Singapore 2nd National Climate Change Study – Phase 1

Introduction

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Contents

Chapter 1. Executive Summary

Chapter 2. Introduction to the Project

Chapter 3. Sub-selection of CMIP5 GCMs for Downscaling over Singapore (Stage 2)

Chapter 4. Dynamical Downscaling – Model Evaluation (Stage 3)

Chapter 5. Climate Change Projections (Stage 3)

Annex 5. A Quantile Matching Bias Correction Technique

Chapter 6. Convective-Scale Modelling (Stage 3b)

Chapter 7. Probabilistic Projections and Wider Uncertainty (Stage 4)

Chapter 8. Changes in Time Mean Sea Level (Stage 5)

Chapter 9. Extreme Sea Level Projections (Stage 5a)

Chapter 10. Long Term Projections Long Term Projections of Sea Level, Temperature and Rainfall Change (Stage 7)

Appendices to Chapters

A3. Sub-selection of CMIP5 GCMs for downscaling over Singapore (Stage 2)

A4. Dynamical Downscaling – Model Evaluation (Stage 3)

A5. Climate Change Projections (Stage 3)

A6. Convective-Scale Modelling (Stage 3b)

A7. Probabilistic Projections and Wider Uncertainty (Stage 4)

A8. Changes in Time Mean Sea Level (Stage 5)

A9. Extreme Sea Level Projections (Stage 5a)

A10. Long Term Projections of Sea Level, Temperature and Rainfall Change (Stage 7)

Supplementary Information

Report 1. 12 km Dynamical Downscaling Documentation

Report 2. Assessment of Empirical Statistical Downscaling for Climate Change Studies over Singapore

Report 3. Key Factors for Sea Level Rise in the Singapore Region

1. Introduction to the project

1.1 This report

This report summarises research and results from the first phase of the Singapore 2nd National Climate Change Study. The content includes findings targeted at issues of interest to the users of future climate information, and includes scientific findings yet to be published in the peer-reviewed literature. In this report, equal weight is given to describing the methods and the results. Due to the broad scope of the project, not every piece of work or every result can be comprehensively reported here. However, additional details on methodologies and results are documented in the appendices and supplementary information reports.

1.2 Background and aims of the project

Driven by increasing awareness of the potential effects of changes in greenhouse gas concentrations in driving past and future climate change, the use of climate models to understand changes to the physical environment has been a focus of scientific research for several decades. As parts of the world start to experience these changes and take adaptation decisions, it is increasingly important to understand specific aspects of those changes that relate directly to societal infrastructure and provision of resources.

The 2nd National Climate Change Study for Singapore consists of two phases: Phase 1, the subject of this report, provides projections of changes in the main climate variables of interest; Phase 2 will assess the vulnerability of different sectors in Singapore to future climate change, through analysis of impacts resulting from the climate changes projected in Phase 1. The results will be used to underpin the next stage of national adaptation planning in Singapore. A 1st National Climate Change Study had previously been undertaken in Singapore. The 2nd National Climate Change Study has an extended scope and generates detailed regional and local information from the latest climate projections that were used to inform the 5th report of the Intergovernmental Panel on Climate Change (IPCC AR5).

This study provides a range of climate information for Singapore, suitable for use in impacts assessments. The centrepiece is the provision of an ensemble of regionally downscaled climate and sea level projections over the region centred on Singapore, out to 2100, and driven by the latest available climate models. In addition this study involves:

- Use of very high resolution modelling to provide confidence in the information on daily rainfall extremes from the main 12 km downscaled projections.
- A broader assessment of uncertainties in future climate change obtained by combining results from different climate model ensembles to provide further context for the downscaled projections.
- A view on plausible longer term changes for sea level, temperature and precipitation out to 2300.

This work was commissioned by the National Environment Agency (NEA) in Singapore, and was undertaken by the Met Office Hadley Centre in the UK jointly with scientists from the Centre for Climate Research Singapore (CCRS) and included important contributions from the National Oceanography Centre, Liverpool (NOC), and the

Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the sea level projections.

