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An introduction to internally consistent climate projections

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EXECUTIVE SUMMARY

This report addresses the need for internally consistent climate projections for use in impact assessments that inform adaptation planning. The most common way of doing this is to use the output from individual global climate model simulations driven by plausible scenarios of greenhouse gas and aerosol emissions. However, using up to 23 models would be a significant undertaking. Many of the scientists undertaking risk assessments have limited resources, so they prefer using a subset of models. Selecting the most suitable subset is a major challenge.

To assist in communicating climate projections and to guide model selection, CSIRO has developed an approach called Climate Futures. It groups projections from the 23 models into a small set of broad categories with simple descriptions, e.g. warmer and wetter, hotter and drier. The novel feature in Climate Futures is the ability to assess the likelihood of combined changes in two climate variables. It is then easy to identify the full range of possibilities including the 'Most Likely', 'Best Case' or 'Worst Case' futures.

A subset of climate futures can be chosen to suit a particular impact assessment. The most relevant futures usually include the 'Most Likely' future, plus one or two others. Each of these futures is represented by results from a number of climate models. An optimisation function identifies which model has projections that are most representative of the mean of each climate future. This small set of representative models can then be used in impact assessments. An example is provided for western Victoria.

The Climate Futures approach has been developed and tested in 14 Pacific nations and East Timor. Feedback from training in the Pacific Climate Futures web-tool has been very positive. Projections from the tool are being used in impact assessments, presentations and reports. A similar tool is being developed for Australia.

1. INTRODUCTION

The climate is changing. Since the year 1900, global average surface temperature has risen about 0.9^{o}C and global average sea level has risen about 21 cm. In many regions, there has been an increase in hot days and heavy rainfall, a reduction in cold days and ice cover, and oceans have become more acidic due to higher levels of carbon dioxide (CSIRO and BoM, 2012).

It is very likely that most of the observed global warming since the mid 20th century is due to man-made increases in greenhouse gases. Discernible human influences extend to other aspects of climate including ocean warming, continental-average temperatures, temperature extremes, wind patterns, reductions in Arctic sea ice, increasing atmospheric moisture, global and regional patterns of precipitation changes, and increases in ocean salinity in the tropical Atlantic (CSIRO and BoM, 2012).

The complexity of the climate system means that we cannot simply extrapolate past trends to forecast future conditions. Instead, scientists use climate models to estimate future climate change. These models are computer programs that represent the climate system based on our understanding of the laws of physics. Model simulations are evaluated against historical climate observations. Simulations of the future have been driven by a number of greenhouse gas and sulphate aerosol emission scenarios, based on a variety of assumptions about demographic, economic and technological factors. These climate projections have been used in impact assessments that inform adaptation planning (IPCC, 2007).

Typically, climate projections are produced for individual climate variables, for selected years and emissions scenarios. Results from different climate models are then combined, and projections are expressed as a central estimate with a range of uncertainty, e.g. a warming of 1.5^{o}C (range 1-2^{o}C) and a rainfall increase of 10% (range 5-15%). Projections for Australia, based on this method, were produced by CSIRO and the Bureau of Meteorology (CSIRO and BoM, 2007).

This is suitable for general communication, but it may not be suitable for detailed risk assessments involving multiple variables, such as temperature, rainfall and wind. Correlations between changes in different variables must be taken into account. For example, if greater warming occurs with larger rainfall increases (Figure 1), then it would be plausible to expect a warming of 2^{o}C with a rainfall increase of 15%, but it would be implausible to expect this warming to occur with a rainfall increase of only 5%. When such correlations are strong, care is needed to ensure that these correlations are represented in the projections. In other words, there should be internal consistency between projected changes in different variables.

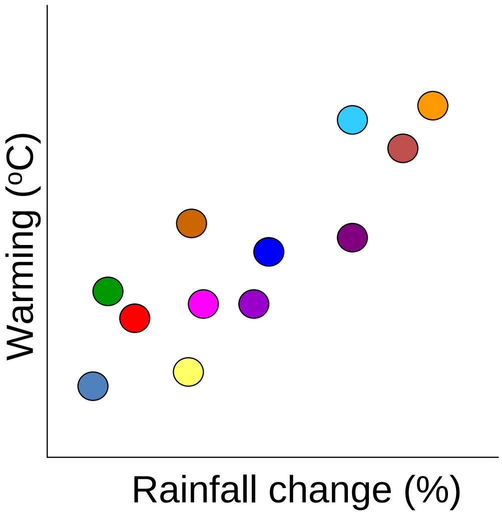


Figure 1: Schematic diagram of projected changes in temperature and rainfall for a given region based on output from 12 climate models. This illustrates a strong correlation between the changes that should be represented in projections for that region.

