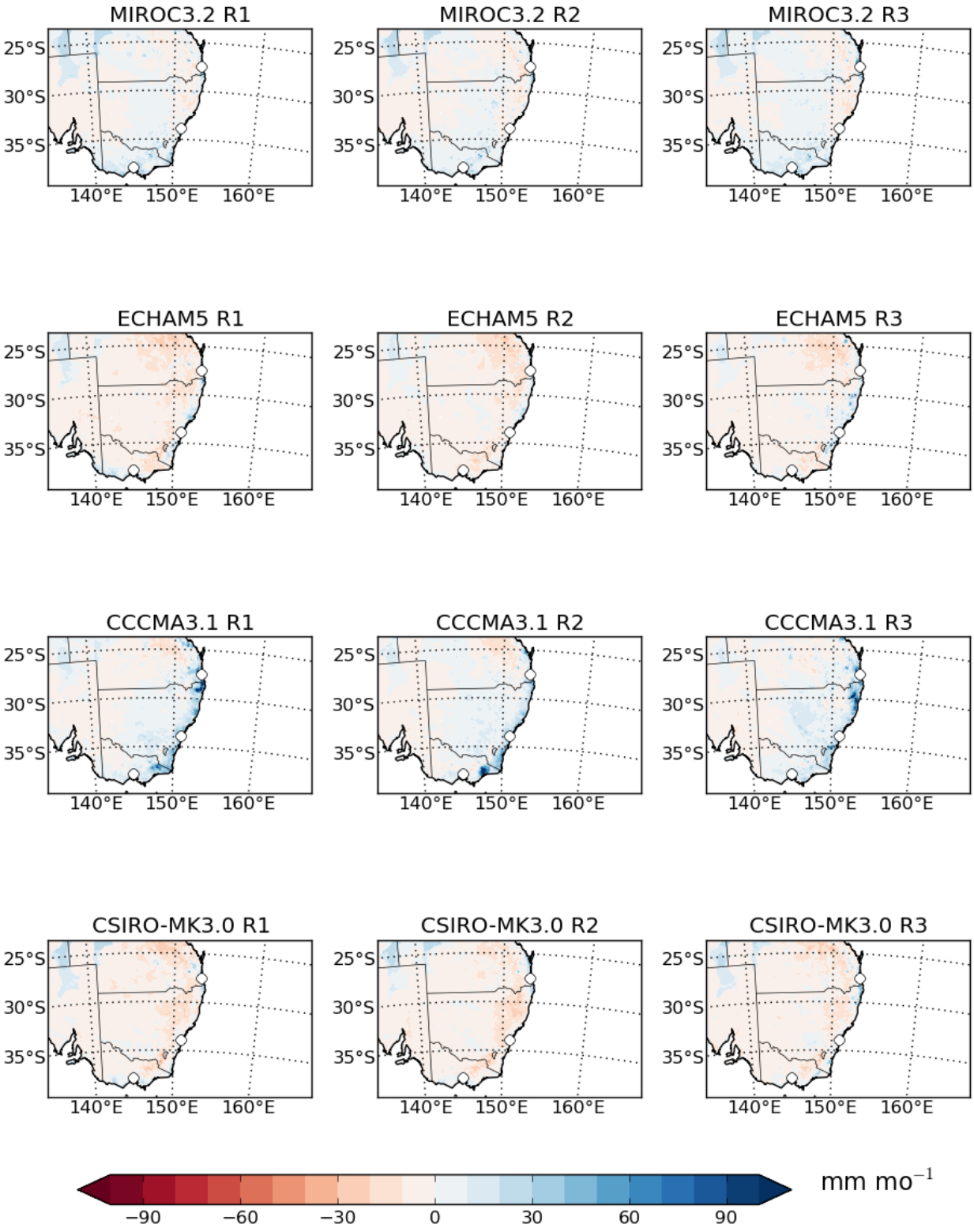

Figure 5.47: SON mean of bias-corrected WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

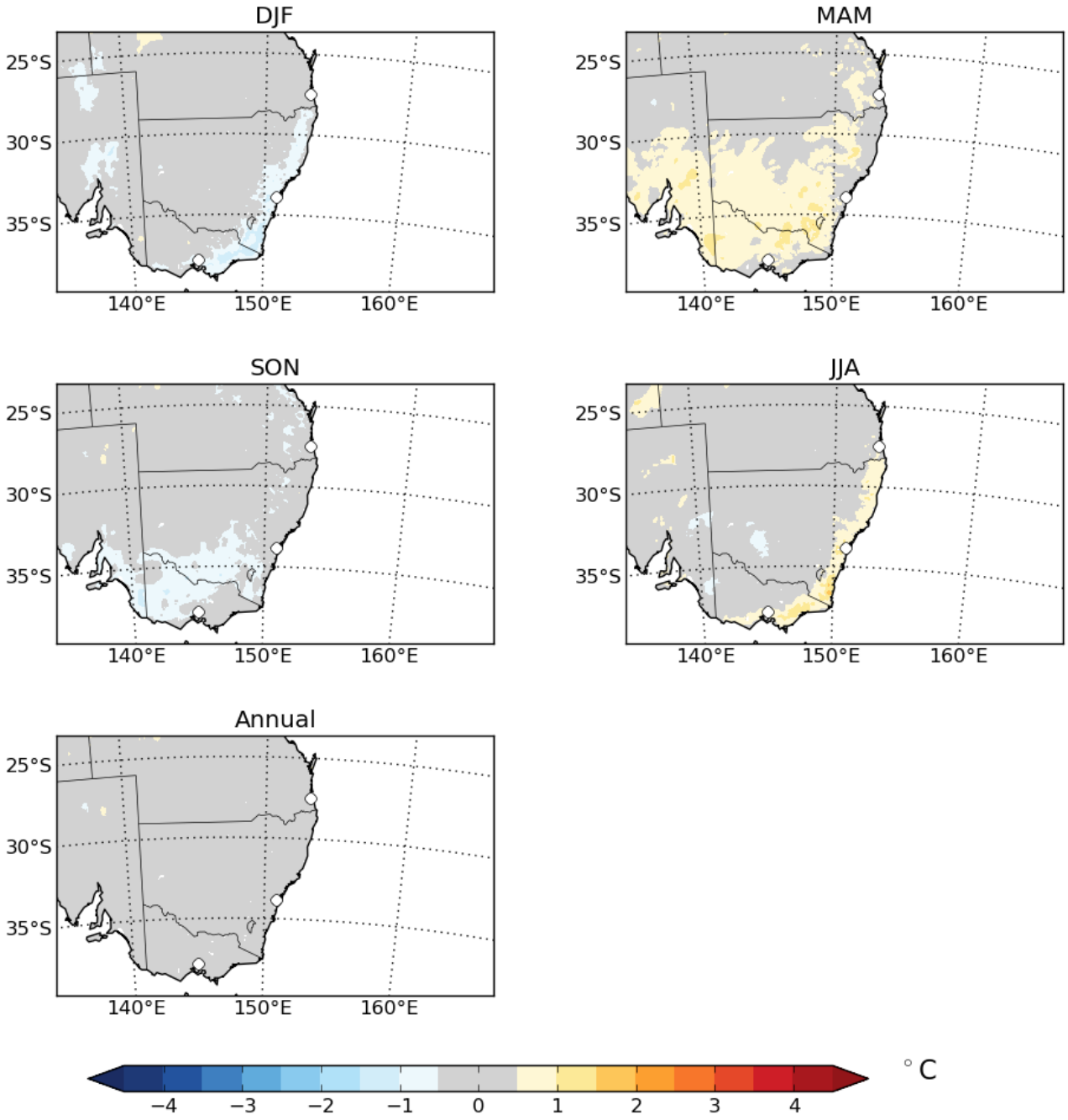

Figure 5.48: Seasonal and annual multimodel means of bias-corrected WRF minus AWAP daily minimum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

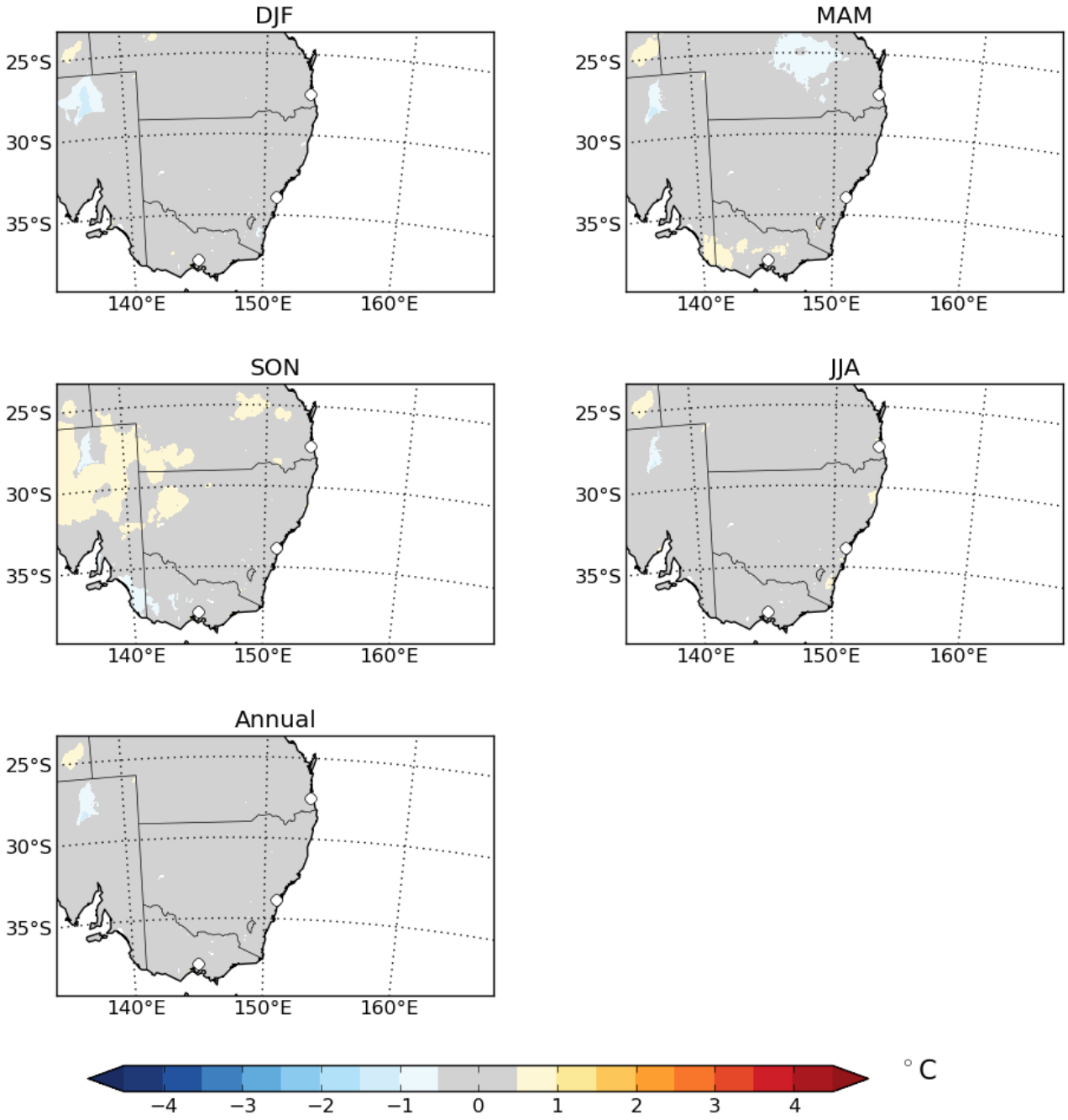

Figure 5.49: Seasonal and annual multimodel means of bias-corrected WRF minus AWAP daily maximum near-surface air temperature for years 1990-2009 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

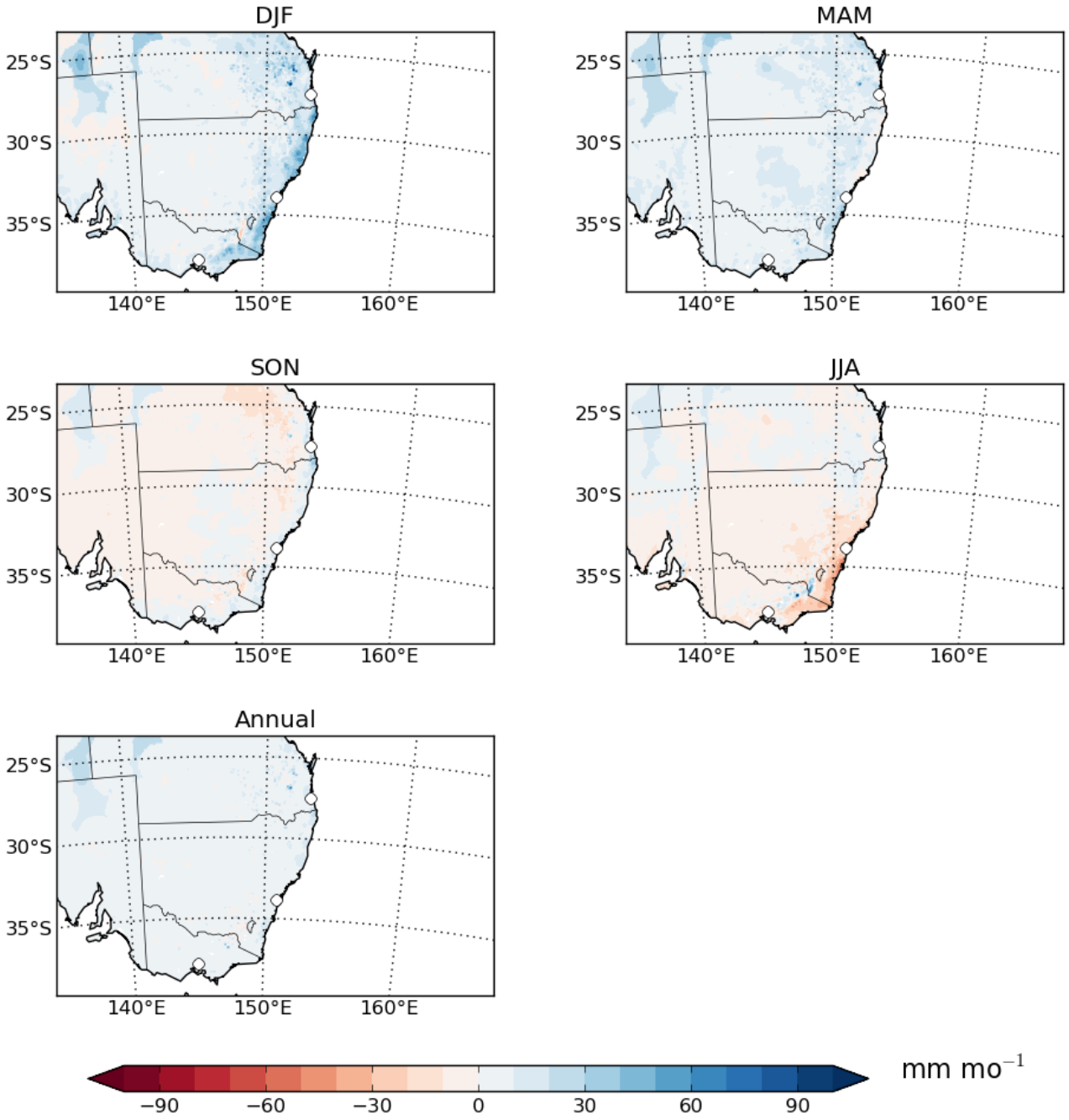

Figure 5.50: Seasonal and annual multimodel means of bias-corrected WRF minus AWAP precipitation for years 1990-2009 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 6

Near Future (2020-2039) Model Climatologies

This chapter contains the climatological seasonal and annual mean projections for near-future near-surface air temperature and precipitation. We first show the results for the GCMs used to drive the RCMs, then for original RCM output, and finally for bias-corrected RCM output. The bias-corrected RCM output is the RCM output corrected for present-day biases between the models and the observations using the methods described here [6].

6.1 2020-2039 Driving GCMs

This subsection contains projected near-future climatologies for near-surface air temperature and precipitation from each of the GCMs used to provide boundary conditions to the RCMs. The plots are ordered first by GCM, and then by variable.

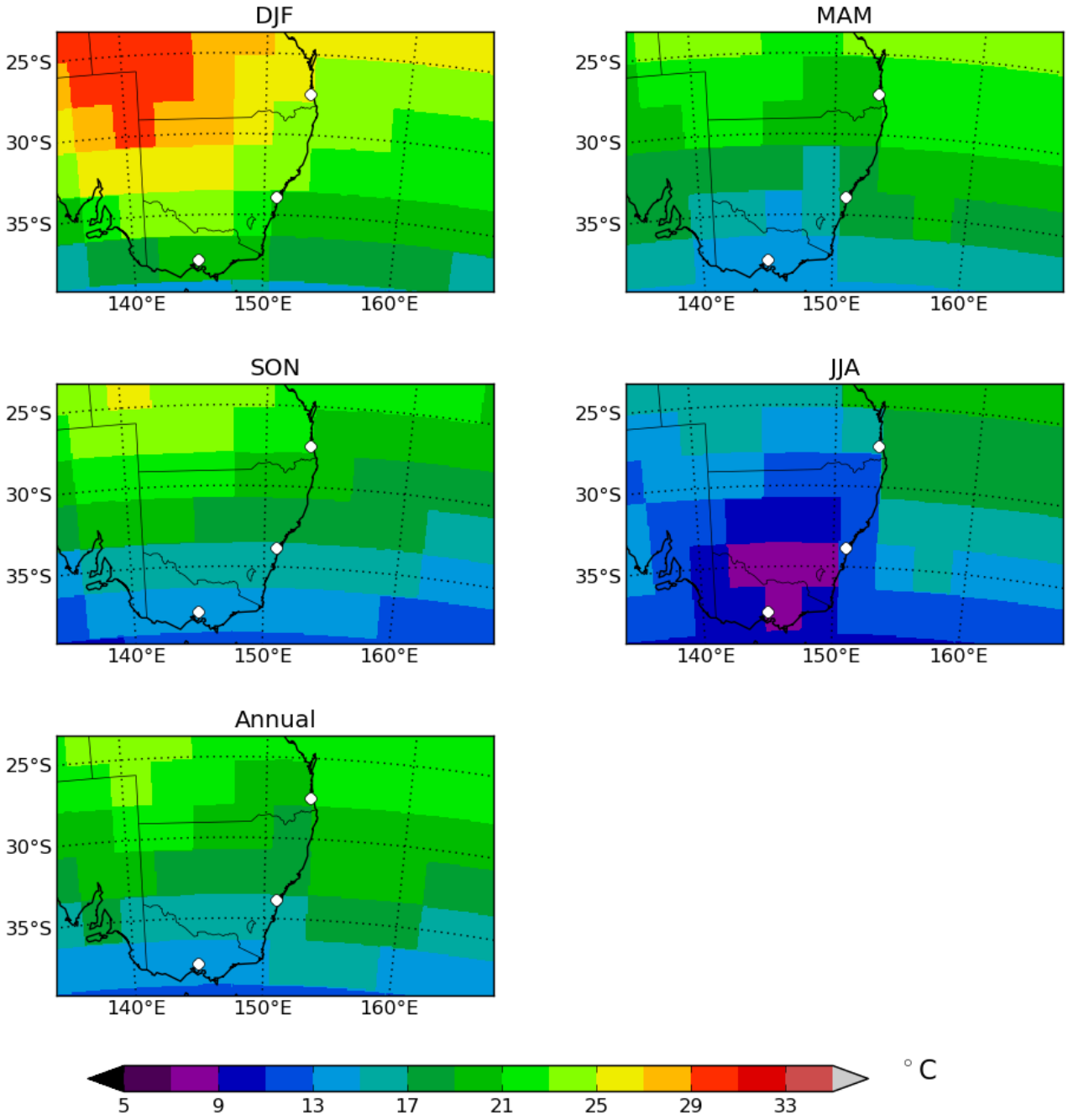

Figure 6.1: Seasonal and annual means of MIROC3.2 near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

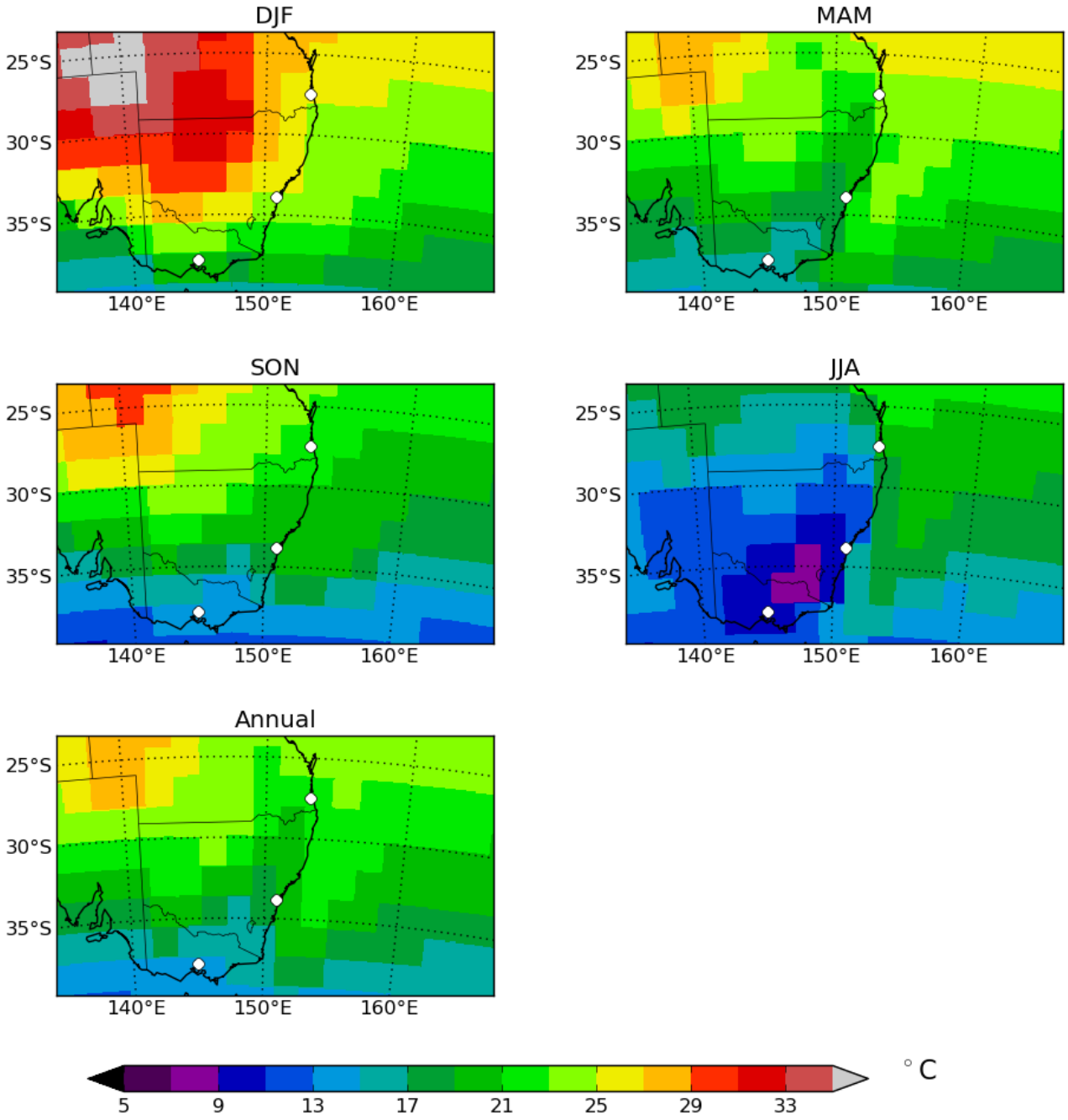

Figure 6.2: Seasonal and annual means of ECHAM5 near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

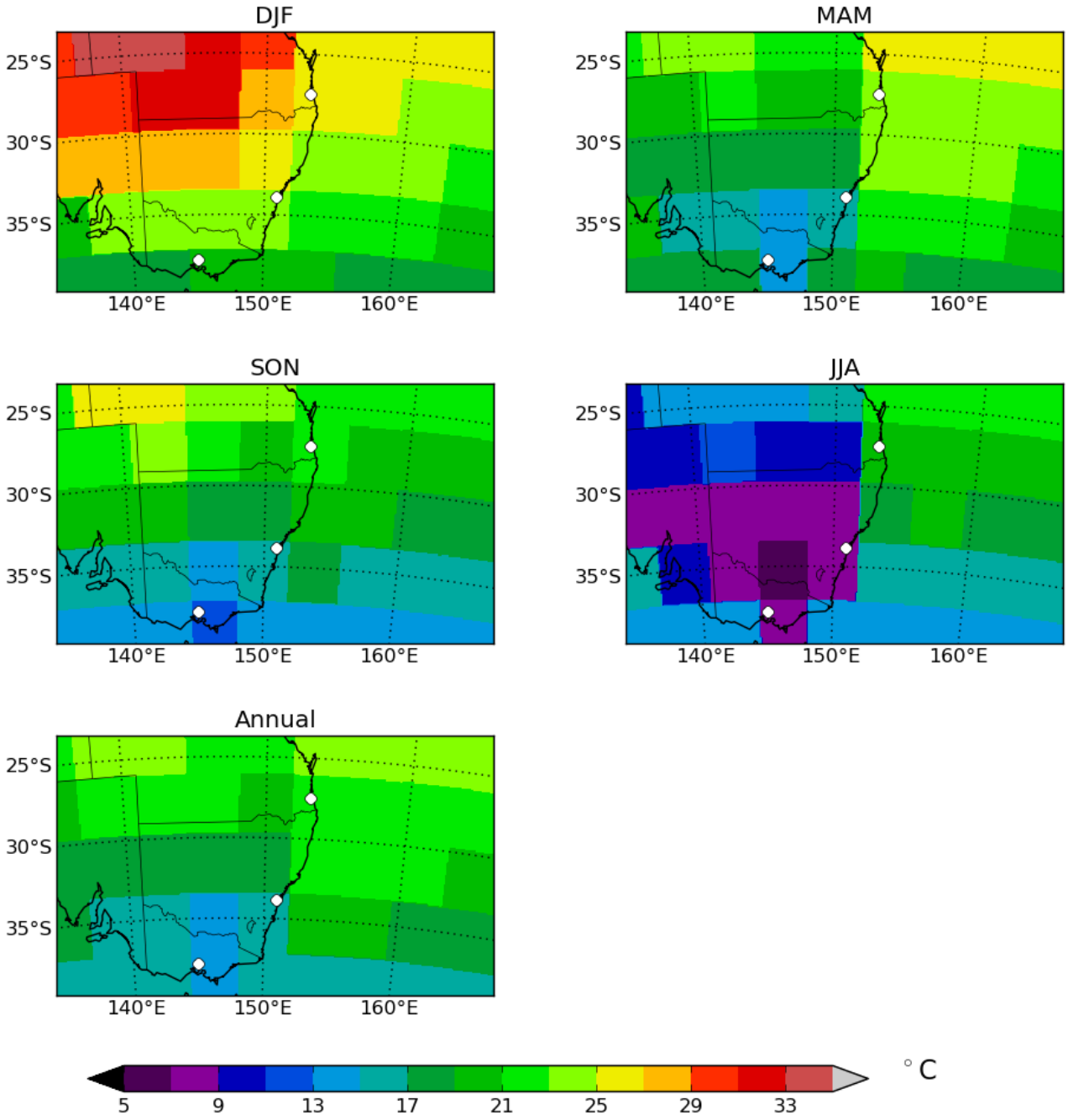

Figure 6.3: Seasonal and annual means of CCCMA3.1 near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

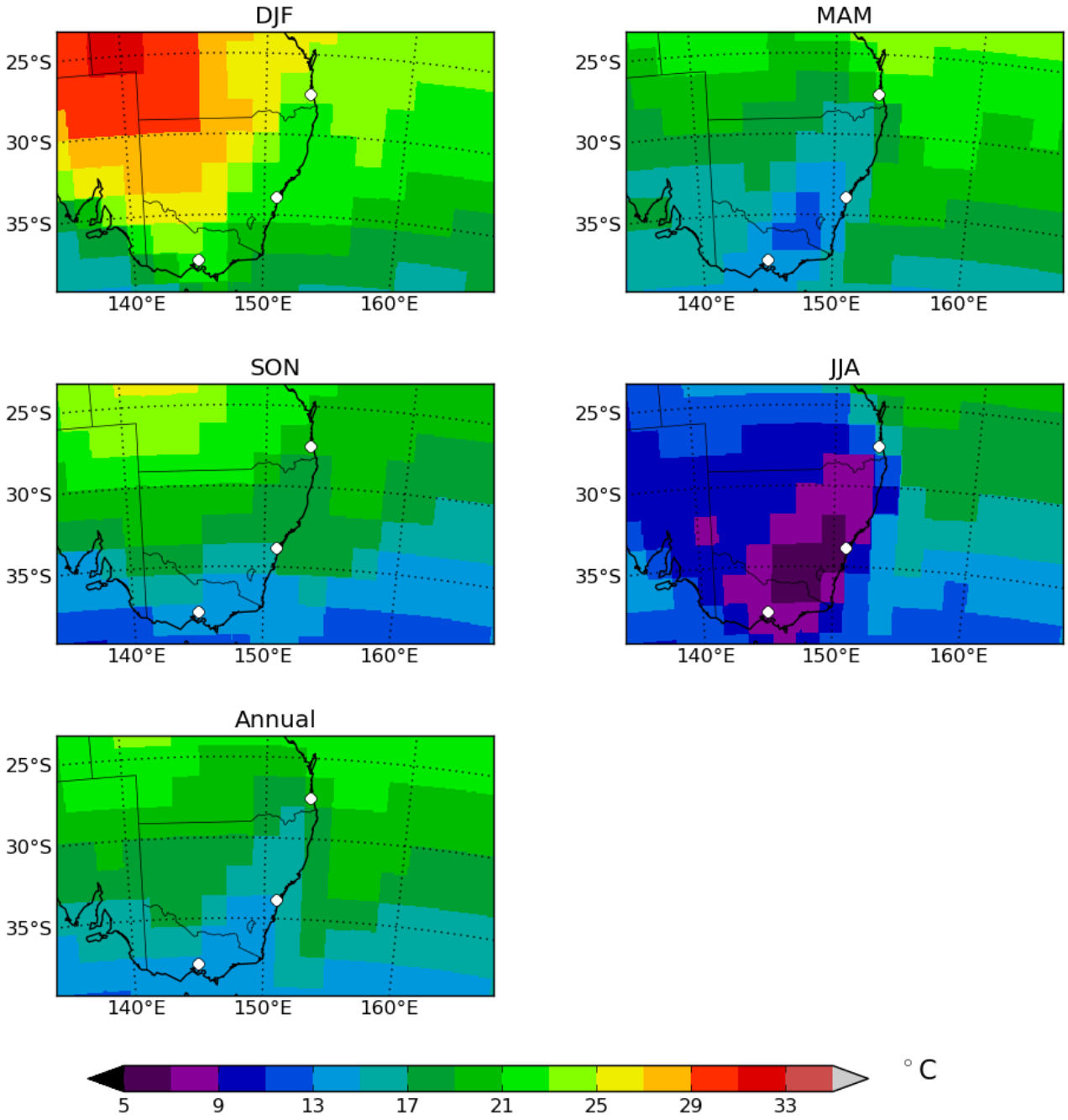

Figure 6.4: Seasonal and annual means of CSIRO-MK3.0 near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

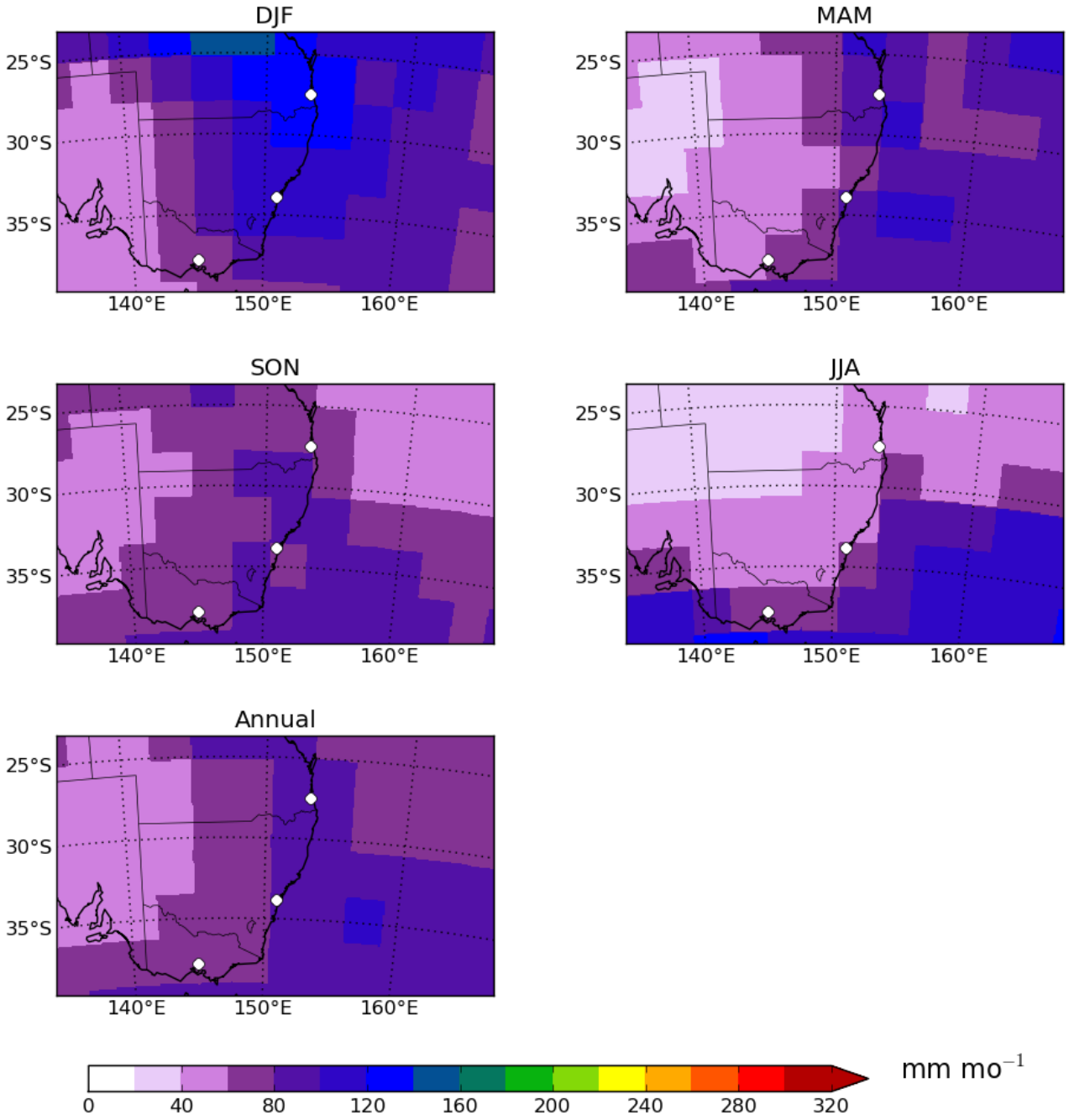

Figure 6.5: Seasonal and annual means of MIROC3.2 precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

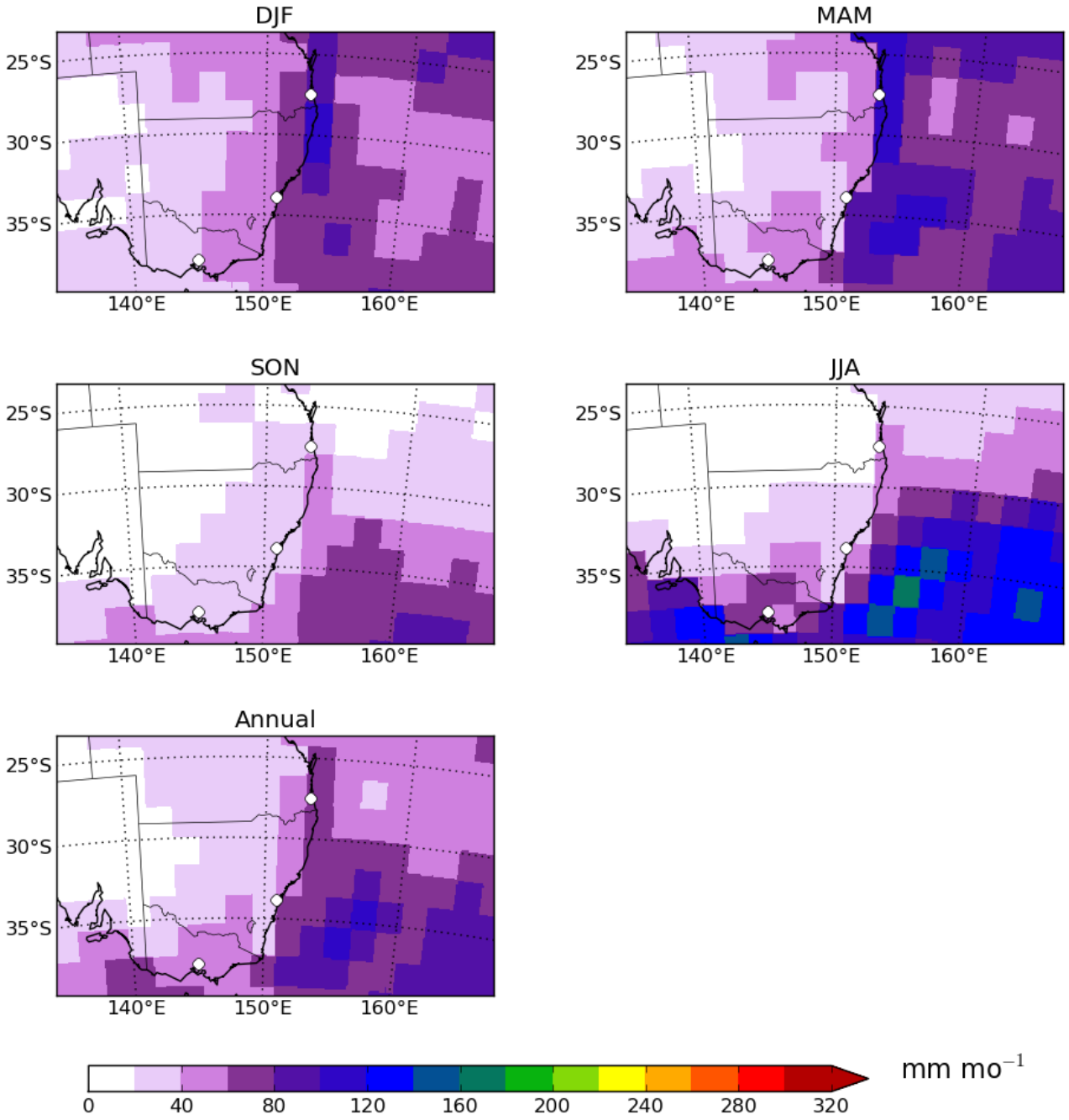

Figure 6.6: Seasonal and annual means of ECHAM5 precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

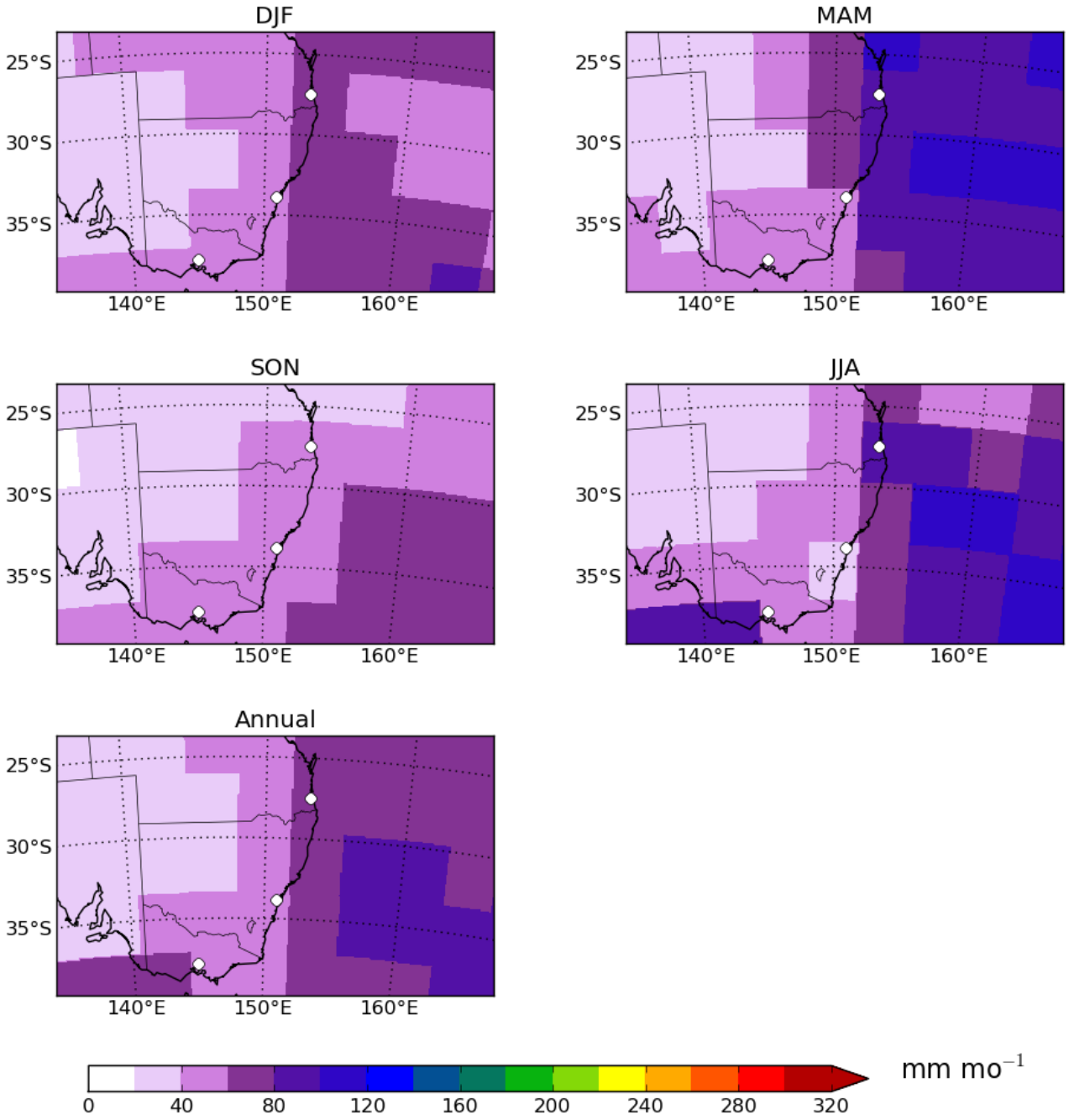

Figure 6.7: Seasonal and annual means of CCCMA3.1 precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

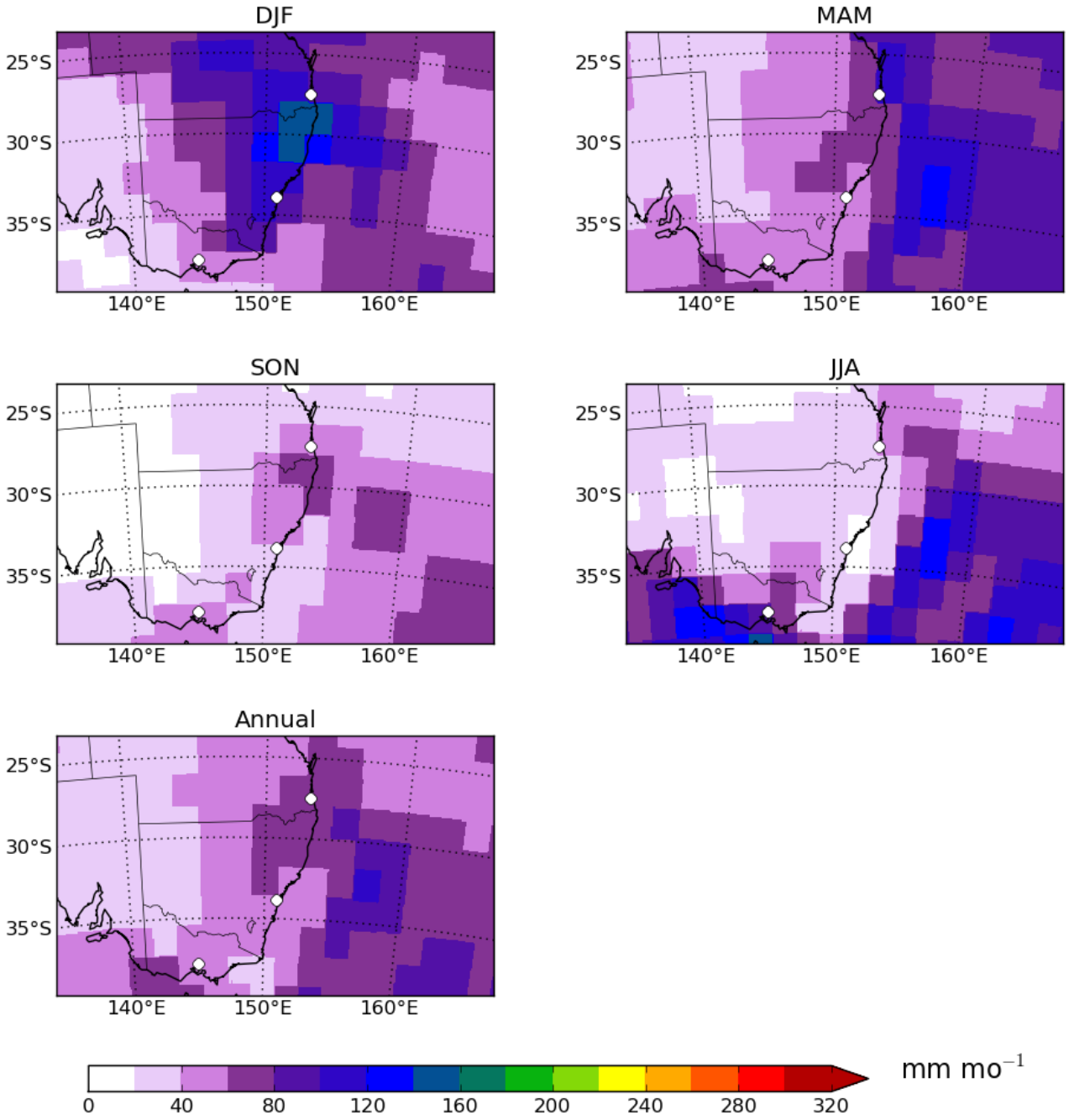

Figure 6.8: Seasonal and annual means of CSIRO-MK3.0 precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

6.2 2020-2039 Regional Model Output

This subsection contains projected near-future climatologies for near-surface air temperature, daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the original RCM output. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected climatologies, whereas the individual-model plots show the level of uncertainty in projected climate.

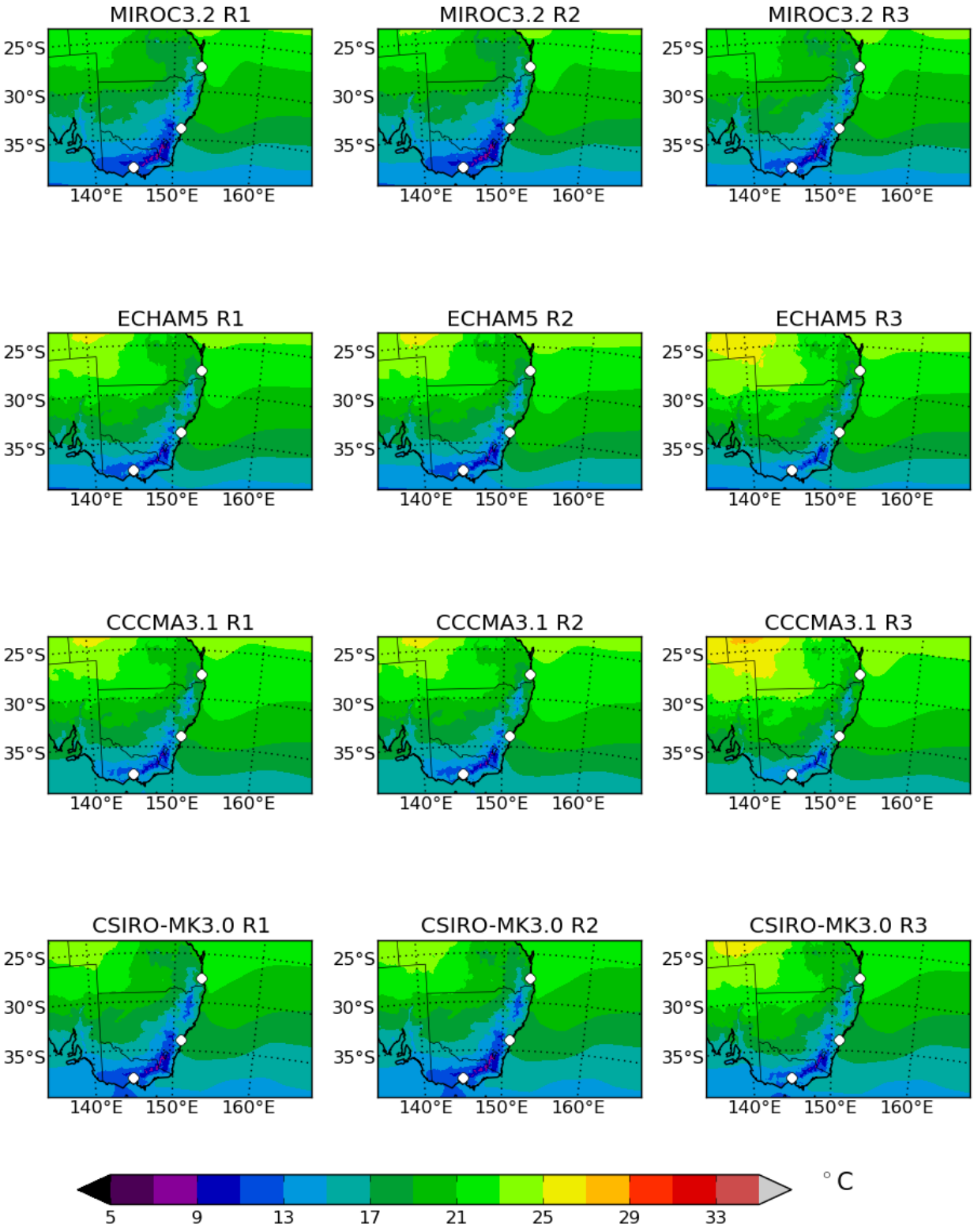

Figure 6.9: Annual mean of near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

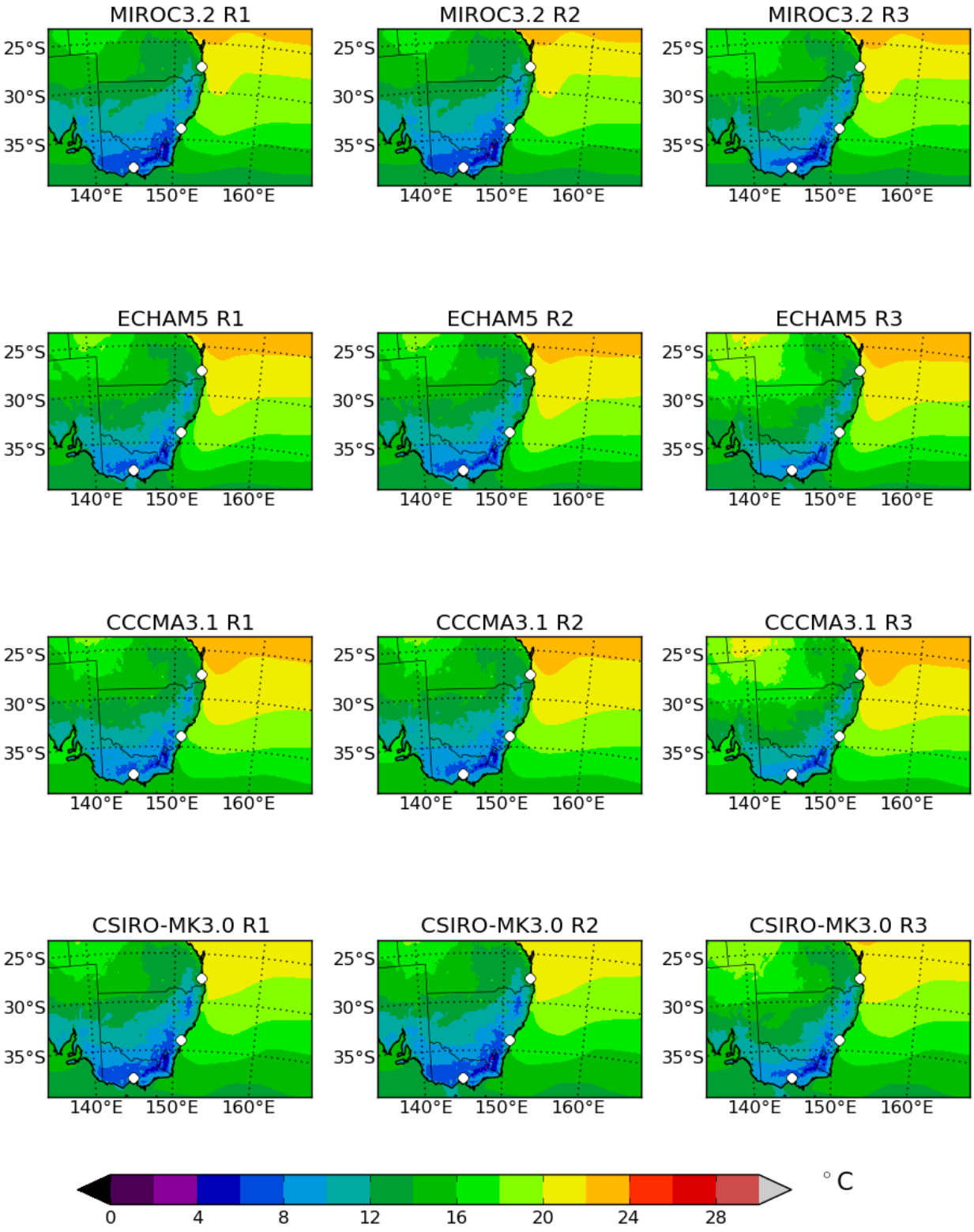

Figure 6.10: Annual mean of daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

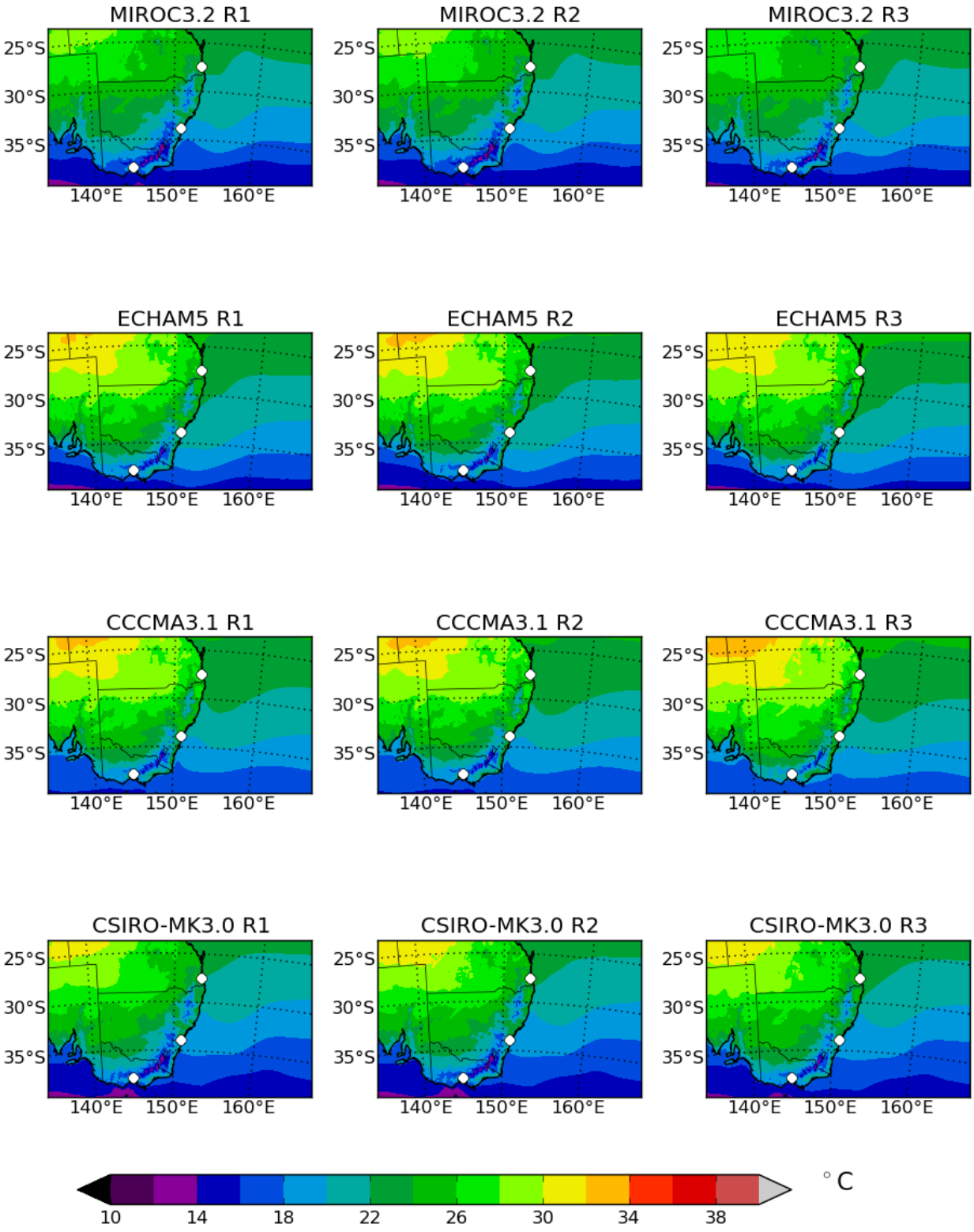

Figure 6.11: Annual mean of daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

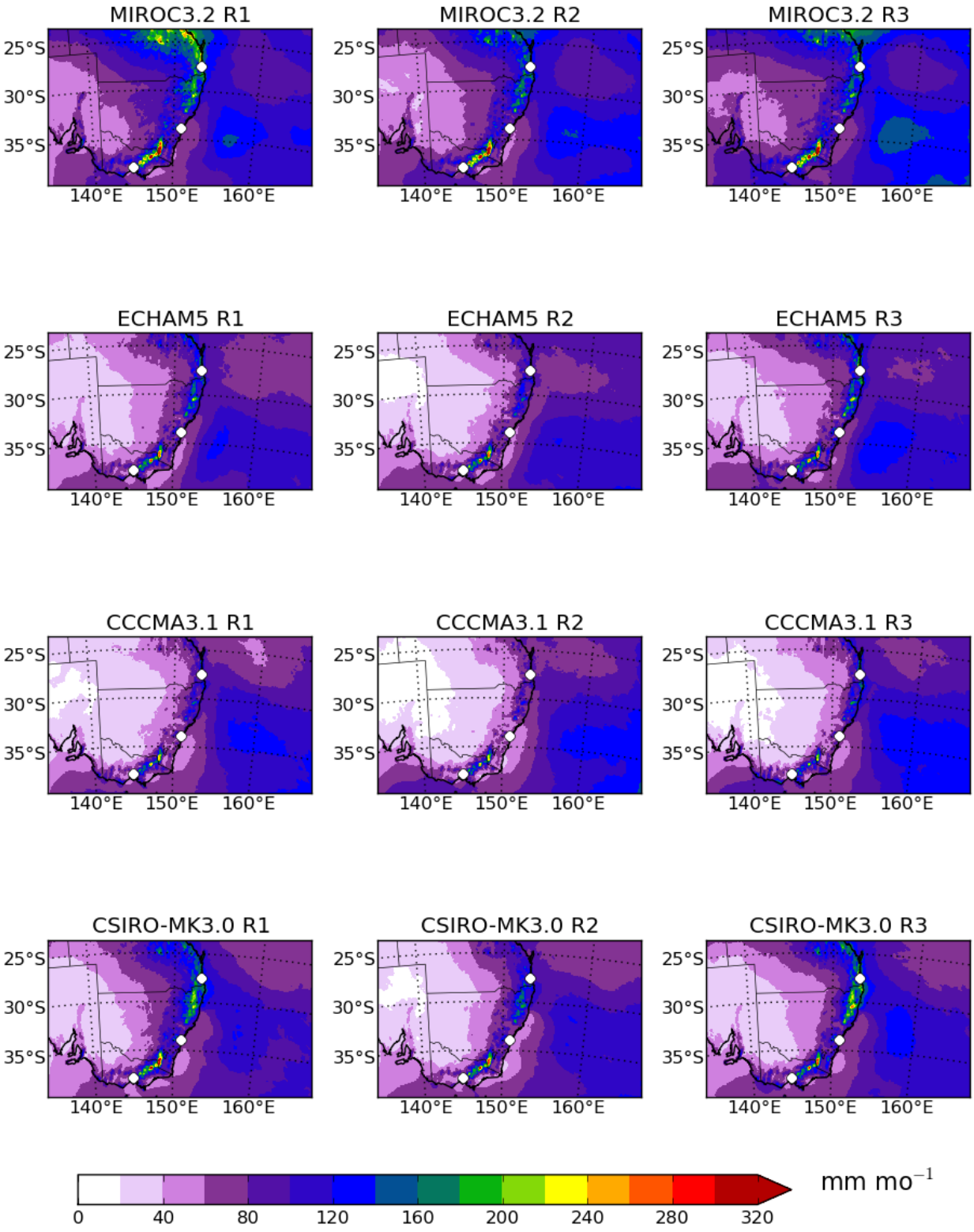

Figure 6.12: Annual mean of precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

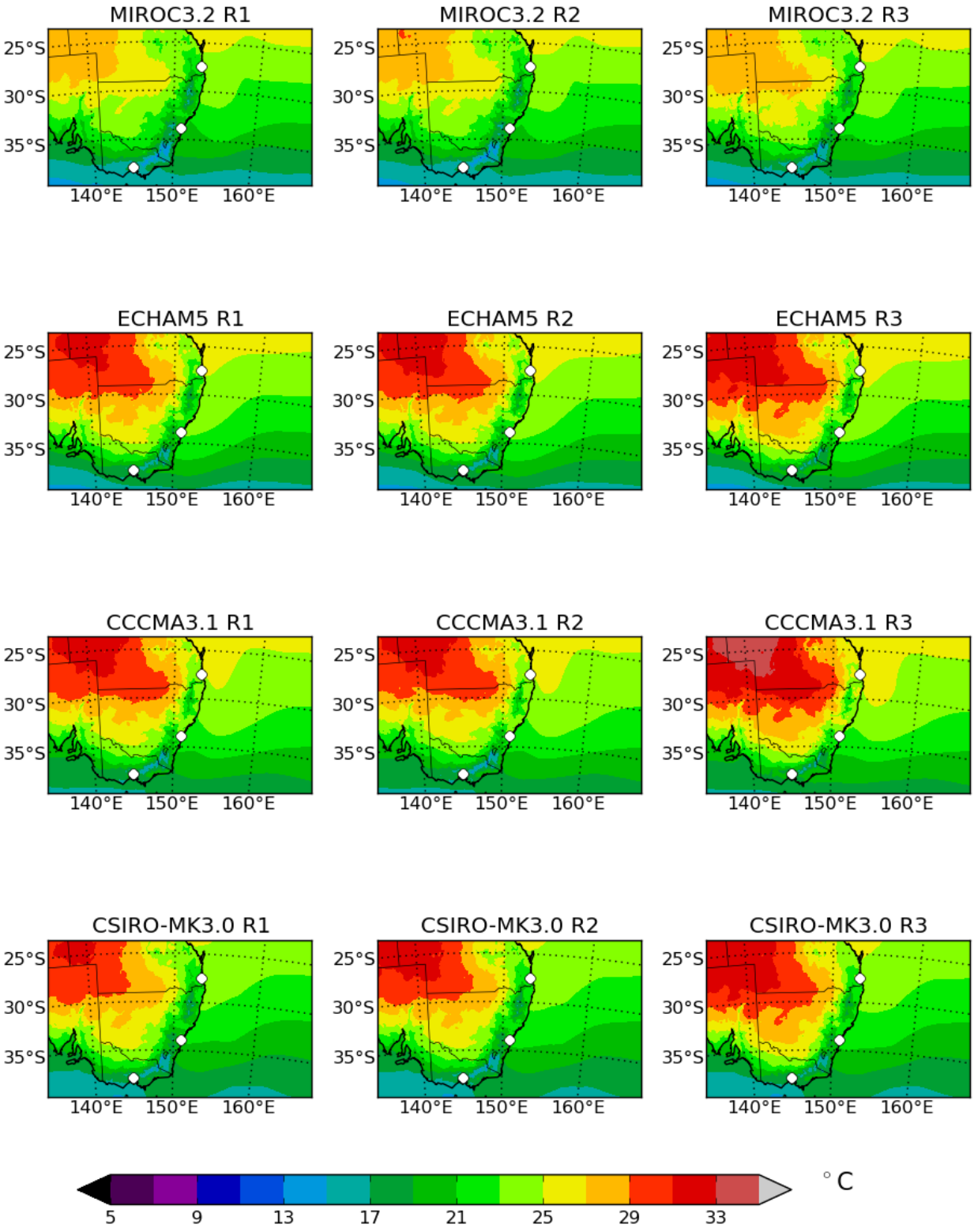

Figure 6.13: DJF mean of near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

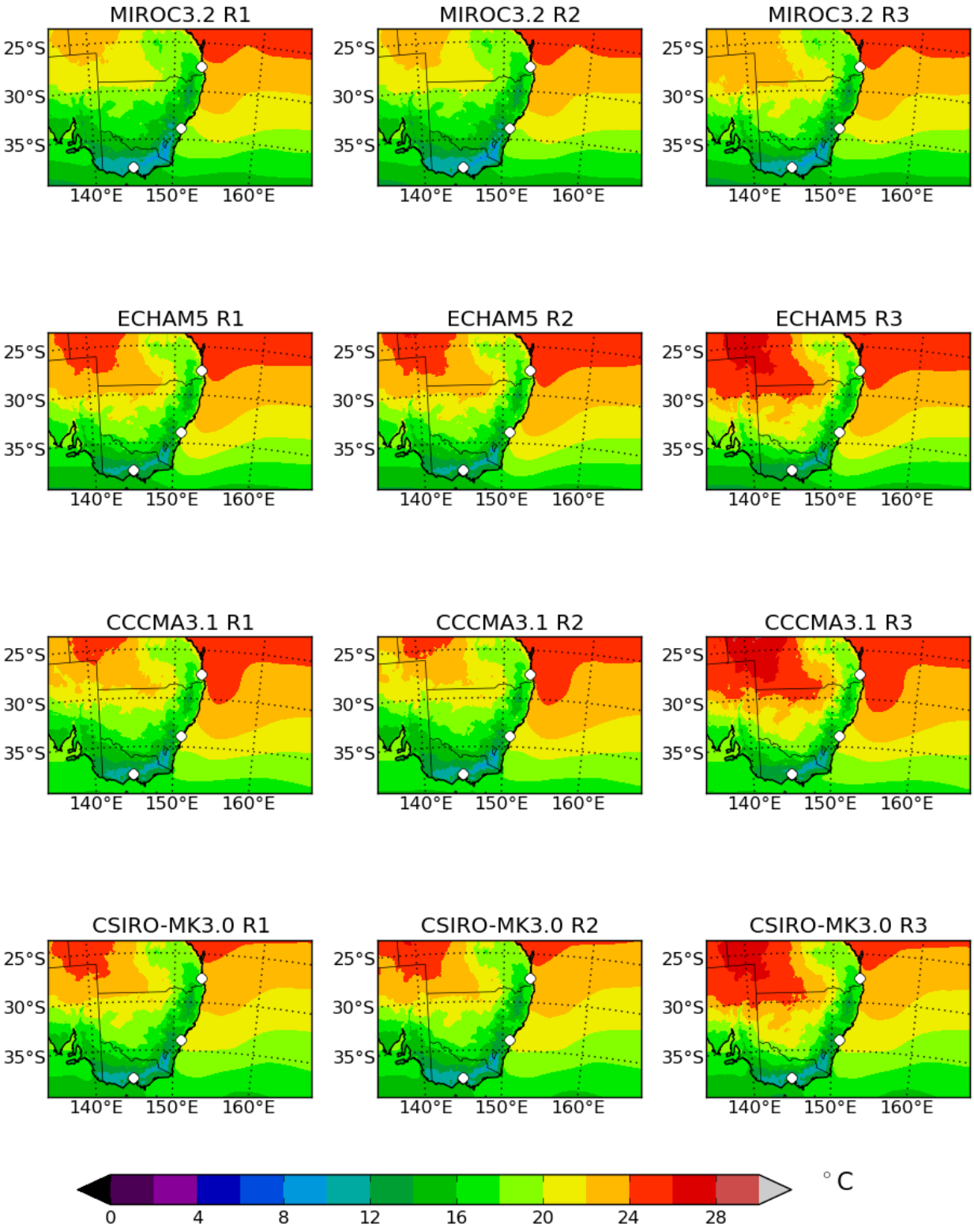

Figure 6.14: DJF mean of daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

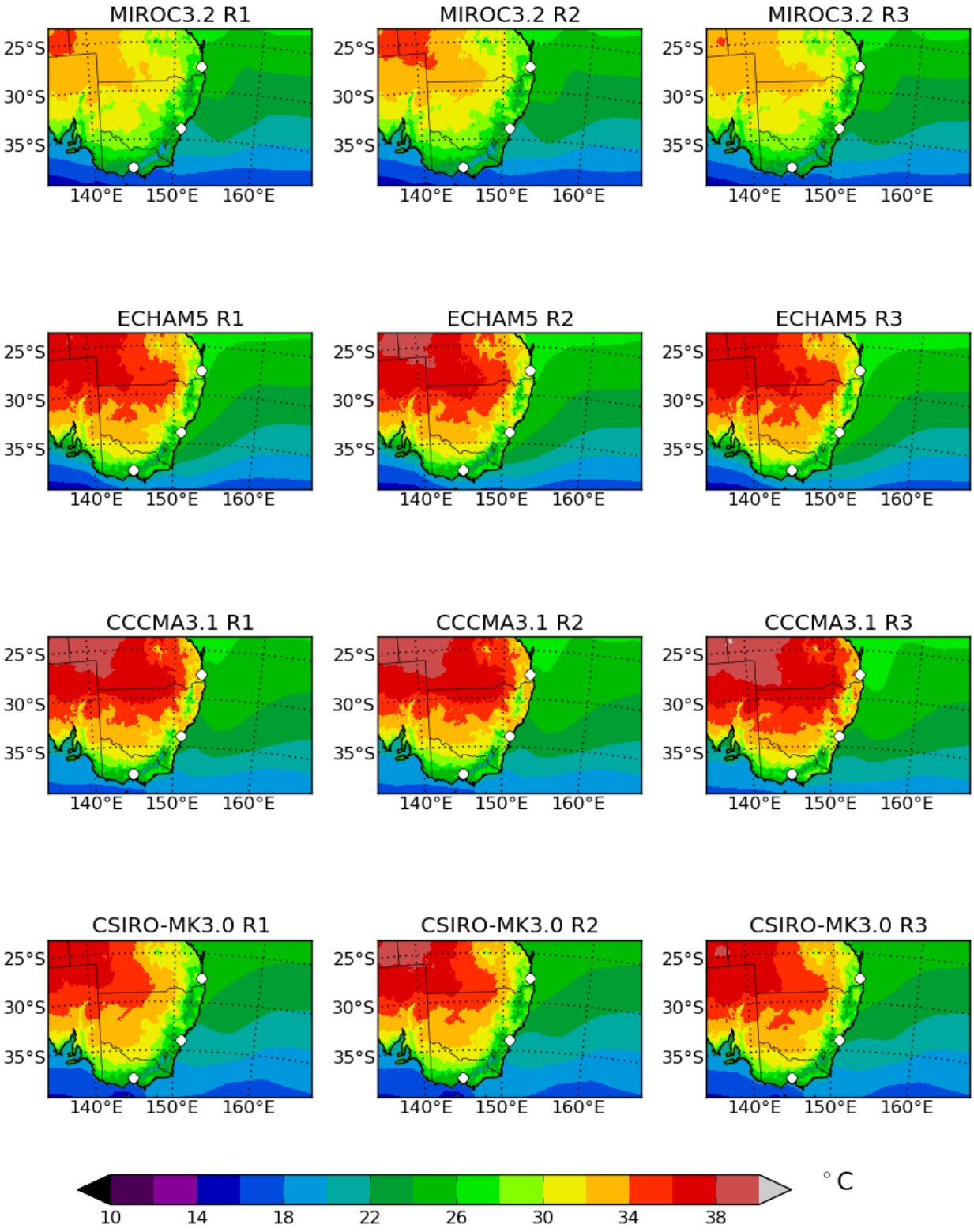

Figure 6.15: DJF mean of daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

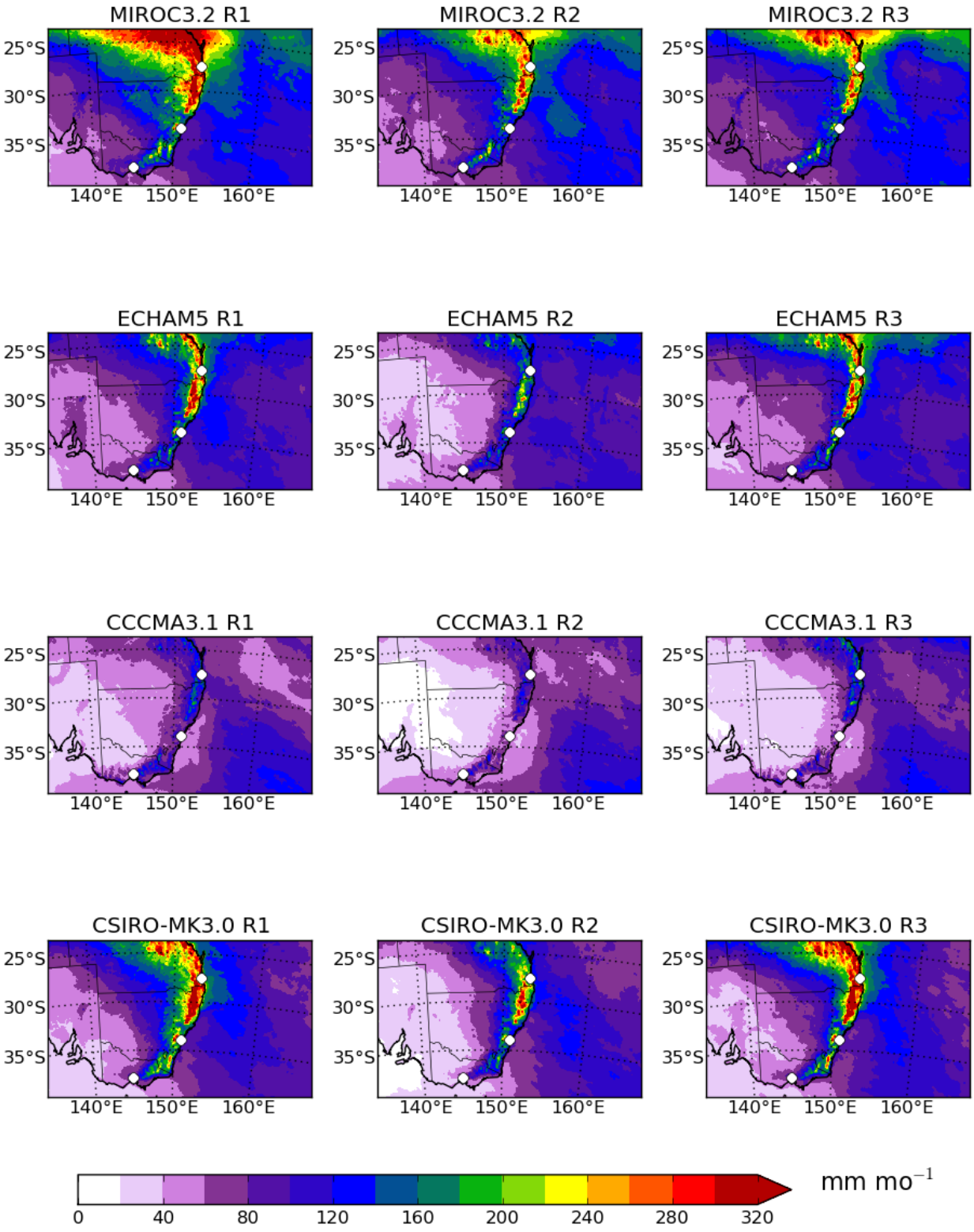

Figure 6.16: DJF mean of precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

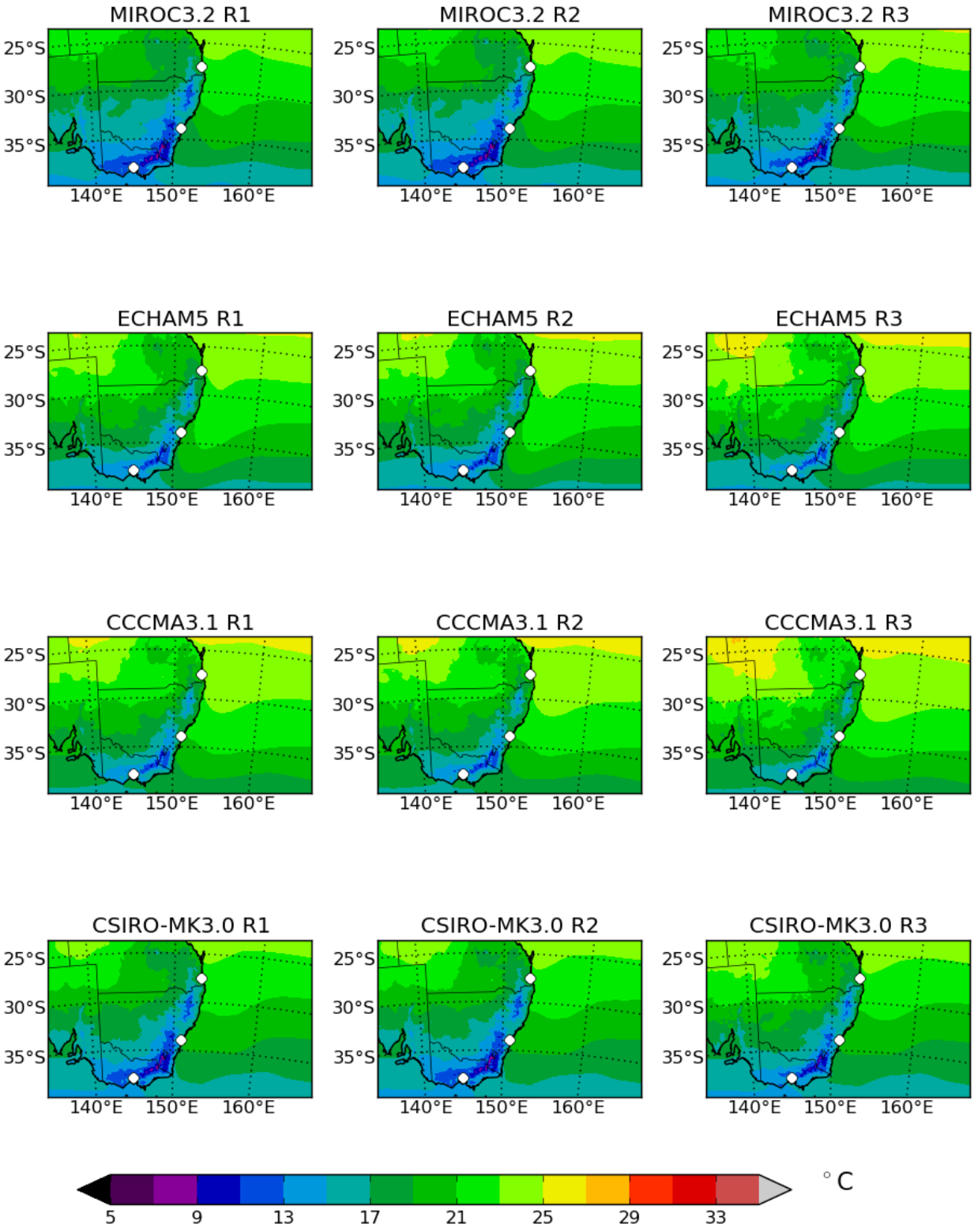

Figure 6.17: MAM mean of near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

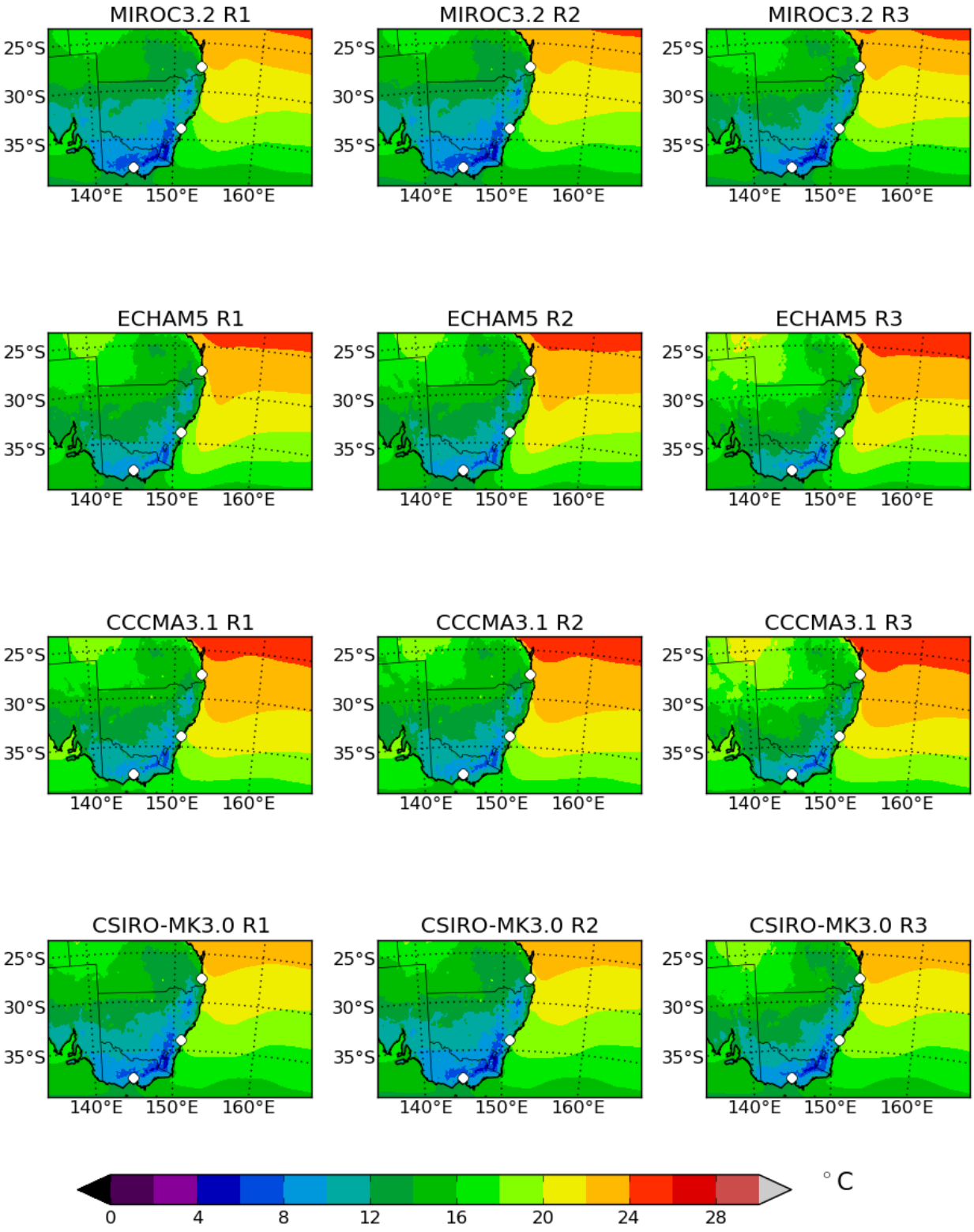

Figure 6.18: MAM mean of daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

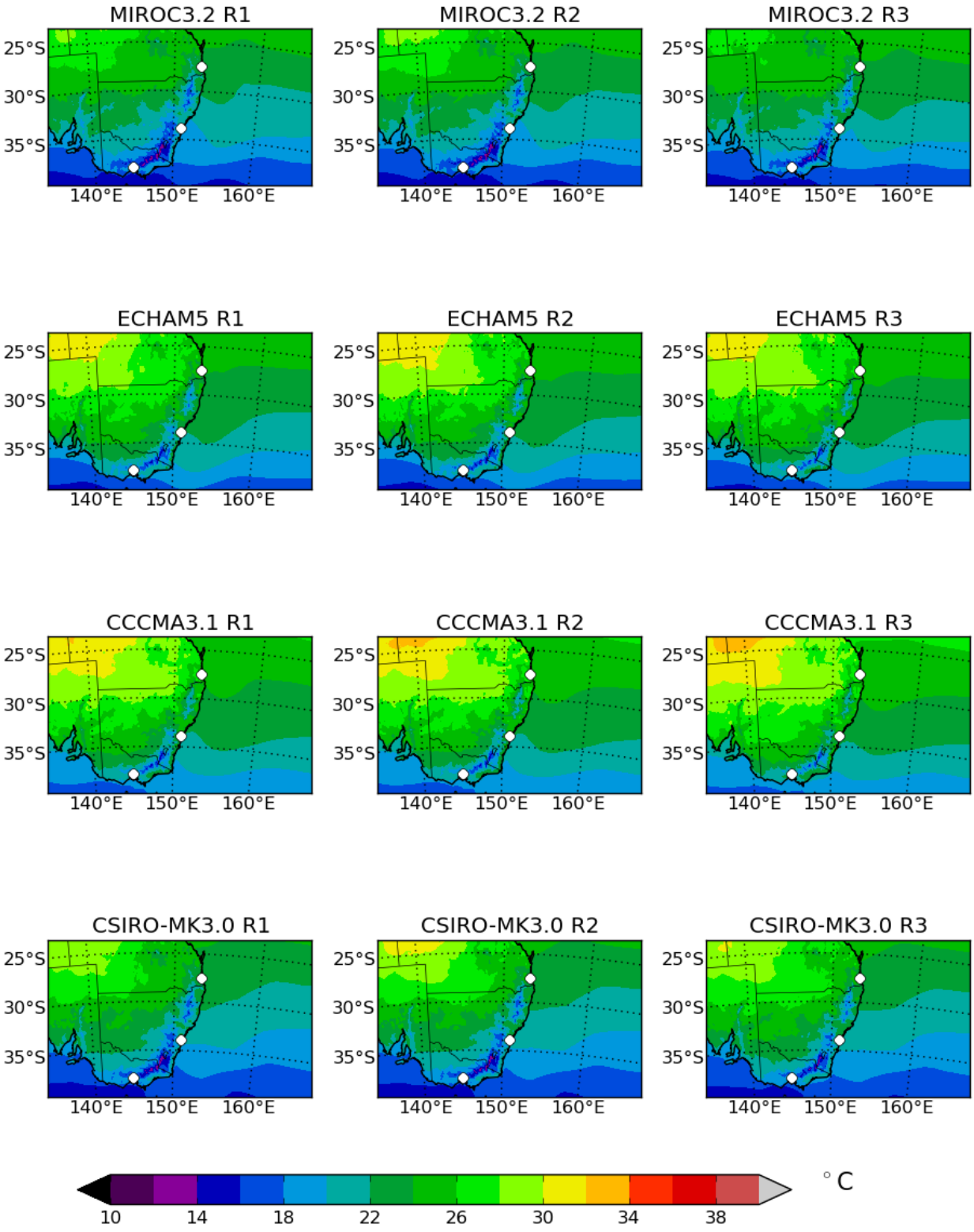

Figure 6.19: MAM mean of daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

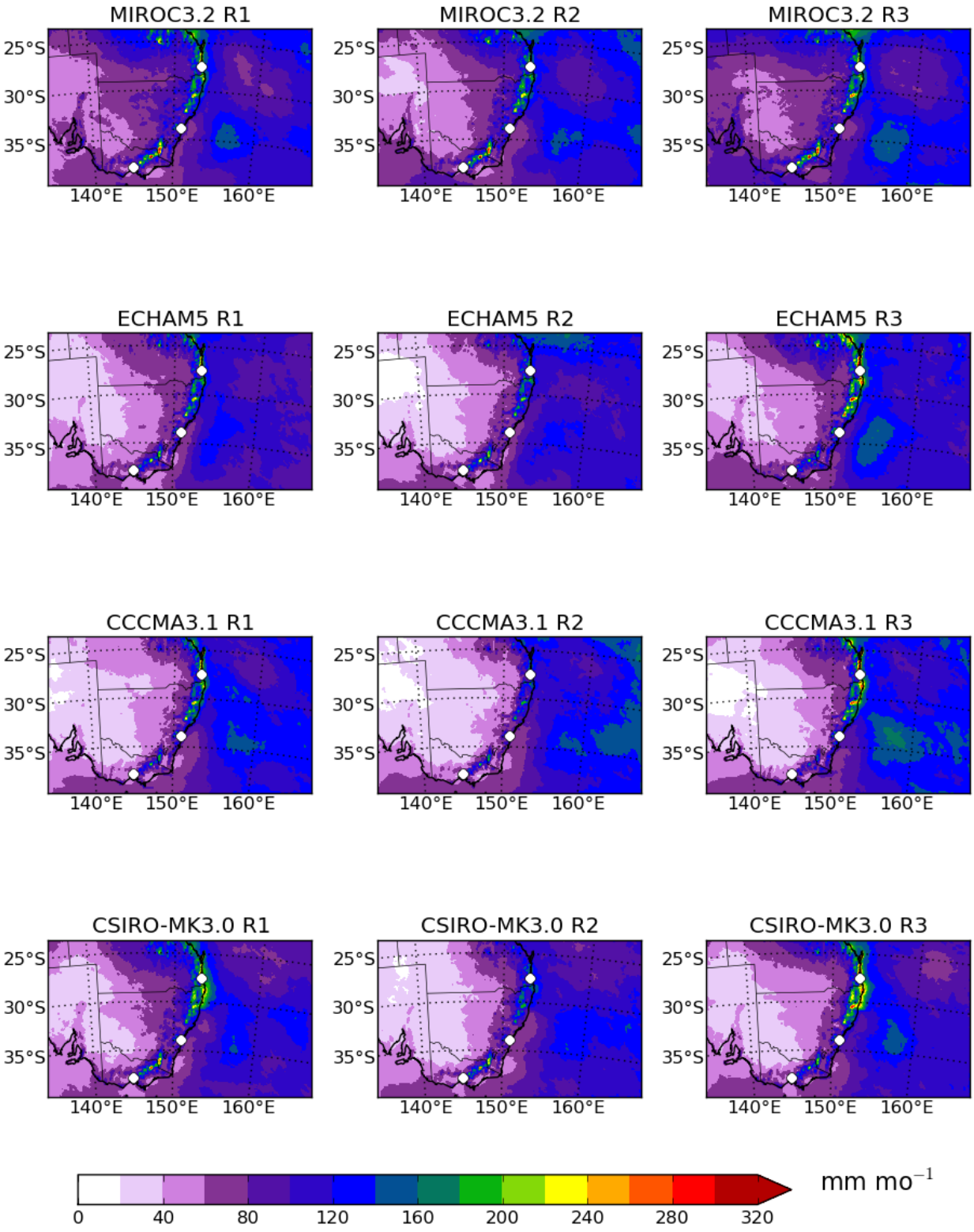

Figure 6.20: MAM mean of precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

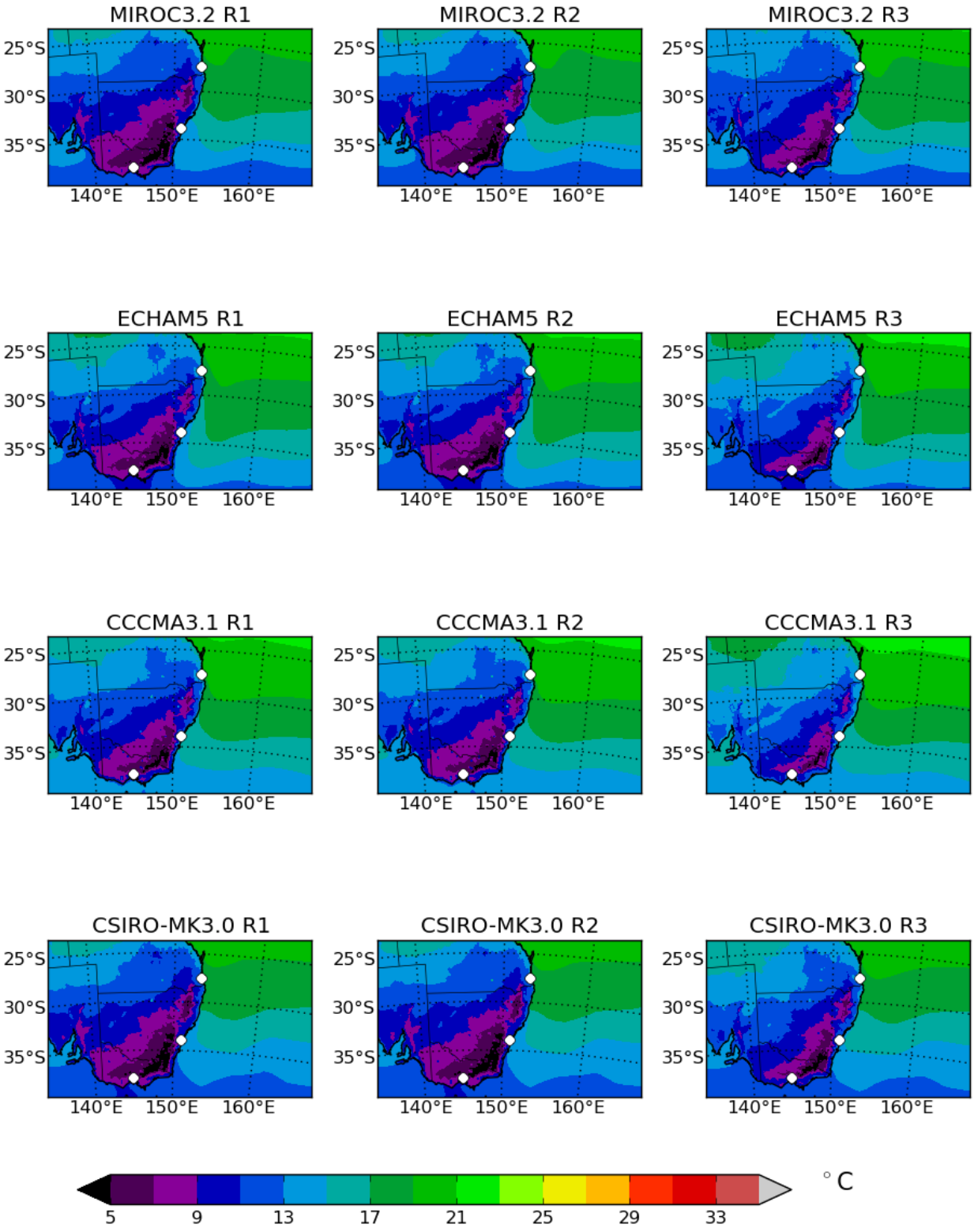

Figure 6.21: JJA mean of near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

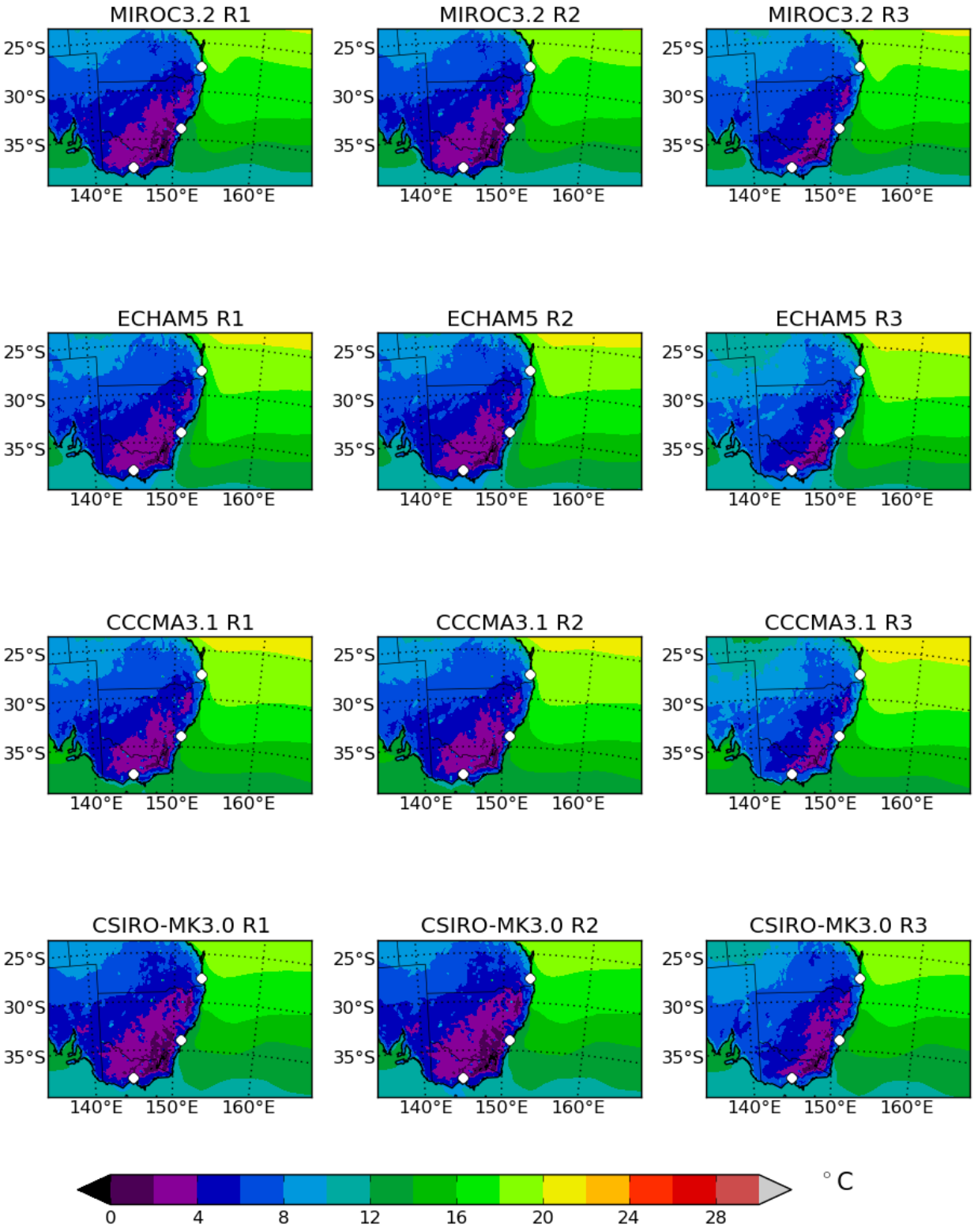

Figure 6.22: JJA mean of daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

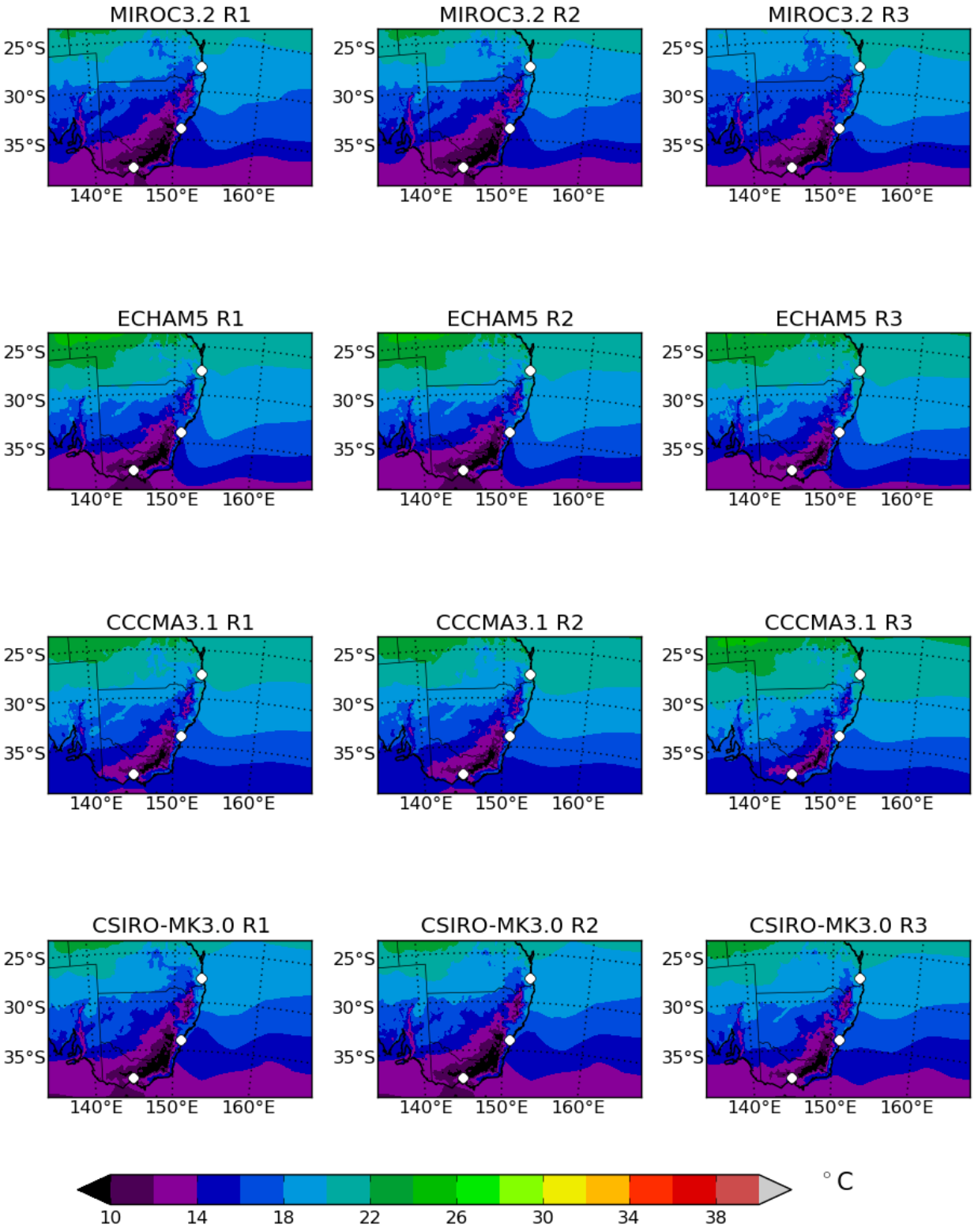

Figure 6.23: JJA mean of daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

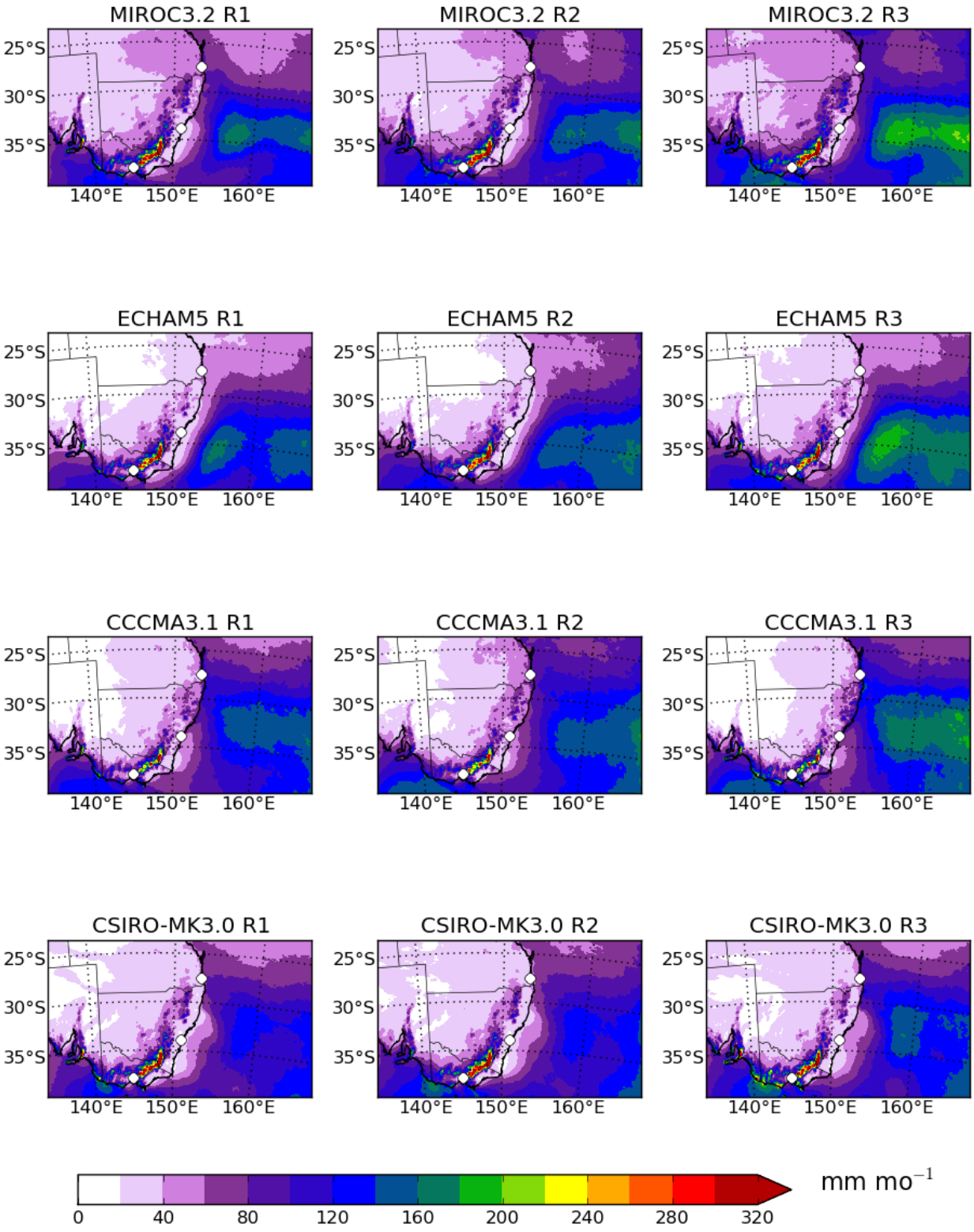

Figure 6.24: JJA mean of precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

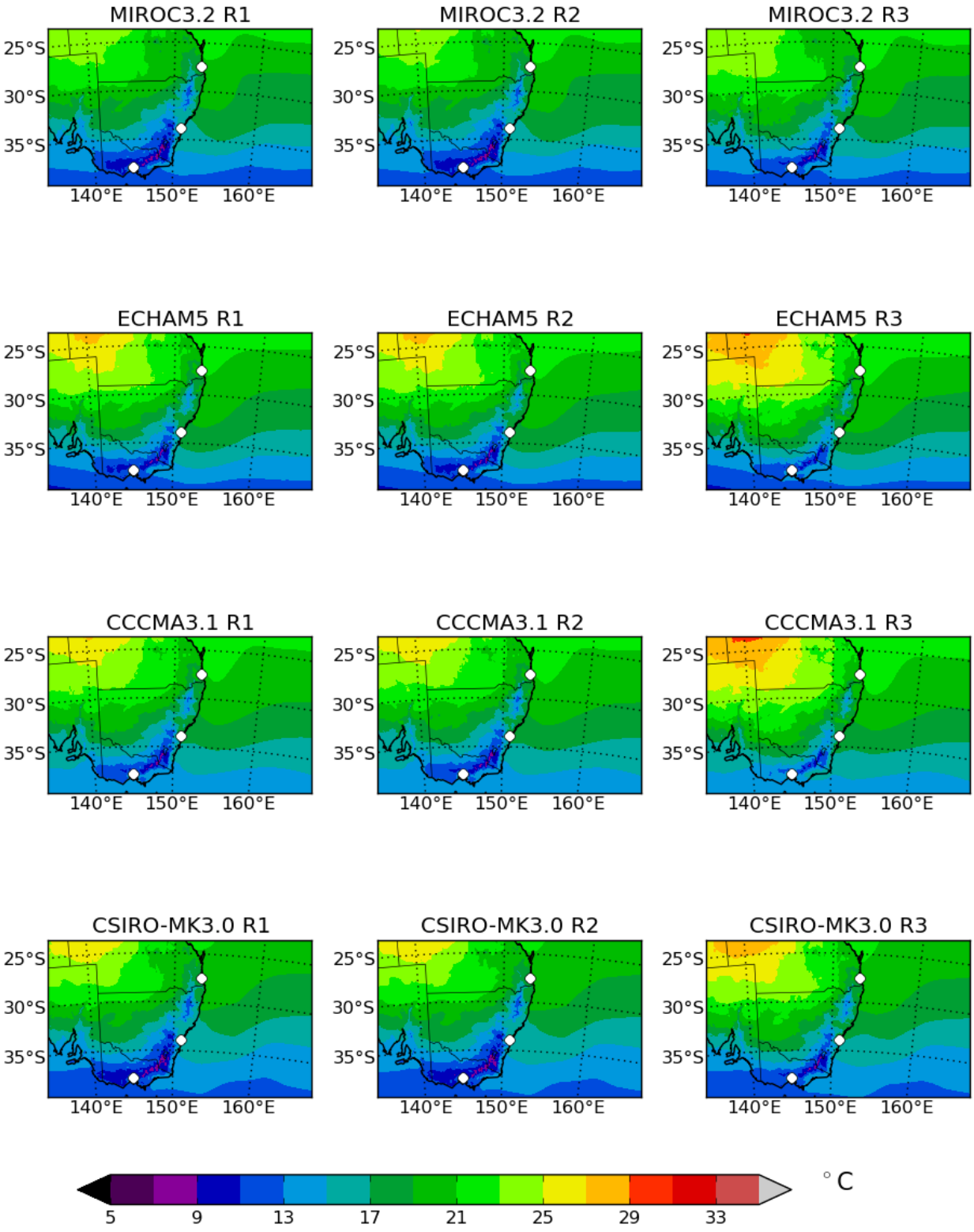

Figure 6.25: SON mean of near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

