DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

Climate change impacts in the NSW and ACT Alpine region

Projected climate

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Cover photo: Winter landscape in Kosciuszko National Park. John Spencer/DPIE

This report should be cited as:

Fei Ji 2019, *Climate change impacts in the NSW and ACT Alpine region: Projected climate*, NSW Department of Planning, Industry and Environment, Sydney, Australia.

Published by:

Environment, Energy and Science
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ISBN 978 1 922318 16 9
EES 2020/0021
January 2020

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ACT	Australian Capital Territory
AWAP	Australian Water Availability Project
CMIP	Coupled Model Intercomparison Project
DJF	December January February
DPIE	Department of Planning, Industry and Environment
ECL	East Coast Low
GCM	Global Climate Model
JJA	June July August
MAM	March April May
MCAS-S	Multi-Criteria Analysis Shell for Spatial Decision Support
mm	millimetre
MM	Murray-Murrumbidgee state planning region
NARCliM	NSW/ACT Regional Climate Modelling project
NetCDF	Network Common Data Form
NSW	New South Wales
RCM	Regional Climate Model
SET	South East and Tablelands state planning region
SON	September October November
SRES	Special Report on Emissions Scenarios
WRF	Weather Research and Forecasting

Summary of findings

Projected climate in the NSW and ACT Alpine region

1. Future changes in climate for the Alpine region are much larger for the far future (2060 to 2079) compared to the near future (2020 to 2039), relative to a 1990 to 2009 baseline.
2. The Alpine region will become drier in the future due to a large reduction in precipitation in spring; however, other areas are getting wetter due to more precipitation in summer, winter and autumn.
3. Compared to surrounding regions, the Alpine region will have fewer moderate and heavy rainfall events in the near future, with a more than 60% decrease in seasonal heavy precipitation events projected for some parts in winter. In the far future, increases in heavy precipitation are projected for most areas except some of the Alpine region, where a 10% decrease is projected annually.
4. *Larger increases in maximum temperature compared to other regions, with the greatest projected increase in summer and spring, with a more than 3 degree increase by the far future compared to the baseline 1990-2009.* Projected increases in minimum temperature are similar across all regions, with 0.5–1°C increases projected for 2020 to 2039, and 2–2.5°C increase projected for most areas for 2060 to 2079 (relative to 1990 to 2009).
5. More hot days are projected for the Murray-Murrumbidgee state planning region. The greatest increase in hot days is projected to occur in summer, where 8–10 more hot days are projected in this region for 2020 to 2039, and 12–32 more for 2060 to 2079 (relative to 1990 to 2009) for the same region. Fewer cold nights are projected across all regions, especially the Alpine region. Winter has the greatest decrease in cold nights in the Alpine region, where more than 20 fewer cold nights are projected for 2060 to 2079. Spring is also projected to have more hot days and fewer cold nights.
6. Fewer cold nights are projected for the alpine region. Winter has the greatest decrease of cold nights in the Alpine region with a decrease of twenty or more by the far future.
7. Mean and maximum wind speed is projected to decrease in the future, mostly in spring, where a more than 8–10% decrease is projected for 2060 to 2079. There is minimal change in strong wind days and gale days in future projections.
8. Overall, seasonal changes are generally larger than annual changes for both the near and far future projection periods.

1. Introduction

1.1 Background

The New South Wales (NSW) and Australian Capital Territory (ACT) Alpine region is located in the south-eastern corner of mainland Australia and is the highest mountain range in Australia. Though it comprises only about 0.16% of Australia in size, it is an important region for ecosystems, biodiversity, energy generation and winter tourism. It forms the southern end of the Great Dividing Range, covering a total area of 1.64 million hectares that extend over 500 kilometres. The highest peak, Mount Kosciuszko, rises to an altitude of 2228 metres.

This report is part of a larger project delivered by the NSW Department of Planning, Industry and Environment on the various impacts from climate change on the NSW and ACT Alpine region, hereafter referred to as the Alpine region. The full study region covers the Murray-Murrumbidgee region (MM), South East and Tablelands (SET) and the ACT, bordering the Victorian border in the south (Figure 1).

The Alpine region is vulnerable to climate change. Observations have shown substantial changes in precipitation and temperature for this area (Di Luca et al. 2018), which have already impacted biodiversity and ecosystems (Hughes 2011). In 2014, the NSW/ACT Regional Climate Modelling (NARCliM) project was delivered. Climate snapshots for each of the 11 NSW planning regions and the ACT were developed to demonstrate observed and projected climate change; however, the snapshots only show changes for some variables and focus on each planning region.

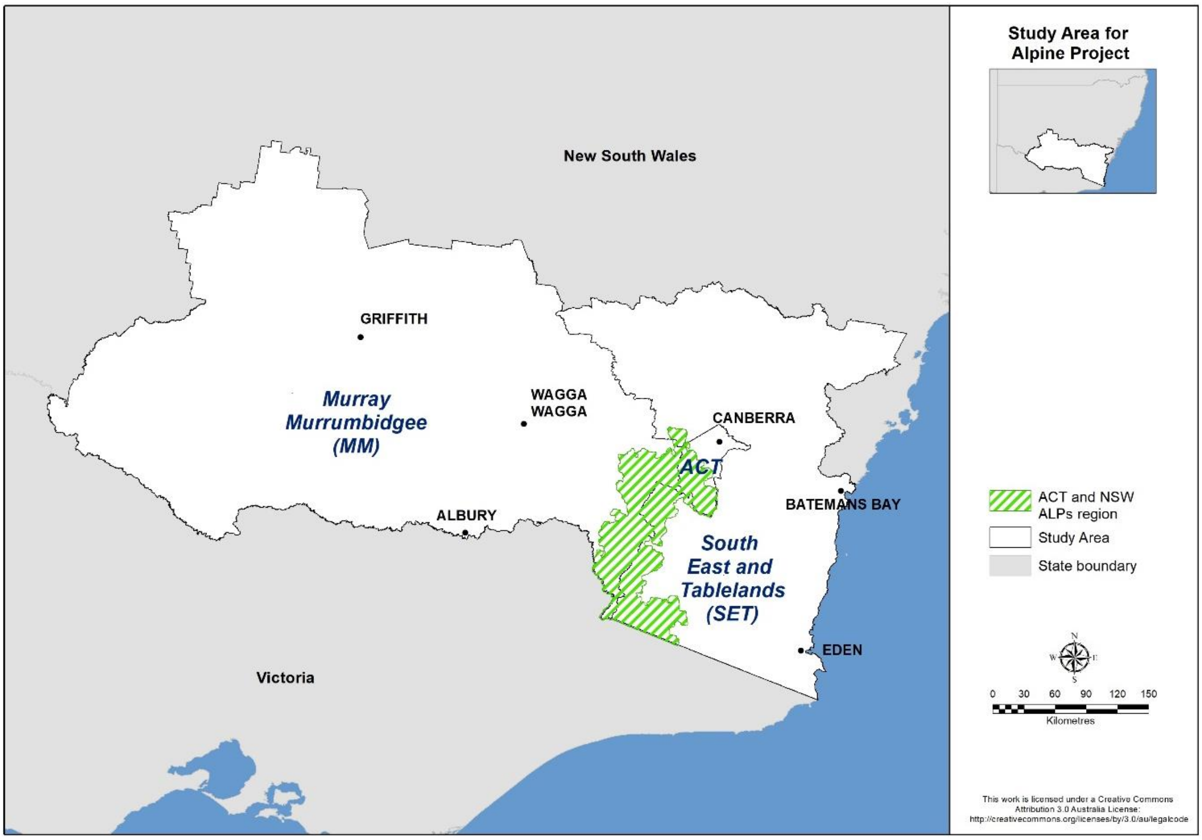

Figure 1 **The study area for the Alpine project, including the NSW and ACT Alpine region, Murray-Murrumbidgee region and South East and Tablelands**

1.2 Objectives

The aim of this study is to provide annual, monthly and seasonal future climate projections for precipitation, temperature and wind for the Alpine region and surroundings. The future climate projections will underpin impact assessments quantifying the magnitude of further impacts for this region under future climate conditions, and direct decisions on adaptation to unavoidable future climate projections for this region.

1.3 Outputs

Output	Details
Precipitation	Bias-corrected, monthly total, dry days, daily totals and heavy rainfall days (>25 mm/d). Network Common Data Form (NetCDF) 10 km^2 gridded data. Provided for reanalysis, near and far future.
Temperature	Maximum, minimum, days over 25°C, days over 35°C, days under 0°C. NetCDF 10 km^2 gridded data. Provided for reanalysis, near and far future.
Wind	Daily average, maximum speed per day, >13 m/s in hours/year, >17 m/s in hours/year. NetCDF 10 km^2 gridded data. Provided for reanalysis, near and far future.

2. Method

2.1 Source of data

NARCliM simulations from four Coupled Model Intercomparison Project phase 3 (CMIP3) Global Climate Models (GCMs) were used to drive three Regional Climate Models (RCMs) to form a 12-member GCM/RCM ensemble (Evans et al. 2014). The four selected GCMs are MIROC3.2, ECHAM5, CCCMA3.1 and CSIRO-MK3.0. For future projections, the Special Report on Emissions Scenarios (SRES) business-as-usual A2 scenario was used (IPCC 2000). The three selected RCMs are three physics scheme combinations of the Weather Research and Forecasting (WRF) model. Each simulation consists of three 20-year runs (1990 to 2009, 2020 to 2039, and 2060 to 2079). The four GCMs were chosen based on a number of criteria: i) adequate performance when simulating historic climate; ii) most independent; iii) cover the largest range of plausible future precipitation and temperature changes for Australia. The three RCMs correspond to three different physics scheme combinations of the WRF V3.3 model (Skamarock et al. 2008), which were also chosen for adequate skill and error independence, following a comprehensive analysis of 36 different combinations of physics parameterisations over eight significant east coast lows (ECLs) (Evans et al. 2012; Ji et al. 2014). For the selected three RCMs, the WRF Double Moment 5-class (WDM5) microphysics scheme and NOAH land surface scheme are used in all cases. Refer to Evans et al. (2014) for more details on each physics scheme.

We acknowledge that the results are model dependent (as all model studies are) but through the use of this carefully selected ensemble we have attempted to minimise this dependence. By using this model selection process, we have shown that it is possible to create relatively small ensembles that are able to reproduce the ensemble mean and variance from the large parent ensemble (i.e. the many GCMs) as well as minimise the overall error (Evans et al. 2013a).

Some initial evaluation of NARCliM simulations shows that they have strong skill in simulating the precipitation and temperature of Australia, with a small cold bias and overestimation of precipitation on the Great Dividing Range (Evans et al. 2013b; Ji et al. 2016). The differing responses of the different RCMs confirm the utility of considering model independence when choosing the RCMs. The RCM response to large-scale modes of variability also agrees well with observations (Fita et al. 2016). Through these evaluations we found that while there is a spread in model predictions, all models perform adequately with no single model performing the best for all variables and metrics. The use of the full ensemble provides a measure of robustness such that any result that is common through all models in the ensemble is considered to have higher confidence.

In total, there were four same GCM driven simulations (average of three members) and three same RCM used simulations (average of four members). The analyses in this study are based on the outputs from these simulations.

Available NARCliM bias-corrected data was used for future precipitation and temperature projections. Wind speed projections, for which no bias-corrected data were available, were also produced. An observational dataset known as AWAP (Australian Water Availability Project) was used to evaluate NARCliM simulations for the baseline period.

2.2 Analysis

Bias-corrected monthly precipitation and maximum and minimum temperatures were used to analyse annual and seasonal averages of precipitation and temperature, as well as changes for the near future (2020 to 2039) and far future (2060 to 2079) relative to the baseline period (1990 to 2009).

Bias-corrected daily precipitation and temperature data were used to analyse changes in annual and seasonal dry days (daily precipitation less than 0.2 mm), moderate precipitation days (daily precipitation greater than 10 mm), heavy precipitation days (daily precipitation greater than 25 mm), hot days (maximum temperature above 35°C) and cold nights (minimum temperature below –2°C).

Post-processed monthly average data of daily maximum wind speed are used to calculate changes in annual and seasonal mean and maximum wind speeds. Post-processed daily maximum wind speed is used to calculate changes in strong wind and gale days.

2.3 Quality control

The NARCliM outputs have been subjected to comprehensive data quality assurance/quality control. The method for quantifying future climate projections is widely used. Annual climate projections are similar to those shown on the AdaptNSW Climate projections for your region webpage. Seasonal and monthly future projections use the same method but for finer timescale outputs.

The data have also been evaluated as conference and journal papers (Evans et al. 2013b; Ji et al. 2016; Fita et al. 2016). Similar climate projections from NARCliM have been published as technical reports (Olson et al. 2014; Di Luca et al. 2016) and peer reviewed scientific publications (Olson et al. 2016; Di Luca et al. 2018).

2.4 Data storage and access

All output data were converted to raster format (ArcGIS ESRI grid) and supplied to the MCAS-S (Multi-Criteria Analysis Shell for Spatial Decision Support) datapacks for distribution and storage. All input data to the model and by-products are stored on hard disk drives. All data are in the NARCliM coordinate system. The extent of the datasets includes the MM region, ACT and SET with the boundary at top: –32.671254, left: 143.317445, right: 150.745676, and bottom: –37.505077.

3. Results

This section reports annual and seasonal means for 1990 to 2009 (baseline period), as well as projected annual and seasonal changes for 2020 to 2039 (near future) and 2060 to 2079 (far future) relative to 1990 to 2009.

3.1 Precipitation

Mean precipitation for the 1990 to 2009 baseline period

Mean annual precipitation for the NARCliM baseline period (1990 to 2009) is shown in Figure 2. The map presents the results of the 12 individual models as an average of all 12, referred to as the ensemble mean. Bias-corrected precipitation data were used in the analyses. Grey box areas within the map (Figure 2) indicate no observations available for those over waterbody grids. The bias-correction method is effective at correcting long-term means. Because bias-corrected precipitation was used in this study, the biases are small relative to AWAP observations (Olson et al. 2016).

There is a clear gradient in annual precipitation with 200–400 millimetres/year precipitation in the western MM region and up to 1800 millimetres/year precipitation over the Alpine region (Figure 2). Annual precipitation is generally more than 800 millimetres/year for coastal regions and less than 600 millimetres/year west of the Great Diving Range, especially for areas between the range and Mt Kosciuszko.

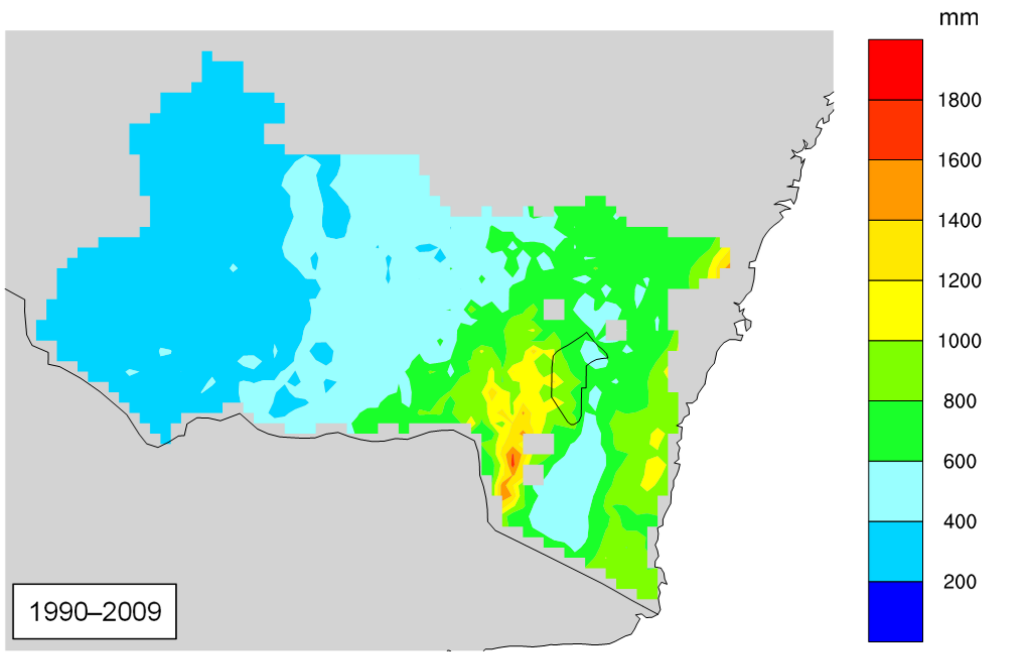

Figure 2 Mean annual precipitation for the 1990 to 2009 baseline period

A clear seasonal variation in precipitation is observed for the Alpine and coastal regions with a wet summer and low winter rainfall for the coast, and wet winter and low summer precipitation for the Alpine region (Figure 3). The central and western MM region has uniform rainfall across the different seasons.

For the summer simulated results, a clear east–west gradient is observed with more than 400 millimetres/season precipitation on the coast and less than 150 millimetres/season precipitation in the central and western MM region. Winter is the driest season for regions along the coast with less than 100 millimetres/season; however, it is the wettest season for the Alpine region with more than 450 millimetres/season precipitation. Spring and autumn are transitional seasons for the Alpine and coastal regions with 200–300 millimetres/season for the coast, and more than 400 and 250 millimetres/season for spring and autumn respectively.

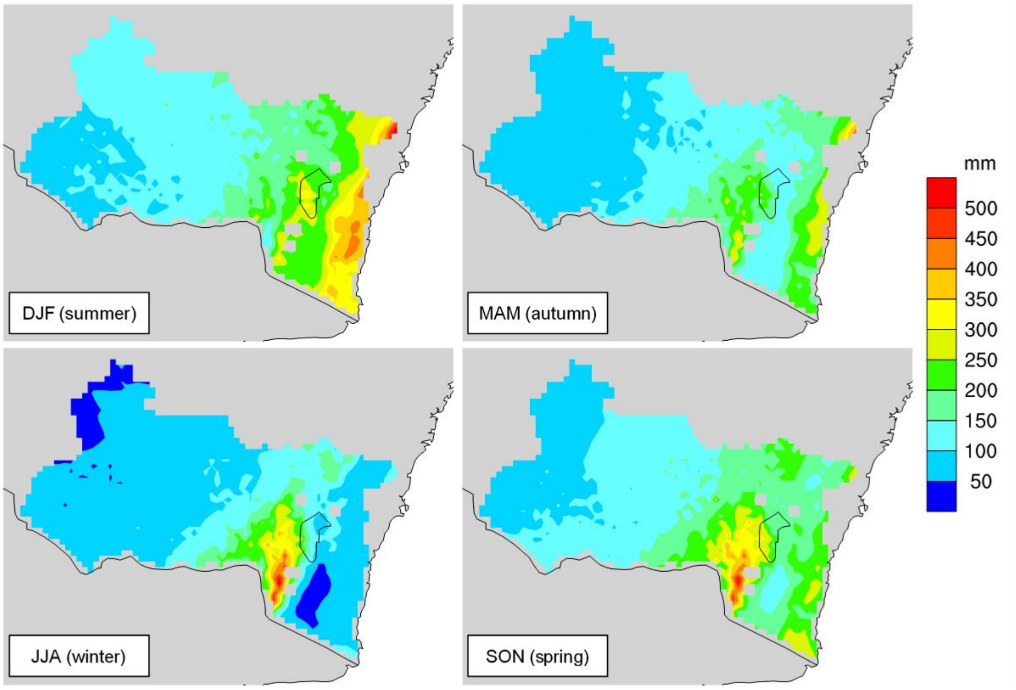

Figure 3 Mean seasonal precipitation for the 1990 to 2009 baseline period

Changes in precipitation for 2020 to 2039

A small decrease in annual precipitation is projected for the entire study region, apart from a small increase for some areas in the MM region (Figure 4).

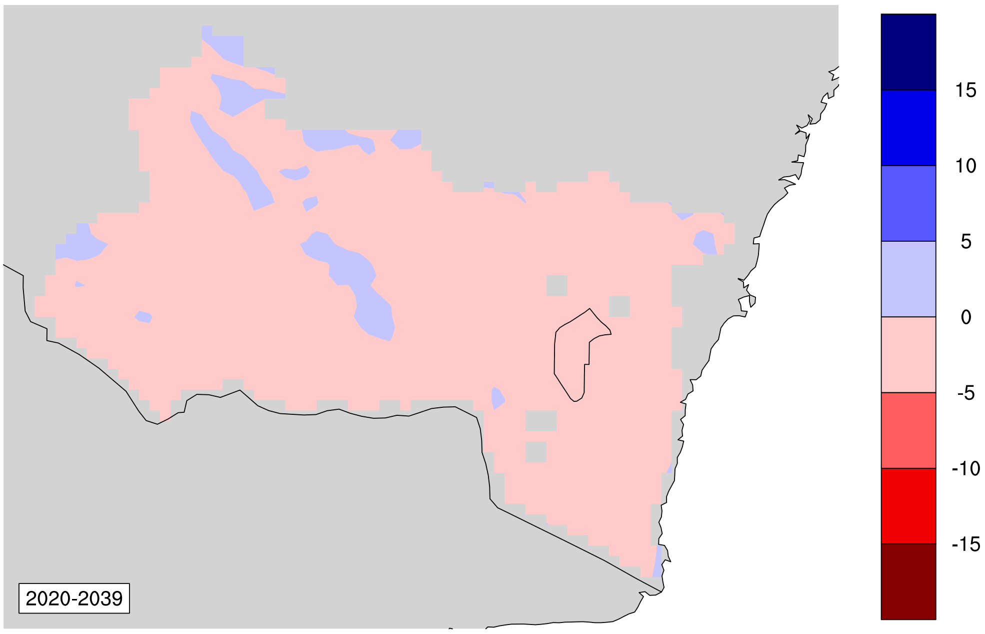

Figure 4 Changes in annual precipitation (%) for 2020 to 2039 relative to 1990 to 2009

Projected precipitation changes vary across seasons and regions (Figure 5). In summer, less than 5% increase in precipitation is projected for the MM region and less than 5% decrease for the SET region. In winter, a less than 5% decrease in precipitation is projected from most of the study area, and 5-10% decrease is projected from southwest MM region and eastern SET region. An increase in precipitation is projected in autumn for the study area, especially for the western MM region where is increase is more than 10%. Decreases in spring precipitation are projected for most areas, especially for the MM region, where a 10–20% decrease is projected.

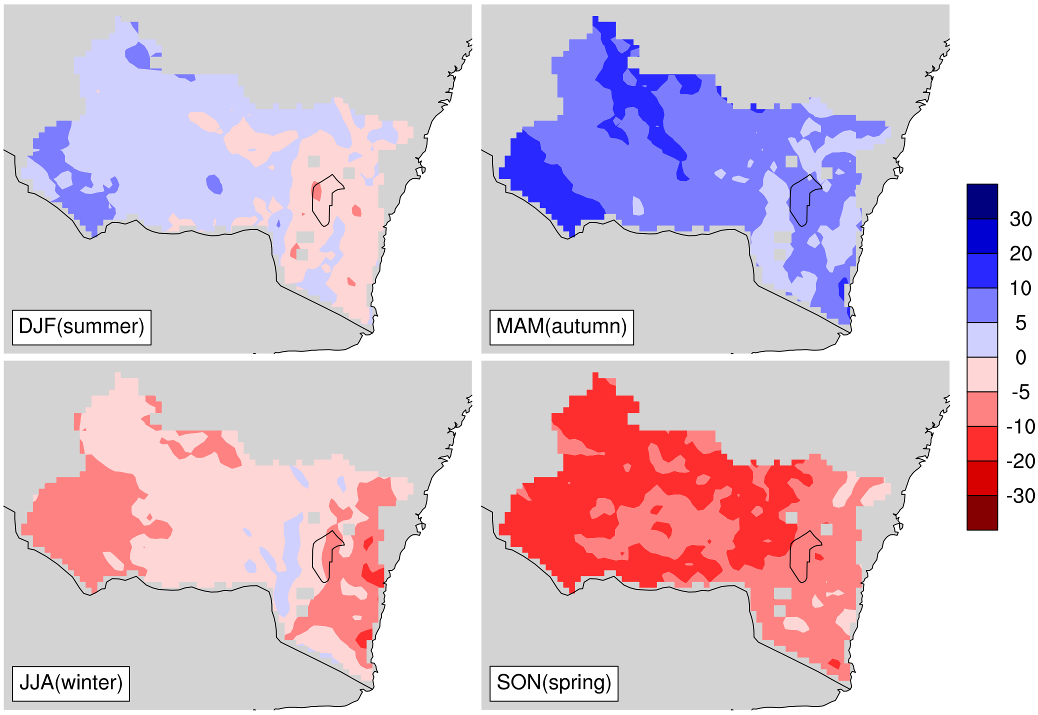

Figure 5 **Changes in seasonal precipitation (%) for 2020 to 2039 relative to 1990 to 2009**

Changes in precipitation for 2060 to 2079

There is a clear difference in changes in annual precipitation in the far future compared with the near future; A small increases in annual precipitation are projected for the study region except for the Alpine region where a up to 10% decrease is expected. Overall, it is getting wetter in 2060 to 2079 compared to the present and 2020 to 2039 period, for most areas except the Alpine region (Figure 6).