1.3 Project stages

The project was designed around 10 complementary work packages or stages. Figure 1.1 details the purpose of each stage, and the relationships and linkages between them.

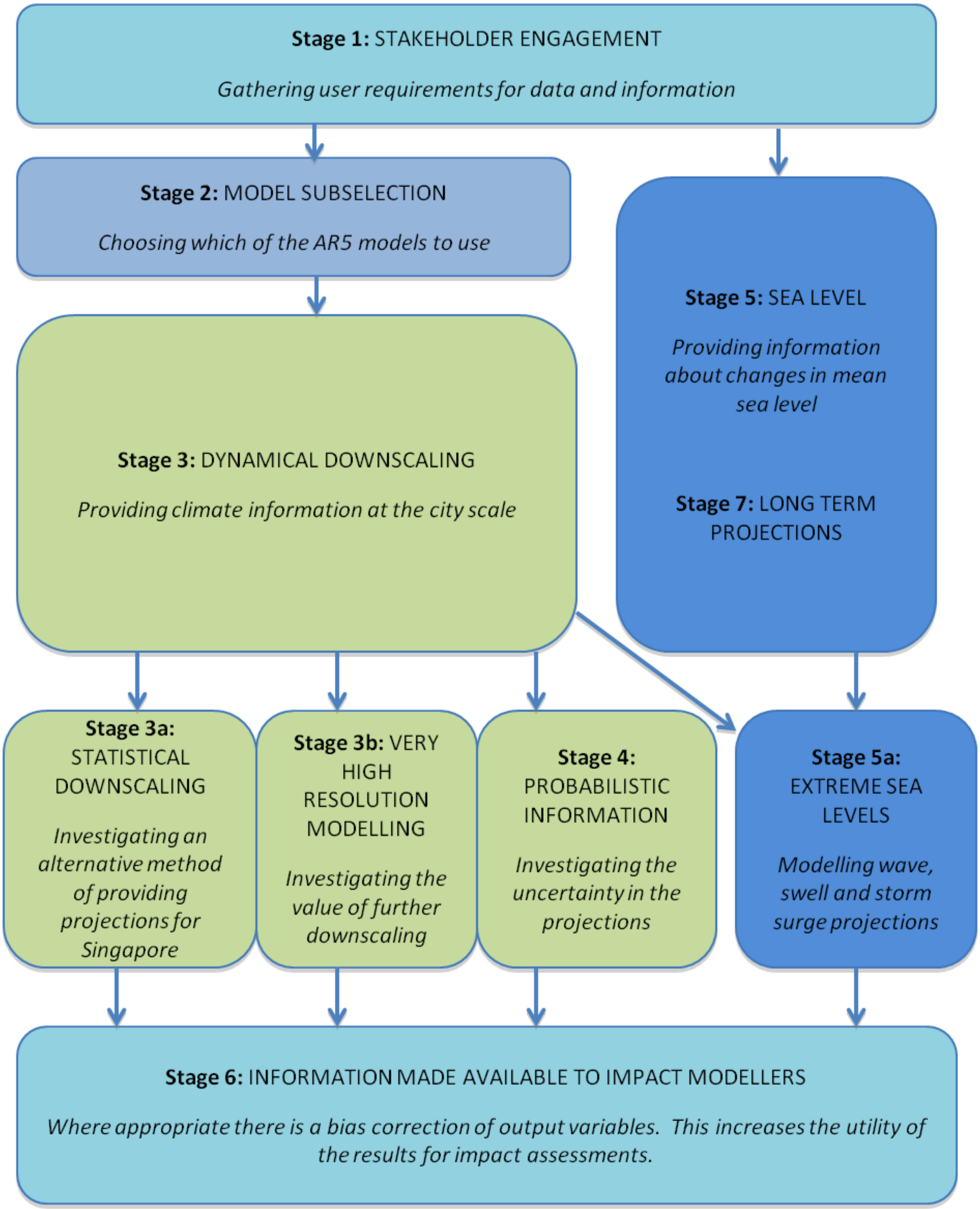

Figure 1.1: Structure of the 2nd National Climate Change Study.