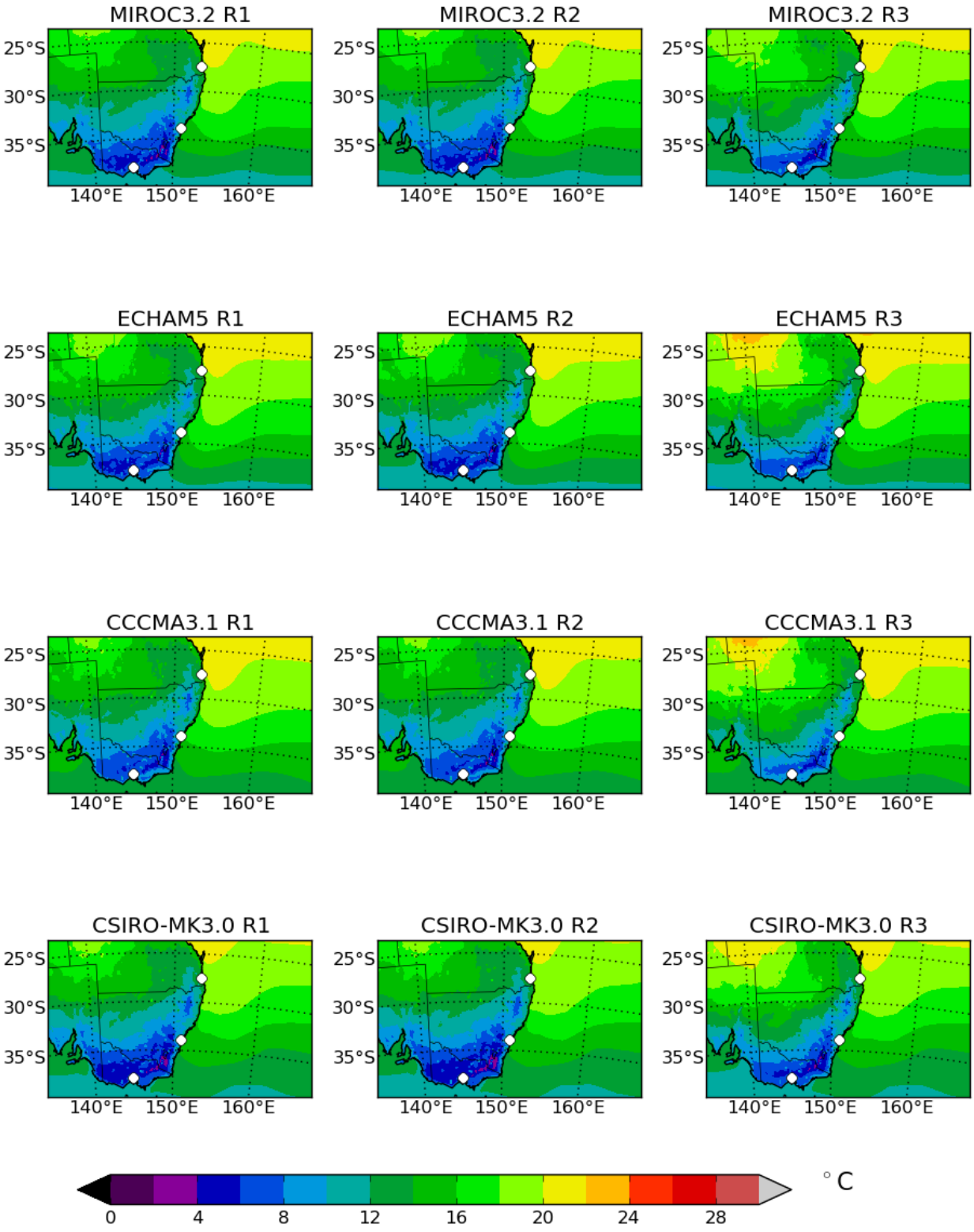

Figure 6.26: SON mean of daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

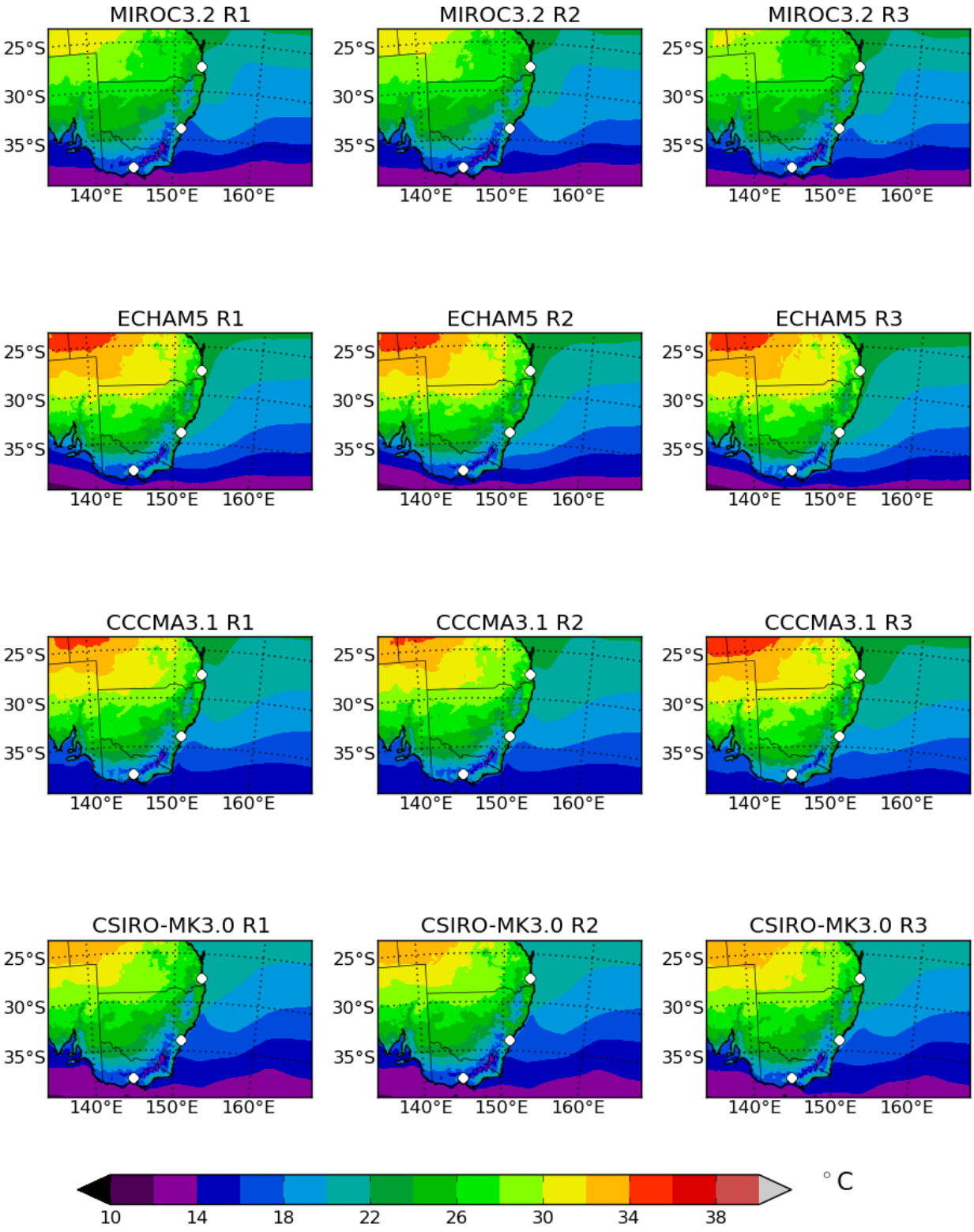

Figure 6.27: SON mean of daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

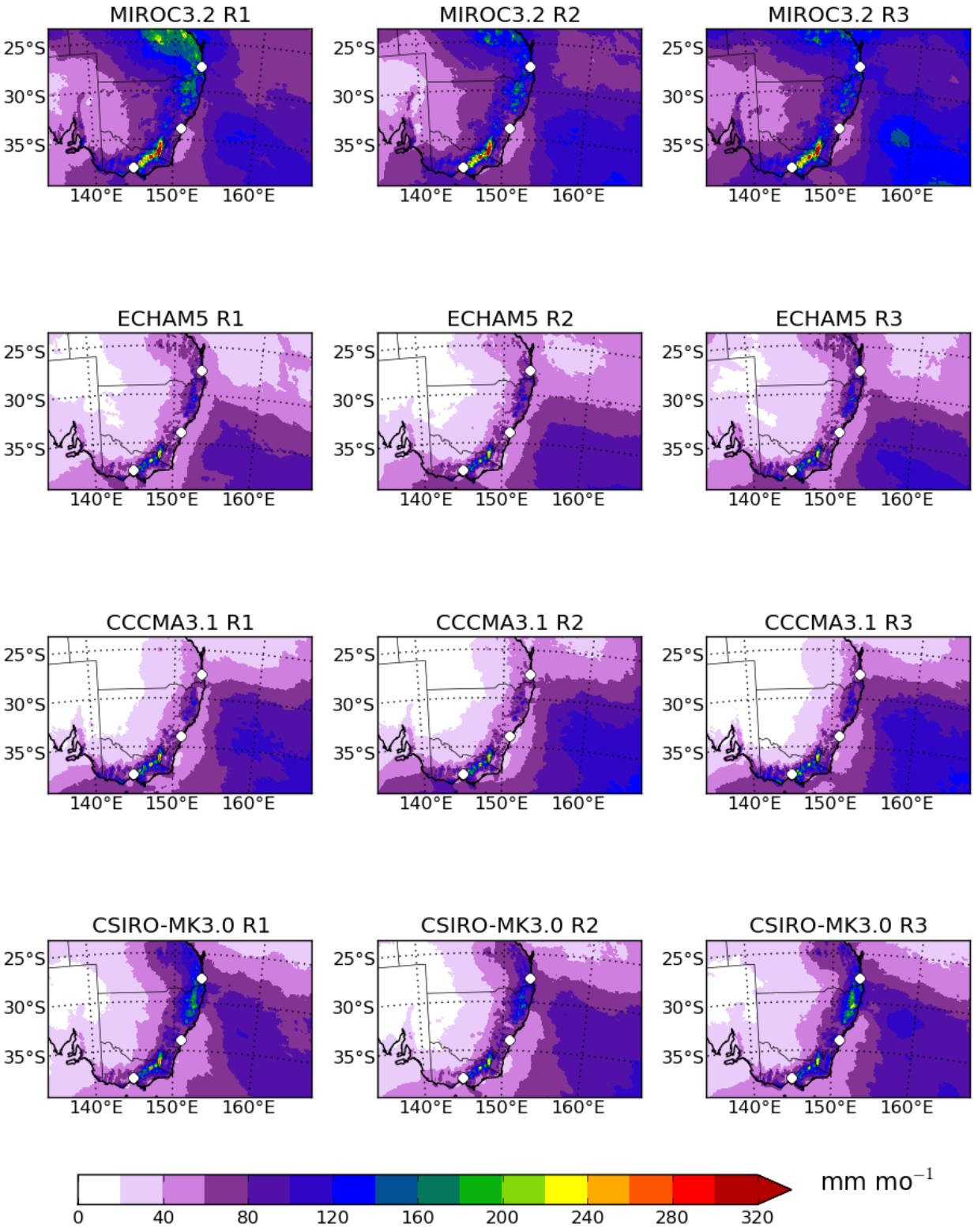

Figure 6.28: SON mean of precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

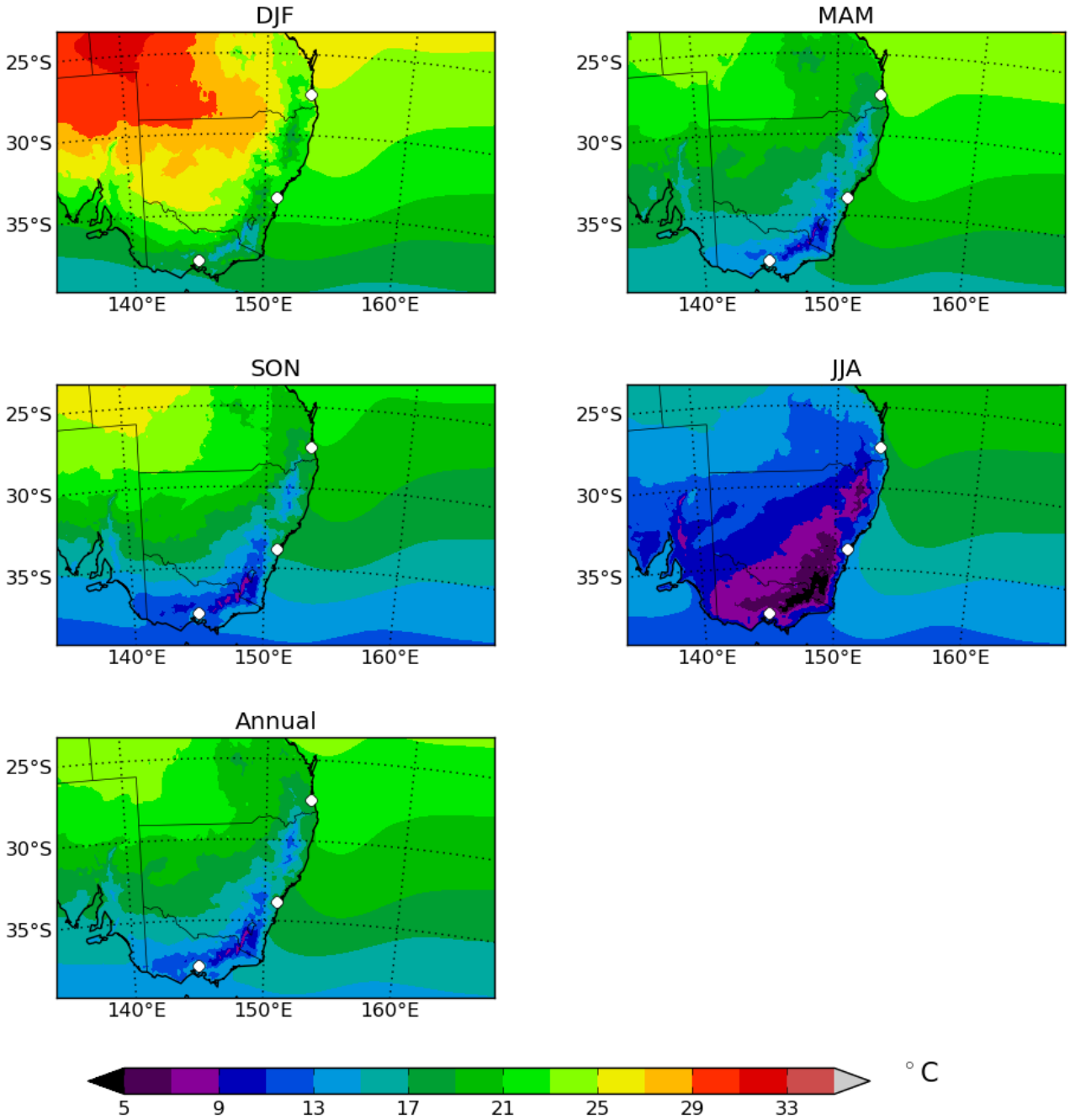

Figure 6.29: Seasonal and annual multimodel means of near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

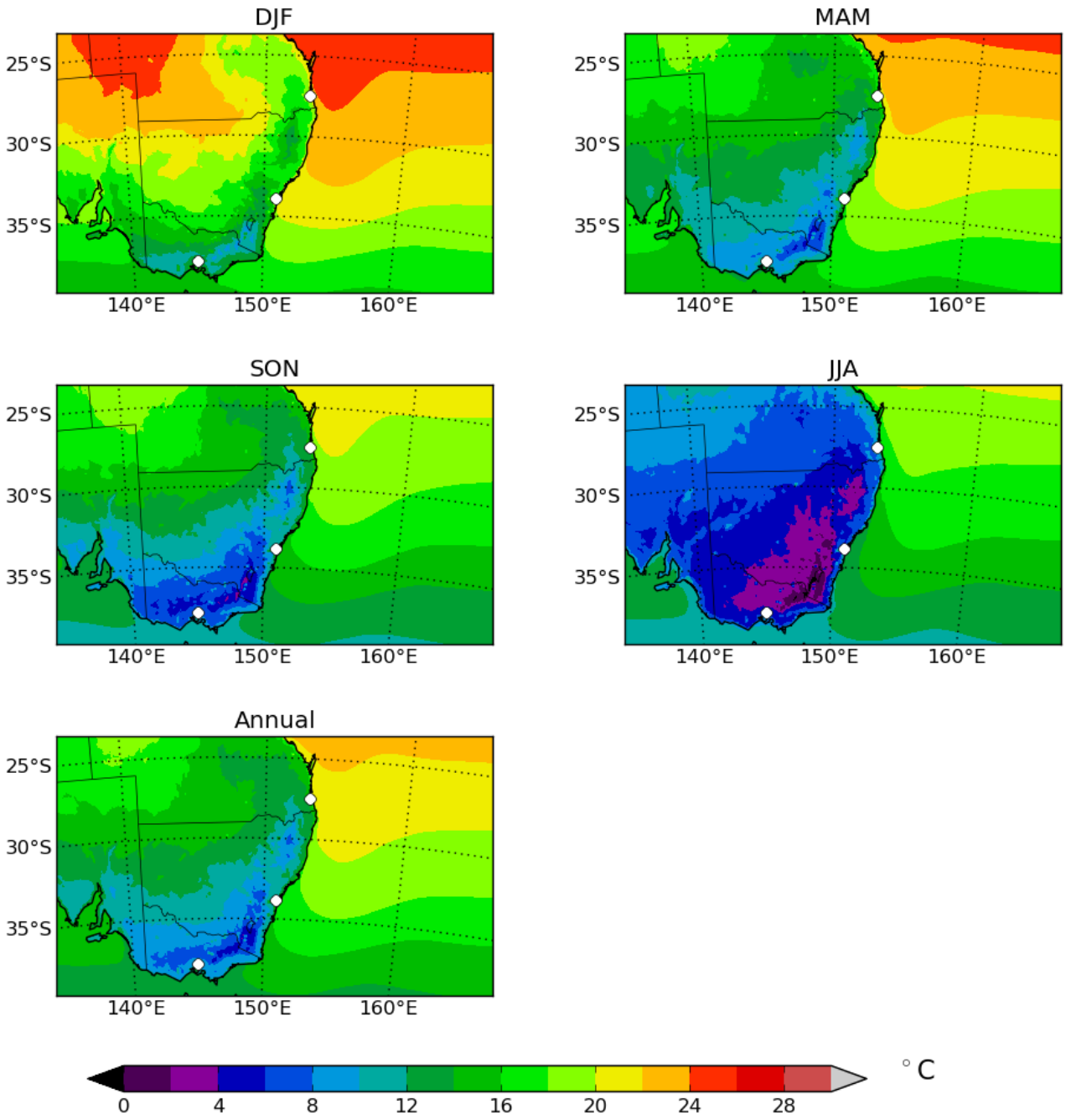

Figure 6.30: Seasonal and annual multimodel means of daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

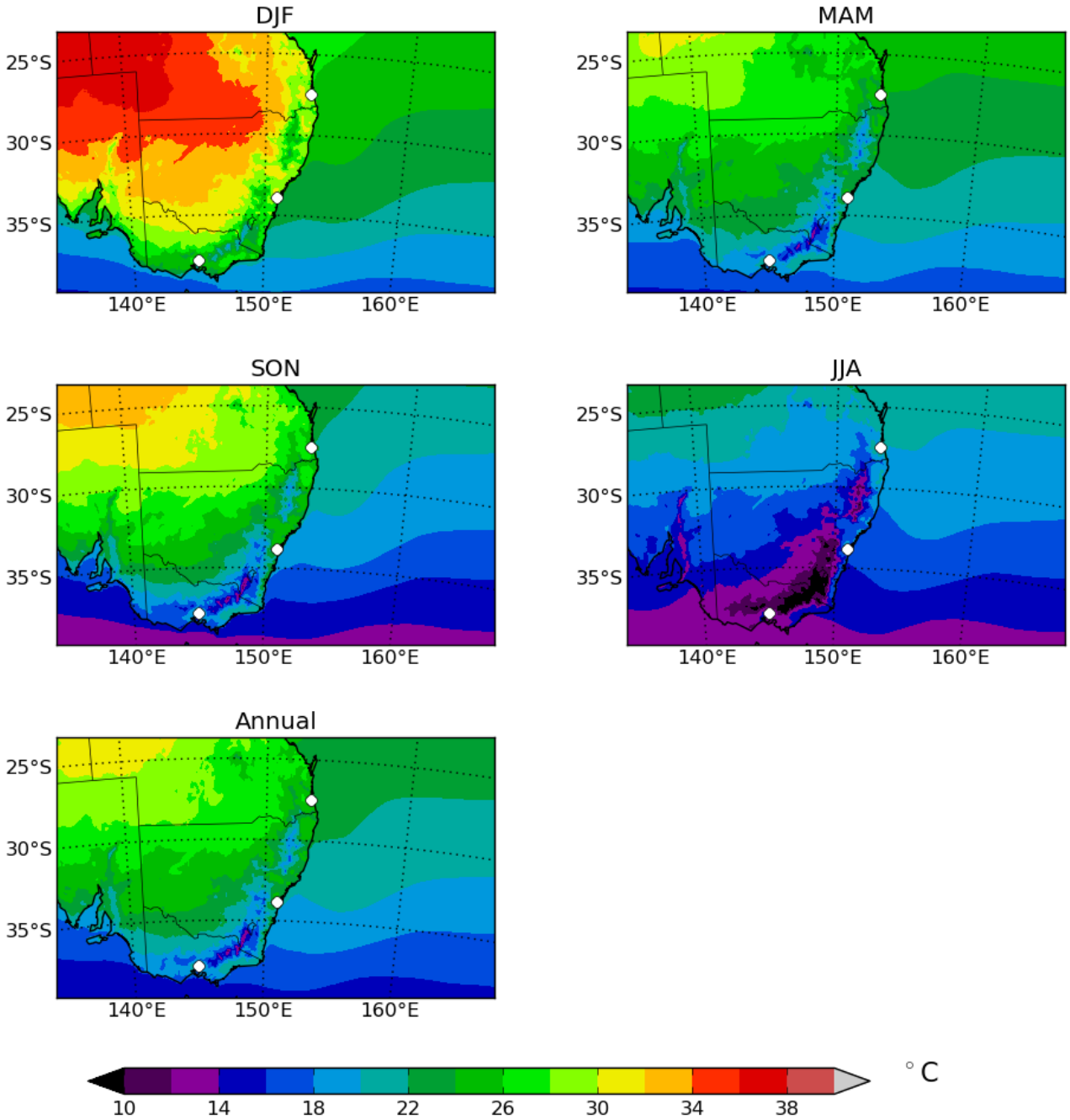

Figure 6.31: Seasonal and annual multimodel means of daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

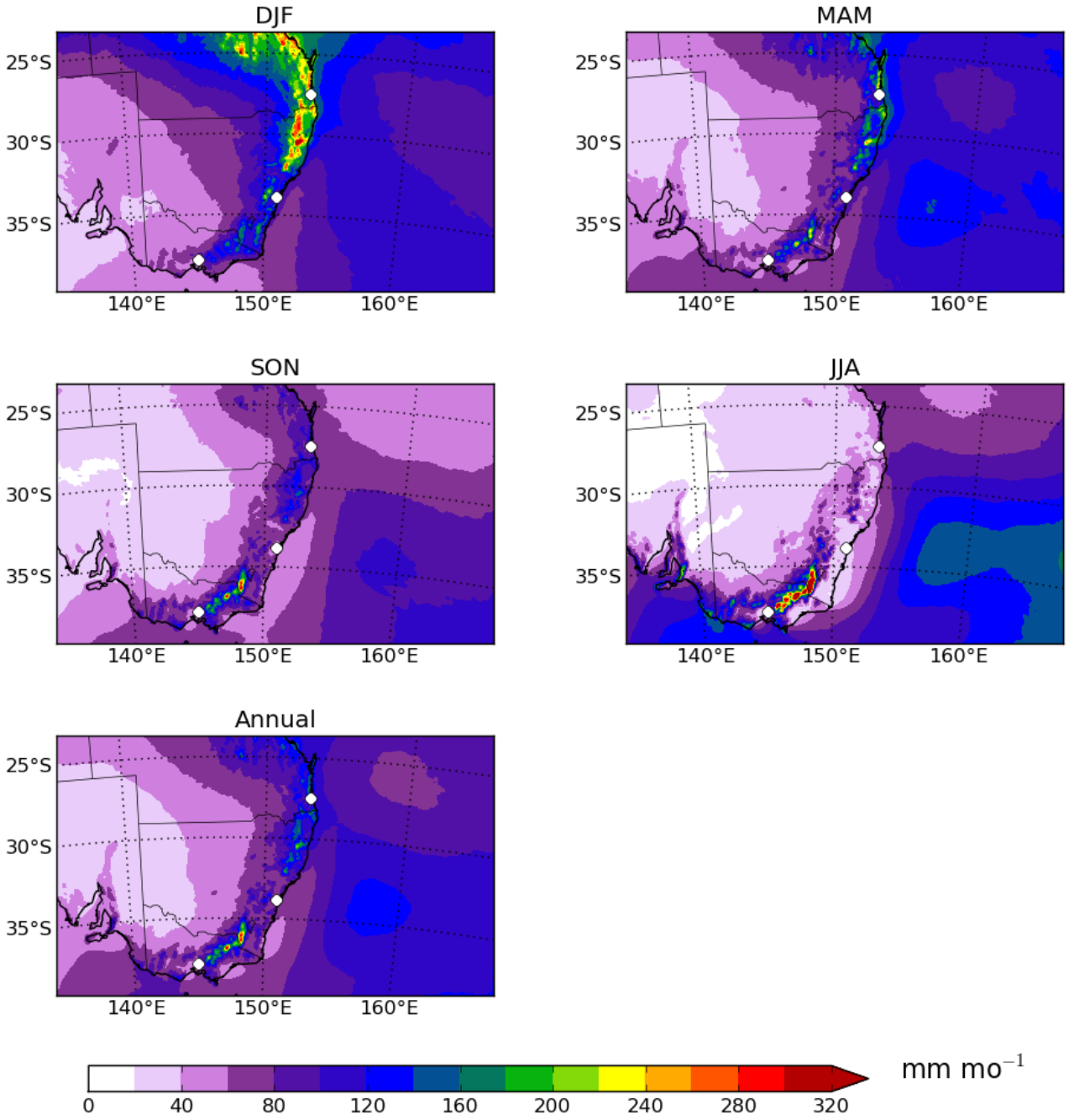

Figure 6.32: Seasonal and annual multimodel means of precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

6.3 2020-2039 Bias-Corrected Regional Model Output

This subsection contains projected climatologies for near-future daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the bias-corrected RCM output (*i.e.* RCM output that has been corrected for the present-day biases between the models and the observations of climate using the methods described here [6]). The corrections are calculated by comparing present-day distributions of daily model output and observations for all seasons. Thus, the corrections are independent of the season. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected climatologies, whereas the individual-model plots show the level of uncertainty in projected climate.

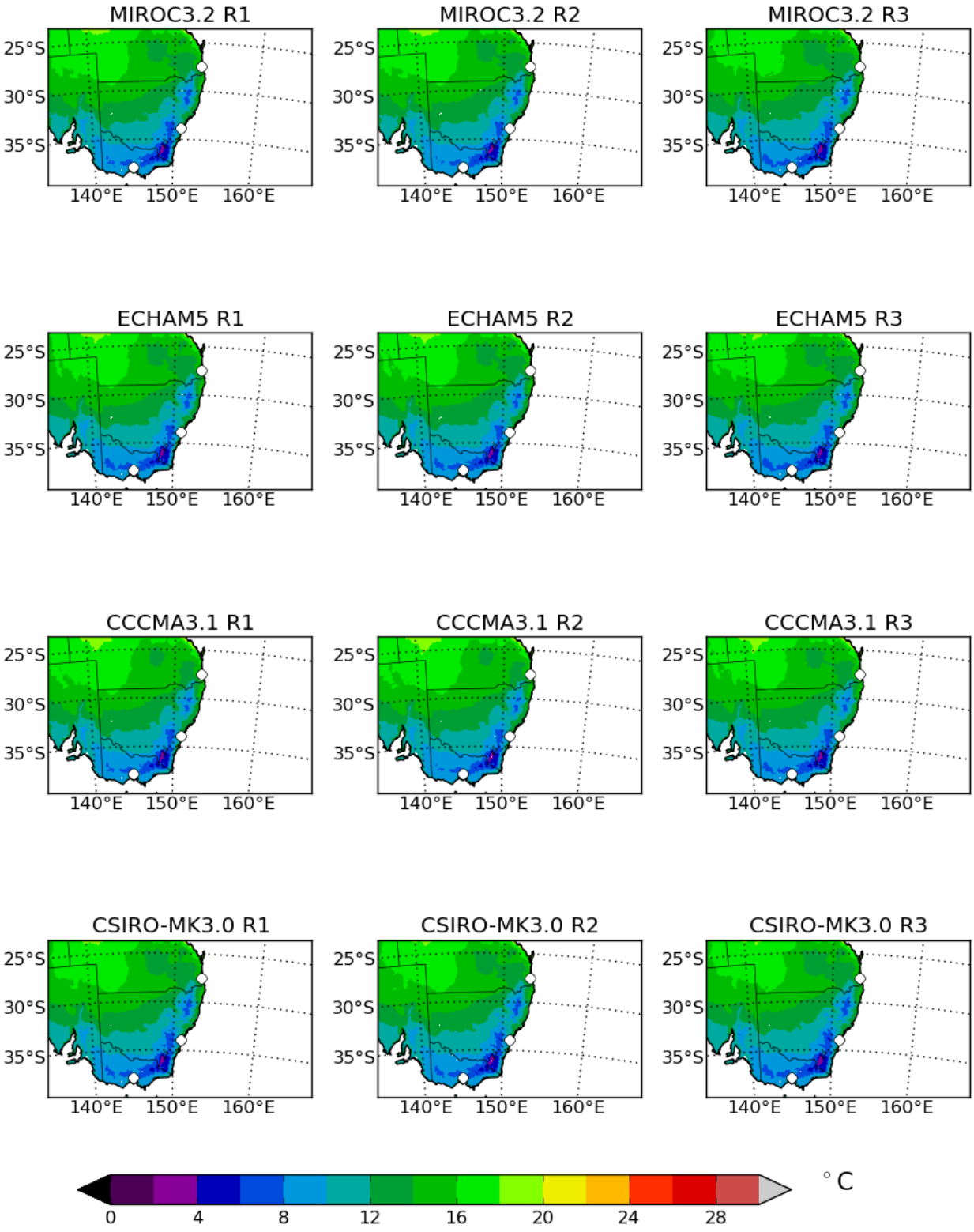

Figure 6.33: Annual mean of bias-corrected daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

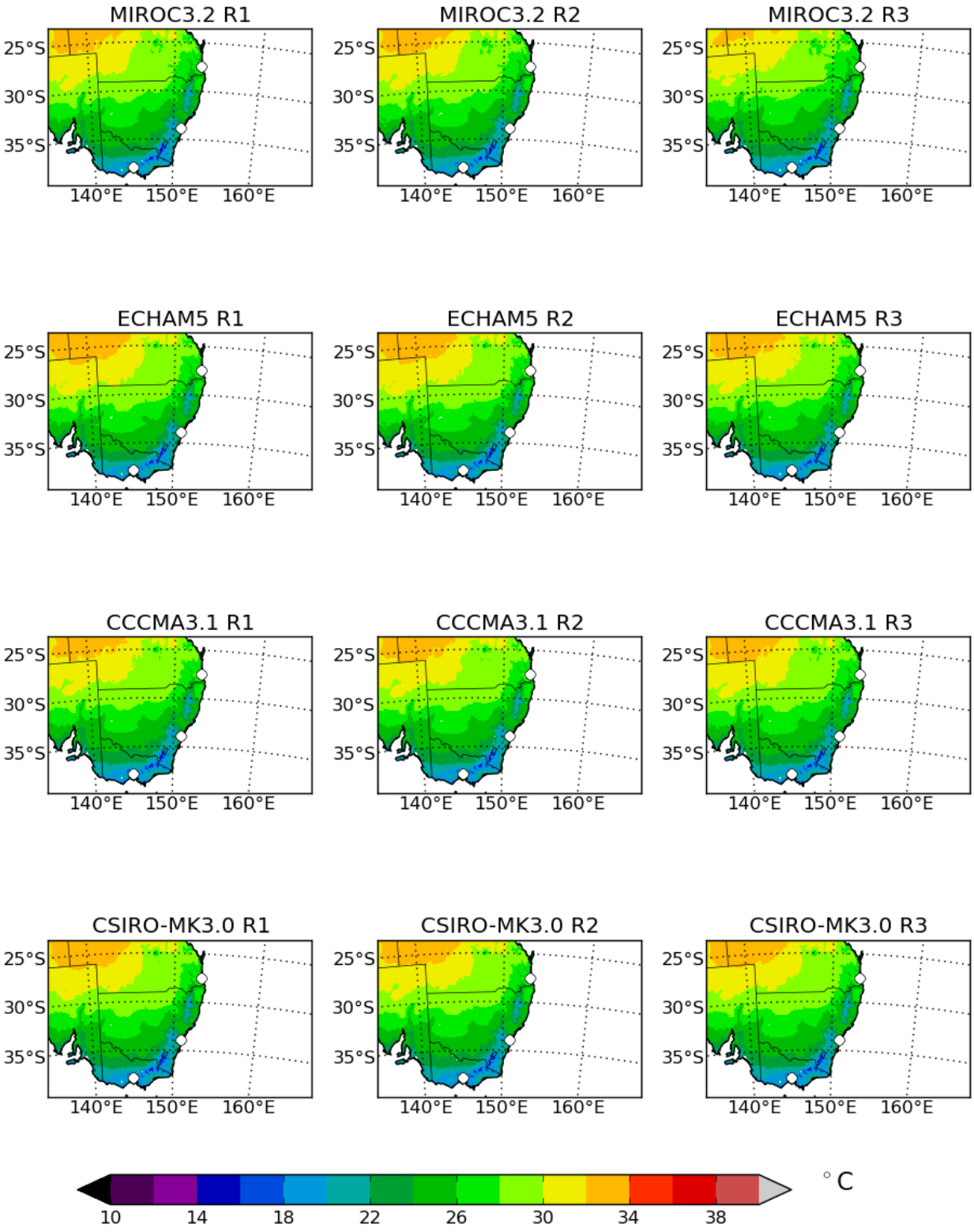

Figure 6.34: Annual mean of bias-corrected daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

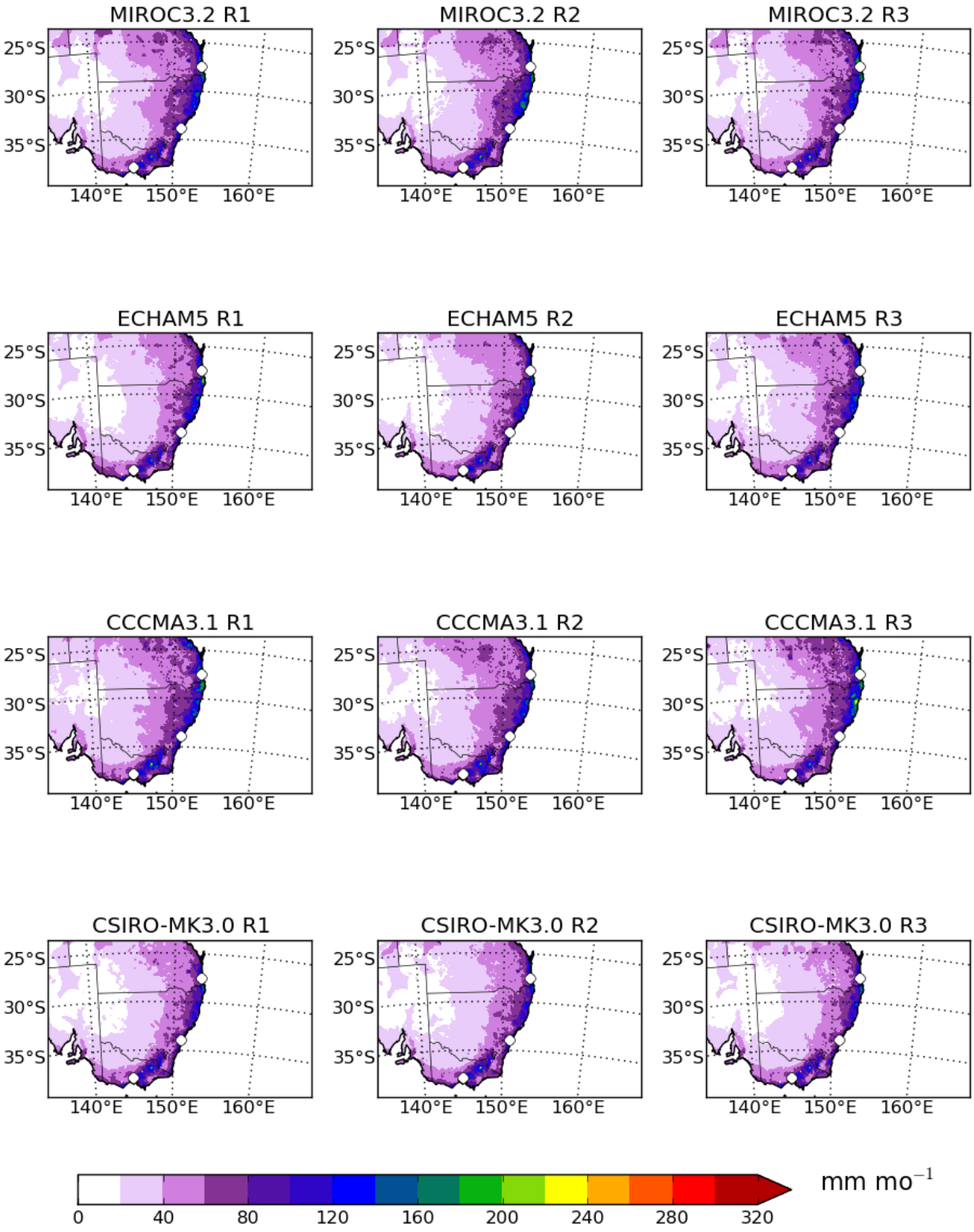

Figure 6.35: Annual mean of bias-corrected precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

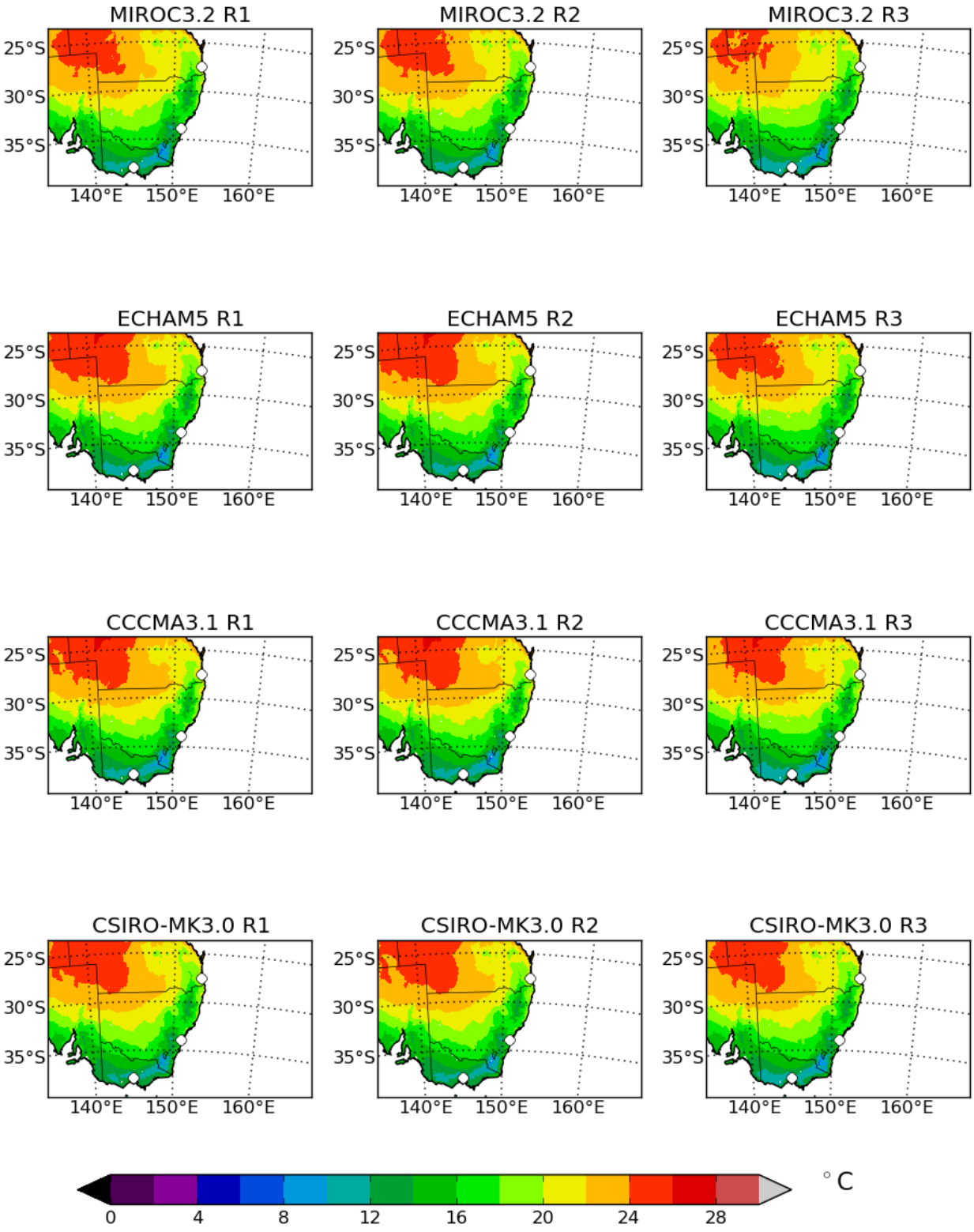

Figure 6.36: DJF mean of bias-corrected daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

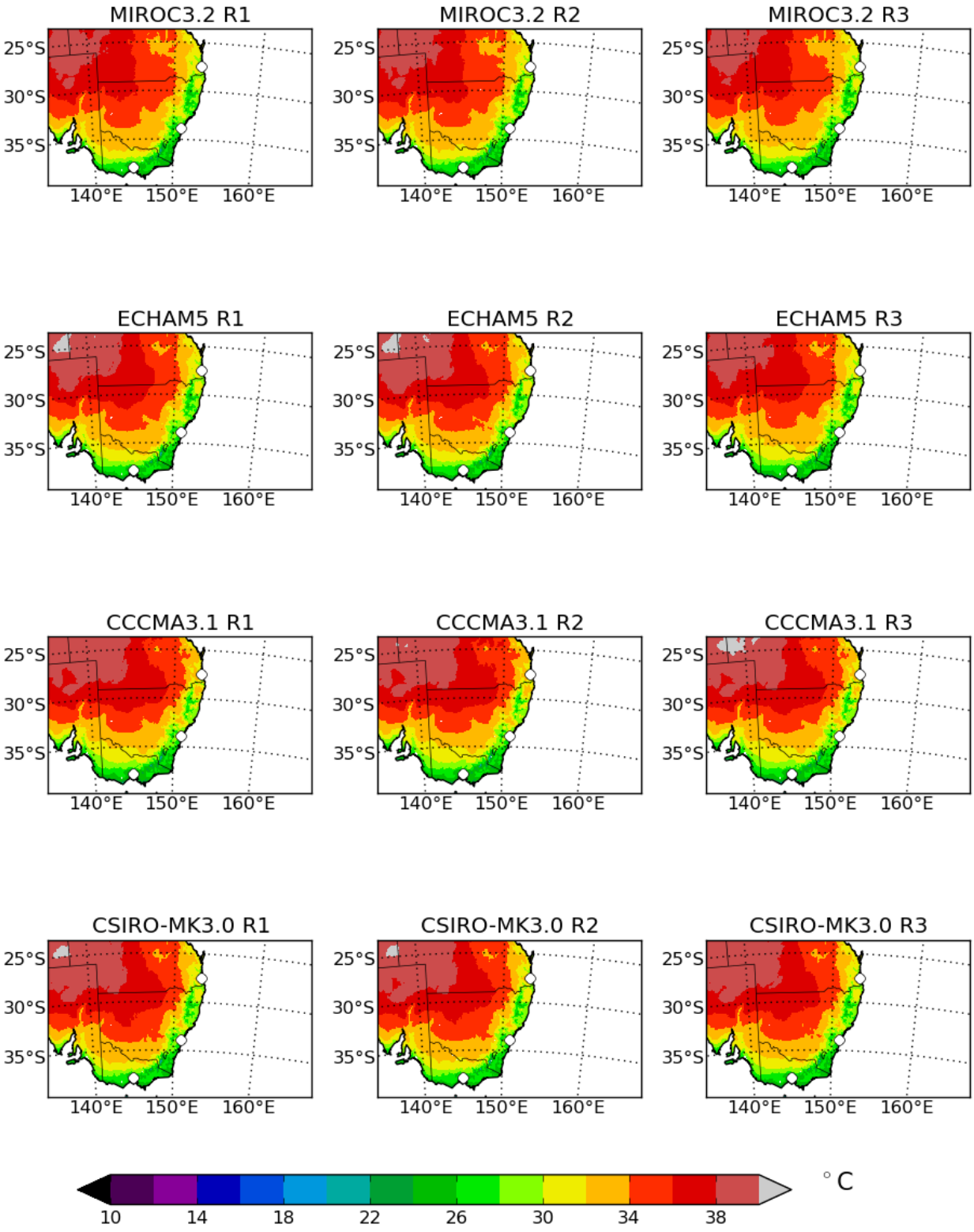

Figure 6.37: DJF mean of bias-corrected daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

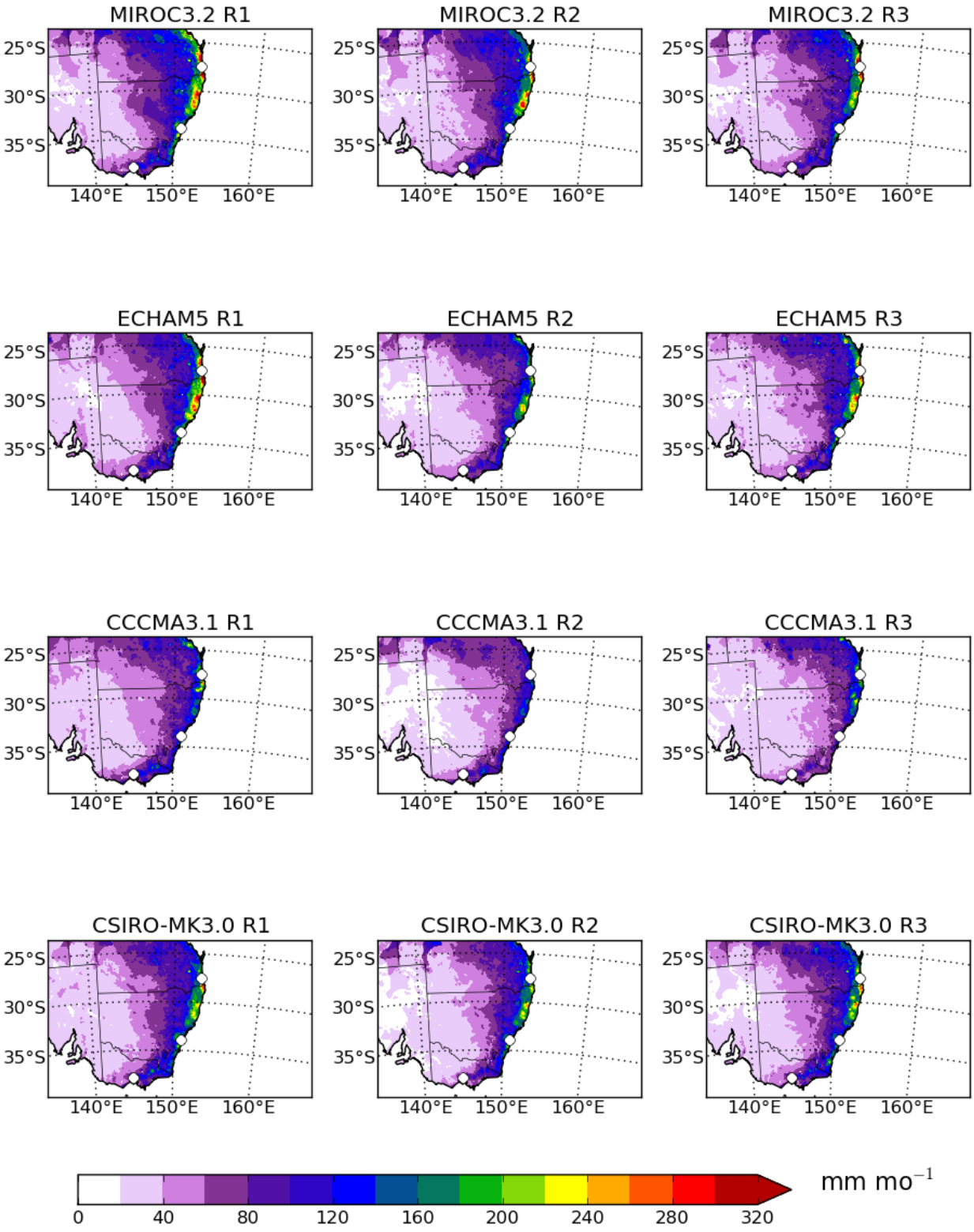

Figure 6.38: DJF mean of bias-corrected precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

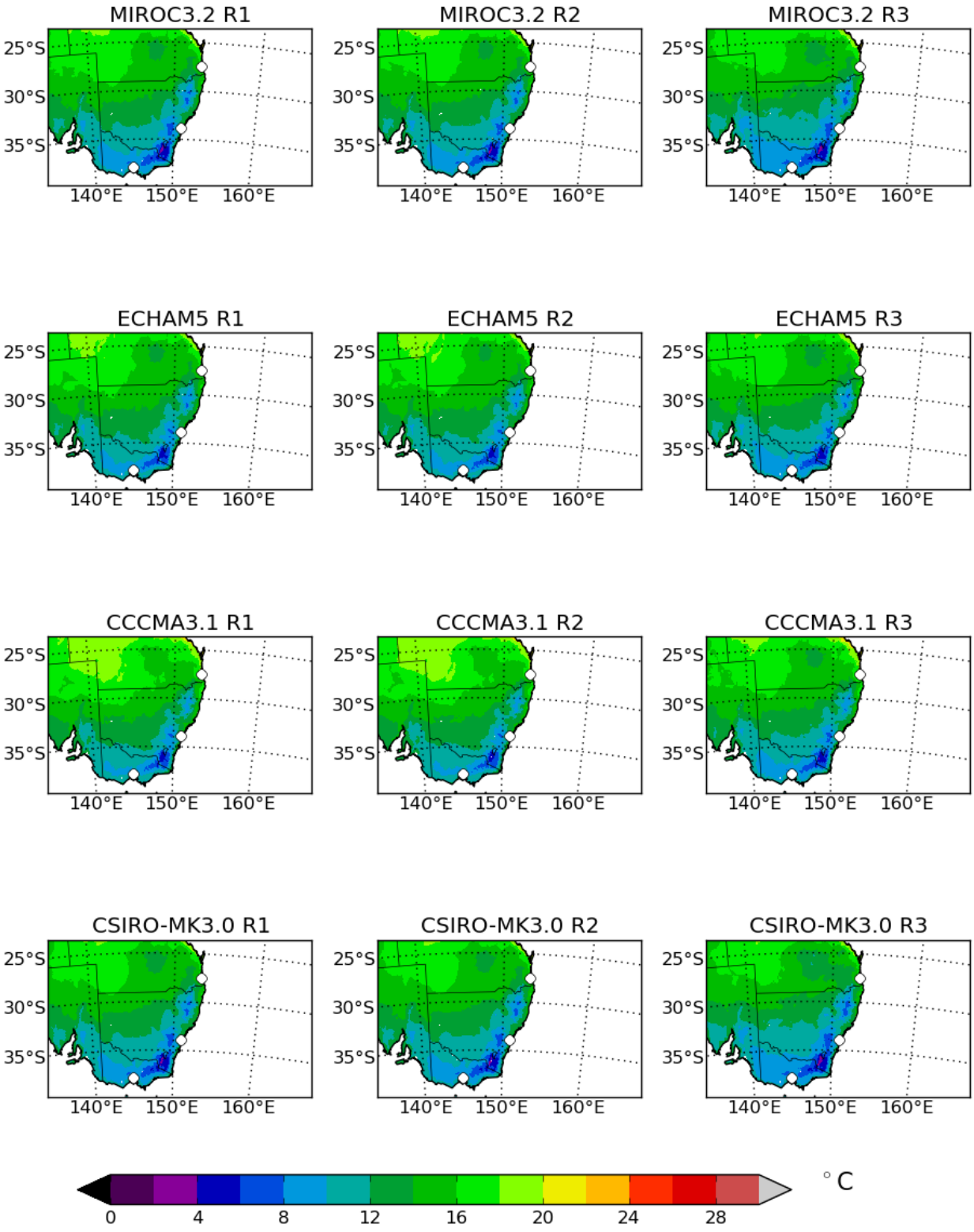

Figure 6.39: MAM mean of bias-corrected daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

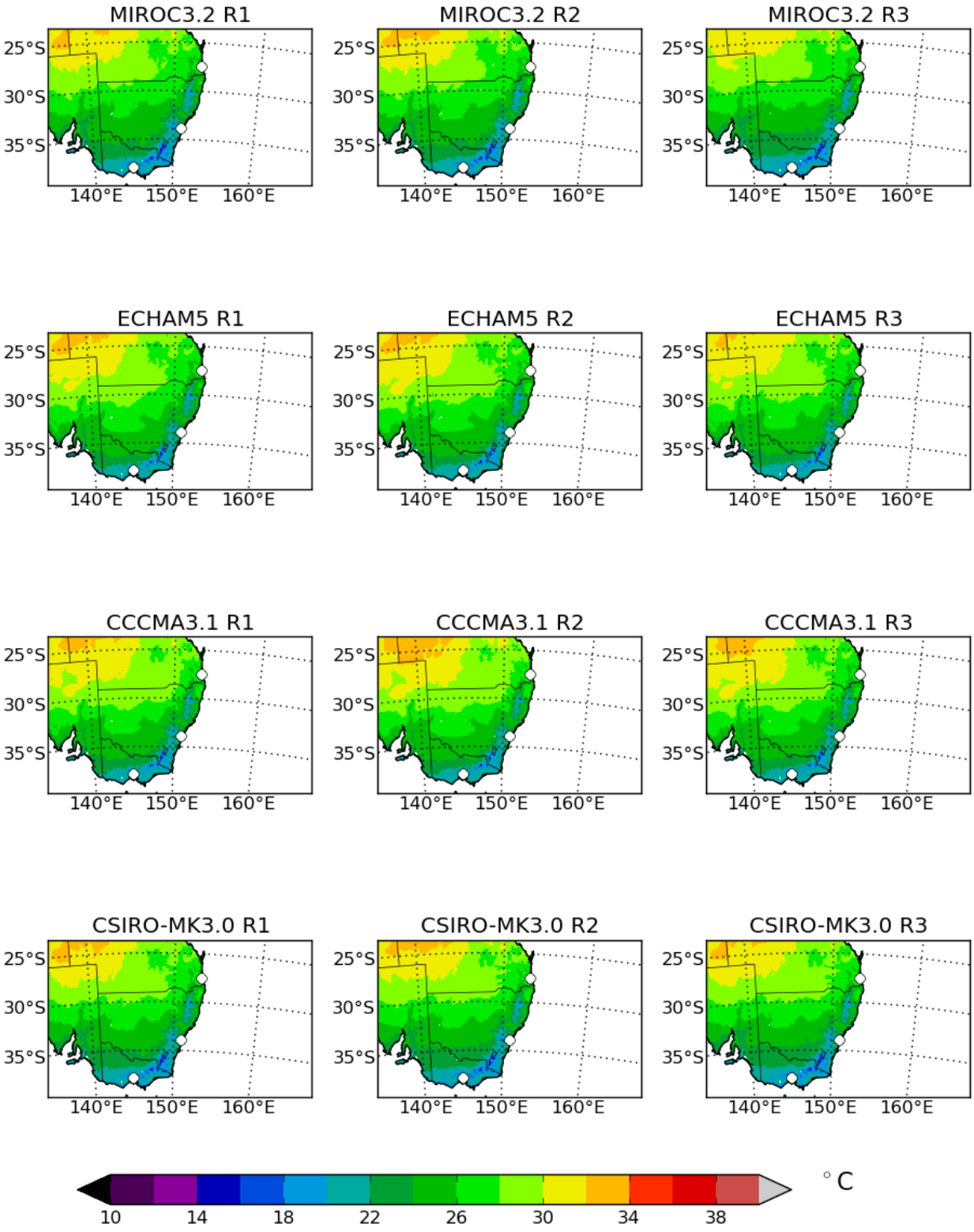

Figure 6.40: MAM mean of bias-corrected daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

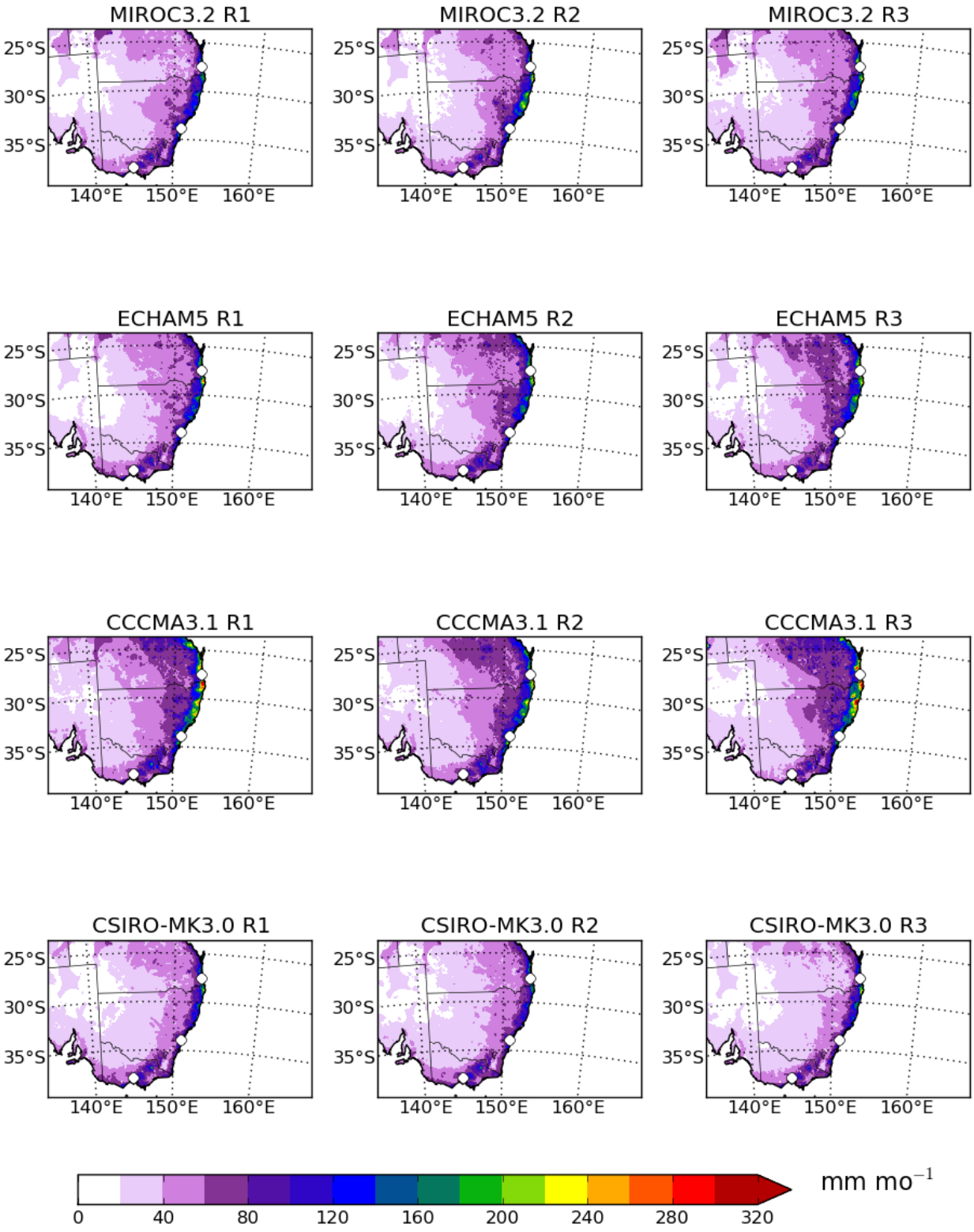

Figure 6.41: MAM mean of bias-corrected precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

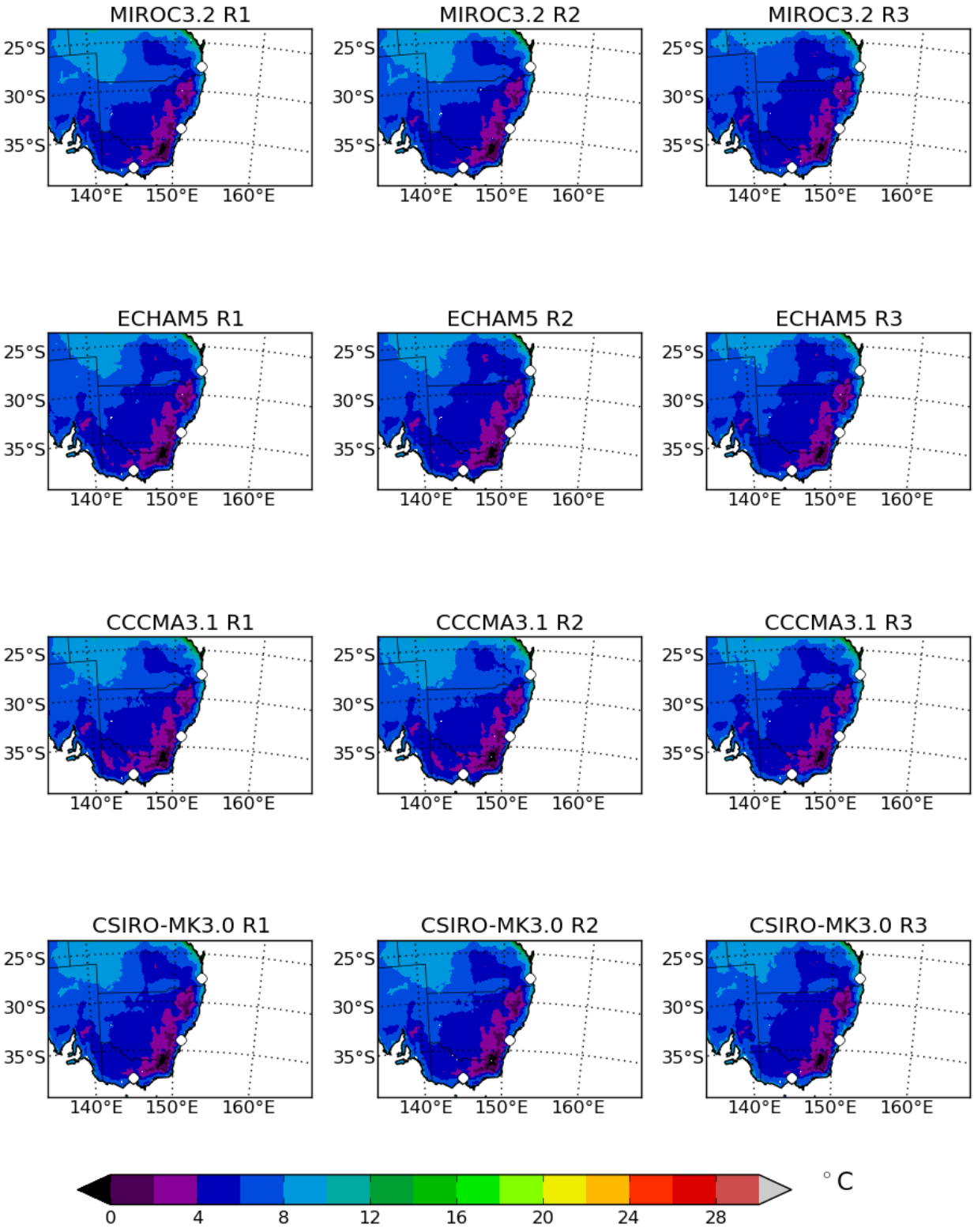

Figure 6.42: JJA mean of bias-corrected daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

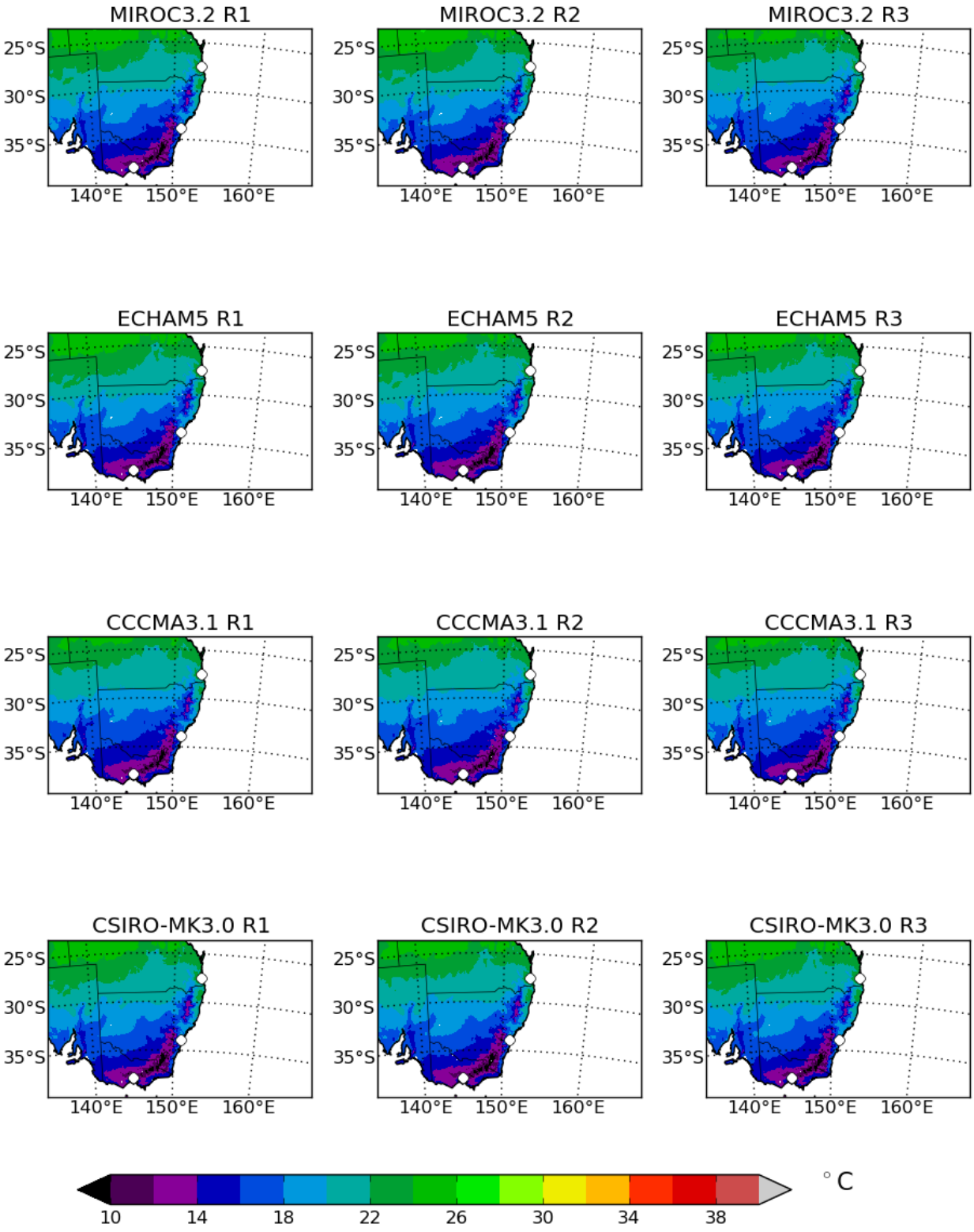

Figure 6.43: JJA mean of bias-corrected daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

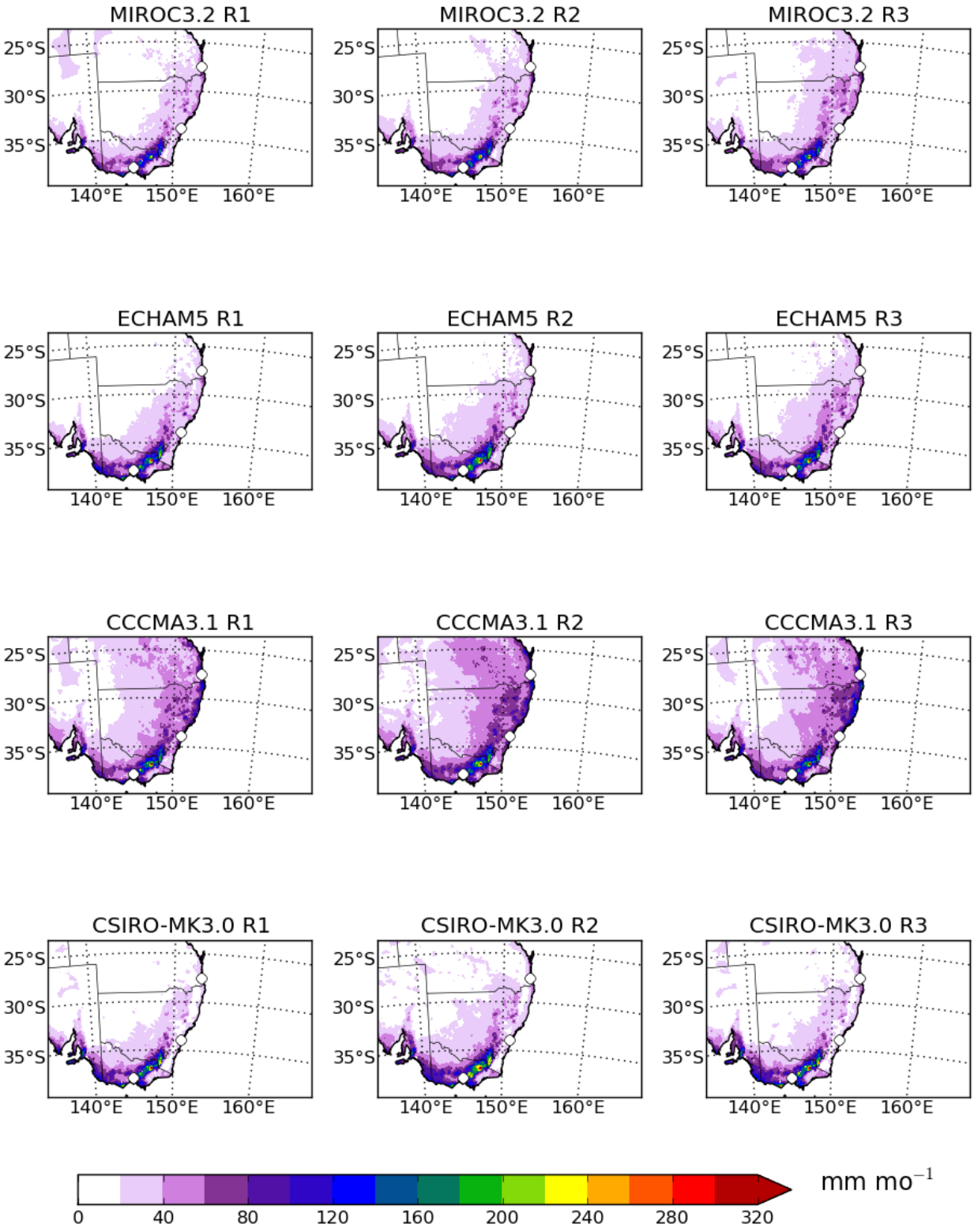

Figure 6.44: JJA mean of bias-corrected precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

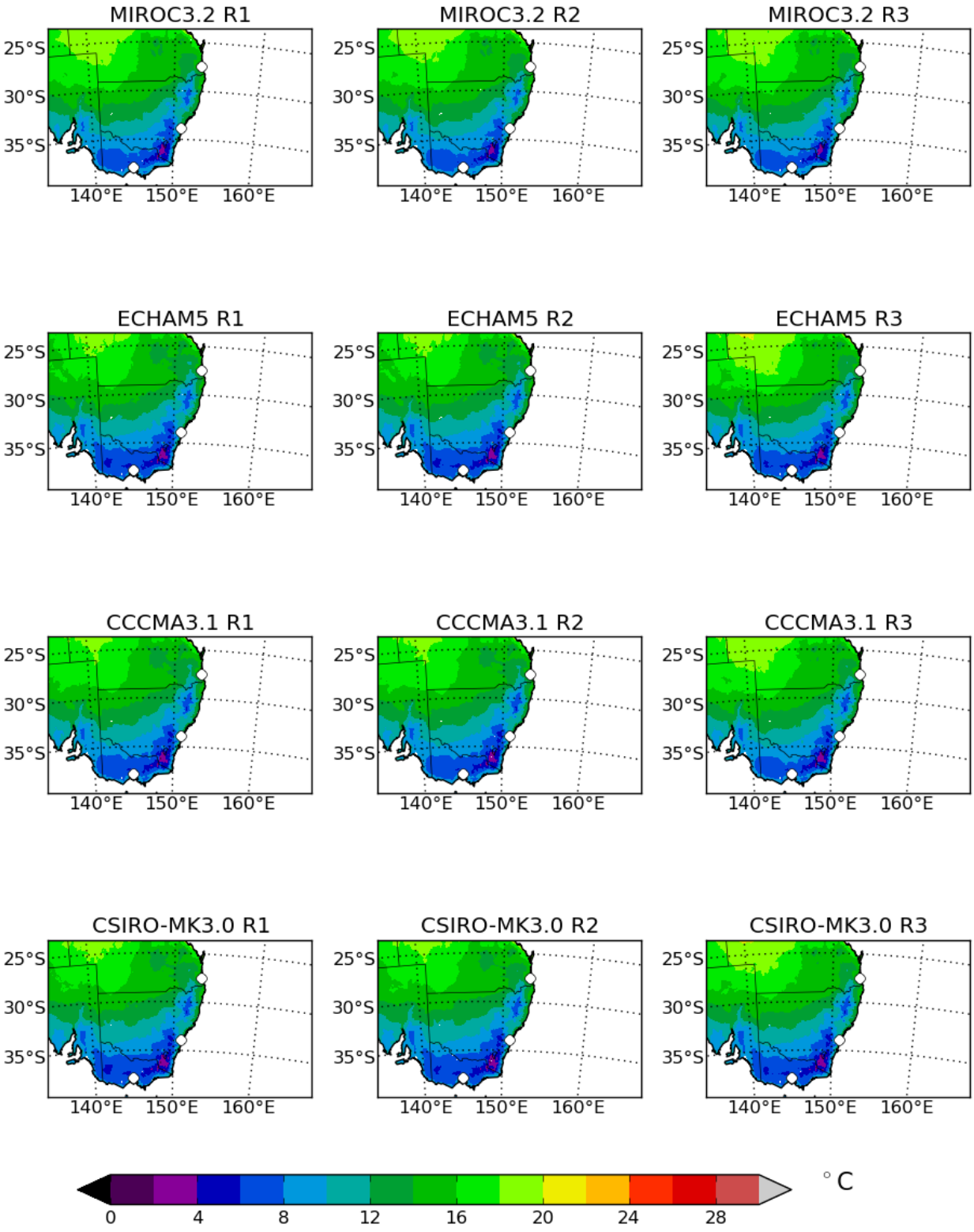

Figure 6.45: SON mean of bias-corrected daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

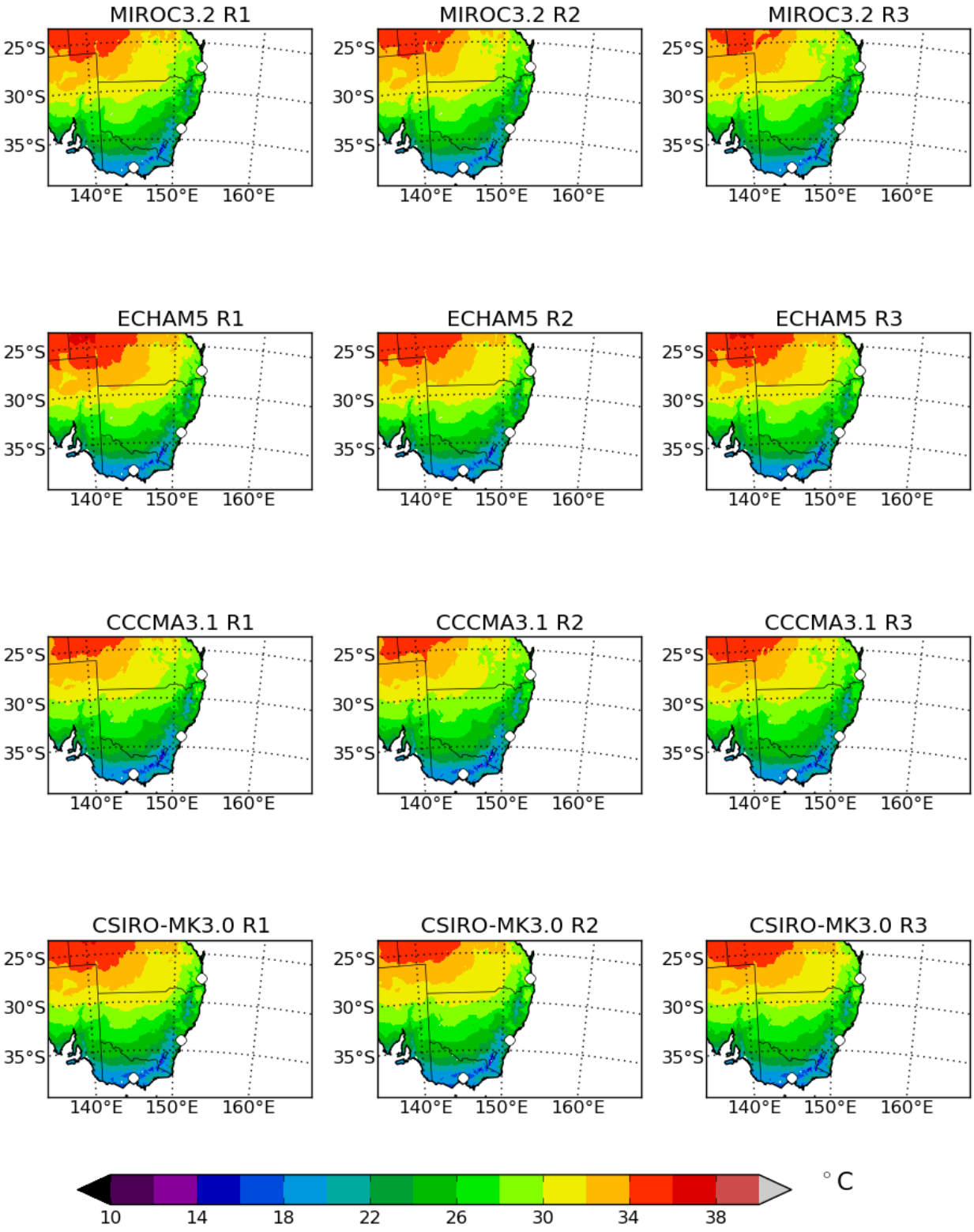

Figure 6.46: SON mean of bias-corrected daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

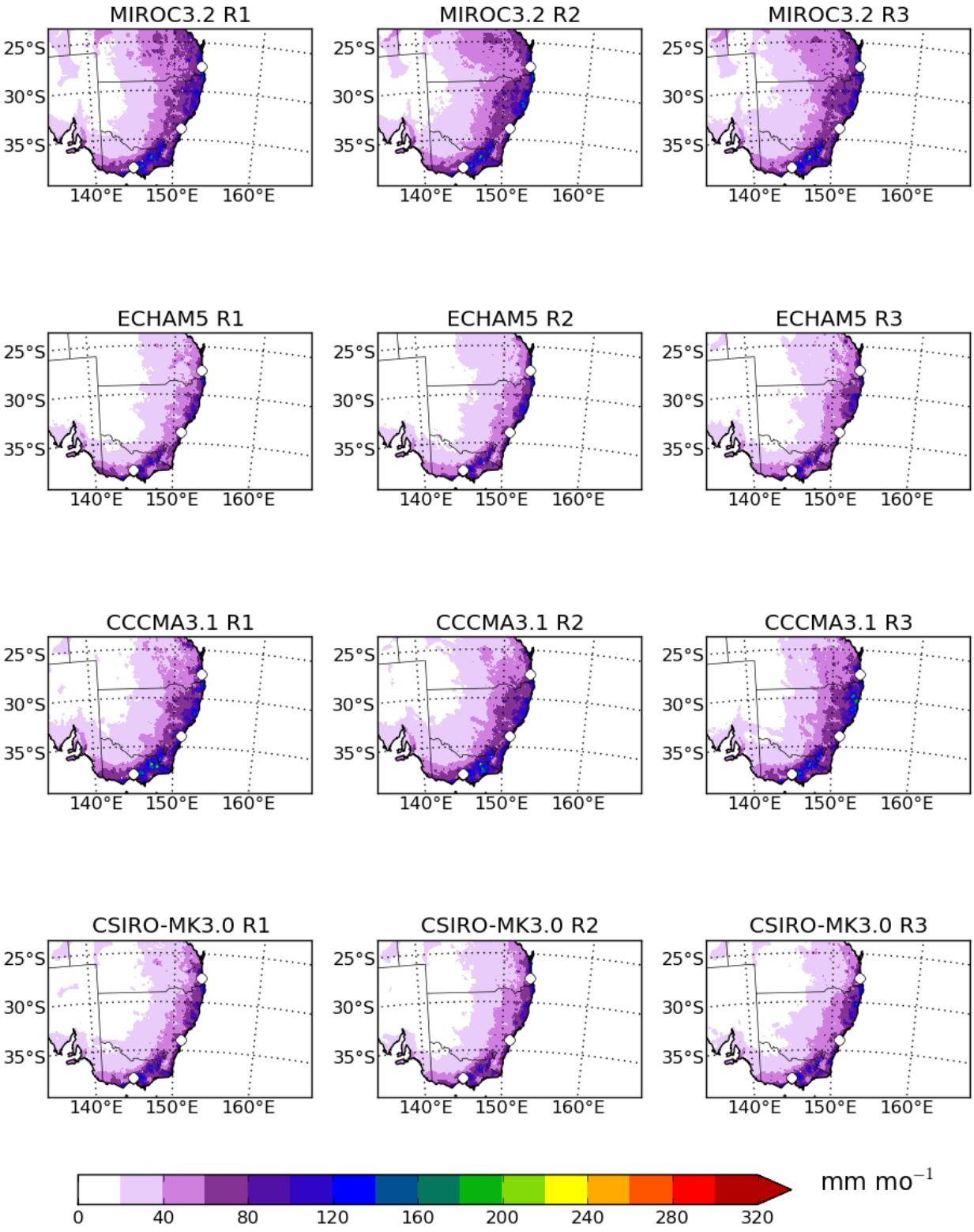

Figure 6.47: SON mean of bias-corrected precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

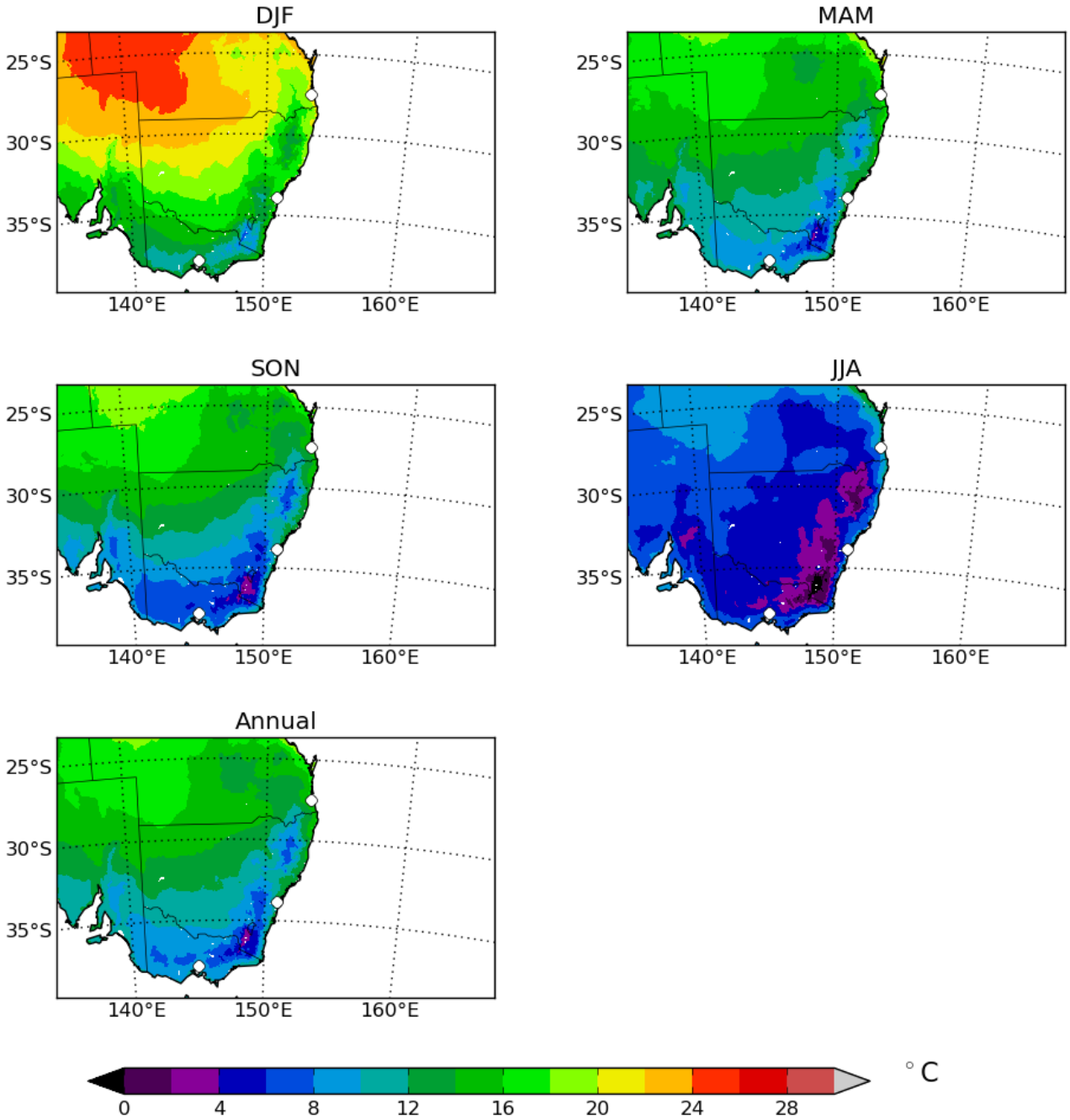

Figure 6.48: Seasonal and annual multimodel means of bias-corrected daily minimum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

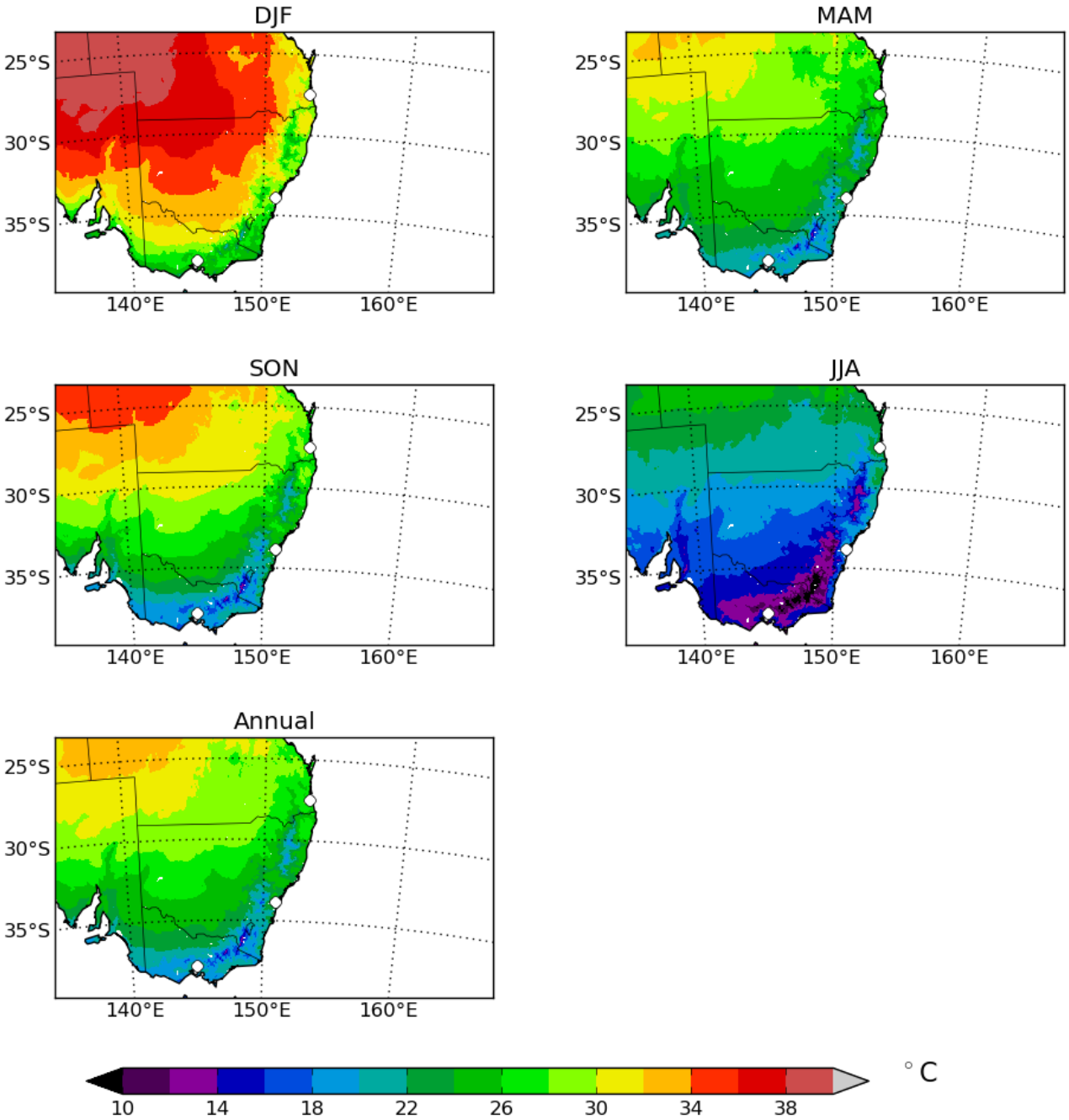

Figure 6.49: Seasonal and annual multimodel means of bias-corrected daily maximum near-surface air temperature for years 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

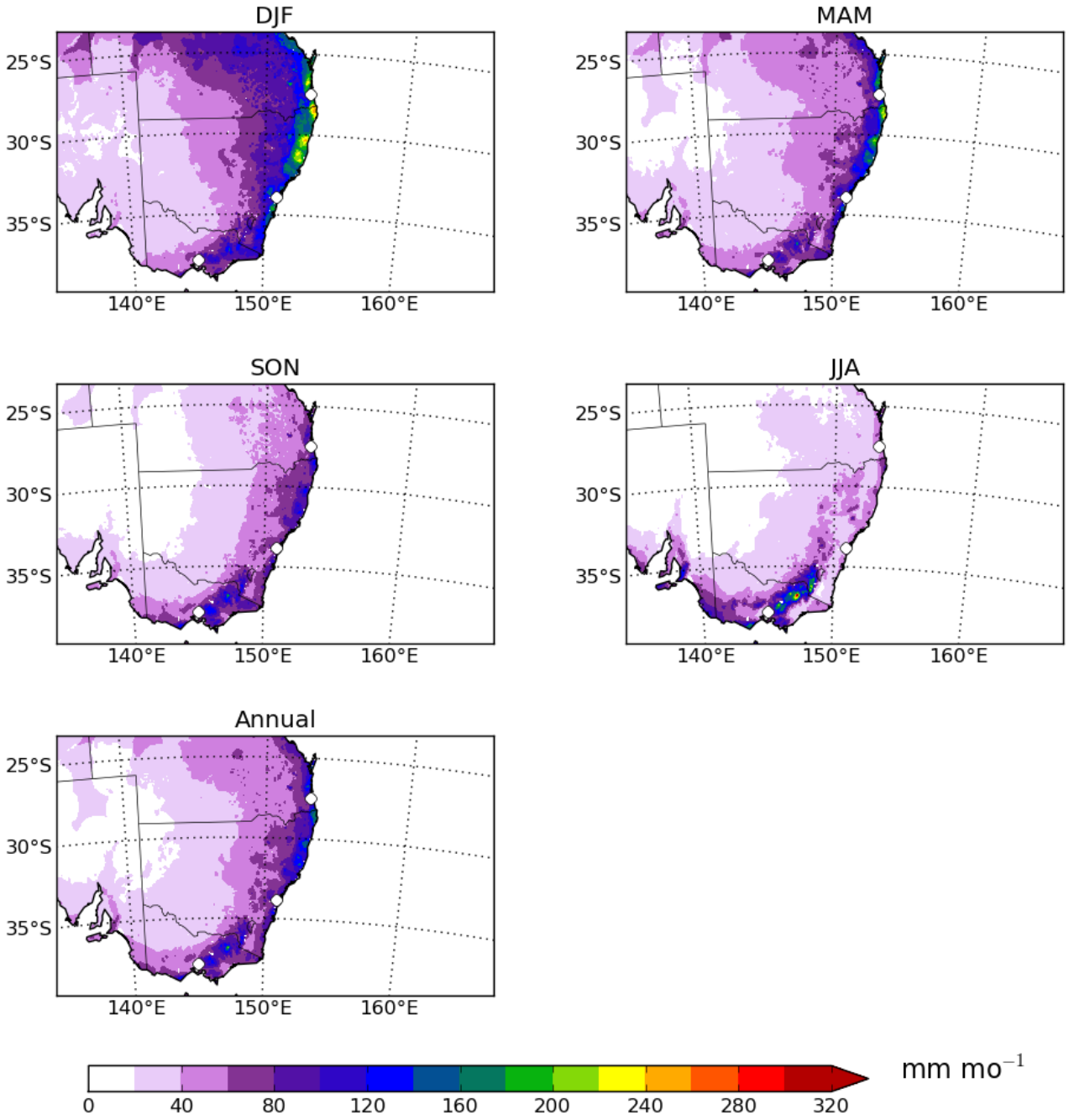

Figure 6.50: Seasonal and annual multimodel means of bias-corrected precipitation for years 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 7

Near Future Modeled Changes Compared to the Present Period

This chapter contains projected seasonal and annual mean changes for near-surface air temperature and precipitation, between present (1990-2009) and near future (2020-2039). We first show the results for GCMs used to drive the RCMs, then for original RCM output, and finally for bias-corrected RCM output. The bias-corrected RCM output is the RCM output corrected for present-day biases between the models and the observations using the methods described here [6].

7.1 Driving GCMs: Changes from 1990-2009 to 2020-2039

This subsection contains projected seasonal and annual mean near-future changes for near-surface air temperature and precipitation from each of the GCMs used to provide boundary conditions to the RCMs. The plots are ordered first by GCM, and then by variable.

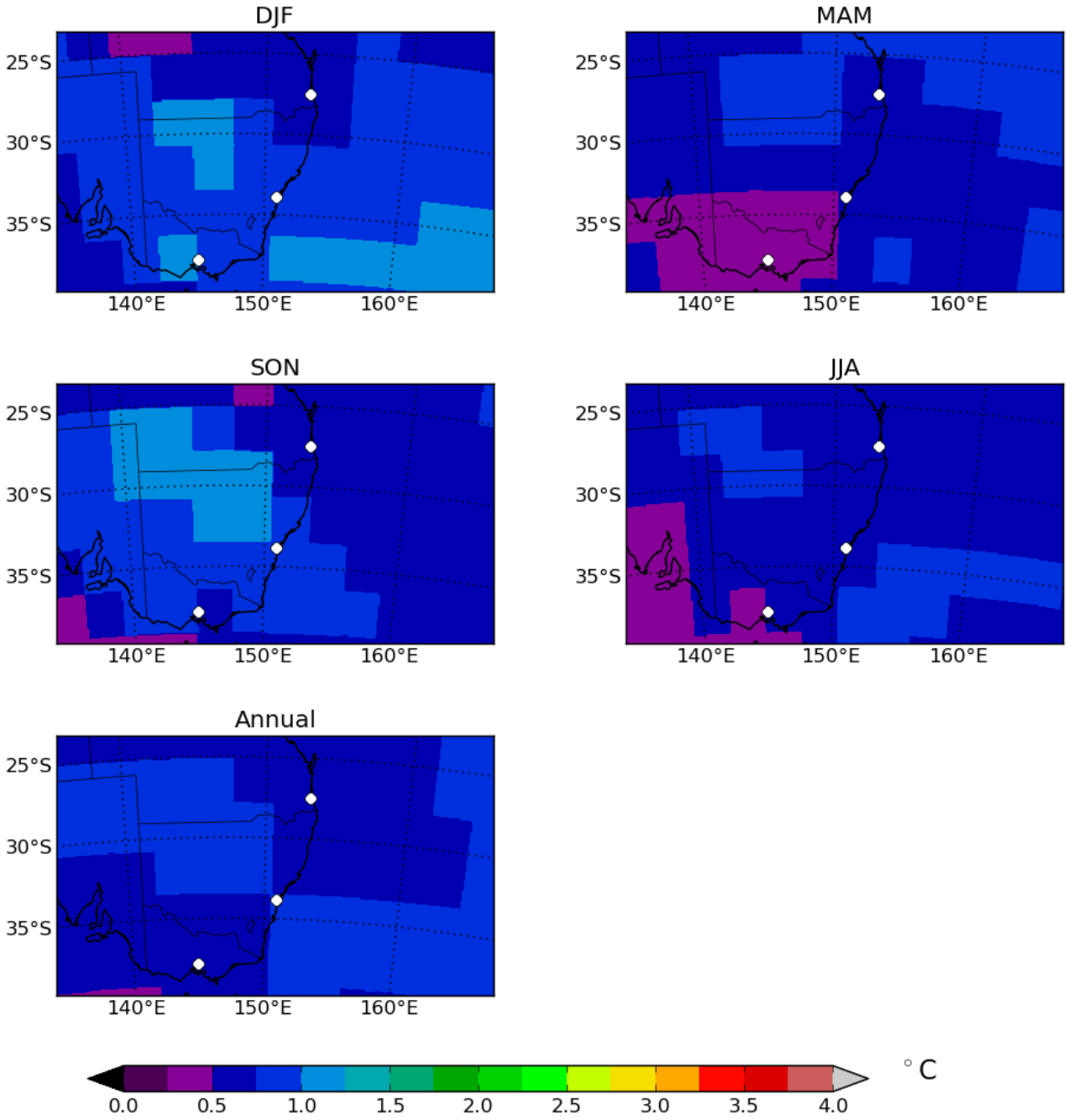

Figure 7.1: Seasonal and annual means of MIROC3.2 near-surface air temperature change between years 1990-2009 and 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

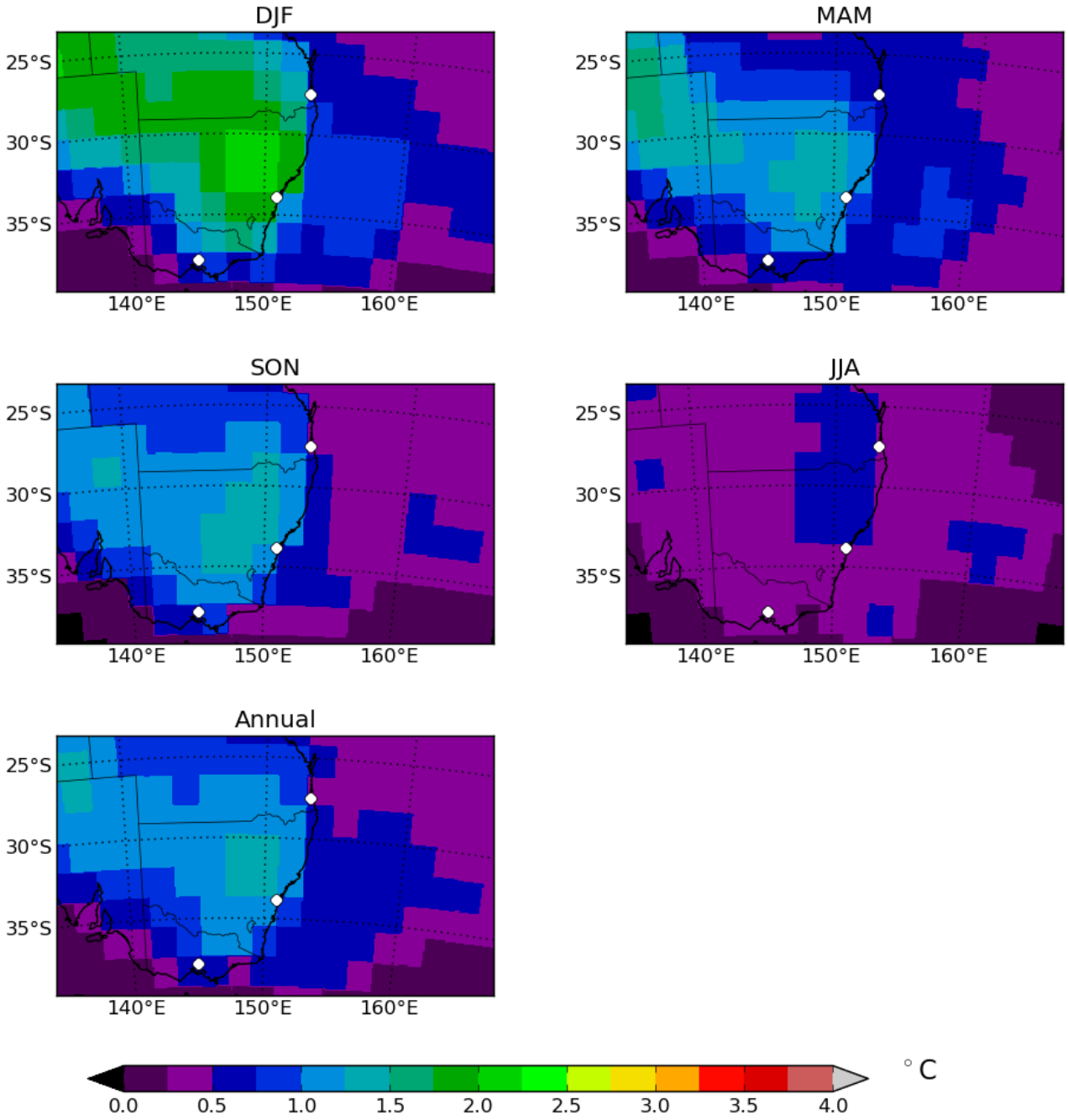

Figure 7.2: Seasonal and annual means of ECHAM5 near-surface air temperature change between years 1990-2009 and 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

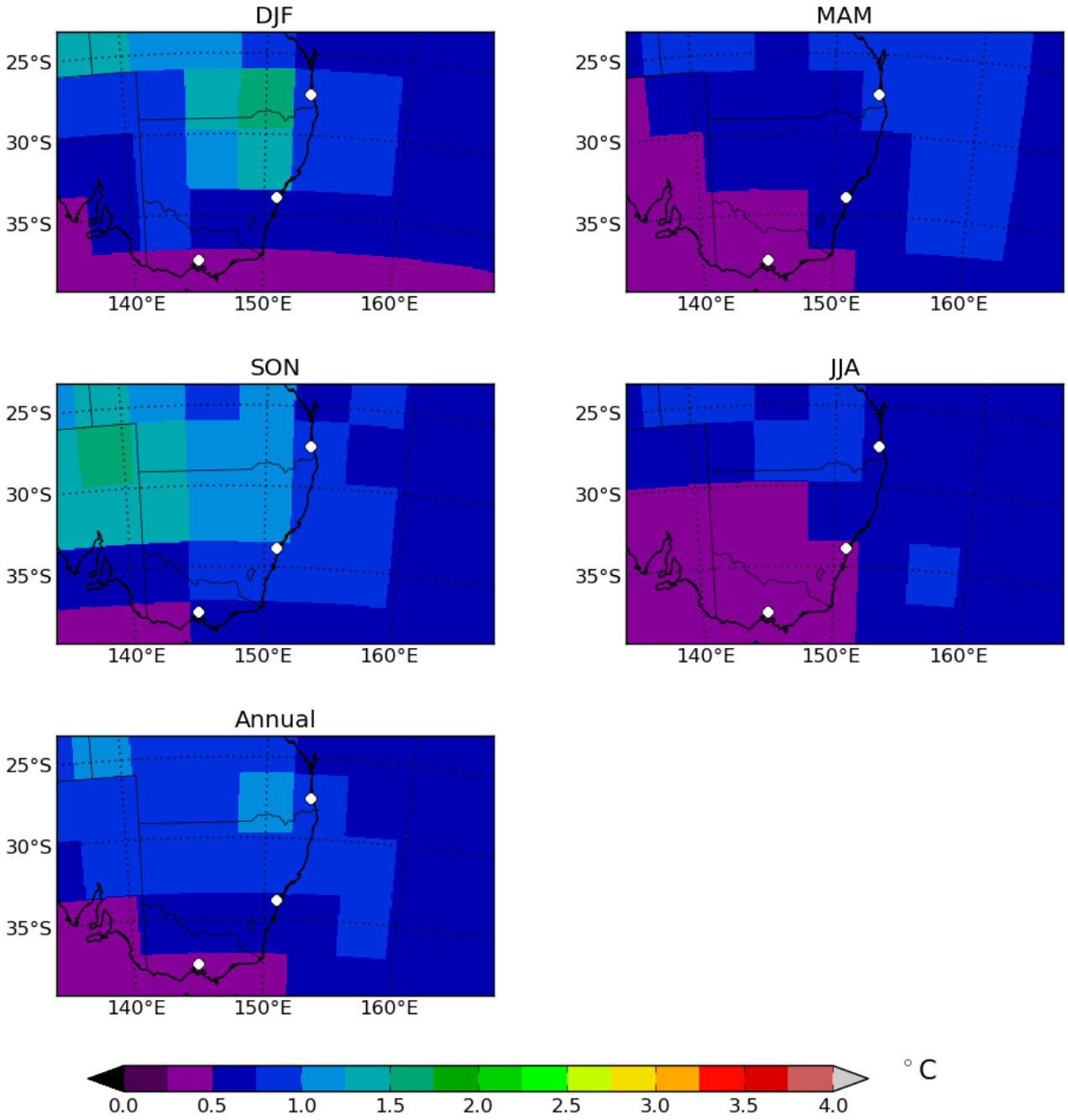

Figure 7.3: Seasonal and annual means of CCCMA3.1 near-surface air temperature change between years 1990-2009 and 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

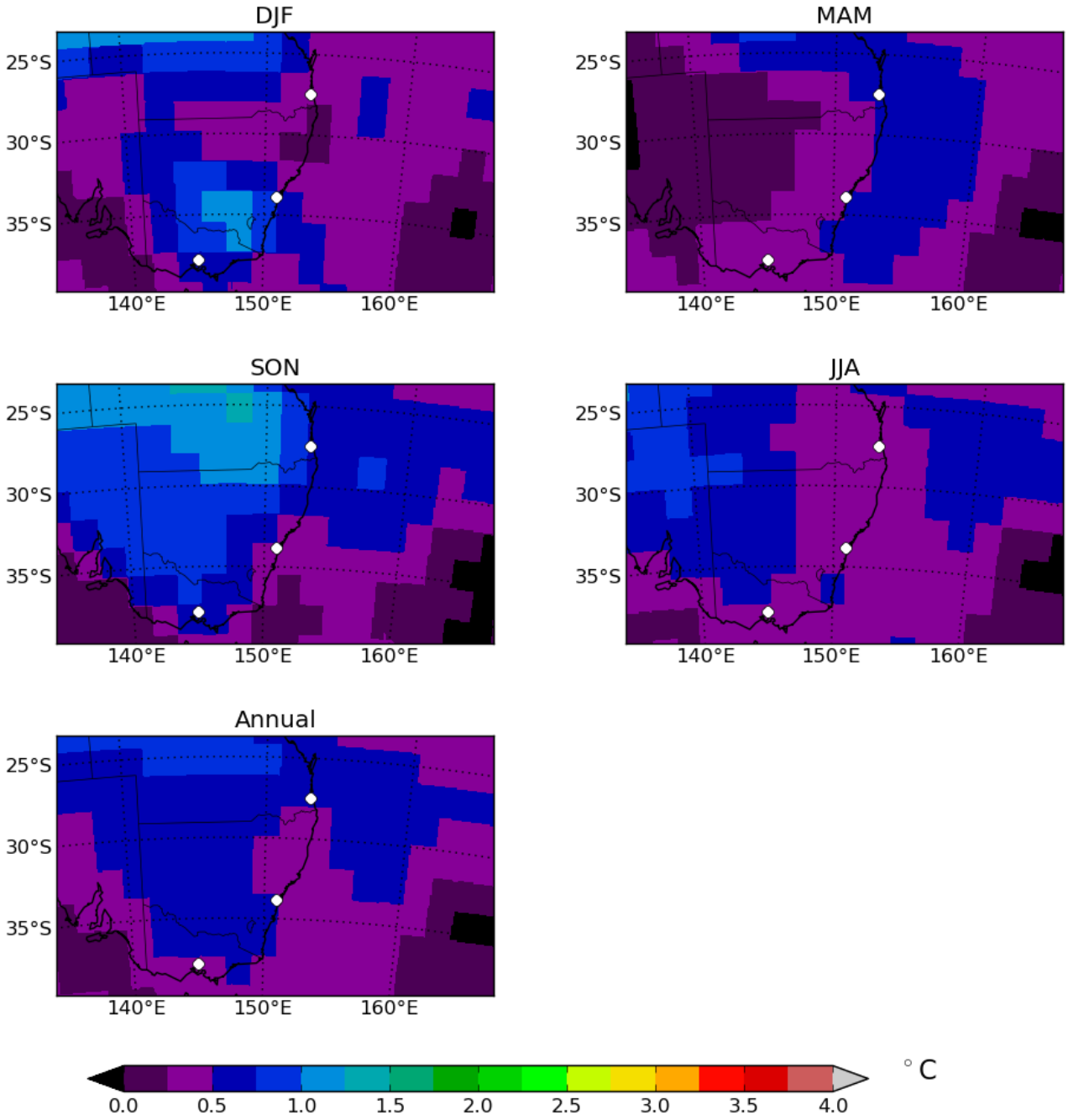

Figure 7.4: Seasonal and annual means of CSIRO-MK3.0 near-surface air temperature change between years 1990-2009 and 2020-2039 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

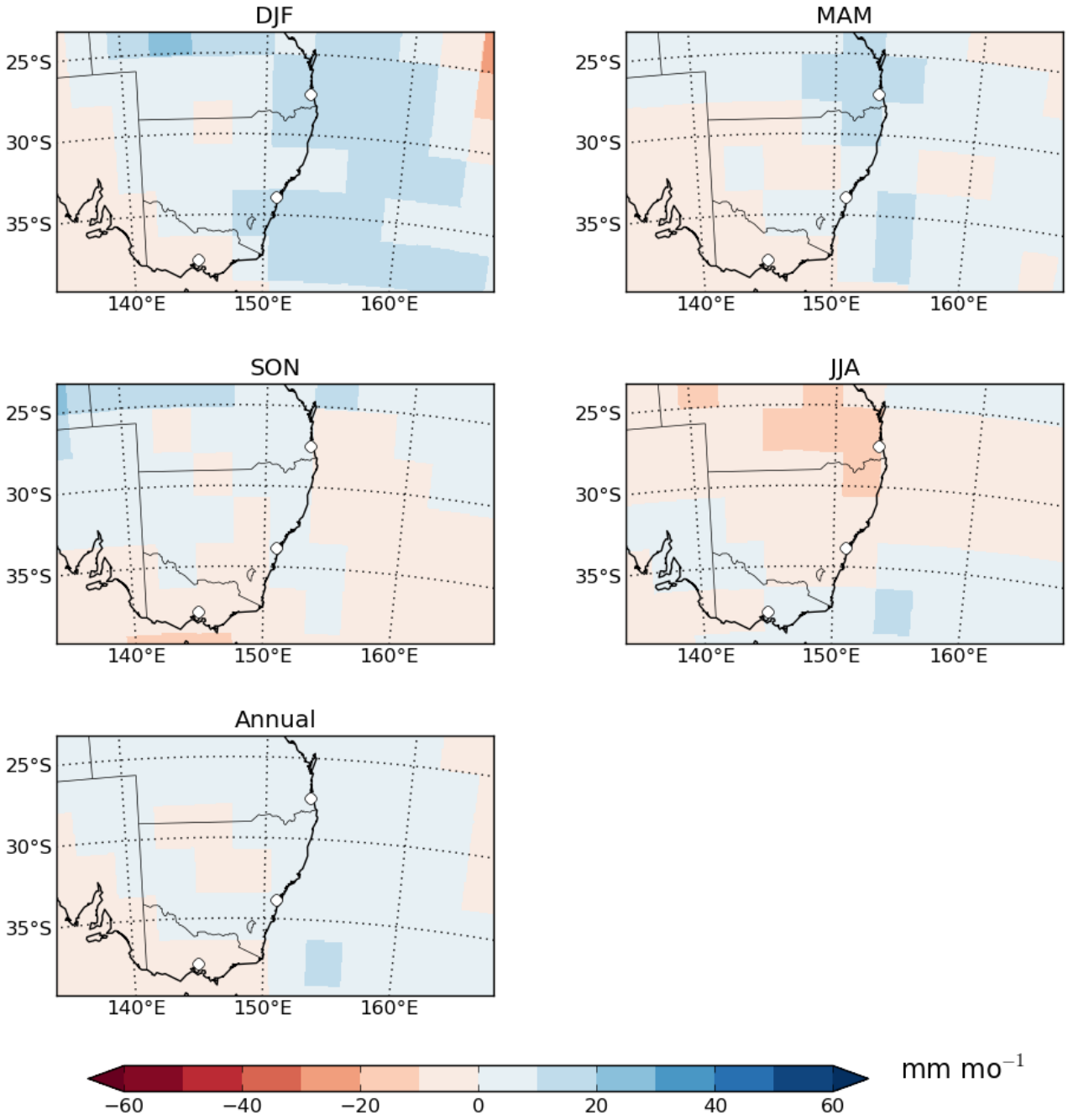

Figure 7.5: Seasonal and annual means of MIROC3.2 precipitation change between years 1990-2009 and 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

