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Future climate data for 100 prospective Australian solar energy sites.

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September 2014

A report for Exemplary Energy

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Citation

Clarke JM, Heady C and Webb L. (2014) Future climate data for 100 prospective Australian solar energy sites. A report for Exemplary Energy. CSIRO, Australia

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Acknowledgments

We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Government Department of Energy.

This work was jointly funded in 2011/12 by the CSIRO and the (then) Commonwealth Department of Climate Change.

The work of the authors also draws upon research findings of many colleagues within CSIRO Marine and Atmospheric Research and overseas research institutions. In particular, Dr Penny Whetton, Kevin Hennessy, Tim Erwin and David Kent were instrumental in the development of the Climate Futures methodology. CSIRO climate models were developed by members of CSIRO Marine and Atmospheric Research.

Executive summary

Exemplary Energy undertook an assessment of the potential suitability of 100 Australian sites for solar energy generation up to 2050.

These standards are based on energy consumption modelling conducted using a standard set of meteorological data, called a Reference Meteorological Year, for each site. In order to evaluate the likely implications of future climate change on these standards, Exemplary Energy modified the Reference Meteorological Years according to the projected regional changes in key meteorological variables identified by Exemplary Energy for 100 sites around Australia.

To support this work, CSIRO provided projected seasonal and monthly change values for each of the 100 sites for 2030 and 2050 for low (B1), mid-range (A1B) and high (A1FI) greenhouse gas and aerosol emissions scenarios. To obtain these data, CSIRO's Representative Climate Futures methodology (Clarke *et al.* 2011; Whetton *et al.* 2012) was used to group regional climate projections from 21 climate models into plausible futures (such as "Hotter and drier").

The change values provided were used by Exemplary Energy to modify the Reference Meteorological Year to produce plausible future time-series datasets (called Ersatz Meteorological Years) to represent the best case, worst case and maximum consensus future climates. The results of Exemplary Energy's analysis will be published elsewhere.

1 Introduction

Exemplary Energy (www.exemplary.com.au) undertook an assessment of 100 sites across Australia to identify their potential suitability for solar energy generation in a changing climate up to 2050. They assessed the suitability of prospective sites using a standard set of meteorological data called a Reference Meteorological Year for each site. In order to evaluate the likely implications of future climate change on site suitability, Exemplary Energy modified the Reference Meteorological Year according to the projected changes in key meteorological variables for each site.

In this report, CSIRO details the methods used to provide projected seasonal and monthly change values for each of the 100 sites for a low (B1), mid-range (A1B) and high (A1FI) greenhouse gas and aerosol emissions scenario for the mean climate of 2030 and 2050. To obtain these data, CSIRO's Representative Climate Futures Framework methodology (Clarke *et al.* 2011; Whetton *et al.* 2012) was used, in consultation with Exemplary Energy, to group regional climate projections from up to 21 global climate models into plausible futures (such as "Hotter and drier"). For each site, representative 'best case', 'worst case' (as defined by Exemplary Energy) and 'most likely case' models were identified. Projected changes from these models were then provided digitally to Exemplary Energy.

The change values provided were used by Exemplary Energy to modify the individual Reference Meteorological Years to produce plausible future time-series datasets representative of each case.

1.1 Global Climate Change Context

In 1988, the United Nations Environment Programme and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC). This comprises many of the world's experts on climate change, and produces authoritative reviews of our knowledge of climate change. The most recent review includes a summary describing observed climate change and its causes (IPCC 2013).

Our understanding of warming and cooling influences on climate has improved in the past decade, leading to extremely high confidence that human activities have had a warming effect since the Industrial Revolution, around 1750. The largest human contribution comes from increases in greenhouse gases, such as carbon dioxide, methane and nitrous oxide, whose atmospheric concentrations have increased by 40%, 150% and 20%, respectively. The carbon dioxide increases are due primarily to fossil fuel use and land-use change, while increases in methane and nitrous oxide are primarily due to agriculture (IPCC 2013).

