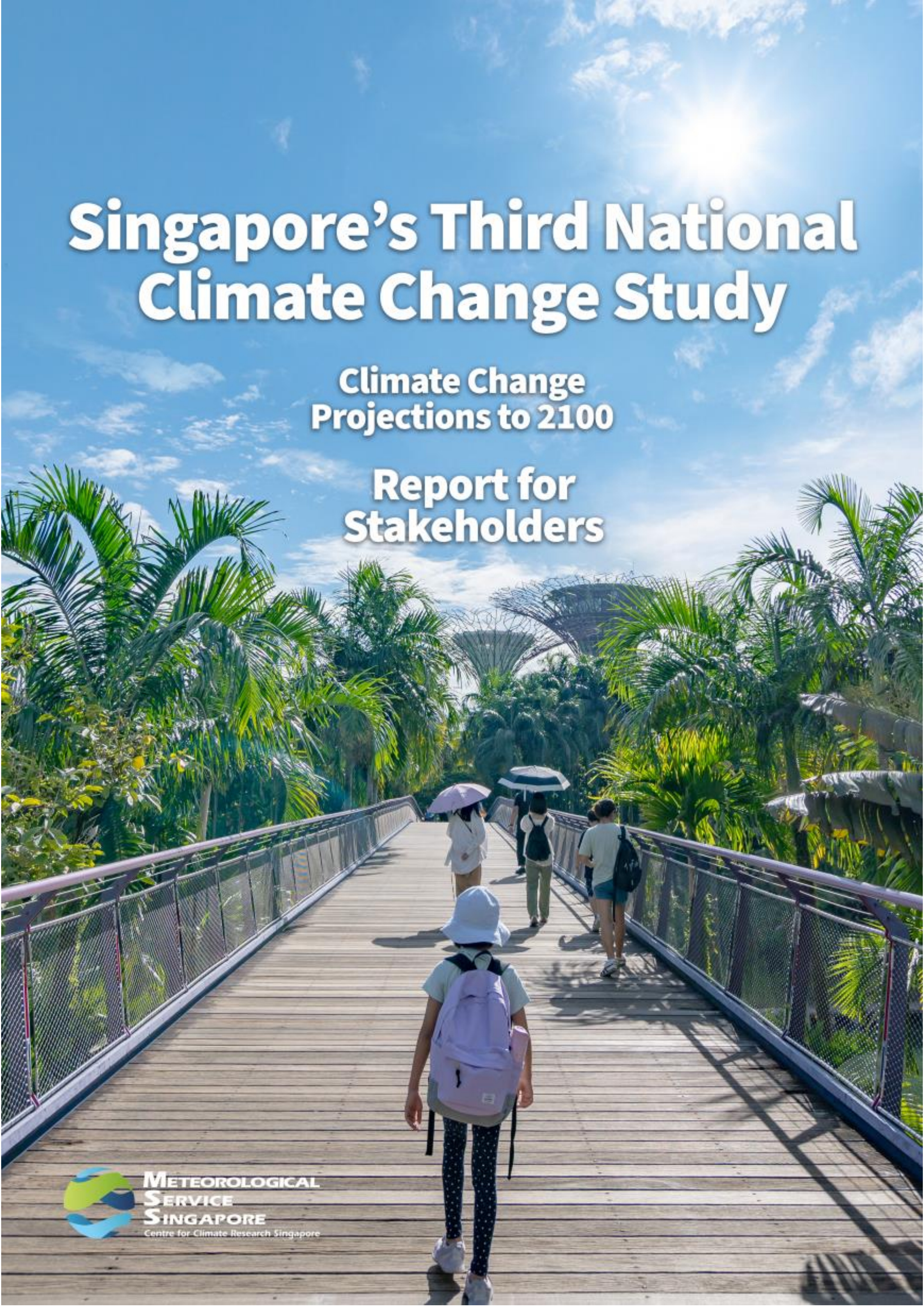
Singapore's Third National Climate Change Study

Climate Change Projections to 2100

Report for Stakeholders



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FRONT COVER IMAGE
People along the Dragonfly Bridge at Gardens by the Bay

BACK COVER IMAGE
Singapore's Central Business District

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FOREWORD

Mr Wong Kang Jet
Chief Executive Officer
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Climate change is no longer a distant threat; it has become an undeniable and immediate challenge for humanity. Its consequences, felt across the globe, are particularly acute for small island nations like Singapore. Globally, the years 2015–2022 were the eight warmest in the 173-year instrumental record. The last 10 years (2013–2022) have been Singapore's warmest decade on record. As our world grapples with the complex and multifaceted risks of climate change, reliable and actionable information is not just a luxury but an imperative for preparedness and adaptation.

This Third National Climate Change Study (V3) conducted by the National Environment Agency's (NEA) Centre for Climate Research Singapore (CCRS) emerges in the context of a changing climate landscape, building upon the foundation laid by its predecessor, Singapore's Second National Climate Change Study (V2).

It is a response to the pressing need for even higher resolution climate change projections that address the specific vulnerabilities of Singapore and the wider Southeast Asian region. These projections are a vital tool for policymakers, researchers, businesses, and the public in understanding and tackling the imminent challenges posed by climate change.

While the Intergovernmental Panel on Climate Change (IPCC) plays a crucial role in synthesising global climate science, it often lacks the granularity required for localised adaptation planning. V3 bridges this gap by dynamically downscaling coarse global climate models to provide finely detailed climate projections for Singapore and its surrounding regions. This invaluable dataset equips stakeholders with the necessary information to develop strategies for safeguarding our nation from the adverse effects of climate change.

This study is not a solitary endeavour but a testament to Singapore's commitment to climate resilience. The success of this study reflects the collaborative spirit that underpins Singapore's approach to climate change. CCRS played a central role in producing the high-resolution downscaled climate projections that form the backbone of V3. The climate simulations alone took 3.5 years to complete using three supercomputers in two countries. The effective collaboration between CCRS and the supercomputing centres involved has been pivotal in this endeavour.

This Stakeholder Report serves as a condensed overview of V3 and its findings. It is intended to serve a wide range of audiences, including government agencies, researchers, corporate entities, and the public at large. In addition to this report, a comprehensive Science Report details the methodology, global and regional projections, and the intricate process behind the generation of these vital climate insights.

As we confront the reality of climate change, it is our hope that the information documented in this report will empower and inspire collective action, foster innovation, and drive Singapore's resilience against the challenges of an ever-changing climate. Together, we can forge a sustainable and vibrant future for our nation and the world.

Executive Summary

Background to Singapore's Third National Climate Change Study

Climate change is an existential threat for humans and other beings on Earth. Hence it needs to be strategically understood and responded to alleviate the various risks associated with it. With increasing evidence of the risks associated with climate change, countries, especially small island nations like Singapore, need reliable and actionable climate change information to be prepared well in advance to adapt to the multi-faceted risks due to climate change.

Every 6–7 years, the Intergovernmental Panel on Climate Change (IPCC) publishes Assessment Reports that provide up-to-date information about the state of scientific, technical, and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place. The IPCC in its latest and sixth assessment cycle produced the Working Group-I (WG-I) report on the Physical Science Basis, the WG-II report on Impacts, Adaptation and Vulnerability, the WG-III report on Mitigation of Climate Change, and finally the Synthesis Report. While these reports are useful to inform global and large-scale climate change, they lack the necessary granularity to assess climate change at the regional and local levels and to guide adaptation planning. Hence, as a follow-up to Singapore's Second National Climate Change Study (V2), Singapore's Third National Climate Change Study (V3) provides the high-resolution climate change projections for Singapore and the wider Southeast Asia (SEA) region, by dynamically downscaling the coarse-resolution global climate model simulations. This new dataset can be readily used for adaptation planning and thus help safeguard Singapore from the adverse effects of climate change.

V3 was conducted by the National Environment Agency (NEA) as part of the work under the inter-agency Resilience Working Group. It will support Singapore's effort to understand the effects of climate change and develop whole-of-government long-term plans that ensure the nation's resilience to future environmental changes. The main body of work on producing the high-resolution downscaled climate projections was undertaken by the Meteorological Service Singapore's (MSS) Centre for Climate Research Singapore (CCRS).

This Stakeholder Report provides a summary of the findings of V3. It is mainly intended for (a) policy makers in the Southeast Asia region that will use the high-resolution projections for downstream impact studies, policy, and adaptation planning; (b) researchers in universities and research entities, locally, regionally, and globally; (c) members of the public interested in climate change and sustainability.

Visualisation of selected V3 data is available at https://www.mss-int.sg/V3-climate-projections.
Complementing the Stakeholder report is a comprehensive Science Report that documents the methodology, global and regional projections from Global Climate Models (GCMs), evaluation and sub-selection of GCMs for downscaling, the main regional climate model SINGapore Variable resolution – Regional Climate Model (SINGV-RCM) used, evaluation of the downscaled simulations, bias-adjustment, regional climate change projections from V3 data, climate change projections over Singapore, and sea-level projections over Singapore and the region.

Recent climate change in Singapore

Singapore's annual mean temperature rose by 0.24℃ per decade in the past 40 years (1984–2022).

Singapore's annual rainfall has been slightly trending up (83mm each decade from 1980 to 2020), but with large year-to-year variations associated with natural climate phenomena such as the El-Niño Southern Oscillation (ENSO). It is important to note that ENSO has a substantial impact on Singapore's rainfall patterns, leading to increased rainfall during La Niña years and decreased rainfall during El Niño years.

Across Singapore, there is an observed rise in mean surface temperatures, daily minimum and maximum temperatures. While there was no discernible trend in annual mean near-surface relative humidity in Singapore during 1983–2010, there is a decreasing trend during 2011–2022.

Methodology to produce climate change projections for Singapore

To produce high-resolution climate change projections for Singapore, the first step was the evaluation and sub-selection of 49 GCMs used in the IPCC's Sixth Assessment Report (AR6) for dynamical downscaling. In addition to the evaluation of GCMs over the region, there were other technical and scientific aspects of the sub-selection process to ensure the regional climate change projections are reliable and capture as much as possible the full range of climate change projected by GCMs. Based on this, six GCMs were finally selected for dynamical downscaling.

Dynamical downscaling of the six GCMs was carried out using a modified version of the SINGV model which is used to generate numerical weather forecasts by MSS. This is an example of seamless modelling wherein the same modelling system is used for generating weather forecasts (few hours to days) as well as climate change projections (many decades). The SINGV modelling system was customised to run in a climate mode by carrying out sensitivity studies at multiple horizontal resolutions over different domain sizes (see Chapter 6 of the Science Report for details).

Table E.1 provides the summary of the downscaling simulations carried out as a part of V3. Simulations were carried out for the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5) and six GCMs for the historical period (1955–2014) and future (2015–2099) for three IPCC AR6 global warming scenarios, namely the Shared Socioeconomic Pathway 1-2.6 (SSP1-2.6), SSP2-4.5 and SSP5-8.5 as the low, mid and high scenarios, respectively, at 8km horizontal resolution over the SEA domain. Additional very high-resolution simulations were carried out at 2km horizontal resolution over the Western Maritime Continent (WMC) domain for the historical period (1995–2014) and the same three SSP scenarios using five GCMs for two 20-year time slices in the future, which are 2040–2059 and 2080–2099.

In parallel to the above downscaling simulations, the other component of V3 focuses on the projections of mean sea level around Singapore and the region. V3 also produces state-of-the-art relative mean sea-level projections for Singapore using the IPCC AR6 methodology. Corrected tide-gauge data is analysed through this methodology to generate the most updated vertical land movement projections for Singapore. Regional sea-level projections in V3 are derived from the IPCC AR6 projections.

Table E.1: Dynamical downscaling simulations

	8km (driven by GCM)	2km (driven by 8km)
Recent past - ERA5 reanalysis	1979–2014	1995–2014
Recent past - CMIP6 GCMs	1955–2014 (6 GCMs)	1995–2014 (5 GCMs)
Future - CMIP6 GCMs	2015–2099 (6 GCMs)	2040–2059, 2080–2099 (5 GCMs)
Future Scenarios	SSP1-2.6, SSP2-4.5, SSP5-8.5	SSP1-2.6, SSP2-4.5, SSP5-8.5

Climate change projections for Singapore—Temperature, rainfall, winds, and sea level

Temperature

V3 projections show that over Singapore the annual average daily mean temperatures will increase by 0.6°C –5.0°C. Mid- to end-century trend in annual average daily mean temperature is projected to be up to 0.55°C per decade. The daily mean wet bulb globe temperature (WBGT), an indicator for heat stress, will increase by 0.5°C –4.3°C by the end of the century.

The daily maximum temperature will increase by 0.5°C –5.3°C, whereas the daily maximum WBGT will increase by 0.5°C –4.0°C.

There will be more days with an incidence of high heat stress with around 54–326 days having WBGT exceeding 33°C for an hour or more during the day.

By end-century annual number of very hot days is projected to be in the range of 41-351. Similarly, annual number of warm nights are projected to be in the range of 312-365.

Rainfall

According to the V3 rainfall projections for Singapore, the rainy months are expected to become even wetter, with a potential increase in climatological mean December–January (considered as the wet phase of the Northeast Monsoon season) combined rainfall of up to 58%, while the dry months may become even drier, with a possible decrease of seasonal mean rainfall by up to 42% (June–September is considered as the Southwest Monsoon season).

The island-wide average seasonal total rainfall during June-through-August could fall significantly below the historical low of 314 mm (recorded in 1997), on average, almost every three years by the end of the century. For the months of November-through-January, the corresponding seasonal total rainfall is projected to exceed the historical high of 1507 mm (recorded in 2006) occasionally.

Extreme rainfall is expected to intensify in all seasons and scenarios, with daily rainfall potentially increasing by 6–92% during April and May, by end-century. Furthermore, dry spells could be more frequent, with Singapore experiencing on average one dry spell every 10–60 months, by end-century.

Winds

V3 projections show that the near-surface wind speed over Singapore will experience changes from −1–20% in the Northeast (December–March) and Southwest monsoon (June–September) seasons and around 1–11% in the inter-monsoon months of April and May by the end of the century.

Sea Level

By 2100, Singapore is projected to experience a relative mean sea level rise of 0.45 ± 0.03 m under SSP1-2.6, 0.57 ± 0.04 m under SSP2-4.5 and 0.79 ± 0.04 m under SSP5-8.5. These are averaged over six locations in Singapore (median). However, Singapore will likely face 0.23–1.15 m of relative sea-level rise by 2100.

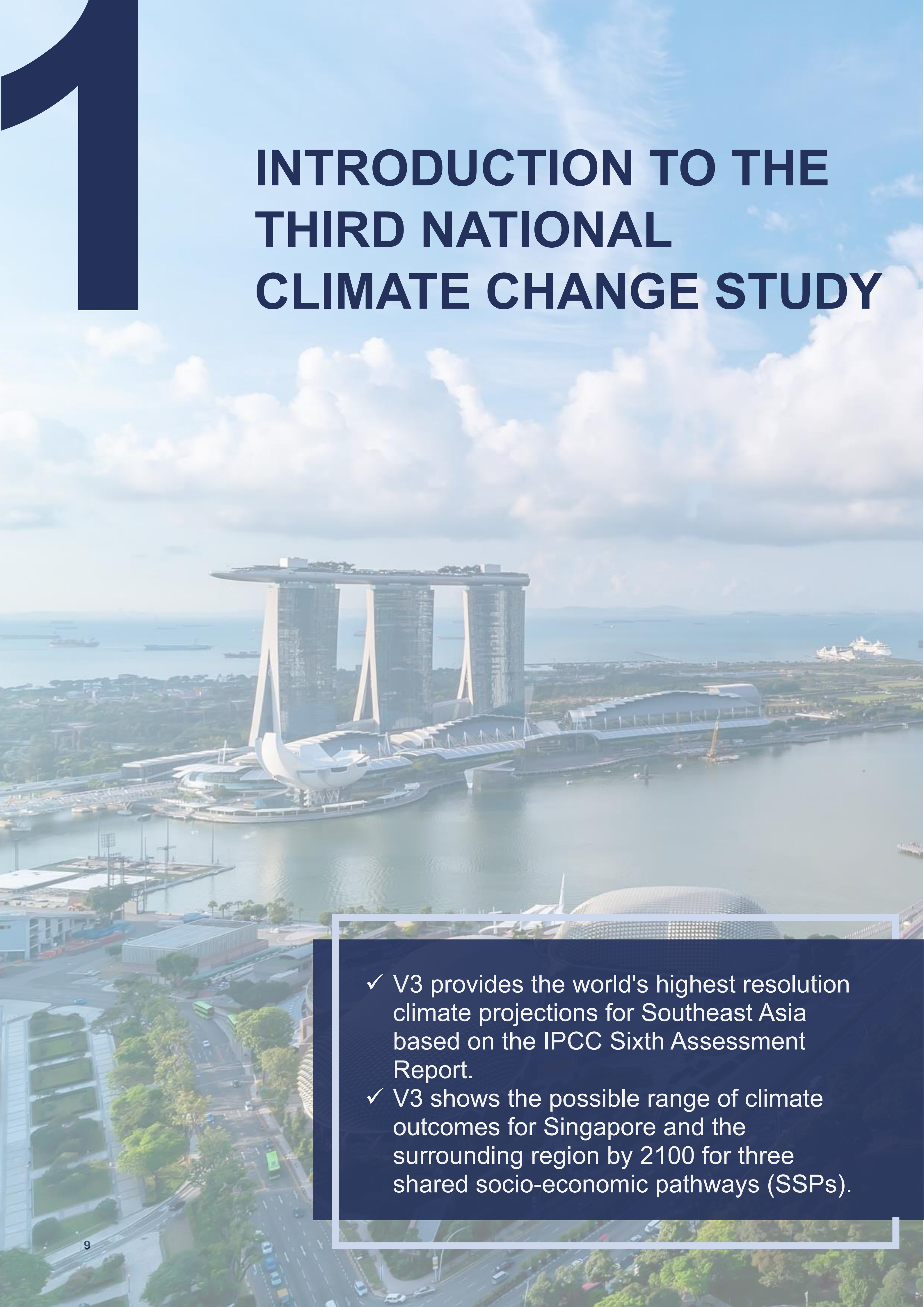
Further into the future, by 2150, the projected rise in relative sea level is 0.72 ± 0.05 m, 0.95 ± 0.06 m and 1.37 ± 0.06 m under SSP1-2.6, SSP2-4.5 and SSP5-8.5, respectively. Similarly, these are the average estimates of the median values at six different locations in Singapore. Relative sea level will, however, likely reach up to around 2 m under SSP5-8.5 by 2150.

Summary table of projections

Table E.2 shows the end-century climate change projections over Singapore for the three SSP scenarios considered in V3.

Table E.2 Table summarizing V3 projections at the end of the century (2080 to 2099).

	V3 Key Findings		
Variable	**SSP1-2.6**	**SSP2-4.5**	**SSP5-8.5**
Increase in mean sea level (m)	0.23 to 0.74	0.34 to 0.88	0.54 to 1.15
Mean daily temperature (°C)	28.5 to 29.5	29.3 to 30.7	30.7 to 32.9
Mean daily WBGT (°C)	27.1 to 28.0	27.8 to 29.0	29.1 to 30.9
Mean maximum daily temperature (°C)	31.9 to 33.1	32.8 to 34.4	34.3 to 36.7
Mean maximum daily WBGT (°C)	30.9 to 31.7	31.6 to 32.6	32.7 to 34.4
No. of very hot days per year	41 to 125	103 to 261	252 to 351
No. of warm nights per year	312 to 361	360 to 365	365
No. of heat stress days per year	54 to 135	107 to 205	207 to 326
Annual average rainfall (mm)	2608 to 3234	2452 to 2921	2295 to 3052
10-m wind	10-m wind speed to increase by up to 20%, by end-century		



1 INTRODUCTION TO THE THIRD NATIONAL CLIMATE CHANGE STUDY

- ✓ V3 provides the world's highest resolution climate projections for Southeast Asia based on the IPCC Sixth Assessment Report.
- ✓ V3 shows the possible range of climate outcomes for Singapore and the surrounding region by 2100 for three shared socio-economic pathways (SSPs).

This chapter introduces Singapore's Third National Climate Change Study (V3). The first section provides key differences between V3 and its predecessor V2. The second section highlights the key differences between the fifth and sixth phases of the Coupled Model Intercomparison Projects (CMIP5 and CMIP6), that form the basis of the fifth and sixth Assessment Reports (AR5 and AR6), respectively. The third section documents the involvement of the Singapore Government Stakeholder agencies in the design of various aspects of V3. The fourth section discusses the sources of uncertainty in the V3 climate projections. Finally, the fifth section documents the scope of V3.

1.1 Key Features of V3

One of the important features of V3 is the strong stakeholder engagement in the planning as well as throughout the execution of the project. Key design components have been adjusted to cater for stakeholder needs, for example on resolution, domain size, and choice of variables required for carrying out impact assessments and planning purposes.

V3 builds upon its predecessor, the Second National Climate Change Study (V2) that was largely contracted to the United Kingdom (UK) Met Office with CCRS contributing to sections of the work. There are several important improvements and enhancements in V3 as compared to V2 (see also Table 1.1 for summary):

- *In-house capabilities*: V3 was entirely planned and conducted within CCRS, which indicates a significant step forward in capability development since V2.
- *Using IPCC AR6 models*: V3 uses the latest and most advanced GCMs which also underpin IPCC AR6. The previous generation GCMs (used for IPCC AR5) were used for V2. The new GCMs have been assessed to provide better global performance.
- *Inhouse downscaling model*: V3 uses the existing CCRS weather modelling system as the basis for a new regional climate model (RCM) for downscaling, called SINGV-RCM. For V2, the UK Met Office's in-house regional model HadGEM3-RA was used. The advantage is that CCRS could modify the model for Singapore climate and use MSS and other local and regional observations to validate the model.
- *Latest climate change scenarios*: V3 uses updated climate change scenarios used in IPCC AR6 (SSP1-2.6, SSP2-4.5, and SSP5-8.5) as opposed to the IPCC AR5 RCPs (RCP4.5 and RCP8.5) used in V2.
- *Expanded sea-level projections*: V3 provides sea-level projections of medium confidence for Singapore and SEA until 2150 using up-to-date vertical land movement projections of Singapore. This is done using the latest IPCC AR6 methodology applied to six key tide gauges around Singapore. Additionally, V3 also provides low confidence sea-level projections for Singapore up to 2300. V2 only provided medium-confidence sea-level projections for Singapore until 2100.

- *Higher spatial resolution* information: Dynamical downscaling for V3 is carried out at a higher spatial resolution (8km over SEA and 2km over the WMC) as opposed to the 12km resolution used in V2. Higher spatial resolution leads to better representation of the hills, coastlines, and land-use-land-cover, leading to more reliable climate change projections.
- *High temporal resolution information*: V3 outputs such as rainfall are provided to stakeholders at much higher resolution (12min@8km and 10min@2km) as compared to V2 (daily). This allows for a more robust assessment of sub-daily rainfall extremes required for design of measures for flood resilience.
- *Larger spatial domains*: The V3 8km domain covers almost the entire SEA and beyond and is 3 times the V2 domain which only partially covered SEA. This makes the V3 domain slightly larger than the CORDEX domain and makes it more useful for sharing with the SEA region and used for climate change and impacts assessment studies.
- *Better bias-adjustment method*: In V3, a more advanced bias-adjustment method, used in ISIMIP3, is used, as opposed to simple quantile mapping used in V2. The advanced bias-adjustment method preserves the trends in downscaled climate variables and only adjusts the values to alleviate known biases, leading to more reliable climate projections.
- *Added uncertainty assessment*: Finally, V3 assesses the dynamical downscaling uncertainty in climate change projections by carrying out downscaling for a subset of GCMs with another regional climate model (WRF). This adds an additional dimension to assess uncertainty in climate change projections, along with scenario and driving model uncertainty, thus adding robustness to the range of projections.

Table 1.1: Comparison of key features in V3 and V2

	V2	V3
Global model	CMIP5	CMIP6 [latest IPCC models]
Regional model	UK Met Office HadGEM3-RA	SINGV-RCM [NEW, CCRS in-house]
Future scenarios	RCP4.5, RCP8.5	SSP1-2.6, SSP2-4.5, SSP5-8.5 [latest IPCC AR6 and more scenarios]
Spatial resolution	12km	8km and 2km [higher resolution]
Temporal resolution of rainfall	Daily	12min@8km and 10min@2km [higher resolution]
Domain size	Partially covers SEA	8km domain covers almost entire SEA and is 3 times the V2 domain. [full SEA coverage]
Bias adjustment	Simple Quantile Mapping	Trend-preserving Quantile Mapping used in ISIMIP3 [more sophisticated method]
Assessment of dynamical downscaling uncertainty	No	Yes [added uncertainty assessment]

1.2 Key features of IPCC AR6 Models

Since V3 uses only six GCMs for downscaling to high resolution, some of the important science concepts to consider are: (a) what is the difference in temperature response of the models to increases in greenhouse gases and how does this determine the likely range of future changes? (b) what choices of future emission and socioeconomic pathways are available? and (c) are the more recent generation global models more skilful in simulating climate?

The first question points to the concept of “Equilibrium Climate Sensitivity”, while the second question requires a brief overview over the IPCC AR6 SSPs used for simulating future climate change. Finally, the answer to the third question is pointing to enhanced modelling capabilities.

1.2.1 Equilibrium Climate Sensitivity

The Equilibrium Climate Sensitivity (ECS) is defined as the global- and annual-mean near-surface air temperature rise that is expected to occur eventually, once all the excess heat trapped (top-of-atmosphere radiative imbalance) by the doubling of CO_2 has been distributed evenly down into the deep ocean (i.e. when both the atmosphere and ocean have reached equilibrium with one another - a coupled equilibrium state). So, ECS is the key factor determining the response of global climate models (and therefore the ‘Spread’) aside from the choice of future emission pathway.

Several AR6 models exhibit an ECS of 5°C or higher, much higher than the upper value of the AR5 range of 4.5°C. Historically, the ECS range reported in previous generations of CMIP models has not shown much variation. The IPCC First Assessment Report (FAR) in 1990 estimated an ECS of 1.5–4.5°C, and the Second and Third Assessment Reports in 1996 and 2001 were both consistent with the ECS range reported in FAR. In AR4 the lower end increased to 2.0°C from the earlier 1.5°C, but in AR5 this reverted to the original range. All these IPCC reports have been largely consistent with the pre-IPCC 1979 US National Academies of Sciences Charney Report—the first comprehensive global assessment of climate change which estimated ECS at 1.5–4.5°C.

Given the ECS values were turning to be higher in many of the AR6 GCMs, the IPCC narrowed down the *Likely Range* for ECS based on different approaches and considering evidence from multiple independent sources such as instrumental records, paleoclimate proxies, physical principles, and climate models. In doing so, the IPCC followed the recommendations given in a seminal study commissioned by the World Climate Research Program (WCRP) on climate sensitivity. The *Likely Range* for ECS now ranges 2.5–4.0°C, being narrower from what was reported in AR5. The IPCC also narrowed the *Very Likely Range* of ECS to be 2.0–5.0°C, down from 1.0–6.0°C (Table 1.2).

Table 1.2: The Equilibrium Climate Sensitivity (ECS) ranges, as assessed by the IPCC in AR6, compared with the corresponding ranges reported in AR5.

IPCC ECS Assessment	AR6	AR5
Likely Range	2.5–4.0°C	1.5–4.5°C
Very Likely Range	2.0–5.0°C	1.0–6.0°C

What does this mean? Adopting this approach, all future projections within IPCC AR6 that relate to temperature have been *scaled* to this *Likely Range* of the ECS. This includes thermal expansion of the ocean as well as all temperature projections. However, CMIP6 models with a ECS larger/smaller than the *Likely Range* were not excluded and are useful to understand more extreme future projections.

1.2.2 Shared Socioeconomic Pathways (SSPs)

A major difference between CMIP5 and CMIP6 (and therefore AR5 and AR6) is the type of future global warming scenarios (or ‘emission pathways’) used for climate change projections. CMIP5 used four RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), defined according to the top-of-the-atmosphere radiative forcing levels reached by 2100, but did not include any socioeconomic storyline to go alongside them.

However, CMIP6 uses scenarios that are rooted in the socioeconomic trajectories that lead to corresponding radiative forcing levels, known as SSPs. Instead of a single dimension (radiative forcing), CMIP6 added this second dimension (socio-economic types) where not all combinations are possible: clearly, to reach the low emissions pathway, the world cannot develop along the 'business as usual' socio-economic path.

Table 1.3: Shared Socioeconomic Pathways used in CMIP6

SSP1-1.9	• SSP1 Socioeconomic + RCP1.9 greenhouse gases (GHG) Concentration Scenarios • ***Taking the green road scenario***; sustainable growth with lower resource and energy intensity
SSP1-2.6	• SSP1 Socioeconomic + RCP2.6 GHG Concentration Scenarios • **Taking the green road scenario**; sustainable growth with lower resource and energy intensity
SSP2-4.5	• SSP2 Socioeconomic + RCP4.5 GHG Concentration Scenarios • **Middle of the road scenario**; social, economic, and technological trends largely follow historical pattern
SSP3-7.0	• SSP3 Socioeconomic + RCP7.0 GHG Concentration Scenarios • **Regional rivalry scenario**; resurgent nationalism, competitiveness pushes countries to focus on domestic, or at most regional issues.
SSP5-8.5	• SSP5 Socioeconomic + RCP8.5 GHG Concentration Scenarios • **Fossil-fuelled development scenario**; rapid non-green technological progress, and ability to manage social and ecological systems, including by geo-engineering if necessary

The five main scenarios include SSP1-1.9, SSP1-2.6 (low), SSP2-4.5 (medium), SSP3-7.0, and SSP5-8.5 (high). There is a mapping between the SSPs and the corresponding RCPs used in CMIP5. The SSPs are mapped with the corresponding radiative forcing they are compatible with. We have focused on only three (SSP1-2.6, SSP2-4.5, and SSP5-8.5) of the five main scenarios for much of the report.

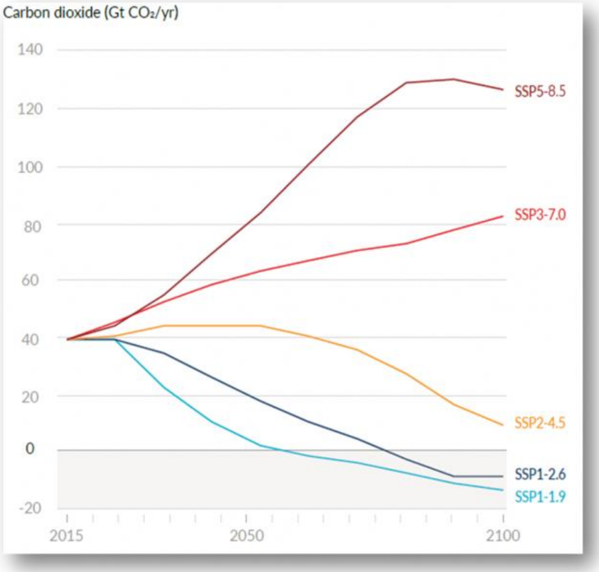


Figure 1.1: Carbon dioxide emissions in Giga-tonnes/per year for the five SSPs. (IPCC AR6)

Note that there is a slight difference in the GHG profile prescribed in corresponding SSP and RCP pairs (e.g., SSP5-8.5 and RCP8.5) and hence future warming.