Projections based on individual climate models preserve internal consistency among climate variables. This consistency is lost when results from different models are combined. Therefore, CSIRO has developed model-specific projections for a variety of climate variables, years and emission scenarios. This report focuses on eastern Victoria, as a test region.

2. CLIMATE FUTURES APPROACH

The problem

CSIRO has monthly data for 12 climate variables from up to 23 global climate models from 1900-2100 for 3 emission scenarios (A1B, A2 and B2). However, working with projections from 23 different climate models is very complex, time consuming and computer-intensive. Clients often ask for a subset of climate models for use in risk assessment, but the process of selecting models depends on a number of criteria:

- Availability of climate data: unfortunately, some climate variables are not available from all climate models. While monthly temperature and rainfall are available from all 23 models, only 19 models have monthly solar radiation and wind-speed, 14 have monthly humidity and evaporation, 8 have daily temperature, 16 have daily rainfall, and 20 have daily wind-speed. Monthly data are available from 1900-2100, but daily data are only available for 1960-1999, 2046-2065 and 2080-2099. If more than one variable is needed for a risk assessment, this is likely to limit the total number of models with suitable data.
- Importance of variables: if higher priority is given to some variables, this may alter the models chosen, e.g. if daily temperature and rainfall are needed, the number of models with both is very limited.
- Reliability of climate models: some models reproduce observed climate processes and statistics better than others. Those that perform poorly should not be used for climate projections.
- Risk framing: does the risk assessment require a “most likely” scenario, or does it include less likely scenarios that may have large / small impacts?

Producing simple climate futures

To guide model selection, CSIRO has developed a web-based tool called Climate Futures (Whetton et al, 2010). It allows the user to choose a year (2030, 2050 or 2070) and an emission scenario (B1-low, A1B-medium or A1FI-high). These options are common to a number of tools, such as MAGICC, OzClim and SimClim. However, the novel feature in Climate Futures is the ability to explore combined changes in two primary climate variables, selected from:

- mean temperature,
- maximum temperature,
- minimum temperature,
- rainfall,
- downward solar radiation,
- wind-speed,
- relative humidity.

Annual, seasonal or monthly average projections can be chosen. All projections are relative to a 30-year period centred on 1990 (the IPCC base year).

A common starting point is to choose annual-average temperature and rainfall, for a given year and emission scenario. A map of Australia is displayed with a 5 degree latitude-longitude grid. The user can select a region of interest by clicking a grid-box. The tool then groups the temperature and rainfall projections into a set of “climate futures”, e.g.

- Warmer, wetter
- Warmer, little rainfall change
- Warmer, drier
- Hotter, drier
- Hotter, much drier
- Warmer, much drier
- Hotter, much wetter

An example for a gridcell over western Victoria is given in Table 1 for 2030 (medium A1B emissions), 2050 (high A1FI emissions) and 2070 (high A1FI emissions). The matrix shows annual mean changes for four temperature categories and five rainfall categories. In each cell, the proportion of models is given in absolute terms and as a percentage (which may be interpreted as a relative likelihood or probability).

Table 1: Climate Futures for western Victoria in 2030, 2050 and 2070, based on changes in annual mean temperature and rainfall from 23 climate models, relative to 30 years centred on 1990.

2030 A1B	Annual temperature change (°C)				
		Slightly warmer 0 to 0.5	Warmer 0.5 to 1.5	Hotter 1.5 to 3.0	Much hotter > 3.0
Annual rainfall change (%)	Much drier < -15				
	Drier -15 to -5		7 of 23 models (30%)		
	Little change -5 to +5	3 of 23 models (13%)	13 of 23 models (56%)		
	Wetter +5 to 15				
	Much wetter > 15				

2050 A1FI	Annual temperature change (°C)				
		Slightly warmer 0 to 0.5	Warmer 0.5 to 1.5	Hotter 1.5 to 3.0	Much hotter > 3.0
Annual rainfall change (%)	Much drier < -15		1 of 23 models (4%)	1 of 23 models (4%)	
	Drier -15 to -5		8 of 23 models (34%)	6 of 23 models (25%)	
	Little change -5 to +5		5 of 23 models (21%)	2 of 23 models (8%)	
	Wetter +5 to 15				
	Much wetter > 15				