The core provision of climate projections was delivered as part of Stage 3 - dynamical downscaling for changes in rainfall, temperature, humidity and winds, and Stage 5 and 5a for mean and extreme sea level projections.

The first four months of the study were dedicated to a phase of engagement with stakeholders to ensure that the effort devoted to development of climate projections was efficiently tailored to the intended uses of the data for impacts studies. This was followed by interaction with stakeholders throughout the project.

Planning adaptation to climate change should account for key uncertainties in climate projections. One of the principal sources of climate change uncertainty is modelling uncertainty i.e. the use of different models and the effects of their incomplete and approximate representation of physical processes in their responses to anthropogenic forcing. To downscale all of the General Circulation Models (GCMs) provided for CMIP5 would be both computationally expensive and time-consuming. A subset of the models was therefore selected for use in this study to address modelling uncertainty. This subset was chosen based on two criteria:

1) Exclude models that have implausible representation of the current regional climate.
2) For the Southeast Asian region as a whole, the models chosen should span the range of future projected changes in all the CMIP5 models as fully as possible.

Chapter 3 describes the rationale of this sub-selection method, the resulting 10 models that were selected and how this ensemble spans the range of future projections for the region around Singapore.

Global climate models cannot explicitly resolve all of the important processes of the Earth’s climate, and many of these, such as the formation of clouds, are therefore represented approximately. In addition some important influences on regional climate, such as the detailed effects of mountains and coastlines on local rainfall, are missing from global models. Therefore where the local details of a region’s climate are being considered, and where data is required at a higher resolution for decision-making, GCMs are downscaled over the region of interest (Figure 1.2), using a regional climate model (RCM). Out of the 10 sub-selected GCMs, 9 were successfully downscaled using the latest Met Office RCM (HadGEM3RA), at a resolution of 12 km.

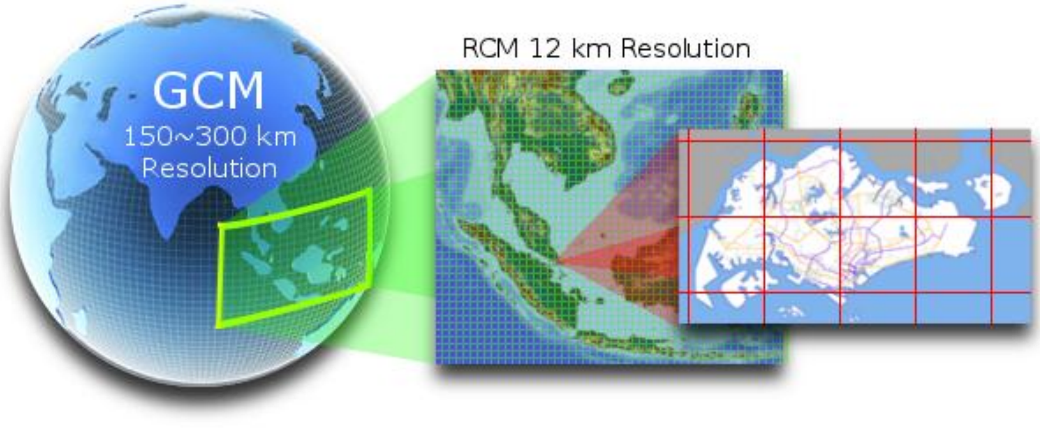

Figure 1.2: Illustration of the nesting of models in the regional dynamical downscaling

The experimental design for the dynamically downscaled simulations was focused on providing a defensible range of future climate projections for Singapore at a resolution relevant to assessment of climate change impacts and adaptations.

The first of these requirements motivated the application of a relatively large, and carefully selected, sub-set of CMIP5 models, coupled with a downscaling methodology necessary to satisfy the second requirement. A dynamical downscaling approach was chosen in order to ensure that the detailed climate scenarios generated for Singapore were (a) as consistent as possible with the driving GCMs, and (b) could be expressed as time-series of physically consistent future climate variables with full spatial, temporal and inter-variable coherency. The specific regional climate model (RCM) configuration was derived from a flexible unified modelling system designed to be suitable for global and regional climate simulations over a wide range of resolutions.