The Earth's average surface temperature has increased by about 0.89°C since the beginning of the 20th Century. The past three decades have all been warmer than any previous decade on record. The past decade was the warmest on record. Most of the warming since 1950 is extremely likely due to increases in atmospheric greenhouse gas concentrations associated with human activities. The warming has been linked with more heatwaves, changes in precipitation patterns, reductions in sea ice extent and rising sea levels (IPCC 2013).

1.2 Climate Change Context for Australia

Australian-average annual temperatures have increased by about 1°C since 1910. Most of this warming has occurred since 1950 (Figure 1), with greatest warming in the east and south-west (Figure 2). The north-west of Australia has seen a small (<0.1°C/decade) cooling trend in this period. The warmest year on record is 2013, which was 1.2°C above the 1961-1990 average, and marked the end of the equal-warmest decade on record (Australian Bureau of Meteorology 2014a). Daytime maximum temperatures have increased by 0.8°C while overnight minimum temperatures have increased by 1.1°C since 1910 (CSIRO and Australian Bureau of Meteorology 2014)

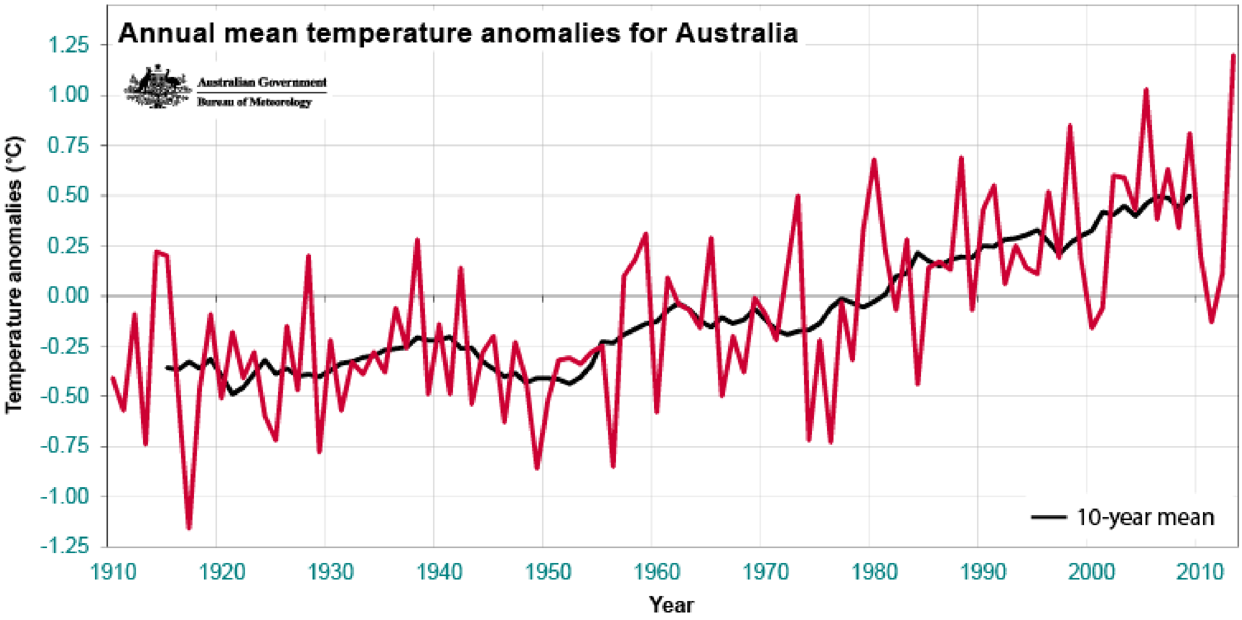

Figure 1 Australian-average annual temperature anomalies from 1910-2013 relative to the average for the 1961-1990 period. Source: Australian Bureau of Meteorology 2014a