Compared to 2020 to 2039, projections for 2060 to 2079 show a large change in seasonal precipitation (Figure 7). The far future is projected to be wetter in summer for all areas, especially for the Alpine region where a small decrease in precipitation is projected. Greater precipitation in autumn is projected for all study areas, especially for the north-west MM and southern SET regions with a greater than10% increase in precipitation. In winter, there is little change for the western region and a 10–20% decrease in precipitation for the Alpine and Southern SET region. During spring, a decrease in precipitation is projected for most areas, especially for the Alpine region where a more than 20% decrease is projected.

Spring and winter will be drier for most areas, while summer and autumn will get wetter, especially for the MM region.

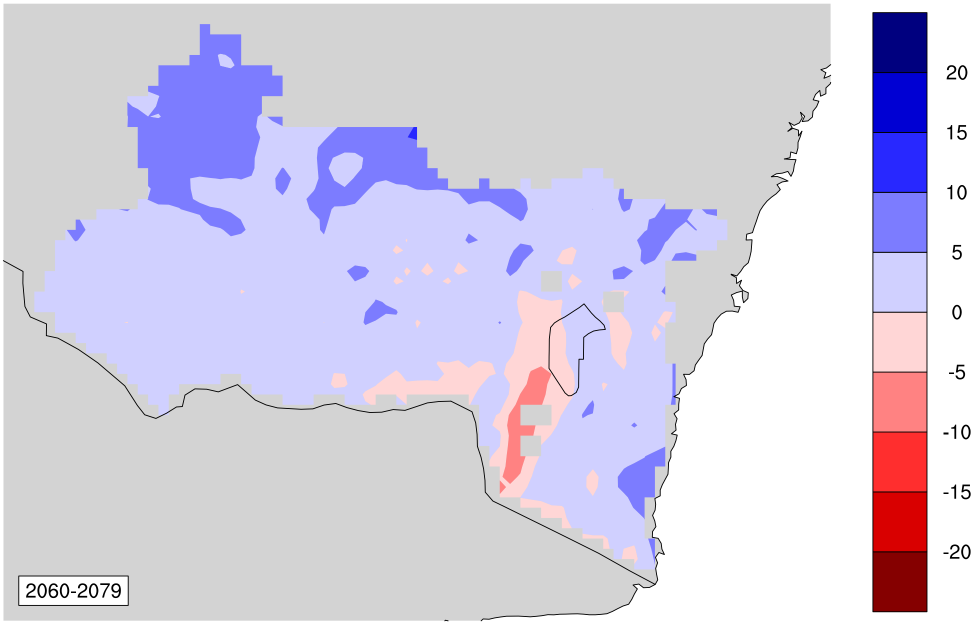

Figure 6 Changes in annual precipitation (%) for 2060 to 2079 relative to 1990 to 2009

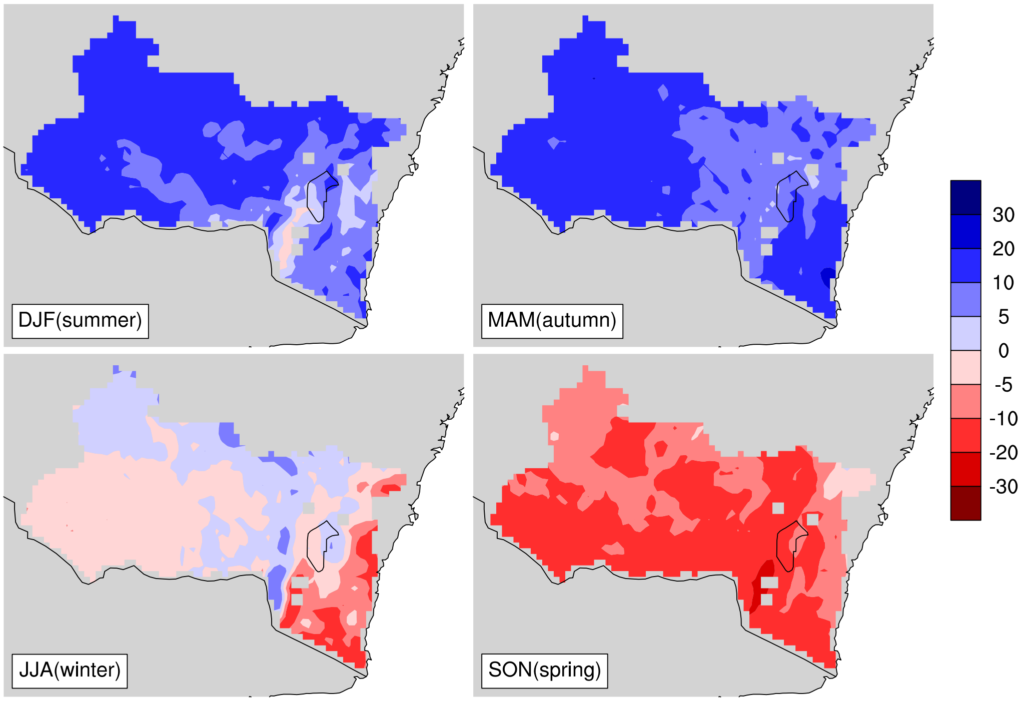

Figure 7 Changes in seasonal precipitation (%) for 2060 to 2079 relative to 1990 to 2009

3.2 Dry days (precipitation below 0.2 mm/day)

Mean number of dry days for the 1990 to 2009 baseline period

Dry days for 1990 to 2009 is shown in Figure 8. It is clear that the MM region has far more dry days compared with the other regions. More than 70% of days in the west of the MM region are dry days; however, more than 50% of days in the Alpine region are wet days.

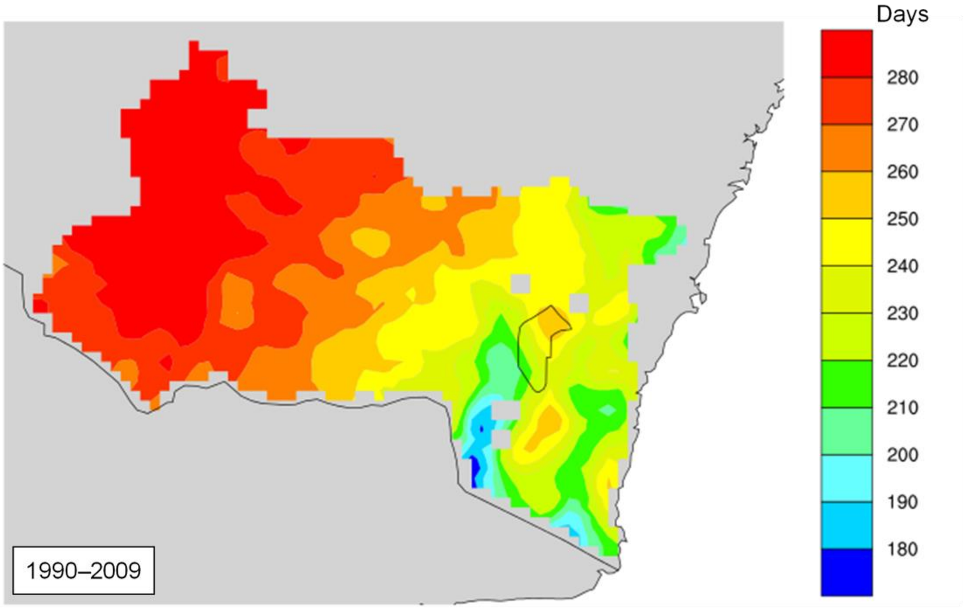

Figure 8 Simulated number of annual dry days for 1990 to 2009

Seasonal variations for different areas are clear (Figure 9). For the MM areas, more dry days are observed in summer, autumn and spring, with relatively few dry days in winter. The least number of dry days are in summer, with the greatest number of dry days for coastal areas being in winter. For the Alpine region, winter has the least number of dry days, with autumn having the most.

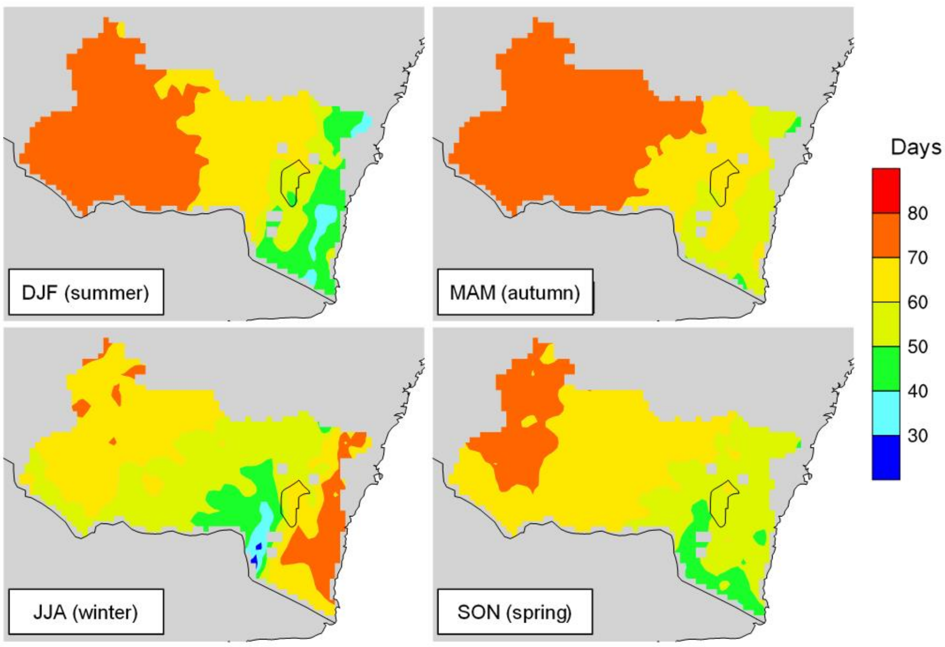

Figure 9 Simulated number of seasonal dry days for 1990 to 2009

Changes in the number of dry days for 2020 to 2039

A small increase in the number of dry days is projected for the 2020 to 2039 period (Figure 10). An up to 2% increase in dry days is projected for the majority of areas, except for the Alpine region where a 2–4% increase is projected. There is seasonal variation in dry day projections with increases in dry days in spring, especially for the Alpine region, where a 6–8% increase in projected (Figure 11). For all other seasons, there are only small changes projected for the number of dry days ranging from –2 to 2%.

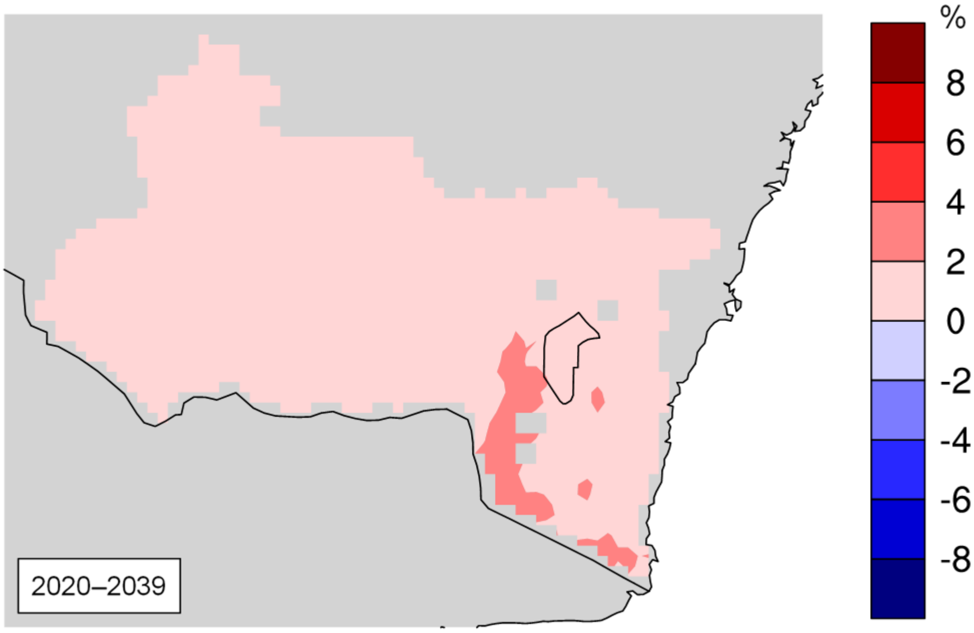

Figure 10 Changes in annual dry days (%) for 2020 to 2039 relative to 1990 to 2009

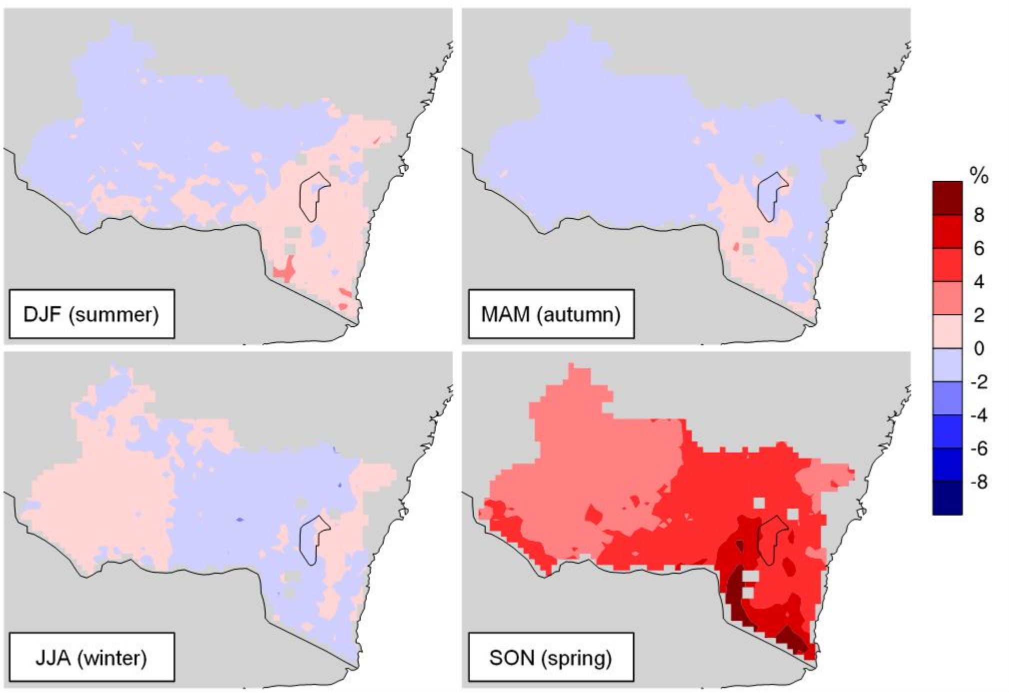

Figure 11 Changes in seasonal dry days (%) for 2020 to 2039 relative to 1990 to 2009

Changes in the number of dry days for 2060 to 2079

More dry days are projected for the 2060 to 2079 projection period when compared to the 2020 to 2039 period, especially for the Alpine region and southern MM area (up to an 8% increase in annual dry days, Figure 12). The northern MM region and coastal regions show mostly small increases in the number of projected dry days.

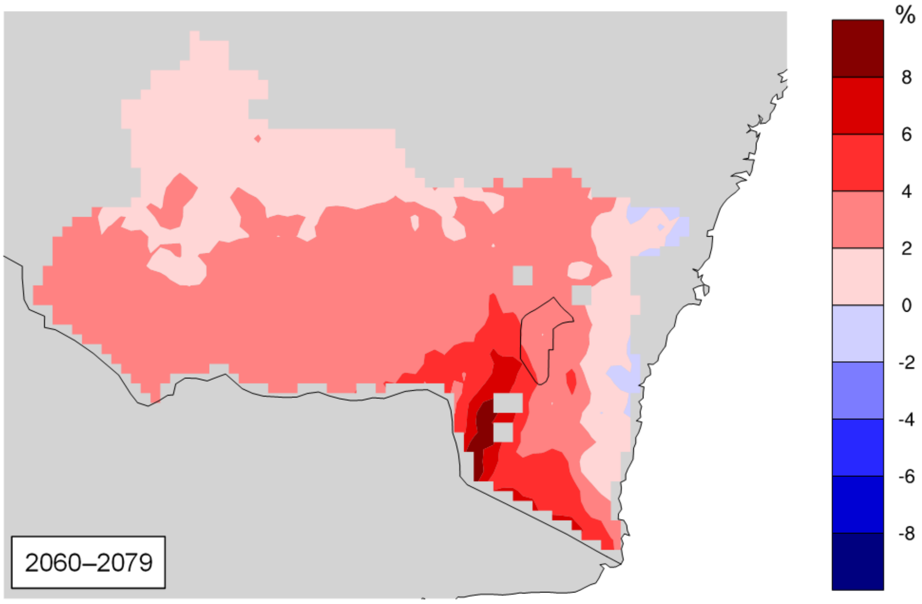

Figure 12 Changes in annual dry days (%) for 2060 to 2079 relative to 1990 to 2009

There is clear variation in seasonal dry day projections for the 2060 to 2079 projection period (Figure 13). Spring and winter will have an increased number of dry days over most of the region, especially in the Alpine region during spring, where at least a 12–16% increase in dry days is projected. Summer and autumn mostly have small changes relative to the baseline period, except for the Alpine region where a slightly larger increase (4–6%) is projected in summer.

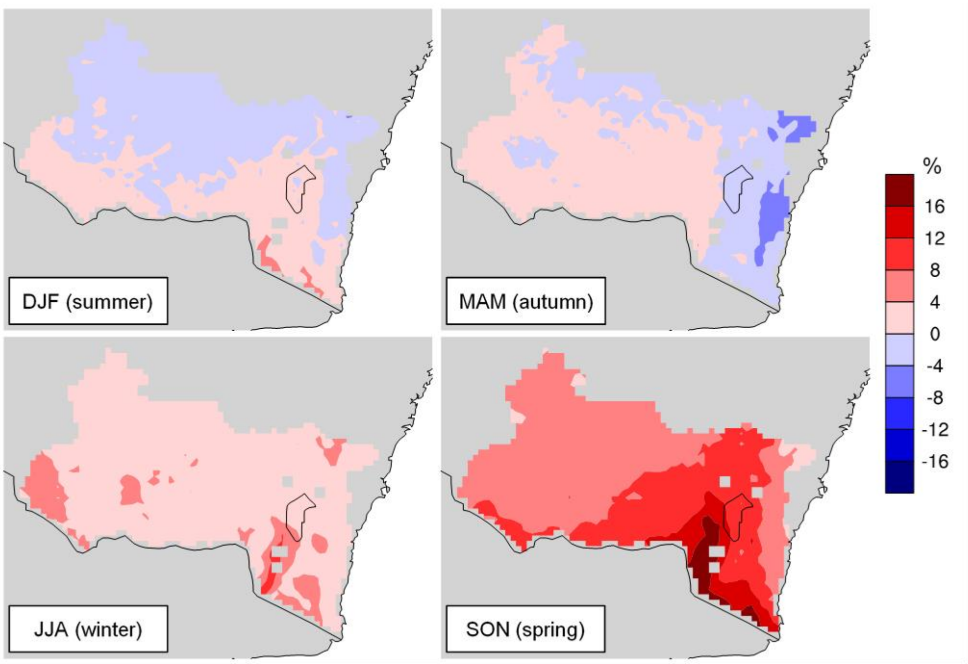

Figure 13 Changes in seasonal dry days (%) for 2060 to 2079 relative to 1990 to 2009

3.3 Moderate precipitation days (rainfall above 10 mm/day)

Mean number of moderate precipitation days for the 1990 to 2009 baseline period

For this study we define 'moderate precipitation' as precipitation in excess of 10 millimetres per day. The mean number of days with moderate precipitation is shown in Figure 14. Ten to 20 days with moderate rainfall are shown for most of areas except for the western MM region which has fewer than 10 days, coastal areas where there are 20–30 days with moderate rainfall, and the Alpine region where more than 40 days have moderate rainfall.

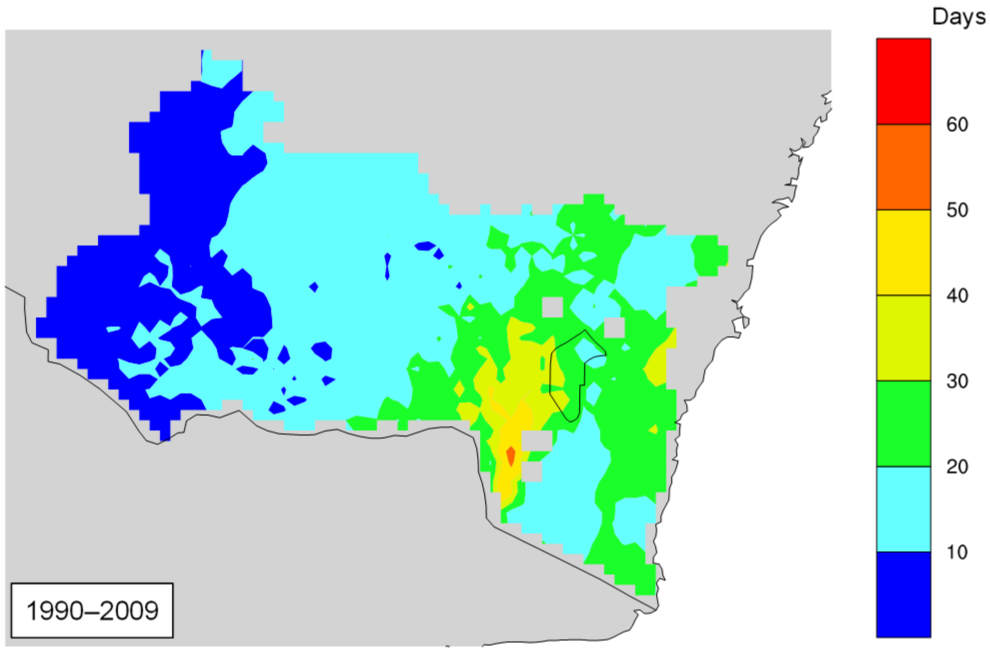

Figure 14 Annual moderate precipitation days for 1990 to 2009

There is little difference in seasonal days with moderate precipitation for the western and central MM region; however, there is a clear seasonal variation for the Alpine region where more than 20 days in winter have moderate precipitation while there are only 6–8 days in summer and autumn (Figure 15). For the coast, the most moderate precipitation days are in summer, with the least in winter.