The choice of future pathway is one of the key determining factors for the range of future climate changes.

1.2.3 Global Climate Models (GCMs)

Any modelling centre able to run a global climate model can participate in the CMIP exercise of running standardised climate experiments. The number of modelling centres contributing to CMIP6 increased by over one-third compared with CMIP5, and the number of individual models nearly doubled. As new generations of GCMs are being built, they are becoming more complex (e.g., simulating more processes within the earth system), higher in spatial resolution (from 100's of kilometres to 50 km per grid cell) and more computationally expensive to run.

The most recent CMIP6 model archive consists of models at higher spatial resolution, more advanced physical parameterisations, and a larger number of them including carbon cycle and biogeochemistry modules.

1.2.4 Sea-level projections in AR6 compared to AR5

The physical science basis of sea-level projections in AR6 largely relied upon paleo-reconstructions, instrumental records, and model simulations. There have been many updates and improvements since AR5, and in general, the advances in the WG-I report of the AR6 primarily stem from the synthesis of (extended) new observations and model simulations.

The temporal and spatial increase in observations of both the ocean and the cryosphere (land ice) has allowed for improved assessment of past change and closure of sea-level budget in a consistent way for the last century. The overall progress has led to improved skill in predicting the ice-sheet contribution to global sea-level rise in latest sea-level projections as compared to previous assessment reports (Shepherd and Nowicki, 2017).

The relative sea-level projections in AR6 also made use of historical tide-gauge sea-level records to estimate the rate of sea-level change from local vertical land movements (VLM) and included that information to obtain more reliable sea-level projections around the world. Apart from advances in our observational systems, the use of a hierarchy of climate models and emulators has also enhanced the projections of oceanic, cryospheric and sea-level change in AR6. For instance, the AR6 included an ice-sheet modelling intercomparison project (ISMIP) for the first time.

Particular modelling advances relevant to sea-level projections include the High-Resolution Model Intercomparison Project (HighResMIP), projections of future glacier (GlacierMIP) and ice sheet (ISMIP6), and many other (see Fox-Kemper et al. 2021).

There are advances in scientific understanding too, with substantial progress over the past decade in the process-understanding of Antarctic and Greenland Ice Sheet changes, glacier physics, and new insights into Arctic Sea ice. In the oceans, new observations and process understanding of ocean heat uptake (Meyssignac et al. 2019; Zanna et al. 2019) have made great implications for ocean climate and sea-level projections.

1.3 How were stakeholders engaged in V3?

For national climate change projections to be useful and impactful, stakeholders need to be part of the project design. For V3, the stakeholder engagement was an important part of the overall study from the planning stage through various delivery stages. There were two types of engagement: (a) large group stakeholder workshops and (b) one-on-one engagements with key stakeholders.

V3 stakeholder workshops have been conducted since 2020, with broad participation from Government agencies across Singapore. Extensive one-on-one engagements were conducted to understand specific data and information needs for different use cases, and user requirements (e.g., on specific temporal and spatial resolutions, additional climate change parameters of interest) have been incorporated into the V3 design where feasible. These engagements happened throughout the project duration.

1.4 What are the sources of uncertainty in V3 projections?

All climate projections (global, regional, and local) are generally ‘probabilistic’ projections, built on information coming from an ensemble of models and future scenarios, leading to a spread in the answers (simulations). This spread in the answers in climate projections is called the ‘uncertainty range’ in projections (sometimes abbreviated as ‘the range’ of projections).

There are three distinct sources of uncertainty in global climate change projections: (a) internal variability uncertainty, (b) model uncertainty, and (c) scenario uncertainty (e.g., Hawkins and Sutton 2009). The relative importance of each of the uncertainty factors changes with the temporal and spatial scale of interest (Figure 1.2). Hawkins and Sutton (2009) compared the roles of internal variability uncertainty, model uncertainty, and scenario uncertainty. Their work indicates that for time horizons of many decades or longer, the dominant sources of uncertainty at regional or larger spatial scales are model uncertainty and scenario uncertainty.

- *Internal variability uncertainty:* As evident from the name, this is due to the internal variability or natural fluctuations of the climate system that arise in the absence of any external changes in the radiative forcing on the earth system.
- *Model uncertainty:* This is also known as a response uncertainty. Each model has its own representation of the processes in the climate system. As such, different models respond differently to the same forcing and hence produce somewhat different climate change projections at global and regional levels.
- *Scenario uncertainty:* This is the difference in response of a given model that can arise due to differences in the external forcing, e.g., greenhouse gas emissions under different pathways, leading to different responses and hence different climate change projections.
- *Dynamical downscaling uncertainty:* In the case of regional climate change projections via dynamical downscaling, an additional uncertainty factor arises that is associated with the different regional climate models used for downscaling. For a given CMIP6 GCM and for a given scenario, two different regional climate models used for dynamical downscaling will produce somewhat different regional climate change projections. This is called the dynamical downscaling uncertainty.

However, for time horizons of a decade or two, the dominant sources of uncertainty on regional scales are model uncertainty and internal variability. In general, the importance of internal variability increases at smaller spatial scales and shorter time scales.

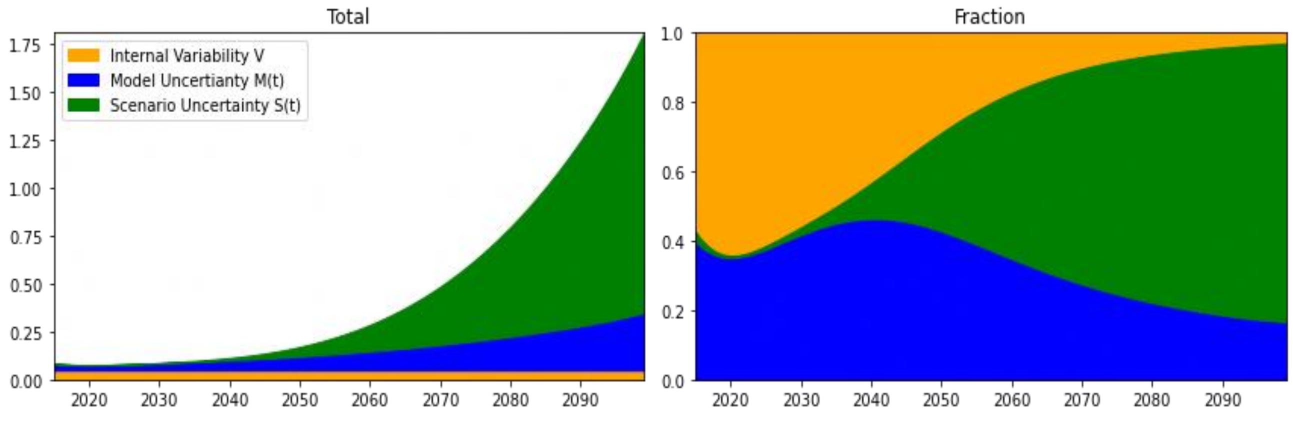


Figure 1.2: Total and fractional variance of surface air temperature over the V3 8 km domain using data from CMIP6 GCMs.

1.5 What is the scope of V3?

Considering the need for Singapore to plan extensively for climate change, using information from the global climate models (CMIP6) is insufficient because of the far too coarse resolution of the information—both in time and space.

Responding to this need, V3 is a climate modelling/projection study which downscales global climate models assessed in the IPCC AR6 to much higher-resolution projections of key climate variables (e.g., temperature, rainfall, humidity, wind) for Singapore and the SEA region up to 2100. V3 also projects sea level changes for six tide-gauge locations around Singapore and a few other tide-gauge locations in the region till 2150 and up to 2300 for some locations.

V3 provides more granular projections of climate variables across space and time compared to V2, which will better inform Singapore's climate adaptation planning. The various stages of this study are shown in Figure 1.3.

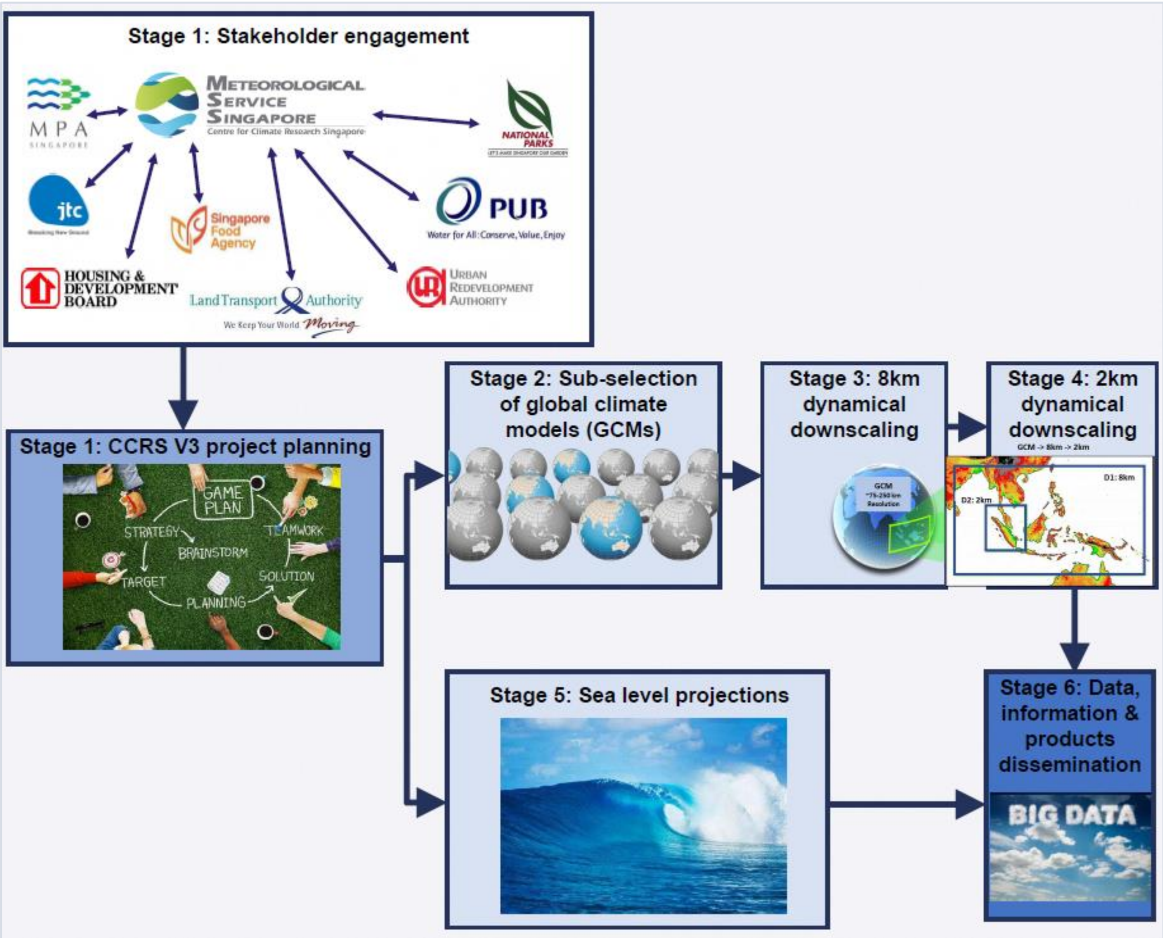
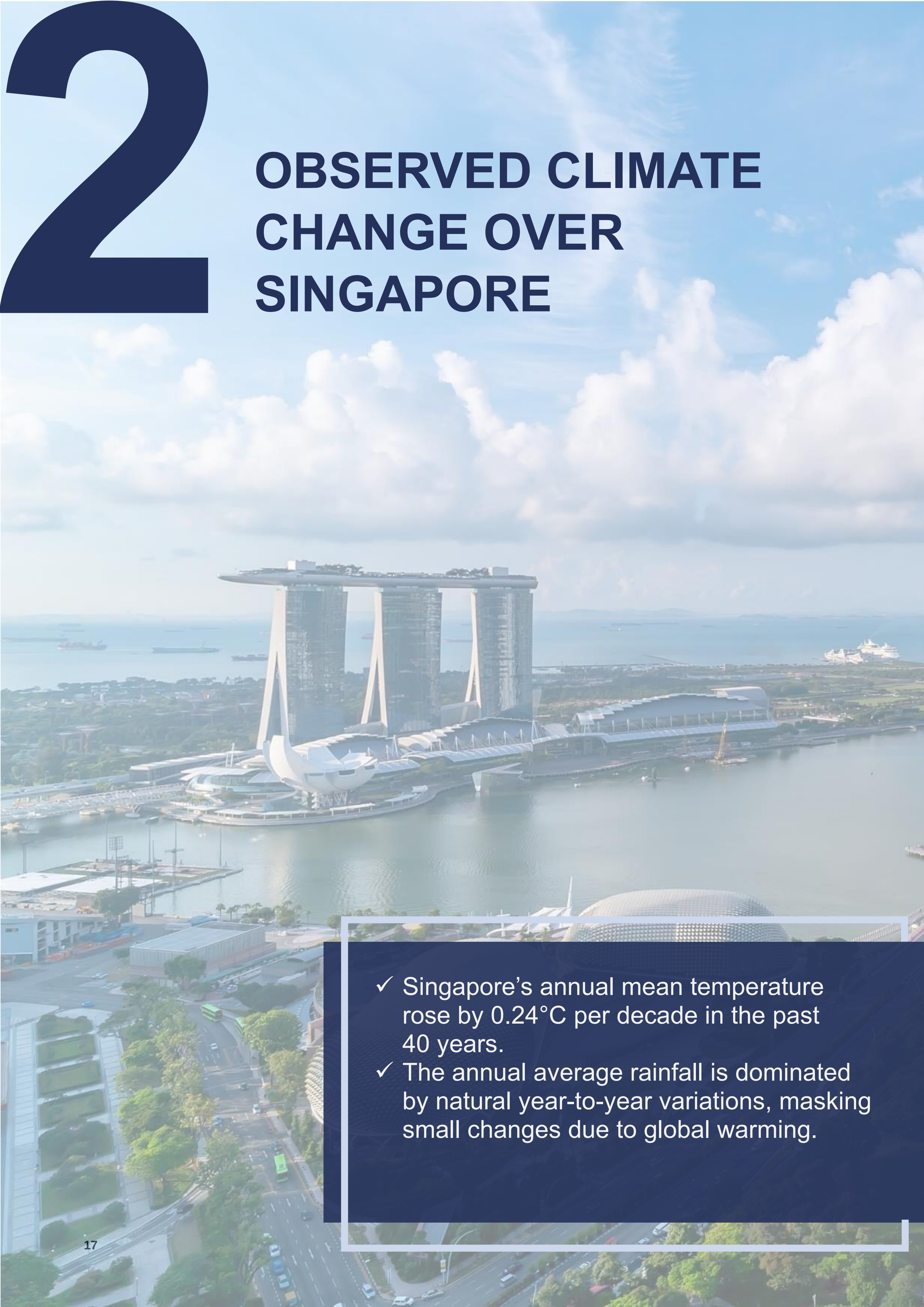


Figure 1.3: V3 Project flow chart.

Aspects that are not included within the scope of V3 are projections of sea level extremes, and effects of the urban heat island (UHI). As a follow up of this study, projections of sea-level extremes will be carried out using high-resolution ocean modelling and projections of UHI effects will be carried out using the urban version of SINGV (u-SINGV).



2 OBSERVED CLIMATE CHANGE OVER SINGAPORE

- ✓ Singapore's annual mean temperature rose by 0.24°C per decade in the past 40 years.
- ✓ The annual average rainfall is dominated by natural year-to-year variations, masking small changes due to global warming.

The IPCC AR6 notes that many of the changes observed in the global climate are unprecedented and have already set in motion changes such as sea-level rise that are irreversible over hundreds to thousands of years (often referred to as the locked-in climate change).

The report states that human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years. It further states that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe. The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area. On the other hand, agricultural and ecological droughts have also increased.

Of more relevance for Singapore is the Annual Climate Assessment Report (ACAR), published by MSS in March each year, which is an annual assessment of Singapore's climate (see https://www.weather.gov.sg/climate-annual-climate-reports/).

2.1 General climate of Singapore and its drivers

Singapore has a tropical climate, which is warm and humid, with an abundant total annual rainfall of approximately 2500 mm. Generally, the eastern parts of Singapore receive less rainfall compared to other parts of the island, as shown in Figure 2.1.

The temperature variation throughout the year is relatively small compared to mid-latitude regions. The daily temperature range has a minimum usually not falling below 23–25°C during the night, and a maximum usually not rising above 31–33°C during the day. The winds are generally light but with a diurnal variation due to land and sea breezes. Singapore's climate is classified into four periods based on the average prevailing wind direction:

1. Northeast Monsoon (December to early March)
2. Inter-monsoon (Late March to May)
3. Southwest Monsoon (June to September)
4. Inter-monsoon (October to November)

The Northeast Monsoon season has a wet phase during December–January and a dry phase during February–early March, whereas there is no strong intraseasonal variation during the Southwest Monsoon season. The transitions between the monsoon seasons occur gradually, generally over a period of two months (the inter-monsoon periods). The winds during the inter-monsoon periods are typically light and variable in direction.

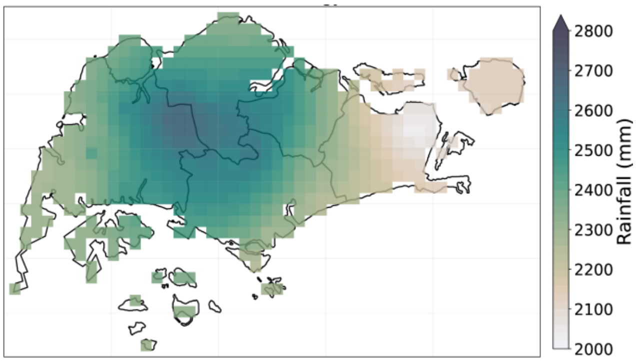


Figure 2.1: Annual rainfall for the 30-year (1991–2020) climatological period based on 28 rainfall stations across Singapore.

The major weather and climate features over Singapore are influenced by climate drivers operating on different temporal and spatial scales, from the seasonal migration of the monsoon (i.e., the Intertropical Convergence Zone [ITCZ]), and other large-scale drivers such as the ENSO, IOD, and MJO, to smaller scale features such as Sumatra squalls, the Borneo Vortex and remote influences from tropical cyclones (see Figure 2.2).

- The **El Niño – Southern Oscillation (ENSO)** is the major driver of climate variability in the western tropical Pacific and the Maritime Continent (MC). It affects the year-to-year chance of droughts, extreme rainfall and floods, tropical cyclones, extreme sea levels, and coral bleaching.

- The **Intertropical Convergence Zone (ITCZ)** is a persistent east-west band of converging low-level winds, cloudiness, and rainfall stretching across the MC into the Pacific Ocean bringing monsoonal rains. It migrates every year southward across the equator and back again, affecting most countries across the MC including Singapore. There are year-to-year variations in the width and strength of the ITCZ that can have a large influence on the rainfall over the region and over Singapore. For example, one of the worst droughts over Singapore that happened in February 2014 was associated with the narrowing of the ITCZ over Singapore (McBride et al., 2015).

- **Indian Ocean Dipole (IOD)**: Sea surface temperatures over the Indian Ocean impact rainfall and temperature patterns across the MC. Warmer than average sea surface temperatures can provide more moisture for weather systems crossing the region. Sustained changes in the difference between sea surface temperatures of the tropical western and eastern Indian Ocean are known as the Indian Ocean Dipole (IOD). The IOD has three phases: neutral, positive, and negative.

- **Madden-Julian Oscillation (MJO)**: MJO can be characterised as an eastward moving "pulse" of cloud and rainfall near the equator that typically takes around 30–60 days to circle the globe, although the signal of the MJO in the tropical atmosphere is not always present. MJO effects are most evident over the Indian Ocean and the MC. Besides influencing the region's wind and bringing more rain, it can also bring periods of drier conditions associated with its dry or 'suppressed' phase.

- **Sumatra Squall Lines**: It is an organised line of thunderstorm that develops over Sumatra or the Strait of Malacca, and typically moves eastward towards Singapore under the influence of south-westerly or westerly winds. It commonly occurs during the Southwest Monsoon and Inter-monsoon periods, and usually affects Singapore overnight or in the morning, often bringing strong gusty surface winds of 40–80 km/h and heavy rain lasting from one to two hours.

- **Northeast Monsoon Surges**: Monsoon surges are a key synoptic feature of the boreal winter circulation over the MC (e.g., Chang et al., 2005) and can lead to extreme rainfall. During the period December through early March, the continental northern Asia including Siberia experiences very low, cold temperatures. From time to time, this cold air surges southward from Central Asia to the South China Sea. This results in a sudden increase in north-easterly winds over the South China Sea blowing toward the warm tropics. The sea warms and moistens the overlying air and the winds converge to bring widespread rain in the tropics. December and January are usually the wettest months of the year in Singapore. The few widespread moderate to heavy rain spells caused by surges of Northeast Monsoon winds contribute significantly to the rainfall in these months. A typical rain spell generally lasts for a few days. The cold surges can also be enhanced by the presence of a favourable phase of the MJO (e.g., Lim et al., 2017) and might also aid the MJO in its passage across the MC (Pang et al., 2018).

- **Borneo Vortex**: It typically appears off the north-western coast of northern Borneo. If a monsoon cold surge event coincides with a vortex, Singapore can experience enhanced rainfall as the convection strengthens over northwest Borneo and weakens north of Java. The lifetime of the vortex is typically a few days.

- **Tropical cyclones (TCs)** typically form over large bodies of relatively warm water away from the equator. Because of the large-scale spatial extent of some TCs, they can have a remote impact on Singapore's weather. Generally tropical cyclones occur between 5° and 30° latitudes, and do not form in the equatorial regions because the Coriolis effect is negligible near the equator. However, the rare occurrence of two colliding systems can lead to cyclone development. In December 2001, typhoon Vamei formed when strong winds from a monsoon surge interacted with an intense circulation system in the South China Sea. Typhoon Vamei came within 50 km northeast of Singapore and brought windy and wet conditions to Singapore.

These features, sometimes several occurring at the same time, affect the regional pattern of rainfall, temperature, winds, ocean currents, and many other aspects of the climate.

Understanding the large- and small-scale features that influence climate variability across the MC is essential in predicting Singapore's weather and climate as well as understanding how the climate may change in the future. Such knowledge helps to inform climate adaptation planning and preparedness. The provision of reliable scientific information for decision-making enables more effective adaptation planning: an essential requirement for securing sustainable development in the region.

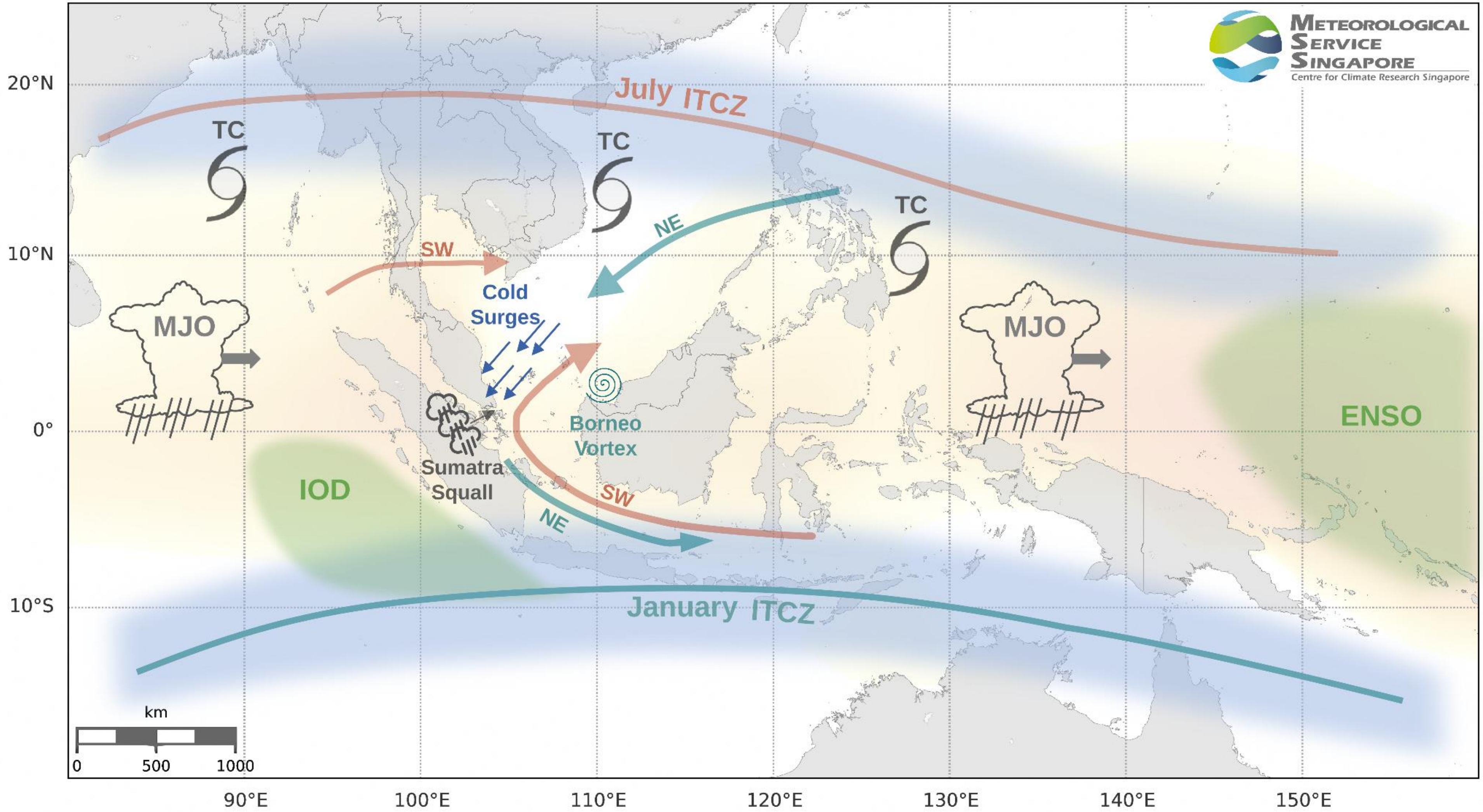


Figure 2.2: Climate drivers influencing weather and climate for the region around Singapore. Included are the average position of the Intertropical Convergence Zone (ITCZ) in blue indicating the furthest northward and southward extent of the seasonal migration of the regional monsoon system. The green and orange arrows indicate the corresponding Northeast and Southwest monsoonal flows. Against the background of warm ocean waters (soft orange colour indicating regions above 28.5°C), the El Niño– Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) impact the region's rainfall patterns on seasonal and inter-annual timescales, while the Madden-Julian Oscillation (MJO) impacts the region's rainfall at weekly to monthly timescales. At shorter timescales, Sumatra Squalls, Cold Surges and the Borneo Vortex can be sources of strong rainfall events. Further afar, tropical cyclones (TCs) can develop near the ITCZ away from the equator.

2.2 Climate monitoring over Singapore

MSS has an island-wide network of meteorological observing stations, which includes manned as well as automated stations that provide real-time observations across Singapore (Figure 2.3). MSS currently operates a network of five manned observation stations, one upper air observatory and around 100 automatic weather stations. All the automatic weather stations measure rainfall, and more than one-fifth measure other meteorological variables, including temperature, relative humidity, pressure, and wind. This observation network serves as the primary source of climate data for this report.

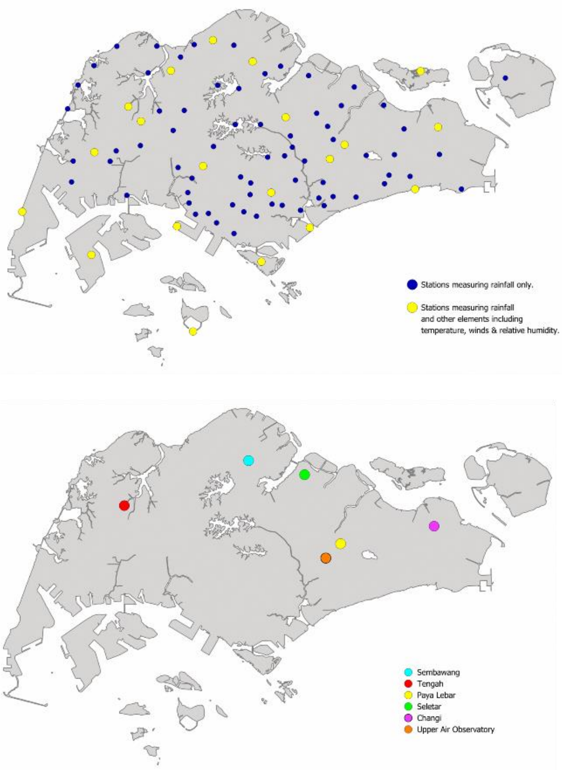


Figure 2.3: Network of automated weather stations (top), and manned weather stations (bottom).

The installation of the automatic weather station network since 2009 greatly expanded the coverage of weather observations across Singapore. For analysing long-term climate trends and establishing climatological averages, only stations with continuous long-term (at least 30 years) records can be used.

Figure 2.4: Changi climate station.

The manned observation station at Changi is MSS's designated climate station for Singapore (see Figure 2.4). The climate station, first located at Outram in 1869, has moved several times over the years due to changes in local land use before moving to its current site at Changi in 1984. The climate station serves as the reference station where its records are used for tracking the national long-term climate trends. The oldest climate station records are for monthly rainfall (starting from 1869) and temperature (starting from 1929, with a break from 1942 to 1947 due to World War II).

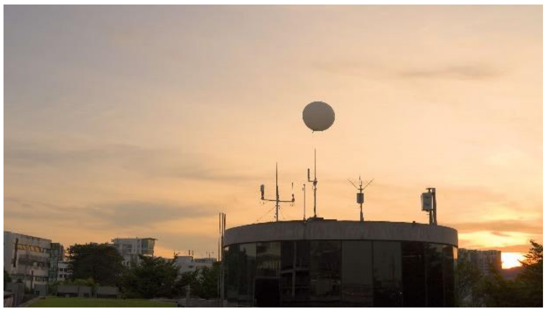


Figure 2.5: Upper Air Observatory.

Twice-daily soundings at MSS' Upper Air Observatory provide the main source of complete upper-air meteorological data to support forecasting operations and research. The observation records from the station can also be useful for monitoring long-term upper air conditions in the equatorial tropics, as the records extend back many decades to the 1950s (see Figure 2.5).

MSS also operates two weather radars covering a radius of up to 480 km, an S-band radar located at Changi and a C-band radar located at Seletar airport, to monitor the development of weather systems.

In addition to the atmospheric monitoring, Singapore also monitors its sea levels using tide gauges. The Marine and Port Authority (MPA) of Singapore has 20 tide gauges, both active and discontinued (Figure 2.6).

