Singapore's Second National Climate Change Study

Climate Projections to 2100

Report for Stakeholders

Meteorological Service Singapore
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Executive Summary

Background to the Climate Projections within the Second National Climate Change Study

Climate change is one of the foremost challenges facing humankind today. As the evidence for greenhouse gas induced climate change continues to mount, there is an increasing need for nations to have access to information that aids planning and adaptation action to understand and reduce the risks of potential future consequences. This is particularly the case for island nations such as Singapore, which could see impacts arising from changes over both land and ocean.

The Intergovernmental Panel on Climate Change (IPCC) produces reports that include future projections for all regions of the world. These reports, however, provide only broad scale regional assessments of projected climate change. The assessments are mostly based upon coarse resolution global climate models that do not represent Singapore and its surroundings in detail. They do, however, provide a very useful context for the finer resolution projections that will be described in this report. The Second National Climate Change Study[1] for Singapore aims to provide the best available scientific information on the spatial and temporal scales most relevant to Singapore. This will inform the discussion and decision-making around the actions that are required to safeguard its population, environment and infrastructure.

The Second National Climate Change Study was commissioned by the National Environment Agency (NEA) under the auspices of the inter-agency Resilience Working Group. Scientific work on the climate projections was undertaken by the Meteorological Service Singapore's Centre for Climate Research Singapore (CCRS) and scientists from the Met Office Hadley Centre in the UK. It also included important contributions for the sea level projections from the National Oceanography Centre, Liverpool (NOC) and the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO).

This Stakeholder Report provides a summary of the study's methodologies and findings. It is intended for those who will be actively engaged in the use of the projections for impact studies and adaptation planning. The data outputs from the study's climate projections have been made available to government agencies and this report provides contextual scientific information to aid the interpretation of the data. A comprehensive Science Report has also been produced to document in detail the methodologies employed, the evaluation of the models against available observations and the more in-depth analysis of the Singapore projections within a regional context.

[1] The First Climate Change Study, commissioned in 2007, was based on the state of scientific information available at the time.

Phase 1 of the study provides projections of changes in the main climate variables of interest to Singapore. A key consideration was to understand the intended uses of the climate projections at an early stage, so as to tailor the projections as far as possible to address the needs of key stakeholders. Stakeholder engagement was a deliberate and continual process, intended to enable use of the resulting information for downstream impacts studies. The centrepiece of this report is the provision of regionally downscaled climate and sea level projections for the 21st century over the region centred on Singapore, derived from the latest available climate models. A brief view on plausible longer term changes for sea level, temperature and precipitation out to 2300 is also provided.

Phase 2 of the study, which started in 2014, will make use of the projections from Phase 1 to examine the climate change impacts on the domains of water resources and drainage, biodiversity and greenery, network infrastructure and building infrastructure. This, in turn, will guide government agencies in their downstream planning and will serve as inputs to help shape Singapore’s resilience plans.

Observed trends in Singapore’s Past Climate

Past temperature records in Singapore show a greater rate of increase than the global temperature trend. Over the last 60 years, global temperatures have risen by 0.12°C per decade, whereas in Singapore the rate has been 0.25°C per decade. However, although global warming is likely to have contributed to this, not all of the increase can be accounted for. The regional climate is also affected by natural decadal variations, which occur regardless of anthropogenic global warming. Human activities can also influence the climate in ways that are not associated with the global warming resulting from increasing greenhouse gas concentrations in the atmosphere. Examples include the emission of pollutants leading to aerosols in the air, which can impact temperatures and rainfall, and land usage changes such as urbanization. All of these factors may have contributed to the observed temperature rise over Singapore.

Past annual rainfall totals shows a statistically significant upward trend over the last 30 years. It is not possible at this stage to confidently attribute the observed changes in local rainfall to particular factors, but global warming may have caused some part of the trend. Natural climate variability in the region is another possible cause. Urbanization can also be important because higher temperatures in urban areas could enhance convective activity that leads to heavy rainfall. Major uncertainties remain in attributing Singapore’s observed rainfall trends and this is an area of active ongoing research.

Scientific Methodology

The starting point for generating projections of climate change at regional and local scales is the global-scale projections produced by the latest generation of climate models. These projections contributed to many of the findings of the IPCC's Fifth Assessment Working Group I Report (IPCC AR5), published in 2013. The next step is to "downscale" the global climate models using a much higher-resolution regional model of Southeast Asia. This provides greater spatial detail in the projections but is expensive computationally.

The models assessed in the IPCC AR5 comprise around 40 global climate models, providing a range of realisations of the future climate. It was necessary to carefully select a subset of these so as to balance computational expense against the requirement to produce a range of plausible outcomes consistent with those assessed in the IPCC AR5. This sub-selection of models was based on the degree of realism in representing past and current climate, and capturing the range of plausible future changes projected by the latest set of global climate models.

The regional climate model used for downscaling was configured to have a 12 km horizontal resolution grid centred on Singapore, and covers much of Southeast Asia. For each of the nine selected global climate models, two future simulations were carried out based on different greenhouse gas Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5. The different RCPs are labelled by the change in the approximate total radiative forcing in the year 2100 relative to 1750, due to the enhanced greenhouse effect associated with each pathway. For example, under RCP4.5 this change is 4.5 Wm^{-2}. RCP4.5 is related to a scenario where emissions peak mid-century and then decline, whereas RCP8.5 is related to a scenario with very high greenhouse gas emissions that continue to increase throughout the 21st century. Both scenarios are likely to lead to a global mean temperature increase significantly greater than the 2°C (above the pre-industrial values) target of the United Nations Framework Convention on Climate Change (UNFCCC).

An important component of the study is the projection of changes in mean sea level and extreme coastal events. Changes in frequency and severity of extreme coastal events were determined from combining changes in large-scale time-mean sea level with characteristics of the wave and storm surge conditions that affect the coastline. These two factors have been considered in turn to project changes in future extreme water levels offshore of Singapore for use in local impacts studies.

Projected changes in large-scale time-mean sea level for the Singapore region over the 21st century, under the RCP4.5 and RCP8.5 greenhouse gas trajectories, have been assessed based on 21 climate model simulations together with a solid Earth response model that simulates both past and future terrestrial ice mass loss and changes in terrestrial water storage. A subset of four out of the nine 12 km downscaled simulations were used to drive coastal models of the Singapore region to assess potential changes in waves and surge activity under the most severe greenhouse gas increases assessed in IPCC AR5, i.e. RCP8.5.

The projected changes for meteorological and sea level parameters represent a state-of-the-art set of plausible alternative outcomes based on the latest available climate modelling technology. However, they are conditional on the experimental design, including in particular the set of climate models chosen to produce them, and the set of earth system processes represented in the models. Therefore, the qualitative possibility that specific aspects of future climate change could lie outside the ranges provided should not be discounted when using the projections for decision-making and risk assessments.

Climate Change Projections for Singapore – Temperature, Rainfall and Wind

The most robust aspects of the climate change projections for the Singapore region are the increases in near surface temperature. Relative to a reference period of 1980-2009, daily mean temperatures are projected to increase by around 2°C (RCP4.5) to 4°C (RCP8.5) for the end-century period (2070-2099). This will lead to temperatures significantly higher than those currently experienced. A seasonal analysis of warm days and nights for February to May (having the highest number of warm days in the current climate) and June to September (having the highest number of warm nights in the current climate) shows that the models project significant increases in both throughout the 21st century. In the case where the world follows an RCP8.5 greenhouse gas trajectory, most models project that by the end-century almost every day in these seasons on average will be a warm day (≥34.1°C) and a warm night (≥26.2°C). An analysis of the wet bulb temperature, which is more directly relevant to the thermal comfort experienced outdoors, shows corresponding increases.

The projections for precipitation changes are far less robust than those for temperature. Analysis of annual mean rainfall changes over Singapore shows considerable variation amongst models, ranging from positive to negative, independent of the RCP that is used. In all cases, the projected long-term trend is smaller than the natural variability as simulated in the models, suggesting that Singapore's annual average rainfall will continue to be dominated by natural variability during the 21st century.

On a seasonal basis, the contrast between the wetter and drier months is projected to become more pronounced, especially for the RCP8.5 trajectory and by the end of the century. The models generally project an upward trend in seasonal mean rainfall during the wet season of November to January, as well as greater dryness during months that are already relatively drier in the current climate (February and June to September). Another important result from these projections is that most models show an increasing trend in the intensity and frequency of heavy rainfall events as the world warms. This is consistent with our current state of physical understanding that the frequency and intensity of heavy rain events increase in a warmer atmosphere with a higher water vapour content.

In terms of future changes in the wind, the climate of Singapore will continue to be dominated by the northeast and southwest monsoons. By the end of the century, there are no substantial changes in wind direction but there is some indication of increasing wind speeds during the northeast monsoon season under RCP8.5. A single very high resolution model simulation suggests that by the end of the century, under RCP8.5, there could be a small increase in wind gust strength (of the order of 5-10%).

Climate Change Projections for Singapore – Sea Level

For mean sea level rise for 2100, a median estimate of 0.53 m is projected under RCP4.5 and 0.73 m under RCP8.5. Up to 2050, the ranges of regional projections of mean sea level rise in the RCP4.5 and RCP8.5 scenarios are similar, with a median value of approximately 0.25 m. Even at 2100 there is substantial overlap between the ranges of projected rise from the two RCPs. The projections presented here do not consider the unlikely event of a collapse of the marine-based sectors of the Antarctic ice sheet. This event could result in additional global sea level rise of several tenths of a metre during the 21st century.

Overall the results indicate that changes in extreme sea levels for the Singapore region over the 21st century are likely to be dominated by the regional time-mean sea level rise, with only small future changes to the storm surge and wave components. The century-scale trends in the extreme surges due to changes in wind patterns are not statistically significant. The upper estimate of the change in surge by 2100 is an increase of a few centimetres (compared with the upper estimate of over 1 m for the change in *mean sea level*). The largest waves at the Singapore coast over the 21st century show no statistically significant upward trend.

Longer Term Projections

The majority of the analysis in this study has focused on the likely changes out to the end of this century, which is the time horizon typical of infrastructure developments. There is, however, benefit in understanding the longer term context. Exploratory projections of temperature, rainfall and sea level rise for the Singapore region over the next three centuries (out to 2300) have also been produced. Sea level is of particular importance due to the long time-lags for the oceans to respond to greenhouse gas increases and also because of the potential for the irreversible collapse of ice sheets to substantially increase sea levels. A plausible upper range of sea level rise for Singapore is 3-6 m by 2300.

Summary Table of Results

The following table presents a summary of the results from this study for the years 2070-2099 relative to the 1980-2009 baseline period. For details on the projected ranges for each variable, please refer to the following sections.

Variable	Scenario RCP4.5	Scenario RCP8.5
Mean daily temperature *(value in baseline period is 27.4°C)*	28.8 to 30.1°C	30.3 to 32.0°C
Mean maximum daily temperature *(value in baseline period is 31.8°C)*	33.3 to 34.6°C	34.9 to 36.7°C
No. of warm days in February-May above 34.1°C *(value in baseline period is 25 days)*	74 to 108 days	105 to ALL days
Annual average rainfall *(departure from baseline value of 2488.4 mm/yr)*	-12.4% to 10.3%	-17.2% to 26.8%
Northeast monsoon rainfall *(departure from baseline value of 261.8 mm/mth)*	-13.6% to 42.9%	-23.1% to 67.5%
Southwest monsoon rainfall *(departure from baseline value of 174.6 mm/mth)*	-12.4% to 12.3%	-30.3% to 1.2%
February rainfall *(departure from baseline value of 142.1 mm/mth)*	-82.4% to 23.9%	-83.2% to 16.5%
% contribution to annual rainfall from very wet days (as defined by historical 95th percentile value) *(value in baseline period is 22.8%)*	21.1% to 35.3%	21.5% to 44.1%
Mean daily WBT* *(value in baseline period is 26.4°C)*	27.6 to 28.9°C	28.9 to 30.7°C
Mean maximum daily WBT *(value in baseline period is 29.2°C)*	30.8 to 31.9°C	32.0 to 33.9°C
No. of days with WBT above 27.7°C *(value in baseline period is 37 days)*	280 to 329 days	313 to 357 days
10 m wind	No significant change in prevailing wind directions. Some indication of increased wind speeds under RCP8.5 during the northeast monsoon season.	
Mean sea level	0.25 to 0.60 m	0.35 to 0.76 m
Storm surge and waves	No statistically significant positive changes	

* WBT refers to wet bulb temperature.

1. Introduction to the Second National Climate Change Study: Climate Projections to 2100

Why do we need climate change projections for Singapore?

The United Nations Intergovernmental Panel on Climate Change (IPCC) in their latest report (Fifth Assessment Report, IPCC AR5) concluded 'it is extremely likely that most of the observed increase in global surface temperature since 1951 was caused by human influence.' The report states that by the end of the century, the increase of global mean surface temperature above 1986-2005 levels is projected to be 0.3-4.8°C, depending on the level of greenhouse gas emissions and taking into account natural variability and climate model uncertainty. It is well understood that a) this warming will be accompanied by changes in the water cycle, sea level and extreme events (to name a few), and b) these changes will not be uniformly distributed across the globe. It is therefore important that, at a regional and local scale, potential changes to the climate system and its impacts on natural and human systems are well understood.

Understanding changes to the physical environment through the use of climate models has been the focus of scientific research for many decades. As parts of the world start to experience these changes and take adaptation decisions, it is increasingly important that these decisions are based on the scientific evidence concerning future climate change.

Climate projections are required for multiple aspects of societal and infrastructure planning, and engagement with users of climate information in Singapore has been an important aspect of this study. In particular, this targeted key sectors of coastal protection, water resources and drainage, biodiversity and greenery, public health, network infrastructure, and building infrastructure. End users were consulted using both large group workshops, that were effective at relaying information about the forthcoming study, and small sector-specific conversations that proved useful in gathering the detailed data needs of decision makers in Singapore. This information was used to scope the research and outputs from the study.

What are the latest global climate projections?

The Fifth Assessment Report of the IPCC (IPCC AR5) Working Group 1 (WG1), published in 2013, includes assessment of models and simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5), an international effort among the climate modelling community aimed at coordinating climate change projections. Many different models were assessed and the results provide a range of possible outcomes. Key differences between the new set of projections and the previous CMIP3 projections used in IPCC AR4 are explained in Boxes 1.1 and 1.2.

Box 1.1: How are the models used in IPCC AR5 (CMIP5) different to those in IPCC AR4 (CMIP3)?

First, there were a larger number of models used in IPCC AR5 than in IPCC AR4. Second, models in IPCC AR5 generally have better spatial resolutions and representations of physical processes, which contribute to an improved simulation of the climate on a finer scale, enabling an enhanced simulation of continental-scale variations in climate. Third, some models used in IPCC AR5 include new interactive 'Earth System' processes, such as the carbon cycle feedback, and are thus able to account for a broader range of potential influences on future climate change.

Models also need to be evaluated before they are deemed reliable enough for use. There has been a more elaborate evaluation of climate models in IPCC AR5, for example the evaluation of the role of cloud processes in climate change.

Box 1.2: How are the future emission scenarios used in the IPCC AR5 different from those in the previous IPCC AR4?

Due to human activities, such as energy production, industrial processes, land clearance and transport, greenhouse gases are emitted into the atmosphere. The gases emitted interact in a complex way within the Earth's carbon cycle, with a sizeable fraction of emissions absorbed into the oceans. The residual gases lead to an increase in the concentration of greenhouse gases in the atmosphere.

The emission scenarios used in IPCC AR4 were based on alternative socio-economic futures for the world. They incorporated a wide range of different assumptions regarding population, economic growth, technological innovation and attitudes to social and environmental sustainability. The scenarios used in IPCC AR5, on the other hand, took a different approach. They did not start by specifying socio-economic storylines of the future and calculating the associated emission scenarios. Instead, greenhouse gas concentration pathways were generated that are compatible with the range of emission scenarios available in the current scientific literature. In other words, it specified a number of trajectories for future concentrations of greenhouse gases in the atmosphere. The relationship between these future concentrations and emissions depends on the strength of carbon cycle feedbacks, which is a major source of uncertainty in current understanding of future climate change. Therefore, a range of emissions pathways can be associated with each concentration pathway.

In addition, the impact of emission reduction mitigation policies were also included in some of these concentration pathways. A representative subset of four of these scenarios, known as Representative Concentration Pathways (RCPs), was then used as the "input" to drive climate models.

The IPCC reports can provide only broad scale regional assessments of projected climate change. The assessments are mostly based upon coarse resolution global climate models that do not represent Singapore and its surroundings in detail. They do, however, provide a very useful context for the finer resolution projections that will be described in this report.

Although improved in resolution compared to IPCC AR4, the climate models assessed in IPCC AR5 are not detailed enough to provide user-relevant projections for a specific location such as Singapore, only providing broad regional outcomes. The Second National Climate Change Study downscales these global scale projections (at a resolution of typically 150-300 km) to the regional scale (12 km) and, as far as is possible, provides tailored analysis of important meteorological variables that are required to better meet the information needs of decision makers.

What are the specific challenges in producing climate projections for Singapore?

The national climate projections for Singapore are required at a city scale. This is a challenge because in order to simulate detailed regional and local features of the climate, models that capture the main weather systems in Southeast Asia are required. Regional models, with a limited geographical domain and a higher spatial resolution than the global models, are used for this purpose. The high computational cost of these regional models typically limits the horizontal resolutions to the range of 10-30 km. In this study the main downscaling model simulations are at 12 km and even at this resolution the island is only covered by a few model grid points (see Figure 3.1).

Singapore's urban landscape has developed rapidly over the last 40 years and studies have documented the impact of the urban environment on the local climate. A simple representation of the developing urban environment is included in the historical runs of the regional model but there is no representation of likely future changes in land-use. Future studies, with much higher spatial resolution models and an explicit urban canopy representation, will be required to properly simulate urban effects.

A particular challenge comes from the predominant convective systems that produce extreme rainfall in Singapore at the local scale. Thunderstorms are driven by convection in the atmosphere, which is widely recognised to be poorly represented in the current generation of global and regional climate models. A particular issue is the poor simulation of the diurnal cycle of rainfall over land in the models. This means that reliable sub-daily rainfall projections cannot be provided from these models. The use of higher resolution kilometre-scale models, in which these processes can be explicitly represented, is one way forward but such models have yet to be used in the production of climate change projections because of their even higher computational cost. In this study, a single 1.5 km model simulation is used to assess the importance of resolving these convective processes. It is worth noting that, even at an appropriate resolution, the regional model may still be unable to simulate the important local weather systems well if the large-scale global models do not provide the correct driving conditions. Conversely, even with the correct driving conditions, the regional model may still struggle to provide enough realism in simulation of local weather systems. A study such as this one therefore has to be seen as providing state-of-the-art projections that are consistent with the current international state of climate science. As the science and modelling advances, future studies will be required to update the projections.

What is the scope of the study?

The Second National Climate Change Study delivers new local climate projections based on downscaled simulations from the models assessed in IPCC AR5. Figure 1.1 illustrates the stages of the study to generate future projections for Singapore.

This report provides a summary of the results of the study. In Chapter 2 an overview of the observed changes in Singapore's climate over recent decades is provided. In Chapter 3 the methodology used in the study is described, with a focus on the downscaling of IPCC AR5 projections to the local scale. Chapters 4, 5, 6 and 7 provide results and analysis from the climate downscaling, and Chapter 8 discusses the sea level projections. The final part of this report briefly describes how the results will be used to underpin Singapore's Resilience Framework. An Annex provides a series of possible questions and answers regarding the recommended use of the projections.

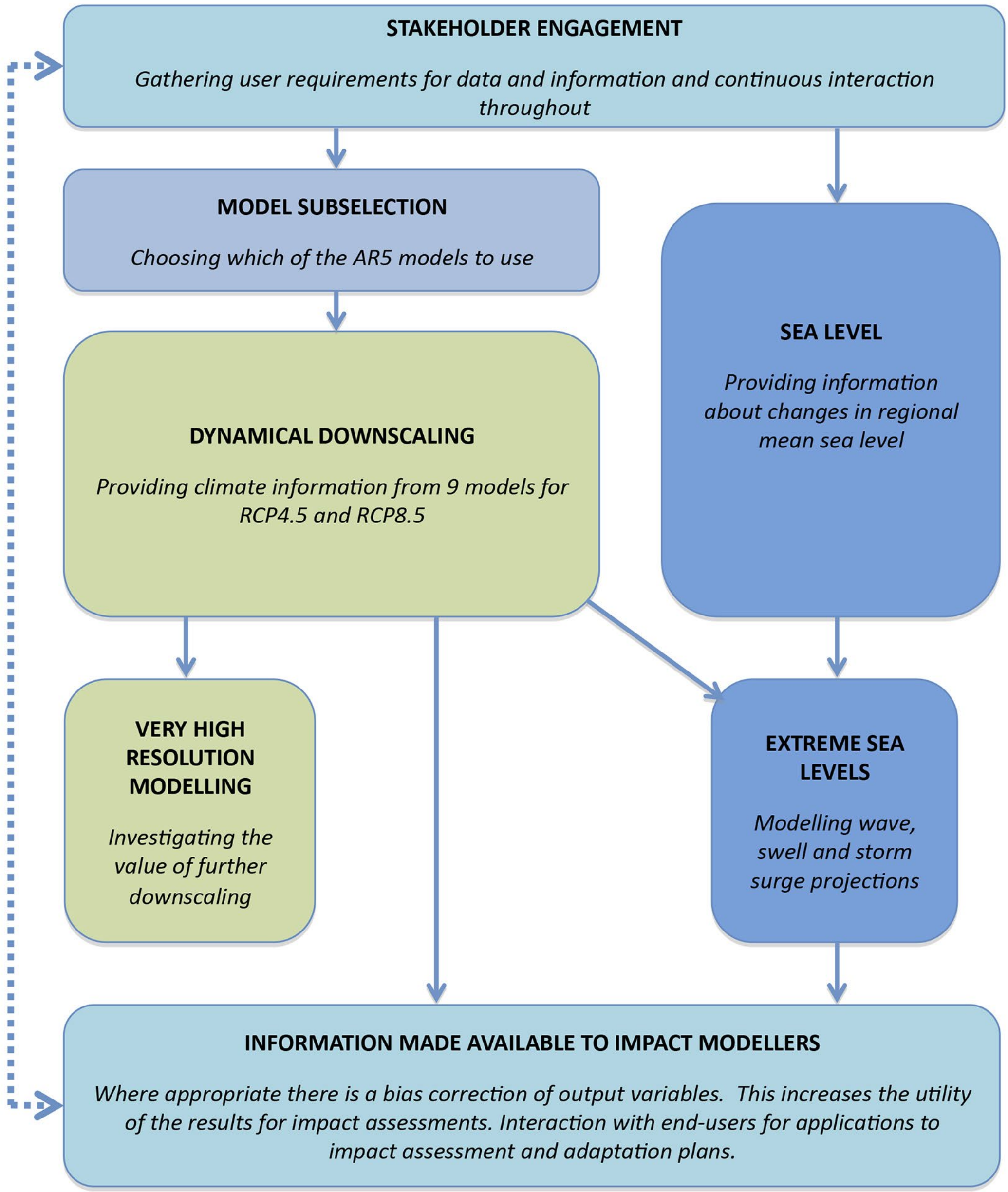


Figure 1.1: Structure of the Second National Climate Change study.

