



Australia's National
Science Agency

Quality Assurance and Quality Control statement

CIHP-1: Application Ready Climate Projections (CMIP5)

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1 Overview

1.1 Dataset description

The CSIRO Climate Innovation Hub's CMIP5 application-ready climate projection product (hereafter CIHP-1) utilises a technique called "QQ-scaling" to develop future climate projection datasets that are able to be used for commercial purposes. These include daily values of climate variables commonly used in climate change impact assessments – daily maximum and minimum temperature, precipitation, solar radiation and relative humidity. These projections are made available for three periods (2016-2045, 2036-2065 and 2056-2085) and for three different CMIP5 representative climate pathways (RCP2.6, RCP4.5 and RCP8.5), also called emission pathways.

Where data were available, projections have been generated from output of the historical and RCP projection experiments of 8 climate models (ACCESS1-0, CanESM2, CESM1-CAM5, GFDL-ESM2M, HadGEM2-CC, MIROC5, NorESM1-M) generated by various international climate modelling centres for the 5th phase of the Coupled Model Intercomparison Project (above and hereafter CMIP5). In addition to these projections products, the appropriate historical baseline data from the AGCD and ERA5 observational datasets that were used in generation of the projections are also available.

Datasets within the CIHP-1 product consist of NetCDF files, one for each combination of climate variable, time period, RCP and climate model; as well as a NetCDF file of historical baseline data for each climate variable.

Further information on the CIHP-1 product can be found in Webb et al. (2024). This document describes the Quality Assurance and Quality Control (QAQC) processes that have been applied to the product, findings from these processes and any action taken as a result of these findings.

1.2 QAQC check overview

We have undertaken a range of checks on the CIHP-1 product to ensure its completeness and integrity. This document outlines the checks undertaken and the outcome of these checks, and those that were not yet undertaken. These checks undertaken include:

- Source-data checks, including the choice of and credibility of data underlying the product and the licence status of source data allowing for free use of output data
- Basic file checks, including that there is a complete set of files, that they are named correctly and that the internal structure of data within the files is correct
- Metadata checks, including the temporal and spatial coordinates of data, that file metadata matches the filename and follows appropriate metadata conventions
- Data checks, including that there is no unexpected missing data and that the data within the file lies within sensible ranges and is consistent over time

- Basic plausibility checks, including that northern and inland Australia are, in aggregate, warmer than southern/coastal Australia, and that the inland dryer regions of Australia receive less rainfall than coastal and wetter parts of Australia.

Quality control checks that are out of scope for this document at this stage are:

- Full quality checks upon input climate model and observational data – errors and issues in the input data are assumed to be minimised through choice of credible and widely used data sources

The quality checks undertaken necessarily comprise a small, but important, subset of a full set of quality checks that could be undertaken. Additional quality checks may be added in the future. Some of these are noted as “**BEYOND CURRENT SCOPE**” in the following sections. They will be documented in an addendum to this statement.

1.3 QAQC results and responses

Based on the results of the above checks, some parts of the initial product have been adjusted and corrected. These adjustments have **not** changed the underlying data of the product, produced through the process described by Webb et al. (2024). Examples of issues found as part of the checks, and responses to them, include:

- Source data checks:
 - *Model not fit for purpose (i.e. model does not well represent Australian climate, or closely emulates another model):* scaled-model output not part of final product
- File checks:
 - *Data stored with incorrect data type:* adjustment of file data type.
 - *Precision issues with coordinate variable:* attempted adjustment/correction of coordinates, precision issue flagged in this document (see section 4.1).
 - *Complete set of operable files:* removal of files not operable (i.e. are corrupted or not working as expected), and identification of files that cannot be generated (see section 3.2 and section 3.3).
- Metadata checks:
 - *Some metadata attribute entries non-compliant with relevant standards:* adjustment of existing metadata attributes to meet conventions
 - *Missing metadata fields:* addition of new metadata attributes required by conventions
- Data checks:
 - *Missing data:* file removed from product and data flagged as missing in this document (see section 5.1).

2 Source Data

2.1 Data credibility

Source data for the CIHP-1 product is sourced from AGCD (Australian Gridded Climate Data, Australian Bureau of Meteorology 2020) and ERA5 (ECMWF Reanalysis version 5, Hersbach et al. 2020) and from models.

AGCD and ERA5 data are externally sourced, independently verified datasets which ingest and are validated against station observations and are the most recent products of their type made available by the Bureau of Meteorology and the European Centre for Medium-range Weather Forecasting respectively. These organizations are reputable data sources for historical weather data and the datasets are widely used by the climate science community. We have made no independent tests as to the quality of these underlying datasets, but ERA5 has its own quality assessment system with reports on the Copernicus climate data store (European Union and ECMWF 2021).

CMIP5 is a decentralised climate modelling project, with a common set of experiments and output variables across multiple global climate models. Model output data must satisfy a fixed data reference syntax and metadata standard, and are uploaded to and hosted on a range of data nodes (Taylor et al. 2012) This process ensures that model data is consistent and interoperable (i.e. data from different models can be read by the same code with no issues), and mitigates against differing versions of the same model output. CMIP data also underpins the basis of globally important climate change decisions and reports, such as reports of the Intergovernmental Panel on Climate Change (IPCC) and inter-governmental compacts and accords, and these reports examine and provide a firm basis for the general applicability of CMIP data. This, however, does not ensure that all model data is fit for purpose in generating application-ready data over Australia, with the selection of fit-for-purpose model data described in more detail below in section 2.3.

Furthermore, while AGCD, ERA5 and CMIP5 datasets are widely used and underpin much climate research, these products all come with disclaimers that they are *research products* and not fully analysed and evaluated. This means that there may be issues with these products that other users may detect, which would then be rectified in new versions of the datasets released by their publishers. These corrections would not be immediately reflected within the CIHP-1 product. However, the widespread use of these products in scientific research and analysis does provide a level of confidence that any potential errors have been identified and rectified before their use in this product.