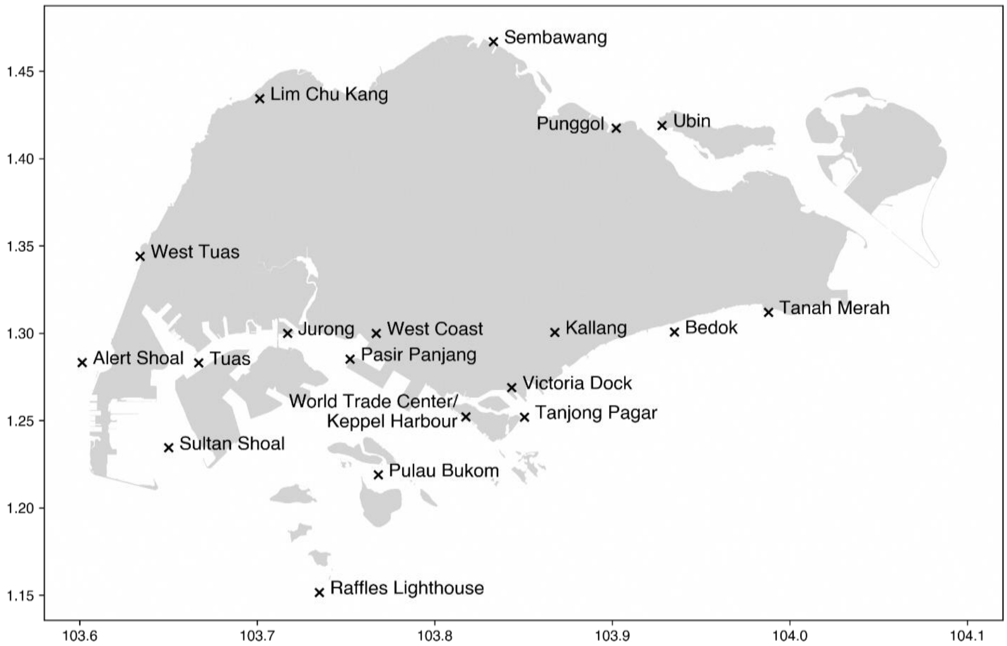


Figure 2.6: Location of the 19 tide gauges around Singapore. The offshore tide-gauge at Horsburgh Lighthouse is not shown.

2.3 Importance of high-quality observations

High temporal and spatial resolution long-term observations which have undergone rigorous quality control are essential for monitoring and understanding the past climate, and for validating how well numerical models simulate the important climate variables. This in turn helps further model development to improve the accuracy of simulations and reliability of future projections.

In addition, high-quality observations play an important role in carrying out post-processing of model simulations such as bias-adjustment, from short and medium-range weather forecasts, sub-seasonal to seasonal predictions, to climate change projections.

2.4 How has the temperature changed?

In this section observed changes in daily mean, daily maximum, and daily minimum temperatures over Singapore are documented using MSS station data. In addition to the temperature change, also shown is the change in the occurrence of the annual number of warm days (defined based on the 90th percentile of daily maximum temperature).

2.4.1 Daily mean temperature

Singapore's climate station shows steady increase in daily mean temperature over time (see Figure 2.7. This rise in temperature is evident even with the year-to-year variability due to the influence of large-scale climate drivers such as ENSO. El Niño events tend to increase annual mean temperatures across Singapore, while La Niña events tend to moderate them.

Singapore's annual mean temperature rose by 0.24 degrees Celsius per decade from 1984–2022. Singapore showed an upward trend of

0.67°C per decade in daily mean temperature during 1973–1992, with a slower rate of increase at 0.17°C per decade during 2003-2022. The high value of the upward trend during 1973–1992 can be attributed to rapid urbanisation in Singapore at the time. The accompanying effect on temperature is called the Urban Heat Island (UHI) effect whereby towns and city areas experience much higher temperatures and remain warmer than their greener surroundings. The effect is most noticeable at night when temperatures in more built-up environments can be several degrees higher than less developed areas surrounded by more trees and/or water bodies (ACAR 2022). This UHI effect is in addition to long-term warming trends due to climate change.

In contrast, the global mean warming rate shows an upward trend of 0.17°C per decade and 0.22°C per decade for the corresponding periods, largely driven by the accelerated warming over the northern hemisphere high latitude regions (Arctic region amplification) in the recent decades.

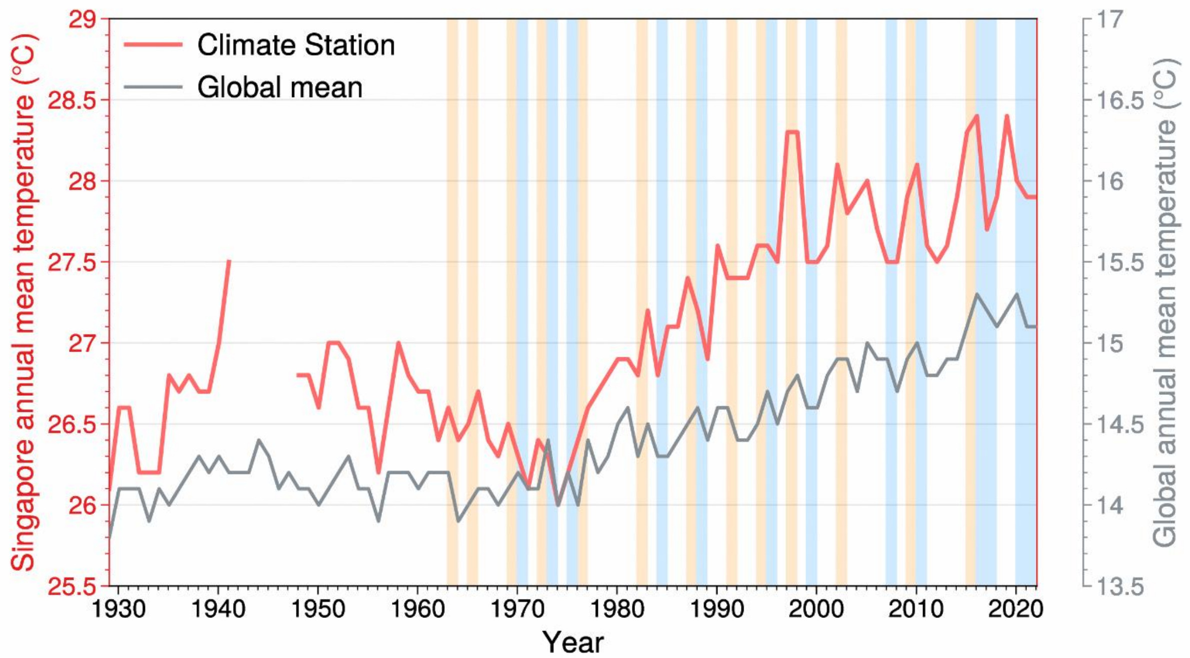


Figure 2.7: Annual mean temperature from 1929-2022 at Singapore's climate station, compared with the global annual mean temperature from the high-resolution (0.25° × 0.25°) Berkeley Earth dataset. The orange and blue bars denote El Niño and La Niña years from 1963, respectively.

2.4.2 Daily Minimum and Maximum Temperatures

Over the last 50 years (1973–2022), the night-time minimum temperature over Singapore has warmed more rapidly (0.21°C per decade, Figure 2.8b) than the daytime maximum temperature, which shows no significant trend (0.06°C per decade, Figure 2.8a). The figure also shows that both diurnal maximum and minimum temperatures are affected by ENSO, with high values during El Niño years and low values during La Niña years.

A consequence of Singapore warming much faster during the night than it does during the day is that there is a significant reduction in its diurnal temperature range (DTR; Figure 2.8c).

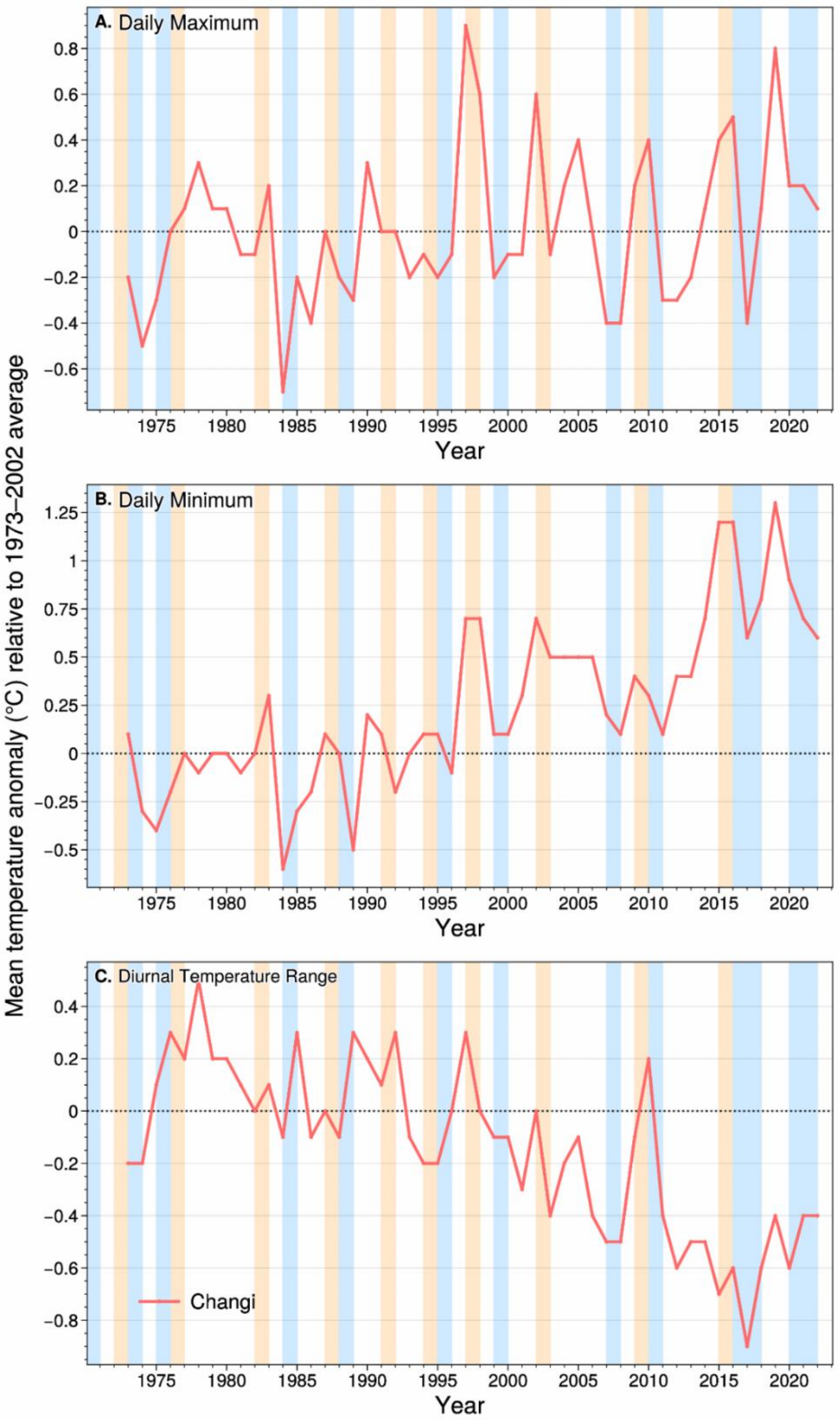


Figure 2.8: The annual average anomaly of (a) daily maximum and (b) daily minimum temperature at Changi. The diurnal temperature range is shown in (c). The anomalies are calculated relative to the 1973–2002 period average. The orange and blue shades denote El Niño and La Niña years, respectively.

2.4.3 Warm Days

Warm days are defined as days with maximum temperature of 34°C or above. The threshold is defined based on the 90th percentile of daily maximum temperature.

The Changi station does not show any trend in warm days during the 1973–2022 period. The characteristics of high temperature vary spatially across the island, with Changi experiencing fewer warm days. One of the reasons behind the fewer warm days observed in the Changi climate station could be the sea breeze effect. However, the frequency of warm days exceeding 20 days per year in Changi has increased in the last two decades.

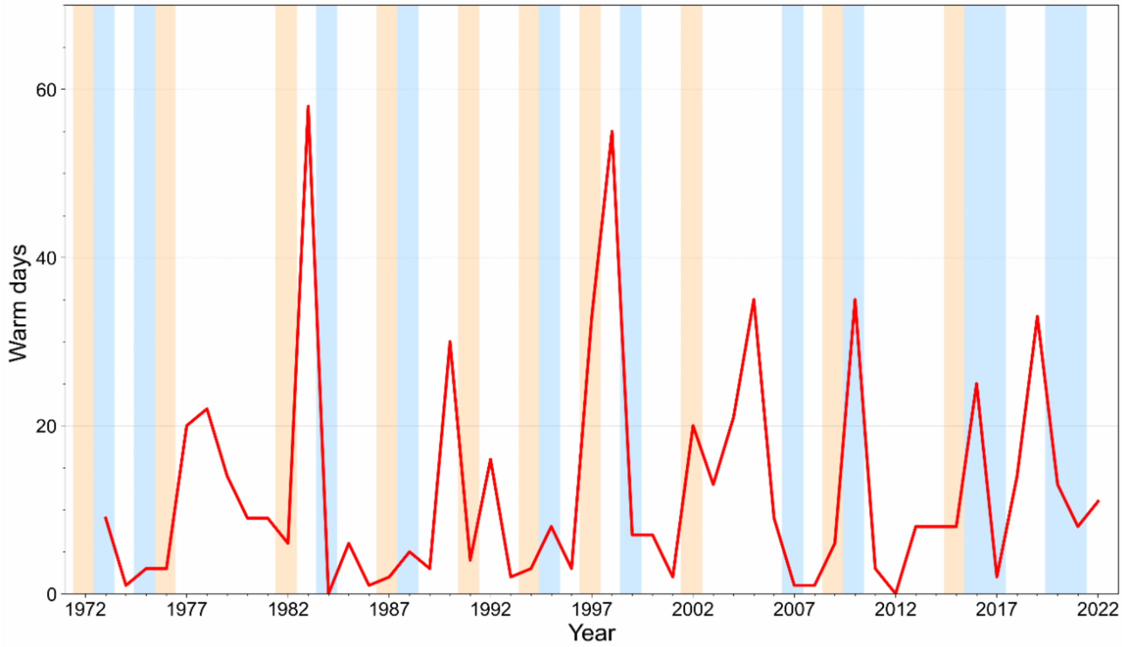


Figure 2.9: The number of warm days per year at the Changi station from 1973 to 2022.

2.5 How has rainfall changed?

In this section the observed changes in annual and seasonal mean rainfall over Singapore using MSS station data are shown, for the period 1980–2022. In addition to the mean rainfall, rainfall extremes defined as the annual maximum rainfall accumulations at 15 min (RX15min), 30 min (RX30min) and 60 min (RX60min) durations are also shown.

2.5.1 Annual rainfall

The annual total rainfall for Singapore averaged across 32 stations with at least 30 years of continuous records shows a gradual increasing trend of 83 mm per decade from 1980 to 2022. However, this trend is not statistically significant (see Figure 2.10). Years that experienced La Niña conditions (e.g., 2011, 2021, 2022) tend to be wetter, while years with either El Niño conditions (e.g., 1982, 1997, 2015) or a strong positive IOD (2019) tend to be drier. The first half of the 1980–2022 period saw more El Niño events (five events between 1980 and 2000) compared to the second half (three events between 2002 and 2022), and fewer La Niña events (four events compared to seven events).

2.5.2 Monthly and seasonal rainfall

For monthly rainfall (Figure 2.11), statistically significant upward trends at the 5% level are seen only for June (18.4 mm/decade) and April (14.6 mm/decade). A strong upward trend is also seen for November (16.8 mm/decade) but this trend is not yet significant at the 5% level.

In contrast, the month of February, which is the driest month of the year climatologically, shows the strongest drying trend (−6.9 mm/decade), though not yet significant. Other months that show slightly negative trends are July (−3.2 mm/decade), March (−2.3 mm/decade), and May (−1.7 mm/decade).

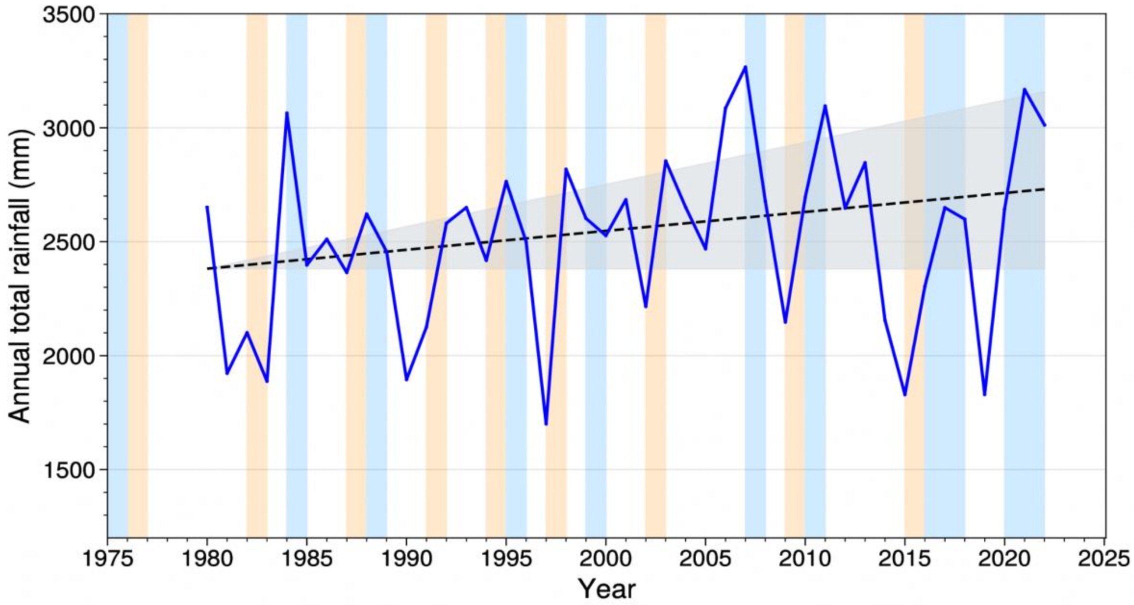


Figure 2.10: Annual total rainfall (solid blue) averaged over 32 stations with continuous records for at least 30 years. The black dashed line depicts an upward but not statistically significant trend (83 mm/decade). The grey shaded area represents the 95% confidence interval of the estimated trend.

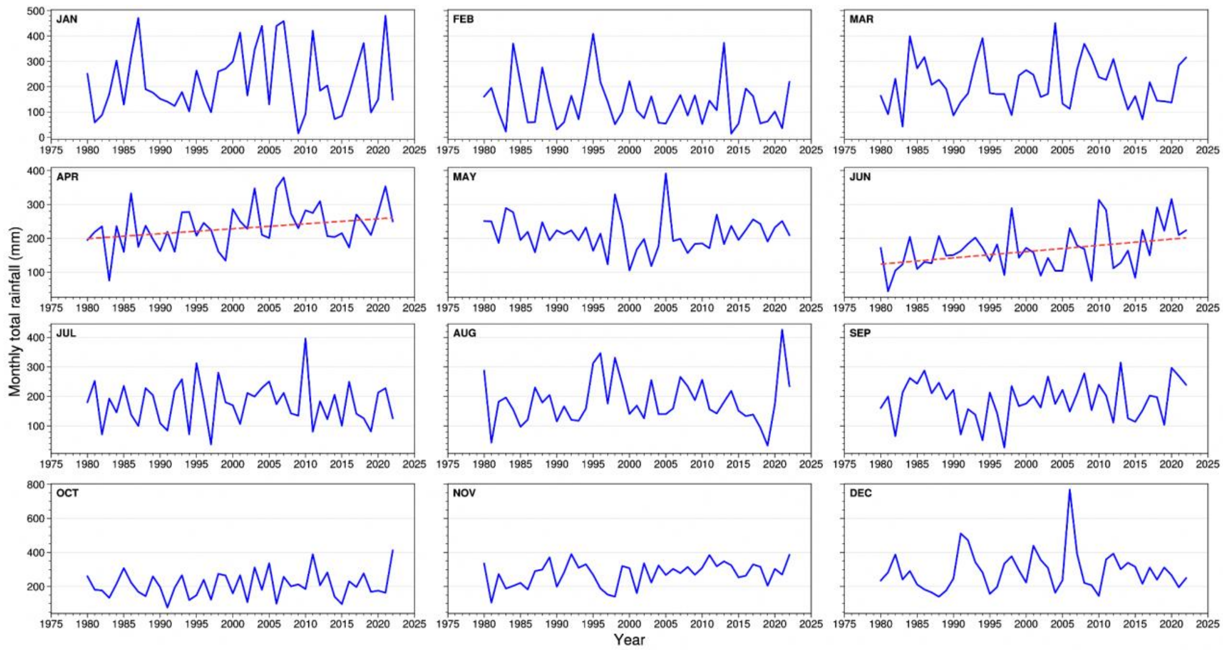


Figure 2.11: Monthly total rainfall averaged from 32 stations with continuous records for at least 30 years. The red dashed line for April (APR) and June (JUN) indicates statistically significant trends at the 5% level.

2.5.3 Rainfall extremes

Singapore's rainfall is largely dominated by convective rainfall, that typically occurs in the mid-to-late afternoon for much of the year. Severe convective storms with very high rainfall rates can often lead to flash floods since they tend to develop quickly on the order of sub-hourly to hourly time scales under very unstable atmospheric conditions with lots of moisture.

Figure 2.12 shows the annual maximum rainfall intensity at 15 min (RX15min), 30 min (RX30min) and 60 min (RX60min) durations. Overall, no trends are detected over the last 43 years in the extreme rain rates across the three time windows, with RX15min showing a small insignificant decrease of −1.0 mm/decade and RX30min showing only a tiny increase of 0.8 mm/decade. RX60min shows no trend at all (0 mm/decade). There also appears to be little correlation with the ENSO phase on yearly time scales. However, RX60min seems to exhibit variability on inter-decadal timescales as shown by the period averages, i.e., 97.3 mm between 1980 and 1994, 111.8 mm between 1995 and 2010, and 96.4 mm between 2011 and 2022. The multi-decadal variability in RX60min suggests the possible influence from long-term climate drivers in the Pacific such as the Inter-decadal Pacific Oscillation (IPO) and warrants further investigation.

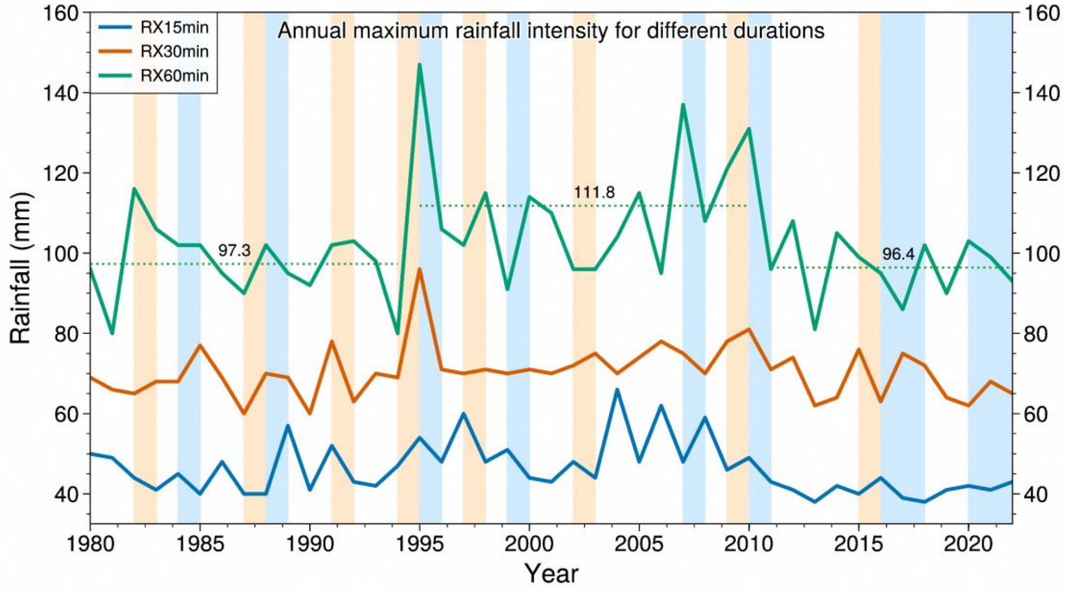


Figure 2.12: Annual maximum rainfall intensity at 15 min (RX15min, blue), 30 min (RX30min, orange) and 60 min (RX60min, green) durations, computed from a set of 23 stations with long-term observations going back to 1980. Numbers above the green dotted lines denote the RX60min averages for the corresponding periods mentioned in the text. Note that El Niño and La Niña years are highlighted by the light orange and blue vertical bars, respectively.

2.6 How has relative humidity changed?

The annual mean near-surface relative humidity (RH) from the Changi station for the period 1983-2022 is shown in Figure 2.13. While there was no discernible trend in RH during 1983-2010, there is a decreasing trend during 2011-2022.

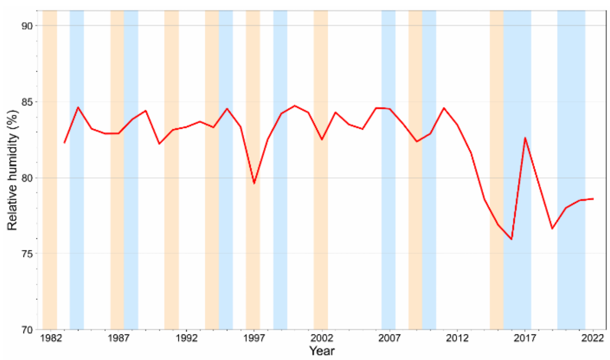


Figure 2.13: Annual mean relative humidity at Changi.

2.7 How have winds changed?

While Singapore does experience a general change in wind direction from the Northeast to Southwest Monsoon the average wind speeds are not large. Over the inter-monsoon period, the winds are even lighter and variable in direction. The annual mean wind speed over the Changi climate station shows inter-annual variability as well as multi-decadal variability (Figure 2.14). However, in the last couple of decades the time series appears to show an increasing trend, but it could also be a part of the multi-decadal variability, since there was an apparent decreasing trend from around 1985 to late 1990s and early 2000, and a reversal after that.

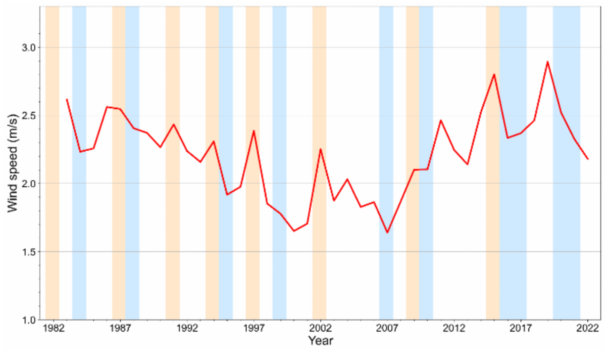


Figure 2.14: Annual mean 10-m wind speed at Changi

2.8 How has the sea level changed?

This section discusses reasons behind changing sea level and by how much has it changed in the SEA region and around Singapore.

2.8.1 Why is sea level changing?

Sea level varies due to many geophysical processes acting over different spheres of the earth system (Figure 2.15). Relative sea level (RSL) refers to sea-level changes measured in reference to land or seafloor (tide-gauge sea-level measurements for example) whereas geocentric sea-level (GSL) refers to sea-level measurements with respect to a fixed terrestrial reference frame (e.g., satellite sea-level measurements).

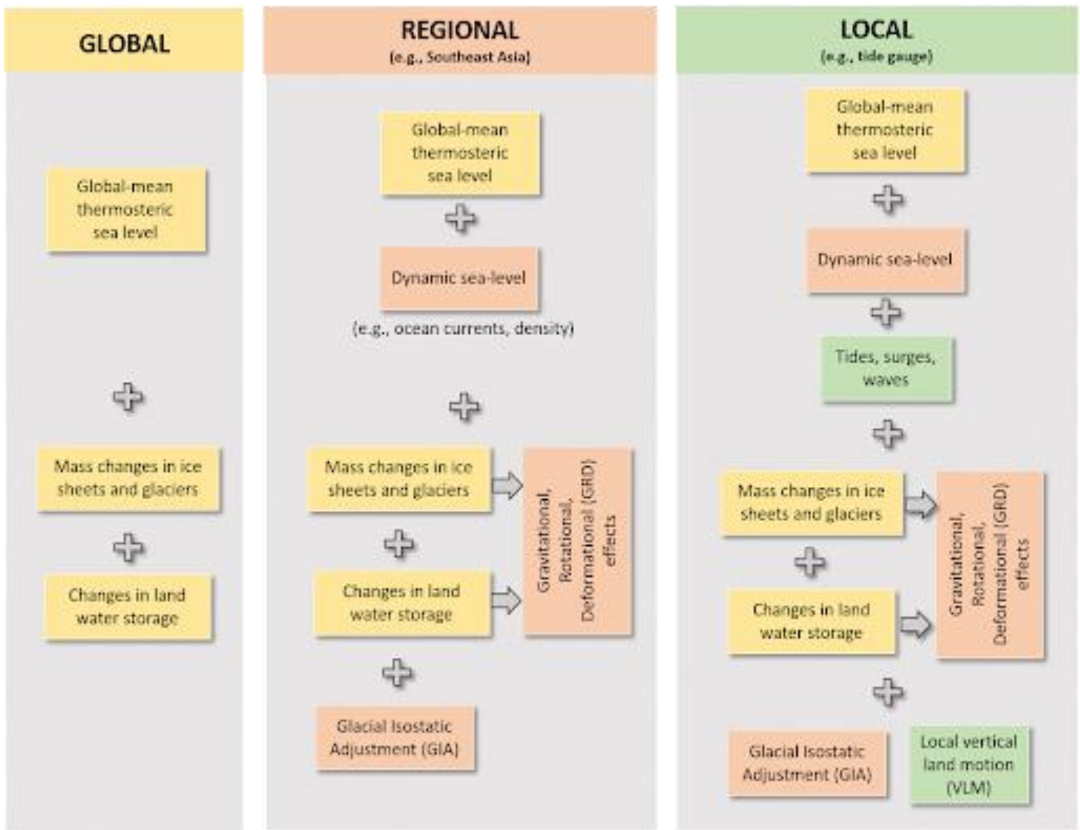


Figure 2.15: Schematic of different geophysical processes contributing to global, regional, and local sea-level change. Note, the color-coding reflects the spatial scales on which the different processes operate, as per the column titles and that these are treated additively as one progresses to smaller scales (left-to-right).

Global processes

Global-mean sea-level change is defined as the global ocean volume changes divided by the ocean surface area. Global ocean volume can vary in two ways: through changes in global ocean density (global-mean thermosteric sea level) and/or through changes in global ocean mass (barystatic sea-level). Heat uptake in the ocean decreases the ocean density and increases its volume (thermosteric sea level) while added water to the ocean (from land ice melting and discharge from terrestrial water storages) directly increases global-mean barystatic sea level.