2. How has the climate of Singapore changed?

To provide a backdrop for the future projections described later in this report, this section describes the observed changes in Singapore's climate in recent decades. As a precursor to the observational analysis, Box 2.1 provides a brief summary of Singapore's climate and the weather systems that influence it.

Box 2.1: Singapore's climate and main weather systems

Singapore has a tropical climate which is warm and humid, with abundant rainfall of about 2400 mm per year. The winds are generally light but with diurnal variation due to land and sea breezes. Singapore's weather is traditionally classified into four periods according to average prevailing wind directions:

a) Northeast Monsoon Season (December to early March).

b) Inter-monsoon period (Late March to May).

c) Southwest Monsoon Season (June to September).

d) Inter-monsoon period (October to November).

The transitions between the monsoon seasons occur gradually, generally over a period of two months. The winds during these transitions, or inter-monsoon periods, are usually light and tend to vary in direction. The three main rain-bearing weather systems that affect Singapore are the northeast monsoon surges, "Sumatra" squalls and convective showers/thunderstorms. Convective showers/thunderstorms can occur throughout the year. "Sumatra" squalls commonly occur during the southwest monsoon and inter-monsoon seasons, while the monsoon surges occur during the northeast monsoon.

Northeast Monsoon Surges: A northeast monsoon surge is a surge of cold air from Central Asia. During the period of December through early March, the heartland of Asia, including Siberia, experiences very low temperatures. From time to time, this cold air rushes out of Central Asia leading to an abrupt increase in northeasterly winds over the South China Sea blowing towards the warm tropics. The sea warms and moistens the overlaying air and the wind eventually converges to bring about widespread rain in the tropical regions. December is usually the wettest month of the year in Singapore and a few heavy rain spells, caused by surges of northeast monsoon winds, contribute to most of the rainfall in the month. A typical rain spell will generally last for a few days.

"Sumatra" Squalls: A "Sumatra" squall is an organised thunderstorm line that develops over Sumatra or the Straits of Malacca, often overnight, and then moves eastward to affect Peninsular Malaysia and Singapore. In a typical event, the squall line can bring about one to two hours of thundery showers. Often this happens in the predawn or morning hours. Some Sumatra Squalls are also accompanied by wind gusts with speeds up to 20 m/s which are strong enough to uproot trees.

Sea Breeze Induced Thunderstorms: Sea breezes are winds formed as a result of temperature differences between the land and the adjoining sea. The sea breeze, carrying large amount of moisture from the sea, blows inland during the day where the moist air mixes with the rising warm land air and, in unstable conditions, form rain clouds in the afternoon. During the inter-monsoon periods when winds are light, sea breezes are more common.

Climate Variability and Trends

The climate varies naturally on multiple timescales and the amplitude of these variations can be comparable to variations induced by man-made climate change, particularly over this region. For multi-decadal timescale climate variations, when the observational record is short, there is always a danger that they will be wrongly attributed to man-made climate change. Figure 2.1 illustrates this issue for temperature observations that have been taken over Singapore during the northeast monsoon season (red line) and sea surface temperatures averaged over the southern part of the South China Sea (green line). At this time of year the prevailing wind is from the northeast direction, hence sea temperatures over the South China Sea can have an influence on temperatures over Singapore. It is useful to consider both of these time series to distinguish the trends over the nearby oceans compared to those over Singapore, since the latter can be influenced by additional anthropogenic factors such as urbanization.

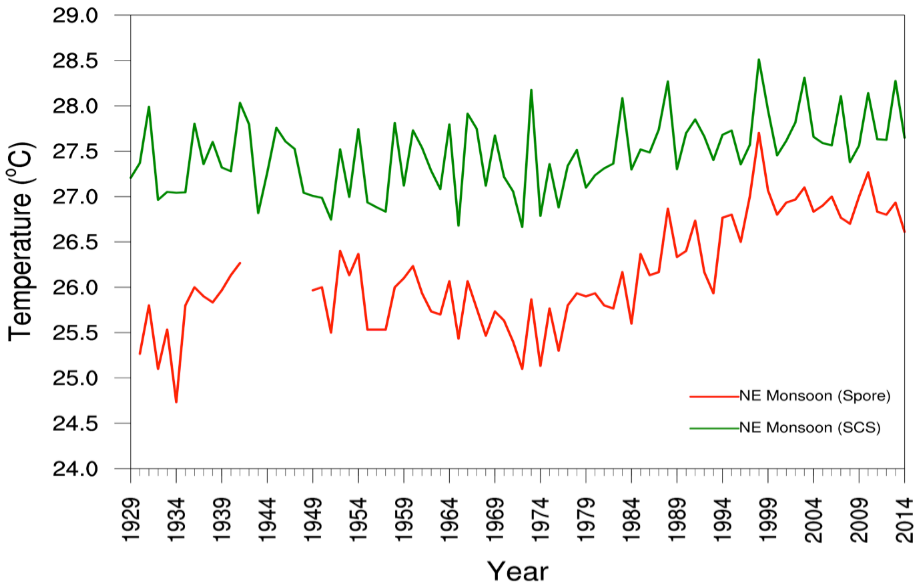


Figure 2.1: Observed average temperature during the northeast monsoon season at the Singapore climate station since 1929 (which has moved location over the years) – red line, and sea surface temperature averaged over the southern flank of the South China Sea (SCS) – green line.

Both time series of temperature in Figure 2.1 exhibit variability on timescales of years to many decades. When looking at these regional (South China Sea) and local (station) temperature changes, the overall global warming trend is masked by the large variability in both time series. In the global record, the most rapid increase in temperature occurred between the early 1970s and the later 1990s. This can also be seen in Figure 2.1, with the South China Sea temperatures (green line) showing a warming trend over this same period. Singapore's temperature (red line) since the early 1970s shows a greater rise than that observed in the surrounding oceans (in the northeast monsoon season, 0.12°C/decade over the sea and 0.23°C/decade in Singapore). A similar enhanced trend at this time is seen over urban and rural sites in Peninsular Malaysia, which suggests part of this may be caused by local climate variability. Rapid urbanisation in Singapore during this period of time will also have contributed to this enhanced temperature trend over Singapore.

Figure 2.2 shows a series of rainfall observations from 3 stations in Singapore. The longest series shown is from 1930 and the other two begin later. There is large variability on year-to-year and decadal timescales. Note that when annually accumulated, there is a strong correlation between the rainfall totals observed at the different stations, increasing the confidence that the variation in total annual rainfall recorded in a single station is generally representative of variation over Singapore as a whole. Overall, there is an upward trend between the 1970s and recent years but note that there were also high rainfall values in the early 1950s.

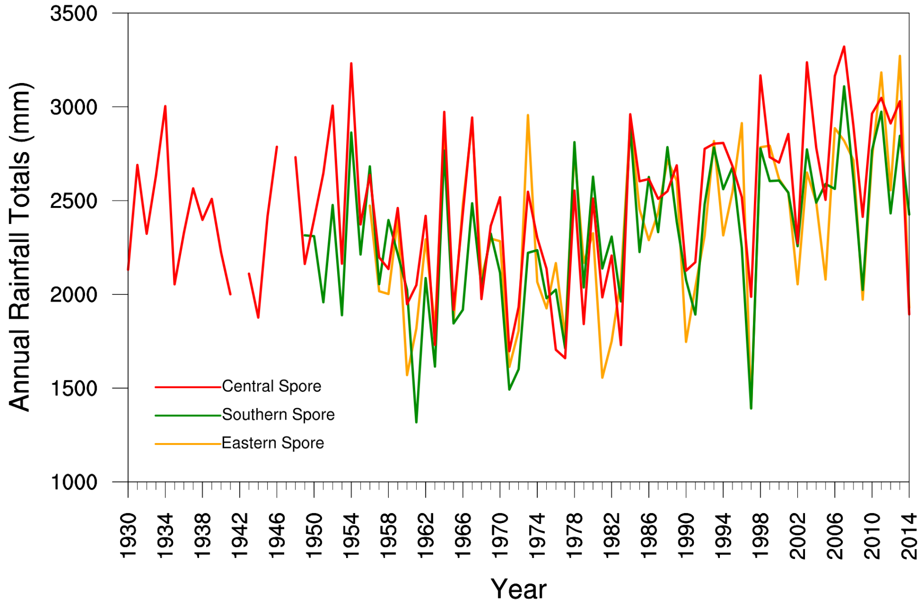


Figure 2.2: Observed annual rainfall totals at 3 stations in Singapore.

The examples of the annual average temperature and rainfall time series illustrate a number of important points:

a) Determining whether an observed trend is actually caused by increasing greenhouse gases, or is simply part of a natural variation, requires both (1) very long observational records, to properly sample the inter-decadal variability, and (2) modelling studies with and without greenhouse gas forcing, so that the climate change and variability signals can be separated. The understanding of the physical mechanisms giving rise to the changes is also important to add confidence to any attribution studies. Thus, it is not possible to attribute causes for trends from the time series alone.

b) In Singapore, the natural variability for rainfall is large and no studies have yet been done that can attribute the changes in rainfall illustrated in Figure 2.2.

Conversely, attribution studies using climate models with and without greenhouse gas forcing, suggest that the overall trend in regional temperatures between the early 1970s and late 1990s has a substantial contribution from increasing greenhouse gases. Other studies have shown that there is a considerable urban temperature enhancement over Singapore but an exact attribution of the relative importance of greenhouse gas induced warming, climate variability and urban effects has yet to be carried out.

The discussion above concerns annual average rainfall. When considering changes in intensity or frequency of heavy rainfall, which is relevant in discussions of flood risk, the situation becomes more complex. This is particularly the case when the main risk is flash flooding caused by weather systems, such as thunderstorms, that have a lifetime of only a few hours and a small spatial scale of only a few kilometres. This is because, as will be illustrated later, trends in intensity of hourly heavy rainfall events can vary considerably from station to station, unlike annual average rainfall. It is for this reason that most of the analysis that follows makes use of the extensive hourly observations available in Singapore from the 28 rainfall stations that have recorded measurements since 1980.

The model simulations of the historical climate that have been undertaken as part of this study suggest that the inter-decadal changes in rainfall observed in Singapore could be a consequence of natural variability in the climate system. These simulations exhibit historical decadal changes in rainfall of similar amplitude to those observed. The increase in the moisture content in the atmosphere that is associated with global warming suggests that greenhouse gas induced climate change may have played some part. More definitive and quantitative attribution statements must await future research.

Observed climate change in recent decades

Observational data reveal several significant changes in temperature and rainfall over Singapore in the last thirty to forty years (Table 2.1). Changes per decade are based on a linear fit for the years indicated and these are in reference to extremes thresholds commonly used for historical climate. The thresholds are used throughout this report and it is therefore useful to provide a summary of these. The following threshold values are for the reference period 1980-2009:

- Warm days: 34.1°C is the 90th percentile of maximum daily temperature.
- Cool days: 29.2°C is the 10th percentile of maximum daily temperature.
- Warm nights: 26.2°C is the 90th percentile of minimum daily temperature.
- Cool nights: 22.3°C is the 10th percentile of minimum daily temperature.
- 40 mm/hour is the 95th percentile of climatological hourly rainfall intensity.
- 70 mm/hour is the 99th percentile of climatological hourly rainfall intensity.

Table 2.1: Long-term changes in (a) temperature and (b) rainfall over Singapore.

a) Temperature	**Change per decade (1972-2014)** Analysis based on records from 2 stations[1] which have records longer than 30 years.
Annual mean temperature	+ 0.27 °C per decade *(26.6 °C in 1972 to 27.7 °C in 2014)*
Annual number of warm days *(Maximum Temperature ≥ 34.1°C)*	+ 12.5 days per decade *(10 days in 1972 to 64 days in 2014)*
Annual number of cool days *(Maximum Temperature ≤ 29.2°C)*	- 6.1 days per decade *(56 days in 1972 to 30 days in 2014)*
Annual number of warm nights *(Minimum Temperature ≥ 26.2°C)*	+ 17.9 days per decade *(Null in 1972 to 69 days in 2014)*
Annual number of cool nights *(Minimum Temperature ≤ 22.3°C)*	- 11.1 days per decade *(72 days in 1972 to 26 days in 2014)*

[1] Tengah and the climate station (which has moved locations)

b) Rainfall	**Change per decade (1980-2014)** Analysis based on records from 28 stations island-wide.
Annual rainfall total	+ 157 mm per decade *(2192 mm in 1980 to 2727 mm in 2014)*
Annual hourly maximum rainfall total	+ 4.9 mm per decade *(97 mm in 1980 to 114 mm in 2014)*
Annual number of days with hourly rainfall totals exceeding 40 mm *(heavy rain)*	+ 4.5 days per decade *(51 days in 1980 to 66 days in 2014)*
Annual number of days with hourly rainfall totals exceeding 70 mm *(very heavy rain)*	+ 1.5 days per decade *(5 days in 1980 to 10 days in 2014)*

How has temperature changed?

There are two stations in Singapore with long-term temperature records of longer than 30 years. These are from the climate station, currently located at Changi, and from the station at Tengah. Analysis of the annual mean temperature from the climate station shows that there was an average rise of 0.25°C per decade from 1948 to 2014 (Figure 2.3, note in Table 2.1 the value quoted is for a shorter period). Figure 2.3 shows the coherent variations in temperature for the two stations.

Nine of the ten warmest years on record in Singapore have occurred since 1998. Singapore's annual average temperature is influenced by the El Niño and La Niña phenomena (see Box 4.5), and El Niño conditions prevailed in 8 of the 10 warmest years recorded in Singapore. In particular, the peaks in temperature in 1997 and 1998 in Singapore are due to the occurrence of one of the strongest El Niño events on record (Figure 2.3).

Accompanying the general warming trend since the 1970s there have been changes in the frequency of extreme high and low temperatures across Singapore (Figures 2.4a and 2.4b). From 1972, Singapore has experienced an increase in warm days, an increase in the number of warm nights and a decrease in the number of cool nights, based on maximum and minimum temperatures extracted from the two stations. As with average temperatures, the frequency of warm days and nights, in particular, occur against a background of year-to-year climate variability, mostly associated with El Niño and La Niña events. For example, Singapore experienced a sharp increase and decrease in the number of warm days in 1998 and 2008, corresponding to strong El Niño and La Niña years respectively.

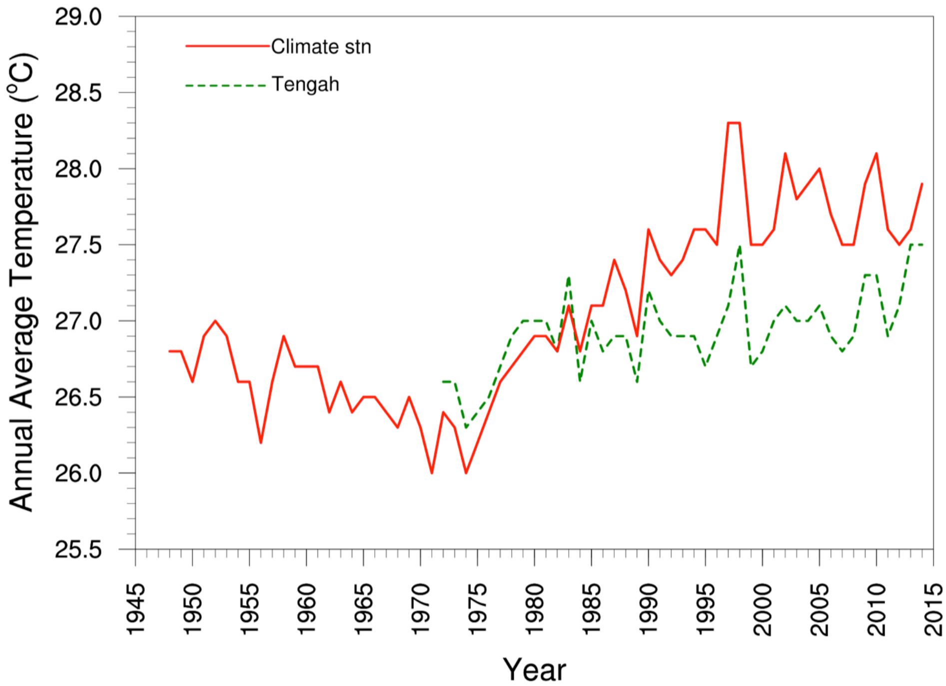


Figure 2.3: Annual mean temperature recorded at climate station (1948-2014), compared to another station, Tengah (1972-2014).

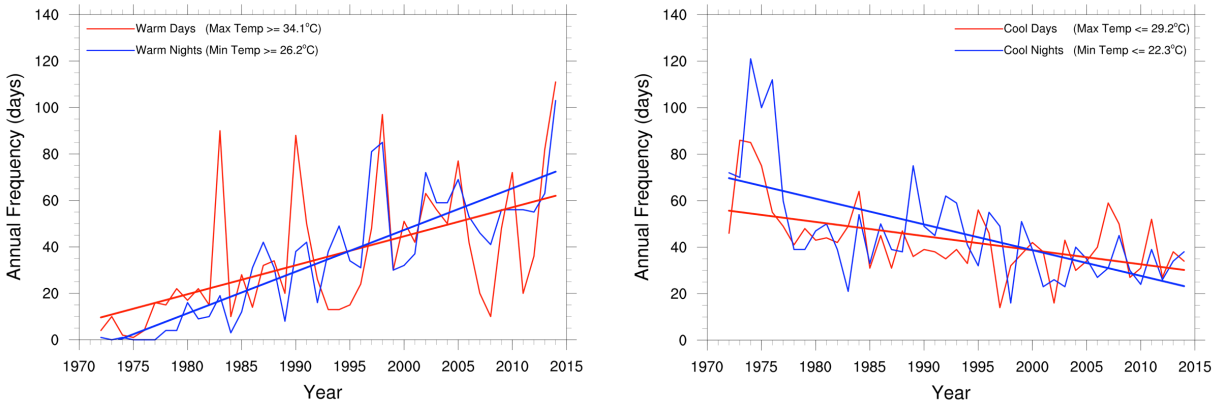


Figure 2.4: a) Time series of the annual average number of warm days (≥ 34.1°C, the 90th percentile of maximum daily temperature, red), warm nights (≥ 26.2°C, the 90th percentile of minimum daily temperature, blue) in Singapore. (b) Time series of the annual average number of cool days (≤ 29.2°C, the 10th percentile of maximum daily temperature, red) and cool nights (≤ 22.3°C, the 10th percentile of minimum daily temperature, blue) in Singapore. Straight lines represent linear trends.

As stated earlier, the upward trend of temperature in Singapore has been greater than the global temperature trend. Over the last 60 years, global annual temperatures have risen by 0.12°C per decade, whereas in Singapore it has increased at a higher rate of 0.25°C per decade. As already noted, in addition to global warming there are other factors contributing to these observed trends.

How has rainfall changed?

Meteorological Service Singapore (MSS) has been collecting and compiling rainfall records for Singapore since 1869. Prior to the 1970s, the network of rainfall stations was relatively sparse and rainfall records were limited to only daily and monthly rainfall totals. Since the 1970s, the rainfall station network has gradually grown. There are now 28 rainfall stations, with a sufficiently long period (1980-2014) of continuous hourly rainfall records, which can be used to investigate trends in the rainfall.

There is considerable year-to-year variability in Singapore's rainfall. The El Niño Southern Oscillation (ENSO, see Box 4.5) plays an important role in this variability during the southwest monsoon season and the succeeding inter-monsoon season. In general, stronger El Niño events tend to have a more significant impact on local rainfall during the southwest monsoon months. During the El Niño of 1997, the strongest on record, Singapore experienced a sharp 53% reduction in June-September rainfall. However, the relationship between the strength of the El Niño and impact on local rainfall is not straightforward, as there have been years when relatively weaker El Niño events (e.g. the El Niño in 1963) had greater impact than stronger ones and vice versa.

In the last thirty years, the average annual rainfall total recorded at 28 island-wide rainfall stations rose at a rate of 15.7 mm per year (Figure 2.5). The spatial variation in the trends in annual rainfall totals since 1980 is depicted in Figure 2.6. Generally, there are consistent rainfall trends across Singapore since 1980: 61% (17 out of 28) of the stations show a statistically significant (at 5% level) upward trend in the annual rainfall total, ranging from +15.7 mm to +28.0 mm per year.

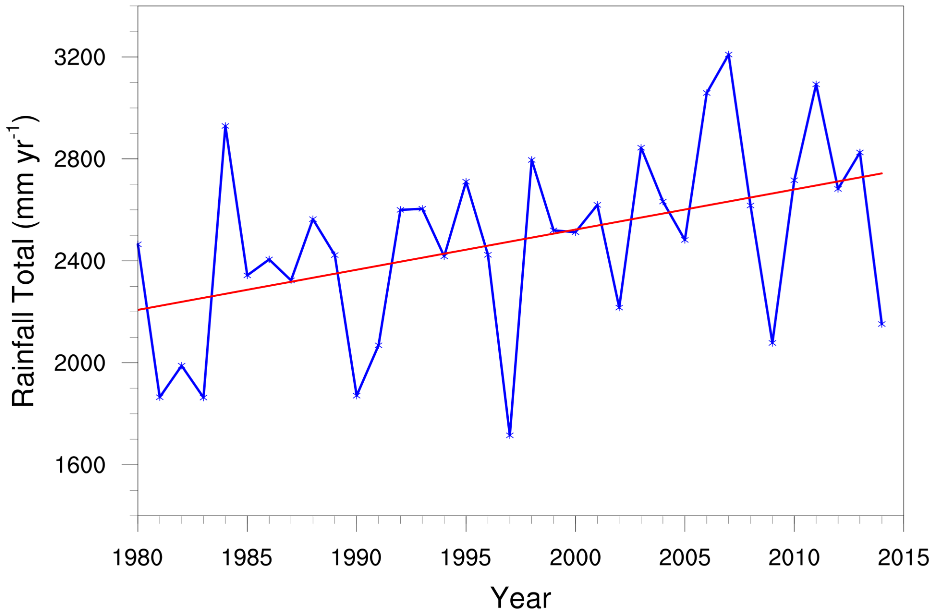


Figure 2.5: Plot of annual rainfall total in Singapore shows a statistically significant (p-value < 0.05) upward trend of 15.7 mm per year, based on linear fit, on average from 1980 to 2014.

