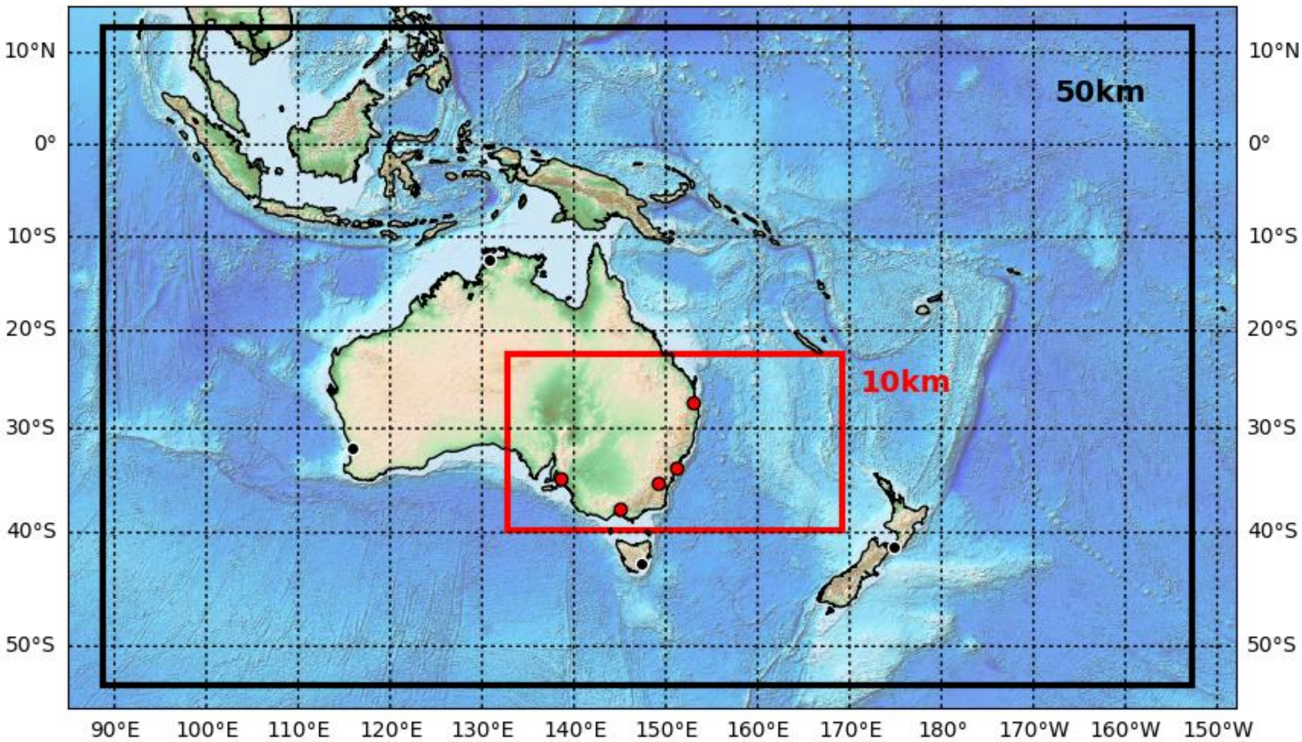
DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

The NSW and ACT Regional Climate Modelling Project: Climate Projections Version 1.5

NARCliM1.5 Technical Methods Report



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Cover photo: NARCliM domains map developed by DPIE

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Contents

List of tables

List of figures

Abbreviations and acronyms

Abbreviation	Meaning
ACT	Australian Capital Territory
AGCD	Australian Gridded Climate Data
AWAP	Australian Water Availability Project, Commonwealth Science and Industry Research Organisation (CSIRO)
CF	Climate and forecast
CMIP	Coupled Model Inter-comparison Project
COP	Conference of Parties
CORDEX	Coordinated Regional Climate Downscaling Experiment
CSV, NetCDF, GeoTIFF	File formats
DPIE, the Department	Department of Planning, Industry and Environment
ENES	European Network for Earth System Modelling
ENSO	El Niño-Southern Oscillation
GCM	Global climate models
ICT	Information and Communication Technology
IOD	Indian Ocean Dipole
IPCC AR5	IPCC Assessment Report version number, e.g AR5 is the IPCC *Fifth Assessment Report*
NARCliM	NSW and ACT Regional Climate Modelling
NCEP	National Centers for Environmental Predictions
NCI	National Computational Infrastructure
NSW	New South Wales
QA	Quality assurance
QC	Quality control
RCM	Regional climate models
RCP	Representative concentration pathways
SDC	Science Data Compute
SRES	Special Report on Emission Scenarios
WP	Western Pacific
WRF	Weather Research and Forecasting Model

Technical summary

Through the Climate Change Fund 2018–2022 program, the Science, Economics and Insights Division of the Department of Planning, Industry and Environment (the Department) is focusing on enhancing and updating regional climate projections for New South Wales (NSW), determining the role of climate change on natural hazards, and assessing climate impacts on critical infrastructure.

The NSW Government's major regional climate projections dataset is the NSW and ACT Regional Climate Modelling (NARCliM) Project which was first released in 2014 (now named 'NARCliM1.0'). This technical methods report details the enhancement of the NARCliM1.0 dataset to produce the next iteration of regional climate projections, 'NARCliM1.5.' The NSW and ACT Regional Climate Modelling (NARCliM) Project is a research partnership between the NSW and ACT governments and the Climate Change Research Centre at the University of NSW. The NSW partners included Sydney Water, Sydney Catchment Authority, Hunter Water, NSW Department of Transport, NSW Department of Primary Industry and NSW Office of Water.The Department partnered with the University of New South Wales for the NARCliM project. UNSW was the primary modeller for NARCliM1.0. NARCliM1.5 on the otherhand was co-modelled with the Department. The Department sought the support of and engaged with the ACT Government and other NSW Government agencies in the design and review of NARCliM1.0; and NARCliM1.5 built off of these engagements and knowledge insights. The technical specifications of NARCliM1.0 and NARCliM1.5 are summarised in Table 1.

This report, together with the NARCliM1.5 Quality Assurance Report, are intended to present process and procedural details for developing NARCliM1.5 and assuring its quality.