Since 1950, most of eastern and south-western Australia has become drier (Figure 2). In New South Wales and Queensland, rainfall trends partly reflect a very wet period around the 1950s, though recent years have been unusually dry. In south-eastern Australia, the twelve-and-a-half year rainfall average from October 1996 to May 2009 was the lowest within the instrumental period since 1900 (Timbal 2009). In contrast, north-western Australia has become wetter over this period, mostly during summer. Since 1950, the frequencies of very heavy rainfall events (over 30 mm/day) and wet days (at least 1 mm/day) have decreased in the south and east but increased in the north (Figure 3). Natural variability continues to be the major contributor to extreme rainfall, with a possible small contribution from climate change (CSIRO and Australian Bureau of Meteorology 2014)

Australian rainfall shows considerable variability from year-to-year, partly due to the El Niño Southern Oscillation (ENSO). El Niño events tend to be associated with hot and dry years in Australia, and La Niña events tend to be associated with mild and wet years (Power *et al.* 2006). There has been a marked increase in the frequency of El Niño events and a decrease in La Niña events since the mid-1970s (Power and Smith 2007).

Solar radiation is closely linked to cloud cover and hence rain. Trends in cloud cover since 1960 (Figure 4) show a mixture of increases (particularly in arid areas) and decreases (e.g. Victoria and large a large part of NSW).

Trends in wind speed are difficult to determine due to a lack of high quality data. A study that used interpolation between high quality stations found that wind speeds declined over the period 1975-2006 (McVicar *et al.* 2008). The majority of Australia (88%) exhibits a reduction in wind-speed, with 57% of the area having statistically significant decreases, *e.g.* between Adelaide and Cape Otway (Figure 4).

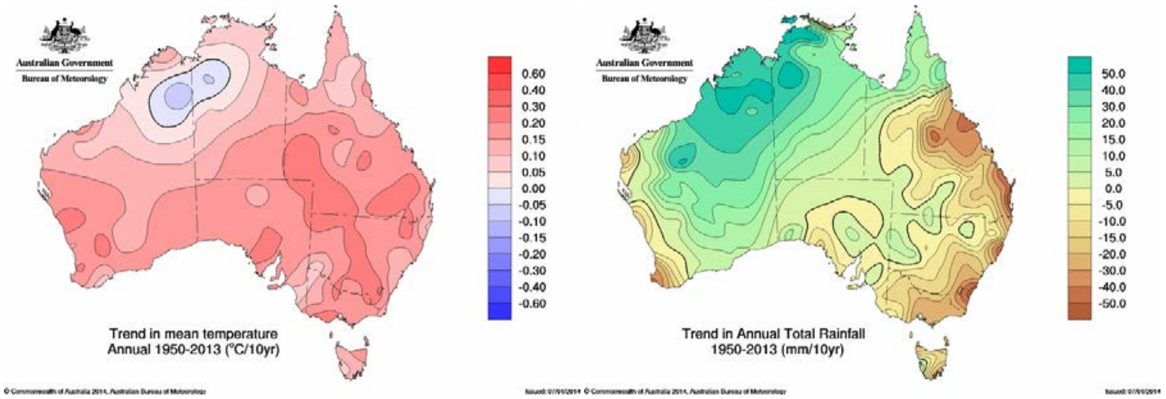

Figure 2 Trends in annual mean temperature and rainfall since 1950. Source: Australian Bureau of Meteorology 2014c