2070 A1FI	Annual temperature change (°C)				
		Slightly warmer 0 to 0.5	Warmer 0.5 to 1.5	Hotter 1.5 to 3.0	Much hotter > 3.0
Annual rainfall change (%)	Much drier < -15		1 of 23 models (4%)	7 of 23 models (30%)	2 of 23 models (8%)
	Drier -15 to -5		1 of 23 models (4%)	8 of 23 models (34%)	
	Little change -5 to +5			3 of 23 models (13%)	1 of 23 models (4%)
	Wetter +5 to 15				
	Much wetter > 15				

Analysing the climate futures

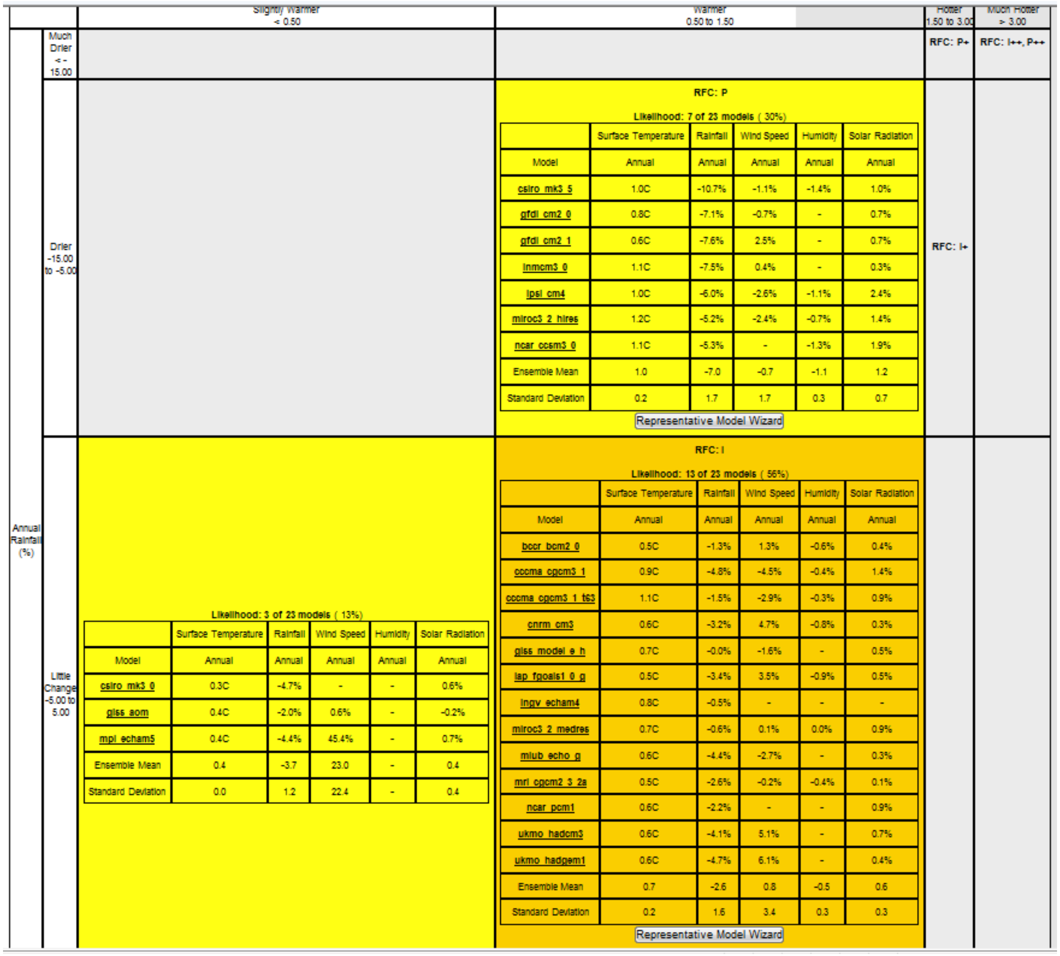
Each matrix provides a simple description of the range of climate futures produced by the climate models. In Table 1, by 2030, the most likely climate future for emission scenario A1B is ‘Warmer – Little change in rainfall’ (13 models). By 2050, the most likely future for emission scenario A1FI is ‘Warmer – Drier’ (8 models). By 2070, the most likely future for emission scenario A1FI is ‘Hotter –Drier’ (8 models). Some of the other futures may represent a low probability ‘best case’ or ‘worst case’, depending on the context, which could be worth considering in a risk assessment. For example, in 2070, there is an 8% chance of a ‘Much hotter - Much drier’ future.