Table 1 Primary differences between NARCliM1.0 and NARCliM1.5

Configuration	NARCliM1.0	NARCliM1.5
Release date	2014	2020
No. combinations	12	6
Years simulated	1990 to 2009, 2020 to 2039, 2060 to 2079	1951 to 2100
Grid resolution of Australasia and NARCliM domains	50 km and 10 km	50 km and 10 km
Global climate models	4 CMIP3 models: CGCM3.1, CSIRO-Mk3.0, ECHAM5, MIROC3.2	3 CMIP5 models: ACCESS1.3, ACCESS1.0, CanESM2
Regional climate models	3 RCMs per GCM (WRF3.3)	2 RCMs used in NARCliM1.0 (WRF3.6.0.5)
Future emission scenarios	SRES A2	RCP4.5 and RCP8.5
Reanalysis-driven simulations	NCEP: 1950 to 2009	ERA-Interim: 1979 to 2013

1. Refers to the global and regional climate model combinations, e.g. 'ACCESS1.0 forcing and WRF configuration 1'.

NARCliM1.0

Released by the Department in 2014, the original NARCliM1.0 project outputs are an ensemble of 12 global-regional climate model combinations. Four Coupled Model Inter-comparison Project phase 3 (CMIP3) global climate models (GCMs) were 'dynamically downscaled' to finer spatial and temporal scales using three regional climate models (RCMs). *Dynamical downscaling* is a climate modelling technique where a model (a RCM) uses physical principles to determine how the climate system behaves over a particular region of the globe. RCMs rely on input data from GCMs at their boundaries to perform this dynamical downscaling. This is different to *statistical downscaling* which relies on developing statistical relationships between large-scale and regional climates and applying these relationships to GCM output to develop more regionally specific data.

Three 20-periods were simulated:

1. recent past (1990 to 2009)
2. near future (2020 to 2039)
3. far future (2060 to 2079).

To quantify the RCMs' capability to simulate observed regional climate over south-east Australia, three National Centers for Environmental Predictions (NCEP) reanalysis (Kalnay et al. 1996) forced simulations were run for 1950 to 2009. In addition, finer dynamical downscaling to 2 kilometres over Sydney (Argüeso et al. 2015) and statistical downscaling to 250 metres and 1 kilometre resolution (Hutchinson & Xu 2015) were developed. The NARCliM1.0 dataset is freely available via the NSW Government's Climate Data Portal (with a new website being developed) and by request.

The selection process for GCMs and RCMs used in NARCliM1.0 is to provide a spread in model output as a measure of uncertainty in climate projections. Outputs from GCMs are used as initial and boundary conditions in the RCMs. After an extensive literature review, GCMs were selected based on their overall performance in representing large-scale climate phenomena (e.g. El Niño patterns) and climate variability in widely used metrics (e.g. rainfall and temperature). Poor-performing GCMs were excluded and those remaining were ranked for independence. The independence ranking was then combined with that for GCMs, which provided a spread in temperature and rainfall projections for south-east Australia. The *Special Report on Emission Scenarios* A2 (SRES A2, IPCC 2000) future emissions scenario was chosen. SRES A2 reflects the 'business-as-usual' scenario in CMIP3 and, at the time of development, best illustrated the assumptions about how global emissions were tracking.

The RCMs chosen for NARCliM1.0 are three variations of the Weather Research and Forecasting (WRF) model. The three RCMs differ by their parameterisations of the planetary boundary layer, land surface and cumulus physics, micro physics, and short- and long-wave radiation physics. The three RCMs were selected from 36 combinations of physics schemes, ranked on their distinct ability to capture temperature, precipitation, mean sea-level pressure and winds, as well as their statistical independence.

The model output from the NARCliM1.0 twelve-member ensemble was processed into two-dimensional files compliant with the Coordinated Regional Climate Downscaling Experiment (CORDEX, Giorgi et al. 2009) convention for temporal resolutions from sub-daily to seasonal. The post-processed data was then interpolated onto a regular latitude-longitude grid from the native rotated pole grid that WRF uses. Temperature and precipitation outputs were then bias-corrected (Evans & Argüeso 2014), which is important for assessing thresholds in the climate system. NARCliM1.0 data are produced in NetCDF format, however the Climate Data Portal also offers data in CSV and GeoTIFF. The methodology and evaluation of NARCliM1.0 is described in detail via several journal papers and technical notes that can be found on the University of NSW's Climate Change Research Centre's NARCliM publications webpage.

The NARCliM1.0 models were simulated on the National Computational Infrastructure (NCI) supercomputing facility in Canberra. The CORDEX 50-kilometre and NARCliM 10-kilometre domains are run together in a one-way nesting set-up. The NARCliM1.0 NetCDF files contain metadata on the spatial and temporal dimensions of the data and the model configuration of the relevant NARCliM1.0 ensemble member. NARCliM1.0 raw and post-processed datasets are stored and backed-up at the Science Data Compute (SDC) facility. The Department has developed a data management plan that includes the systematic data storage facilities and ICT infrastructure, the scheduled transfer of data files between supercomputing facilities and SDC (i.e. between NCI and the Department via Australia's Academic and Research Network at AARNet), and a robust filename structure for the NARCliM1.0 data.

Since the release of NARCliM1.0, the Department has held end-user needs workshops, face-to-face meetings and developed surveys for key stakeholders to obtain feedback on the usability and accessibility of NARCliM1.0. This stakeholder engagement was accompanied by an independent evaluation of the NARCliM1.0 project technical approach and experimental design [internal report], and independent reviews and recommendations for enhanced data delivery services and software and ICT infrastructure. The main feedback from users was the need for:

- more easily accessible datasets
- continuous data throughout the 21st century
- the latest generation of GCMs to be used
- multiple future emission scenarios
- higher resolution simulations

The Department has addressed the majority of these needs through the delivery of NARCliM1.5.

NARCliM1.5

NARCliM1.5 is comprised of six regional climate projections that continuously span the period from 1951 to 2100 under two future emission scenarios. NARCliM1.5 consists of three CMIP5 GCMs (ACCESS1.0, ACCESS1.3 and CanESM2) downscaled using two WRF RCMs used in NARCliM1.0. CMIP5 uses emissions scenarios called 'representative concentration pathways' (RCPs) and NARCliM1.5 uses both RCP4.5 and RCP8.5. These scenarios reflect a medium level of mitigation and a business-as-usual approach, respectively. RCP8.5 is most comparable to the SRES A2 scenario used in NARCliM1.0.

The six projections are available in two resolutions: 50-kilometre (the Australasia CORDEX domain) and 10-kilometre (the south-east Australian NARCliM domain). The 50-kilometre and 10-kilometre domains are the same as NARCliM1.0. The third RCM from NARCliM1.0 was excluded due to unsatisfactory performance.

The GCMs used in NARCliM1.5 were selected following a similar evaluation and ranking process used for NARCliM1.0. An additional selection step was employed ensuring the CMIP5 GCMs complemented the CMIP3 GCMs that were used in NARCliM1.0. This means that NARCliM1.5 GCMs add to the spread of projections of temperature and precipitation in south-east Australia first presented in NARCliM1.0. Therefore, the full suite of NARCliM projections provides a range of projections, and NARCliM1.5 is not meant to be a replacement for NARCliM1.0 (see Section 3, Figure 2).

NARCliM1.5 was run on the supercomputing facilities at NCI and the Pawsey Supercomputing Centre in Perth, Western Australia. After quality assurance – quality control (QAQC) and data post-processing was undertaken, the NARCliM1.5 dataset, which is approximately 1.5 petabytes in size, was transferred to the Science Data Compute (SDC) data facility.

1. Introduction

This technical report details the experimental design of NARCliM1.5 and the associated GCM and RCM model selection, post-processing, bias correction, QAQC procedures and data dissemination.