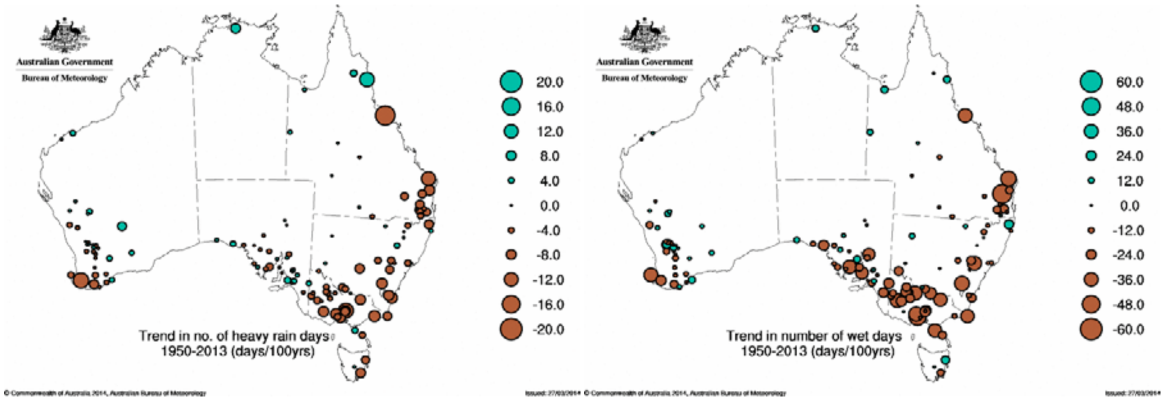

Figure 3 Trends in the frequencies of very heavy rain days (over 30 mm/day) and wet days (at least 1 mm/day) since 1950. Source: Australian Bureau of Meteorology 2014b

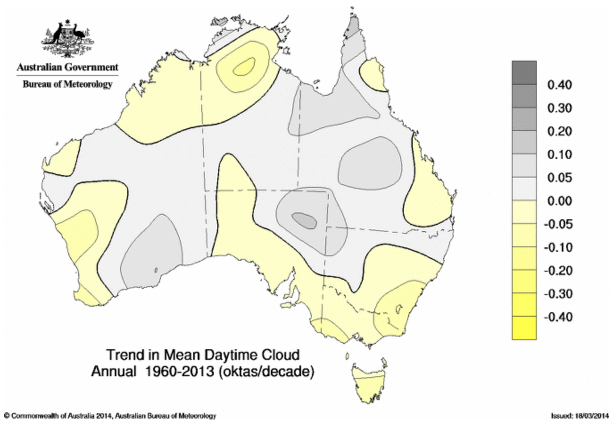

Figure 4 Trends in mean daytime cloud cover (in oktas per decade) since 1960 Source: Australian Bureau of Meteorology 2014c

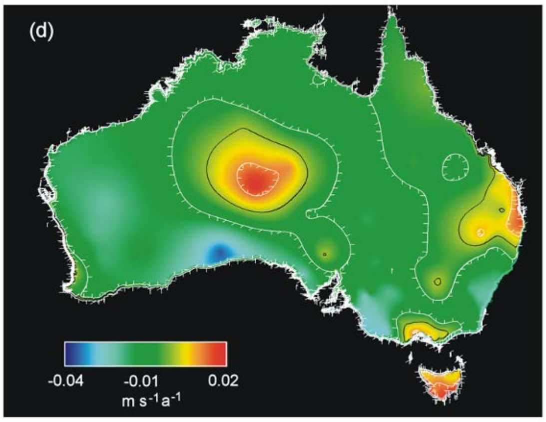

Figure 4: Wind-speed trends from 1975-2006. Black lines show no change and white lines show significant trends with barbs pointing to increased significance. Source: McVicar *et al.* 2008).

1.3 This Study

Exemplary Energy undertook an evaluation of prospective solar energy sites throughout Australia.

The suitability of a site for solar energy applications is dependent primarily on the quantity of incoming direct solar radiation. Daily maximum temperatures are also important as the efficiency of photovoltaic cells diminishes as temperature increases. Housing energy rating standard representative climate data sets called Reference Meteorological Years (RMYs) were available for each of the 100 sites selected for analysis. These comprise a 12-month set of representative hourly data selected from weather observations from a 41 year period centred on 1987. Equivalent datasets were generated by Exemplary Energy to align with the climate projections reference baseline – the two decades centred on 1990. In order to evaluate the influence of a changed future climate for this study, Exemplary Energy chose to 'perturb' the RMY hourly values by the projected changes in key meteorological variables to create a plausible synthetic future RMY (Exemplary Energy refer to this as an "ersatz future meteorological year" - EFMY).

