Climate science workshop, Samoa

Chapter 4
Climate Projection Methodology

Summary

In general, the Pacific Climate Change Science Program (PCCSP) climate projections were derived using output from global climate model simulations of the future climate, performed as part of the international Coupled Model Intercomparison Project (CMIP3). The projections focused on simulations corresponding to three Intergovernmental Panel on Climate Change (IPCC) future scenarios representing B1 (low), A1B (medium) and A2 (high) greenhouse gas emissions respectively, for three 20-year time periods (centred on 2030, 2055 and 2090). Since the skill of global climate models decreases at smaller spatial scales (e.g. at the scale of an individual country or island), a number of methods were used to enhance the resolution of the CMIP3 output locally (known as downscaling):

- Dynamical downscaling was conducted at 60 km horizontal resolution for the entire PCCSP region, using a high resolution atmospheric model driven by the changes in sea-surface temperature simulated by six CMIP3 models under the A2 (high) emissions scenario, with a focus on two 20-year future time periods (centred on 2055 and 2090).
- Dynamical downscaling was conducted at 8 km horizontal resolution for seven PCCSP Partner Country regions (each measuring approximately 1000 km x 1000 km), using a high resolution atmospheric model driven by the changes in sea-surface temperature simulated by three CMIP3 models under the A2 (high) emissions scenario, for two 20-year future time periods (centred on 2055 and 2090).
- Statistical downscaling was conducted for selected sites, using a statistical model that combines information regarding observed trends over recent decades with projected changes from the 60 km dynamical downscaling. Projections were calculated out to either 2040 or 2065 under the A2 (high) emissions scenario, depending on the quality and length of time that observational data is available.

Substantial and additional analysis of CMIP3 and/or dynamical downscaled output was required in order to provide sea-level, tropical cyclone and ocean acidification projections.

4.1 Introduction

The complexity of the climate system means that we cannot simply extrapolate past trends to forecast future conditions. Instead, mathematical representations of the Earth's climate system, called global climate models (Section 4.3), are used to simulate the fundamental processes driving weather and climate. These models are very complex and require substantial supercomputer resources. Over recent decades, global climate models have been developed and utilised extensively not only to project future climate change, but also to help better understand the present and past climate.

One of the key conclusions of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report was that most of the global warming since the mid-20th century is very likely due to increases in greenhouse gas emissions from human activities (IPCC, 2007). Given the important role that these emissions have played in the climate of the past century, estimates of the evolution of these emissions over the coming decades are needed to simulate future climate change using climate models. Such estimates were provided by the IPCC Special Report on Emissions Scenarios (SRES), for use in climate research (Section 4.2). A number of research groups participated in a recent international climate model intercomparison project, for which they were required to apply a selection of the IPCC emissions scenarios to global climate model simulations of the future climate (Section 4.3.1). In this publication, climate projections for the broad PCCSP region were calculated from the output of this project (Section 4.4.1), while projection information at the country and/or individual island scale was obtained by further processing the output, using techniques known as dynamical downscaling and statistical downscaling (Sections 4.4.2, 4.5 and 4.6). For projections of sea level, tropical cyclones and ocean acidification, substantial additional analysis of the intercomparison project output and/or dynamically downscaled results was undertaken (Sections 4.7, 4.8 and 4.9).

4.2 Emissions Scenarios

Greenhouse gases such as water vapour, carbon dioxide (CO_2), methane and nitrous oxide are a vital feature of the Earth's climate, because they are able to trap long-wave radiation emitted from the Earth and therefore act to warm the lower atmosphere. In fact, in the absence of atmospheric greenhouse gases, the average temperature on Earth would be below freezing. However, the atmospheric concentration of these gases has been increasing since 1750, due to a rise in emissions from human activities. Most of the global warming since the mid-20th century is very likely due to this increase in human-related greenhouse gas emissions (IPCC, 2007).

To assist in modelling the future climate, the IPCC prepared 40 greenhouse gas and sulphate aerosol emissions scenarios for the 21st century that combine a variety of plausible assumptions about demographic, economic and technological factors likely to influence future emissions (IPCC, 2000). These include assumptions regarding population growth, energy generation and transport using fossil fuels, agriculture, land-clearing, industrial processes and waste. Each future scenario represents a variation within one of four storylines: A1, A2, B1 and B2 (Box 4.1), leading to a range of projected CO_2, methane, nitrous oxide, and sulphate aerosol emissions.

Box 4.1: Intergovernmental Panel on Climate Change Emissions Scenarios

The IPCC Special Report on Emissions Scenarios (SRES) developed 40 plausible futures based on various assumptions about demographic change, economic development and technological change (IPCC, 2000). These were grouped into four 'storylines' (A1, A2, B1 and B2).

A1. The A1 storyline describes a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences with respect to per capita income. The A1 storyline develops into three scenario groups that describe alternative directions of technological change in the energy system. They are distinguished by their technological emphasis: fossil intensive (A1FI); non-fossil intensive energy sources and technologies (A1T); or a balance across all sources (A1B) (where balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in a continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than for the other storylines.

B1. The B1 storyline describes a convergent world with the same global population as in the A1 storyline (one that peaks in mid-century and declines thereafter) but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with a continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid, and more diverse technological change than in the B1 and A1 storylines. Whilst the scenario is also oriented towards environmental protection and social equity, it is focused on local and regional levels.

Rather than consider all 40 future emissions scenarios, climate projection studies typically focus on a maximum of six scenarios: four so-called marker scenarios (A1B, A2, B1 and B2) and two additional illustrative scenarios (A1FI and A1T). For the purposes of the PCCSP, it was considered sufficient to consider only the B1, A1B and A2 scenarios, as these represent a low, medium and high emissions future respectively (Figure 4.1).

The final greenhouse gas concentration in the atmosphere depends not only on the rate of anthropogenic emissions, but also on the lifetime of the gases in the atmosphere and the ability of the biosphere and oceans to withdraw them from the atmosphere. For instance, CO_2 is continuously cycled between the atmosphere, ocean and land, which involves a range of processes with different time scales. Around half of the emitted CO_2 is removed from the atmosphere on a time scale of 30 years, a further 30% is removed within a few centuries, and the remaining 20% may stay in the atmosphere for thousands of years (Denman et al., 2007).

Due to its relatively high atmospheric concentration and potency as an absorber of long-wave radiation, CO_2 is often discussed alone, without reference to greenhouse gases that have a lesser cumulative influence on the temperature of the lower atmosphere (such as methane and nitrous oxide).