2. Experimental design

The NARCliM1.5 experimental design focused on addressing user needs based on stakeholder workshops, face-to-face discussions and an independent evaluation of NARCliM1.0 [internal report]. A summary of suggested improvements from technical user workshops for the NARCliM1.5 experimental design are described in Table 2. Some suggestions are addressed in NARCliM1.5, however most will be addressed in the next iteration of NARCliM.

Table 2 Key feedback and actions provided by technical users of NARCliM1.0

Suggested improvement	DPIE actions to date
Use the next generation of CMIP GCMs	NARCliM1.5 uses CMIP5 GCMs; NARCliM2.0 will use CMIP6 GCMs
Provide continuous simulations of past and future climate (rather than three 20-year periods like NARCliM1.0)	NARCliM1.5 projections continuously span 150 years (1951 to 2100)
Simulate the future climate under multiple climate scenarios	NARCliM1.5 has projections for two scenarios: RCP4.5 and RCP8.5
Increase spatial grid resolution to better capture local changes (e.g. metropolitan regions)	Not addressed in NARCliM1.5; will be addressed in NARCliM2.0
Undertake more sophisticated methods of GCM selection	Not addressed in NARCliM1.5; will be addressed in NARCliM2.0
Improve atmospheric and land parameterisations in the RCMs	Not addressed in NARCliM1.5; will be addressed in NARCliM2.0
Incorporate a regional three-dimensional ocean model	Not addressed in NARCliM1.5; optimal in NARCliM2.0
Provide more global climate model ensemble members to reduce risk and uncertainty in climate projections	Not addressed in NARCliM1.5; will be addressed in NARCliM2.0
Introduce bias corrections in the GCMs prior to the running of downscaled regional climate projections	Not addressed in NARCliM1.5; optimal in NARCliM2.0
Incorporate local land usage knowledge into the RCMs	Not addressed in NARCliM1.5; optimal in NARCliM2.0

The finalised NARCliM1.5 experimental design is as follows:

- three GCMs from CMIP5 that had been robustly evaluated in the scientific literature
- two RCMs of the same WRF configuration as NARCliM1.0 (Note: All three RCM configurations from NARCliM1.0 were planned to be used in NARCliM1.5, however, the third RCM configuration performed significantly below expectations and thus has not been released)
- 10-kilometre and 50-kilometre domains, like NARCliM1.0

- continuous simulations that cover the period from when anthropogenic climate change signals rapidly increased, up to the end of the 21st century (i.e. 1951 to 2100)
- two widely available future representative concentration pathways (RCP4.5 and RCP8.5)
- adherence to international regional climate modelling guidelines (CORDEX).

The details of model evaluation and selection is presented in the next section.

Future emission scenario selection

NARCliM1.5 provided an opportunity to use the CMIP5 GCMs whichtake a different approach to future emissions scenarios than were taken by CMIP3 GCMs. The NARCliM1.5 CMIP5 GCMs are associated with the IPCC *Fifth Assessment Report* (IPCC AR5, IPCC 2014), whereas the NARCliM1.0 CMIP3 GCMs are associated with IPCC AR4 (IPCC 2007). CMIP3 and CMIP5 have different types of future emission scenarios. The RCPs in CMIP5 focus on identifying and quantifying changes in the physical forcing to global climate resulting from combinations of socio-economic, technological and environmental reasons; whereas the storylines in the *Special Report on Emission Scenarios* (SRES, IPCC 2000) focus on identifying changes associated with policy, mitigation and socio-economic projections, and the resulting enhanced greenhouse gas concentrations imposed to the GCMs. The two future pathway types and their respective ranges of projected future warming are illustrated in Figure 1. NARCliM1.0 projects climate using the SRES A2 (high greenhouse gas emissions) future pathway (left; red line). NARCliM1.5 projects the RCP4.5 (moderate cuts to greenhouse gas emissions) and RCP8.5 (high greenhouse gas emissions with no/minimal policy changes) pathways (right; light blue and red lines, respectively).

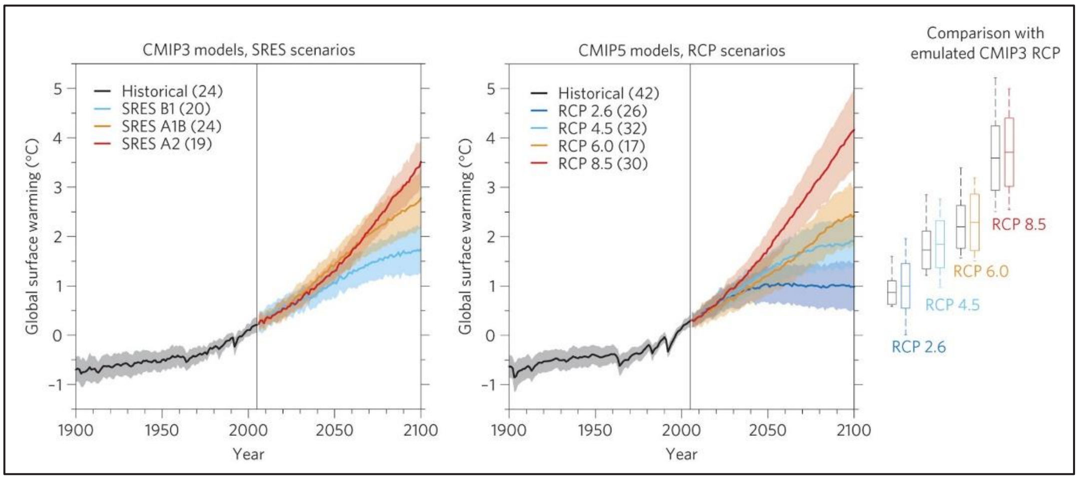

Figure 1 **SRES (left) and RCP (right) future pathways from the CMIP3 and CMIP5 models, respectively.** (**Source: Knutti & Sedláček 2013)**

The SRES are future greenhouse gas emissions associated with combinations of economic, global, regional and environmental factors. The SRES does not incorporate mitigation strategies that would lead to reduced climate change impacts. Conversely, the RCPs are the greenhouse gas emissions that are required to support an increase in total radiative forcing of 2.6, 4.5, 6.0 or 8.5 watts per square metre (W m^{-2}) at the year 2100 (Moss et al. 2010). The RCPs are based on specific combinations of socio-economic status, population growth, technological development, etc. and may be any combination of these. Instead, these details in the scenarios were analysed through the integrated assessment models in parallel with the climate model simulations (van Vuuren et al. 2011). RCP2.6 to RCP8.5 span a global temperature increase of 0.9 to 5.4°C by 2100.

The SRES A2 and RCP8.5 pathways are both considered 'high emissions scenarios' (i.e. no mitigation or policies in place to reduce greenhouse gas emissions). RCP4.5 is a medium-emission scenario, with some mitigation in place. Neither NARCliM1.0 nor NARCliM1.5 include a low emission scenario similar to the Conference of Parties (COP) Paris Agreement 2°C warming cap at this time. This type of future scenario would be considered for future NARCliM datasets if it remains viable.