BEYOND CURRENT SCOPE: Full, exhaustive quality checks upon input climate model and observational data

2.2 Licence status and suitability of input data

A 'freedom to operate' check for the end-product has been performed, through an IP and licence status check for the input data listed above. ERA5 and CMIP5 data are used in CIHP-1 under an

unrestricted licence with attribution, and AGCD is used here under a paid licence from the Australian Bureau of Meteorology where derived products such as CIHP-1 are freely sublicensable. As all input data is used in CIHP-1 with either an unrestricted licence or a licence which allows for freely sublicensable derivatives, the input data has been deemed to be suitable for the CIHP-1 product.

2.3 Review of methods (including model data quality assessment)

The process of generating output, including the selection process of suitable input models, is fully described in the technical report (Webb et al. 2024). This technical report has been reviewed both within CSIRO and externally by referees with expert knowledge in the generation and use of application-ready climate projections.

Of note for source data quality checks is the selection of CMIP5 models to be used in the generation of the final product. This followed that of the Climate Change in Australia project (CSIRO and Bureau of Meteorology 2015) and was the result of a quality assessment based on three criteria – ability to simulate the Australian climate, availability of data, and sufficient diversity in future climates represented. This resulted in 8 CMIP5 models being selected (ACCESS1-0, CanESM2, CESM1-CAM5, CNRM-CM5, GFDL-ESM2M, HadGEM2-CC, MIROC5 and NorESM1-M).

3 File Quality

3.1 Data Reference Syntax (DRS)

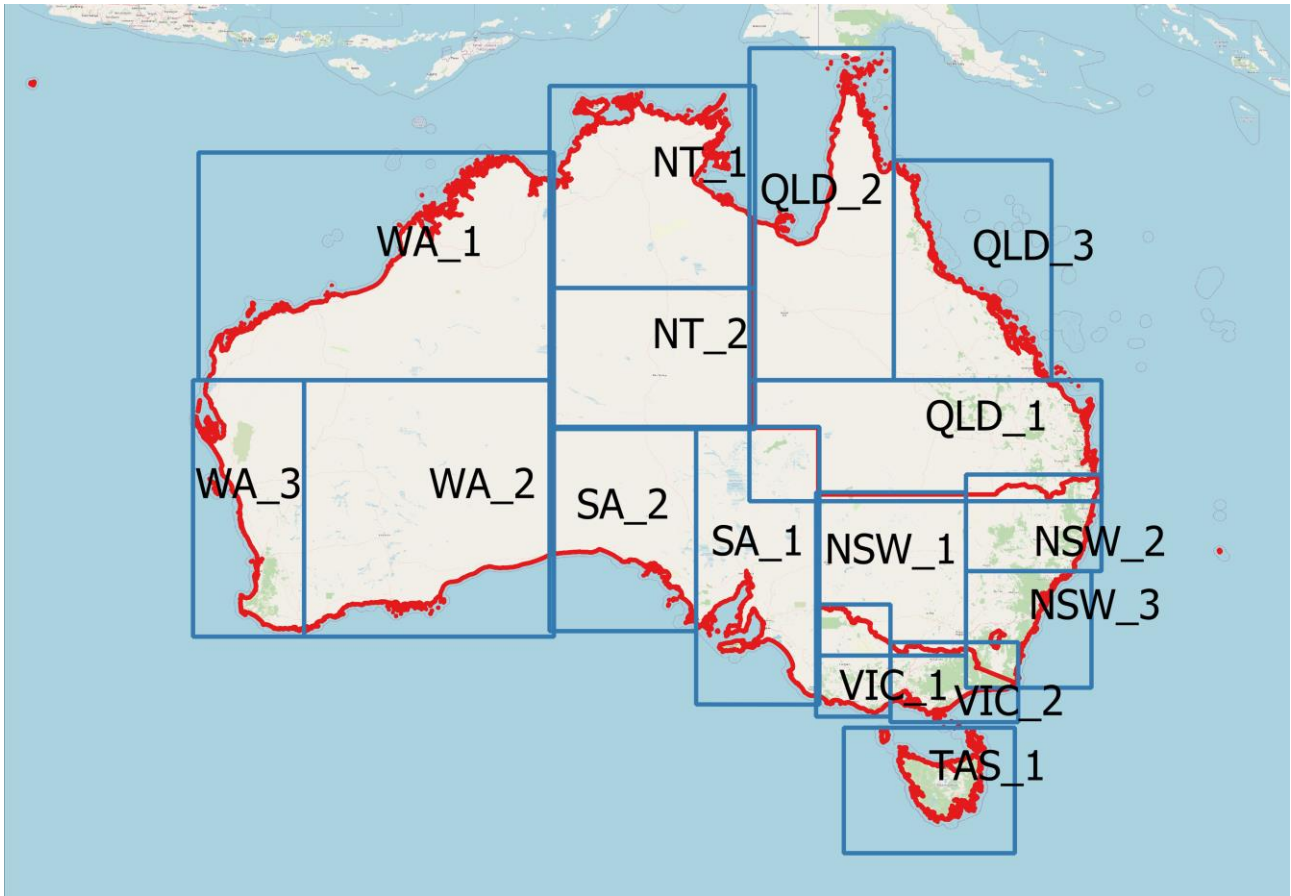


Figure 1: Regions of Australia for which sub-sets of the data are available, and referred to in the Data Reference Syntax (DRS).