Carbon cycle models are used to calculate the atmospheric greenhouse gas concentrations that will arise from a given emissions scenario. These models include the uptake of emissions by the land and ocean, relevant climate feedbacks, and the gas transport and chemical reactions occurring in the atmosphere. For the 40 SRES emissions scenarios, carbon cycle models give estimates of atmospheric CO_2 concentrations for the year 2100 ranging from 500 to 1200 parts per million (ppmv) (Figure 4.1; Meehl et al., 2007b), compared to the 2010 concentration of 390 ppmv and the pre-industrial value of 280 ppmv (http://www.csiro.au/greenhouse-gases/; Meure et al., 2006; Etheridge et al., 1996). Since the release of the SRES report in 2000, observed greenhouse gas emissions have been tracking near the high end of the emissions scenarios (between A1B and A1FI), although there was a drop in 2008 due to the global financial crisis (Manning et al., 2010; Friedlingstein et al., 2010; Raupach and Canadell, 2010).

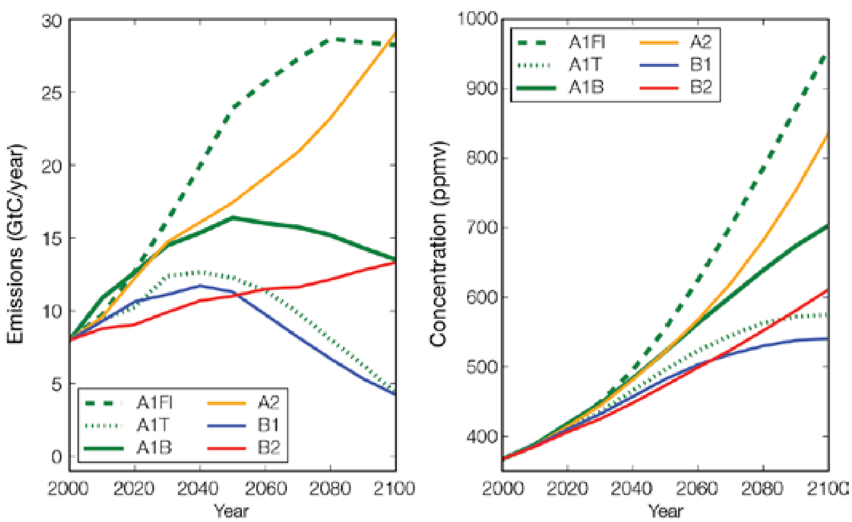

Figure 4.1: Global average carbon dioxide emissions in gigatonnes (thousand million tonnes) of carbon per year (GtC/yr) for the four marker (A1B, A2, B1 and B2) and two illustrative (A1FI and A1T) SRES future emissions scenarios (left), and the estimated resulting atmospheric carbon dioxide concentration in parts per million (ppmv; right). Projected changes in other greenhouse gases and aerosols can be found in Figure 10.26 of the IPCC Fourth Assessment Report (IPCC, 2007).

4.3 Global Climate Models

Global climate models are used to simulate the behaviour of the atmosphere, oceans, land surface and cryosphere (ice covered areas) over the entire planet. Variables such as temperature, rainfall and wind are calculated over a three-dimensional array of grid cells covering the globe and spaced typically 100–400 km apart, with around 40 layers through the depth of the ocean and around 40 layers through the height of the atmosphere, depending on the model (Figure 4.2). Typically, the time step is about half an hour, so climate models can simulate hourly to daily weather (the average weather over 30 years or more is called climate; Section 1.1). Weather conditions in the model change according to a set of mathematical rules based on the laws of physics, such as conservation of mass, energy and momentum. Processes that occur at spatial scales smaller than the model grid spacing, such as water droplet formation in clouds and turbulence in near-surface winds, are represented by parameterising the influence of these processes on the larger scale. Parameterisation is basically a complex method of estimation, which typically combines well-established laws of physics with observational data.

Many research institutions around the world develop and maintain their own global climate models. While these models are similar in many ways, subtle variations exist with respect to factors such as grid characteristics (e.g. spatial resolution), parameterisation schemes and model sub-components (e.g. some models include a representation of atmospheric chemistry, while others do not), which means that climate simulations arising from these models differ. In an attempt to coordinate the analysis of these differences, a number of international model intercomparison projects have been conducted in recent decades (Meehl et al., 2000). The most recent is known as the Coupled Model Intercomparison Project Phase 3 (CMIP3; Meehl et al., 2007a), and the output from this project formed the basis for many of the climate projections presented in both this publication (Section 4.4) and the IPCC Fourth Assessment Report (IPCC, 2007).

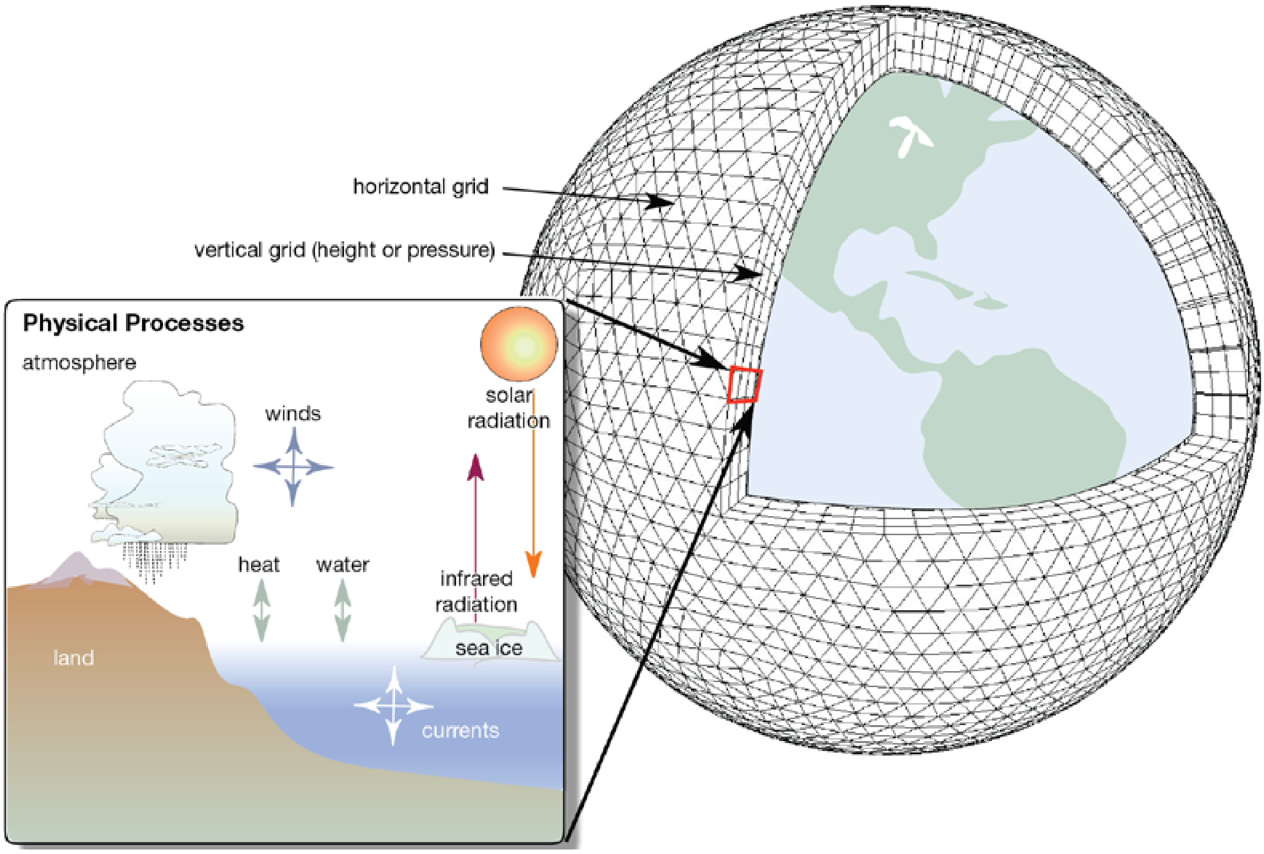

Figure 4.2: Schematic illustrating how the Earth is represented by a series of grid cells in global climate models. Some of the physical processes simulated in a typical global climate model are shown inset. (Source: Centre for Multiscale Modelling of Atmospheric Processes[1]).