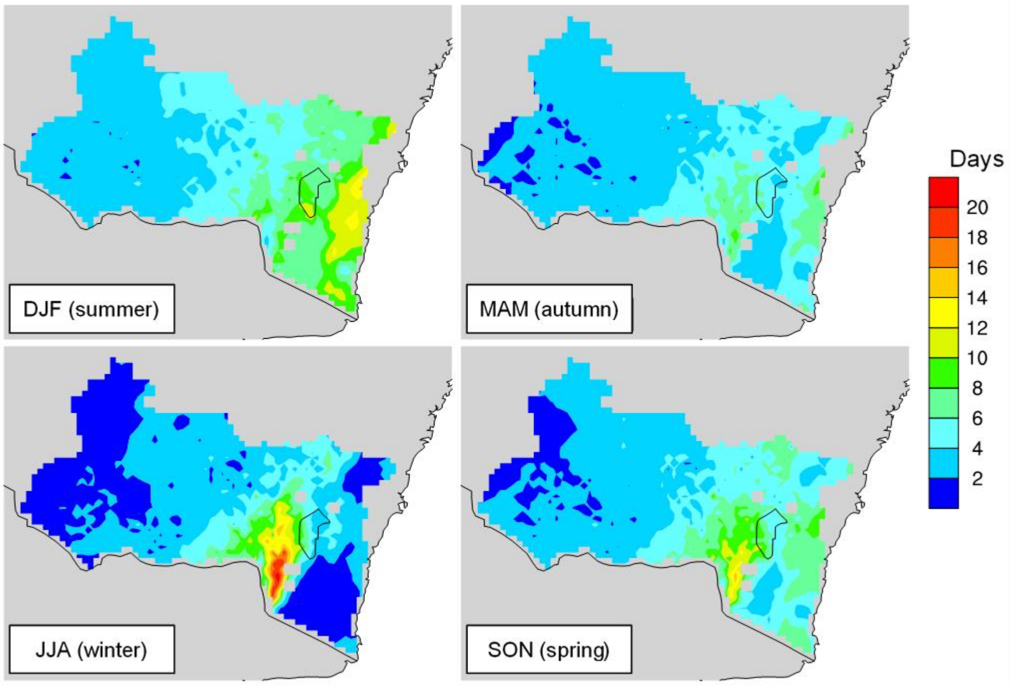

Figure 15 **Seasonal moderate precipitation days for 1990 to 2009**

Changes in the number of moderate precipitation days for 2020 to 2039

Changes in the number of days with moderate precipitation are small with a less than 5% increase for the western domain and a less than 5% decrease for the eastern domain (Figure 16).

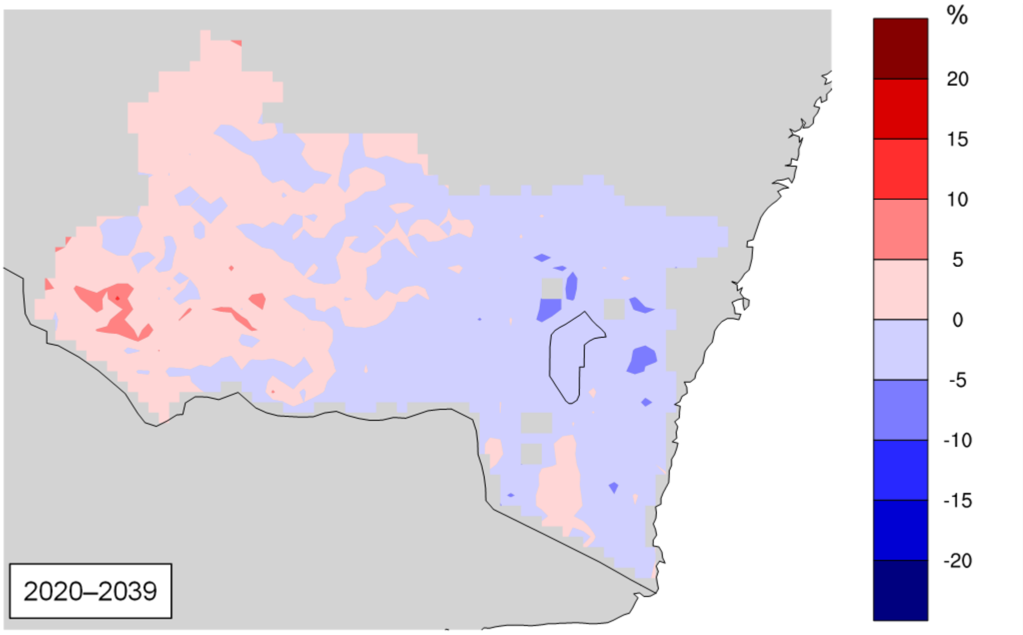

Figure 16 **Changes in annual moderate precipitation days (%) for 2020 to 2039 relative to 1990 to 2009**

There is a clear seasonal variation of changes in days with moderate precipitation (Figure 17). Summer and autumn will generally have more moderate precipitation days, especially for autumn when a more than 20% increase is projected for some areas in the MM region. Winter and spring will have fewer moderate precipitation days, especially in winter when a more than 10% decrease is projected for some parts of the Great Dividing Range.

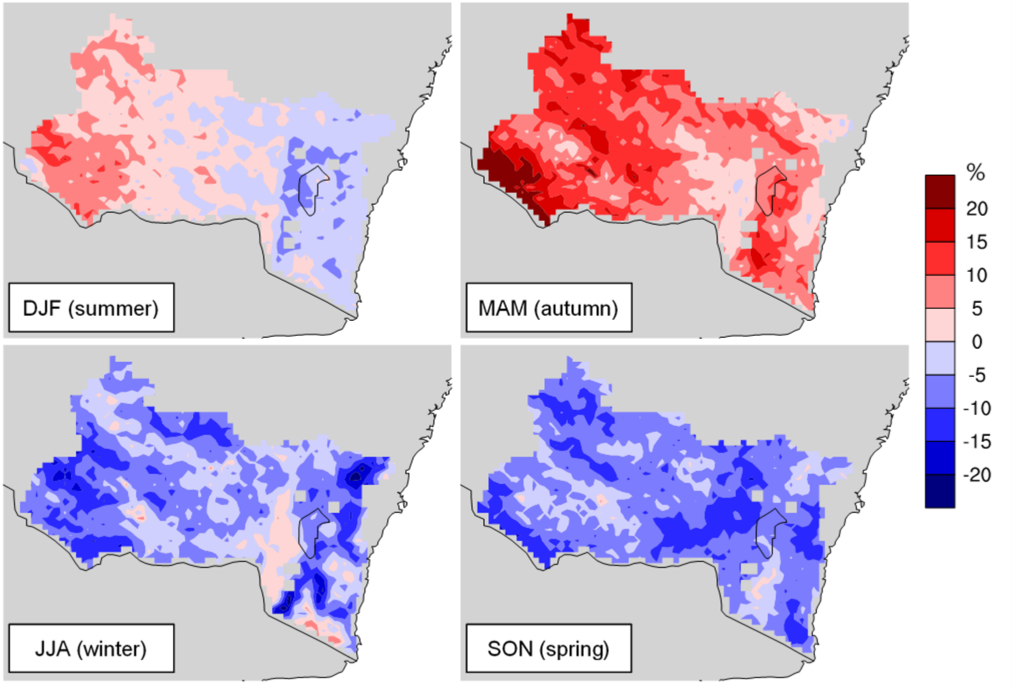

Figure 17 **Changes in seasonal moderate precipitation days (%) for 2020 to 2039 relative to 1990 to 2009**

Changes in the number of moderate precipitation days for 2060 to 2079

Changes in the number of days with moderate precipitation for 2060 to 2079 are much larger relative to 2020 to 2039 (Figure 18). A more than 15% increase is projected for some areas in the western MM region and a more than 10% decrease is projected for some areas in the Alpine region. This indicates that most areas will have more moderate precipitation in the far future, except for the Alpine region where much fewer moderate precipitation days will occur.

Similar to the results for 2020 to 2039, summer and autumn will have more days with moderate precipitation, but the magnitude of change for 2060 to 2079 is much larger than that for 2020 to 2039 when compared with 1990 to 2009 (Figure 19). A more than 10% increase in days with moderate precipitation is projected for most of the study region during summer and autumn. More moderate precipitation days are also projected for winter except for the coastal and Alpine regions where a more than 15% decrease is projected in some areas for 2060 to 2079. Larger decreases are projected for spring, especially in parts of the Alpine region, where a more than 20% decrease in moderate precipitation days is projected.

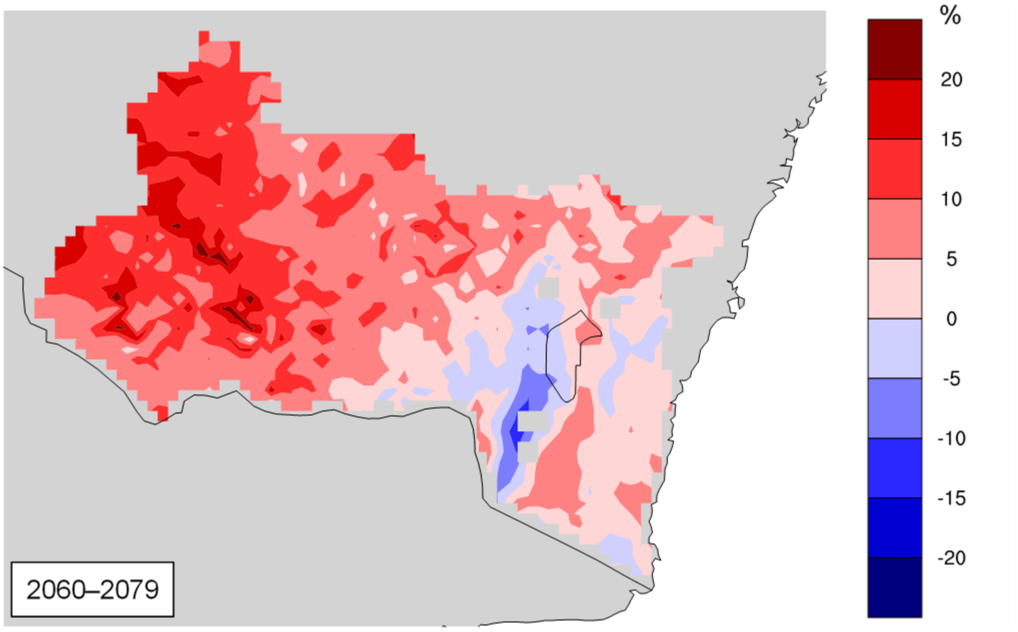

Figure 18 **Changes in annual moderate precipitation days (%) for 2060 to 2079 relative to 1990 to 2009**

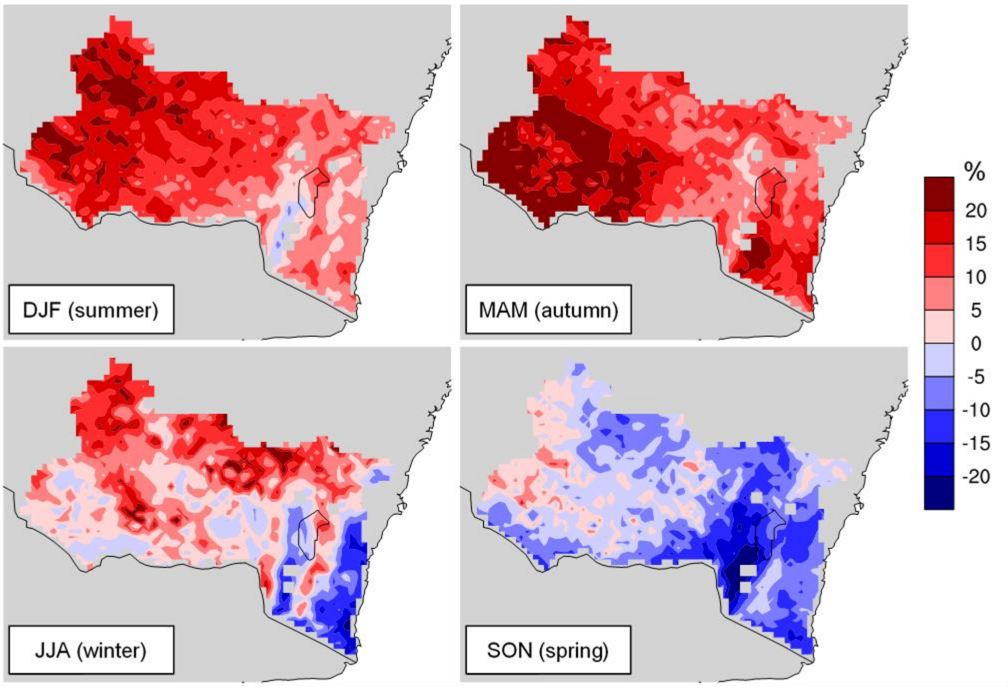

Figure 19 **Changes in seasonal moderate precipitation days (%) for 2060 to 2079 relative to 1990 to 2009**

3.4 Heavy precipitation days (rainfall above 25 mm/day)

Mean number of heavy precipitation days for the 1990 to 2009 baseline period

Precipitation above 25 millimetres/day is taken as a threshold of daily precipitation for a heavy precipitation day. Simulations indicate there are few heavy precipitation days for the western MM region, and a few events for western SET. Most of the heavy precipitation events are shown in the coastal and Alpine regions with 8–15 events in a year (Figure 20).

Heavy precipitation days mostly occur in summer for the coast and in winter for the Alpine region (Figure 21). The Alpine region can have some heavy precipitation events in other seasons, but the coast has no heavy precipitation events in winter.

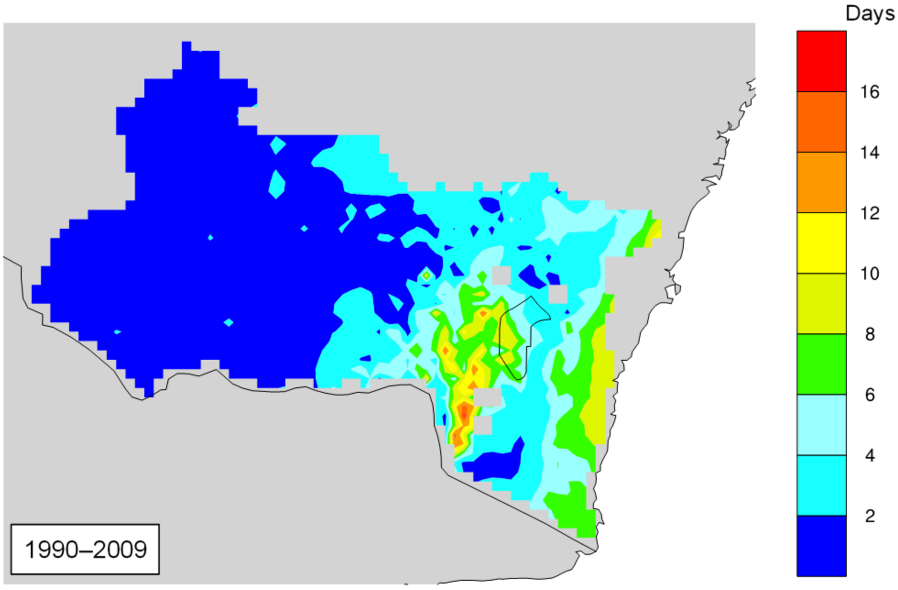

Figure 20 Annual heavy precipitation days for 1990 to 2009

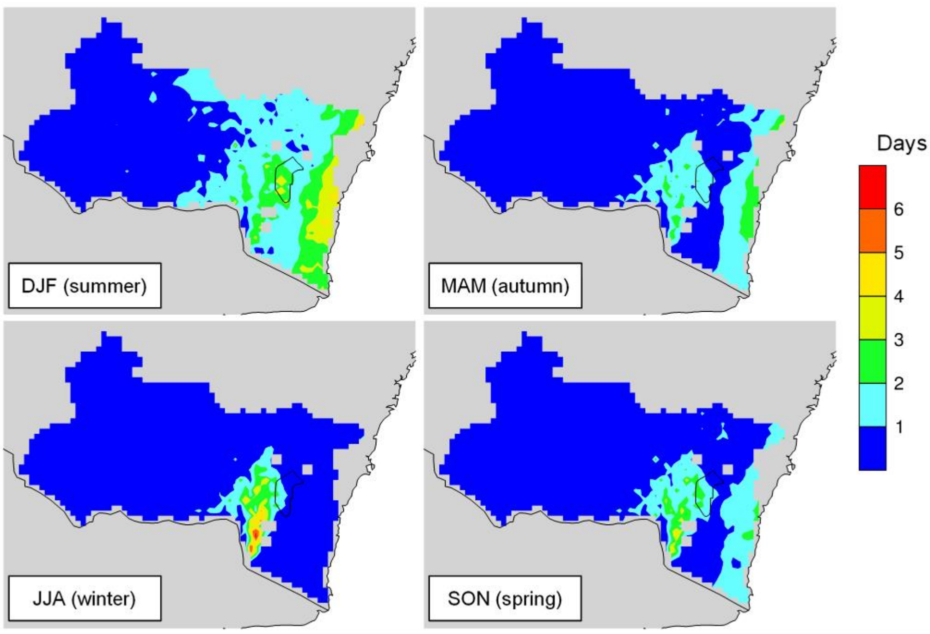

Figure 21 Seasonal heavy precipitation days for 1990 to 2009

Changes in the number of heavy precipitation days for 2020 to 2039

Future projections for heavy precipitation days are summarised in Figure 22. Broadly, the western MM region will expect to have more heavy precipitation events in 2020 to 2039; however, the eastern MM region and SET will have fewer heavy precipitation events in the same period.

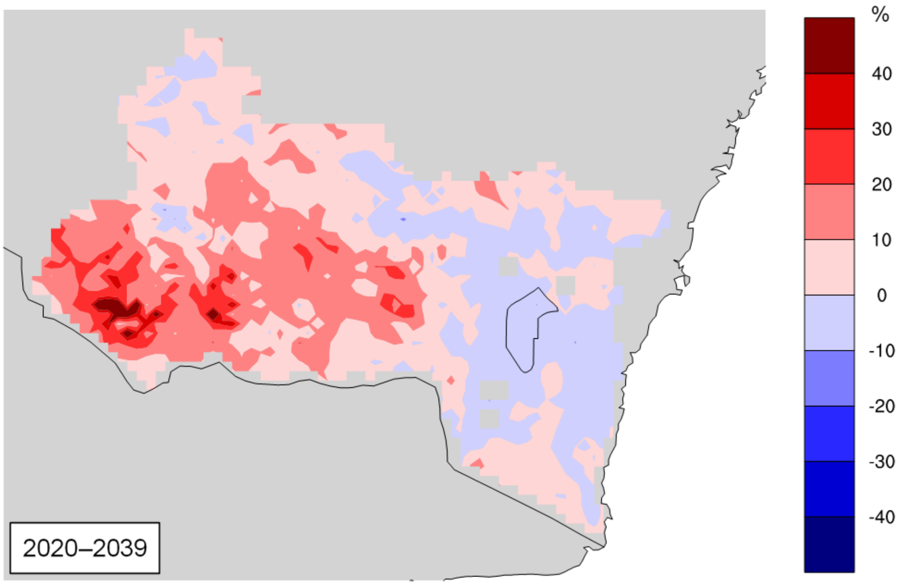

Figure 22 Changes in annual heavy precipitation days (%) for 2020 to 2039 relative to 1990 to 2009

Larger increases in seasonal heavy precipitation events for the western MM region are mostly in autumn and winter, when a more than 60% increase is projected for some areas (Figure 23). A more than 60% decrease in seasonal heavy precipitation events is projected for some parts of the Alpine region in winter. There is little seasonal variation in changes in heavy precipitation days in coastal areas.

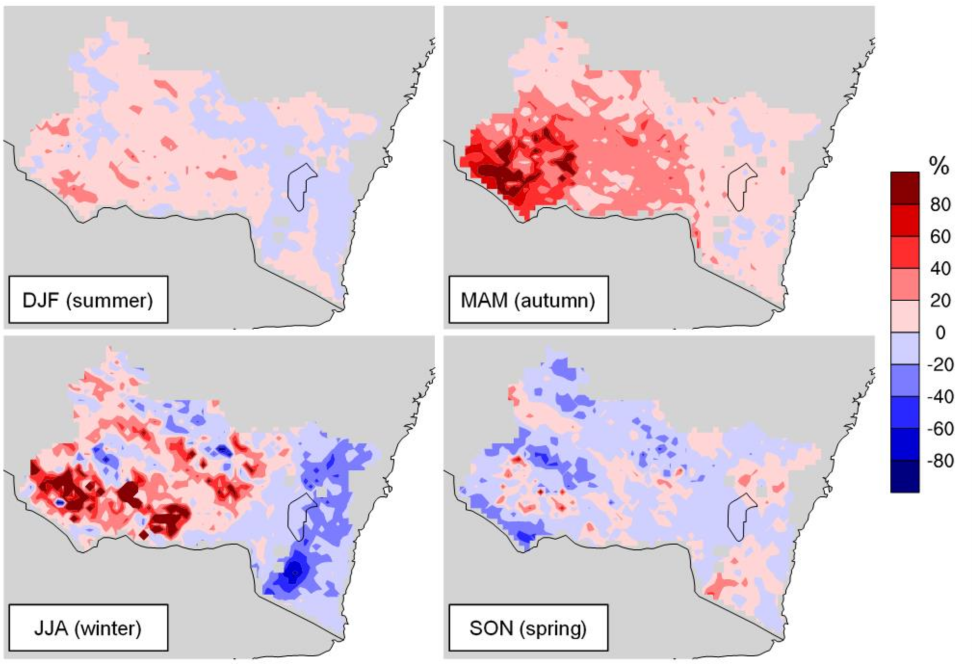

Figure 23 Changes in seasonal heavy precipitation days (%) for 2020 to 2039 relative to 1990 to 2009

Changes in the number of heavy precipitation days for 2060 to 2079

For 2060 to 2079 increases in heavy precipitation days are projected for most areas except for some of the Alpine region, where about a 10% decrease is projected. A more than 40% increase can be seen over most of the MM region and a 10–20% increase for coastal regions (Figure 24).

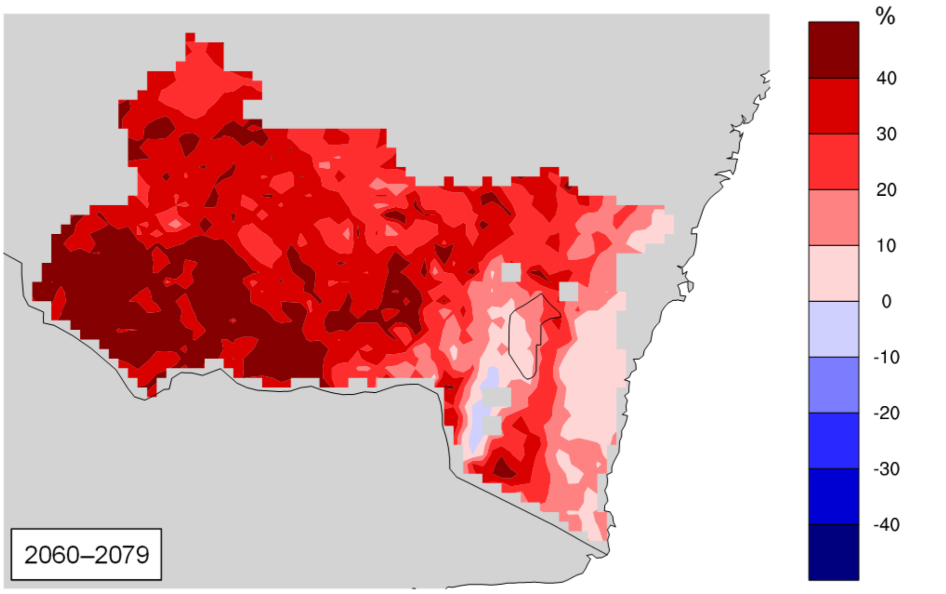

Figure 24 **Changes in annual heavy precipitation days (%) for 2060 to 2079 relative to 1990 to 2009**

A more than 60% increase in heavy precipitation days is projected for autumn and winter in the MM region, where a 20–40% increase is projected for the other two seasons (Figure 25). A 20% increase is projected for the coastal and Alpine regions in summer and autumn, and a 20% decrease is projected for the other two seasons for the same areas.