The experimental design implemented in the project was to use a large number of 9 (initially 10, of which one was later dropped) driving GCMs with a single RCM. Whilst recent studies (e.g. Gbobaniyi et al., 2013; Nikulin et al., 2012;) demonstrate a range of outcomes when using different RCMs to simulate regional climate, a few previous studies (e.g. Deque et al., 2005; Rowell, 2005; Kendon et al., 2010; Mearns et al., 2013) have shown that downscaling uncertainty can be important for precipitation changes (less so for temperature), but is often secondary to global modelling uncertainty, thus sampling the range of GCMs effectively could be considered a higher priority than including multiple RCMs. However, there is, as far as we know, no previous study partitioning model uncertainty into global and downscaling components specifically for the Singapore region.

For each of the sub-selected CMIP5 GCMs, three experiments have been run, based upon the experimental design used in CMIP5:

- Historical – run from 1959 to 2010 using observed changes in greenhouse gas concentrations. The simulation for this period is used to evaluate model performance via comparisons with observed data. A subset of this simulation from 1980 to 2009 is also used as the baseline against which future climate change is identified.
- RCP8.5 – The Representative Concentration Pathways (RCPs) used in the CMIP5 experimental design provide a range of scenarios of future forcing out to 2100. RCP8.5 represents a scenario where greenhouse gas concentrations continue to rise strongly throughout the 21st century.
- RCP4.5 – Under this scenario greenhouse gas emissions peak around 2040 then decrease, resulting in radiative forcing that levels off in the second half of the century, with radiative forcing levels that are intermediate between the historical levels and those used in RCP8.5. In general, therefore, the model response under RCP4.5 is anticipated to be intermediate between the historical conditions and the RCP8.5 projections. In consequence, greatest focus has been placed on the RCP8.5 results, with some inclusion of RCP4.5 results to provide additional context.

In addition, a simulation forced by boundary data derived from the ERA interim reanalysis and observed SSTs was completed for the period of 1982-2010 to allow evaluation of the regional model when driven by quasi-observed boundary conditions.

The detail of the experimental design is provided in the Supplementary Information report 1. Key variables and processes of interest from the outputs of the 9 downscaled historical simulations are evaluated in Chapter 4. Chapter 5 details the results from the future projections for Singapore and the wider Southeast Asian region, including the bias-correction method that is used to improve the utility of data from the simulations provided to Singapore impact modellers. Projections of changes in heavy rainfall are of particular importance to Singapore. The poor simulation of the diurnal cycle over land is a common problem in global and regional climate models. This can lead to substantial limitations in the ability of these models to realistically simulate extermes of rainfall. The shortcoming of these simulations over land means that the direct model outputs cannot be used. A methodology has been developed to apply more realistic information from the surrounding ocean and how this can be applied to Singapore.

The national climate projections for Singapore are at a city-scale and this presents various challenges. Although RCMs are able to represent many features of the regional climate beyond the scope of GCMs, the extent of their capabilities depends on their spatial resolution. For this reason, part of this study, focussed on investigating the additional value that could be gained by dynamical downscaling the main 12 km model simulations to 1.5 km scale (Chapter 6).

In contrast to the 12km results, the very high-resolution simulations have the ability to represent, to some degree, the dynamics of convective systems explicitly, such as those bringing heavy rainfall to Singapore. The high computational expense of the 1.5 km model meant that only a pair of decade-long simulations from a single CMIP5 driving model (HadGEM2-ES) could be produced. However, these simulations provide valuable information for future changes in heavy rainfall events, and can be used to test the assumptions made in the bias correction methods referred to above.

Although the main focus in this study is on dynamical downscaling, an alternative statistical method is also investigated in the Supplementary Information report 2. This is based on the identification of relationships between “predictor” variables representing weather and climate variability in an extended region, and local “predictand” variables derived from specific Singapore observing stations. These relationships are initially calibrated using historical observations, and can then be fed with historical and future time series of bias-corrected predictor values from CMIP5 models to produce synthetic time series of downscaled daily local weather suitable for impacts assessments.