[1] http://www.cmmap.org/learn/modeling/whatIs2.html

4.3.1 Coupled Model Intercomparison Project Phase 3

A total of 24 global climate models contributed model output to the CMIP3 project (Table 4.1), which is freely available from the Program for Climate Model Diagnosis and Intercomparison at Lawrence Livermore National Laboratory (www-pcmdi.llnl.gov). Participating institutions were required to perform a number of model simulations, each differing in terms of the external forcing applied to the climate system. External climate forcings are factors that can alter the energy balance of the Earth system (and thus the climate), and can be either natural (e.g. volcanic activity) or human-related (e.g. greenhouse gas and aerosol emissions).

The CMIP3 simulations relevant to the PCCSP include:

- **Pre-industrial control simulation (PIcntrl).** Incorporates a seasonally varying but annually unchanging external forcing indicative of the late 19th century (usually corresponding to 1870 conditions).
- **Climate of the 20th century simulation (20c3m).** Modelling groups initiated their global climate model from the PIcntrl (circa 1870) simulation and then imposed the natural and human-related forcing thought to be important for simulating the climate of the 20th and late 19th centuries.
- **Climate of the 21st century simulations.** Modelling groups initiated their global climate model from the 20c3m (circa 2000) simulation and then imposed the human-related forcing associated with one or more of the B1, A1B or A2 SRES emissions scenarios (Section 4.2). None of the modelling groups used the A1FI emissions scenario. These simulations were run until the end of the 21st century (and sometimes beyond).

Output from the PIcntrl and 20c3m simulations was used extensively in evaluating the CMIP3 models over the PCCSP region (Chapter 5), while a number of SRES emissions scenario simulations were used in determining PCCSP climate projections (Section 4.4). It should be noted that many institutions did not provide output for all the variables and SRES emissions scenarios requested by the CMIP3 organisers. In addition, the availability of monthly output is greater than for daily output, due to the extra data storage requirements associated with the latter. The availability of CMIP3 output relevant to this publication is outlined in Appendix 1.

Table 4.1: Participating CMIP3 climate models. For additional details see www-pcmdi.llnl.gov, Randall et al. (2007) and Santer et al. (2009).

	Model name	Institute (country)	Forcings[a]
1	BCCR-BCM2.0	Bjerknes Centre for Climate Research (Norway)	G,SD
2	CCSM3	National Center for Atmospheric Research (USA)	G,O,SD,BC,OC,SO,U
3	CGCM3.1(T47)[b]	Canadian Centre for Climate Modelling & Analysis (Canada)	G,SD
4	CGCM3.1(T63)[b]	Canadian Centre for Climate Modelling & Analysis (Canada)	G,SD
5	CNRM-CM3	Centre National de Recherches Météorologiques (France)	G,O,SD,BC
6	CSIRO-Mk3.0	CSIRO Marine and Atmospheric Research (Australia)	G,O,SD
7	CSIRO-Mk3.5	CSIRO Marine and Atmospheric Research (Australia)	G,O,SD
8	ECHAM5/MPI-OM	Max Planck Institute for Meteorology (Germany)	G,O,SD,SI
9	ECHO-G[b]	Meteorological Institute of the University of Bonn and Korea Meteorological Administration (Germany/Korea)	G,SD,SI
10	FGOALS-g1.0	Institute of Atmospheric Physics (China)	G,SD
11	GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory (USA)	G,O,SD,BC,OC, LU,SO,V
12	GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory (USA)	G,O,SD,BC,OC, LU,SO,V
13	GISS-AOM	Goddard Institute for Space Studies (USA)	G,SD,SS
14	GISS-EH	Goddard Institute for Space Studies (USA)	G,O,SD,SI,BC,OC,MD,SS,LU,SO,V
15	GISS-ER	Goddard Institute for Space Studies (USA)	G,O,SD,SI,BC,OC,MD,SS,LU,SO,V
16	INGV-SXG	Instituto Nazionale di Geofisica e Vulcanologia (Italy)	G,O,SD
17	INM-CM3.0[b]	Institute for Numerical Mathematics (Russia)	G,SD,SO
18	IPSL-CM4	Institut Pierre Simon Laplace (France)	G,SD,SI
19	MIROC3.2 (hires)	Center for Climate System Research (Japan)	G,O,SD,BC,OC,MD,SS,LU,SO,V
20	MIROC3.2 (medres)	Center for Climate System (Japan)	G,O,SD,BC,OC,MD,SS,LU,SO,V
21	MRI-CGCM2.3.2[b]	Meteorological Research Institute (Japan)	G,SD,SO
22	PCM	National Center for Atmospheric Research (USA)	G,O,SD,SO,V
23	UKMO-HadCM3	Hadley Centre for Climate Prediction and Research (UK)	G,O,SD,SI
24	UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research (UK)	G,O,SD,SI,BC,OC,LU,SO,V

[a] **The climate forcing factors are G: Well-mixed greenhouse gases; O: Ozone; SD: Sulphate direct effect; SI: Sulphate indirect effect; BC: Black carbon; OC: Organic carbon: MD: Mineral dust; SS: Sea salt; LU: Land use; SO: Solar irradiance; and V: Volcanic aerosol.**

[b] Model adds artificial fluxes of heat (and in some cases fresh water and momentum) at the air-sea interface in order to prevent the model drifting towards an unrealistic state over long climate simulations. This process is known as flux adjustment and attracts concern because of its inherently non-physical nature, and because flux adjustments based on the present climate may not be valid in future climate simulations.

4.4 Climate Projection Methods

Climate models generate output for a wide range of variables, including temperature, rainfall, wind, humidity, evaporation, ocean salinity and solar radiation. The determination of climate projections for these variables therefore involves the direct analysis of climate model output. In particular, the CMIP3 archive of climate model output was used to determine the PCCSP large-scale climate variable projections (i.e. at the scale of the entire PCCSP region; Section 4.4.1).