In some cases, the most likely future is unclear because adjacent cells in the matrix have the equal-highest likelihood. In the Appendix, Table A1 shows an example for eastern Victoria where ‘Hotter and much drier’ and ‘Hotter and Drier’ are both 26% likely. The most likely future could be interpreted as ‘Hotter and Drier to Much drier’ with a 52% likelihood.

This level of detail is useful for general understanding of the changes that are projected by the climate models. It also allows identification of the particular climate futures that are of most relevance to the risk being assessed, e.g. water resource management, emergency management, renewable energy, agriculture, health. Further detail can be produced using various display options, such as showing:

- the magnitude of change for selected variables for each model (Table 2)
- changes for annual, half-yearly, three-monthly or monthly averaging periods
- likelihoods for different parings of variables, e.g. wind-speed and temperature (Table 3).

Table 2: Climate Futures for western Victoria in 2030 for the A1B emission scenario, based on changes in annual mean temperature and rainfall from 23 climate models, relative to 30 years centred on 1990. Units are % for all variables except temperature (^{o}C).



RFC: P

Likelihood: 7 of 23 models (30%)

	Surface Temperature	Rainfall	Wind Speed	Humidity	Solar Radiation
Model	Annual	Annual	Annual	Annual	Annual
csiro mk3 5	1.0C	-10.7%	-1.1%	-1.4%	1.0%
gfdl cm2 0	0.8C	-7.1%	-0.7%	-	0.7%
gfdl cm2 1	0.6C	-7.6%	2.5%	-	0.7%
inmcm3 0	1.1C	-7.5%	0.4%	-	0.3%
ipsl cm4	1.0C	-6.0%	-2.6%	-1.1%	2.4%
miroc3 2 hires	1.2C	-5.2%	-2.4%	-0.7%	1.4%
ncar ccsm3 0	1.1C	-5.3%	-	-1.3%	1.9%
Ensemble Mean	1.0	-7.0	-0.7	-1.1	1.2
Standard Deviation	0.2	1.7	1.7	0.3	0.7

Likelihood: 3 of 23 models (13%)

	Surface Temperature	Rainfall	Wind Speed	Humidity	Solar Radiation
Model	Annual	Annual	Annual	Annual	Annual
csiro mk3 0	0.3C	-4.7%	-	-	0.6%
giss aom	0.4C	-2.0%	0.6%	-	-0.2%
mpi echam5	0.4C	-4.4%	45.4%	-	0.7%
Ensemble Mean	0.4	-3.7	23.0	-	0.4
Standard Deviation	0.0	1.2	22.4	-	0.4

RFC: I

Likelihood: 13 of 23 models (56%)

	Surface Temperature	Rainfall	Wind Speed	Humidity	Solar Radiation
Model	Annual	Annual	Annual	Annual	Annual
bccr bcm2 0	0.5C	-1.3%	1.3%	-0.6%	0.4%
cccma cgcm3 1	0.9C	-4.8%	-4.5%	-0.4%	1.4%
cccma cgcm3 1 t63	1.1C	-1.5%	-2.9%	-0.3%	0.9%
cnrm cm3	0.6C	-3.2%	4.7%	-0.8%	0.3%
giss model e h	0.7C	-0.0%	-1.6%	-	0.5%
iap fgoals1 0 g	0.5C	-3.4%	3.5%	-0.9%	0.5%
ingv echam4	0.8C	-0.5%	-	-	-
miroc3 2 medres	0.7C	-0.6%	0.1%	0.0%	0.9%
miub echo g	0.6C	-4.4%	-2.7%	-	0.3%
mri cgcm2 3 2a	0.5C	-2.6%	-0.2%	-0.4%	0.1%
ncar pcm1	0.6C	-2.2%	-	-	0.9%
ukmo hadcm3	0.6C	-4.1%	5.1%	-	0.7%
ukmo hadgem1	0.6C	-4.7%	6.1%	-	0.4%
Ensemble Mean	0.7	-2.6	0.8	-0.5	0.6
Standard Deviation	0.2	1.6	3.4	0.3	0.3

Table 3: Climate Futures for western Victoria in 2030 for the A1B emission scenario, based on changes in annual-mean temperature and wind-speed from 19 climate models (limited by the availability of wind data), relative to 30 years centred on 1990.