Trends of the annual number of days with hourly rainfall totals exceeding 40 mm (the 95th percentile, heavy rain) vary across the island (Figure 2.7). There are statistically significant upward trends at 10 rainfall stations, with an average rate of about 1 day per decade. The rest of the stations show no statistically significant trends.

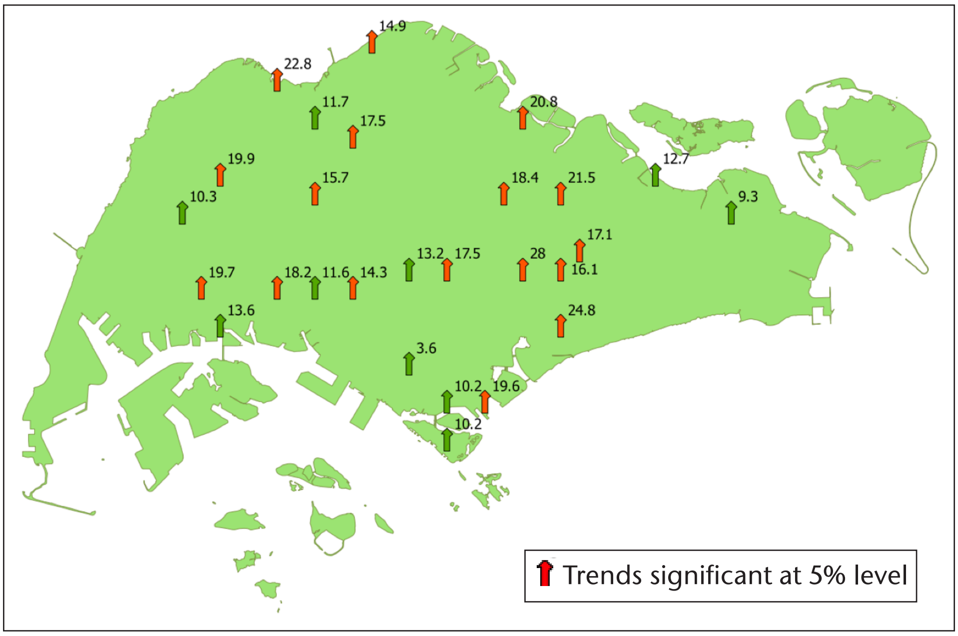


Figure 2.6: Map showing the past trends of annual rainfall total at individual stations in mm/year. All stations indicate upward trends (up-arrow). Red arrows represent statistically significant (p-value < 0.05) trends and green arrows are non-statistically significant changes. The numerical value next to each arrow indicates the annual rate of change for the period 1980-2014 (17 out of the 28 stations show a statistically significant upward trend).

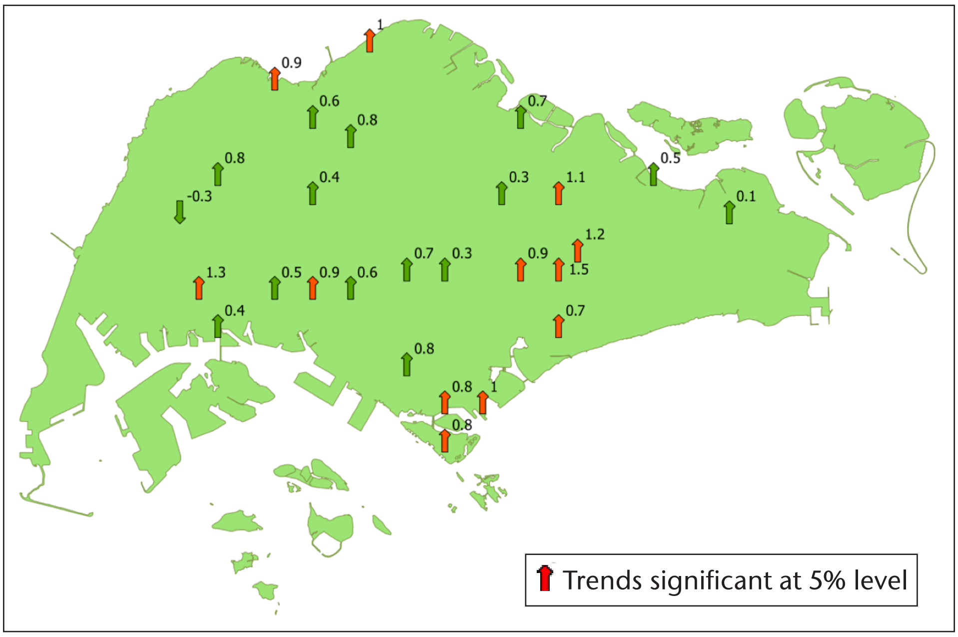


Figure 2.7: Map showing the past trends of number of days with hourly maximum rainfall totals exceeding 40 mm (heavy rain) at individual stations. Upward and downward trends are depicted by up-arrow and down-arrow respectively. Red arrows represent statistically significant (p-value ≤ 0.05) trends and green arrows are non-statistically significant changes. The numerical value next to each arrow indicates the rate of change per decade for the period 1980-2014 (12 out of the 28 stations show a statistically significant upward trend).

As stated earlier, it is not possible at this stage to confidently attribute the observed changes in local rainfall to particular factors, although global warming may account for some part of the trend. As the atmosphere has warmed, the moisture in the atmosphere has also increased. There are physical reasons to expect this moisture to lead to an increased intensity and frequency of heavy rainfall events. However, the trends expected from this process are considerably smaller than those reported above. Natural climate variability is another possible cause. Urbanization can also be important because higher temperatures in urban areas could enhance convective activity that leads to heavy rainfall. Major uncertainties remain in attributing observed heavy rainfall trends and this is an area of active ongoing research.

How has relative humidity changed?

There are two stations in Singapore, located at Changi (the climate station) and Tengah with a reasonably long period (1982-2014) of continuous hourly relative humidity records. These records indicate no significant change in humidity over the last 33 years (Figure 2.8).

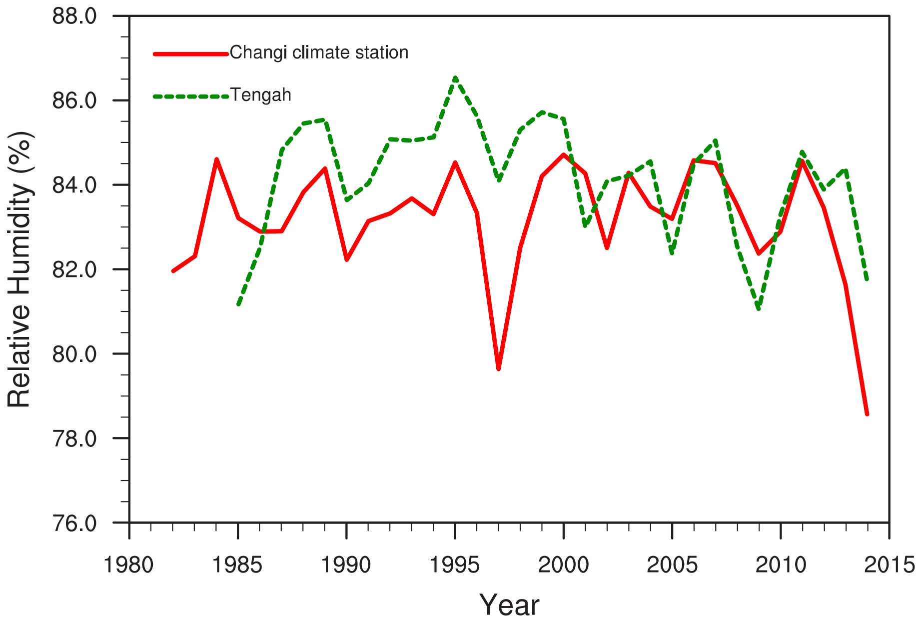


Figure 2.8: Annual mean relative humidity recorded (1982-2014).

How has the level of heat stress changed?

Heat stress refers to the effect of heat that would generate stress or discomfort on the human body. Heat stress is conventionally measured by quantities such as the "wet-bulb globe temperature" (WBGT) and "apparent temperature". These are essentially empirical measures of how a person would feel, taking into account the sunlight, wind, humidity and the temperature.

The wet-bulb temperature (WBT) can also be used as a basic indicator of heat stress because it relates to the heat loss from damp skin. When temperature and humidity become high enough, heat removal becomes impossible. This critical situation happens if the wet bulb temperature exceeds 35°C. WBT will be used as an indicator of heat stress in this study. A more sophisticated measure of heat stress that is commonly used is the Wet Bulb Globe Temperature (WBGT), however, historical observational data do not exist for a sufficiently long period to enable robust analysis of WBGT to be carried out.

Similar to temperature and relative humidity records, there are two stations in Singapore, located at Changi (the climate station) and Tengah, with a sufficiently long period (1982-2014) of continuous hourly wet-bulb temperature records. Records from both stations indicate statistically significant upward trends in the annual mean WBT from 1982 to 2014 (Figure 2.9). The highest WBT recorded in Singapore over this period is 31.4°C.

The ten warmest WBT-years have occurred since 1995. As with temperature, Singapore's annual average WBT is influenced by the El Niño and La Niña phenomena; La Niña conditions prevailed only once in the ten warmest WBT-years. In particular, the peak in WBT in 1998 coincides with the occurrence of one of the strongest El Niño events on record (Figure 2.9).

Accompanying the general warming signal since the 1980s, have been changes in the frequency of warm wet-bulb temperatures (days with WBT ≥ 27.7°C, the 90th percentile value) across Singapore (Figure 2.10). Since 1982, Singapore has experienced an increase in the number of warm WBT days based on maximum wet-bulb temperatures extracted from the two stations. As with the mean WBT values, this frequency of warm WBT days occurs against a background of year-to-year climate variability, mostly associated with El Niño and La Niña events. For example, Singapore recorded the highest number of warm WBT days in 1998 (strong El Niño year) and a sharp decrease in the frequency of warm WBT days in 2008 (moderate La Niña year).

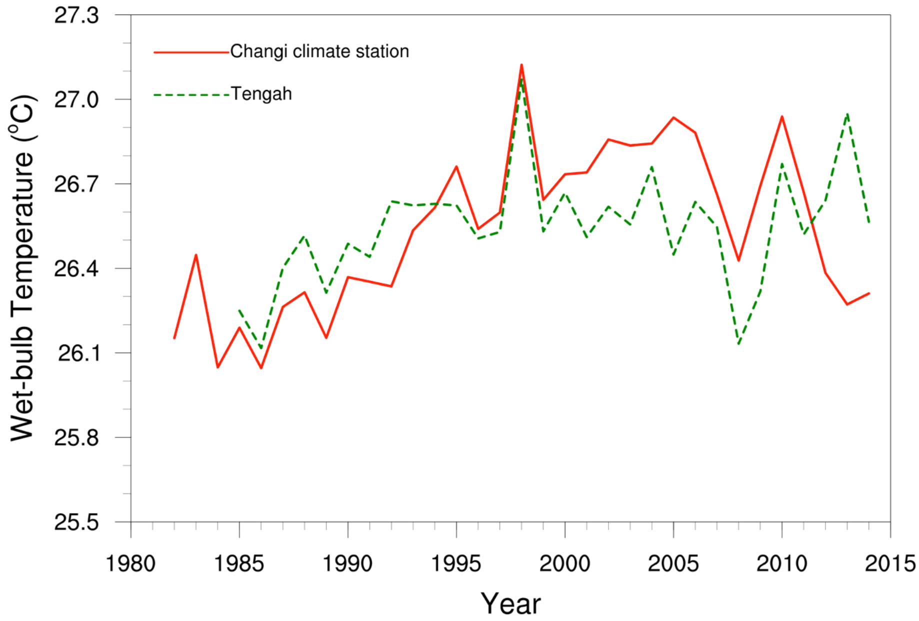


Figure 2.9: Annual mean wet-bulb temperature recorded (1982-2014).

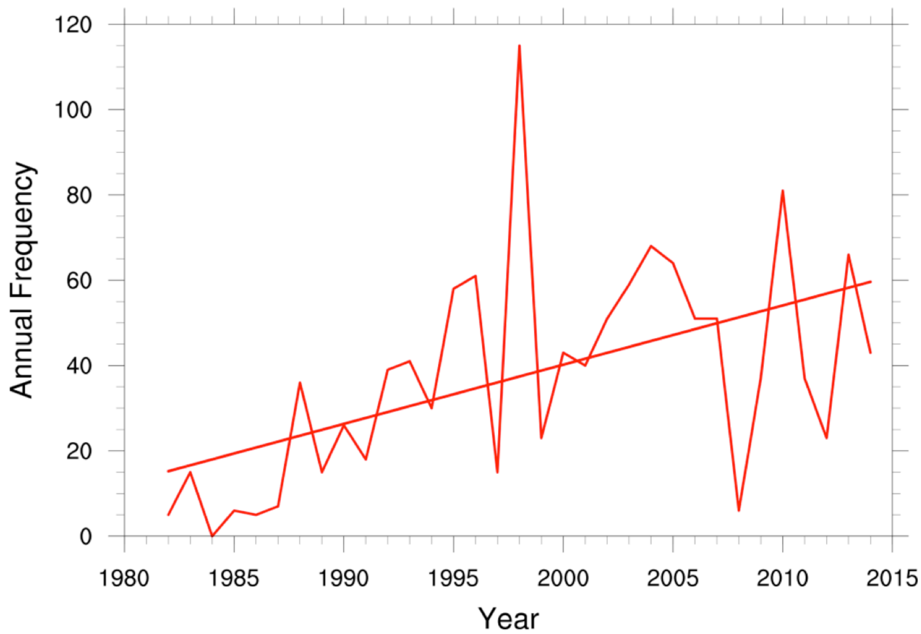


Figure 2.10: Time series of the annual average number of warm WBT-days (WBT ≥ 27.7°C, the 90th percentile) in Singapore. The straight line represents a linear trend.

How has wind changed?

Trends in wind speed are difficult to determine directly from observations. There is only one station in Singapore with long-term continuous wind records of longer than 30 years, which is the climate station at Changi. Records of wind speed at any given station are highly sensitive to changes in the local environment (e.g. construction of buildings, removal of trees etc.) and many such changes have occurred alongside Singapore's development. For this reason it is hard to define a clear trend in wind speeds.

Wind gusts are important because they can potentially damage buildings, uproot trees and disrupt airport operations. Strong wind gusts are mainly associated with thunderstorms and squall lines. As with average winds, it is not possible to determine clear trends in wind gust strength. The strongest wind gust ever recorded in Singapore is 40 m/s at Tengah.

How has sea level changed?

In the IPCC AR5, it was shown that based on historical data the rate of global mean sea level rise has accelerated during the last two centuries. The mean rate of global averaged sea level rise is estimated at 1.7 mm yr^{-1} for 1901–2010 (i.e. a total rise over this period of 0.19 m) and 3.2 mm yr^{-1} for 1993–2010. Recent published studies carried out by the Tropical Marine Science Institute (TMSI) at the National University of Singapore (NUS), and based on Singapore's tide gauge records going back to the mid-1970s, show that the annual measured sea levels in the Straits of Singapore rose at the rate 1.2–1.7 mm yr^{-1} in the period 1975-2009.

3. How are the climate projections for the future created?

How is the regional climate modelled?

Climate models simulate the Earth's climate by solving mathematical equations that describe the motion and exchanges of heat, water, momentum and energy throughout the atmosphere, land and oceans. Global Climate Models (GCMs) do this at a coarse scale and cannot explicitly resolve all of the important processes. Many of these processes, such as the formation of clouds, are therefore represented through mathematical approximations of their composite behaviour at coarse resolution. These approximations are known as parameterisations. 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 at their current resolution. Therefore where the local details of a region's climate are being considered, and where data are required at a higher resolution for decision-making, GCMs are downscaled over the region of interest (Figure 3.1) using Regional Climate Models (RCMs). The RCM solves the same set of mathematical equations but over a smaller region with a higher grid resolution. The meteorological variables at the RCM boundaries are taken from the 'parent' global climate model.

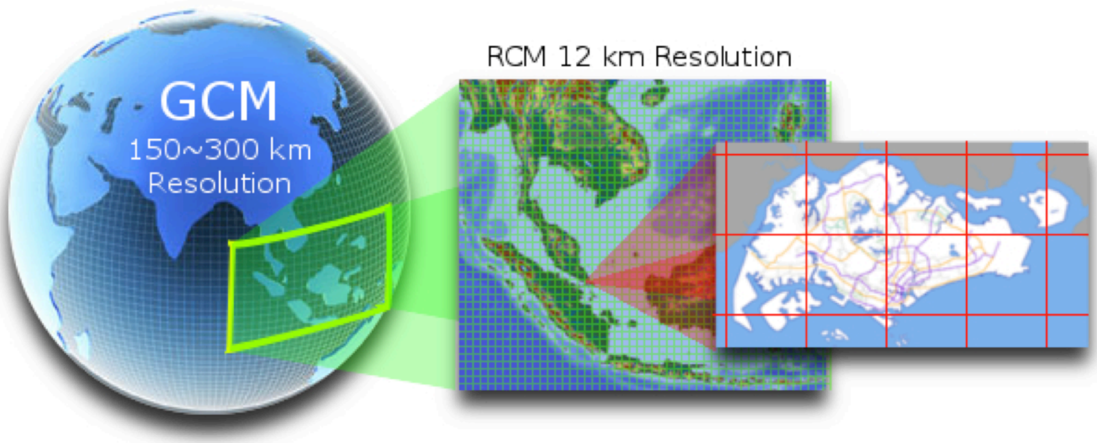


Figure 3.1: Downscaling of a global climate model to regional scale. The output from a global climate model with low resolution can be used to drive a regional climate model with finer scale grid boxes (higher resolution).

Dynamical downscaling

In this study, the latest UK Met Office RCM (PRECIS vn3.0) was used to dynamically downscale climate projections for a number of GCMs from the Coupled Model Intercomparison Project Version 5 (CMIP5). The RCM has a resolution of 12 km and covers the geographical domain shown in Figure 3.2.

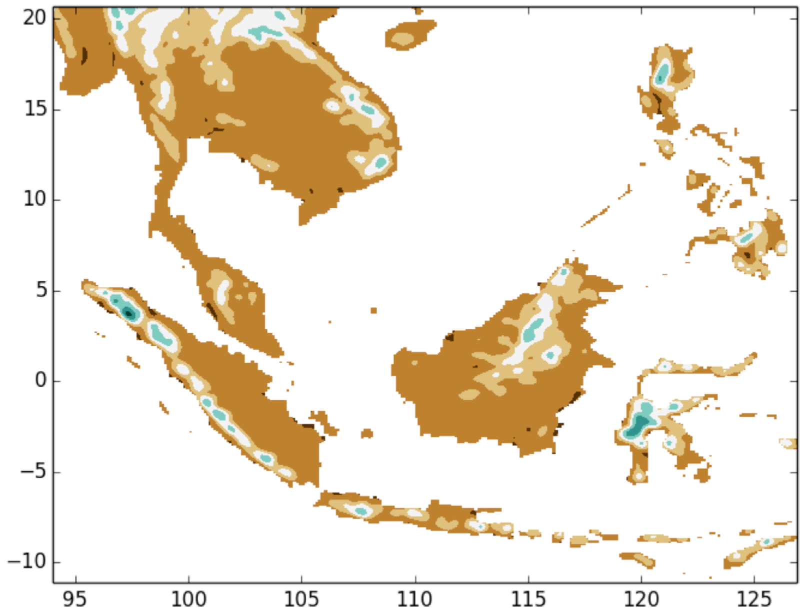


Figure 3.2: The geographical domain and representation of orography used for dynamical downscaling in the study.

How much uncertainty is there in the projections?

Any decision-making framework that aims to make adaptation plans resilient to climate change, must account for the key uncertainties in climate projections. The principal sources of climate change uncertainty are:

(i) The range of possible future emissions of greenhouse gases and other forcing constituents, such as aerosols. See Box 1.2.

(ii) Natural climate variability, on a range of time scales.

(iii) Modelling uncertainty, arising from an incomplete understanding and the approximate representation of relevant physical processes in climate models, and their effects in driving future climate variability and change.

Emissions uncertainty

The future development of technology, changes in energy generation, water and land use, population growth, and global and regional economic circumstances are unknown. All of these factors affect the cycling of carbon and other greenhouse gases between the earth, oceans and atmosphere, and therefore influence the changing climate. The IPCC AR5 WG1 uses a set of scenarios describing specific future pathways for concentrations of greenhouse gases in the atmosphere. These Representative Concentration Pathways (RCPs) are fed into climate models, which produce a range of climate responses at global and continental scales.

This study uses RCP4.5 and RCP8.5, which span scenarios consistent with low-medium future emissions (RCP4.5) and a high-end scenario (RCP8.5). Only two scenarios are used so as to reduce the overall computational requirements of the project and also because these two scenarios had the largest number of models with available data for downscaling.

As the name implies, the greenhouse effect leads to the alteration of the radiative balance of the Earth. The different RCPs are labelled by the change in the approximate total radiative forcing in year 2100 relative to 1750, for example this change is 4.5 Wm^{-2} for RCP4.5.