This approach provides a computationally cheap method of obtaining local scenarios from a potentially wider range of CMIP5 models than the nine used for dynamical downscaling, however its credibility is dependent on the target variable of interest, the CMIP5 model being used for downscaling, and the extent to which predictor-predictand relationships can be assumed not to change in the future. For precipitation, which comes largely from convective local systems, the methodology was not able to produce acceptable calibration relationships between large-scale drivers and local rainfall for Singapore and was hence is deemed unsuitable for rainfall downscaling. For this reason, a set of statistically downscaled projections have not been produced in this study.

Whilst the CMIP5 ensemble of coupled ocean-atmosphere models provides the latest generation of core projections assessed by IPCC, it was (in common with previous multi-model ensembles) an *ad hoc* construction assembled on an opportunity basis, and constrained by design choices which should not be assumed to cover all plausible outcomes for future climate consistent with current knowledge. The present study therefore provides in Chapter 7 a set of results for future temperature and precipitation changes constructed by including information from multiple lines of evidence, thus locating the CMIP5 results (and the downscaling derived from them) in a broader envelope of uncertainties in future changes during the 21st century. This information includes probabilistic surface temperature changes, derived from a formal statistical methodology combining results from several ensembles of perturbed variants of

HadCM3, an earlier Met Office Hadley Centre model, with information from the CMIP3 multi-model ensemble run for the previous IPCC assessment (AR4). The results also account for uncertainties in carbon cycle feedbacks, not considered in the CMIP5-driven regional climate model simulations described above. For precipitation, although PDFs could not be derived, results from one of the HadCM3 perturbed parameter ensembles is combined with CMIP5 results to illustrate the presence of wider uncertainties beyond the CMIP5 range, in order to provide context for future risk assessments for Singapore.

Sea level rise is of significant concern to many decision makers in Singapore, and this study therefore includes new advice on potential future changes. Changes in extreme sea levels arise through some combination of: (i) changes in time-mean regional sea level; (ii) changes driven by regional processes that control the most extreme sea levels, which are often linked to local meteorology. Future changes in global and regional mean sea level are presented in Chapter 8. The main components of global average sea level rise are the thermal expansion of water associated with global temperature rise and the addition of water to the oceans due to glacial melt, changes to the Greenland and Antarctica ice sheets, with a smaller contribution from changes in land water storage. Changes in global mean sea level are estimated from the set of CMIP5 climate model simulations used to assess sea level rise in the IPCC AR5.

Extreme sea levels are generated by wave and surge events – driven by low atmospheric pressures and strong winds. The outputs from regional climate model (RCM) experiments (Chapter 5) have been used to drive high resolution (10 km) storm surge and wave models focussed around Singapore to study the effect of changes in atmospheric storminess on local water levels (Chapter 9). This resolution does not resolve coastal details, however, projected changes in mean sea level and surge are both expected to have large spatial scales compared with the scale of Singapore. Therefore *changes* in extreme sea level are expected to be approximately uniform around Singapore. Local effects could result in some spatial variation in how the large scale changes are felt at different locations in Singapore. This could be addressed in principle by a high resolution, second level of downscaling. Key uncertainties for projections of sea level for Singapore are discussed.

Changes beyond the end of the 21st century are not usually considered in national climate scenarios, partly reflecting the priorities of most decision-makers, and partly because the uncertainty inherent in climate projections increases as we look further into the future. However, for some decision makers considering long-term infrastructure, it will be useful to understand what may be expected on longer timescales. As part of this study, a brief analysis of the extended model simulations to 2300 (provided as part of CMIP5) is provided in Chapter 10. The main focus is on changes in sea level rise, but projected changes in temperature and rainfall are also considered. These results should be interpreted as a limited set of plausible outcomes provided by current climate models in combination with two extended emissions scenarios, both assuming stabilisation of greenhouse gas concentrations.

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