While global climate models are useful for making large-scale climate projections, their skill decreases at finer temporal and spatial scales (Chapter 5). For instance, these models typically have insufficient horizontal grid resolution to explicitly represent small islands (i.e. the model just sees an area of ocean). This means that while they can simulate the large-scale climate conditions, they cannot account for some important local climate effects resulting from island shape and topography. A number of methods have been developed to try and overcome this limitation by enhancing the resolution of model output locally (Section 4.4.2). Of these methods, dynamical and statistical downscaling techniques were used to provide small-scale (i.e. country- and/or individual island-scale) PCCSP climate projections (Sections 4.5 and 4.6).

Unlike for typical climate variable projections, the PCCSP sea level, tropical cyclone and ocean acidity projections required substantial and additional analysis of CMIP3 and/or downscaled output, which sometimes incorporated other sources of information (see Sections 4.7, 4.8 and 4.9 respectively).

4.4.1 Large-Scale Projections

Large-scale ocean and atmosphere projections for the PCCSP region were calculated from CMIP3 climate model output for a B1 (low), A1B (medium) and A2 (high) SRES emissions scenarios (Box 4.1). Projections were given for three 20-year time periods centred on 2030 (2020–2039), 2055 (2046–2065) and 2090 (2080–2099), relative to 1990 (1980–1999) (Figure 4.3).

When formulating climate projections based on results from a number of different global climate models, a pragmatic and well-accepted approach is to combine the output and calculate a multi-model average (Knutti et al., 2010). However, while the practice of reporting multi-model average projections is well established, there are many variations on the precise methods used to formulate this average (Tebaldi and Knutti, 2007). These variations are typically associated with issues surrounding model skill in simulating the current climate, or the differing availability of data across emissions scenarios.

With respect to model skill, a number of CMIP3 models were found to simulate various key aspects of the Indo-Pacific climate less skilfully than other models (Section 5.5.1). For associated climate projections in this publication, these models were eliminated when calculating the multi-model average. Besides this skill-based elimination, all available CMIP3 models were typically included in calculating multi-model average projections, regardless of how many emissions scenarios they provided data for (see Appendix 1 for CMIP3 data availability). This approach is advantageous in terms of maintaining the largest possible sample size, however inconsistencies may arise in comparing projections between different variables and emissions scenarios. All included models were assigned equal weight in determining average projections, as opposed to an individual weight reflecting their respective skill, in accordance with recently published recommendations (Weigel et al., 2010). Unless otherwise stated, only the first model run was used for those models where multiple simulations are archived, for consistency with models that have only one simulation in the CMIP3 archive.

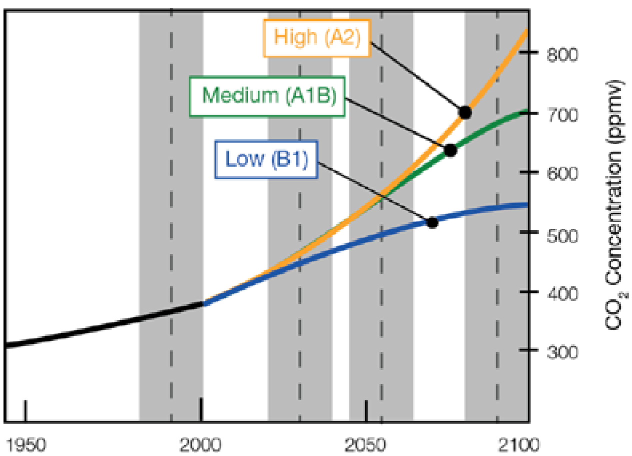

Figure 4.3: Large-scale projections for the PCCSP region were calculated from CMIP3 global climate model output for three 20-year periods centred on 2030, 2055 and 2090, relative to 1990 (shaded bars). These projections were determined for a low (B1), medium (A1B) and high (A2) future greenhouse gas emissions scenario (corresponding carbon dioxide concentrations are shown as blue, green and orange lines, respectively).

4.4.2 Small-Scale Projections

Given the relatively coarse spatial resolution of global climate model output, a variety of different methods have been developed to produce regional-scale projections for use in risk assessments (e.g. at the scale of an individual country or island). The choice of method must be matched to the intended application, taking into account local constraints of time, resources, human capacity and supporting infrastructure (Wilby et al., 2009). Options include:

- Sensitivity analysis. This entails running a climate impact model with observed climate data to establish a baseline level of risk, then re-running the model with the same input data, modified by selected changes in climate (e.g. a warming of 1, 2 or 3°C).
- Change factors. The changes in mean climate between a present and future period, as simulated by a climate model, are applied to observed climate data (e.g. the warming pattern from a CMIP3 model could be applied to observed data from the meteorological station in Rarotonga, Cook Islands).
- Climate analogues. Past climate data are used as an analogue for the future (e.g. the warming and sea level that occurred during the last interglacial period, 125,000 years ago).
- Trend extrapolation. Extension of recent climate trends into the future.
- Weather generation. Involves the use of a model that simulates time series of weather data, with statistical properties similar to observed weather data. These statistical properties can be modified for future climates using information from climate models.
- Dynamical downscaling. Involves the use of a finer resolution atmospheric climate model, driven by output from a global climate model. This provides better representation of topography and associated effects on local climate, such as rainfall in mountainous regions, as well as the potential to better simulate extreme weather features, such as tropical cyclones. This method is computationally intensive and the results are strongly dependent on the choice of both global climate model and fine resolution atmospheric model. In some cases, the projected changes can be applied directly to observed data, or statistically downscaled using observed data, for use in risk assessment.
- Statistical downscaling. This can be as simple as interpolating climate model output to a particular location, or as complex as constructing a statistical model that relates large-scale atmospheric variables and local-scale surface variables. Models of intermediate complexity are also popular. High-quality observed data are required for a number of decades to calibrate the statistical model, and results are strongly dependent on the choice of climate model.

The first five methods (sensitivity analysis, change factors, climate analogues, trend extrapolation and weather generation) are relatively easy to use, with low resource demands, but have significant disadvantages (Table 4.2). The remaining two methods (dynamical downscaling and statistical downscaling) are considered to have the most merit, despite increased complexity and higher demands on resources, and have been used to provide information regarding small-scale (i.e. country- and/or individual island-scale) climate change projections in the PCCSP (Sections 4.5 and 4.6).

Table 4.2: Options for creating regional climate projections, in order of increasing complexity and resource demands (modified from Table VI in Wilby et al. (2009)).