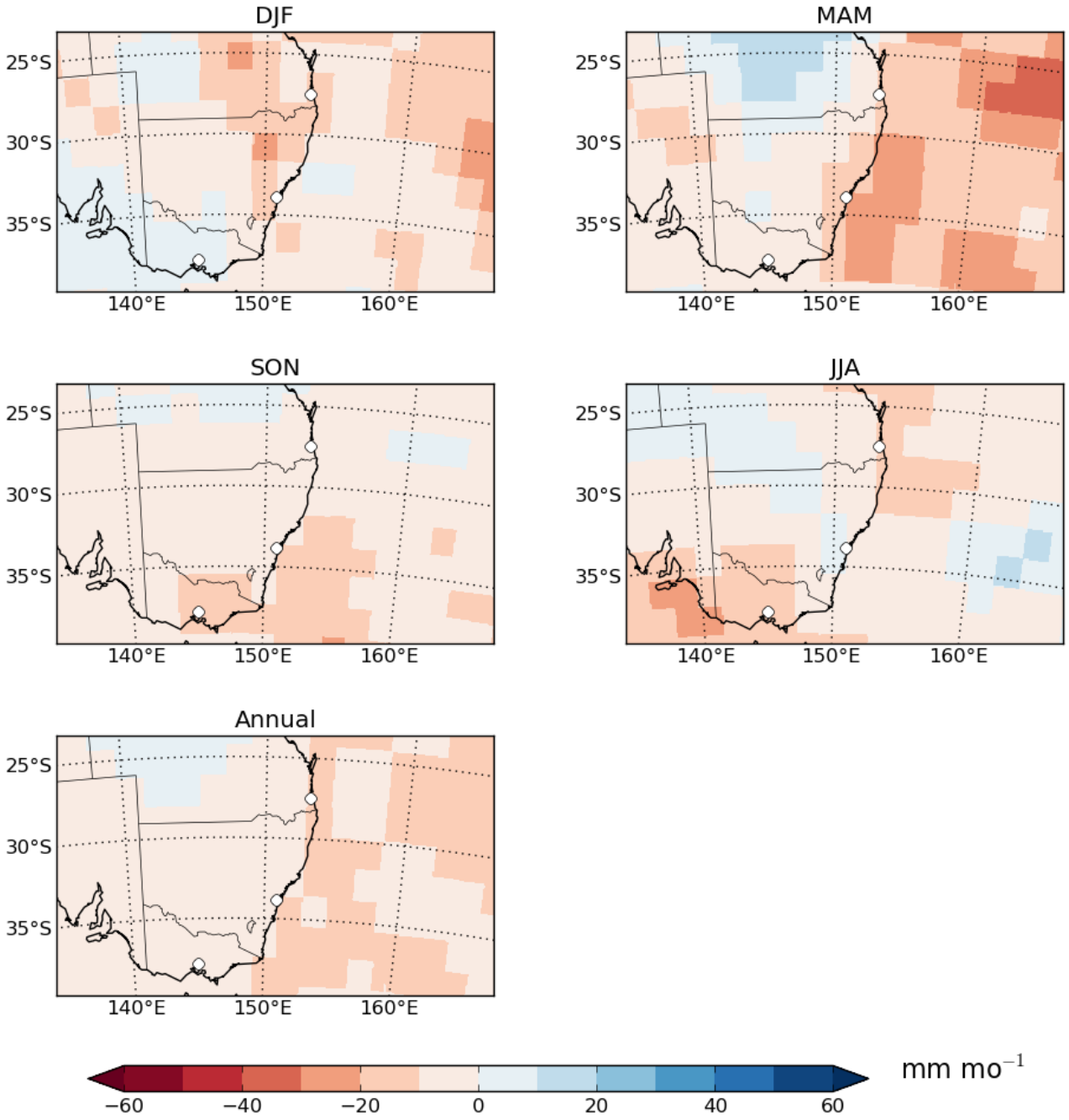

Figure 7.6: Seasonal and annual means of ECHAM5 precipitation change between years 1990-2009 and 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

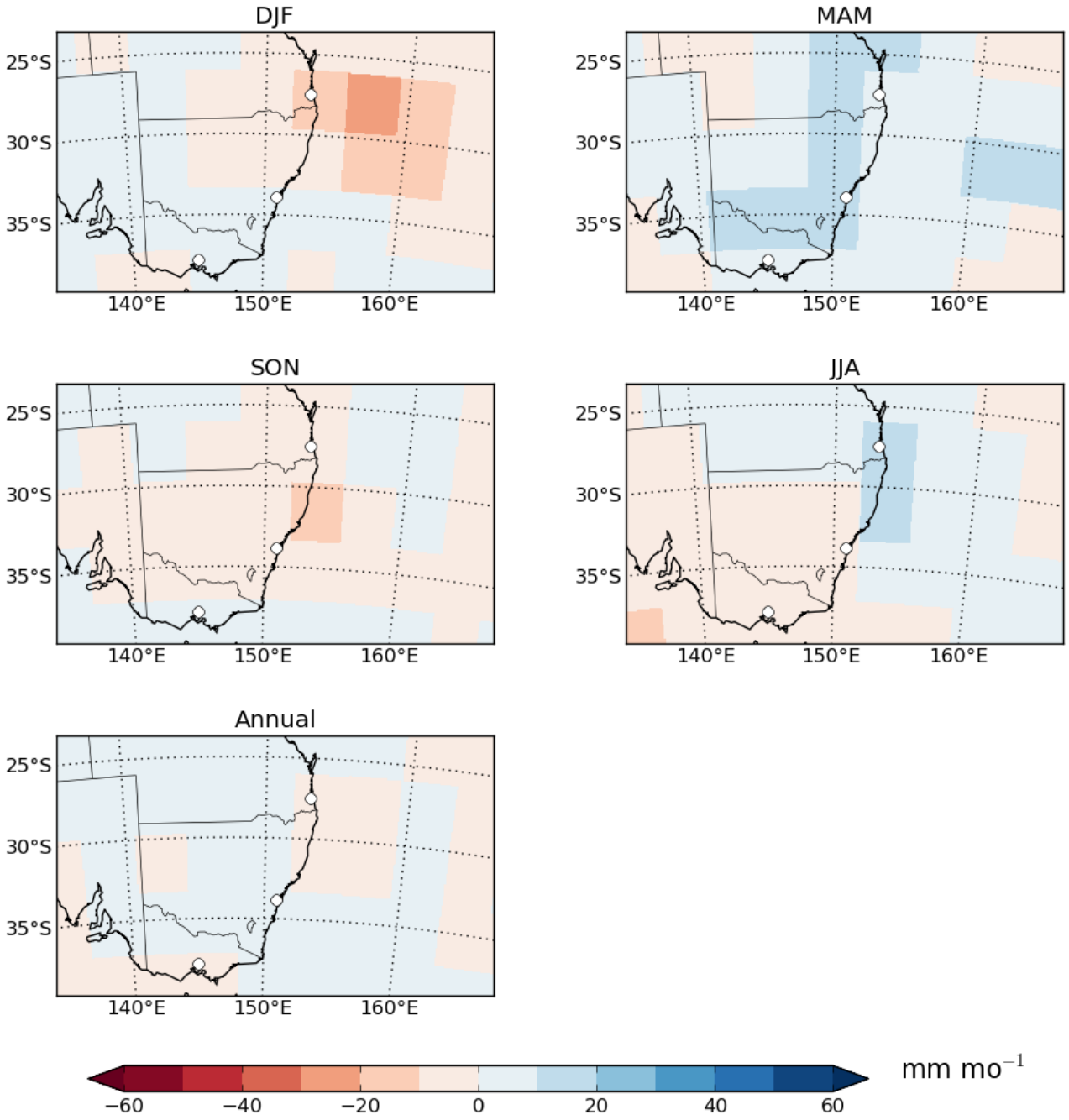

Figure 7.7: Seasonal and annual means of CCCMA3.1 precipitation change between years 1990-2009 and 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

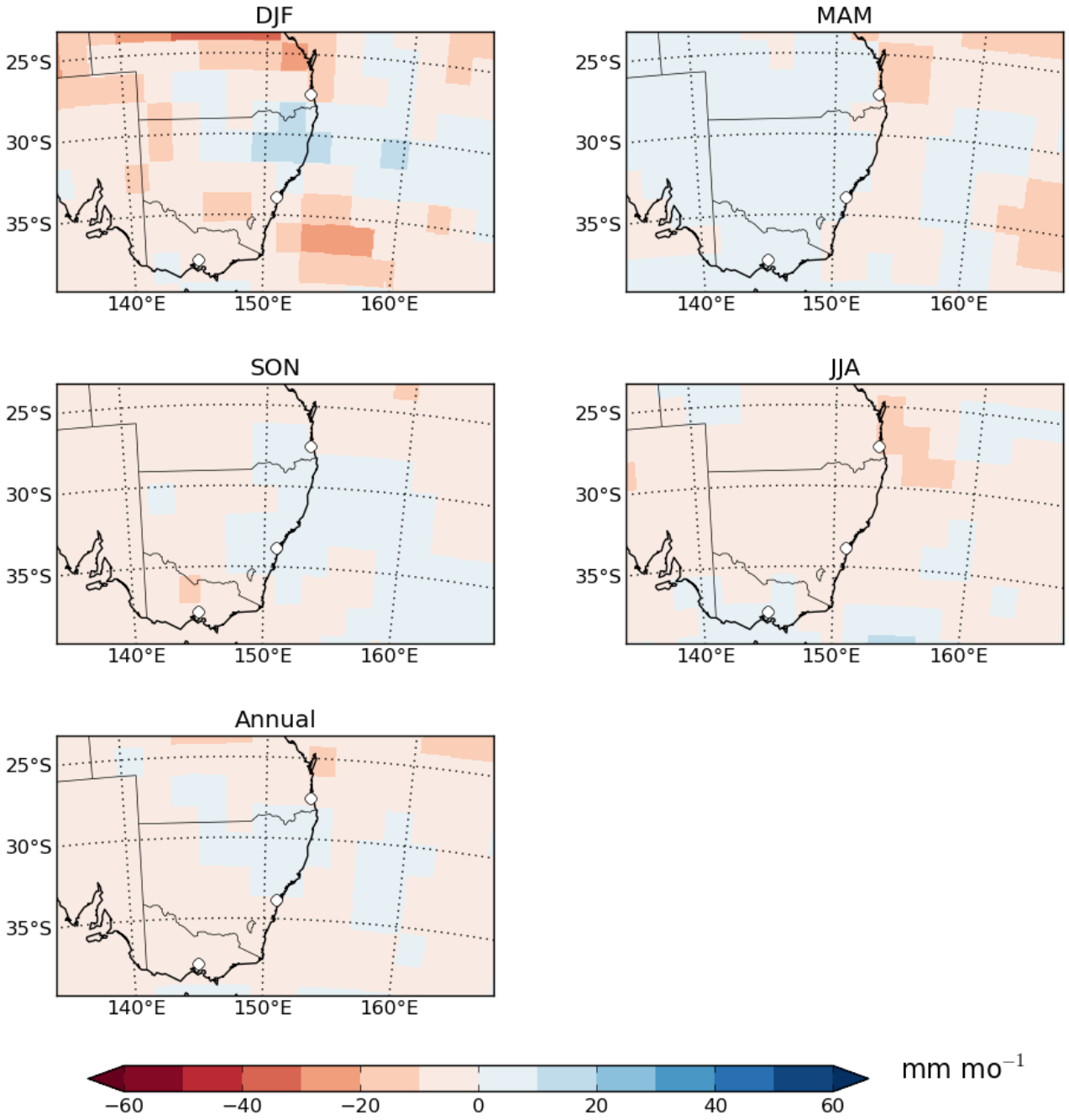

Figure 7.8: Seasonal and annual means of CSIRO-MK3.0 precipitation change between years 1990-2009 and 2020-2039 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

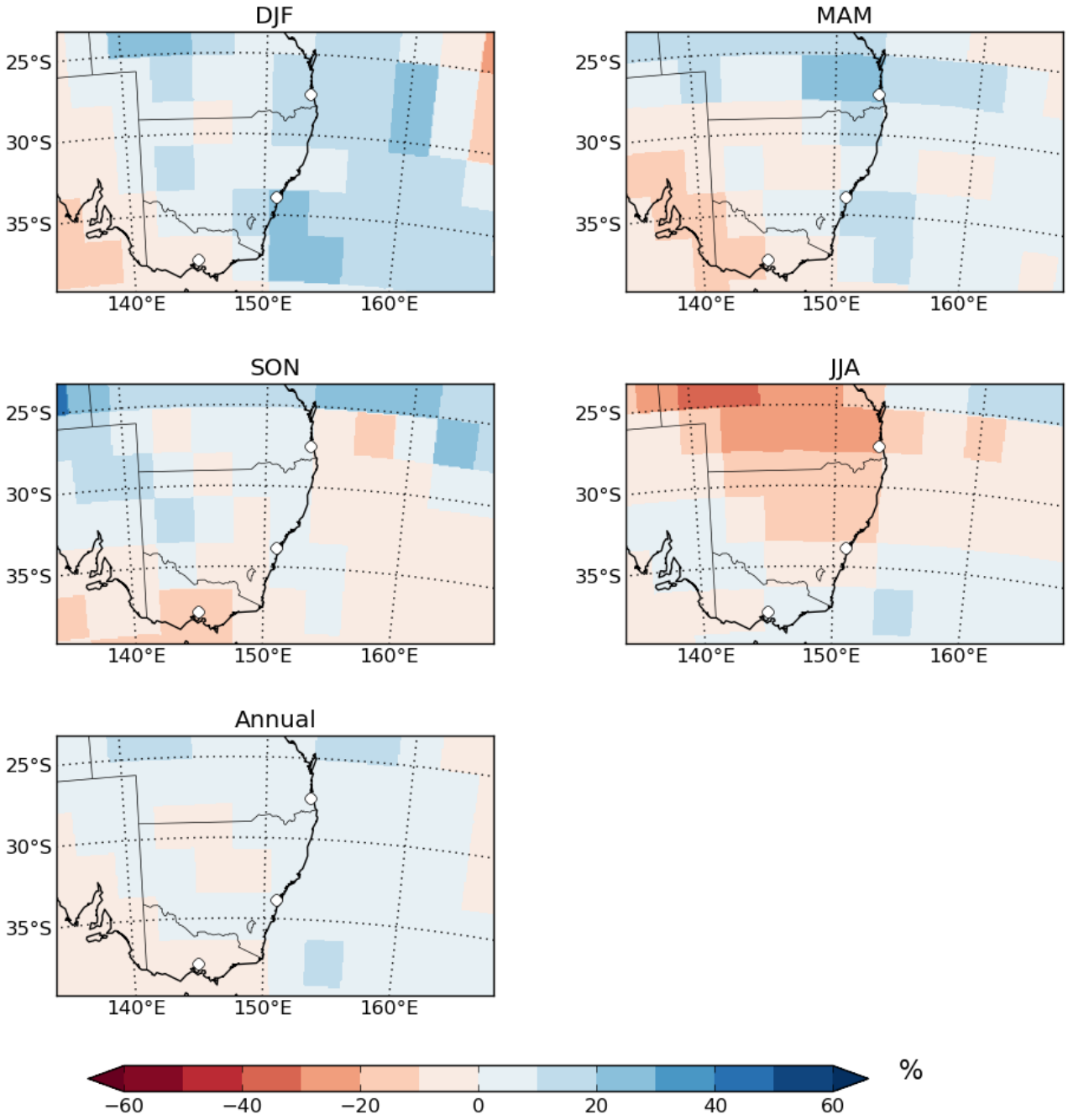

Figure 7.9: Seasonal and annual means of MIROC3.2 precipitation change between years 1990-2009 and 2020-2039 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

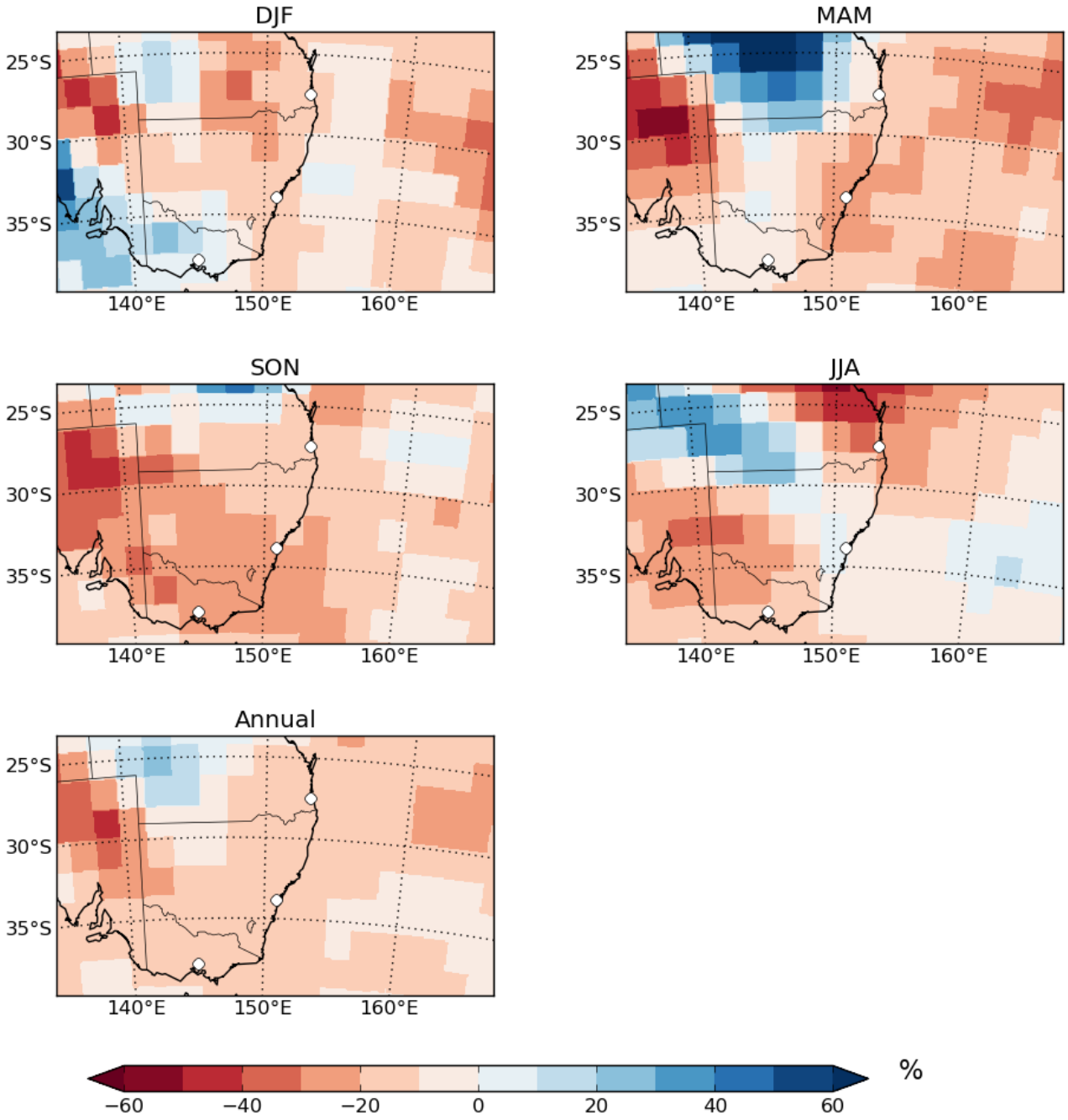

Figure 7.10: Seasonal and annual means of ECHAM5 precipitation change between years 1990-2009 and 2020-2039 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

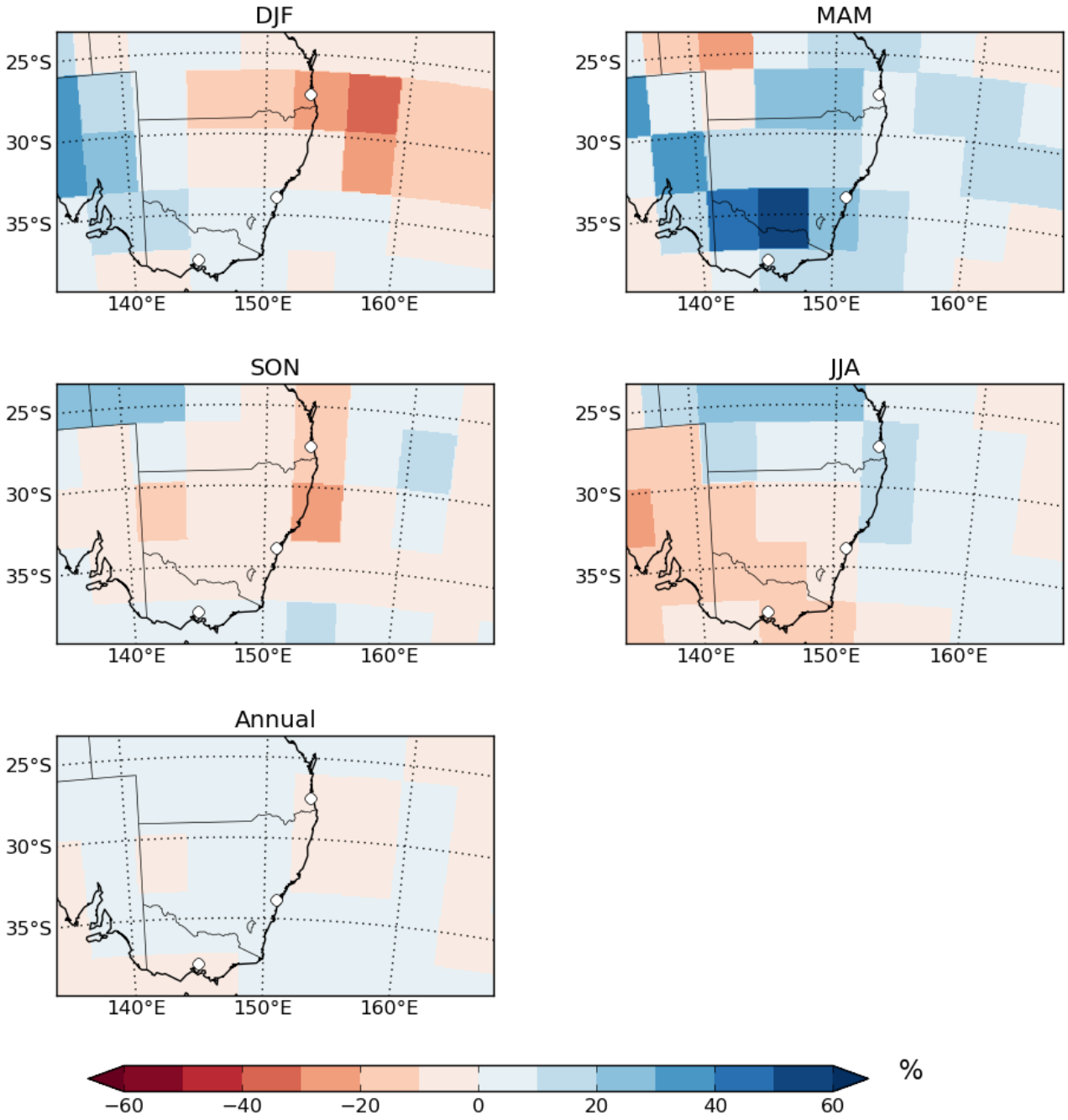

Figure 7.11: Seasonal and annual means of CCCMA3.1 precipitation change between years 1990-2009 and 2020-2039 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

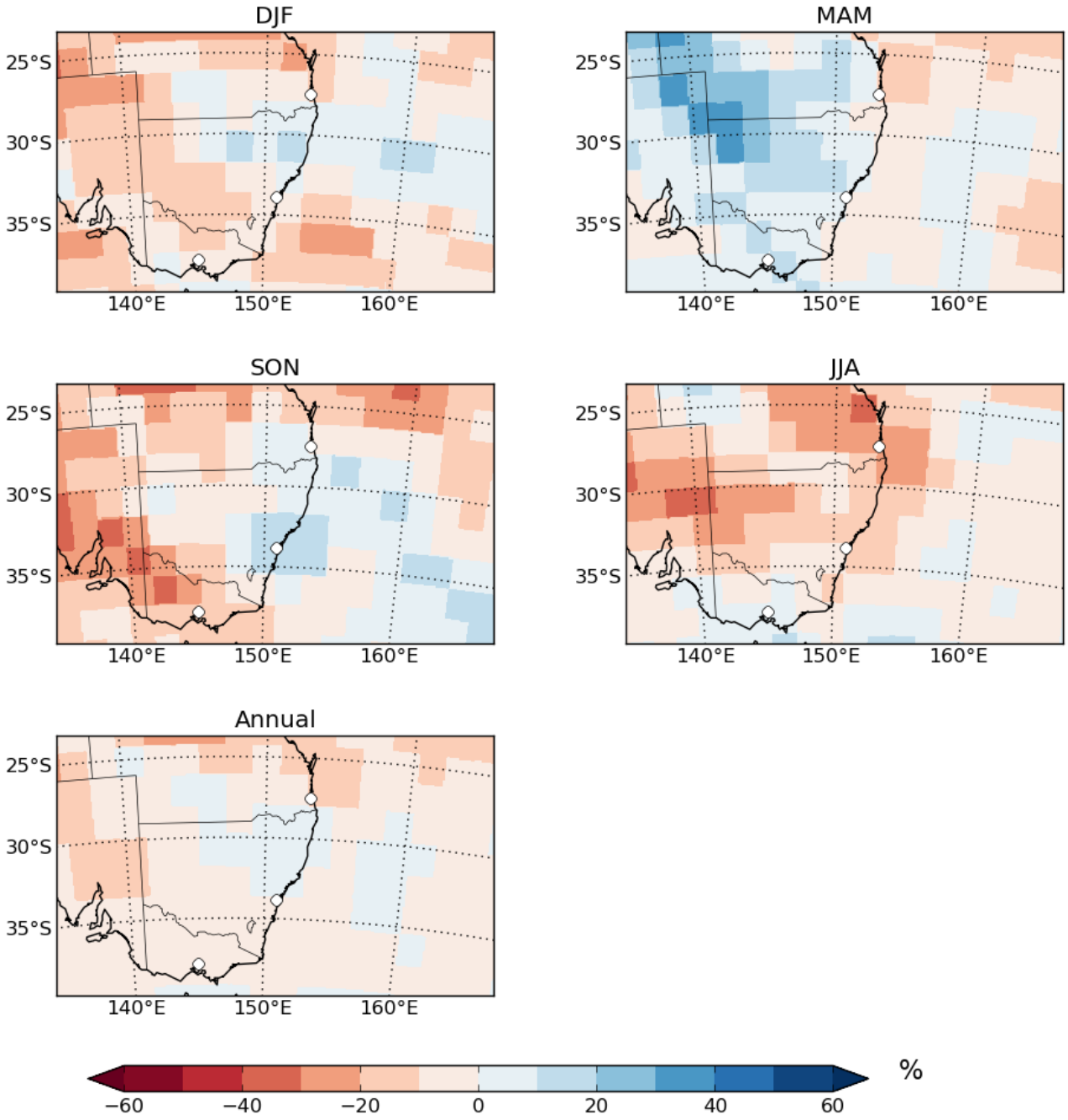

Figure 7.12: Seasonal and annual means of CSIRO-MK3.0 precipitation change between years 1990-2009 and 2020-2039 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

7.2 Regional Model Output: Changes from 1990-2009 to 2020-2039

This subsection contains projected seasonal and annual mean near-future changes for near-surface air temperature, daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the original RCM output. Precipitation changes are plotted as both absolute values (in mm mo^{-1}), and percent changes. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected changes, whereas the individual-model plots show the level of uncertainty in projected changes.

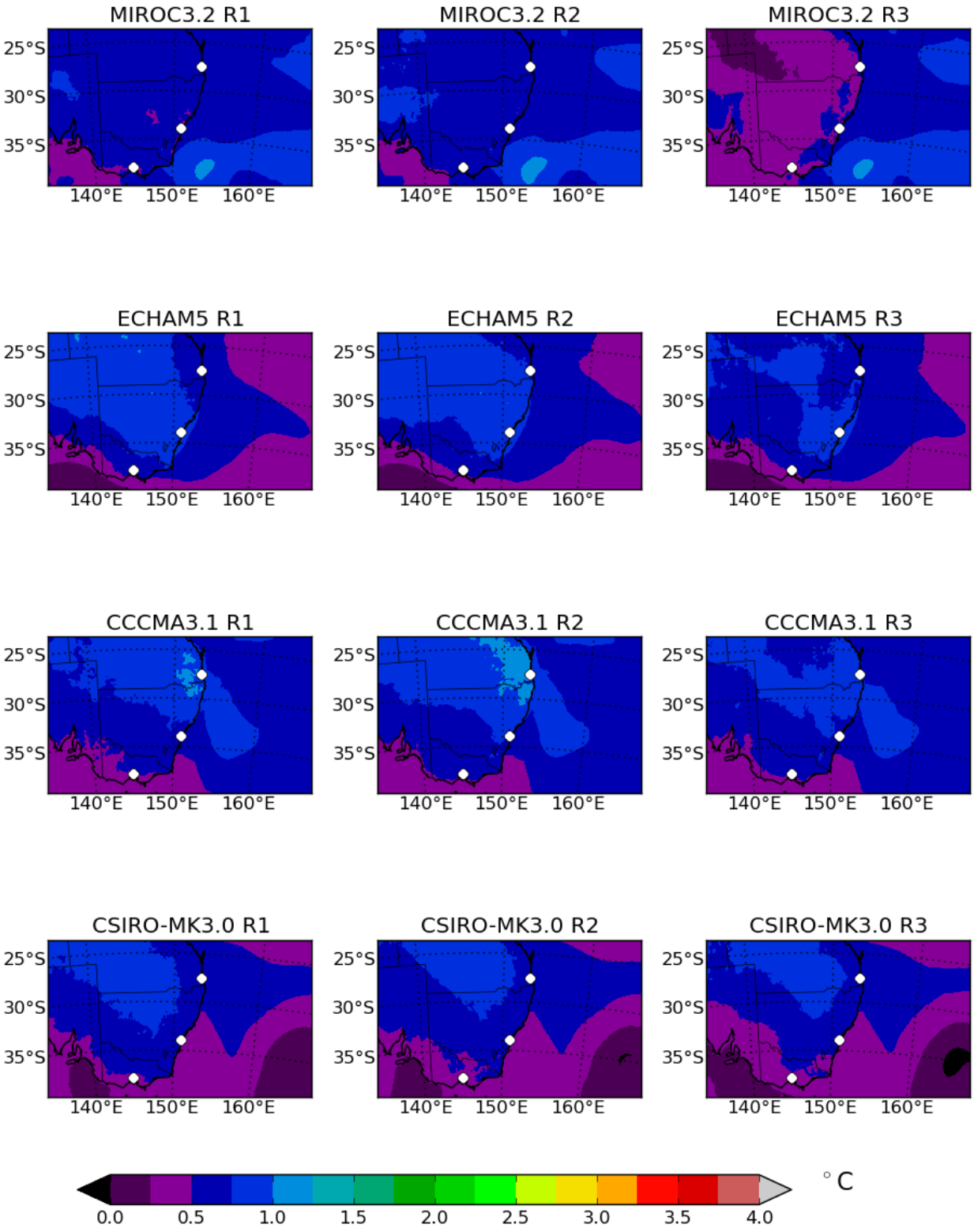

Figure 7.13: Annual mean change between years 1990-2009 and 2020-2039 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

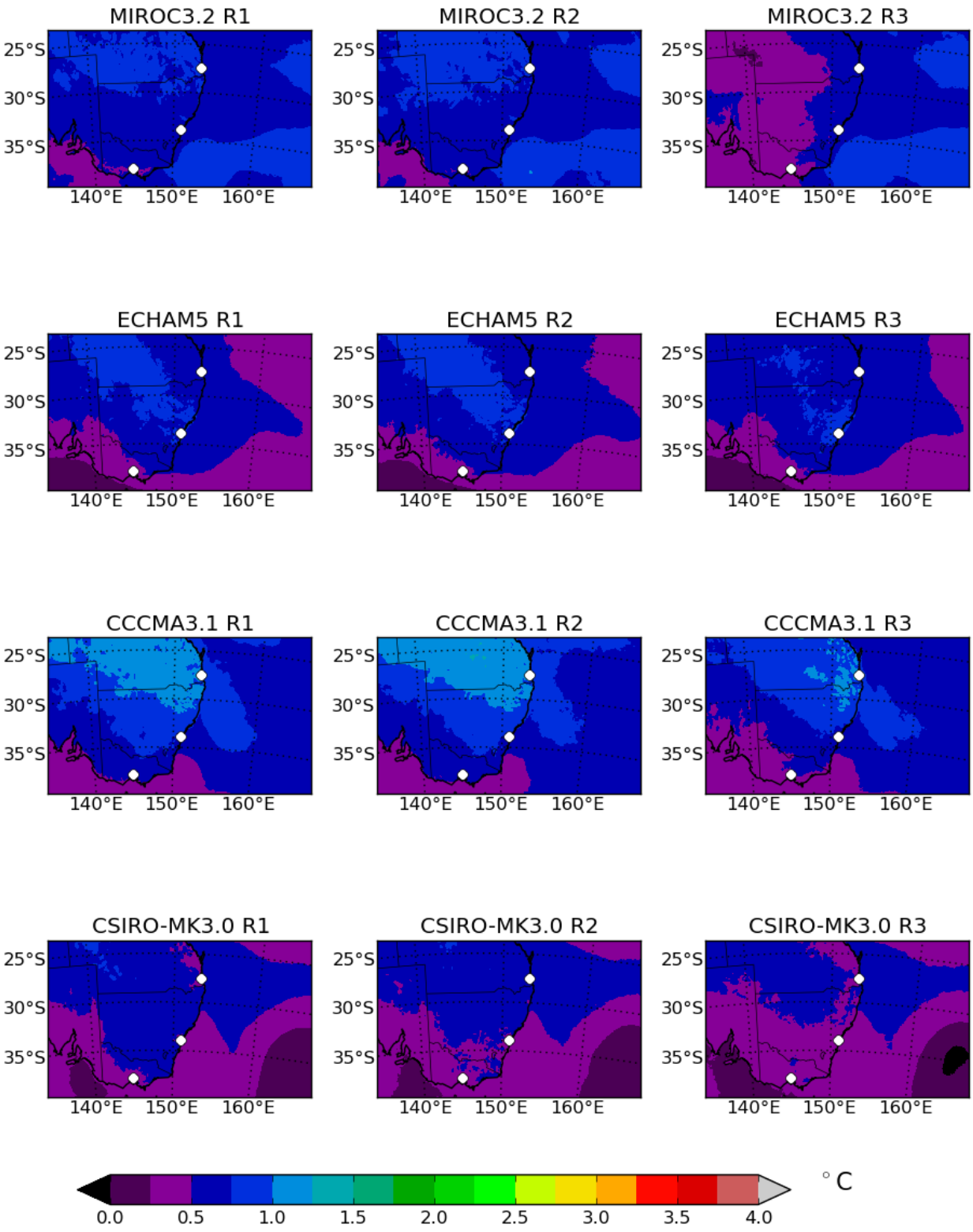

Figure 7.14: Annual mean change between years 1990-2009 and 2020-2039 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

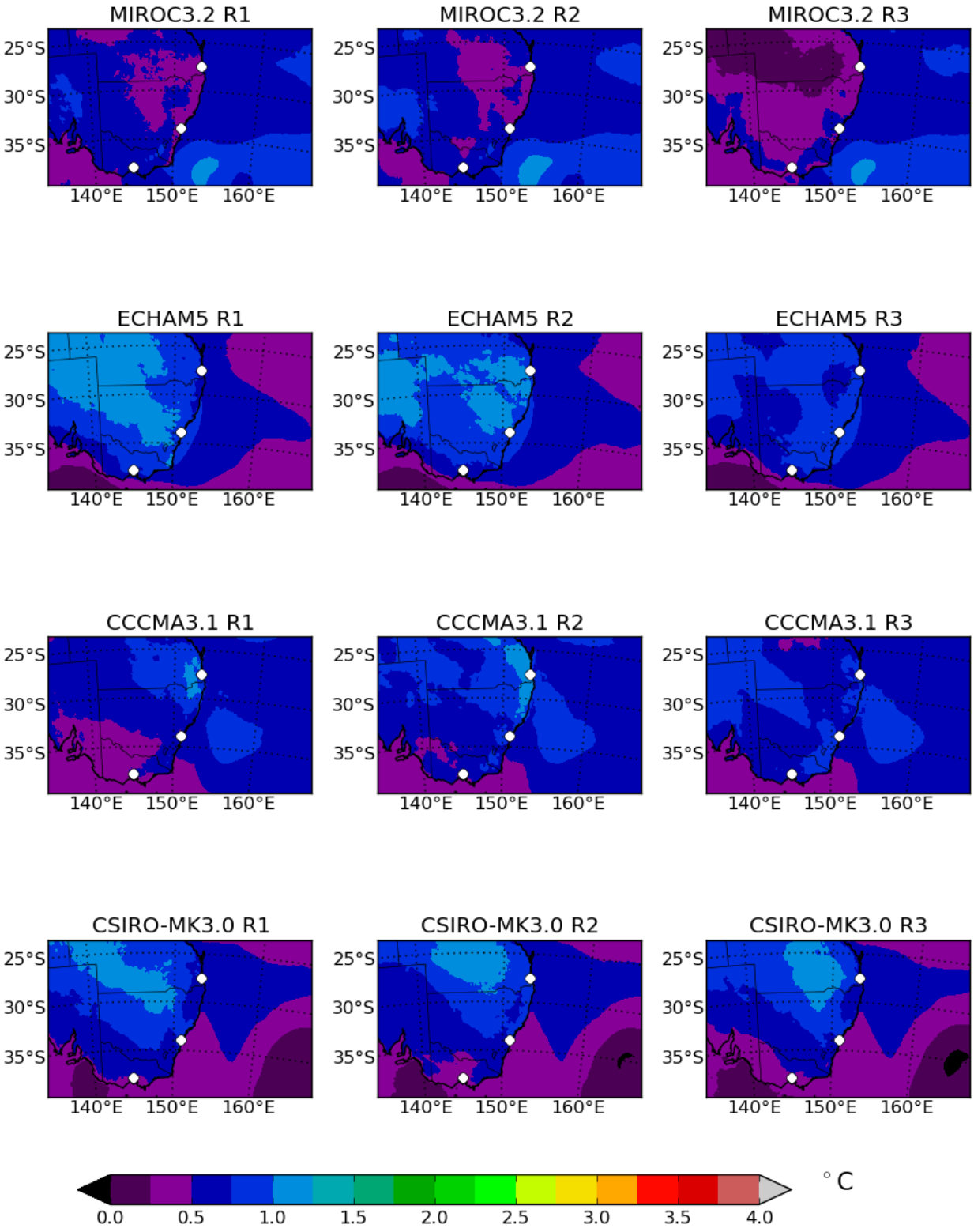

Figure 7.15: Annual mean change between years 1990-2009 and 2020-2039 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

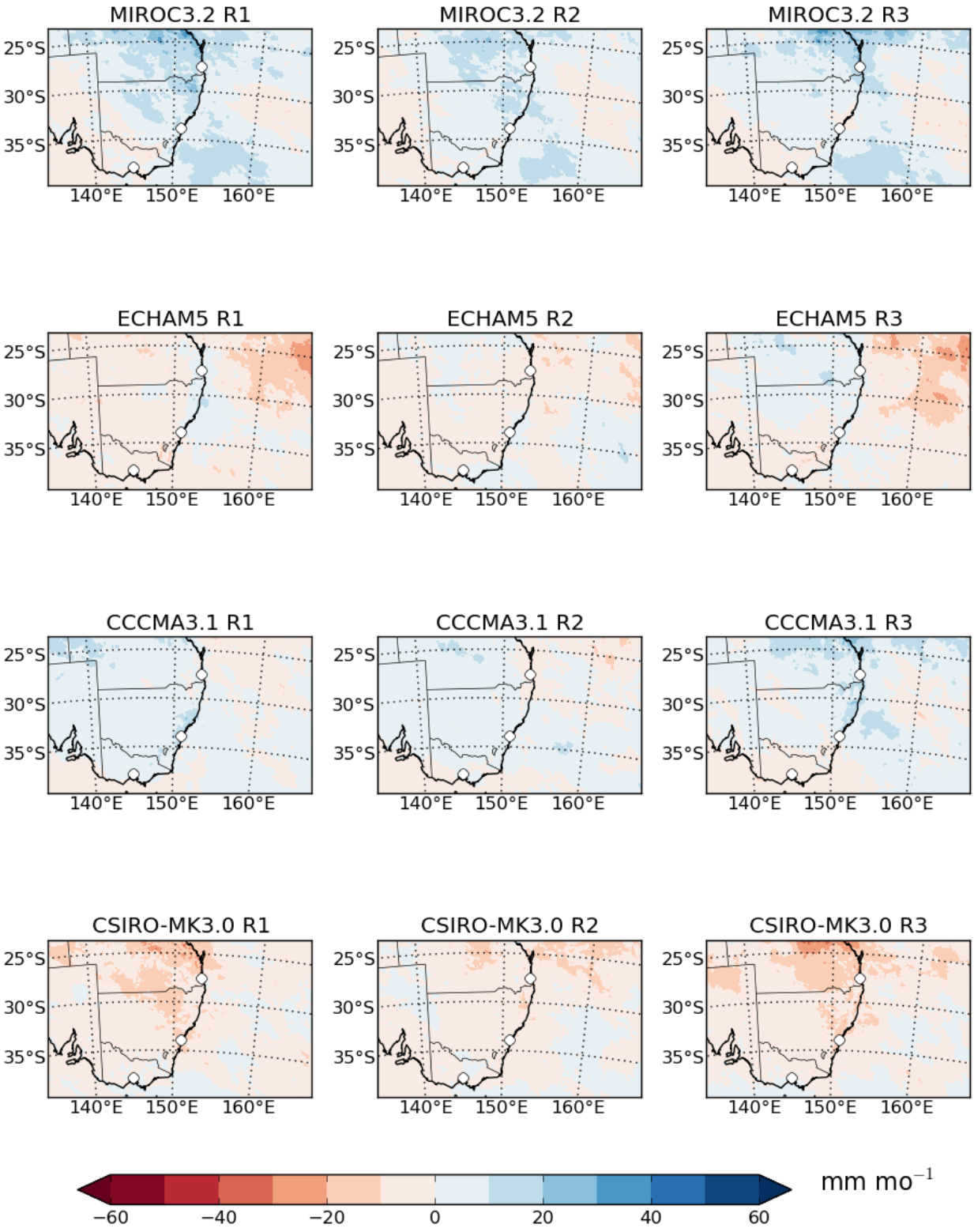

Figure 7.16: Annual mean change between years 1990-2009 and 2020-2039 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

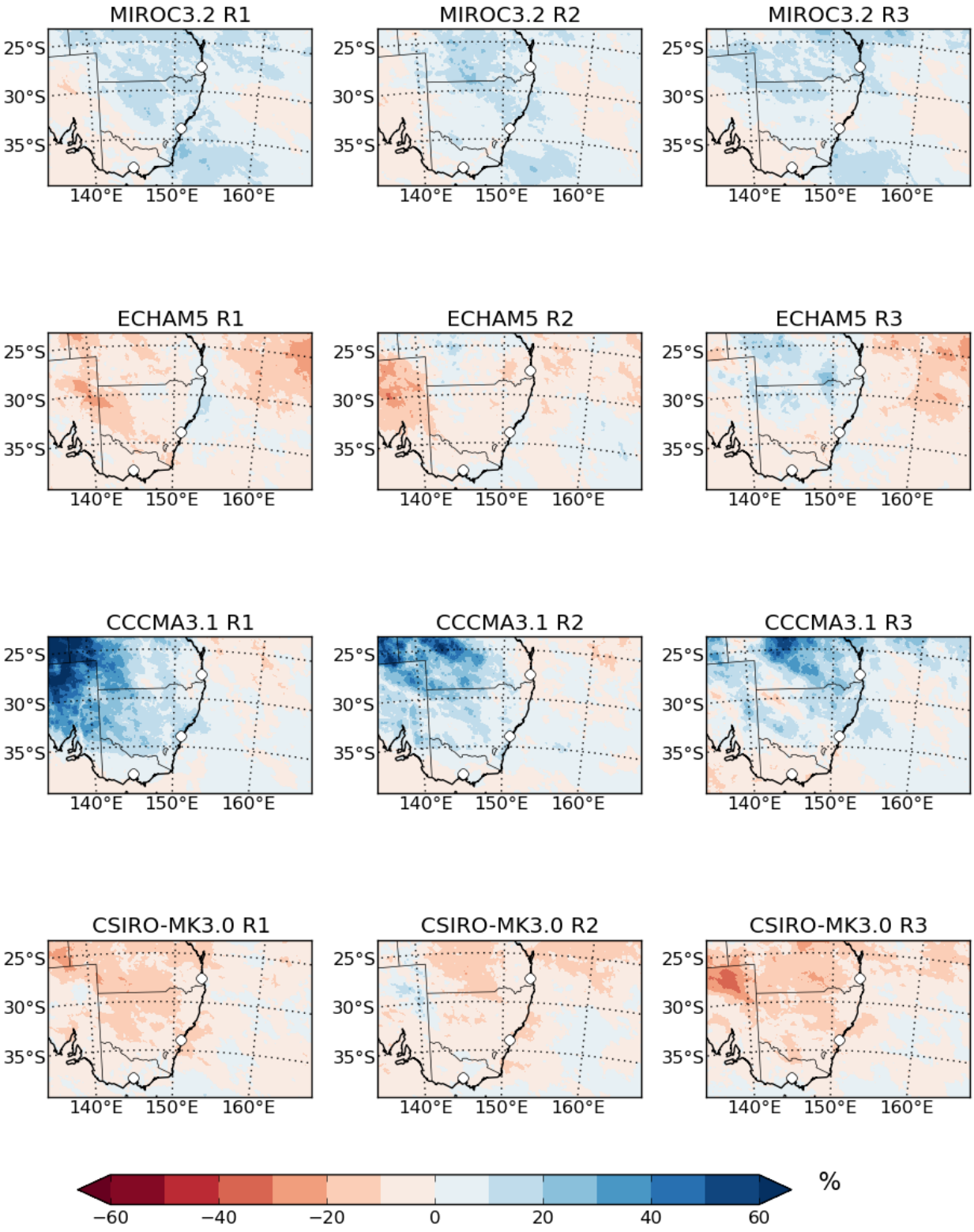

Figure 7.17: Annual mean change between years 1990-2009 and 2020-2039 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

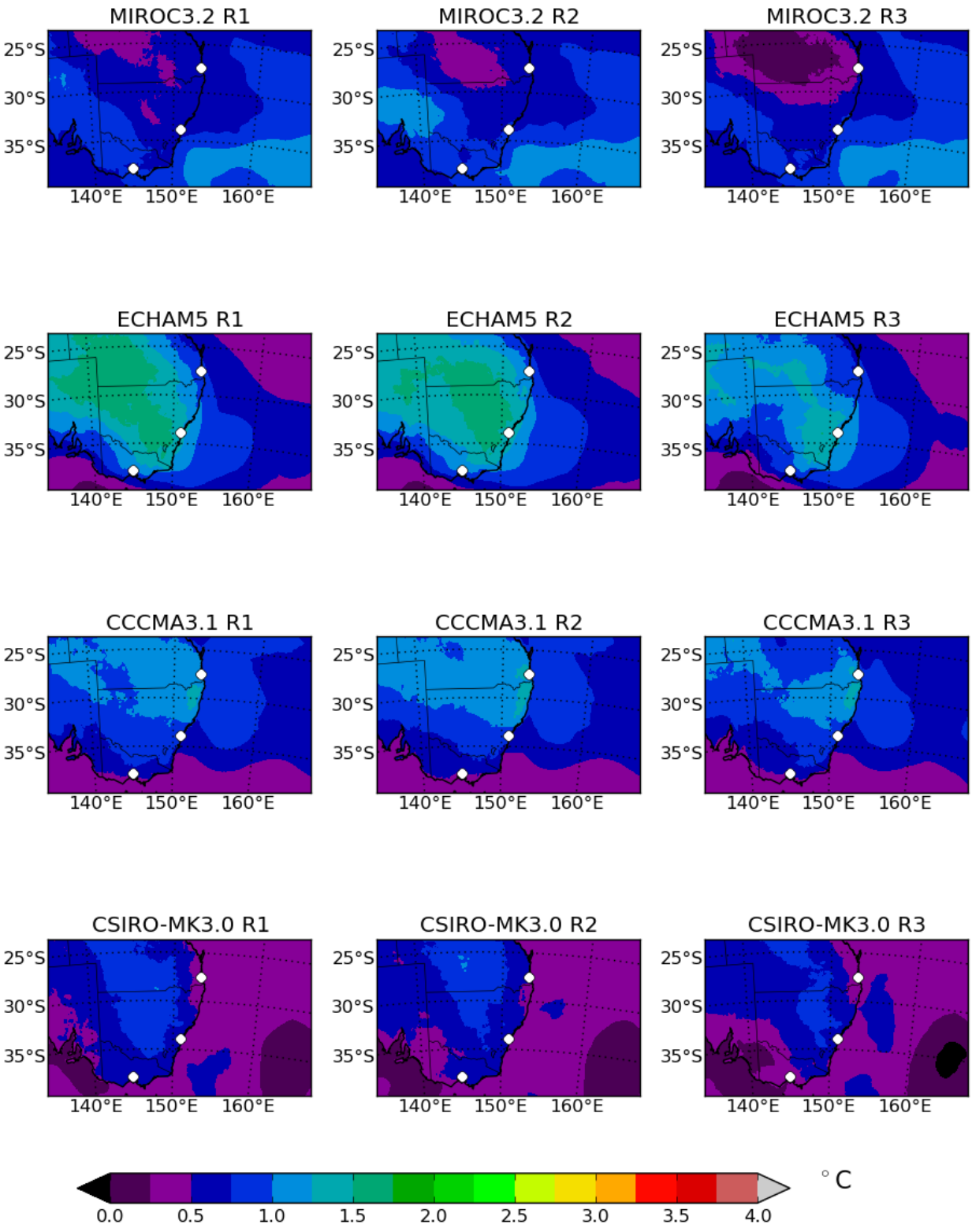

Figure 7.18: DJF mean change between years 1990-2009 and 2020-2039 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

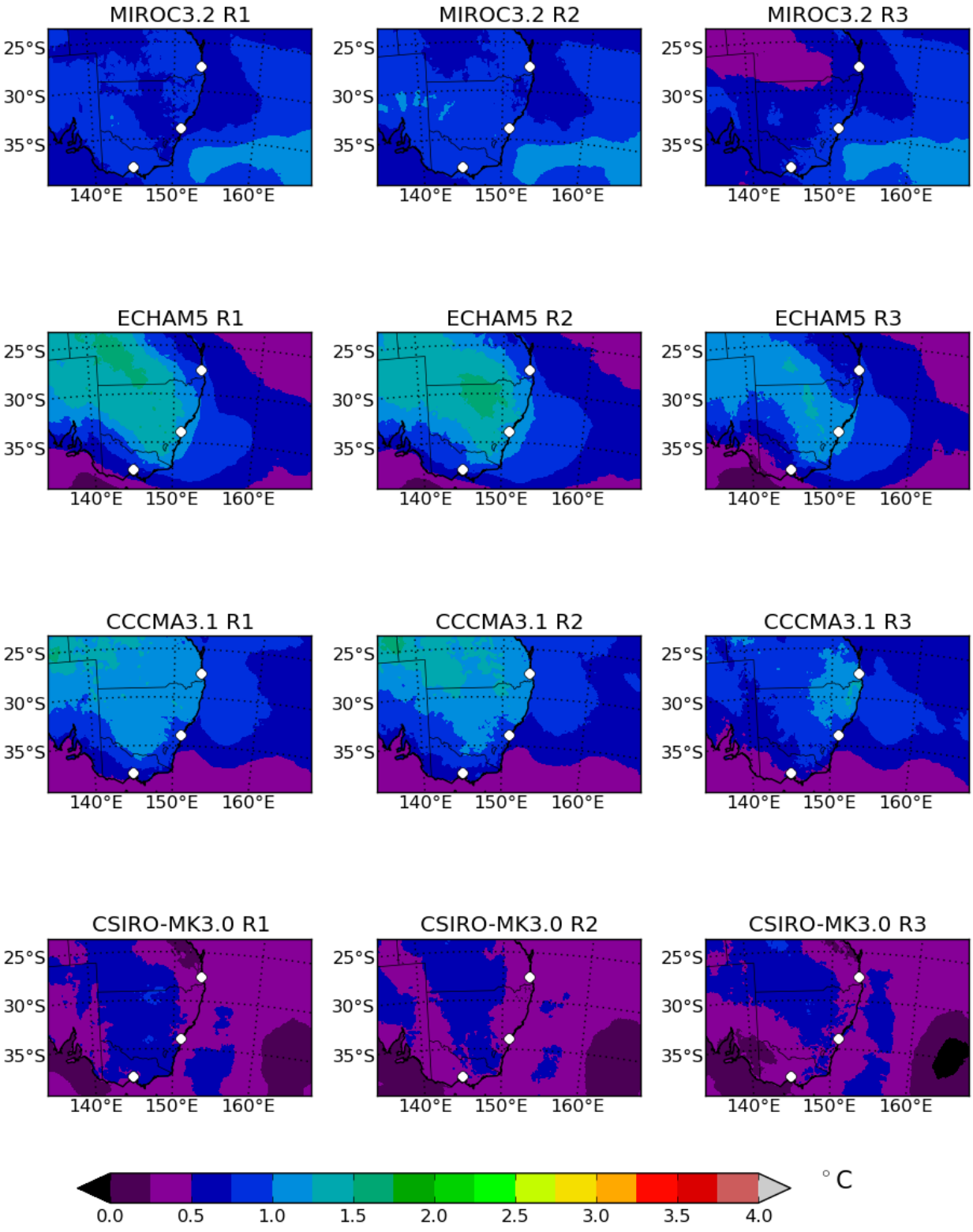

Figure 7.19: DJF mean change between years 1990-2009 and 2020-2039 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

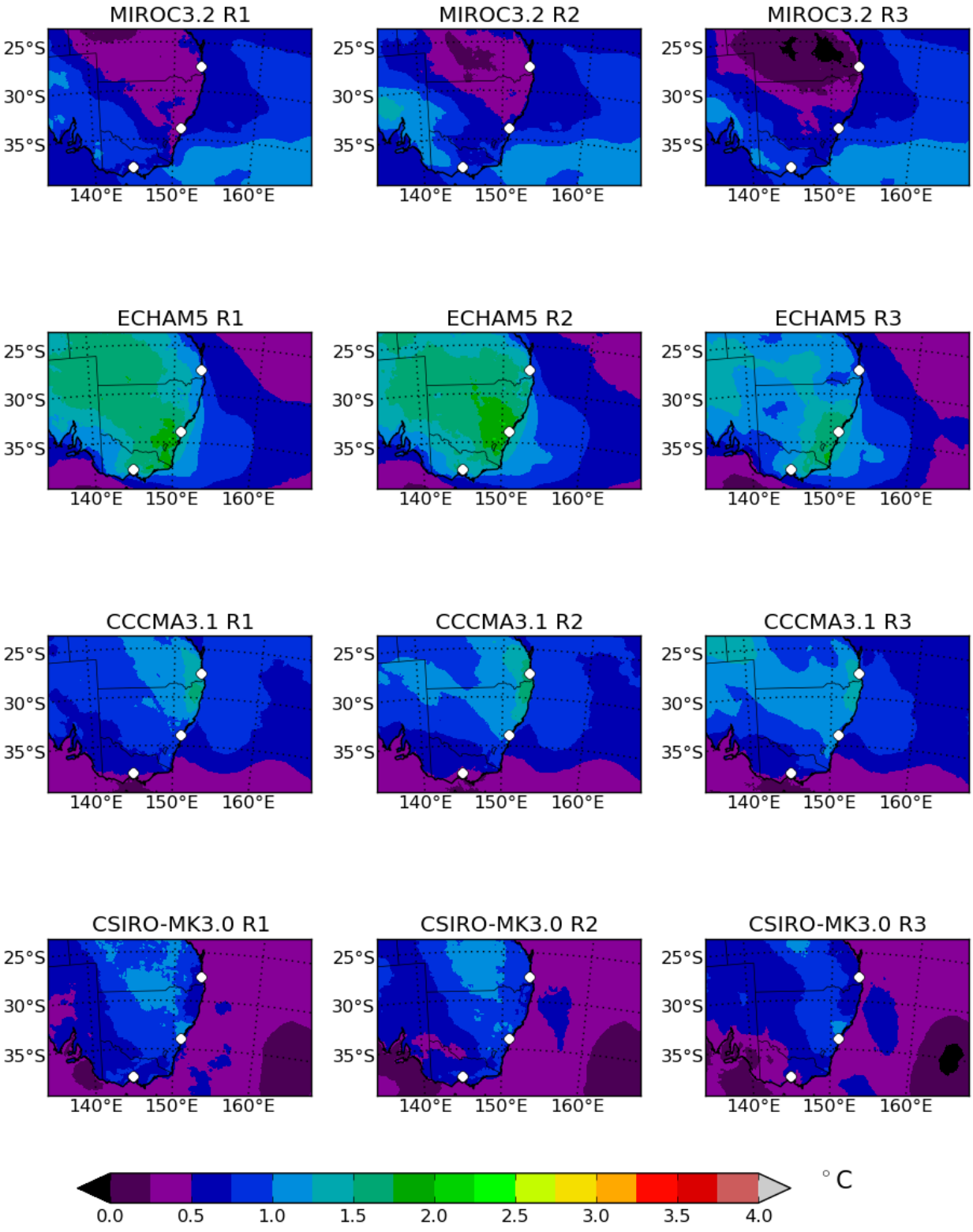

Figure 7.20: DJF mean change between years 1990-2009 and 2020-2039 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

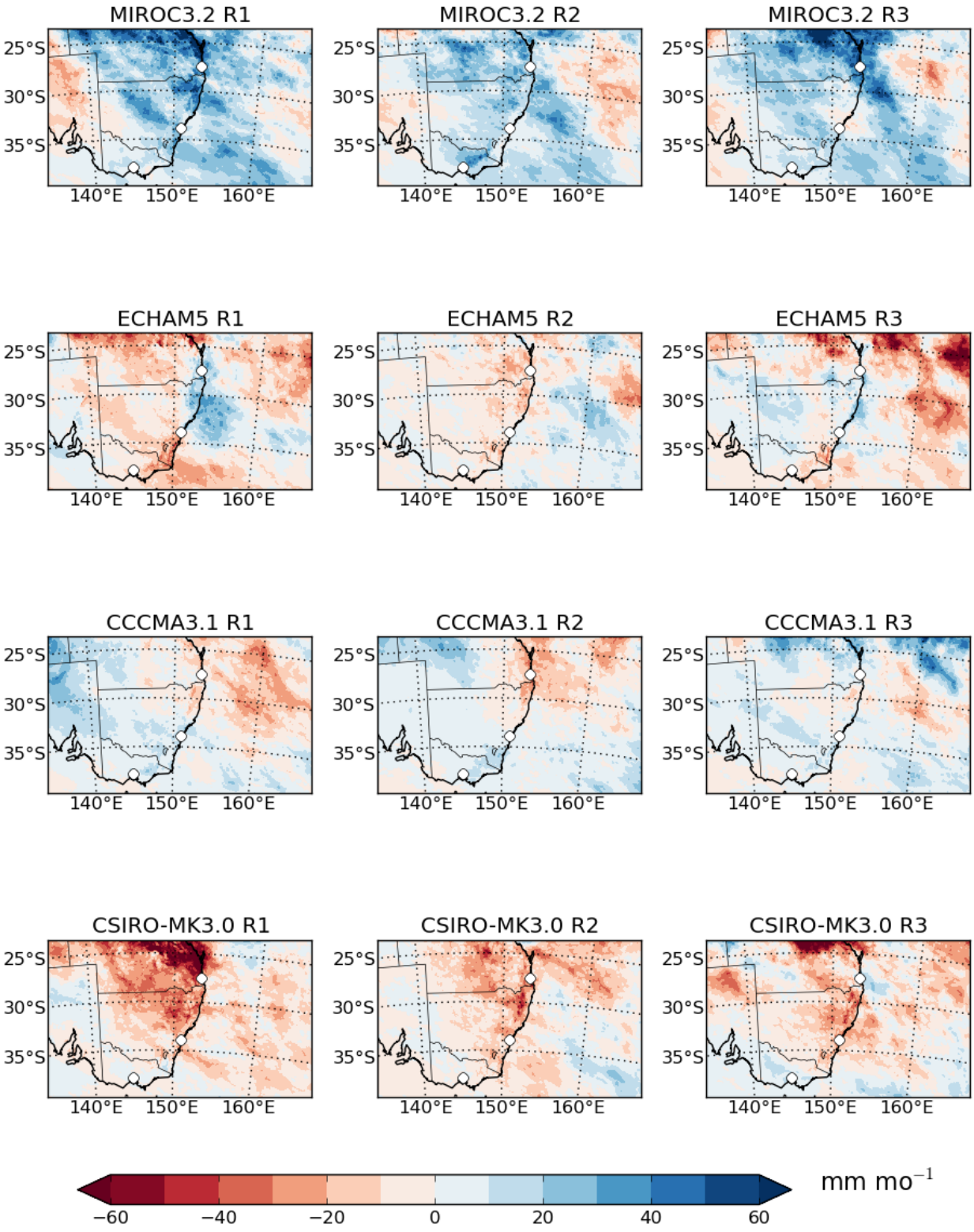

Figure 7.21: DJF mean change between years 1990-2009 and 2020-2039 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

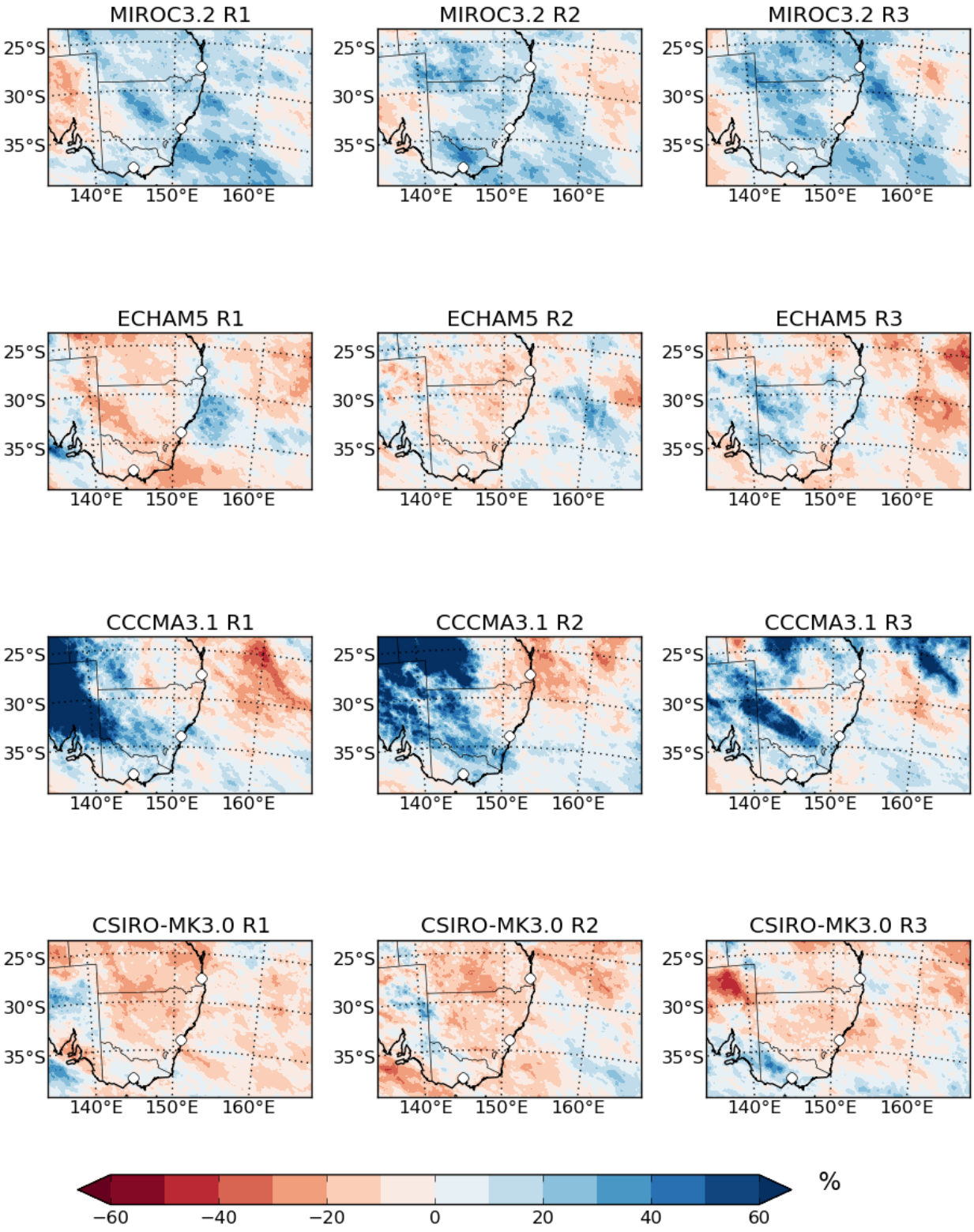

Figure 7.22: DJF mean change between years 1990-2009 and 2020-2039 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

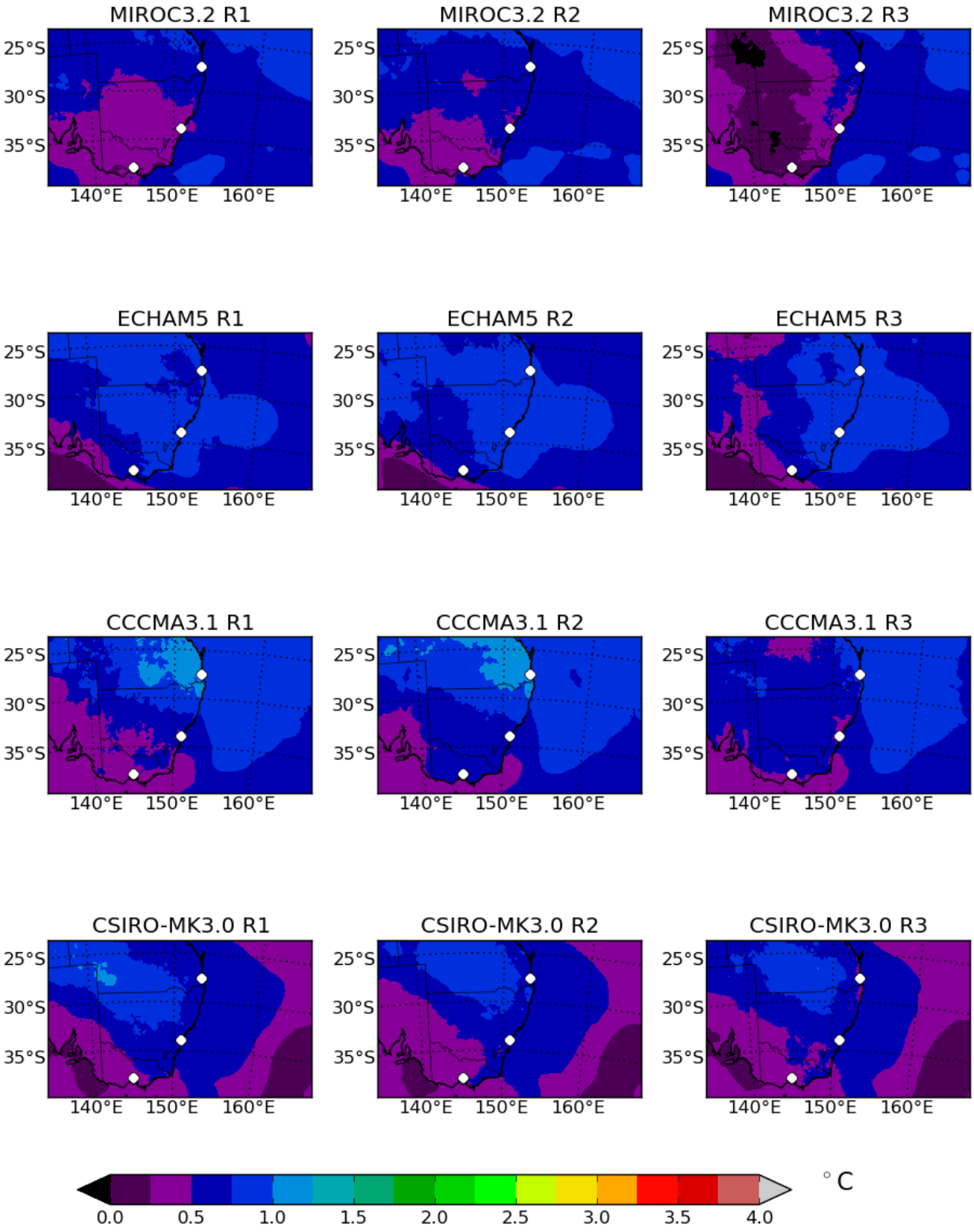

Figure 7.23: MAM mean change between years 1990-2009 and 2020-2039 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

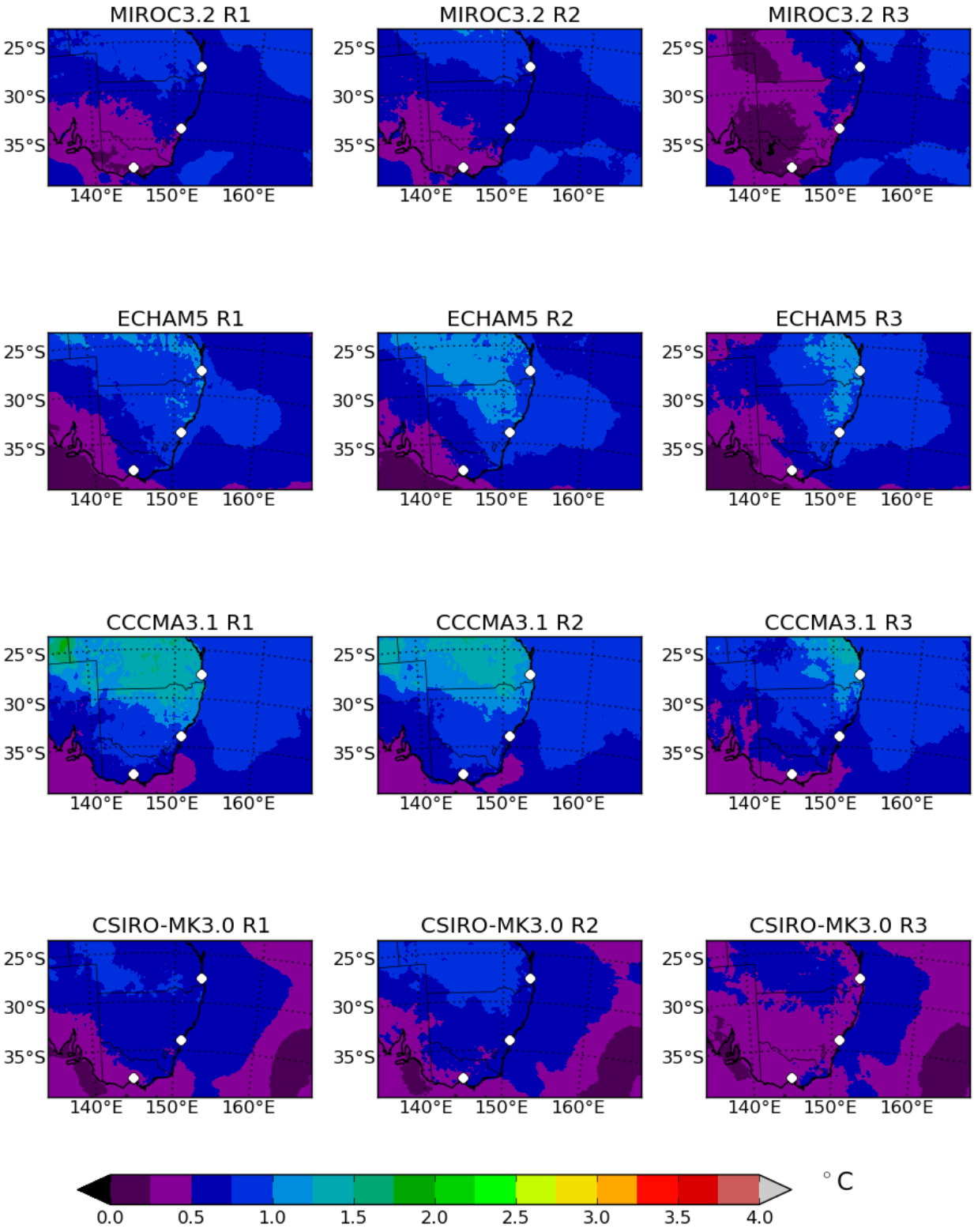

Figure 7.24: MAM mean change between years 1990-2009 and 2020-2039 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

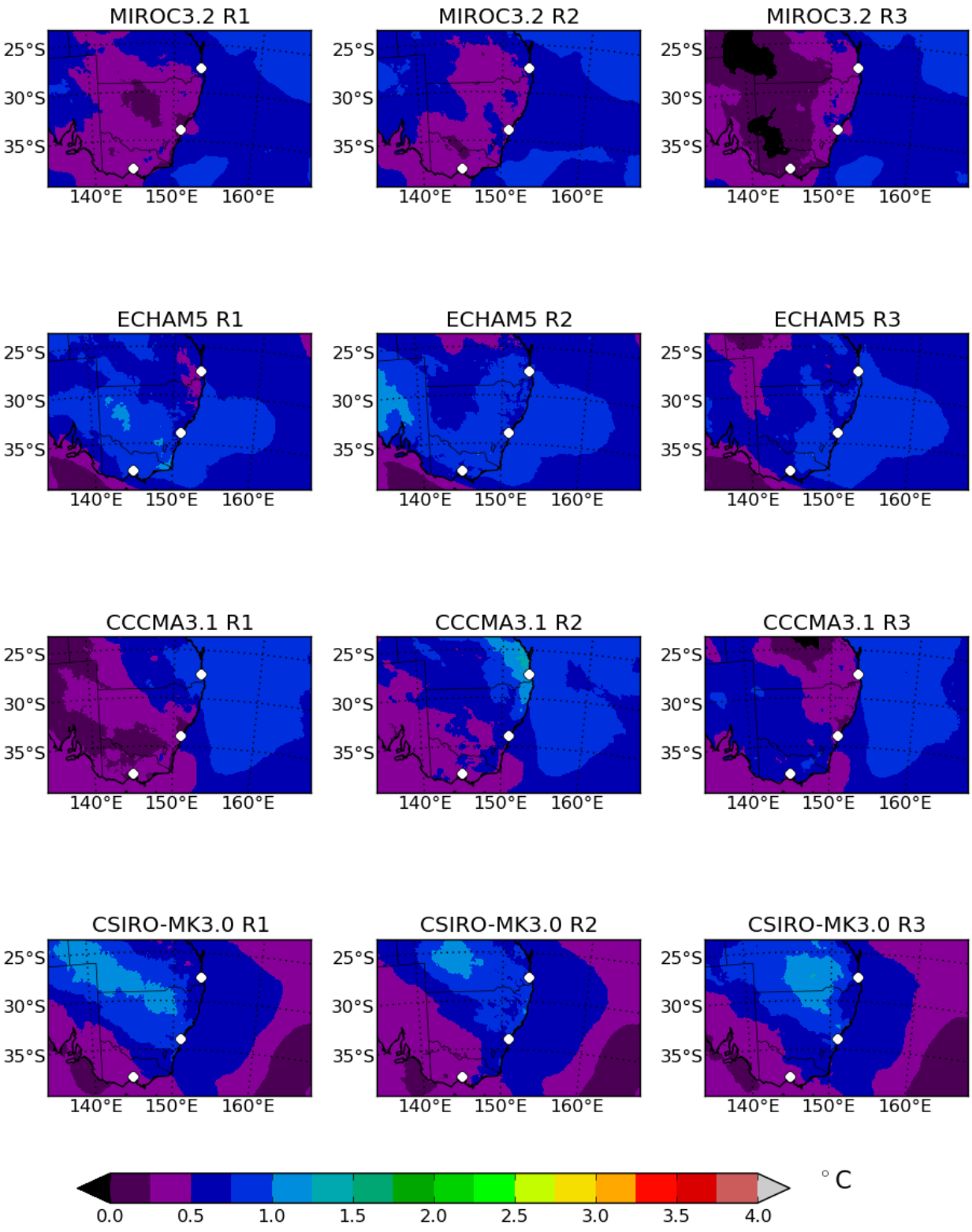

Figure 7.25: MAM mean change between years 1990-2009 and 2020-2039 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

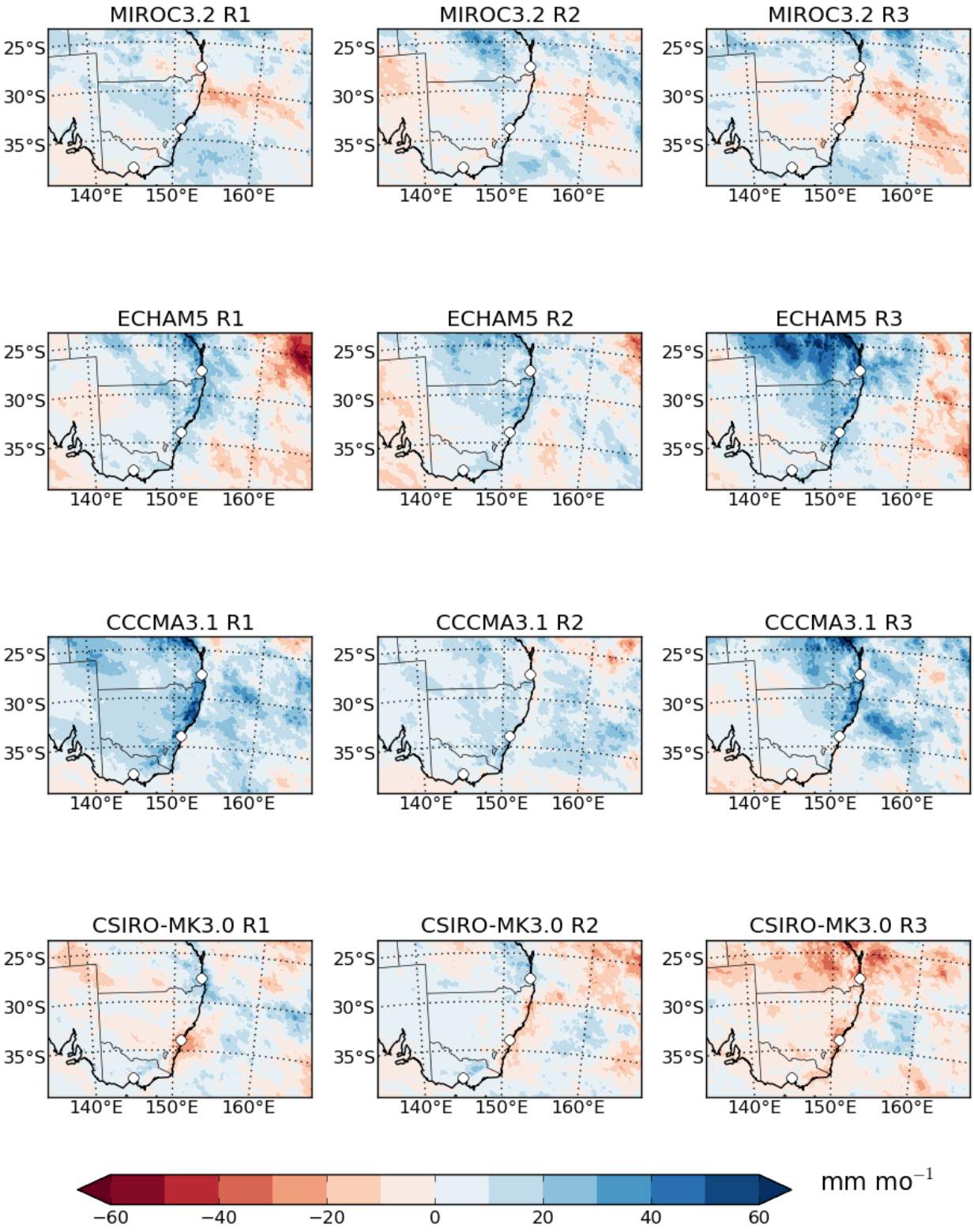

Figure 7.26: MAM mean change between years 1990-2009 and 2020-2039 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

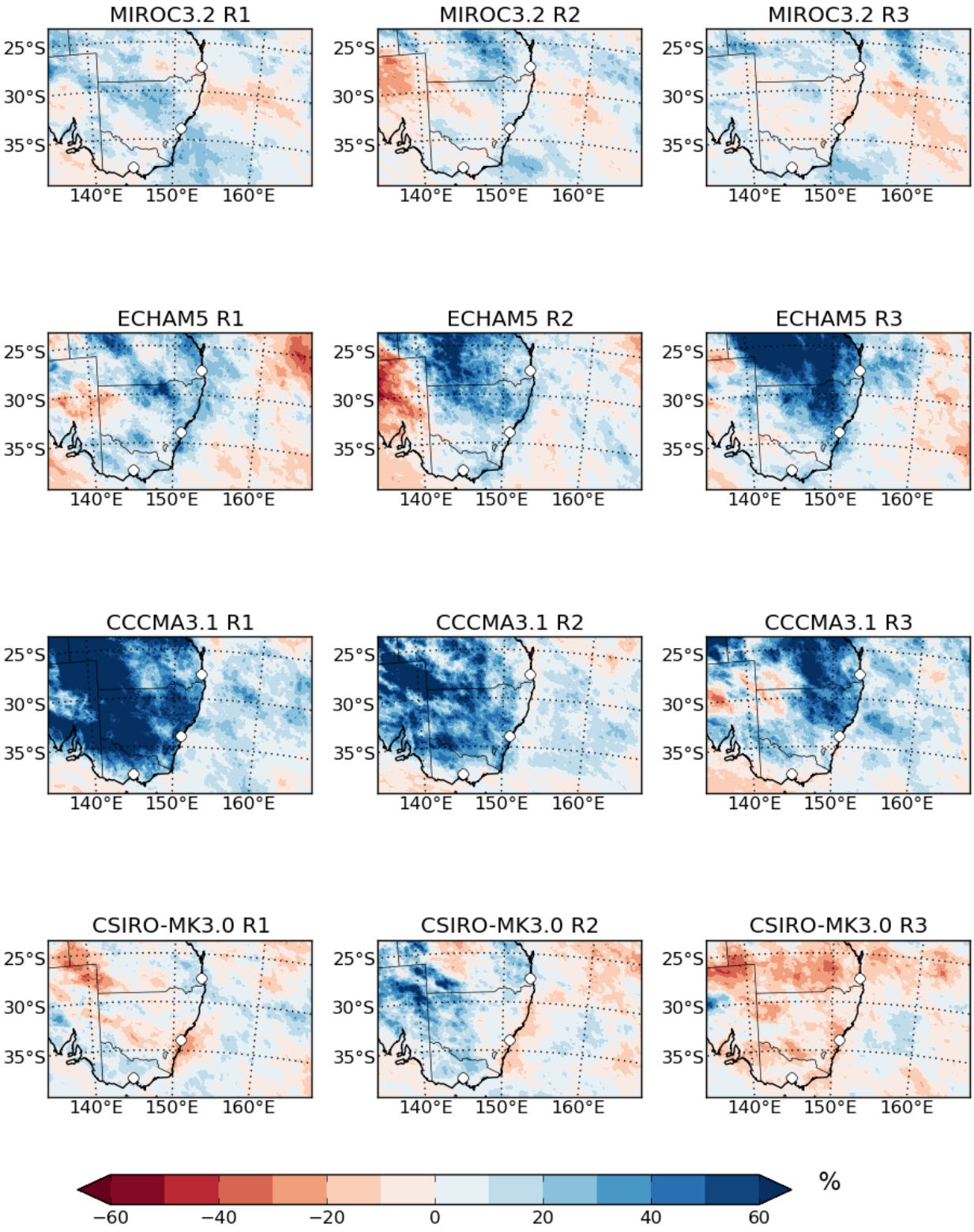

Figure 7.27: MAM mean change between years 1990-2009 and 2020-2039 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

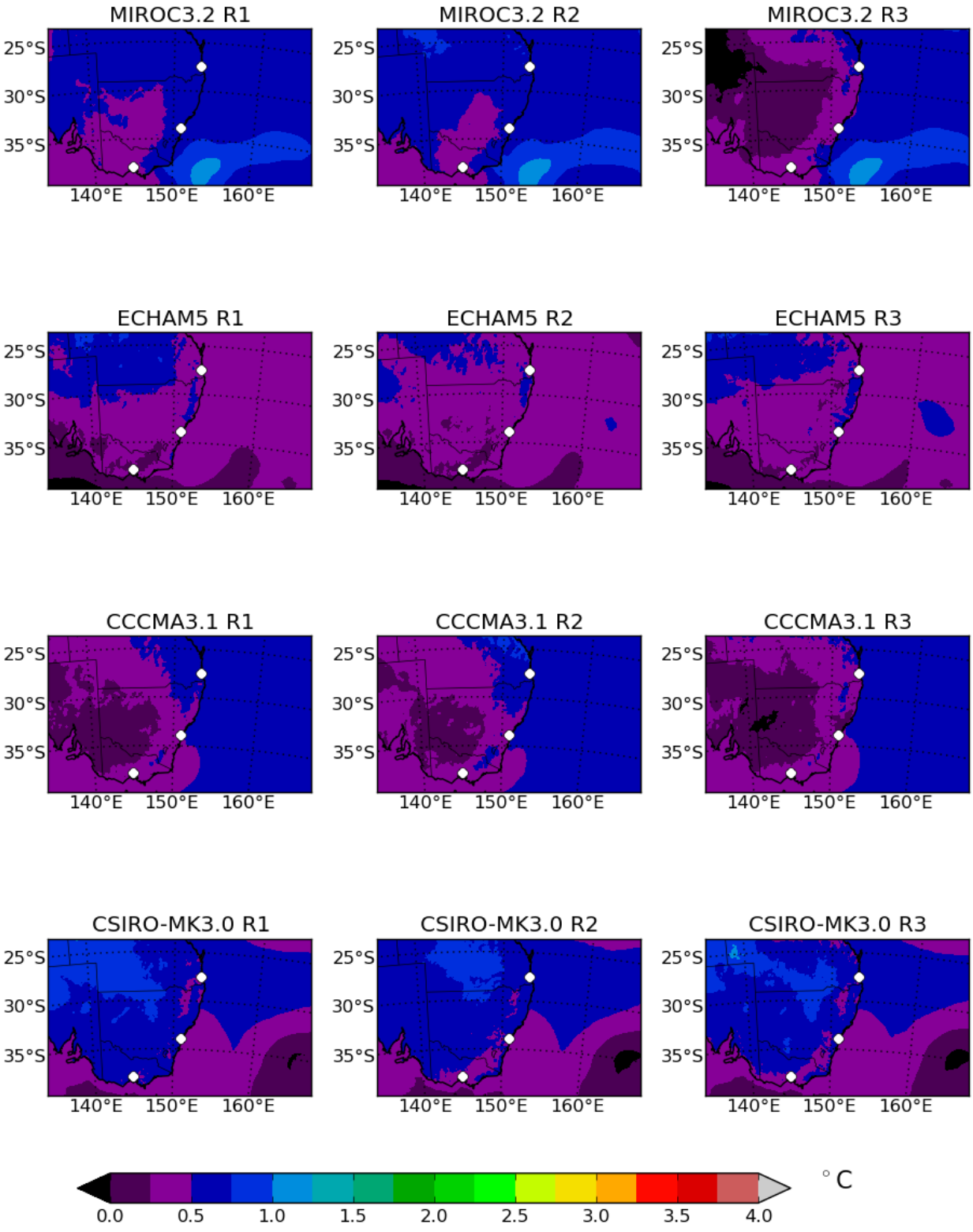

Figure 7.28: JJA mean change between years 1990-2009 and 2020-2039 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

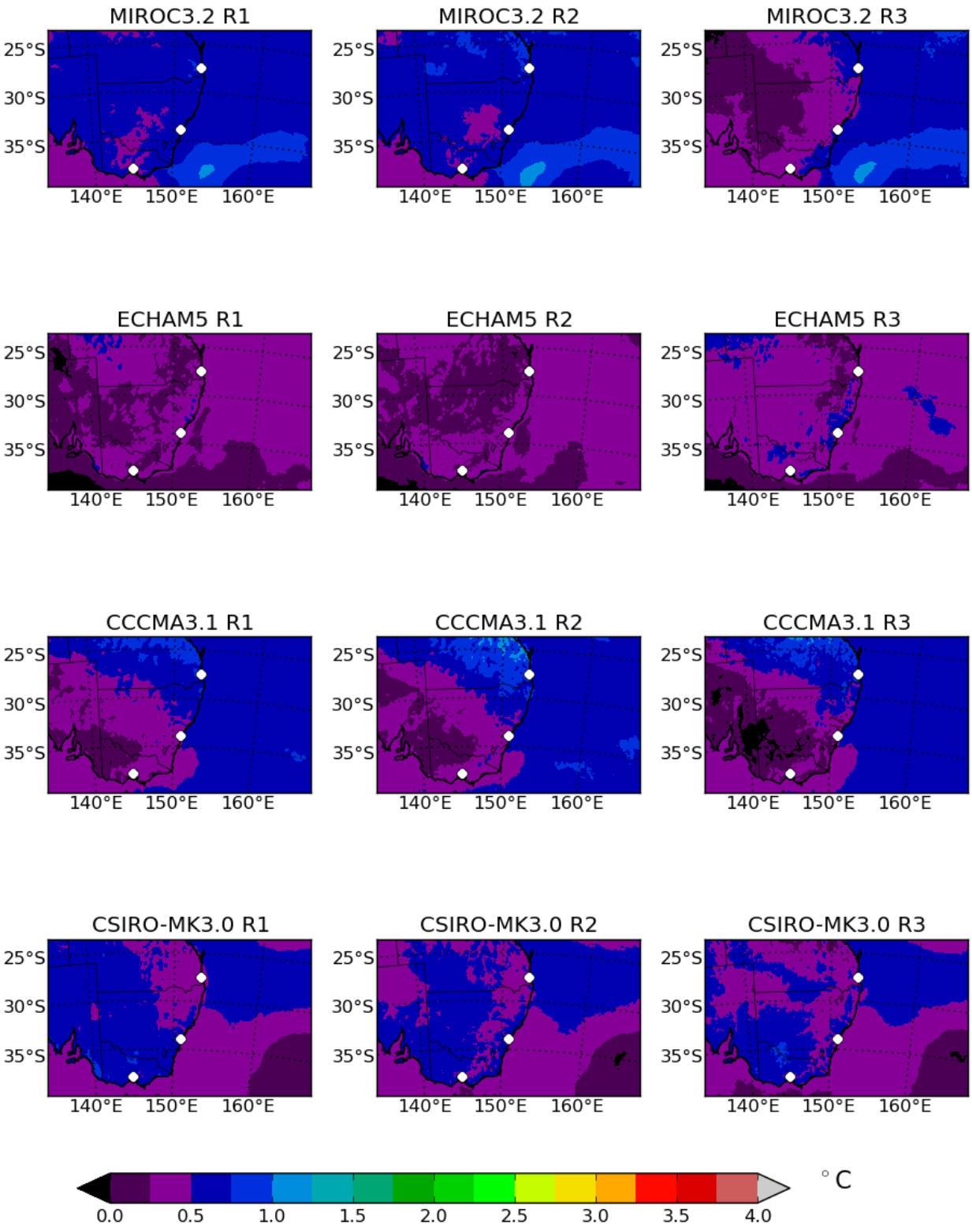

Figure 7.29: JJA mean change between years 1990-2009 and 2020-2039 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

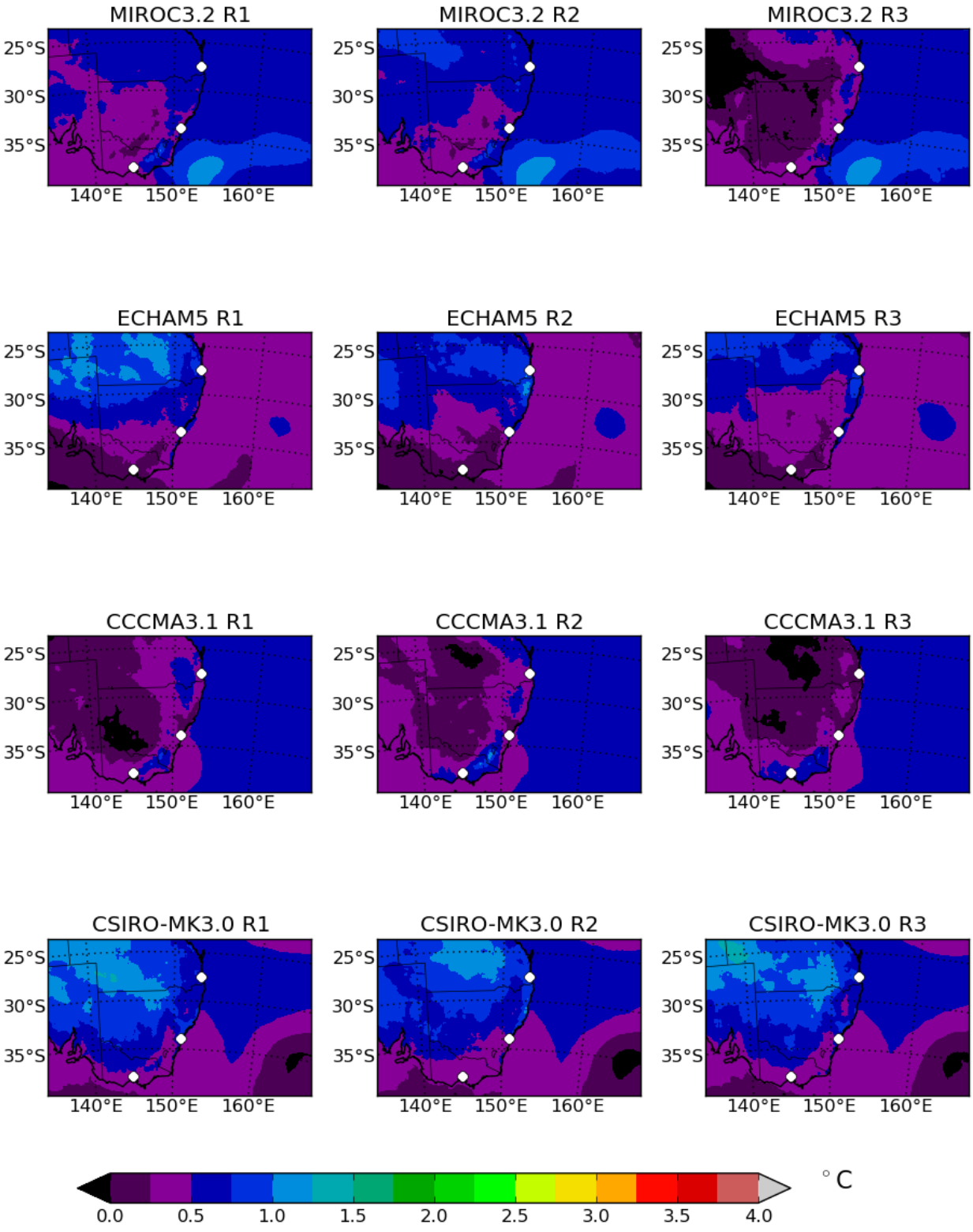

Figure 7.30: JJA mean change between years 1990-2009 and 2020-2039 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

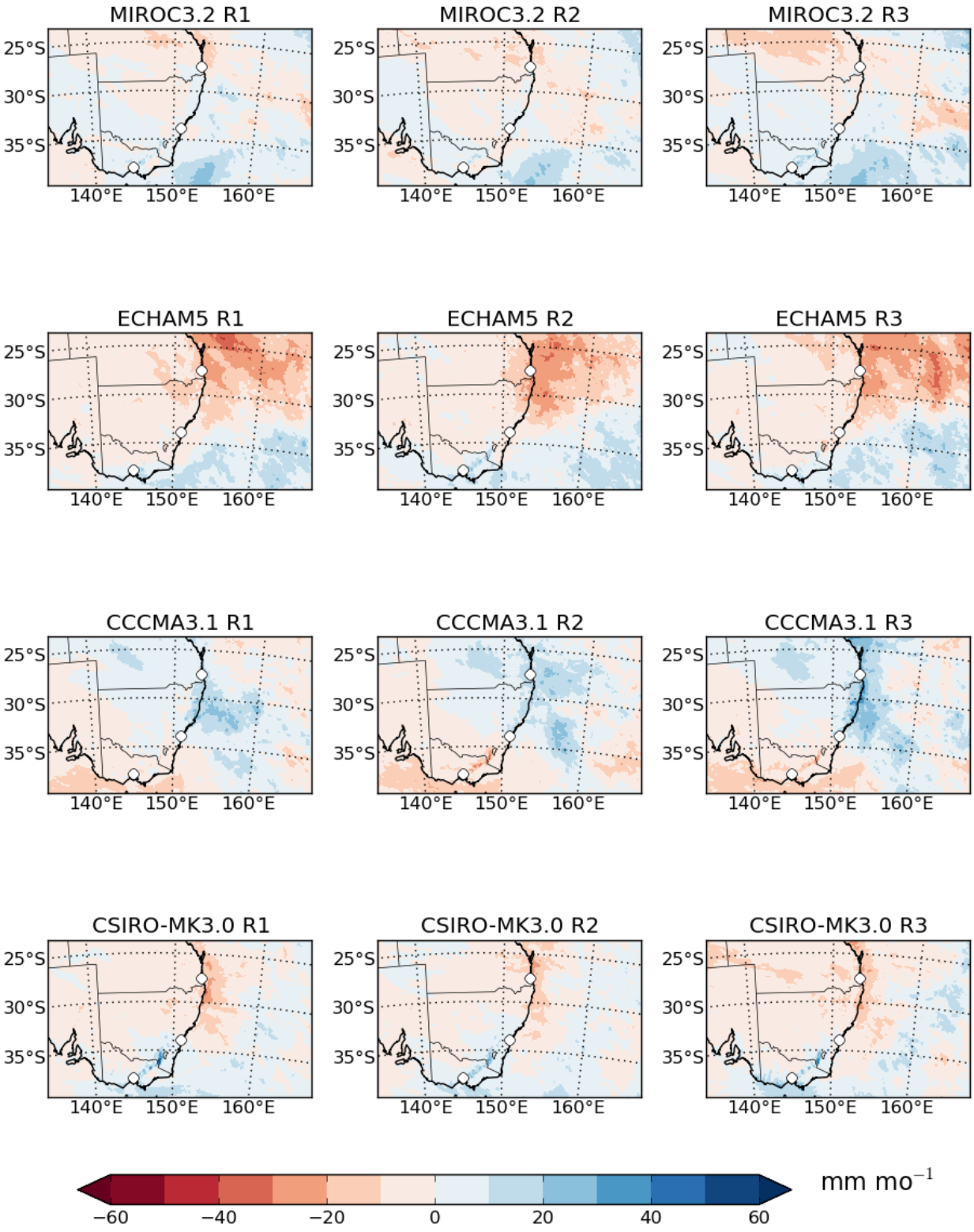

Figure 7.31: JJA mean change between years 1990-2009 and 2020-2039 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

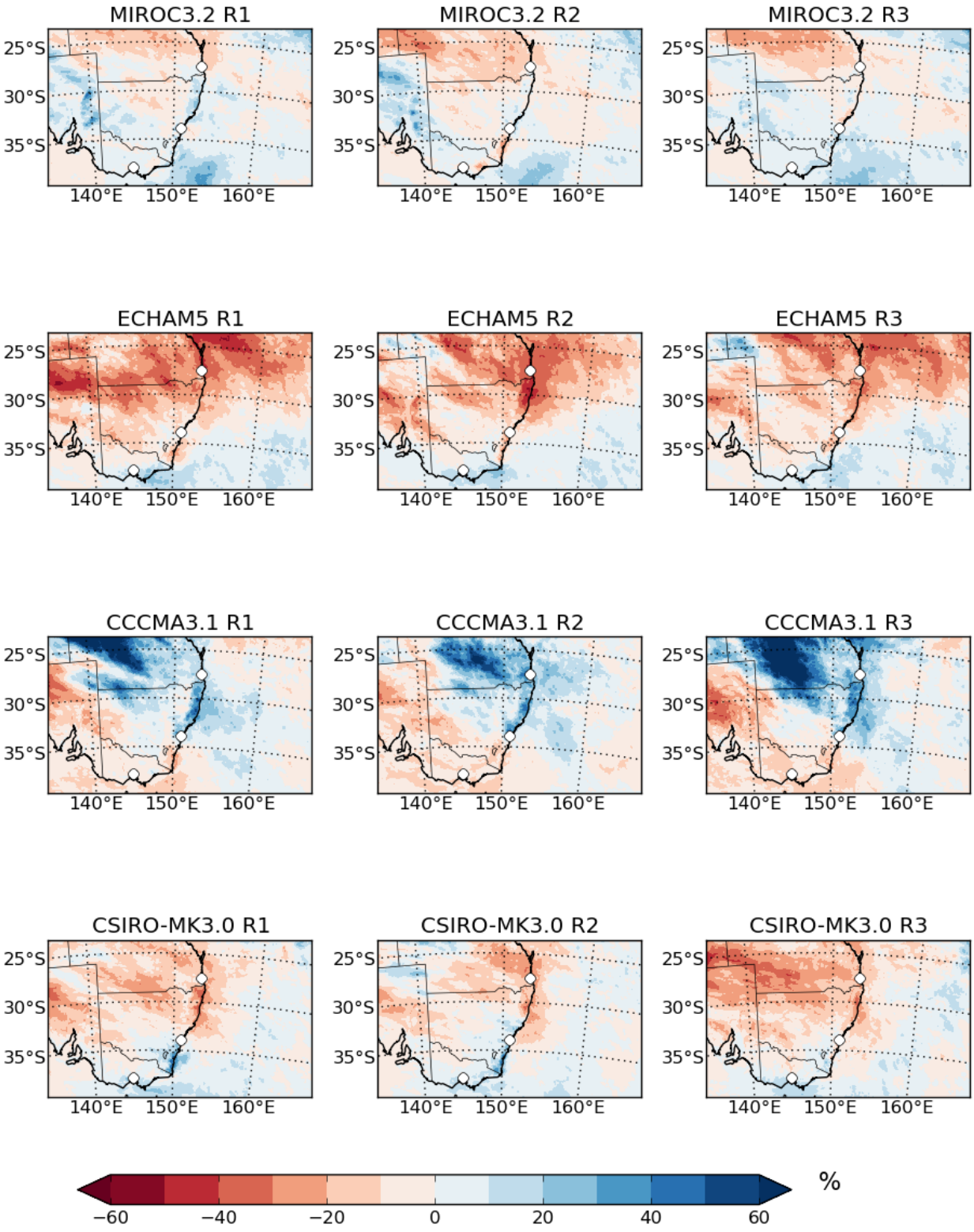

Figure 7.32: JJA mean change between years 1990-2009 and 2020-2039 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

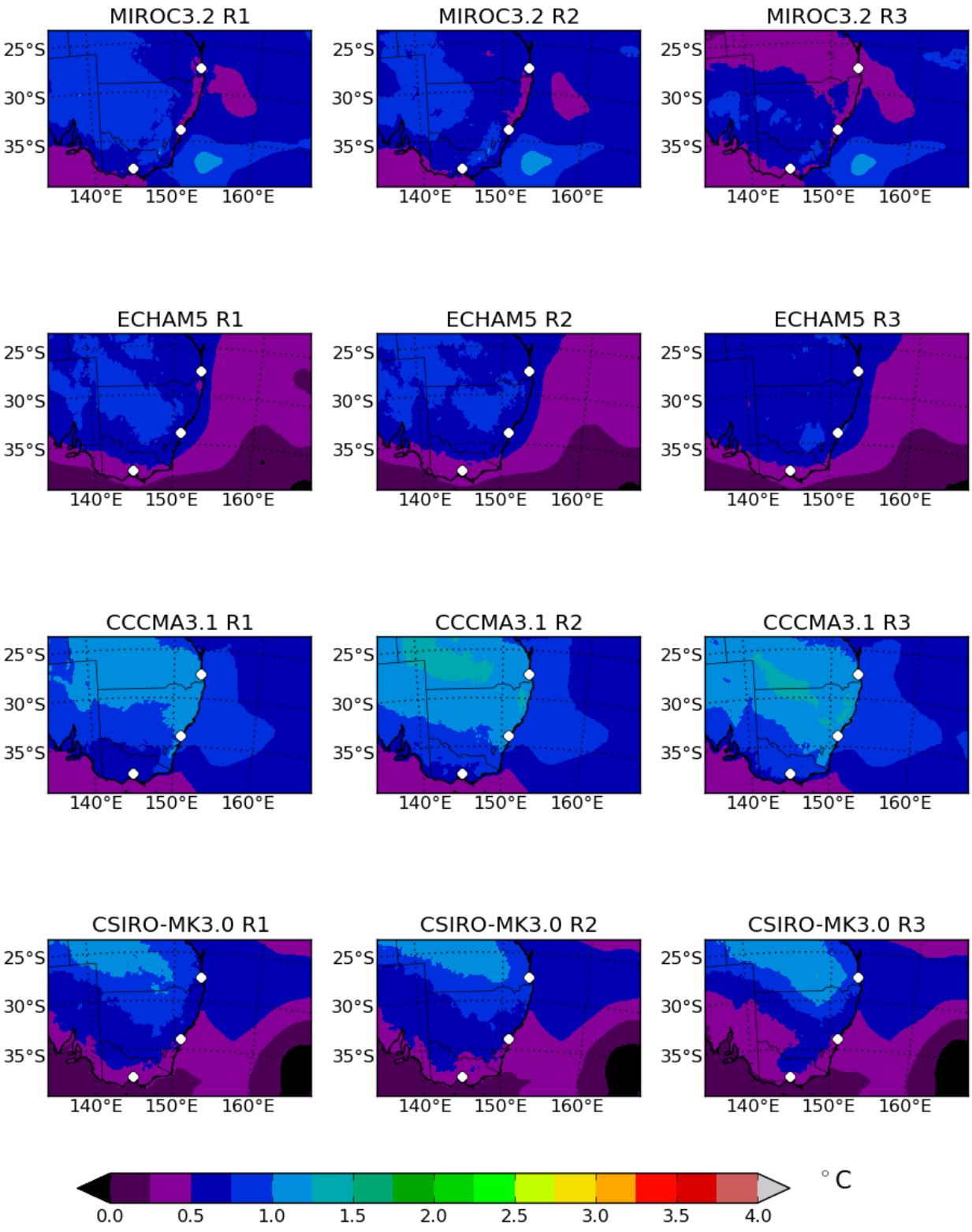

Figure 7.33: SON mean change between years 1990-2009 and 2020-2039 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

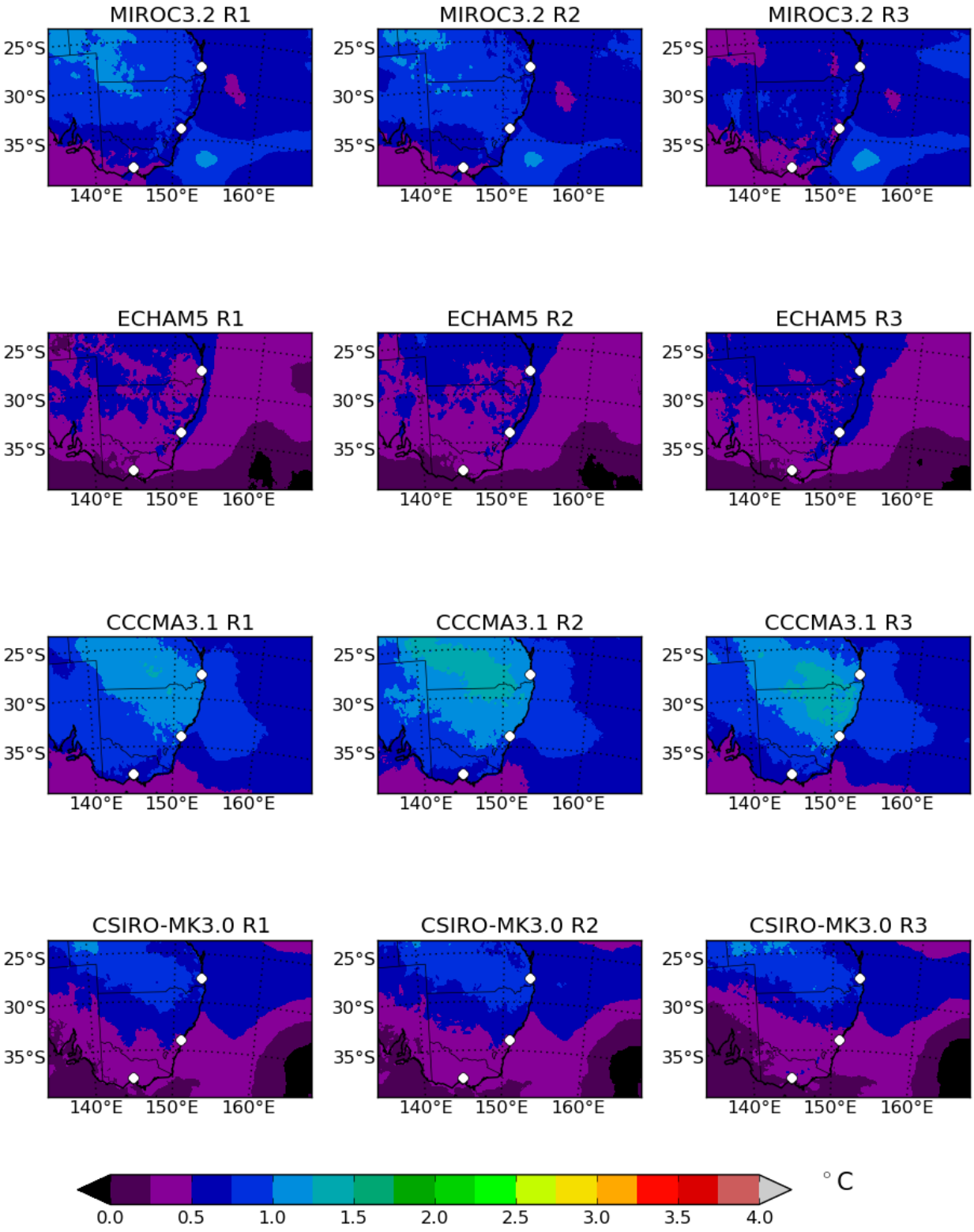

Figure 7.34: SON mean change between years 1990-2009 and 2020-2039 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