The CIHP-1 product consists of several sub-products, each available for separate download, with a separate data file for each combination of variable, period, RCP, climate model and, where applicable, agglomeration period (daily, monthly, seasonal, annual). The name for these data files fits the following data reference syntax (DRS), where each file has a name of the format:

$$\{variable\}_{model}_{rcp}_{iteration}_{downscaling\ method}_{period}\{-agglom\}\{-agglom\ method\}_{g-\{region\}}.nc$$

where the part in square brackets is only for smaller tiles (or regions (Figure 1)) of the full Australian dataset, the following being suitable options for each part of the file name:

- {variable}: pr, rhs, rsds, tasmax or tasmin
- {model}: ACCESS1-0, CanESM2, CESM1-CAM5, CNRM-CM5, GFDL-ESM2M, HadGEM2-CC, MIROC5, NorESM1-M
- {rcp}: rcp26, rcp45, rcp85
- {iteration}: r1i1p1

- {downscaling method}: CSIRO-QQS-AGCD-1981-2010_day_wrt_1986-2005, CSIRO-QQS-ERA5-1981-2010_day_wrt_1986-2005
- {period}: 2016-2045, 2036-2065, 2056-2085
- {agglom}: daily, monthly, seasonal, annual
- {agglom method}: mean
- {region}: SAMPLE, NSW1, NSW2, NSW3, NT1, NT2, QLD1, QLD2, QLD3, SA1, SA2, TAS1, VIC1, VIC2, WA1, WA2, WA3

The historical baseline data files fit the following naming format:

{variable}_{source}_historical_1981-2010-{agglom}-{agglom method}[_g-{region}].nc

where {source} is either ERA5 or AGCD, and the suitable options for other parts of the file name are as above.

3.2 File existence

Existence of files is checked by a simple python script that iterates against each appropriate combination of different file names given by the DRS above and creates a list of file names which are anticipated to be in the final output. The code then searches for files with the expected names, and outputs a list of files which are anticipated in the final output but are. The following table describes the result of these checks:

✓		Files exist for all regions and RCPs			
		Some files exist (see notes)			
X		No files exist (see notes)			
	Precipitation (pr)	Relative humidity (rhs)	Downwards shortwave radiation at surface (rsds)	Daily maximum temperature (tasmax)	Daily minimum temperature (tasmin)
ACCESS1-0	[1]	[1]	[1]	[1]	[1]
CanESM2	✓	✓	✓	✓	✓
CESM1-CAM5	[2]	X [3]	X [3]	[2]	[1]
CNRM-CM5	✓	[1]	✓	✓	[4]
GFDL-ESM2M	✓	[1]	✓	✓	✓
HadGEM2-CC	[1]	[1]	[1]	[1]	[1]
MIROC5	✓	[1]	✓	✓	✓
NorESM1-M	✓	[1]	✓	✓	✓

NOTES:

[1]: RCP 2.6 data does not exist for this combination of models and variables.

[2]: Due to some incomplete output files (see next section), a RCP2.6 file for this combination of model and variables has been removed from the available files.

[3]: Relative humidity and downwards shortwave radiation data does not exist for CESM1-CAM5 model.

[4]: Due to some missing data (see section 5.1.2), a RCP4.5 file for this combination of model and variables has been removed from the available files.

3.3 File structure and completeness

The file structure is checked through implementing a python script that parses the DRS name and checks the file in order that all data variables match the DRS name, as well as checking the data for time, latitude, and longitude coordinates. The datatype of the data variables is also checked, to ensure that they are stored as 32-bit floats.

File completeness is checked through a simple check, parsing the DRS name and checking that the spatial extent of the file matches the geographic area designation in the file, and that the temporal period of the data matches the period in the file name.

✓	Existing files are complete and have correct structure, with no missing timesteps
	Some files are incomplete or incorrectly structured, with missing timesteps (see notes)
X	No existing files are complete/have correct structure (see notes)

	Precipitation (pr)	Relative humidity (rhs)	Downwards shortwave radiation at surface (rsds)	Daily maximum temperature (tasmax)	Daily minimum temperature (tasmin)
ACCESS1-0	✓	✓	✓	✓	✓
CanESM2	✓	✓	✓	✓	✓
CESM1-CAM5	[1]	N/A	N/A	[2]	✓
CNRM-CM5	✓	✓	✓	✓	✓
GFDL-ESM2M	✓	✓	✓	✓	✓
HadGEM2-CC	✓	✓	✓	✓	✓
MIROC5	✓	✓	✓	✓	✓
NorESM1-M	✓	✓	✓	✓	✓

NOTES:

[1]: CESM1-CAM5 RCP2.6 precipitation output for the 2016-2045 period ends in 2043 and has thus been removed from available output.

[2]: CESM1-CAM5 RCP2.6 tasmax data for the 2036-2065 period starts in 2061 and has thus been removed from available output.

4 Metadata Quality checks

4.1 Grid and timeseries spacing consistency

The projection data provided has been checked to ensure consistent timeseries spacing, with an appropriate gap of 24 hours between each timestep in each file for daily data, 1 month for monthly data, 3 months for seasonal data and a 365-day year for the annual data (all years in the projections in this dataset have 365 days, and no leap days). The spatial grid of the data is also checked to ensure a consistent grid spacing of .05 degrees in both latitude and longitude consistent with a subsection of the Australia-wide grid. The description of the Australia-wide grid (in CDO grid description format) from which the subregional data has been extracted, is below:

```
gridtype = lonlat
gridsize = 612226
datatype = float
xsize    = 886
ysize    = 691
xname    = lon
xlongname = "Longitude"
xunits   = "degrees_east"
yname    = lat
ylongname = "Latitude"
yunits   = "degrees_north"
xfirst   = 112
xinc     = 0.05
yfirst   = -44.5
yinc     = 0.05
```

All data matches this grid and the 24-hour temporal spacing, albeit with some precision issues (some grid values differ from the expected values in the 6th decimal place).

4.2 Metadata conventions

The metadata within the projection files has been checked for compliance against the version 1.8 of the NetCDF Climate and Forecast metadata conventions (CF1.8, Eaton et al. 2020), and version 1.3 for the Attribute Convention for Data Discovery (ACDD1.3, ACDD Steering Committee 2015). CF conventions allow for simple interoperability with a range of systems and programs that use netCDF data, and ACDD conventions allow for the netCDF files to contain appropriate metadata for use in data discovery systems like data libraries, as well as simple mappings between the netCDF metadata and other metadata formats such as ISO 19115. ACDD is also a useful convention standard for mapping netCDF files in GIS software, as it associates a coordinate reference system and geospatial boundaries to the data in a way easily understood by GIS software. These checks are undertaken using the IOOS compliance checking code (<https://github.com/ioos/compliance-checker>).