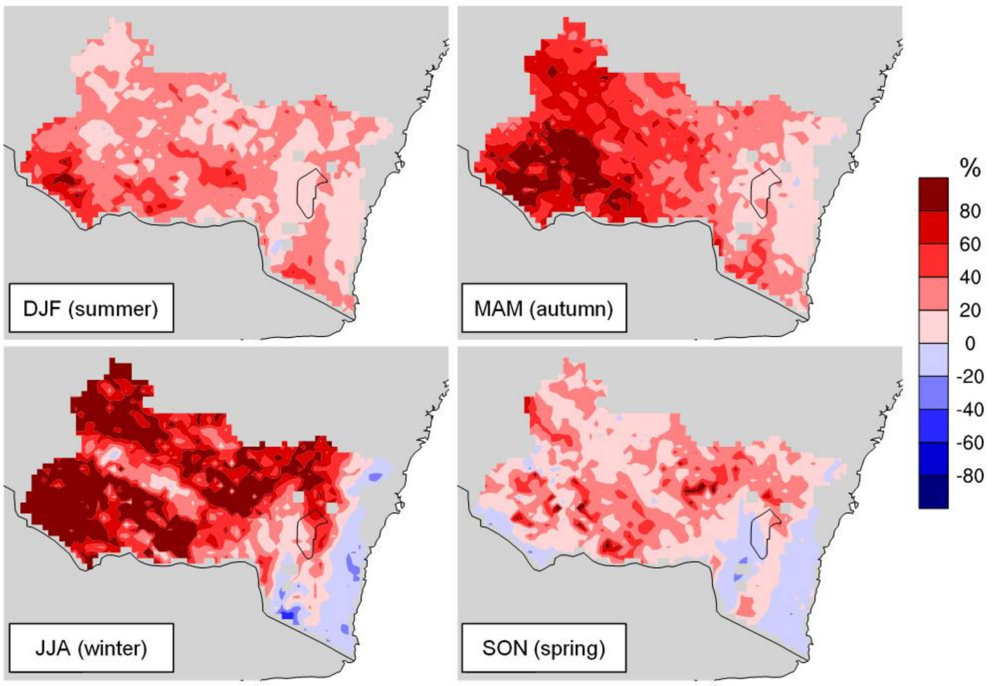

Figure 25 **Changes in seasonal heavy precipitation days (%) for 2060 to 2079 relative to 1990 to 2009**

3.5 Maximum temperature

Mean maximum temperature for the 1990 to 2009 baseline period

There is a clear west–east temperature gradient in the MM region with more than 25°C annual maximum temperature for the north-western MM region and 17–19°C in the east (Figure 26). For the SET region, a weak temperature gradient is shown from the coast to inland, with 20–22°C shown for the coast and 17–19°C inland. The lowest mean annual maximum temperature is observed in the Alpine region where annual mean maximum temperature is below 10°C in some areas.

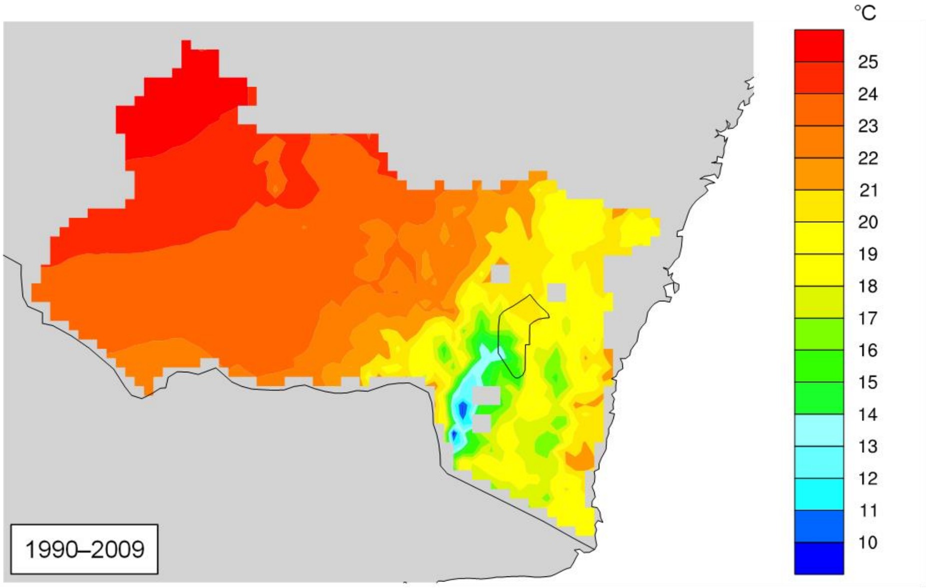

Figure 26 Mean annual maximum temperature for 1990 to 2009

Substantial seasonal variation in maximum temperature can be observed for the MM and Alpine region, but small seasonal variation is observed for the coast (Figure 27). Mean maximum temperature for the western MM region is largely above 32°C in summer; however, it is generally below 8°C in winter for the Alpine region.

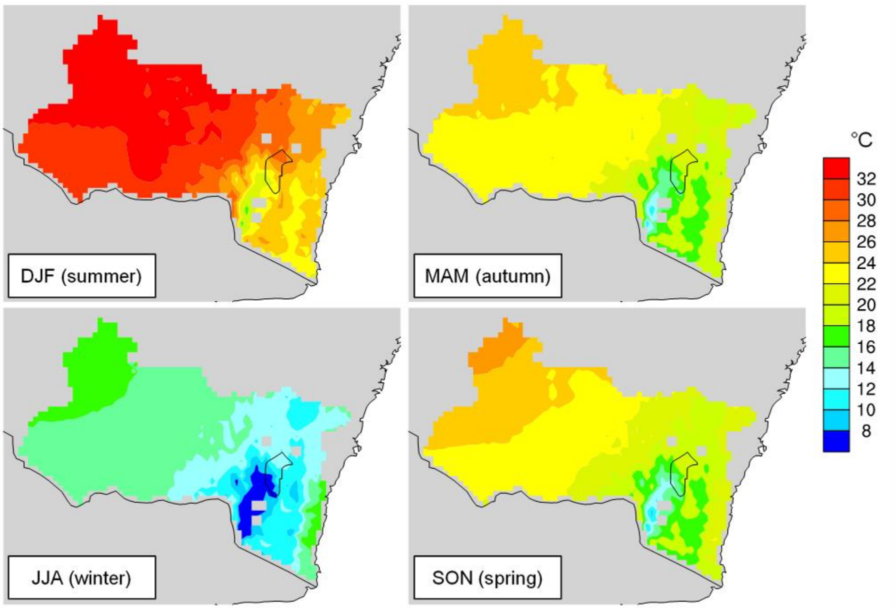

Figure 27 Mean seasonal maximum temperature for 1990 to 2009

Changes in maximum temperature for 2020 to 2039

Changes in maximum temperature for 2020 to 2039 is quite small with a 0.5–0.75°C increase for most of the study area except for the northern Alpine region where 0.75-1°C increase is projected (Figure 28).

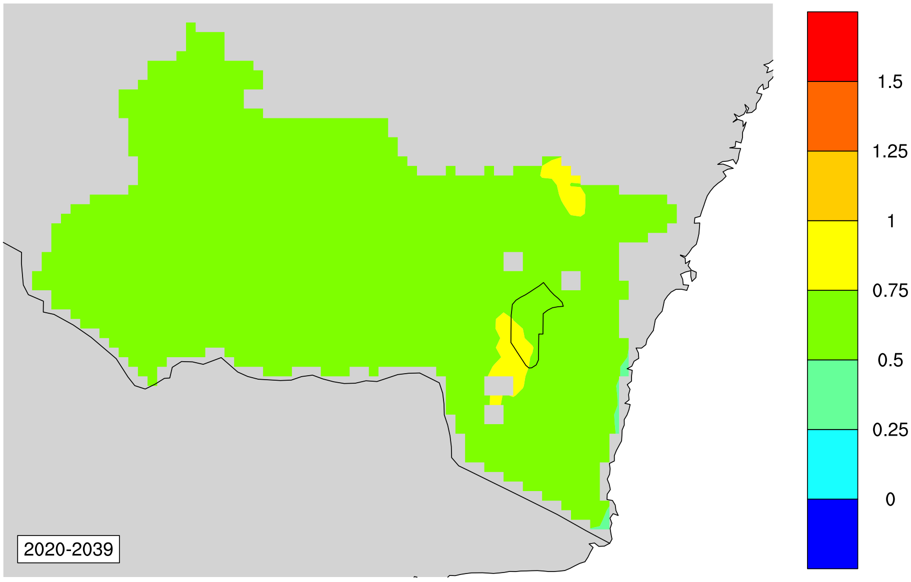

Figure 28 Changes in mean annual maximum temperature for 2020 to 2039 relative to 1990 to 2009

Seasonal increases in maximum temperature are also small with a 0.75–1°C increase in spring and summer and a 0.5-0.75°C increase for the autumn for most areas. Less than 0.5°C increase is expected for winter for majority area except for the Alpine region with 0.5–0.75°C increase (Figure 29).

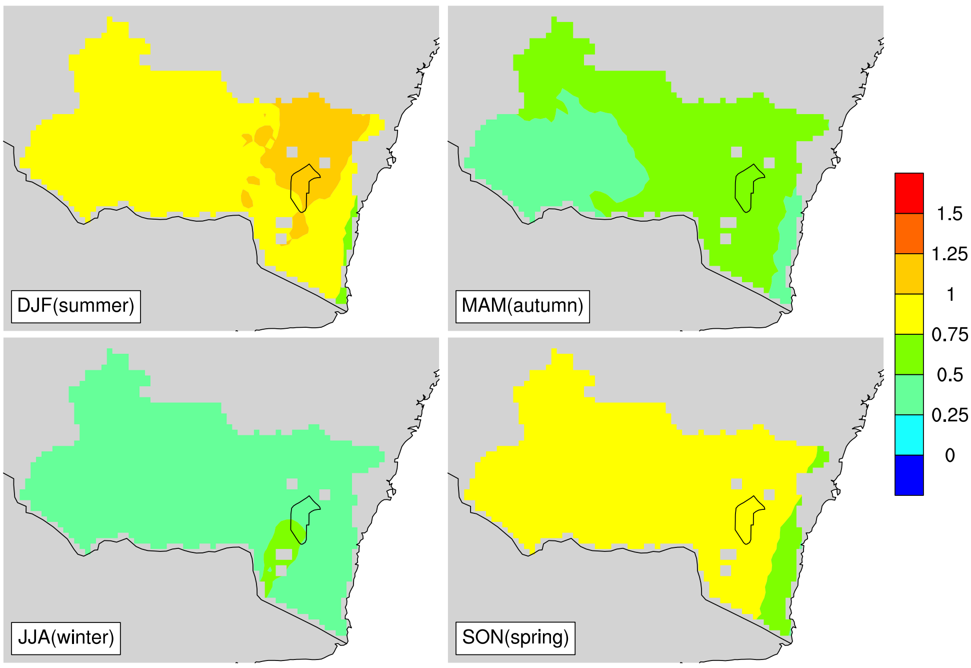

Figure 29 Changes in mean seasonal maximum temperature for 2020 to 2039 relative to 1990 to 2009

Changes in maximum temperature for 2060 to 2079

Changes in maximum temperature are much larger for 2060 to 2079 (Figure 30) when compared to changes for 2020 to 2039. A 1.5–2°C increase is projected for eastern SET and southwest MM regions while more than 2°C increase is projected for other regions especially for the Alpine with more than 2.25°C increase.

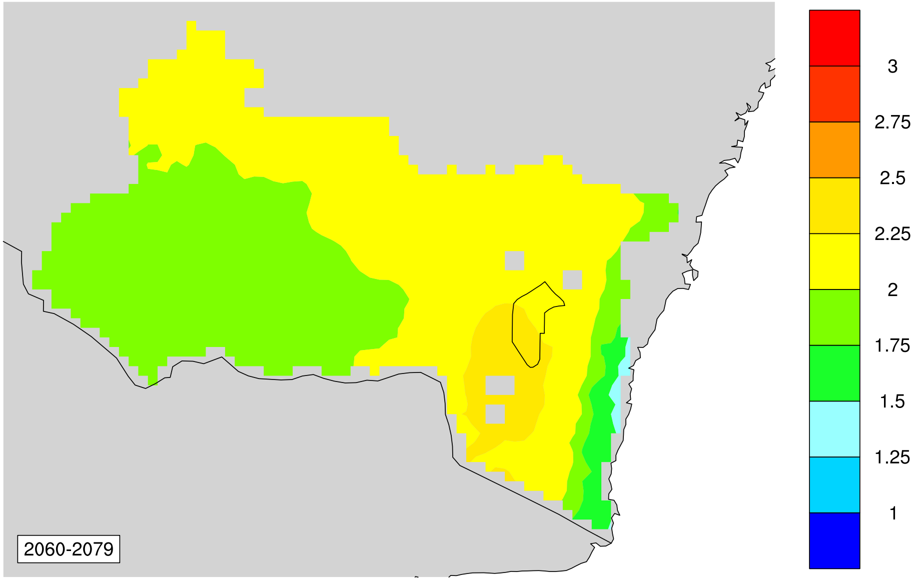

Figure 30 Changes in mean annual maximum temperature for 2060 to 2079 relative to 1990 to 2009

A larger increase in maximum temperature is projected in summer and spring compared with the other two seasons (Figure 31). Little seasonal variation in increases in maximum temperature is projected for the coast. Generally, a larger increase in maximum temperature is projected for the Alpine region than surrounding regions with a more than 2.5°C increase in spring and a 2–2.5°C increase in other three seasons.

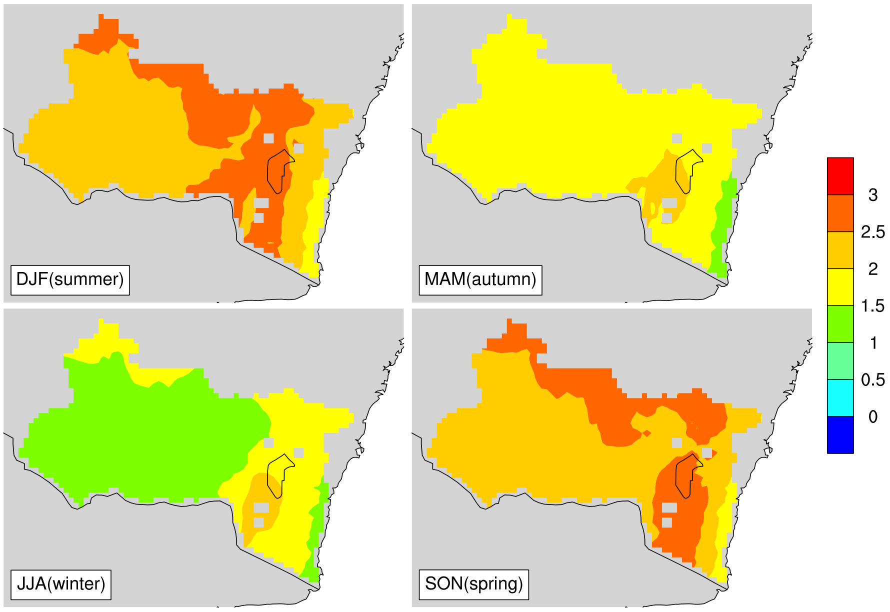

Figure 31 **Changes in mean seasonal maximum temperature for 2060 to 2079 relative to 1990 to 2009**

3.6 Hot days (maximum temperature above 35°C)

Mean number of hot days for the 1990 to 2009 baseline period

There is a clear north-west to south-east gradient in the number of hot days with more than 50 days in a year for the north-west of the MM region and fewer than five days in a year for the SET and Alpine region (Figure 32).

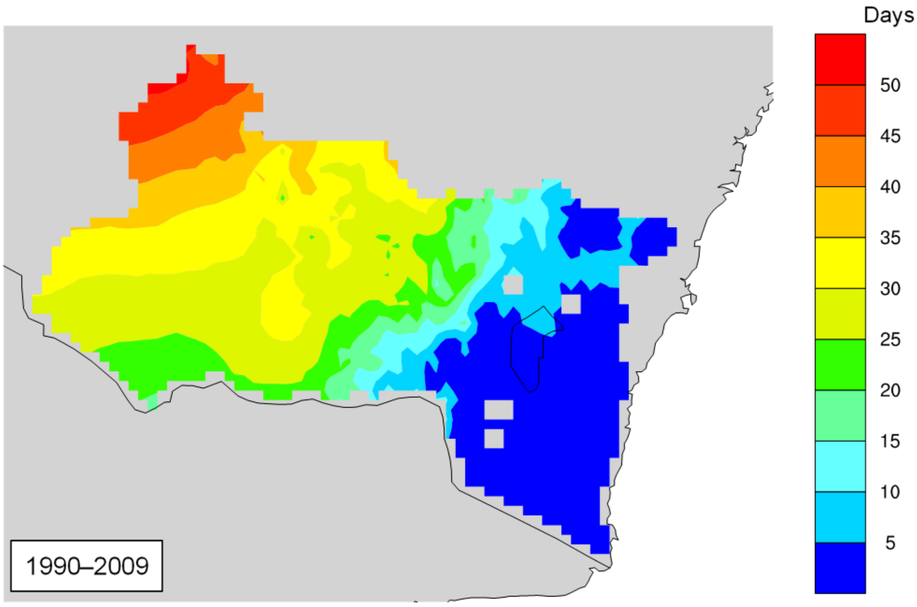

Figure 32 **Mean annual number of hot days for 1990 to 2009**

Unsurprisingly, the majority of hot days are in summer for the MM region and there are no hot days in winter, but spring and autumn also have a few days with maximum temperature above 35°C, especially for the north-west MM region (Figure 33). Annually, there are few hot days for other regions.

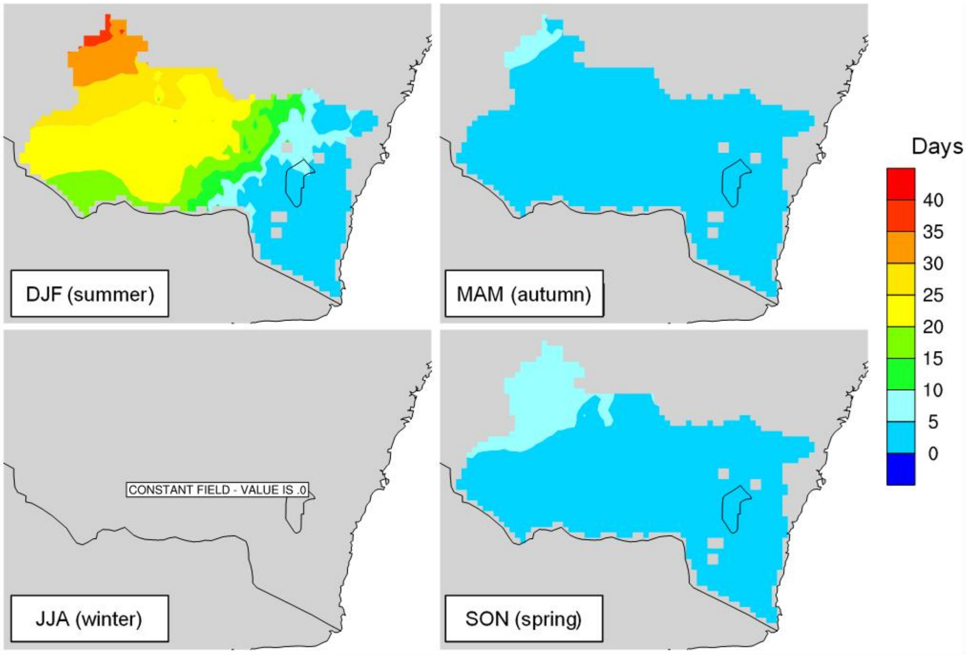

Figure 33 **Mean seasonal number of hot days for 1990 to 2009**

Note that JJA has no values plotted as there are no instances where the maximum temperature exceeds 35°C

Changes in the number of hot days for 2020 to 2039

For most of the MM region, 8–10 more hot days are projected, while 3–5 more hot days are projected for the northern SET region, with only a small increase for the remaining areas (Figure 34).

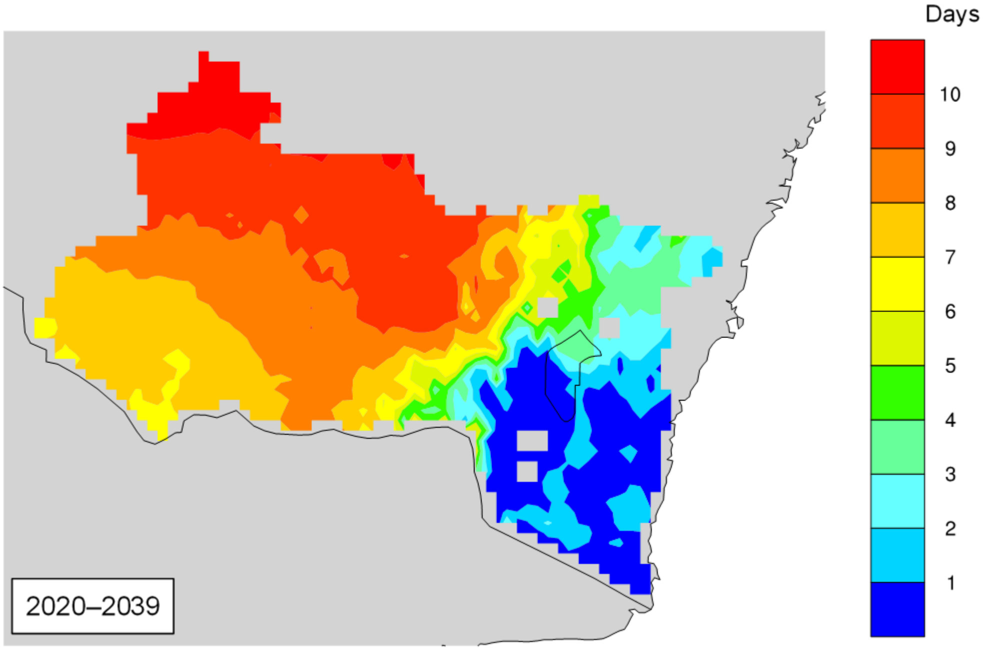

Figure 34 **Changes in annual hot days for 2020 to 2039 relative to 1990 to 2009**

Increases in extreme days are mostly in summer, with some increases in spring, small increases in autumn and no change in winter (Figure 35).