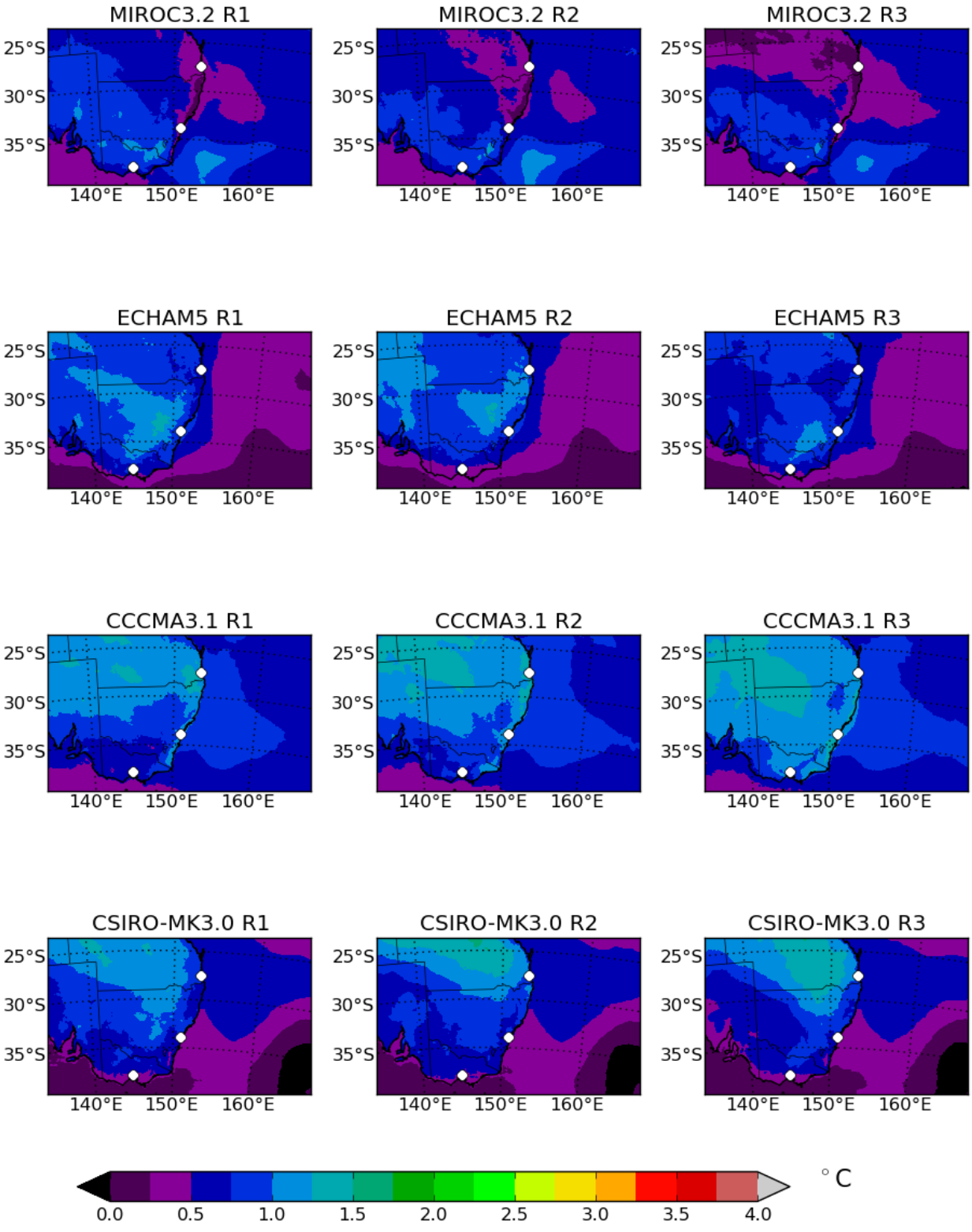

Figure 7.35: SON mean change between years 1990-2009 and 2020-2039 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

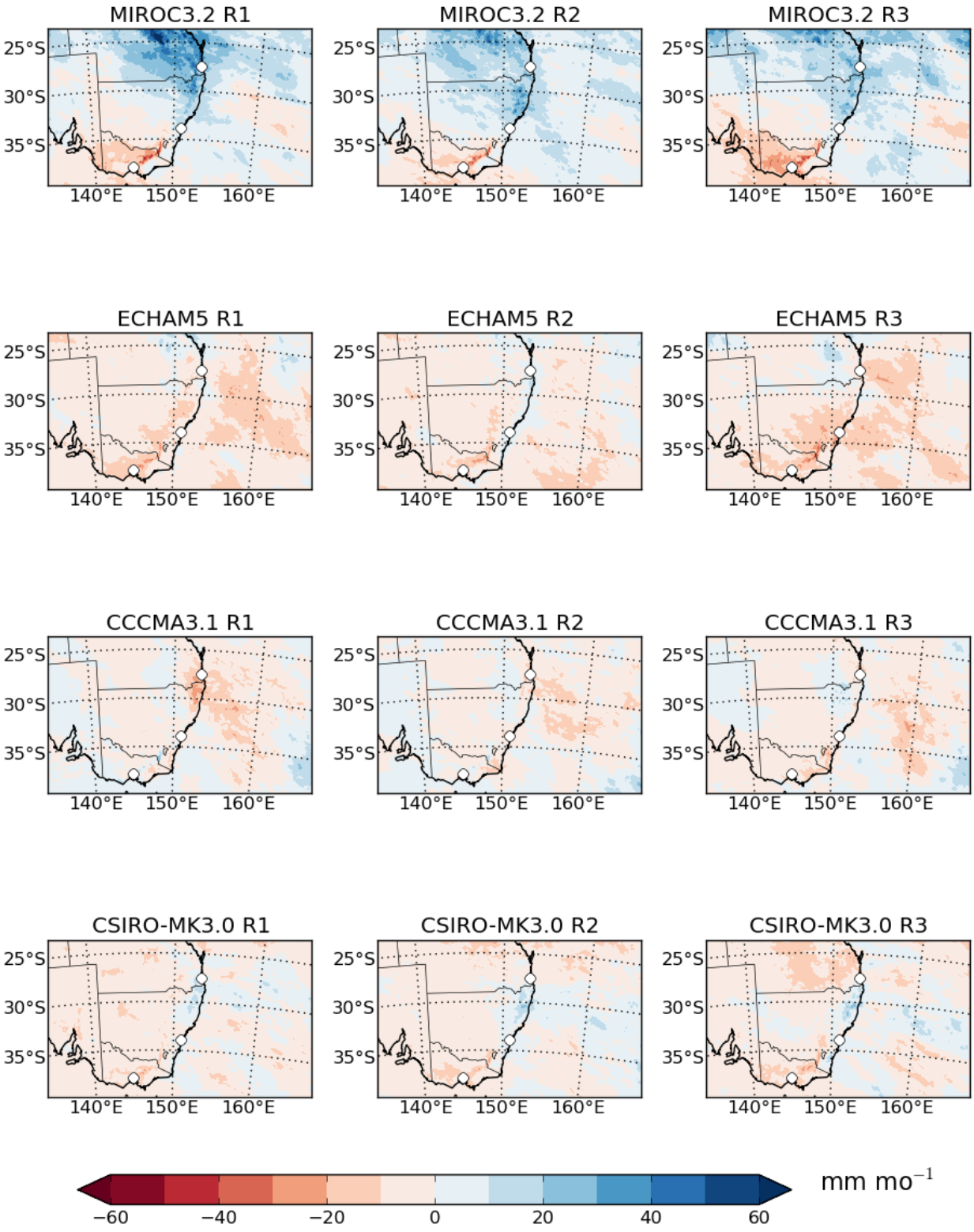

Figure 7.36: SON mean change between years 1990-2009 and 2020-2039 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

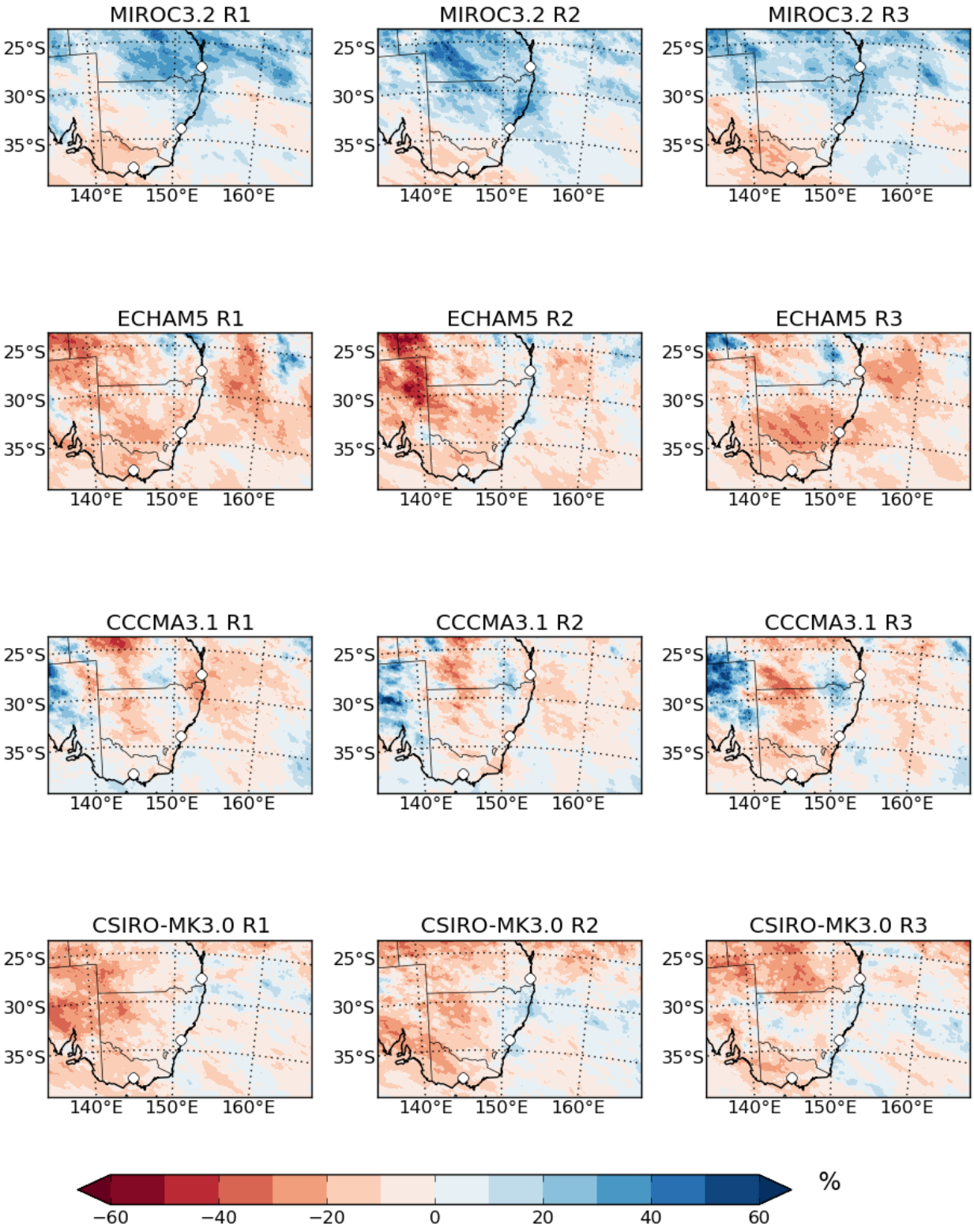

Figure 7.37: SON mean change between years 1990-2009 and 2020-2039 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

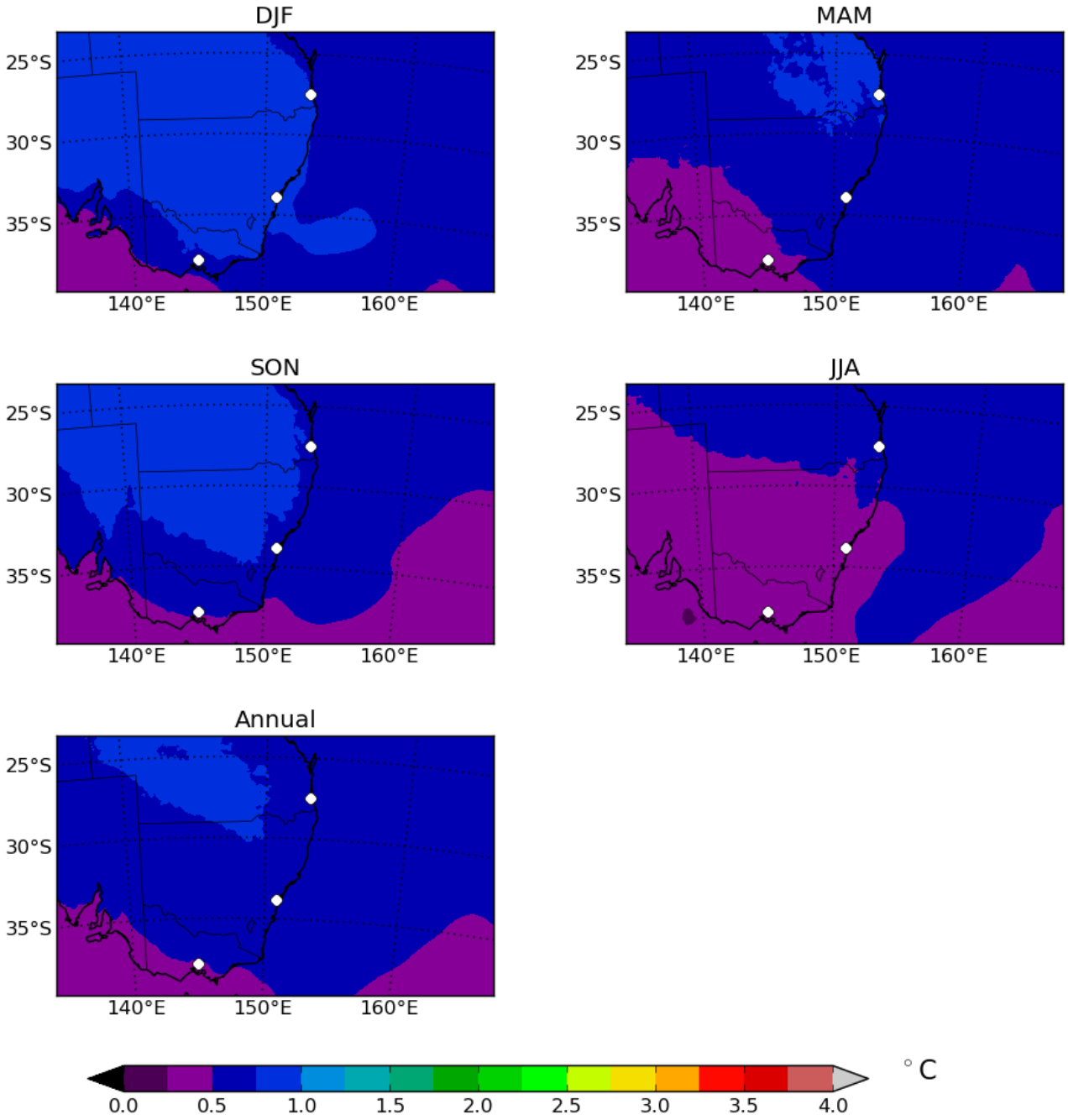

Figure 7.38: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

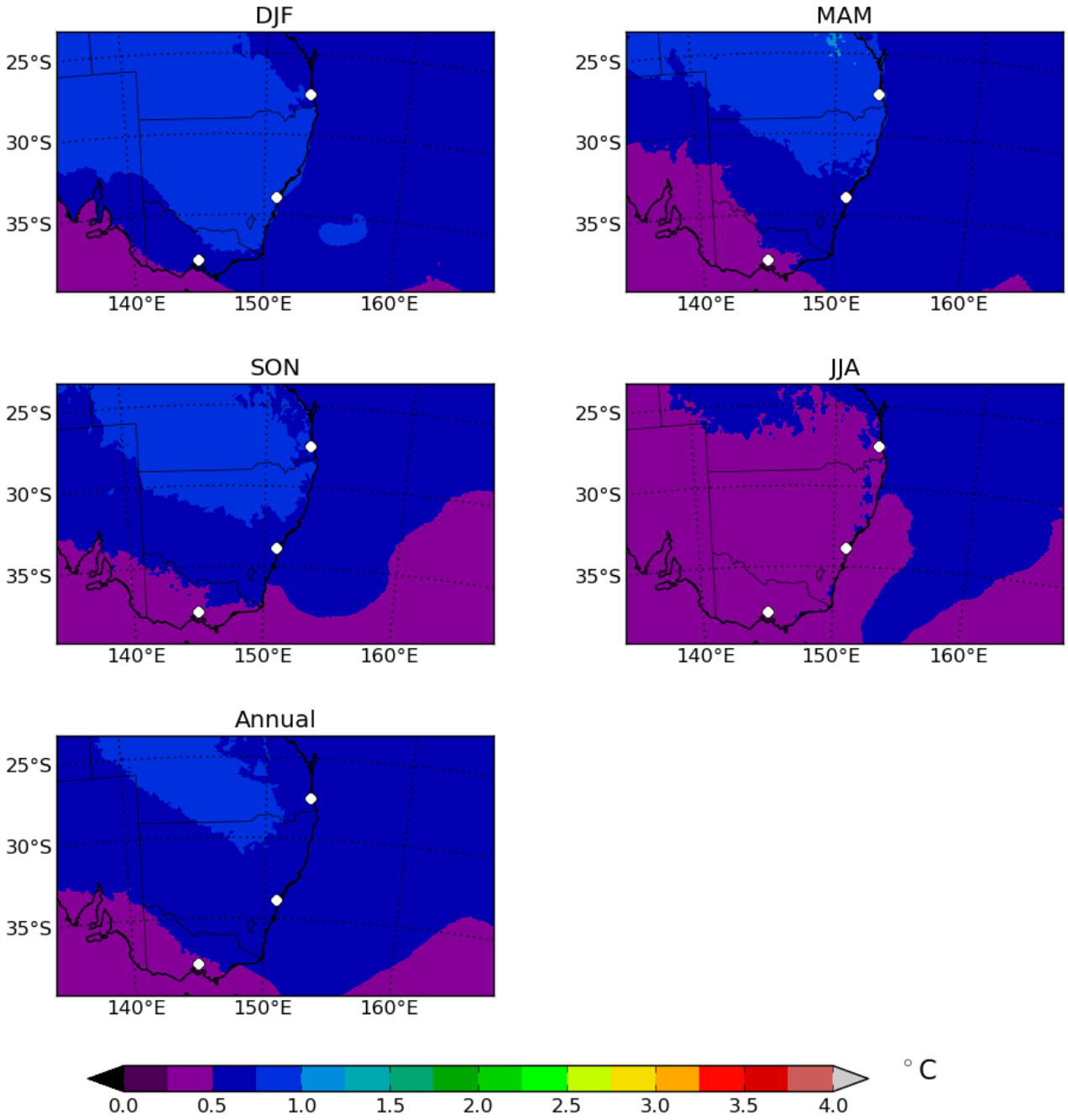

Figure 7.39: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

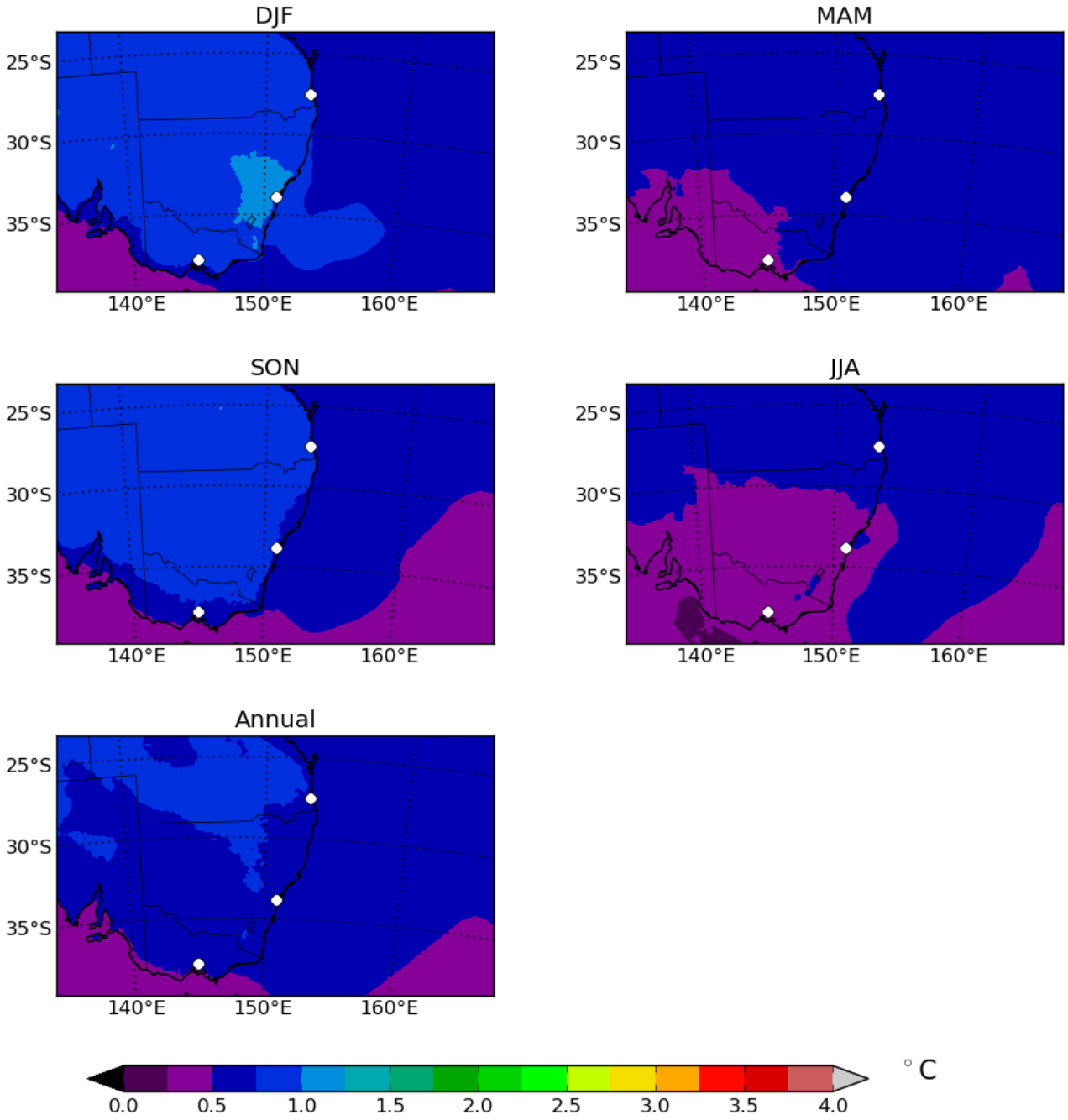

Figure 7.40: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

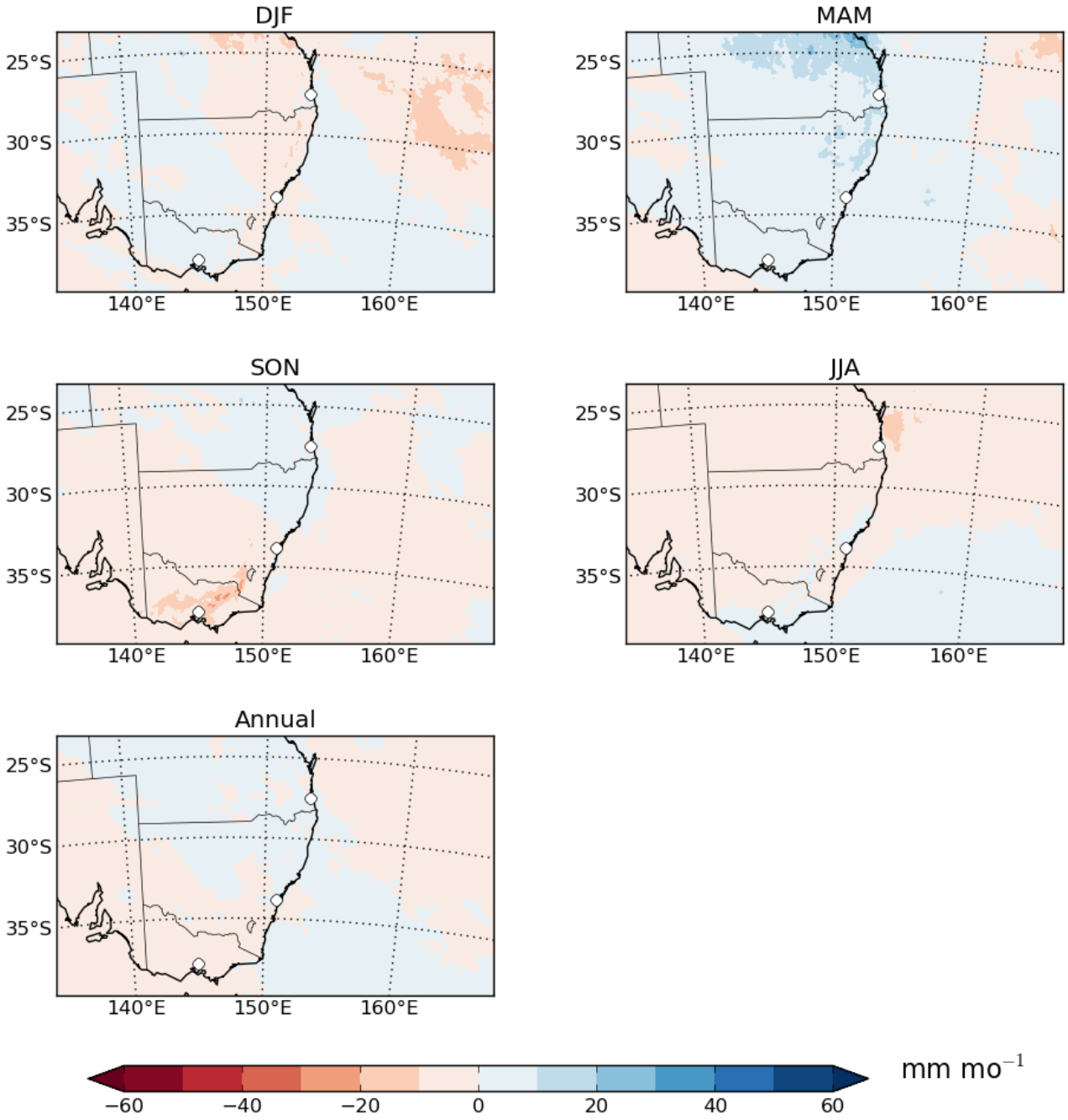

Figure 7.41: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

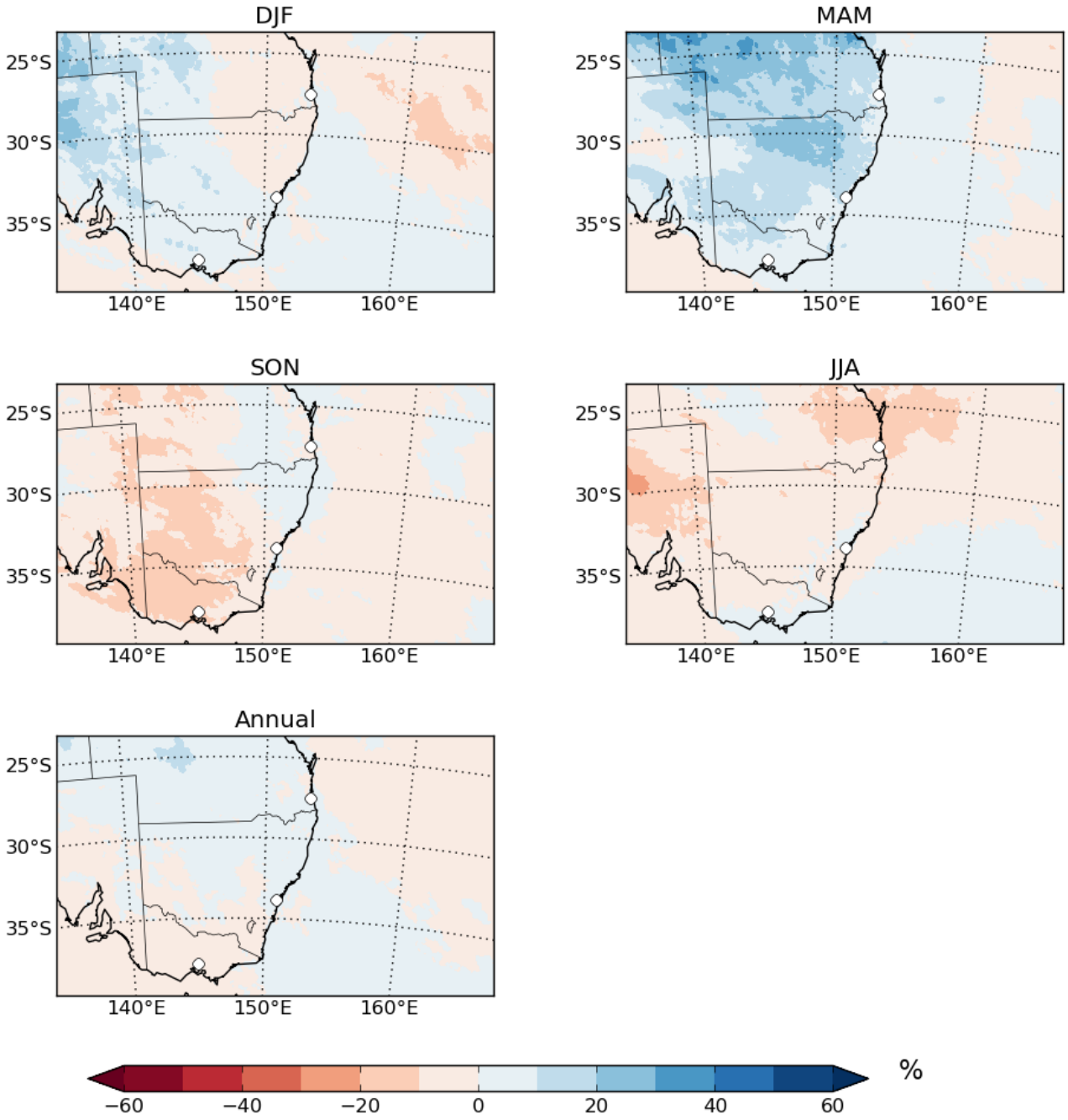

Figure 7.42: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

7.3 Bias-Corrected Regional Model Output: Changes from 1990-2009 to 2020-2039

This subsection contains projected seasonal and annual mean near-future changes in daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the bias-corrected RCM output (*i.e.* RCM output that has been corrected for the present-day biases between the models and the observations of climate using the methods described here [6]). The corrections are calculated by comparing present-day distributions of daily model output and observations for all seasons. Thus, the corrections are independent of the season. Precipitation changes are plotted as both absolute values (in mm mo^{-1}), and percent changes. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected changes, whereas the individual-model plots show the level of uncertainty in projected changes.

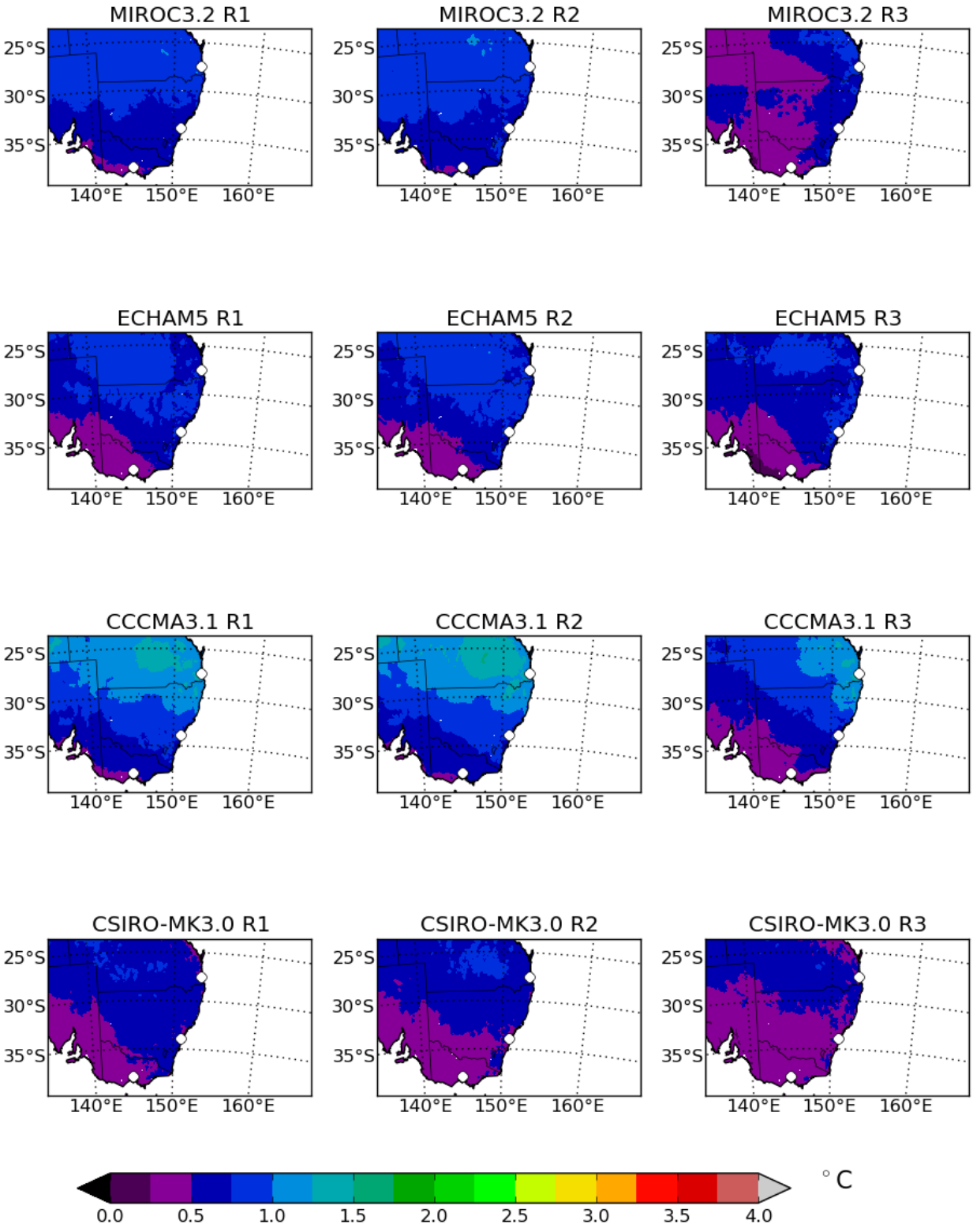

Figure 7.43: Annual mean change between years 1990-2009 and 2020-2039 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

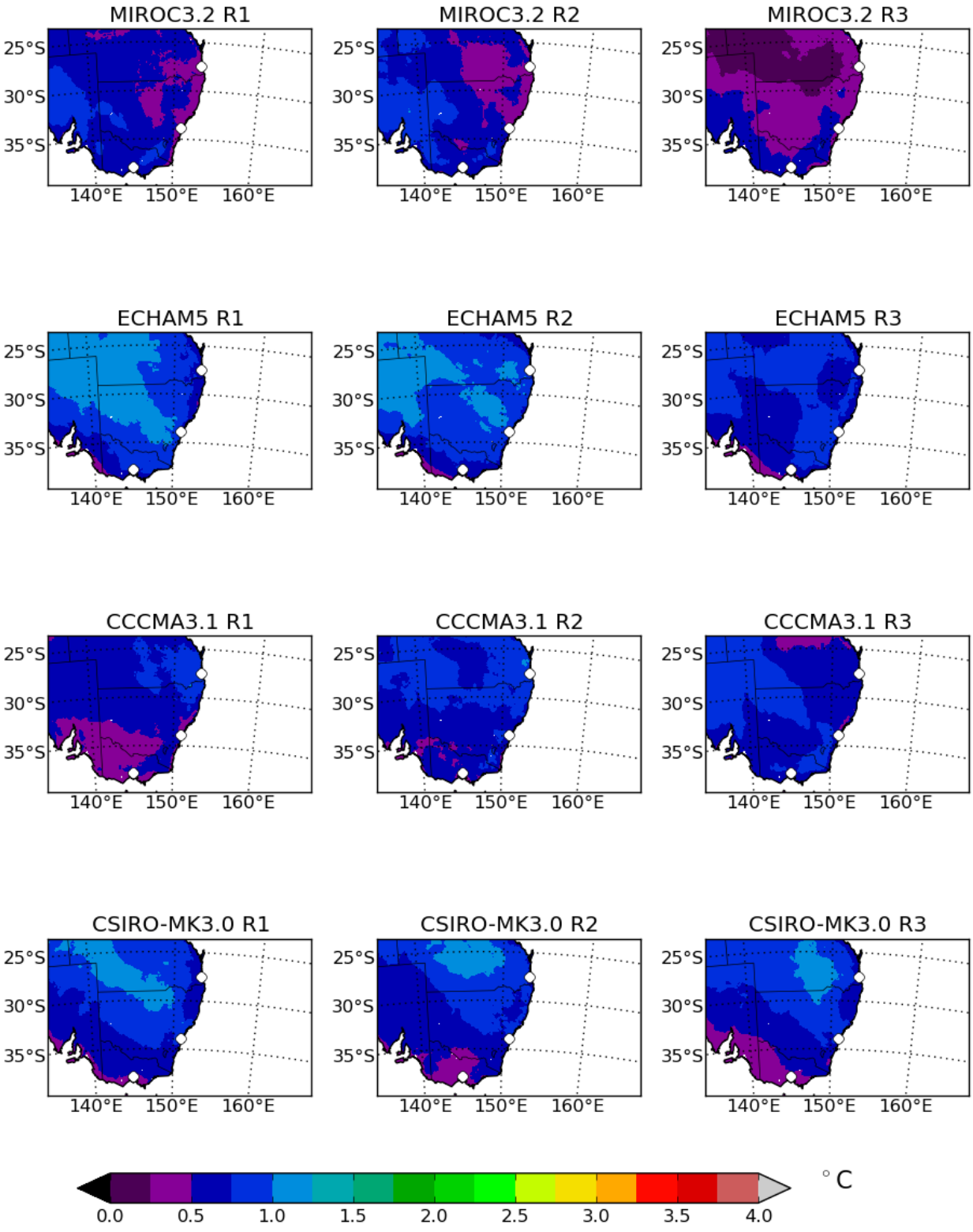

Figure 7.44: Annual mean change between years 1990-2009 and 2020-2039 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

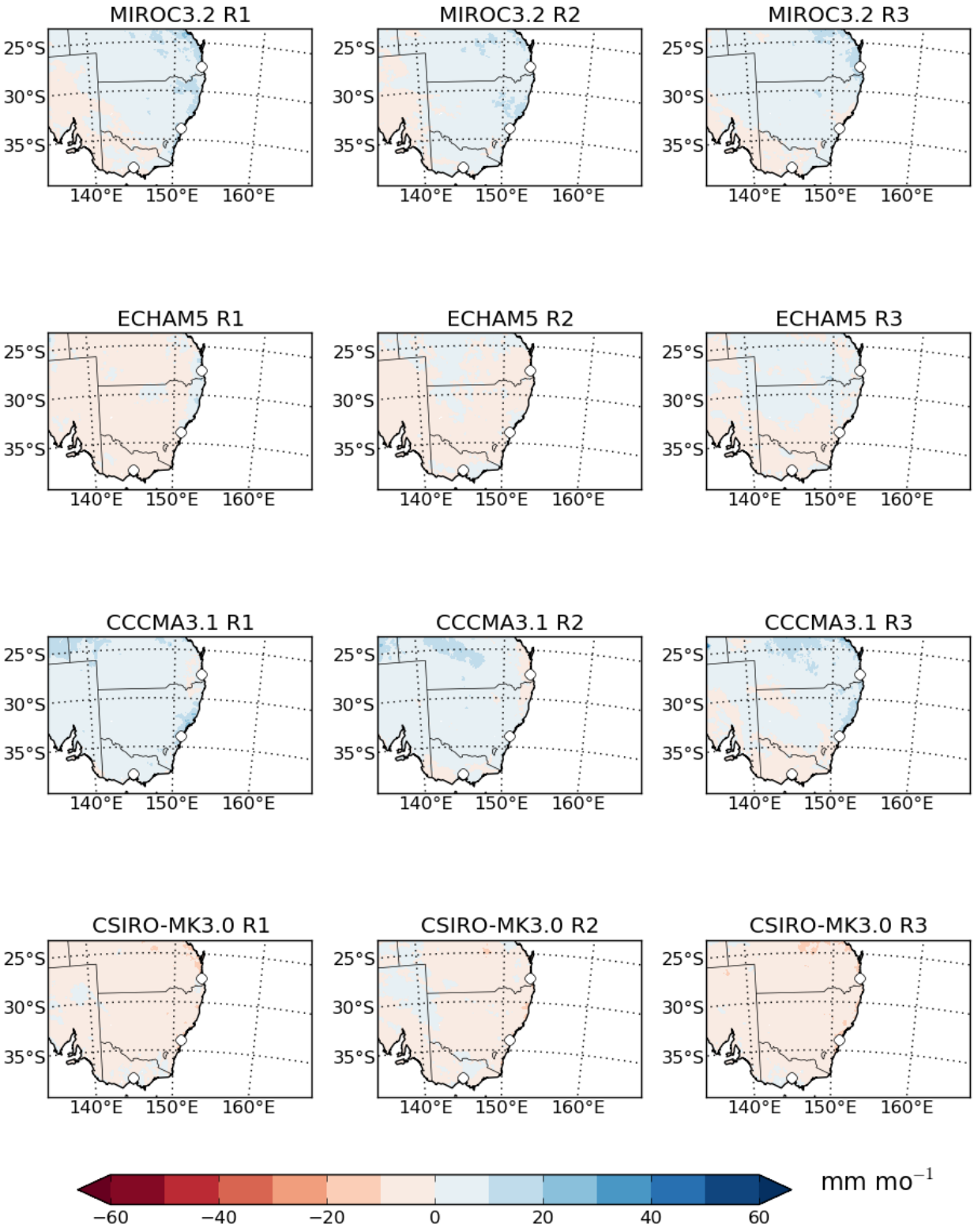

Figure 7.45: Annual mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

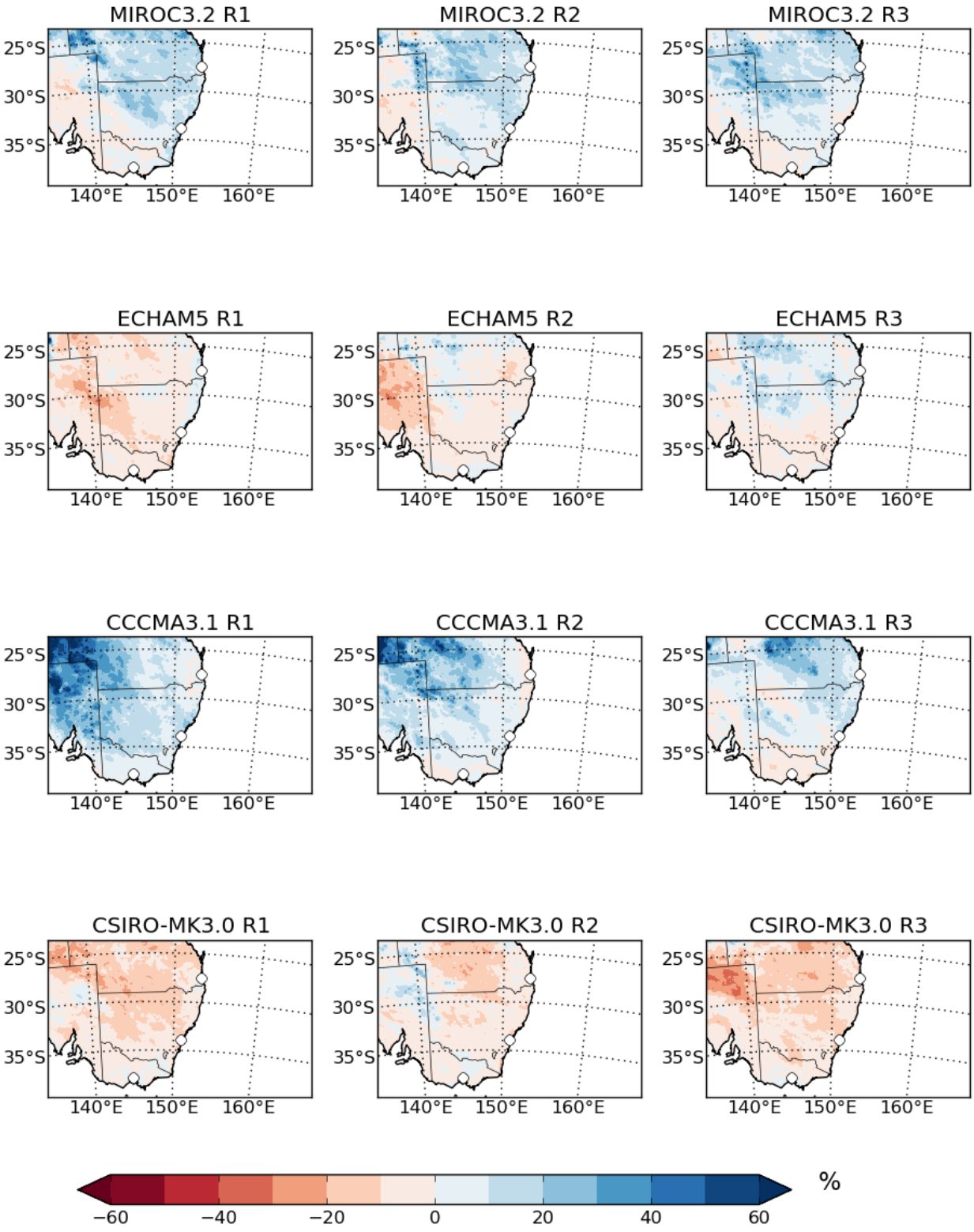

Figure 7.46: Annual mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

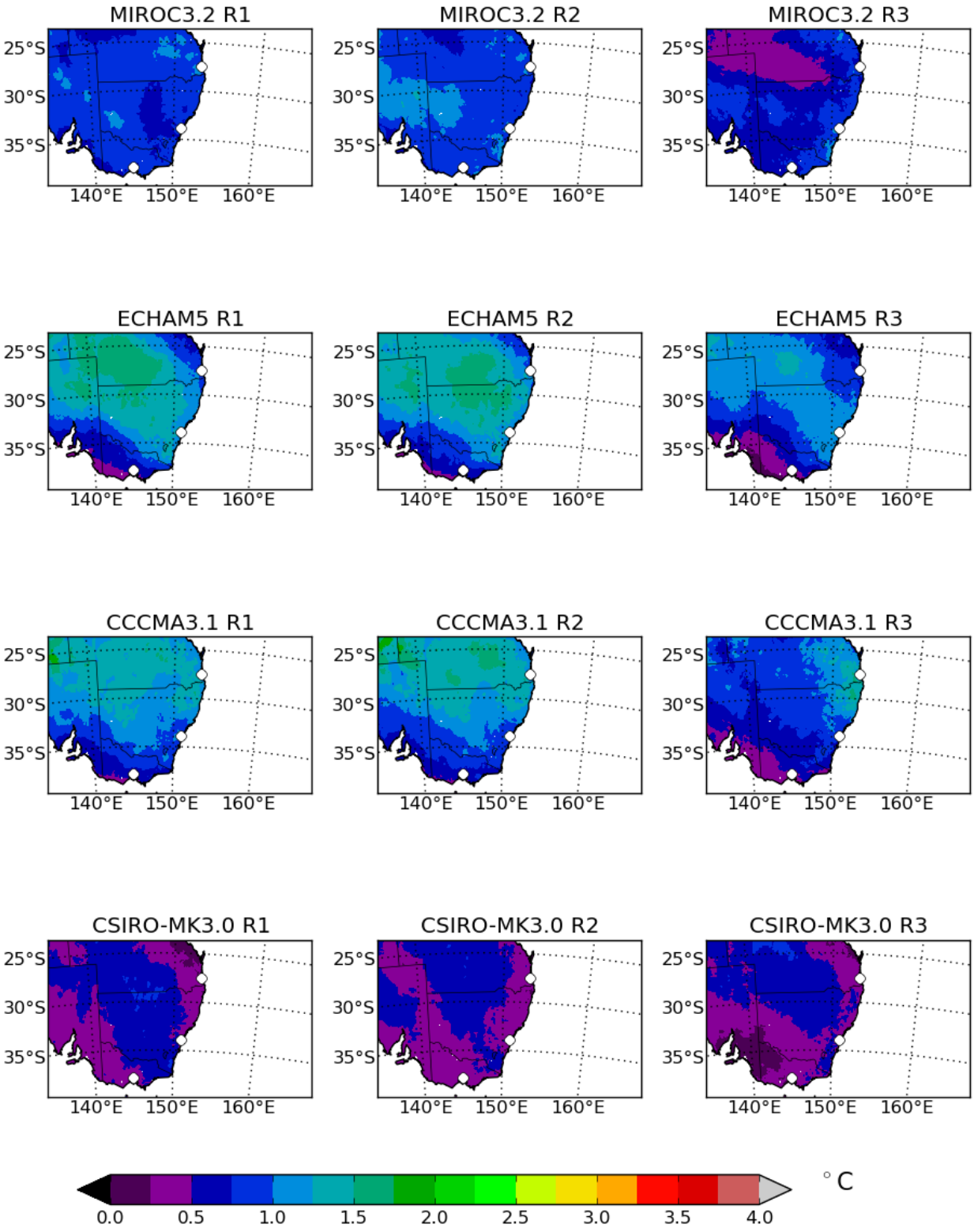

Figure 7.47: DJF mean change between years 1990-2009 and 2020-2039 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

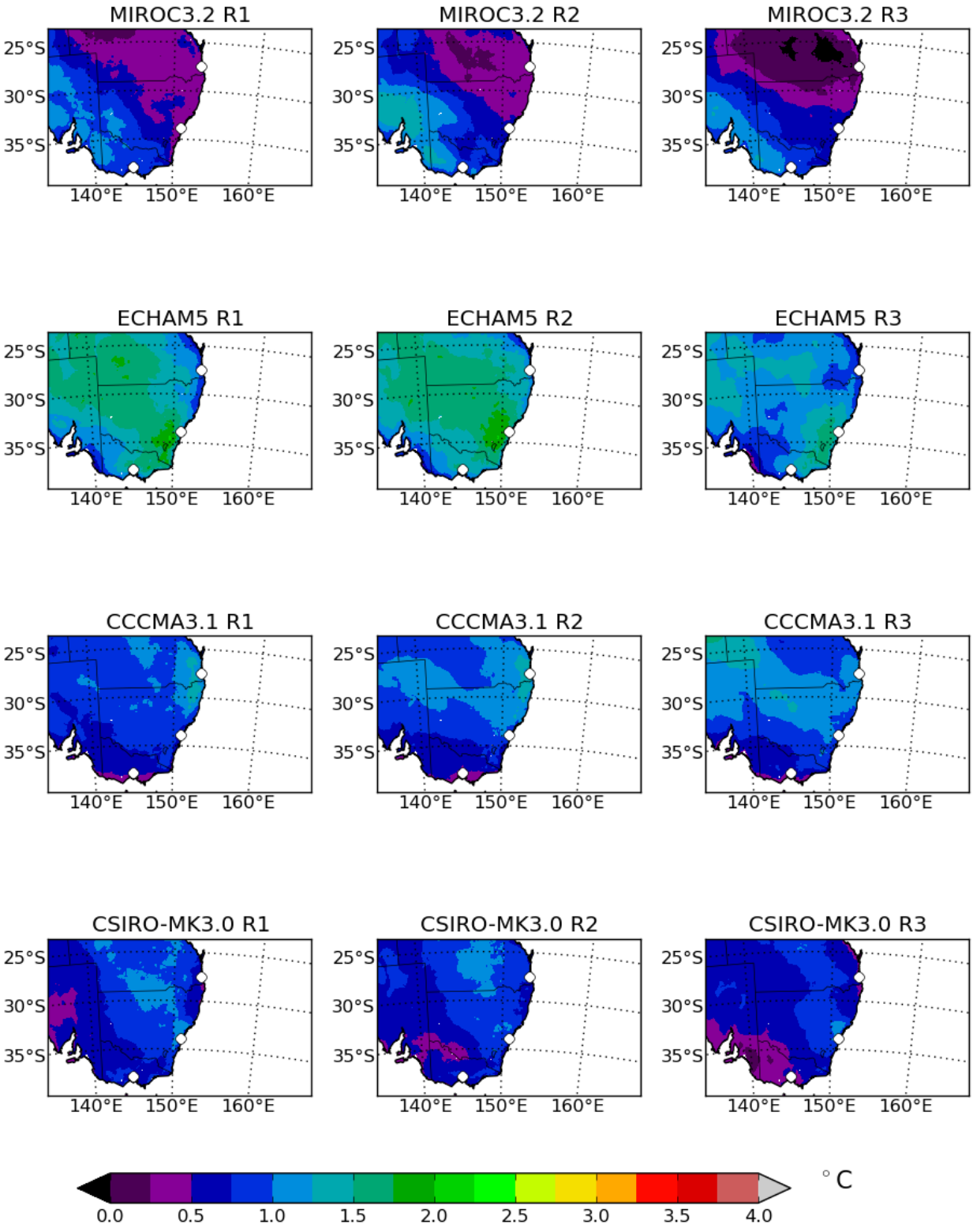

Figure 7.48: DJF mean change between years 1990-2009 and 2020-2039 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

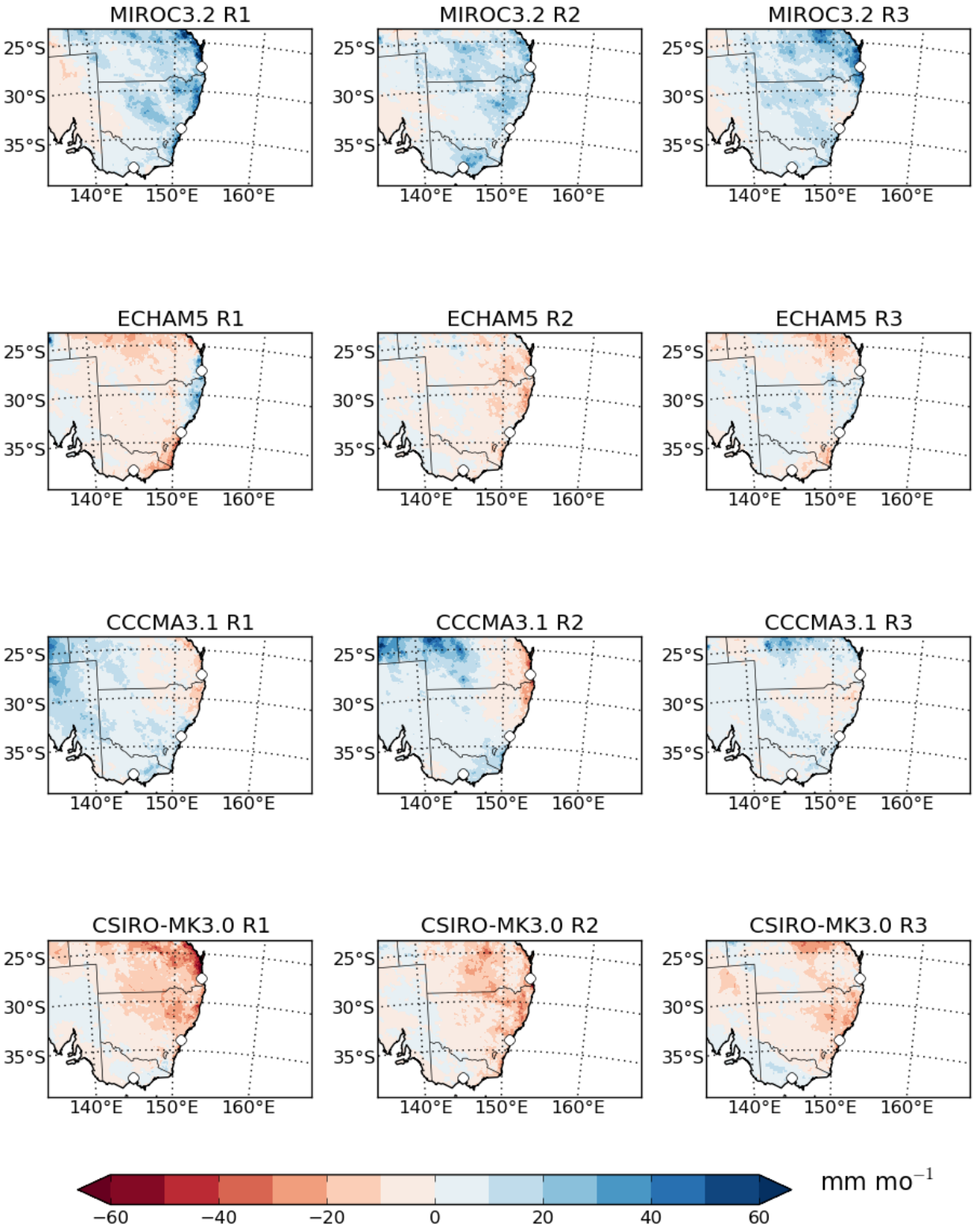

Figure 7.49: DJF mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

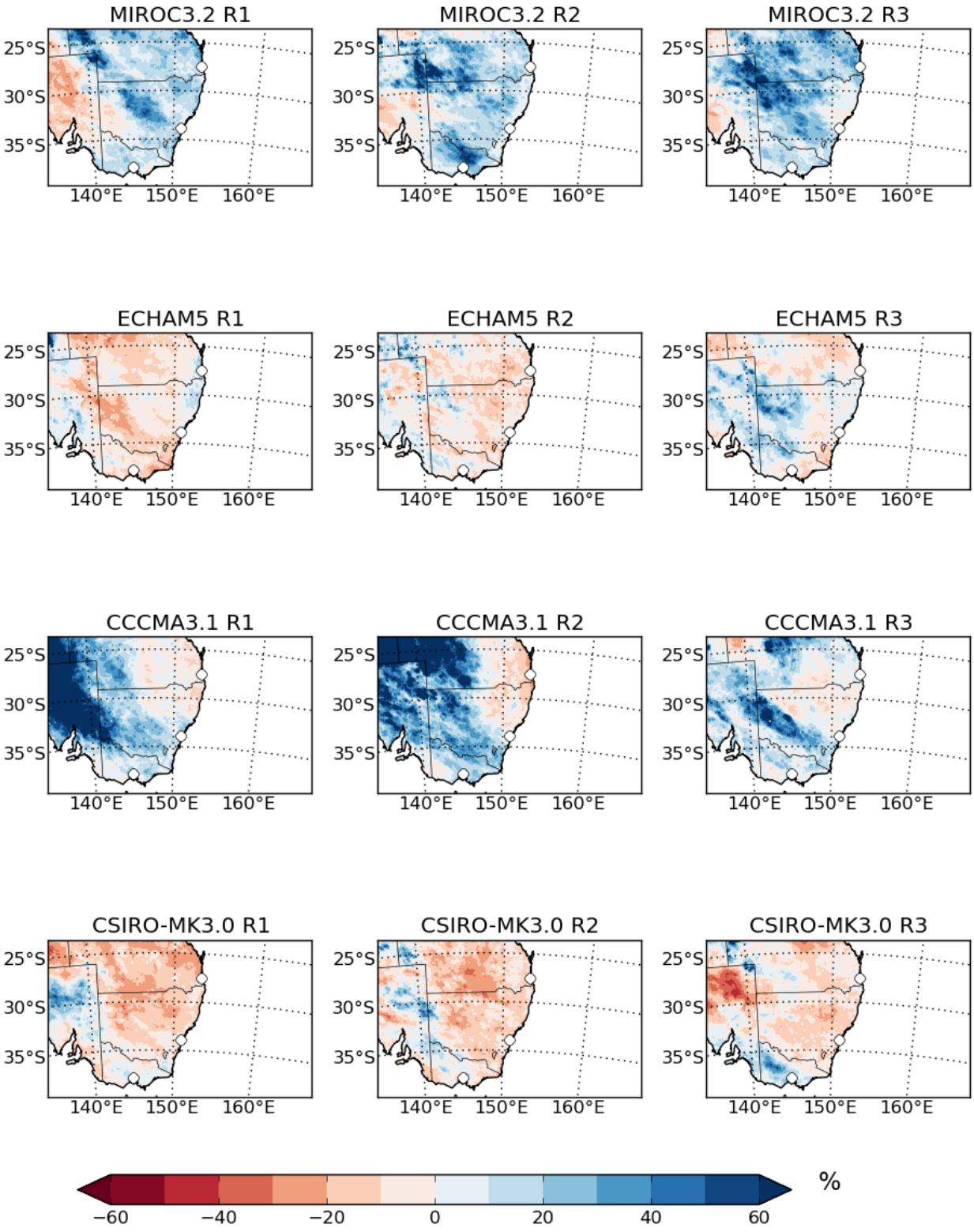

Figure 7.50: DJF mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

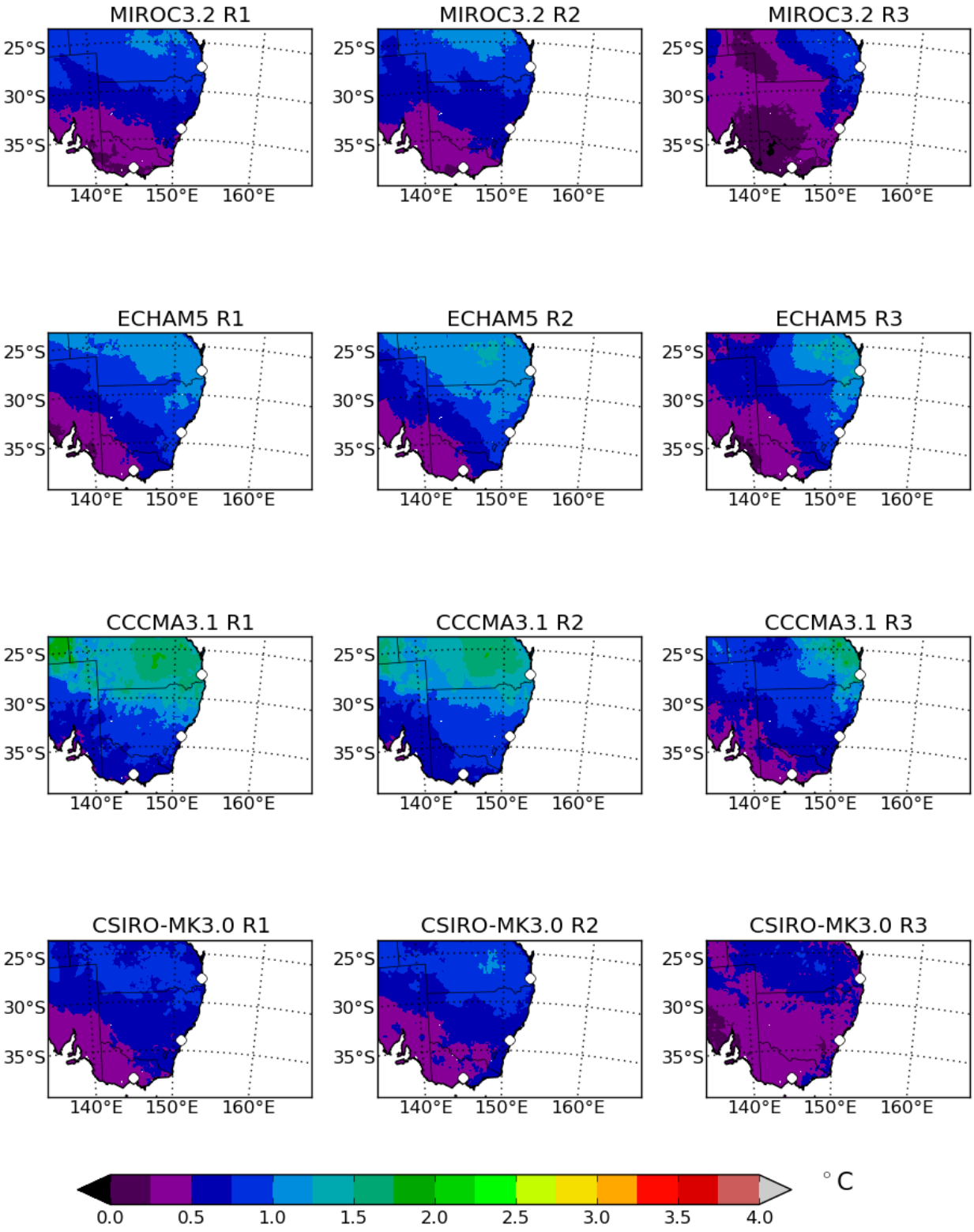

Figure 7.51: MAM mean change between years 1990-2009 and 2020-2039 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

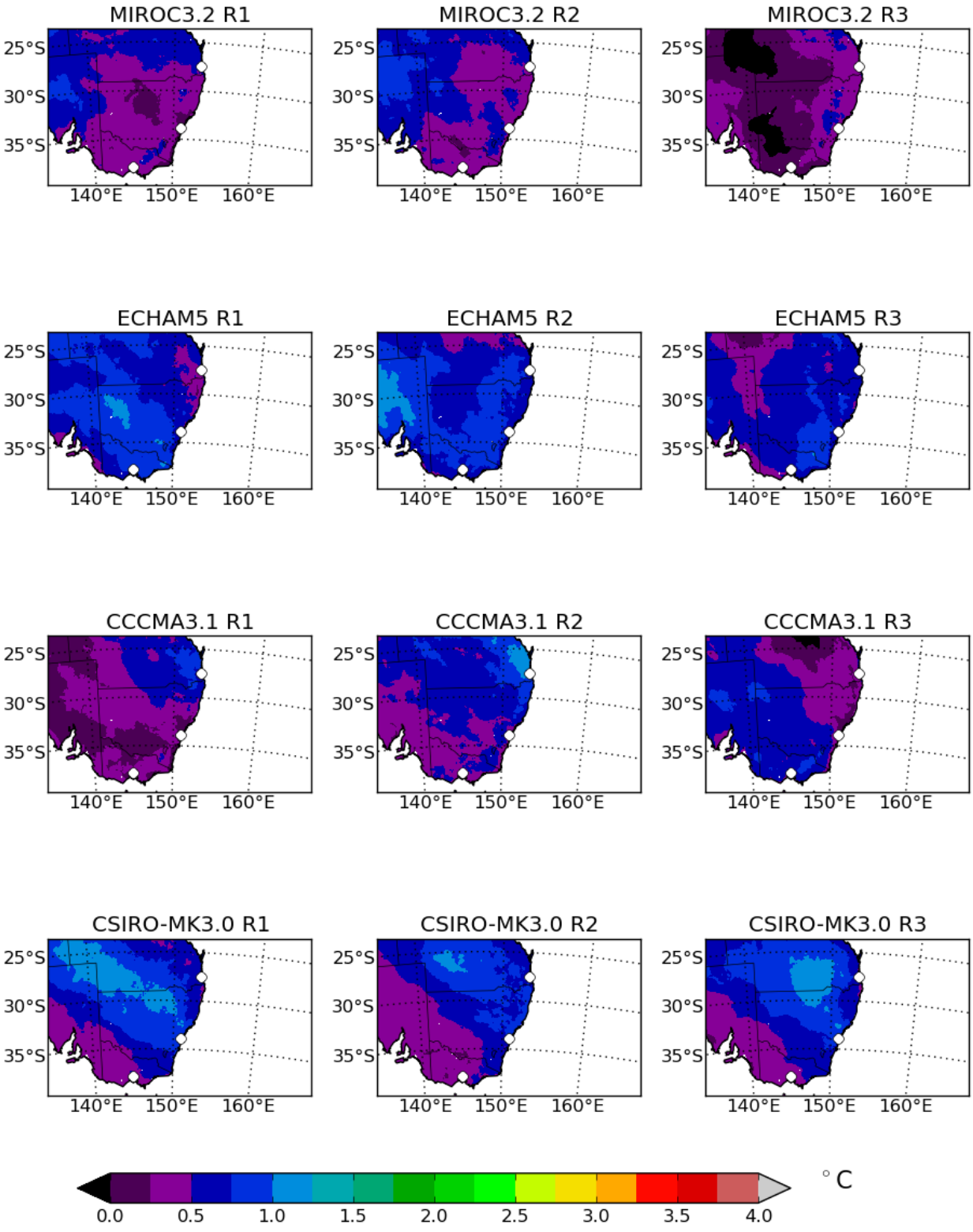

Figure 7.52: MAM mean change between years 1990-2009 and 2020-2039 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

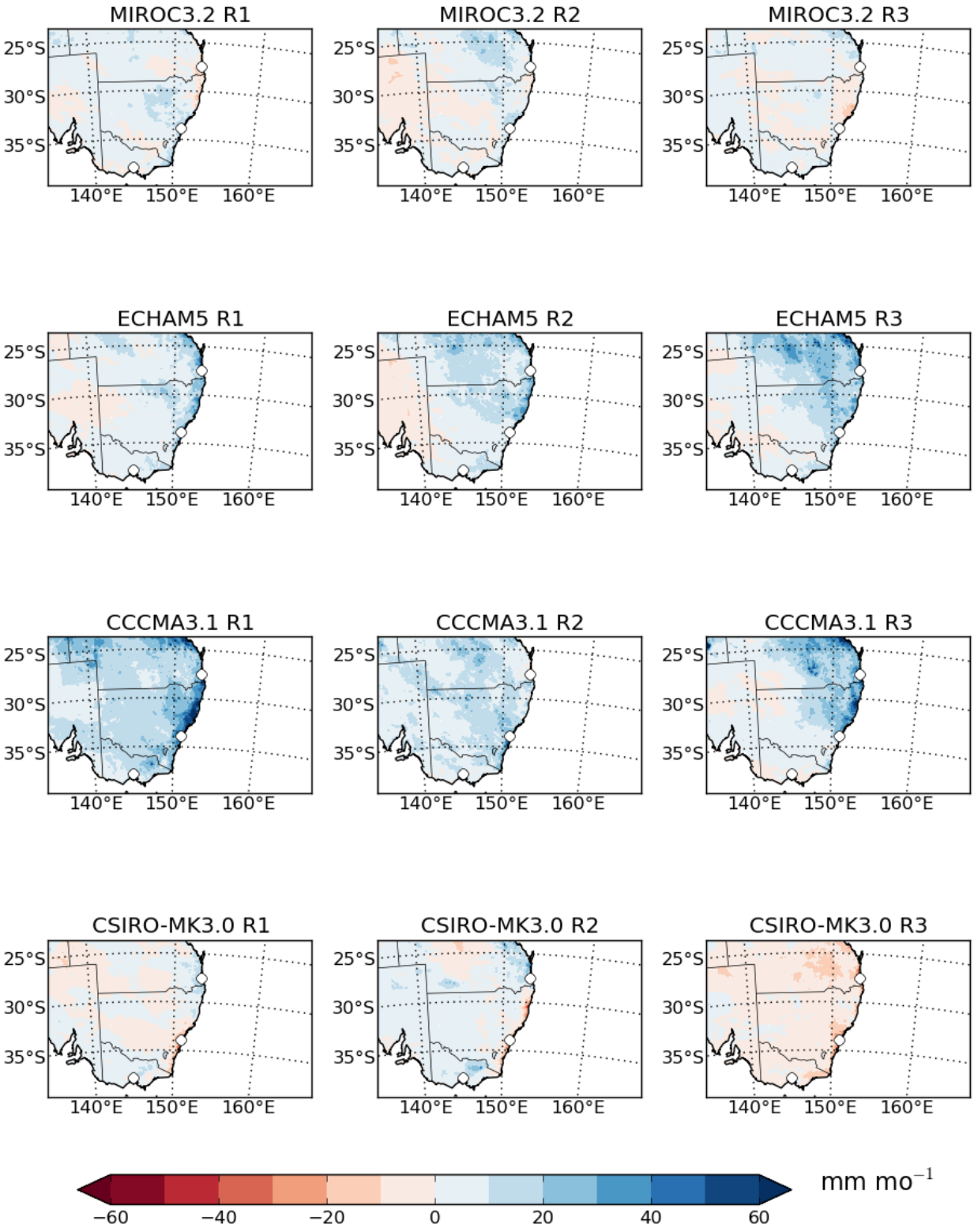

Figure 7.53: MAM mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

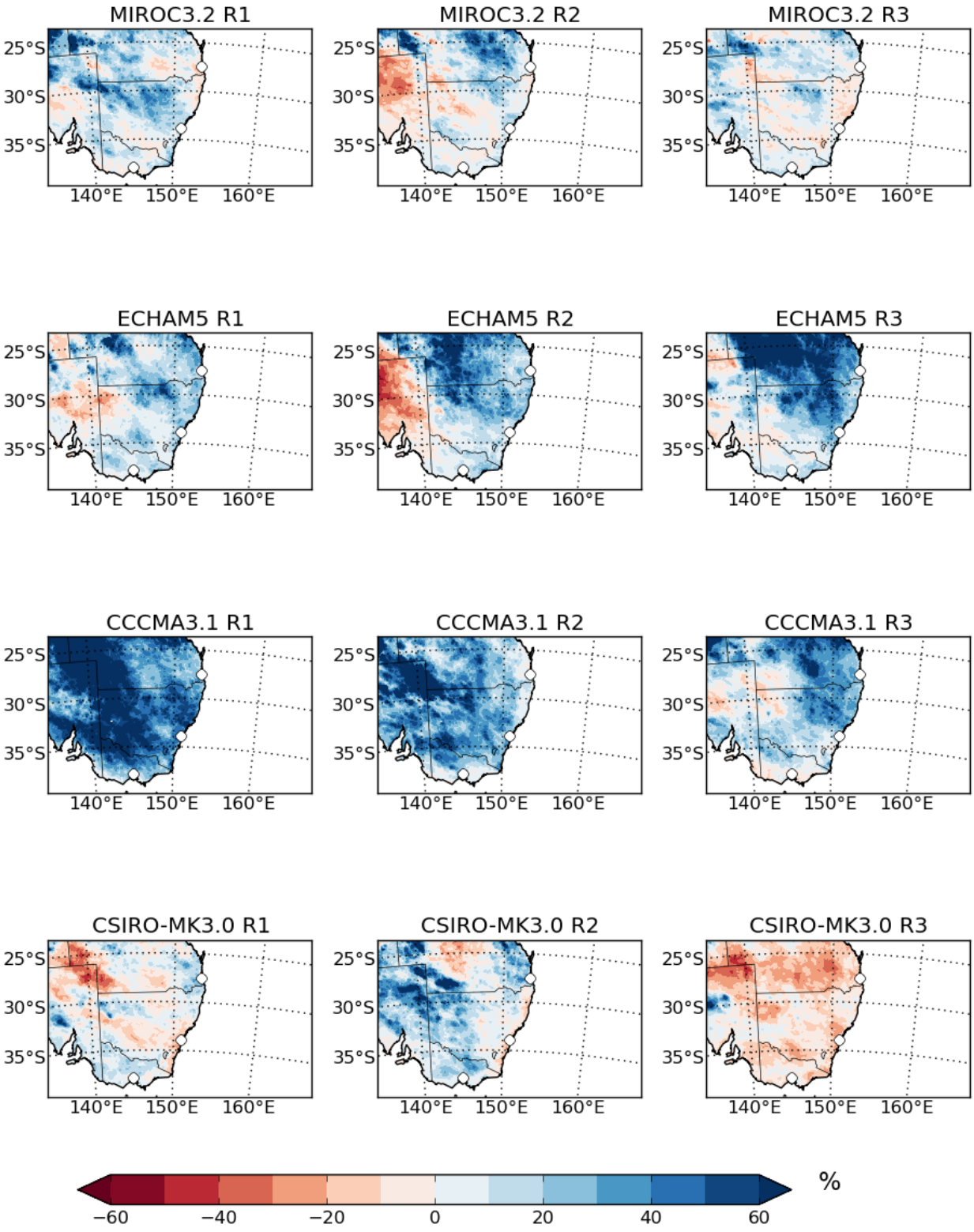

Figure 7.54: MAM mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

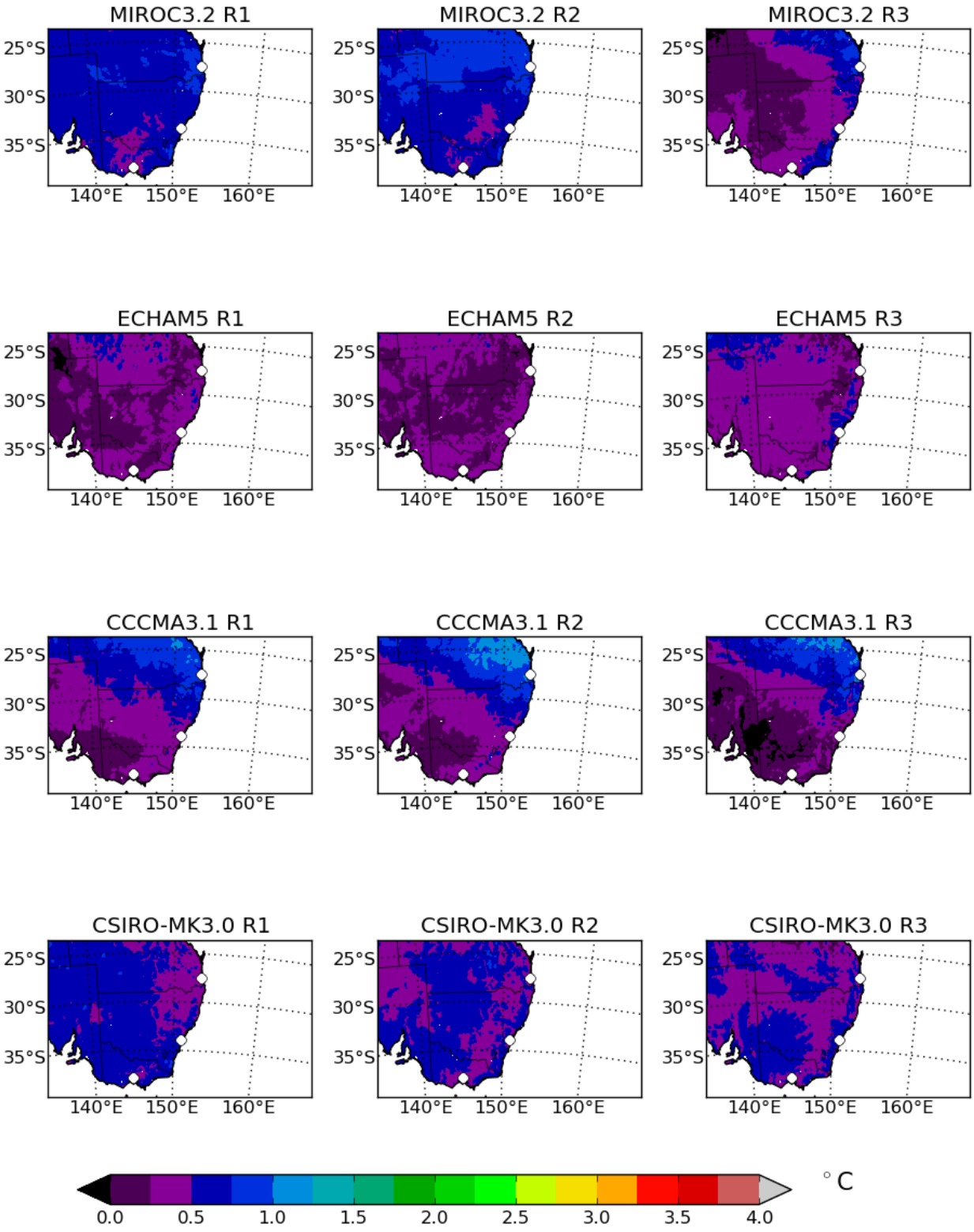

Figure 7.55: JJA mean change between years 1990-2009 and 2020-2039 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

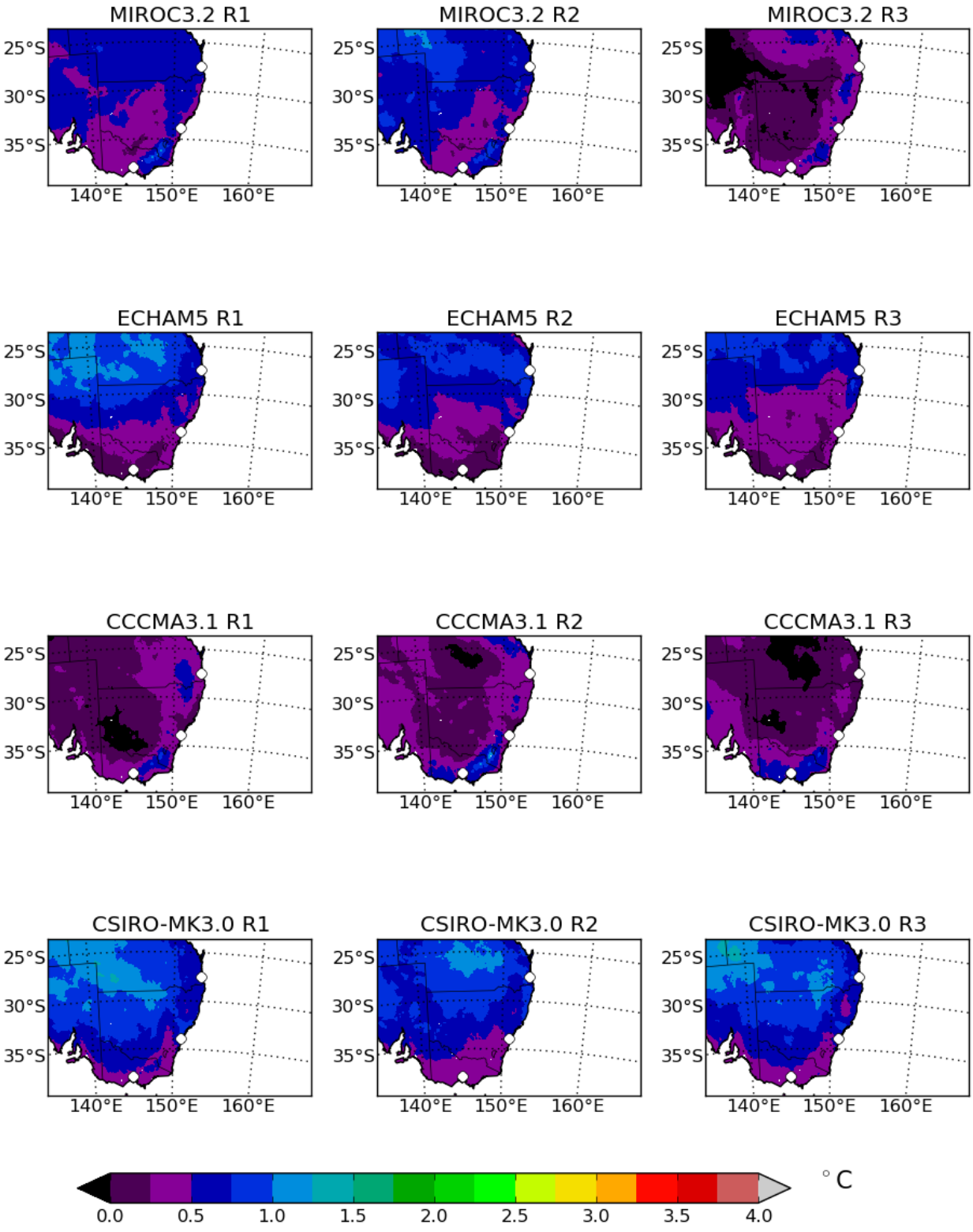

Figure 7.56: JJA mean change between years 1990-2009 and 2020-2039 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

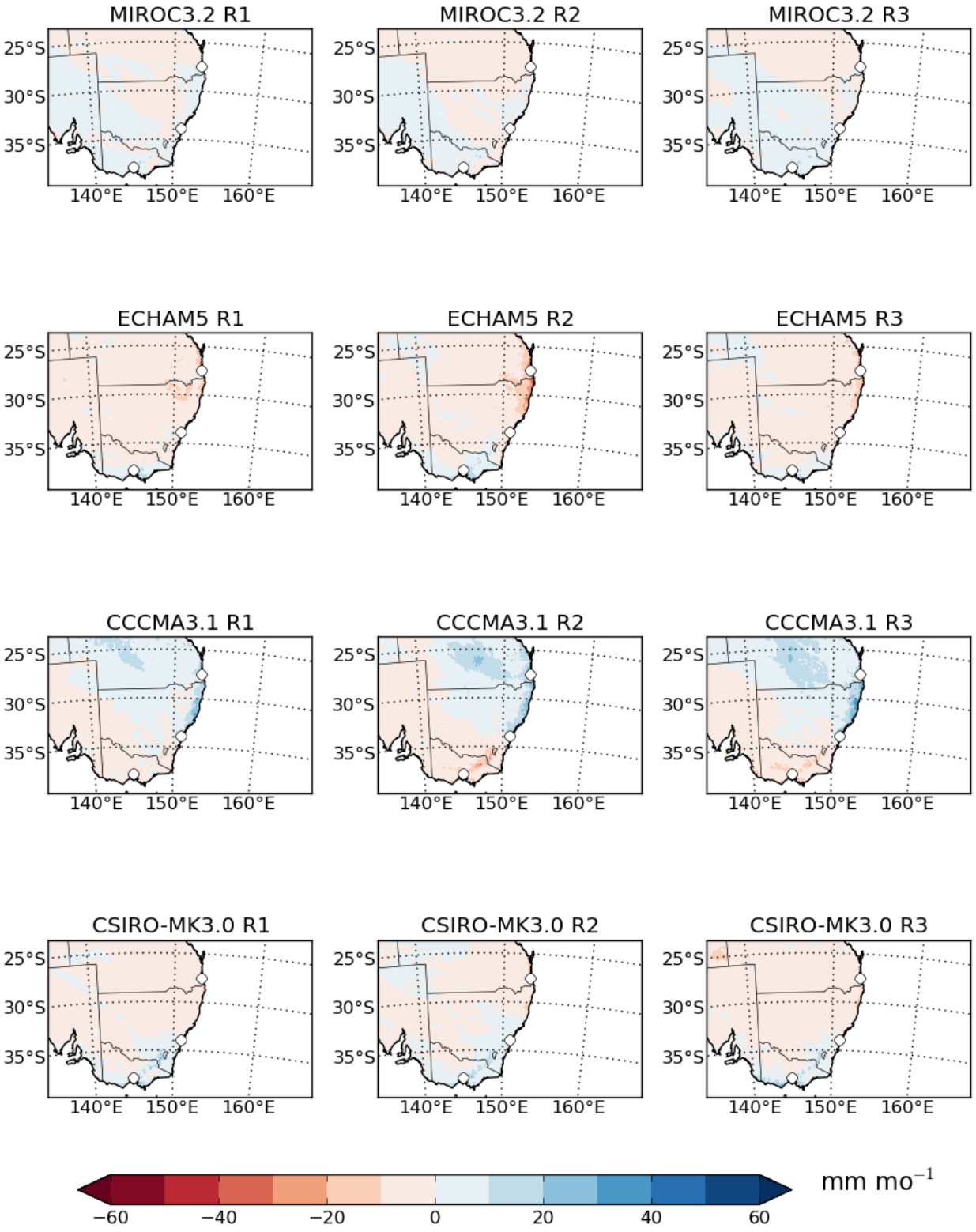

Figure 7.57: JJA mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

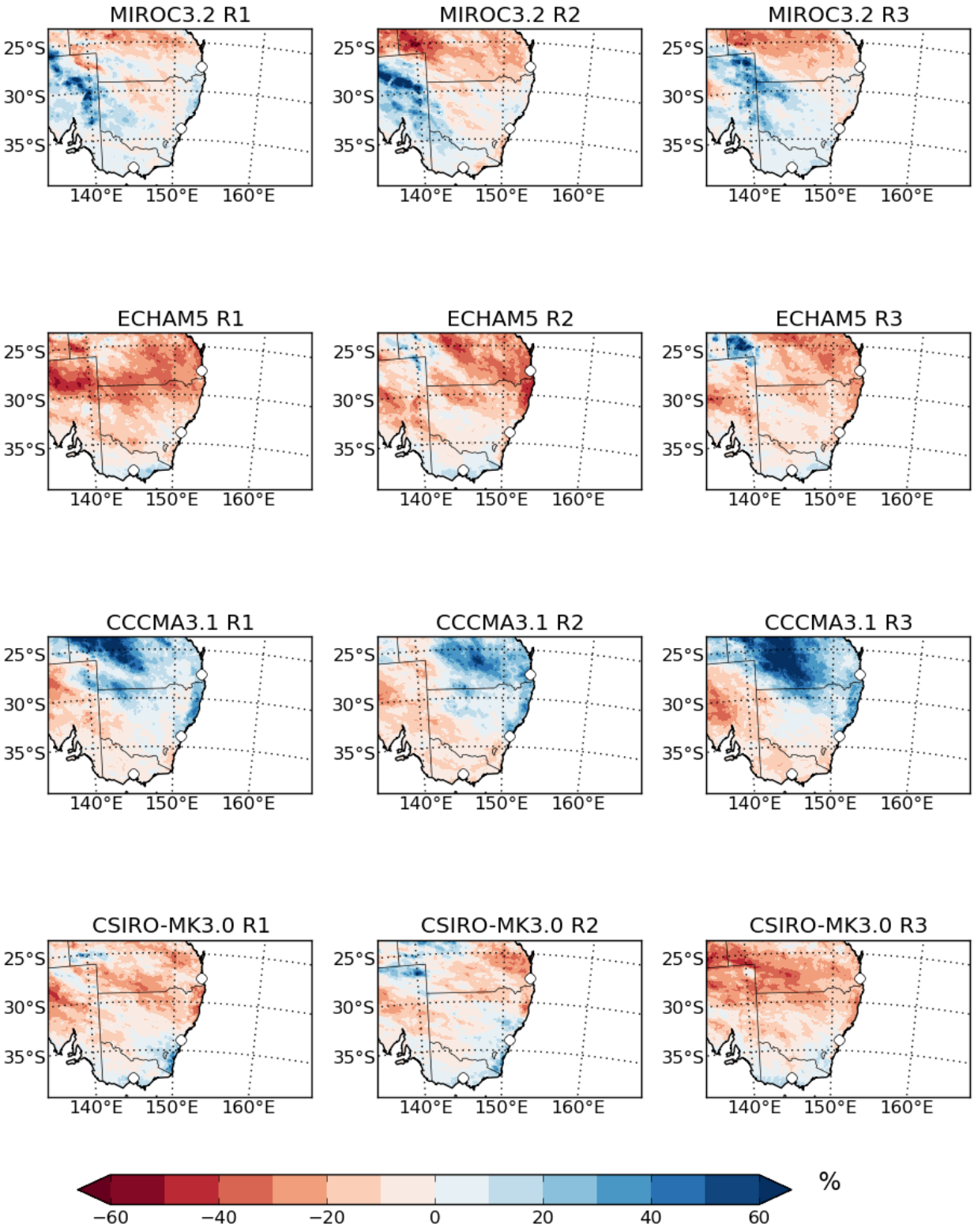

Figure 7.58: JJA mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

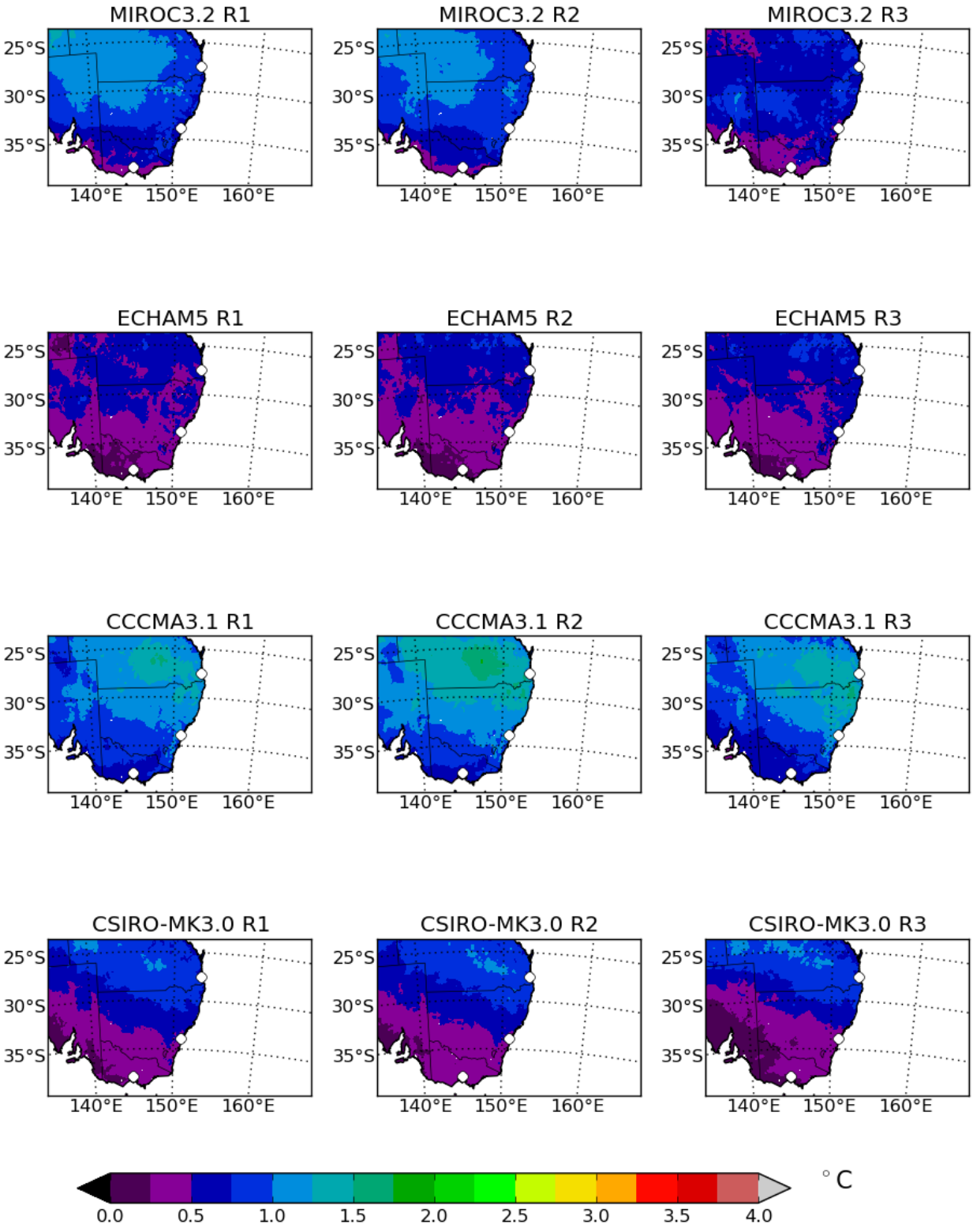

Figure 7.59: SON mean change between years 1990-2009 and 2020-2039 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

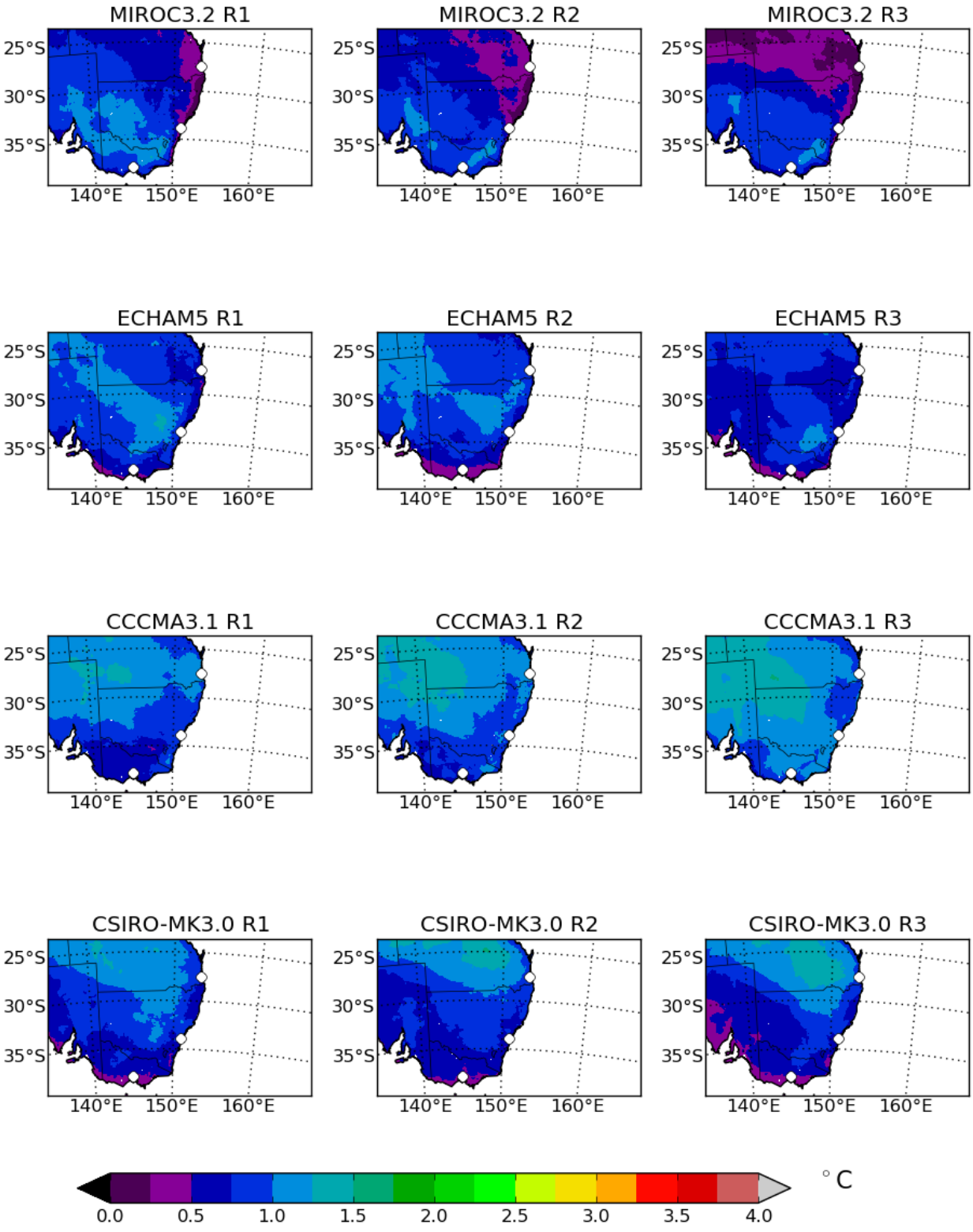

Figure 7.60: SON mean change between years 1990-2009 and 2020-2039 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

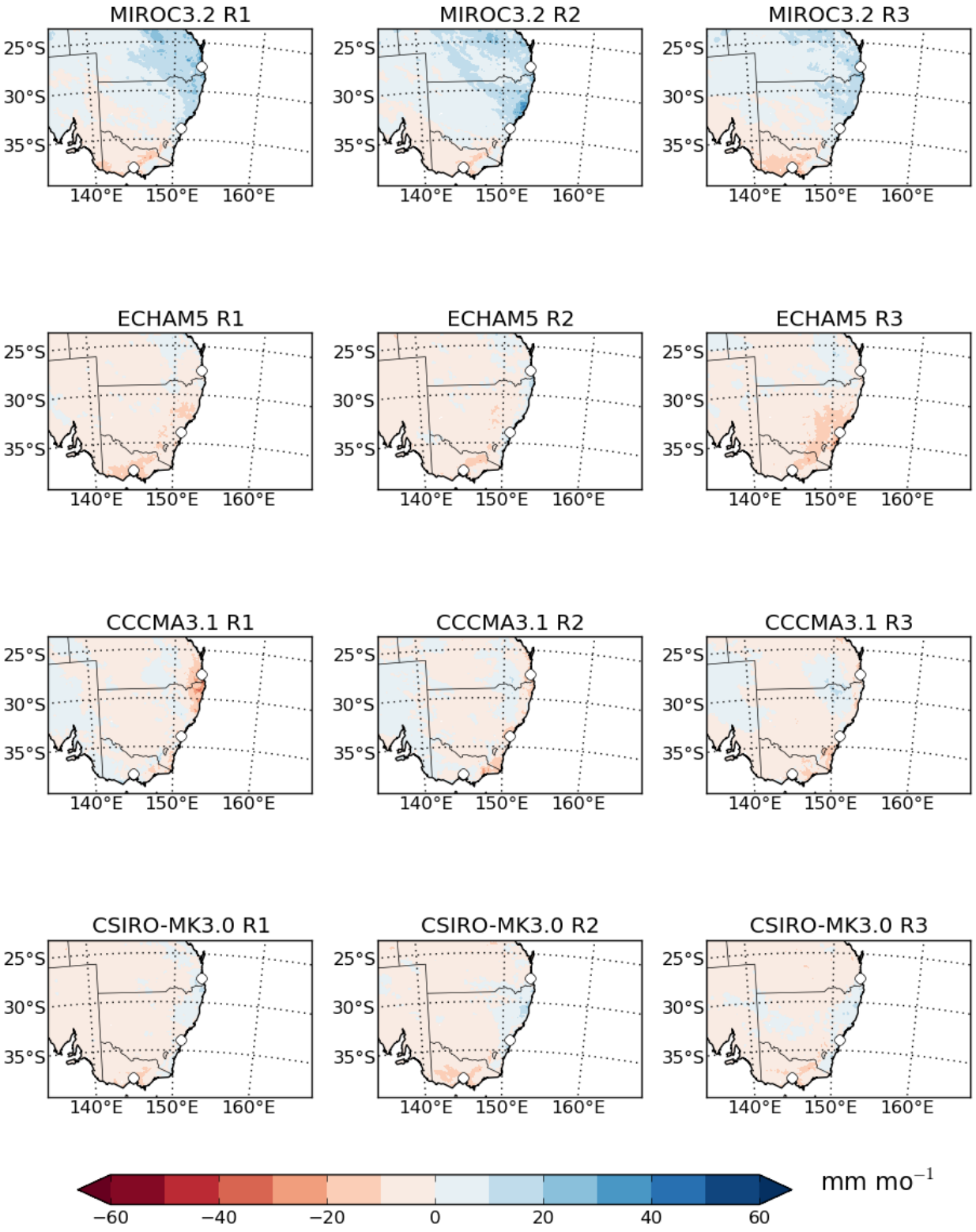

Figure 7.61: SON mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

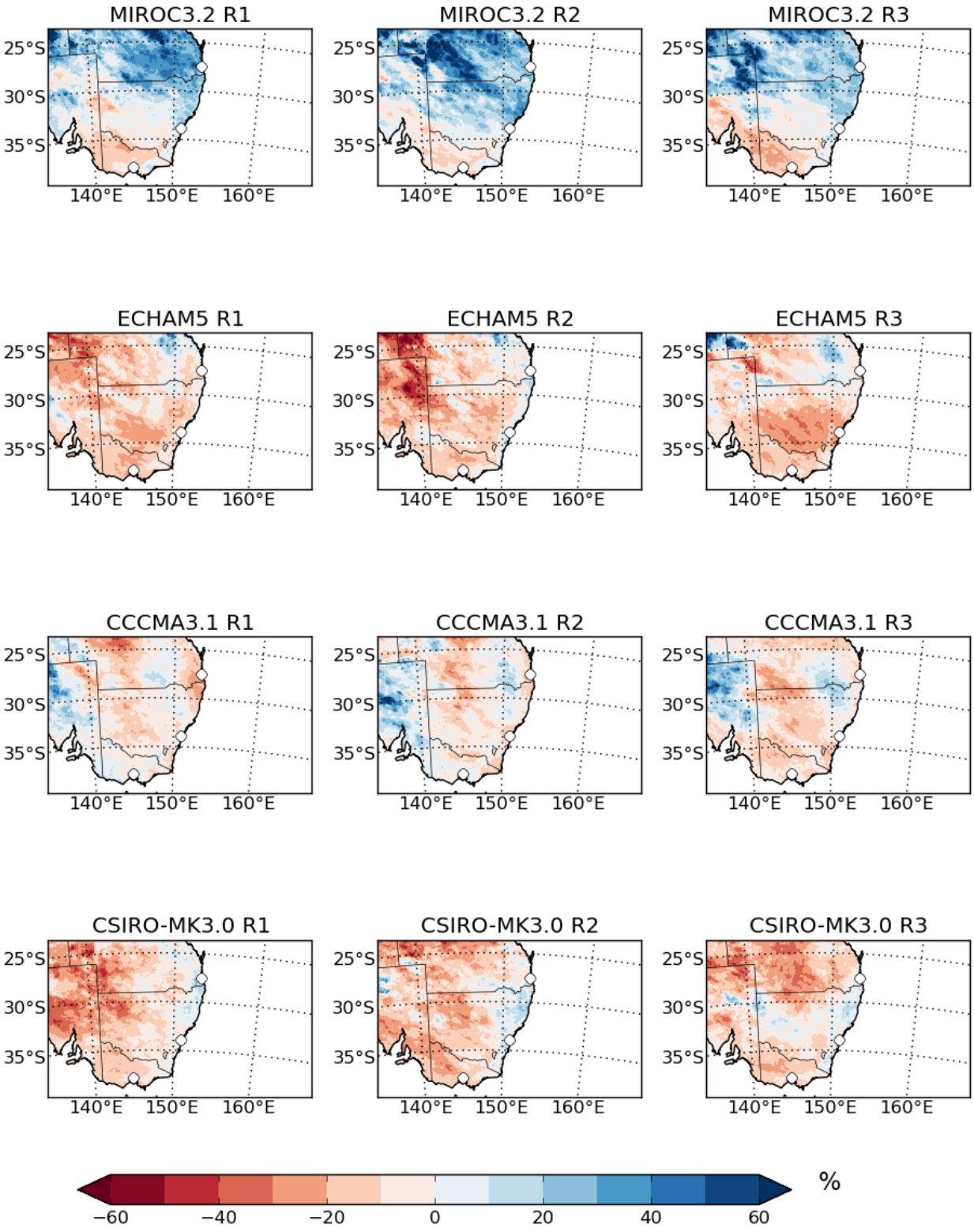

Figure 7.62: SON mean change between years 1990-2009 and 2020-2039 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

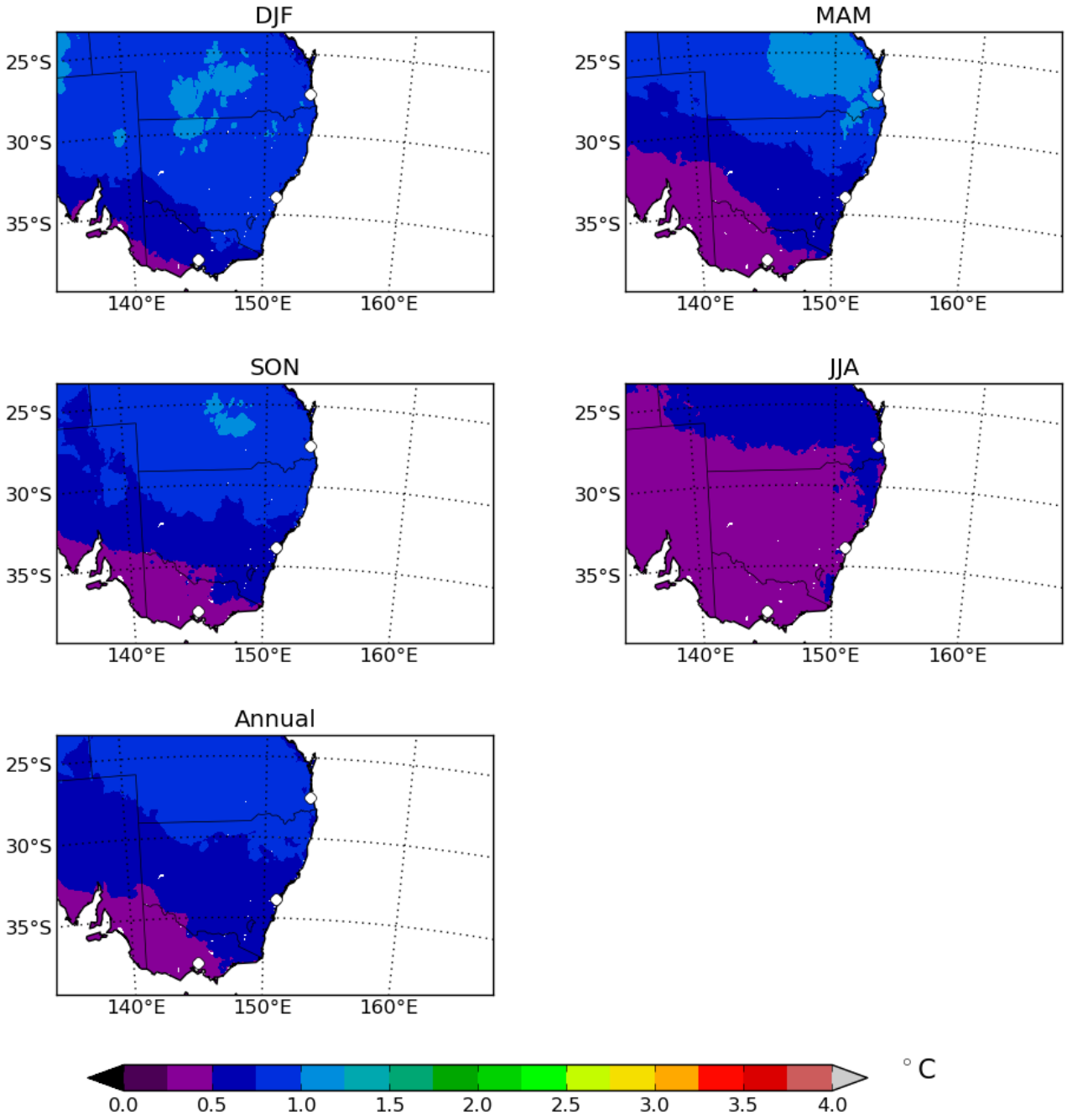

Figure 7.63: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

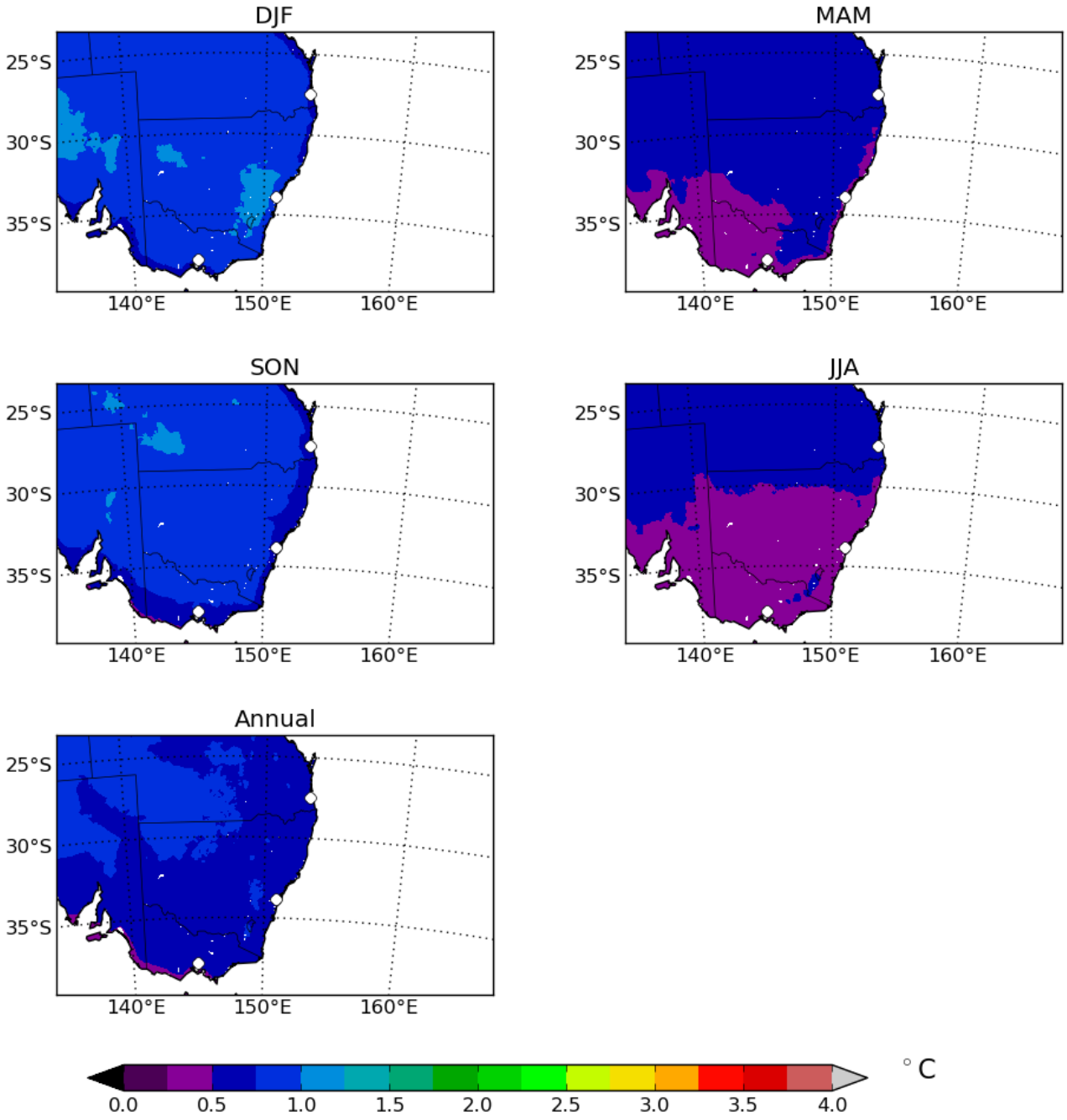

Figure 7.64: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

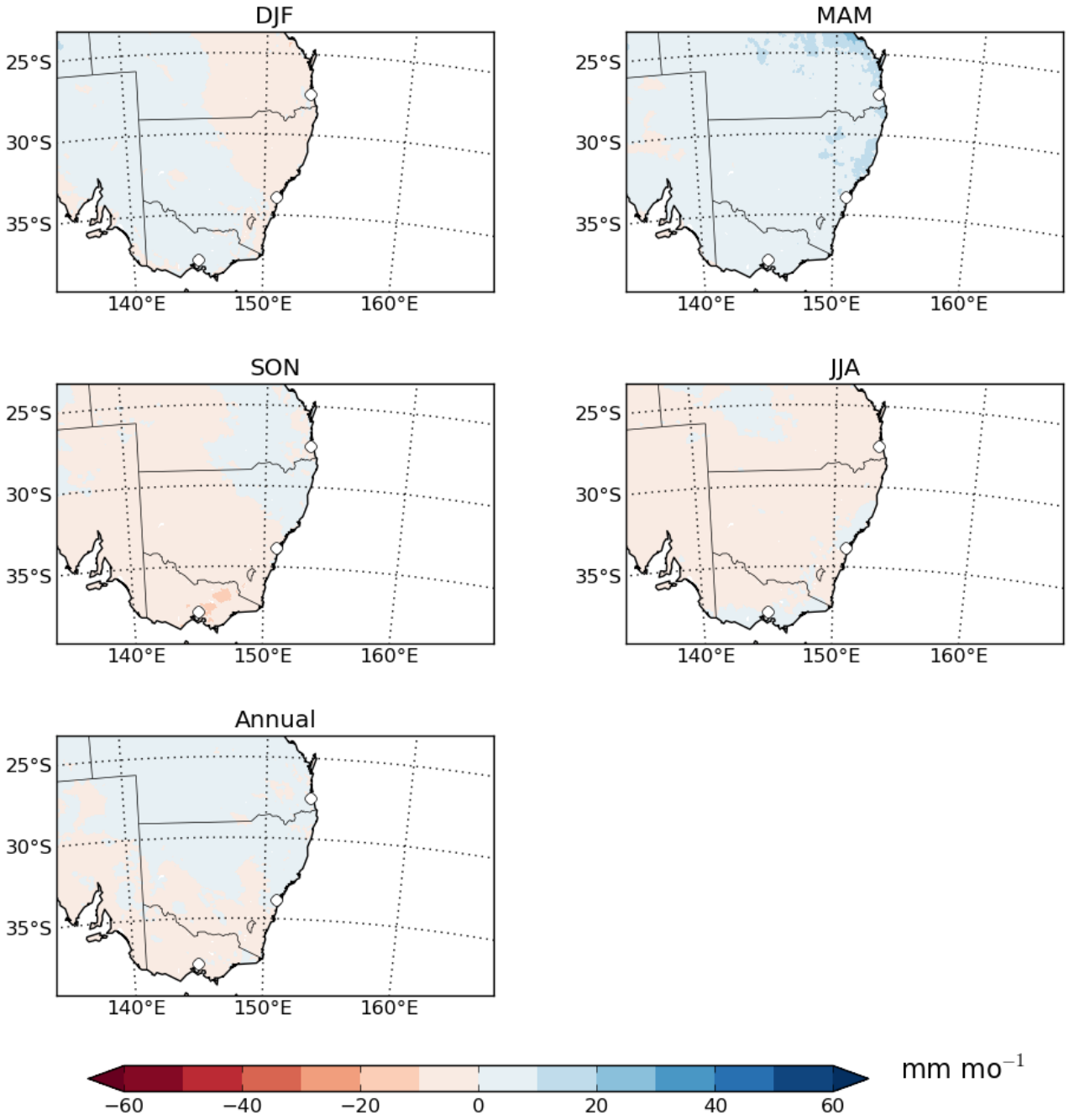

Figure 7.65: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

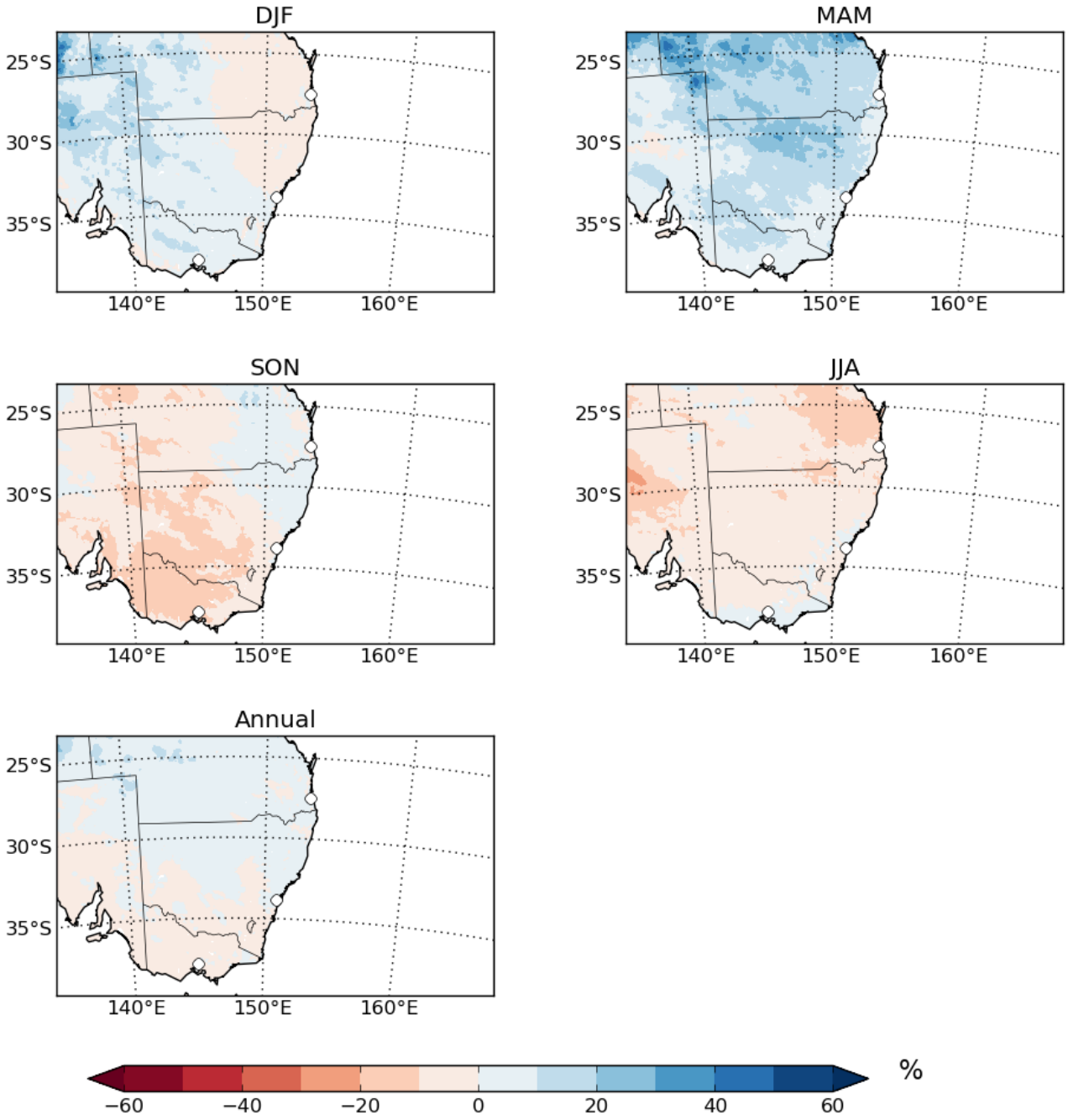

Figure 7.66: Seasonal and annual multimodel mean changes between years 1990-2009 and 2020-2039 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 8

Far Future (2060-2079) Model Climatologies

This chapter contains the climatological seasonal and annual mean projections for far-future near-surface air temperature and precipitation. We first show the results for GCMs used to drive the RCMs, then for original RCM output, and finally for bias-corrected RCM output. The bias-corrected RCM output is the RCM output corrected for present-day biases between the models and the observations using the methods described here [6].