Currently, files meet the minimal requirements of both the CF1.8 and ACDD1.3 conventions.
Further issues which need addressing for maximal compliance:

- CF1.8
 - missing_value and _FillValue need to be equal to each other
 - repository-code and repository-commit should contain a string beginning with a letter.
- ACDD1.3, as above plus:
 - Many recommended, but not essential, global attributes missing.

5 Data Quality checks

5.1 Missing data

Data in the available files has been checked for missing data, with spatial and temporal missing data checks performed.

5.1.1 Spatial description of missing data

Most files in this product have been subject to a land-sea mask, which masks all values over ocean points and thus returns missing data for these points. Except for the precipitation variables, this land-sea mask describes the maximal spatial pattern of missing data (Figure 2a).

Due to the large spatial variability of precipitation, precipitation data remote from weather stations and radars is flagged as low quality in the input AGCD dataset and has been masked from the projections in the CIHP-1 product. The regions where the precipitation projections are missing are shown in Figure 2b, and are confined to remote regions of WA, SA and NT.

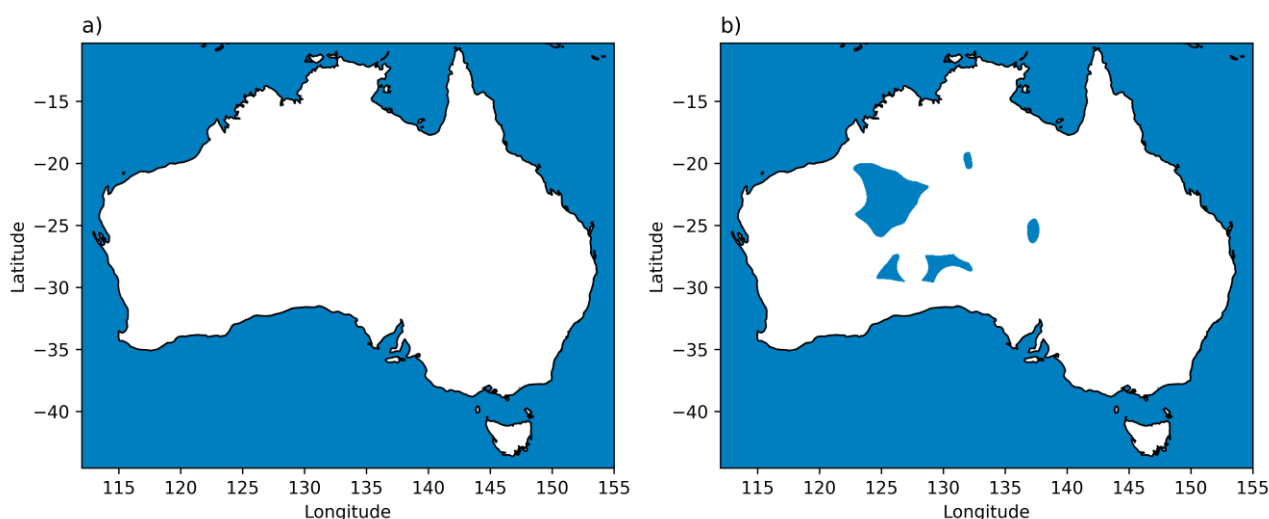


Figure 2: Areas of missing data in the CIHP-1 product (shaded), for all variables where the land-sea mask has been applied apart from precipitation (a, left) and for precipitation (b, right).

Furthermore, around 12 RCP2.6 projection files and 2 RCP4.5 have been found to not have any land-sea mask applied, and thus have non-missing data over the ocean. These files are:

- RCP 2.6:
 - pr, CanESM2, 2016-2045
 - pr, CanESM2, 2036-2065
 - pr, CanESM2, 2056-2085
 - pr, CESM1-CAM5, 2056-2085
 - pr, GFDL-ESM2M, 2016-2045
 - pr, GFDL-ESM2M, 2036-2065
 - pr, GFDL-ESM2M, 2056-2085

- pr, MIROC5, 2016-2045
- pr, MIROC5, 2036-2065
- pr, MIROC5, 2056-2085
- tasmax, CESM1-CAM5, 2056-2085 (n.b.: this file has other issues and is not included in final release, see section 5.2)
- tasmin, CESM1-CAM5, 2056-2085
- RCP 4.5:
 - tasmax, MIROC5, 2016-2045
 - tasmax, MIROC5, 2036-2065

These files are kept in the available output, but a land-sea mask needs to be applied to these datasets if they are to be compared to files that were subject to a land-sea mask in areas which contain both land and ocean points.

5.1.2 Spatio-temporal description of missing data

Spatial and temporal changes in missing data points have been checked by examining if data at a point is missing across the entire timeseries in an output file – ideally, if data is missing at a point, it should be for the entire timeseries in a file. For all but one file checked file, missing data status of points do not change over the time dimension of the file, however for the file where this does happen, every point which has non-missing data does also have missing data for some of the timeseries (Fig 3).