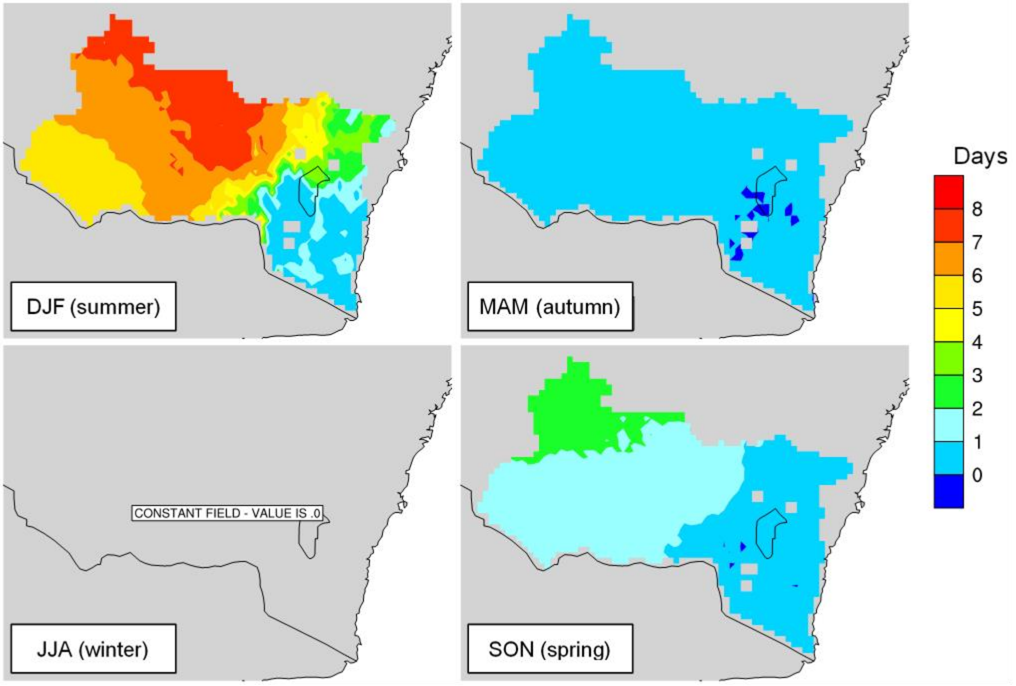

Figure 35 **Changes in seasonal hot days for 2020 to 2039 relative to 1990 to 2009**
Note that JJA has no values plotted as there are no instances where the maximum temperature exceeds 35°C

Changes in the number of hot days for 2060 to 2079

The change pattern for 2060 to 2079 is similar to that of 2020 to 2039; however, the magnitude of change is much larger in the far future (Figure 36). An increase of more than 24 hot days in a year is projected for 2060 to 2079 for most of the MM region, with 8–12 more hot days for northern SET and fewer than four days for the remaining regions.

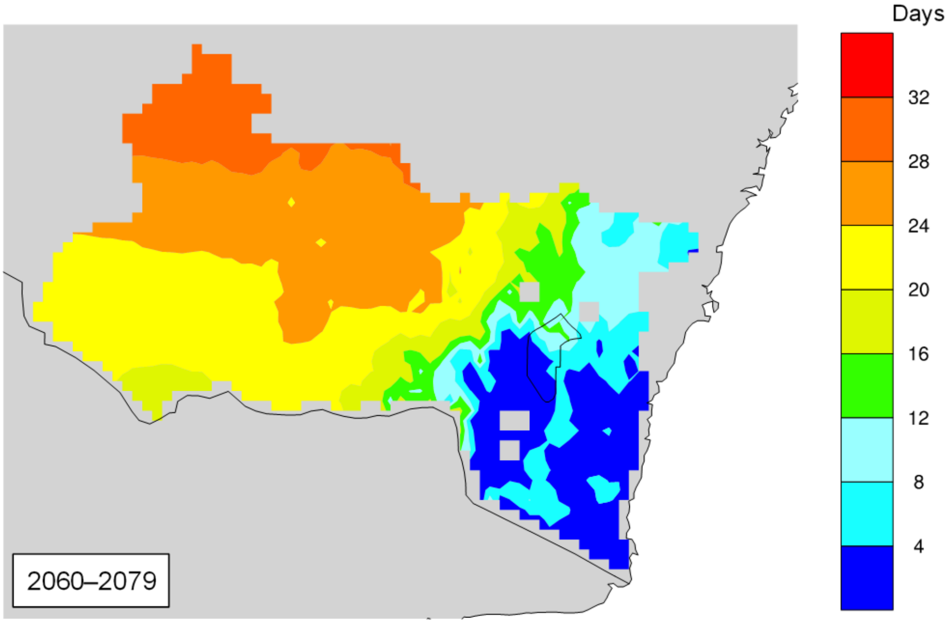

Figure 36 **Changes in annual hot days for 2060 to 2079 relative to 1990 to 2009**

For the MM region, increases in hot days are mostly in summer, with 4–8 day increases in spring, 2–4 day increases in autumn and no change in winter (Figure 37). For northern SET

8–10 more hot days are projected in summer, as well as a few more hot days in other northern areas. No changes for the Alpine and southern SET regions are projected apart from minor increases in summer in some areas.

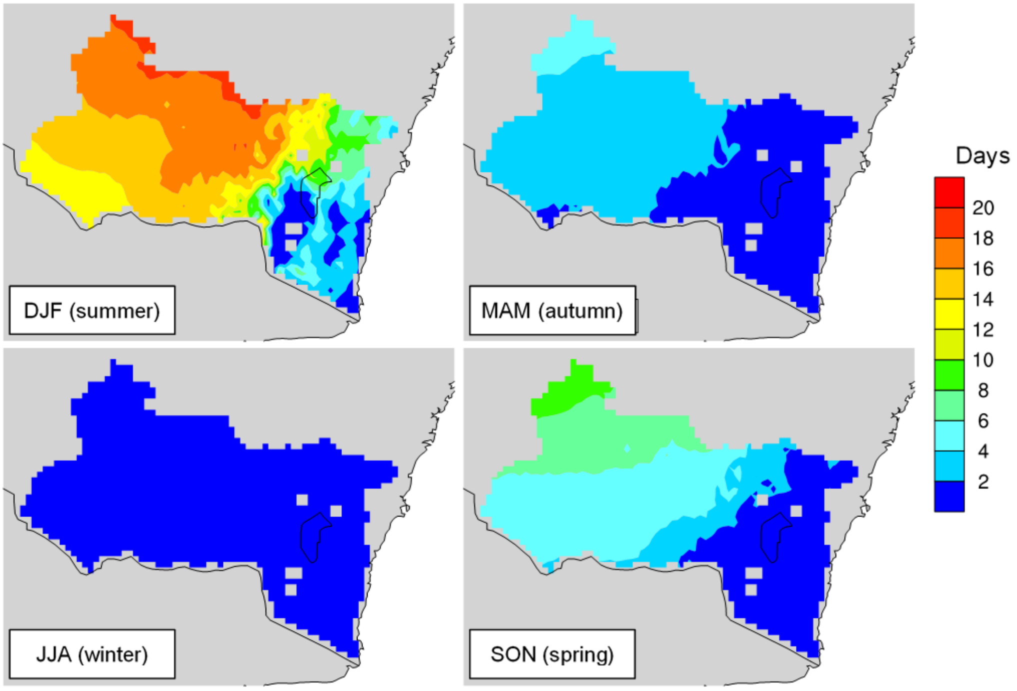

Figure 37 Changes in seasonal hot days for 2060 to 2079 relative to 1990 to 2009

3.7 Minimum temperature

Mean minimum temperature for the 1990 to 2009 baseline period

Annual average daily minimum temperature has a similar pattern of gradients as annual average daily maximum temperature, with more than 10°C minimum temperature in the west MM region and along the coast and less than 2°C minimum temperature in the Alpine region (Figure 38).

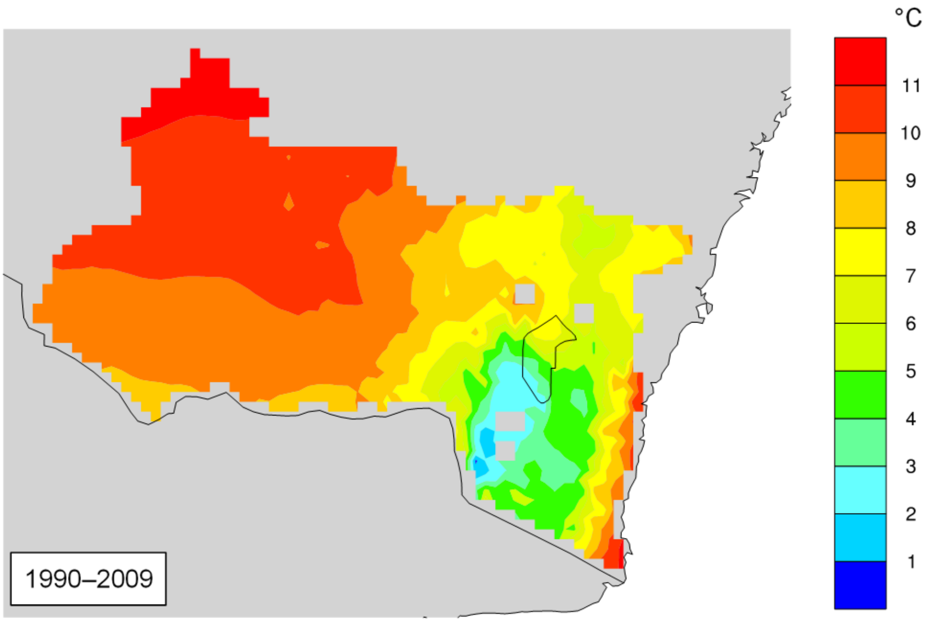

Figure 38 **Mean annual minimum temperature for 1990 to 2009**

There is a clear seasonal variation in minimum temperature with high minimum temperature in summer and low minimum temperature in winter (Figure 39). On average, above 18°C minimum temperature is observed for the north-west MM region in summer, with below –2°C minimum temperature observed for the Alpine region in winter.

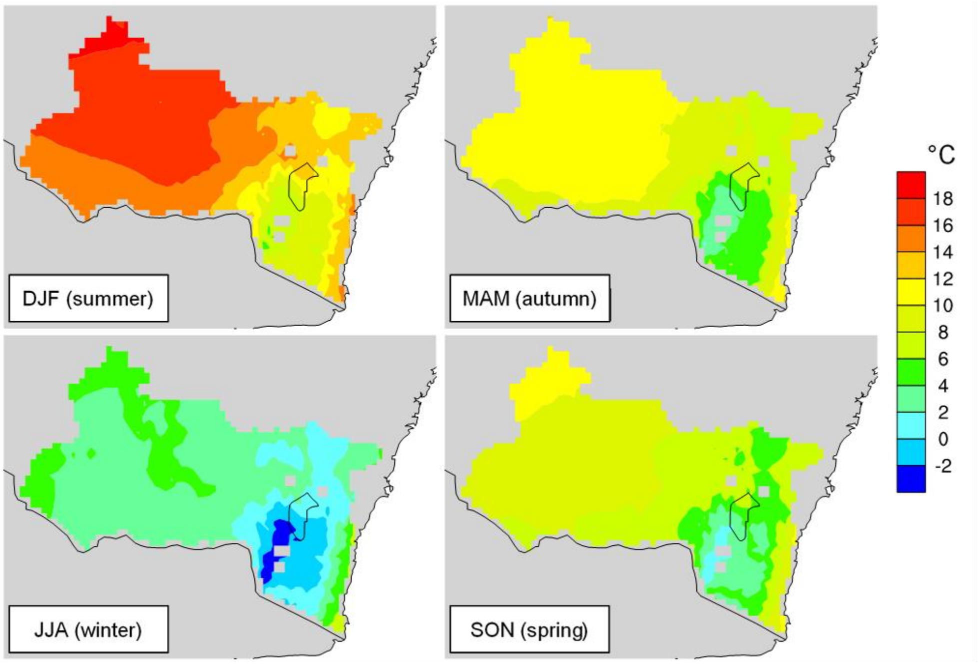

Figure 39 **Mean seasonal minimum temperature for 1990 to 2009**

Changes in minimum temperature for 2020 to 2039

The change in minimum temperature for the 2020 to 2039 projection period is small, with a 0.5–0.75°C increase projected across the study area (Figure 40). The seasonal variation in projected change is also quite small with slightly more increases in summer compared with spring and autumn while winter is projected with the least increase (Figure 41).

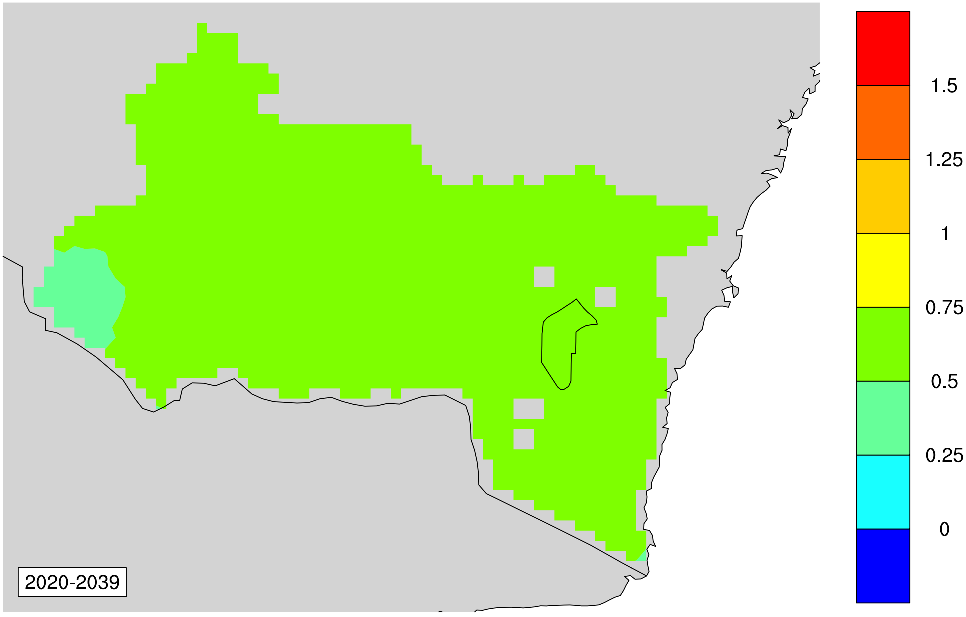

Figure 40 **Changes in mean annual minimum temperature for 2020 to 2039 relative to 1990 to 2009**

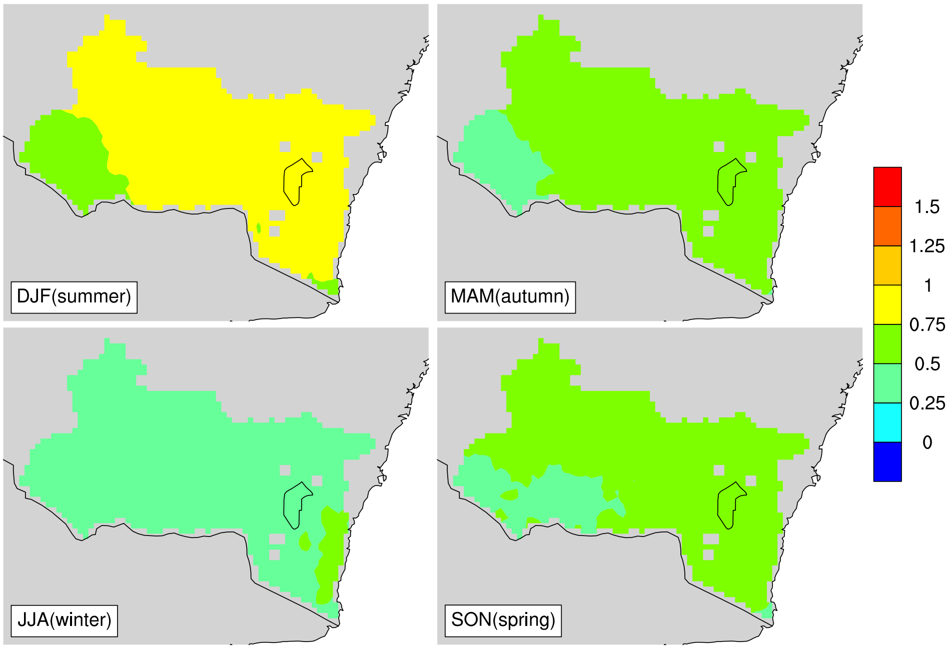

Figure 41 **Changes in mean seasonal minimum temperature for 2020 to 2039 relative to 1990 to 2009**

Changes in minimum temperature for 2060 to 2079

For 2060 to 2079 a 1.5–2°C increase in minimum temperature is projected for most areas, except for the south-SET region where a 2–2.5°C increase is projected (Figure 42).

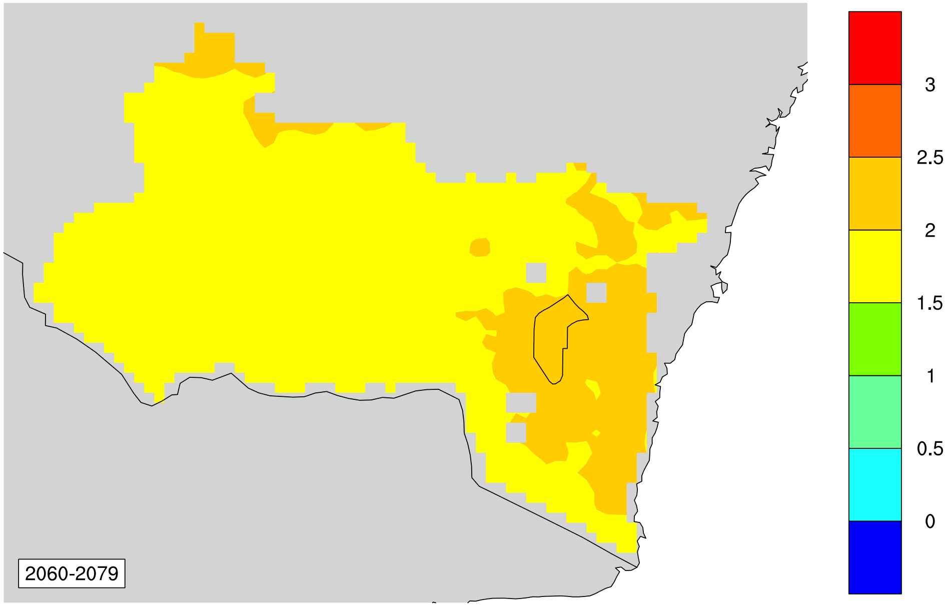

Figure 42 **Changes in mean annual minimum temperature for 2060 to 2079 relative to 1990 to 2009**

Increases in minimum temperature are larger in summer compared with the other three seasons. A 2–2.5°C increase in minimum temperature is projected for most areas (Figure 43). Changes look similar for spring and autumn with a 2–2.5°C increase in SET and northern MM, and a 1.5–2°C increase for the remaining regions. Minimum temperature is projected with least increase in winter with 1-1.5°C increase in the MM region and 1.5-2°C for the SET region.

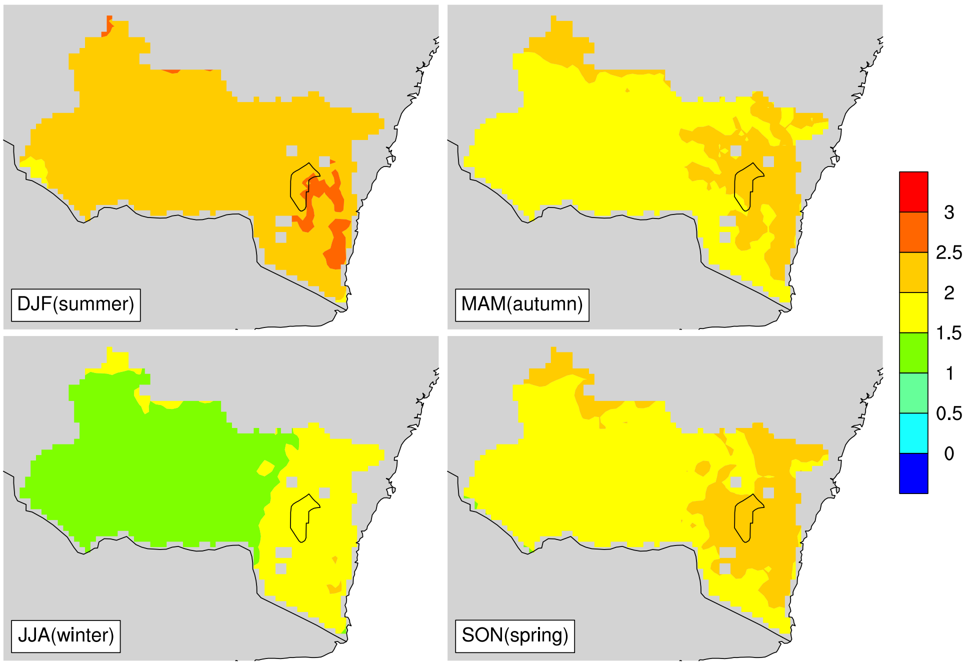

Figure 43 **Changes in mean seasonal minimum temperature for 2060 to 2079 relative to 1990 to 2009**

3.8 Cold nights (minimum temperature below –2°C)

Mean number of cold nights for the 1990 to 2009 baseline period

A minimum overnight temperature below –2°C is recorded as a cold night. There are more than 110 cold nights in a year for the Alpine region, 40–60 cold nights in surrounding areas, and fewer than 10 cold nights in a year for coastal areas and most of the MM region (Figure 44).

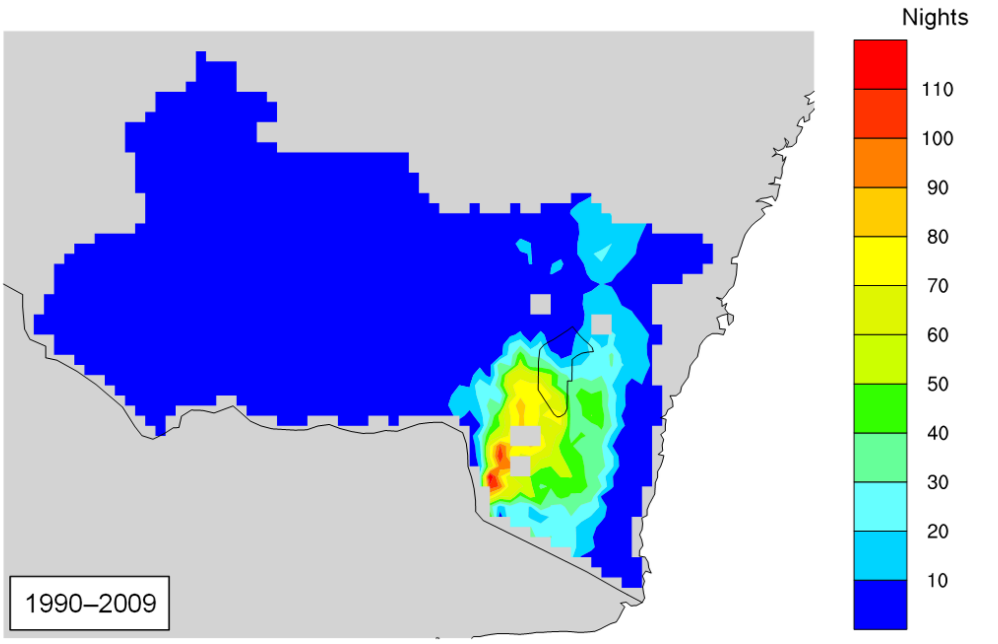

Figure 44 Mean annual cold nights for 1990 to 2009

Unsurprisingly, the majority of cold nights are in winter; however, there are 10–20 cold nights in spring and a few cold nights in autumn for the Alpine region and surrounding areas (Figure 45).