Steric sea-level changes are caused by changes in ocean density. Ocean density can vary through changes in ocean temperature (thermosteric) and/or salinity (halosteric sea level). The ocean temperature changes cause thermal expansion/contraction of the seawater and an increase in salinity generally lowers the ocean volume and sea level. Global-mean sea-level changes are mostly driven by thermosteric changes and contribution of halosteric changes to global-mean sea level is negligible.

The Greenland and Antarctic ice sheets hold huge amounts of water in the form of ice, and they are potentially the largest contributor to global sea-level rise in the coming decades. Mass imbalance in ice sheets occurs as there is a net change in the mass accumulation minus mass loss. As both Greenland and Antarctic ice sheets extend to the sea at their periphery, ongoing ocean warming and melting of ice from below sea surface is important. Even though there is high confidence in the ice sheet dynamics, there is low confidence in the forcing that alters the mass balances. Surface mass balance changes in Glaciers turned out to be the single largest contributor to global-mean sea-level changes in the twentieth century (Fox-Kemper et al. 2021), and potentially a large contributor in this century too. There is medium to high confidence in the whole process of glacier mass loss.

Land-water storage includes all sources of land water excluding glaciers and ice sheets. Changes in land-water storage can occur either by human activities or climate variations. Our confidence in understanding land-water storage varies greatly (from very low to very high) for different components and processes.

Regional and local processes

Ocean dynamic sea-level change refers to sea-level changes due to ocean circulation and ocean density variations, and it is usually estimated with reference to a geoid surface. Ocean dynamic sea level has zero global mean. There is medium confidence in the process of understanding ocean dynamic sea-level changes.

Changes in Earth Gravity, Earth Rotation, and viscoelastic solid Earth Deformation (GRD) arise due to the redistribution of mass between the cryosphere (land ice), water reservoirs and oceans. The sea-level response to GRD is known as GRD sea-level fingerprints. For example, changes in contemporary terrestrial water loss (groundwater extraction) leads to elastic solid earth uplift and a nearby (~ 2000km) RSL sea-level fall. Further away, sea level rises more than global average due to gravitational effects. There is high confidence in the understanding of GRD effects.

Ongoing GRD changes and the corresponding sea-level changes in response to past changes in the distribution of water (in the form of ice and water) on earth is called Glacial Isostatic Adjustment (GIA). The GIA response lasts over long periods - decadal to millennial time scales – because of the viscous response of Earth's mantle against mass loading (a process called isostatic adjustments). There is medium confidence in the GIA understanding.

Vertical land movement (VLM) refers to the change in land height due to several processes in addition to GRD and GIA related motions. Subsidence due to compaction of sediments in deltaic regions in response to removal of water, oil, and gas cause local VLM in many parts of the world. Tectonic deformations of the Earth's crust because of earthquakes and volcanic eruptions can also drive local VLM. There is medium confidence in the understanding of VLM processes.

Extreme sea level is an exceptionally low or high sea level arising from combined short term coastal phenomena like tides, storms, and waves. RSL change directly affects ESL by shifting the mean water levels, and indirectly by altering the water depth over which waves, tides and surges pass through. ESLs are also characterised by changing weather and extremes in the atmosphere, and inclusion of wave set up and swash is required for a right assessment of ESL and associated coastal exposure. In fact, flood situations arise at the coast as a dynamic interaction of these various coastal processes, influenced significantly by background RSL changes.

2.8.2 Sea-level rise in the Southeast Asian Seas

Satellite sea-level observations since 1993 show that the sea level is rising everywhere in the southeast Asian region (80E–160E; 12S–24N) with a regional-mean rate of ~4.4 mm/yr. The regional-mean rate is slightly higher than the rate of global-mean sea-level (GMSL) rise (~3.4 mm/yr) over the same period (1993–2021). Notably, the western tropical Pacific and eastern Indian Oceans exhibit slightly larger rates of sea-level rise (~5 mm/yr) whereas the rate in the Sunda Shelf region (~3.8 mm/yr) is close to the rate of GMSL rise over the 1993–2021 period.

The higher rates in the western tropical Pacific and eastern Bay of Bengal would primarily be linked to regional ocean circulation effects associated with large-scale climate modes in the two basins (Nidheesh et al., in preparation). On the other hand, the rate of sea-level rise in tide-gauge-measured and satellite-measured sea-level records deviate from each other at many selected tide-gauge locations in the southeast Asian seas, suggesting that local vertical land movements (VLM) contribute significantly to relative sea-level rise in the region. More details on VLM are given in the Science Report.

Further analyses combining satellite sea-level data with ocean reanalysis suggest that the (satellite) observed sea-level rise in the Southeast Asian seas during 1993–2021 is largely driven by contemporary mass redistribution (CMR) between the ocean and land. In terms of regional-mean change, the CMR contribution (~2.9 mm/yr) appears to be nearly twice the contribution from ocean sterodynamic effects (~1.5 mm/yr).

The sterodynamic (SD) sea-level rise is primarily driven by steric sea-level rise (sea-level rise due to ocean warming and freshening) over deep basins while SD changes in the shallow shelves (Sunda shelf region where Singapore situates for instance) are dominated by manometric sea-level rise (ocean internal mass adjustments). In general, the analyses suggest that the geocentric sea-level rise in the Sunda Shelf is largely (>90%) mass-driven (driven by CMR and manometric sea-level rise).

2.8.3 Sea-level rise around Singapore

Singapore’s tide-gauge records (Figure 2.16) show that the rate of observed sea-level rise around Singapore (with a mean rate of ~3.5 mm/yr across six gauges) is consistent with the rate of global-mean sea-level (GMSL) rise during the 1993–2021 period. Importantly, the rate of sea-level rise at Singapore's six tide-gauge locations conforms between tide-gauges and satellite data, indicating that the VLM in Singapore’s coastal zones might be relatively weaker compared to many other coastal locations in the southeast Asian seas. Note that, even though the rate of sea-level rise around Singapore (as estimated from tide-gauges) is consistent with the rate of GMSL rise, the relative contributions (or physical processes) that drive the GMSL and sea-level rise around Singapore are systematically different. As mentioned in the previous section, about 90% of the net sea-level rise around Singapore has a ‘mass-origin’ meaning that the observed rise is almost fully driven by contemporary mass redistribution and manometric sea-level change. Nevertheless, considerable uncertainty exists in the sea-level rise trend estimates from different contributions.

Apart from large uncertainties that exist for the mass-balance change estimates of ice-sheets and glaciers, our analyses suggest that better understanding the local VLM and dynamic sea-level changes (sea-level change due to secular changes in ocean circulation and density) is key in reducing the overall uncertainty in sea-level projections around Singapore (Section 5).

Robust projections of dynamic sea-level rise in the Southeast Asian seas calls for high-resolution ocean (sea-level) downscaling which would be a key priority for CCRS climate research initiatives in the coming years.

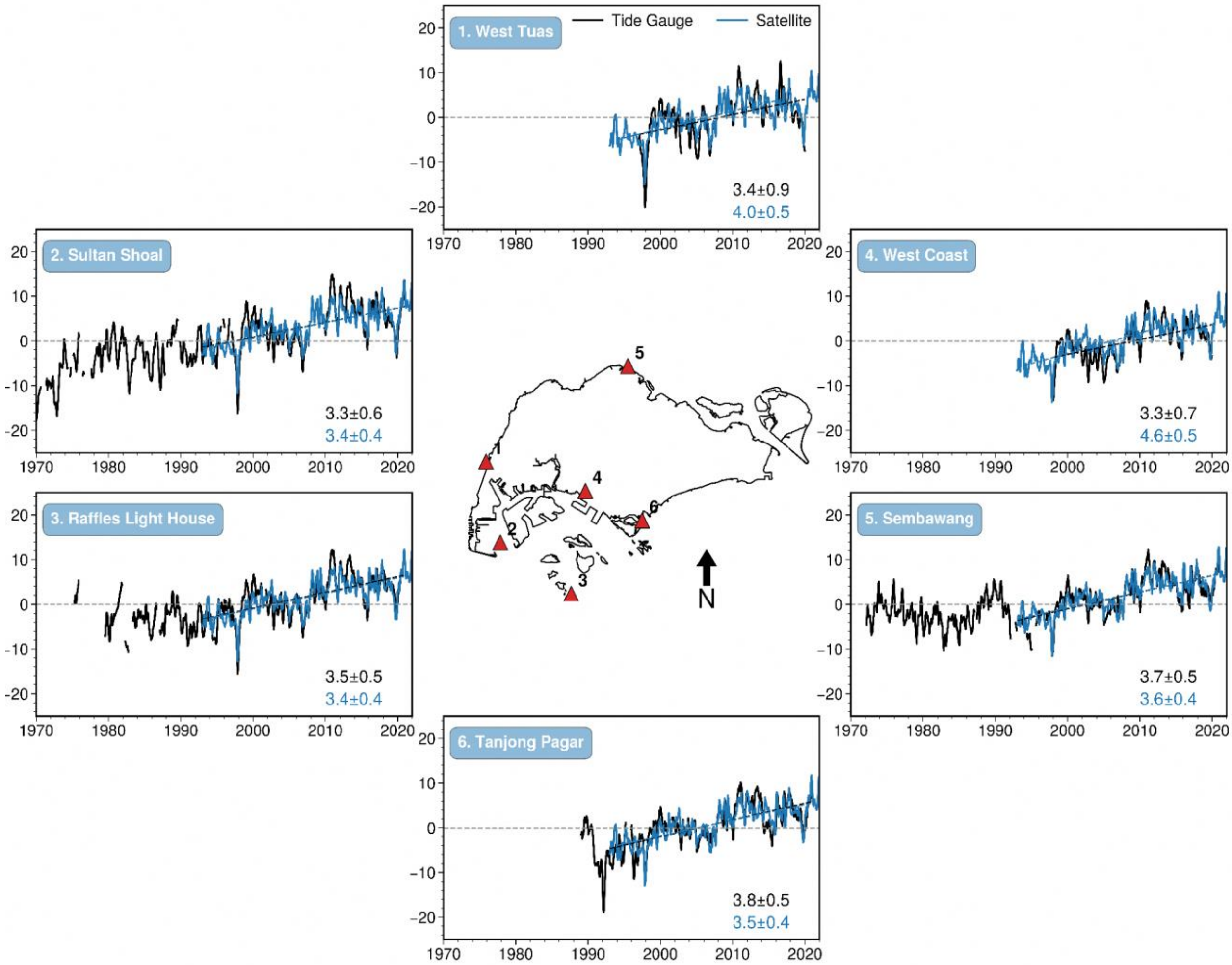
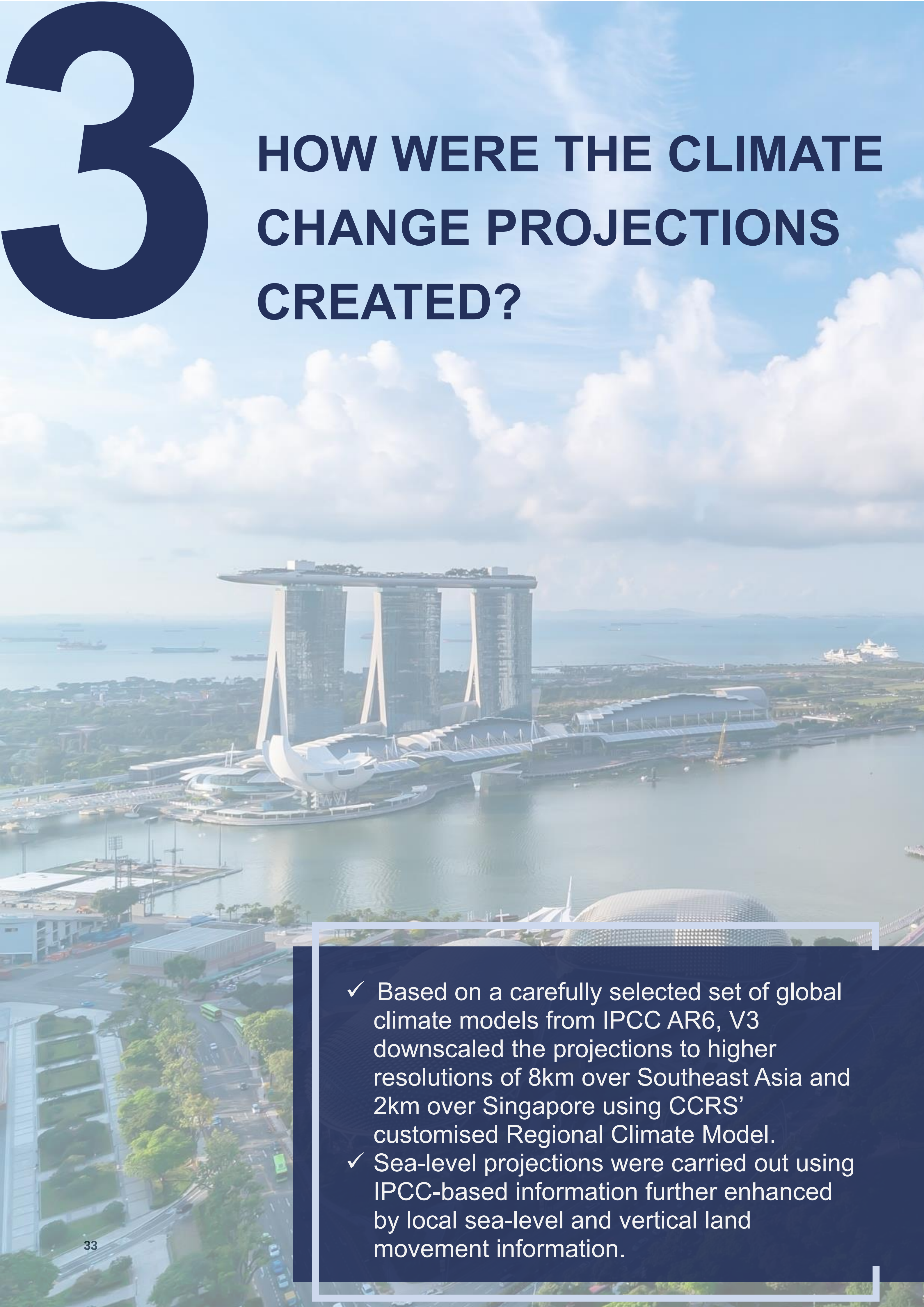


Figure 2.16: Time series of monthly sea-level anomalies (with respect to mean seasonal cycle, unit is in cm) from Singapore's six tide gauges (black curves). The locations of the tide-gauge stations are shown in the map. Sea-level anomalies from satellite altimetry (blue curve, averaged over 1 degree around each tide-gauge location) are overlaid on each tide-gauge time series. A linear trend corresponding to both tide-gauge and satellite sea-level time series based on a least-square method is also plotted as a dashed line over each record (black - tide-gauge, blue - satellite). The rate of sea-level rise (slope of the trend line) and the corresponding uncertainty (based on a student's t-test at 95% confidence level) are also given in each panel (rate from tide-gauge [black], satellite [blue]).



3 HOW WERE THE CLIMATE CHANGE PROJECTIONS CREATED?

- ✓ Based on a carefully selected set of global climate models from IPCC AR6, V3 downscaled the projections to higher resolutions of 8km over Southeast Asia and 2km over Singapore using CCRS' customised Regional Climate Model.
- ✓ Sea-level projections were carried out using IPCC-based information further enhanced by local sea-level and vertical land movement information.

V3 climate projections were created following best practices used by the international scientific community working on regional climate change projections. The key ingredients to produce regional climate change projections using dynamical downscaling are: (a) high-frequency (preferably at least 6-hourly) driving fields (vertical profiles of temperature, winds, and humidity, surface pressure, and sea surface temperature) from the GCMs, and (b) a regional climate model to dynamically downscale the coarse-resolution GCM projections to high-resolution regional and local projections (the need and methodology for dynamical downscaling is shown in Figures 3.1–3.3). Once the key ingredients are there, the next step is to carry out the actual process of producing regional climate change projections. While the GCM data is produced by the global climate modelling community, the regional climate model used in V3 was customised in-house at CCRS.

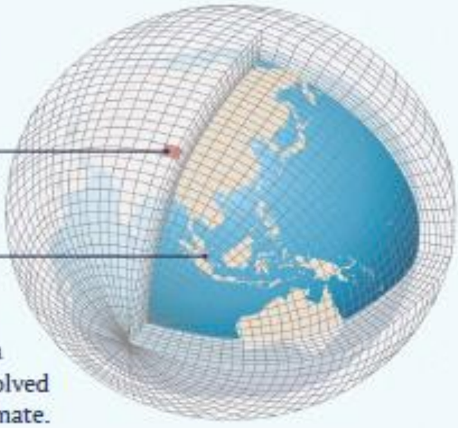
For V3, projections of atmospheric variables (temperature, rainfall, winds, humidity, etc.) were carried out using dynamical downscaling, whereas the sea-level projections were carried out using CMIP6 GCM-based data further enhanced by local sea-level and vertical land movement information.

The key steps in producing the V3 regional climate projections for atmospheric variables were (a) the evaluation and sub-selection of CMIP6 GCMs, (b) dynamical downscaling of the sub-selected GCMs using the regional climate model to 8km resolution covering Southeast Asia and beyond, (c) further downscaling to 2km over Singapore and the surrounding region, and (d) bias-adjustment of downscaled climate projections over Singapore.

This chapter documents the various important aspects of producing the atmospheric and sea-level projections.

Global Climate Models

- Developed by leading climate research centres around the world, global climate models (GCMs) consist of computer code that solves mathematical equations used to represent the physical processes in Earth's climate system.
- Generally, the latest GCMs have a resolution of 75–250 km, which means that Earth's atmosphere is divided into grid cells that are 75–250 km along each side.



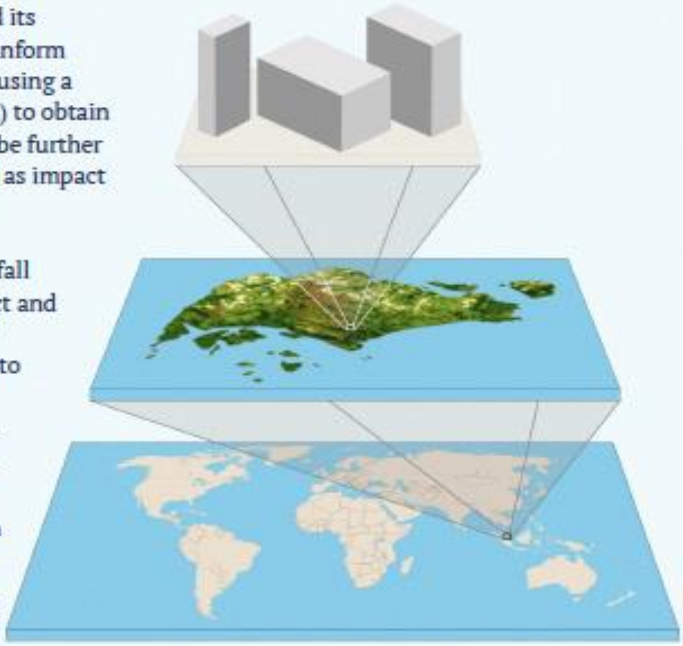
In each grid cell, climate information, such as temperature, humidity and topography, has only a single value.

At the coarse resolution of GCMs, Singapore is not represented as being a separate island because it is smaller than the size of one grid cell.

- GCMs are the primary tools for providing climate projections. Once a climate simulation has been initiated, mathematical equations are solved by supercomputers over a number of time-steps to project future climate.

The Need for Finer-resolution Regional and Local Climate Information

- Most climate change impacts (especially those resulting from extreme events) take place at regional and/or local scale.
- Due to the coarse resolution of GCMs, they cannot be used to understand details of climate processes occurring at more modest regional and local scales.
- For scientists to understand climate change and its impacts at regional and local scales in order to inform climate change adaptation, downscaling GCMs using a higher-resolution regional climate model (RCM) to obtain more details is necessary. The RCM output can be further processed to provide even more local info, such as impact of buildings and hills (illustrated on the right).
- Typically, GCMs are also unable to capture rainfall and temperature extremes. The ability to predict and project these extremes is important for climate change adaptation in Southeast Asia (SEA) due to the region's topography, complex coastlines, and thousands of small islands. RCMs are often much more skilful in capturing extreme events.



A schematic of how coarse-scale climate information from a GCM can be translated to fine-scale regional and local information through downscaling. This is done using a RCM that can represent more details (e.g. topography and coastlines) and the corresponding physical processes.

Figure 3.1: The 'Climate Change – From Global to Local' brochure begins with a brief introduction to GCMs and their limitations, subsequently explaining the needs for finer-resolution climate information for climate change adaptation.

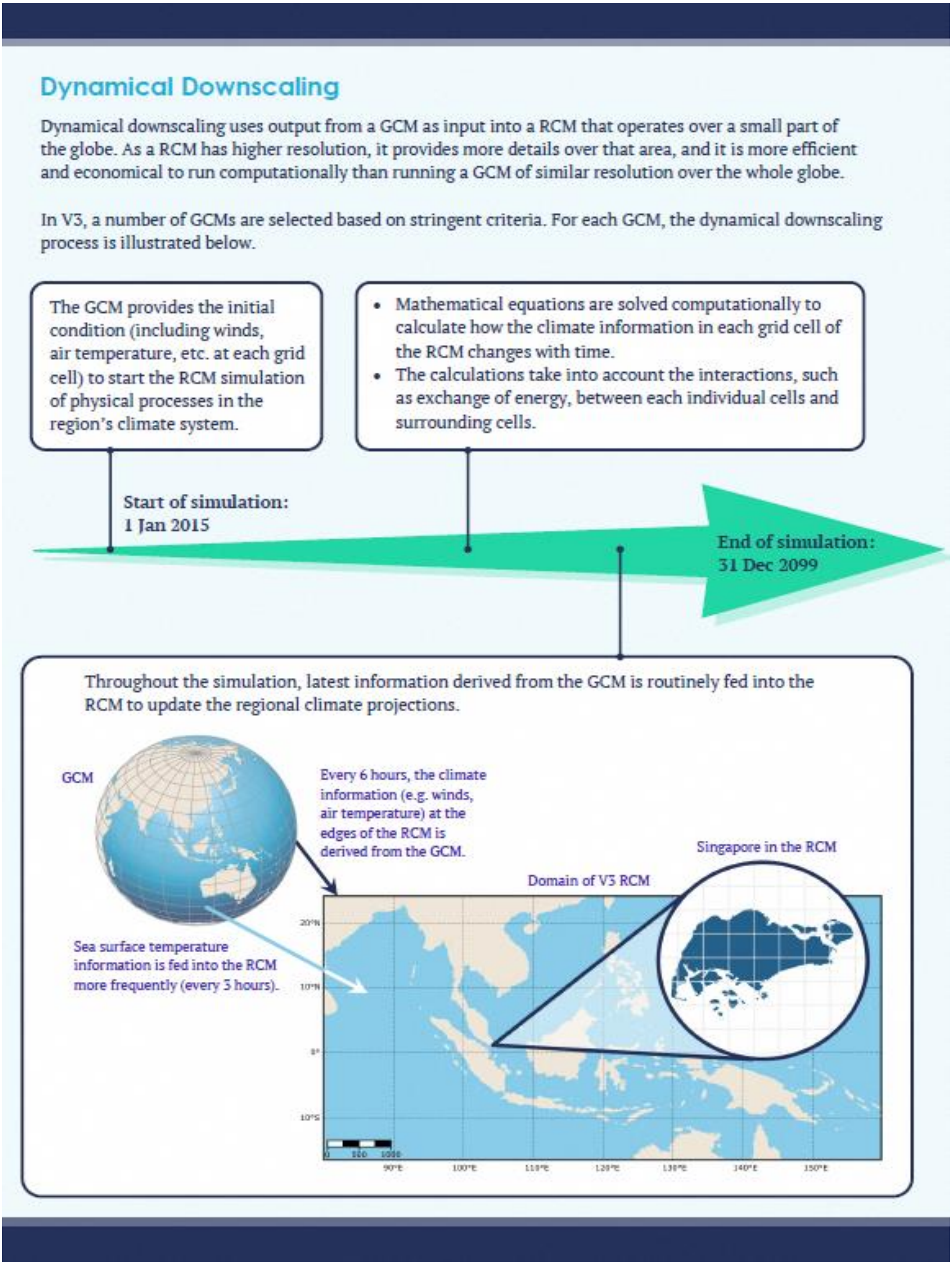
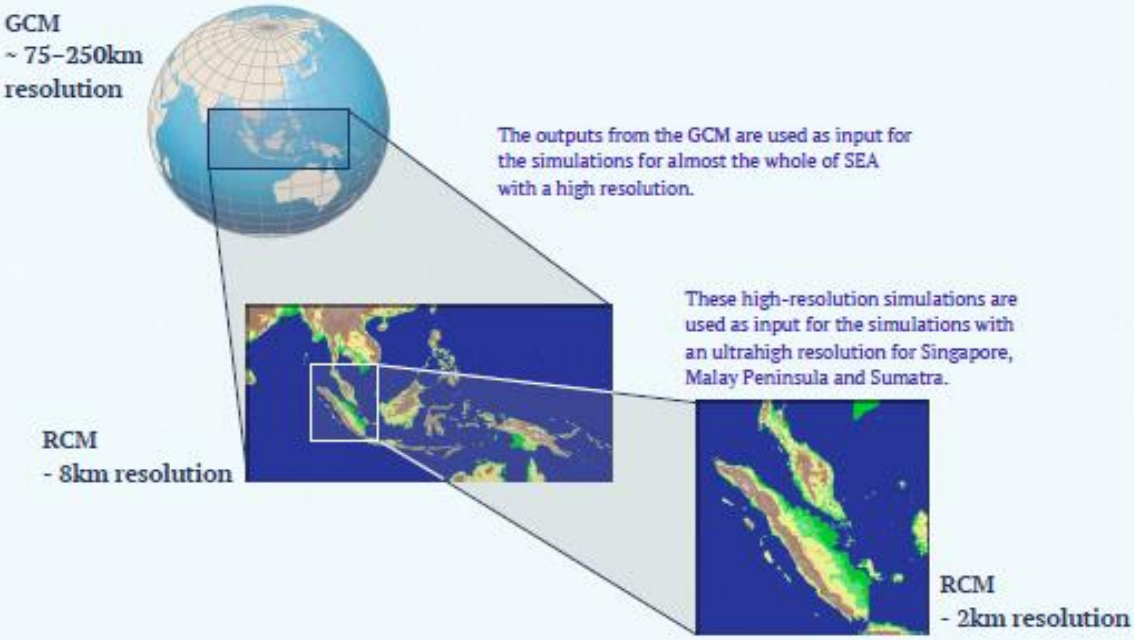


Figure 3.2: The ‘Climate Change – From Global to Local’ brochure introduces the concept of dynamical downscaling, using the V3 project as an example to illustrate the concept.

Two-stage Downscaling Process in V3

The downscaling model employed by CCRS for V3 is called SINGV-RCM[1], which is the RCM. The downscaling is performed in two phases to reach first 8km resolution and then finally 2km resolution (illustrated below).



Building Trust in V3 Data

- To test whether V3 climate projections are reliable, V3 historical simulations are compared against observational and reanalysis[2] data over the period 1995–2014. This is in accordance with the Intergovernmental Panel on Climate Change's (IPCC) recommendations. A generally accepted view is that if a model simulates historical climate well, it can be more trusted for simulations of future climate.

- V3 data agrees with observational and reanalysis data over the SEA region better than the GCMs, indicating higher accuracy and reliability. This results in higher confidence to use V3 data for climate change impact modelling over Singapore and the SEA region.

1 SINGV-RCM is adapted from CCRS' SINGV operational numerical weather prediction model that is extensively validated with local and regional observations, thus giving higher confidence in its ability to simulate key weather and climate processes over the region.
2 To address observational data scarcity at many locations on the globe, reanalysis combines GCMs' past weather forecasts with observations to create global data that describe the recent history (several decades) of Earth's climate system more comprehensively than observations.

Figure 3.3: The 'Climate Change – From Global to Local' brochure shows the two-stage downscaling process in V3 and explains how the reliability and robustness of V3 projections are demonstrated.

3.1. Global climate model evaluation and sub-selection

There is no universally accepted methodology on how to select a subset of GCMs for downscaling, but to be consistent with the practice of the international dynamical downscaling community, a methodology in-line with the Coordinated Regional Climate Downscaling Experiment (CORDEX) standard is followed, as discussed below.

The sub-selected GCMs should: (a) perform satisfactorily in the historical climate so that there is confidence in their future projections,

(b) span the range of GCM projections of temperature and precipitation over SEA, so that the sub-selection does not lead to large underestimation of the full range of GCM projections, (c) span the range of model diversity in terms of genealogy (e.g., Knutti et al. 2013), so that the sub-selected GCMs are quite independent in their formulation, and (d) have 6-hourly lateral boundary conditions (LBCs) available to drive the regional climate model.

For the first step, various statistical measures such as pattern correlation coefficient (PCC), mean absolute error (MSE), and root mean square error (RMSE) were used to assess the performance of the models against observations and reanalysis. Both, key climate variables (temperature, rainfall, winds, humidity, and mean sea level pressure) and key climate processes (monsoon, ENSO, IOD, equatorial Pacific cold tongue, Northeast Monsoon surge, and MJO) were evaluated for 49 CMIP6 GCMs. This led to discarding the poor performing models that were deemed infeasible to realistically project future climate over the SEA region.

Based on the availability of 6-hourly LBCs, around 10 models were available that could be used for downscaling. With the application of criteria 2 and 3 above (span the range of GCM projections of temperature and precipitation change over SEA and span the range of model diversity in terms of genealogy), the final set reduced to 8 models. The final list of sub-selected models is shown in Table 3.1 with the ones that made it to the final list of models that made available all the forcing data needed for downscaling highlighted in dark grey.

Table 3.1: List of sub-selected CMIP6 GCMs for V3 dynamical downscaling

Sub-selected CMIP6 Model	ECS	Family	End-century change over SEA under SSP5-8.5	
			Precipitation (mm/day)	Temperature (° C)
ACCESS-CM2	4.66	9	0.06	4.08
CNRM-CM6-1	4.90	3	0.35	3.99
EC-EARTH3	4.26	4	0.40	3.62
GFDL-CM4	3.89	Independent	0.34	3.20
HadGEM3-GC31-LL	5.44	9	-0.05	4.21
MIROC6	2.60	7	0.27	2.52
MPI-ESM1-2-HR	2.98	8	0.15	2.57
NorESM2-MM	2.49	2	-0.05	2.93

While the CMIP6 GCMs were being sub-selected, the various modelling groups were still in the process of uploading data to the central database, so some of the models that only had partial data and were expected to upload the remaining in due time were also sub-selected.

Finally, because of data availability, three (CNRM-CM6-1, GFDL-CM4, and HadGEM3-GC31-LL) out of the eight models could not be used. Given the higher resolution, an additional scenario, and larger domain size used in V3 (as compared to V2), up to six GCMs could be used for downscaling. Hence, HadGEM3-GC31-LL was replaced with an almost similar performing model (UKESM1-0-LL) from the same model family for downscaling.