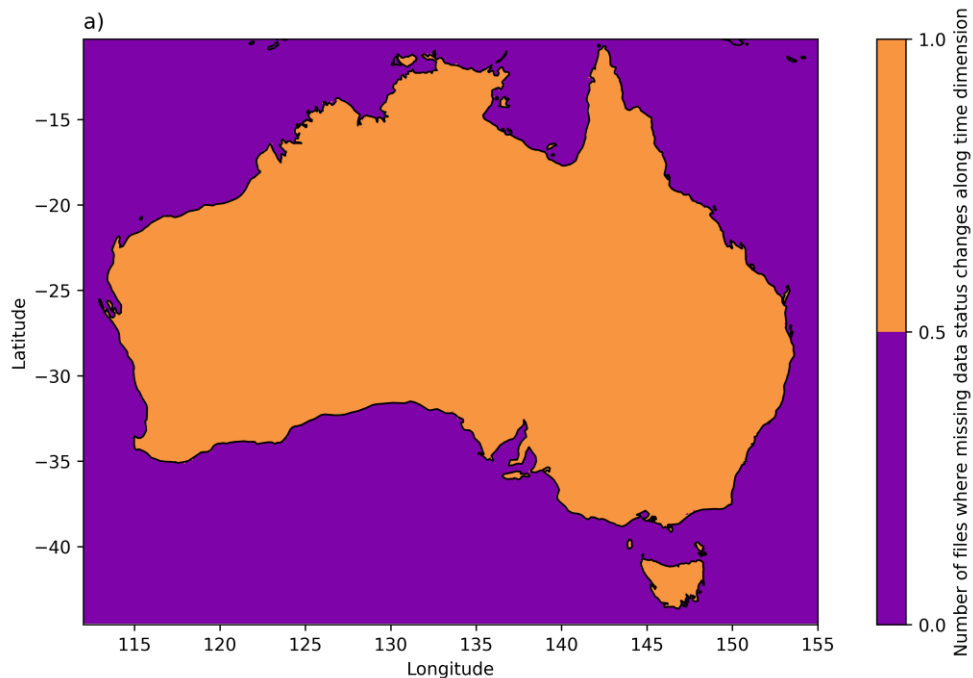


Figure 3: Number of generated output files where both missing and non-missing data exists for at least one timestep in the file.

The singular file discovered to have spatio-temporal variability in missing data status (that is, both existing and missing data for along the timeseries) is CNRM-CM5 RCP 4.5 tasmin file for the period 2036-2065, where all data from 2040 onwards is masked from the file. This incomplete file has been removed from the product.

5.2 Data variability and value checks

Checks on both the plausibility of the magnitude of projections and their variability over time are performed by plotting the spatial minimum, maximum and mean of each file along the temporal dimension.

Issues in magnitude are detected where these values are outside physical plausibility ranges (that is, far above or below global observational records for temperature, below 0 and far above observational records for precipitation, outside the range 0 – 100% for relative humidity, and outside the range from 0 to 600 W m⁻² for daily mean downwards solar radiation, see table 1 below).

Table 1 Upper and lower bounds used for physical plausibility checks, with a description of the rationale for each limit

VARIABLE	LOWER BOUND	UPPER BOUND
Precipitation (pr)	0 mm day ⁻¹ (physical limit)	400 mm day ⁻¹ (approx. observed global maximum + 50%)
Temperature (tasmin, tasmax)	-80°C (approx. lowest temperature recorded outside Antarctica - 10°C)	65°C (approx. highest temperature recorded + 10°C)
Downwards solar radiation (rsds)	0 W m ⁻² (physical limit)	600 W m ⁻² (approx.. 50% of solar constant)
Relative humidity (rhs)	0% (physical limit)	100% (physical limit)

Issues in the variability were flagged if, upon human inspection:

- The annual cycle is not present in the file
- The minimum, maximum and/or mean are inconsistent with other files
- There are temporal inconsistencies in any of these values.

No inconsistencies or issues with precipitation projections were found using this method (see Figure 4). Some maximum monthly precipitation projections are above the historical Australian record of 173.8 mm/day (recorded at Mt Bellenden Ker in January 1979), but most are between this and the global record of 299.7 mm/day (recorded at Cherrapunji, India in July 1861). A few files have values above this but less than 400 mm/day, and are not excluded from the available output. Minimum precipitation projections are all 0 mm/day or above in output files.

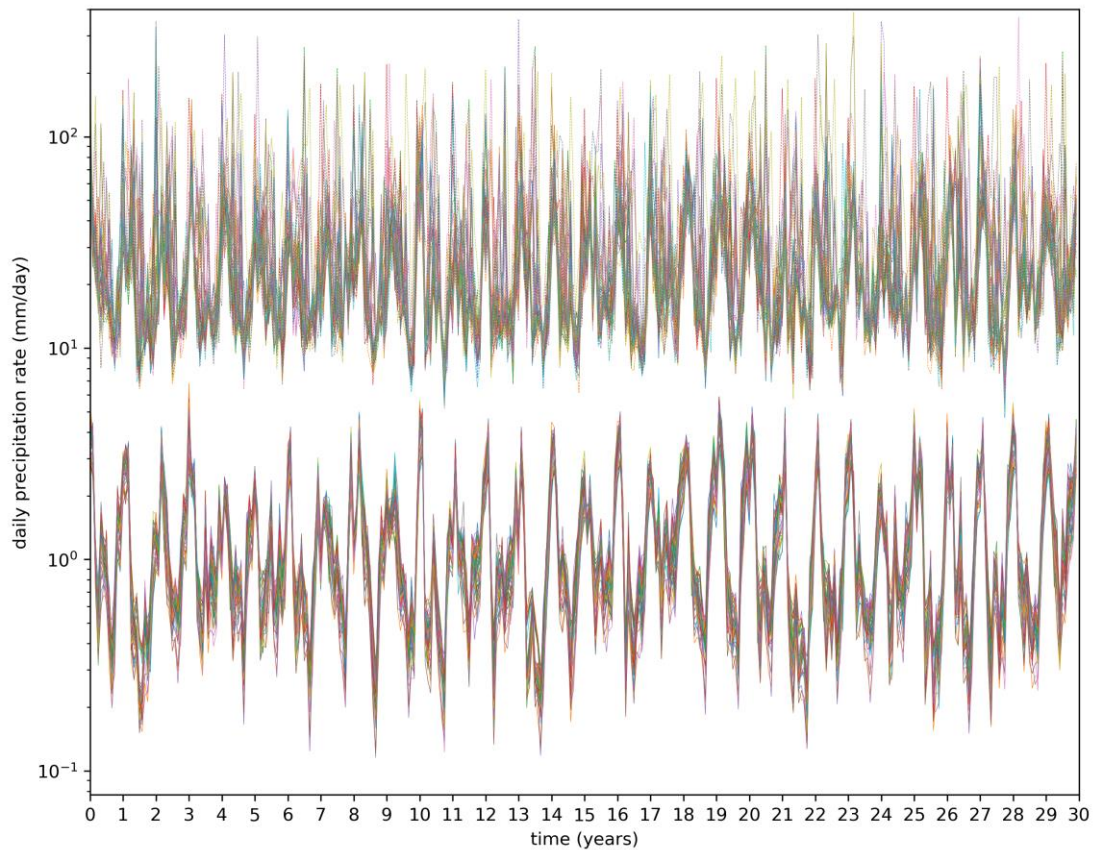


Figure 4: Timeseries of spatial mean (lower lines) and maximum (upper lines) monthly-mean daily precipitation rate over the 30 years of each output precipitation projection file.