8.1 2060-2079 Driving GCMs

This subsection contains projected far-future climatologies for near-surface air temperature and precipitation from each of the GCMs used to provide boundary conditions to the RCMs. The plots are ordered first by GCM, and then by variable.

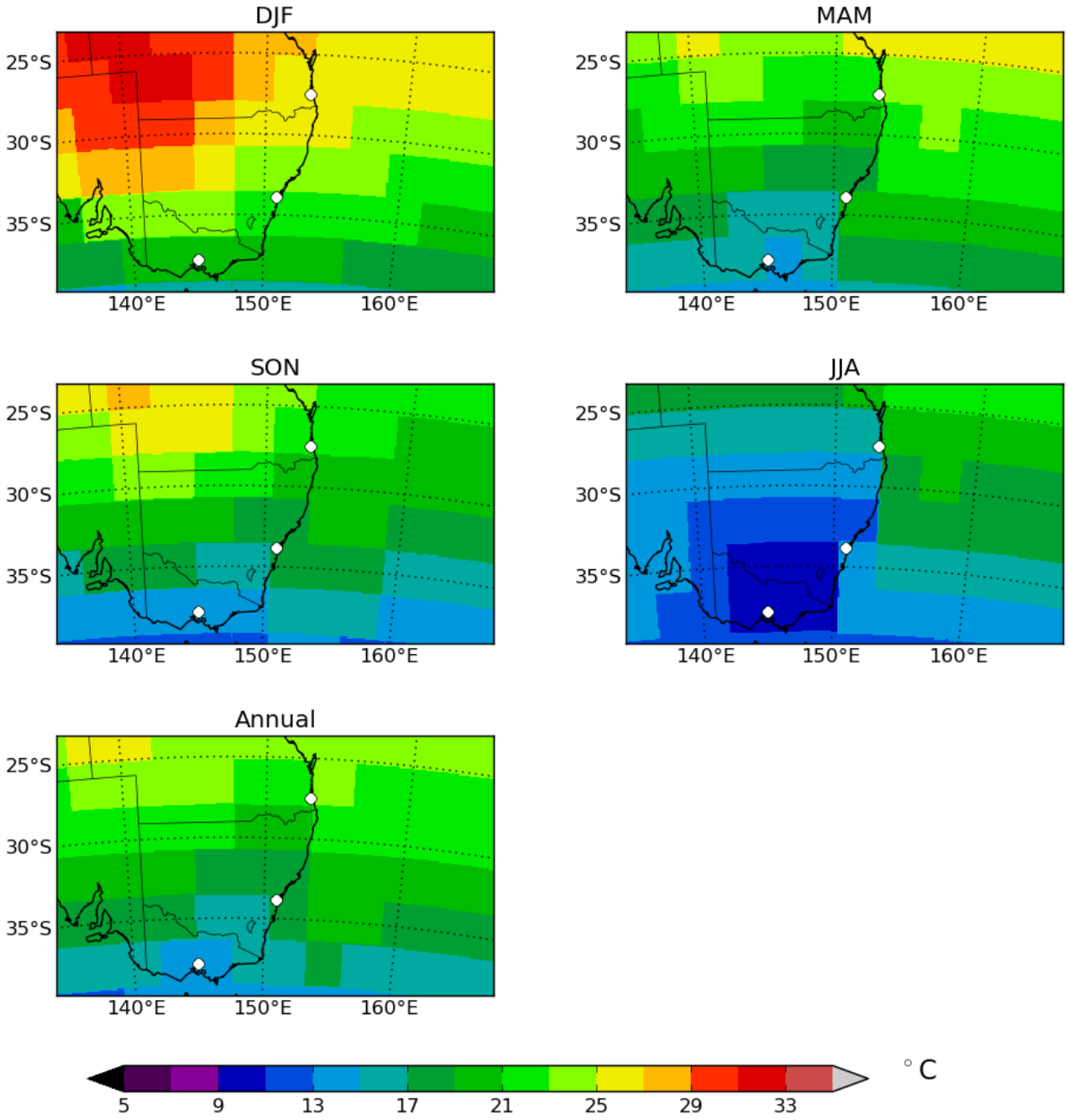

Figure 8.1: Seasonal and annual means of MIROC3.2 near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

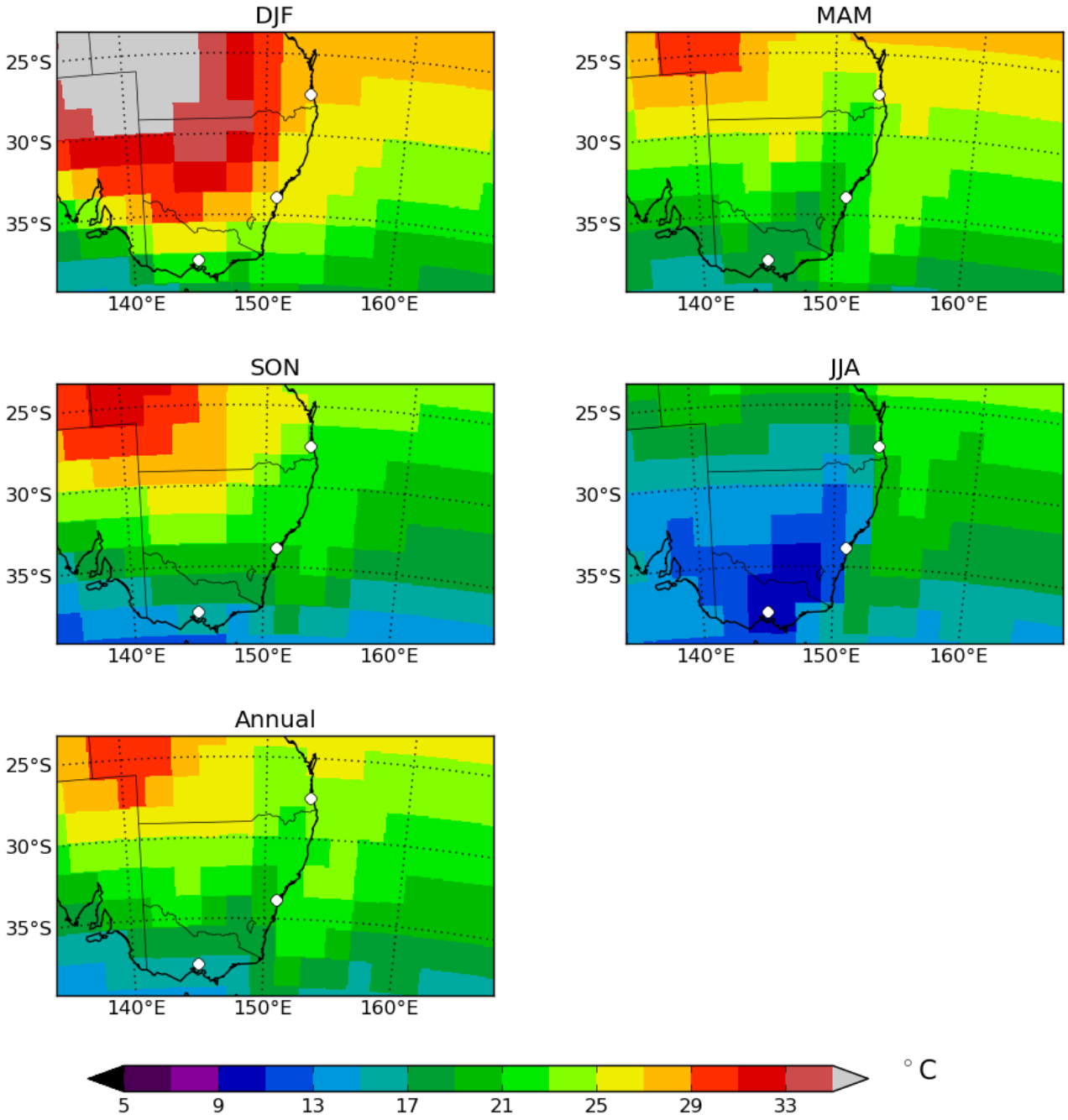

Figure 8.2: Seasonal and annual means of ECHAM5 near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

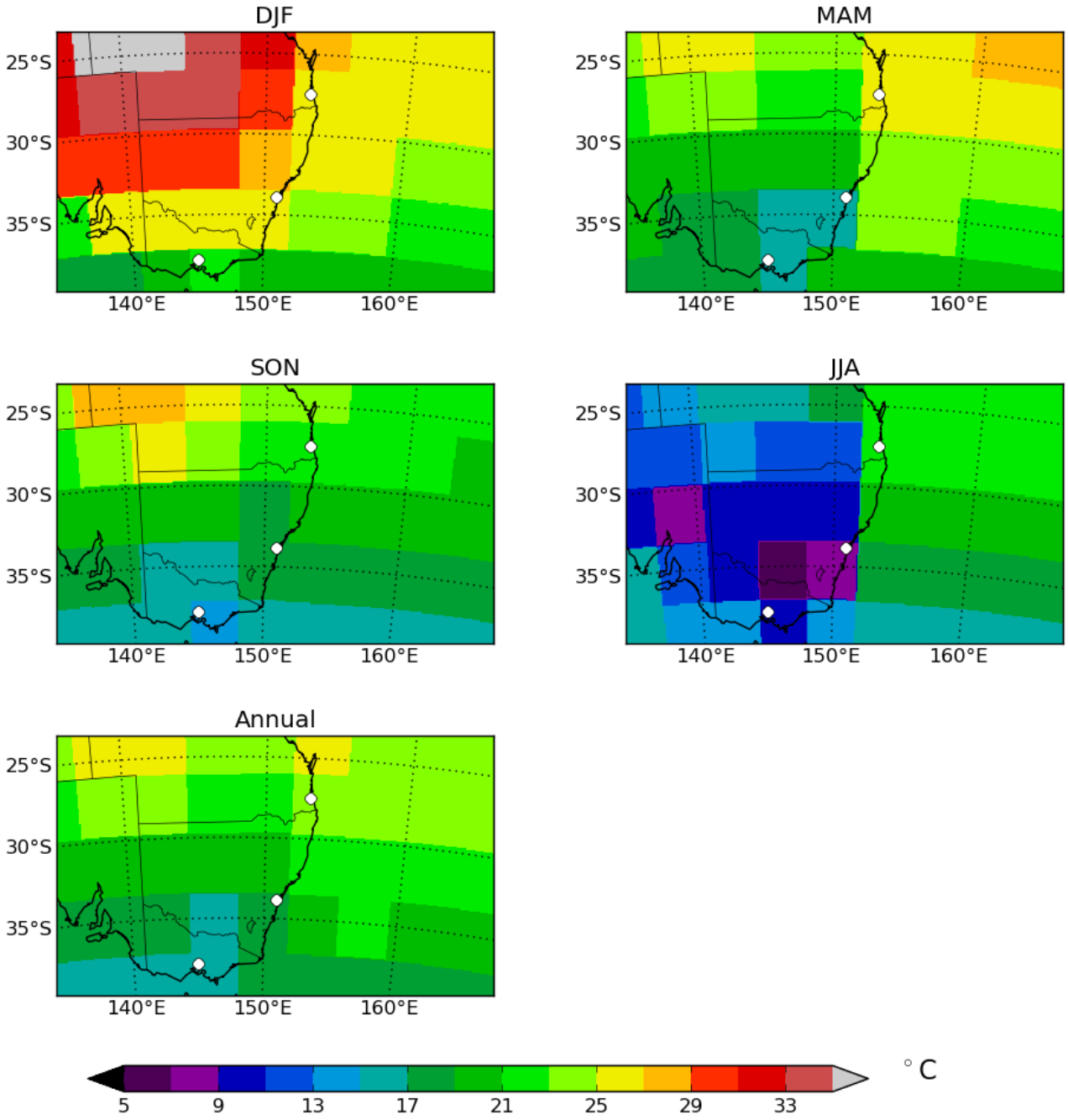

Figure 8.3: Seasonal and annual means of CCCMA3.1 near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

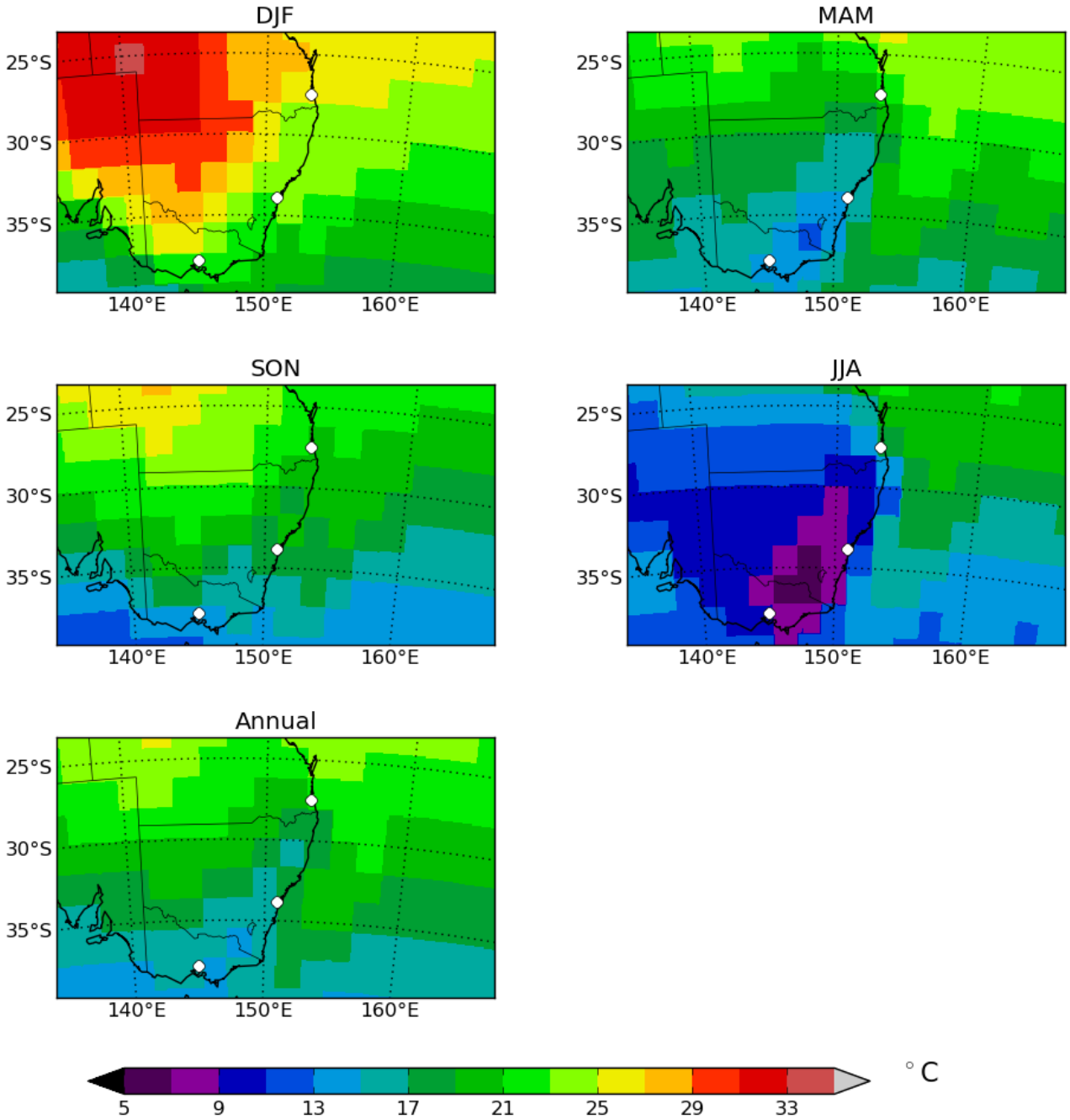

Figure 8.4: Seasonal and annual means of CSIRO-MK3.0 near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

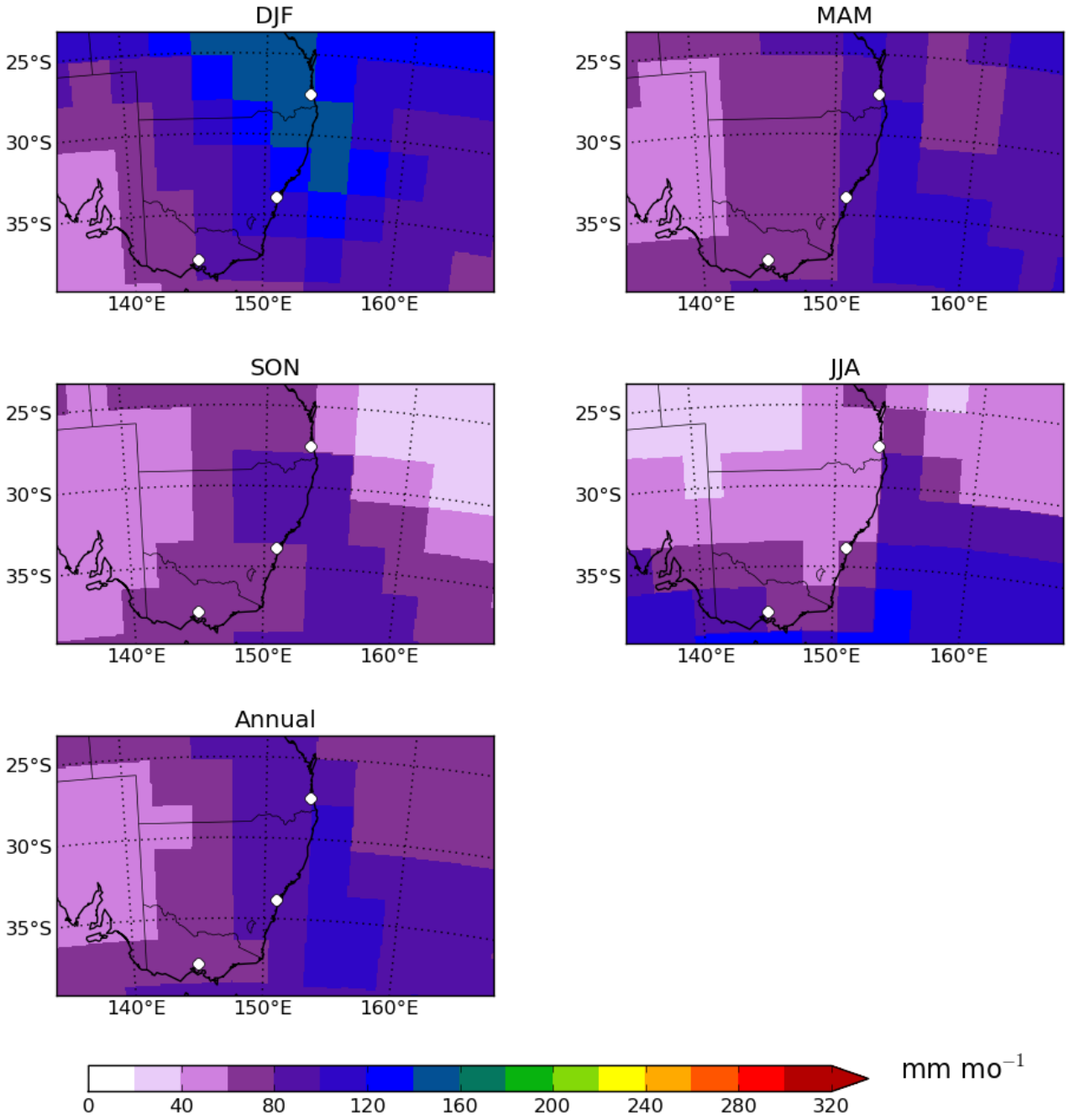

Figure 8.5: Seasonal and annual means of MIROC3.2 precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

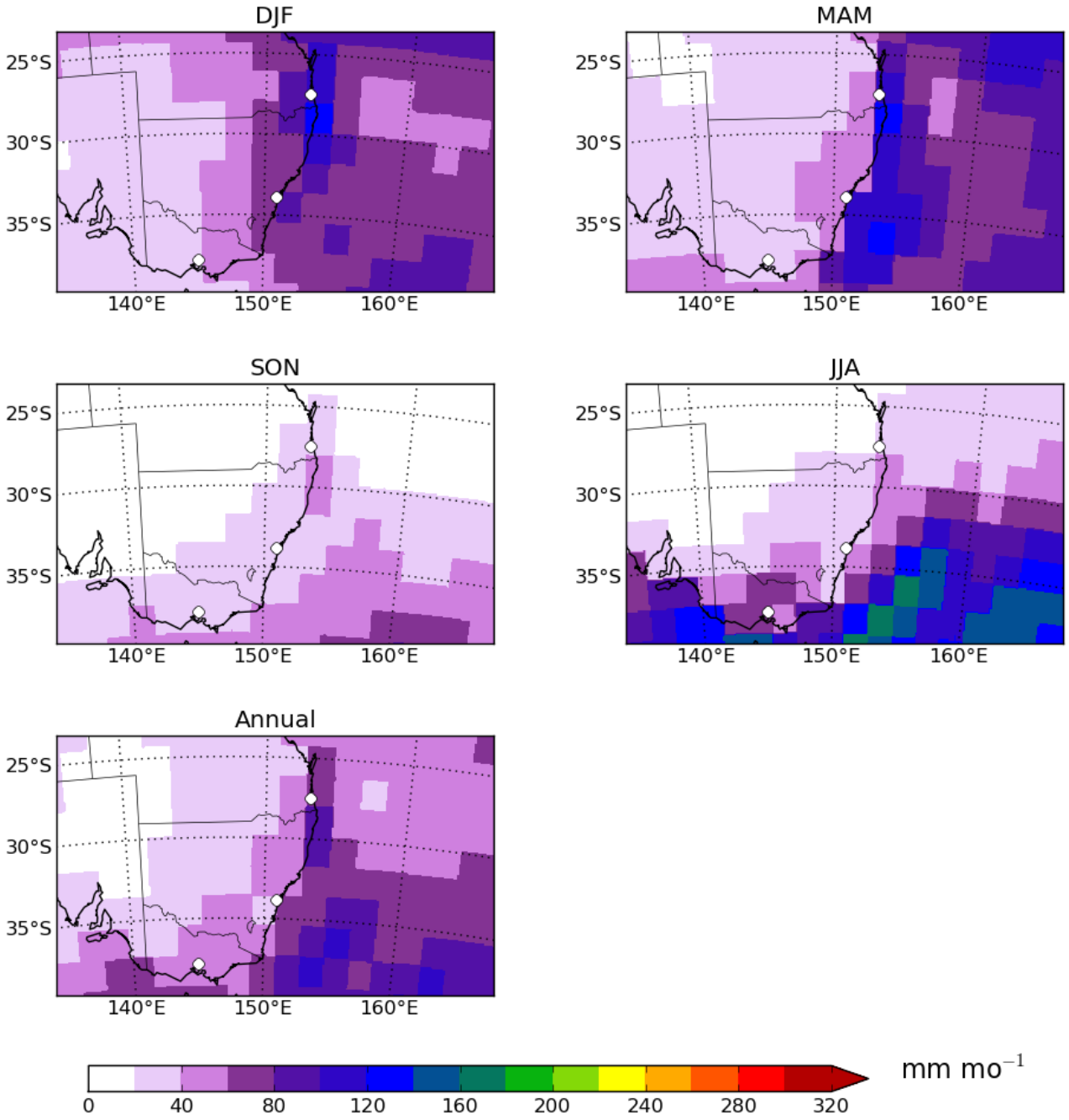

Figure 8.6: Seasonal and annual means of ECHAM5 precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

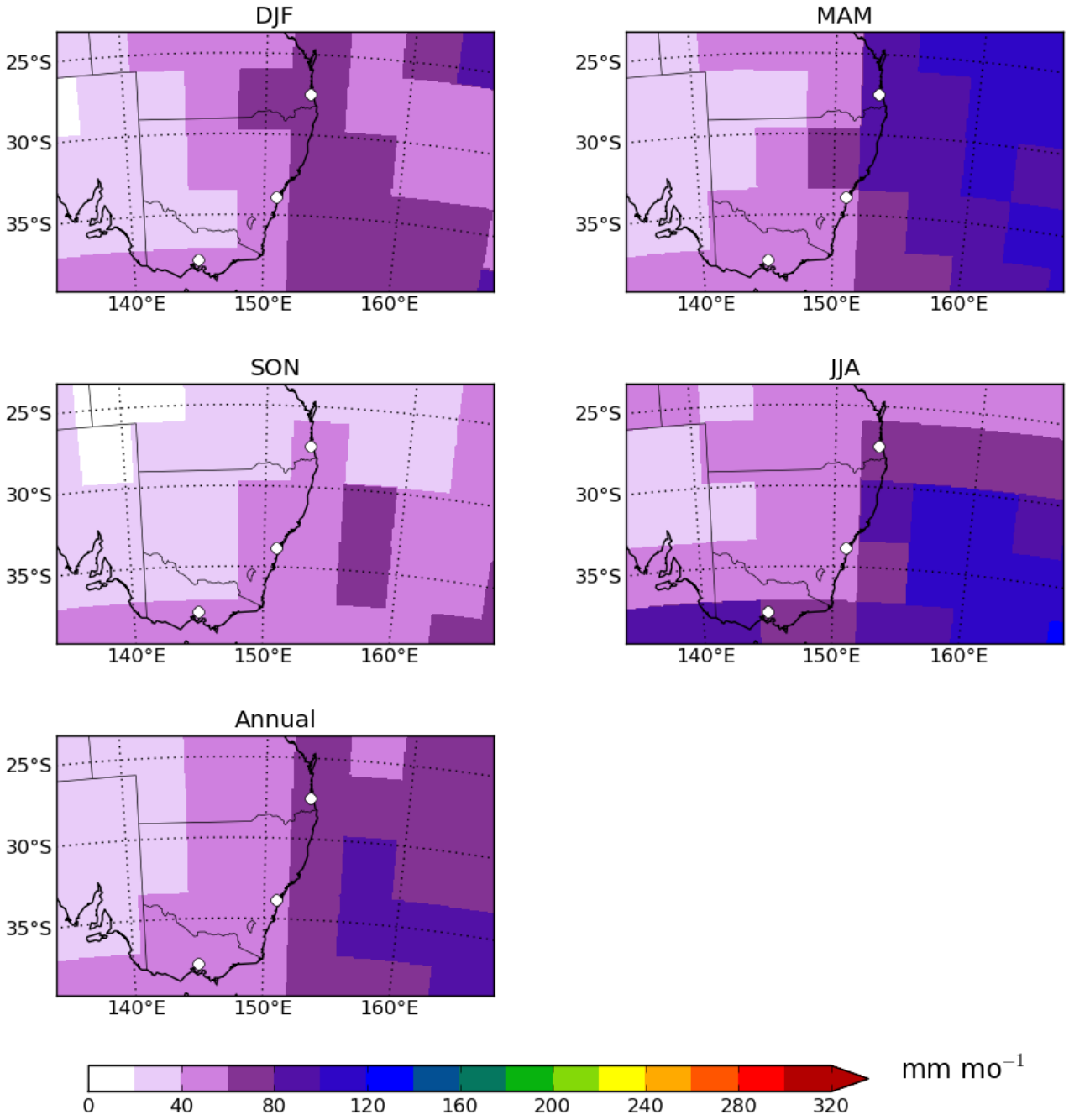

Figure 8.7: Seasonal and annual means of CCCMA3.1 precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

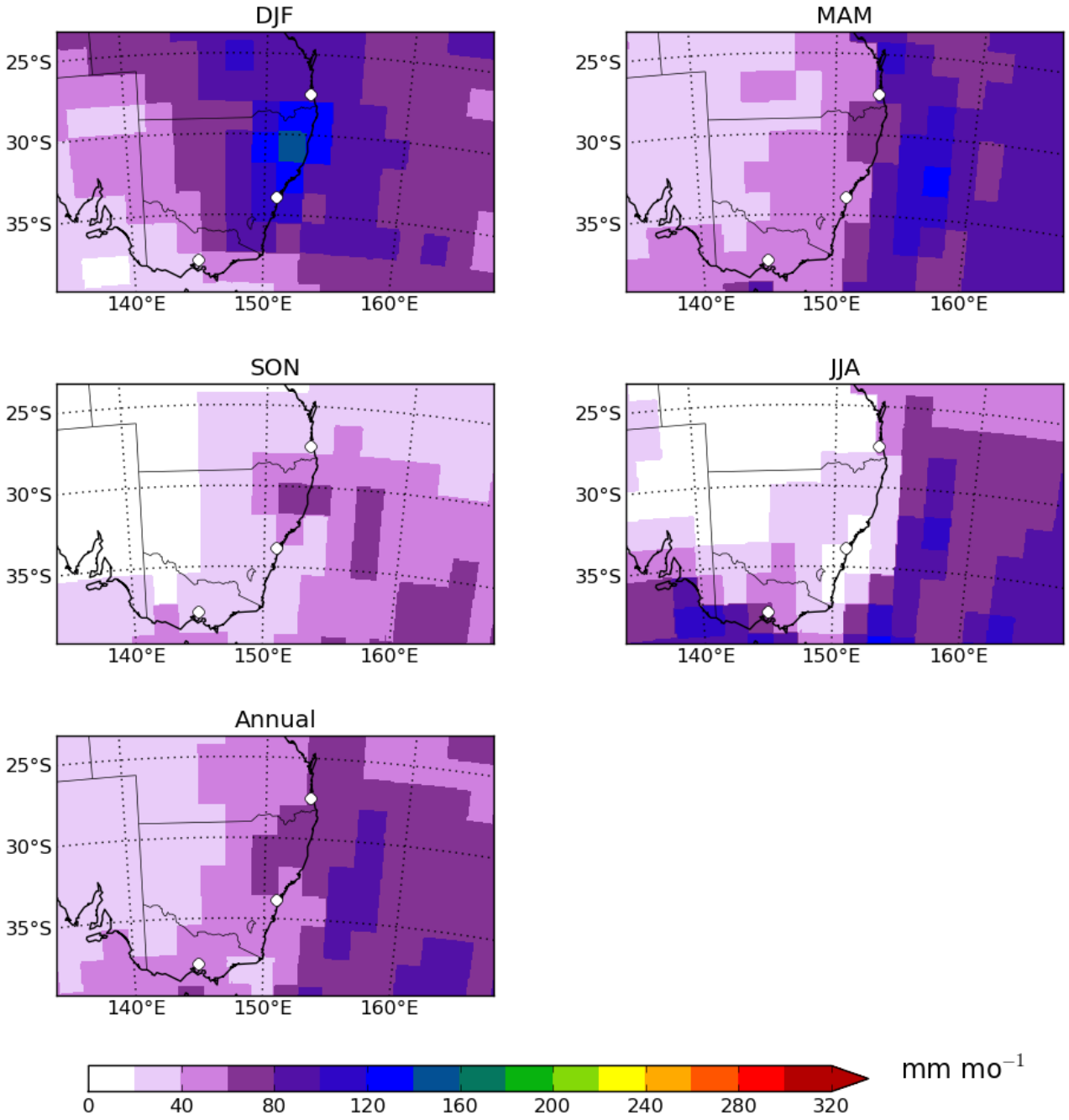

Figure 8.8: Seasonal and annual means of CSIRO-MK3.0 precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

8.2 2060-2079 Regional Model Output

This subsection contains projected far-future climatologies for near-surface air temperature, daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the original RCM output. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected climatologies, whereas the individual-model plots show the level of uncertainty in projected climate.

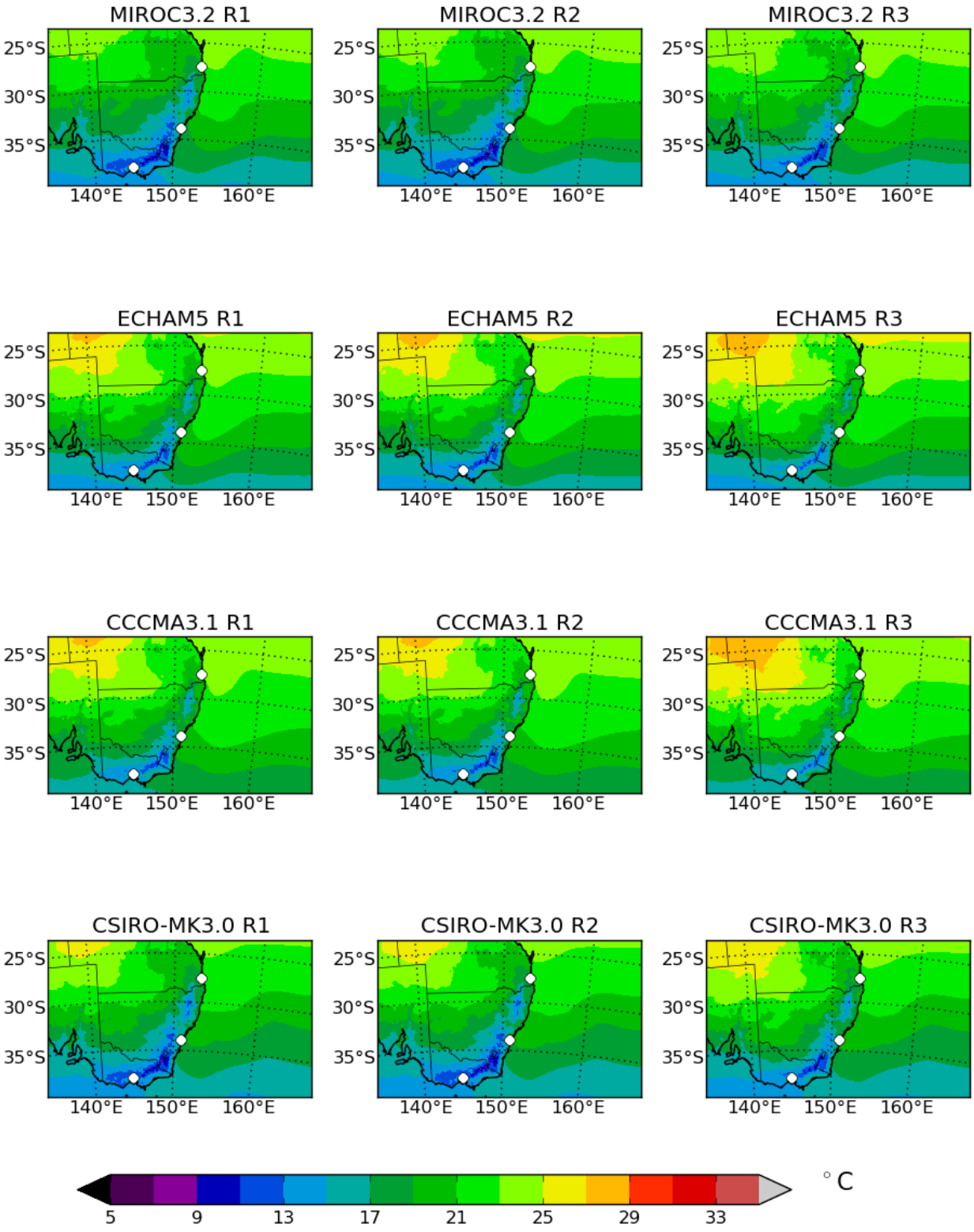

Figure 8.9: Annual mean of near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

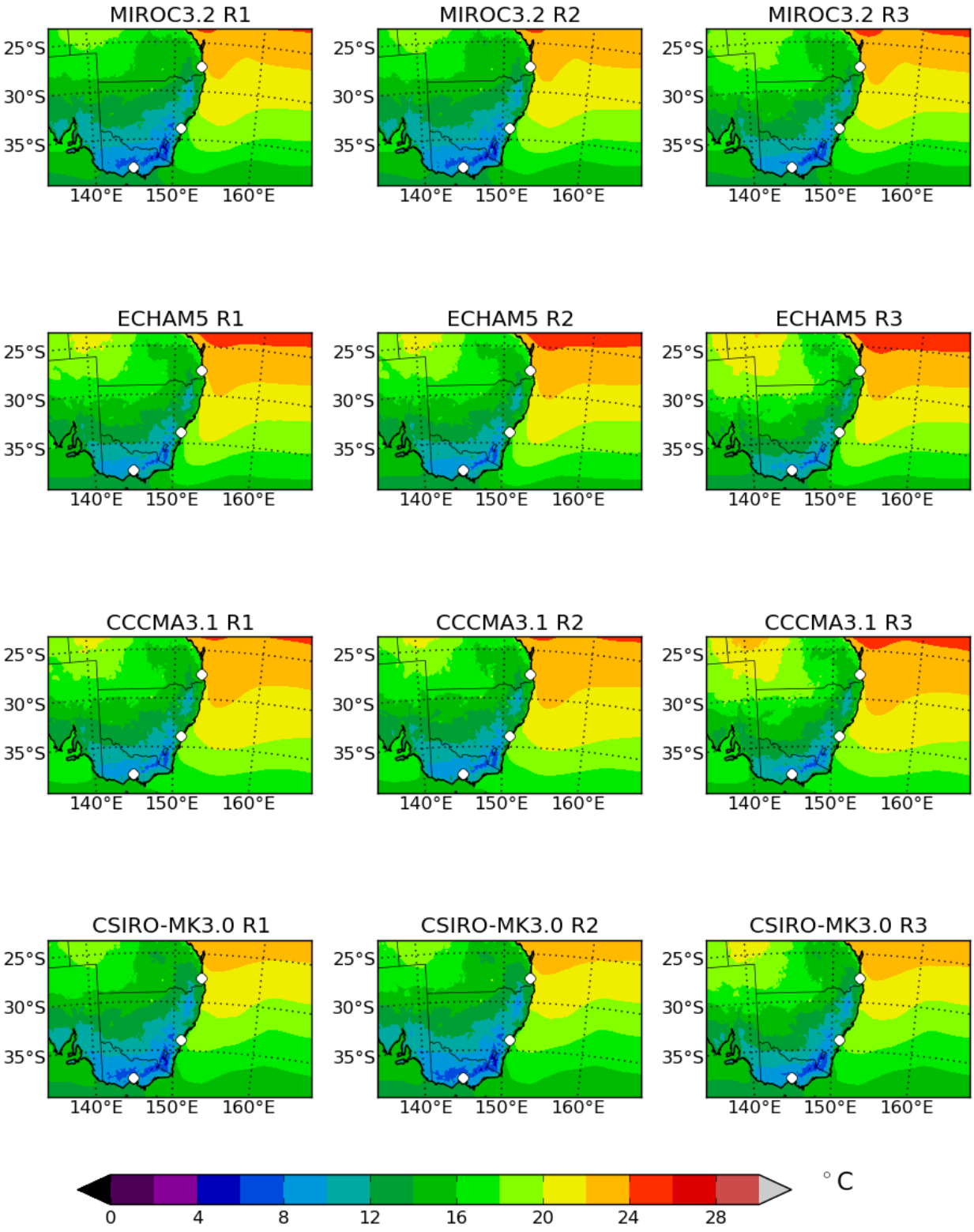

Figure 8.10: Annual mean of daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

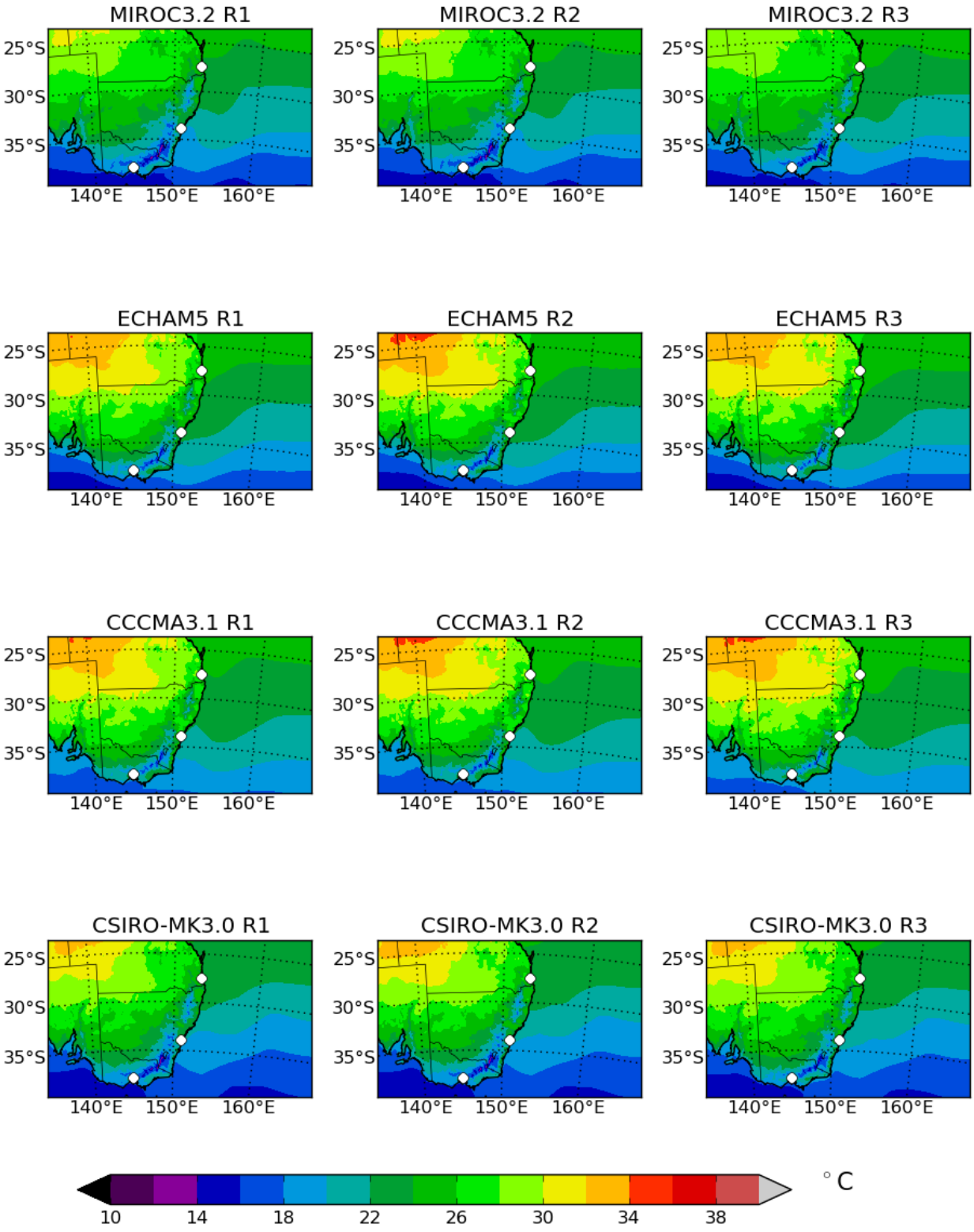

Figure 8.11: Annual mean of daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

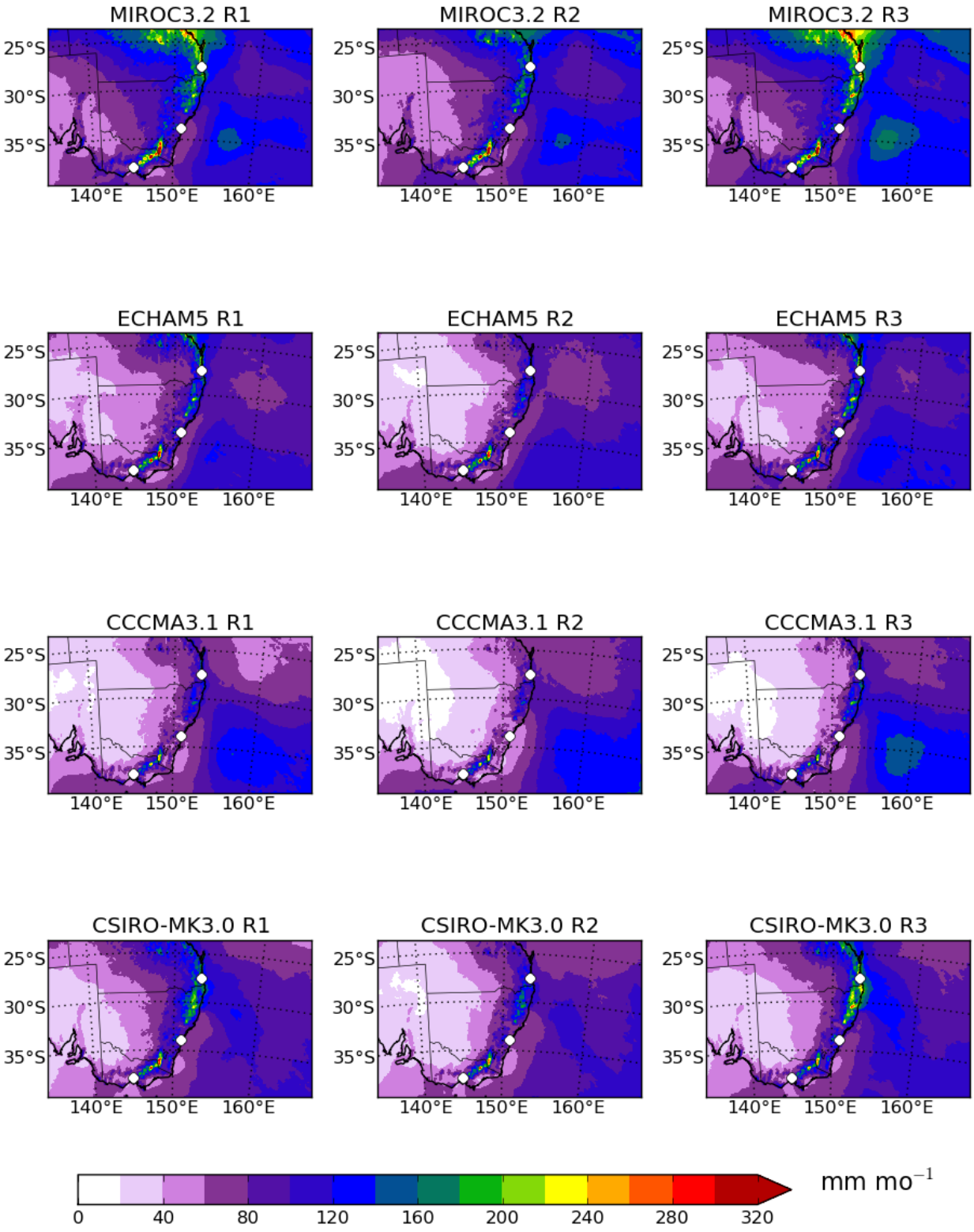

Figure 8.12: Annual mean of precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

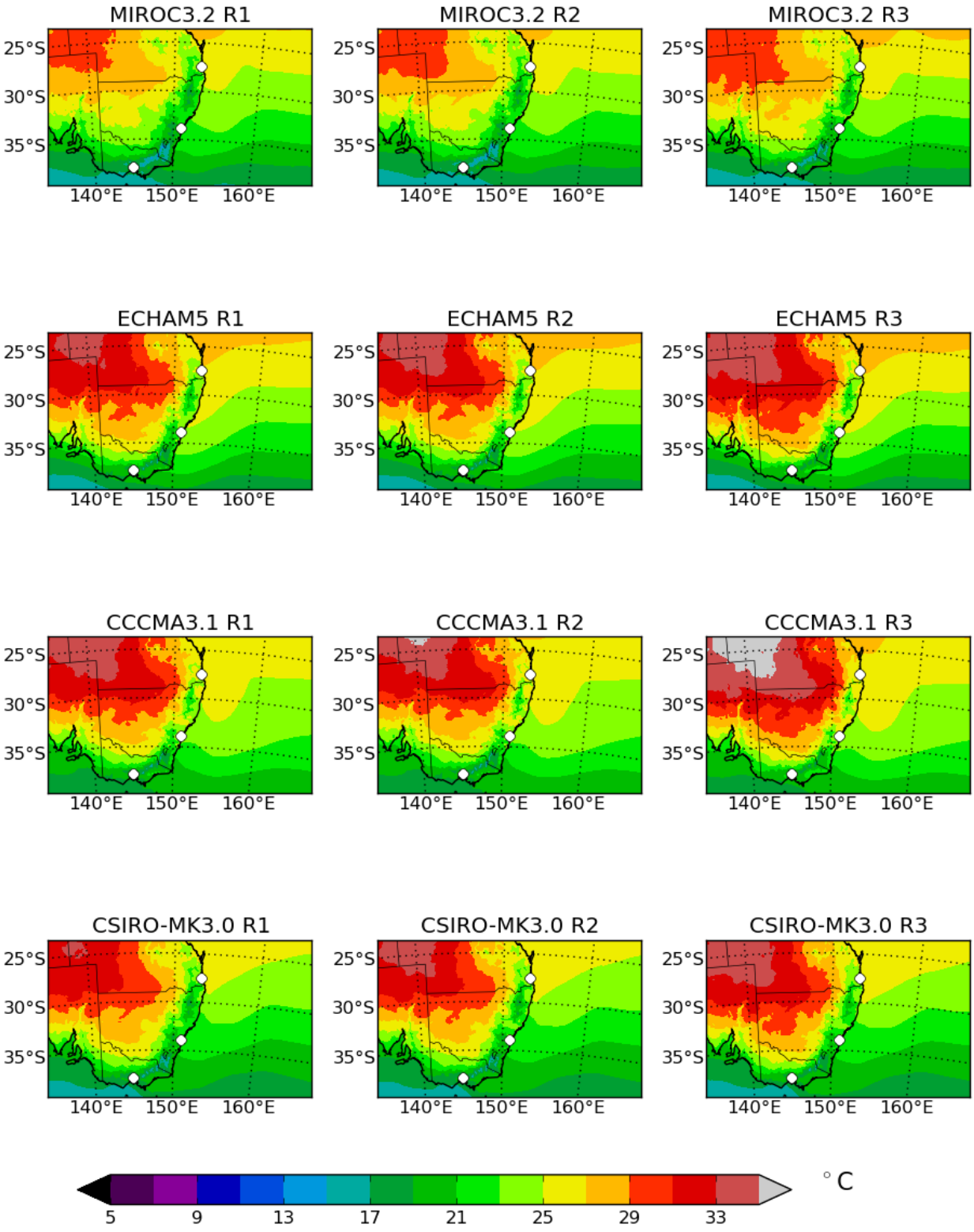

Figure 8.13: DJF mean of near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

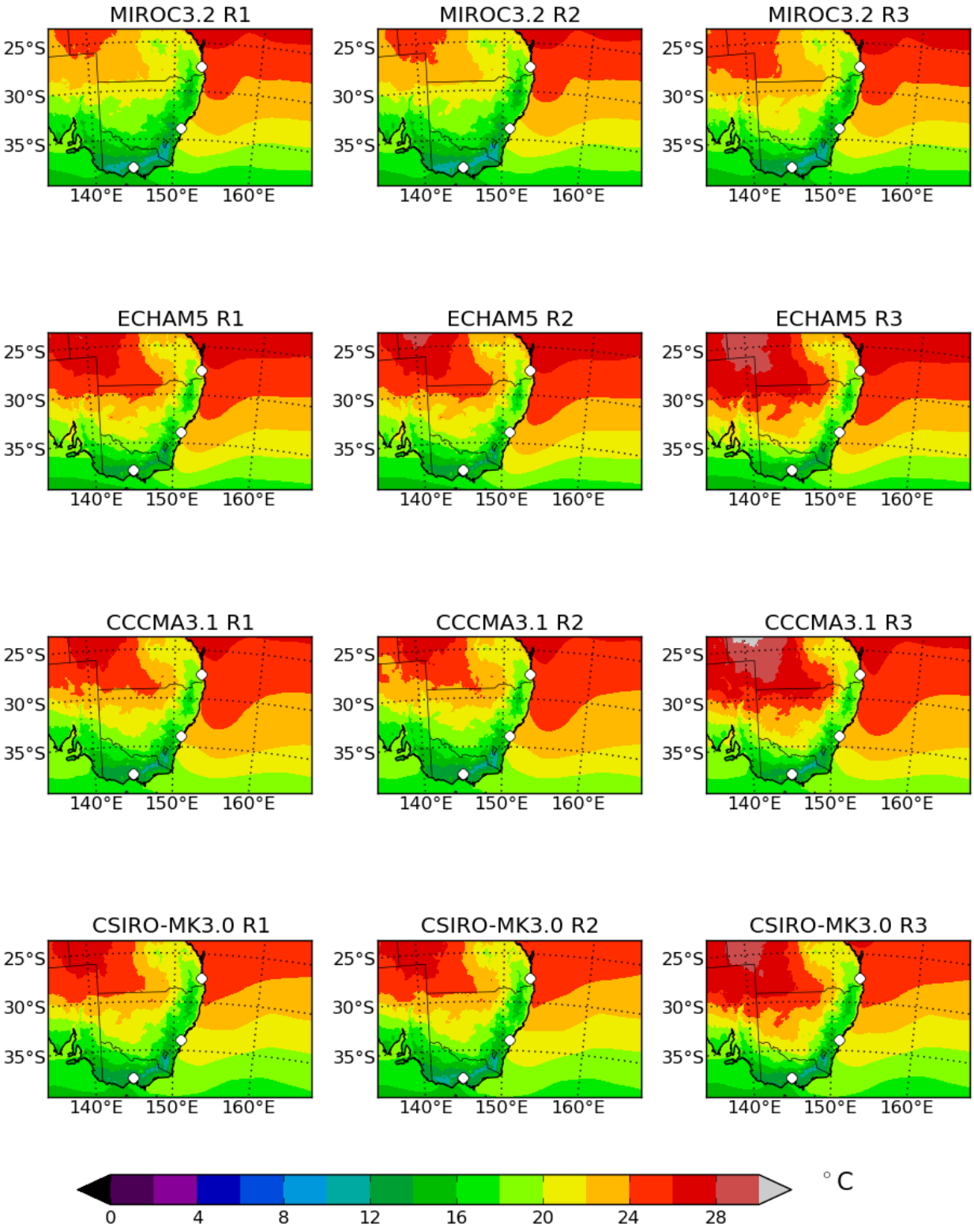

Figure 8.14: DJF mean of daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

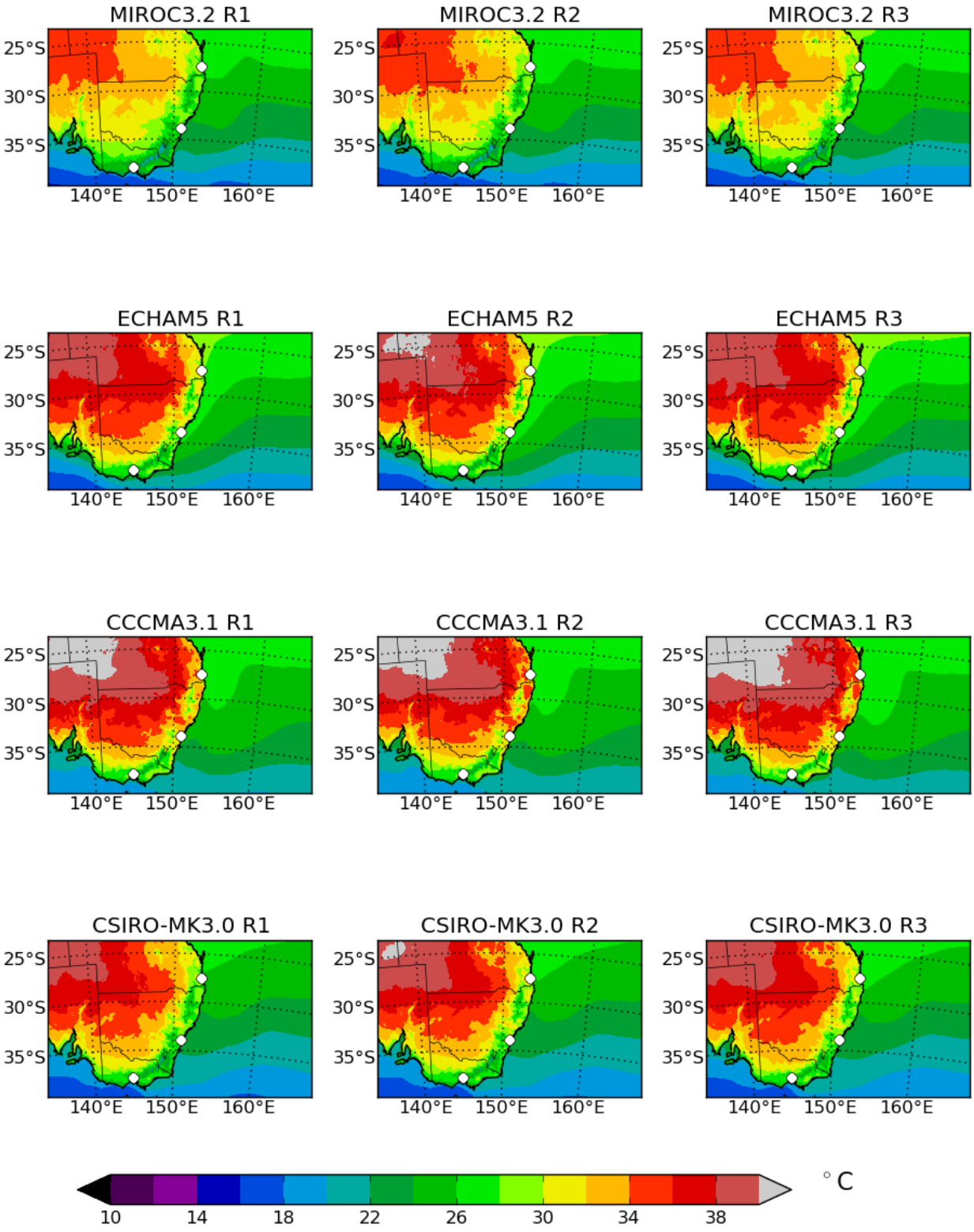

Figure 8.15: DJF mean of daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

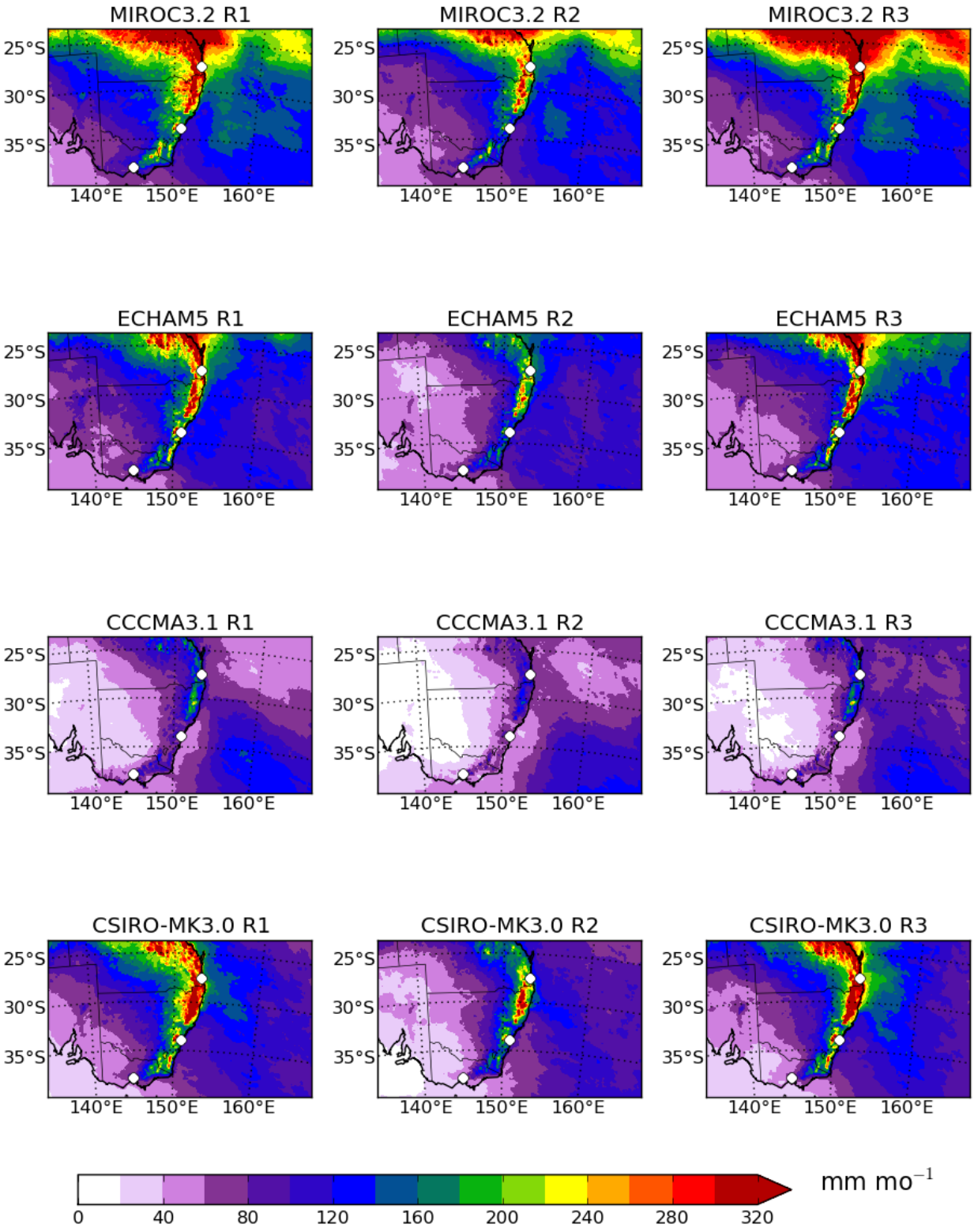

Figure 8.16: DJF mean of precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

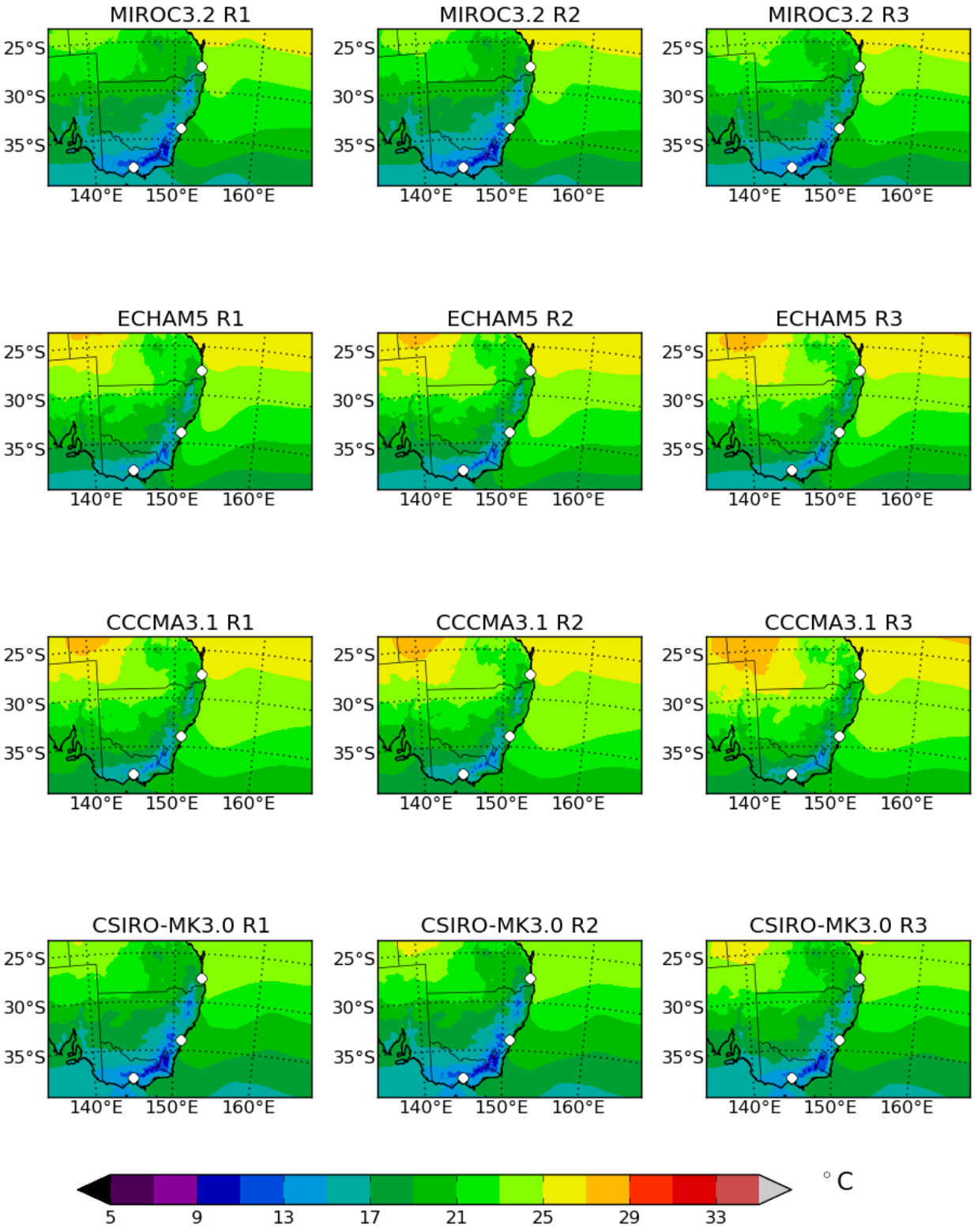

Figure 8.17: MAM mean of near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

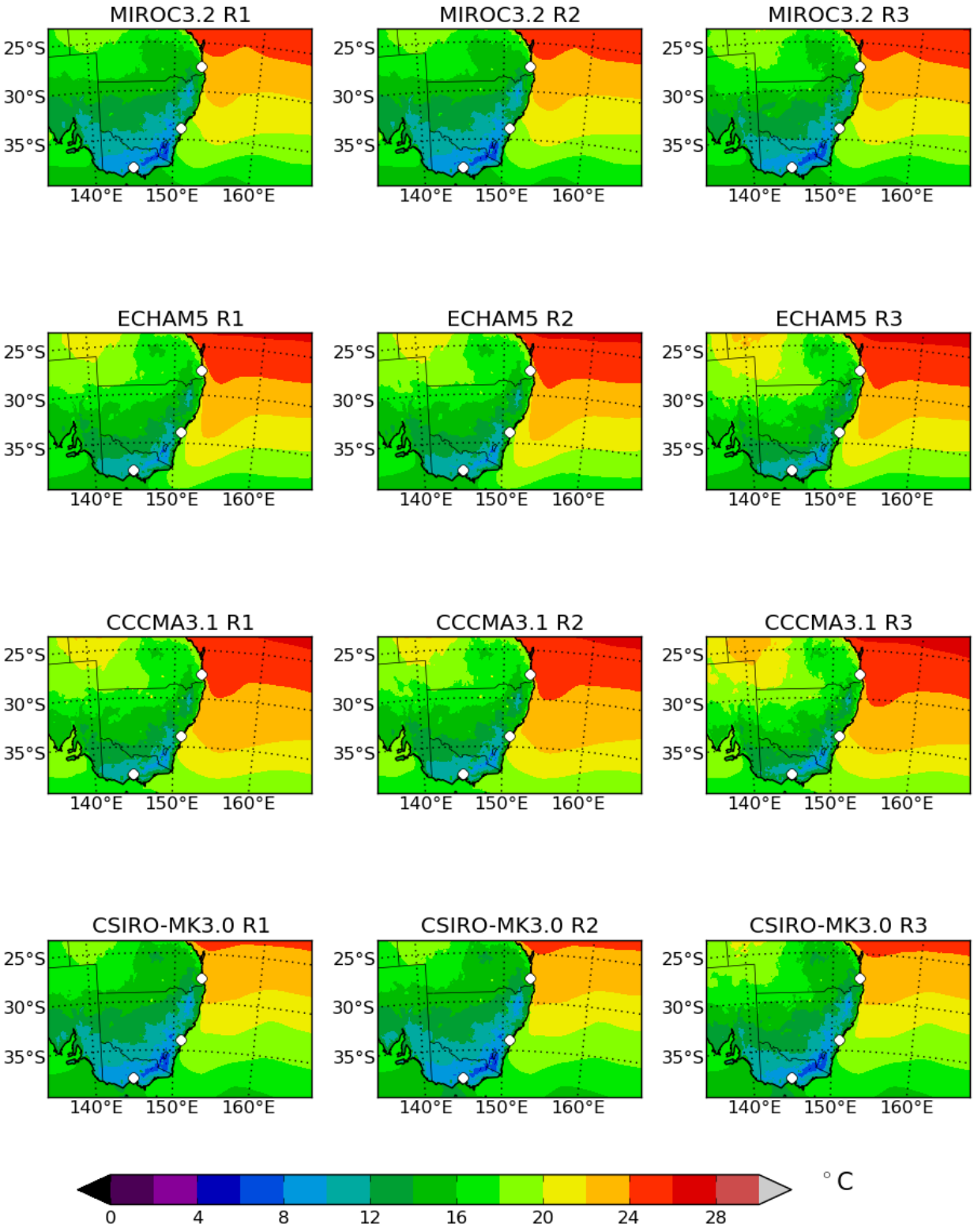

Figure 8.18: MAM mean of daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

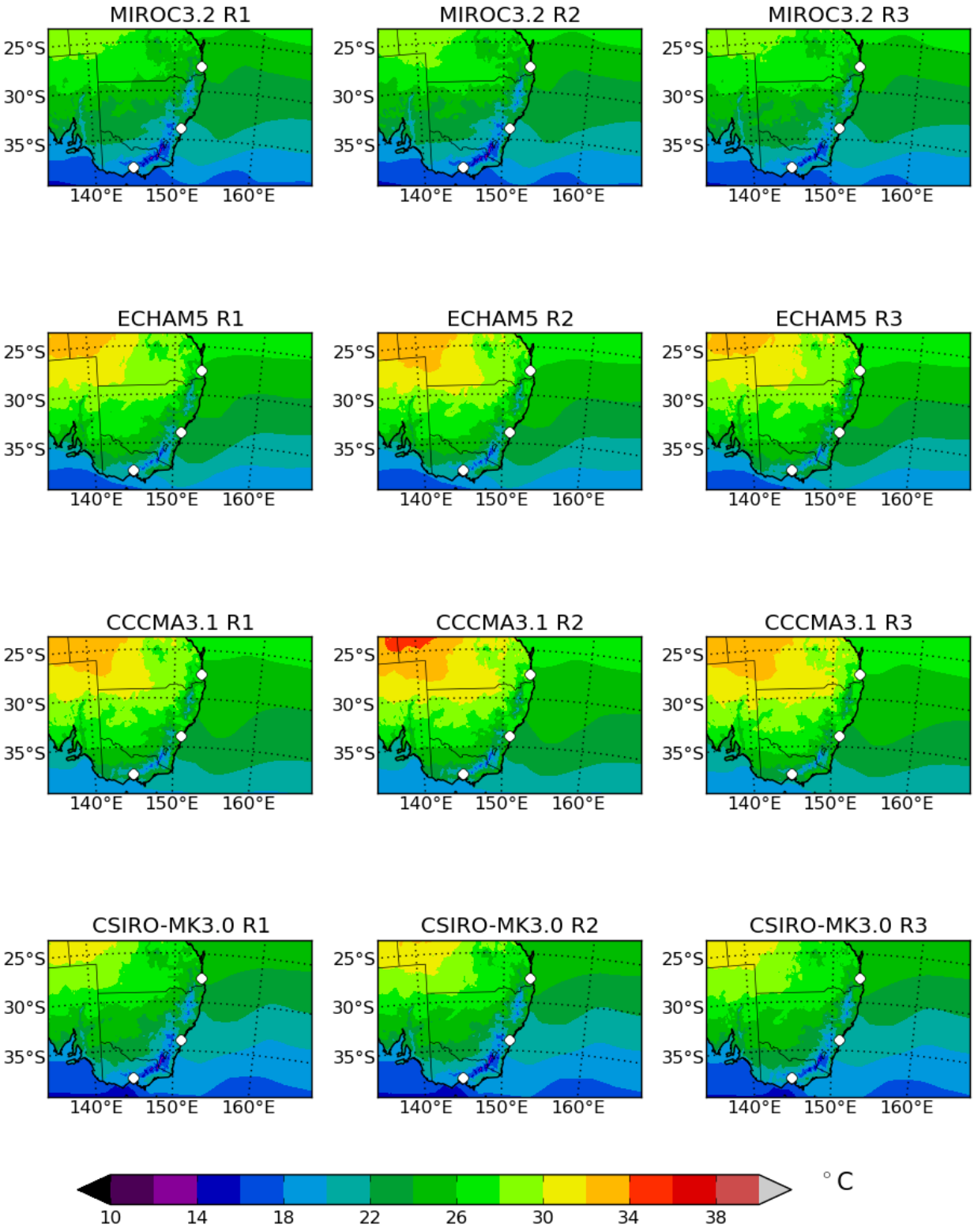

Figure 8.19: MAM mean of daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

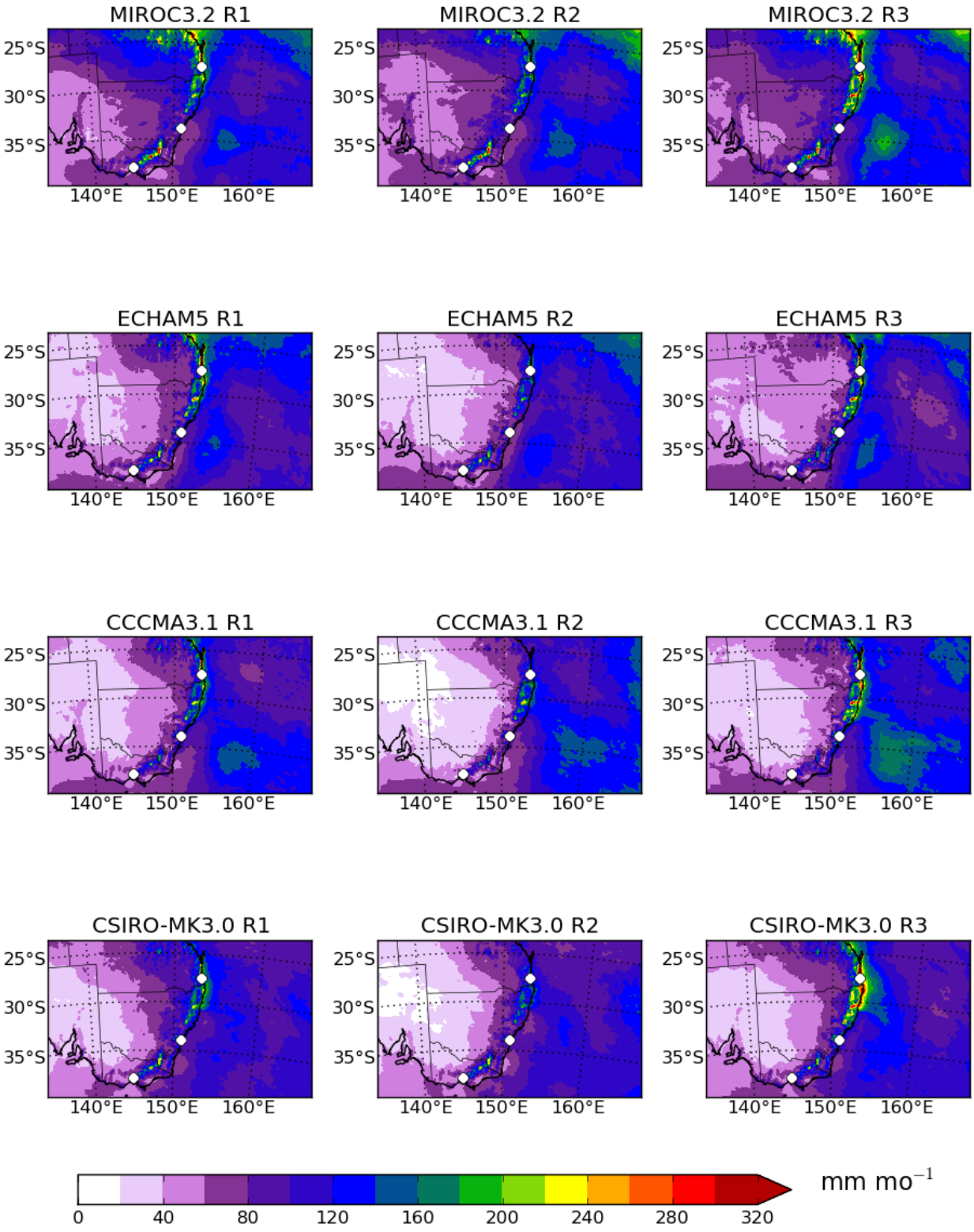

Figure 8.20: MAM mean of precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

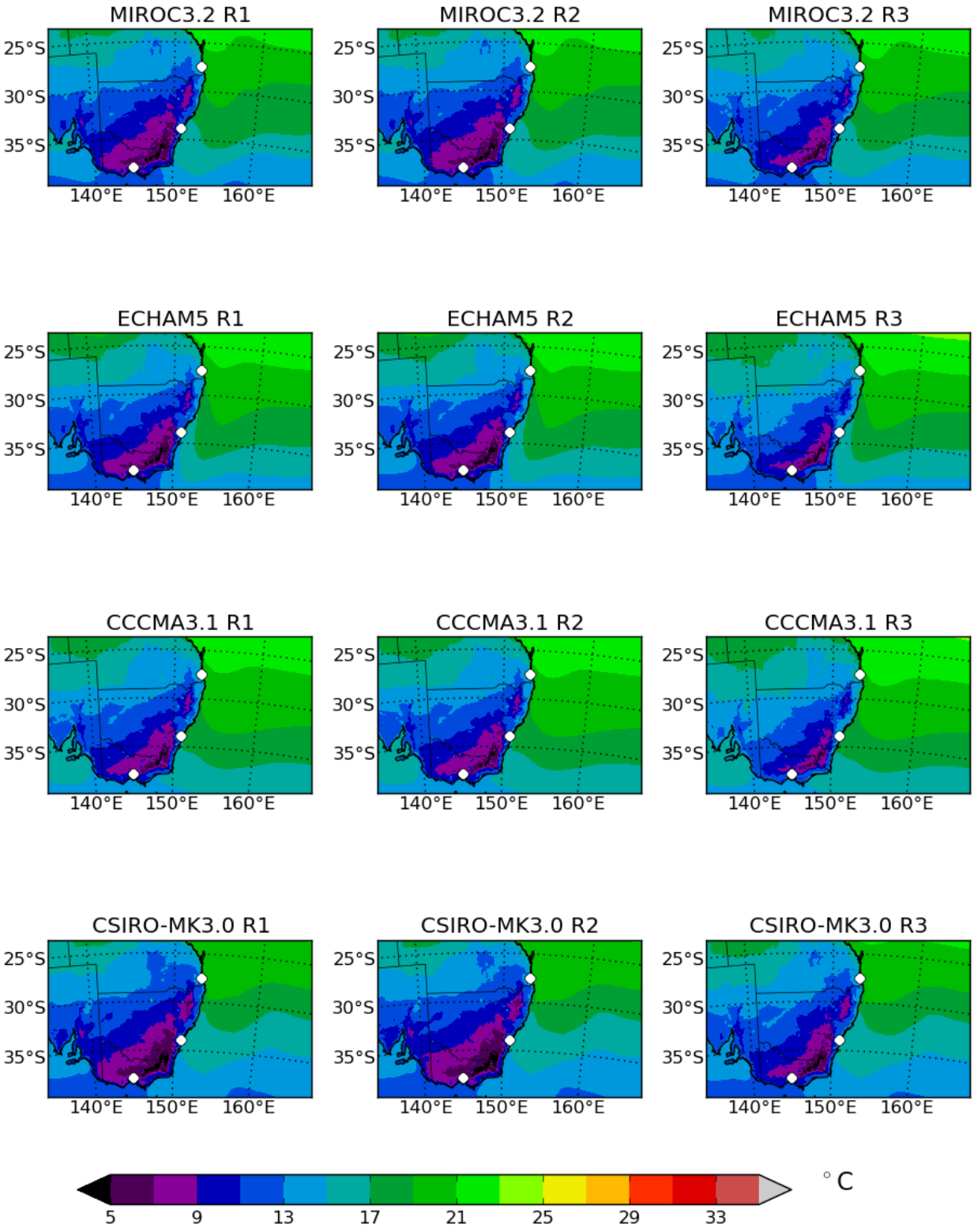

Figure 8.21: JJA mean of near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

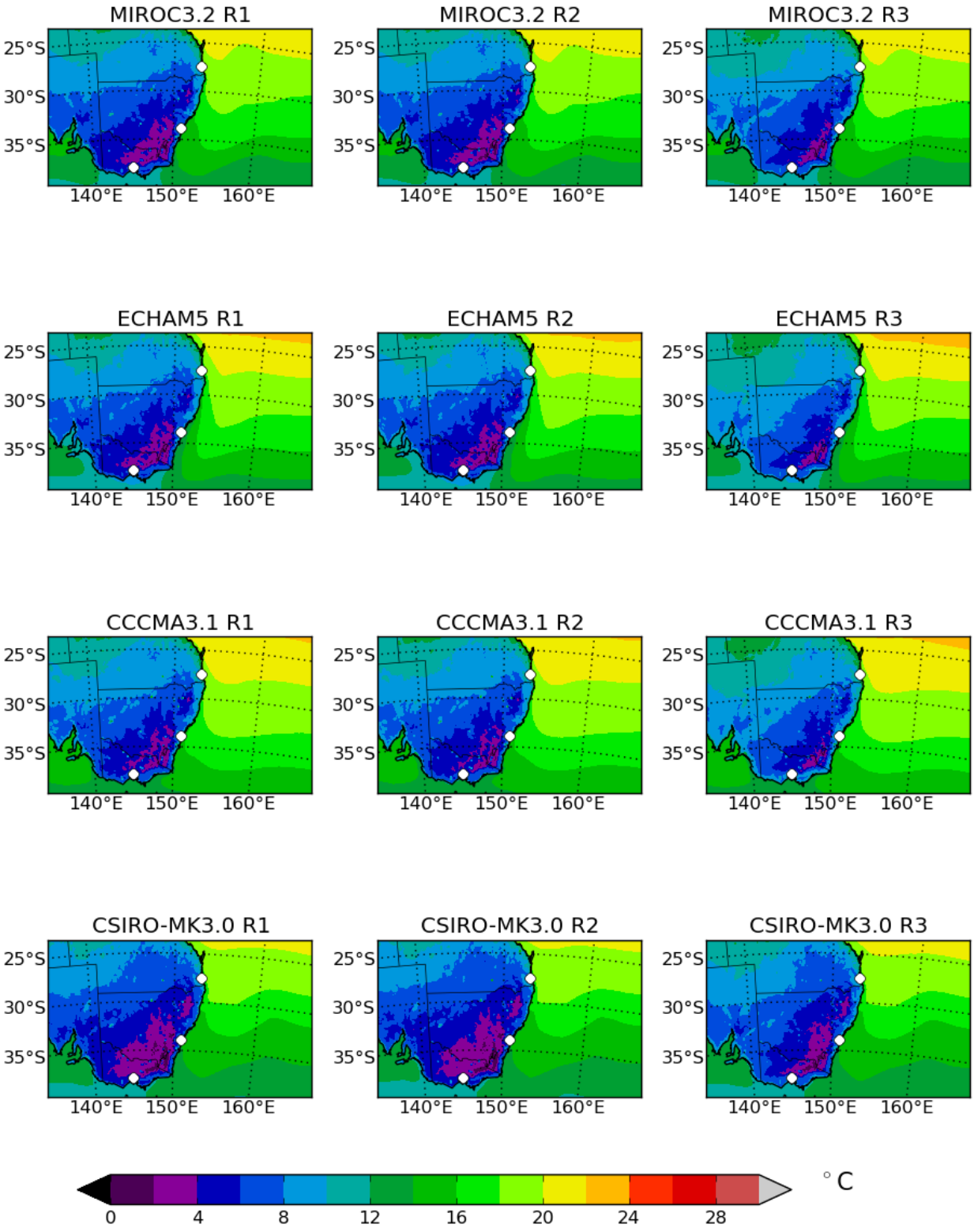

Figure 8.22: JJA mean of daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

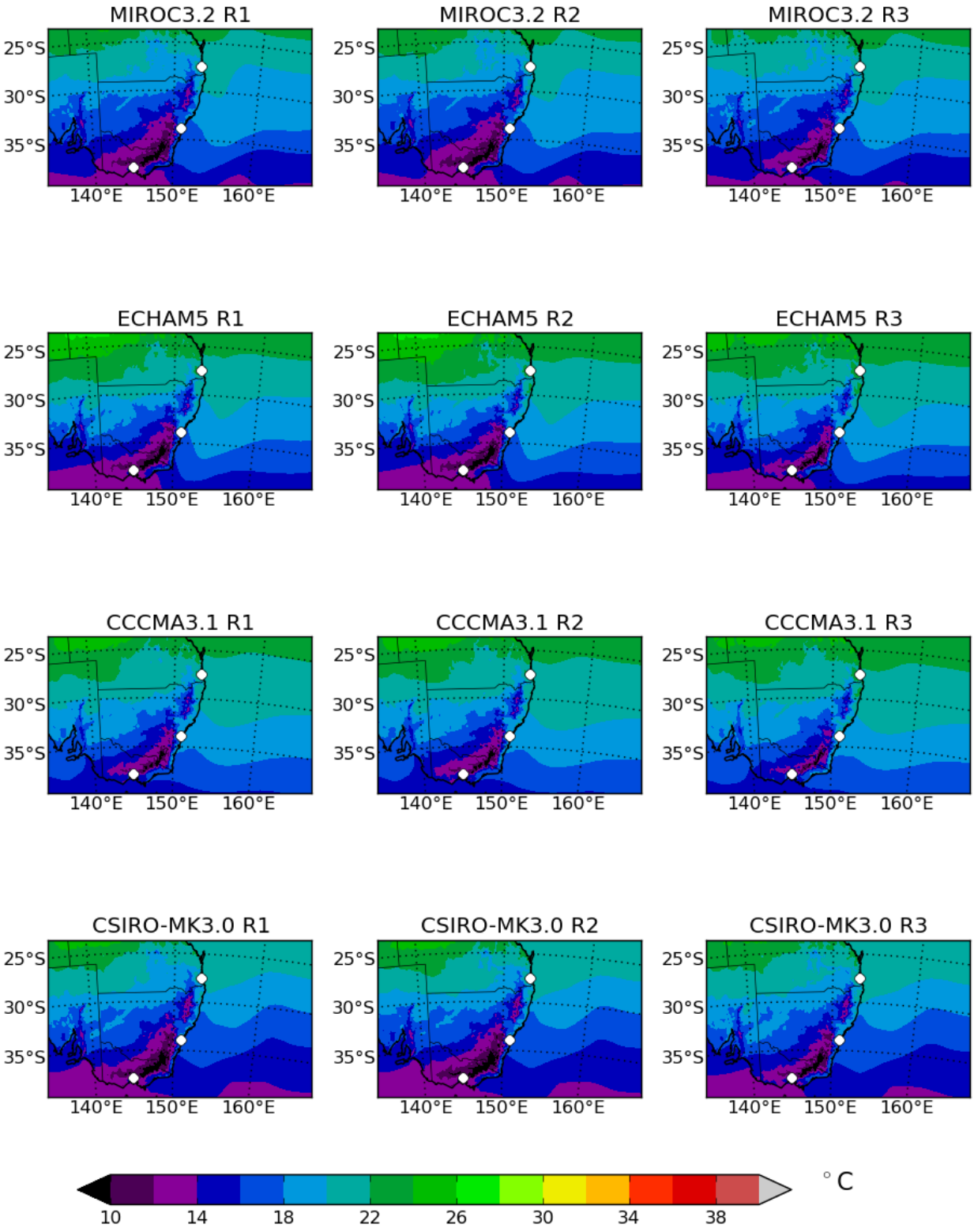

Figure 8.23: JJA mean of daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

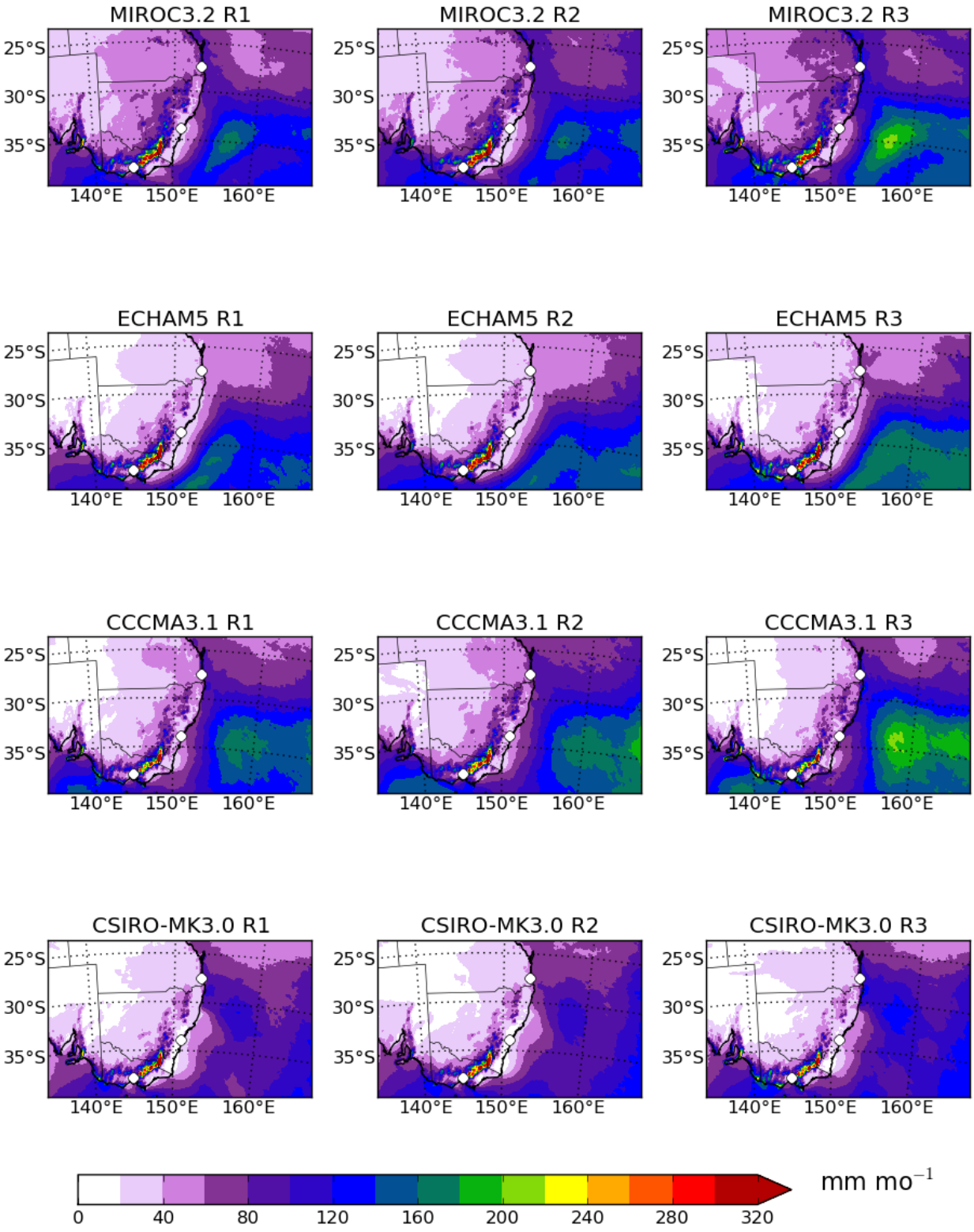

Figure 8.24: JJA mean of precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

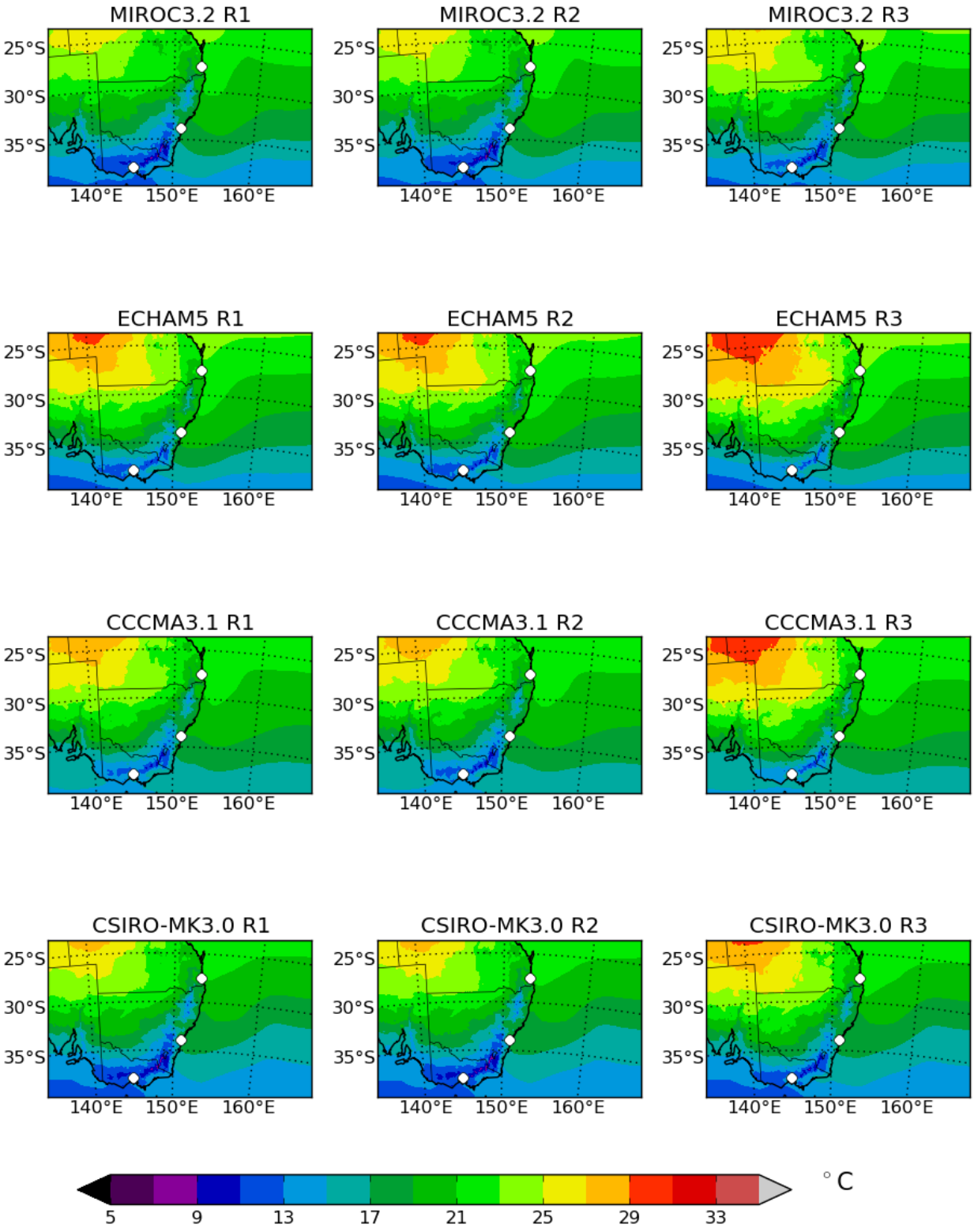

Figure 8.25: SON mean of near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

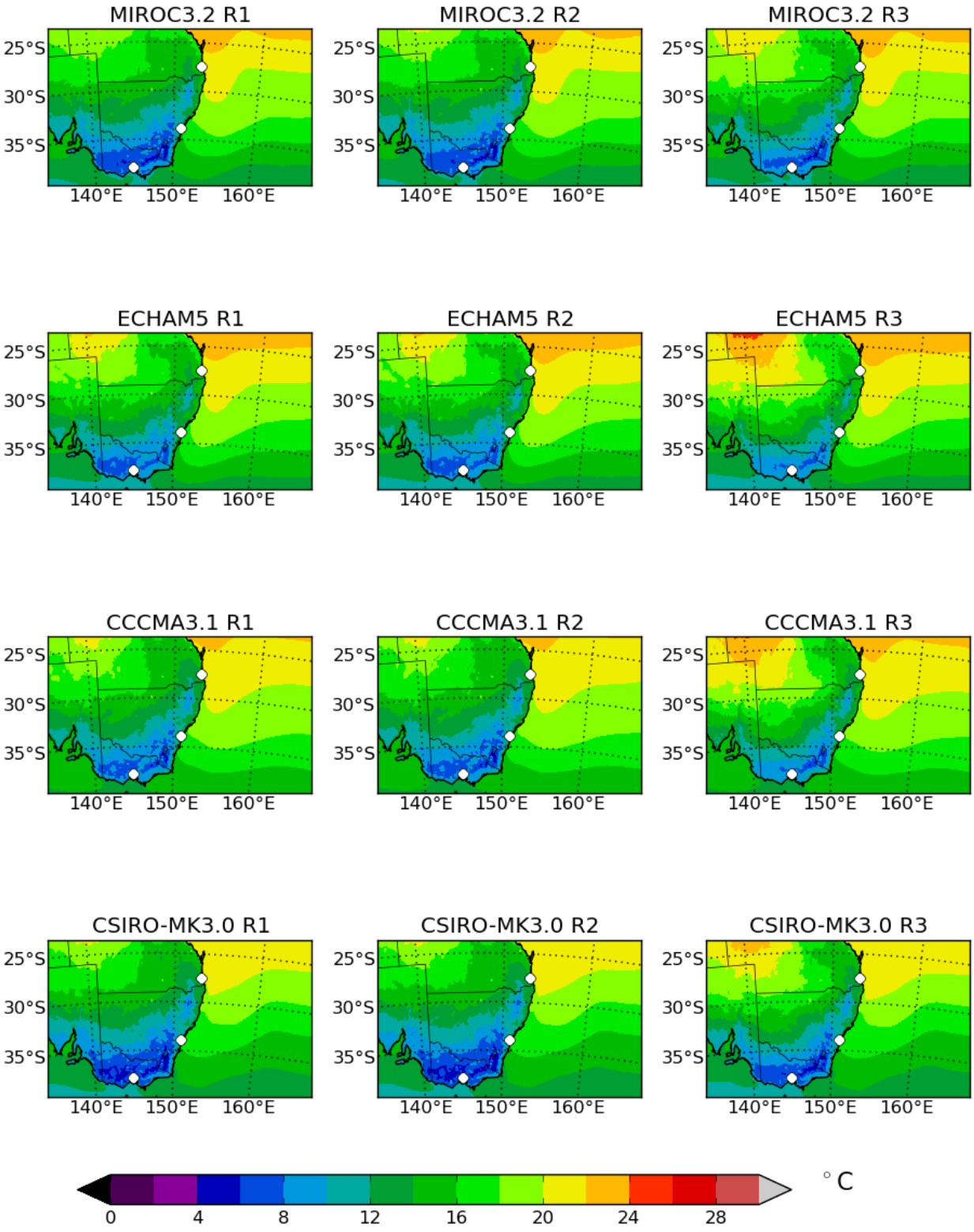

Figure 8.26: SON mean of daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

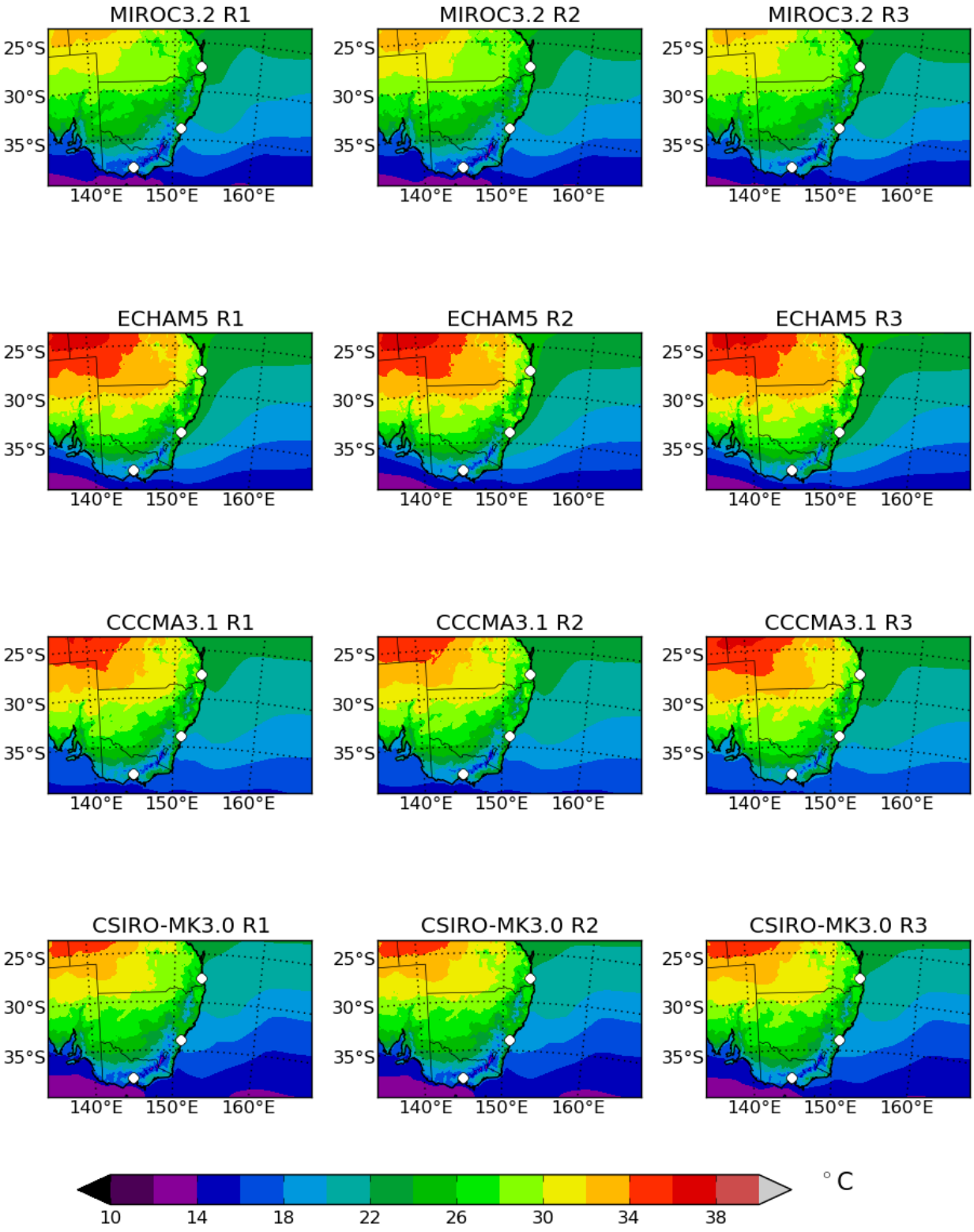

Figure 8.27: SON mean of daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

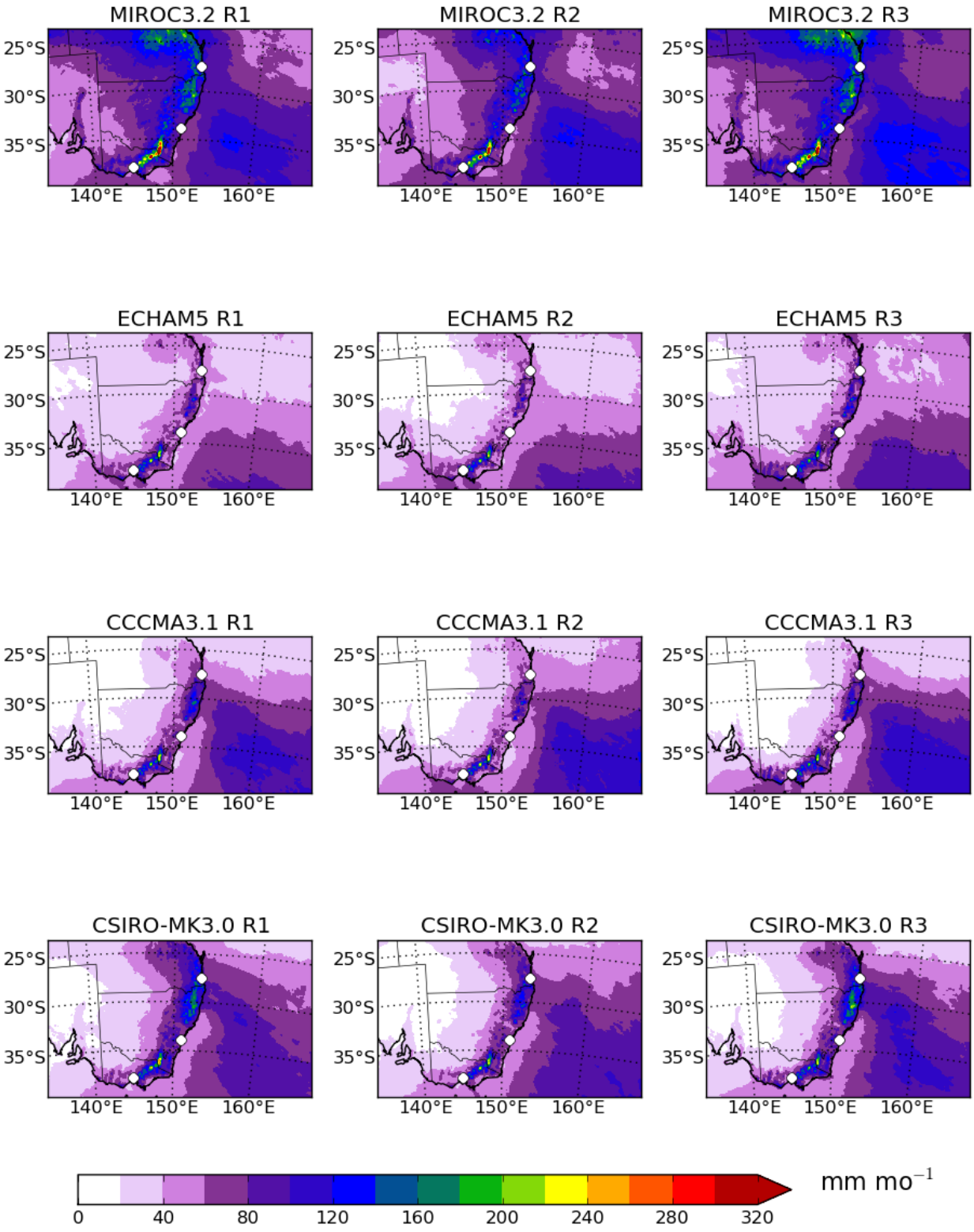

Figure 8.28: SON mean of precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