3. Model selection

GCM selection

Overview

The selection of the three GCMs for downscaling generally followed the same approach used for NARCliM1.0 (Evans & Ji 2012). To be selected for NARCliM1.5, a GCM needed to:

1. produce adequate simulations of present-day climate
2. provide independent biases of the climate when compared with observations of the climate
3. when used with the CMIP3 GCMs in NARCliM1.0, span as much of the range of future climate changes projected for south-east Australia as possible
4. provide consistently frequent outputs (i.e. six-hourly for WRF) that act as boundary conditions for the RCMs.

The first three criteria are described in further detail below.

Performance of present-day climate from the scientific literature

Many evaluation studies of CMIP5 GCMs focusing on Australia and the surrounding region have been undertaken. A literature review was conducted using evaluation metrics to assess possible GCMs to use in NARCliM1.5. Consistent with methods used by other dynamical downscaling groups (e.g. McSweeney et al. 2015), the evaluation did not aim to identify the best performing GCM, but rather to exclude GCMs that produced consistently poor results across a wide range of assessments. In total, 49 GCMs were evaluated from 18 studies (see Appendix A). Six GCMs were evaluated in less than five studies and were excluded from further analysis on the basis that they could not be comprehensively assessed.

For each GCM, a fractional demerit score (Evans et al. 2014) was calculated to indicate the model's overall performance. The lower the fractional demerit the better the performance. Demerit points are added to a GCM in two ways:

1. For evaluations which provided a binary pass/fail outcome, any fail equals one demerit point.
2. For evaluations that provided a continuous measure, any GCM that falls in the 25% worst performing GCMs receives one demerit point.

All demerit points across the published studies were totalled for each GCM. Since not every GCM was present in every study, this demerit total was then divided by the total number of studies the GCM appeared in to calculate the fractional demerit. In this way, fractional demerit scores of 0.5 or above indicate that the GCM was among the 25% worst GCMs (or failed the test) in at least half of the tests (see Evans et al. 2014, Table 2). The consistently worst performers were removed from further analysis. In total, five GCMs (GISS-E2-H, IPSL-CM5A-LR, MIROC-ESM-CHEM, CSIRO-Mk3-6-0 and MIROC-ESM) were excluded due to poor performance across most of the studies. Thirty-eight GCMs remained for subsequent evaluation.

The robustness of the results of the 25% threshold was tested by altering the 25% threshold to 20%, 30%, 40% and 50%. A sensitivity analysis showed that the set of GCMs excluded by the original threshold is not sensitive to the alternations in the threshold.

Determination of GCM error independence

For NARCliM1.0, the method of Bishop and Abramowitz (2013) was used to determine the level of independence of the adequately performing GCMs. Model independence is characterised using the correlation of model errors. Errors are calculated by comparing the GCM daily values of mean temperature and precipitation over Australia's land areas for the 1970 to 1999 period with corresponding observations from the Bureau of Meteorology Australian Water Availability Project

The Australian Gridded Climate Data (AGCD) under the Australian Water Availability Project (AWAP) (Jones et al. 2009) was applied for GCM evaluation. An anomaly time series for each grid cell is then produced. These time series are then used to create a 'model error covariance matrix' containing the errors for all GCMs under consideration.

Bishop and Abramowitz (2013) showed that the coefficients of a linear combination of the models that optimally minimises the mean square error depends on both model performance and model dependence. The solution of this minimisation problem can be written in terms of the covariance matrix. The size of the coefficients assigned to each model reflects a combination of model performance and independence. Highly independent models have different errors when they simulate the current climate. The models with the largest coefficients are the best performing models with the most independent errors when compared with observations.

Of the 38 GCMs that passed the performance test (see previous section), four had no future simulations and were therefore excluded from the independence analysis. The remaining 34 CMIP5 GCMs were analysed. Since the new RCM simulations are designed to complement, rather than replace, the existing ensemble of NARCliM1.0 projections, a combined ensemble of the 34 CMIP5 GCMs and the four CMIP3 GCMs downscaled in NARCliM1.0 were analysed (Table 3).

The coefficients were calculated for temperature and precipitation independently, and their magnitudes summed to give the overall performance/independence of each model. The GCMs were then ranked according to the relative level of model independence. The GCMs that demonstrated greater independence were chosen preferentially in the model selection process. The results for this step are summarised in Table 4. The top ranked models are those that have the **most** independent errors when assessing errors compared to observations.

The four CMIP3 GCMs selected for NARCliM1.0 (highlighted in **bold** in Table 4) are: MIROC3.2, ECHAM5, CGCM3.1 and CSIRO-Mk3.0. The three CMIP5 GCMs selected for NARCliM1.5 (highlighted in ***bold italics*** in Table 4) are: ACCESS1-0, ACCESS1-3 and CanESM2. An additional step (described below) was undertaken to select NARCliM1.5 models and is explained below.

Table 3 GCM independence ranking results for temperature and precipitation.

Number	GCM	Precipitation coefficient	Temperature coefficient	Average of magnitudes	Ranking
1	***ACCESS1-0***	***-0.00998***	***0.0199***	***0.01494***	***31***
2	***ACCESS1-3***	***0.104443***	***0.080186***	***0.092314***	***1***
3	BNU-ESM	-0.0094	0.011258	0.010329	35
4	CCSM4	0.071547	0.029916	0.050732	12
5	CESM1-BGC	0.029053	-0.05327	0.04116	17
6	CESM1-CAM5	-0.01042	0.001937	0.006178	36
7	CESM1-WACCM	0.036833	0.037232	0.037033	20
8	CMCC-CESM	-0.0135	0.015953	0.014725	32
9	CMCC-CMS	-0.00076	0.020666	0.010711	34
10	CMCC-CM	0.039382	-0.03824	0.038812	19
11	CNRM-CM5	0.024772	-0.0337	0.029235	25
12	***CanESM2***	***-0.05877***	***0.029917***	***0.044342***	***16***
13	EC-EARTH	-0.04618	0.081995	0.064086	8
14	FGOALS-g2	0.031062	-0.00687	0.018964	28
15	GFDL-CM3	-0.06924	0.051083	0.060162	10
16	GFDL-ESM2G	0.071718	0.077745	0.074732	5
17	GFDL-ESM2M	0.072417	0.085767	0.079092	4
18	GISS-E2-H-CC	0.074777	0.098841	0.086809	3
19	GISS-E2-R-CC	0.099832	0.077132	0.088482	2
20	GISS-E2-R	0.04333	0.03854	0.040935	18
21	HadGEM2-AO	0.004236	0.005362	0.004799	37
22	HadGEM2-CC	0.022959	-0.00368	0.013322	33
23	HadGEM2-ES	0.00236	-0.03423	0.018295	29
24	IPSL-CM5A-MR	-0.00677	0.06069	0.033728	23
25	IPSL-CM5B-LR	-0.00732	-0.00171	0.004516	38
26	MIROC5	0.131389	-0.00972	0.070553	6
27	MPI-ESM-LR	-0.00974	0.0305	0.020119	27
28	MPI-ESM-MR	0.015766	0.057585	0.036675	21
29	MRI-CGCM3	0.03635	0.014125	0.025237	26
30	MRI-ESM1	0.07274	0.025025	0.048882	14
31	NorESM1-M	0.097913	0.001912	0.049912	13
32	bcc-csm1-1-m	0.079845	0.016889	0.048367	15
33	bcc-csm1-1	0.11187	-0.028	0.069936	7
34	inmcm4	-0.02815	0.084708	0.056431	11
35	**MIROC3.2**	**0.069517**	**0.002534**	**0.036026**	**22**
36	**ECHAM5**	**-0.00054**	**0.033037**	**0.016786**	**30**
37	**CGCM3.1**	**-0.05977**	**0.068149**	**0.063961**	**9**
38	**CSIRO-MK3.0**	**-0.01359**	**0.050833**	**0.03221**	**24**