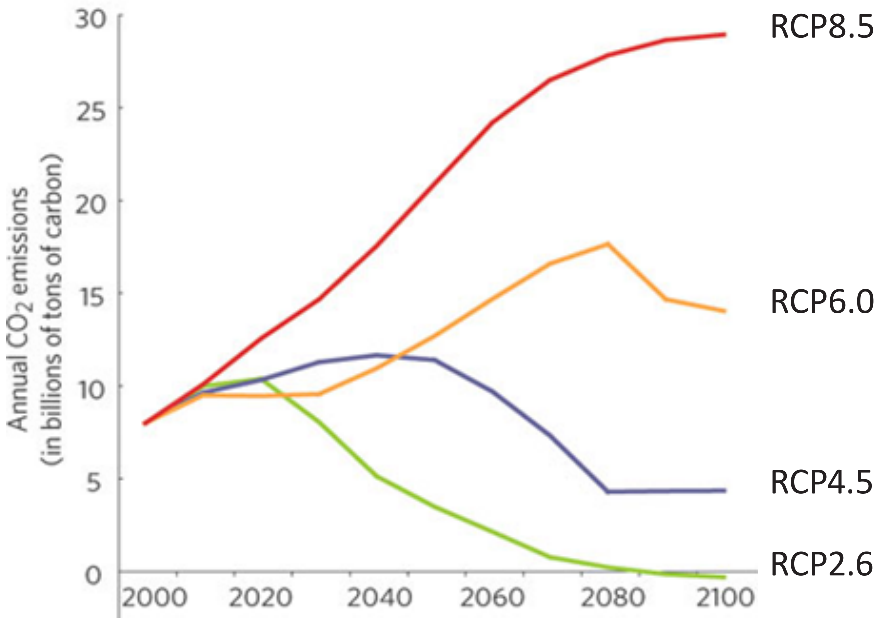


Figure 3.3: Future annual CO_2 emissions associated with each RCP scenario[2].

[2] van Vuuren et al (2011). The Representative Concentration Pathways: An Overview. Climatic Change, 109 (1-2), 5-31.

Each RCP can correspond to a range of emission scenarios. See Box 1.2 for an explanation of the relationship between greenhouse gas emissions and the RCPs. One 'representative' example of the CO_2 emissions associated with each RCP is shown in Figure 3.3. The four RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6) and in IPCC AR5 this is shown to lead to temperature changes that are generally below 2°C (with reference to a baseline period of 1986-2005). The range of model projections using RCP4.5 spans a median increase of approximately 2°C, relative to the same baseline. An international target to keep global temperatures less than 2°C above pre-industrial temperatures has been widely discussed. Note, however, the temperature rises quoted above from IPCC AR5 are relative to 1986-2005 and not the pre-industrial baseline values, which are 0.6°C lower.

Climate variability

There are two types of natural climate variability: 1) external variability, which comes from factors such as the sun's output or volcanic activity; and 2) internal variability, which represents the inherently chaotic nature of the climate system and leads to phenomena on all timescales, from individual storms, to longer term cycles such as El Niño/La Niña and decadal and longer time scale variations in the regional climate associated with phenomenon such as the Pacific Decadal Oscillation.

The natural variations of climate will occur regardless of the anthropogenic influence of global warming. How these natural and man-made climate variations interact to produce the total climate change at some future time is an area of active research. See Box 4.5 and the Annex for further information on climate variability.

Modelling uncertainty

Different global models include different assumptions on how best to represent the processes that are important for the climate and are successful in representing specific phenomena to different extents. This study therefore uses a range of climate models to sample this uncertainty. To downscale all of the GCMs provided for CMIP5 would be both very expensive computationally and time-consuming. A subset of the models was therefore selected for use in this study. This subset was chosen based on two criteria:

- Models that have a poor representation of the current regional climate, for example in the simulation of the regional monsoon systems were excluded.
- For the Southeast Asian region as a whole, the models chosen should span the range of future projected changes across all the CMIP5 models as fully as possible for key variables, such as temperature and rainfall.

The following 9 models from CMIP5 were eventually chosen for downscaling:

ACCESS1-3	CMCC-CM	GFDL-CM3
Bcc-csm1-1-m	CNRM-CM5	HadGEM2-ES
CanESM2	CSIRO-Mk3-6-0	IPSL-CM5A-MR

The 12 km projections provided by this study use two RCPs and are driven by this subset of CMIP5 GCMs to account for modelling uncertainty. These simulations therefore attempt to sample the three main sources of uncertainty described above.

Box 3.3: Why is only one regional climate model used?

This study samples modelling uncertainty by using a range of GCMs, but relies on a single RCM. In principle, additional downscaling uncertainty should be explored in using multiple RCMs to assess how the representation of detailed regional processes might affect projections of future features of local climate. This would allow a more comprehensive assessment of the risks associated with future climate projections.

Some previous studies have shown that downscaling uncertainty can be important for precipitation changes (less so for temperature), but is often secondary to global modelling uncertainty. Also, there is, as far as we know, no previous study partitioning model uncertainty into global and downscaling components specifically for the Singapore region. Thus, as using multiple RCMs in addition to an ensemble of GCMs would require significantly more resources, a single RCM has been used. In the future, it will be useful for other studies to test the sensitivity of the projections described here to the use of different RCMs.

Model evaluation

In addition to the assessment of the GCMs as part of the sub-selection procedure, the regionally downscaled simulations provided by this study have also undergone extensive evaluation. The evaluation shows that we can be broadly confident in the use of most of the variables. The simulations capture the variability and duration of northeast monsoon cold surges well, but underestimate their frequency. The models represent the broad scale patterns of precipitation associated with cold surges realistically, but lacked the enhanced precipitation that is observed over the Malay Peninsula during these events. The El Niño Southern Oscillation (ENSO) is another key mode of variability that directly impacts the climate of Singapore. Future changes in ENSO could, in particular, change the frequency and intensity of droughts affecting the region; however, there is not enough confidence in the projected changes in ENSO in the CMIP5 ensemble (as stated in the IPCC AR5) to draw conclusions. At 12 km, the regional model is not expected to simulate mesoscale weather systems such as Sumatra Squalls.

A significant shortcoming found in the results is the poor simulation of heavy rainfall events over land, though these are better represented over the ocean. Even at the higher resolution of the 12 km RCM, the model is still unable to explicitly represent the convective processes that lead to these events familiar to Singapore's climate. Most model parameterisations of these rainfall processes are known to be of limited realism and this can lead to significant errors and, in this case, the underestimation of extreme rainfall over land. Analysis of observed extreme rainfall shows that values over Singapore's land and nearby ocean values are statistically very similar. This allows us to address the shortcomings of the 12 km model results by using rainfall over nearby ocean grid-boxes. A model at a higher resolution that is able to explicitly represent convective processes has also been used to investigate these issues.

How are the sea level projections created?

Sea level rise is of particular interest to decision makers in Singapore, and therefore as part of this study a methodology has been developed for estimating potential changes. There are a number of contributions to future sea level rise and these are illustrated in Figure 3.4. Future changes are presented in three categories: changes to global mean sea level, changes to regional sea level, and changes to sea level extremes. In each case, the methodologies used follow the methods and data used in the IPCC AR5.

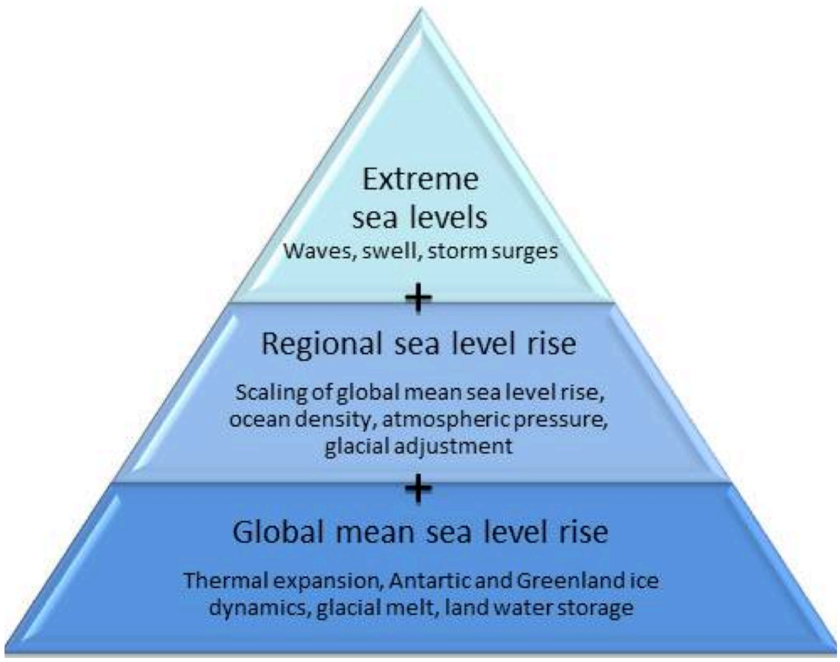


Figure 3.4: Components of sea level rise projections considered in this study.

Changes to global mean sea level

The main components of global average sea level rise are due to the thermal expansion of sea water associated with global temperature rise and the addition of water to the oceans due to glacial melt. Also included are changes to the water stored in the Greenland and Antarctica ice sheets, with a smaller contribution from changes in land water storage. IPCC AR5 found that global mean sea level rise for 2081-2100 relative to 1986-2005 will likely be in the ranges of 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5.

Changes to regional sea level

To provide projections for Singapore it is necessary to account for the geographical variations in sea level rise. Contributions include the spatial patterns associated with non-uniform uptake of heat by the ocean, and with the addition of water to the oceans by glaciers and ice sheets. The corresponding mean sea level changes will be non-uniform across the globe and in this study the increase in the region around Singapore from these factors has been determined. There are other factors that can be important for regional sea level rise that come from changes in ocean circulation, atmospheric pressure and the continued adjustment in the land surface since the end of the last ice age.

For the components outlined above, and for both RCPs, an estimate for each process is combined to arrive at values for total mean sea level change for Singapore. In addition, other local vertical land movements must be taken into consideration. The only vertical land movement process assessed here is the glacial adjustment mentioned above. For any impact assessments further information will be required on current vertical land movement observations and the underlying processes. While Singapore is not in immediate proximity of tectonically active areas in Sumatra and Java, research at the Earth Observatory Singapore (EOS) indicates that major subduction earthquakes on the plate boundary are capable of producing subsidence effects. This can lead to an associated sea level rise at some distance depending on the response of the tectonic plate to stress. Such an effect would more likely be gradual and on the order of 15 cm over a few decades (personal communication). This is an area of active research by geoscientists.

Changes to sea level extremes

Future changes to sea level extremes come about from both the increasing background mean sea level and possible changes in wind driven waves and currents. Wind waves are locally driven, whereas swell is generated by remote wind forcing. If winds change in the future, there will be corresponding changes in waves and swell. Storm surges are anomalies (relative to the predicted astronomical tide) in the observed water level, caused by the effect of atmospheric pressure and wind on the sea surface. In the region around Singapore, large storm surges are rare and generally generated by periods of unusually strong winds during the northeast monsoon season. If the storm surge coincides with a high tide, there is an increased risk of coastal flooding.

To identify potential changes in extreme sea levels associated with changes in storminess, projections of wind and atmospheric pressure from 4 of the 12 km RCM simulations were used to drive the NEMO (Nucleus for European Modelling of the Ocean) surge model and the Wavewatch III wave model. The 4 driving models were selected based on data availability and to span the range of projected wind circulation changes over the region.

The NEMO model takes into account tides and therefore captures the interaction between tides and surges. A standard measure used to analyse changes in surge is the "skew surge" (see Figure 3.5a), which is the difference between the predicted astronomical high tide and the highest water level experienced during the same tidal cycle. Skew surge is commonly used in preference to the surge residual because the latter can result in spurious residuals arising due to timing differences between observed and predicted tides (see Figure 3.5b).

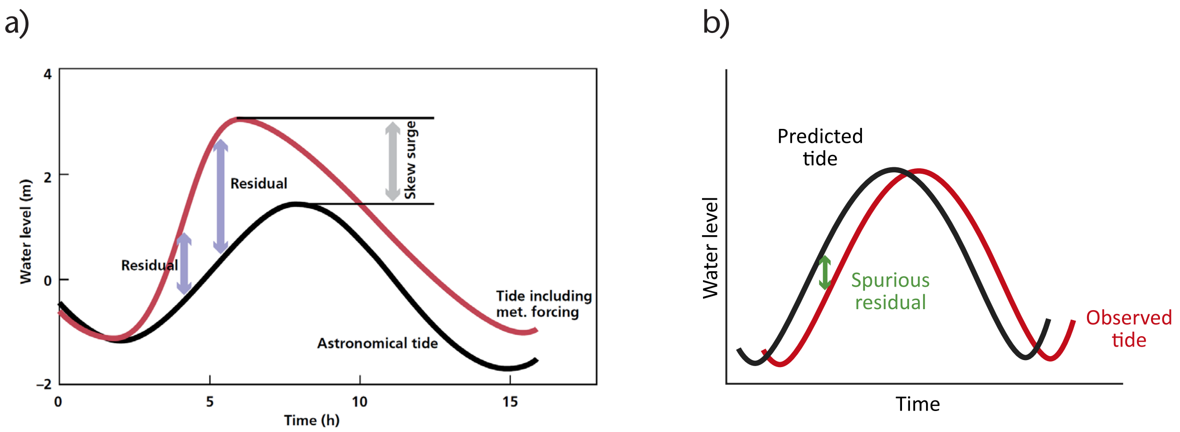


Figure 3.5: Schematic diagram showing how skew surge and surge residual are evaluated. The surge residual evolves throughout the tidal cycle, typically peaking before the astronomical or meteorologically forced tide, whereas the skew surge is evaluated once and is a more useful measure.

Wind wave and swell simulations were produced using the Wavewatch III wave model (both the surge and wave models were run at approximately 9 km resolution). The Wavewatch III model captures swell entering the region by using a 50 km resolution model driven by atmospheric data from the global climate models. Both wave and surge models were evaluated using tide gauge and satellite observations, and were generally found to capture the leading constituents of extreme sea levels well.

What about climate and sea level beyond 2100?

Changes beyond the end of the 21st century are not usually considered in national climate projections, 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 infrastructure for the longer-term, it will be useful to understand what may be expected on longer timescales. As part of this study we provide a brief analysis of the extended global model simulations to 2300 (provided as part of CMIP5). The main focus is on changes in sea levels, but projected changes in temperature and rainfall are also considered. These results should be interpreted as indicative of a small range of future projections provided by current climate models in combination with the two extended scenarios, both assuming stabilisation of greenhouse gas concentrations.

Supporting analysis carried out as part of the study

As described in this section so far, the main methodology for the production of the climate projections is dynamical downscaling, which is used to provide estimates of meteorological changes and to produce the wind fields to drive the extreme sea level calculations. However, in addition to the dynamical downscaling, two additional methods were investigated to provide further evidence to support the climate change projections.

The first method involved Empirical Statistical Downscaling (ESD) which has been widely used to generate climate projections at local scales. This is based on statistical relationships which link the local scale meteorological variables to the large scale variables describing the state of the atmosphere. It has been more widely used to generate downscaled climate projections for mid-latitude sites than for tropical regions; a likely factor being that local weather at mid-latitudes is typically more strongly influenced by the large scale state of the atmosphere than is the case in the tropical regions, where smaller scale convective processes are often more important.

An assessment of the applicability of ESD based on linear regression models was carried out as part of this study. The results show that it is possible to use ESD to provide plausible scenarios of future change in distributions of daily surface temperature or wind speed. However, it was not possible to produce acceptable rainfall calibration relationships for Singapore. Large scale drivers of rainfall were found to only explain a relatively small fraction of the observed variability in local rainfall. For this reason it was not possible to produce robust statistically downscaled meteorological projections. Further research is required to determine whether more advanced techniques can be found to link historical changes in local rainfall to larger scale regional drivers.

The second method aimed to provide a wider context for the projections than by the 9 models used centrally in this study. A much larger number of lower resolution global model simulations have also been considered, combining the CMIP5 models as well as the previous CMIP3 models (assessed in IPCC AR4), along with a large number of variants of the Hadley Centre model. The results using this wider set of models are not described in detail in this report but they generally support the results from the 9 downscaled models in terms of key messages (see Section 4), in particular, of increases in rainfall during the northeast monsoon season and a potential future drying during the southwest monsoon season. Whilst the 9 dynamically downscaled projections provide a plausible set of alternative outcomes based on current state-of-the-art climate models, the results from the wider set of earlier models also demonstrate that stakeholders should not discount the possibility that specific aspects of future change could lie outside the ranges given in Section 4.

4. What changes are projected for the climate of Singapore?

How will temperatures across the region change?

Annual mean temperatures

Global climate model projections for the region show an unequivocal warming signal. The downscaled model simulations from this study similarly show a consistent warming projected for the whole Southeast Asian region, in all seasons, and under all scenarios.

Seasonal temperature variations

Figure 4.1 illustrates the ensemble median of the projected average temperature changes for RCP8.5 for a 30-year period centred on the 2080s (averaged over years 2070-2099 compared to 1980-2009). The downscaled projected changes are similar to those from the driving GCMs, but with a tendency for the maximum temperature changes in the RCM projections to be slightly higher. There is considerable range in the magnitude of warming, which is illustrated in Box 4.1.

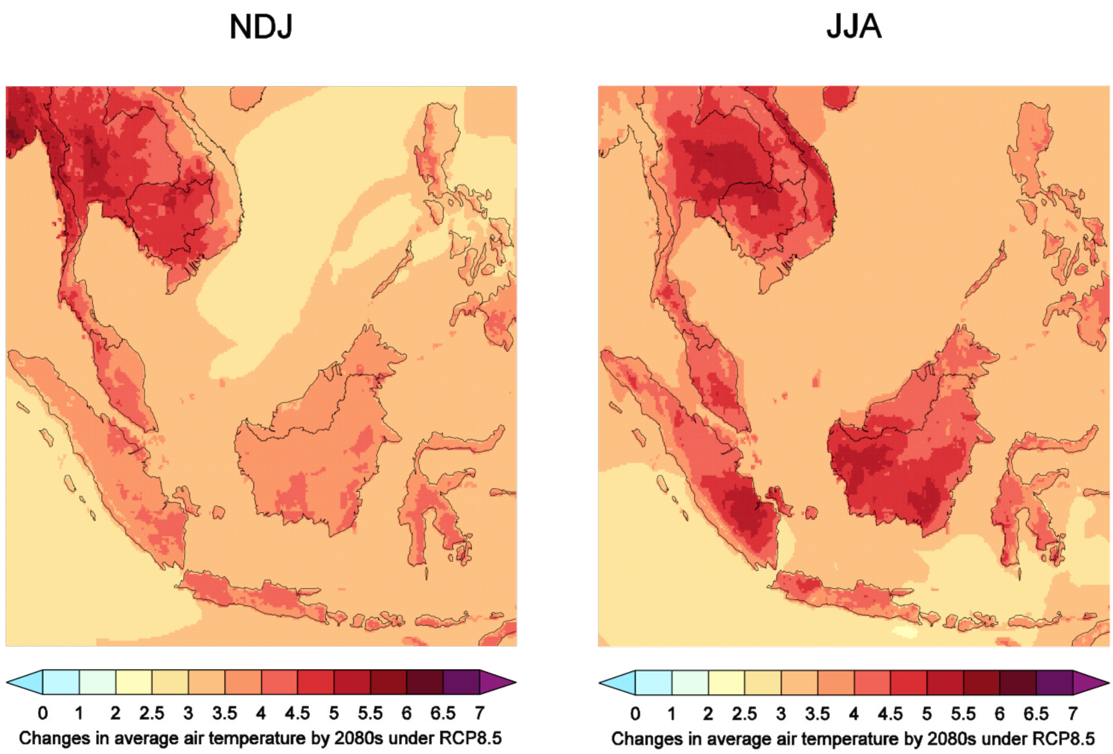


Figure 4.1: Ensemble median projected change in average surface air temperature in the November–December–January (NDJ) and June–July–August (JJA) seasons from the 9 dynamically downscaled CMIP5 models. The figures show the differences in temperature in 2070-2099 compared to the reference period 1980-2009, under the RCP8.5 scenario.

Box 4.1: Regional Projection Ranges for Risk Assessments

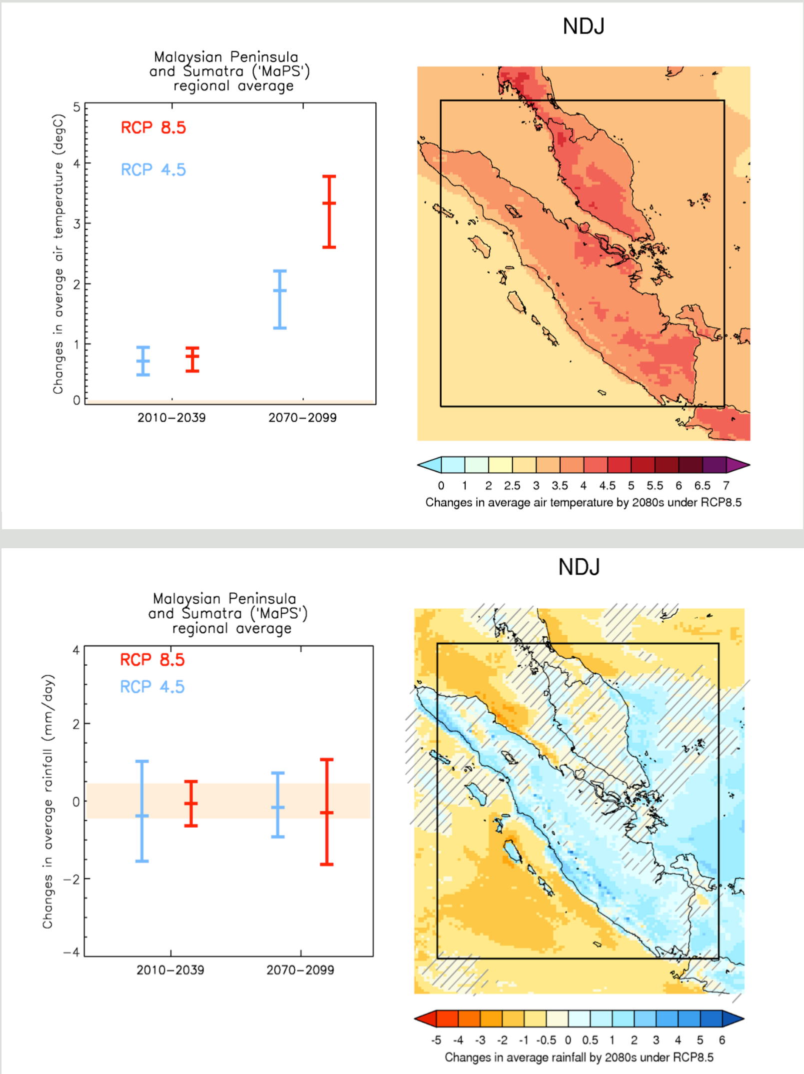


Figure B4.1: Projected changes in average air temperature (top, °C) and precipitation (bottom, mm/day) in the NDJ season for the 9 dynamically downscaled CMIP5 models (coloured bars in the boxes) averaged over the boxed region. The middle line represents the median and the ends the minimum and maximum values. Ranges of changes are displayed for the near-term (2010-2039) and for the end of the century (2070-2099) compared to a baseline of 1980-2009 for both RCP4.5 (blue) and RCP8.5 (red). The orange shading (left column figures) represents the standard deviation of 30-year averages calculated from long historical runs of the GCMs used in IPCC AR5, and the hatched areas (bottom right figure) correspond to regions where the projected median change is less than this standard deviation.