2 Models, Emissions, Assumptions and Limitations

To provide a basis for estimating future climate change, 40 greenhouse gas and sulphate aerosol emission scenarios were prepared for the 21st century by the IPCC (Nakićenović and Swart 2000), based on a variety of assumptions about demographic, economic and technological factors likely to influence future emissions. The climatic effects of projected changes in emissions can be simulated using climate models, which are mathematical representations of the Earth's climate system based on well-established laws of physics, such as conservation of mass, energy and momentum. CSIRO has access to monthly data for up to 12 climate variables from up to 24 global climate models from 1900-2100 for 3 emission scenarios (A1B, A2 and B1). Some results can also be scaled for the highest emission scenario (A1FI).

The future climate is strongly influenced by inherently uncertain factors, so it is not possible to make definitive climate predictions for decades ahead. Uncertainties in projected regional climate to 2030 are mostly due to the natural variability simulated by the climate models rather than the different emissions scenarios. Nevertheless, to facilitate direct comparison between time periods, projections for 2030 and 2050 were developed for the IPCC's low B1, mid-range A1B and high A1FI emissions scenarios (Nakićenović and Swart 2000).

Projections can be created in a number of ways, depending on the intended purpose. Two common examples are described below.

If projections are needed for general communication, with a focus on quantifying the range of possibilities across all available models for one climate variable at a time, then it is appropriate to combine results from multiple climate models. This has been done using a method that produces probabilistic distributions for future changes in a range of climate variables for Australia (CSIRO and Australian Bureau of Meteorology 2007a, Ch 5) and Victoria (Vic DSE 2008).

If projections are needed for a detailed risk assessment, with a focus on internally consistent changes between climate variables, then it is inappropriate to combine multi-model results (CSIRO and Australian Bureau of Meteorology 2007a, Ch 6). Projections should instead be based upon individual model results.

However, working with projections from 24 different climate models and multiple emissions scenarios and time scales can be very complex. This can be simplified for a given region by grouping the individual model projections into a set of "Climate Futures" (Clarke *et al.* 2011; Whetton *et al.* 2012), such as:

- Warmer, wetter (10 models)
- Warmer, drier (4 models)
- Hotter, drier (5 models)
- Hotter, much drier (1 model)
- Warmer, much drier (2 models)
- Hotter, much wetter (2 models)

These can then be used to select Climate Futures that are considered by the client as being relevant for the risk assessment in question. Within those Climate Futures, data from representative models can be derived.

3 Climate Change Analysis

3.1 Data and methods

Projections

The data provided are derived from the Climate Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. CSIRO applied a 'pattern-scaling' method (see CSIRO and Australian Bureau of Meteorology 2007b) to these model results to enable calculation of projections for emissions scenarios for which no model runs exist (such as the A1FI scenario). This method has the effect of 'smoothing' the interannual variability from the projections thus largely isolating the climate change 'signal' from the natural variability.

Although 24 global climate models from the CMIP3 archive were available, five models (CGCM3.1-T47, IPSL-CM4, GISS-AOM, GISS-EH and PCM) were identified as performing poorly against multiple criteria, while a sixth (GISS-ER) was found to poorly represent variability in the El Niño – Southern Oscillation (ENSO; Smith and Chandler 2010), which is important for rainfall, temperature and humidity in Australia. A seventh model (INM-CM3) has also been shown to perform poorly in multiple tests in the Pacific region, including its simulation of ENSO (Irving *et al.* 2011). Consequently, these seven models were excluded for this work. This reduced the pool of available models from 24 to 17 models.

For this study, internally consistent Climate Futures were determined in consultation with Exemplary Energy. The climate variables of interest were (with priority) seasonal-mean changes in:

- solar radiation (1),
- maximum temperature (1),
- minimum temperature (1),
- wind speed (2) and,
- relative humidity (3).

To facilitate generation of the projections for each of the 100 sites, Australia was divided into grids of 5° latitude and 5° longitude (Figure 5). The Climate Futures approach was then used to identify two key climate futures of interest to Exemplary Energy: the 'maximum consensus' climate future (that is the future represented by the greatest number of models) and the 'worst case' climate future (defined by Exemplary Energy as that with the greatest increase in temperature, particularly in summer). The Australian Climate Futures research tool (Clarke *et al.* 2011) was then used to identify one model to represent each case for 2030 and 2050 (B1, A1B and A1FI).