Note: Models in **bold** were used to develop the NARCliM1.0 simulations; models in ***bold italics*** were used to develop NARCliM1.5 simulations.

Examination of future climate changes in CMIP3 and CMIP5 GCMs

For risk management purposes, climate projections should reflect as much of the range of plausible future climate changes as possible (Whetton & Hennessy 2010). The NARCliM1.0 GCMs were chosen to span a wide range of future changes in annual mean temperature and precipitation simulated for south-east Australia by the CMIP3 ensemble. The future changes were calculated for 2060 to 2079 relative to 1990 to 2009 for the NARCliM1.0 domain for land areas using historical and SRES A2. The analysis has been repeated for CMIP5 historical and RCP8.5 simulations for NARCliM1.5. Figure 2 shows future changes in temperature and rainfall for the 34 CMIP5 RCP8.5 simulations (dark green) and the 14 CMIP3 SRES A2 simulations evaluated for NARCliM1.0 (light green). Those highlighted GCMs (i.e. the larger dots) are used in NARCliM1.5 and NARCliM1.0 respectively.

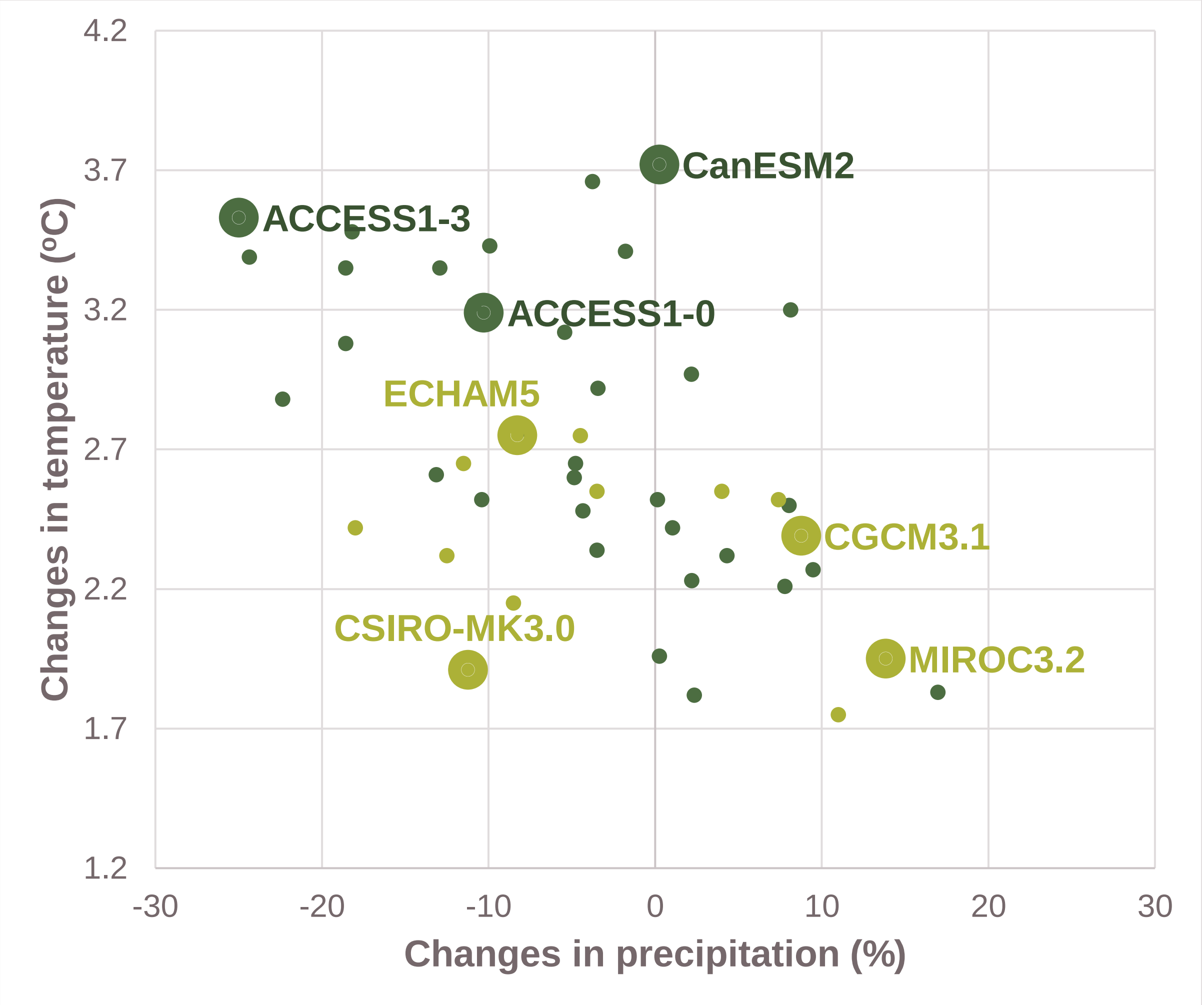

Figure 2 Changes in annual mean temperature and precipitation for 2060–2079 relative to 1990–2009 for NARCliM1.5 GCMs (dark green) and NARCliM1.0 GCMs (light green).

Many CMIP5 GCMs simulate greater warming and drying over south-east Australia that reflect improved modelling of atmospheric greenhouse gas concentrations than the CMIP3 GCMs selected for downscaling in the NARCliM1.0 Project. This is partly due to the greater greenhouse-induced energy imbalance of the climate in the RCP8.5 scenario used by CMIP5 than in the SRES A2 emission scenario used by CMIP3. Nevertheless there is no evidence of higher climate sensitivity in the CMIP5 GCMs compared with those in CMIP3, the improved physical processes in the later generation of models resulted in the larger range of warming.

An additional step was undertaken in the selection of NARCliM1.5 GCMs to ensure that they complemented the NARCliM1.0 GCMs and spanned a greater range of temperature and precipitation change. Referencing Figure 2, the selected GCMs for NARCliM1.5 are:

1. ACCESS1-3, which gives the greatest drying
2. CanESM2, which gives the greatest warming
3. ACCESS1-0, which gives more moderate warming and drying.