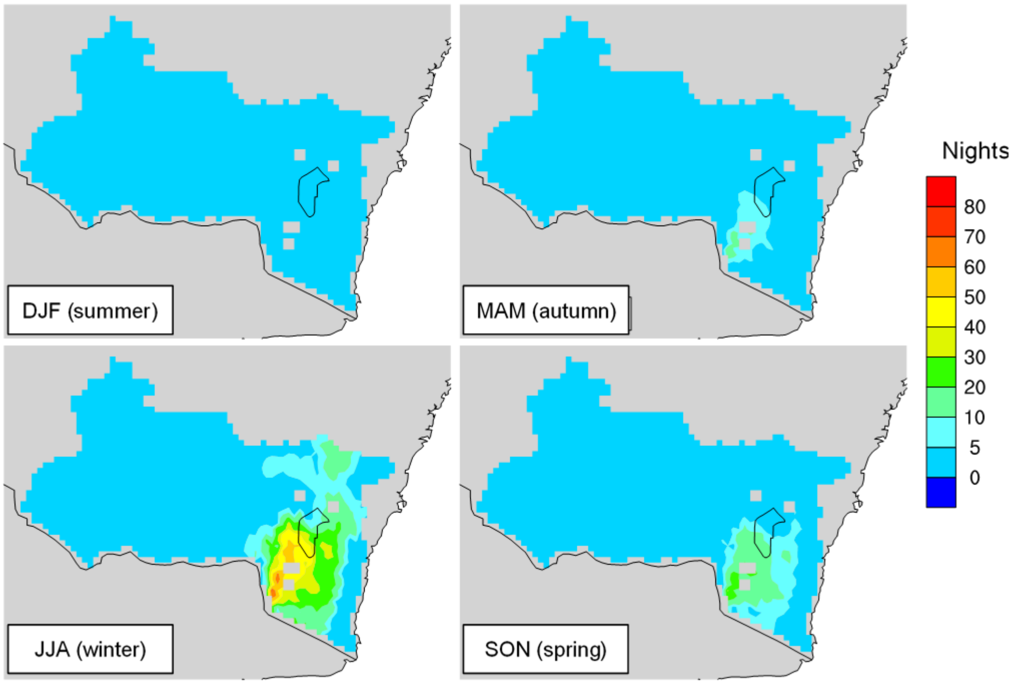

Figure 45 Mean seasonal cold nights for 1990 to 2009

Changes in the number of cold nights for 2020 to 2039

Overall, there will be fewer cold nights across the study area in 2020 to 2039. The largest decrease in cold nights is projected for the Alpine region, where a decrease of more than 13 nights a year is projected in some areas (Figure 46).

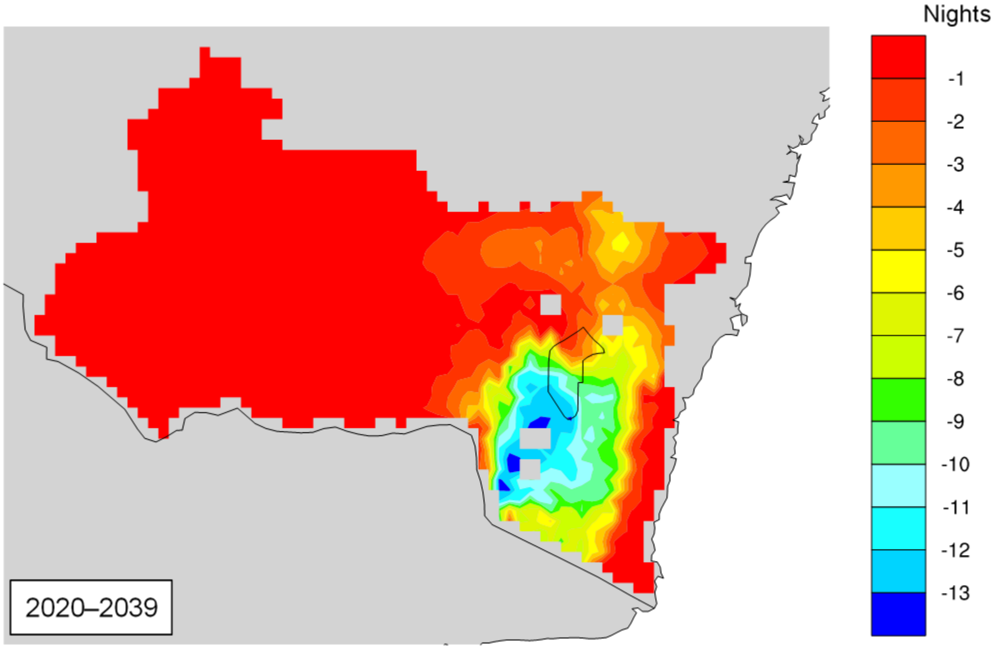

Figure 46 Changes in annual cold nights for 2020 to 2039 relative to 1990 to 2009

Similar to the seasonal distribution of the absolute number of cold nights, the reduction in cold nights will mostly occur in winter, when eight fewer cold nights are projected on average compared with 1990 to 2009 (Figure 47). In addition, some reduction in cold nights is shown in autumn and spring for the Alpine region.

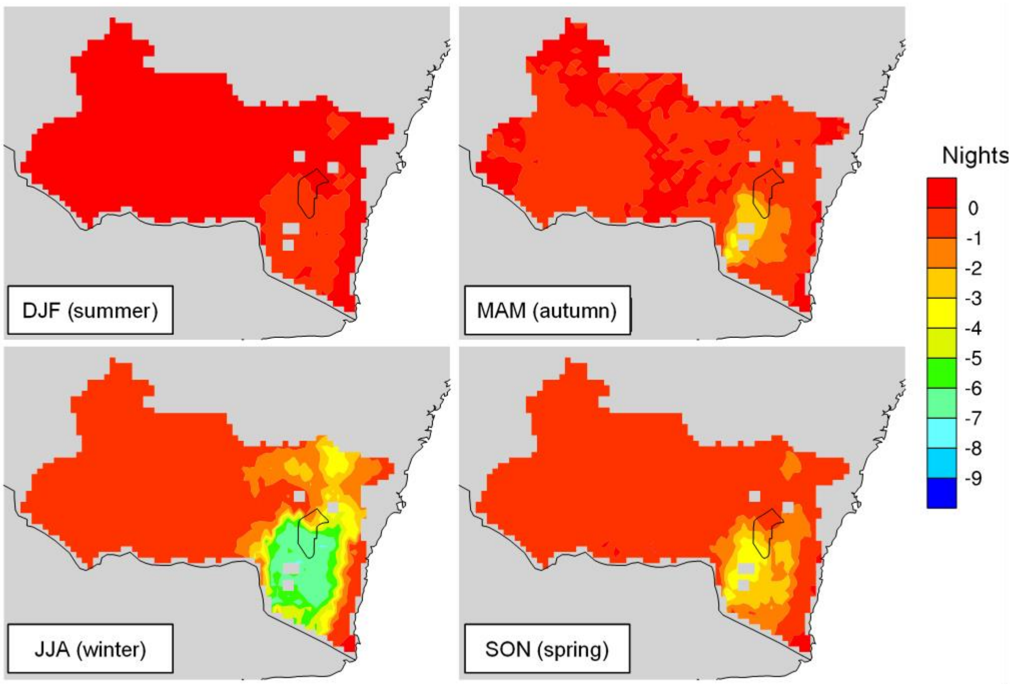

Figure 47 Changes in seasonal cold nights for 2020 to 2039 relative to 1990 to 2009

Changes in the number of cold nights for 2060 to 2079

More than 20 nights a year will no longer be considered a cold night (as per the definition used in this report) for the Alpine region, and more than 40 nights a year for mountain peaks (Figure 48).

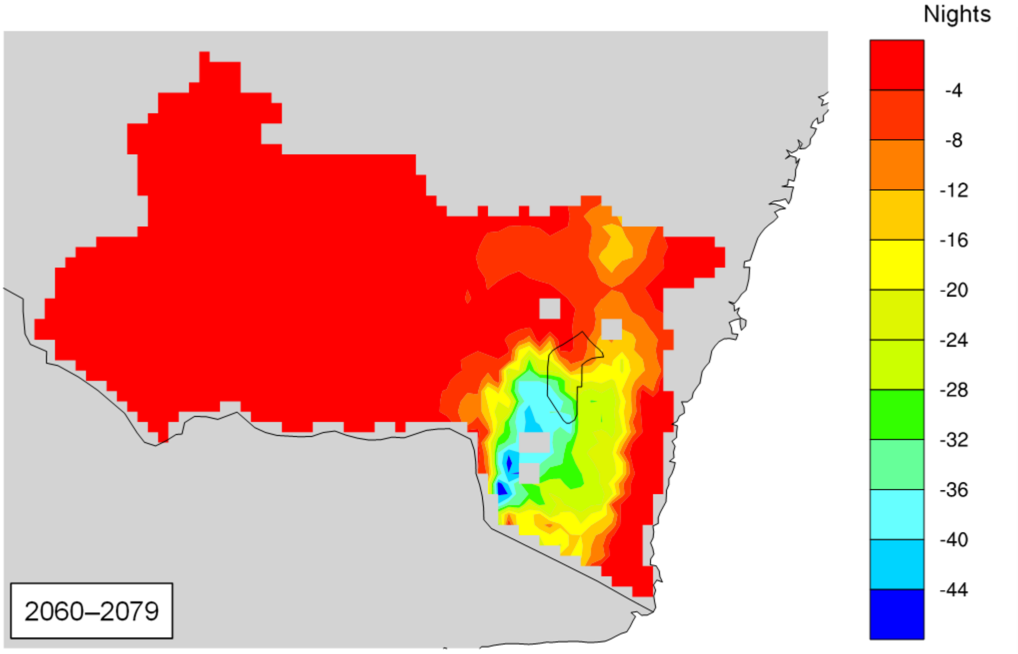

Figure 48 Changes in annual cold nights for 2060 to 2079 relative to 1990 to 2009

The largest reduction in cold nights is in winter when 20 fewer cold nights are projected for the Alpine region (Figure 49). Spring will have a more than 10-night reduction in some parts of the Alpine region.

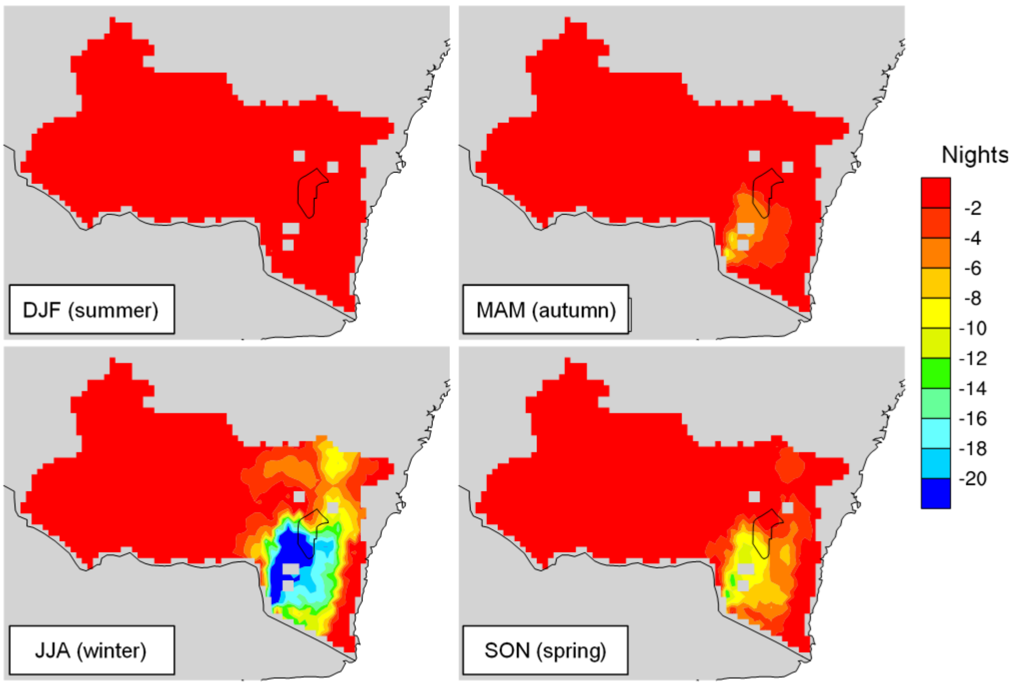

Figure 49 Changes in seasonal cold nights for 2060 to 2079 relative to 1990 to 2009

3.9 Mean wind speed

Mean wind speed for the 1990 to 2009 baseline period

The annual mean wind speed using the multi-model mean for the 1990 to 2009 period is shown in Figure 50. More than 8 m/s wind is seen in the Alpine region and 6–7 m/s for high topography areas in SET. Wind speed is generally small (less than 5 m/s) in the MM region as terrain is relatively flat.

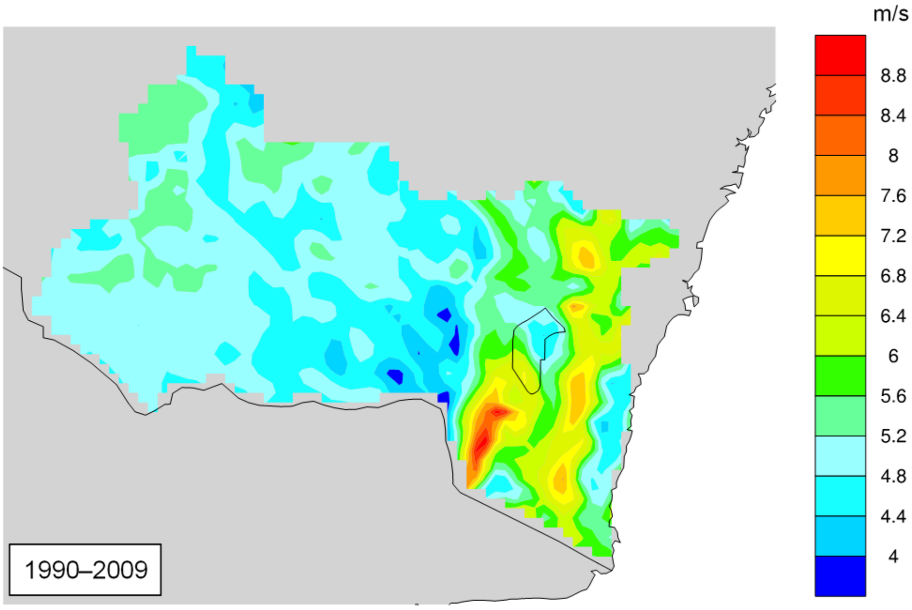

Figure 50 Simulated annual mean wind speed for 1990 to 2009

Seasonal variation in wind speed is seen for different areas (Figure 51). The MM region has higher wind speed in summer and spring compared to winter and autumn; however, the Alpine region and high topography areas in SET have much higher wind speed in winter and spring compared to summer and autumn. The seasonal variation in wind speed along the coast is very small.

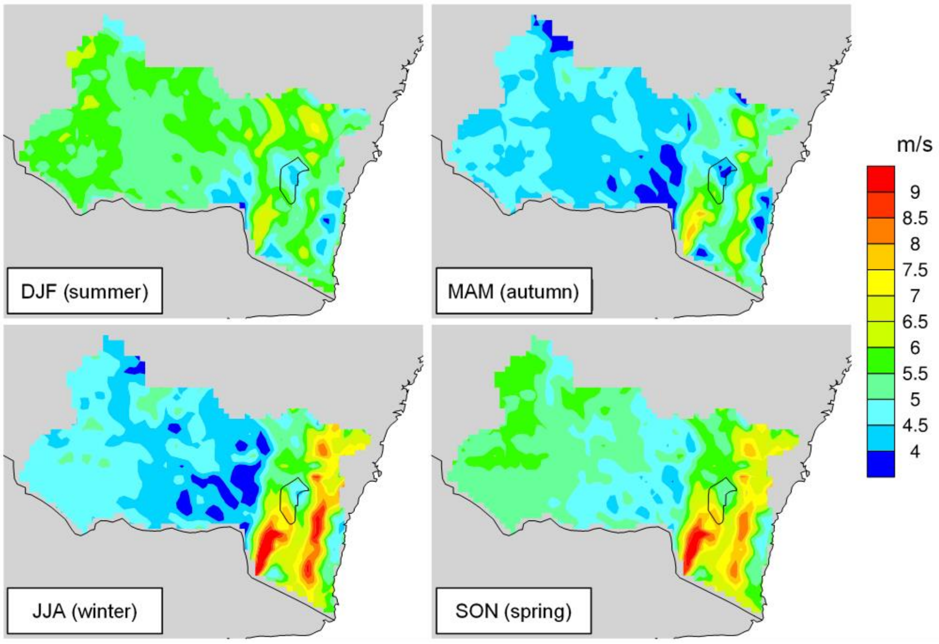

Figure 51 Simulated seasonal mean wind speed for 1990 to 2009

Changes in mean wind speed for 2020 to 2039

A less than 2% decrease in annual mean wind speed is projected for the study area except for the Alpine region and high topography areas in SET where a 2–4% decrease is simulated for 2020 to 2039 (Figure 52).

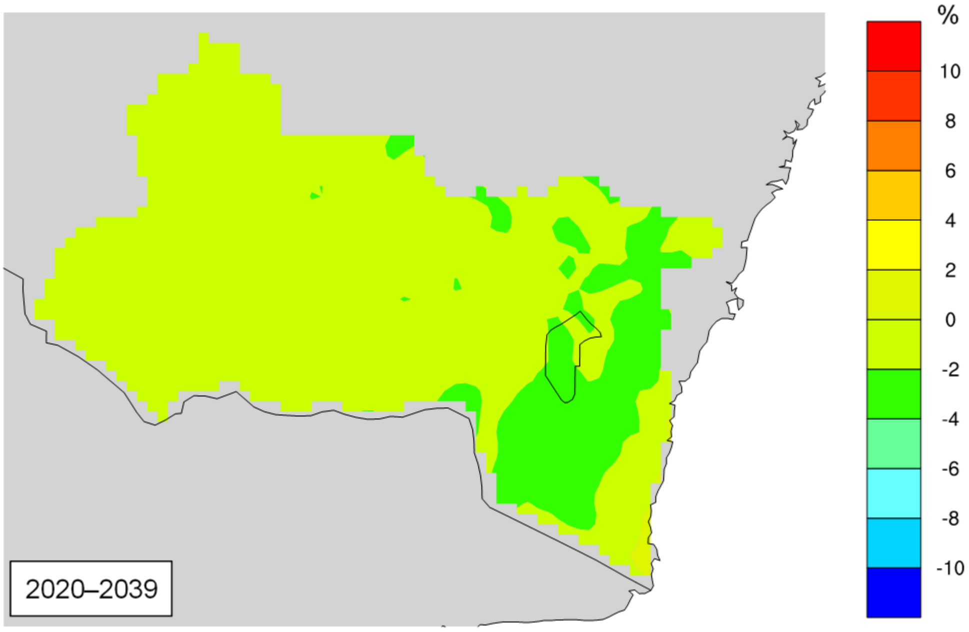

Figure 52 **Changes in annual mean wind speed (%) for 2020 to 2039 relative to 1990 to 2009**

Wind speed generally increases a little across all regions in summer and winter. During spring and autumn, wind speed decreases, especially for the Alpine region and high topography areas in SET, where a more than 4–6% decrease is expected in spring (Figure 53).

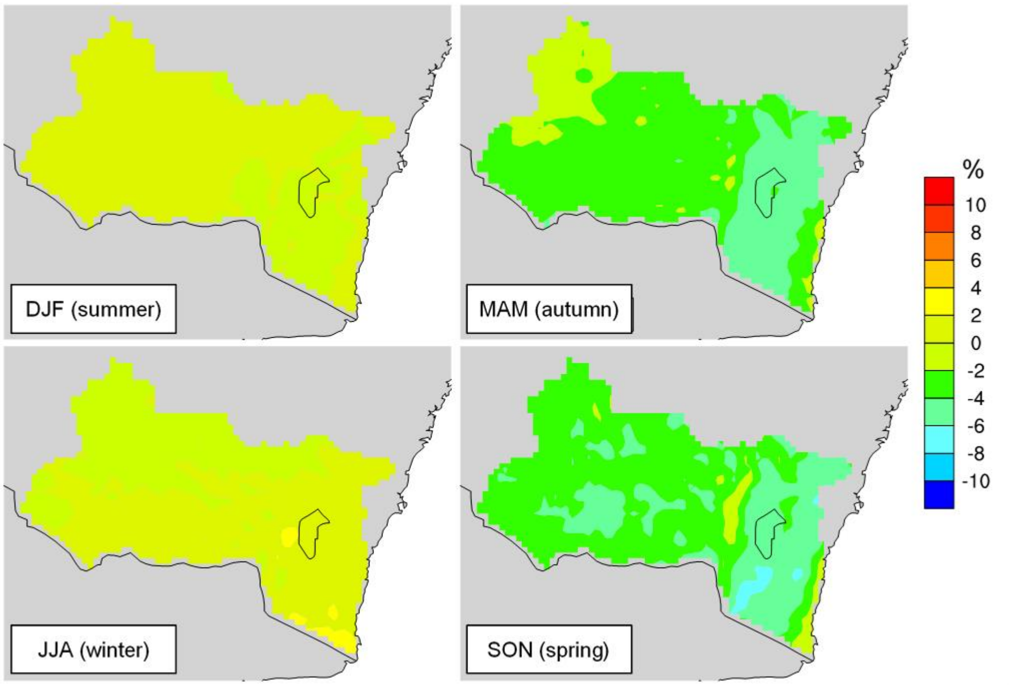

Figure 53 **Changes in seasonal mean wind speed (%) for 2020 to 2039 relative to 1990 to 2009**

Changes in mean wind speed for 2060 to 2079

Wind speed is projected to further decrease by the 2060 to 2079 period. Decreases of 4–6% are projected for most of the study region except for the south-east MM region and the coast where a 2–4% decrease is projected for 2060 to 2079 (Figure 54).

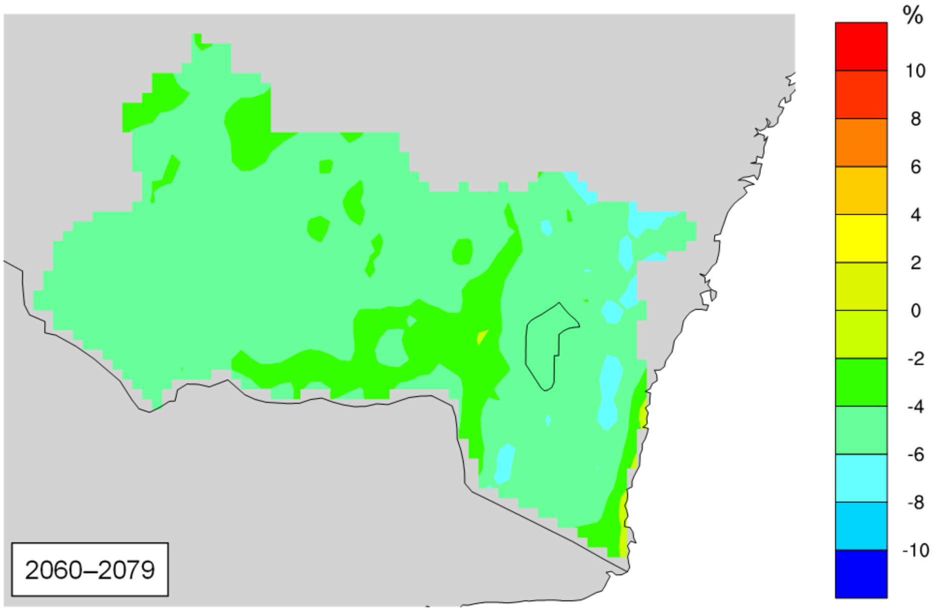

Figure 54 **Changes in annual mean wind speed (%) for 2060 to 2079 relative to 1990 to 2009**

Mean wind speed projected in summer and winter seasons shows little change relative to 1990 to 2009; however, it is projected to have a 6–8% decrease for the Alpine region and high topography areas and a 4–6% decrease for other areas in autumn (Figure 55). A larger decrease is projected for spring when a more than 8–10% decrease in mean wind speed is projected, especially for the Alpine region and high topography areas in SET, where a more than 10% decrease is expected.