3.2. Regional climate downscaling

In recent times, to tailor to the needs of the end-users and policy makers, the climate research community is producing high-resolution climate data for downstream applications in various sectors. With the advancements in the availability of high-performance computing (HPC) resources GCMs are now capable of simulations for hundreds of years at a horizontal spatial resolution of about 50–100 km. Further need of more detailed representation of climate at regional/local scales have pushed the model resolutions to 5–10 km. Small Island states like Singapore demand even finer scale resolutions higher than 5 km, (i.e., 1–2 km) owing to its size and the need for various impacts and climate adaptation studies. Geographically, Singapore and the WMC have a tropical climate dominated by diurnal convection and intense thunderstorms (Ichikawa and Yasunari, 2006; Fong and Ng, 2012).

SINGV-RCM benefitted from in-house sustained development and evaluations carried out over several years over our region by CCRS (Huang et al., 2019; Dipankar et al. 2020; Prasanna et al. 2024).

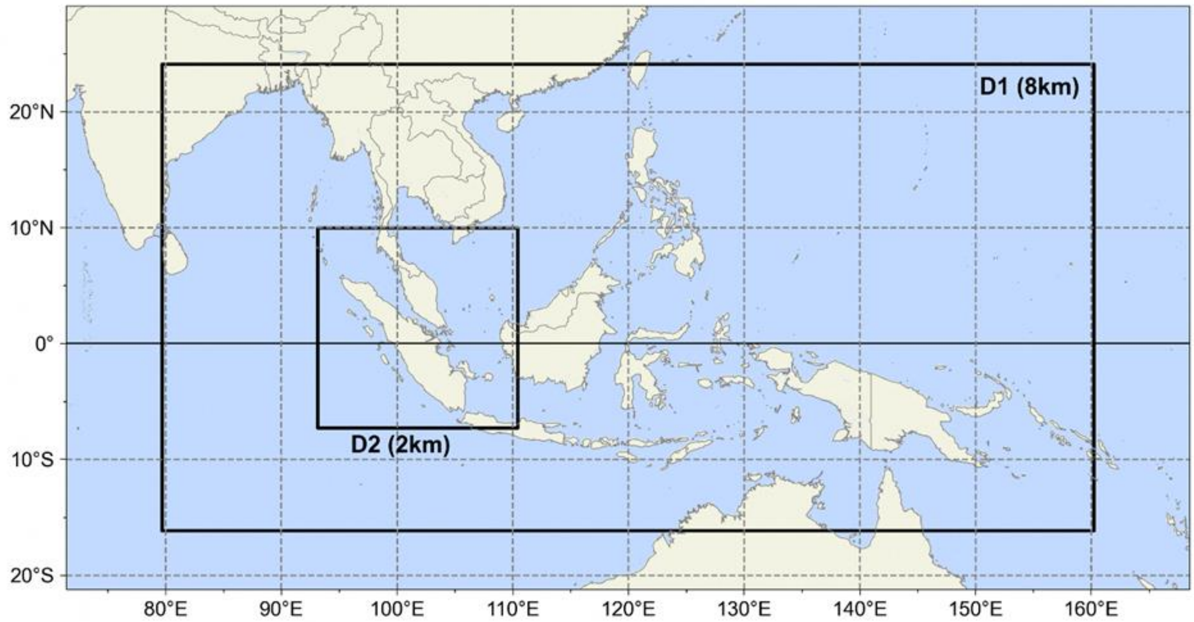


Figure 3.4: Downscaling domains for V3. D1 (16.16 S–24.08 N; 79.68 E–160.248 E) is the 8km domain, and D2 (7.29 S–9.972 N; 93.16 E–110.422 E) is the 2km domain (in solid line).

The SINGV-RCM model setup updates sea surface temperatures (SSTs) at six hourly intervals. The motivation for imposed diurnal variability of SST comes from the earlier studies (Yang and Slingo (2001); Ichikawa H and Yasunari T 2006; Peatman et al. 2015; Dipankar et al., 2019) that have indicated its importance in forecasting precipitation in the region. The V3 downscaling domain is shown in Figure 3.4. See Chapter 6 of the V3 Science report for more details.

3.3. Bias-adjustment for projections over Singapore

High-resolution simulations from V3 have demonstrated excellent performance over the MC. However, these high-resolution RCMs also exhibit model biases when compared to local observations. Bias-adjustment was carried out for several key climate variables to alleviate some of the known biases to produce more reliable climate change projections. These variables include daily mean air temperature, daily maximum air temperature, daily minimum air temperature, precipitation, relative humidity, and 10-m wind speed. By applying bias-adjustments to these selected variables, the RCM simulations are expected to be aligned more closely with the observed local climate conditions in Singapore (Figure 3.5).

To perform bias-adjustment it is crucial to have gridded observation reference data that is specifically tailored to the high-resolution (8km and 2km) required for Singapore. However, finding existing observation products at such fine resolutions can be challenging. To overcome this limitation, a 2-step approach was adopted. For precipitation, data from 28 stations with long-term continuous records was used to create gridded precipitation data at resolutions of 2km and 8km using advanced techniques. Thus, gridded precipitation reference datasets that closely represent the spatial variability of rainfall in Singapore was generated. Evaluations conducted on this gridded precipitation data demonstrated its suitability as a reference dataset, as it exhibited strong consistency with the station precipitation data.

For other variables besides precipitation, the number of available stations with long-term continuous records was insufficient for converting them into gridded products. Evaluations conducted using the downscaled simulations driven by ERA5 demonstrated excellent consistency with the available station data across Singapore. Hence, the ERA5 downscaled 8km and 2km data over Singapore served as the gridded reference for conducting bias-adjustments.

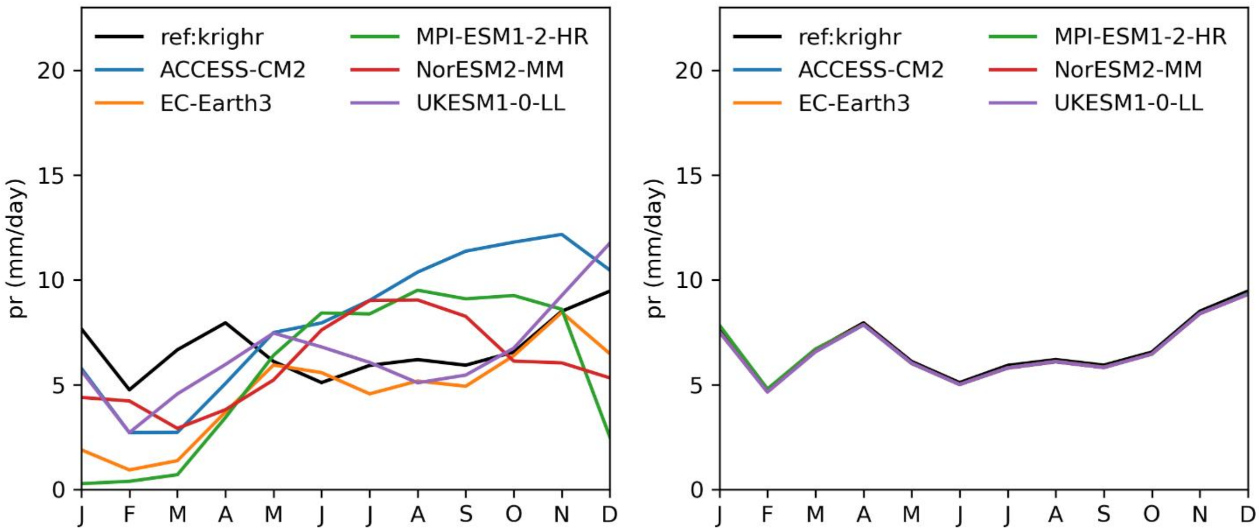


Figure 3.5: Singapore domain-averaged rainfall (pr) in the historical period (1995-2014) at 2km resolution. Non-bias-adjusted and bias-adjusted simulations are compared with observed reference (gridded station rainfall) in the left and right panels, respectively.

For the bias adjustment process in V3, there was a need for advanced features beyond the straightforward quantile-mapping based bias adjustment method used in V2. These new requirements included preserving trends, correcting rainfall frequency, and customizing distribution fits for each variable, among others. To meet these demands, the latest and widely used ISIMIP3 (Lange 2019) bias-adjustment methods were used. The results of the bias-adjustment process demonstrated the successful removal of biases in the adjusted historical simulations. Importantly, the adjustments were able to preserve the future change signals present in the raw simulations, ensuring that the projected climate changes remained intact.

To provide further confidence in the reliability of the bias-adjustments, pseudo-reality experiments were conducted. In these experiments, one model was designated as the reference, with known historical and future data. Bias-adjustments to the other test models were then applied and assessment of the performance and added value of the adjustments was carried out. The results of these tests revealed that the simulations after bias adjustments were more realistic compared to the raw simulations. By incorporating the advanced features and conducting rigorous evaluations, the bias-adjustments performed in V3 produced more reliable climate simulations. These adjusted simulations provide greater confidence in their use for assessing climate change impacts in Singapore.

In conclusion, the bias-adjustments conducted in V3 have demonstrated very good performance. The successful implementation of bias-adjustments enhances the confidence in the climate projections and their suitability for assessing and addressing the impacts of climate change in Singapore. More details can be found in the V3 Science report Chapter 9: Bias Adjustment.

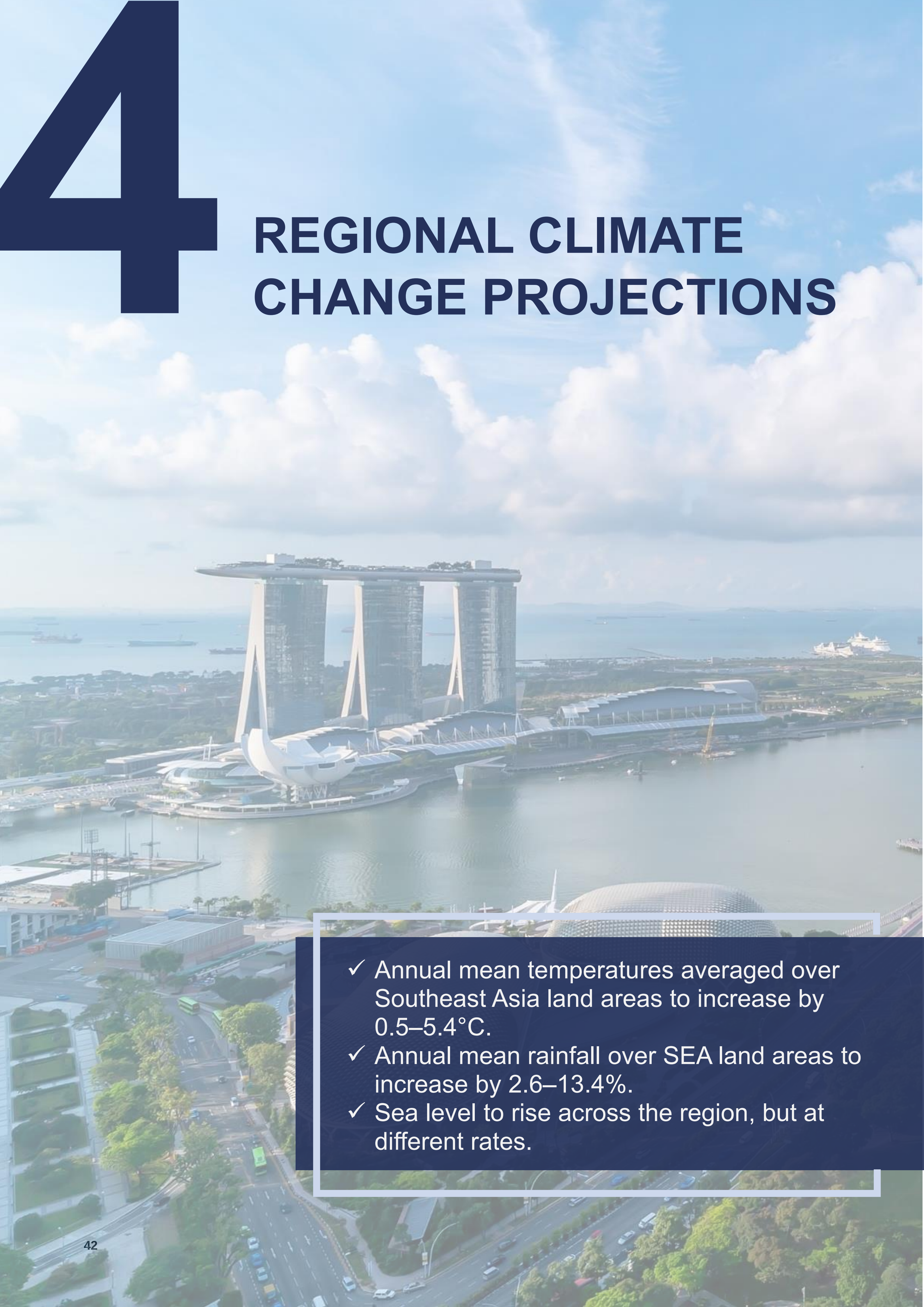
3.4. Sea-level projections for Singapore

The sea-level projections for the global mean and Southeast Asia region adhere directly to the IPCC AR6, while for Singapore, a distinct approach is taken. In Singapore's case, our proprietary tide-gauge data was utilised while aligning with the AR6 methodology to ensure the latest relative sea-level projections.

This process heavily relies on tide-gauge data sourced from the Permanent Service for Mean Sea-Level (PSMSL). To estimate vertical land movement (VLM), an analysis is conducted using tide gauges with data spanning over 30 years. This analysis leverages a spatiotemporal Gaussian process model introduced by Kopp et al. (2014), mirroring the model employed in AR6 for generating sea-level projections on a global network of tide gauges.

During our meticulous quality assessment of Singapore's tide-gauge data within the PSMSL database, discrepancies were unearthed in the Sembawang annual tide-gauge records prior to 1960's. Collaborative efforts with the PSMSL and the National Oceanography Centre (NOC) were undertaken to rectify these inaccuracies in the Sembawang tide-gauge dataset.

Subsequently, the refined dataset underwent reprocessing using the Kopp et al. (2014) model, enabling the integration of updated VLM projections for all tide gauges across Singapore, as stipulated by the AR6 methodology. Therefore, the sea-level projections for Singapore in V3 are derived through the application of the cutting-edge AR6 methodology, enhanced with the most up to date VLM projections available.



4 REGIONAL CLIMATE CHANGE PROJECTIONS

- ✓ Annual mean temperatures averaged over Southeast Asia land areas to increase by 0.5–5.4°C.
- ✓ Annual mean rainfall over SEA land areas to increase by 2.6–13.4%.
- ✓ Sea level to rise across the region, but at different rates.

While the focus of V3 and this report is on climate change projections over Singapore, V3 also covers regional projections for the SEA region. This is because Singapore's climate is affected by what happens in the region, and Singapore's interest in sharing high-resolution regional projections with ASEAN countries for their use in national climate change assessments and impact studies.

In this chapter regional climate change projections for some of the key climate variables that include temperature, rainfall, winds, and relative humidity are shown.

4.1 How will temperature change over the region?

Projected changes in daily mean and maximum temperatures in the Southeast Asian region are shown in the following sub-sections.

4.1.1 Daily mean temperature

Figure 4.1 shows the projected changes in the seasonal mean near-surface air temperatures over the SEA domain during the end-century under the high emissions scenario. Daily mean temperature over the SEA region is expected to increase in the end-century, with higher increases over land compared to the surrounding seas.

During the December-January-February (DJF) season, annual average daily mean temperature increase is expected to be in the range of 2.0–5.5°C, in the end-century, with higher values over Myanmar, Thailand, Laos and Cambodia. For the MAM season, the corresponding increase is in the range of 2.5–6.0°C, with higher increases over Myanmar, Thailand, and Laos. For the JJA season, it is in the range of 2.0–6.0°C with higher increases over Laos, Vietnam, and Indonesia. For the SON season, it is in the range of 2.0–6.0°C.

4.1.2 Daily maximum temperature

Figure 4.2 shows the projected changes in the average seasonal maximum of daily maximum temperatures (alternatively, the hottest day of the season), over the SEA domain in the end-century under the high emissions scenario. On average, the hottest day of the season is expected to become hotter over the SEA region in the end-century across seasons with higher increase over land compared to seas.

During the DJF season, the expected increase is in the range of 2.0–6.0°C. For the MAM season, it is in the range of 1.5–6.5°C, with higher increases over Laos, Vietnam, Indonesia, and New Guinea. For the JJA season, it is in the range of 2.0–6.5°C, with higher increases over Thailand, Cambodia, Laos, Vietnam, and Indonesia. For the SON season, it is in the range of 2.5–6.5°C with higher increases over Cambodia, Laos, Vietnam, and Indonesia.

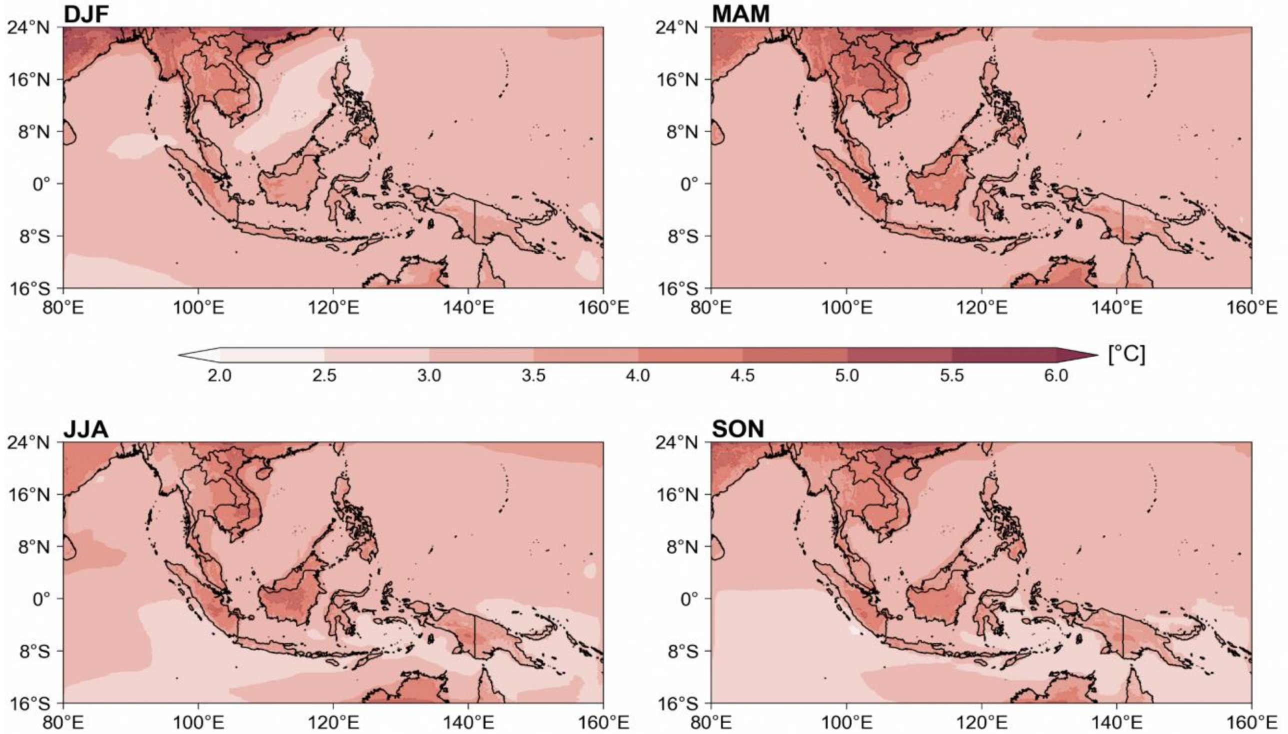


Figure 4.1: Projected changes in seasonal mean near-surface air temperature during end-century (2080–99) relative to the historical period (1995–2014) under the high emissions scenario.

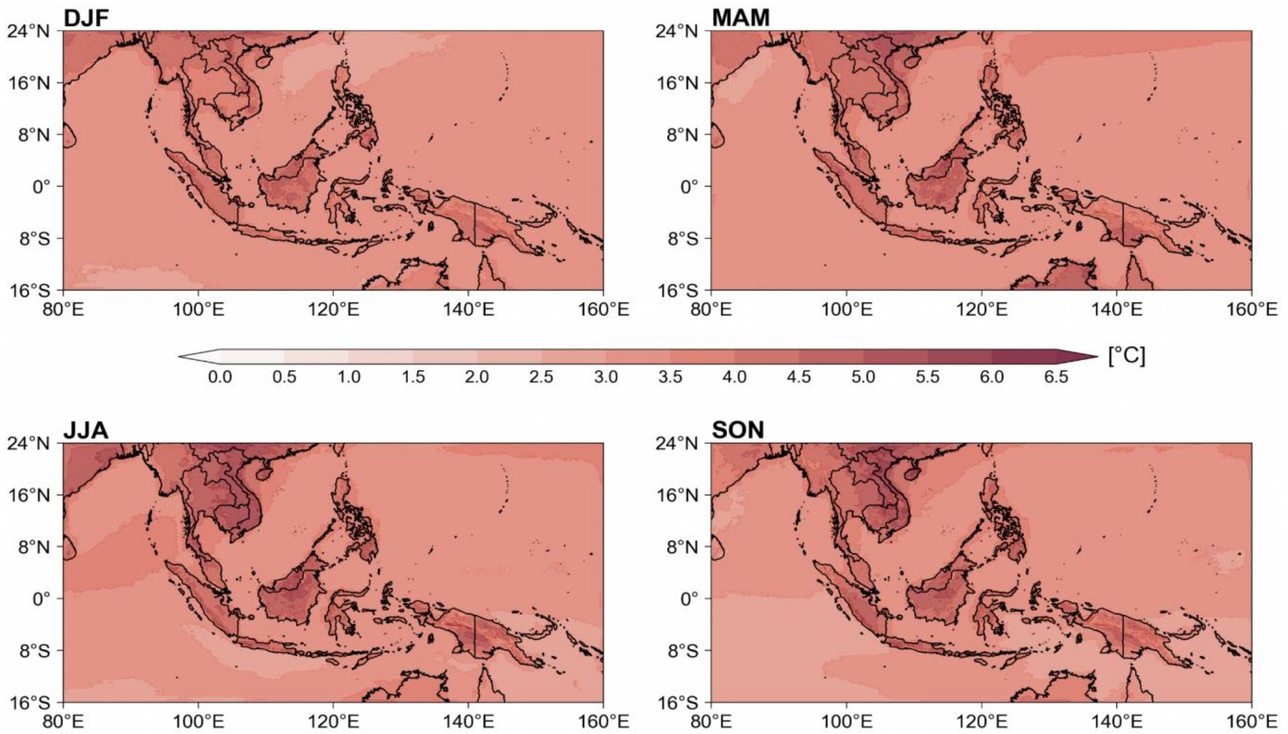


Figure 4.2: Ensemble-mean (six downscaled GCMs 8 km) changes in seasonal maximum of daily maximum temperature (TXx) over end-century (2080-99) relative to the historical period (1995–2014) over the SEA domain under the SSP5-8.5 scenario.

4.2 How will rainfall change over the region?

Projected changes in annual and seasonal mean rainfall along with rainfall extremes in the Southeast Asian region are shown in the following sub-sections.

4.2.1 Seasonal mean rainfall

Figure 4.3 shows the percentage changes in the seasonal mean rainfall over the V3 SEA domain in the end-century under the high emissions scenario. Seasonal mean rainfall changes vary with seasons over land and ocean regions. Increase in rainfall is expected over parts of Indochina across the four seasons.

For the DJF season, there is large increase (>90%) over the climatologically dry regions of Thailand. For the MAM season, the seasonal mean rainfall is projected to increase (10–70%) over many SEA land areas.

For the JJA season, the mean rainfall projections show increases (10–90%) over Myanmar, Thailand, Malaysia, and around Java. Note that Java climatologically experiences little rainfall in JJA. There is a decrease (10–30%) in the mean rainfall over parts of Cambodia, Vietnam, Borneo, and New Guinea. For the SON season, there are increases of at least 10% over parts of SEA with higher increases over Myanmar and around Nusa Tenggara.

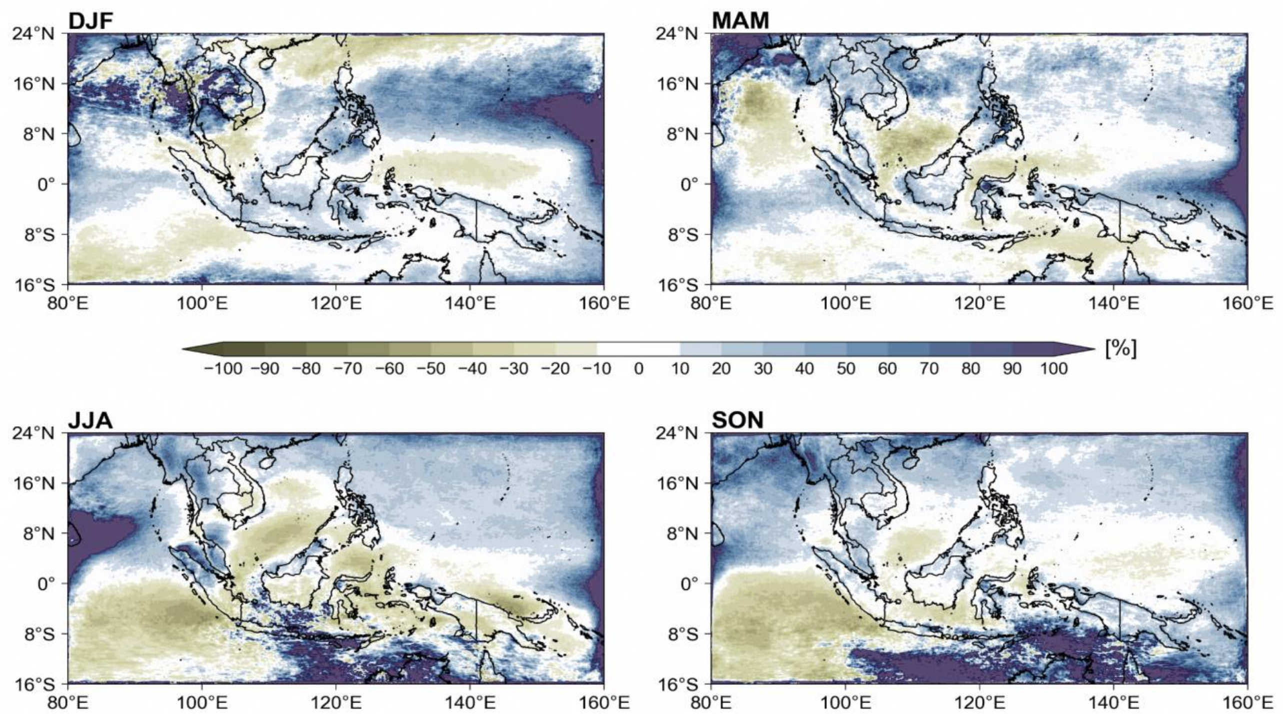


Figure 4.3: Percentage change of ensemble-mean downscaled (8km) changes in seasonal mean rainfall over end-century (2080-99) relative to the historical period (1995–2014) over the SEA domain under the SSP5-8.5 scenario.

Table 4.1 shows the projected changes in annual and seasonal mean rainfall over the V3 SEA domain land points during end-century for the three SSPs. Overall, rainfall on annual and seasonal timescales is projected to increase under all emissions scenarios. Largest projected increases are mostly associated with the high emissions scenario. The average annual total rainfall is projected to increase by up to 13.4% under the high emissions scenario. For DJF season, the projected increase is up to 14.5%, for MAM it is up to 16.8%, for JJA it is up to 14.6% (under the medium emissions scenario), and for SON it is up to 19%.

Table 4.1: Projected percentage changes in annual and seasonal mean rainfall during end-century over SEA domain land points for the three SSPs. The number outside the brackets shows the mean from the six models, and the ones in the brackets show the range from minimum to maximum.

Months	End-Century rainfall changes (%)		
	SSP1-2.6	SSP2-4.5	SSP5-8.5
Annual	3.9 (2.6–5.5)	5.8 (3.8–7.9)	8.7 (4.2–13.4)
DJF	2.4 (−0.3–10.6)	5.0 (0.0–10.5)	8.0 (2.5–14.5)
MAM	2.8 (0.2–5.8)	5.3 (0.4–10.6)	7.5 (0.2–16.8)
JJA	5.0 (0.8–10.7)	5.1 (−3.7–14.6)	7.4 (−1.7–13.4)
SON	4.9 (1.7–8.0)	8.0 (3.3–13.8)	12.7 (5.1–19.0)

4.2.2 Rainfall extremes

Figure 4.4 shows the percentage changes in the maximum 1-day rainfall (RX1day) over the V3 SEA domain across different seasons in the end-century under the high emissions scenario. End-century RX1day is expected to increase in most of the SEA land areas across the four seasons.

During the DJF season, the projected percentage increases in RX1day are largest over Thailand, Laos, and Cambodia. For the MAM season, the RX1day projections show increases (30–70%) over the SEA land regions. During the JJA season, the projected RX1day increases (at least 10%) over most of the SEA land regions with decreases (−5–40%) around the Java Sea. For the SON season, the RX1day projections increase (at least 30%) across the SEA land regions. Some of the largest percentage increases occur over climatologically dry regions (e.g., Indochina in DJF, and around the Java Sea in JJA).

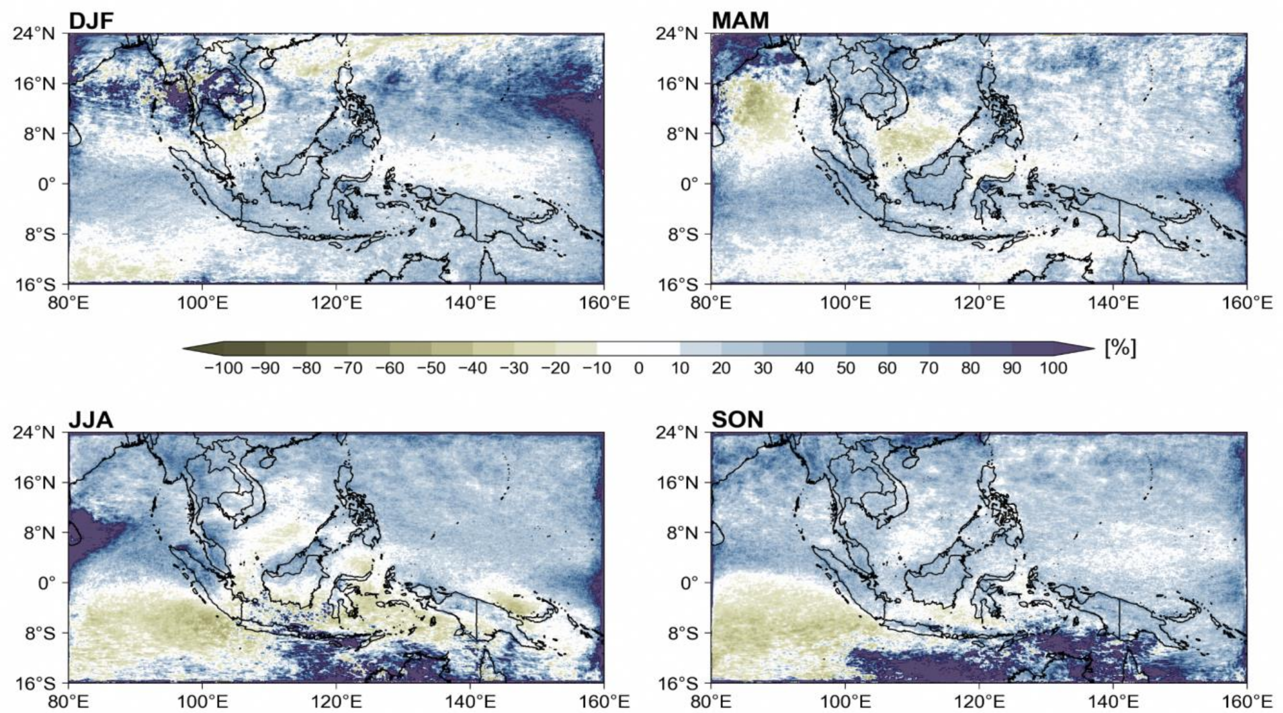


Figure 4.4: Percentage change of ensemble-mean downscaled (8km) changes in seasonal RX1day over end-century (2080–99) relative to the historical period (1995–2014) over the SEA domain under the SSP5-8.5 scenario.