The CESM1-CAM5 model was considered, as it projects a wetter future than the other GCMs selected. However, six-hourly output required for the RCM simulations was unavailable and therefore this model was not used.

Table 5 lists selected GCMs for NARCliM1.5 and NARCliM 1.0 and their change in temperature and precipitation over the land area in the NARCliM domain. The three GCMs selected for NARCliM1.5 varied considerably in their error independence ranking (Tables 3 and 4) but were deemed suitable for spanning a greater range of projected temperature and precipitation changes. It should be noted that model evaluation revealed that the large precipitation decreases are dominated by changes in the area of Victoria.

Table 4 GCMs independence ranking and future changes in annual mean temperature and precipitation between 2060 to 2079 and 1990 to 2009

No.	GCM	Precip. change (%)	Temp. change (°C)	Ranking
NARCliM1.5				
1	ACCESS1-0	–10.29	3.19	31
2	ACCESS1-3	–24.99	3.53	1
12	CanESM2	0.26	3.72	16
NARCliM1.0				
35	MIROC3.2	13.85	1.95	22
36	ECHAM5	–8.27	2.75	30
37	CGCM3.1	8.77	2.39	9
38	CSIRO-MK3.0	–11.23	1.91	24

In summary, the GCMs were chosen on overall performance as per the literature, model error independence, their ability to capture the span of future simulated changes in south-east Australia and being complementary to the GCM spread in NARCliM1.0. Part of the GCM selection process in NARCliM1.5 is a compromise between spanning future changes and spanning errors in biases compared to observations.

RCM selection

The regional climate models (RCMs) in NARCliM1.0 and NARCliM1.5 are simulated over the 50-kilometre Australasia (CORDEX) domain and 10-kilometre south-east Australia (NARCliM) domain. These domains are shown in the image on front cover. The Australasia domain has been determined by CORDEX which provides international methodologies, processes and standards for regional climate modelling (see ENES CORDEX data structure). The south-east Australia 10-kilometre NARCliM1.0 and NARCliM1.5 domain includes five capital cities (Adelaide, Brisbane, Canberra, Melbourne and Sydney) and entirely covers New South Wales, the Australian Capital Territory and Victoria.

In NARCliM1.0, four CMIP3 GCMs were downscaled with three different configurations of the WRF model version 3.3 (Evans et al. 2014). The physics schemes for the three WRF RCMs are described in Table 5 below. These were chosen for adequate skill and error independence, following a comprehensive analysis of 36 different combinations of physics parametrisations (Evans et al. 2012) and the simulated rainfall for eight significant east coast lows (Evans et al. 2012; Ji et al. 2014).

The NARCliM1.5 simulations are performed using WRF version 3.6 with the R1 and R2 RCM physics combinations shown in Table 5. WRF3.6 version includes new land surface models and new micro physics. However, to maintain consistency with the physics schemes in the NARCliM1.0 RCMs, these additional schemes were not utilised in NARCliM1.5.

Table 5 Physics schemes used in the three regional climate models for NARCliM1.0 and NARCliM1.5.

RCM	Planetary boundary layer physics/ surface layer scheme	Cumulus convection scheme	Radiation physics
R1	Mellor-Yamada-Janjic (MYJ)/Eta similarity	Kain-Fritsch (KF)	Dudhia short wave / (Rapid Radiative Transfer Model (RRTM) long wave
R2	Mellor-Yamada-Janjic (MYJ)/Eta similarity	Betts-Miller-Janjic (BMJ)	Dudhia short wave/ (Rapid Radiative Transfer Model (RRTM) long wave
R3	Yonsei University (YSU)/MM5 similarity	Kain-Fritsch (KF)	NCAR Community Atmosphere Model (CAM) short / NCAR Community Atmosphere Model (CAM) long wave

Exclusion of a RCM post-evaluation

The third configuration listed in Table 6 (i.e. R3) was simulated using the ACCESS1.3 and ACCESS1.0 GCMs. After extensive evaluation of all R3 simulations compared with observations, it was determined that the R3 consistently performed poorly (Di Vigilio et al. 2019). As such, data from only two (R1 and R2) of the three RCMs is being publicly provided for NARCliM1.5. The same poor performance was not found for the GCM-driven R3 simulations in NARCliM1.0.

4. Generation of NARCliM1.5 data

Generation of raw output

The NARCliM1.5 projections were calculated on the NCI and Pawsey high-performance computing facilities in Australia. The simulations were developed by the Department and the University of NSW between 2017 and 2020.

The RCM simulation process involved the creation of initial and boundary conditions from GCM fields which were interpolated to the RCM grid. The initial conditions were used only at the start of the RCM simulation and had relatively little influence on the simulation after a couple of months. The boundary conditions were supplied to the RCM every six hours at the lateral boundaries of the RCM atmosphere and as sea surface temperatures. These boundary conditions were supplied throughout the RCM simulation.

Occasionally, a phenomena occurs within the RCM domain that causes computational instability in the model. When this occurs the model timestep is reduced for the month in which the instability occurs. On rare occasions, reducing the timestep for the month does not prevent the instability. For ACCESS-driven simulations, this resulted in a 'cold restart' being performed whereby the model is reinitialised from the GCM fields two months prior to the unstable month. This allows two months for the model parameters, especially the soil moisture fields to 'spin-up' before continuing the simulation. For CanESM2 simulations, the two months prior to the unstable month were re-run with a shorter timestep. This prevented both the instability and the requirement for a cold restart.

The NARCliM1.5 models generated 1.5 petabytes of data. This large dataset was reduced to variables more appropriate for analysis of climate impacts via post-processing. The post-processed files are available via the Climate Data Portal.

Post-processing of simulation outputs

For NARCliM1.5, the raw WRF output files (which contained data for many variables) were post-processed using a suite of Python scripts to facilitate analysis of the simulations. Post-processed data files were created containing one climate variable per file for the most frequently examined variables. Depending on the variable, post-processed data were available for hourly to seasonal timescales and saved in NetCDF format.

Post-processed files of NARCliM1.5 simulations were produced in a similar way to the NARCliM1.0 post-processed files (all in NetCDF format), with three important differences. The NARCliM1.5 post-processed files:

1. follow the CORDEX conventions for post-processing, facilitating their use by standard software and by the international research community
2. include data on daily maximum values of surface wind speeds and precipitation intensity
3. contain a complete set of data reprojected from the rotated pole grid of WRF to a regular latitude-longitude grid, allowing the data to be easily used by a broader range of users, including those unfamiliar with reprojection software.

Variables developed via post-processing

Variables were produced as a result of post-processing procedures. Table 6 below shows all the NARCliM1.5 variables that were post-processed. The NARCliM1.0 variables that were post-processed are listed in ***bold italics*** text with an "***x***" and are a subset of NARCliM1.5 variables. Post-processing was requested by technical stakeholders. Most NARCliM1.5 variables follow CORDEX conventions and standards. Variables with an asterisk (*) are not required by CORDEX. Codenames can be used when comparing the full list of CORDEX requested variables. NARCliM1.5 variables are available for hourly, three-hourly, six-hourly, daily, monthly and seasonal temporal scales. Descriptor name of the variable, the name used in model code and filenames and units are given. The listed variables are to be freely available through the Climate Data Portal or by contacting the DPIE scientists via email at narclim@environment.nsw.gov.au.