Method	Advantages	Disadvantages
Sensitivity analysis	1. Easy to apply 2. Requires no future climate change information 3. Shows most important variables/system thresholds 4. Allows comparisons between studies	1. Provides no insight into the plausibility/likelihood of associated impacts unless benchmarked to other scenarios 2. Impact model uncertainty seldom reported or unknown
Change factors	1. Easy to apply to observed data, assuming data from global climate models (GCMs) are available	1. Only changes baseline mean of the observed data, so changes in variability and sequencing of events remain unchanged 2. Limited applicability where changes in extreme events are important
Cliamte Analogues	1. Easy to apply 2. Requires no future climate change information 3. Reveals multi-sector impacts/vulnerability to past climate conditions or extreme events, such as a flood or drought episode	1. Assumes that the same socio-economic or environmental responses recur under similar climate conditions 2. Requires data on confounding factors such as population growth, technological advance, conflict
Trend extrapolation	1. Easy to apply 2. Reflects local conditions 3. Uses recent patterns of climate variability and change 4. Tools freely available	1. Typically assumes linear change 2. Trends (sign and magnitude) are sensitive to the choice/length of record 3. Assumes recent trend will persist, despite evidence for abrupt changes in the past 4. Needs high quality observational data for calibration
Weather generators	1. Modest computational demand 2. Provides daily or sub-daily weather variables 3. Preserves relationships between weather variables 4. Already in widespread use for simulating present climate 5. Tools freely available	1. Needs high quality observational data for calibration and verification 2. Assumes a constant relationship between large-scale circulation patterns and local weather 3. Scenarios are sensitive to choice of predictors and quality of GCM output 4. Scenarios are typically timeslice rather than transient 5. Difficulty reproducing interannual variability (e.g. due to ENSO) and tropical weather phenomena such as monsoons and tropical cyclones
Dynamical downscaling	1. Maps regional climate scenarios at 10–60 km resolution 2. Reflects underlying land-surface controls and feedbacks 3. Preserves relationships between weather variables 4. Often gives a better representation of coastal and mountain effects, and extreme weather events 5. Simulations with bias-corrected sea-surface temperatures should make the present climate simulation more realistic than the host GCM 6. Potentially can apply projected changes to observed data for risk assessments	1. Has a high computational and technical demand, which limits the number of GCMs, emissions scenarios and time periods that can be downscaled, so the range of uncertainty in projections tends to be sub-sampled 2. Projections are sensitive to choice of host GCM and high-resolution atmospheric model 3. Requires high quality observational data for model verification 4. Some biases potentially remain in the present climate simulation (e.g. too wet/dry), so caution is needed in using data directly in risk assessments 5. Need to assess model reliability before using in risk assessment 6. It should not be assumed that the dynamically downscaled projections are necessarily more reliable than projections based on the host model
Statistical downscaling	1. Modest computational demand 2. Site specific time series and other statistics, e.g. extreme event frequencies 3. Reduces biases in climate model data 4. Tools freely available	1. Requires high quality observational data over a number of decades for calibration and verification 2. Assumes a constant relationship between large-scale circulation patterns and local weather 3. Scenarios are sensitive to choice of forcing factors and host GCM or dynamical downscaling model 4. Choice of host GCM or dynamical downscaling model constrained by archived outputs 5. Hard to choose from the large variety of methods, each with pros and cons

4.5 Dynamical Downscaling

In dynamical downscaling, large-scale climate information from a global climate model is used as input to a finer resolution atmospheric model with more detailed topography, land use and coastal boundaries (the global climate model information is said to drive the finer resolution model). This allows atmospheric processes to be simulated with greater detail, possibly resulting in an improved representation of weather events (particularly extremes). However, finer resolution comes at the cost of increased computer time and data storage. This constrains the number of global climate models and emissions scenarios that can be downscaled, as well as the duration and geographic area of downscaled simulations. Therefore, dynamical downscaling tends to sub-sample the broader range of possible future climates simulated by global climate models.

4.5.1 Downscaling Methods

As for global climate models, there are many scientific institutions around the world that are involved in dynamical downscaling. There are a number of different approaches taken by these institutions, which can be summarised into three types:

- Limited time slice experiments with fine-resolution global atmospheric models.
- Fine-resolution atmospheric models embedded within global climate model output over a limited area (known as limited-area models).
- Stretched-grid atmospheric models with finer resolution over a region of interest and coarser resolution over the rest of the globe.

Given the computationally expensive nature of fine resolution atmospheric simulations over the entire globe, time slice simulations of only 20 or 30 years duration are run, as opposed to an entire climate run of 100 years or more. These simulations provide the most comprehensive depiction of the climate, at the expense of full temporal coverage.

Fine resolution, limited-area models are less computationally demanding, as they only simulate a restricted region of the globe. They are therefore able to provide much greater temporal coverage, but require significant amounts of input data from a host global climate model at their lateral boundaries (the limited-area model is said to be nested in the host model). Problems can arise at these boundaries due to differences in resolution, model physics and evolution of weather events between the global climate model and limited-area model.

Stretched-grid models provide a compromise between the global high resolution and limited-area approaches by providing finer resolution over the area of interest, while maintaining a coarser resolution for the remainder of the globe. Although a stretched-grid model simulates the atmosphere of the entire globe, the resolution can vary from approximately 60 km in the region of interest up to 400 km in other areas. This approach allows for better representation of local climate factors (e.g. topography), however it may compromise the simulation of distant factors that influence the regional climate of interest (e.g. the El Niño-Southern Oscillation influences regions located thousands of kilometres from the tropical Pacific Ocean).

4.5.2 Downscaling in the Pacific Climate Change Science Program

The dynamical downscaling conducted in the PCCSP consisted of a primary set of simulations from which climate projections were derived, as well as a series of additional simulations designed to assess the uncertainty associated with those projections. All primary simulations were completed using CSIRO's global stretched-grid, Conformal Cubic Atmospheric Model (CCAM; McGregor and Dix, 2008) run at 60 km horizontal resolution over the entire globe, while further downscaling to 8 km was conducted for selected Partner Countries. The additional simulations involved repeating the primary CCAM simulations with an alternative configuration for atmosphere/ocean interaction, as well as a series of simulations using five different limited-area models, in order to assess the influence of the selection of downscaling method on regional climate projections.

The CCAM model was chosen for the downscaling because it is a global atmospheric model, so it was possible to bias-adjust the sea-surface temperature in order to improve upon large-scale circulation patterns (Section 4.5.2.1). In addition, the use of a stretched grid eliminates the problems caused by lateral boundary conditions in limited-area models. The model has been well tested in various model intercomparisons and in downscaling projects over the Australasian region (Corney et al., 2010).

4.5.2.1 CCAM 60 km Global Simulations

These simulations were performed for six host global climate models (CSIRO-Mk3.5, ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2 (medres) and UKMO-HadCM3) that were deemed to have acceptable skill in simulating the climate of the PCCSP region (Section 5.5.1). For these simulations:

- The period 1961–2099 was simulated using the equivalent CO_2, direct aerosol effect and ozone distribution for the A2 (high) emissions scenario (except in simulating the current climate, which used 20c3m equivalents).
- Monthly, bias adjusted sea-surface temperature and sea-ice fraction output from the host global climate models was used. Bias adjustment refers to the removal of model errors in the present day, mean state climate. In this case, the sea-surface temperature bias adjustment was calculated by computing the monthly average biases of the global models for the 1971–2000 period, relative to the observed climatology, based upon the method of Reynolds (1988). These monthly biases were then subtracted from the global climate model monthly sea-surface temperature output throughout the simulation. This approach preserves the inter- and intra-annual variability and the climate change signal of the host global climate models (Nguyen et al., in press).
- No atmospheric input from the global climate models was used, as the bias adjusted sea-surface temperature is considered sufficient information to drive CCAM. In addition, the bias adjustment makes the global climate model atmospheric fields incompatible with the sea-surface temperature distributions. This procedure may be viewed as somewhat akin to the flux adjustment used in some global models (Table 4.1), however because no attempts are made to predict the ocean temperatures, only to downscale the atmosphere, the technique is acceptable in this context. It is assumed that the fixed, monthly adjustment is appropriate over the entire course of the simulation, which may be a disadvantage/limitation of the approach.
- The period 1961–2099 was simulated for the A2 (high) emissions scenario only.