Across almost all grids, the CSIRO-Mk3.5 model was determined to adequately represent the worst case future for all time periods and emissions scenarios. The most representative model for the maximum consensus climate future varied with location. The model selections are shown in Table 1. In some cases, there was no clearly identifiable maximum consensus future. In these instances, a model that produced a mid-range summer temperature change was deemed to represent the maximum consensus future. In other cases, there was no clearly identifiable worst case future. In these instances, a model that produced the highest summer temperature change was selected.

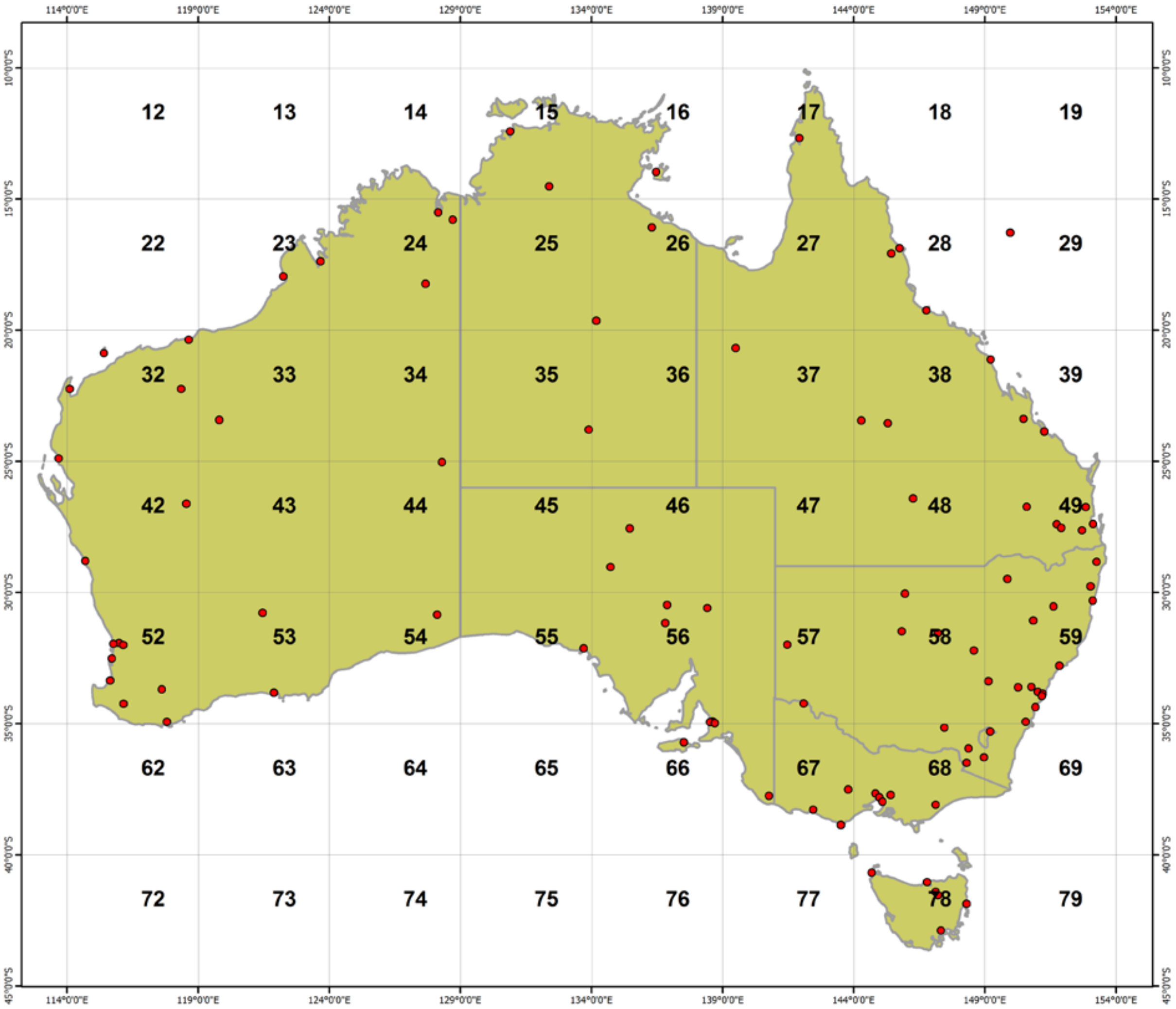

Figure 5 Numbered grids used to generate projections for each of the 100 sites (red dots). Each grid is 5° latitude × 5° longitude in size.