Errors in the magnitude of one set of daily maximum temperature files were identified by this process, with the CESM1-CAM5 RCP2.6 projections for 2056-2085 having values which are implausibly low, often below the physical minimum temperature of -273.15 C (Figure 5). This is due to areas within these files having large negative values for some timesteps, which propagates through to temporally averaged files. As such, this file is flagged to be removed from the available output. For the remaining files in the available output, there is no identified errors in the mean and variability of the daily maximum temperature projections, however it is worth noting that MIROC5 projections appear to have colder mean daily maximums than the other projections during summer.

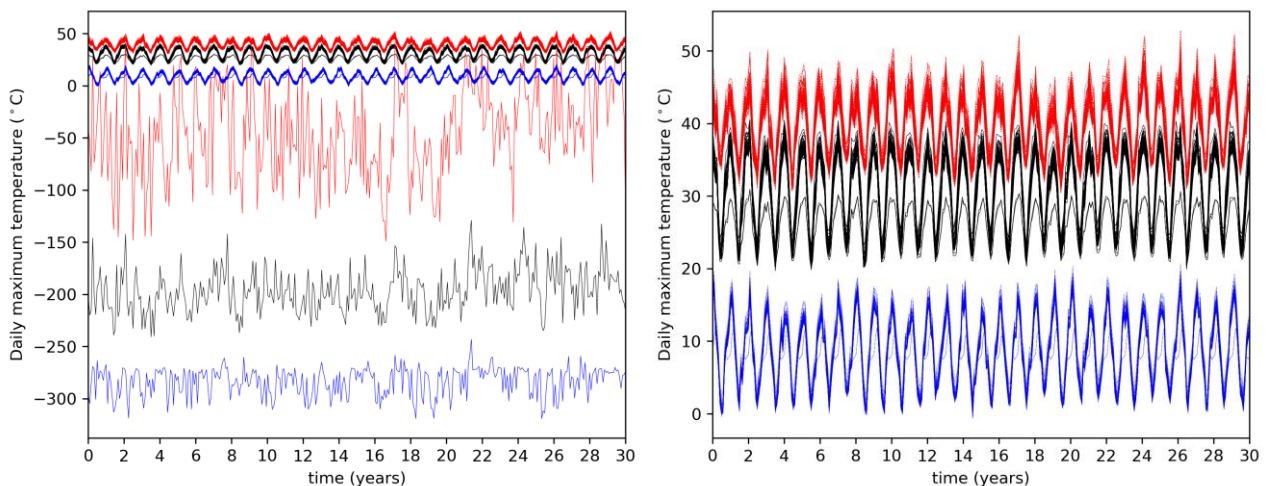


Figure 5: Timeseries of maximum (red), mean (black) and minimum (blue lines) monthly-mean daily maximum temperatures over Australia for the 30 years of each QQ-scaled output daily maximum temperature projections file (left) and with the outlier CESM1-CAM5 RCP2.6 projections for 2056-2085 removed (right).

No issues are apparent with daily minimum temperatures, with values within a plausible range and no step-changes or issues with the annual cycle visible (Figure 6).

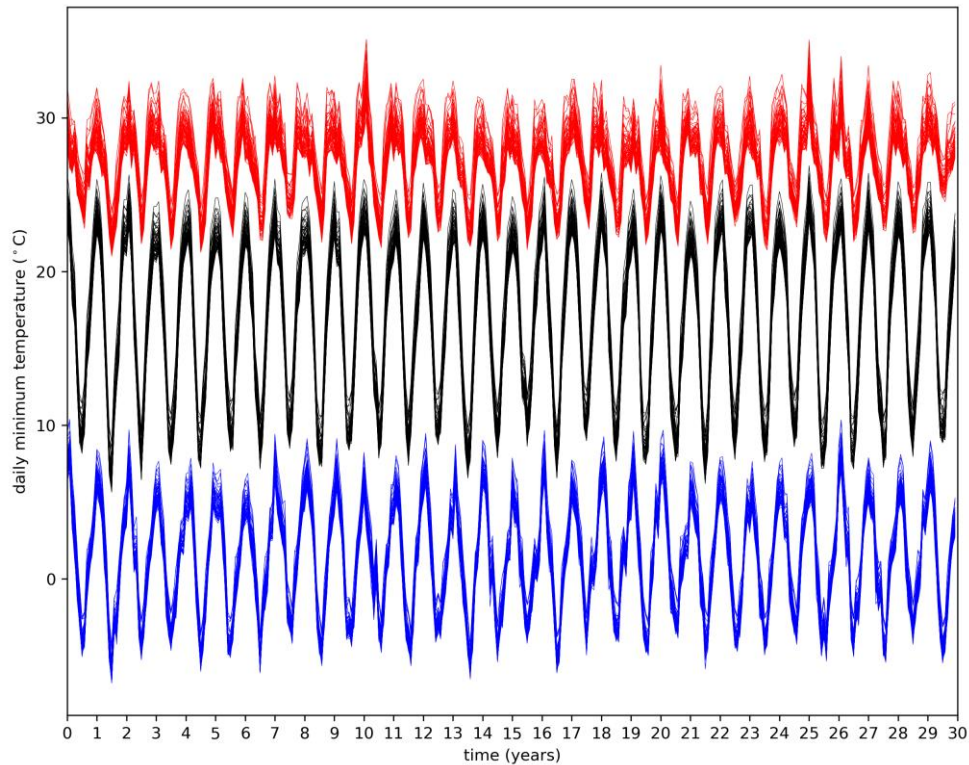


Figure 6: Timeseries of maximum (red), mean (black) and minimum (blue lines) monthly-mean daily minimum temperatures over Australia for the 30 years of each output QQ-scaled daily minimum temperature projection file.