The orange shading and the hatching are useful to provide an indication of the significance of the climate changes relative to the natural multi-decadal variability simulated within the global climate models. The coloured bars show the range of projections indicated by the 9 downscaled models used in this study. Given our current knowledge on future climate change, these bars are indicative of the range of plausible regional changes which should be considered when assessing risks resulting from future climate scenarios generated from these projections.

The projected warming over much of the land is larger in the southwest monsoon season (June-July-August, JJA) than in the northeast monsoon season (November-December-January, NDJ). This is likely to be because of the projected drying in the JJA season shown in Figure 4.2 and the different prevailing wind directions in NDJ and JJA. Also note the enhancement of the warming over land compared to the ocean regions. These future changes in temperature far exceed the modelled natural decadal variability across the region (see Box 4.1).

Extreme temperatures

The projected changes in average temperature will also influence temperature extremes, with increases in the number of hot days and warm nights expected. The top 10 percent (90^{th} percentile) of daily maximum and minimum temperatures have been used to evaluate these changes. Increases in this top 10 percent of extreme temperatures from RCP8.5 during JJA are at least 4.5°C in many areas, and up to increases of 8°C in some locations. The night-time temperatures increase similarly in the projections, leading to more 24-hour periods with persistently higher temperatures. These large changes are generally outside of the range of temperature variations in the historical record.

How will rainfall change across the region?

Annual mean rainfall

Regarding changes in annual mean rainfall over the region, there is little consensus among the regional model projections. This is consistent with the rainfall projections presented in the IPCC AR5 for this region. The plausible range of future changes from the models include both increases and decreases that are significant yet small compared to the interannual variations of rainfall over the region. Thus, no specific conclusion can be drawn regarding the direction or magnitude of change in the annual mean rainfall.

Seasonal mean rainfall

The regional model projections show rainfall changes that vary with season and location. Figure 4.2 illustrates the ensemble median projected rainfall changes under the RCP8.5 scenario for a 30-year period centred on the 2080s (2070-2099 compared to 1980-2009). In November to January (the wet phase of the northeast monsoon season for Singapore), there are increases in seasonal rainfall over much of the southern and eastern parts of the domain. The hatching on the figure shows regions where the projected change is less than the standard deviation of 30-year averages calculated from long historical runs of the GCMs used in IPCC AR5 (see Box 4.1). Over Singapore, the southern Malay Peninsula and Sumatra the signal is smaller than this estimate of internal decadal climate variability.

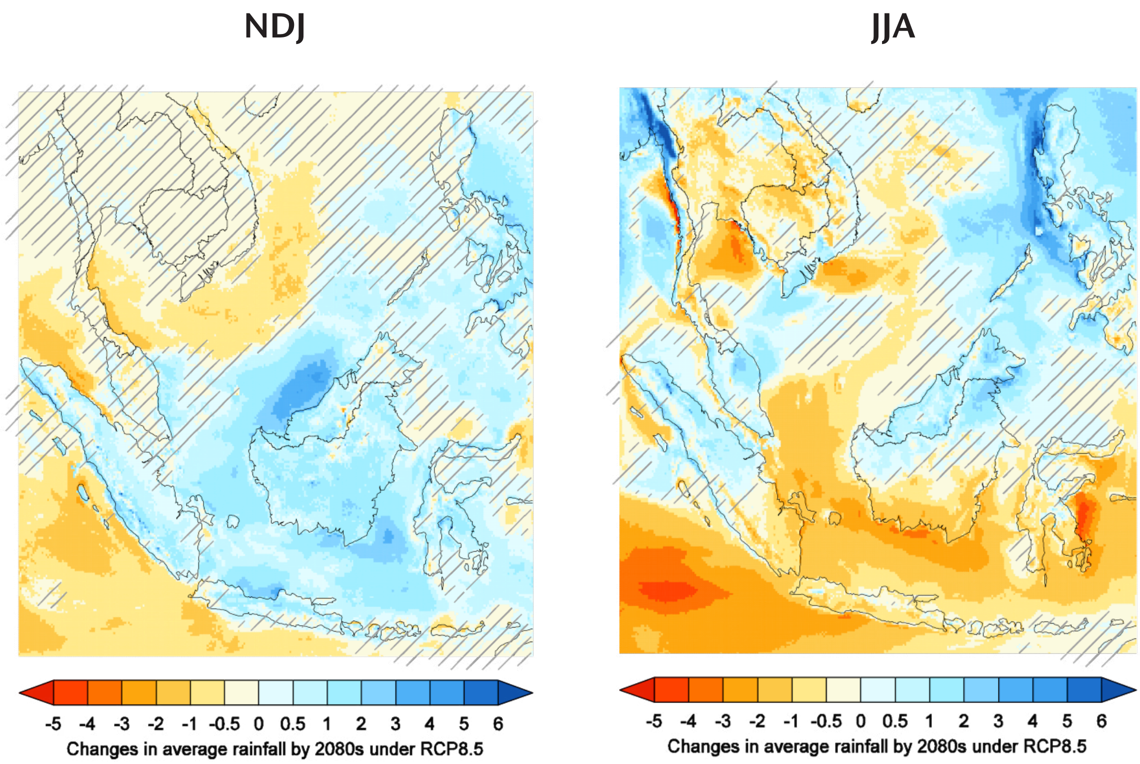


Figure 4.2: Ensemble median projected changes in average rainfall (mm/day) in the NDJ and JJA seasons for the 9 dynamically downscaled CMIP5. The figures show the differences in rainfall in 2070-2099 compared to the reference period 1980-2009, under the RCP8.5 scenario. The hatching represents regions where the projected median change is less than the standard deviation of 30-year averages calculated from long historical runs of the GCMs used in IPCC AR5.

During the southwest monsoon season (JJA) there is a north-south pattern to the projected rainfall changes with the southern part of the domain, and the southern part of the South China Sea, showing a drying that is generally larger than the estimated variability. Note that Singapore in Figure 4.2 lies on the boundary between the regions of projected wetter and dryer conditions.

Extreme rainfall

Although not shown here, there is greater agreement in model results for regional extremes of rainfall than for mean changes. For instance all models agree that the number of days with heavy rainfall will increase in most sub-regions of Southeast Asia. This is consistent with the IPCC AR5 statement that: *"Extreme precipitation events over the wet tropical regions will very likely become more intense and more frequent by the end of the century, as global mean surface temperature increases"*. For the Malay Peninsula sub-region including Singapore, this increase is significant, and there is broad agreement between the driving GCMs and the regional results, adding confidence to this result. This signal for this sub-region is strongest in the

November-January season, although similar changes with a smaller magnitude are found in other seasons.

As temperatures increase, the air can hold more moisture and physical reasoning suggests that where and when the air is nearly saturated, additional moisture could lead to more intense heavy rainfall events. However, other effects associated with changes in the monsoon circulation are also very important. The results for changes in extreme rainfall over Singapore will be described in greater detail below.

How will regional winds change?

Seasonal winds

From the results of this study there is no clear consensus on how the regional monsoon circulation will change in the future. Among models that show changes in the northeast monsoon (NDJ) circulation, two show increases in the seasonal average wind-speeds over the South China Sea, while two others project weakening. In regard to the southwest monsoon (JJA), models generally project larger regional changes, but again with little consensus in the direction of change (positive or negative), and therefore little confidence in the projections. Five out of the nine models indicate increases in average wind-speeds during this season. Given the range of wind projections, the possibility of either a future strengthening or weakening of the regional monsoon circulations cannot be ruled out. Similarly, there is no consistent signal in the projected changes of the daily extreme winds (95th percentile). The above refers to large-scale changes in the regional monsoon wind systems and the specific results for Singapore region will be discussed later.

How will regional humidity change?

Over the Southeast Asian region, the IPCC AR5 for RCP8.5 projects a general decrease in near-surface relative humidity over land of around 2-3%, and an increase over oceans by a similar amount. This is consistent with the land generally warming more than the oceans. There are two mechanisms that are at play. Over the oceans, as temperatures rise the moisture in the air increases at a rate higher than its maximum moisture holding capacity, thus increasing the relative humidity. As the wetter oceanic air moves over land it encounters the higher temperatures, which reduces the relative humidity of the air.

Future climate projections for Singapore

This section presents the local projections for Singapore. Box 4.2 introduces how the projections are presented for the variables relevant to Singapore's weather and climate.

Box 4.2: Presentation of projected climate changes over Singapore

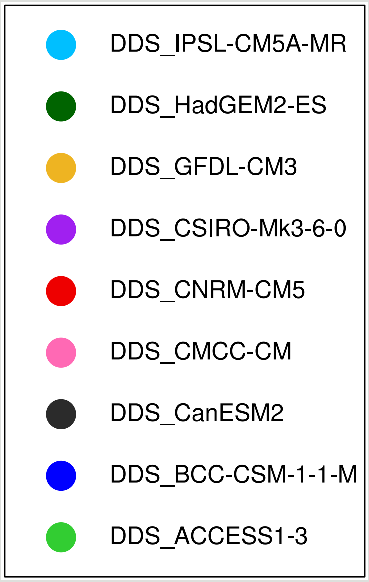
This study presents sets of projections for temperature, rainfall, relative humidity, 10 m wind and wet bulb temperature changes over Singapore.

Each of the 9 downscaled models should be taken as providing plausible climate change scenarios and the range among the models is a representation of the uncertainty in the projections.

In some instances there is a need to be cautious about a particular model's projection of a specific variable. These instances are highlighted in the text.

In each figure a consistent colour coding to designate the models has been used.

As with the regional climate projections it is useful to identify whether the projected changes are significant compared to current natural climate variability.



How will temperatures change?

Annual average daily mean, minimum and maximum temperatures

Projected changes in Singapore's average daily temperatures by the end of the century under both RCP scenarios are presented in Figure 4.3. Summaries for both scenarios at mid- and end-century are provided in Table 4.1. In particular, daily mean temperatures are projected to increase by around 2°C (RCP4.5) to 4°C (RCP8.5) for the end-century period (2070-2099) relative to a reference period of 1980-2009. Figure 4.3 also shows that some models have changes up to 3°C for RCP4.5 and 5°C for RCP8.5.

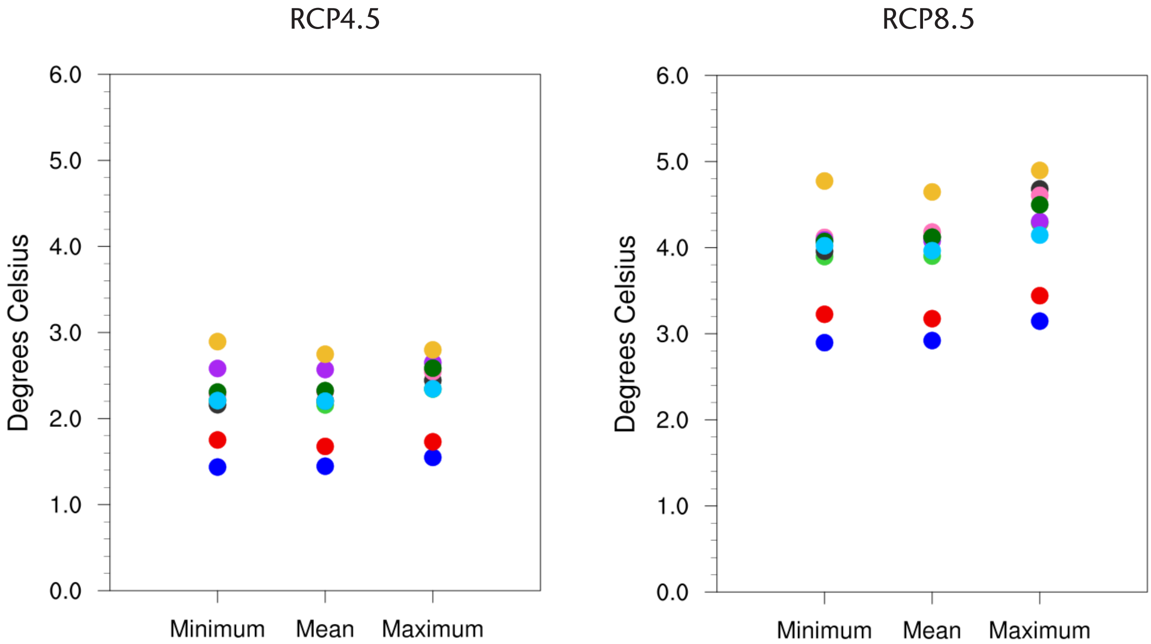


Figure 4.3: Change in average daily minimum, mean and maximum temperature for end-century (2070-2099) with respect to baseline period 1980-2009 for the RCP4.5 (left) and RCP8.5 (right).

		Mid-century (2040 - 2069)				End-century (2070 - 2099)			
Mean observed (1980 - 2009)		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Minimum Temp (deg C)	24.1	25.4	26.4	25.9	27.1	25.5	27.0	27.0	28.9
Mean Temp (deg C)	27.4	28.7	29.6	29.2	30.3	28.8	30.1	30.3	32.0
Maximum Temp (deg C)	31.8	33.1	34.5	33.8	34.9	33.3	34.6	34.9	36.7

Table 4.1: Projected ranges in the average daily minimum, mean and maximum temperature for mid- and end-century for the RCP4.5 and RCP8.5 scenarios. The two values in each pair give the lower and upper range for each of the variables and these changes are statistically significant.

Seasonal temperature extremes

Increase in frequency of warm days and nights

The projected changes in seasonal frequency of warm days (Figure 4.4) and nights (Figure 4.5) per season are presented for February to May (FMAM; warmer days climatologically) and June-September (JJAS; warmer months and warmer nights climatologically). Results are summarised in Table 4.2.

The projections show that, under RCP8.5, the annual number of warm days (days with a maximum temperature of 34.1°C, the 90th percentile, or above) and warm nights (nights with a minimum temperature of 26.2°C, the 90th percentile, or above) per season, are expected to increase significantly in the 21st century.

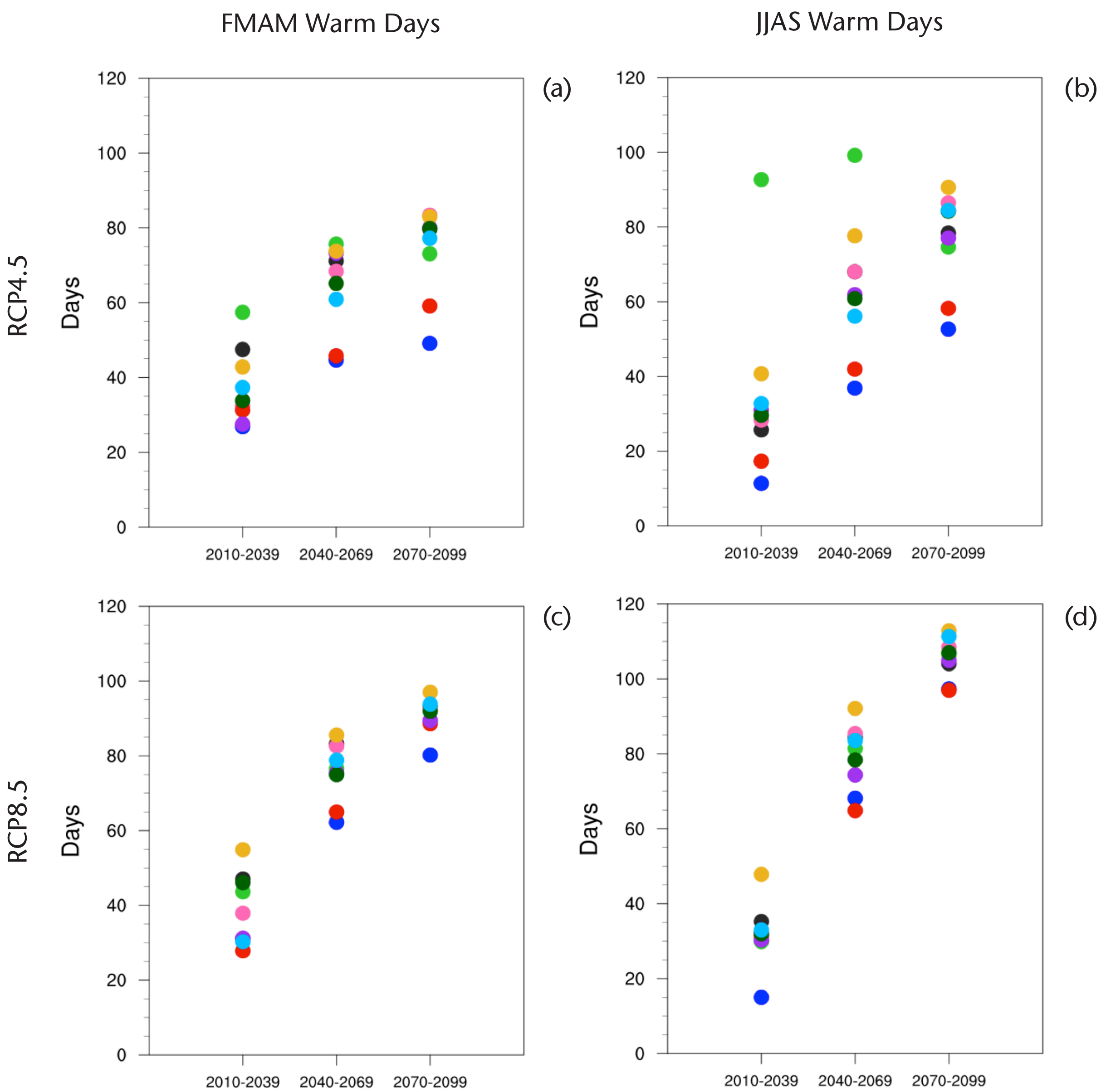


Figure 4.4: Change in average seasonal frequency for warm days (historical 90th percentile Tmax= 34.1°C) for season (a) February to May (FMAM), (b) June to September (JJAS) for early century (2010-2039), mid-century (2040-2069), and end-century (2070-2099) under RCP4.5, and (c) February to May (FMAM), (d) June to September (JJAS) for early century (2010-2039), mid-century (2040-2069), and end-century (2070-2099) under RCP8.5, with respect to baseline period 1980-2009.

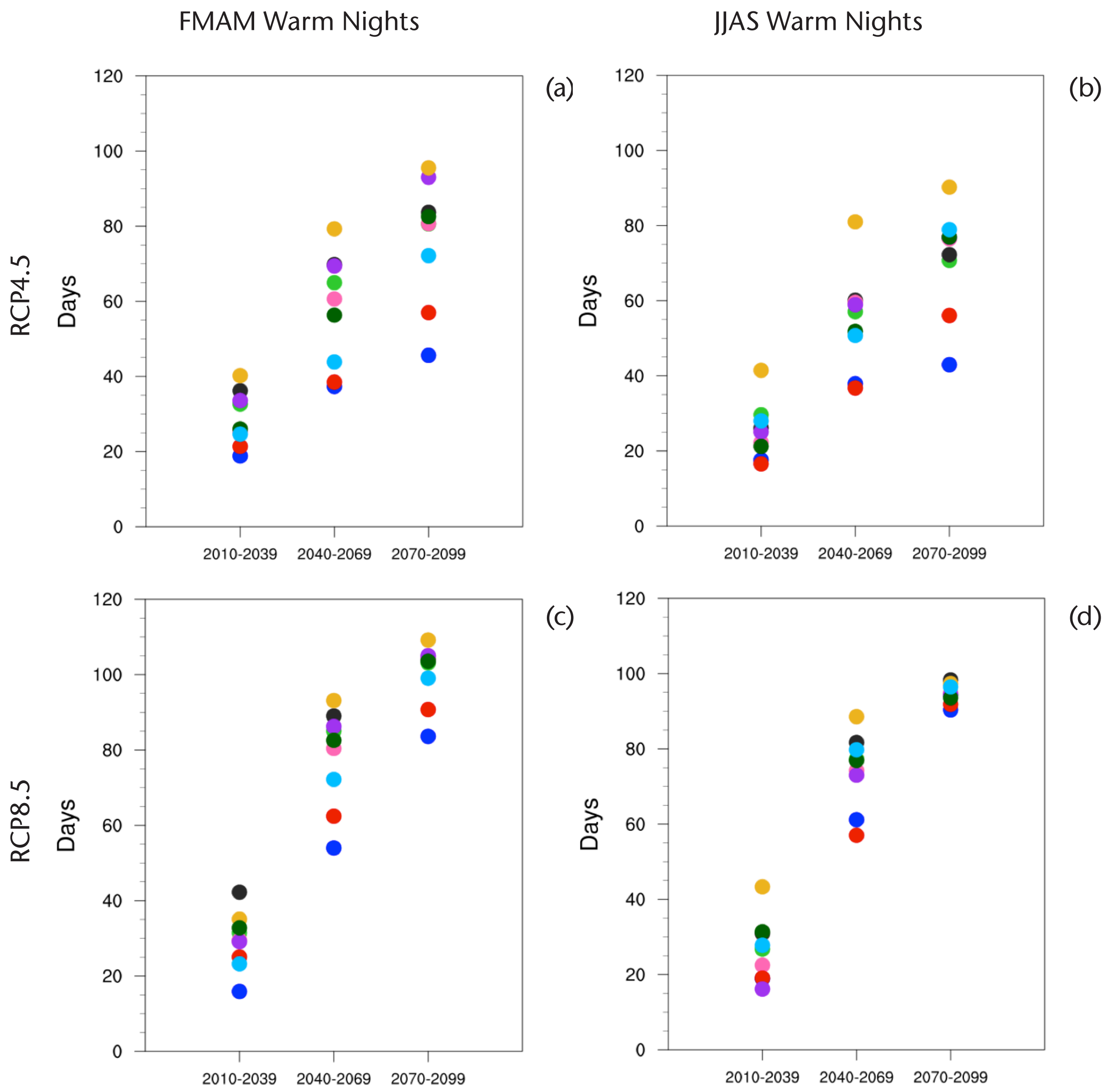


Figure 4.5: Change in average seasonal frequency for warm nights (historical 90th percentile Tmin = 26.2°C) for season (a) February to May (FMAM), (b) June to September (JJAS) for early century (2010-2039), mid-century (2040-2069), and end-century (2070-2099) under RCP4.5, and (c) February to May (FMAM), (d) June to September (JJAS) for early century (2010-2039), mid-century (2040-2069), and end-century (2070-2099) under RCP8.5, with respect to baseline period 1980-2009.