Climate Variables

The climate variables obtained from the model projections are provided as changes relative to the period 1975 – 2004 (*i.e.* 30 years centred on 1990). This is comparable to the IPCC reference period of 1981 – 2000 (a 20-year period centred on 1990). Details of the climate variables, their units of measure and their units of projected change are given in Table 2.

In some cases, data for maximum and minimum temperature were not available from the selected representative climate model. In this case, mean, maximum and minimum temperature data were provided from additional models for comparative purposes only. This allowed Exemplary Energy to evaluate the likely effect of using the projected changes in mean temperature as a substitute for maximum and minimum temperature change values.

Table 1 Sites and representative models for each of the 31 grids

Grid	Sites	Max Consensus model	Worst Case model
15	Darwin NT, Katherine NT	CNRM-CM3	CSIRO-Mk3.5
16	Angurugu (Groote Eylandt) NT	CNRM-CM3	MIROC3.2(medres)
17	Weipa NT	CNRM-CM3	MIROC3.2(medres)
23	Derby WA, Broome WA	CNRM-CM3	CSIRO-Mk3.5
24	Wyndham WA, Kununurra WA, Hall's Creek WA	CNRM-CM3	CSIRO-Mk3.5
26	Borroloola (Macarthur River) NT, Tennant Creek NT	CNRM-CM3	CSIRO-Mk3.5
28	Cairns Qld, Atherton Tableland Qld, Townsville Qld	FGOALS-g1.0	CNRM-CM3
29	Willis Island	CNRM-CM3	MIROC3.2(medres)
32	Port Headland WA, Barrow Island WA, Learmonth WA, Pilbara WA, Carnarvon WA	CNRM-CM3	CSIRO-Mk3.5
33	Newman WA	CNRM-CM3	CSIRO-Mk3.5
35	Giles NT, Alice Springs NT	CNRM-CM3	CSIRO-Mk3.5
37	Mt Isa Qld	CNRM-CM3	CSIRO-Mk3.5
38	Longreach Qld, Barcaldine Qld	FGOALS-g1.0	CSIRO-Mk3.5
39	Mackay Qld, Rockhampton Qld, Gladstone Qld	CNRM-CM3	CSIRO-Mk3.5
42	Meekatharra WA, Geraldton WA	CNRM-CM3	CSIRO-Mk3.5
46	Oodnadatta SA, Coober Pedy SA	CNRM-CM3	CSIRO-Mk3.5
48	Charleville Qld	CNRM-CM3	CSIRO-Mk3.5
49	Kogan Creek Qld, Maleny Qld, Brisbane Qld, Oakey Qld, Toowoomba Qld, Amberley Qld, Lismore NSW, Moree NSW, Grafton NSW	CNRM-CM3	CSIRO-Mk3.5
52	Perth WA, Swanbourne WA, Bickley WA, Mandurah WA, Bunbury WA, Katanning WA, Manjimup WA, Albany WA	FGOALS-g1.0	CSIRO-Mk3.5
53	Kalgoorlie WA, Esperance WA	CNRM-CM3	CSIRO-Mk3.5
54	Forrest WA	CNRM-CM3	CSIRO-Mk3.5
55	Ceduna SA	MRI-CGCM2.3.2	CSIRO-Mk3.5
56	Roxby Downs SA, Leigh Creek SA, Woomera SA, Adelaide SA, Adelaide Airport SA, Mt Loft SA	MRI-CGCM2.3.2	CSIRO-Mk3.5
57	Broken Hill NSW, Mildura Vic	CNRM-CM3	CSIRO-Mk3.5
58	Bourke NSW, Cobar NSW, Nyngan NSW, Dubbo NSW	CNRM-CM3	CSIRO-Mk3.5
59	Coffs Harbour NSW, Armidale NSW, Tamworth NSW, Williamtown NSW, Orange NSW, Richmond NSW, Blue Mountains NSW, Parramatta NSW, Sydney NSW, Mascot (Sydney Airport) NSW, Wollongong NSW, Nowra NSW	MRI-CGCM2.3.2	CSIRO-Mk3.5
66	Kingscote (Kangaroo Is) SA	MRI-CGCM2.3.2	CSIRO-Mk3.5
67	Mt Gambier SA, Ballarat Vic, Warrnambool Vic, Cape Otway Vic	CNRM-CM3	CSIRO-Mk3.5
68	Wagga Wagga NSW, Cabramurra NSW, Thredbo NSW, Tullamarine Vic, Coldstream Vic, Melbourne Vic, Moorabbin Vic, East Sale Vic	MIROC3.2(medres)	CSIRO-Mk3.5
69	Canberra ACT, Cooma NSW	MRI-CGCM2.3.2	CSIRO-Mk3.5
78	Cape Grim Tas, Low Head Tas, Launceston (Ti Tree Bend) Tas, Launceston Tas, Bicheno Tas, Hobart Tas	MIROC3.2(medres)	CSIRO-Mk3.5