4.5.2.2 CCAM 8 km Regional Simulations

The GFDL-CM2.1, UKMO-HadCM3 and ECHAM5 60 km CCAM global simulations were selected for further downscaling to 8 km. Of the six host models, these show a low, middle and high amount of global warming into the future, respectively. Due to the very high demand for computer resources when downscaling at 8 km resolution, the temporal and spatial extent of the simulations was limited. Only the 1980–1999, 2046–2065 and 2080–2099 time periods were simulated for seven 1000 km x 1000 km regions, including Papua New Guinea, East Timor, Fiji, Solomon Islands, Vanuatu, Samoa and the Federated States of Micronesia. These country regions were selected on the basis of five criteria:

1. Likely impact of model resolution on weather characteristics.
2. The desire to capture a range of climate regimes across the selected regions.
3. Mountainous terrain.
4. Population.
5. Discussion with Partner Countries.

4.5.2.3 Additional CCAM Simulations Using Alternative Settings

The primary 60 km CCAM and regional 8 km CCAM simulations were repeated with the inclusion of a 20-level mixed-layer ocean model and a thermodynamic sea-ice model, to allow for a more realistic interaction of the atmosphere, ocean and ice. A digital filter (Thatcher and McGregor, 2009) was used for the top 200 m of the mixed-layer ocean in order to keep the ocean simulation similar to the host global climate model.

4.5.2.4 Additional Limited-Area Model Simulations

Simulations at 50 km resolution were completed with five different limited-area models: PRECIS model (Jones et al., 2004), WRF model (Skamarock et al., 2008), Zetac model (Pauluis & Garner, 2006), MM5 model (Grell et al., 1994; Chen and Dudhia, 2001) and the RegCM3 model (Pal et al., 2007). The domain chosen was 145°E–170°W, 25°S–10°N and three sets of simulations were completed:

1. A simulation nested within the NCEP/DOE R-2 reanalyses dataset (Section 2.2) for the period 1981–2000, in order to evaluate the ability of the limited-area models to simulate the present day climate.
2. Simulations for the periods 1981–2000 and 2045–2065 nested in the output from the CCAM 60 km simulation driven by the GFDL-CM2.1 model, in order to evaluate projections arising from the limited-area models.
3. Additional simulations for some of the limited-area models using finer resolution and different model settings.

A summary of the downscaled simulations conducted for the PCCSP is given in Figure 4.4.

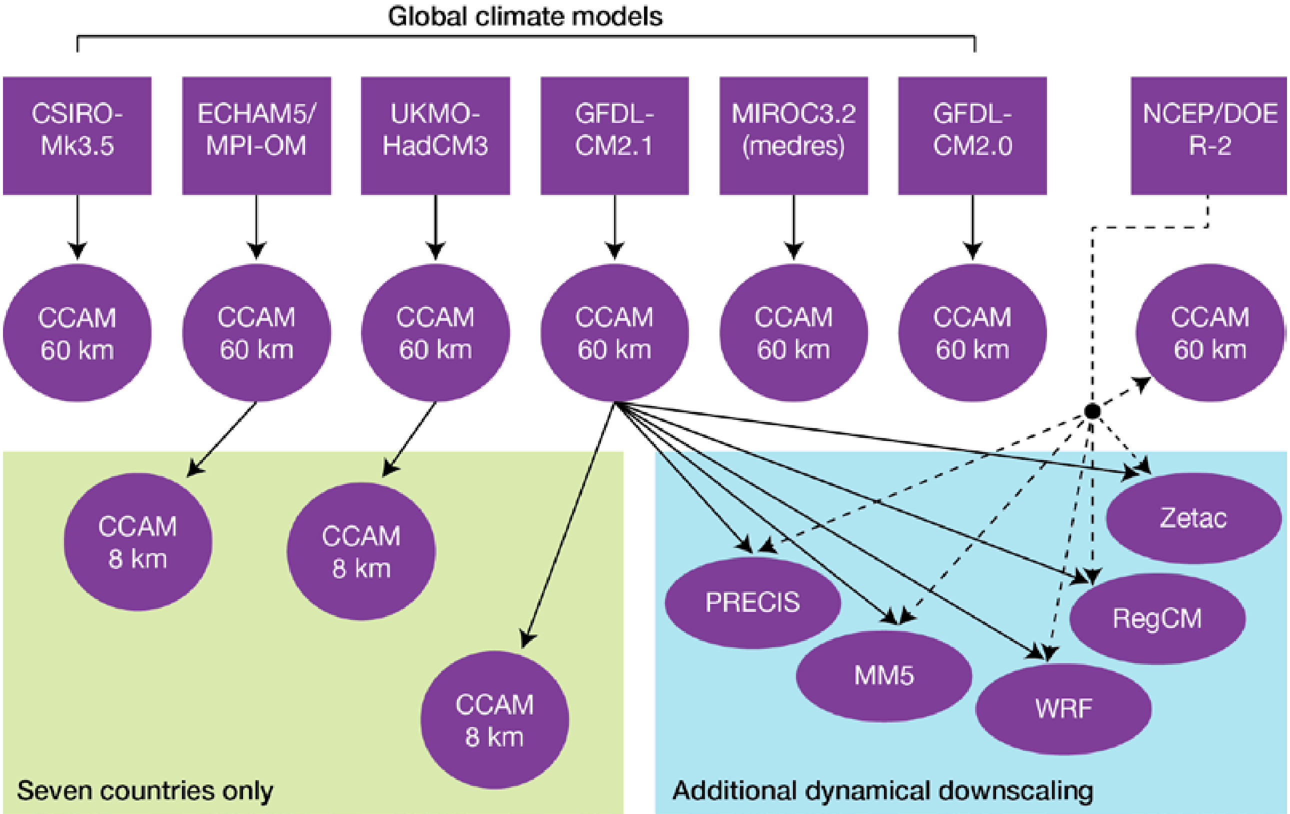

Figure 4.4: Summary of dynamical downscaling conducted in the PCCSP. All future time periods were simulated using the high (A2) emissions scenario.

4.6 Statistical Downscaling

Engagement with Partner Countries and other stakeholders has repeatedly emphasised that for strategic decision making there is often a preference for location-specific climate information over the large-scale information generally provided by global climate models (cf. Fowler et al., 2007; Murphy et al., 2009; Crimp et al., 2009; Kokic et al., 2007; Cao et al., 2003). This can be provided by statistical downscaling.