2030 A1B	Annual temperature change (^{o}C)				
		Slightly warmer 0 to 0.5	Warmer 0.5 to 1.5	Hotter 1.5 to 3.0	Much hotter > 3.0
Annual wind-speed change (%)	Large decrease < -3		1 of 19 models (5%)		
	Decrease -1 to -3		6 of 19 models (31%)		
	Little change -1 to +1	1 of 19 models (5%)	4 of 19 models (21%)		
	Increase +1 to 3		2 of 19 models (10%)		
	Large increase > 3	1 of 19 models (5%)	4 of 19 models (21%)		

Choosing a subset of climate models for risk assessment

The next step is to simplify the information by choosing a subset of climate models that can be used in a risk assessment. The “Model Selection” menu allows the user to choose which variables are most important for their risk assessment, and the tool then selects a climate model that is most representative of a particular climate future, e.g. it can select the model that has changes closest to the multi-model mean in each cell of the matrix. Representative models for the ‘Most Likely’, ‘Best Case’ and “Worst Case’ futures for a water resource risk assessment are provided in Table 4.

For consistency, the same model should be selected across all time periods for a given future, e.g. the CNRM, HadCM3, MRI and IAP models represent the ‘Most Likely’ future for all time periods, the CSIRO Mk3.5 model represents the ‘Worst Case’ future for all time periods, and the GISS-EH model represents the ‘Best Case’ for all time periods. In some situations, the ‘Best Case’ or ‘Worst Case’ may also be the ‘Most Likely’.

Once the representative models have been chosen, projections for a variety of climate variables can be produced for each model. Examples for western Victoria are given in Tables 5, 6, and 7 for 2030, 2050 and 2070, respectively. It should be noted that using temperature and rainfall as the classifying variables provides internal consistency across most of the other variables too. For example, changes in relative humidity and solar radiation have at least moderate correlation with mean temperature or precipitation change. However, changes in wind-speed tend to be independent of changes in temperature and rainfall.

Improvements in our methods for populating the Climate Futures matrix are ongoing, so the values presented here should be considered preliminary in nature and may be adjusted in due course.

Table 4: Climate futures and representative models for western Victoria.

		Most Likely	Best Case	Worst Case
2030 A1B	**Description**	Warmer – Little rainfall change	Warmer – Little rainfall change	Warmer – Drier
	No. of models	13 of 23	13 of 23	1 of 23
	Representative model	CNRM	GISS-EH*	CSIRO-Mk3.5
2050 A1FI	**Description**	Warmer – Drier	Warmer – Little rainfall change	Hotter – Much drier
	No. of models	8 of 23	5 of 23	1 of 23
	Representative model	CNRM	GISS-EH	CSIRO-Mk3.5
2070 A1FI	**Description**	Hotter – Drier	Hotter – Little rainfall change	Much hotter – Much drier
	No. of models	8 of 23	3 of 23	2 of 23
	Representative model	CNRM	GISS-EH	CSIRO-Mk3.5

* considered Best Case because rainfall change is smallest

Table 5: Projected changes in annual mean temperature, rainfall, wind-speed, solar radiation and relative humidity for western Victoria. Changes are for the year 2030 and the A1B emission scenario for three internally-consistent climate futures (see Table 1), relative to 30 years centred on 1990. All changes are in %, except for temperature (^{o}C).

2030 A1B	**Climate future**		
	Most likely	**Best case**	**Worst case**
	Warmer, little rainfall change	***Warmer, little rainfall change***	***Warmer, drier***
	CNRM	**GISS-EH**	**CSIRO-Mk3.5**
Temperature	+0.6	+0.7	+1.0
Rainfall	-3.2	0	-10.7
Wind-speed	+4.7	-1.6	-1.1
Solar radiation	+0.3	+0.5	+1.0
Relative humidity	-0.8	N/A	-1.4

Table 6: Projected changes in annual mean temperature, rainfall, wind-speed, solar radiation and relative humidity for western Victoria. Changes are for the year 2050 and the A1FI emission scenario for three internally-consistent climate futures (see Table 1), relative to 30 years centred on 1990. All changes are in %, except for temperature (^{o}C).