Table 6 Two-dimensional variables post-processed in NARCliM1.5

Variable	Code name	Units	1H	3H	6H	Daily	Mon	Seas
Precipitation	pr	kg m^{-2} s^{-1}	*x*	●	●	*x*	*x*	●
Convective precipitation	prc	kg m^{-2} s^{-1}	*x*	●	●	*x*	*x*	●
Temperature at 2 m above surface	tas	K	*x*	●	●	*x*	*x*	●
Specific humidity at 2 m above surface	huss	kg/kg	*x*	●	●	*x*	*x*	●
Surface air pressure	ps	Pa	*x*	●	●	*x*	*x*	●
10 m wind speed	wss	ms^{-1}	*x*	●	●	*x*	*x*	●
10 m northward wind	uas	ms^{-1}	*x*	●	●	*x*	*x*	●
10 m eastward wind	vas	ms^{-1}	*x*	●	●	*x*	*x*	●
Surface albedo	alb	no unit	●	*x*	●	*x*	*x*	●
Surface evaporation	evspsbl	kg m^{-2} s^{-1}	●	*x*	●	*x*	*x*	●
Upward latent heat flux at surface	hfls	W m^{-2}	●	*x*	●	*x*	*x*	●
Upward sensible heat flux at surface	hfss	W m^{-2}	●	*x*	●	*x*	*x*	●
Near surface relative humidity	hurs	percent (%)	●	*x*	●	*x*	*x*	●
Downward longwave surface radiation	rlds	W m^{-2}	●	*x*	●	*x*	*x*	●
Downward short-wave surface radiation	rsds	W m^{-2}	●	*x*	●	*x*	*x*	●
Upwelling shortwave surface radiation	rsus	W m^{-2}	●	*x*	●	*x*	*x*	●
Snow depth	snd	m	●	*x*	●	*x*	*x*	●
Surface emissivity	emiss	no unit		*x*	●	*x*	*x*	●
Total soil moisture content	mrso	kg m^{-2}		*x*	●	*x*	*x*	●
Upwelling longwave surface radiation	rlus	W m^{-2}		*x*	●	*x*	*x*	●
Sea surface temperature	sst	K		*x*	●	*x*	*x*	●
Total cloudiness (fraction)	clt	percent (%)		●	●	●	●	●
Specific humidity at 850 hpa	hus850	kg/kg		●	●	●	●	●
Soil frozen water content	mrfso	M		●	●	●	●	●
Total runoff	mrro	kg m^{-2} s^{-1}		●	●	●	●	●
Surface runoff flux	mrros	kg m^{-2} s^{-1}		●	●	●	●	●

Variable	Code name	Units	1H	3H	6H	Daily	Mon	Seas
Mean sea level pressure	psl	Pa		●	●	●	●	●
Top-of-atmosphere outgoing long-wave radiation	rlut	W m^{-2}		●	●	●	●	●
Sea ice fraction	sic	%		●	●	●	●	●
Snow area fraction	snc	%		●	●	●	●	●
Snow melt	snm	kg m^{-2} s^{-1}		●	●	●	●	●
Snow amount	snw	kg m^{-2}		●	●	●	●	●
Sunshine duration	sund	s		●	●	●	●	●
Air temperature at 200 hpa	ta200	K		●	●	●	●	●
Air temperature at 500 hpa	ta500	K		●	●	●	●	●
Air temperature at 850 hpa	ta850	K		●	●	●	●	●
Northward wind at 200 hPa, 500 hPa, 850 hPa	ua200, ua500, ua850	m s^{-1}		●	●	●	●	●
Eastward wind at 200 hpa, 500 hpa, 850 hpa	va200, va500, va850	m s^{-1}		●	●	●	●	●
Geopotential height at 200 hpa	zg200	m		●	●	●	●	●
Geopotential height 500 hPa	zg500	m		●	●	●	●	●
Atmospheric boundary layer thickness	zmla	m		●	●	●	●	
Maximum 5, 10, 20 or 30 minute time-window moving average precipitation rate*	pr5maxstep pr10maxstep pr20maxstep pr30maxstep	kg m^{-2} s^{-1}				***x***	***x***	●
Daily maximum 10m wind speed*	sfcWindmax	m s^{-1}				***x***	***x***	●
Daily maximum 2 m temperature*	tasmax	K				***x***	***x***	●
Daily minimum 2 m temperature*	tasmin	K				***x***	***x***	●
Maximum 5, 10, 20, 30, or 60 minute time-window moving average surface wind speed*	wss5maxstep wss10maxstep wss20maxstep wss30maxstep wss1Hmaxstep	m s^{-1}				***x***	***x***	●
Maximum wind speed*	sfcWindmaxmax	m s^{-1}					●	●

Notes: Variables included in NARCliM1.0 are in ***bold italics*** and "***x***". 1H, 3H and 6H refer to one-hourly, three-hourly and six-hourly respectively. Mon = monthly; Seas = seasonal

Bias correction

The NARCliM1.0 post-processed data also incorporated daily maximum and minimum temperature and daily precipitation data bias-corrected towards the AWAP observational dataset (Argüeso et al. 2013; Evans & Argüeso 2014). Studies have demonstrated the value of the bias-corrected data for analysis of some climate change impacts (e.g. Gross et al. 2016; Macadam et al. 2016). The same method used in NARCliM1.0 has been used to generate bias-corrected data for the NARCliM1.5 simulations.

NARCliM1.5 bias correction uses a quantile matching technique described in Piani et al. (2010) that allows correction of the full distribution of daily precipitation, maximum and minimum temperatures. Gamma distributions were fitted to the observed and modelled daily precipitation time series, and Gaussian distributions to the observed and modelled daily maximum and minimum temperature time series. Then, corrections were applied to allow the fitted distributions of daily RCM output to match the fitted distributions of daily observations. The AWAP observations (Jones et al. 2009) for the period 1990 to 2009 were used to calculate the corrections. These corrections were assumed to be independent of future climate change and the same corrections were also applied respectively to the future precipitation and temperature values.

Recently, improved bias correction methods have made bias correcting several variables possible in regional downscaled projections. NARCliM1.5 will also provides multivariate bias correction productions for the NARCliM domain, which include precipitation, humidity, evaporation and wind speed over the 10-kilometre NARCliM domain. The multivariate bias correction will take into account the relationships between corrected variables. The bias-corrected files will accompany NARCliM1.5 and be made freely and publicly available by the Department via the NSW Government's Climate Data Portal.