A recent IPCC guidance paper (Knutti et al., 2010) stated that four factors should be considered in assessing the likely future climate change in a region: historical change, process change (e.g. changes in the driving circulation), global climate change projected by global climate models and downscaled projected change. In the PCCSP, a statistical downscaling approach was developed and used that is consistent with these objectives. By establishing empirical relationships between coarse resolution climate variables and the local climate, the technique maintains important information regarding locally observed historic trends and variability, but also introduces important drivers of change from global climate models. Known as Linear Mixed Effect State-Space Modelling (Kokic et al., 2011), this technique was used in conjunction with a bootstrap (i.e. repeat sampling) simulation procedure based on quantile matching (Li et al., 2010) to simulate future daily climate. Compared to alternative approaches (Fowler et al., 2007), this technique has several advantages:

- The modelling and simulation accounts for seasonality and temporal and cross-variable dependencies in the locally observed data. The simulated daily data therefore exhibit quite realistic behaviour, which is important for subsequent application in research and risk assessments.
- The method forecasts the joint distribution of the climate variables, so the local climate variability as well as the change in the mean is projected.
- Time series can be generated continuously from past to future, which are suitable for direct use in risk assessments.

The Linear Mixed Effect State-Space method was used to downscale daily maximum temperature, minimum temperature and rainfall projections for 17 locations in seven Partner Countries (Table 4.3). Daily climate data archived by the US National Oceanic and Atmospheric Agency were used to build the statistical models, with the exception of Vanuatu, where high quality daily climate records from four climate stations were provided by the Vanuatu Meteorology and Geo-hazard Department. The selection of locations in each Partner Country was based on the length and quality of data available. In cases where data quality was severely compromised, these parts of the time series were removed.

Some specific aspects of the methodology are:

- Projections for a range of monthly summary statistics were made out to 2040 at all 17 locations, while for 12 locations the observational data were of sufficient length and quality to allow projections to be extended out to 2065 (Table 4.3).
- Daily time series were generated at all 17 locations for the period 1981–2000 and 2021–2040, and at 12 locations for 2046–2065.
- The projections were based on large-scale changes simulated by the CCAM 60 km simulations driven by the GFDL-CM2.1, UKMO-HadCM3 and ECHAM5 models, under the high (A2) emissions scenario.

Table 4.3: Climate station sites used for statistical downscaling. Locations where projections were made out to 2065 (as opposed to 2040) are indicated with an asterisk.

Country	Station names
Cook Islands	Rarotonga*
Federated States of Micronesia	Pohnpei*
Fiji	Matuku Nabouwalu Nadi airport* Nasouri* Vunisea*
Marshall Islands	Kwajalein Missle Majuro*
Samoa	Apia* Faleolo airport
Solomon Islands	Auki Honiara*
Vanuatu	Aneityum* Lamap* Pekoa* Sola*

4.7 Sea Level

Many factors need to be considered when making projections of future global sea level. These include:

- **Expansion / contraction of sea water (i.e. steric effects).** The ocean will expand if heated, and contract if cooled (known as the 'thermosteric' component of sea level).
- **Antarctic and Greenland ice sheets.** The melting and sliding into the ocean of these large ice sheets acts to raise sea level, while water is taken from the ocean and deposited on ice sheets (via evaporation and rainfall) when they grow.
- **Glaciers and ice caps.** These comprise all land ice except for the ice sheets of Greenland and Antarctica. While relatively small in comparison to the ice sheets, they have contributed more to sea-level rise during the 20th century than the ice sheets and are likely to provide a significant contribution to 21st century sea-level rise.
- **Terrestrial storage of water.** The storage of water on land by the building of dams and the depletion of ground water can act to lower and raise global sea level, respectively.

When considering regional sea level projections, there are two additional factors to consider:

- **Ocean dynamics.** Changes in ocean currents (often associated with changes in the surface winds) can alter the sea level of a given region. This is reflected in changes in ocean temperatures and salinity and changes in bottom pressure.
- **Mass distribution.** The redistribution of mass in response to changes in ice sheets, terrestrial reservoirs and glaciers and ice caps alters the loading of the Earth (resulting in vertical crustal motion) and the gravitational field, leading to a regional distribution in the amount of sea-level rise.

The CMIP3 models are only able to provide projections regarding the steric and ocean dynamics components of sea level (termed the modelled components of the projection). To obtain information regarding the Antarctic and Greenland ice sheets, glaciers and ice caps, terrestrial water storage or mass distribution, additional modelling techniques are required (i.e. the CMIP3 models do not include a representation of processes such as ice-sheet dynamics or terrestrial water storage).

Projections for the PCCSP region were calculated using essentially the same techniques as in the IPCC Fourth Assessment Report (Meehl et al., 2007b). The only difference was that unlike in that report, which provided no total sea-level rise projections on a regional scale, the regional distribution (including the mass distribution component) was calculated so that all the sea-level components could be summed regionally (Table 4.4; see Church et al. (2011) for more details). See Appendix 1 for a listing of the CMIP3 models used to formulate these projections.

Table 4.4: Summary of sea level projection methods used in the PCCSP. See Meehl et al. (2007b) and Church et al. (2011) for details.

Component	Method
Steric & ocean dynamic effects	Calculated using output from the CMIP3 models.
Ice sheets	Calculated using an empirical calibration scheme for surface mass balance as a function of temperature change, using the ice sheet mass balance temperature sensitivities reported by Gregory and Huybrechts (2006) and the temperature changes simulated by the CMIP3 models. As these sensitivities do not account for the possibility of further mass loss from a rapid dynamic response of the ice sheets (e.g. the discharge of ice into the ocean as icebergs), an additional component related to surface temperature change and the current estimated dynamic response of the ice sheets was also included. This additional component is known as the rapid ice contribution.
Glaciers & ice caps	Calculated using the CMIP3 projected temperature changes with respect to a climate in which glaciers were estimated to be in a steady state (somewhat cooler than the late 19th century), an estimate of the present volume of the world's glacier and ice caps, and an estimate of the sensitivity to temperature of the global glacier surface mass balance (Kaser et al., 2006).
Terrestrial storage	Recent research suggests that the global rate of dam building has slowed and reservoir storage is likely to be approximately stable to 2025, as sedimentation offsets any building of new dams (Lettenmaier and Milly, 2009). The depletion of ground water has increased over the last two decades and was likely greater than increases in reservoir storage by up to a few tenths of a millimetre per year (Konikow and Kendy, 2005; Wada et al., 2010). Continuation of recent trends would therefore suggest an additional sea-level rise of a few centimetres at most, however there are no formal projections of how this depletion will evolve through to 2100. Due to this lack of formal projections and the fact that recent trends suggest that sea level change associated with terrestrial storage is likely to be relatively small, this component was not included in the PCCSP projections.
Mass distribution	The changes in vertical land motion and the gravitational field resulting from changes in the mass balances of glaciers, ice caps and ice sheets were estimated, using the calculated projected changes in the ice sheets and by assuming that the spatial pattern of glacial and ice cap mass loss to the ocean in the 21st century would have a similar pattern to that observed from 1993 to 2007 (Cogley, 2009).
Other vertical land motion	Other than the response to changing glacier and ice sheet mass, no estimates of vertical land motion from the ongoing response of the Earth to changes in ice sheets since the last glacial maximum (or other local issues) were included in the projections.