		Mid-century (2040 - 2069)				End-century (2070 - 2099)			
Mean observed (1980 - 2009)		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Frequency of warm days (Day-time temperature ≥ 34.1°C)									
Feb - May (day)	25	70	101	87	111	74	108	105	ALL
Jun - Sep (day)	6	43	105	71	98	59	97	103	119
Frequency of warm nights (Night-time temperature ≥ 26.2°C)									
Feb - May (day)	15	52	94	69	108	61	111	99	ALL
Jun - Sep (day)	26	63	107	83	115	69	116	116	ALL
Frequency of cold days (Tmax ≤ 29.2°C) and nights (Tmin ≤ 22.3°C) during {Nov - Dec - Jan}									
Cold days (day)	19	12	6	9	3	9	4	5	0
Cold nights (day)	5	1	0	1	0	1	0	1	0

Table 4.2: Projected range in the number of warm days (Tmax ≥ 34.1°C) and warm nights (Tmin ≥ 26.2°C) per season for February to May (FMAM) and June to September (JJAS), and cold days (Tmax ≤ 29.2°C) and cold nights (Tmin ≤ 22.3°C) per season for November to January (NDJ). The two values in each pair give the lower and upper range for each of the variables and the orange to red shading indicates that these changes are statistically significant. See Table 2.1 for the definition of historical thresholds used here.

How will rainfall change?

Annual mean rainfall

The projection of changes in rainfall is of particular importance to Singapore. As expected, the results presented earlier for the regional changes in rainfall are broadly consistent with those reported in the IPCC AR5. The report shows that in this region the projected changes in annual mean rainfall from different models show both increases and decreases. In addition to this, the report also shows an increase in some heavy rainfall extremes in this region, as well as an increase in the occurrence of dry conditions.

Figure 4.6 shows the projected 10-year running annual mean rainfall totals for the two models with the largest positive and negative trends and also the range of responses in the remaining 7 models. Consistent with the regional results, there is no agreement between models about the projected change in annual mean rainfall for Singapore. The running 10-year mean is used to emphasise the long-term trend and multi-decadal natural variability in the projections. For example, the median model (green line) shows oscillations of decadal and multi-decadal timescales (see Box 4.5 for more information on the role of natural decadal variability in future climate projections). Note that the largest changes by 2100 are projected to be around a 25% increase or decrease from current values and with most models projecting changes of half this amount.

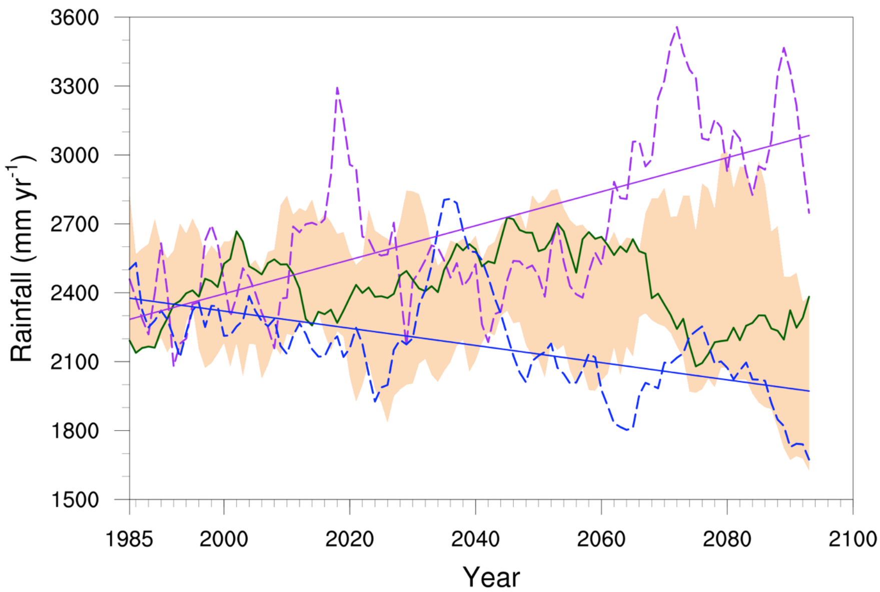


Figure 4.6: Running 10-year annual mean rainfall totals. Purple: Model with strongest positive projected change signal (statistically significant upward trend) and Blue: Model with strongest negative projected change signal statistically significant downward trend). The orange shading shows the spread of the 7 remaining models. Green: Model with median projected change signal (non-statistically significant trend). The solid lines show the least-squares fit through the annual data. 3 models have statistically significant upward trends; 4 models have statistically significant downward trends.

Heavy rainfall events

There is a greater agreement among models in the projected annual extreme rainfall totals from days with rainfall accumulations greater than the 95th percentile value (56 mm per day based on wet days in Singapore) in the reference period 1980-2009. Figure 4.7 shows the 10-year running mean annual rainfall totals contributed by heavy rainfall days. For RCP8.5 there is a general trend towards the number of events with rainfall greater than 56 mm per day (the historical 95th percentile for wet days) increasing, with only one model showing a statistically significant downward trend. Note that the percentage changes are considerably larger than those projected for annual average rainfall.

It is noteworthy that one model (the downscaled CSIRO model represented by the purple line) shows a larger signal in this rainfall statistic when compared to the other models (also the case for mean rainfall, figure 4.6). The results from the CSIRO model for rainfall should be viewed with some caution because the historical simulation of the downscaled northeast monsoon rainfall, the main rain-bearing season, was found to be too dry when compared to the observed climate.

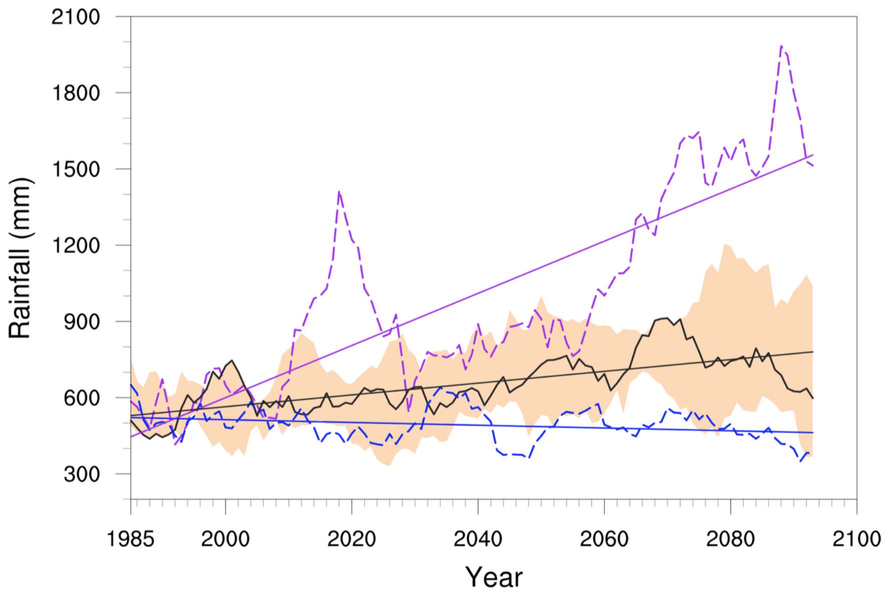
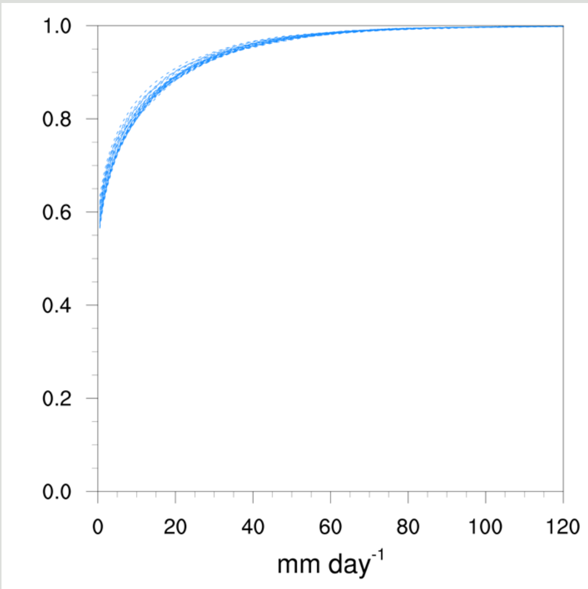


Figure 4.7 Running 10-year values of the contribution to annual rainfall totals from days with rainfall accumulations greater than the observed (1980-2009) 95th percentile of rainfall totals on wet days in Singapore for RCP8.5 scenario (value of 56 mm/day). Seven out of the nine models show statistically significant upward trends; only 1 model projects a statistically significant downward trend. The orange shading shows the spread of the 7 remaining models. Purple: Model with strongest positive projected change signal (statistically significant upward trend); Green: Model with median projected change signal (statistically significant upward trend); and Blue: Model with strongest negative projected change signal (statistically significant trend).

To present the current and projected distributions of rainfall intensity, we use the daily Cumulative Distribution Function (CDF) (see Box 4.3 for an explanation of the CDF curve). Analysis of seasonal change in the upper percentiles of the daily precipitation CDF over Singapore shows projected increases in intensity in the northeast monsoon wet season NDJ. By contrast, negative changes (of a smaller magnitude) are seen in the relatively drier southwest monsoon season JJAS (Figure 4.8). The final row in Table 4.3 summarises the fractional changes in the contribution to the total annual rainfall coming from heavy rainfall above 56 mm/day.

Box 4.3: The Rainfall Cumulative Distribution Function (CDF)

The figure below shows the CDF curves for the 28 observational stations over Singapore based on 30 years of daily data from 1980 to 2009.



The horizontal axis represents the daily rainfall in units of mm per day (daily rainfall accumulations) and the vertical axis is the fraction of the total days. For the Singapore stations, the CDF curve shows that no rain is experienced on more than half of all days in a year. 90% of days have less than about 20 mm of rainfall per day. This also means that 10% of days have accumulated rainfall of greater than 20 mm/day. Alterations in the shape of the CDF curve due to climate change illustrate how the rainfall distributions may change in the future.

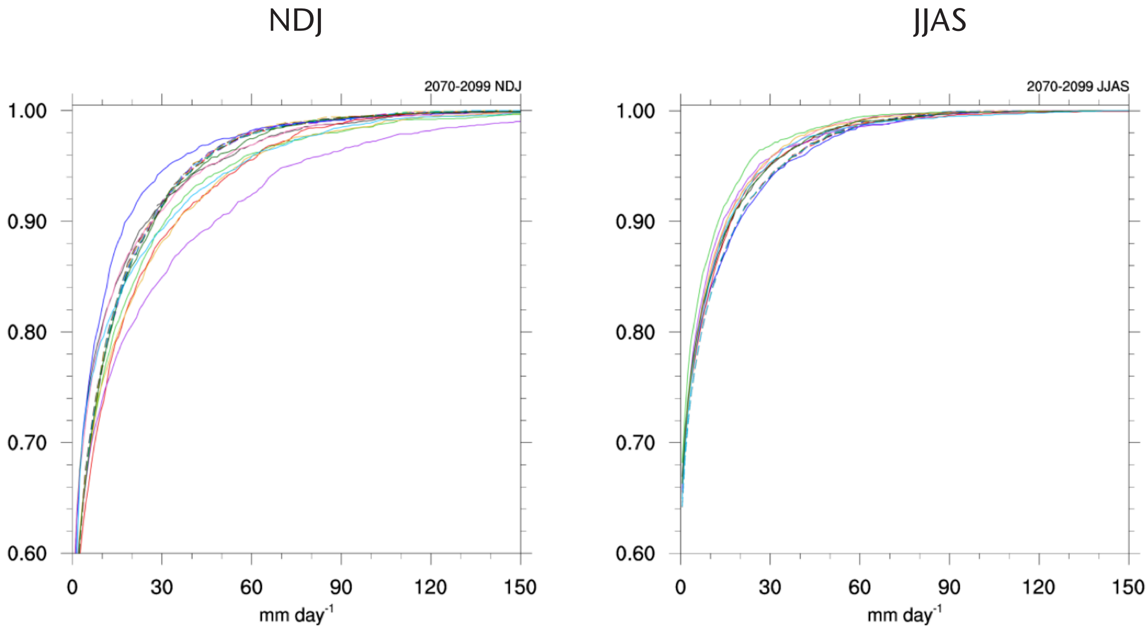


Figure 4.8: Upper percentile CDF curves for NDJ (left panel) and JJAS (right panel) daily rainfall accumulations. The dashed line shows the historical CDF for a 12 km grid point over central Singapore. Coloured lines show the projected CDFs for 2070-2099 under RCP8.5.

Providing robust projections of changes in heavy rainfall is one of the most challenging aspects of this study. The 12 km model is able to provide a realistic simulation of the large scale monsoon systems but it does not adequately represent the influence of convective thunderstorms on the statistics of heavy rainfall events. The results presented here are based on a bias correction of the modelled 12 km CDF to the observed CDF and it is assumed that correction factors will not change in the future climate. To test the assumptions made, a single simulation was performed at 1.5 km, in which the convective weather systems are substantially better represented (see Box 4.4).

Box 4.4: Use of a very high resolution model to investigate rainfall extremes

The ability of the RCM to represent the effects of convective processes is of particular relevance in this region. The current generation of climate models are often deficient in simulating these convective processes, particularly over land. To some extent, these model deficiencies have been compensated by the bias correction procedure. In order to investigate these issues explicitly, a single projection has been carried out that can permit convective processes to be partially resolved. The major disadvantage of using a convection permitting RCM is its high computational cost, which has meant that multi-year convection permitting RCM simulations have only recently been attempted by the global climate modelling community.

The simulations that have been carried out in this study are centred on Singapore with a 1.5 km resolution model 'nested' inside a 4.5 km resolution model, which is further nested within the 12 km RCM. The aim is to improve the understanding of daily and sub-daily rainfall variability and change, which is deficient in 12 km RCM simulations. Three simulations, each of 10 years duration, have been performed. In the first, the 12 km RCM was driven by an estimate of the observed climate conditions from 2000 to 2010. The other two simulations were driven by the HadGEM2-ES climate model, one of the nine models used in this study. One present-day simulation (1995 to 2005) and one end-of-century RCP8.5 simulation (2089 to 2099) were performed.

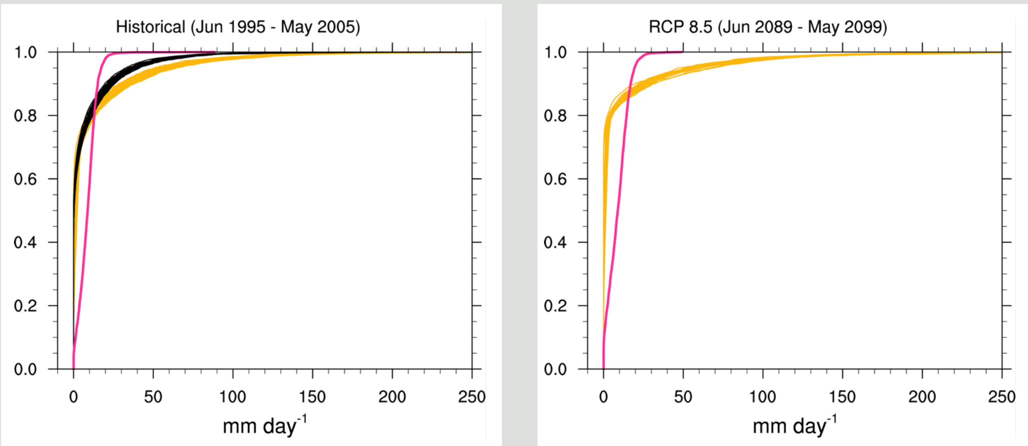


Figure B4.2 The left hand panel shows the daily rainfall CDF curves for observations from 28 stations (black), the 12 km resolution model over land (magenta) run for historical climate and the 1.5 km resolution model (yellow). Note than no rainfall is experienced climatologically on over half the days. The right hand panel shows the CDF curves for the period 2089-2099 under the RCP8.5 scenario.

In the historical simulation the 1.5 km resolution simulations show a substantially improved rainfall distribution compared to the 12 km resolution model. The 12 km resolution model has too much light rainfall (below the 85th percentile) and too little heavy rainfall (above the 85th percentile). By contrast, the 1.5 km resolution model largely corrects the light rainfall problem and somewhat overestimates heavy rainfall intensities. Under the RCP8.5 scenario at end of century there is an increase in intensities in the upper percentiles. These simulations are only 10 years in length, and there is considerable decade-to-decade variation in the results (see Box 4.5). It is therefore not possible to make direct quantitative comparisons of these results with those from the 12 km resolution bias corrected projections. Despite this, the increase in upper percentile heavy rainfall events is found to be a robust feature in the projections.

Seasonal and monthly changes in rainfall:

Wet periods get wetter and dry periods get drier

For November to January (NDJ, the wetter season in Singapore climatologically), positive and negative changes in rainfall totals are projected under both the RCP4.5 and RCP8.5 scenarios (Figure 4.9). The spread of the projections widens throughout the century, with one model projecting a 60% increase and another model projecting a decrease of 25% at the end of the 21st century. Under RCP8.5 the models tend to show an increasing trend in rainfall in this season.

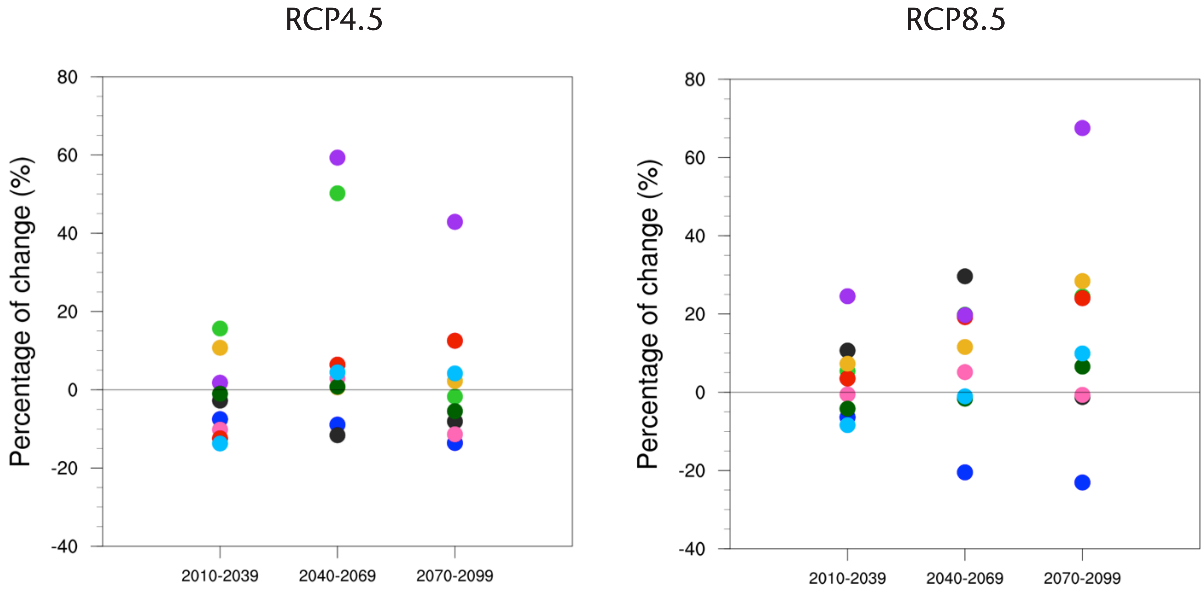


Figure 4.9: Mean rainfall anomalies for the months November-December-January for the three 30-year time periods, relative to the mean of 1980-2009 for the two RCP scenarios. For RCP8.5, 4 models suggest statistically significant (at 5% level) upward trends and only 1 model suggests a statistically significant downward trend over the period 2010-2099. There is no clear signal under RCP4.5 scenario; only 1 model projects a statistically significant increase and another model projects a statistically significant decrease in the signal at the end of the century. A couple of models project stronger increasing signals in the mid-century compared to the end-of-century, likely an indication of multi-decadal variability dominating the response.

For the climatologically drier southwest monsoon months (June to September), there is little consensus in the rainfall projections for mid-century. However by the end of the century RCP8.5 results show a decreasing signal and no model predicts a statistically significant increasing signal (Figure 4.10). Rainfall projections for the climatologically driest month, February, show a strong decreasing signal under the RCP8.5 scenario (Figure 4.11). The drying pattern in the southwest monsoon season is a local manifestation of the broader regional scale drying signal presented earlier.

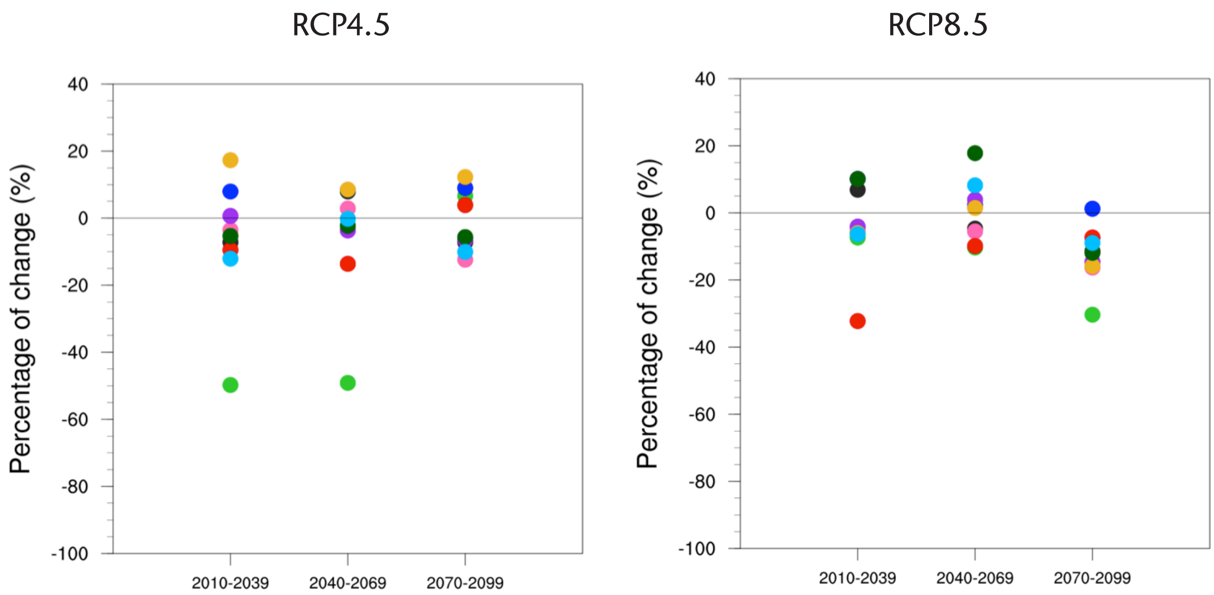


Figure 4.10: Mean daily rainfall anomalies in southwest monsoon (June-September) for the three 30-year time periods, relative to the mean of 1980-2009 for the two RCP scenarios. Four out of the nine models show statistically significant decreasing signals at the end of the 21st century under RCP8.5 scenario. Only 1 model projects a statistically significant decreasing signal at the end of the 21st century under RCP4.5 scenario. No model projects statistically significant increasing signal under both scenarios.