Similarly, no apparent issues are detected in the relative humidity projections using this method. The annual cycle is consistent in all the output files; no step changes in the maximum, mean or minimum are seen; and all values are within the range between 0% and 100%, the physical limits of relative humidity (Figure 7).

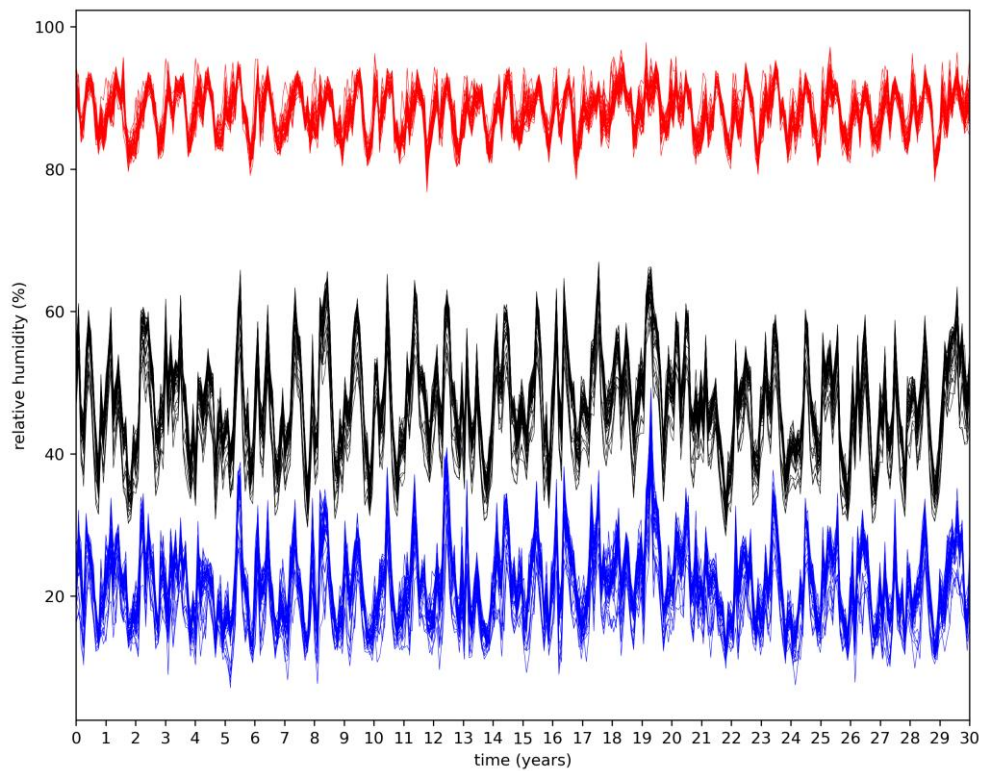


Figure 7: Timeseries of maximum (red), mean (black) and minimum (blue lines) monthly-mean relative humidity over Australia for the 30 years of each output QQ-scaled relative humidity projection file.

Downwards solar radiation at the surface projections also all appear to have correct annual cycles, values within expected ranges, and no sudden changes in the mean, maximum or minimum (Figure 8).

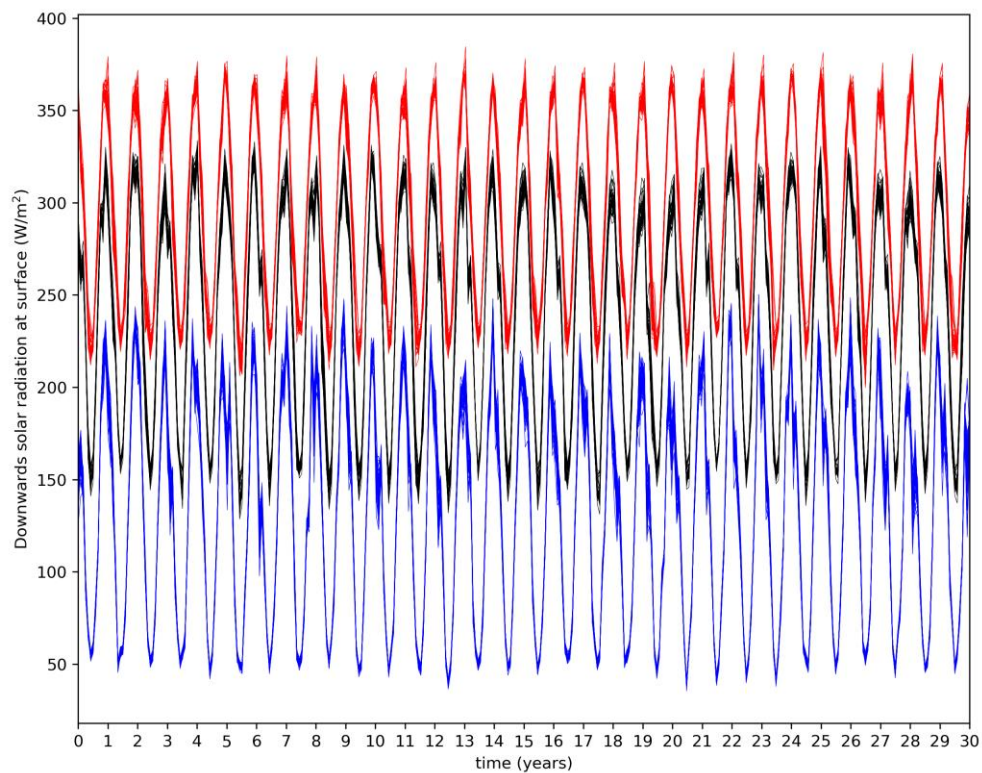


Figure 8: Timeseries of maximum (red), mean (black) and minimum (blue lines) monthly-mean downwards solar radiation at surface over Australia for the 30 years of each output QQ-scaled downwards solar radiation projection file.