5. Quality assurance

The NARCliM1.5 quality assurance (QA) process is aimed at ensuring model outputs are complete, reliable and credible; and that modelling errors at various levels of post-processing have been identified. As a measure of quality control (QC), samples of the data outputs from NARCliM1.5 modelling were inspected to ensure data reliability . Quality control is an ongoing process beyond the methodology described here and also incorporates feedback from NARCliM1.5 users. To help us ensure the highest quality possible, registered Climate Data Portal data users should provide descriptions of issue(s) to the Department via email at narclim@environment.nsw.gov.au. Please identify the variable, location and model; and the time the issue was encountered; and the name of the file containing the issue.

Technical quality assurance for each variable

Most of the following QA tests in Table 7 are implemented automatically through our computer scripts and apply to both the raw model output files and the post-processed files. Other tests have been applied manually.

Table 7 NARCliM1.5 quality assurance tests

Test	Description
File external appearance	File size, file checksum, file name (for automated access) and file extension are tested for consistency
Metadata	Within each post-processed file, the metadata is evaluated to ensure that it conforms to the CORDEX standard and CF1.4 (Climate and Forecast) conventions, as appropriate
Dimensions	Check various variable dimensions (time, latitude, longitude, vertical levels) and data type (integer, float and double). For time variables, check calendar type and the temporal resolution
Other checks (particularly for post-processed files)	File is readable; file format is recognised, consistent and correct; file size zero is within 4 standard deviations to related files (those which are more than 4σ smaller than the mean of their counterparts are manually checked); number of data files is correct (dataset completeness); where relevant, check data is readable on the GIS platform

Scientific quality assurance

Basic scientific quality assurance for post-processed variables

Basic QA for NARCliM1.5 checks that post-processed variables at the daily temporal frequency fall within a realistic range. For example, values of precipitation rates have been checked to ensure they fall within the range [0, 1200] in mm/day. Daily data are focused on given the availability of AWAP data at this frequency.

Intermediate scientific quality assurance for key variables

The intermediate quality assurance for key variables (rainfall, temperature, wind, mean sea-level pressure, etc.) consisted of the evaluation of the performance of the NARCliM1.5 simulations compared with observations. Several aspects of the climate have been evaluated by the Department and collaborators, including means, variability and extremes. Metrics such as mean biases, spatial correlations and spatial variances in errors were used to test the skill of the ensemble. These evaluation results will be available in additional reports and publications.

Advanced scientific quality assurance for special systems

Advanced scientific quality assurance refers to the evaluation of the performance of more sophisticated and complex NARCliM1.5 diagnostics, such as when testing the ability of the models to represent monsoon systems and/or cyclonic activity. If these diagnostics can be applied successfully, it could be concluded that the data has production grade quality. Such applications for these diagnostics are being developed progressively by experienced researchers, and results will be documented in separate reports and publications.

Metadata

NARCliM1.5 data are compliant with CORDEX and climate and forecast version 1.4 (CF v 1.4), with additional metadata included as required for derived datasets.

Licensing

NARCliM1.5 projections are available for unrestricted use, provided the terms of use are complied with and referenced. The terms of use for CMIP5 datasets include correct citation and acknowledgment of the use of the CMIP5 data. Downstream NARCliM1.5 datasets will need to comply with these terms of use. While some CMIP5 GCMs are available only for non-commercial or educational purposes, the NARCliM1.5 GCMs do not hold such restrictions.

6. Data retention and destruction details

Retaining the NARCliM1.5 data indefinitely is unnecessary and costly, even with future reductions in the cost of storage. Two primary scenarios result in the potential end of life for NARCliM1.5 data:

1. **Erroneous data**

   It is recognised that there is both potential value and costs in storing erroneous data. The NARCliM1.5 directory structure follows CORDEX conventions in allowing for retention of erroneous data in different directories from the most up-to-date version of the data. However, we note that where erroneous data is retained, users will be blocked from accessing the relevant directories via any data access services implemented, and the data will only be available on request.

2. **Data is superseded by data from future NARCliM datasets**

   NARCliM1.5 data will ultimately be superseded by future NARCliM datasets. However, users need to be able to compare analyses based on the multiple NARCliM datasets. Thus, the removal of NARCliM1.5 data for this reason is unlikely to happen before the mid-2020s. At this point, the value of the NARCliM1.5 data and the cost of retaining it will be reviewed.

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Appendices

Appendix A. Literature reviewed to assess GCM performance and number of GCMs evaluated in each study

Authors	Title of publication	Aspect of climate evaluated	No. GCMs
Bhend & Whetton 2015	Evaluation of simulated recent climate change in Australia	Daily maximum and minimum temperature trends and rainfall trends for 1956-2005	44
Brown et al. 2013a	The South Pacific Convergence Zone in CMIP5 simulations of historical and future climate	The South Pacific Convergence Zone	26
Brown et al. 2013b	The western Pacific monsoon in CMIP5 models: Model evaluation and projections	The western Pacific (WP) monsoon	35
Brown et al. 2015	Projected sea surface temperature changes in the equatorial Pacific relative to the Warm Pool edge	Sea surface temperature	19
CSIRO & BoM 2015	Climate change in Australia technical report – Chapter 5 evaluation of climate models	Temperature, rainfall, sea level pressure M-score for rainfall and temperature.	40
Gibson et al. 2016	Evaluating synoptic systems in the CMIP5 climate models over the Australian region	Synoptic system	24
Grose et al. 2014a	Assessment of the CMIP5 global climate model simulations of the western tropical Pacific climate system and comparison to CMIP3	The western tropical Pacific climate	27
Grose et al. 2014b	Can we constrain CMIP5 rainfall projections in the tropical Pacific based on surface warming patterns?	Rainfall in the tropical Pacific	38
Grose et al. 2015a	Comparison of various climate change projections of eastern Australian rainfall	Rainfall	39
Grose et al. 2015b	The subtropical ridge in CMIP5 models, and implications for projections of rainfall in southeast Australia	The sub-tropical ridge (mean, SD, trend)	35
Grose et al. 2017	Constraints on southern Australian rainfall change based on atmospheric circulation in CMIP5 simulations	Circulation features and southern Australian rainfall	40
Jourdain et al. 2013	The Indo-Australian monsoon and its relationship to ENSO and IOD in reanalysis data and the CMIP3/CMIP5 simulations	Indo-Australian monsoon rainfall	35
King et al. 2015	The ENSO-Australian rainfall teleconnection in reanalysis and CMIP5	Teleconnection of ENSO and rainfall	35
Knutti et al. 2013	Climate model genealogy: Generation CMIP5 and how we got there	Model similarity in CMIP5 and CMIP3	38
Kug et al. 2012	Corrigendum: Improved simulation of two types of El Nino in CMIP5 models	Two types of El Niño events	21

Moise et al. 2015	Evaluation of CMIP3 and CMIP5 models over the Australian region to inform confidence in projections	Mean climate, variability measures and teleconnections	47
Pepler et al. 2016	Zonal winds and southeast Australian rainfall in global and regional climate models	Zonal wind and rainfall	37
Watterson et al. 2013	What influences the skill of climate models over the continents?	Rainfall, temperature and sea-level pressure for each continent	25