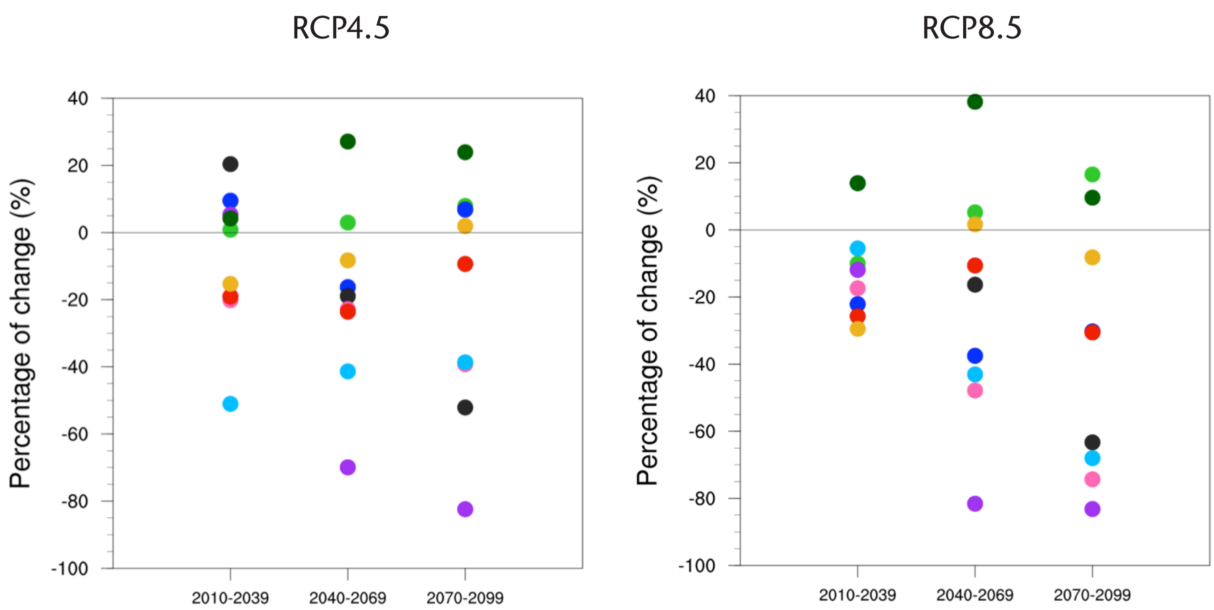


Figure 4.11: Mean rainfall anomalies in February for the three 30-year time periods, relative to the mean of 1980-2009 for the two RCP scenarios. Under RCP8.5 scenario, 6 out of the 9 models projected a statistically significant decreasing signal of more than 30% in the mean February rainfall towards the end of the century. Four models projected decreasing signals of more than 65% in the 2080s. Four models project statistically significant decreasing signals at the end of the century under RCP4.5 scenario.

The contrast of mean rainfall between dry and wet months over Singapore is therefore projected to increase over the 21st century (Table 4.3). As expected, there is considerable year-to-year and decade-to-decade natural variations in the rainfall in the region around Singapore. This is apparent in both observations and climate model simulations. The statistical significance of the projected changes in rainfall has been described above and this is represented by the colour shading in Table 4.3.

		Mid-century (2040 - 2069)				End-century (2070 - 2099)			
		Departure (%) in rainfall totals from the observed 1980-2009 average							
Mean observed (1980 - 2009)		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Annual	2488.4 mm/yr	-4.3	12.0	-16.3	11.3	-12.4	10.3	-17.2	26.8
Nov-Jan	261.8 mm/mth	-11.6	59.3	-20.5	29.6	-13.6	42.9	-23.1	67.5
Feb	142.1 mm/mth	-69.9	27.1	-81.6	38.2	-82.4	23.9	-83.2	16.5
Jun-Sep	174.6 mm/mth	-49.1	8.5	-10.3	17.8	-12.4	12.3	-30.3	1.2
Percentage contribution to annual rainfall totals from very wet days (daily rainfall total ≥ 56 mm)									
	22.8%	21.6%	36.3%	20.8%	32.7%	21.1%	35.3%	21.5%	44.1%

Table 4.3: Projected changes in annual and seasonal rainfall for the mid- and end-century under the two RCPs. The two values in each pair give the lower and upper range for each of the variables. Statistical significance is indicated by the coloured shading, with blue representing statistically significant increasing rainfall signals and orange drying signals. Grey shading indicates signals that are not statistically significant.

Box 4.5: The role of natural variability in climate projections for Singapore

Climate varies on multiple timescales due to both natural causes and anthropogenic influences. Natural causes include the climatic response to volcanic eruptions and the varying radiative input from the Sun. It also includes the local manifestation of planetary scale modes of climate variability. The El Niño Southern Oscillation (ENSO) is an example of particular relevance to the region. During El Niño and La Niña events, Singapore generally receives less and more rainfall than average respectively. Future changes in ENSO could substantially change droughts affecting the region; however, there is not enough confidence in the projected changes to ENSO in the CMIP5 ensemble (as stated in the IPCC AR5) to draw conclusions.

There are also natural modes of variability that occur on longer decadal and multi-decadal timescales, such as the Pacific Decadal Oscillation (PDO) and the Atlantic Meridional Oscillation (AMO). These longer timescales natural variations can also influence climatic conditions in the Singapore region, although the precise local linkages to these and other modes of decadal variability have not been studied in detail, partly due to the lack of the long timeseries of relevant data from across the region.

Based on 28 observation stations across Singapore, there was an increasing trend in annual average rainfall from 1980 to 2009 (see Section 2). However, the few station observational records that extend back to the 1950s show that the rainfall had a downward trend from the 1950s to 1970s (see Figure 2.2). This illustrates the importance of inter-decadal variability and emphasizes that not all long-term trends in climate are due to anthropogenic climate change. While climate models simulate these long timescale modes of climate variability, the realism of the simulation varies considerably between models. When looking at future projections from climate models, it is important to understand that it is often a combination of these natural signals, with the anthropogenic climate change signal, that is being simulated by the models. The inter-decadal 'up and down' oscillations seen in many of the results presented here can only be taken as an example of what may happen in future, rather than a definite prediction of the phase of these oscillations.

Climate Model Decadal Prediction Systems are being developed to help predict the natural and man-made climate signals on decadal timescales but these are at an early stage of development. Results from such systems were, for the first time, included in the latest IPCC AR5 assessment but the current models show little skill in predicting decadal oscillations beyond a few years ahead.

How will humidity change?

All models used in this study project statistically significant negative changes in Singapore's average relative humidity under both RCP scenarios throughout the century (Figure 4.12). The models, on average, project a decrease of 2.8% and 4.6% in the mean annual relative humidity at the end of the century with respect to the reference period under RCP4.5 and RCP8.5 scenarios, respectively (i.e. decrease from 83.0% in 1980-2009 to 79.2% (RCP8.5) and 80.7% (RCP4.5) in 2070-2099).

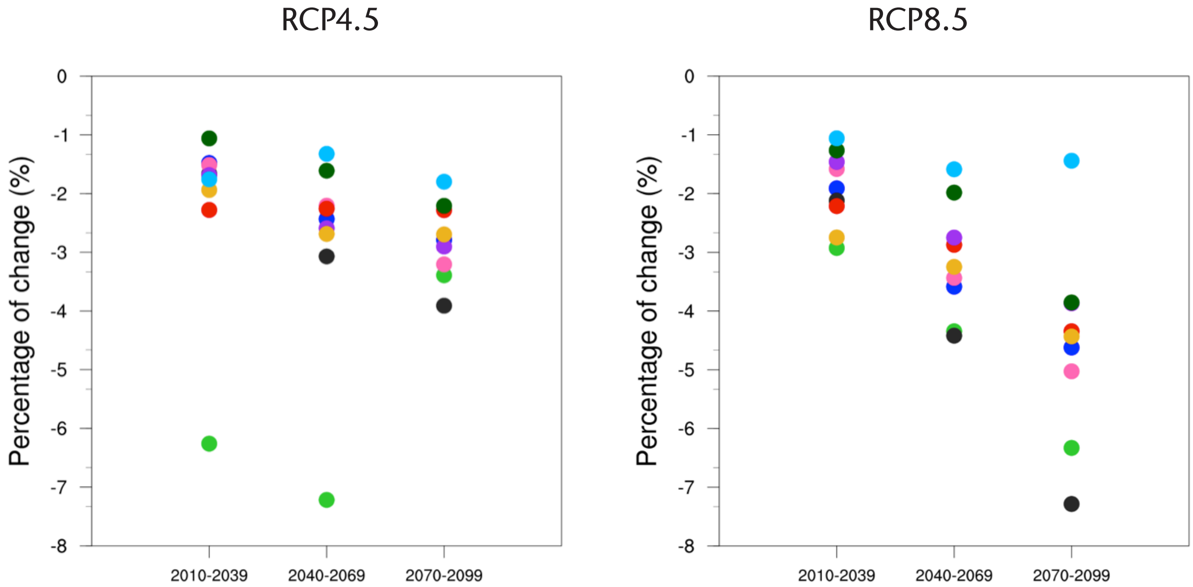


Figure 4.12: Mean annual relative humidity anomalies for the three 30-year time period, relative to the mean of 1980-2009 for the two RCP scenarios.

How will the level of heat stress change?

The projection of changes in wet-bulb temperature (WBT), a measure of heat stress, is of importance as severe heat stress can reduce outdoor activities and affect labour capacity considerably.

Annual average daily mean, minimum and maximum wet-bulb temperatures

Projected ranges in average daily maximum WBTs under both RCP scenarios are presented in Figure 4.13. All models project statistically significant increases throughout the 21st century. Summaries for ranges in average daily mean, minimum and maximum WBTs under both RCP scenarios at mid- and end-century are provided in Table 4.4. These figures show increases of up to approximately 2°C under RCP4.5 and 3°C increase under RCP8.5 by mid-century (2040-2069). For the end-century (2070-2099) period, these figures increase up to 2.5°C under RCP4.5 and 4°C under the RCP8.5 scenario. Note that under RCP8.5, 8 out of the 9 models project the average daily mean WBT at the end-century period to be higher than 29.2°C, which is the historical average daily maximum WBT.

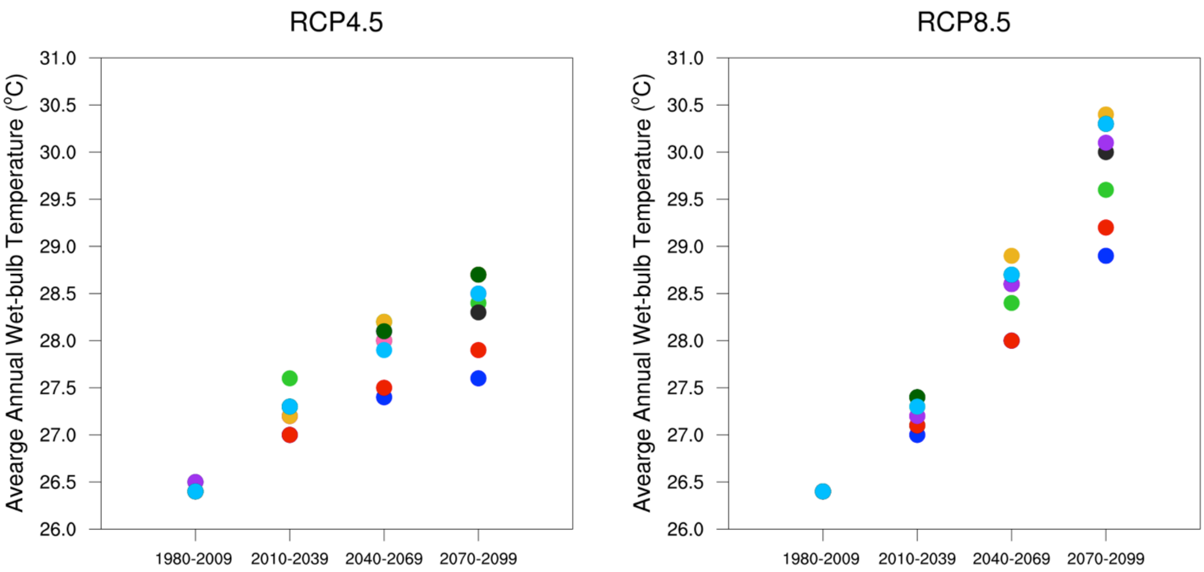


Figure 4.13: Ranges in average daily maximum wet-bulb temperature for the RCP4.5 (left) and RCP8.5 (right).

Increase in frequency of warm wet-bulb temperature days

The projected ranges in frequency of warm wet-bulb temperature days (days with a maximum WBT of 27.7°C, the historical 90th percentile, or above) are summarised in Table 4.4. The projections show that the annual number of warm wet-bulb temperature days is expected to increase significantly in the 21st century. However, no model projects days with WBTs above 35°C within the 21st century, the threshold at which the human body becomes unable to dissipate excess heat.

		Mid-century (2040 - 2069)				End-century (2070 - 2099)			
Mean observed (1980 - 2009)		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Minimum WBT (deg C)	22.1	22.7	24.4	23.1	25.1	23.3	24.7	24.2	26.5
Mean WBT (deg C)	26.4	27.4	28.4	28.0	29.1	27.6	28.9	28.9	30.7
Maximum WBT (deg C)	29.2	30.4	31.4	31.1	32.0	30.8	31.9	32.0	33.9
Frequency of warm WBT days (WBT ≥ 27.7°C, the historical 90th percentile threshold)									
Annual	37	224	301	234	328	280	329	313	357

Table 4.4: Projected ranges in the average daily minimum, mean, maximum wet-bulb temperature (WBT) and the annual number of warm WBT days (defined as days with WBTmax ≥ 27.7°C, the historical 90th percentile) for mid- and end-century under RCP4.5 and RCP8.5 scenarios. The two values in each pair give the lower and upper range for each of the variables and the orange to red shading indicates that these changes are statistically significant.

How will local winds change?

Seasonal mean winds

For mean winds over Singapore, there is no indication that the direction of the monthly climatological winds will change. In regard to the seasonal winds, there is an indication of increasing mean wind strength during the northeast monsoon; 3 out of the 9 models show statistically significant increasing signals and no model projects a statistically significant decreasing signal at the end of the century under RCP8.5. There is little agreement between models about the projected change in mean wind strength during the southwest monsoon; 3 out of the 9 models show statistically significant increasing signals and 2 models project statistically significant decreasing signals at the end of the century under RCP8.5 (Figure 4.14 and Table 4.5).

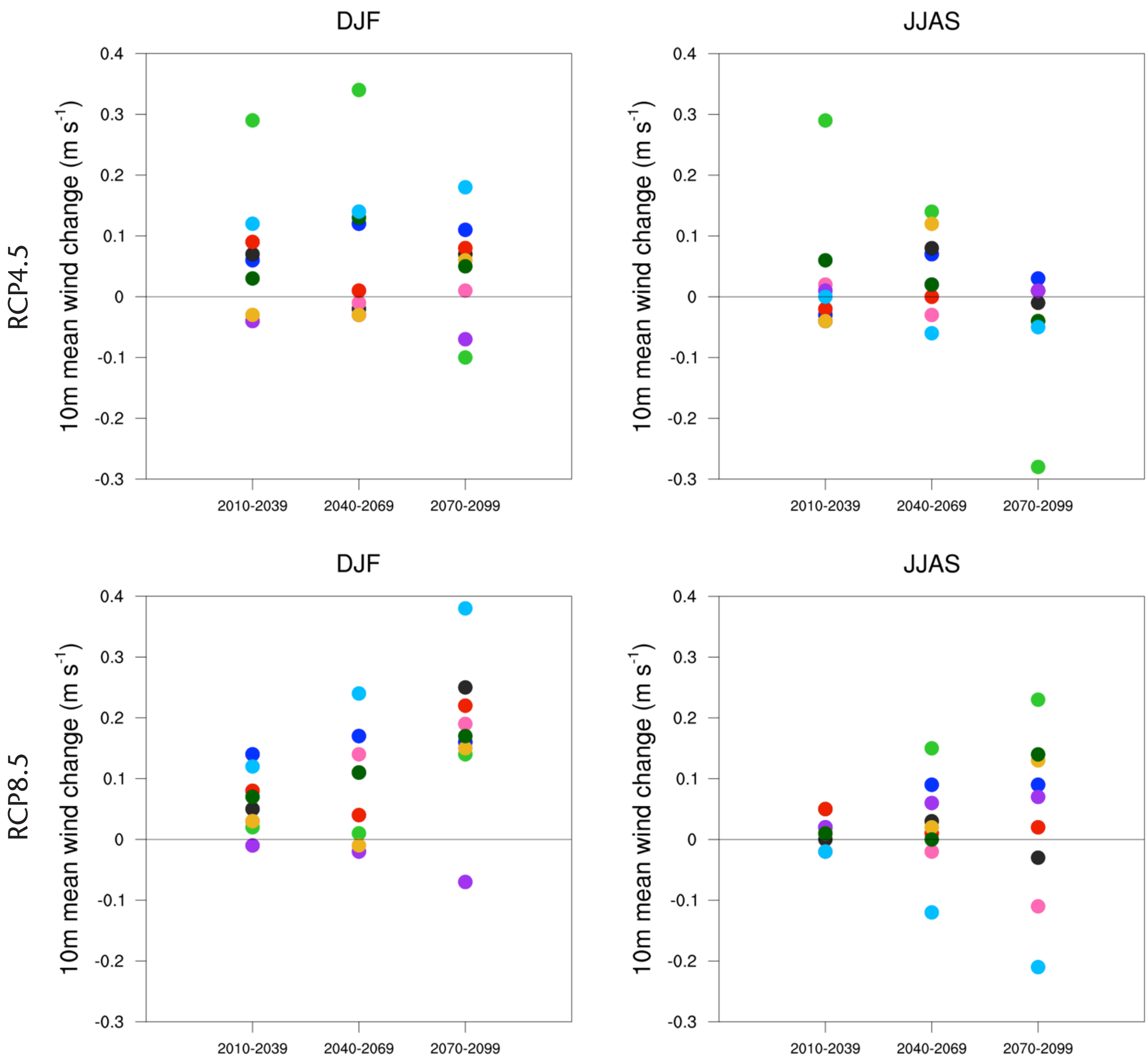


Figure 4.14: 10 m daily mean wind speeds, showing the DJF and JJAS mean for both RCP scenarios, during historical (1980-2009), early-century (2010-2039), middle-century (2040-2069), and end-century (2070-2099) periods.

		Middle Century (2040 - 2069)				End Century (2070 - 2099)			
		Departure (%) in mean wind from the observed 1980-2009 average							
Mean observed (1980-2009)		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Annual	1.7 m/s	0	21	1	6	-1	4	-1	6
Dec - Feb	2.2 m/s	-1	15	1	11	-3	8	-3	17
Jun - Sep	1.8 m/s	-3	8	-7	5	-15	2	-11	13

Table 4.5: Summary of projected 10 m seasonal wind changes over Singapore. The values show the percentage change relative to the 1980-2009 climatological values. The two values in each pair give the lower and upper range for each of the variables and the red and blue shading indicates statistically significant increases and decreases respectively and grey indicates no statistical significance.

Extreme winds

The daily variations in low-level (10 m) wind strength over Singapore are not well captured by models and the seasonal cycle of daily wind variability is poorly simulated. For this reason, the extreme statistics based on daily mean winds from the 12 km downscaled models should be treated with caution. Hourly and sub-hourly wind gusts are mainly produced by thunderstorms and squall lines and these cannot be resolved in the 12 km model. For this reason the higher resolution 1.5 km model (see Box 4.4) has been used to estimate possible future changes in wind extremes and associated wind gust statistics. Although there is only one model simulation available, it can be used to provide some indication of changes in wind gust intensity and frequency. The hourly 10 m winds from the 1.5 km resolution downscaled runs for the historical and RCP8.5 scenarios were used to estimate changes in the wind gust frequency and intensity. It is reasonable to use hourly wind speeds as a proxy for hourly maximum wind gusts as they are highly correlated.

For the end century under RCP8.5 there is found to be a 5-10% increase in hourly wind gust speeds and a 50-75% increase in the frequency of exceeding the historical 95th and 99th percentile of wind gust strength. These values are only based on one model simulation of 10 years duration and the results can only be treated as a first estimate. Future research with convective resolving models is required before more definitive results can be given.

Changes to the climate beyond 2100

Projections of annual average temperature rise for Singapore continue, as expected, beyond the end of the 21st century, although under RCP4.5 the trend slows soon after 2100 and average temperature is essentially stabilised from that point. Under RCP8.5 this slowing occurs much later and there is a potential of reversal of this trend by 2300. The temperature rise under RCP8.5 by 2300 ranges from about 5°C to 12°C, although such large changes would only be realised if there is no mitigation action on climate change. There is no clear signal for changes in annual average rainfall beyond 2100, consistent with the results presented here for the 21st century.

5. What changes are projected for sea level?

The IPCC AR5 states that, under RCP8.5, global average sea levels are likely to rise by 0.45-0.82 m in 2081-2100 compared to 1986-2005. Only the collapse of marine-based parts of the Antarctic ice sheet, leading to glacier acceleration and thinning, could cause global average sea level to rise substantially above this range during the 21st century, and while the risk of this is not precisely quantified, current research gives medium confidence that the additional sea level rise would not exceed a few tens of centimetres this century.

Sea level change represents the combination of a complex range of processes that vary by time and location. The response of different processes around the world to global temperature rise means that estimates of average (mean) sea level rise for Singapore differ from the global average (see Box 5.1). In addition to this 'mean sea level' rise, there are local factors affecting sea level extremes (waves, surges and tides) around the coasts of Singapore.

What changes are projected for mean sea level?