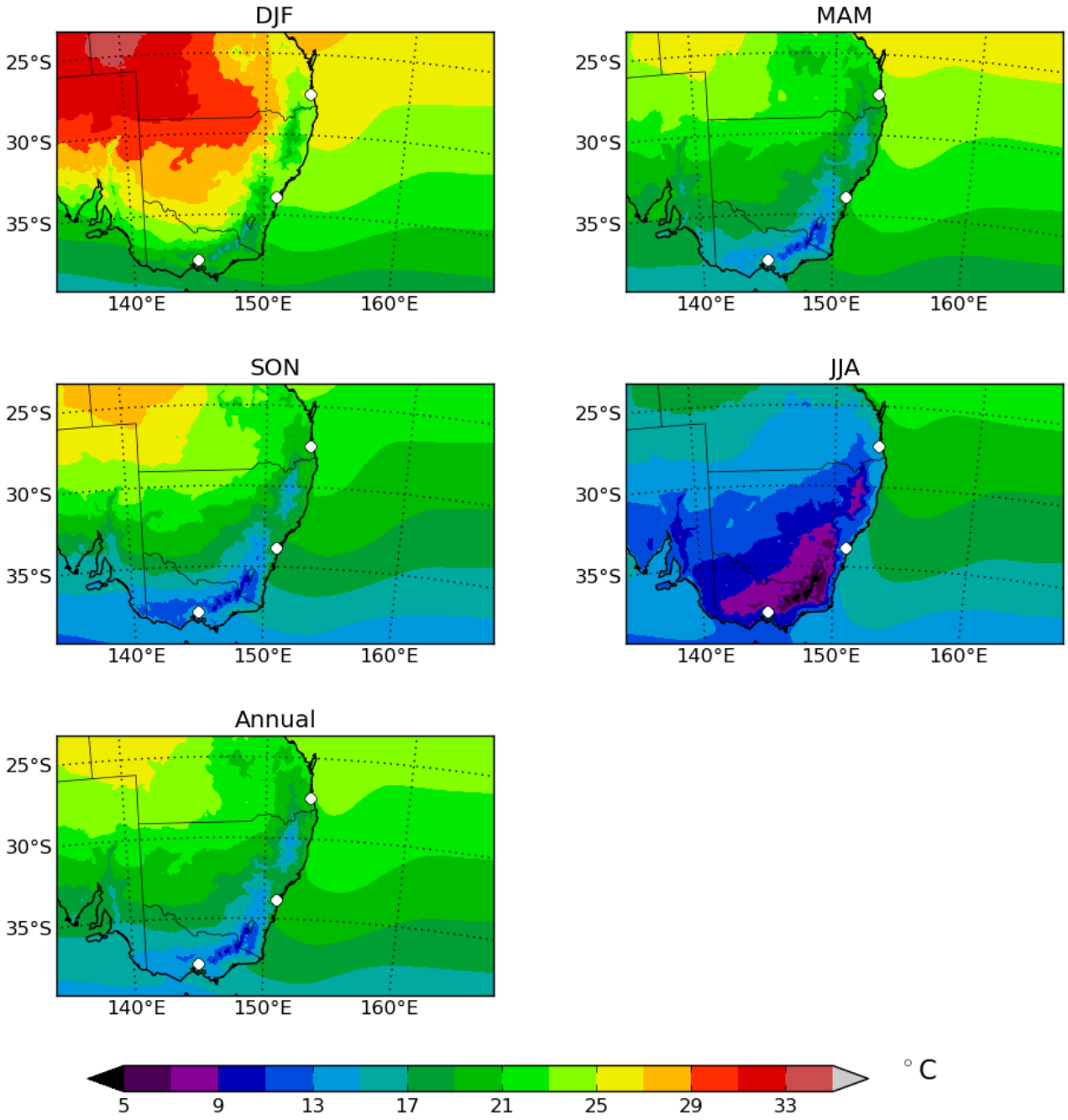

Figure 8.29: Seasonal and annual multimodel means of near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

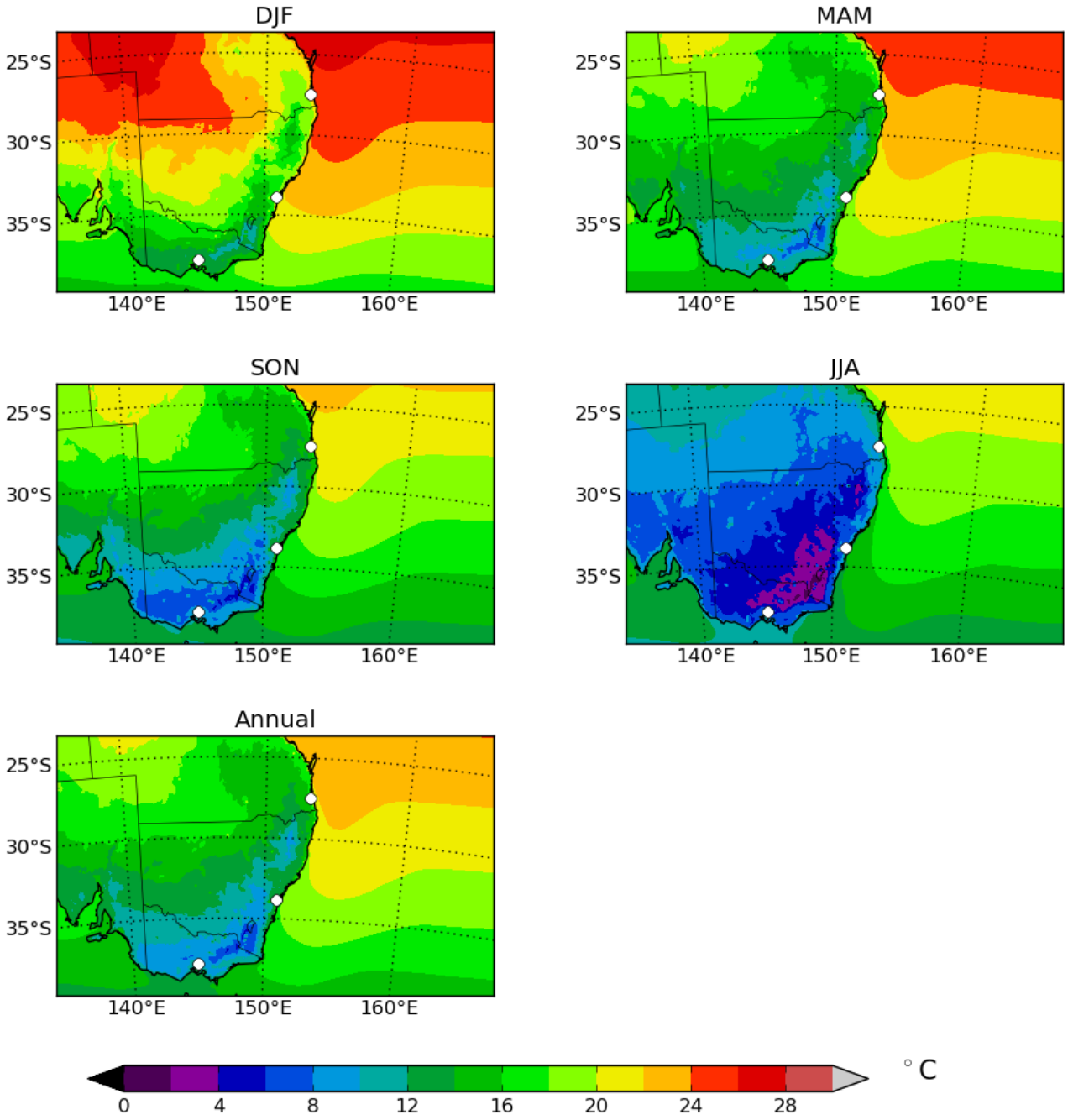

Figure 8.30: Seasonal and annual multimodel means of daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

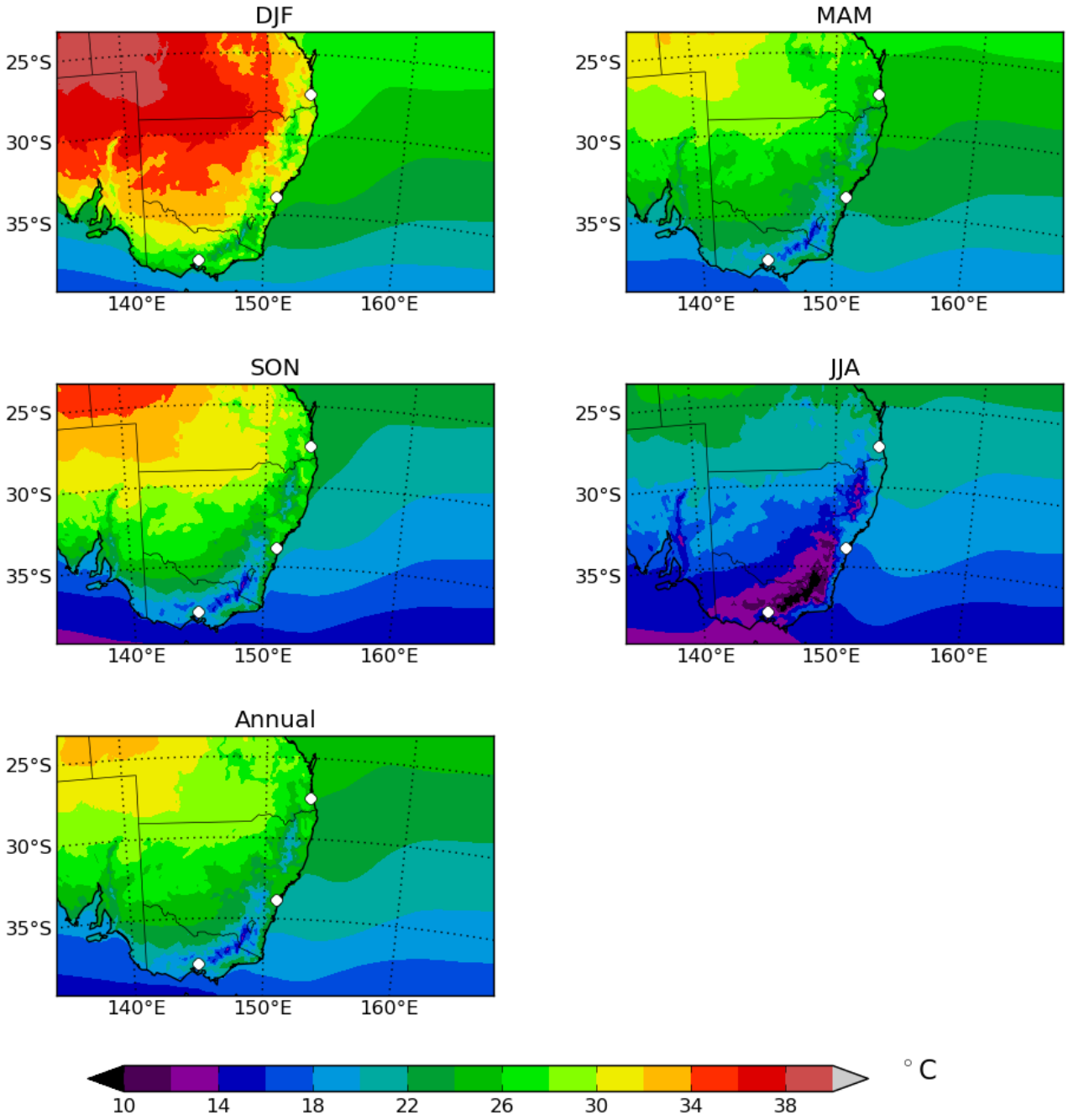

Figure 8.31: Seasonal and annual multimodel means of daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

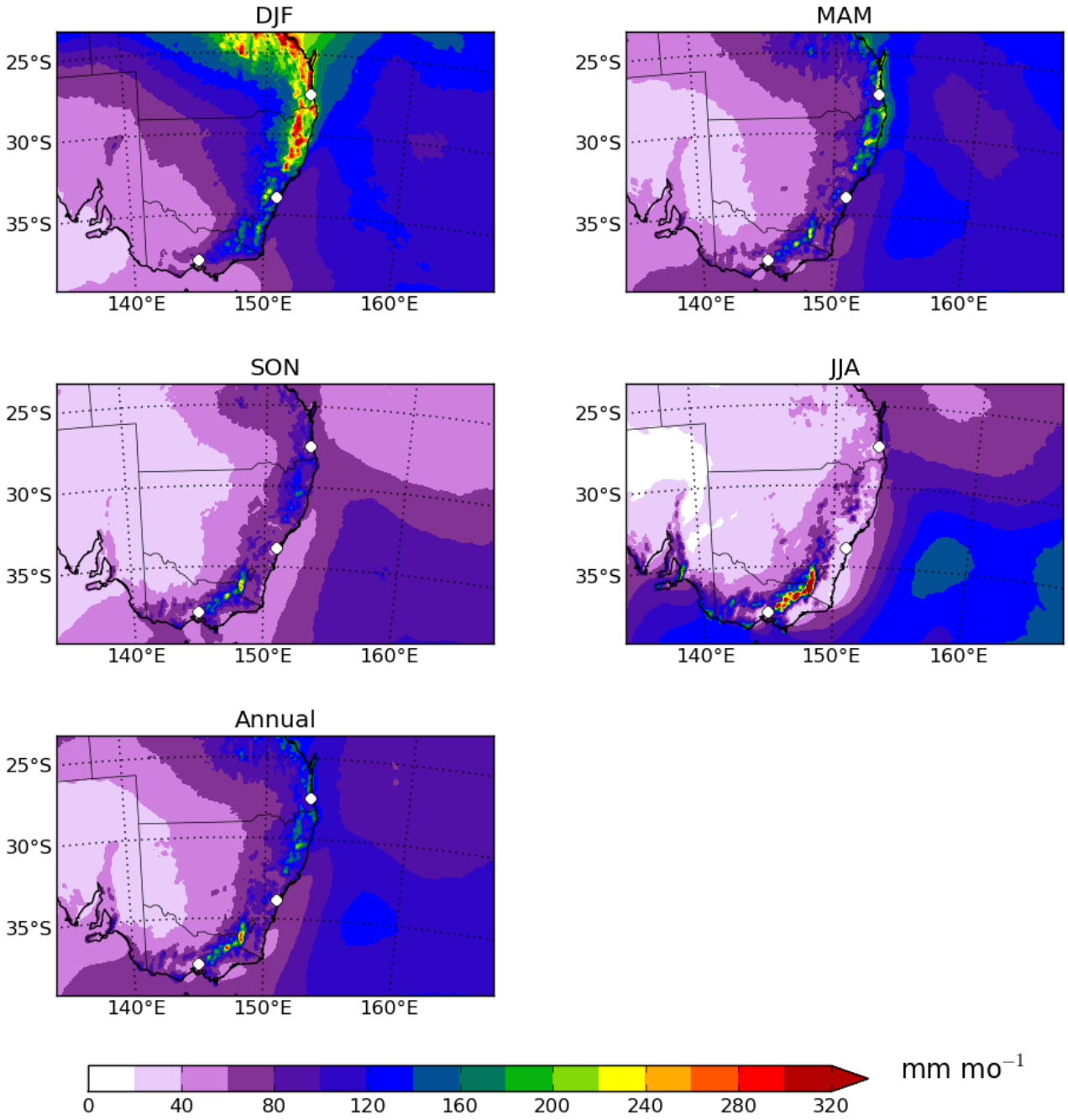

Figure 8.32: Seasonal and annual multimodel means of precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

8.3 2060-2079 Bias-Corrected Regional Model Output

This subsection contains projected climatologies for far-future daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the bias-corrected RCM output (*i.e.* RCM output that has been corrected for the present-day biases between the models and the observations of climate using the methods described here [6]). The corrections are calculated by comparing present-day distributions of daily model output and observations for all seasons. Thus, the corrections are independent of the season. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected climatologies, whereas the individual-model plots show the level of uncertainty in projected climate.

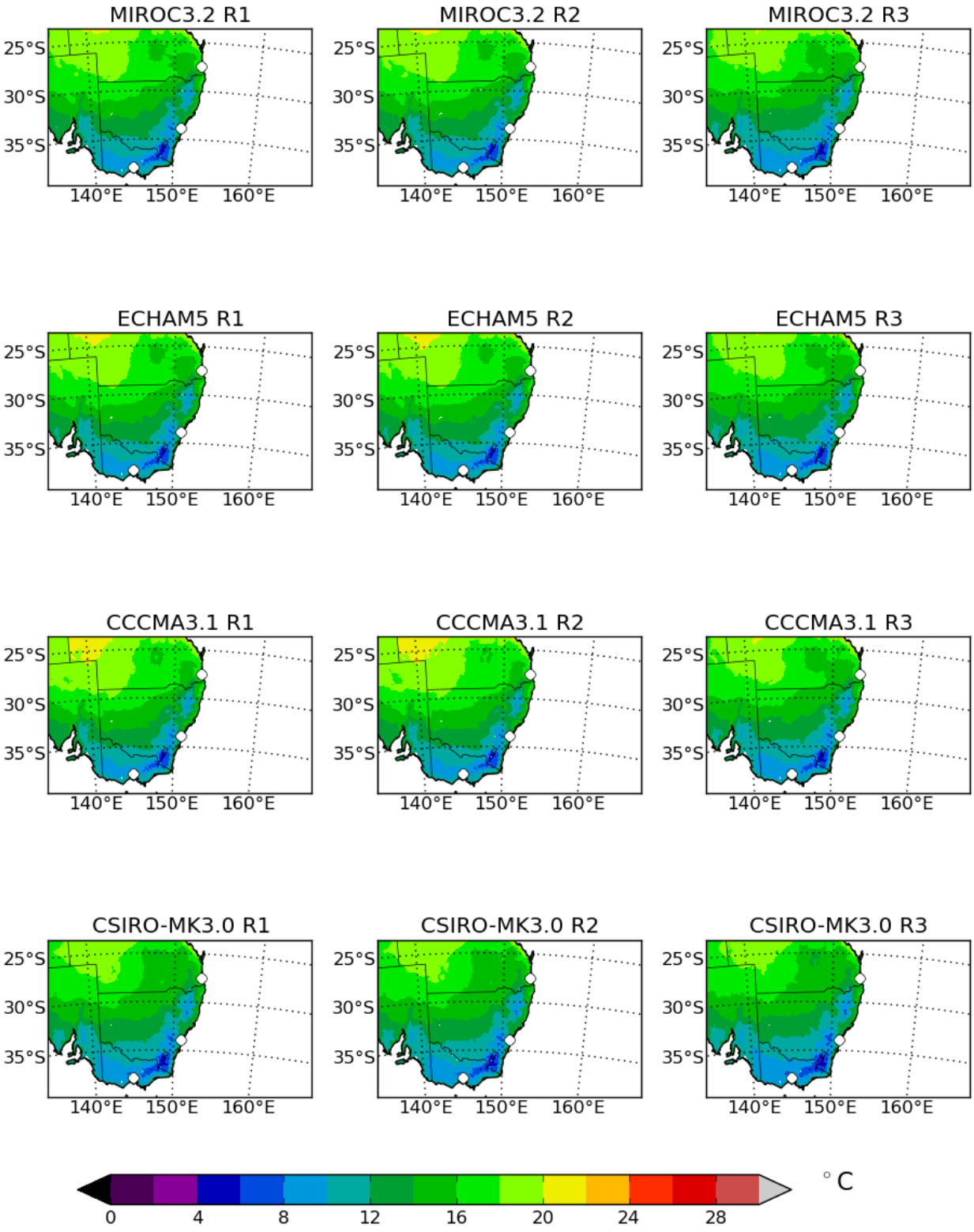

Figure 8.33: Annual mean of bias-corrected daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

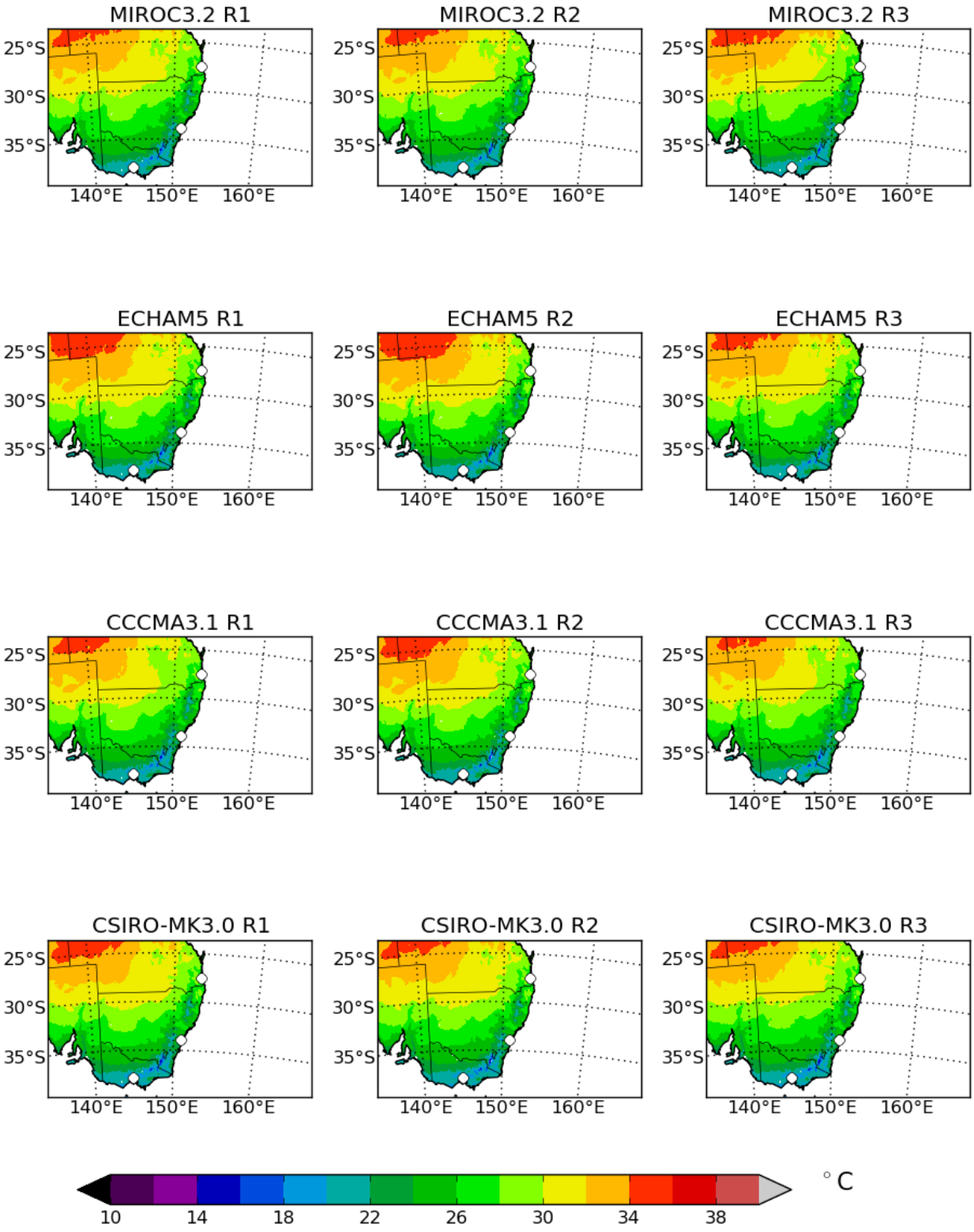

Figure 8.34: Annual mean of bias-corrected daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

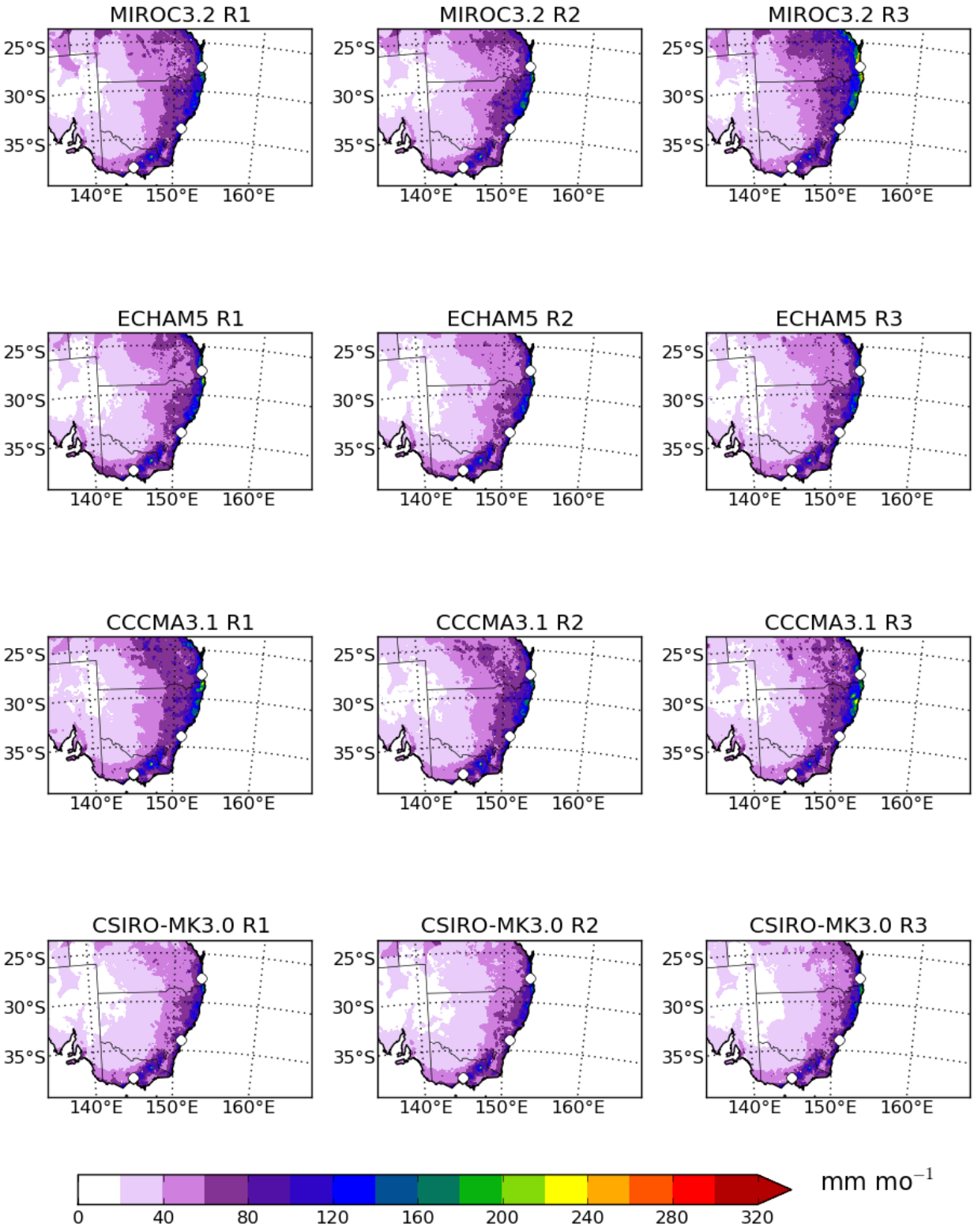

Figure 8.35: Annual mean of bias-corrected precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

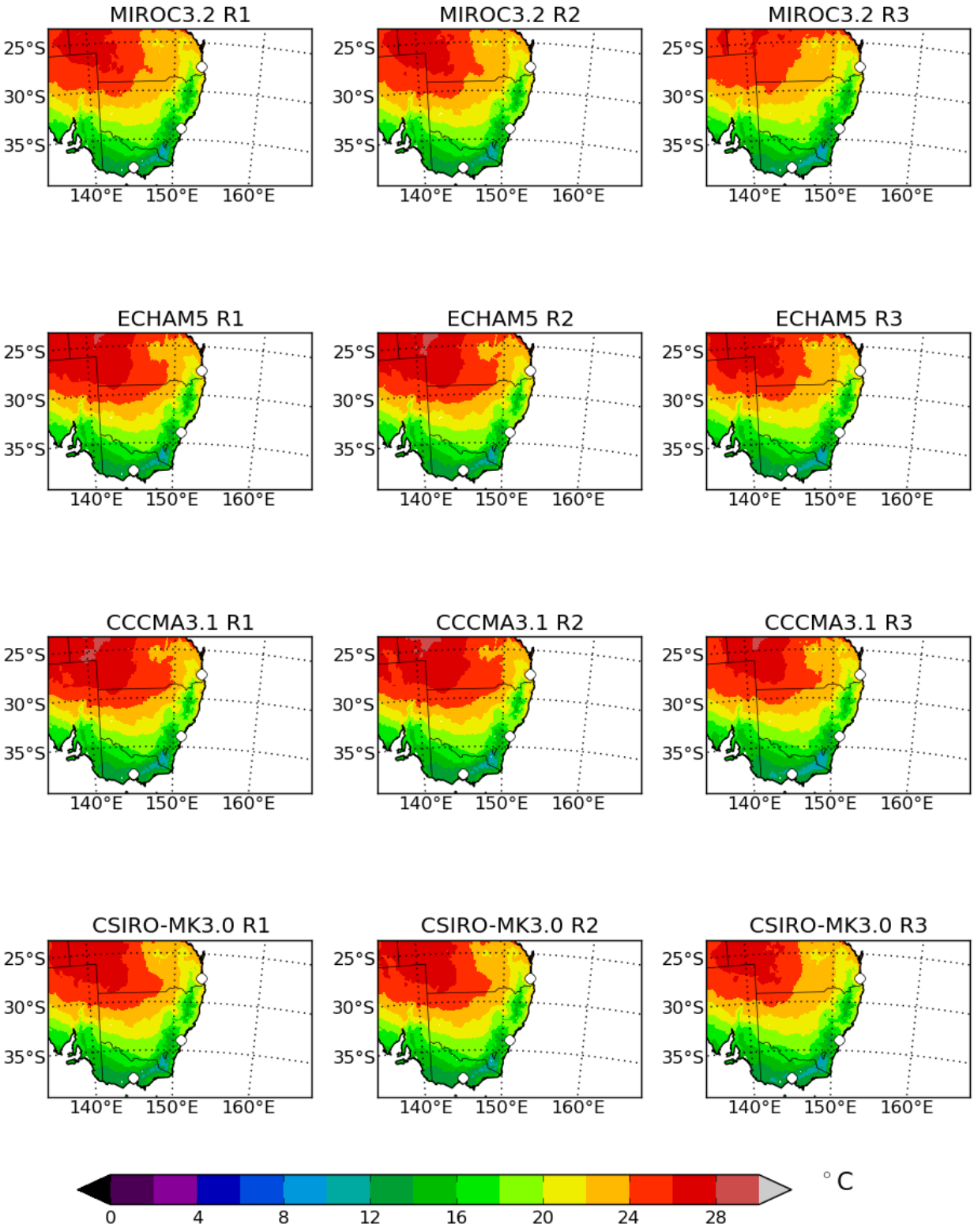

Figure 8.36: DJF mean of bias-corrected daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

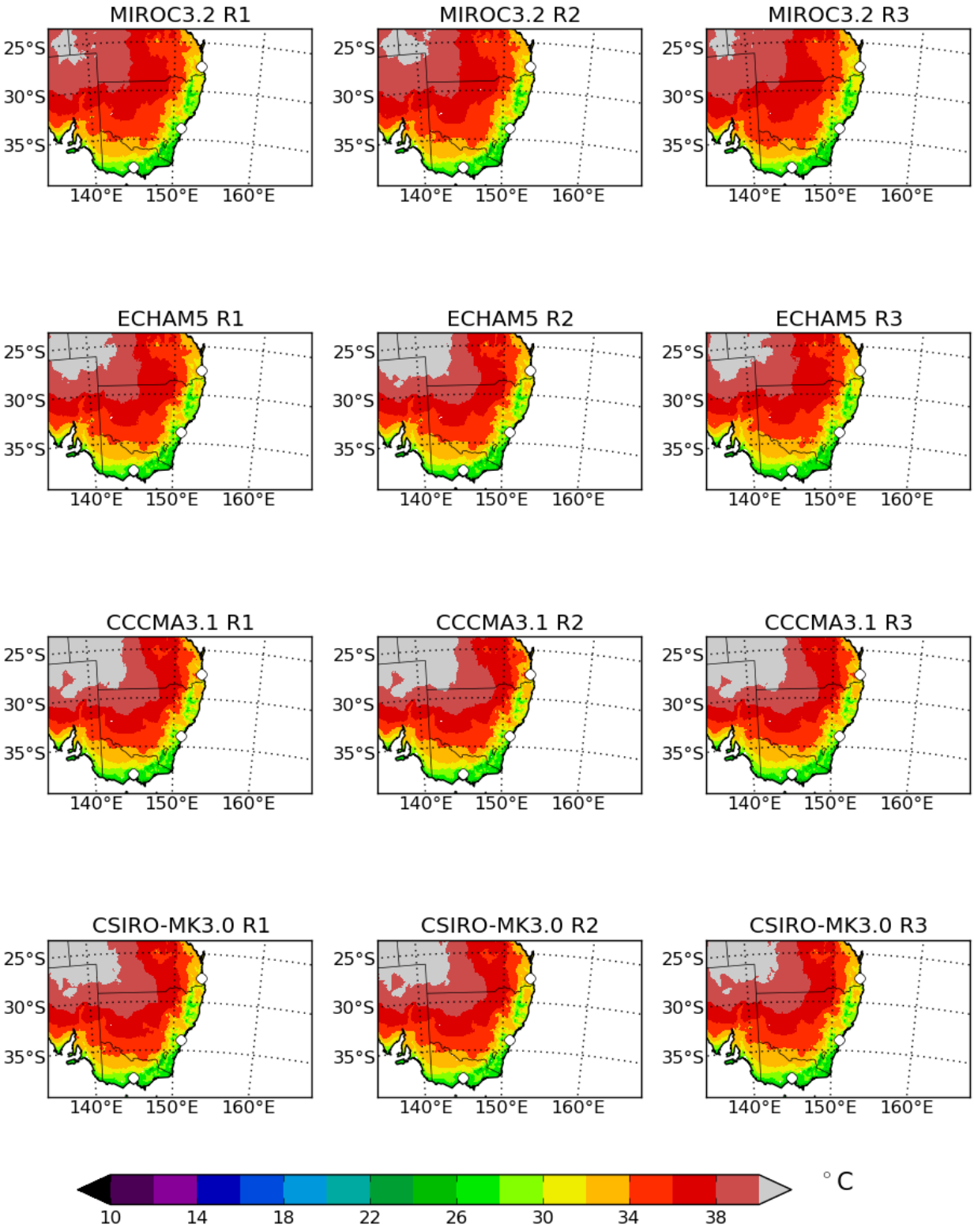

Figure 8.37: DJF mean of bias-corrected daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

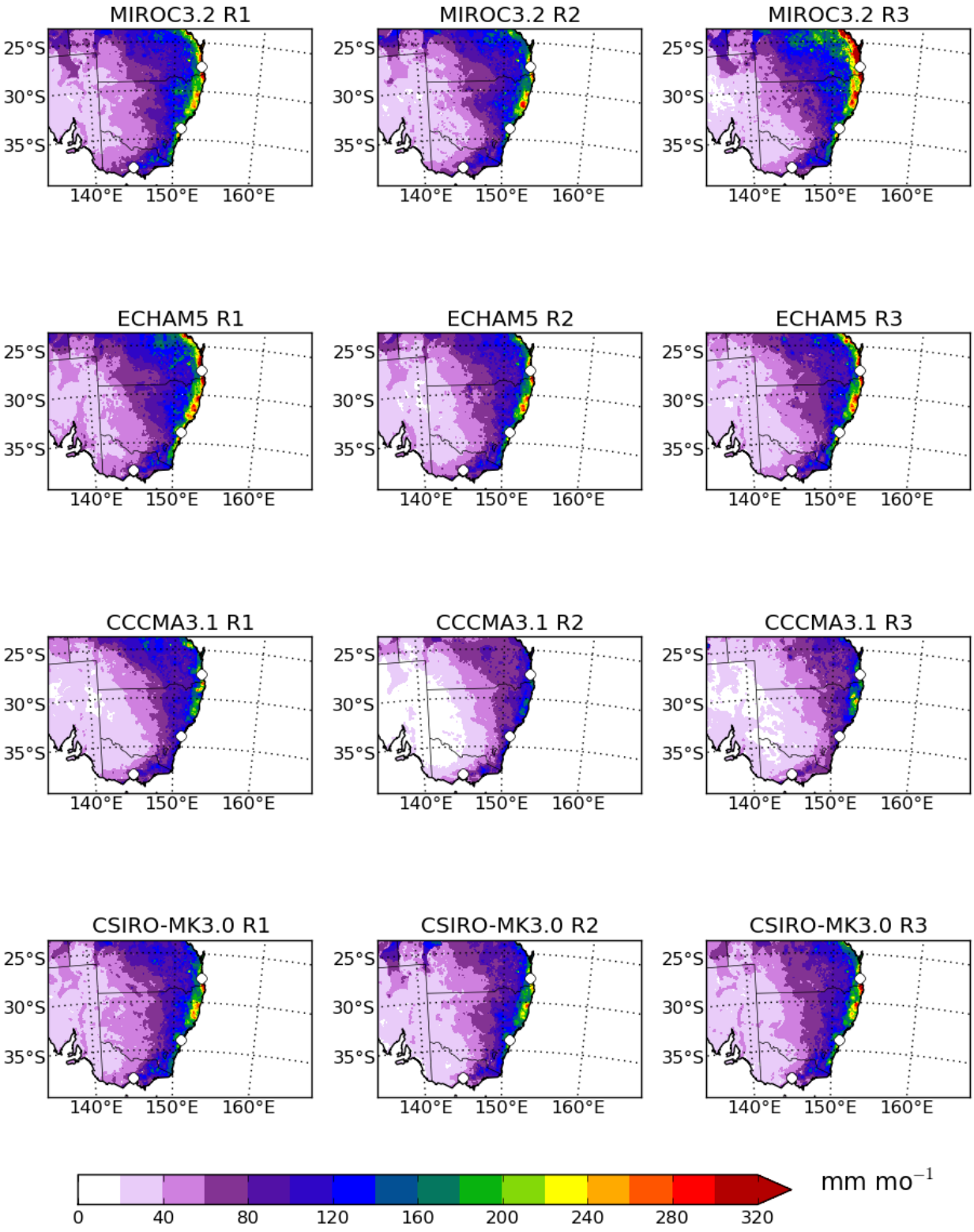

Figure 8.38: DJF mean of bias-corrected precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

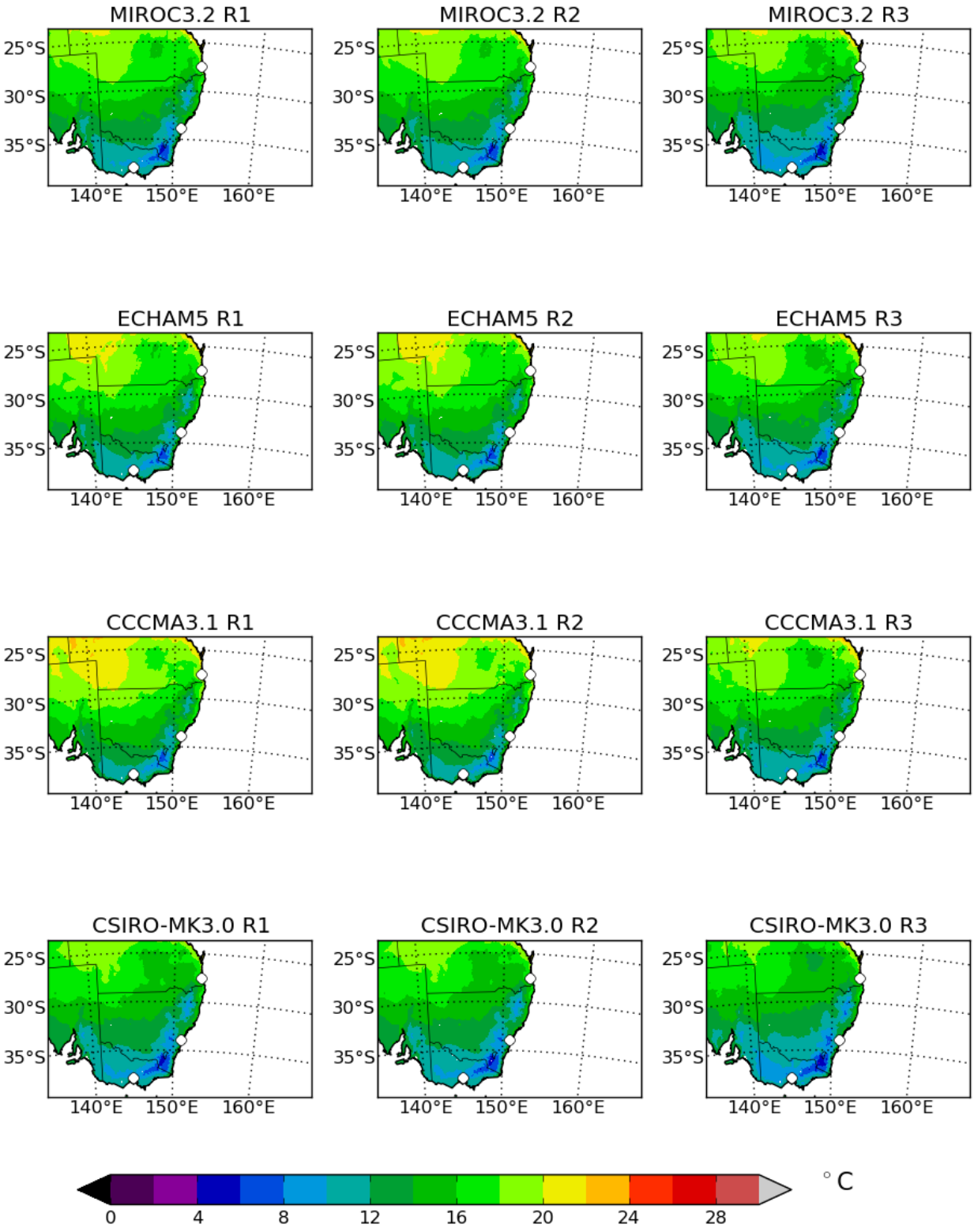

Figure 8.39: MAM mean of bias-corrected daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

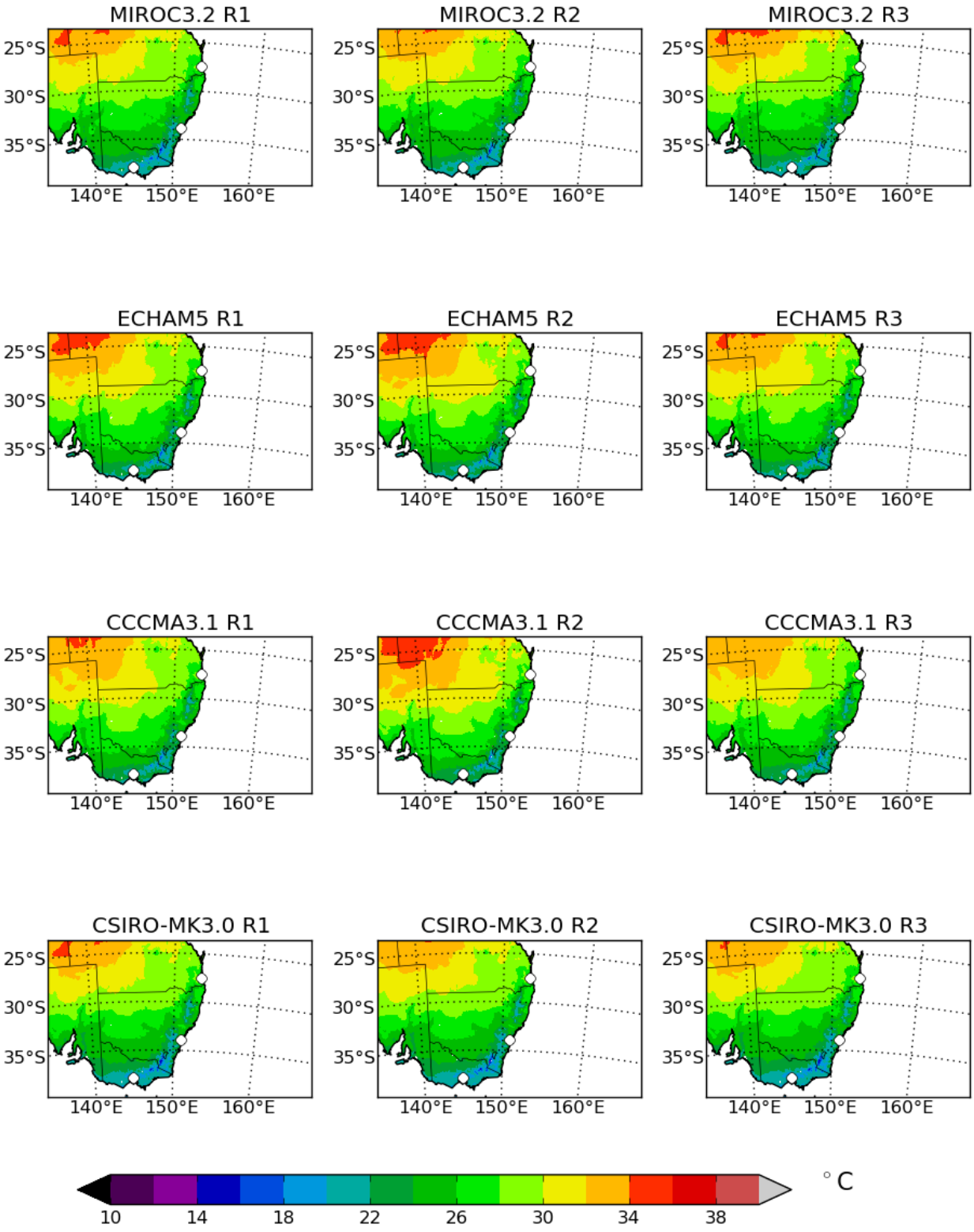

Figure 8.40: MAM mean of bias-corrected daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

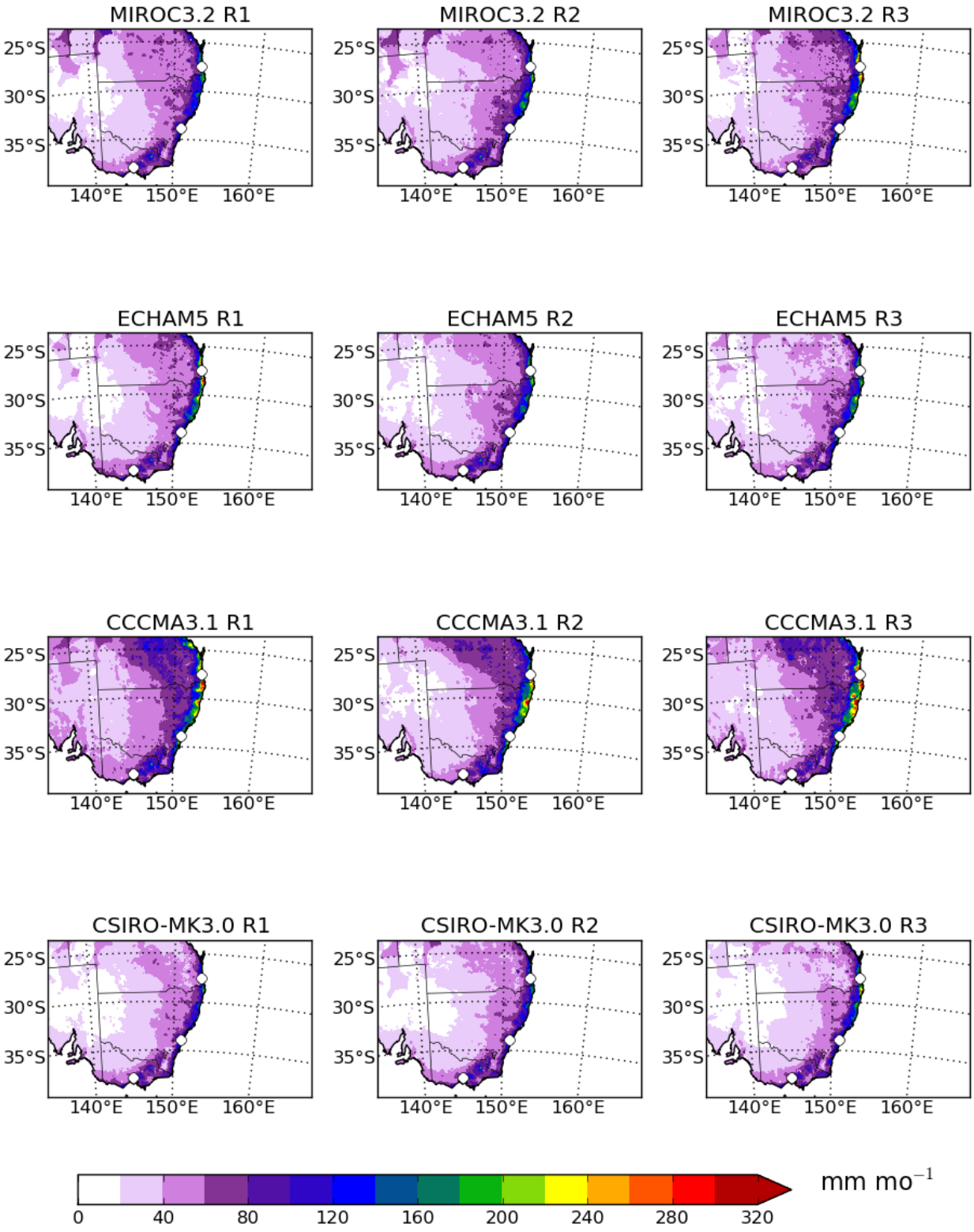

Figure 8.41: MAM mean of bias-corrected precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

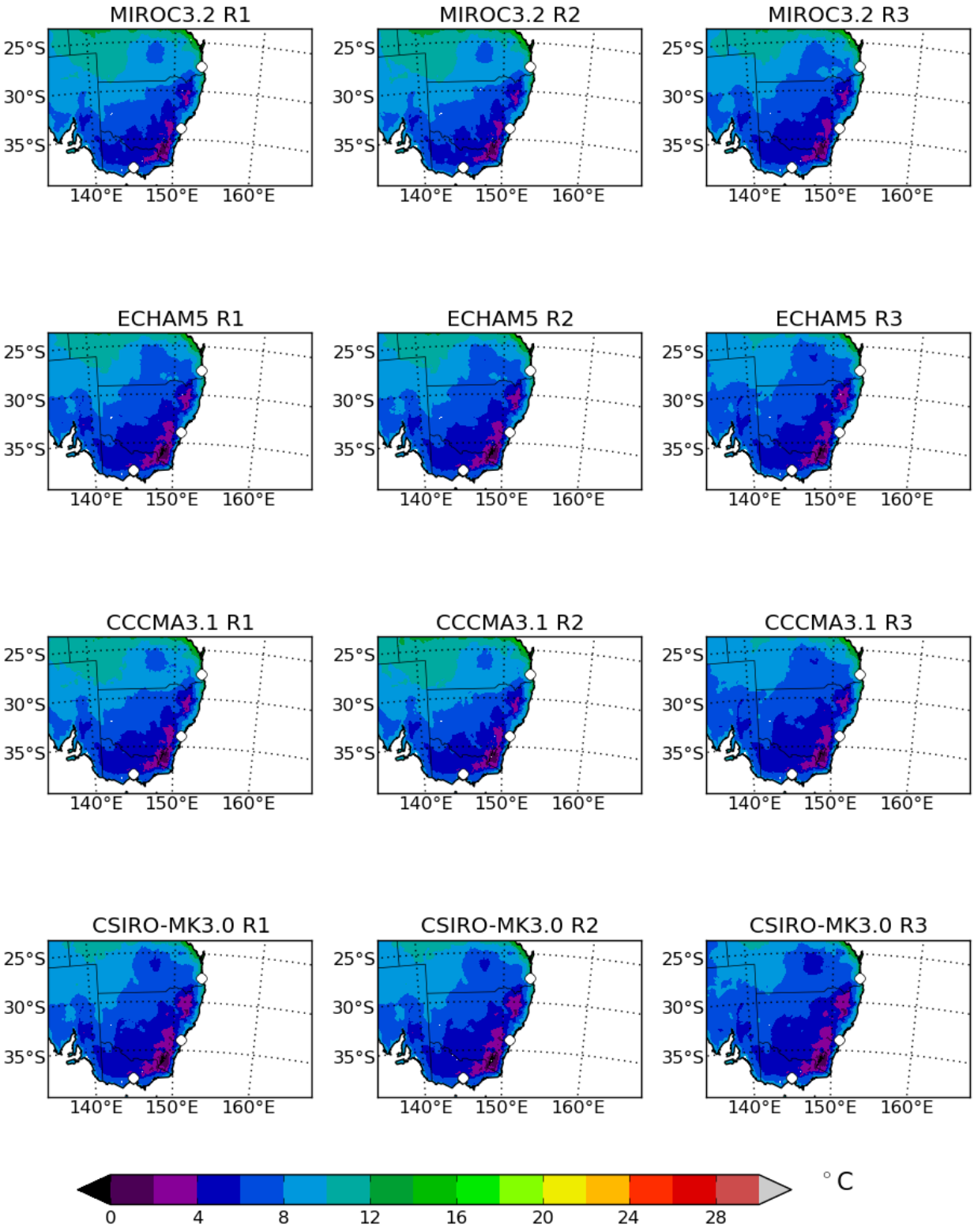

Figure 8.42: JJA mean of bias-corrected daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

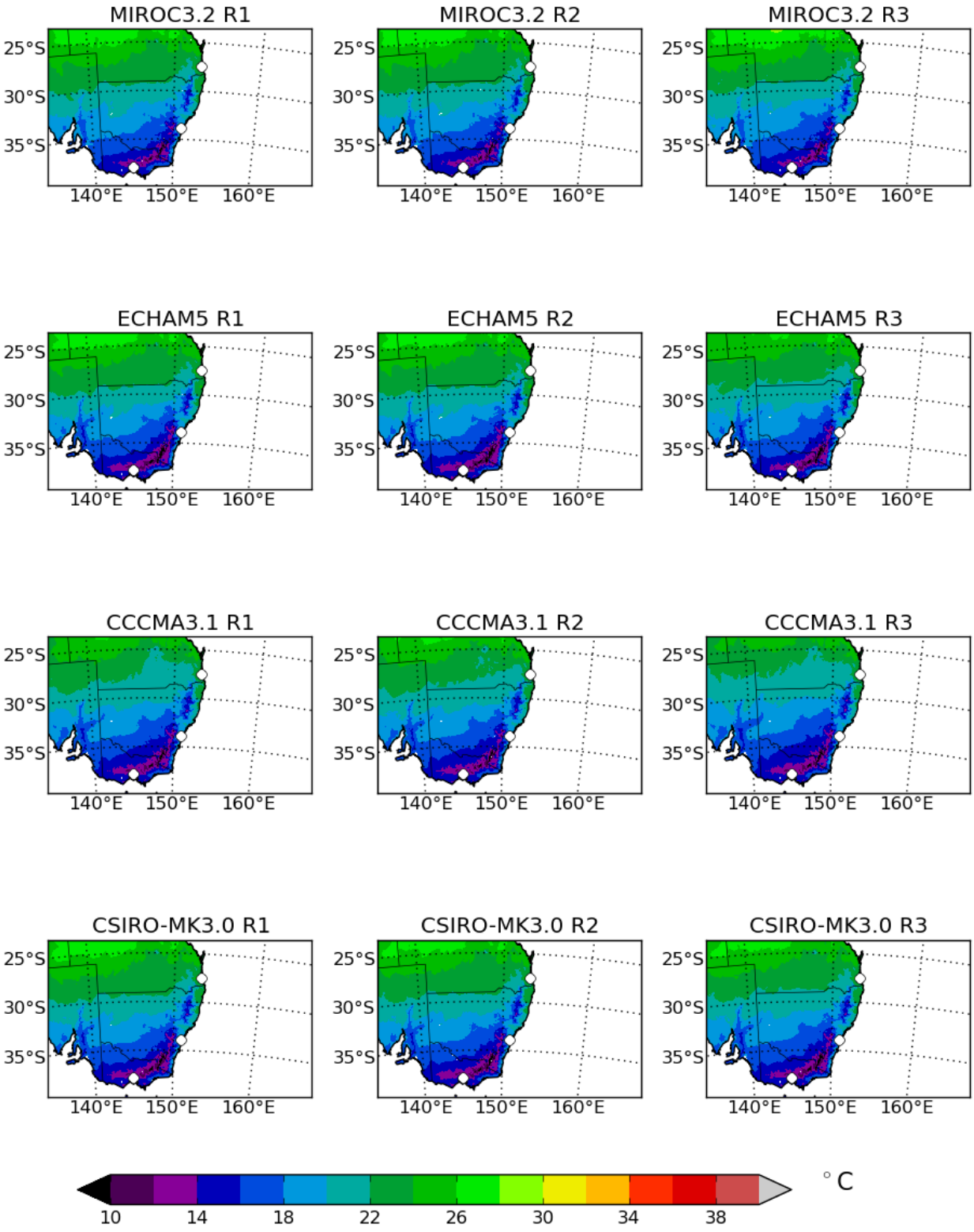

Figure 8.43: JJA mean of bias-corrected daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

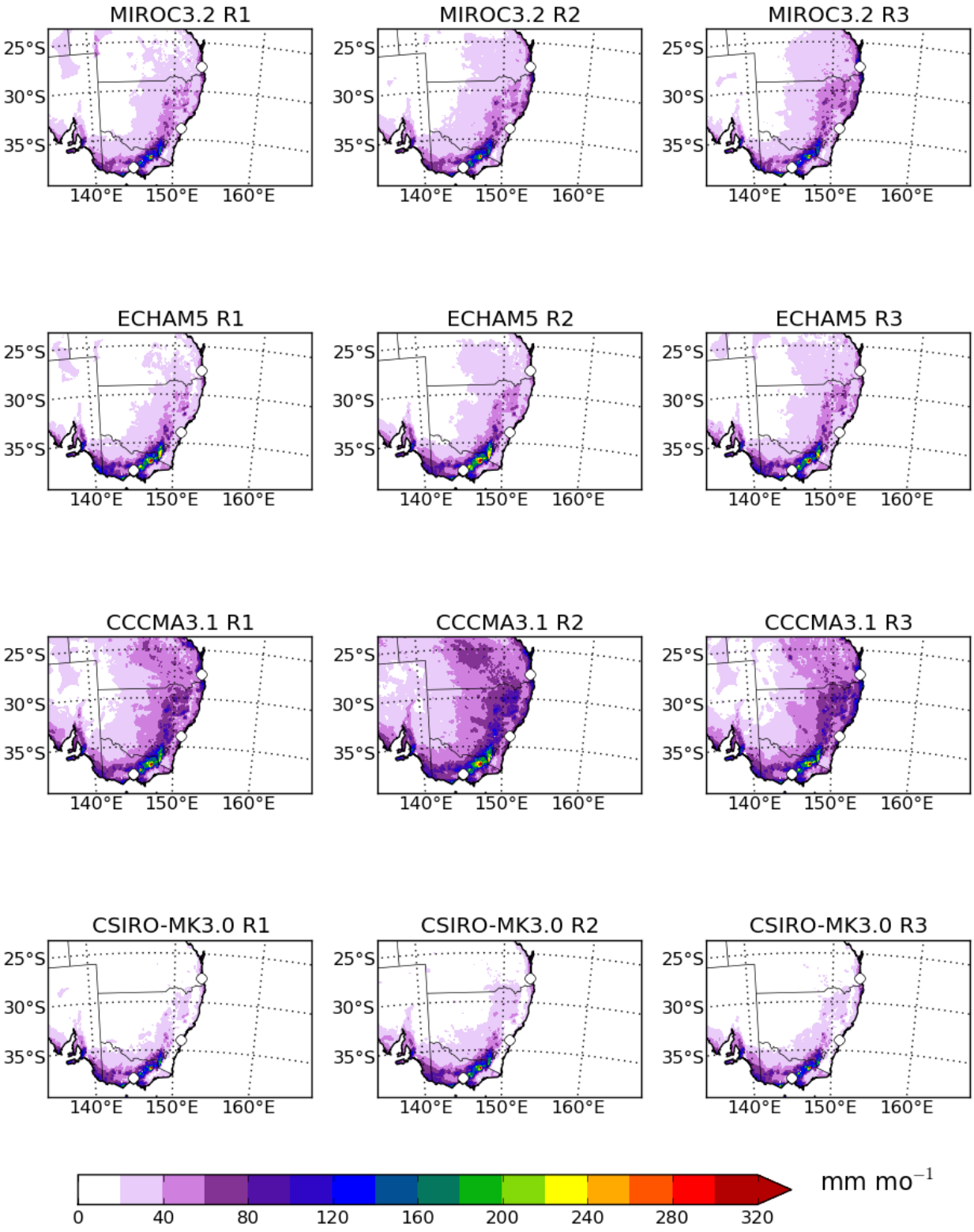

Figure 8.44: JJA mean of bias-corrected precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

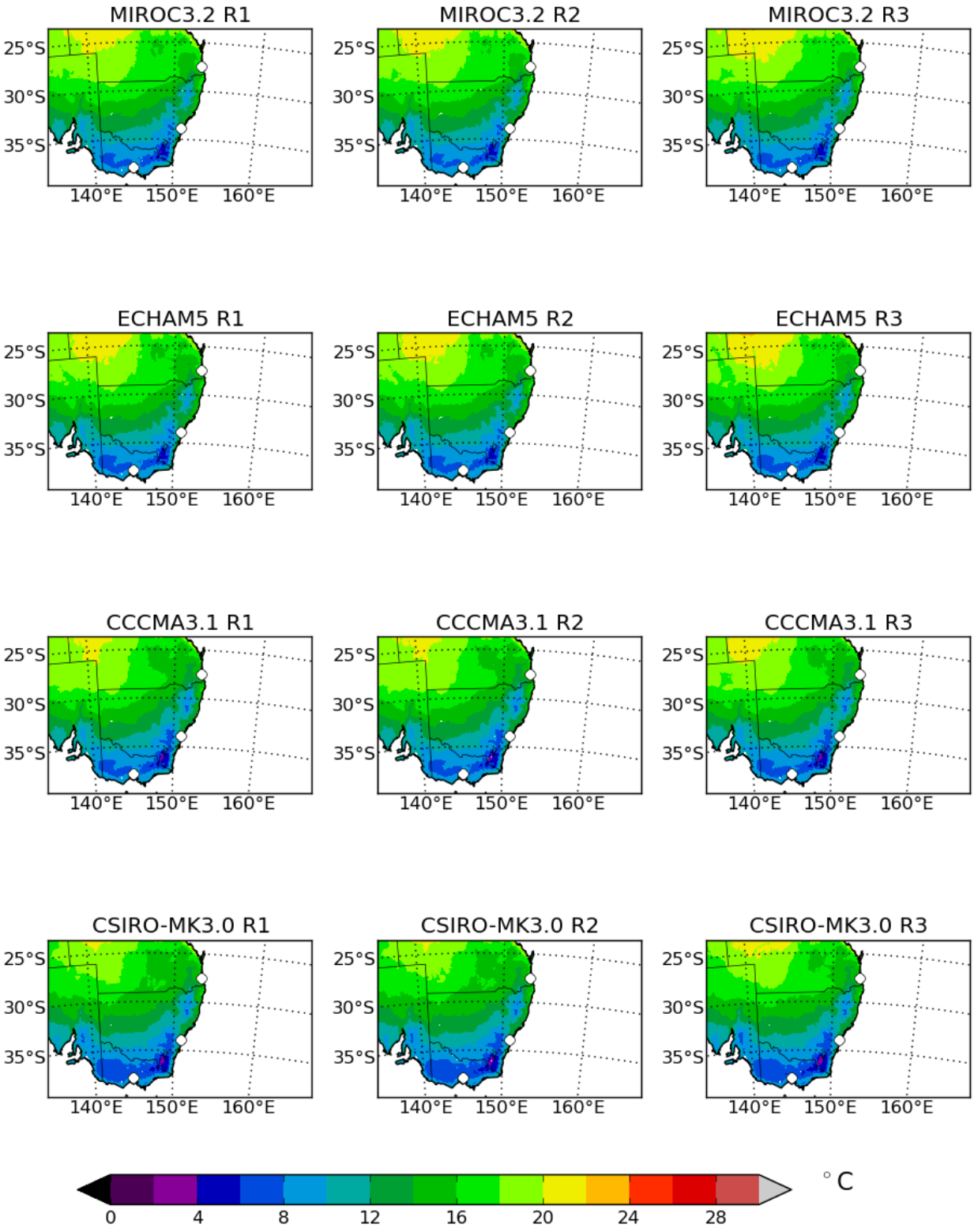

Figure 8.45: SON mean of bias-corrected daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

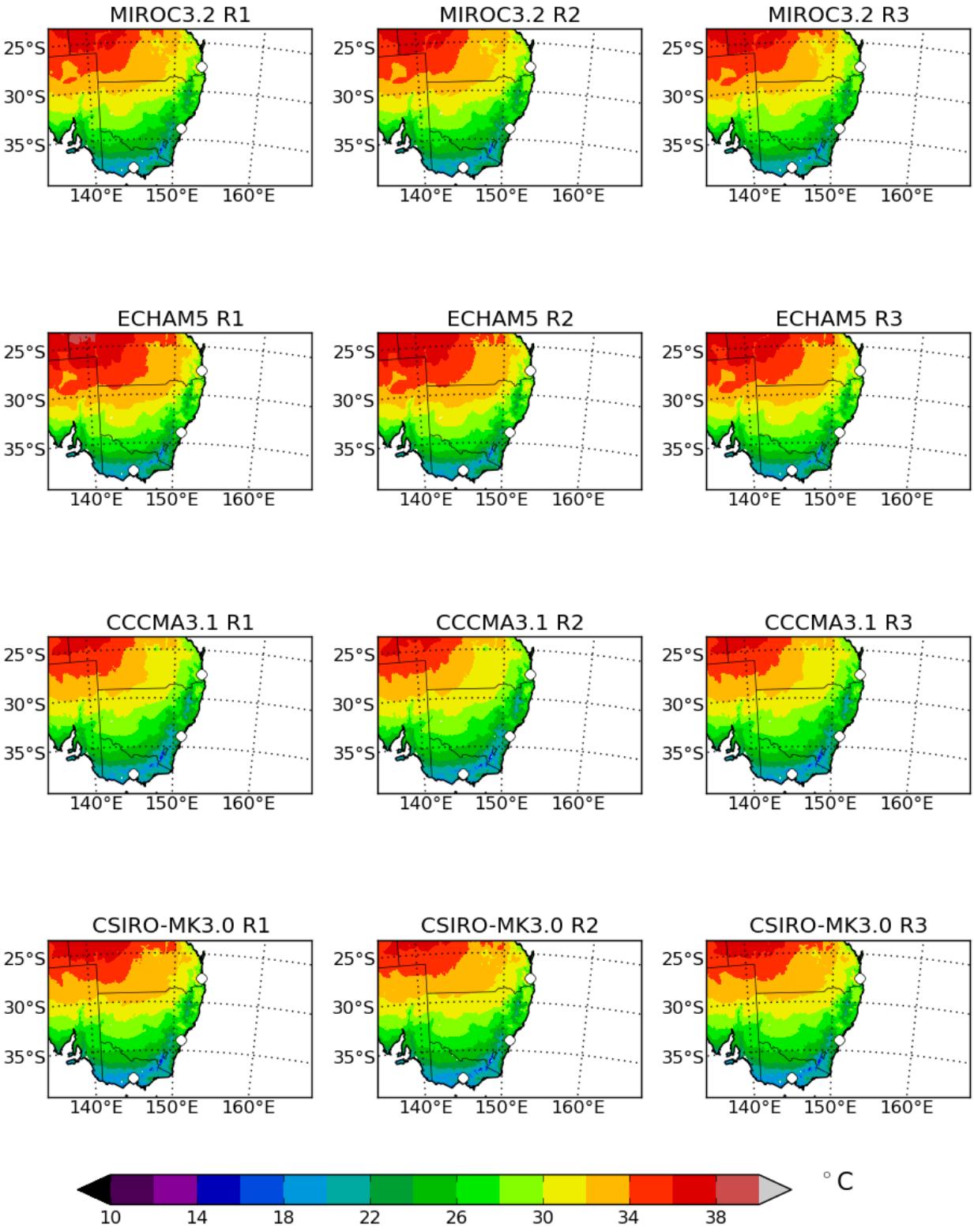

Figure 8.46: SON mean of bias-corrected daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

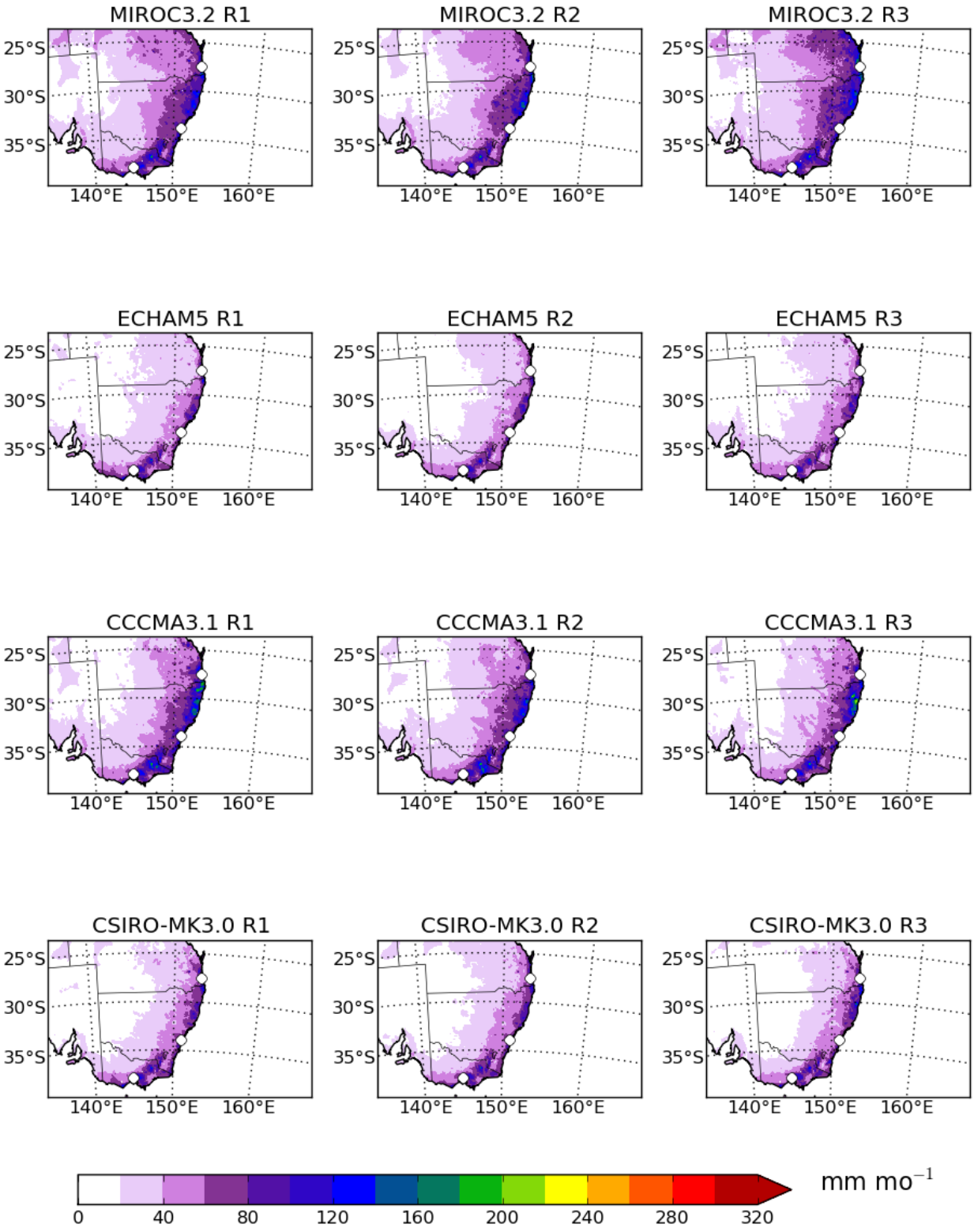

Figure 8.47: SON mean of bias-corrected precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

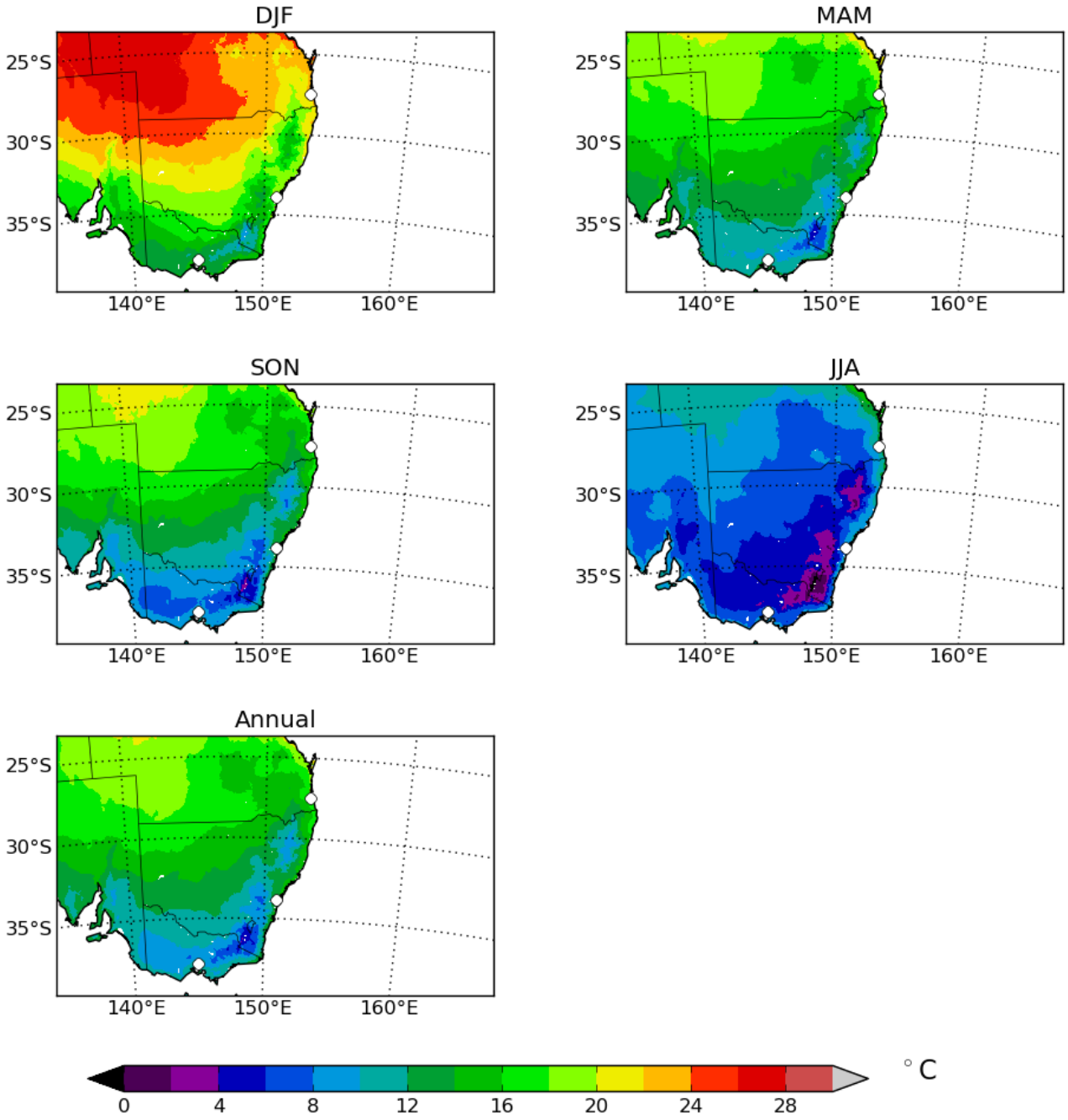

Figure 8.48: Seasonal and annual multimodel means of bias-corrected daily minimum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

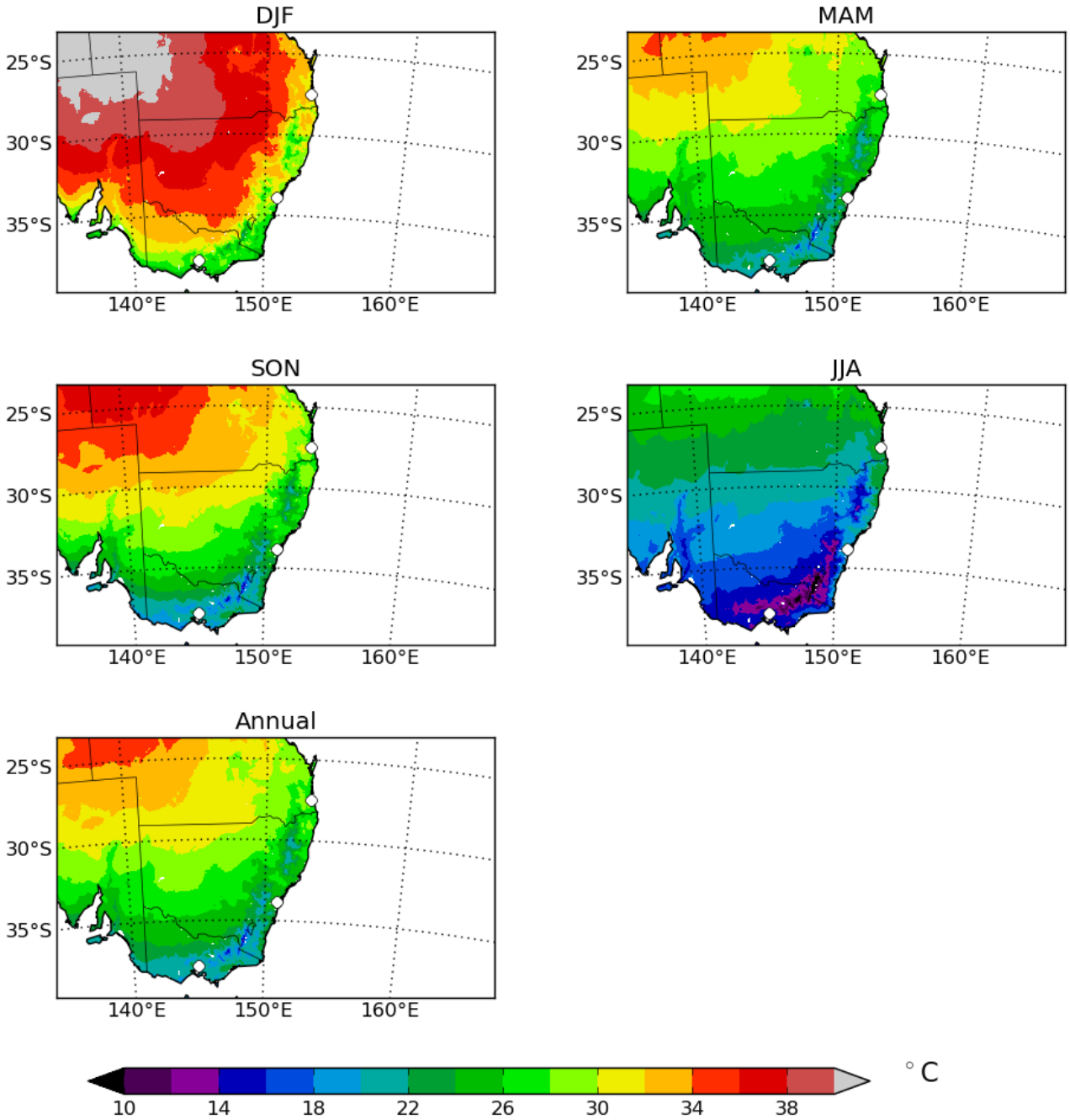

Figure 8.49: Seasonal and annual multimodel means of bias-corrected daily maximum near-surface air temperature for years 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

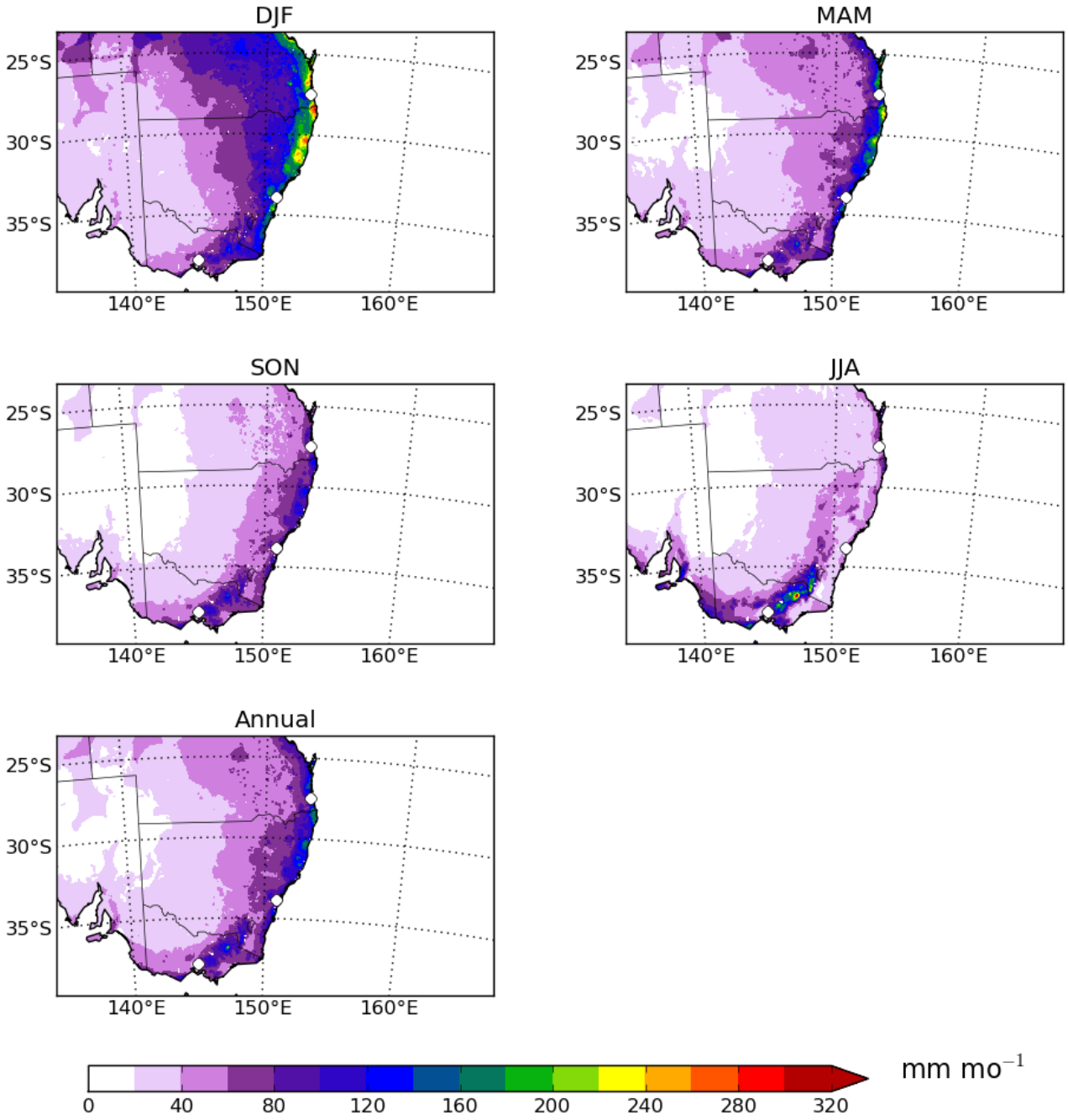

Figure 8.50: Seasonal and annual multimodel means of bias-corrected precipitation for years 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

Chapter 9

Far Future Modeled Changes Compared to the Present Period

This chapter contains projected seasonal and annual mean changes for near-surface air temperature and precipitation, between present (1990-2009) and far future (2060-2079). We first show the results for the GCMs used to drive the RCMs, then for original RCM output, and finally for bias-corrected RCM output. The bias-corrected RCM output is the RCM output corrected for present-day biases between the models and the observations using the methods described here [6].

9.1 Driving GCMs: Changes from 1990-2009 to 2060-2079

This subsection contains projected seasonal and annual mean far-future changes for near-surface air temperature and precipitation from each of the GCMs used to provide boundary conditions to the RCMs. The plots are ordered first by GCM, and then by variable.

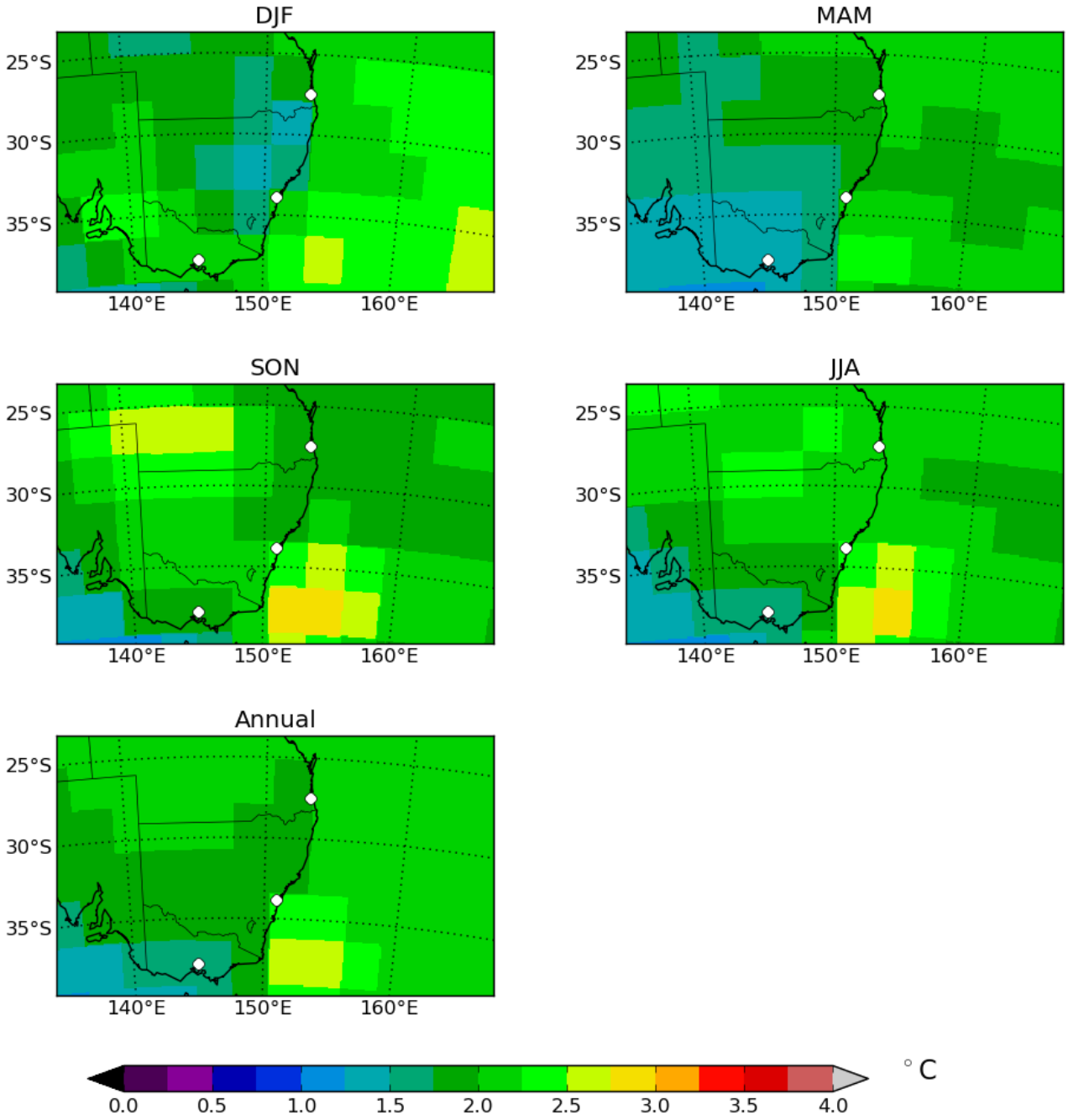

Figure 9.1: Seasonal and annual means of MIROC3.2 near-surface air temperature change between years 1990-2009 and 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

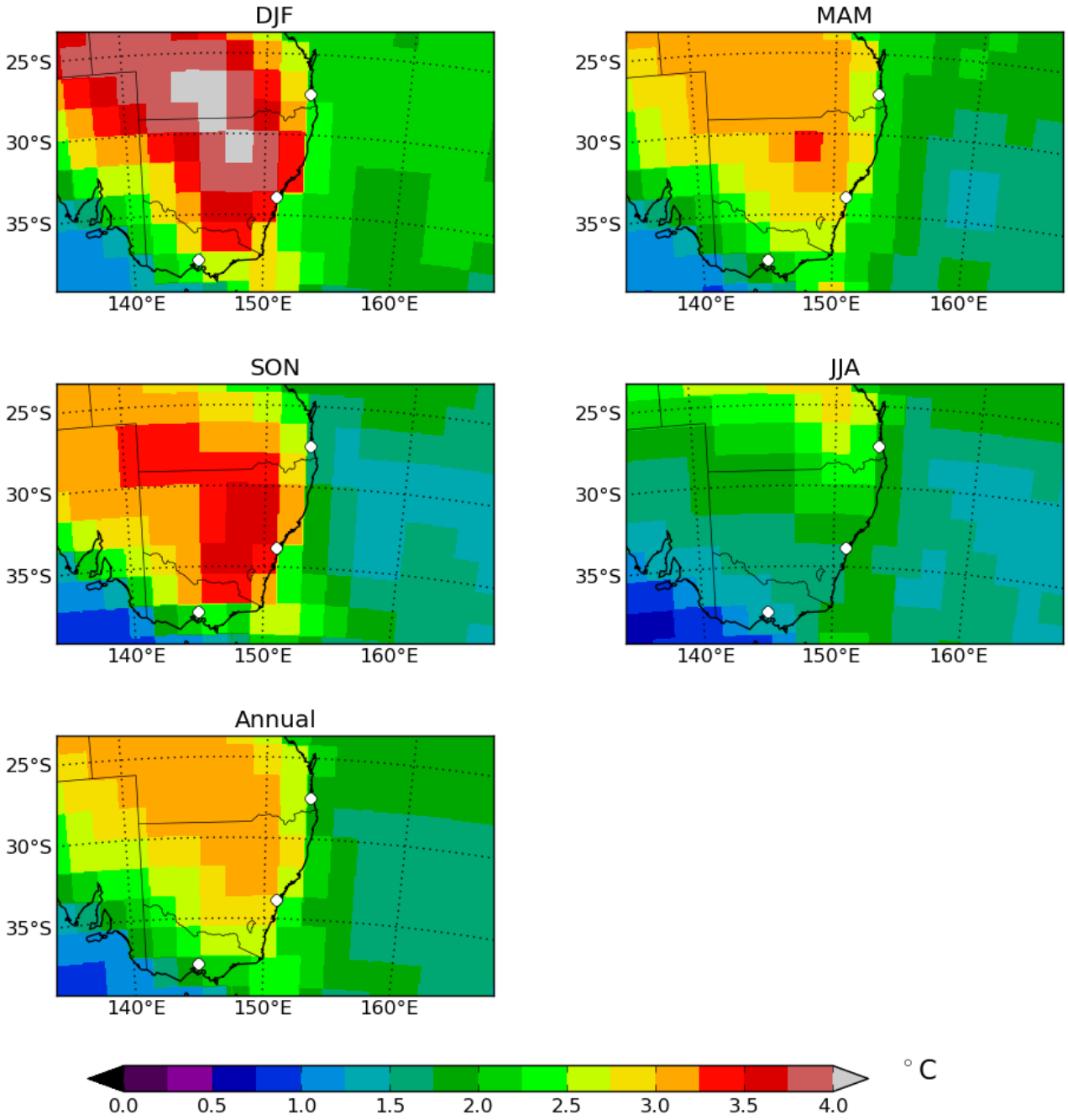

Figure 9.2: Seasonal and annual means of ECHAM5 near-surface air temperature change between years 1990-2009 and 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

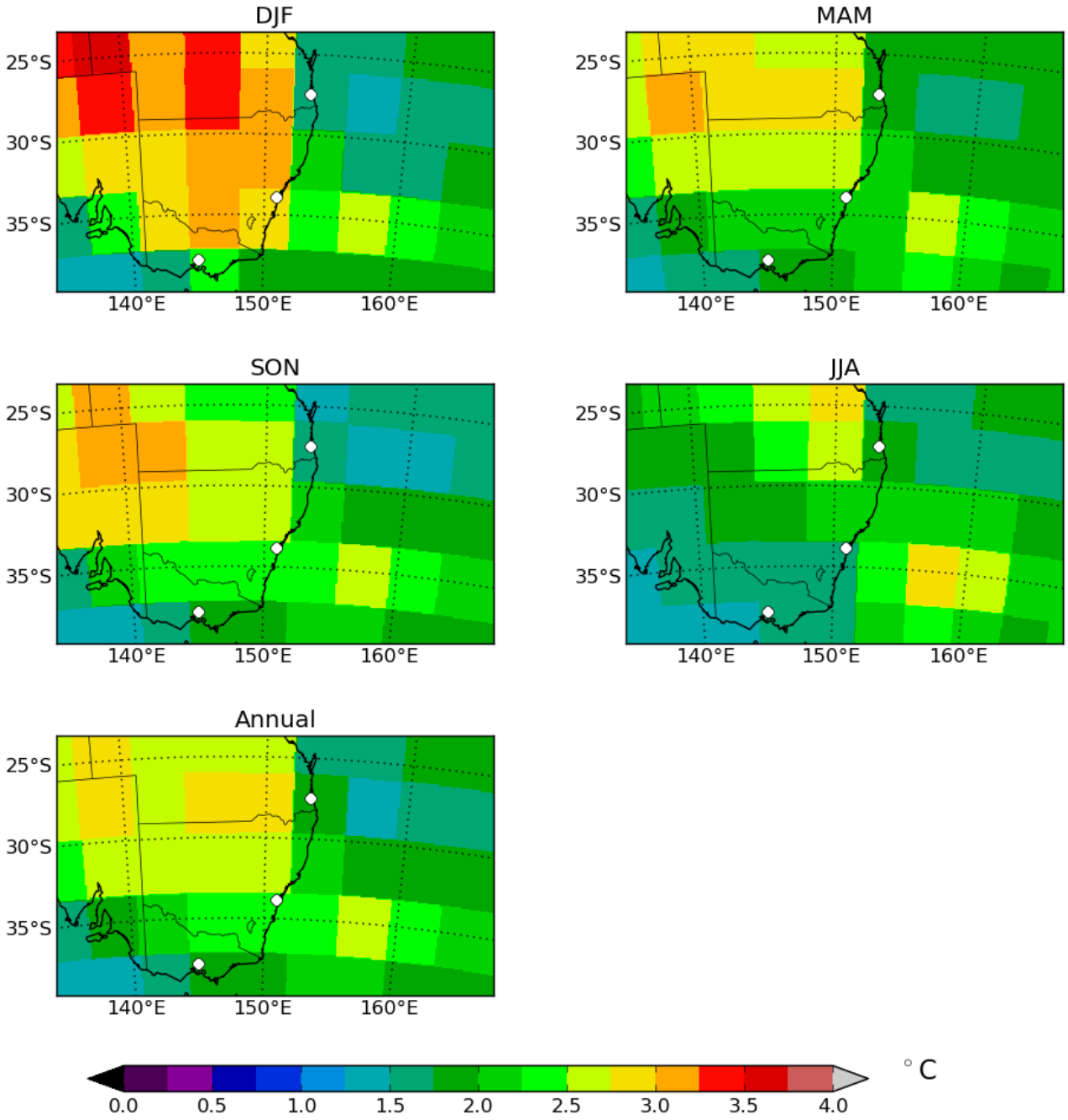

Figure 9.3: Seasonal and annual means of CCCMA3.1 near-surface air temperature change between years 1990-2009 and 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

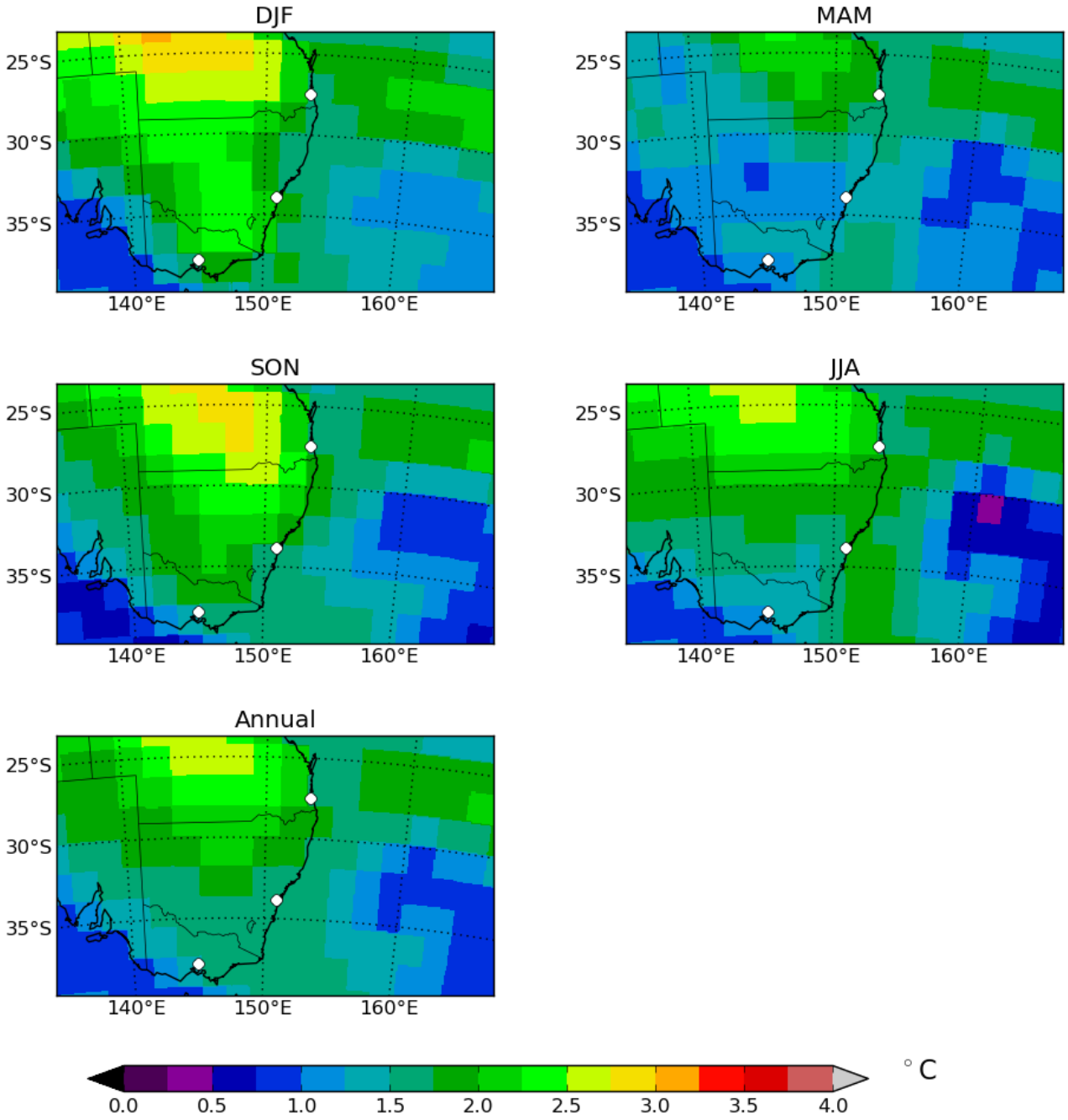

Figure 9.4: Seasonal and annual means of CSIRO-MK3.0 near-surface air temperature change between years 1990-2009 and 2060-2079 [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

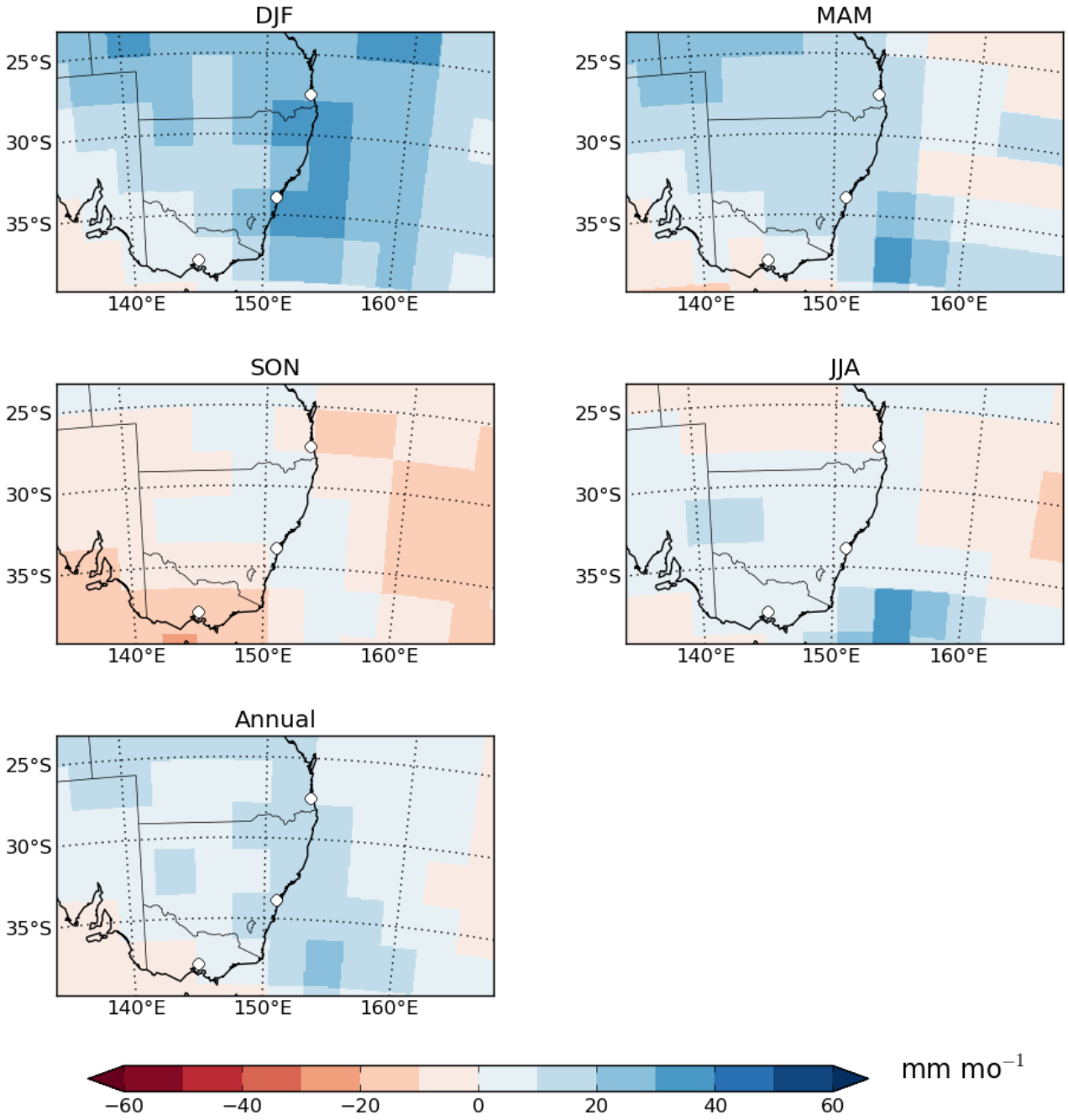

Figure 9.5: Seasonal and annual means of MIROC3.2 precipitation change between years 1990-2009 and 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

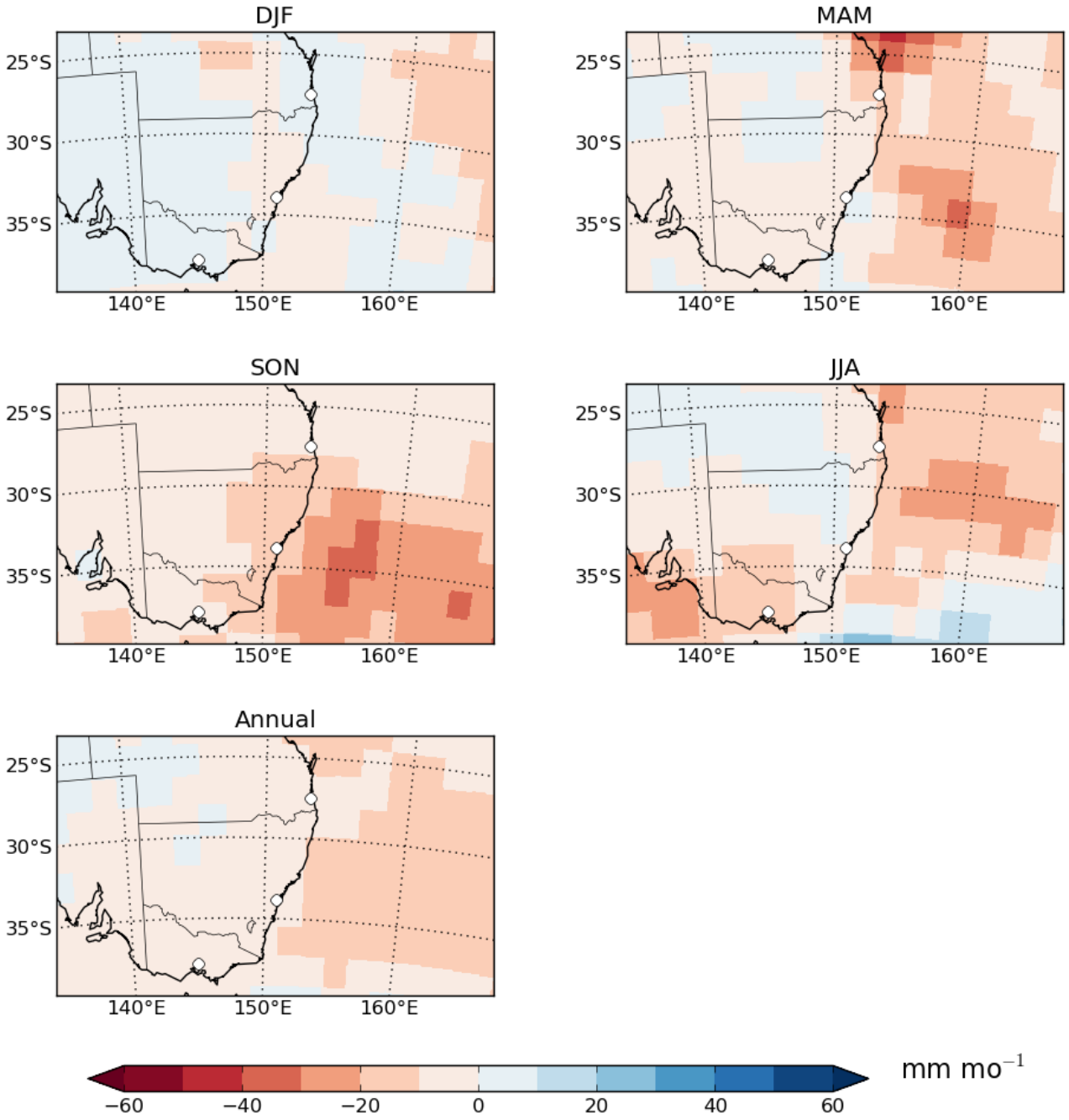

Figure 9.6: Seasonal and annual means of ECHAM5 precipitation change between years 1990-2009 and 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

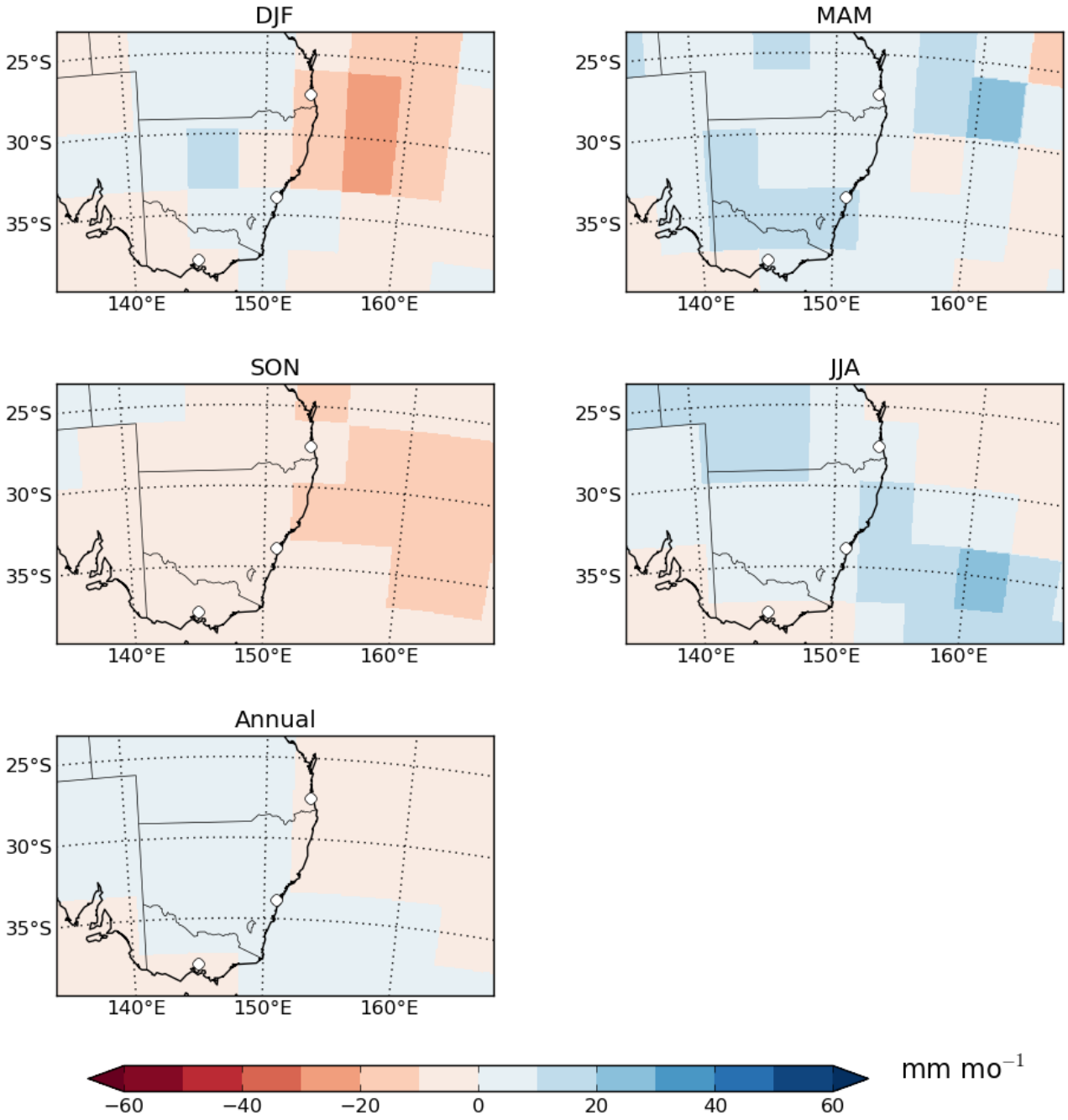

Figure 9.7: Seasonal and annual means of CCCMA3.1 precipitation change between years 1990-2009 and 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