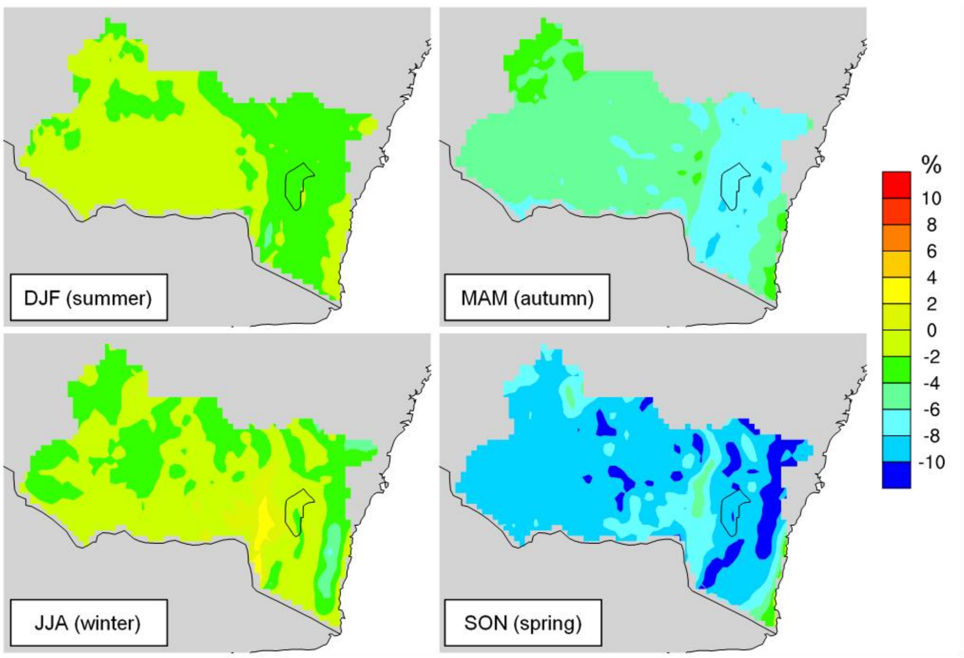

Figure 55 **Changes in seasonal mean wind speed (%) for 2060 to 2079 relative to 1990 to 2009**

3.10 Maximum daily wind speed

Mean maximum wind speed for the 1990 to 2009 baseline period

Maximum wind speed is also larger for the Alpine region and high topography areas in SET, especially for the Alpine region where more than 20 m/s maximum wind speed is simulated (Figure 56). The MM region and coastal areas generally have smaller maximum wind speeds.

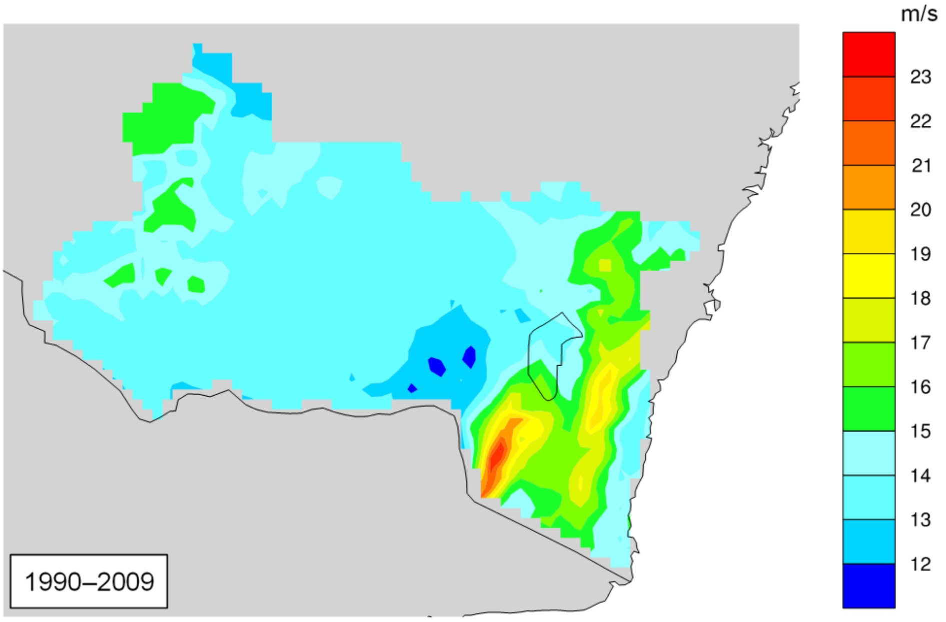

Figure 56 Annual mean maximum wind speed for 1990 to 2009

Maximum wind speed has similar seasonal variation to mean wind speed (Figure 57). Slightly larger maximum wind speed (14–16m/s) is simulated in spring and summer for the MM region. Much larger maximum wind speed (more than 22 m/s) is simulated in winter and spring for the Alpine region and high topography areas in SET relative to summer and autumn.

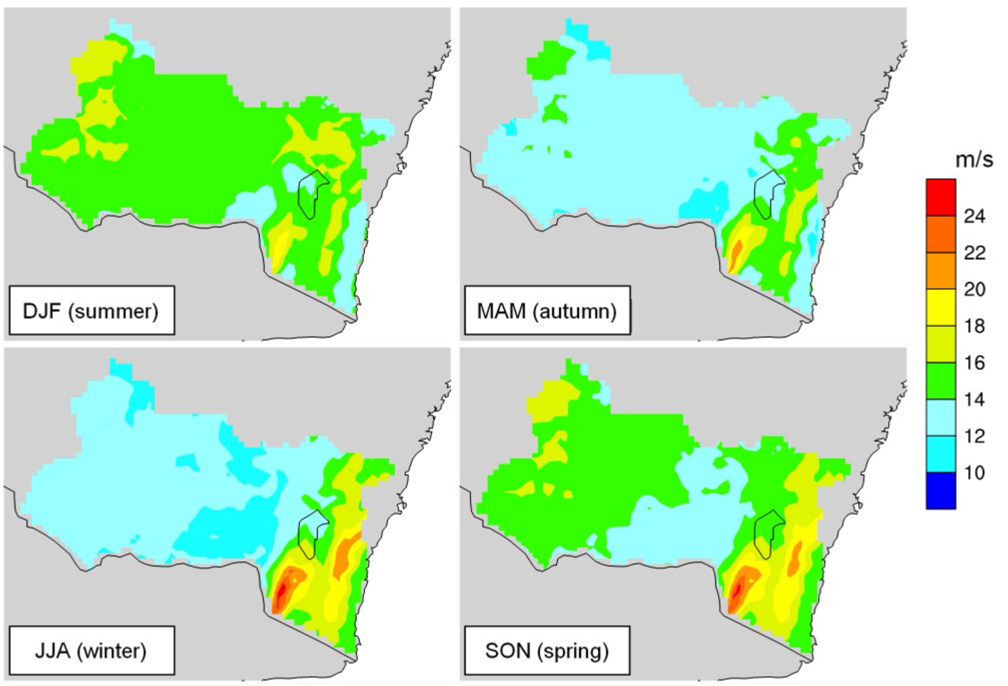

Figure 57 Seasonal mean maximum wind speed for 1990 to 2009

Changes in maximum wind speed for 2020 to 2039

Little change in maximum wind speed is projected for 2020 to 2039 (Figure 58). Overall, a less than 2% decrease in maximum wind speed is simulated for most of the study area, especially for the Alpine region where a slightly larger (2–4%) decrease is projected for some areas.

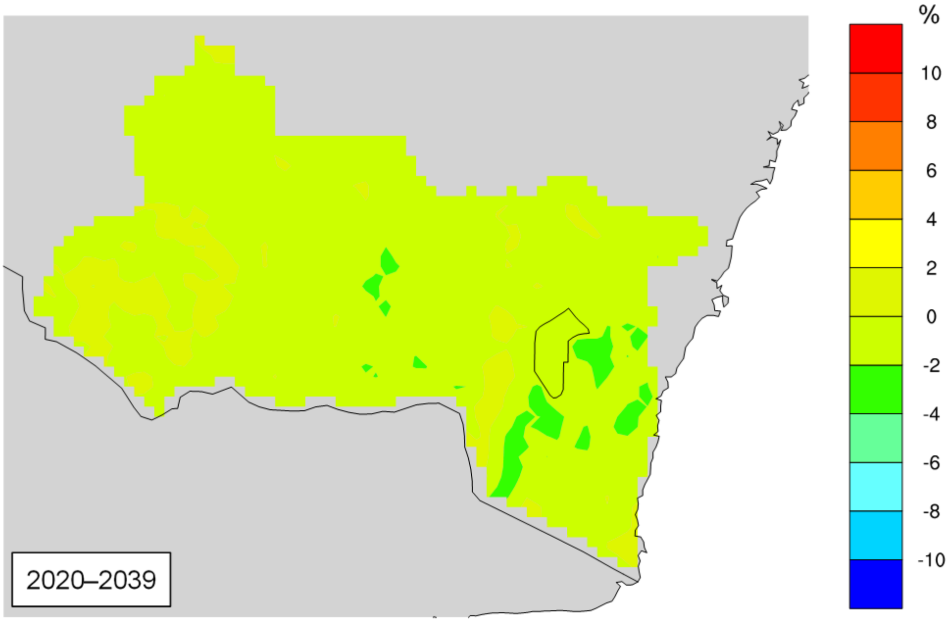

Figure 58 **Changes in annual mean maximum wind speed (%) for 2020 to 2039 relative to 1990 to 2009**

Small seasonal variations in changes in maximum wind speed are projected for 2020 to 2039 (Figure 59). Slightly larger variation is projected for the Alpine region, where a larger decrease is expected in spring and autumn, and a slight increase is projected for summer and winter.

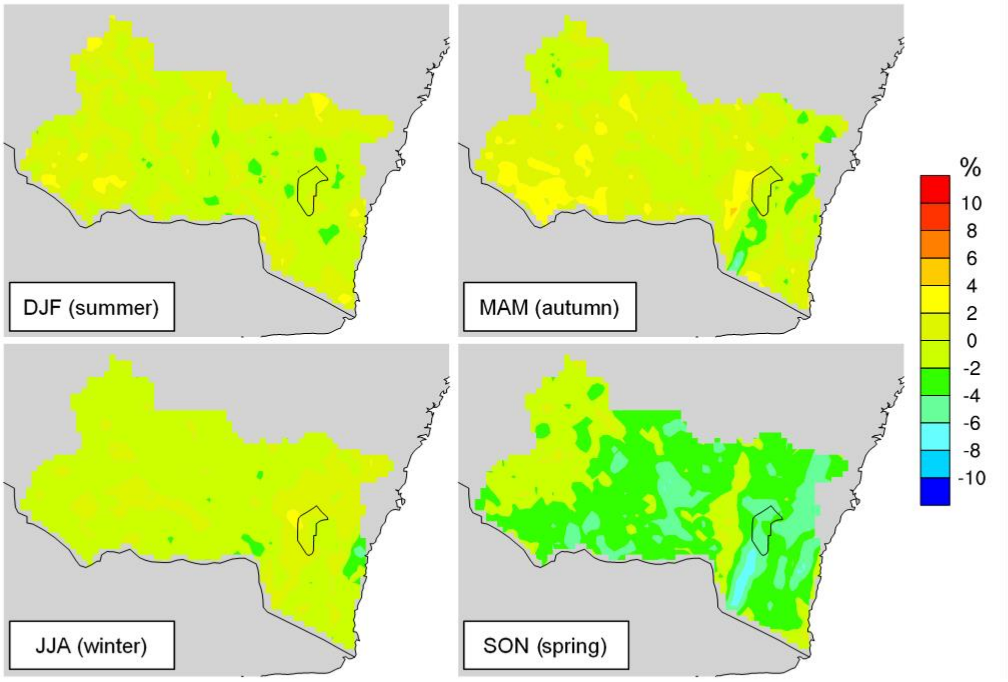

Figure 59 **Changes in seasonal mean maximum wind speed (%) for 2020 to 2039 relative to 1990 to 2009**

Changes in maximum wind speed for 2060 to 2079

Changes in maximum wind speed for 2060 to 2079 are similar to those projected for 2020 to 2039. The only difference is in changes of maximum wind speed for the Kosciuszko National Park, where a slightly larger decrease in maximum wind speed is projected (Figure 60).

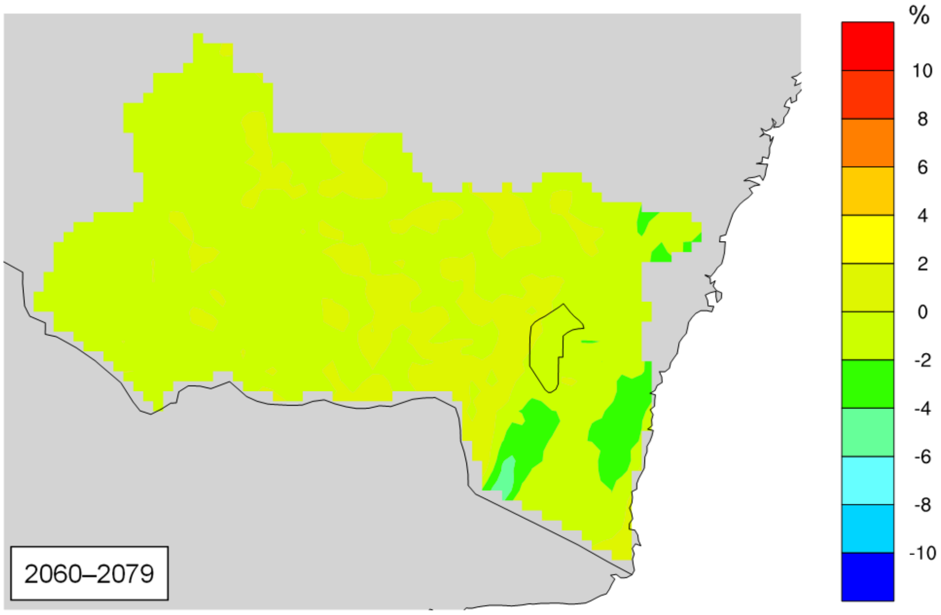

Figure 60 **Changes in annual mean maximum wind speed (%) for 2060 to 2079 relative to 1990 to 2009**

Seasonal variations in changes in maximum wind speed are slightly larger for 2060 to 2079 relative to the 2020 to 2039 period (Figure 61). Some increase in maximum wind speed is projected in the western and eastern MM region in summer and winter respectively; however, decreases will generally be expected for these areas. Relatively larger decreases can be seen in spring and autumn for the Alpine region.

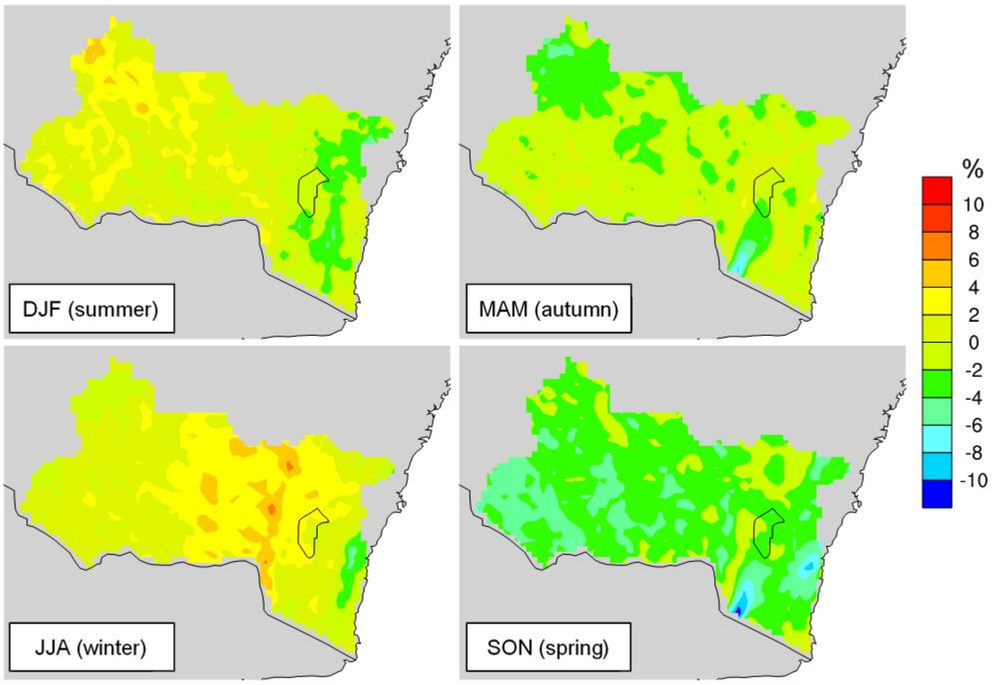

Figure 61 **Changes in seasonal mean maximum wind speed (%) for 2060 to 2079 relative to 1990 to 2009**

3.11 Strong wind days (max. wind speed above 13 m/s)

Mean number of strong wind days for the 1990 to 2009 baseline period

A daily maximum wind speed above 13 m/s is recorded as a strong wind day. It is apparent that strong wind days have a good correlation with the topography of the region. On average, there are more than 120 days a year with strong wind for the Alpine region and 60–80 days a year with strong wind for high topography areas in SET. Fewer than 30 days a year have strong wind for most of the MM region and the coastal region (Figure 62).

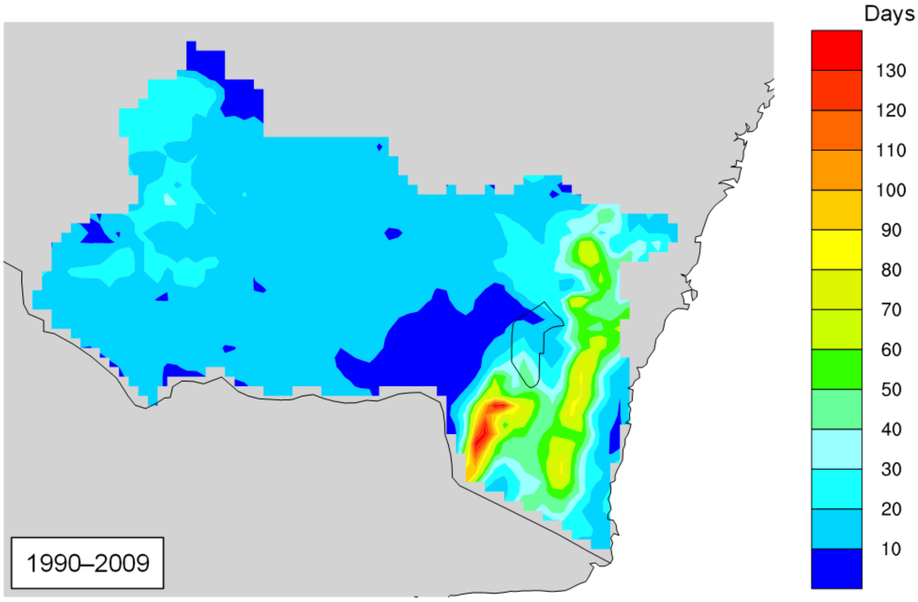

Figure 62 Annual strong wind days for 1990 to 2009

The MM region has a few days with strong wind in winter and autumn, with slightly more strong wind days in the other two seasons. Most of the strong wind days are in winter and spring for the Alpine region and high topography areas, where more than 50 and 20 days, respectively, have strong wind in winter, and more than 30 and 20 days in spring for the Alpine region and high topography areas in SET, respectively (Figure 63).

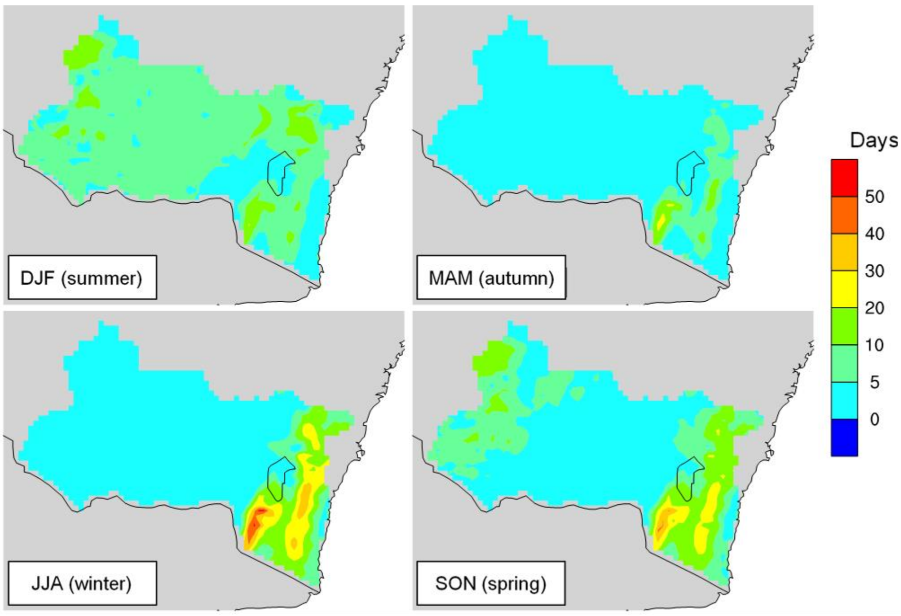

Figure 63 Seasonal strong wind days for 1990 to 2009

Changes in the number of strong wind days for 2020 to 2039

Changes in the number of strong wind days for 2020 to 2039 is very small (Figure 64). On average, about 2–3 more strong wind days are projected for the Alpine region and high topography areas in the SET region, with only around one additional strong wind day projected elsewhere.

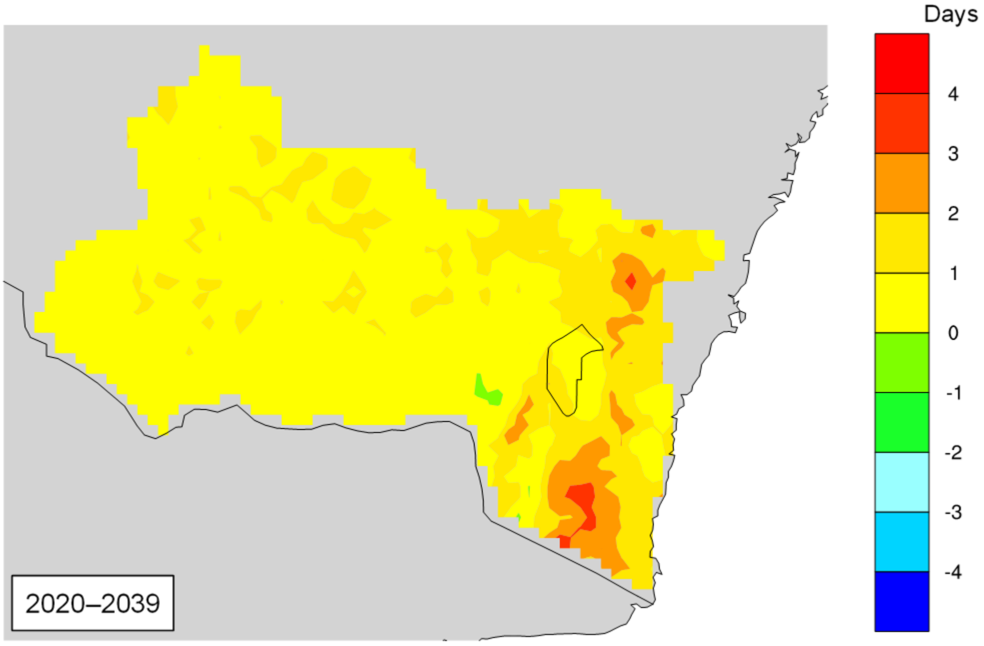

Figure 64 Changes in annual strong wind days for 2020 to 2039 relative to 1990 to 2009

Small increases (3–4 days a year) in strong wind days are mainly in winter for the Alpine region and high topography areas in SET (Figure 65), and small decreases (~1–2 days a year) are projected for the other three seasons in the same region. Almost no change is projected for other areas.