This study provides an assessment of potential changes in mean sea level for the Singapore region over the 21st century under the RCP4.5 and RCP8.5 using data from 21 climate models from the CMIP5. The baseline period of 1986-2005 is used to enable direct comparisons with the global sea level rise results presented in IPCC AR5.

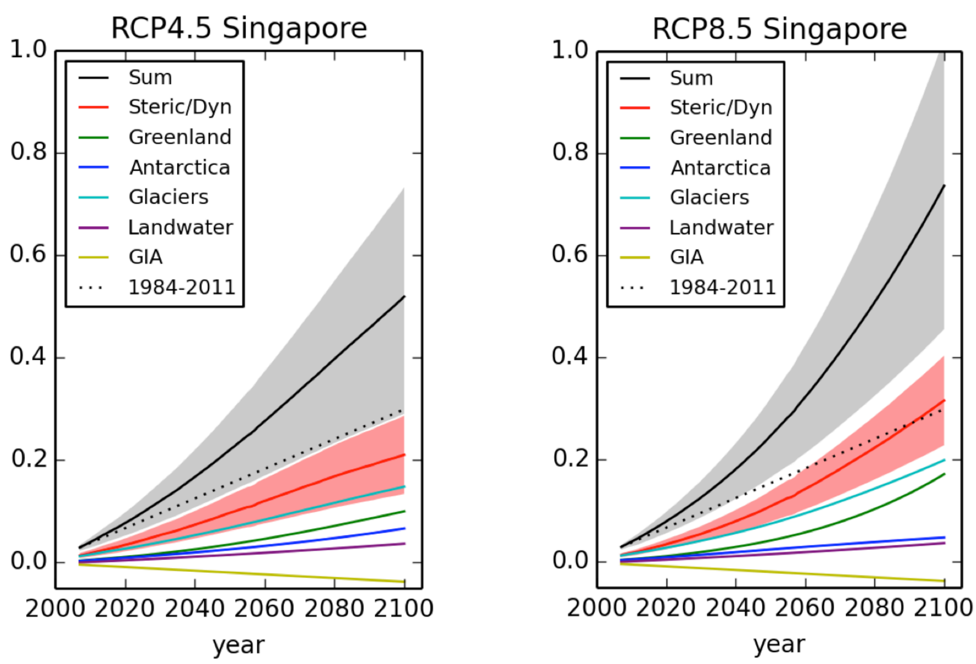


Figure 5.1: Projections of sea level rise relative to 1986-2005 for the Singapore region for the RCP4.5 scenario (left) and the RCP8.5 scenario (right). The lines show the median projections. The likely ranges for the thermal expansion and ocean circulation ('Steric/Dyn') changes (red), and for the total change (grey) are shown by the shaded regions. The contributions from ice sheets include the contributions from ice sheet rapid dynamical change. GIA refers to Global Isostatic Adjustment, which is the adjustment of the land surface since the last ice age. The dotted line shows the simple continuation of the 1984-2011 rate of sea level change for the Singapore Strait.

The projections shown in Figure 5.1 suggest trends in mean sea level far greater than those already experienced in the last few decades. The results are comparable to the global rates presented in the IPCC AR5. Rates of sea level rise due to glacial melt and ice sheet melt are somewhat higher for Singapore due to its position near the equator. However results from this study suggest that this increase is somewhat offset due to long-term glacial adjustment (a negative contribution, see Box 5.1). By 2050, there is little difference in projected sea level rise between RCP4.5 and RCP8.5, and even at 2100 there is substantial overlap between the two scenarios. However, as expected, there is substantial uncertainty in the magnitude of sea level rise projected by different models. Table 5.1 summarises the estimated mean sea level rise for Singapore by 2050 and 2100. To allow for exploration of uncertainties beyond the quoted likely ranges, a high end sea level rise scenario has been developed (H++). This range is constructed from a number of strands of evidence and uses expert judgement. It can be interpreted as covering values that current models or other approaches cannot rule out. Although we cannot place a precise probability on the values in the H++ range the upper end is expected to be associated with a very low probability. This H++ scenario adds a further approximately 1m to the top of the likely range of mean sea-level rise at 2100 (see Table 5.3).

	2050			2100		
	Lower	**Median**	**Upper**	**Lower**	**Median**	**Upper**
RCP4.5	0.14	0.22	0.30	0.30	0.53	0.74
RCP8.5	0.17	0.25	0.32	0.45	0.73	1.02

Table 5.1: Median values and likely ranges for projections of mean sea level rise in metres relative to 1986-2005. All the projected changes are statistically significant.

Box 5.1: Why would Singapore's mean sea level rise differ from the global average?

There are a number of factors that can cause mean, or average, sea level for a given location to be higher or lower than the global average. As the oceans absorb additional heat from the atmosphere, that heat will be redistributed around the globe. The way this happens will depend on the existing ocean circulation system, or it may cause changes to ocean currents. This movement of water is expected to cause sea levels to rise more in some areas than others, and is modelled in the GCMs.

As ice sheets and glaciers melt, the additional water also needs to be redistributed. Rather than causing higher sea levels at the poles, near the sources of the water, scientists expect the opposite effect. Large bodies of ice have a gravitational pull, causing their local sea levels to be slightly higher. As these bodies of ice melt, their gravitational pull is reduced, leading to lower sea levels in their vicinity and higher sea levels further away at the equator. This means the ice melt components of sea level rise are projected to be higher around Singapore.

However, the glacial adjustment component of sea level rise is expected to counter this. As large areas of ice melted at the end of the last ice age, this lifted a weight off the land surface. In some areas the land surface is still making vertical adjustments to account for this. In Singapore this produces a negative contribution to sea level rise.

As already noted in Section 3, a major regional earthquake could lead to an additional rise in sea level of the order 15 cm over a few decades.

What changes are projected for extreme sea levels?

Extreme sea levels near Singapore are driven by strong winds, often associated with the northeast monsoon. This study has considered changes to surges and to average and extreme waves affecting Singapore.

The wave model results show no consistent change between present-day and the end of the century. In the absence of any mean sea level change, projected century-scale changes in mean significant wave height around the coast of Singapore are less than 20 mm per century. There is no statistically-significant projection of positive century-scale change in annual maximum significant wave height around the coast of Singapore.

Similarly, the results from the tide and surge model show no significant change in skew surges in the absence of mean sea level rise. There is a large amount of uncertainty in the results but even the highest projected changes are small compared to the changes in mean sea level. The results for an ocean point to the south of Singapore are illustrated in Figure 5.2. There is no clear indication of an increase in surge heights. Annual maximum skew surge at neighbouring locations around Singapore are strongly correlated, which suggests that the (absence of) century-scale change will be similar at all grid points around Singapore.

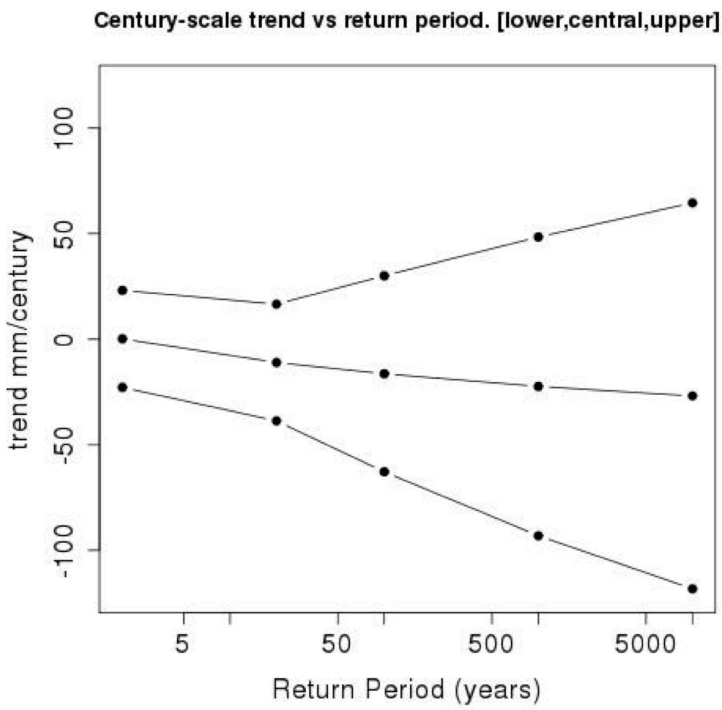


Figure 5.2: Projected century-scale trends in skew surge for five return periods due to storminess changes only (i.e. excluding mean sea level change) (mm per century). The lower and upper bounds are derived from a statistical fit to results from the 4 surge simulations, including an estimate of additional uncertainty to compensate for the small ensemble size.

The uncertainty in projections of surge extremes can be combined with the uncertainty in mean sea level to give projected changes in extreme still water level. The results for RCP4.5 and RCP8.5 are presented in Table 5.2. To obtain future sea levels at a given location for events of different return periods, the recommendation is to linearly add the present day return level observed from tide gauge stations to projected changes in extreme water level.

2050 RCP8.5					
Period (years)	**2**	**20**	**100**	**1000**	**10000**
Lower	0.16	0.15	0.14	0.13	0.12
Upper	0.33	0.33	0.33	0.34	0.34
2100 RCP8.5					
Period (years)	**2**	**20**	**100**	**1000**	**10000**
Lower	0.44	0.42	0.40	0.38	0.35
Upper	1.04	1.04	1.05	1.07	1.07
2050 RCP4.5					
Period (years)	**2**	**20**	**100**	**1000**	**10000**
Lower	0.14	0.13	0.12	0.11	0.11
Upper	0.30	0.30	0.31	0.31	0.32
2100 RCP4.5					
Period (years)	**2**	**20**	**100**	**1000**	**10000**
Lower	0.29	0.27	0.26	0.25	0.23
Upper	0.75	0.75	0.76	0.77	0.78

Table 5.2: Projected changes in extreme still water level due to changes in mean sea level and changes in atmospheric storminess (metres) at a point in the Singapore Straits for different return periods. The lower and upper bounds show a representative range of projections derived by combining mean sea level projections with results from the 4 storm surge simulations, including an estimate of additional uncertainty to compensate for the small ensemble size of surge simulations.

Changes beyond 2100

Two sets of experiments corresponding to high and low responses to the increase in greenhouse gas forcing to 2300 were considered in this study. In what follows these experiments are labelled 'low' and 'high' sensitivity. The use of these experiments provides a plausible indication of the range of future change, taking into account the large inherent uncertainties in both the modelling and the greenhouse gas forcing. No consideration is made of the effects of future climate change mitigation policy on the likelihood of the scenarios considered.

The lower end of projections for sea level rise for Singapore at 2300 is 0.36-2.10 m (based on the low sensitivity experiment and RCP4.5). This range could be considered a useful guideline for minimum future adaptation requirements. The upper end of projections ranges from 0.94-5.48 m (based on the high sensitivity experiment and RCP8.5). For sensitivity testing of adaptation options, a plausible upper limit range of sea level rise at Singapore of 1-2 m per century is recommended. This equates to a range of 3-6 m for 2300, a plausible but highly uncertain value. Table 5.3 provides a summary of plausible ranges in the longer-term projections of sea level rise.

	2100		2200		2300	
	Lower	Upper	Lower	Upper	Lower	Upper
RCP4.5 IPCC AR5 Method	0.29	0.73 m	-	-	-	-
RCP8.5 IPCC AR5 Method	0.46	1.02 m	-	-	-	-
RCP4.5 "low sensitivity"	0.19	0.65 m	0.30	1.42 m	0.36	2.10 m
RCP8.5 "high sensitivity"	0.47	1.29 m	0.88	3.57 m	0.94	5.48m
Hi-end "H++" scenario	1.00	2.00 m	2.00	4.00 m	3.00	6.00m

Table 5.3: Illustrative ranges for sea level rise at Singapore based on the different methods. The "H++" scenario gives a plausible high-end range for sensitivity testing of adaptation options. All ranges expressed as a change relative to a baseline period of 1986-2005.

6. How will the projections from this study be used?

Scientific climate information has become increasingly important in policy-making. This information helps to answer questions related to the effectiveness and cost of plans to protect Singapore against the negative impacts of climate change and climate variability. While the IPCC Assessment Reports provide valuable information to lay the scientific foundation for Singapore's adaptation planning, it is necessary for Singapore to supplement this with studies that translate these findings into the local context through further modelling and an understanding of climate science.

Even with international efforts to limit the rise in global temperatures, there is a need for Singapore to tackle climate risks as early as possible to maximise the benefits and reduce the economic costs of adaptation. Formulation of Singapore's resilience strategy is dependent on our understanding of climate science and this has been incorporated it into the government's Resilience Framework (shown below), a process taken by Singapore to adapt to climate change.

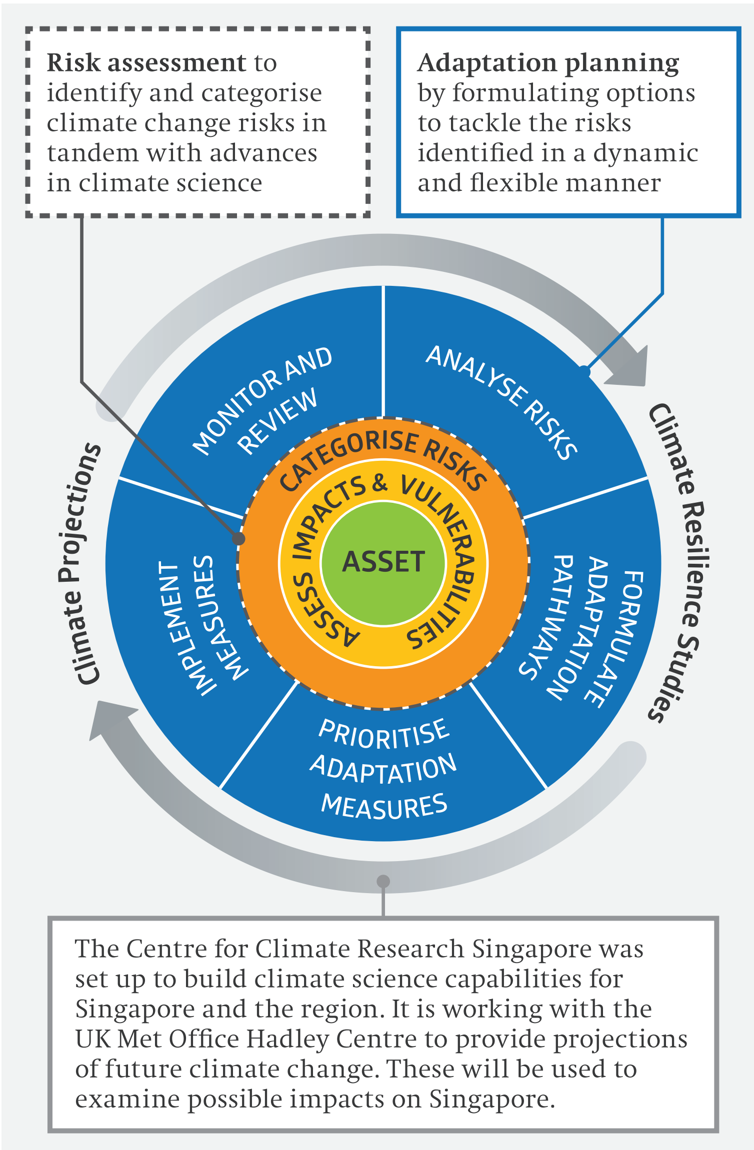


Figure 6.1: Resilience Framework

The findings from the Second National Climate Change Study will not only build climate capability in providing climate projections but will also improve our understanding of the local climate and the risks faced. Phase 2 of the Second National Climate Change study, which started in 2014, will serve this purpose and make use of the projections from Phase 1 to examine the climate change impacts on the domains of water resources and drainage, biodiversity and greenery, network infrastructure and building infrastructure. This, in turn, will guide government agencies in their downstream planning and will serve as inputs to help shape Singapore's resilience plans.

Climate science will continue to evolve and improve. New models and data will need to be incorporated, and new methods and approaches are being explored. Robust, updated projections of future climate will continue to play a key role in supporting Singapore's efforts to build resilience to climate change, but these will need to be continually updated as the understanding of climate science improves.

Annex.
Guidance on the use of projections

Which RCP do I use?

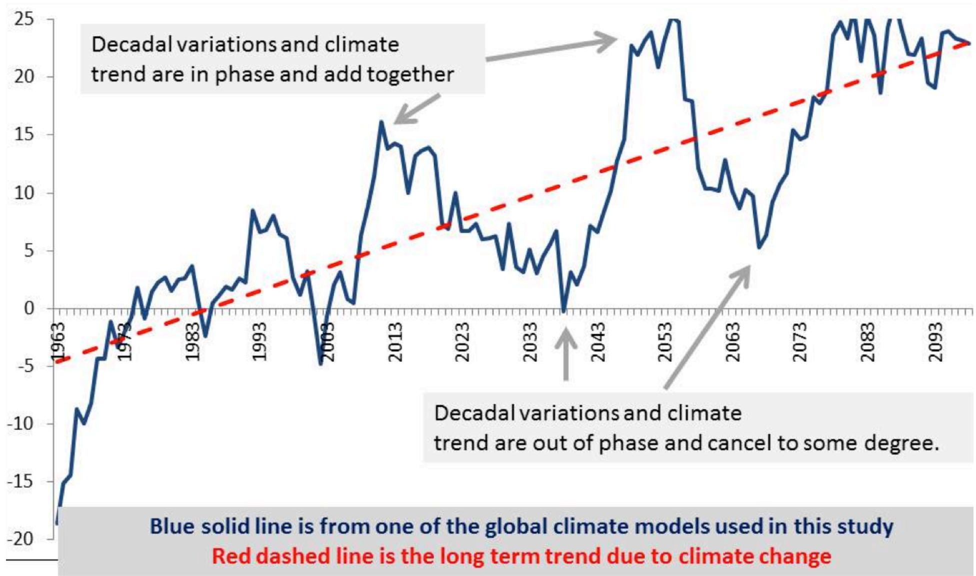
The two Representative Concentration Pathways (RCPs) used in this study aim to span much of the uncertainty in future concentrations of greenhouse gases which drive climate change. RCP8.5 is a scenario with very high greenhouse gas concentrations that continue to increase throughout the 21^{st} century, whereas RCP4.5 is a scenario where concentrations peak mid-century and then decline. The changes projected under RCP8.5 are generally greater than those under RCP4.5, and this needs to be taken into consideration when making adaptation decisions.

Note that RCP4.5 represents the low-end scenario in this study and it projects global temperature rises of 2°C and above by 2100 (above pre-industrial temperatures). This projected temperature range is above the international target of keeping temperature rise to below 2°C. However, the lower end of the RCP4.5 temperature range approximately meets the target.

RCP8.5 is consistent with current levels of increasing greenhouse gas emissions and it can be regarded as a business-as-usual scenario. It provides a reasonable estimate of the high end impacts of climate change. It should be considered for use in adaptation planning where high investment is required and decisions cannot easily be updated. The results in the study also indicate the need for mitigation action by quantifying the large climatic changes that may occur if no action is taken.

Why are mid-century projected changes sometimes larger than those at the end of the century?

At a given time in the future the total ‘change’ that may be observed in the climate can be thought of as a combination of long-term trends and the natural variations for the climate system (see Box 4.5). The natural climate variation, as simulated in any particular model, can enhance or reduce the effect of the long term trend in that model. This is particularly important if the modelled amplitude of the decadal variations is of a similar size to the climate change signal. This is the case for changes in mean and extreme rainfall in the Singapore region. Although the models can capture to some degree the natural decadal variations in the climate system, they cannot predict the evolution of their phases into the future.



The figure above schematically illustrates this issue with an example. The blue line shows the annual daily maximum rainfall time series as a percentage change from current values. This is taken from one of the global climate model simulations used in this study and it relates to the region surrounding Singapore. The red line represents the anthropogenic part of the long term trend. It can be estimated by averaging over multiple model simulations and thereby averaging out the natural decadal fluctuations.

In reality the anthropogenic climate change signal will not be linear and it can interact in complex ways with natural variability. Despite this, the basic point illustrated in the schematic above remains valid. At any point in the future, both anthropogenic and natural climate variations will be important.

Why are projected changes under the RCP4.5 scenario sometimes larger than those under RCP8.5?

This can happen for the same reason as illustrated in the above question. As already noted, this will generally only be an issue when the natural decadal fluctuations of climate are of a similar or greater magnitude to the overall change signal. Out to 2100 this is often the case for rainfall variables but projected future temperature changes are considerably larger than the natural variability.

How can I use the group of model results?

This study provides results from 9 different global climate models (GCMs) which have been downscaled over Singapore. This report has given an overview of the range of results from all 9 models as well as average (median) changes where appropriate, but it has not discussed the results from individual models. This is because we have no greater confidence in any particular model, and all provide plausible climate futures. Hence, it is advised that the full ensemble should be used.

However, for further modelling work needed for some decision making, it will be necessary to select one or more model results to use. For robust decision making, it is useful to consider the models showing the largest and smallest increases in variables of interest. Just the median model should not be used as this does not equate to the most likely change. If very large impacts and adaptation costs associated with the high-end scenario are anticipated, it would be useful to consider possible changes beyond this, e.g. H++ scenario for sea-level rise.

What about information not provided by the study?

As part of this study, the model simulation of the current climate has been evaluated, and in general the models provide a good estimate of the observed historical climate. However, in some instances, where we have limited confidence in the outputs, this data are not being made available for use in decision making. In some cases data may just require further post-processing or downscaling. In others, the model is not able to reproduce a good estimation of the climate, and it is recommended to use current day observations to fill the gaps in data. Present day observations may be a better indication of the range for which resilience is required than a climate change projection in which there is low confidence.

How can I downscale the data further to conduct analyses at higher resolution?

The data available in the dissemination portal is on a 12 km grid, see Figure 3.1. The temperature, rainfall, wind and relative humidity data have all been bias corrected using observations from 1980-2009. Interpolation can be used to provide data at a specific site in Singapore if this is required for impact modelling. This is a pragmatic solution but note that interpolation assumes spatial smoothness in the microclimate and therefore requires caution when being applied because this assumption may be invalid.

Are urban effects taken account of in the projections?

A simple representation of the urbanisation of the Singapore landscape is included in the historical simulation of the 12 km model. It assumes the urban fraction increased from around 20% in 1960 to 60% in 2010. For future projections, the urban fraction is held constant at the 2010 value. Even for the historical simulations it is important, however, to emphasise that the detailed urban environment cannot be properly represented in the 12 km model and more sophisticated modelling will be required to realistically incorporate urban affects. Where future changes to the landscape, and their impact on the microclimate is concerned, such effects are not incorporated in the projections and additional studies will be required to address these.