4.3 How will winds change over the region?

End-century projections of 10m wind speed over the region for the four seasons under the high emissions scenario are shown in Figure 4.5. One of the prominent features is increased wind speeds, especially during the months of JJA over the northern ASEAN region, Sumatra, and Borneo, by up to and potentially exceeding 30%.

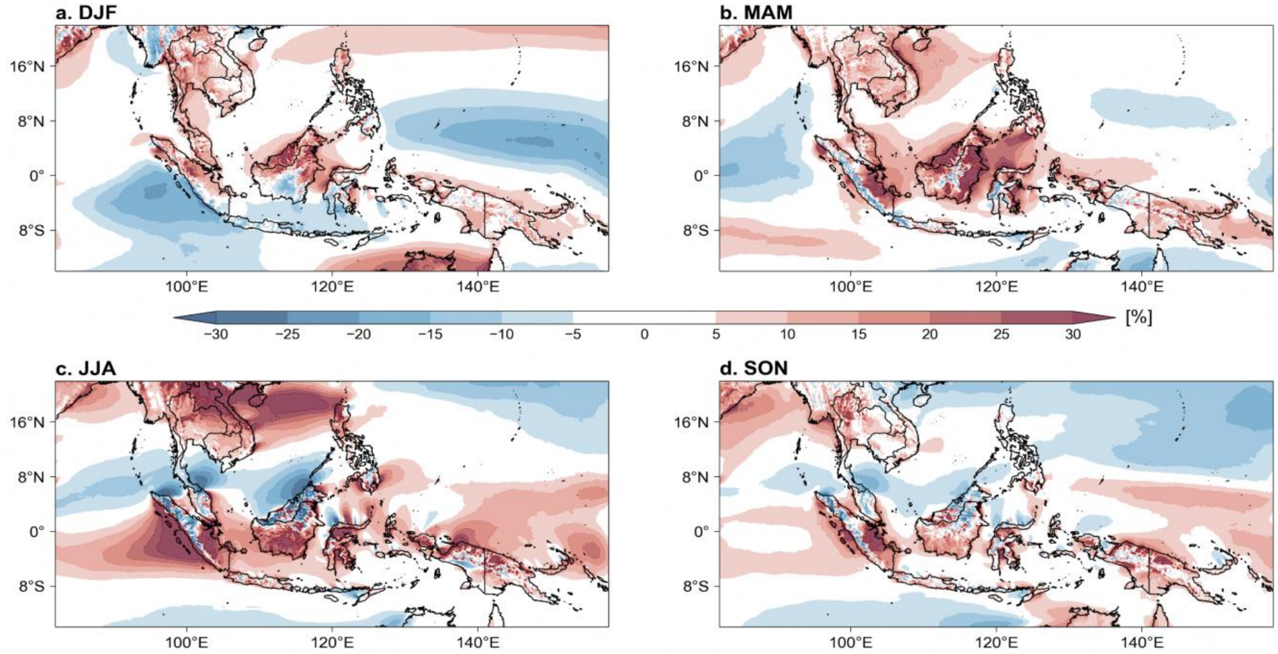


Figure 4.5: Projected change in seasonal 10-m wind speed during the end-century (2080–99) relative to the historical period (1995–2014) over the SEA domain under the high emissions scenario.

4.4 How will relative humidity change over the region?

Table 4.2 shows the end-century projected changes in average seasonal mean near-surface relative humidity for the three SSP scenarios. The largest projected changes are under the high emissions scenario. During the DJF season, the projected change is up to −1.8%, for MAM season it is up to -2.7%, for JJA it is up to −3.7%, and for SON season it is up to −3.0%. Overall, JJA shows the largest decrease, followed by SON.

Table 4.2: Projected changes (%) in seasonal mean near-surface relative humidity for the three SSP scenarios. The number outside the brackets shows the mean from the 6 models, and the ones in the brackets show the range from minimum to maximum.

Seasons	End-Century relative humidity changes (%)		
	SSP1-2.6	SSP2-4.5	SSP5-8.5
DJF	0.0 (−0.4 to 0.4)	−0.3 (−0.5 to 0.1)	−0.9 (−1.8 to −0.3)
MAM	−0.6 (−1.3 to 0.3)	−0.8 (-1.6 to 0.2)	−1.3 (−2.7 to −0.4)
JJA	−0.2 (−0.6 to 0.2)	−0.8 (−1.9 to −0.1)	−1.9 (−3.7 to −0.7)
SON	0.0 (−0.6 to 0.4)	−0.4 (−1.3 to 0.2)	−1.3 (−3.0 to 0.1)

4.5 How will relative sea-level change over the region?

The mechanisms driving Global Mean Sea Level (GMSL) rise primarily encompass two main contributors: thermal expansion of ocean waters and mass loss from ice sheets. However, additional physical processes such as ocean circulation patterns, density changes, and vertical land movement introduce spatial variability in sea-level change across the globe. This results in non-uniform relative sea-level change around the world.

V3 provides sea-level projections for 13 locations within the Southeast Asian region, excluding the six tide gauges in Singapore, for up to 2100 and 2150. Here, a subset of these locations is shown, and it includes Cebu City, Manila, Phuket, Bangkok, Johor Bahru, Kota Kinabalu, Penang, Danang and Yangon (Figure 4.6). Refer to Chapter 12 of the Science Report for projections of the full list of locations. Note that the IPCC AR6 did not provide projections for any locations within Indonesia.

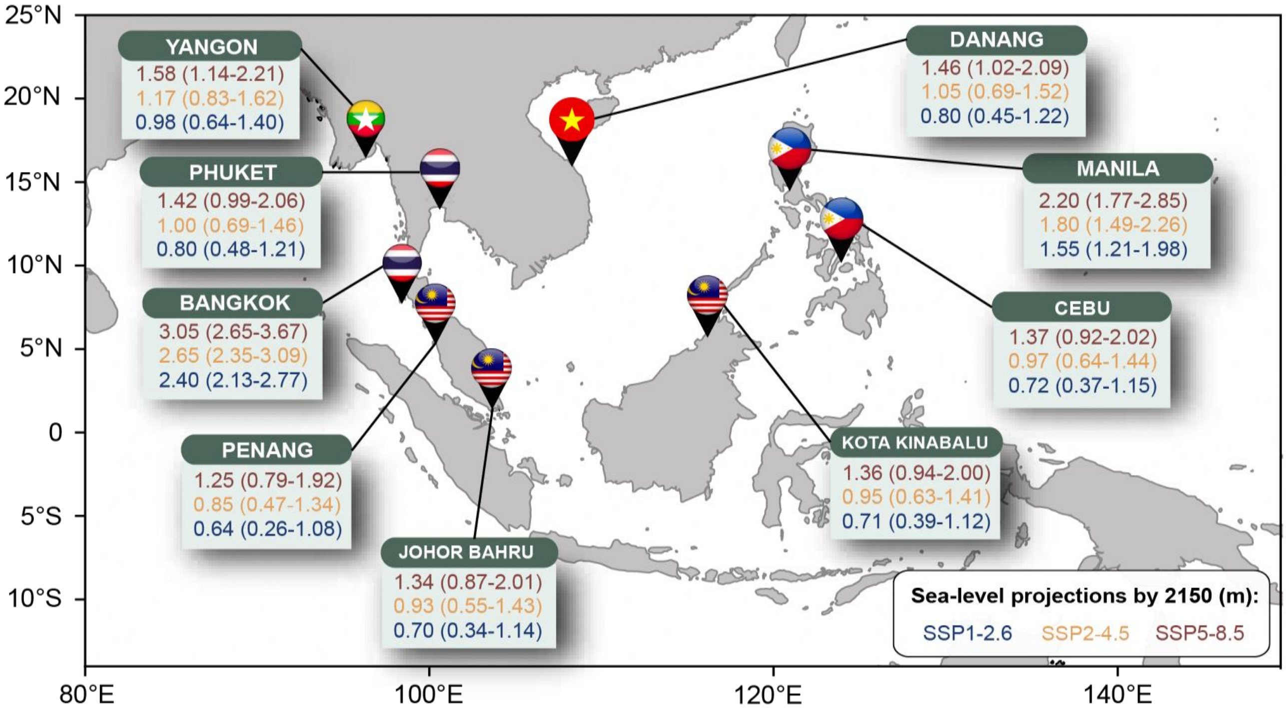
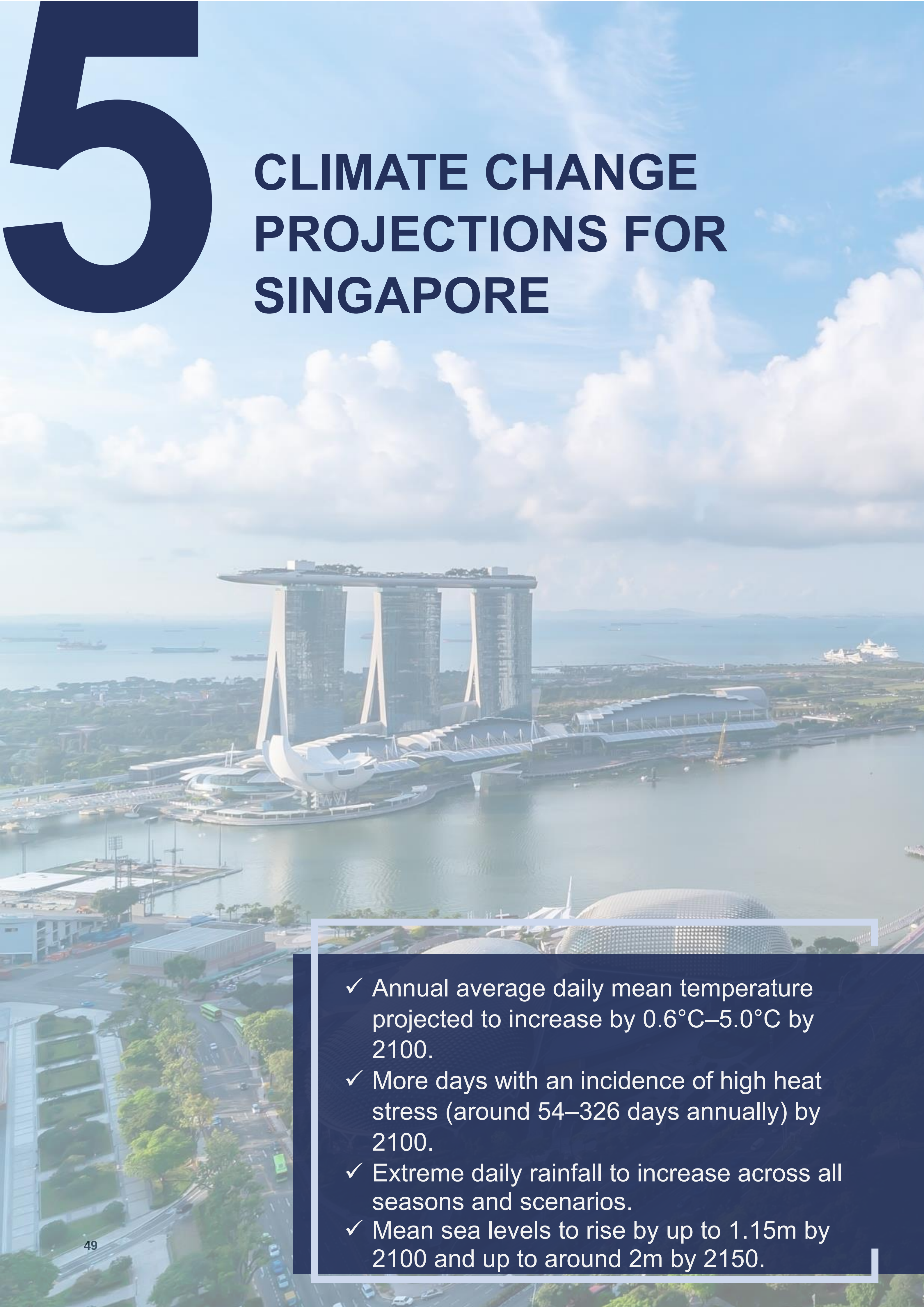


Figure 4.6: Projected relative sea-level rise at some of the most densely populated Southeast Asian cities by 2150 under all emission scenarios considered in V3. Projections are relative to the baseline period 1995–2014. More locations are included in Chapter 12 of the V3 Science Report.

In the coming century and next, relative sea level will rise significantly across these various locations, with Bangkok emerging as the city that has twice the projected sea-level rise than most of the other cities by 2150 under the high emissions scenario, as shown in Figure 4.6.

Under the low emissions scenario the "locked-in" relative sea level rise could likely reach up to 1 m in most of these cities and up to 2 to 3 m in Manila and Bangkok by 2150. Under the high emissions scenario relative sea-level rise could likely reach up to 2 m in most cities and exceed 3m in Bangkok by 2150.

The main driver behind the rapid relative sea-level rise at Manila and Bangkok is the excessive depletion of groundwater, which has caused land subsidence and consequent rise in relative sea-level since the 1970s. See Chapter 12 of the Science Report for more detailed references.



5 CLIMATE CHANGE PROJECTIONS FOR SINGAPORE

- ✓ Annual average daily mean temperature projected to increase by 0.6°C–5.0°C by 2100.
- ✓ More days with an incidence of high heat stress (around 54–326 days annually) by 2100.
- ✓ Extreme daily rainfall to increase across all seasons and scenarios.
- ✓ Mean sea levels to rise by up to 1.15m by 2100 and up to around 2m by 2150.

In this chapter climate change projections over Singapore are documented, using the 2km dynamically downscaled bias-adjusted simulations.

The climate change projections over Singapore are shown for both annual and seasonal time scales. For the seasons, periods corresponding to Singapore's monsoon and inter-monsoon months were selected: the Northeast Monsoon season, the Southwest Monsoon season and the two inter-monsoons. The Northeast Monsoon season is further divided into the wet phase comprising the months of December and January, and the dry phase comprising the months February and March. The Southwest Monsoon season comprises the months of June-through-September (considered as dry months for Singapore), and the first and second inter-monsoon periods comprise April–May and October–November, respectively.

Specifically, changes in the mean state and extremes of some key variables under the three SSP scenarios for the mid- and end-century 20-year periods are shown.

5.1 How will the daily mean temperature and WBGT change?

Projected changes in the annual average daily mean temperature and daily mean WBGT, during mid- and end-century under the three SSP scenarios are shown in Table 5.1. The table shows:

- Annual average daily mean temperature to increase by 0.6–5.0°C.
- Mid- to end-century trend in annual average daily mean temperature is projected to be up to 0.55°C per decade, based on the temperature change of 2.2°C between the 2 periods.
- Annual average daily mean WBGT to increase by 0.5–4.3°C.

The WBGT is a measure of heat stress. It is a composite measure that considers air temperature, humidity, wind, and solar radiation. It is calculated as the weighted sum of the wet bulb temperature T_w, the globe temperature T_g, and the air temperature T_{as}:

$$WBGT = 0.7\ T_w + 0.2\ T_g + 0.1\ T_{as}$$

T_w: temperature read by a thermometer covered by a cotton wick that is exposed to the natural prevailing air movement as well as radiation.
T_g: temperature measured by a dry bulb thermometer inserted into a standard black metal globe and it represents the integrated effect of air temperature, wind speed and radiant heat.
T_{as}: temperature of the ambient air measured in the shade.

As of January 2024, MSS has a network of nine WBGT stations spread across the island.

Table 5.1: Observed and projected annual average daily mean temperature and WBGT, during mid- and end-century under the three SSP scenarios. The number outside the brackets is the mean of five models and the numbers inside the bracket are the minimum and maximum values.

Scenario	Daily Average			
	Air Temperature (°C)		WBGT (°C)	
Observed	27.9		26.6 observed at current 9 stations	
Future	Mid-Century	End-Century	Mid-Century	End-Century
SSP1-2.6	28.9 (28.5 to 29.2)	29.0 (28.5 to 29.5)	27.4 (27.1 to 27.8)	27.5 (27.1 to 28.0)
SSP2-4.5	29.1 (28.7 to 29.6)	29.9 (29.3 to 30.7)	27.6 (27.3 to 28.1)	28.4 (27.8 to 29.0)
SSP5-8.5	29.5 (28.8 to 30.1)	31.7 (30.7 to 32.9)	28.0 (27.6 to 28.5)	30.0 (29.1 to 30.9)

5.2 How will the annual occurrence of warm days change?

The frequency of occurrence of warm days is projected to increase in the future. Based on the observations record, Singapore has around 76 warm days annually, and this number is projected to increase in the future, with almost every day in the year being a warm day, by end-century, under the high emissions scenario. Projected changes for the mid- and end-century for all SSPs are shown in Table 5.2.

Table 5.2: Observed and projected number of warm days annually, during mid- and end-century under the 3 SSP scenarios.

Scenario	Number of warm days with daily maximum temperature exceeding 34 °C annually	
Observations	76 days *observed at any of the 4 stations with long term records*	
Future	Mid-Century	End-Century
SSP1-2.6	178 (142 to 216)	188 (132 to 246)
SSP2-4.5	201 (164 to 257)	266 (212 to 325)
SSP5-8.5	234 (186 to 287)	340 (315 to 359)

5.3 How will the annual occurrence of warm nights change?

The frequency of occurrence of warm nights (daily minimum temperature equal to or exceeding 26.3 °C) is projected to increase in the future. Based on the observations record, Singapore has around 76 warm nights annually, and this number is projected to increase in the future, with warm nights becoming an everyday occurrence, by end-century, under the high emissions scenario. Projected changes for the mid- and end-century for all SSPs are shown in Table 5.3.

Table 5.3: Observed and projected number of warm nights annually, during mid- and end-century under the 3 SSP scenarios.

Scenario	Number of warm nights annually	
Observations	76 nights	
Future	Mid-Century	End-Century
SSP1-2.6	336 (317 to 352)	342 (312 to 361)
SSP2-4.5	347 (327 to 360)	362 (360 to 365)
SSP5-8.5	354 (335 to 364)	365 (365)

5.4 How will daily maximum temperature and WBGT change?

Projected changes in the annual mean of the daily maximum temperature and daily maximum WBGT, during mid- and end-century under the 3 SSP scenarios are shown in Table 5.4. The table shows:

- Average daily maximum air temperature to increase by 0.5–5.3°C
- Average daily maximum WBGT to increase by 0.5–4.0°C

Table 5.4: Observed and projected daily maximum temperature and WBGT annually, during mid- and end-century under the 3 SSP scenarios.

Scenario	Daily Maximum			
	Air Temperature (°C)		WBGT (°C)	
Observed	31.4		30.4 (*Observed at current 9 stations*)	
Future	Mid-Century	End-Century	Mid-Century	End-Century
SSP1-2.6	32.4 (32.0 to 32.8)	32.5 (31.9 to 33.1)	31.2 (30.9 to 31.5)	31.3 (30.9 to 31.7)
SSP2-4.5	32.6 (32.2 to 33.2)	33.5 (32.8 to 34.4)	31.4 (31.1 to 31.8)	32.2 (31.6 to 32.6)
SSP5-8.5	33.0 (32.3 to 33.6)	35.4 (34.3 to 36.7)	31.8 (31.4 to 32.2)	33.7 (32.7 to 34.4)

Figure 5.1 shows the multi-model mean projections of daily maximum temperature (TXx) over Singapore across annual and monthly timescales under the SSP5-8.5 scenario. The TXx is expected to increase on annual and monthly timescales in the end-century and is expected to increase by about 3.5–4.5°C with warming across Singapore on annual and seasonal time scales with mean increases closer to 4.5 degrees over the northern, central, and western parts. This warming change across Singapore could be largely driven by large scale warming in the region (mainly land masses of Sumatra and peninsular Malaysia). Future more detailed urban studies will provide additional information on urban additional warming.

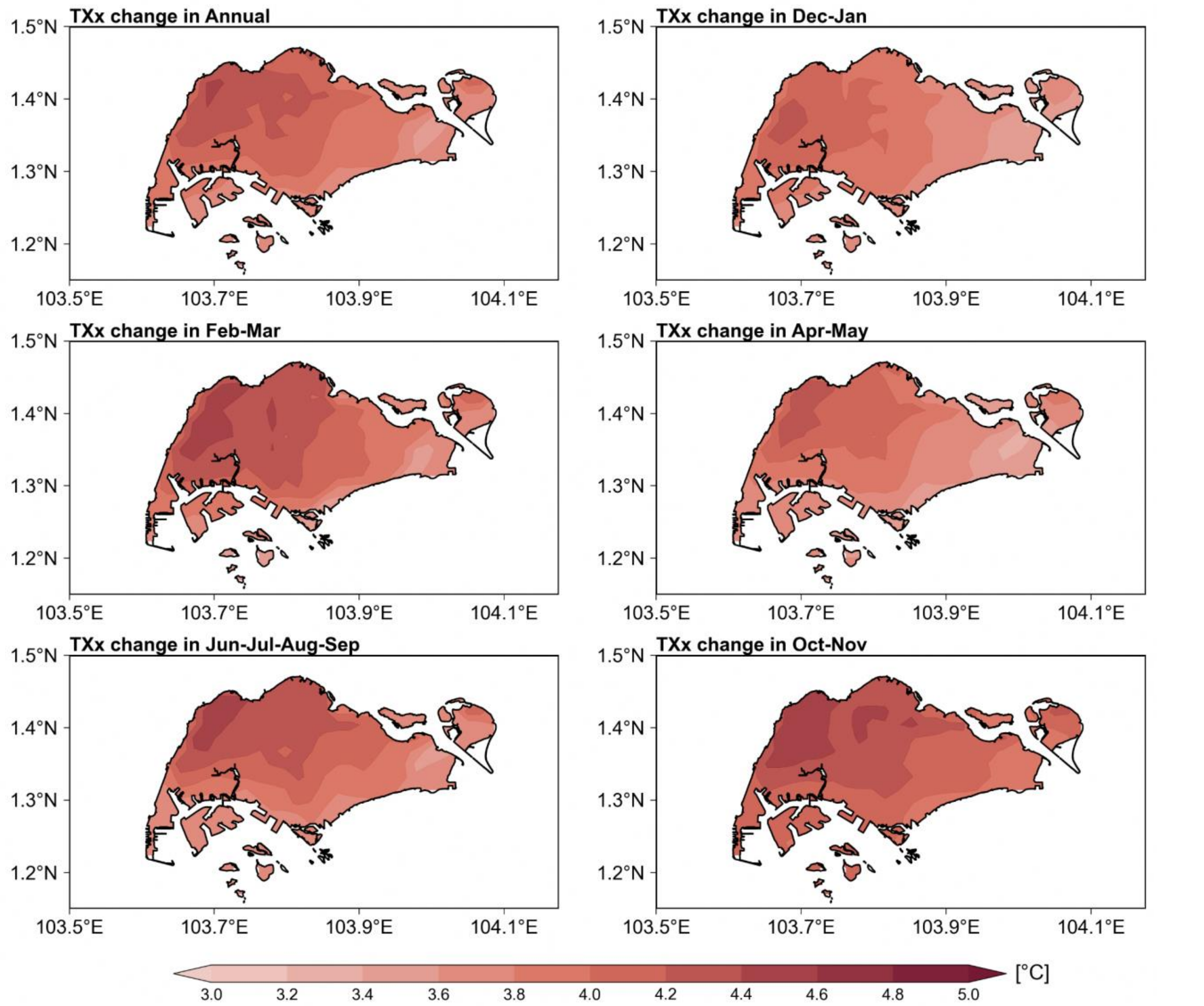


Figure 5.1: Projected spatial changes in the daily maximum temperature annually, and for each of the seasons during the end-century under SSP5-8.5.

5.5 How will the annual occurrence of very hot days change?

Very hot days are defined as days with daily maximum temperature exceeding 35 °C, based on the 99th percentile of daily maximum temperature. Historically, the average annual occurrence of very hot days are 21.4 days.

The frequency of occurrence of very hot days is projected to increase in the future. Based on the observations record, Singapore has around 21 very hot days annually, and this number is projected to increase in the future, with the worst case of almost every day being a very hot day by the end century under the high emissions scenario.

Projected changes for the mid- and end-century for all SSPs are shown in Table 5.5.

Table 5.5: Observed and projected number of very hot days annually, during mid- and end-century under the three SSP scenarios.

Scenario	Number of very hot days annually	
Observed	*21.4 days*	
Future	Mid-Century	End-Century
SSP1-2.6	73 (47 to 93)	85 (41 to 125)
SSP2-4.5	95 (63 to 134)	173 (103 to 261)
SSP5-8.5	129 (76 to 189)	305 (252 to 351)

5.6 How will the annual occurrence of days with high heat stress change?

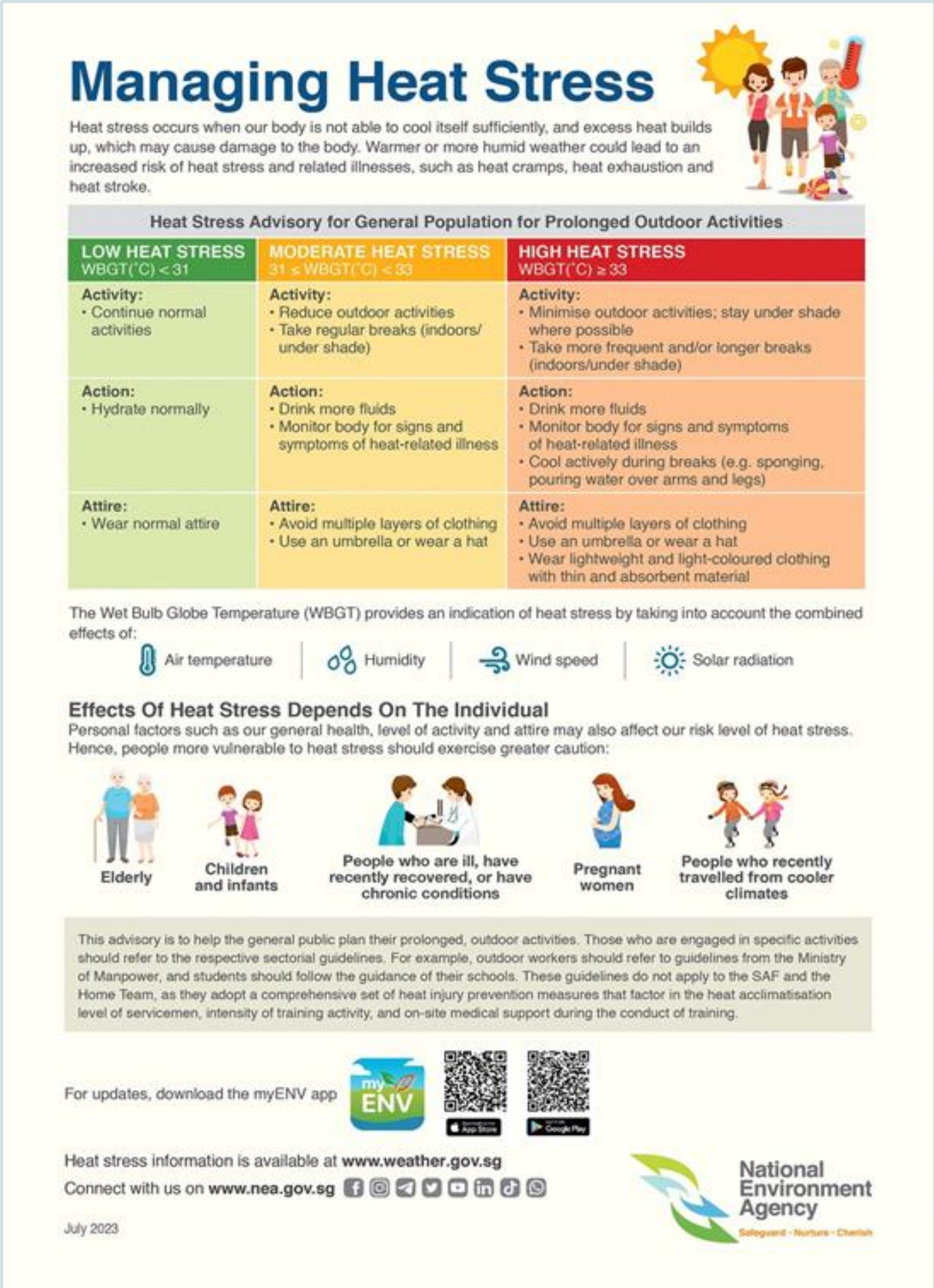
Based on the NEA heat stress advisory that was released in July 2023 (shown in Figure 5.2), WBGT is used as an indicator of heat stress, and following are the various categories of heat stress:

- Low: WBGT < 31°C
- Moderate: 31°C ≤ WBGT < 33°C
- High: WBGT ≥ 33°C

V3 projections show that the number of days with an incidence of high heat stress (as defined above) will increase, with the current annual occurrence of 24 days increasing to 54–326 days of high heat stress days annually, by end-century. Projected changes for the mid- and end-century for all SSPs are shown in Table 5.6.

Table 5.6: Observed and projected heat stress days annually, during mid- and end-century under the three SSP scenarios.

Scenario	Number of days with daily maximum WBGT equal to or exceeding 33°C annually	
Observations	24 days *observed at current 9 stations*	
Future	Mid-Century	End-Century
SSP1-2.6	75 (53 to 112)	81 (54 to 135)
SSP2-4.5	87 (61 to 131)	142 (107 to 205)
SSP5-8.5	113 (86 to 155)	270 (207 to 326)



Managing Heat Stress

Heat stress occurs when our body is not able to cool itself sufficiently, and excess heat builds up, which may cause damage to the body. Warmer or more humid weather could lead to an increased risk of heat stress and related illnesses, such as heat cramps, heat exhaustion and heat stroke.