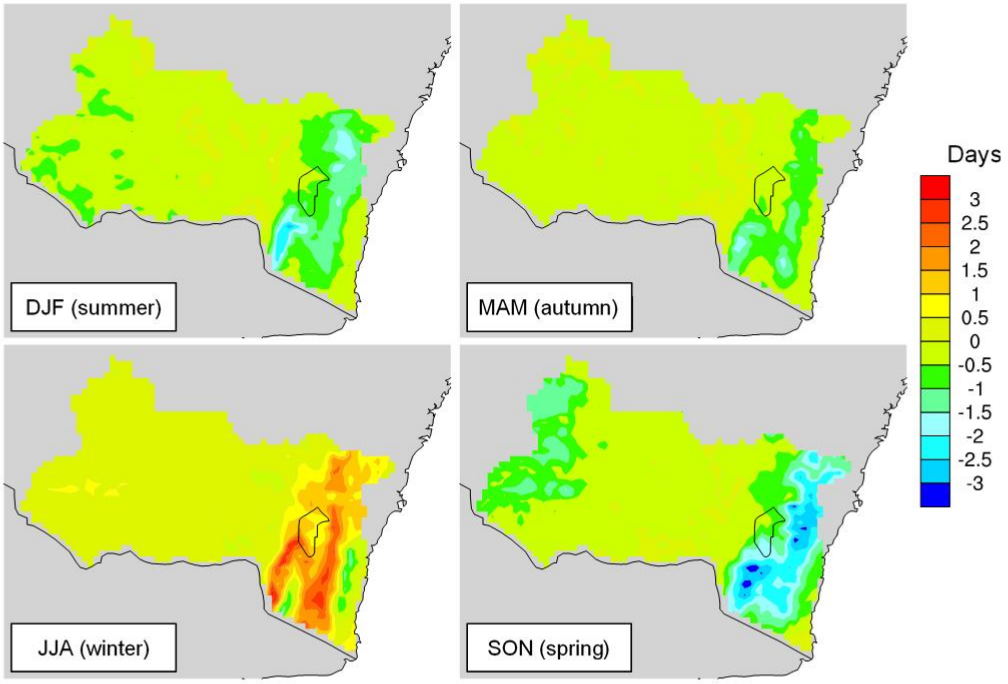

Figure 65 Changes in seasonal strong wind days for 2020 to 2039 relative to 1990 to 2009

Changes in the number of strong wind days for 2060 to 2079

A slight decrease in strong wind days is projected for most areas, especially for the Alpine region and high topography areas in the SET region, where 4–6 fewer strong wind days are expected in 2060 to 2079 (Figure 66). The smaller decrease is mostly in spring, summer, and autumn; however, a small increase is projected for winter for the whole study area, which is largest for areas of high topography (Figure 67).

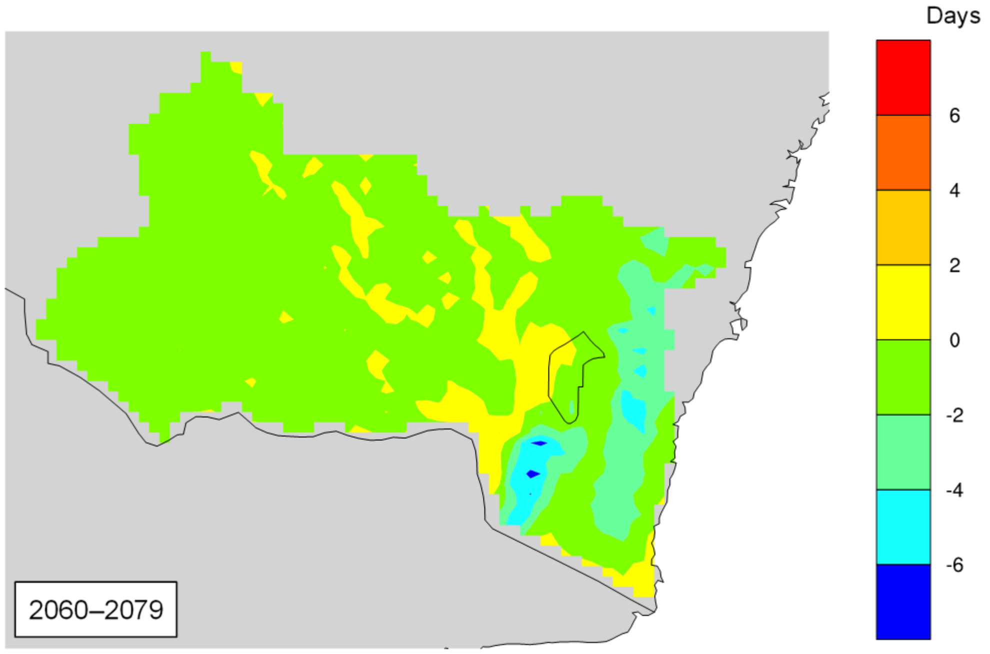

Figure 66 **Changes in annual strong wind days for 2060 to 2079 relative to 1990 to 2009**

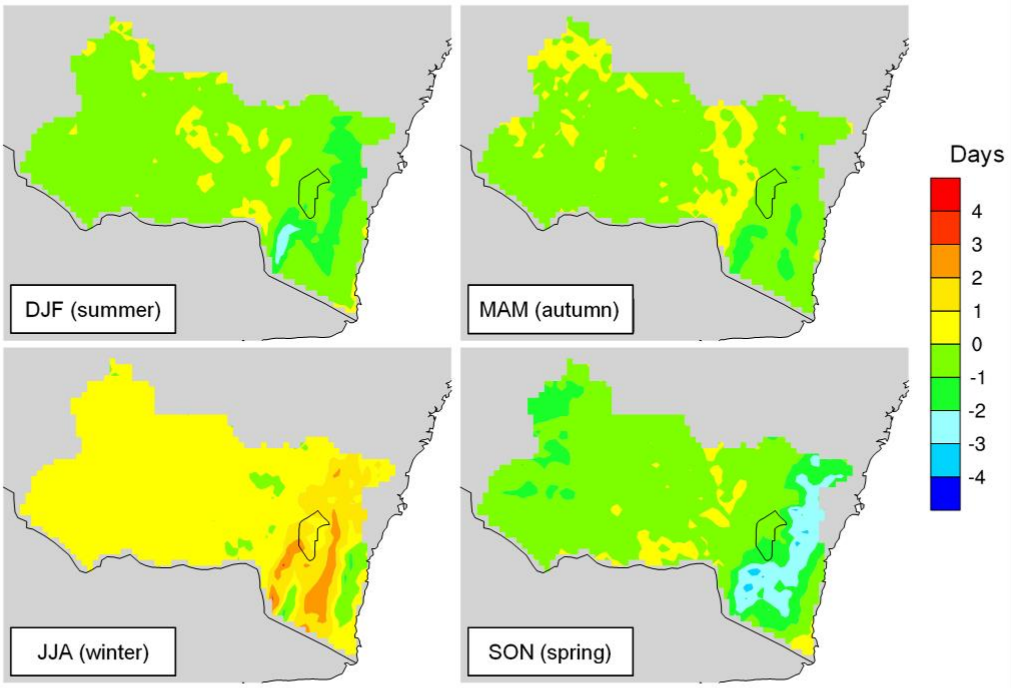

Figure 67 **Changes in seasonal strong wind days for 2060 to 2079 relative to 1990 to 2009**

3.12 Gale days (maximum wind speed above 17 m/s)

Mean number of gale days for the 1990 to 2009 baseline period

Like strong wind days, gale days mostly occur in the Alpine region and high topography areas in the SET region. More than 50 gale days a year are simulated for the Alpine region and more than 20 gale days are simulated for the SET region, with almost no gale days elsewhere (Figure 68). Though gale days can occur at any time, most occur during winter and spring (Figure 69).

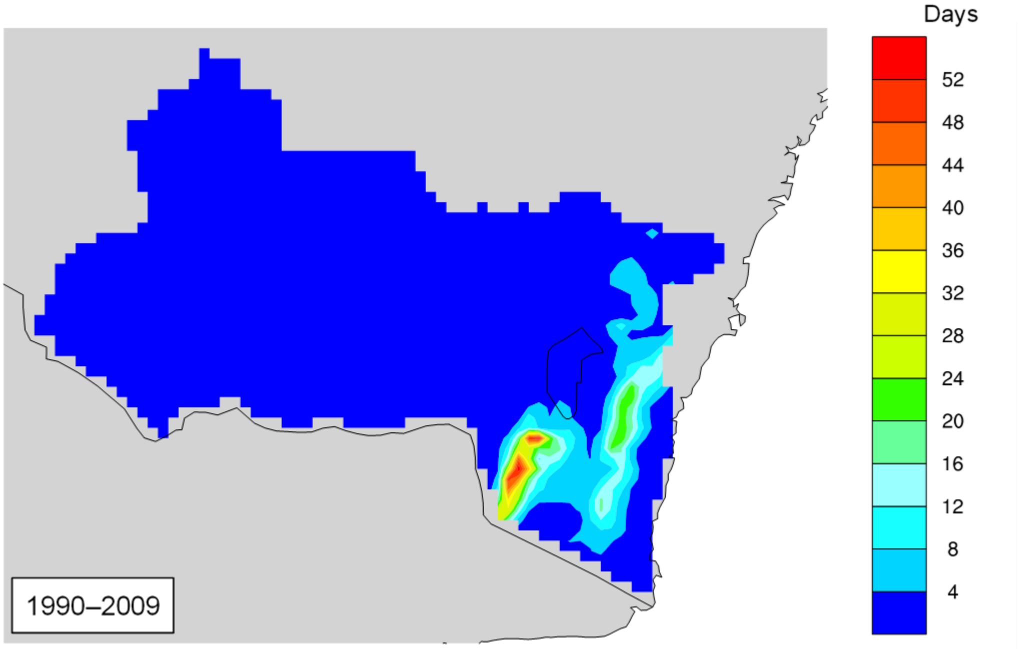

Figure 68 **Annual gale days for 1990 to 2009**

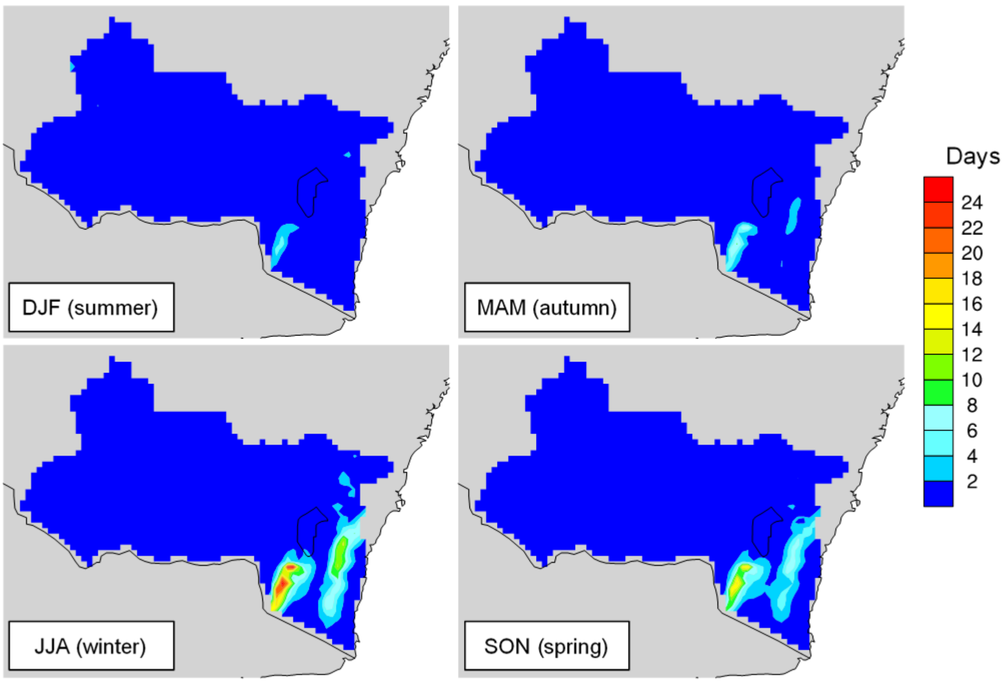

Figure 69 **Seasonal gale days for 1990 to 2009**

Change in the number of gale days for 2020 to 2039

A few more gale days are projected for the Alpine region and high topography areas in the SET region, with almost no changes in other areas for 2020 to 2039 (Figure 70). The few small increases are mostly in winter, with no change in the other seasons (Figure 71).

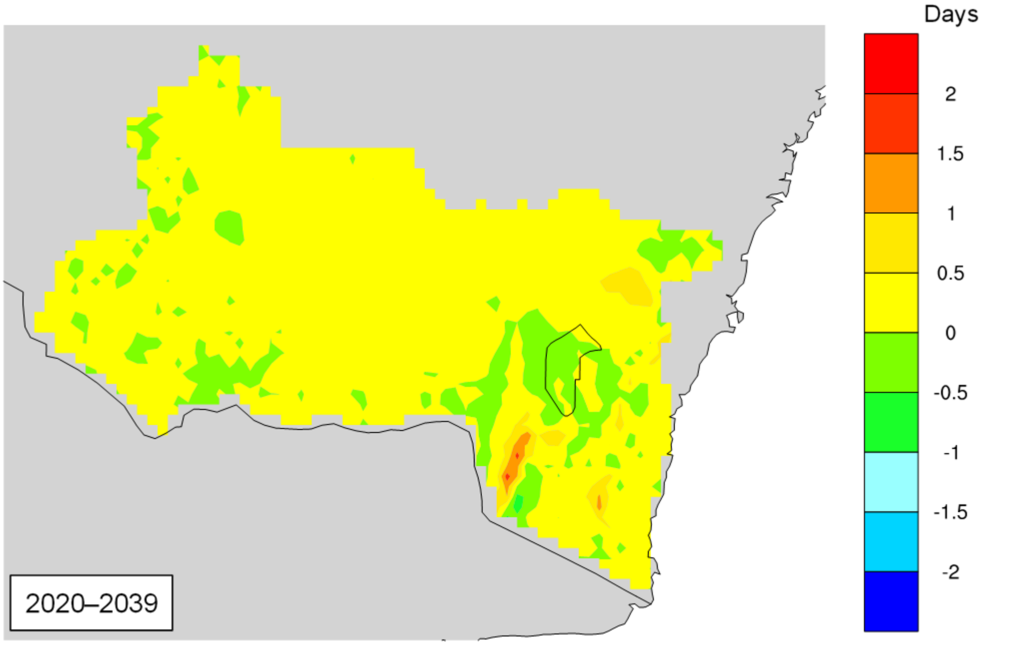

Figure 70 Changes in annual gale days for 2020 to 2039 relative to 1990 to 2009

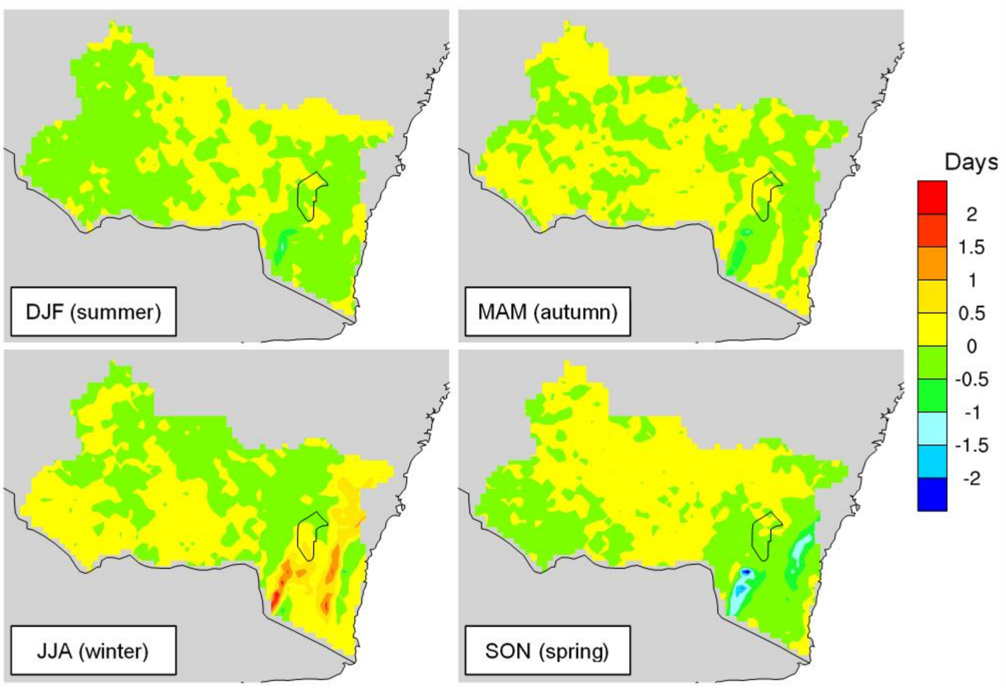

Figure 71 Changes in seasonal gale days for 2020 to 2039 relative to 1990 to 2009

Change in the number of gale days for 2060 to 2079

Similar to 2020 to 2039, there is little change in the number of gale days for 2060 to 2079, with 2–4 fewer gale days a year projected at the top of the Alpine region (Figure 72). Projected decreases in the number of gale days are mostly in winter, with almost no change in the other seasons (Figure 73).

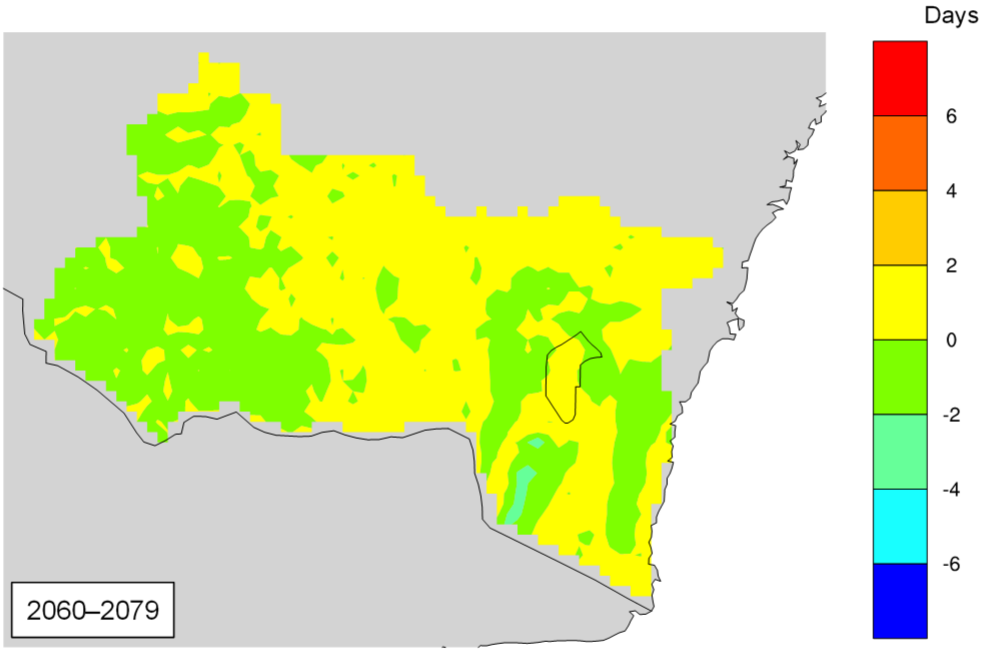

Figure 72 Changes in annual gale days for 2060 to 2079 relative to 1990 to 2009

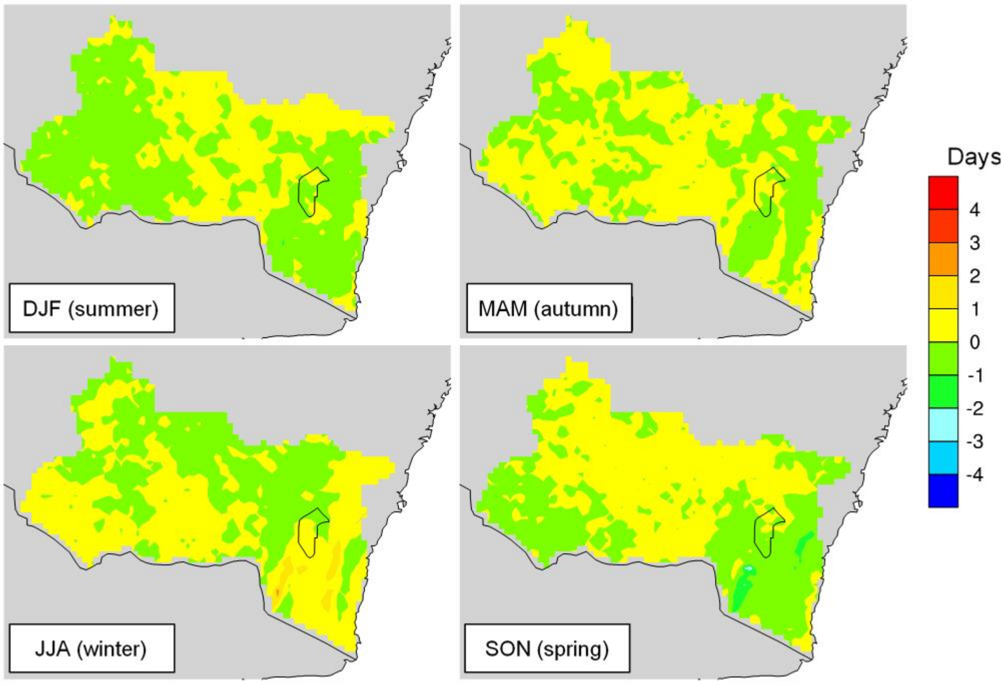

Figure 73 Changes in seasonal gale days for 2060 to 2079 relative to 1990 to 2009

4. Discussion

4.1 Key findings

The results of this report show a number of changes that are projected for the Alpine region and surrounding areas, including changes in precipitation, temperature and wind. The overall key findings indicate:

- The Alpine region will become drier in the future due to a large reduction in precipitation in spring; however, other areas are getting wetter due to more precipitation in summer, winter and autumn.
- The Alpine region will have fewer moderate and heavy rainfall events, which is the opposite of other regions; however, more dry days are expected in the future for all regions.
- Greater increases in maximum temperature are projected for the Alpine region compared with other regions, with the greatest increase occurring in winter. There are no major differences in increases in minimum temperature between the different regions.
- More hot days and fewer cold nights are projected for the MM region and Alpine region, respectively. The greatest of these increases and decreases are in summer and winter respectively; however, spring will also have more hot days and fewer cold nights.
- Mean and maximum wind speed will decrease, mostly in spring; however, little change in strong wind days and gale days are projected for the future.

4.2 Limitations and further research

NARCliM data has its limitations, such as using an older generation CMIP ensemble (i.e. CMIP3), being at a relatively coarse resolution, having limited ensemble members and having only short time periods for analysis.

Only daily rainfall and temperature were bias-corrected on the annual base. Available evaluation (Liu et al. 2018) showed that seasonal or monthly biases are relatively larger even if annual biases are quite small. This has some impacts on threshold-specific variables such as heavy rainfall days, hot days and cold nights.

Results presented in the report are based on the multi-model mean. The same weight was used for each of the 12 GCM/RCM ensemble members. Four GCMs were selected to represent the CMIP3 ensemble. A selected GCM represents different numbers of GCMs in the CMIP3 ensemble. We should consider giving a different weight to each GCM according to the number of GCMs in the ensemble it represents. We should also consider the simulation performance to adjust the weight factor.

Given the short duration of the project, we did not look at the statistical significance and model agreement. This should be assessed in further research.

5. Conclusion

NARCliM post-processed variables and bias-corrected rainfall and temperature data are used in this study. Results for the multi-model mean, rather than each individual ensemble member, are presented. The results show:

- In the far future, a 2–3°C increase in temperature is projected across the study area. The greatest projected increase in maximum temperature is in the Alpine region during winter, when a more than 3°C increase is expected.
- Less rainfall is projected for the Alpine region in the far future; however, more rainfall is projected for other regions. The reduction in rainfall is mostly due to decreases in spring precipitation, with the increases in rainfall mostly projected to occur in the summer, winter and autumn months.
- More extensive rainfall events are projected for the study area, except for the Alpine region. More dry days are projected across the entire study area.
- Along with larger increases in temperature, more hot days and fewer cold nights are expected in the future.
- Mean and maximum wind speed will decrease; however, little change to the number of strong wind days and gale days is expected in the far future.

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