Monthly change data

These data were provided from the relevant global climate model output, averaged (using an equal area average method) over the 5° latitude × 5° longitude grid-square encompassing the location of interest (see Figure 5).

Table 2 Details of climate variables provided by the model projections

Variable	Units of measure	Units of change	Notes
Monthly mean temperature	°C	°C	Temperature at 2 m above the ground
Monthly mean solar radiation	$W.m^{-2}$	%	Surface downward shortwave radiation (equivalent to 'global radiation')
Monthly mean minimum temperature	°C	°C	Minimum temperature at 2 m above the ground
Monthly mean maximum temperature	°C	°C	Maximum temperature at 2 m above the ground
Monthly mean wind speed	$m.s^{-1}$	%	Calculated from eastward and northward components at 10 m above the ground
Monthly mean relative humidity	%	%	

4 Climate projections

Data were provided in electronic form. Due to the volume of data, they are not reproduced here however they can be obtained by contacting the authors.

In 26 of the 31 grids, data for maximum and minimum temperature (Tmax and Tmin, respectively) were not available from the selected models. This is indicated by "N/A" in the data tables supplied. In these cases, a set of maximum, minimum and mean temperature changes for the appropriate grid were supplied for analysis. Exemplary Energy used these data to develop a method to estimate changes in maximum and minimum temperature with periodic interpolation for temperatures at other times of the day.

5 Applying the projections

Projected seasonal and monthly changes were calculated relative to a 30 year period centred on 1990. This is close to the time period from which the Reference Meteorological Year (RMY) is derived (40 years centred on 1987). Accordingly, the change values can be applied directly to the RMY without additional processing.

Temperature (mean, maximum and minimum)

Since temperature change values are expressed in degrees Celsius, temperature values in the Reference Meteorological Year (RMY) can be scaled up for a selected future time-frame by simply adding the corresponding change value.

Relative humidity, solar radiation and wind speed

Relative humidity (%), solar radiation ($W.m^{-2}$) and wind speed ($m.s^{-1}$) change values are expressed as percentage change. Thus to modify a value from the RMY for a selected future time period, the projected percentage change should be added. In the case of relative humidity, applying a percentage change to a value that is expressed in percentage is potentially confusing, so an example is provided below.

Relative humidity value (hypothetical) for location on 15 July from RMY: 50%

Projected winter change for location in 2050 under the A1FI emissions scenario: -10%

Projected relative humidity value for 15 July in the 2050 RMY = 50 + (50 × -0.10) = 45%

If the scaling method is to be applied, we would suggest applying the change in maximum temperature for the relevant month to RMY data for 2 pm and the change in minimum temperature to RMY data for the sunrise hour, with linear interpolation of the scaling factor in between.

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