Heat Stress Advisory for General Population for Prolonged Outdoor Activities

LOW HEAT STRESS WBGT(°C) < 31	MODERATE HEAT STRESS 31 ≤ WBGT(°C) < 33	HIGH HEAT STRESS WBGT(°C) ≥ 33
Activity: • Continue normal activities	**Activity:** • Reduce outdoor activities • Take regular breaks (indoors/ under shade)	**Activity:** • Minimise outdoor activities; stay under shade where possible • Take more frequent and/or longer breaks (indoors/under shade)
Action: • Hydrate normally	**Action:** • Drink more fluids • Monitor body for signs and symptoms of heat-related illness	**Action:** • Drink more fluids • Monitor body for signs and symptoms of heat-related illness • Cool actively during breaks (e.g. sponging, pouring water over arms and legs)
Attire: • Wear normal attire	**Attire:** • Avoid multiple layers of clothing • Use an umbrella or wear a hat	**Attire:** • Avoid multiple layers of clothing • Use an umbrella or wear a hat • Wear lightweight and light-coloured clothing with thin and absorbent material

The Wet Bulb Globe Temperature (WBGT) provides an indication of heat stress by taking into account the combined effects of:

Air temperature | Humidity | Wind speed | Solar radiation

Effects Of Heat Stress Depends On The Individual

Personal factors such as our general health, level of activity and attire may also affect our risk level of heat stress. Hence, people more vulnerable to heat stress should exercise greater caution:

Elderly | Children and infants | People who are ill, have recently recovered, or have chronic conditions | Pregnant women | People who recently travelled from cooler climates

This advisory is to help the general public plan their prolonged, outdoor activities. Those who are engaged in specific activities should refer to the respective sectorial guidelines. For example, outdoor workers should refer to guidelines from the Ministry of Manpower, and students should follow the guidance of their schools. These guidelines do not apply to the SAF and the Home Team, as they adopt a comprehensive set of heat injury prevention measures that factor in the heat acclimatisation level of servicemen, intensity of training activity, and on-site medical support during the conduct of training.

For updates, download the myENV app

Heat stress information is available at **www.weather.gov.sg**

Connect with us on **www.nea.gov.sg**

National Environment Agency

Safeguard · Nurture · Cherish

July 2023

Figure 5.2: NEA heat stress advisory released in July 2023.

5.7 How will average annual and seasonal rainfall change?

Projected end-century changes in average annual rainfall totals are strongly dependent on the emissions scenario used. For the medium and high emissions scenarios, the projected changes could either be negative or positive.

For average seasonal rainfall totals, by end-century, the wet months of December-January are expected to get wetter by up to 58% (occurs under the low emissions scenario), and the dry months of June-through-September are expected to get drier by up to 42% (occurs under the high emissions scenario).

Indeed, the Island-wide average seasonal total rainfall during the Southwest Monsoon dry season of June-through-August could fall significantly below the historical low of 314 mm (recorded in 1997), on average, almost every three years by the end of the century. For the Northeast Monsoon wet season of November-through-January, the corresponding seasonal total rainfall is projected to exceed the historical high of 1507 mm (recorded in 2006) occasionally.

Projected end-century changes for average annual and seasonal rainfall totals for all SSPs are shown in Table 5.7.

Table 5.7: Projected percentage changes in the average annual and seasonal total rainfall during the end-century under the three SSP scenarios.

Months	End-Century Rainfall Change (%)		
	SSP1-2.6	SSP2-4.5	SSP5-8.5
Annual	11 (0 to 24)	5 (−6 to 12)	0 (−12 to 17)
DJ (wet)	20 (−12 to 58)	6 (−9 to 28)	2 (−20 to 44)
FM	13 (−2 to 49)	−7 (−39 to 48)	−18 (−43 to 30)
AM	13 (−5 to 23)	10 (−15 to 33)	18 (−6 to 52)
JJAS (dry)	5 (−10 to 17)	0 (−17 to 22)	−14 (−42 to 6)
ON	8 (−4 to 24)	14 (−2 to 31)	14 (−8 to 41)

5.8 How will heavy daily rainfall change?

Heavy daily rainfall documented in this chapter is based on RX1day, and it varies for different months and for different 2km grid locations over Singapore. RX1day is defined as the maximum daily rainfall for annual or seasonal timescale.

Figure 5.3 shows percentage change in RX1day annually, and for December–January, February–March, April–May, June-through-September, and October–November months, during end-century under the high emissions scenario.

The areas with the highest increase vary with season.

Overall, the largest changes occur during the inter-monsoon periods, with changes potentially exceeding 40% over the western and central parts of Singapore during April-May.

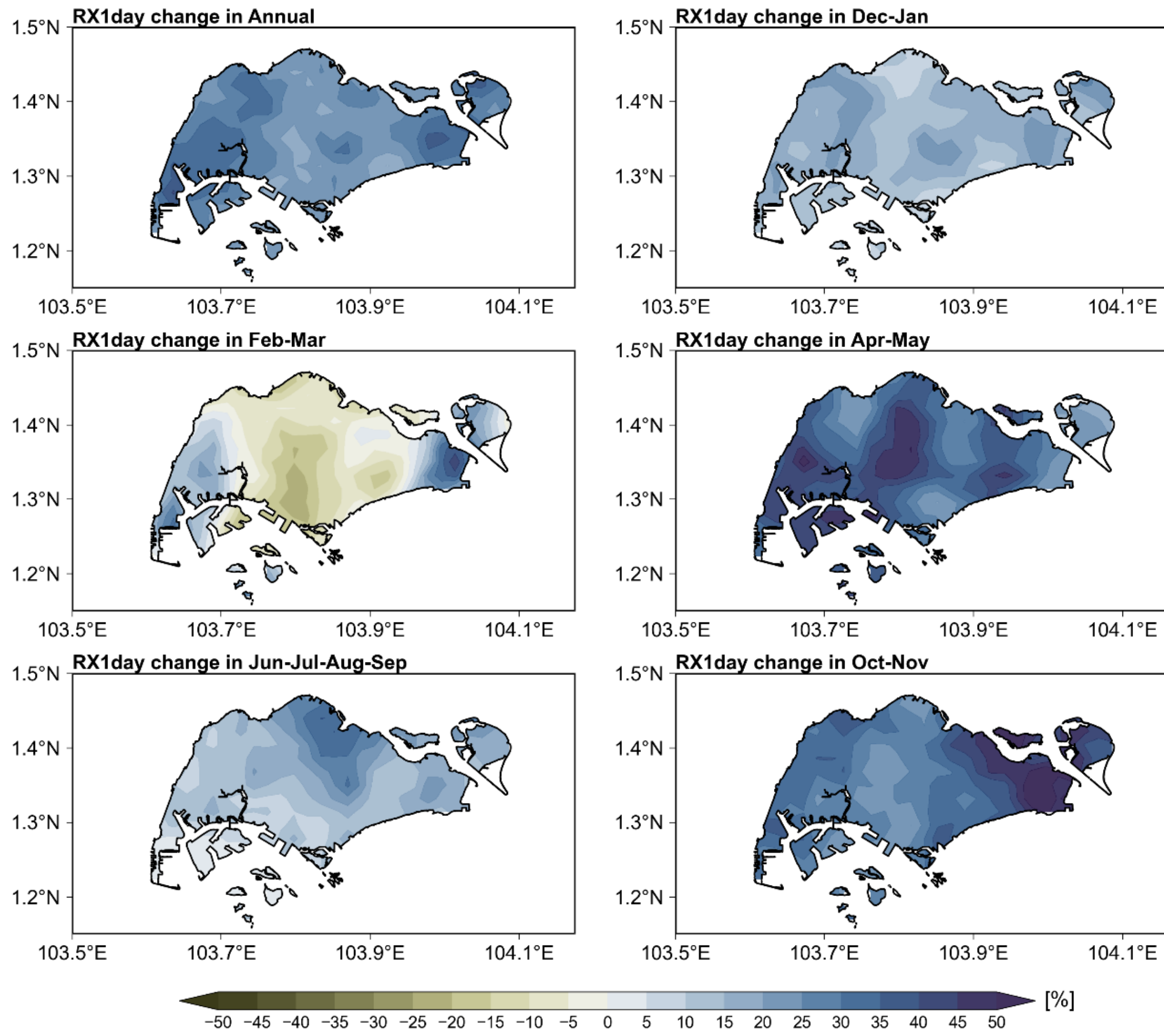


Figure 5.3: Percentage change in daily maximum rainfall annually, in December–January, February–March, April–May, June–July–August–September, and October–November months, during end-century (2080–2099) period relative to the baseline (1995–2014) under the high emissions scenario.

5.9 How will very heavy daily rainfall change?

Very heavy daily rainfall documented in this chapter is defined as the 99.9th percentile of daily rainfall, and it varies for different months and for different 2km grid locations over Singapore.

Figure 5.4 shows projected end-century changes in very heavy daily rainfall annually, and for each of the seasons under the three SSP scenarios.

Extreme daily rainfall is expected to increase across all seasons and scenarios, with up to 92% increase in the inter-monsoon months of April and May, under the high emissions scenario.

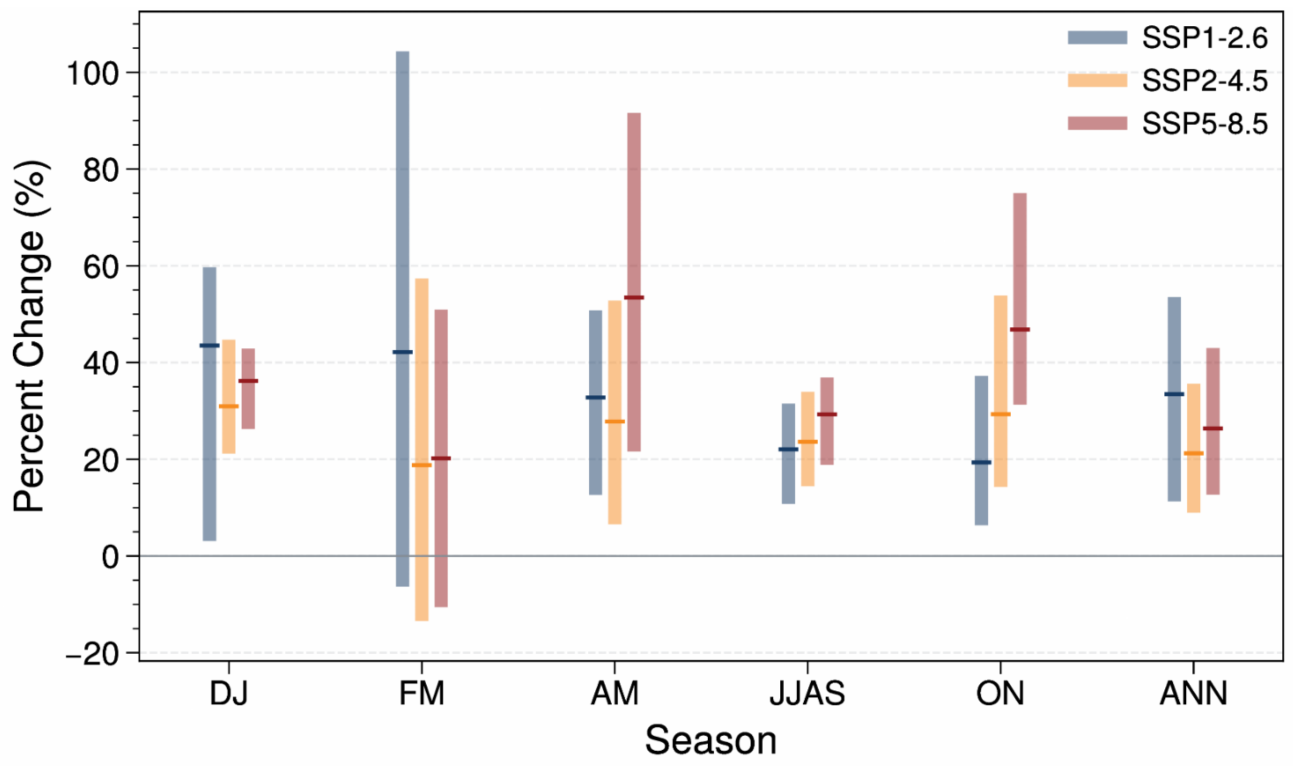


Figure 5.4: Projected changes in very heavy daily rainfall annually, and for each of the seasons during the end-century under the three SSP scenarios.

5.10 How will dry spells change?

MSS defines dry spells over Singapore as a period of at least 15 consecutive days with an island-wide average of daily total rainfall less than 1.0 millimetre (mm) for each of the days.

Figure 5.5 shows projected changes in the average number of dry spells, and average maximum duration of dry spells, expected annually, during the mid- and end-century, under the three SSP scenarios. It is expected that dry spells over Singapore will be more frequent.

On an average, there will be one dry spell every 10-60 months, with maximum duration of around 3 weeks, by end-century.

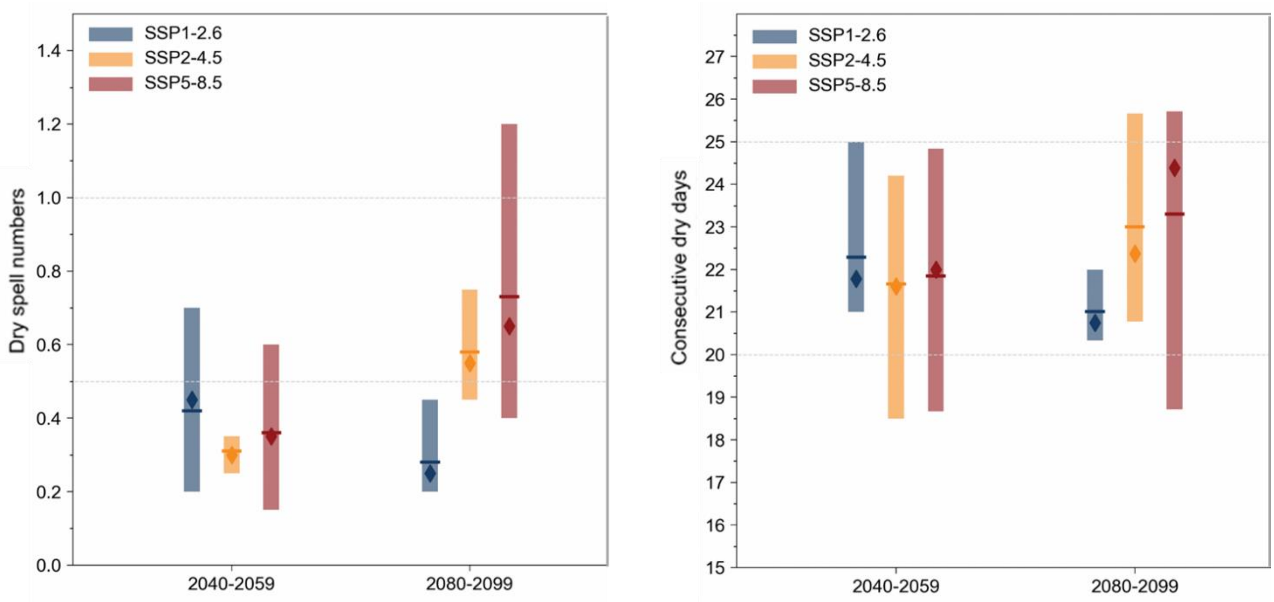


Figure 5.5: Projected annual average number of dry spells (left), annual average maximum duration of dry spells (right) under three SSP scenarios.

5.11 How will mean winds change?

Wind speed, combined with temperature and relative humidity, plays an important role in the level of heat stress and outdoor thermal comfort.

Projected changes in 10-m wind speeds for each season during the end-century under the three SSP scenarios are shown in Table 5.8. Overall, 10-m wind speeds are expected to change from -1–20% during the Northeast and Southwest Monsoon seasons, and from 1–11% in the inter-monsoon months of April and May.

Table 5.8: Projected percentage changes in 10m wind speeds for each season during the end-century under the three SSP scenarios.

Months	End-century wind speed change (%)		
	SSP1-2.6	SSP2-4.5	SSP5-8.5
Northeast Monsoon (DJFM)	3.1 (−1.0 to 5.5)	6.6 (2.6 to 11.9)	11.0 (4.5 to 19.8)
First Inter-monsoon (AM)	3.5 (1.2 to 6.9)	3.3 (1.0 to 6.0)	8.6 (5.3 to 11.1)
Southwest Monsoon (JJAS)	3.9 (1.4 to 7.7)	7.3 (2.9 to 12.4)	13.8 (10.3 to 20.3)
Second Inter-monsoon (ON)	0.0 (−2.2 to 1.4)	0.5 (−6.6 to 3.5)	5.8 (−4.7 to 11.2)

5.12 How will daily maximum wind gusts change?

Strong wind gusts are often associated with thunderstorms and Sumatra squall lines and can potentially cause substantial damage to Singapore's infrastructure (buildings and roads), uprooting of trees, and threat to the safety of human beings.

Figure 5.6 shows the projected change in the average daily maximum wind gusts over Singapore during the mid- and end-century under the high emissions scenario.

Overall, there is an upward trend in the speed of the daily maximum wind gusts, with expected mid-century increase of up to 3%, and that during end-century of up to 10%.

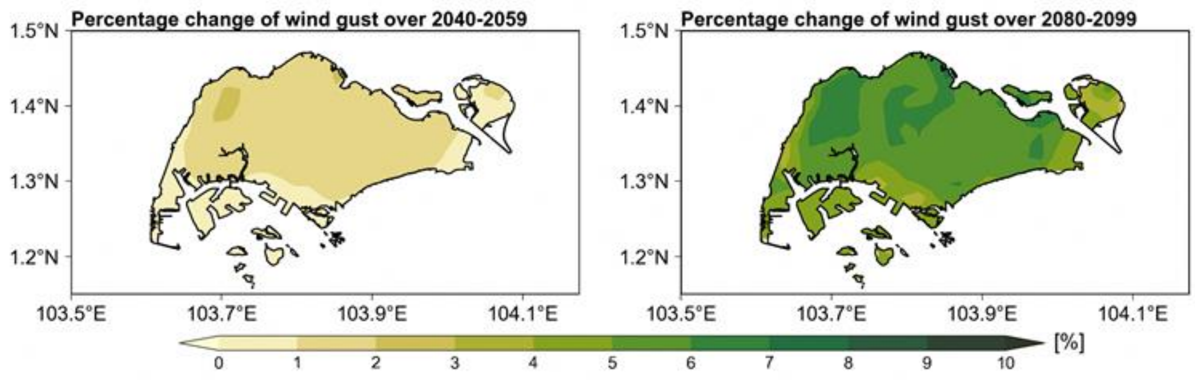


Figure 5.6: Projected percentage change in the average daily maximum wind gusts over Singapore in the mid-century (left) and end-century (right) under the high emissions scenario.

5.13 How will relative humidity change?

Table 5.9 shows projected changes in mean 1.5m relative humidity on annual and seasonal timescales during the end-century under the three SSP scenarios. Overall, relative humidity is projected to decrease in the future. For example, projected change in the months of February and March by end-century is in the range of -5.3 – 0.7%.

Relative humidity is expressed as a percentage and is a measure of saturation of the ambient air. It includes the combined effect of temperature and water vapour in the air. In simple terms, it is an indicator of how much water vapour the air contains compared to the maximum it could contain at a given temperature and pressure.

With increase in temperature, the amount of water vapour in the air is expected to increase. This is because of the Clausius-Clapeyron (CC) equation, which suggests that the air can generally hold around 7% more water vapour for every 1°C increase in air temperature. Therefore, under global warming, for the relative humidity to be constant the water vapour content in the air should increase at the same rate i.e. 7% increase for every 1°C increase in air temperature.

However, Singapore's observation records show a decreasing trend in relative humidity. The reasons for this are: (1) large part of water vapour in the air over land comes from the seas surrounding Singapore, and (2) the land surface has been warming at a faster rate than the surrounding seas. Hence, the moisture from the surrounding seas is *not enough* to increase the water vapour over land at the CC rate, leading to a decreasing trend in RH.

Table 5.9: Projected percentage changes in the relative humidity annually, and for each season during the end-century under the three SSP scenarios.

Months	End-Century Relative Humidity Change (%)		
	SSP1-2.6	SSP2-4.5	SSP5-8.5
Annual	−0.5 (−1.2 to −0.1)	−0.9 (−2.0 to −0.5)	−1.9 (−3.6 to −1.0)
DJ	−0.4 (−1.5 to 1.1)	−0.7 (−1.9 to 0.8)	−1.9 (−3.6 to 0.4)
FM	−1.2 (−2.0 to -0.2)	−1.8 (−3.3 to 0.1)	−2.6 (−5.3 to 0.7)
AM	−0.5 (−1.1 to 0.2)	−0.5 (−1.3 to 0.4)	−0.8 (−1.1 to −0.3)
JJAS	−0.5 (−1.3 to 0.4)	−0.9 (−2.2 to 0.1)	−2.0 (−3.8 to −0.6)
ON	−0.5 (−1.3 to 0.4)	−0.8 (−1.7 to 0.7)	−2.2 (−3.9 to 0.3)

5.14 How will relative sea-level change around Singapore?

In the following sub-sections, a comprehensive exploration of anticipated relative sea-level changes in Singapore for both the current century and the next is documented. To set the stage, a concise overview of the projected global mean sea level is first discussed, as outlined in the IPCC AR6.

This introduction is paramount due to the influential role of global mean sea-level drivers, including thermal expansion of seawater and polar ice cap mass loss, which exert a significant impact on local projections.

5.14.1 How will global-mean sea-level change?

According to the IPCC AR6 WGI Report, global-mean sea-level (GMSL) is projected to rise across all future climate scenarios. Until 2050, in accordance with the AR5 and Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) reports, the projected global mean sea level (GMSL) rise shows little variation depending on different scenarios.

There is medium confidence in these projections, with a likely sea-level rise of 0.19 (0.16–0.25) m under SSP1-2.6 and 0.23 (0.20–0.30) m under SSP5-8.5 (Figure 5.7). However, after 2050, the scenarios start to show more significant differences (Fox-Kemper et al., 2021).

The IPCC AR6 suggests an alternative approach to addressing uncertainty in future GMSL rise by factoring in the uncertainty associated with the timing of specific sea-level rise thresholds. Focusing on projections that only incorporate processes with medium confidence, it is likely that GMSL will surpass 0.5 m sometime between 2080 and 2170 under SSP1-2.6 and between 2070 and 2090 under SSP5-8.5.

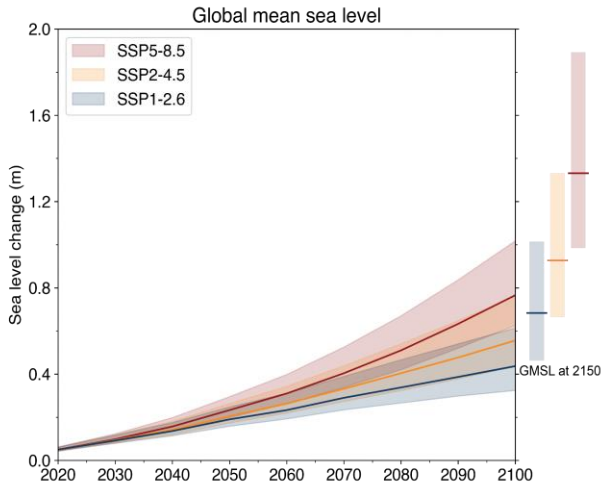


Figure 5.7: Projected rise in global-mean sea-level up to 2150, relative to IPCC AR6 baseline 1995 - 2014, under three emission scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5). Solid curves represent the median (50th percentile), whilst the shaded bands represent the likely range (17th to 83rd percentile).

It is likely that GMSL will exceed 1.0 m between 2150 and beyond 2300 under SSP1-2.6, and between 2100 and 2150 under SSP5-8.5. However, it is unlikely to surpass 2.0 m until after 2300 under SSP1-2.6, whereas it is likely to do so between 2160 and 2300 under SSP5-8.5 (Fox-Kemper et al., 2021).

5.14.2 How will sea-level change around Singapore by 2150?

V3 provides an overview of mean sea-level projections extending up to the year 2300. These projections encompass varying degrees of confidence—namely low and medium. This section places its focus on the medium confidence projections up to 2150. For a comprehensive documentation of the methodology underpinning these projections, we direct readers to delve into Chapter 12 of the Science Report. All sea-level projections are computed in relation to the AR6 baseline period of 1995–2014.

Relative sea-level projections by 2100 and 2150 are provided at the six tide-gauges in Singapore by 2150 under all three emission scenarios (Figure 5.8 and Table 5.10). Our results indicate a small spatial variance of projected relative sea-level rise across the six locations.

Under SSP1-2.6, the average (average of the median value at all six tide gauges) projected rise stands at 0.45 ± 0.03 m by 2100 and 0.72 ± 0.05 m by 2150. Similarly, the moderate emissions scenario, SSP2-4.5, suggests a likely rise of 0.57 ± 0.04 m by 2100 and 0.95 ± 0.06 m by 2150. Under the highest emissions scenario, SSP5-8.5, the projections point to an average relative sea level rise of 0.79 ± 0.04 m by 2100 and 1.37 ± 0.06 m by 2150. The one standard error reflects the spatial variations observed across the median values recorded at the tide gauges.

Sultan Shoal emerges with the largest projected rise by 2100 and 2150 under all emission scenarios. At this station by 2100, relative sea level is projected to likely rise by up to 0.74 m under the low emission scenario (SSP1-2.6) and up to 1.15 m under the high emissions scenario (SSP5-8.5). By 2150, this could likely reach up to 1.24 m under SSP1-2.6, and up to 2.12 m under SSP5-8.5 (Figure 5.8).

Table 5.10: Projected relative sea-level rise and global-mean sea-level rise by 2100 and 2150 (median and *likely* range in brackets), under three emission scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5) of *medium confidence*.

Tide Gauges	SSP1-2.6		SSP2-4.5		SSP5-8.5	
	2100	2150	2100	2150	2100	2150
Sultan Shoal	0.51 (0.34 – 0.74)	0.82 (0.50 – 1.24)	0.63 (0.46 – 0.88)	1.05 (0.72 – 1.52)	0.85 (0.66 – 1.15)	1.47 (1.03 – 2.12)
Sembawang	0.42 (0.26 – 0.63)	0.67 (0.38 – 1.07)	0.53 (0.38 – 0.77)	0.9 (0.59 – 1.36)	0.75 (0.58 – 1.04)	1.32 (0.90 – 1.95)
Raffles Light House	0.42 (0.24 – 0.65)	0.68 (0.35 – 1.09)	0.54 (0.36 – 0.79)	0.9 (0.56 – 1.38)	0.76 (0.56 – 1.06)	1.32 (0.88 – 1.97)
Tanjong Pagar	0.44 (0.24 – 0.69)	0.71 (0.35 – 1.16)	0.56 (0.36 – 0.82)	0.94 (0.56 – 1.43)	0.78 (0.56 – 1.10)	1.36 (0.89 – 2.02)
West Coast	0.46 (0.24 – 0.72)	0.74 (0.34 – 1.21)	0.58 (0.35 – 0.86)	0.97 (0.55 – 1.49)	0.80 (0.55 – 1.13)	1.39 (0.88 – 2.07)
West Tuas	0.45 (0.23 – 0.72)	0.72 (0.33 – 1.19)	0.57 (0.34 – 0.85)	0.95 (0.54 – 1.47)	0.79 (0.54 – 1.12)	1.37 (0.87 – 2.05)
Singapore Average	0.45 ± 0.03	0.72 ± 0.05	0.57 ± 0.04	0.95 ± 0.06	0.79 ± 0.04	1.37 ± 0.06
Global mean	0.44 (0.32 – 0.62)	0.68 (0.46 – 0.99)	0.56 (0.44 – 0.76)	0.92 (0.66 – 1.33)	0.77 (0.63 – 1.01)	1.32 (0.98 – 1.88)

Figure 5.8: Projected relative sea-level rise in Singapore at six tide-gauges (Sembawang, West Tuas, West Coast, Tanjong Pagar, Raffles Light House and Sultan Shoal) by 2150 under three emission scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5). Values shown reflect the median (*likely* range) projected sea-level change by 2150 relative to the IPCC AR6 baseline 1995 - 2014.

The projected median values for global-mean sea-level closely align with the average relative sea-level projections for Singapore by 2100 and 2150 (Table 5.10).

However, across all emission scenarios, the upper bounds (83rd percentile) of Singapore's relative sea-level projections at all six tide gauges consistently exceed those of the global projections for both 2100 and 2150. This is primarily attributed to local factors, particularly vertical land movement, which contributes to some degree of land subsidence in Singapore, consequently driving relative sea-level rise.

More importantly, these projections emphasise a pragmatic reality: even under the most optimistic low-emission scenarios, both Singapore and the global community are facing an inevitable ‘locked-in’ sea-level rise in the coming decades.

Difference between V2 and V3

V3's sea-level projections mark a significant advancement over its predecessor, V2, in several critical aspects. Firstly, it extends its medium confidence sea-level projections up to the year 2150, providing a more extensive outlook for Singapore's climate resilience planning. Unlike V2, which relied on the RCPs, V3 adopts the more comprehensive SSPs introduced in AR6, aligning its projections with the latest scientific advancements. Notably, V3 introduces a more localised perspective by offering projections for six crucial tide gauges around Singapore, a significant departure from V2's singular representation.

In V2, the projected total mean sea-level rise for the year 2100 under RCP4.5 and RCP8.5 was 0.53 m (median) and 0.73 m (median), respectively. These figures are remarkably similar to the median relative sea-level rise values projected in V3 under SSP2-4.5 and SSP5-8.5 scenarios. However, a closer examination focused on the tide-gauge with the highest projections, Sultan Shoal, reveals notable disparities. In this case, both the median and the upper limit of the likely range (83rd percentile) in V3 exceed the projections in V2 by tens of centimetres.

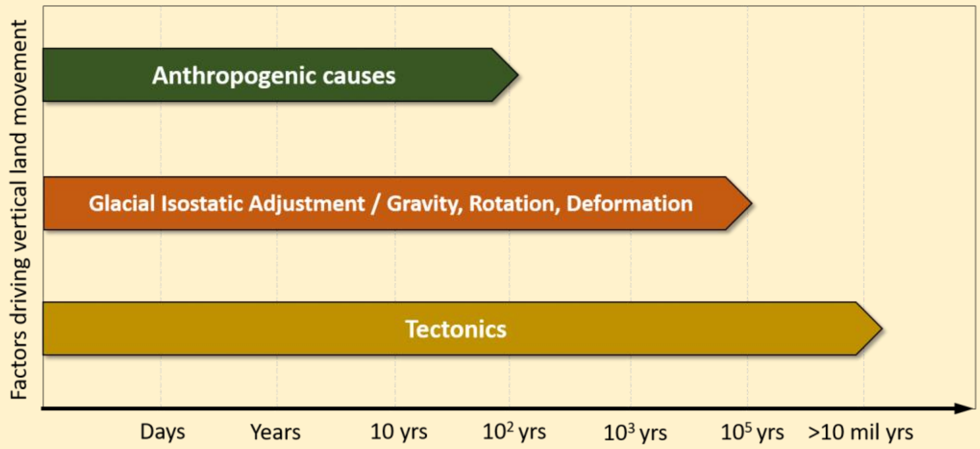
The substantial differences observed between V2 and V3, particularly in the context of the Antarctic ice sheet, can be primarily attributed to advancements in modelling introduced in AR6 compared to its predecessor, AR5, which formed the foundation of V2's methodology. AR6 incorporates more sophisticated ice-sheet models that consider a wider range of processes and feedback mechanisms. This enhanced modelling includes improved representations and understanding of ice shelf dynamics and ice dynamics.