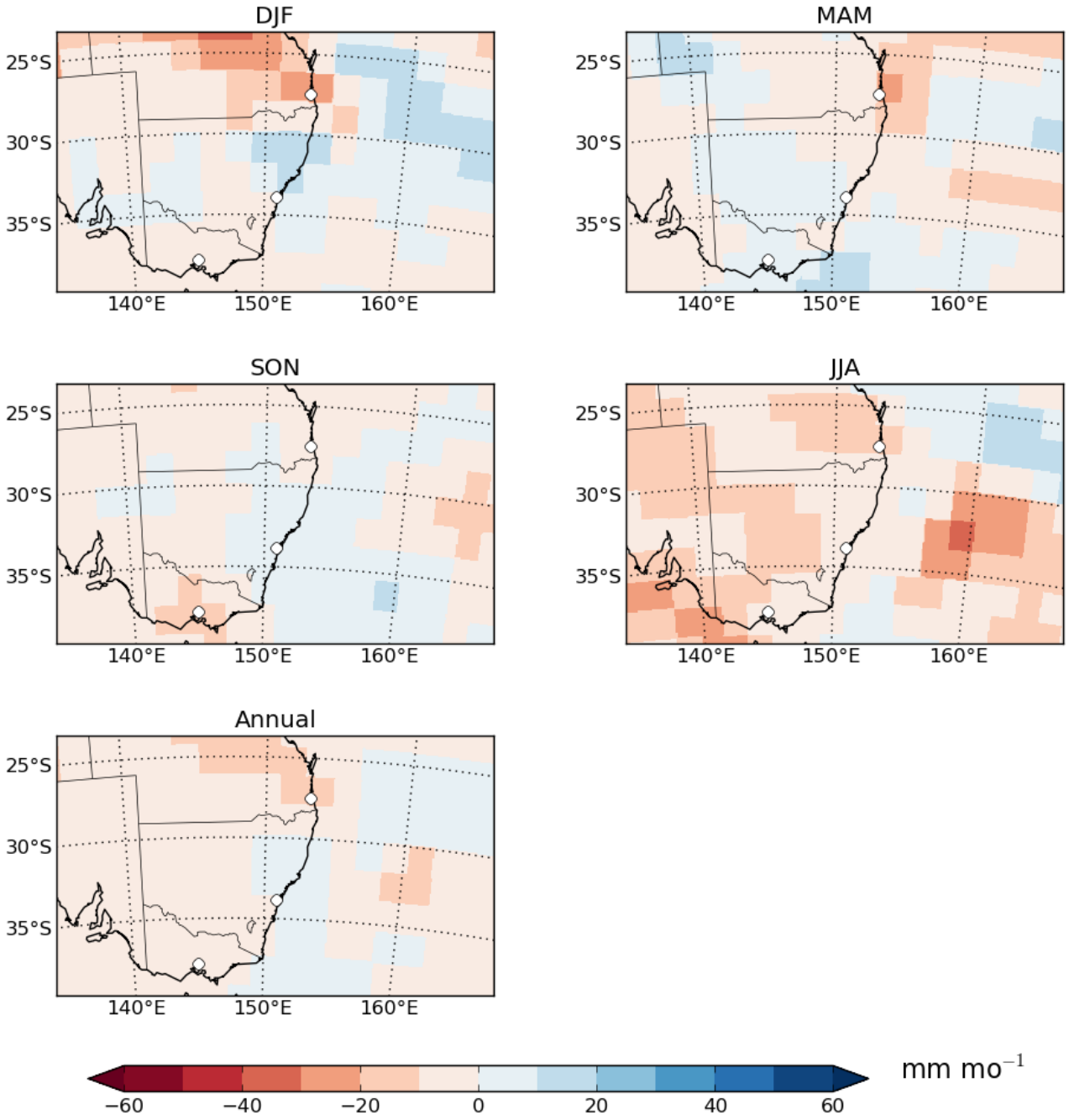

Figure 9.8: Seasonal and annual means of CSIRO-MK3.0 precipitation change between years 1990-2009 and 2060-2079 [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

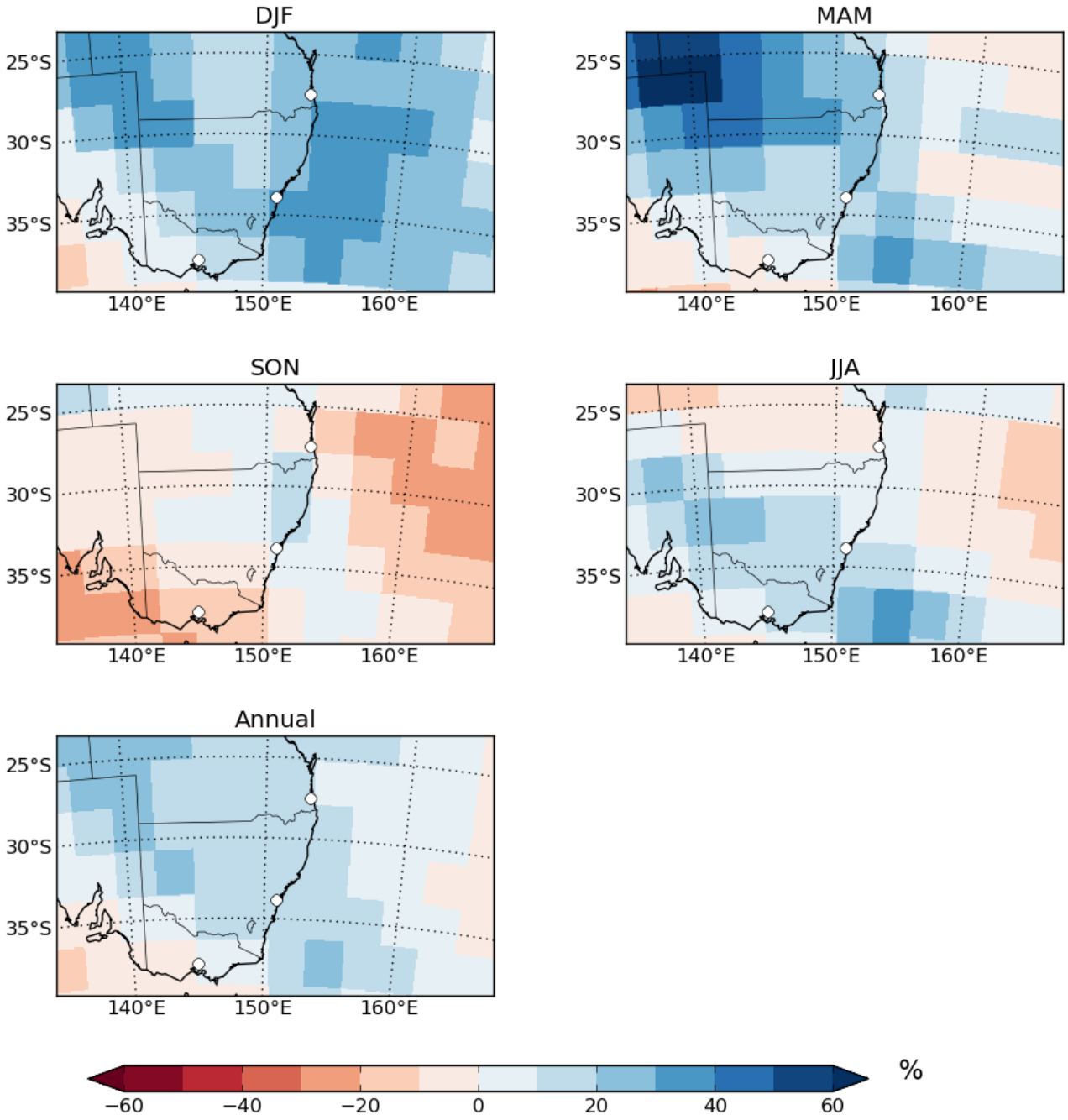

Figure 9.9: Seasonal and annual means of MIROC3.2 precipitation change between years 1990-2009 and 2060-2079 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

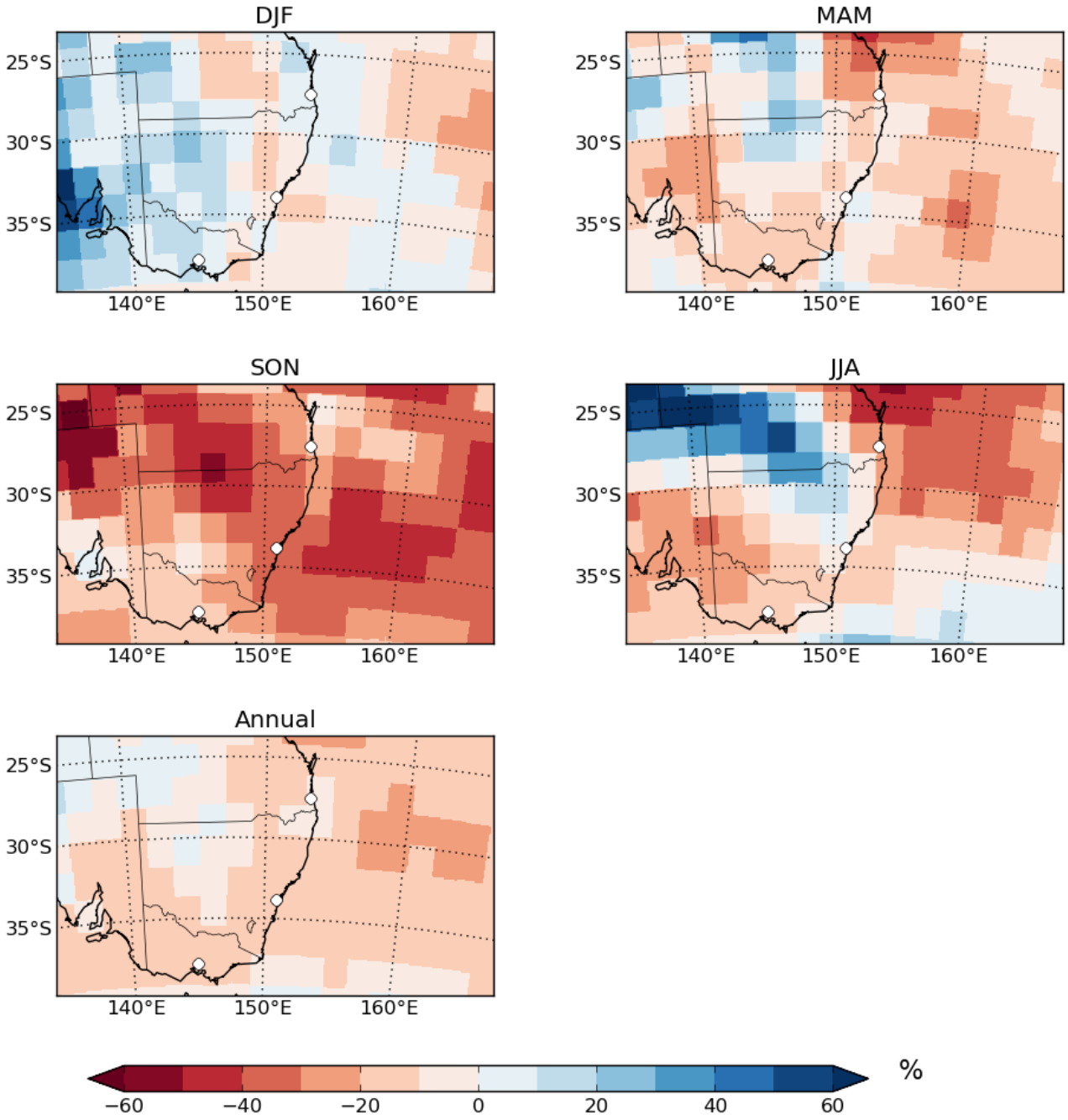

Figure 9.10: Seasonal and annual means of ECHAM5 precipitation change between years 1990-2009 and 2060-2079 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

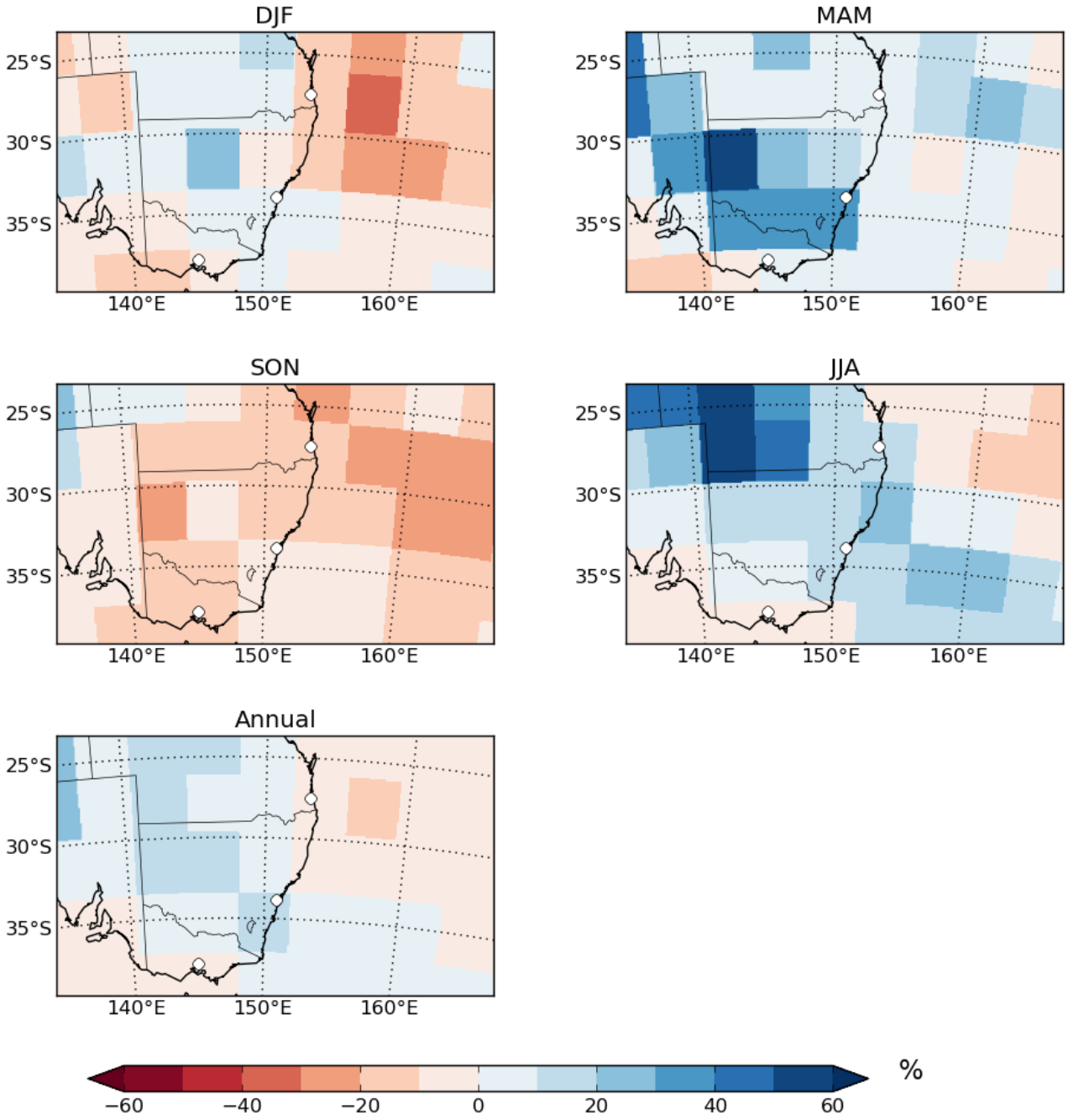

Figure 9.11: Seasonal and annual means of CCCMA3.1 precipitation change between years 1990-2009 and 2060-2079 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

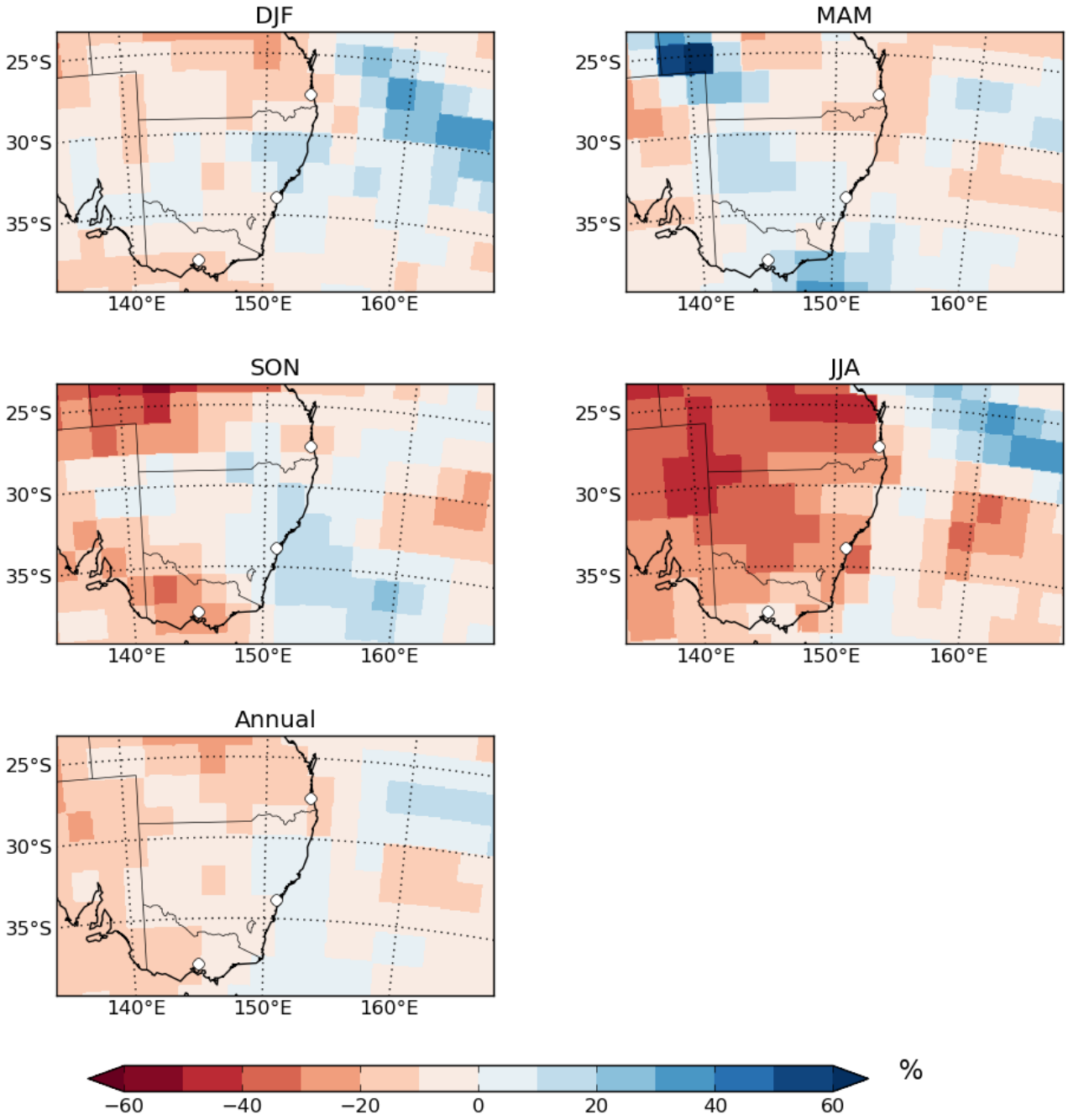

Figure 9.12: Seasonal and annual means of CSIRO-MK3.0 precipitation change between years 1990-2009 and 2060-2079 [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

9.2 Regional Model Output: Changes from 1990-2009 to 2060-2079

This subsection contains projected seasonal and annual mean far-future changes for near-surface air temperature, daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the original RCM output. Precipitation changes are plotted as both absolute values (in mm mo^{-1}), and percent changes. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected changes, whereas the individual-model plots show the level of uncertainty in projected changes.

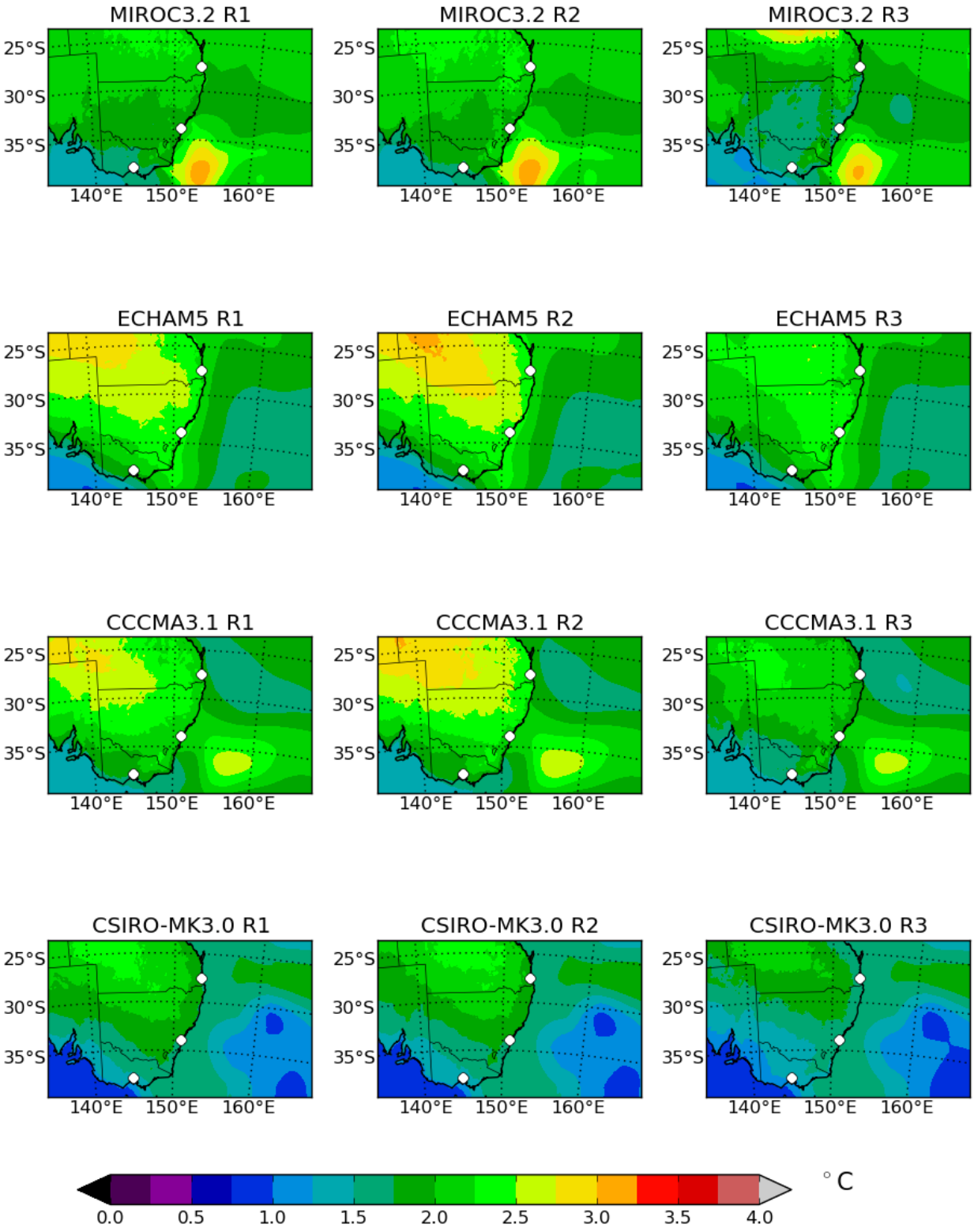

Figure 9.13: Annual mean change between years 1990-2009 and 2060-2079 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

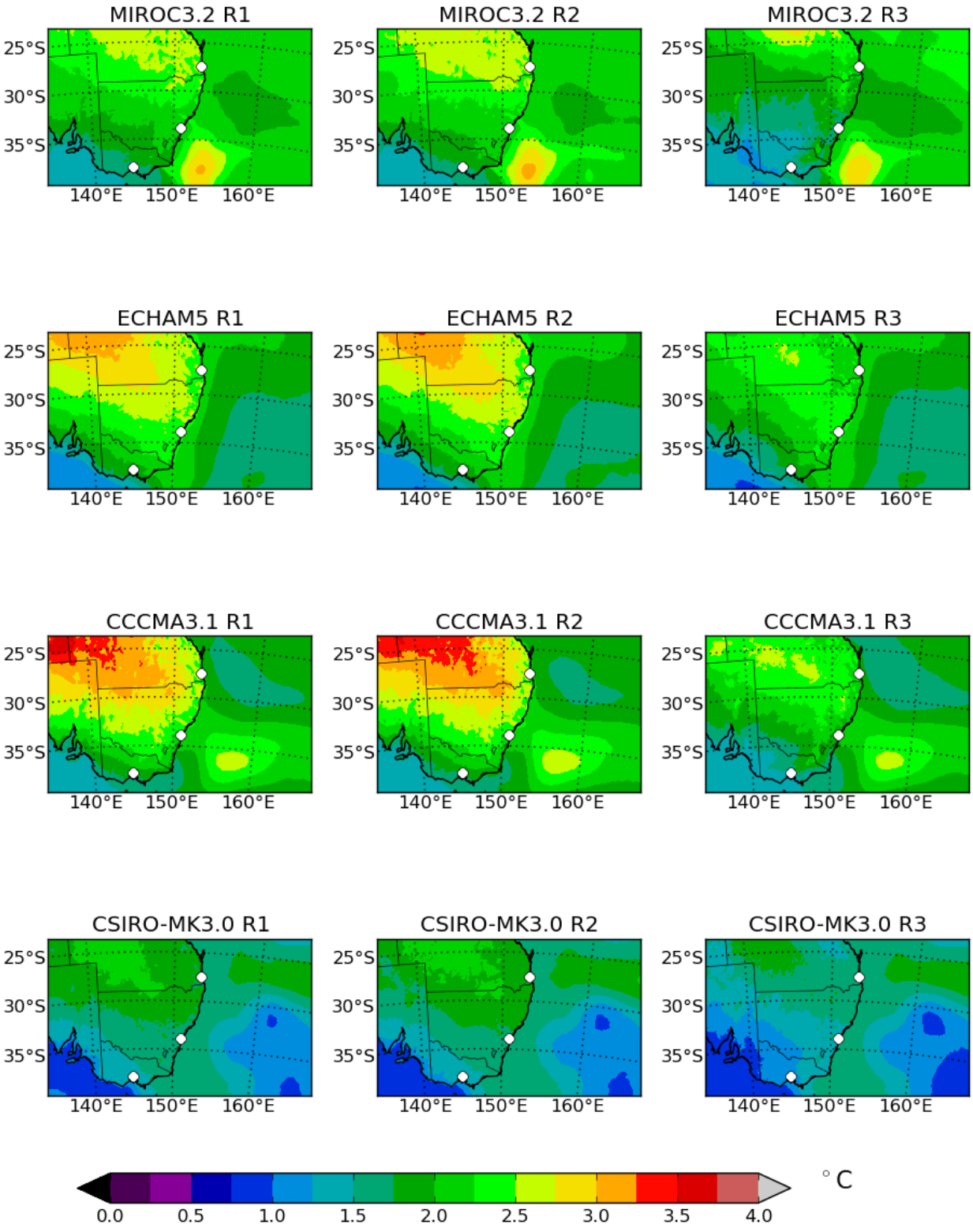

Figure 9.14: Annual mean change between years 1990-2009 and 2060-2079 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

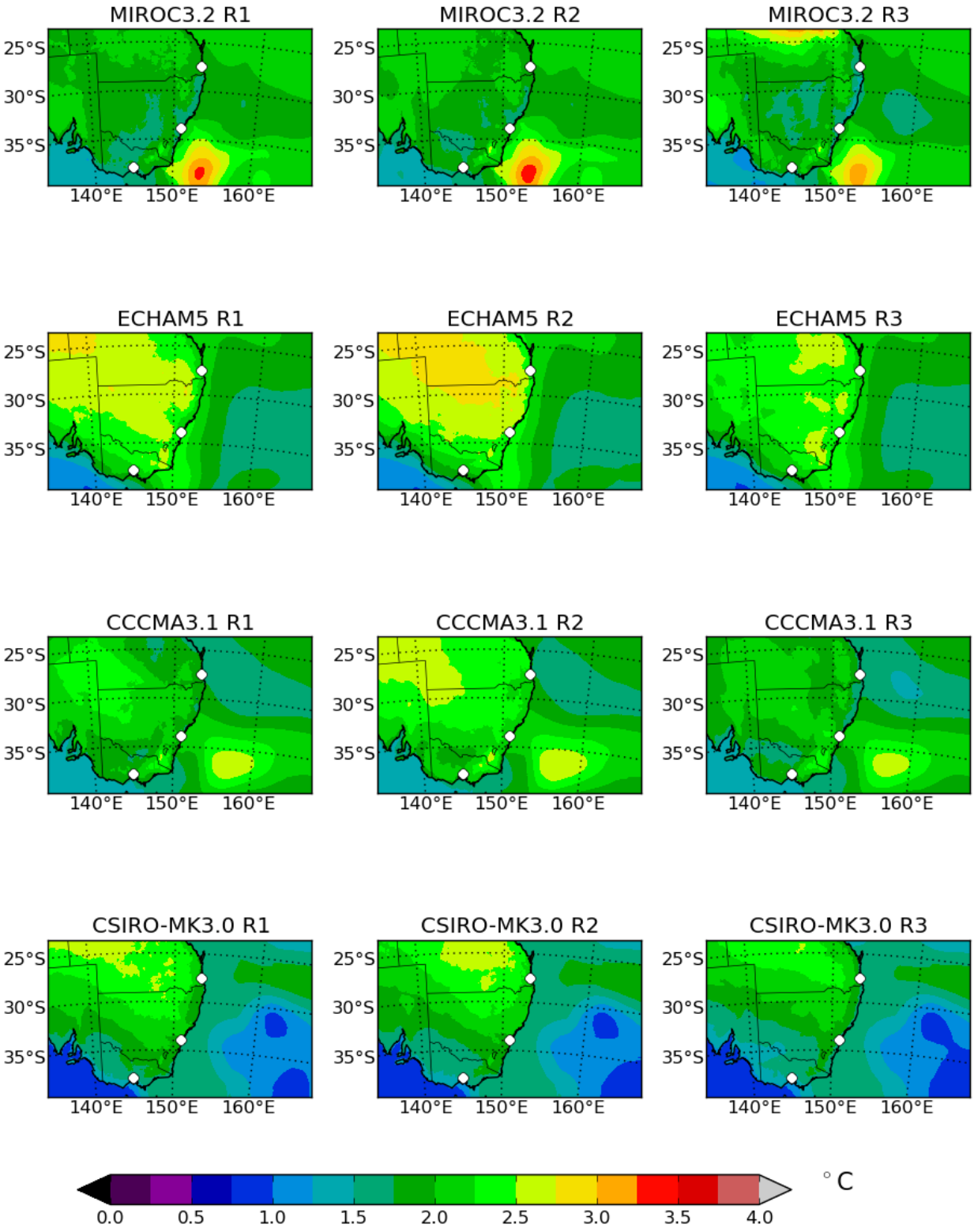

Figure 9.15: Annual mean change between years 1990-2009 and 2060-2079 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

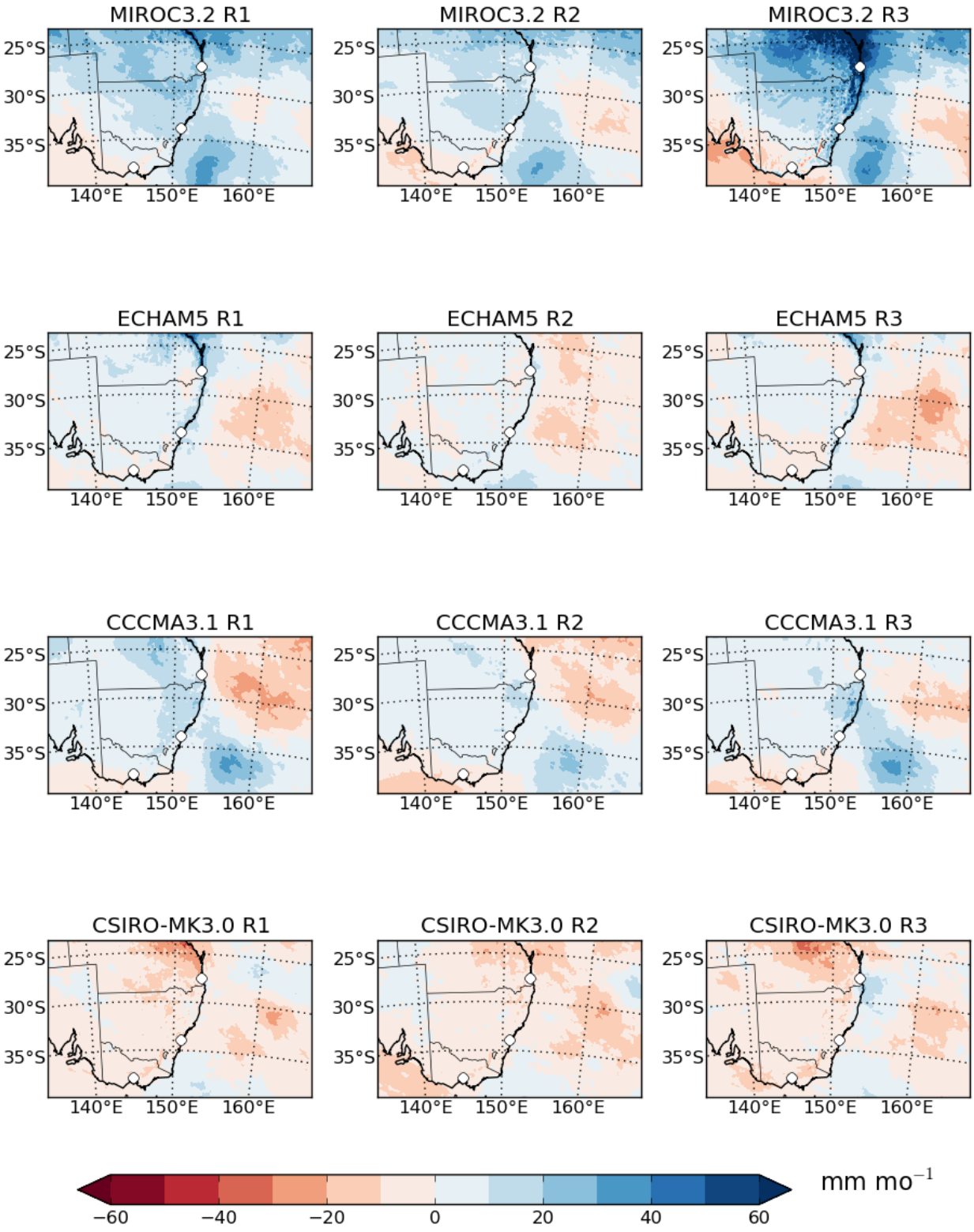

Figure 9.16: Annual mean change between years 1990-2009 and 2060-2079 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

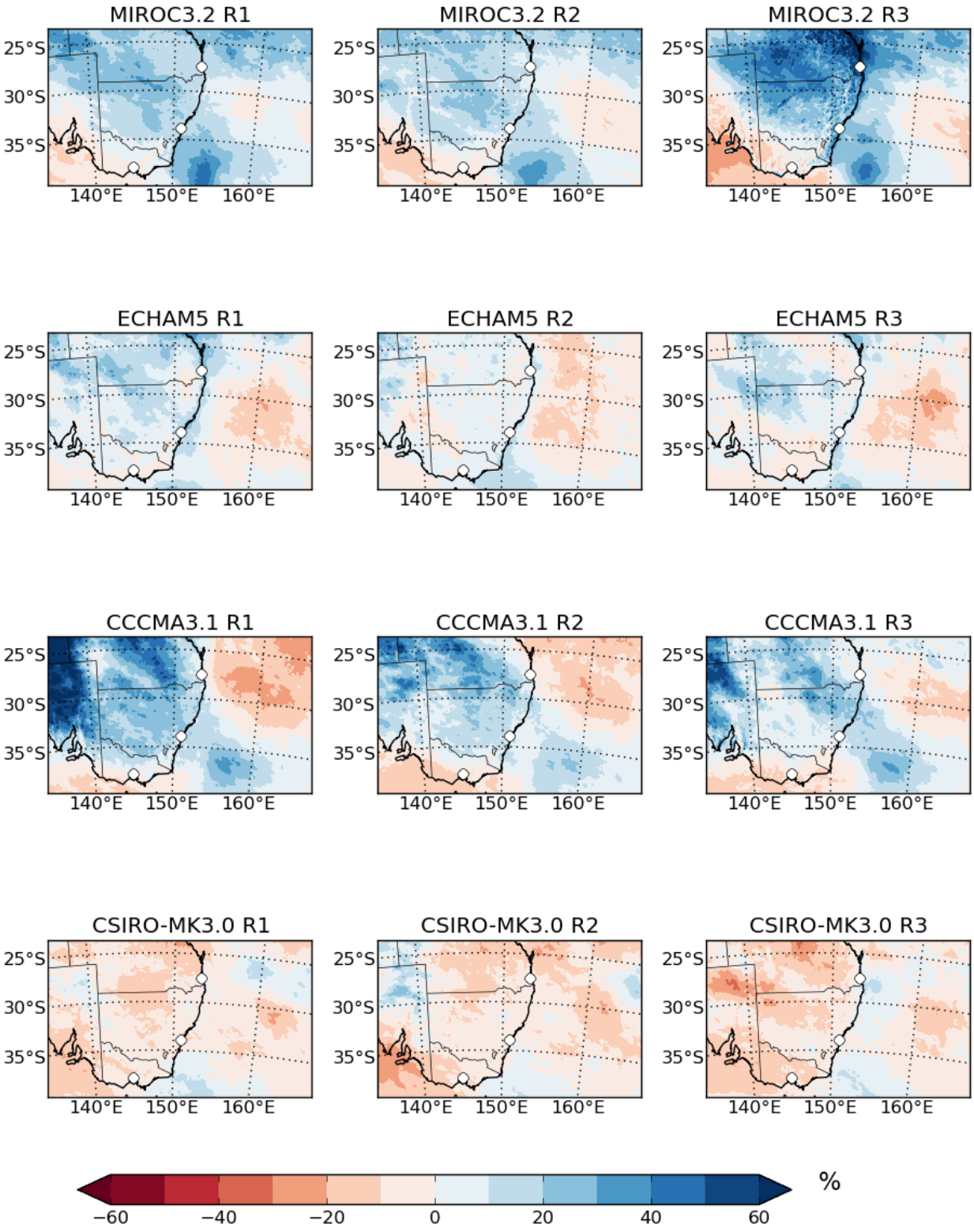

Figure 9.17: Annual mean change between years 1990-2009 and 2060-2079 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

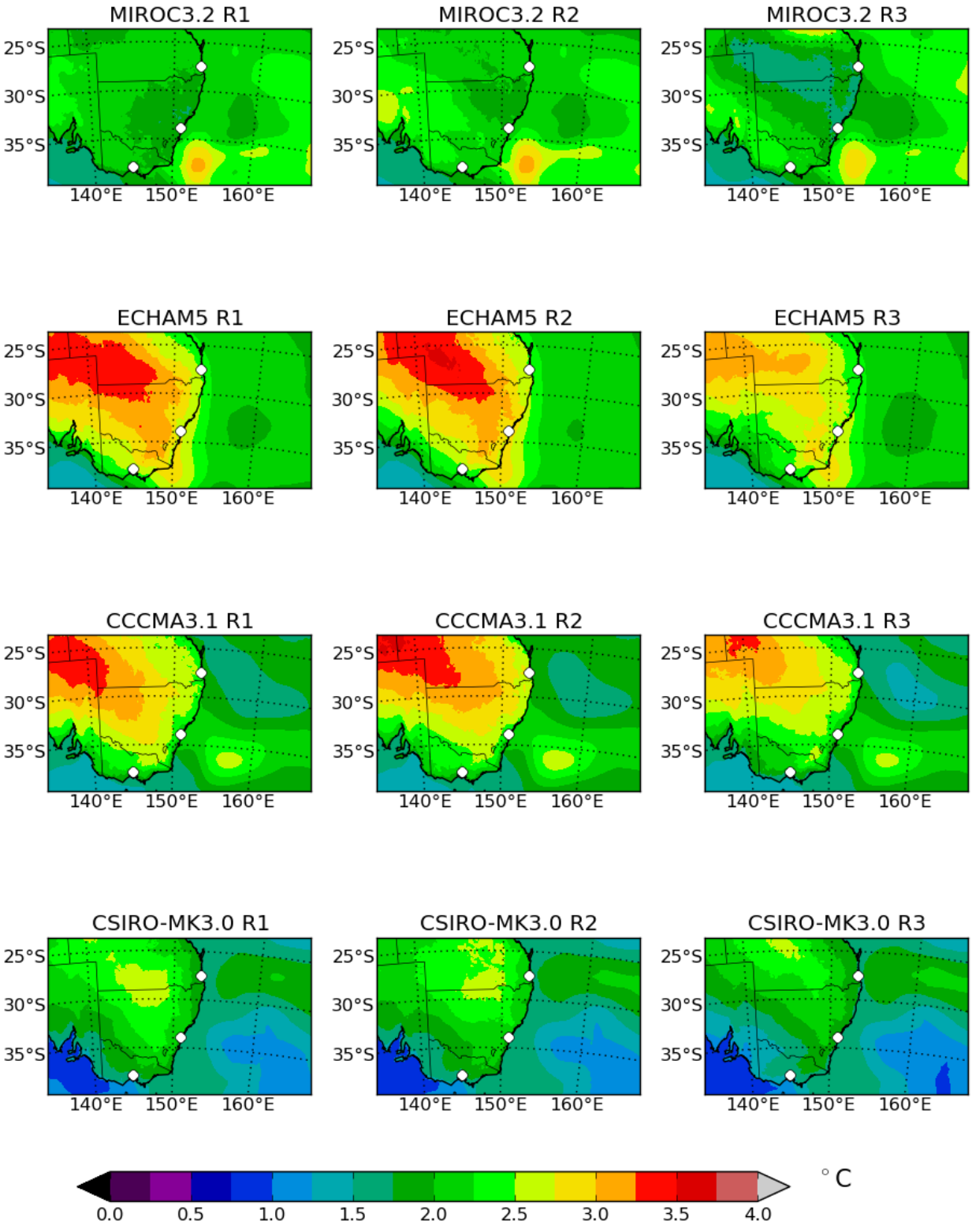

Figure 9.18: DJF mean change between years 1990-2009 and 2060-2079 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

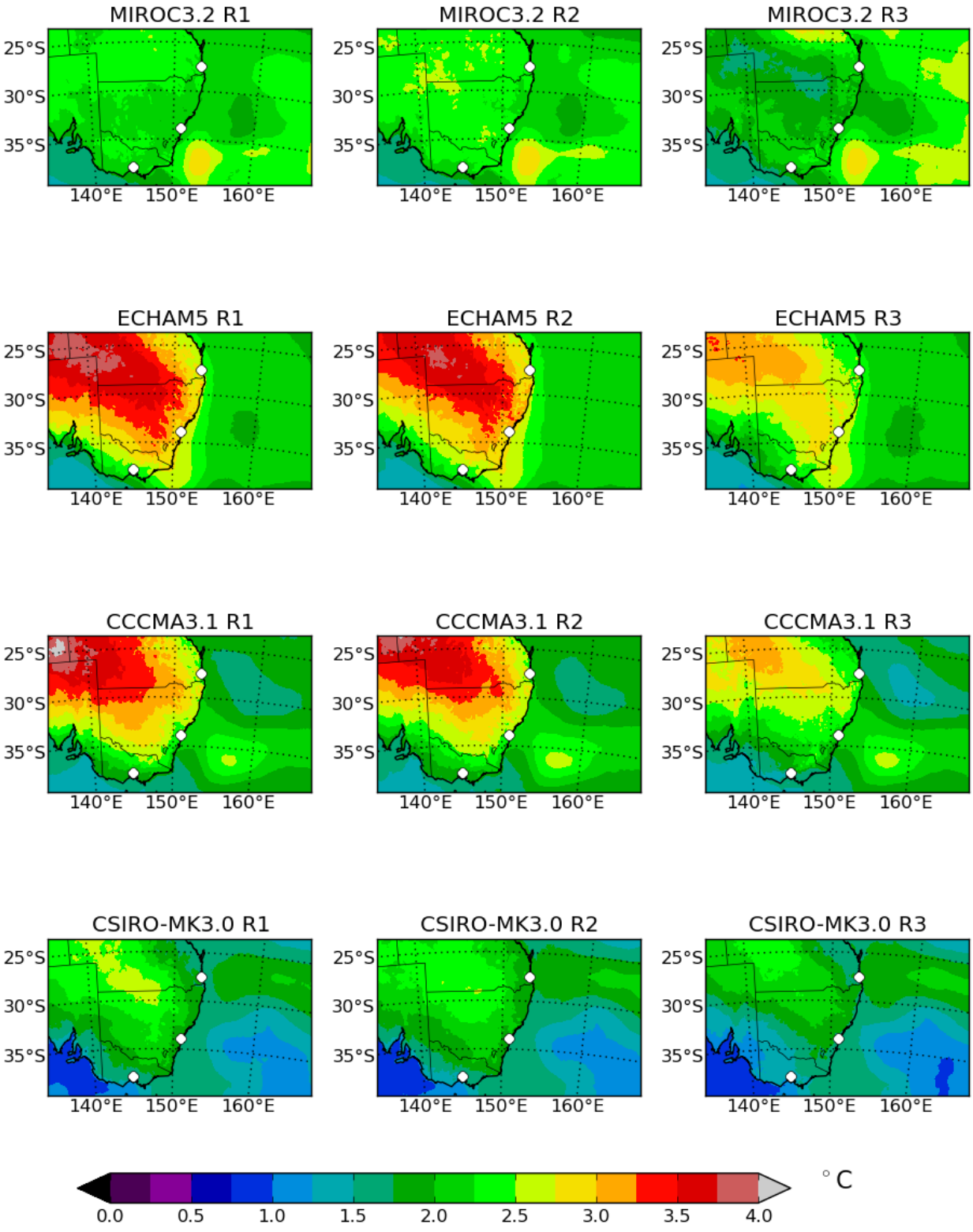

Figure 9.19: DJF mean change between years 1990-2009 and 2060-2079 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

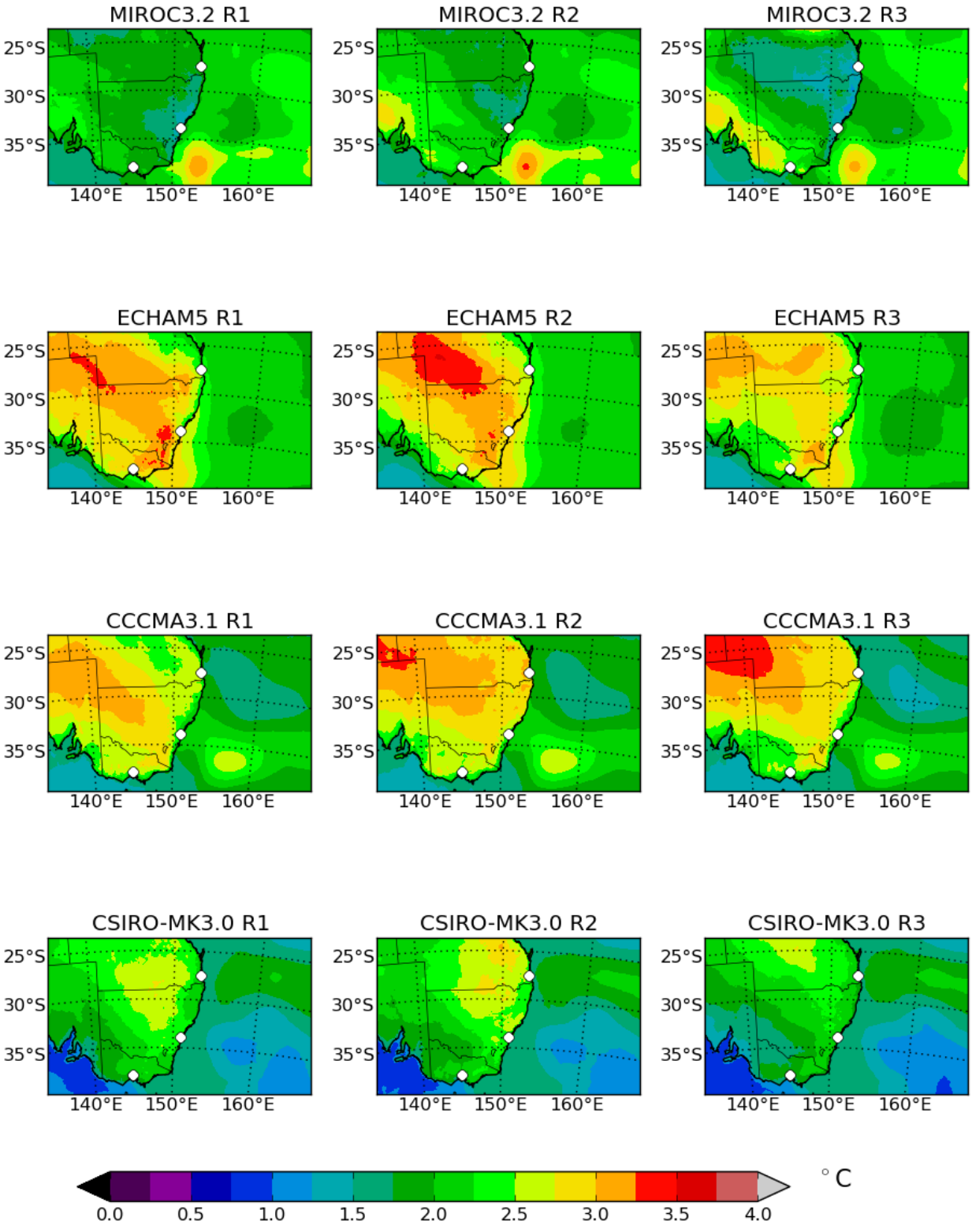

Figure 9.20: DJF mean change between years 1990-2009 and 2060-2079 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

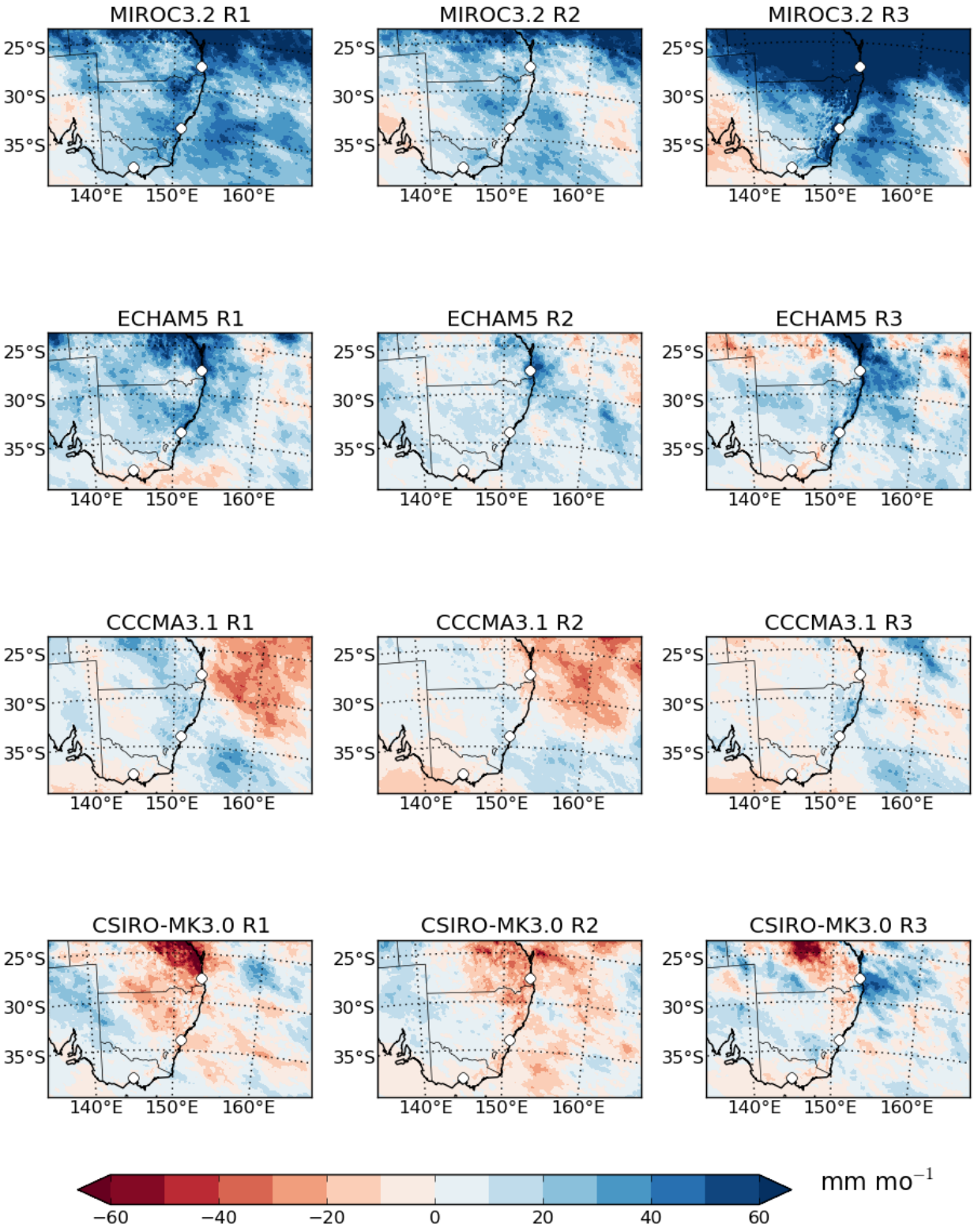

Figure 9.21: DJF mean change between years 1990-2009 and 2060-2079 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

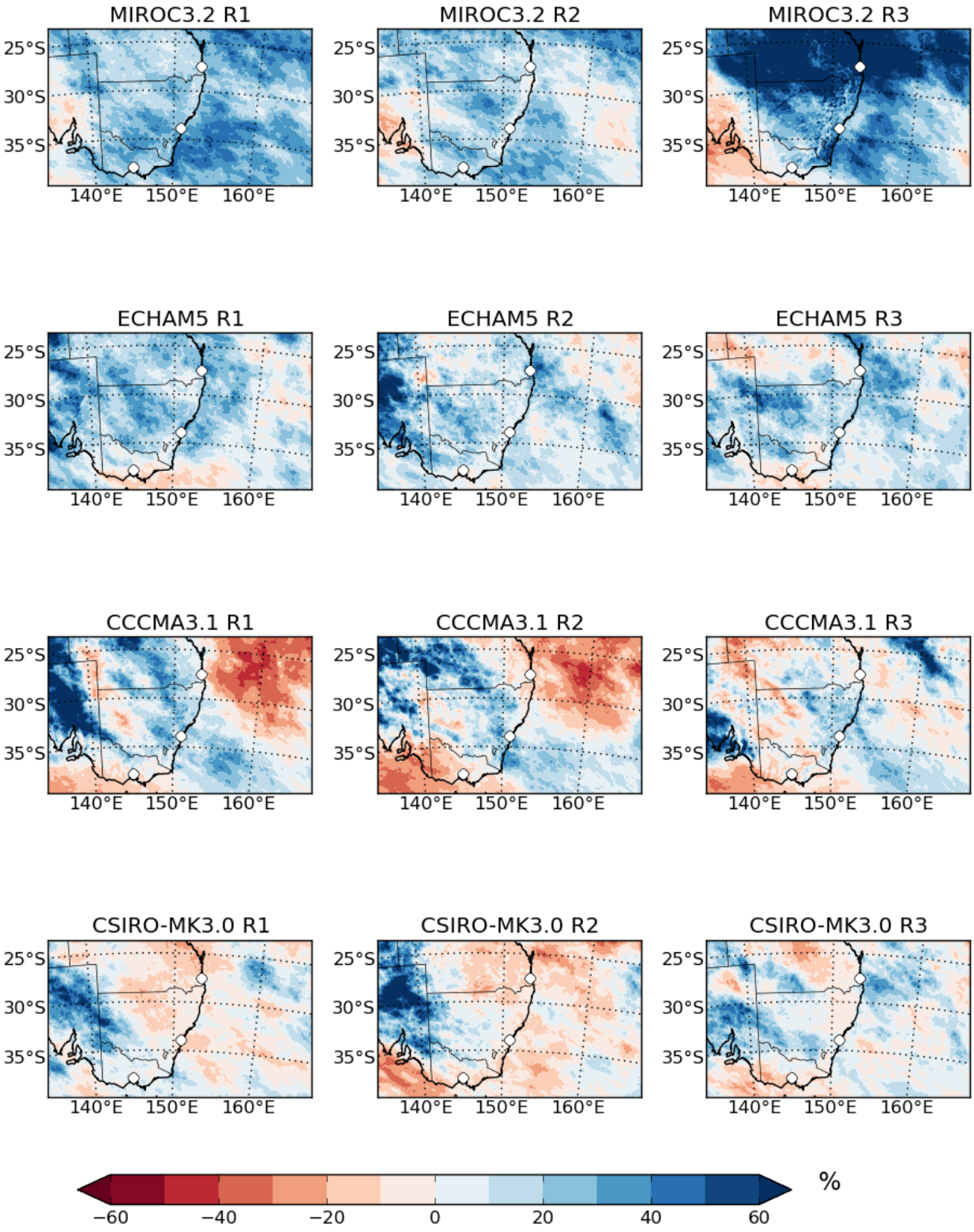

Figure 9.22: DJF mean change between years 1990-2009 and 2060-2079 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

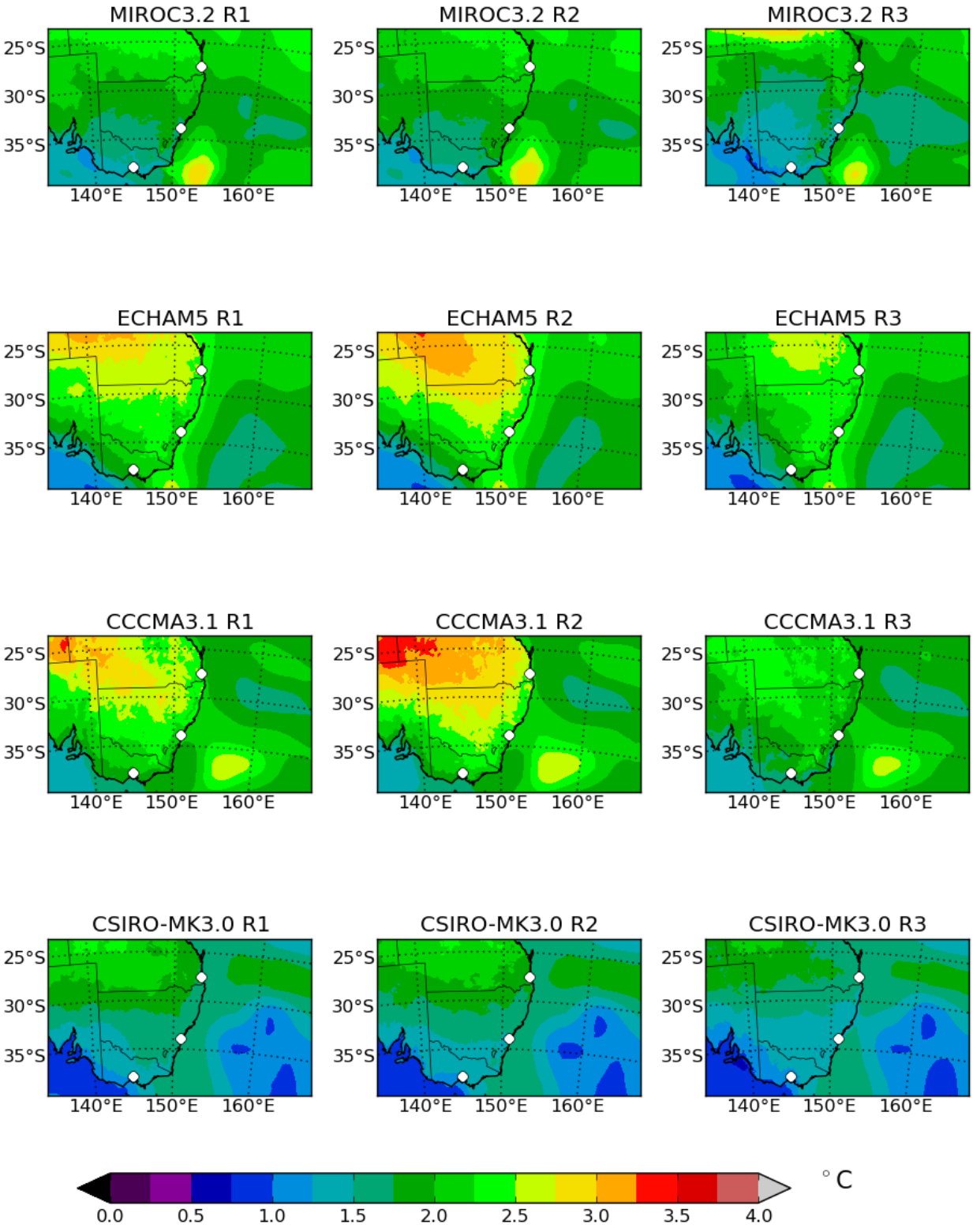

Figure 9.23: MAM mean change between years 1990-2009 and 2060-2079 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

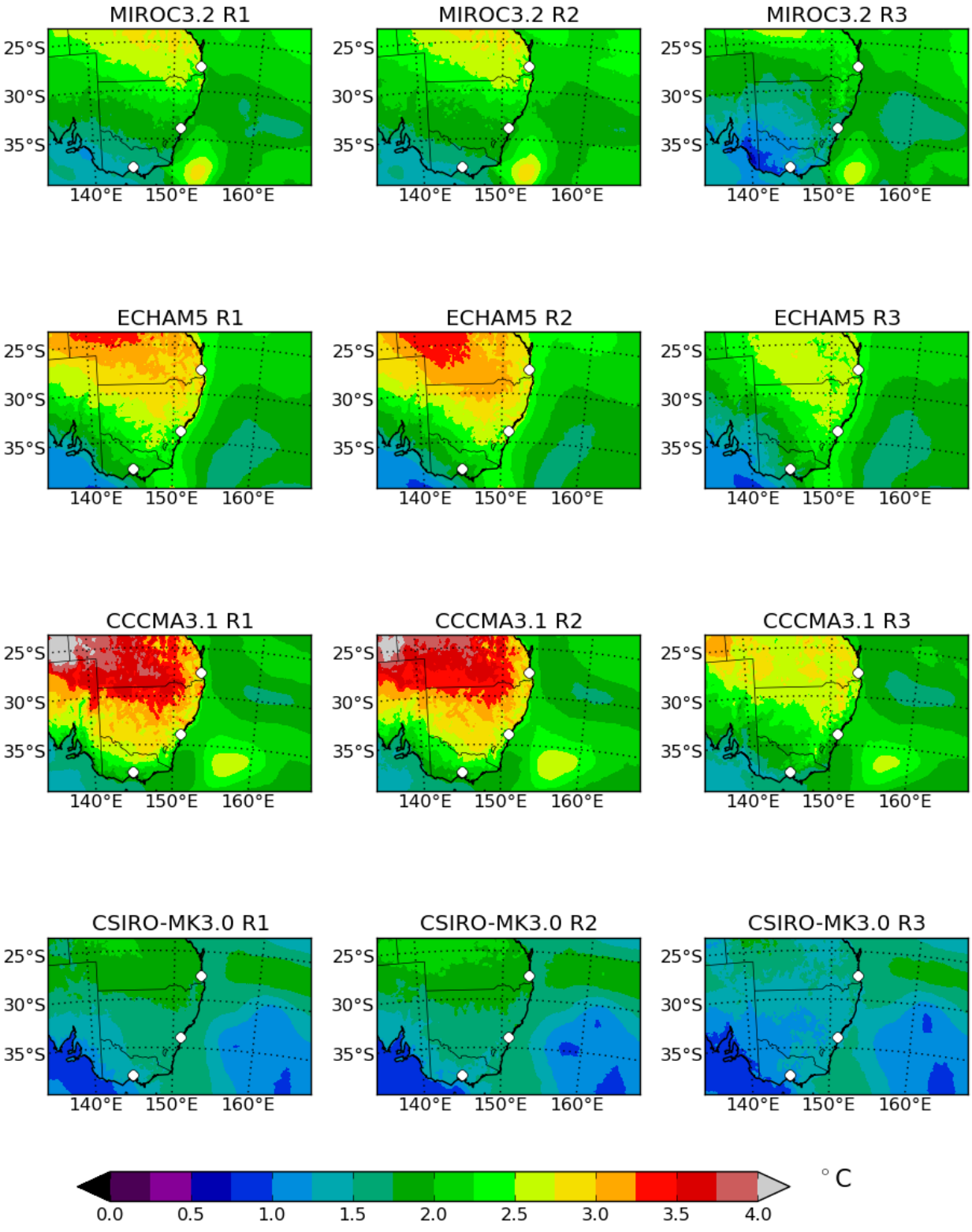

Figure 9.24: MAM mean change between years 1990-2009 and 2060-2079 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

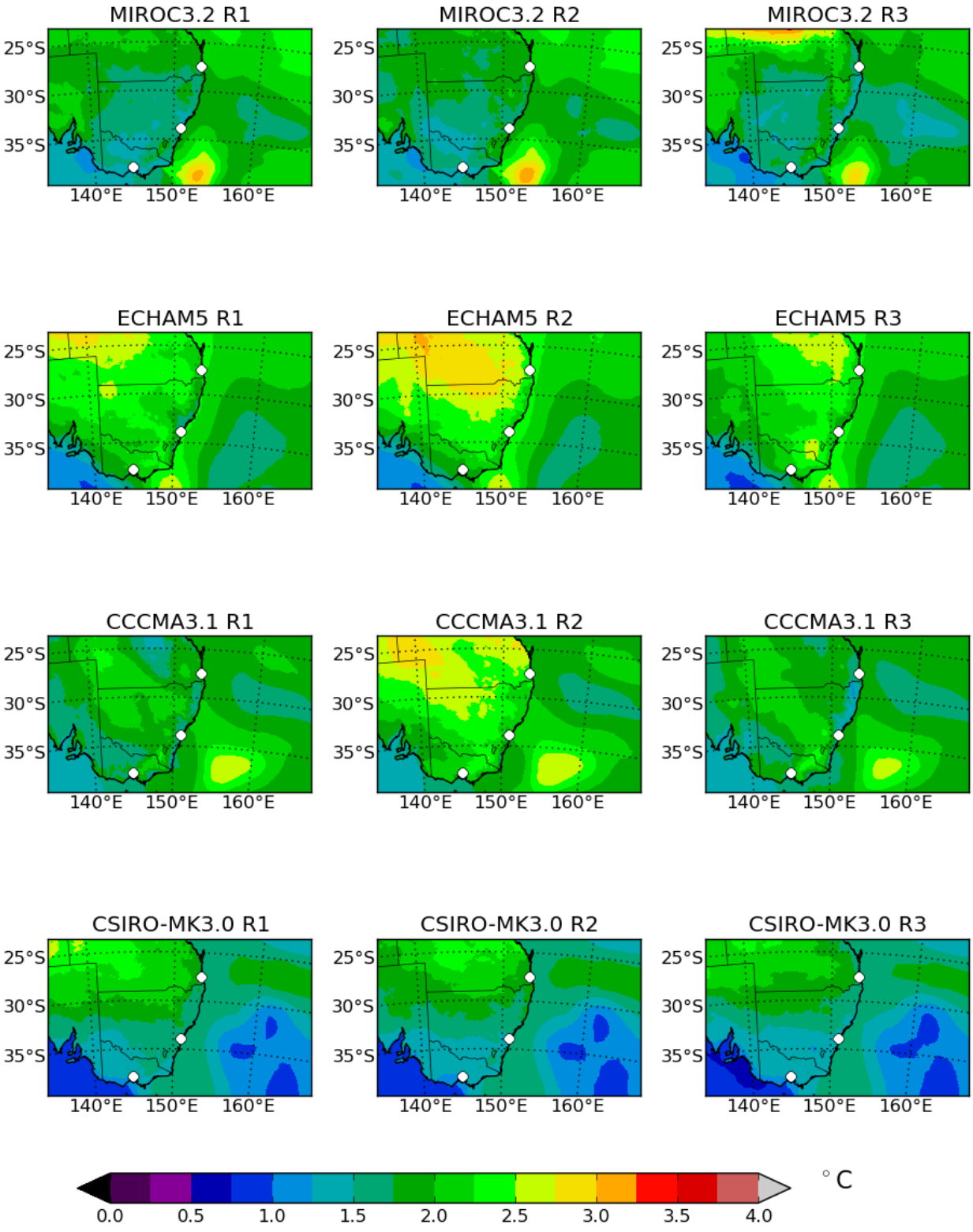

Figure 9.25: MAM mean change between years 1990-2009 and 2060-2079 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

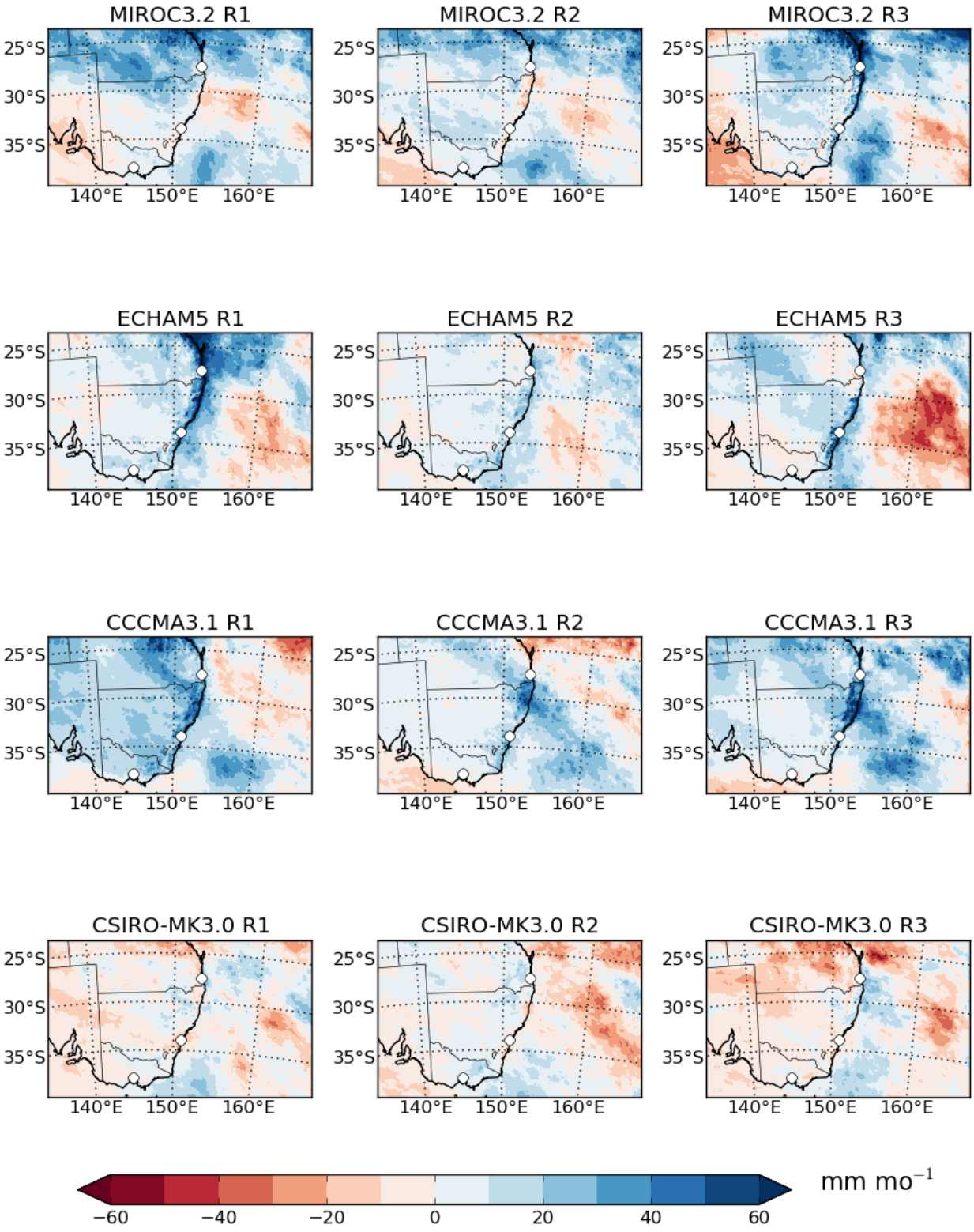

Figure 9.26: MAM mean change between years 1990-2009 and 2060-2079 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

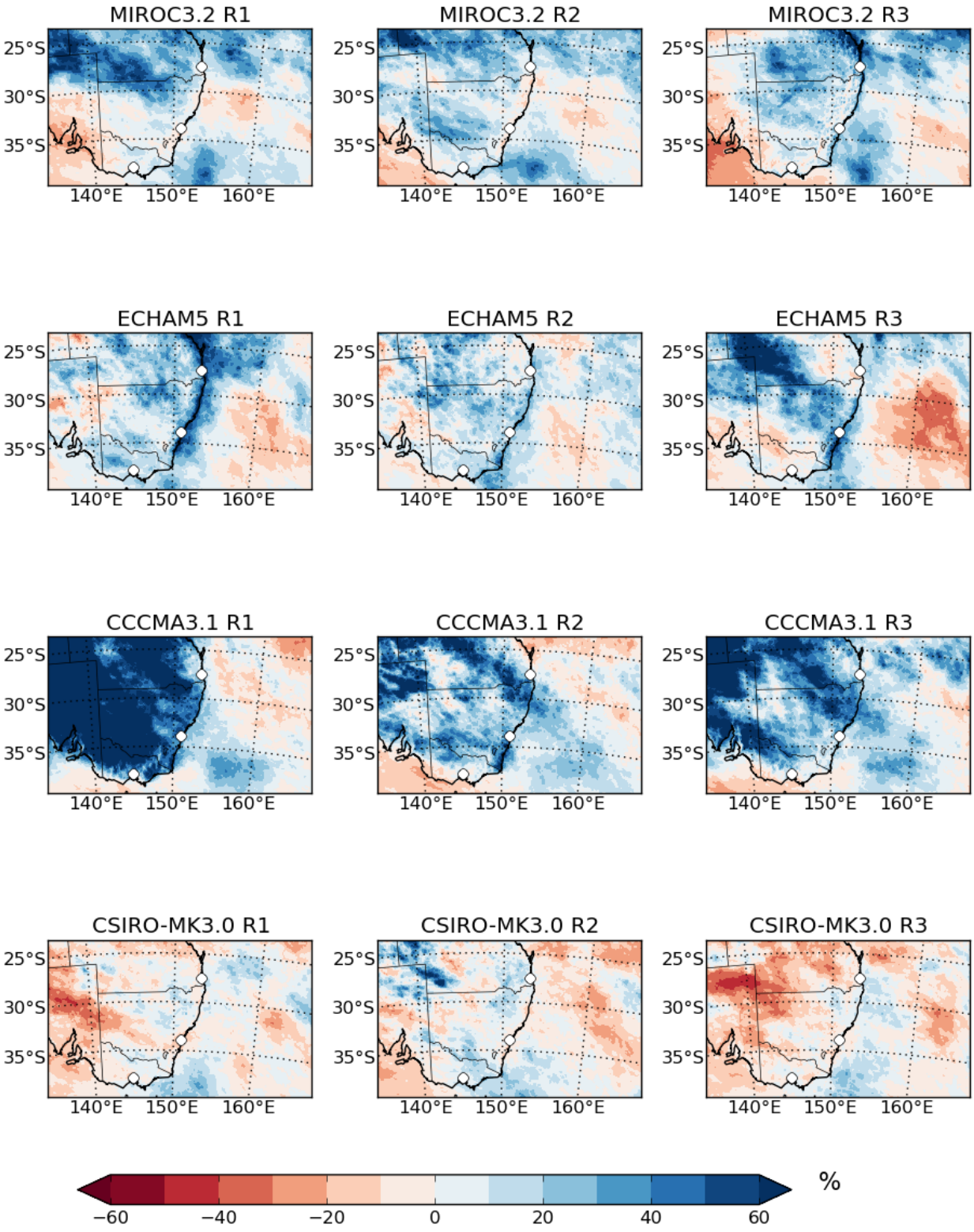

Figure 9.27: MAM mean change between years 1990-2009 and 2060-2079 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

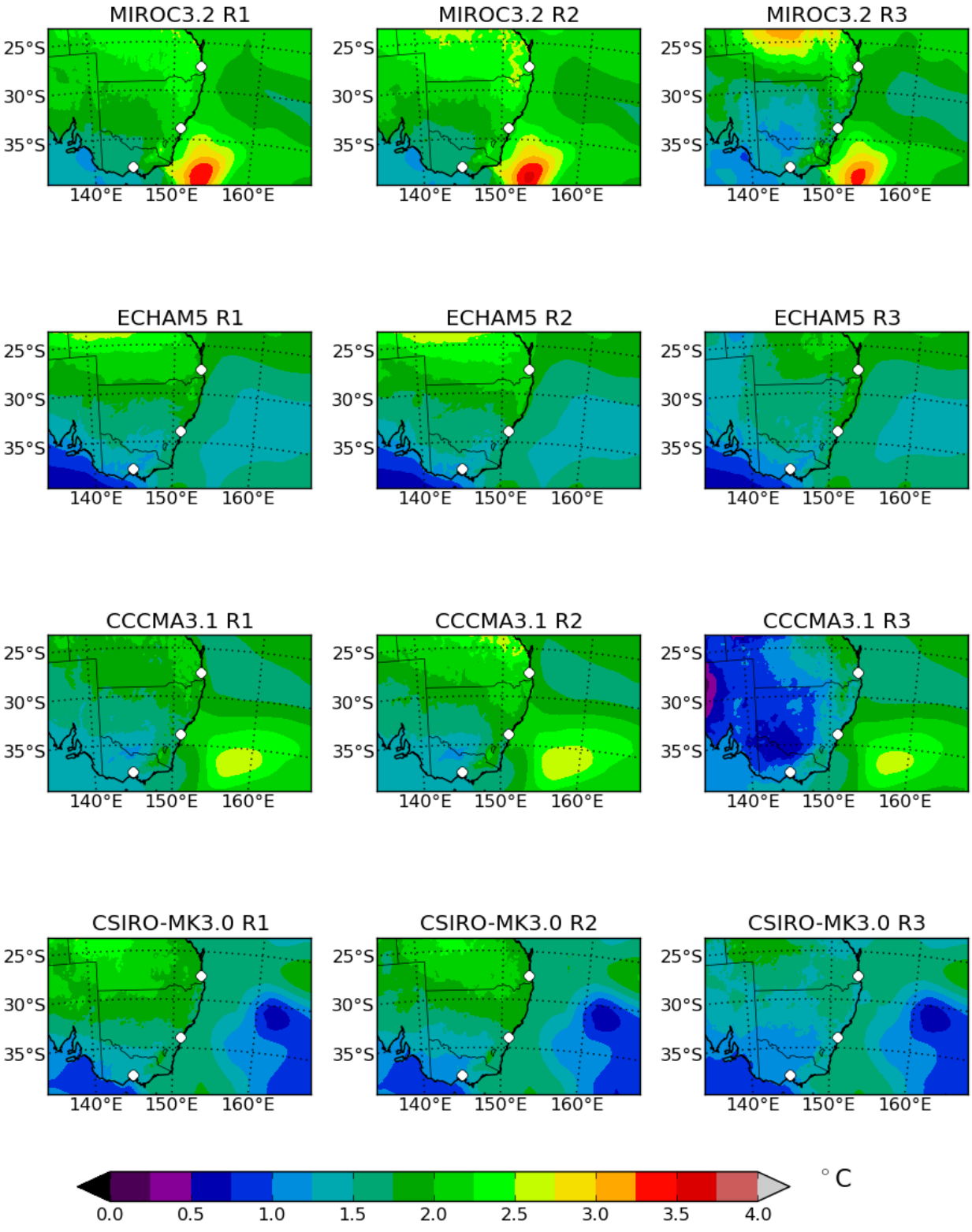

Figure 9.28: JJA mean change between years 1990-2009 and 2060-2079 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

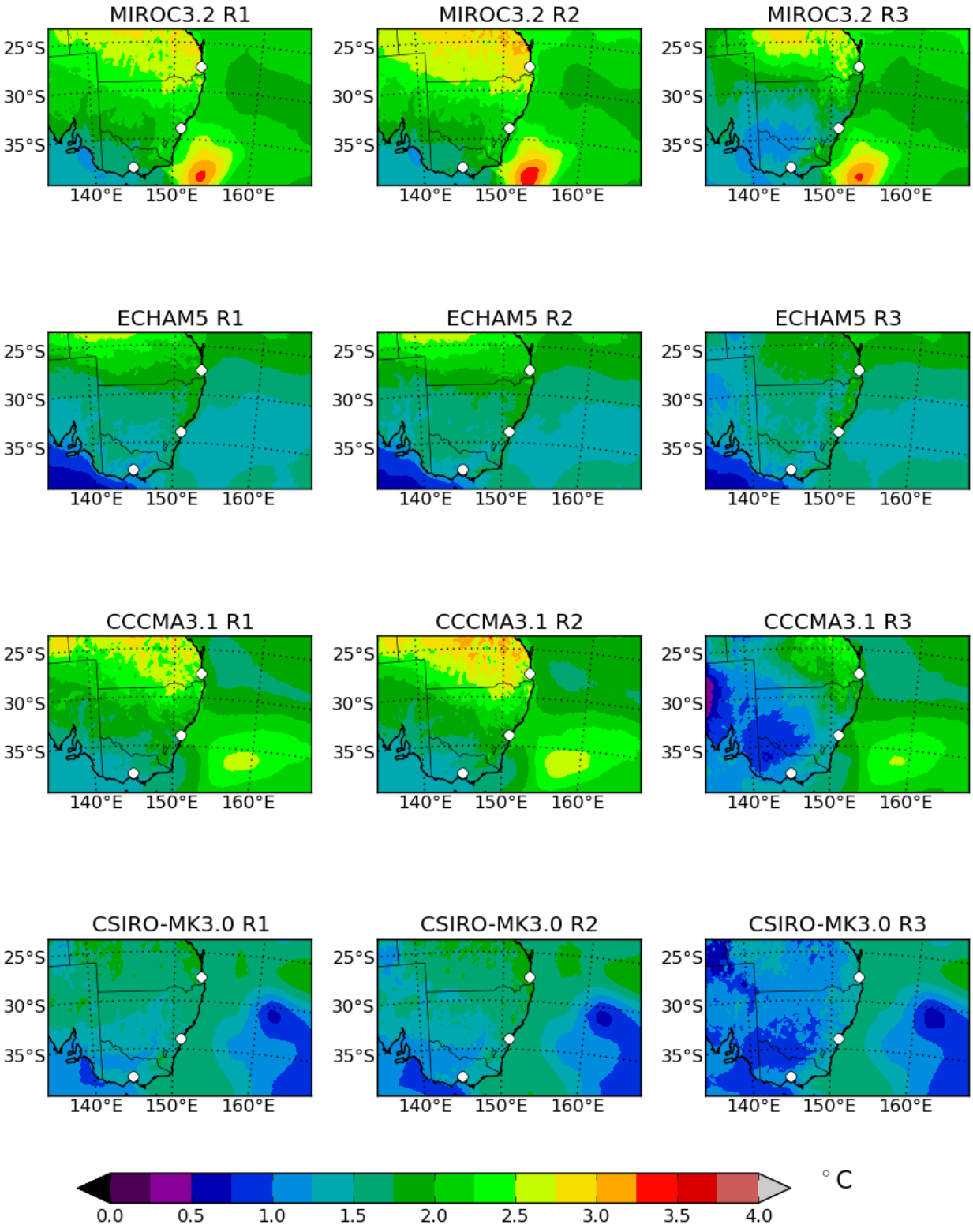

Figure 9.29: JJA mean change between years 1990-2009 and 2060-2079 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

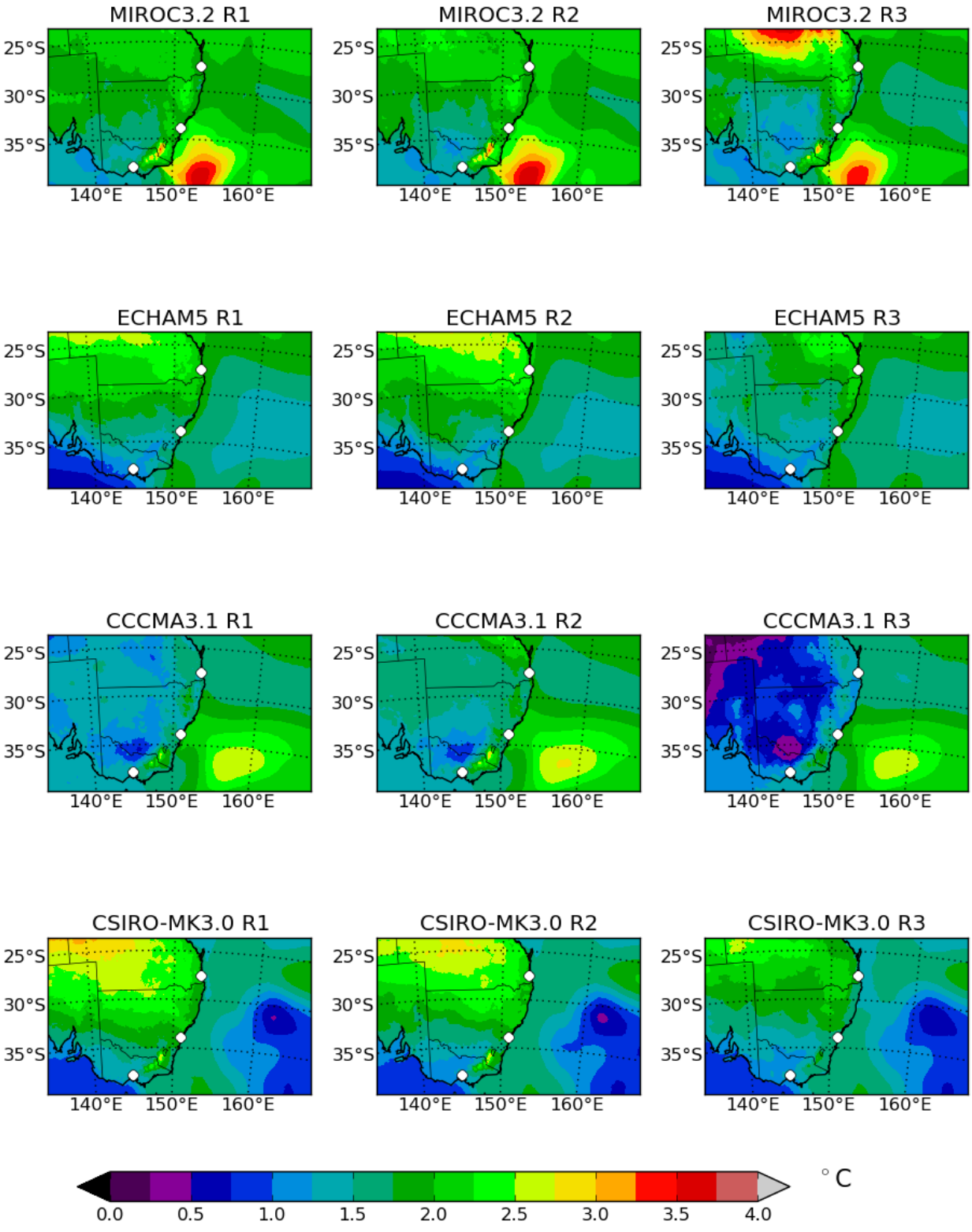

Figure 9.30: JJA mean change between years 1990-2009 and 2060-2079 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

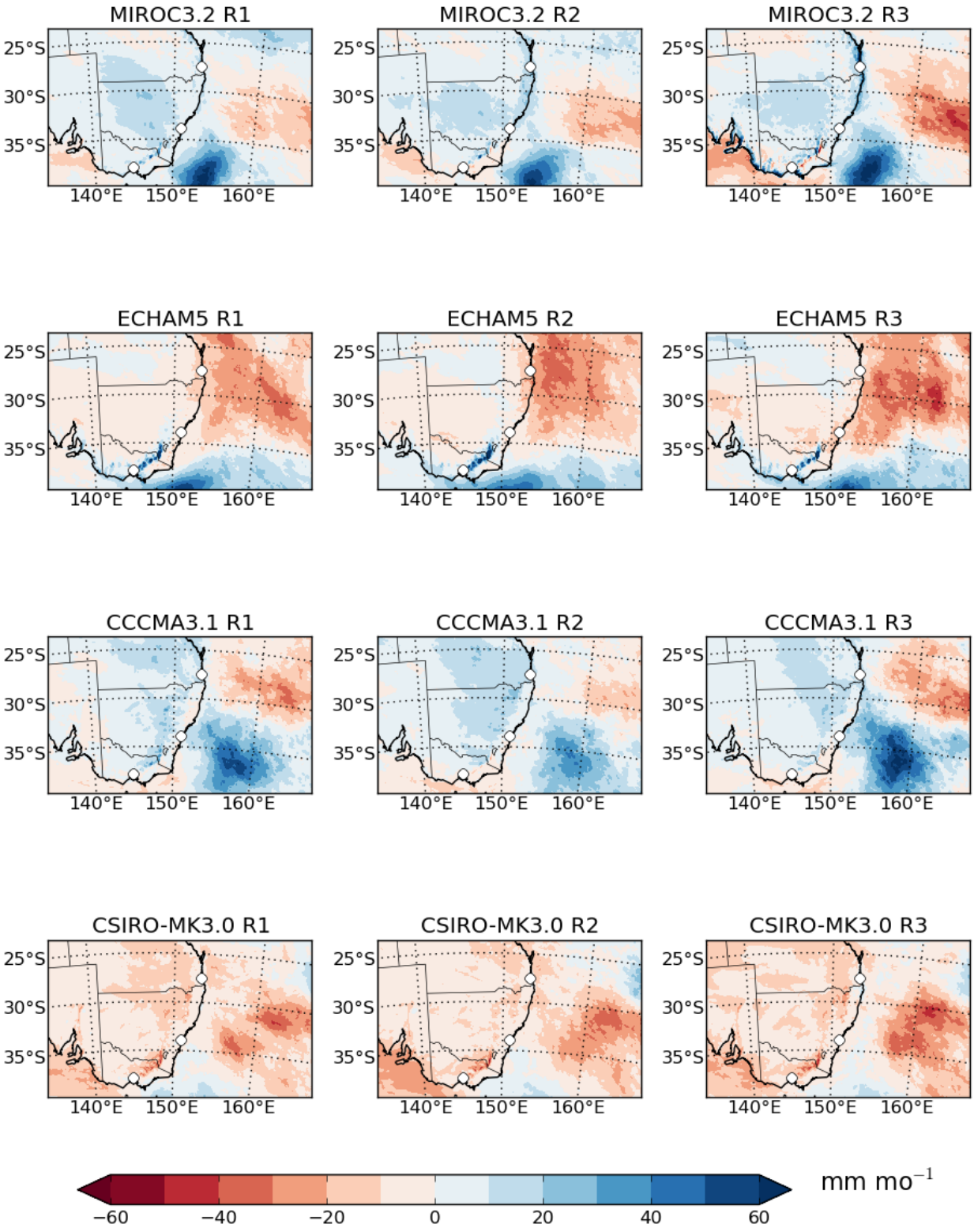

Figure 9.31: JJA mean change between years 1990-2009 and 2060-2079 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

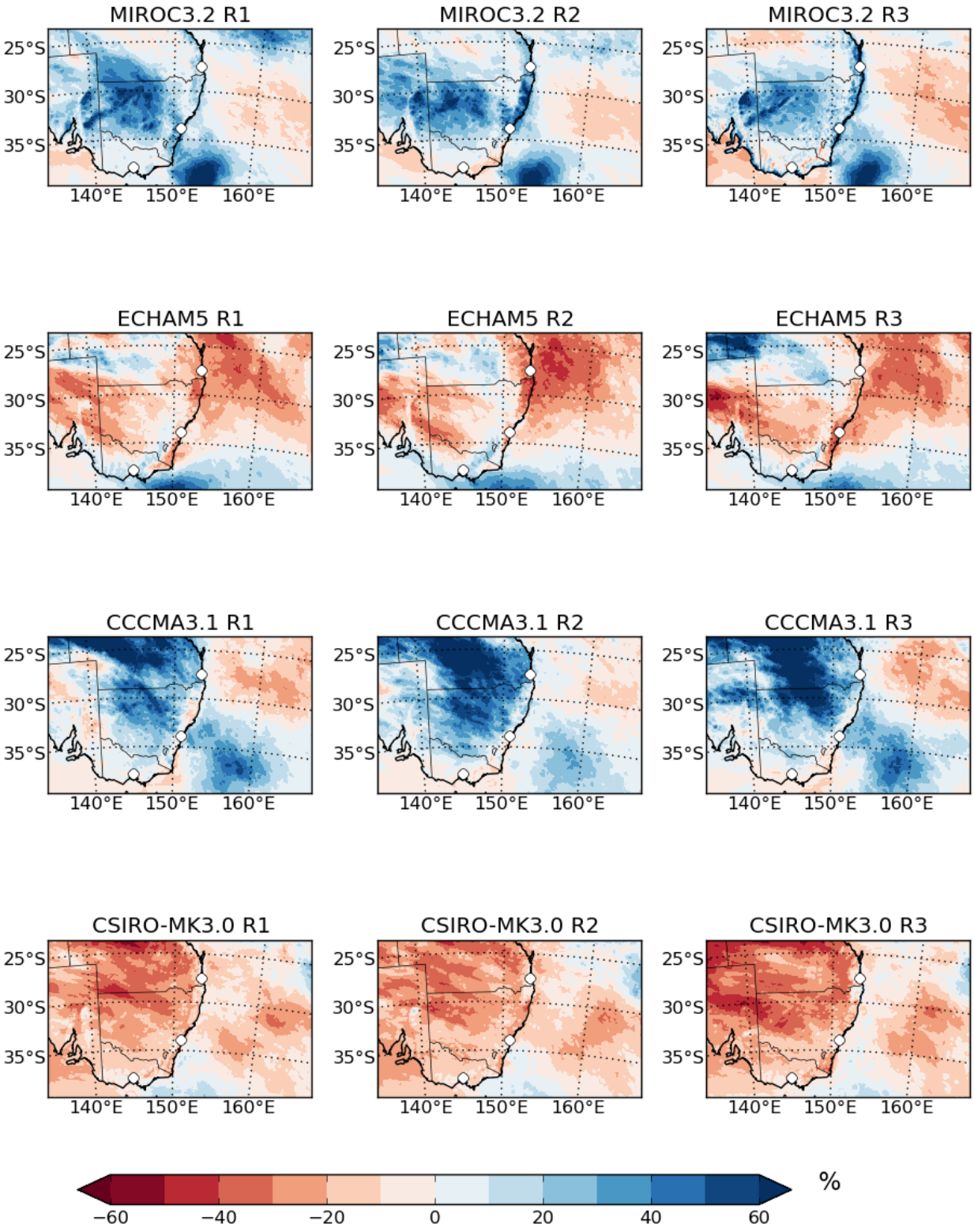

Figure 9.32: JJA mean change between years 1990-2009 and 2060-2079 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

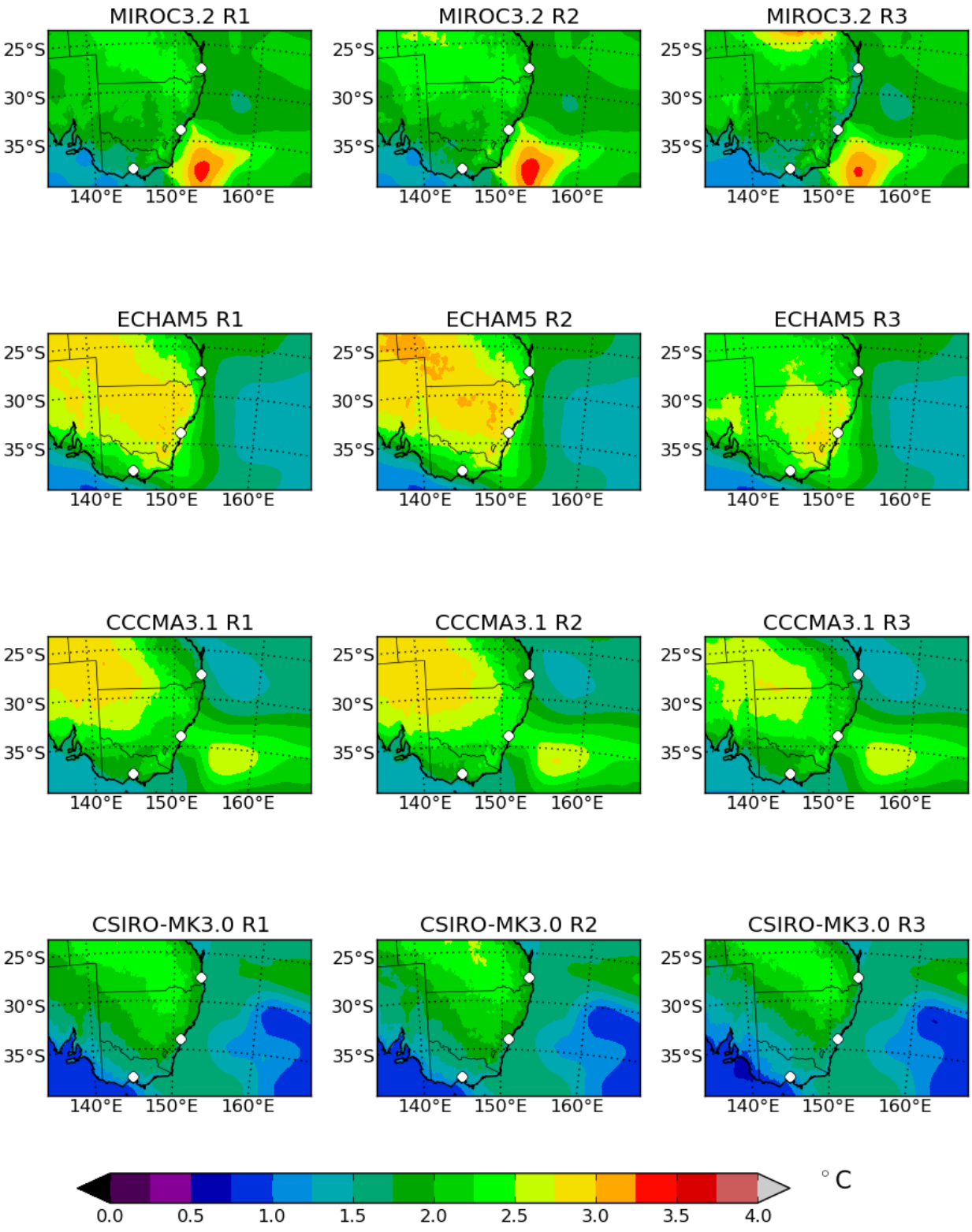

Figure 9.33: SON mean change between years 1990-2009 and 2060-2079 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

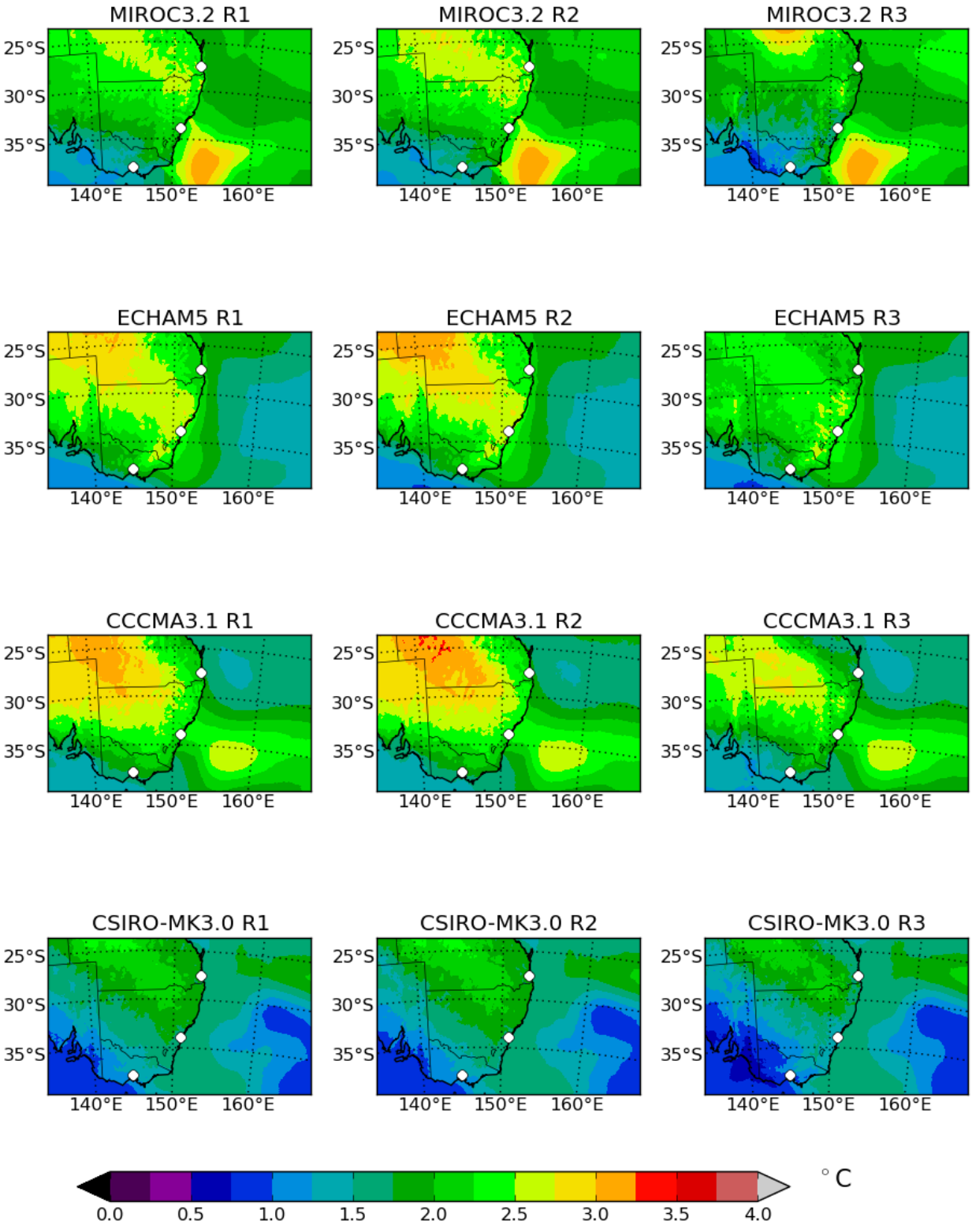

Figure 9.34: SON mean change between years 1990-2009 and 2060-2079 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

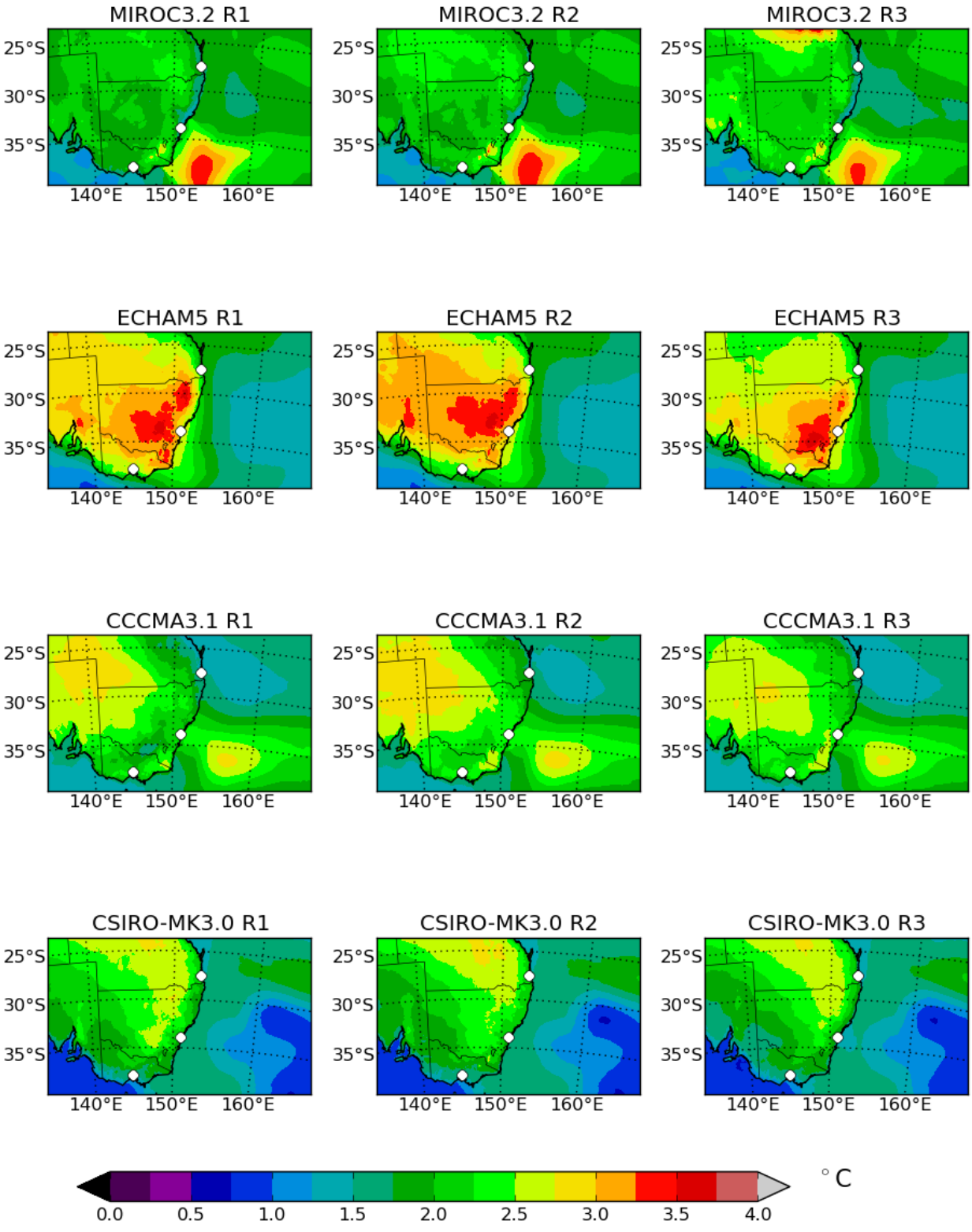

Figure 9.35: SON mean change between years 1990-2009 and 2060-2079 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

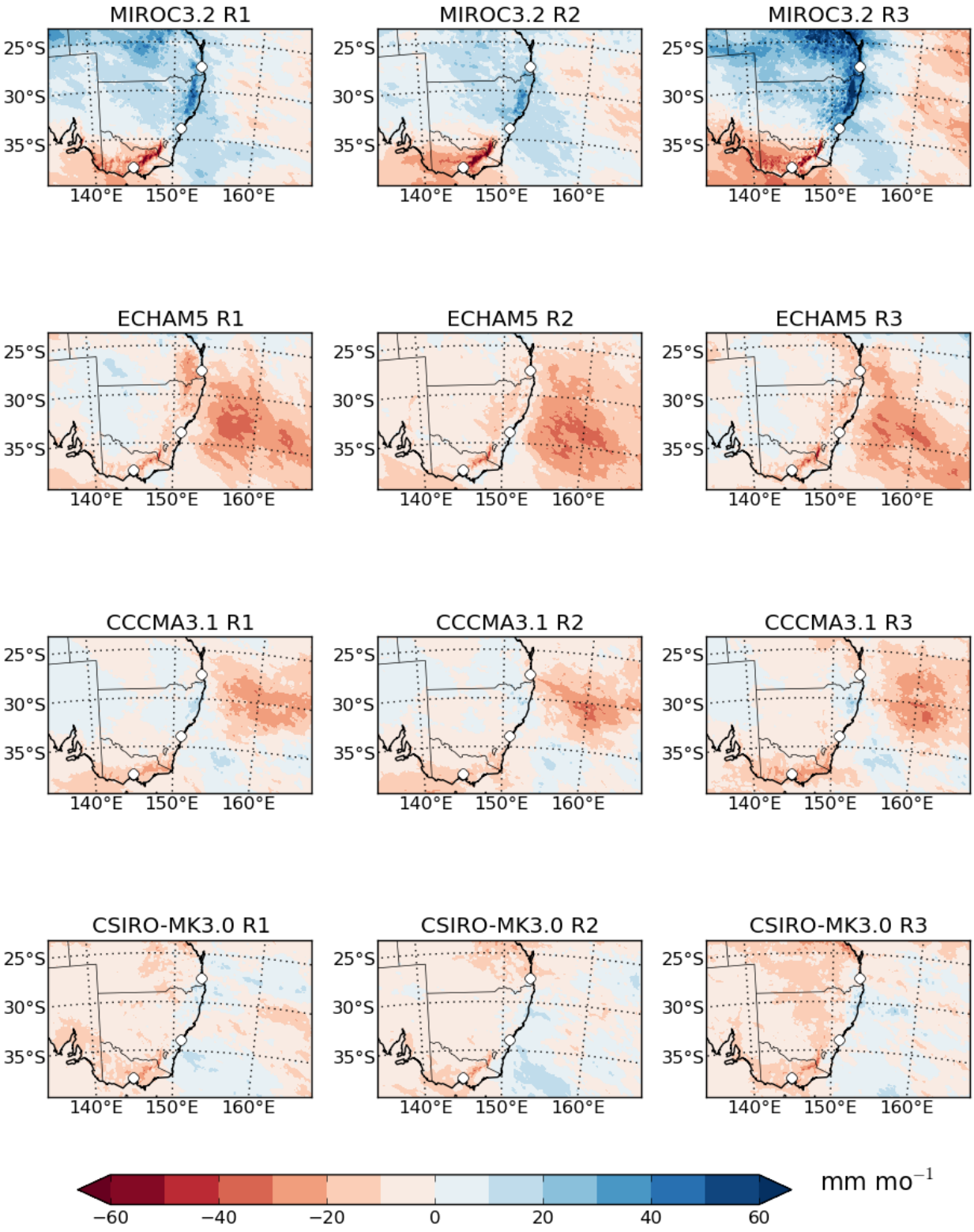

Figure 9.36: SON mean change between years 1990-2009 and 2060-2079 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