2050 A1FI	**Climate future**		
	Most likely	**Best case**	**Worst case**
	Warmer, drier	***Warmer, little rainfall change***	***Hotter, much drier***
	CNRM	**GISS-EH**	**CSIRO-Mk3.5**
Temperature	+1.3	+1.4	+2.0
Rainfall	-6.7	-0.1	-21.0
Wind-speed	+9.8	-3.2	-2.1
Solar radiation	+0.6	+1.0	+2.1
Relative humidity	-1.6	N/A	-2.9

Table 7: Projected changes in annual mean temperature, rainfall, wind-speed, solar radiation and relative humidity for western Victoria. Changes are for the year 2070 and the A1FI emission scenario for three internally-consistent climate futures (see Table 1), relative to 30 years centred on 1990. All changes are in %, except for temperature (^{o}C).

2070 A1FI	**Climate future**		
	Most likely	**Best case**	**Worst case**
	Hotter, drier	***Hotter, little rainfall change***	***Much hotter, much drier***
	CNRM	**GISS-EH**	**CSIRO-Mk3.5**
Temperature	+1.9	+2.1	+3.1
Rainfall	-9.7	-0.1	-32.6
Wind-speed	+14.4	-4.7	-3.2
Solar radiation	+0.8	+1.5	+3.2
Relative humidity	-2.3	N/A	-4.4

Conclusions

To assist in communicating climate projections and to guide climate model selection, CSIRO has developed an approach called Climate Futures. It groups projections from 23 models into a small set of broad categories with simple descriptions, e.g. warmer and wetter, hotter and drier. The novel feature in Climate Futures is the ability to assess the likelihood of combined changes in two climate variables, e.g. temperature and rainfall. It is then easy to identify the full range of possibilities including the ‘Most Likely’, ‘Best Case’ or ‘Worst Case’ futures. Knowing the likelihood of the best or worst case is important since risk is defined as the combination of impact and likelihood.

For a given region, time-fame and emission scenario, there might be 3-10 climate futures. A subset of climate futures can be chosen to suit a particular impact assessment. The most relevant futures usually include the ‘Most Likely’ future, plus one or two others. Each of these futures is represented by results from a number of climate models. An optimisation function identifies which model has projections that are most representative of the mean of each climate future. This small set of representative models can then be used in impact assessments. An example is provided for western Victoria for 20-year periods centred on 2030, 2050 and 2070 for two emission scenarios (A1B and A1FI).

The climate futures approach has been developed and tested in 14 Pacific nations and East Timor. Feedback from training in the Pacific Climate Futures web-tool http://www.pacificclimatefutures.net has been very positive. Projections from the tool are being used in impact assessments, presentations and reports. A similar tool is being developed for Australia.

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APPENDIX 1: CLIMATE FUTURES FOR EASTERN VICTORIA

Table A1: Climate Futures for eastern Victoria in 2030, 2050 and 2070, based on changes in annual mean temperature and rainfall from 23 climate models, relative to 30 years centred on 1990.

2030 A1B	Annual temperature change (^{o}C)				
		Slightly warmer 0 to 0.5	Warmer 0.5 to 1.5	Hotter 1.5 to 3.0	Much hotter > 3.0
Annual rainfall change (%)	Much drier < -15				
	Drier -15 to -5		7 of 23 models (30%)		
	Little change -5 to +5	1 of 23 models (4%)	15 of 23 models (65%)		
	Wetter +5 to 15				
	Much wetter > 15				

2050 A1FI	Annual temperature change (^{o}C)				
		Slightly warmer 0 to 0.5	Warmer 0.5 to 1.5	Hotter 1.5 to 3.0	Much hotter > 3.0
Annual rainfall change (%)	Much drier < -15			1 of 23 models (4%)	
	Drier -15 to -5		4 of 23 models (17%)	10 of 23 models (43%)	
	Little change -5 to +5		4 of 23 models (17%)	4 of 23 models (17%)	
	Wetter +5 to 15				
	Much wetter > 15				

2070 A1FI	Annual temperature change (^{o}C)				
		Slightly warmer 0 to 0.5	Warmer 0.5 to 1.5	Hotter 1.5 to 3.0	Much hotter > 3.0
Annual rainfall change (%)	Much drier < -15			6 of 23 models (26%)	3 of 23 models (13%)
	Drier -15 to -5		1 of 23 models (4%)	6 of 23 models (26%)	1 of 23 models (4%)
	Little change -5 to +5			5 of 23 models (21%)	1 of 23 models (4%)
	Wetter +5 to 15				
	Much wetter > 15				