4.8 Tropical Cyclones

The current generation of global climate models have difficulty in adequately simulating the features of the current climate known to strongly influence tropical cyclone numbers and intensity, (e.g. regional patterns of sea-surface temperature, ENSO, the West Pacific Monsoon and the SPCZ), and they have insufficient temporal and spatial resolution to capture the high wind speeds and other small-scale features associated with these systems. Despite these limitations, a number of methods exist for making projections of the frequency and location of tropical cyclone activity from global climate model output (Knutson et al., 2010). In general terms, these methods seek to either identify and utilise relationships between tropical cyclones and the large-scale environmental conditions that are known to affect their development, or to identify weather features that have the characteristics of a tropical cyclone (i.e. a closed low pressure system accompanied by strong winds and a warm core through the depth of the atmosphere) directly from climate model output (known as direct detection schemes).

The PCCSP projections of tropical cyclone frequency and location were derived using methods falling under both of these general categories:

- A method for inferring tropical cyclone activity from the large-scale environmental conditions, known as the Genesis Potential Index, was used to determine projections from CMIP3 model output (Section 4.8.1).
- The CSIRO Direct Detection scheme was applied to both CMIP3 and CCAM 60 km model output (Section 4.8.2).
- A new tropical cyclone detection method known as the Curvature Vorticity Parameter scheme was developed, which was applied to CMIP3 model output (Section 4.8.3).

In addition, the cyclonic wind hazard for both the current climate and for the future climate was assessed using Geoscience Australia's Tropical Cyclone Risk Model (Section 4.8.4).

4.8.1 Genesis Potential Index

Approaches that use the mean characteristics of the large-scale environment to build empirical indices that replicate the key features of tropical cyclone formation are all essentially updates of the Yearly Genesis Parameter (Gray, 1979). For instance, Royer et al. (1998) showed that the Yearly Genesis Parameter could not be used to address climate change and therefore refined this index by modifying the thermal component. More recently, Emanuel and Nolan (2004) have proposed the Genesis Potential Index (GPI), which uses the concept of Potential Intensity (Bister and Emanuel, 1998) to account for thermal conditions. The GPI was developed and tuned using the large-scale environmental conditions of the NCEP/DOE R-2 reanalyses and has since been used in a number of studies to infer tropical cyclone formation from global climate model output (Camargo et al., 2007b). In this study, the GPI was calculated for CMIP3 models deemed to have acceptable skill in simulating the Indo-Pacific climate (Section 5.5.1) and for which relevant daily model output was available (Appendix 1).

4.8.2 CSIRO Direct Detection Scheme

A number of approaches exist for the direct detection and tracking of tropical cyclone-like vortices in global climate model and downscaled model simulations (Bengtsson et al., 1982; Broccoli and Manabe, 1990; Walsh and Watterson, 1997; Camargo and Zebiak, 2002). However, due to the low resolution of global climate models and possible model biases and other deficiencies, tropical cyclone detection procedures invariably need to be adjusted to reproduce observed climatologies. Subjective adjustment can lead to model-specific and even basin-specific detection criteria (Camargo and Zebiak, 2002) which is less than ideal because model deficiencies are compensated for by the detection procedure, and the same model deficiencies are assumed to be present in the projected future climate. An effort to objectively determine detection criteria was proposed by Walsh et al. (2007), which incorporated a resolution-dependent wind speed threshold. While arguably an improvement because of its increased objectivity, it effectively retains model-dependent thresholds for all models of differing grid resolution.

The PCCSP approach to the direct detection of tropical cyclone-like vortices used a modified version of the Nguyen and Walsh (2001) detection scheme, coupled with the tracking scheme of Hart (2003), and is hereafter referred to as the CSIRO Direct Detection (CDD) method. The CDD method uses a wind speed threshold set at 70% of the value recommended by Walsh et al. (2007) and was tested on 20-years of ERA-Interim reanalysis data and tuned to best reproduce the International Best Track Archive for Climate Stewardship (IBTrACS) observed database (see Section 2.2 for details of reanalysis and observational data). It was applied to outputs from the six CCAM 60 km simulations and CMIP3 models deemed to have acceptable skill in simulating the Indo-Pacific climate (Section 5.5.1) and for which suitable model output was available (Appendix 1).

4.8.3 Curvature Vorticity Parameter Scheme

An independent and objectively determined detection method (based on a Curvature Vorticity Parameter, CVP) was developed for use in the PCCSP. It draws on the large-scale processes known to be essential to tropical cyclone formation, which should be resolvable even in the output generated by relatively coarse resolution global climate models. In particular, recent studies (Dunkerton et al., 2009; Nolan, 2007) have identified the importance of high curvature vorticity and low- to mid-tropospheric relative humidity immediately prior to tropical cyclone formation. Thus, elevated curvature vorticity and relative humidity, as well as minimal vertical wind shear, have been incorporated into the detection algorithm.

As for the CDD method, the CVP scheme was tested on 20 years of ERA-Interim reanalysis data and tuned to best reproduce the IBTrACS observed database. No additional tuning or adjustments were made prior to applying the method to global climate model output, which provides greater confidence that future changes in tropical cyclone frequency actually represent changes in the frequency of tropical cyclone-like circulations that develop in the global models. The CVP scheme was applied to a subset of four CMIP3 models deemed to have acceptable skill in simulating the Indo-Pacific climate (Section 5.5.1) and for which suitable model output was available (Appendix 1).

4.8.4 Tropical Cyclone Wind Hazard

Geoscience Australia's Tropical Cyclone Risk Model (TCRM) is a statistical parametric model of tropical cyclone behaviour, enabling users to generate synthetic records of tropical cyclones representing many thousands of years of activity. It uses an auto-regressive model, similar to the model developed by Hall and Jewson (2007), to create synthetic tracks of tropical cyclone events based on the characteristics (speed, intensity, bearing, size and genesis location) of a record of tropical cyclone events. Once a set of synthetic tropical cyclone events has been created, a parametric wind field (Powell et al., 2005) and boundary layer model (Kepert, 2001) is applied to each track, and the maximum wind speed over the life of each event is captured. A generalised extreme value distribution is then fitted to the maximum wind speed values for each location (Hosking, 1990).

The wind hazard associated with current climate tropical cyclone activity was estimated by applying TCRM to the historical cyclone track record (from IBTrACS) over the PCCSP region. For future projections of wind hazard, TCRM was applied to tracks of tropical cyclone-like vortices detected in the CCAM 60 km simulations (using the CDD method).