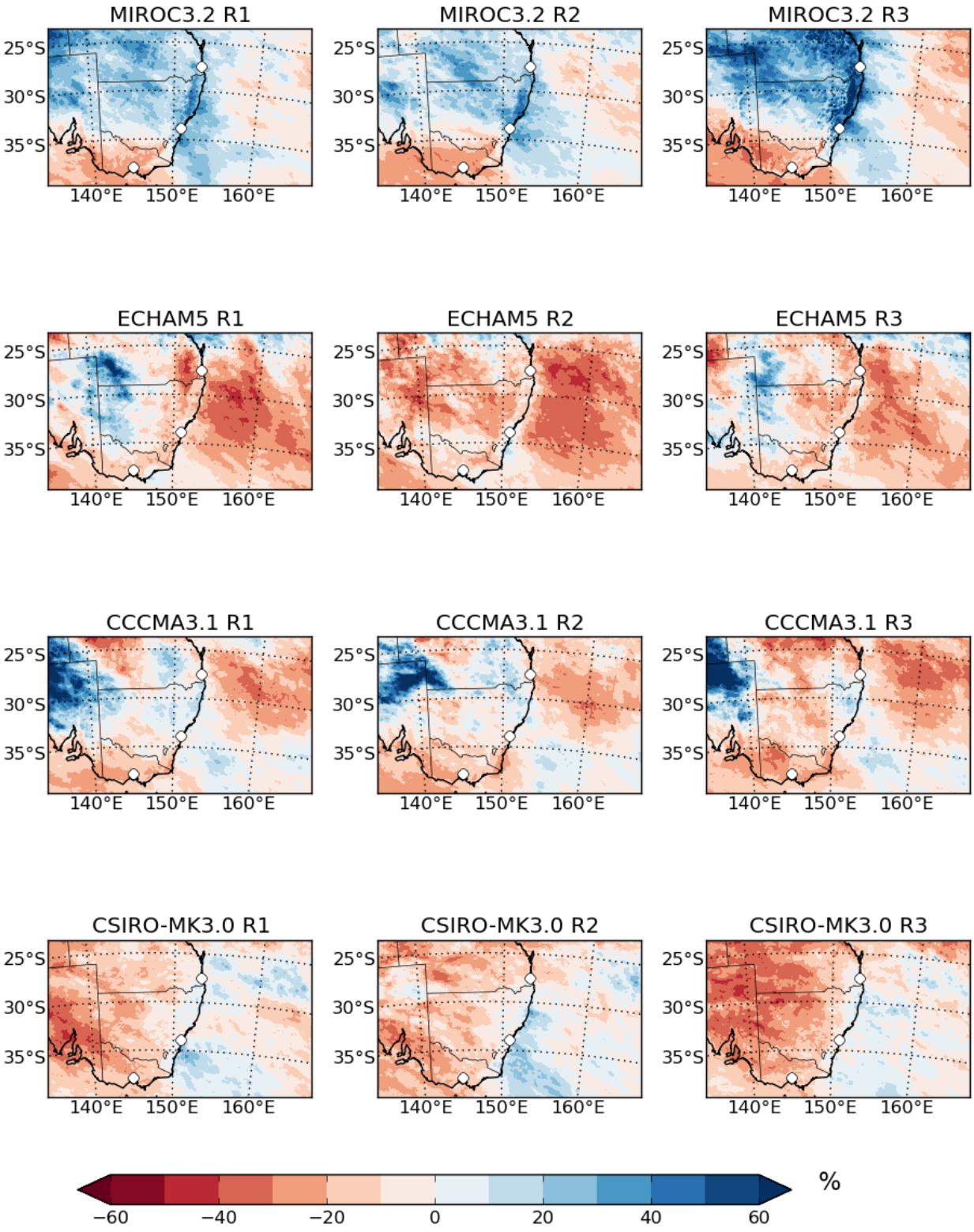

Figure 9.37: SON mean change between years 1990-2009 and 2060-2079 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

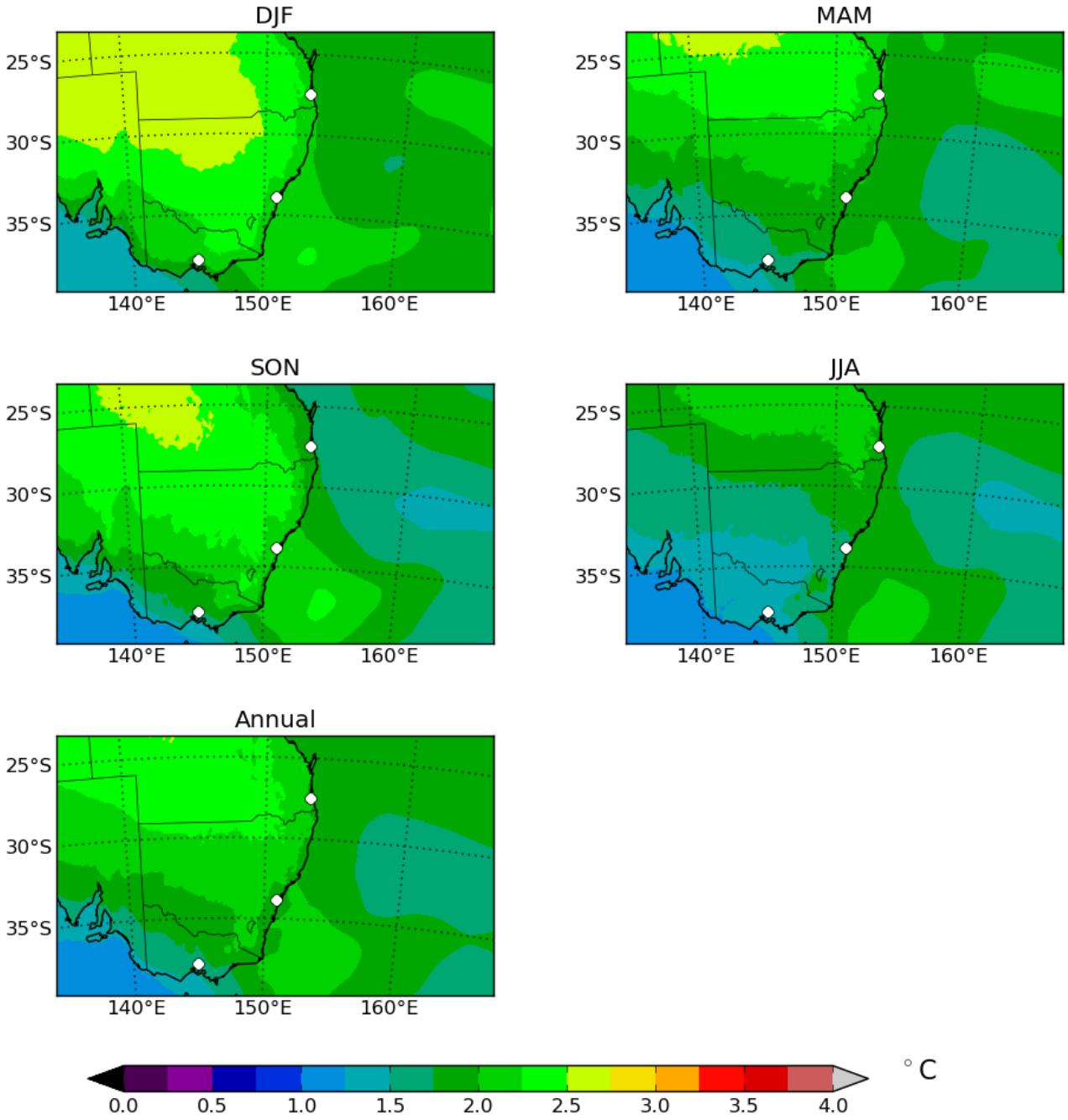

Figure 9.38: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

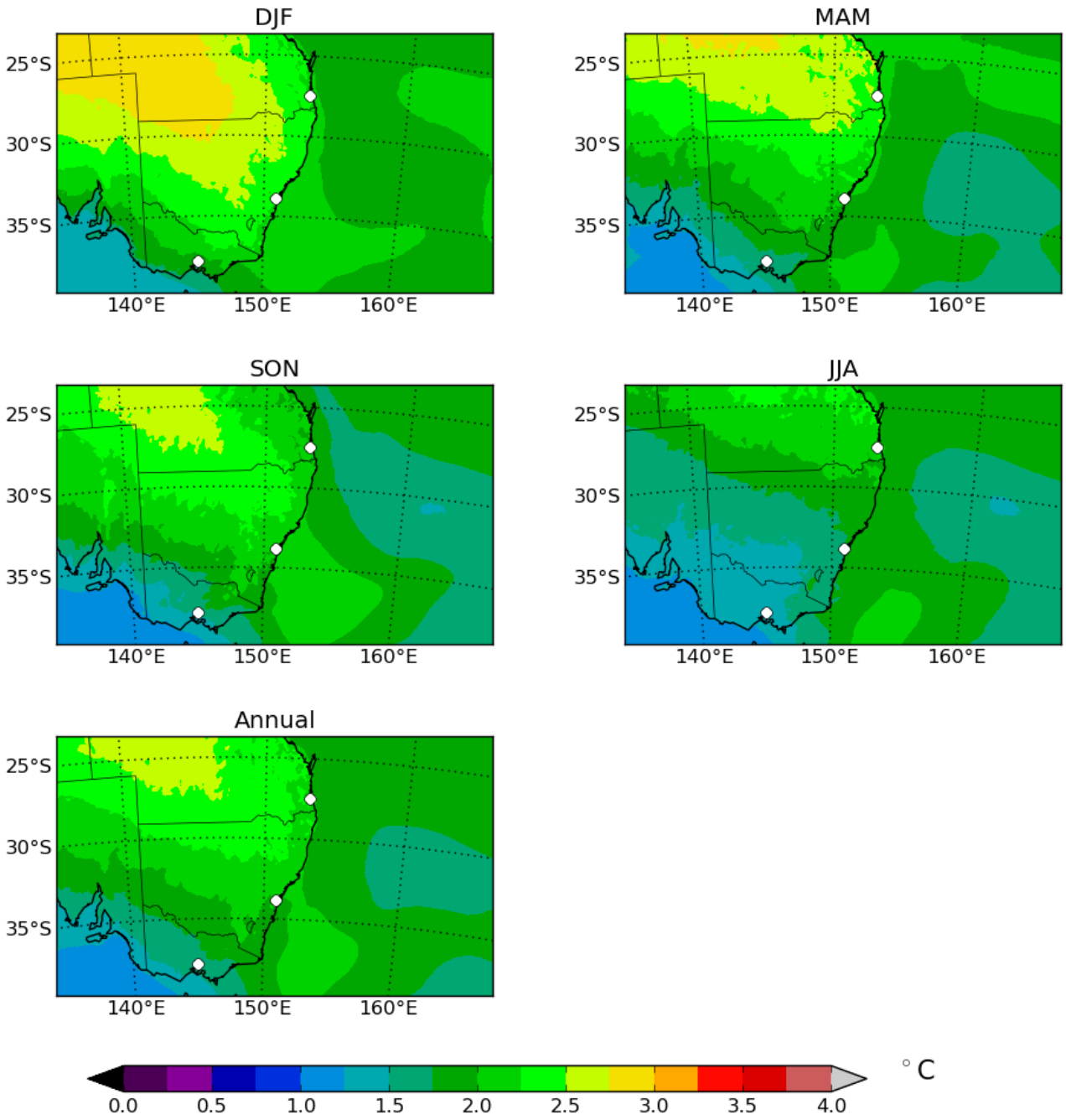

Figure 9.39: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

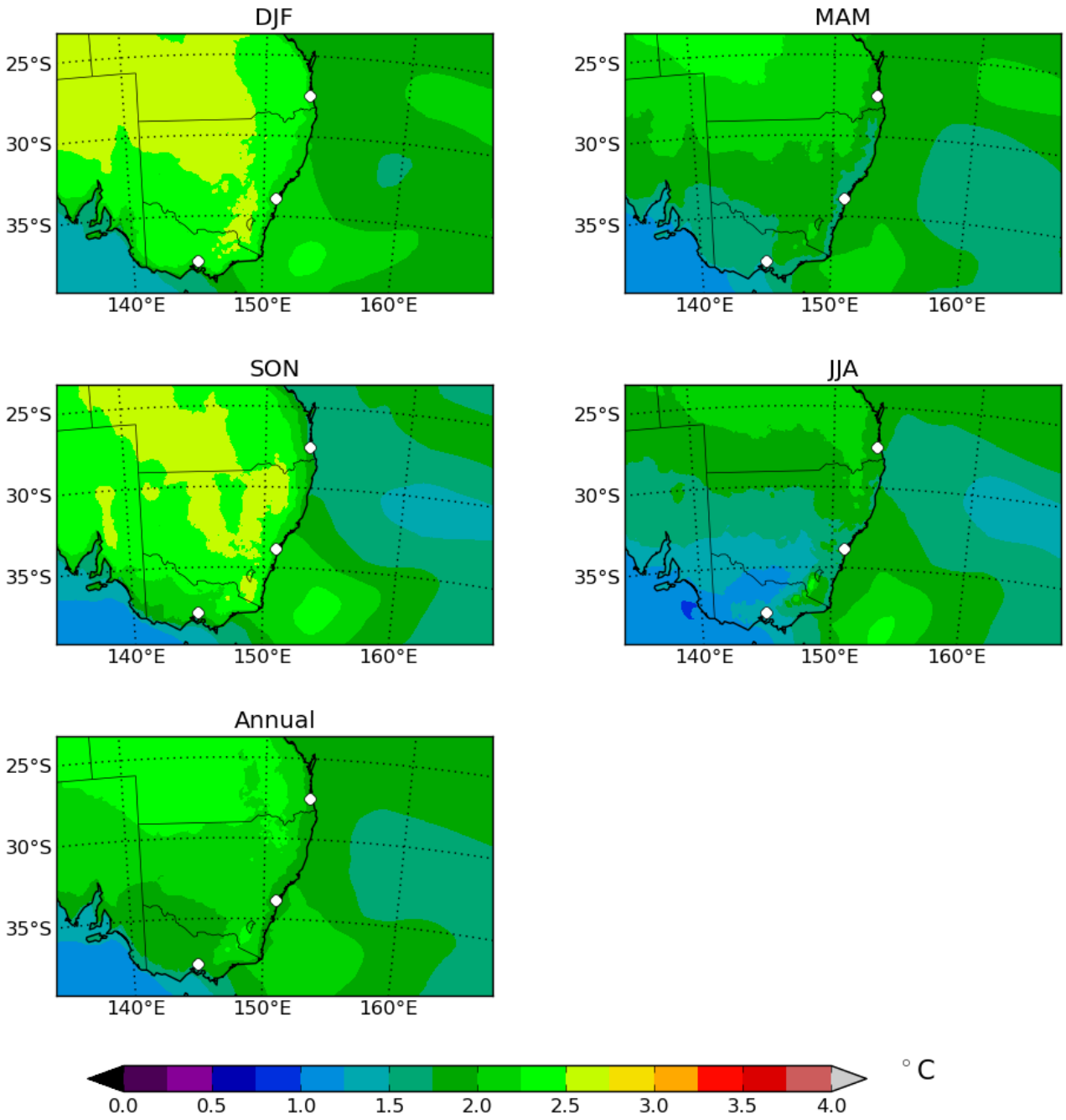

Figure 9.40: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

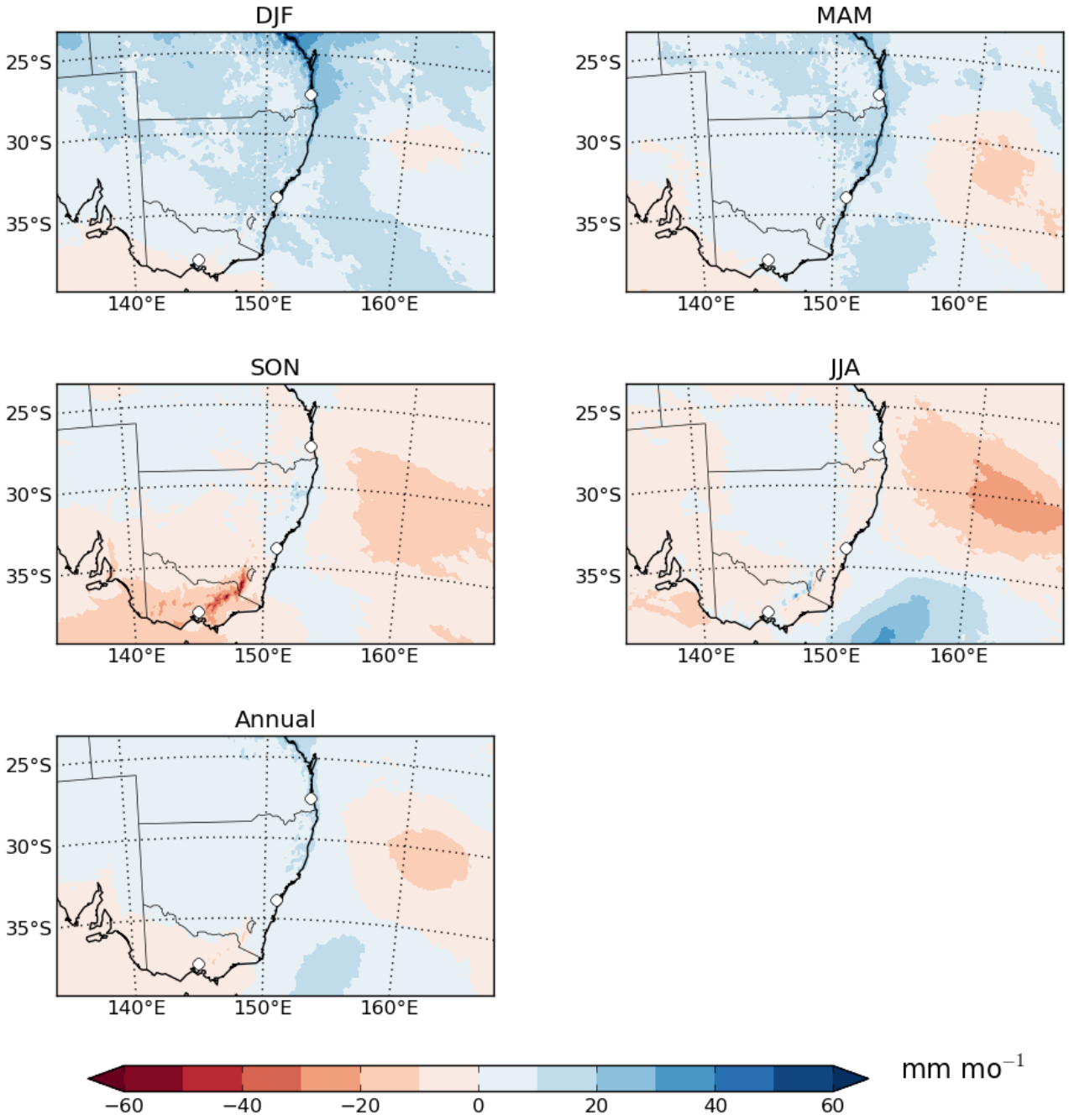

Figure 9.41: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

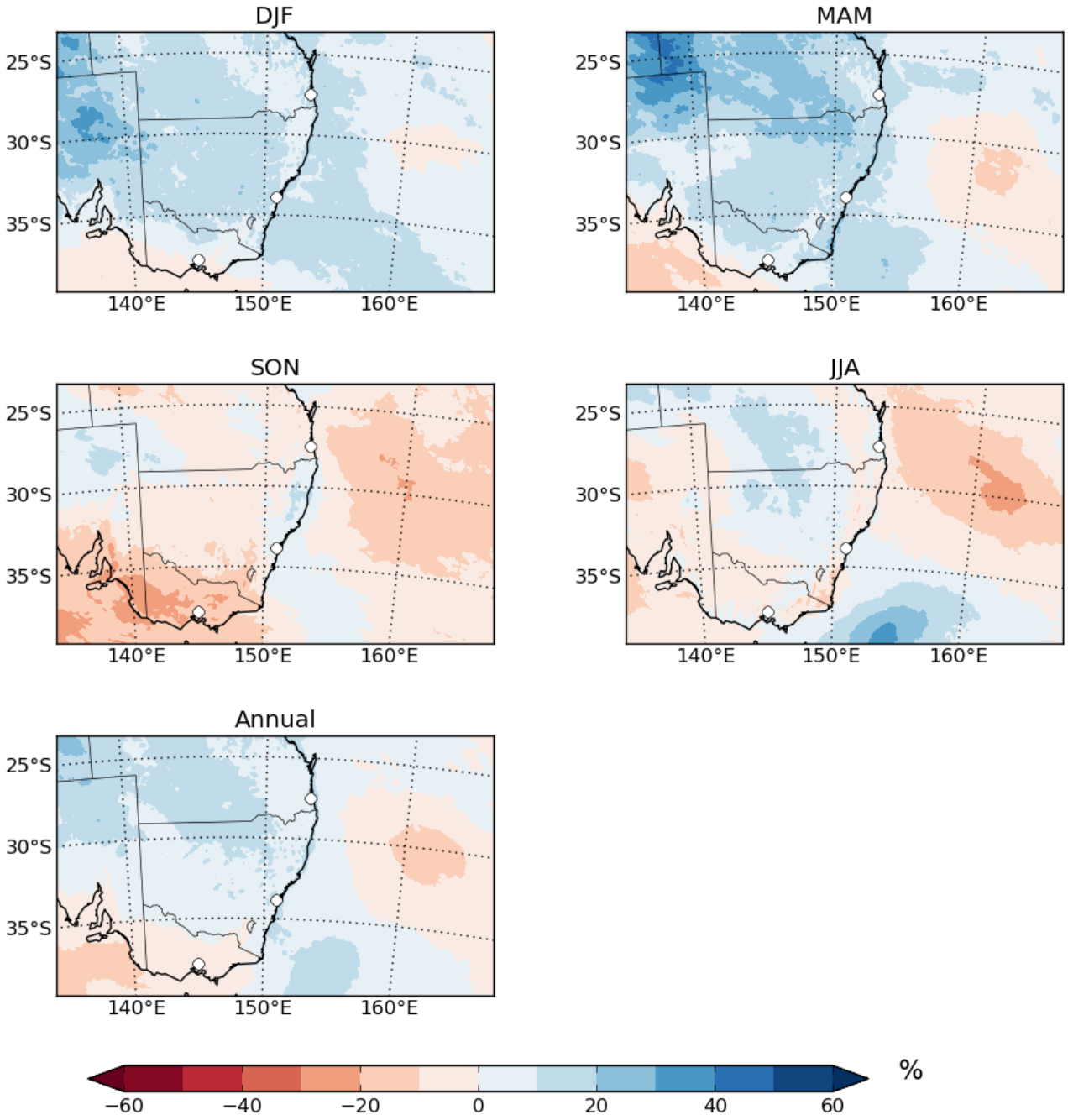

Figure 9.42: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

9.3 Bias-Corrected Regional Model Output: Changes from 1990-2009 to 2060-2079

This subsection contains projected seasonal and annual mean far-future changes in daily minimum near-surface air temperature, daily maximum near-surface air temperature, and precipitation from the bias-corrected RCM output (*i.e.* RCM output that has been corrected for the present-day biases between the models and the observations of climate using the methods described here [6]). The corrections are calculated by comparing present-day distributions of daily model output and observations for all seasons. Thus, the corrections are independent of the season. Precipitation changes are plotted as both absolute values (in mm mo^{-1}), and percent changes. First we show individual model plots for each variable and season. Then we show seasonal multi-model mean climatologies for each variable. The multi-model mean plots provide information on average projected changes, whereas the individual-model plots show the level of uncertainty in projected changes.

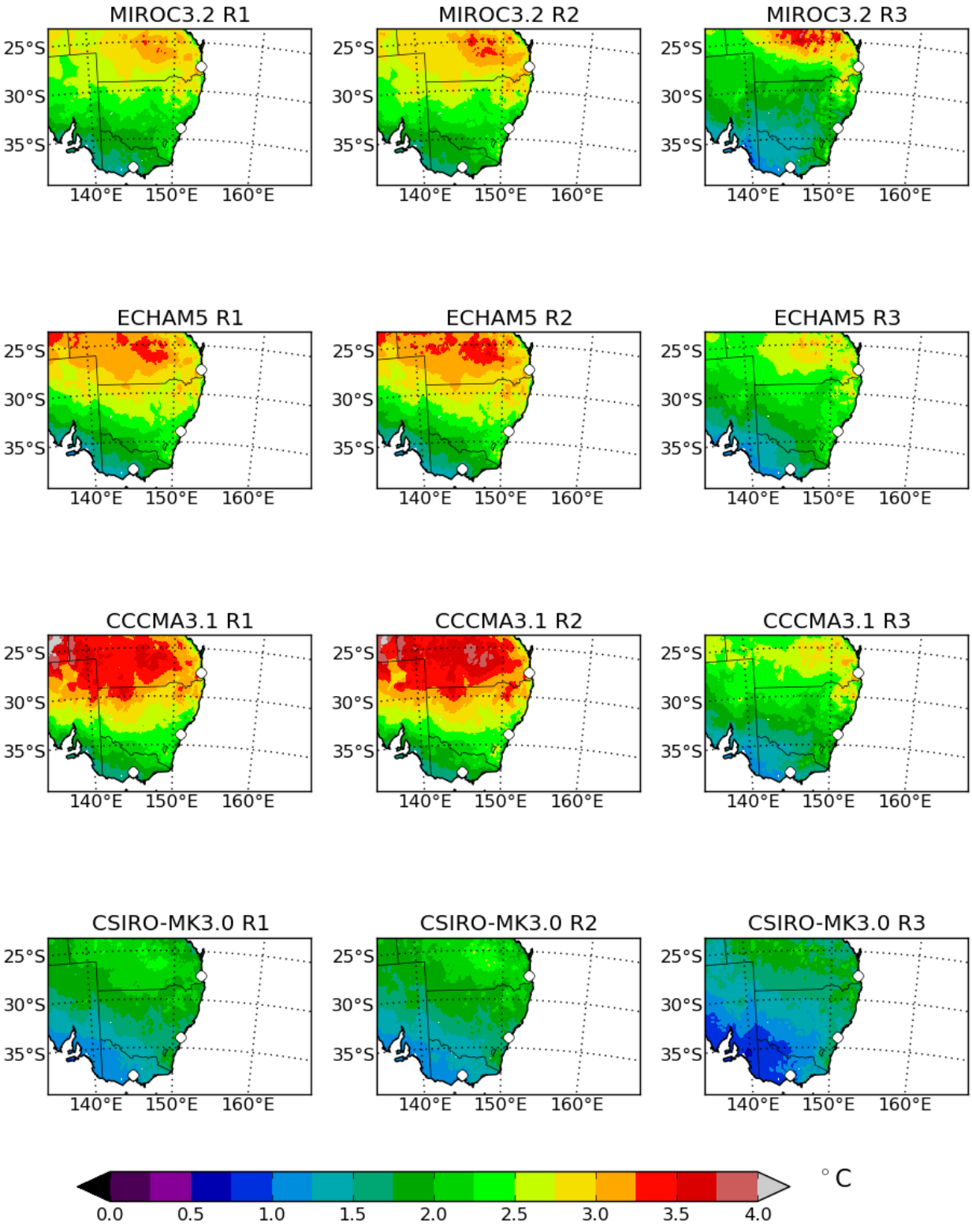

Figure 9.43: Annual mean change between years 1990-2009 and 2060-2079 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

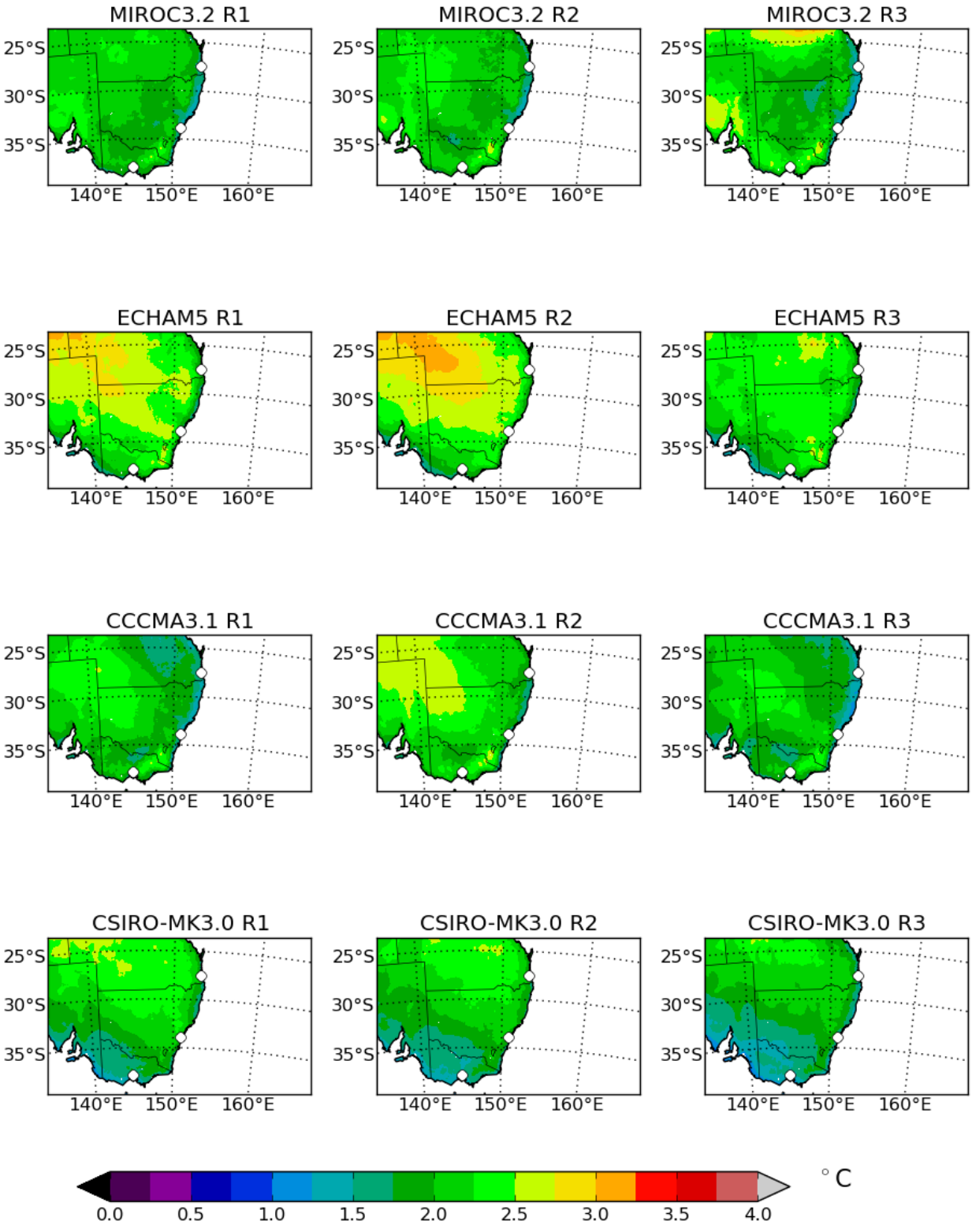

Figure 9.44: Annual mean change between years 1990-2009 and 2060-2079 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

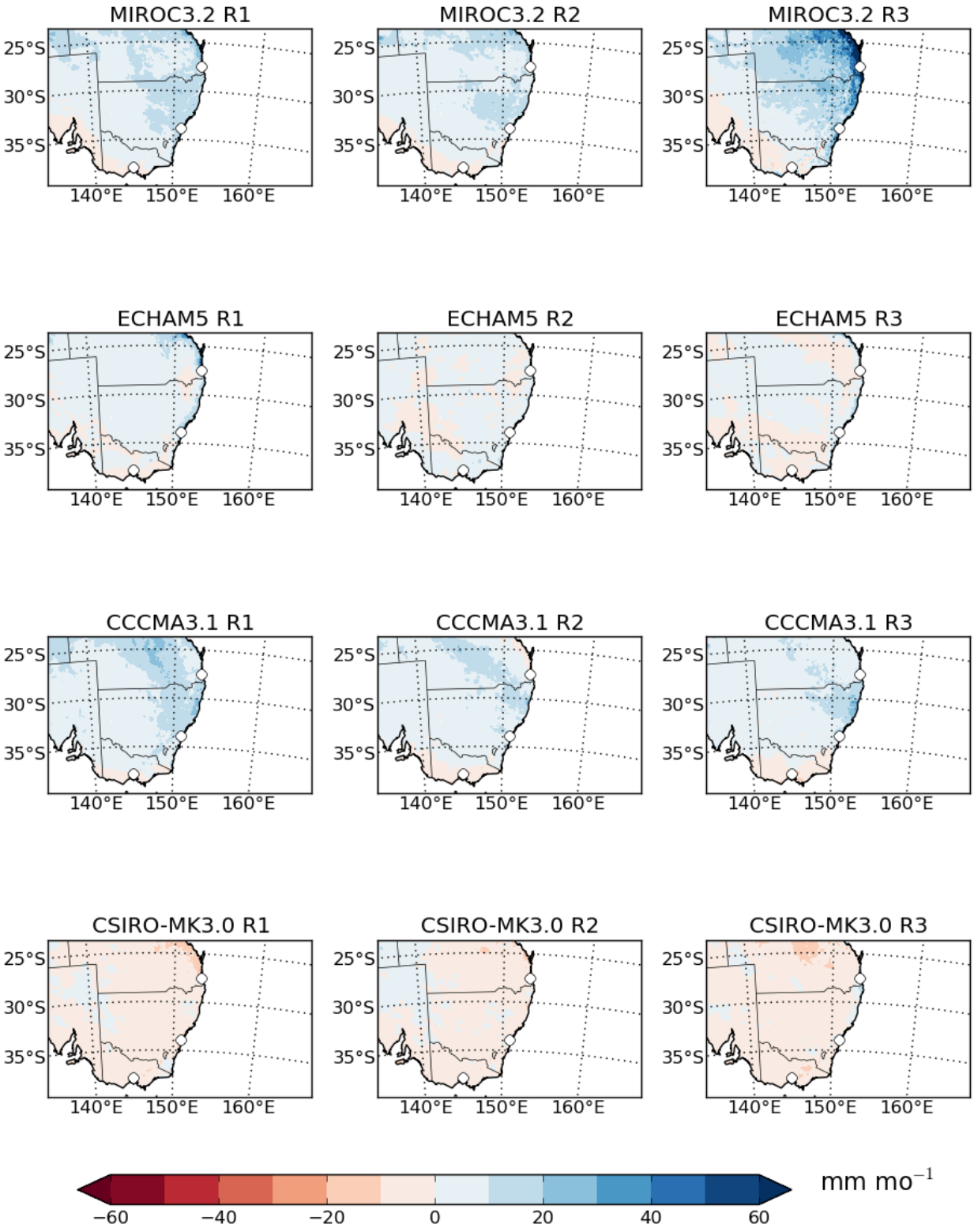

Figure 9.45: Annual mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

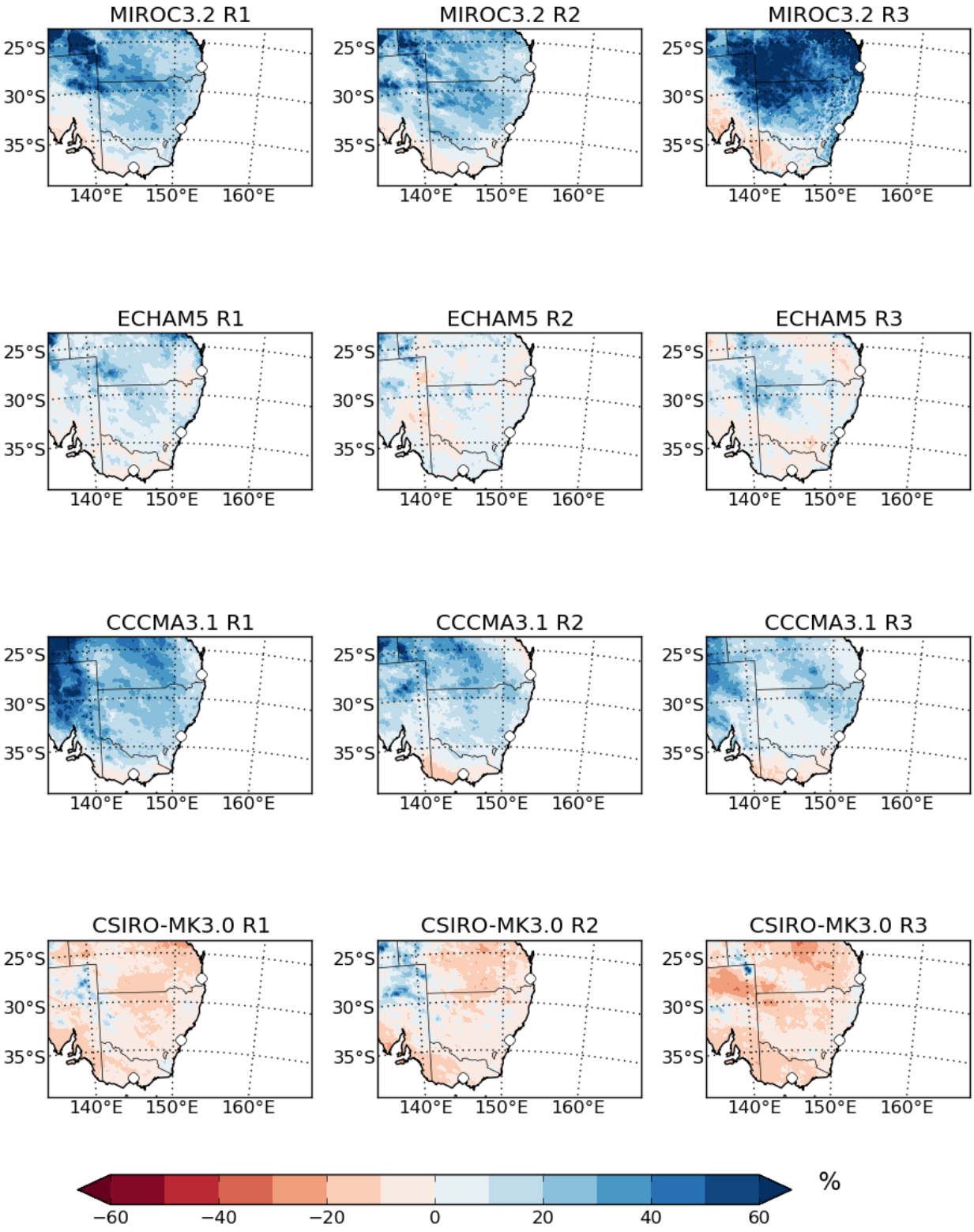

Figure 9.46: Annual mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

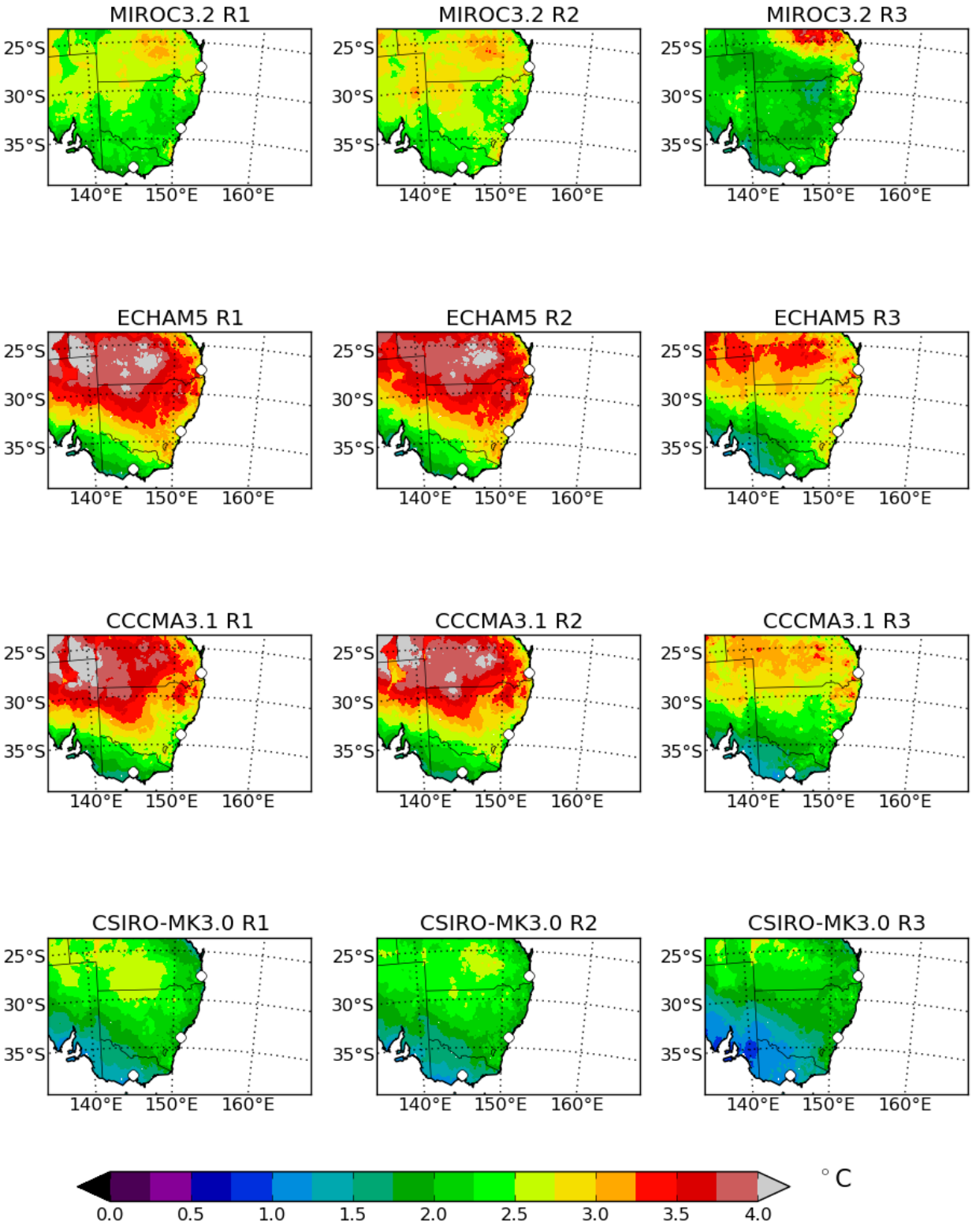

Figure 9.47: DJF mean change between years 1990-2009 and 2060-2079 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

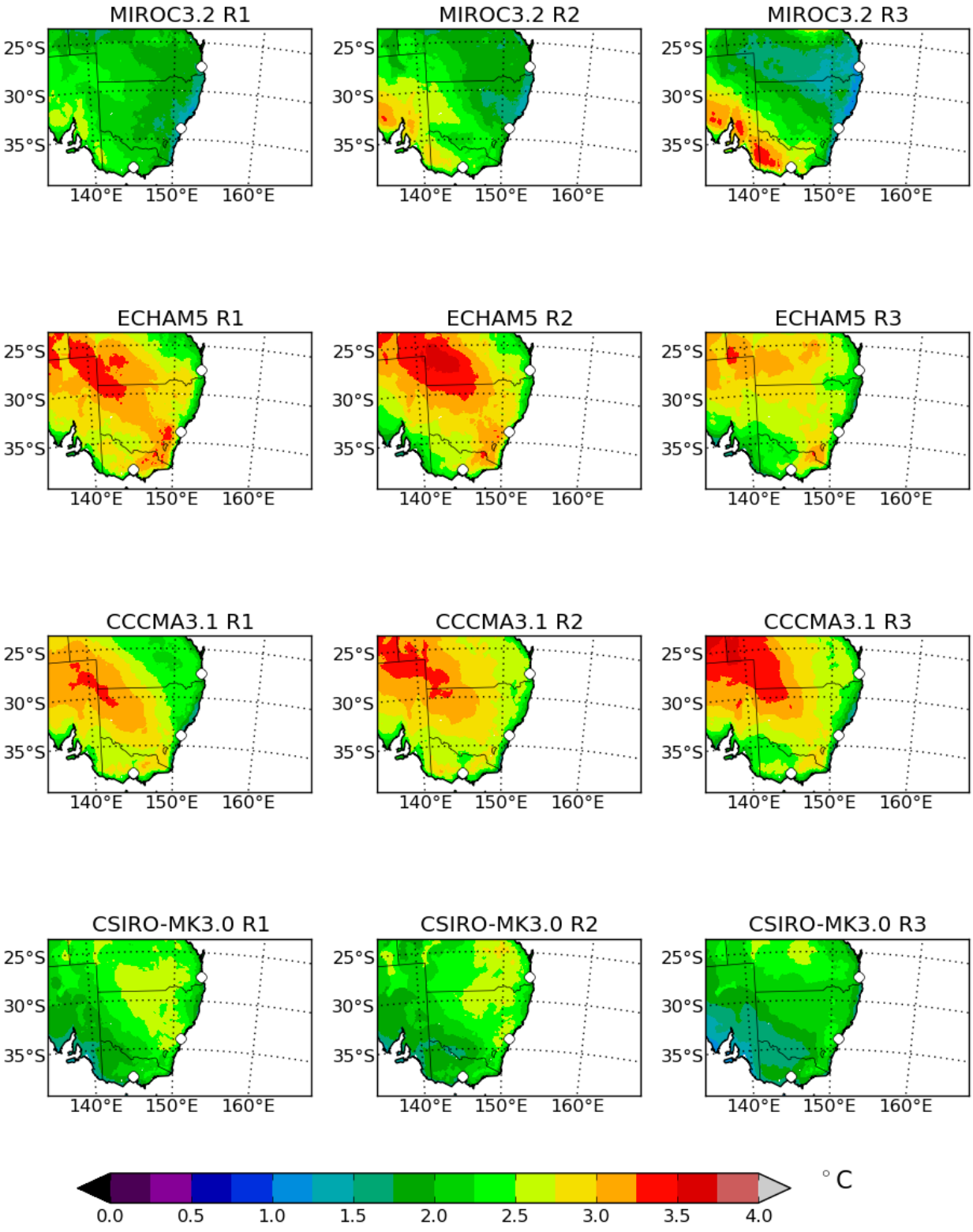

Figure 9.48: DJF mean change between years 1990-2009 and 2060-2079 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

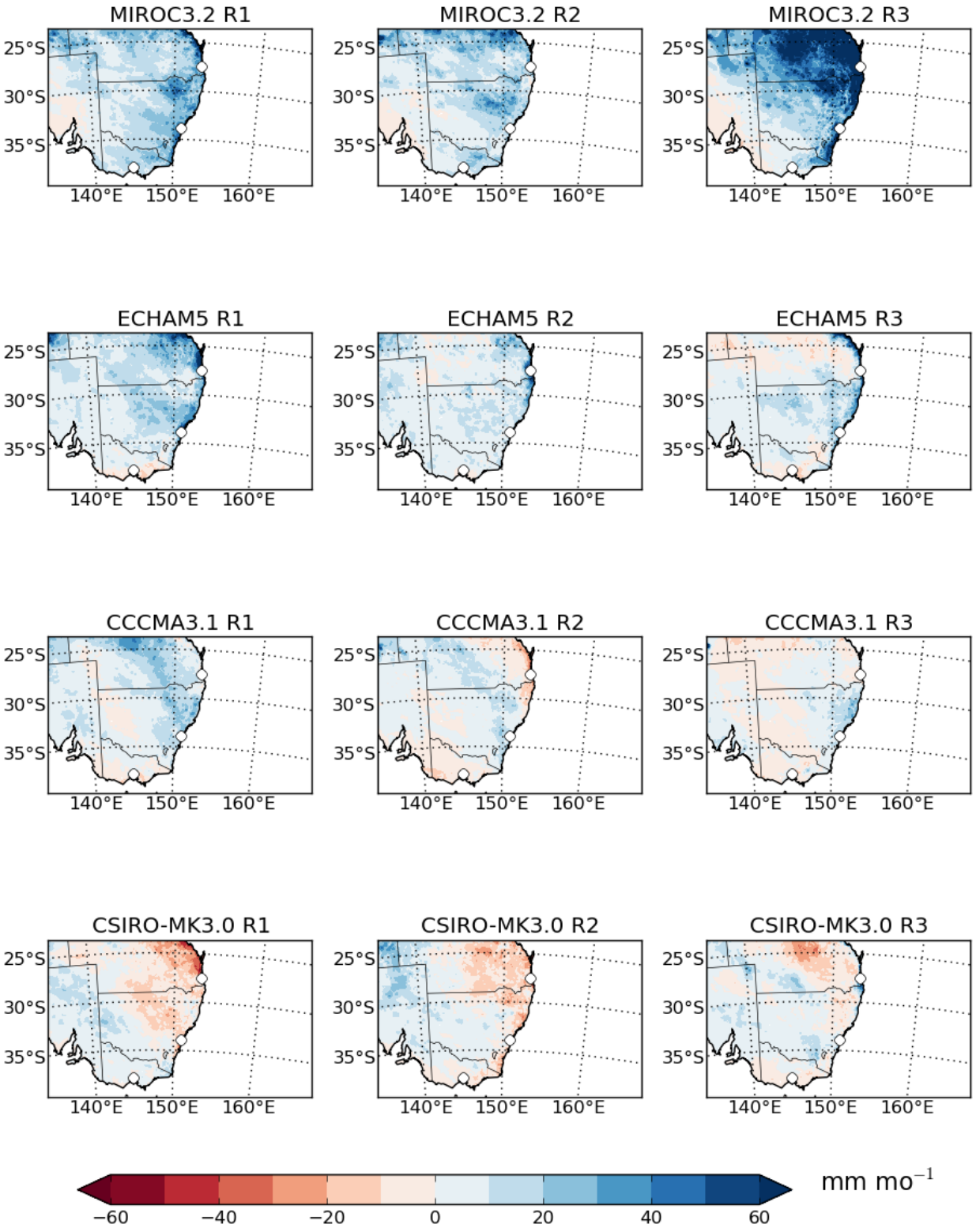

Figure 9.49: DJF mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

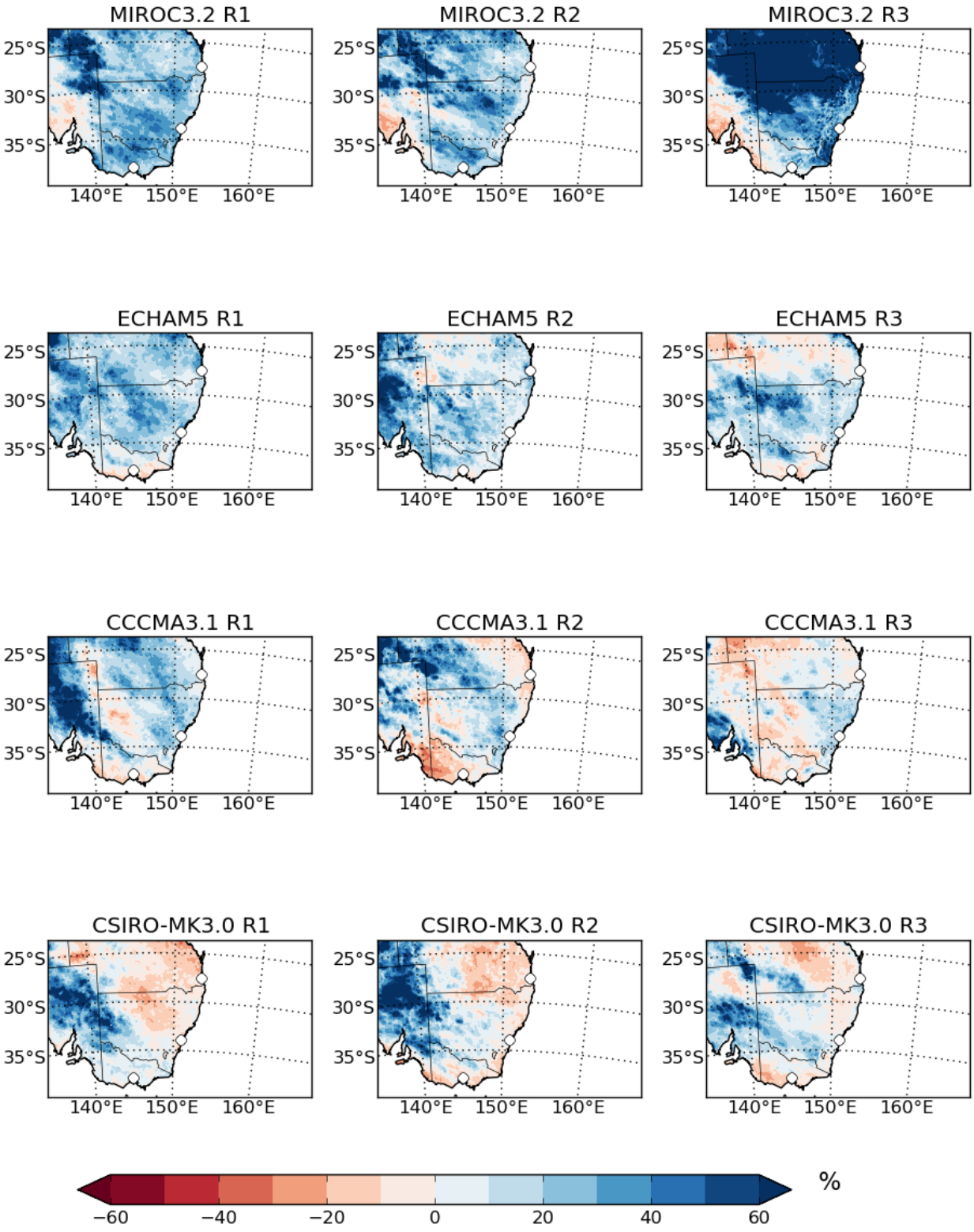

Figure 9.50: DJF mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

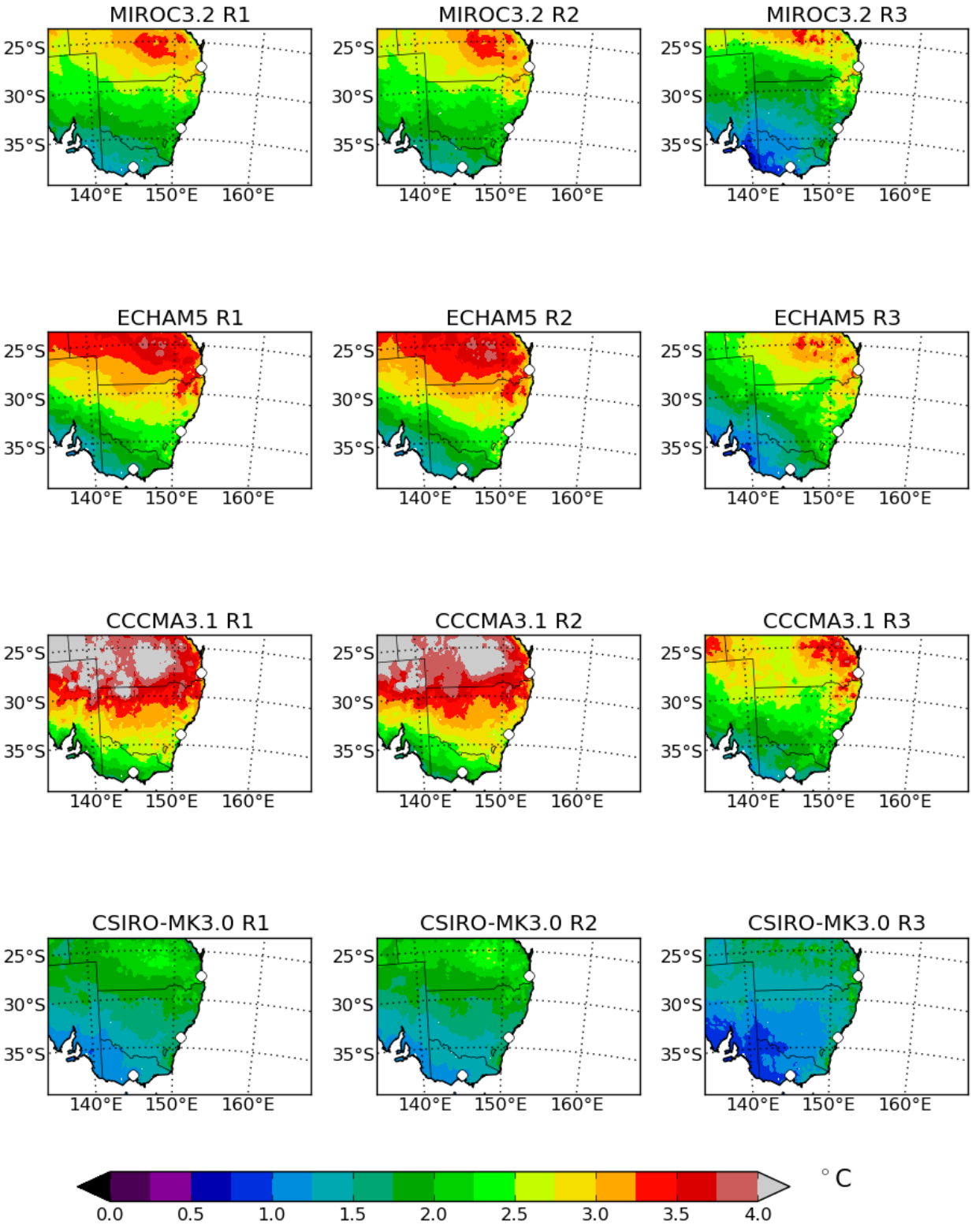

Figure 9.51: MAM mean change between years 1990-2009 and 2060-2079 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

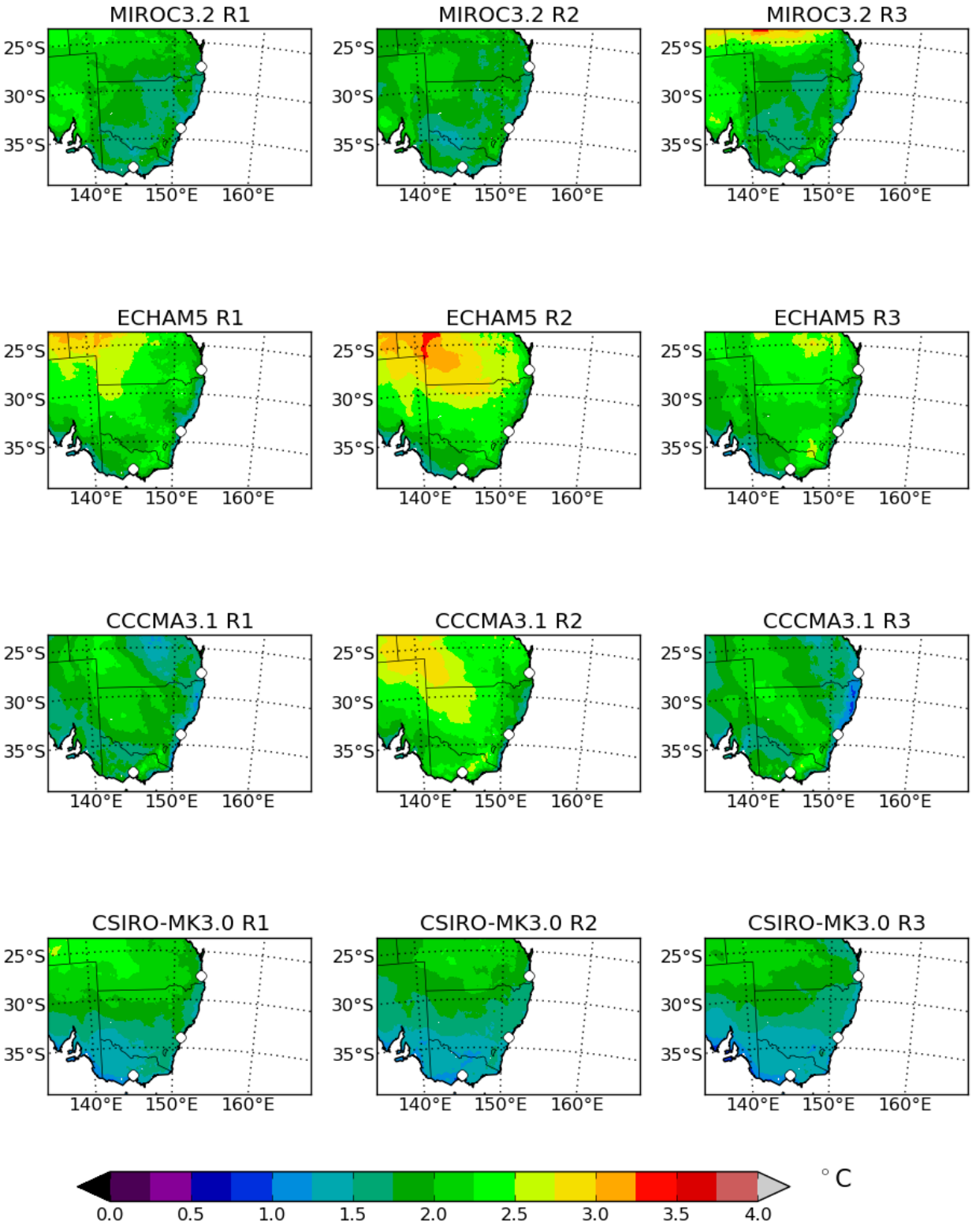

Figure 9.52: MAM mean change between years 1990-2009 and 2060-2079 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

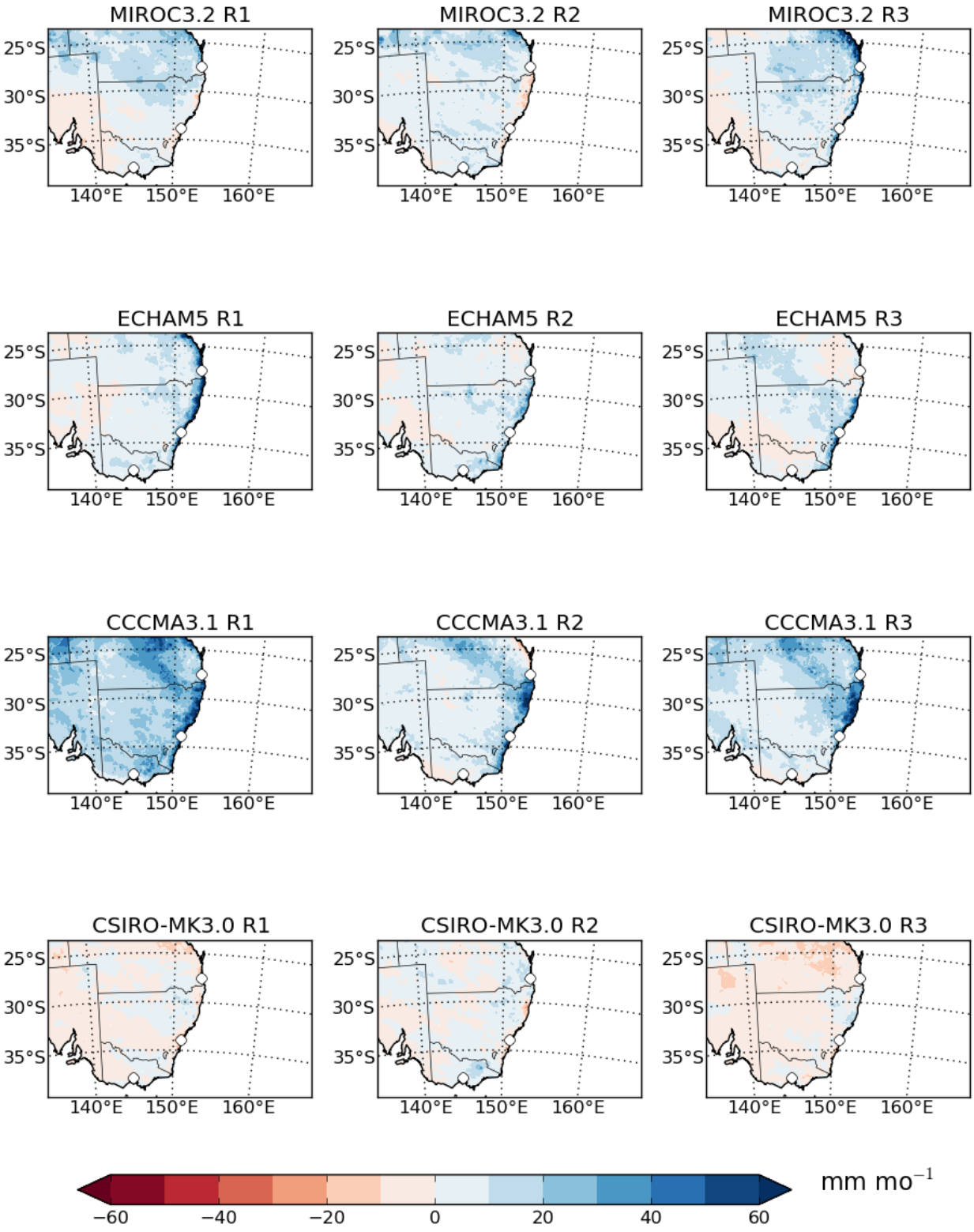

Figure 9.53: MAM mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

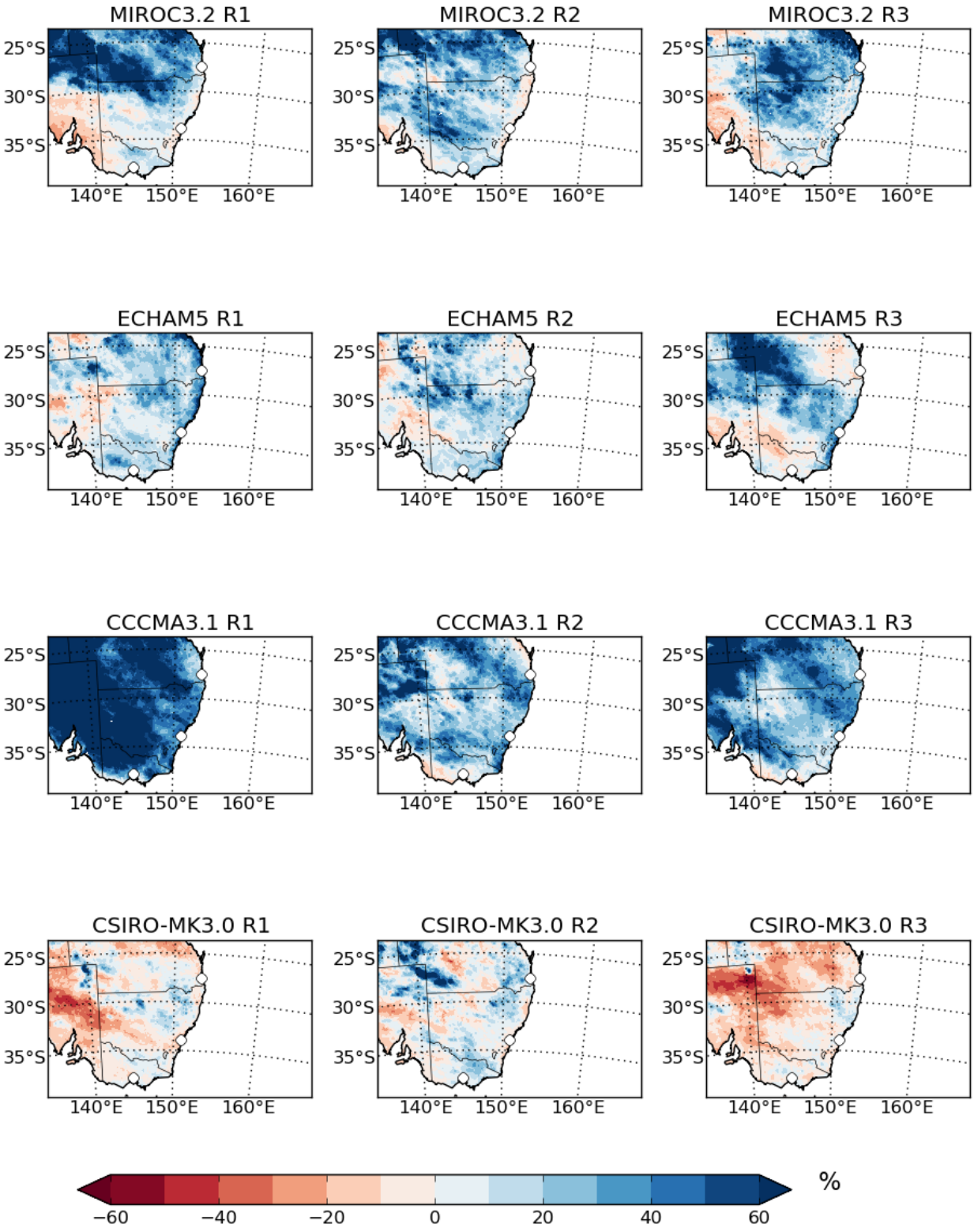

Figure 9.54: MAM mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

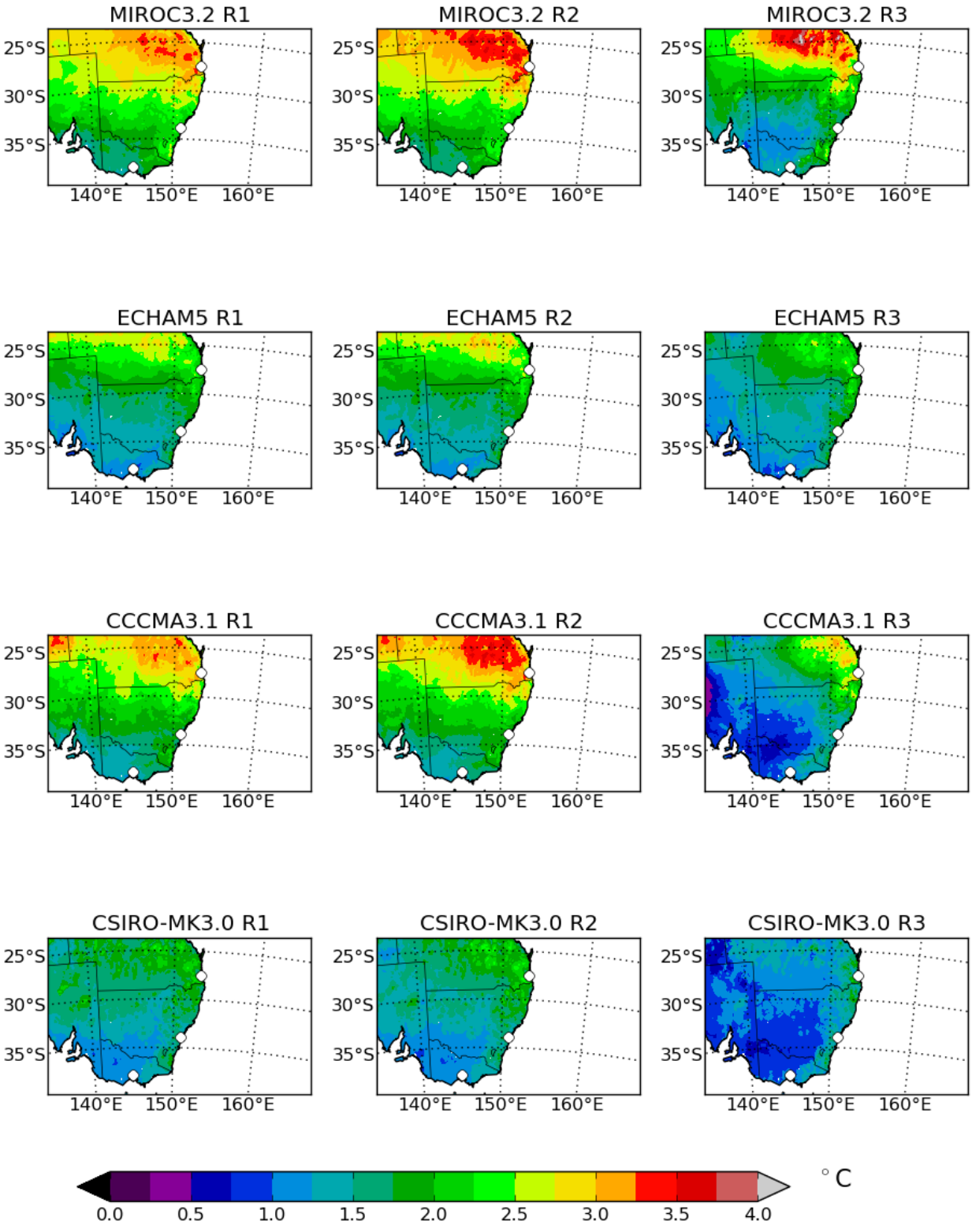

Figure 9.55: JJA mean change between years 1990-2009 and 2060-2079 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

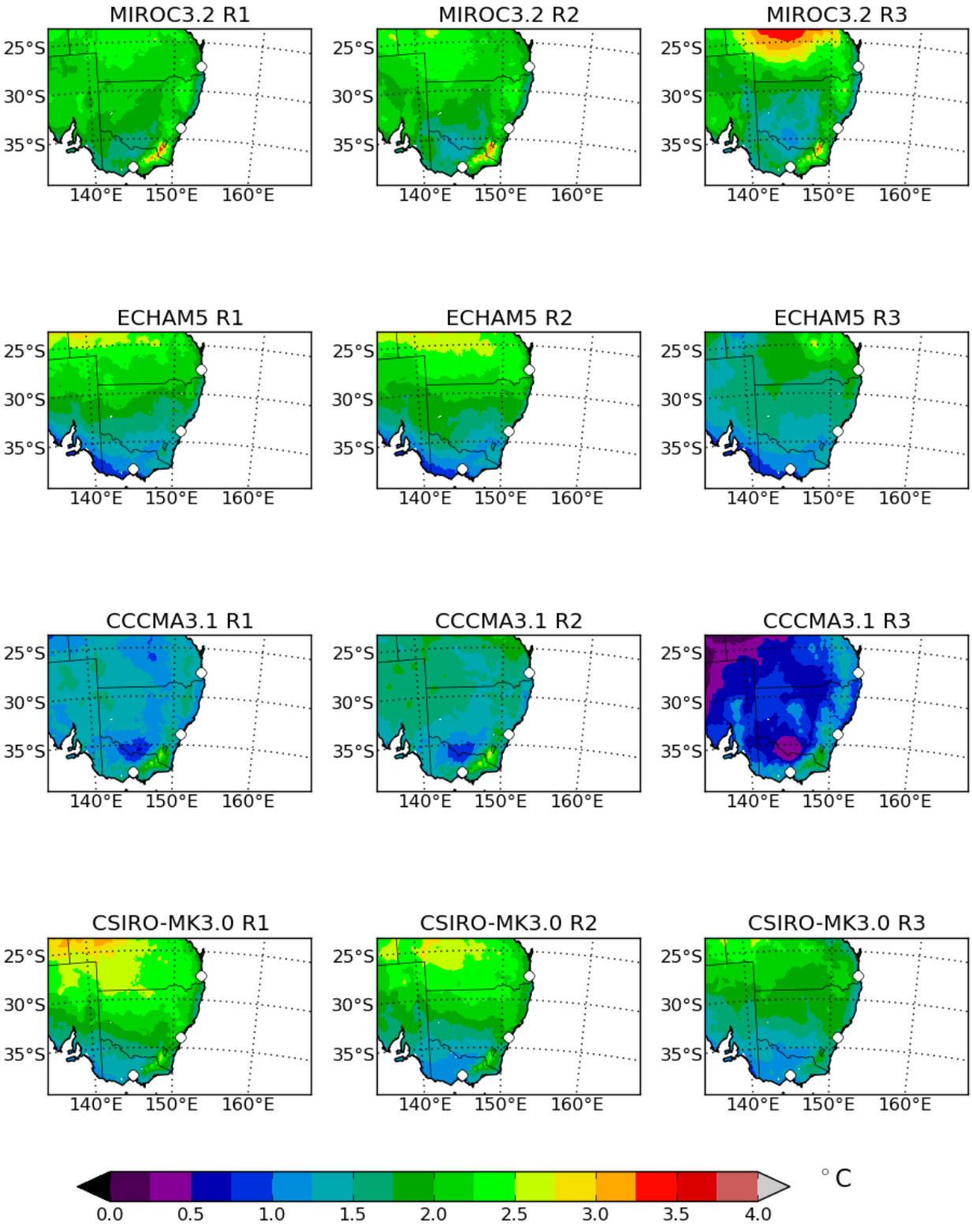

Figure 9.56: JJA mean change between years 1990-2009 and 2060-2079 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

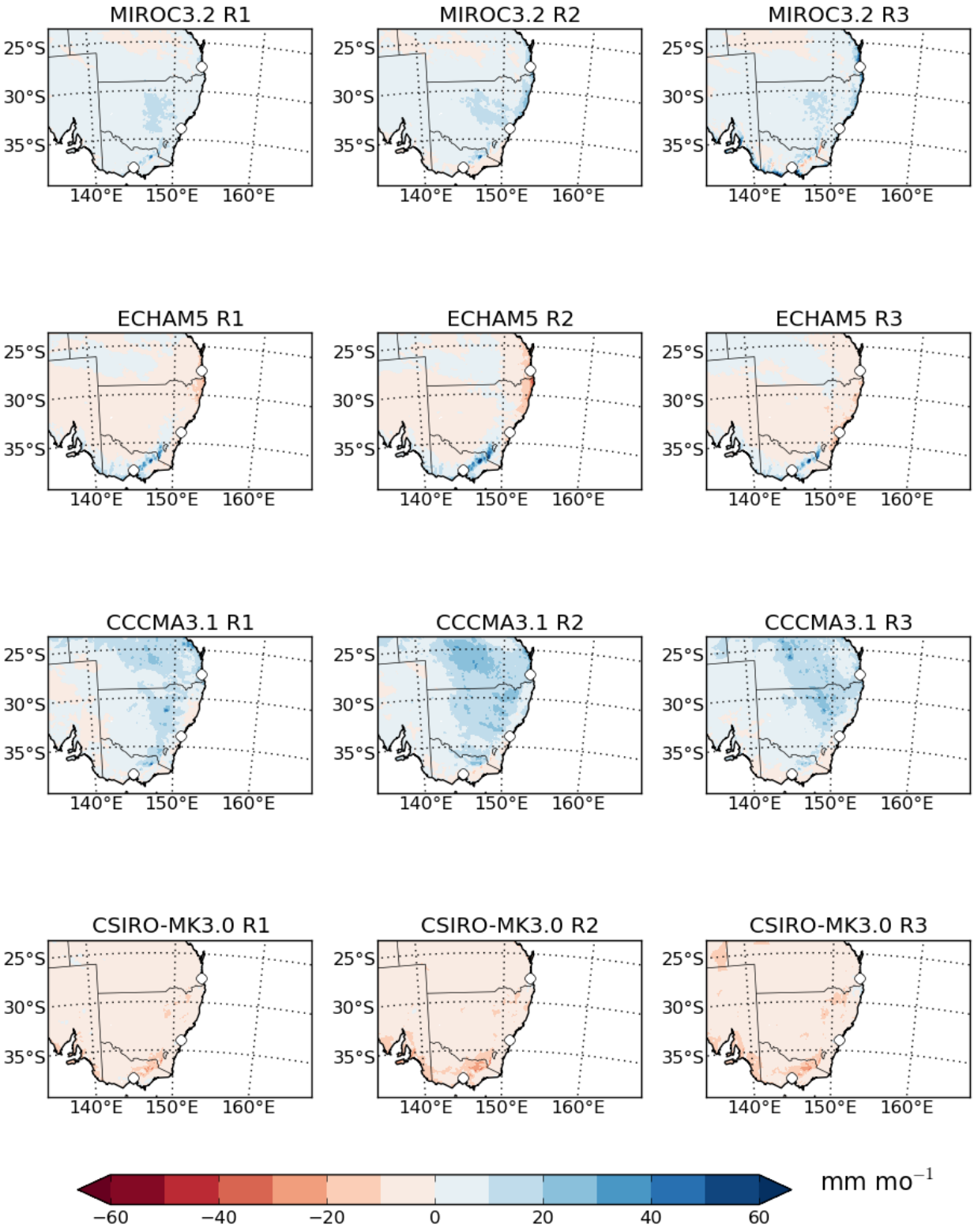

Figure 9.57: JJA mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

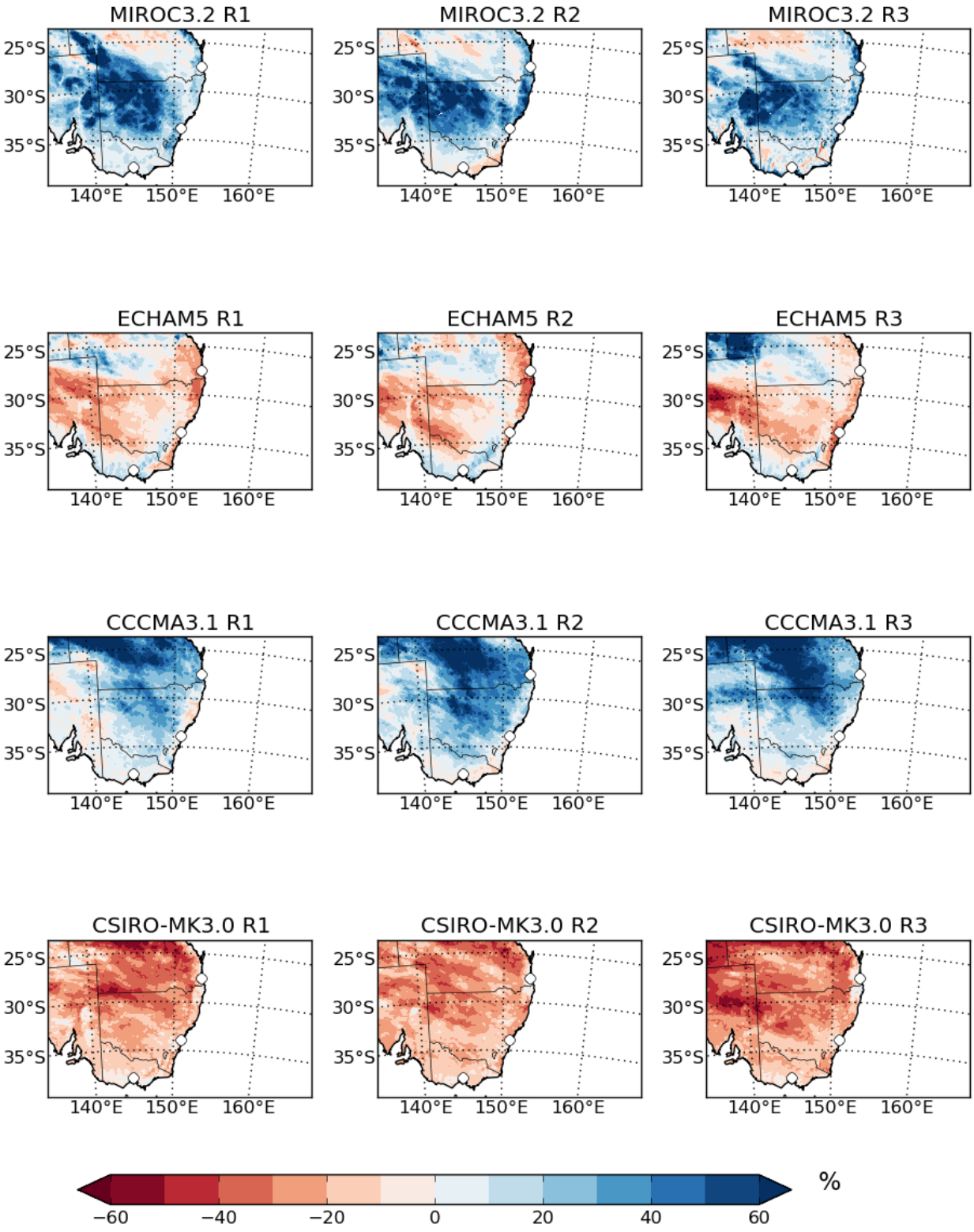

Figure 9.58: JJA mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

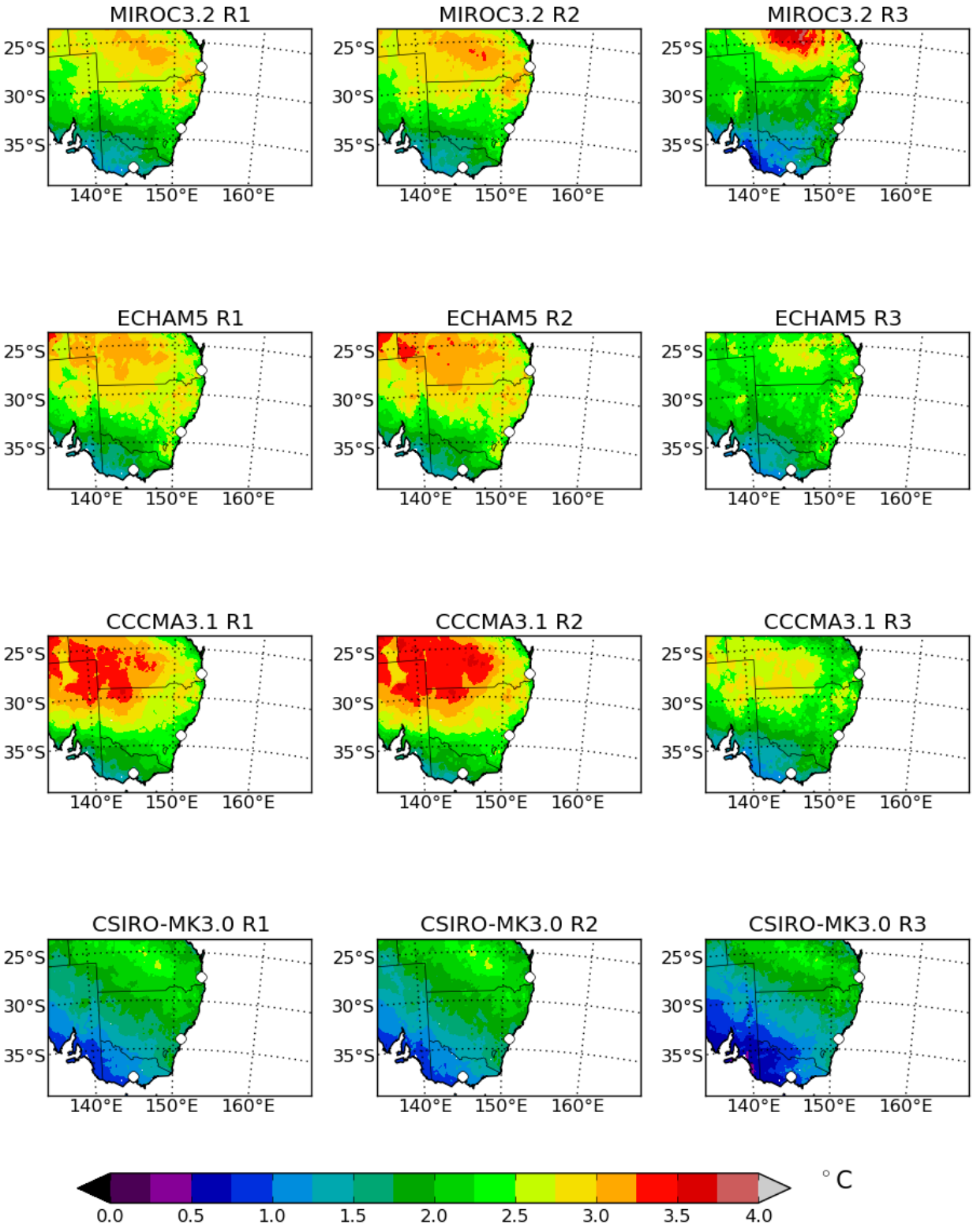

Figure 9.59: SON mean change between years 1990-2009 and 2060-2079 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

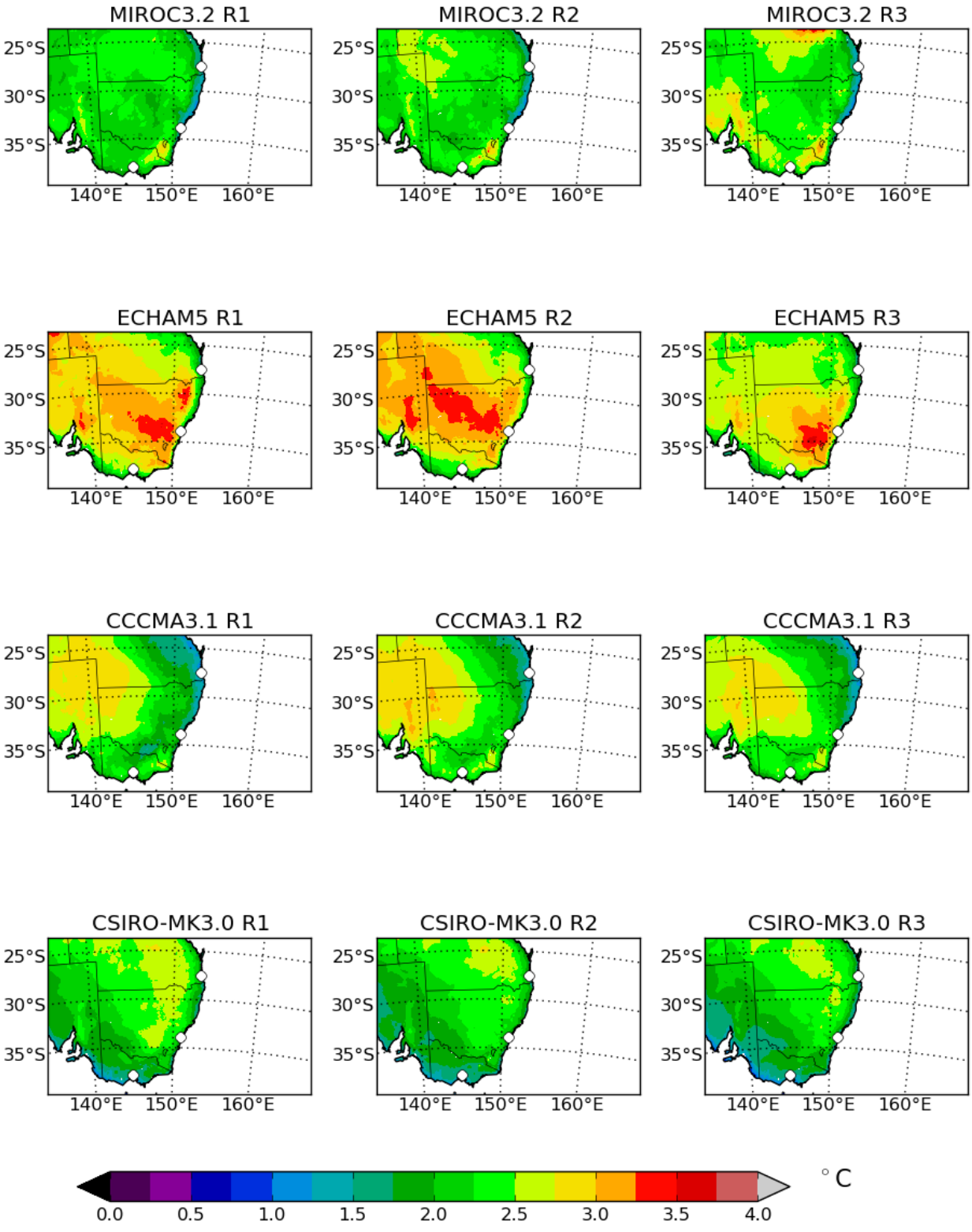

Figure 9.60: SON mean change between years 1990-2009 and 2060-2079 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

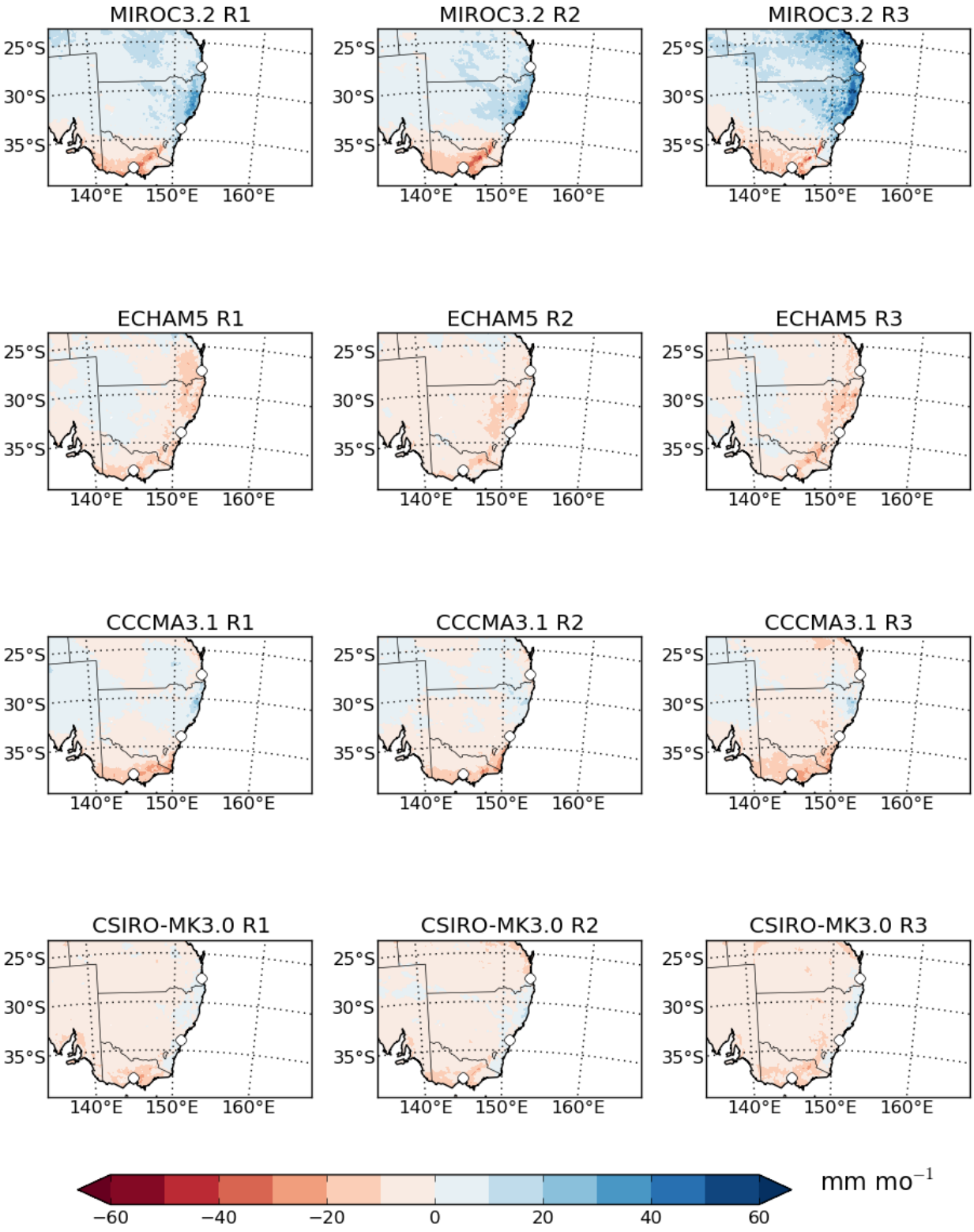

Figure 9.61: SON mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

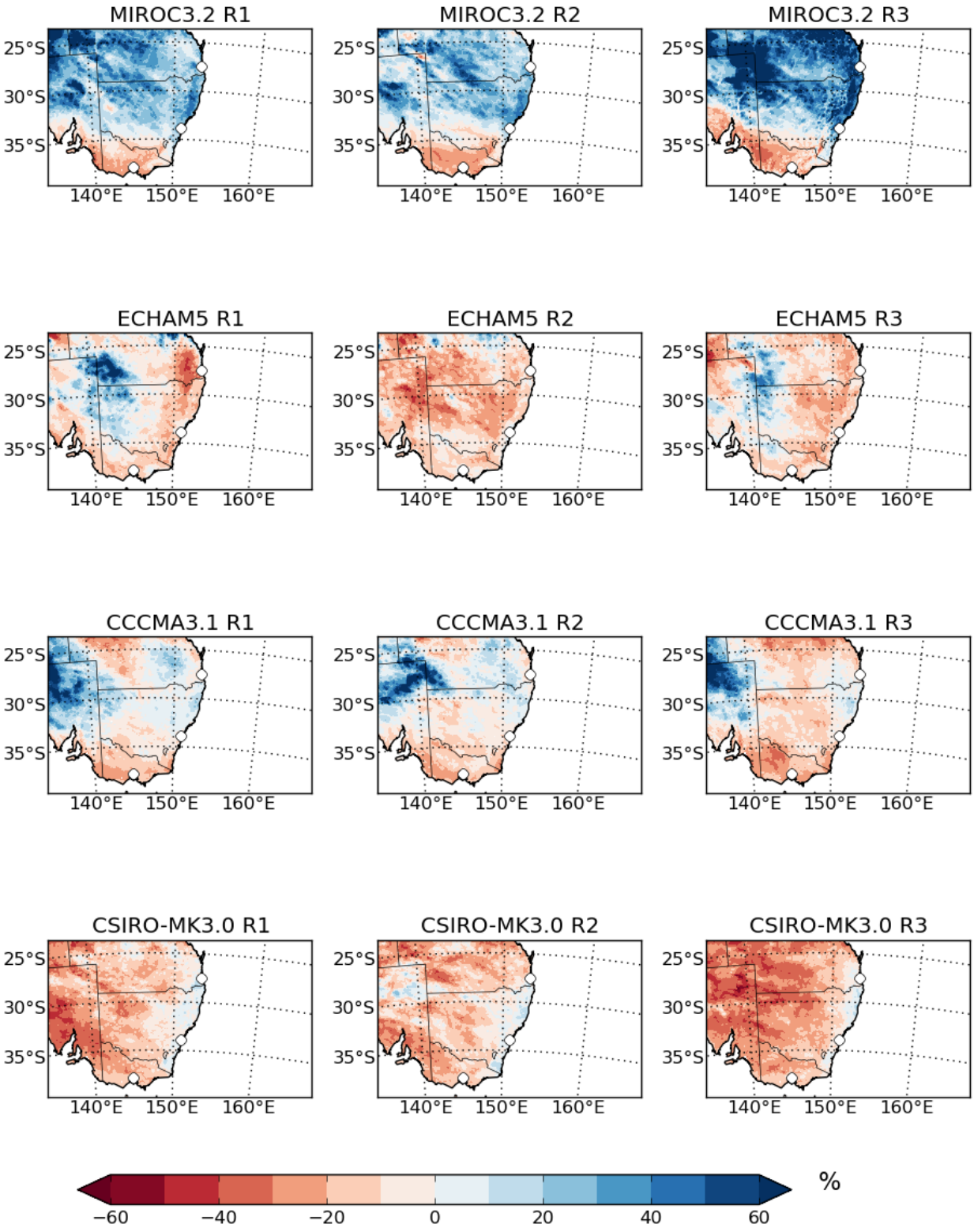

Figure 9.62: SON mean change between years 1990-2009 and 2060-2079 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

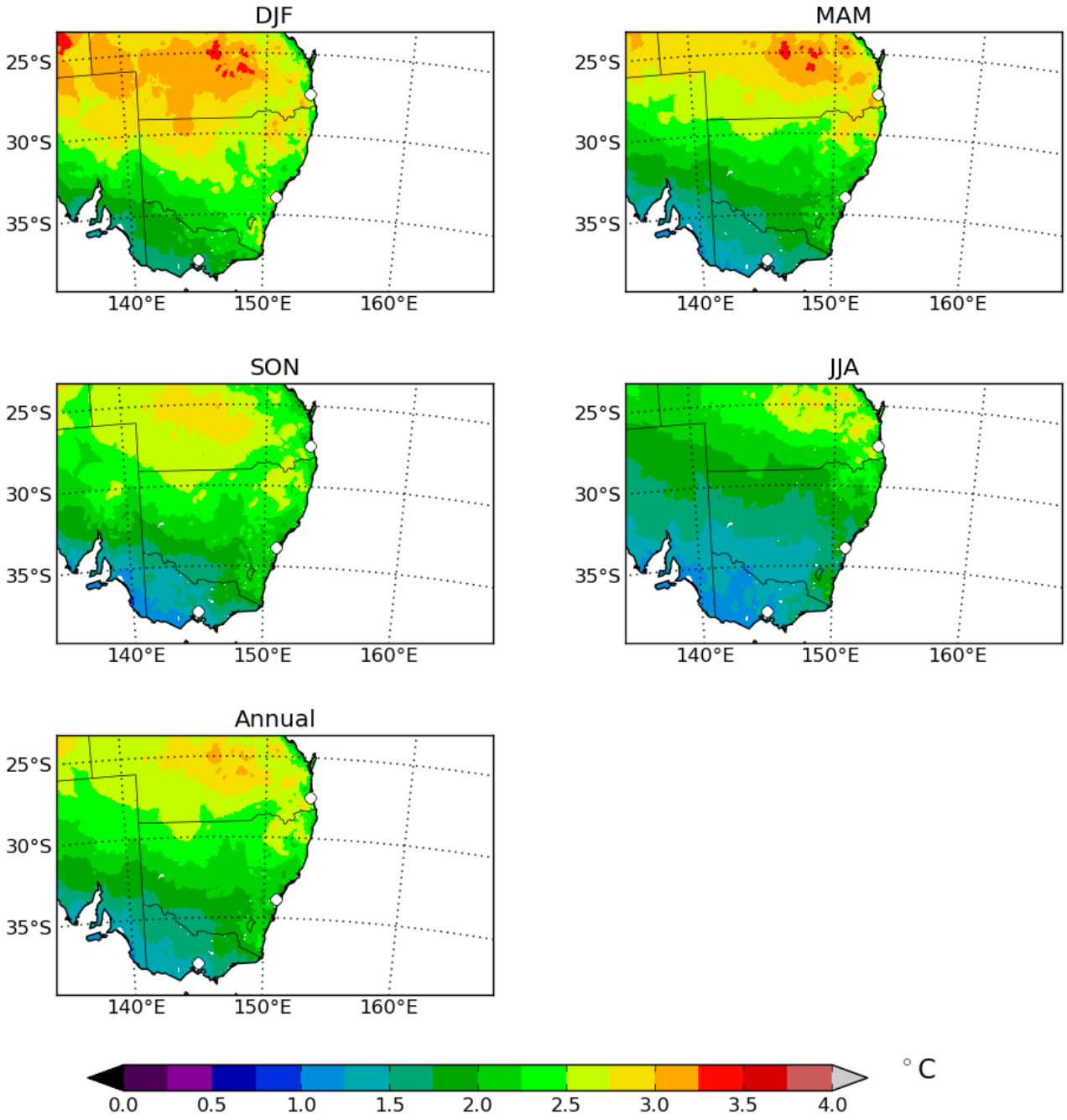

Figure 9.63: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for bias-corrected daily minimum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

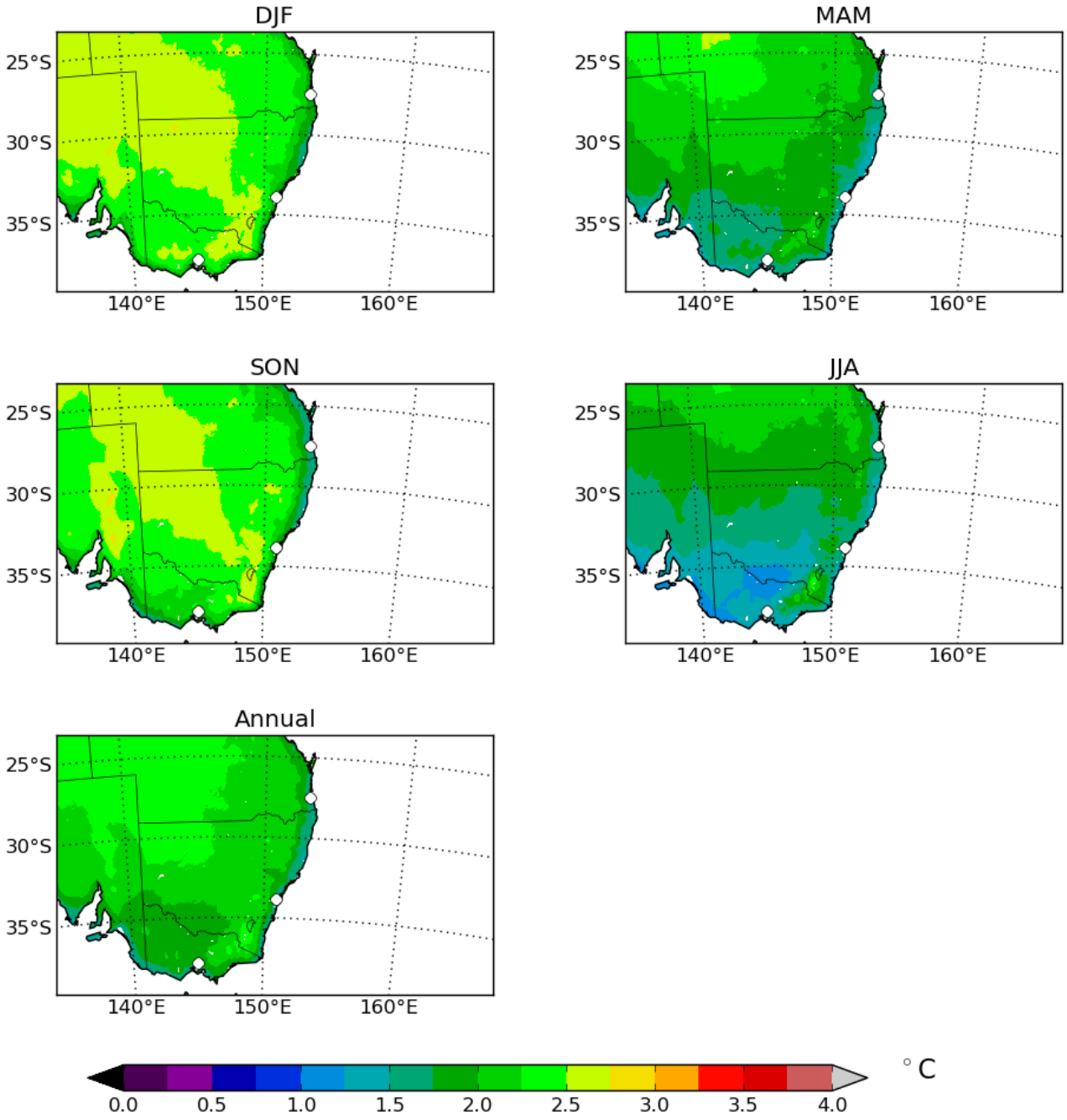

Figure 9.64: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for bias-corrected daily maximum near-surface air temperature [°C]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

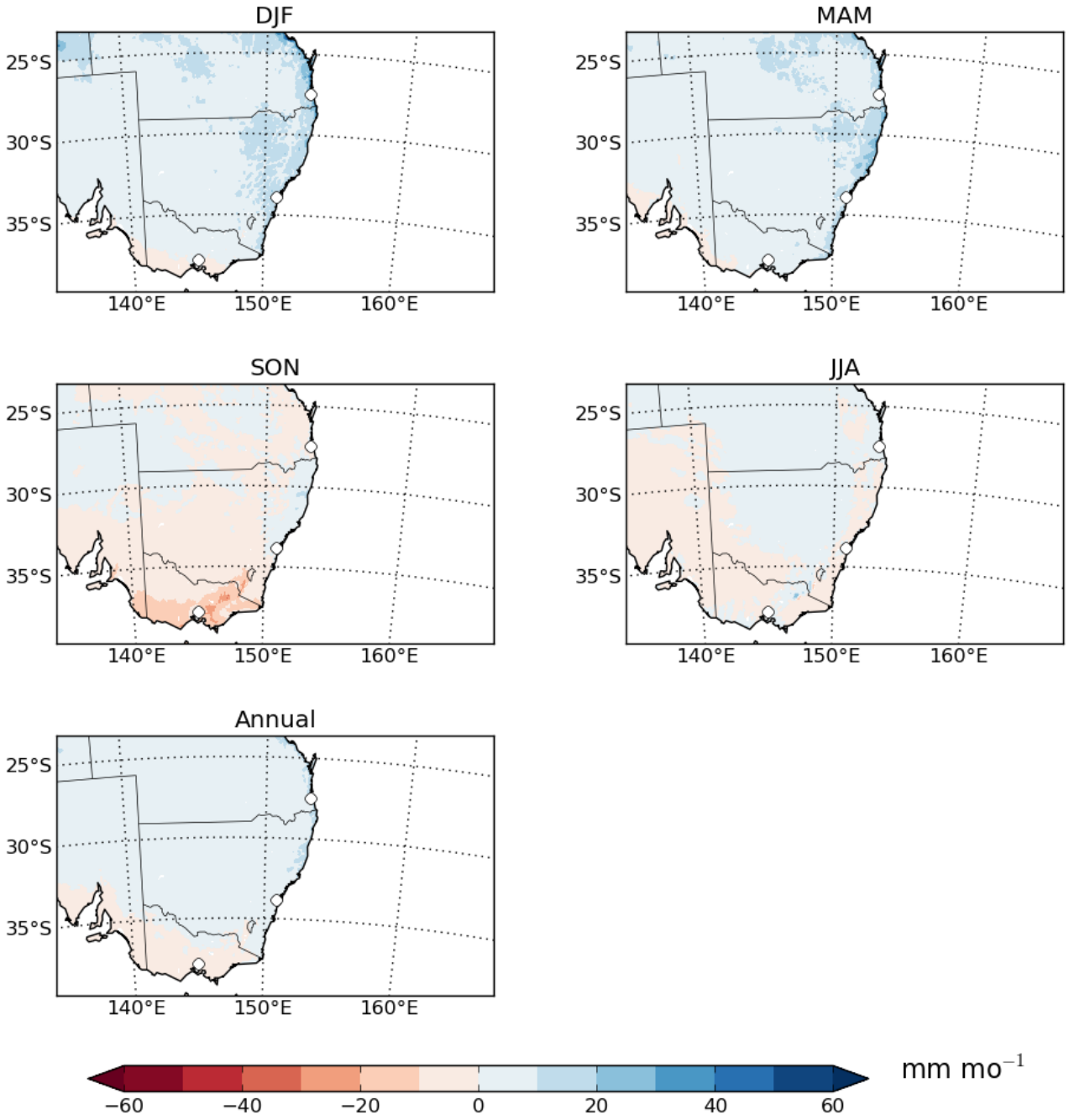

Figure 9.65: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for bias-corrected precipitation [mm mo^{-1}]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

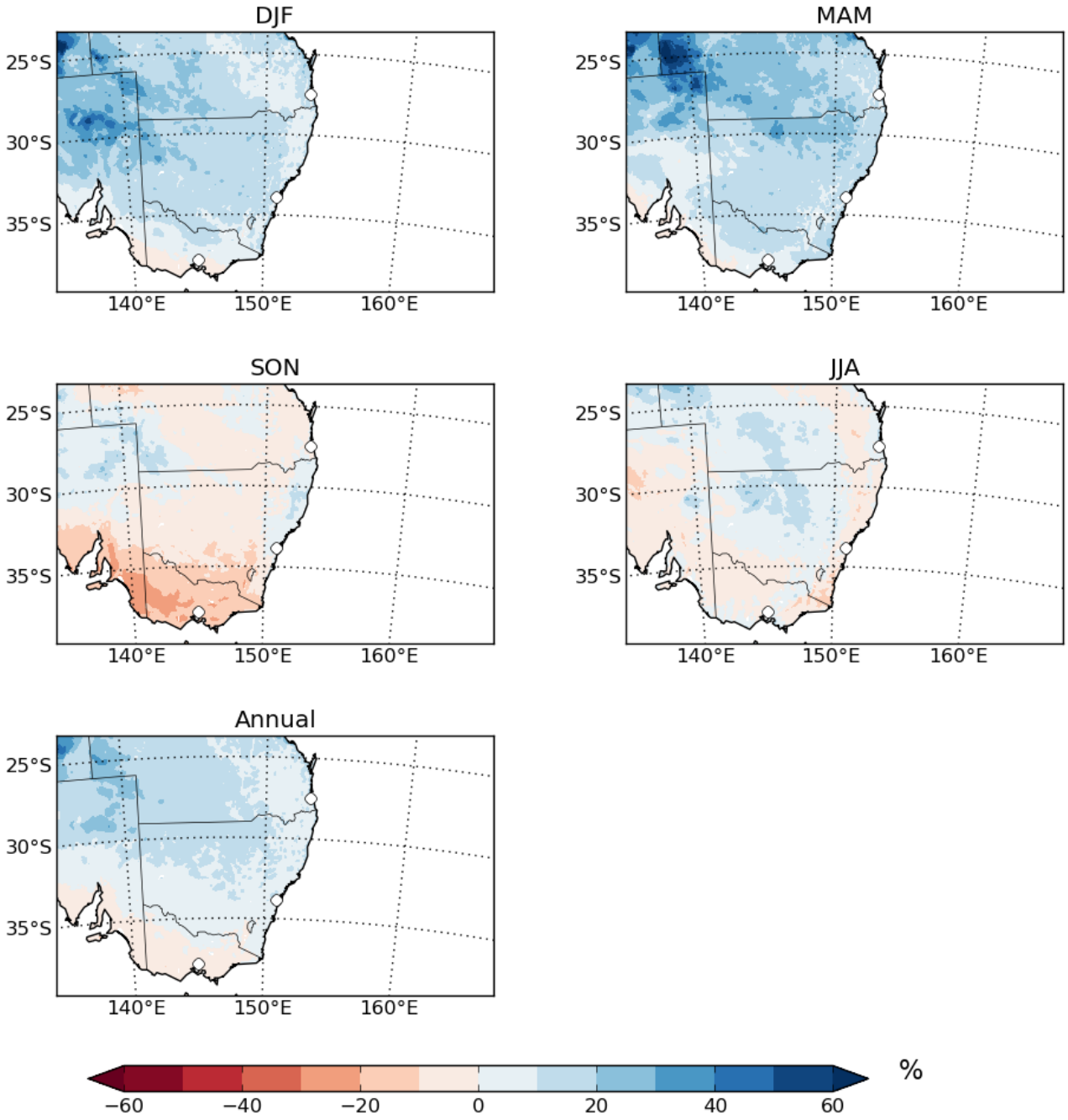

Figure 9.66: Seasonal and annual multimodel mean changes between years 1990-2009 and 2060-2079 for bias-corrected precipitation [%]. White circles (top to bottom): Brisbane, Sydney, Melbourne.

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