A histogram of the distribution of the data in every file is also examined, to ensure that the data values within the file are plausibly distributed, with clear modes and tails in the distribution. Based on these checks, the data within the files checked appears to be suitable for use, with the exception of the CESM1-CAM5 RCP2.6 projections for 2056-2085 for tasmax identified above. An example histogram, for the NorESM1-M RCP4.5 2056- 2085 tasmax projection, is below, showing a clear mode and well defined tails (Figure 9).

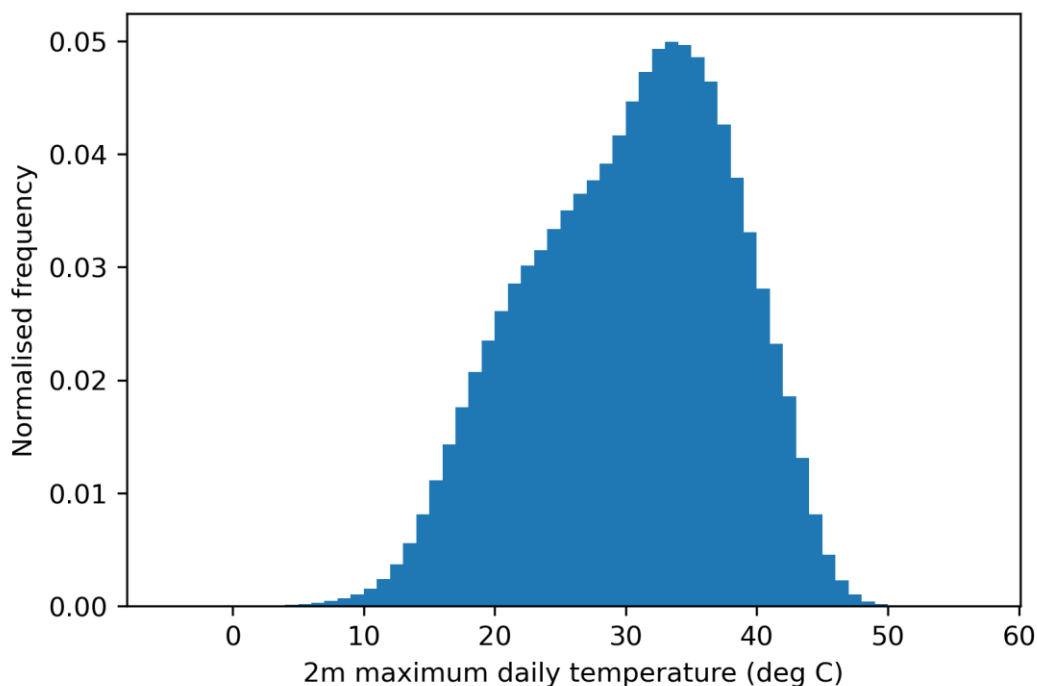


Figure 9: Histogram of daily maximum temperatures at all gridpoints from the NorESM1-M RCP4.5 2056- 2085 projection file.

BEYOND CURRENT SCOPE: Checks for value errors or variability errors that do not cause apparent issues in the mean or minimum/maximum values for each dataset.

BEYOND CURRENT SCOPE: Direct comparison in the values and variability between the projections and the baseline data (due to the nature of the QQ-scaling, it is assumed that projection values correlate to the baseline data where there are no errors in the output files).

5.3 Spatial patterns/orientation checks

Assurance that the data within the files meets the expected spatial orientation (with longitude/latitude as the default x/y axis in the data) as well as meeting a plausible spatial pattern. This process is undertaken by visual inspections of snapshots of the spatial pattern of data at two randomly selected timesteps in each file (Figure 10). Only the CESM1-CAM5 RCP2.6 2056-2085 daily maximum temperature file had spatial patterns that were vastly implausible, related to the issues flagged in section 5.2 – however, this file is not included in the final product.

Some small orientation issues were found with the 3 following CESM1-CAM5 output files, where latitude is the default x-axis instead of longitude:

- pr, RCP2.6, 2036-2065
- pr, RCP2.6, 2056-2085
- tasmin, RCP2.6, 2056-2085

This issue should not be a problem within robust code, but can be circumvented by reordering data before plotting, or explicitly calling latitude and longitude dimensions in plotting.

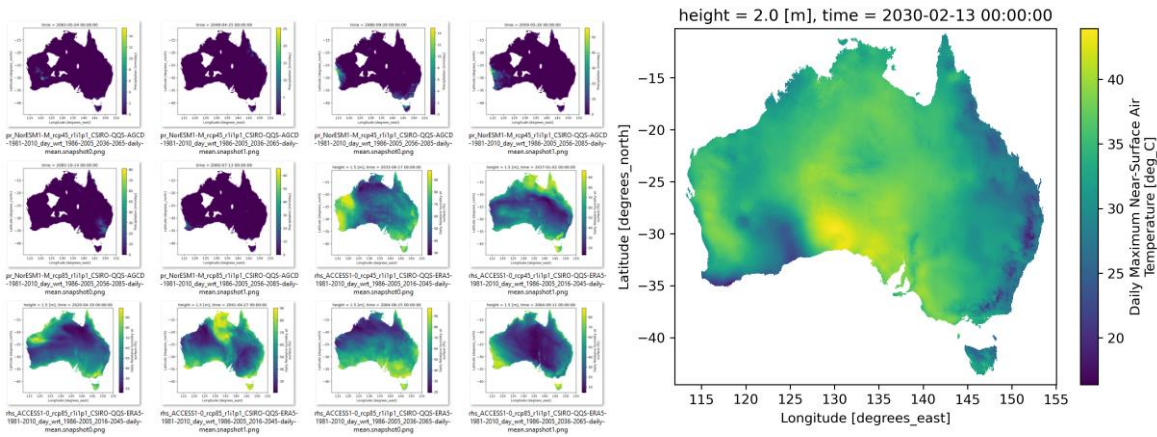


Figure 10: Examples of some of the spatial pattern snapshots used in the visual assessment (left), along with a detail of a snapshot for the NorESM1-M RCP4.5 2016-2045 daily maximum temperature projections (right).

BEYOND SCOPE: Full inspection of spatial patterns at all timesteps within datasets.

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