Consequently, V3 shows higher estimates of future sea-level rise as AR6 includes more considerable uncertainties surrounding the behaviour of the Antarctic ice sheet, diverging notably from the methodology of V2.

Furthermore, V3's approach to estimating vertical land movement and its contribution to relative sea-level rise represents another significant enhancement. While V2 primarily considered glacial isostatic adjustment, V3 now encompasses a wider spectrum of potential outcomes and processes, leading to a larger range of uncertainties in relative sea-level rise projections for all scenarios.

5.14.3 How will sea-level change around Singapore up to 2300?

However, when accounting for inherently unstable processes such as marine ice cliff instability (MICI) and marine ice shelf instability (MISI), Singapore's projected mean sea-level rise increases significantly. These projections, while produced with low confidence, introduce a new perspective. Low confidence projections up to 2300 are provided in the Science Report.



Vertical Land Movement: Significant factors driving vertical land movement (VLM) in Southeast Asia that are explained in Section 12.6.1 of the Science Report. The temporal extent to which these factors affect VLM vary from days to millions of years (tectonics). Information is adapted from Pfferfer et al. (2017).

While global sea-level rise results from various factors, VLM, which can lead to land subsidence or uplift, is a significant contributor for many coastal cities other than Singapore. VLM stems from natural and human-induced processes, affecting regions like Southeast Asia and exacerbating the impact of sea-level rise. Understanding VLM is essential for accurate sea-level projections, as it can either raise or lower local sea levels relative to land occupants while the global mean sea level remains constant.

VLM is influenced by various factors, including natural and anthropogenic mechanisms. One key natural factor is GIA, a response to the loss of ice sheets from the Last Glacial Maximum, leading to ongoing vertical displacements worldwide. Contemporary changes in ice sheets and land water storage also impact VLM and contribute to relative sea-level changes. Seismic activity, such as earthquakes, can cause sudden land uplift or subsidence, affecting local sea-level rise. The extent of these movements depends on factors like earthquake magnitude, fault location, and geological properties. Anthropogenic factors, including groundwater withdrawal, can induce land subsidence, impacting cities like Mexico City, Bangkok, and Jakarta (shown in Figure 5.9). Additional anthropogenic activities like oil extraction, mining, and dam construction can also lead to land subsidence. Further discussion on VLM's effects on projected sea-level rise in Southeast Asia is provided in the V3 Science Report (Section 12.5.3).

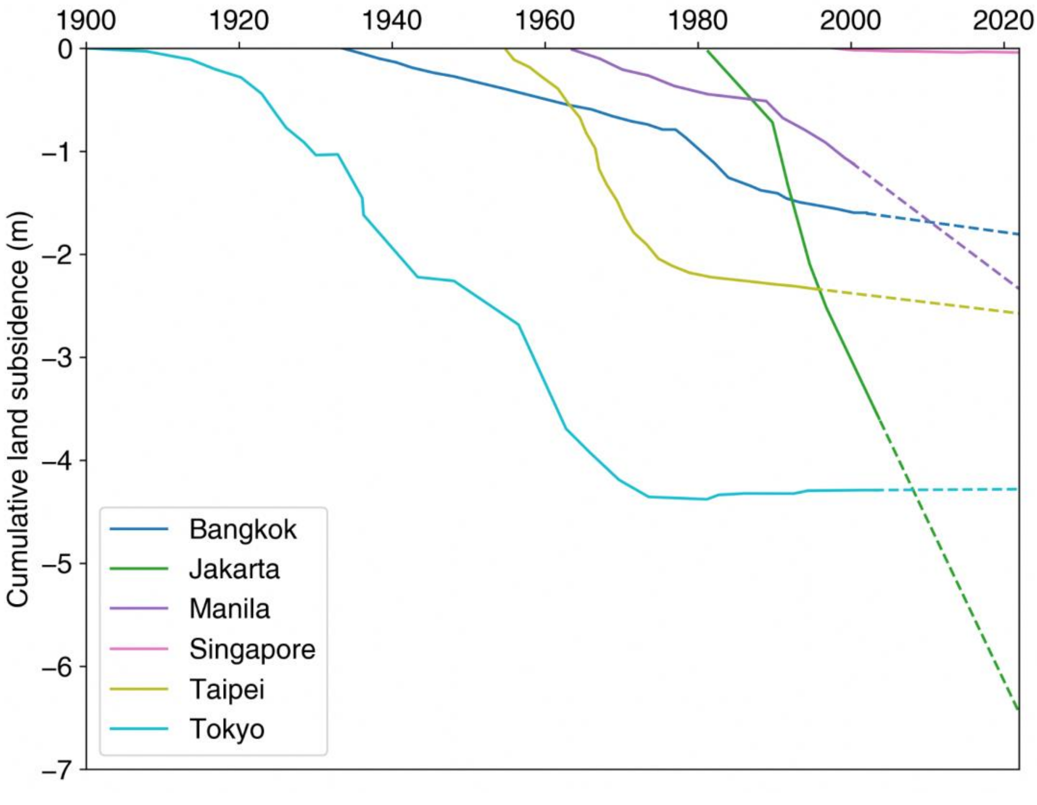


Figure 5.9: Cumulative land subsidence at Bangkok, Jakarta, Manila, Singapore, Taipei, and Tokyo. Solid curves were recreated from Kaneko and Toyota (2011), except for Singapore where data was taken from the GNSS station NTUS from Nevada Geodetic Lab on 13 September 2023. Dashed lines represent the projected cumulative subsidence in the respective cities until 2022, assuming a consistent rate of VLM observed over the past 5 years.

6 HOW WILL THE PROJECTIONS FROM THIS STUDY BE USED?

- ✓ V3 supports Singapore Government policy and adaptation planning into the future.
- ✓ V3 supports downstream climate impacts research and collaborations.
- ✓ V3 supports SEA regional research and development.
- ✓ V3 supports global initiatives on climate projections.

The data produced by V3 constitute a unique dataset for Singapore and the SEA region, using the latest climate models and global warming scenarios used in the IPCC AR6. The data and the V3 Stakeholder and Science reports, together, constitute the most advanced information on climate change available over Singapore and SEA. V3 will form the basis of new as well as continuing adaptation planning efforts (e.g., based on V2) for Singapore, to prepare for the impact of climate change in various sectors, such as water, food, human health, energy, infrastructure, biodiversity, etc.

In addition to the use of V3 to inform long-term planning efforts for Singapore, the findings of the study also lead to improved understanding of the science of climate change and their drivers over Singapore and SEA region.

The 8km V3 data for the region will also be shared with the research community and with international partners and collaborations like the Food and Agriculture Organization of the United Nations to enable new research in climate change and impacts studies for Southeast Asia.

6.1 Adaptation planning in Singapore

Singapore takes a science-based approach to adaptation planning. We will use the scientific climate information in our policy making, such as in planning the adaptation features required to combat future climate change, and in assessing the effectiveness and cost-benefit analysis of plans to protect Singapore against the negative impacts of climate change and climate variability.

Despite international efforts to limit the rise in global temperatures, the effects of climate change are already upon us. V3 findings tell us that we can expect higher sea levels, hotter days, and more extreme weather events from now to 2100 under the worst-case scenario. To be prepared, Singapore will further strengthen and accelerate our climate defences, and review our adaptation plans.

Climate science will continue to evolve and improve, and Singapore must continue to keep up with the scientific advancements. New models and data will need to be incorporated, and new methods and approaches will need to be 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.

6.2 Climate Impacts Science Research

V3 data will also form the basis for deeper research in climate impacts science for Singapore, including through the National Sea Level Programme (NSLP) and the Climate Impact Science Research (CISR) Programme launched in July 2022. Focusing on five key priority areas—sea level rise; water resource and flood management; biodiversity and food security; human health and energy; and cross-cutting research to bridge science-policy translation – the CISR will study climate impacts issues relevant for long term climate adaptation planning for Singapore.

6.3 Regional outreach

In addition to supporting local adaptation planning efforts of Singapore Government agencies, V3 data will also be shared in the region with regional and international agencies and the scientific community.

6.3.1 ASEAN Specialised Meteorological Centre (ASMC)

MSS hosts the ASEAN Specialised Meteorological Centre (ASMC), which was officially established in January 1993 under the auspices of the ASEAN Sub-Committee on Meteorology and Geophysics. The key roles of the ASMC include:

- Undertaking research and development to improve scientific understanding and prediction of weather and climate systems of significance to the region.

- Serving as the ASEAN regional centre for monitoring and assessment of land/forest fires and haze, including provision of early warning for transboundary haze.

- Conducting regional capability development programmes to enable ASEAN National Meteorological Services leverage advances in science and technology to support important economic sectors.

In line with the above functions, the ASMC plans to share the V3 data and findings with ASEAN Member States to support the scientific understanding of climate change and impacts within the region. The ASMC will *inter alia* organise activities to train participants from the ASEAN region on the use and interpretation of V3 data and findings, including through workshops and other engagements.

6.3.2 United Nations Food and Agriculture Organisation (UNFAO)

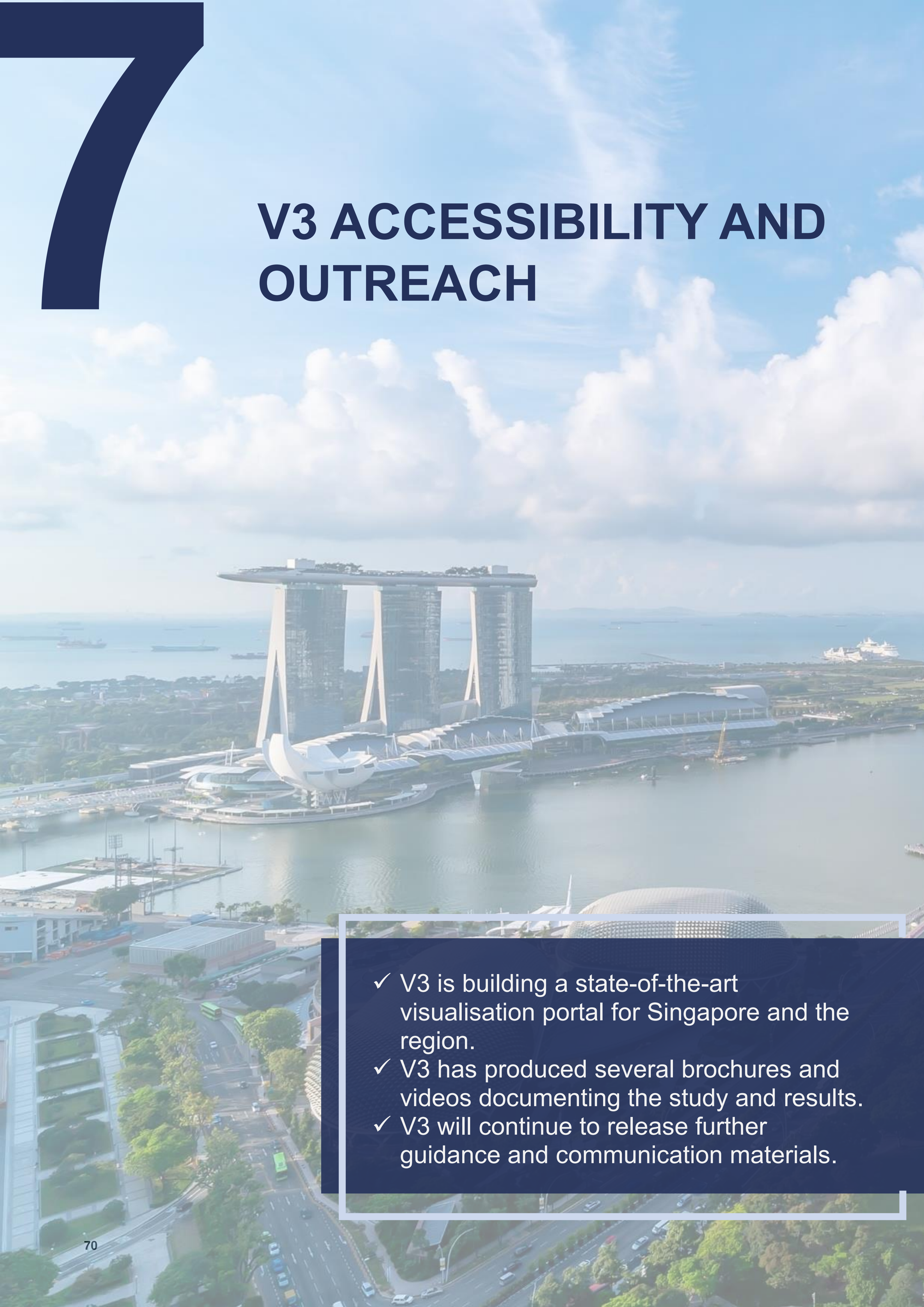
Under the ambit of the Singapore – UNFAO Memorandum of Understanding, CCRS has also embarked on a collaboration with the UNFAO on climate-resilient agri-food systems in SEA. The collaboration will entail CCRS sharing V3 climate projections data over the Southeast Asian region for incorporation into UNFAO's climate risk assessment tools. CCRS and the UNFAO are also exploring joint workshops to train ASEAN Member States in using the UNFAO's tools and the V3 data. These would enable regional users of UN FAO's tools to conduct more detailed agricultural climate impact assessments at the national level.

6.3.3 Coordinated Regional Climate Downscaling Experiment (CORDEX)

The CORDEX-Southeast Asia (CORDEX-SEA) is an important regional branch of the global CORDEX community focusing on providing regional climate change projections in the SEA region. While there are overlaps between the two efforts (CORDEX-SEA CMIP6 regional projections and V3) there are important differences too that make them complement each other for carrying out more robust physical climate change assessment and impact studies over the SEA region.

There are overlaps such as (a) some similar CMIP6 GCMs, (b) similar domains with small differences in latitudinal and longitudinal extents, and (c) some common scenarios (SSP1-2.6 and SSP2-4.5). There are some important differences such as (a) CORDEX-SEA uses SSP3-7.0 as their highest emission scenario, whereas V3 uses SSP5-8.5, and (b) the CORDEX-SEA primary spatial resolution for regional climate change projections is 25 km, whereas for V3 it is 8 km. Thus, the two datasets are highly complementary.

7 V3 ACCESSIBILITY AND OUTREACH



- ✓ V3 is building a state-of-the-art visualisation portal for Singapore and the region.
- ✓ V3 has produced several brochures and videos documenting the study and results.
- ✓ V3 will continue to release further guidance and communication materials.

There are multiple target audiences for V3 that include government agencies, scientific community, businesses, and the public. A differentiated communications and engagement plan will be used to make V3 more accessible. For example, V3 findings and its use for subsequent adaptation planning will be shared with national and regional stakeholders by conducting relevant workshops.

Topical brochures and videos have been produced on the following topics to engage the stakeholder agencies and the public:

1. V3 Explained
2. Climate Change - From Global to Local
3. Past and Future Sea-level Change
4. Understanding Climate Extremes

Additional brochures and videos will be produced after the public launch of V3 as part of continued outreach efforts.

V3 gives us an opportunity to bolster Singapore's international contributions and efforts towards understanding and addressing climate change. V3 data will be shared with regional countries/partners to understand the effects of climate change on the region.

V3 findings and outreach material (Stakeholder and science reports, images/charts, brochures, videos and more), along with information on upcoming events will be made available through the V3 portal (https://www.mss-int.sg/V3-climate-projections).

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Annex A: Guidance on using projections

Which SSP do I use?

The three Shared Socioeconomic Pathways (SSPs) used in V3 aim to capture a range of uncertainties in future concentrations of greenhouse gases, which drive climate change. SSP5-8.5 is a scenario representing a future with very high greenhouse gas concentrations that continue to increase throughout the 21st century, similar to the characteristics of RCP8.5. SSP2-4.5 is a scenario where concentrations peak mid-century and then decline, resembling aspects of RCP4.5. SSP1-2.6 represents a low-emission scenario with strong mitigation efforts, aiming to limit global temperature increases to well below 2°C above pre-industrial levels.

Note that the projected changes under SSP5-8.5 are generally greater than those under SSP2-4.5 and SSP1-2.6, and this should be taken into consideration when making adaptation decisions.

SSP1-2.6, with its focus on sustainable development and significant mitigation efforts, aligns with a pathway that meets the international target of keeping temperature rise below 2°C. SSP2-4.5 represents a moderate scenario with some efforts towards mitigation, while SSP5-8.5 aligns with a high-emission scenario and can be regarded as a business-as-usual pathway. SSP5-8.5 provides a reasonable estimate of the high-end impacts of climate change and should be considered for use in adaptation planning where high investment is required and decisions cannot easily be updated.

V3 results emphasise the need for mitigation action by quantifying the substantial climatic changes that may occur if no action is taken under SSP5-8.5 scenario, underscoring the importance of considering SSP1-2.6 to SSP2-4.5 as pathways involving significant and moderate mitigation efforts, respectively.

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

Total 'change' in climate is a combination of long-term trends and natural variations within the climate system. The natural climate variation, as simulated in any specific model, has the potential to either amplify or reduce the impact of the long-term trend in that model.

This becomes particularly significant when the modelled amplitude of decadal variations is similar in size to the climate change signal, as is observed in changes in mean and extreme rainfall in the Singapore region. Although the models can capture, to some extent, the natural decadal variations in the climate system, predicting the evolution of these variations into the future remains challenging.

In reality, the anthropogenic climate change signal is not linear, and its interaction with natural variability is complex. Despite this complexity, the fundamental point remains valid: both anthropogenic and natural climate variations will play crucial roles in shaping the net change in climate at any given point in the future.

Why are projected changes under the SSP2-4.5 scenario sometimes larger than those under SSP5-8.5?

This can occur for the same reasons illustrated in the preceding question. As mentioned earlier, this issue typically arises when the natural decadal fluctuations of climate are of a comparable or greater magnitude than the overall change signal. This is particularly relevant for rainfall variables, where the modelled natural decadal variations can be similar to or even exceed the anticipated changes. However, it's important to note that this issue is often less pronounced when considering projected future temperature changes. In this context, the anticipated temperature changes are generally considerably larger than the natural variability.

How can I use the group of model results?

This study presents outcomes from six distinct GCMs that have been downscaled over Singapore and SEA. While the report provides an overview of the range of results from all six models and presents average (or median) changes where applicable, it intentionally does not delve into individual model results. The reason is that no particular model is afforded greater confidence, and all offer plausible climate futures. Consequently, it is recommended to utilise the entire ensemble for comprehensive insights.

However, in cases where specific model results are required for further modelling work related to decision-making, careful selection of one or more models becomes necessary. For robust decision-making, it is beneficial to consider models that indicate both the largest and smallest increases in variables of interest. Relying solely on the median model is discouraged, as it does not necessarily represent the most likely change. In instances where significant impacts and adaptation costs are anticipated, particularly associated with high-end scenarios, it is advisable to explore potential changes beyond the conventional scenarios.

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

V3 data will be provided on 8km and 2km grids. Notably, temperature, rainfall, winds, and relative humidity data over Singapore have undergone bias adjustments using observations.

For studies focusing on even finer resolutions, particularly those requiring insights into urban microclimates, utilising an urban-scale model with detailed urban morphology may be more suitable. Such models can offer a more nuanced and accurate representation of local conditions in urban areas, providing valuable information for impact modelling and detailed analyses.

Moreover, it is crucial to exercise caution when employing interpolation techniques, as they assume spatial smoothness in the microclimate. This assumption may not always be valid, and the results should be interpreted with this in mind.

Are urban effects taken account of in the projections?

The projections in the 8km and 2km simulations include a basic representation of the urbanisation of the Singapore landscape. However, it is crucial to highlight that detailed aspects of the urban environment cannot be comprehensively captured in models with such resolutions. More sophisticated sub-km scale urban modelling is essential to realistically incorporate the full spectrum of urban effects. Such models can provide more accurate insights into the complex interactions between urbanisation and climate, ensuring a more comprehensive assessment of future climatic conditions in urban areas.

It is also important to note that the future projections in the V3 study align with the latest SSP scenarios. Nevertheless, these projections do not explicitly consider changes in the Singapore urban landscape and their potential impact on the microclimate.

Annex B: Glossary

A

Adaptation Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change impacts.

Adaptive capacity A system's ability to implement adaptation measures to climate change (including climate variability and extremes).

Anomaly Value that represents the difference between the value for a given year or season from the normal of the reference period.

Anthropogenic climate change Human-made climate change - climate change caused by human activity as opposed to natural processes.

AR4 Abbreviation for the Fourth Assessment Report produced by the Intergovernmental Panel on Climate Change (IPCC), which was published in 2007. The report assessed and summarised the science of climate change at the time of its release.

AR5 Abbreviation for the Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC), which was published over 2013 and 2014.

AR6 Abbreviation for the Sixth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC), which was published over 2021 and 2022.

Atmosphere The atmosphere is a mixture of gases that surrounds the Earth. It helps make life possible by providing us with air to breathe, shielding us from harmful ultraviolet (UV) radiation coming from the Sun, trapping heat to warm the planet, and preventing extreme temperature differences between day and night.

Atmospheric aerosols Microscopic particles suspended in the lower atmosphere that reflect sunlight back to space. These generally have a cooling effect on the planet and can mask global warming. They play a key role in the formation of clouds, fog, precipitation, and ozone depletion in the atmosphere.

B

Barystatic sea-level change Global-mean sea-level change due to the addition of water that is formerly residing on land or atmosphere, or the removal of water from the oceans.

Bias Adjustment A sophisticated statistical method used to correct systematic errors (biases) in climate model outputs to make them more similar to climate observation data. The biases can occur when models do not accurately represent real-world conditions. Bias adjustment techniques are applied to improve the reliability of climate change impact assessments for various sectors like water resources, agriculture, and more. Bias adjustment in The Third National Climate Change Study (V3) makes use of the trend-preserving ISIMIP3BASD (V1.0) method described by: *Lange, S.: Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0), Geosci. Model Dev., 12, 3055–3070, https://doi.org/10.5194/gmd-12-3055-2019, 2019.*

Bioenergy Bioenergy is a form of renewable energy generated when we burn biomass fuel. Biomass fuels come from organic material such as harvest residues, purpose-grown crops and organic waste from our homes, businesses and farms.

Biofuels Gas or liquid fuel made from plant material. Includes wood, wood waste, wood liquors, peat, railroad ties, wood sludge, spent sulphite liquors, agricultural waste, straw, tires, fish oils, tall oil, sludge waste, waste alcohol, municipal solid waste, landfill gases, other waste, and ethanol blended into motor gasoline.

Business as usual (BAU) A scenario used for projections of future emissions assuming no action, or no new action, is taken to mitigate the problem. Within IPCC AR6, the BAU scenario is the SSP5-8.5 scenario.

C

Carbon capture and storage The collection and transport of concentrated carbon dioxide gas from large emission sources, such as power plants. The gases are then injected into deep underground reservoirs. Carbon capture is sometimes referred to as geological sequestration.

Carbon Cycle All parts (reservoirs) and fluxes of carbon. The cycle is usually thought of as four main reservoirs of carbon interconnected by pathways of exchange. The reservoirs are the atmosphere, terrestrial biosphere (usually includes freshwater systems), oceans, and sediments (includes fossil fuels). The annual movements of carbon, the carbon exchanges between reservoirs, occur because of various chemical, physical, geological, and biological processes. The ocean contains the largest pool of carbon near the surface of the Earth, but most of that pool is not involved with rapid exchange with the atmosphere.

Carbon dioxide (CO_2) Carbon dioxide is a gas in the Earth's atmosphere. It occurs naturally and is also a by-product of human activities such as burning fossil fuels. It is the principal greenhouse gas produced by human activity.

Carbon dioxide (CO_2) equivalent Six greenhouse gases are limited by the Kyoto Protocol and each has a different global warming potential. The overall warming effect of this cocktail of gases is often expressed in terms of carbon dioxide equivalent - the amount of CO_2 that would cause the same amount of warming.

Carbon footprint The amount of carbon emitted by an individual or organisation in a given period of time, or the amount of carbon emitted during the manufacture of a product.

Carbon sink Any process, activity or mechanism that removes carbon from the atmosphere. The biggest carbon sinks are the world's oceans and forests, which absorb large amounts of carbon dioxide from the Earth's atmosphere.

CCRS Centre for Climate Research Singapore. CCRS is the research division of the Meteorological Service Singapore (MSS) and was established on 23 March 2013.

Climate The long-term average (typically spanning decades to centuries) of weather patterns and conditions observed in a particular region or globally. It is characterised by temperature, precipitation, humidity, wind and other atmospheric conditions. Climate is influenced by various factors including latitude, altitude, topography, ocean currents and the distribution of land and water bodies.

Climate change A pattern of change affecting global or regional climate, as measured by yardsticks such as average temperature and rainfall, or an alteration in frequency of extreme weather conditions. This variation may be caused by both natural processes and human activity. Global warming is one aspect of climate change.

Climate change scenario A description of the evolution in the climate for a given time period in the future, using a specific modelling technique and under specific assumptions about the evolution of greenhouse gas emissions and other factors that may influence the climate in the future. Climate projections from climate models often serve as the raw material for constructing climate scenarios in the most widely-used method of climate scenario construction.

Climate feedback An interaction in which a perturbation in one climate quantity causes a change in a second, and that change ultimately leads to an additional (positive or negative) change in the first.

Climate information Refer to climatic data that describe either past conditions, obtained from meteorological observations (stations, satellites, radars), or the future, obtained from the outputs of climate models.

Climate model A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for most of its known properties.

Climate projection A climate projection refers to the response of the climate system over the next several decades and beyond under a given scenario of future global greenhouse gas emissions and certain assumptions of human activity. Different scenarios of human activity and associated global emissions lead to different levels of global warming, thus giving a range of possible future outcomes. In this way, climate projections are distinguished from climate predictions as the latter are climate model forecasts of the most likely future climate conditions in the next few months and years based on the current observed conditions, its natural variability and expected changes from global emissions in the near future.

Climate scenario A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models.

Climate sensitivity The effective climate sensitivity (units; °C) is an estimate of the global mean surface temperature response to doubled carbon dioxide concentration that is evaluated from model output or observations for evolving non-equilibrium conditions.

Climate services An organisation that supplies climate information to users. The roles of these organisations may include providing historical climate data, running climate simulations, and tailoring their outputs to suit the needs of individual users.

Climate variability The variations above or below a long-term mean state of the climate. This variability can be due to natural internal processes within the climate system (internal variability) or to variations in anthropogenic external forcing (external variability).

Cloud condensation nuclei Airborne particles that serve as an initial site for the condensation of liquid water, which can lead to the formation of cloud droplets. A subset of aerosols that are of a particular size.

CMIP5 Coupled Model Intercomparison Project, Phase 5. CMIP5 is a coordinated climate modelling exercise involving 20 climate-modelling groups from around the world. It has provided a standard experimental protocol for producing and studying the output of many different global climate models. The output from CMIP5 ensemble experiments is used to inform international climate assessment reports, such as those from the IPCC.

CMIP6 Coupled Model Intercomparison Project Phase 6

CO2 See carbon dioxide

Confidence The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. IPCC uses standard confidence thresholds such as "*low*", "*medium*" and "*high*" to indicate probabilities of occurrence of projected changes to "*very unlikely*" (<10 Percent), "*likely*" (17 – 83 Percent) and "*Very likely*" (>90 Percent).

Contemporary Mass Redistribution (CMR) sea-level change Satellite altimetry sea-level without sterodynamic and GIA-induced sea-level. 2. Composed of barystatic sea-level change and GRD fingerprints.

CORDEX Coordinated Regional Climate Downscaling Experiment.

D

Dangerous climate change A term referring to severe climate change that will have a negative effect on societies, economies, and the environment as a whole. The phrase was introduced by the 1992 UN Framework Convention on Climate Change, which aims to prevent "dangerous" human interference with the climate system.

Decadal variability Fluctuations, or ups-and-downs of a climate feature or variable at the scale of approximately a decade (typically taken as longer than a few years such as ENSO, but shorter than the 20-30 years of the IPO).

Deforestation The permanent removal of standing forests that can lead to significant levels of carbon dioxide emissions.

Delta Difference between the future value and the reference period (or baseline) value of a climate variable, as simulated by a climate model.

Detection and attribution Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, less than 10 per cent. Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence.

Downscaling A method that can provide climate model outputs at a finer resolution than their original resolution. Two different approaches are prioritised: statistical downscaling and dynamical downscaling.

Dynamical downscaling This type of downscaling relies on the use of regional climate models that are driven at their boundaries by global climate models.

E

Earth Science Earth science is the study of the Earth's structure, properties, processes, and four and a half billion years of biotic evolution. Understanding these phenomena is essential to maintenance of life on the planet.

El Niño Southern Oscillation (ENSO) A fluctuation in global scale tropical and subtropical surface pressure, wind, sea surface temperature, and rainfall, and an exchange of air between the south-east Pacific subtropical high and the Indonesian equatorial low. Often measured by the surface pressure anomaly difference between Tahiti and Darwin or the sea surface temperatures in the central and eastern equatorial Pacific. There are three phases: neutral, El Niño and La Niña. During an El Niño event the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the eastern tropical surface temperatures warm, further weakening the trade winds. The opposite occurs during a La Niña event.

Emissions scenario A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g. greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.

Ensemble Term used to refer to the complete set of climate simulations or climate scenarios used for a given study. Because no one model can be considered best, it is standard practice in climate change studies to use the outputs of many models when studying the projected changes. Consequently, ensemble is usually a synonym for the term multimodel ensemble. Note, however, that other, more restrictive, definitions exist for ensembles designed to study very specific scientific questions (for example, an ensemble could represent a set of simulations made with the same climate model, using the same emissions scenario, but initialised using different starting conditions).

Extreme weather An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations.

F

Feedback loop In a feedback loop, rising temperatures on the Earth change the environment in ways that affect the rate of warming. Feedback loops can be positive (adding to the rate of warming), or negative (reducing it). The melting of Arctic ice provides an example of a positive feedback process. As the ice on the surface of the Arctic Ocean melts away, there is a smaller area of white ice to reflect the Sun\'s heat back into space and more open, dark water to absorb it. The less ice there is, the more the water heats up, and the faster the remaining ice melts.

Fossil fuels Natural resources, such as coal, oil and natural gas, containing hydrocarbons. These fuels are formed in the Earth over millions of years and produce carbon dioxide when burnt.

G

GCM Global Climate Model

Geocentric sea-level change The change in local mean sea level with respect to the terrestrial reference frame. This does not include effects of vertical land movement.

GIA-induced sea-level change GRD due to ongoing changes in the solid Earth caused by past changes in land ice (i.e., during the Last Glacial Maxima).

Global average temperature The mean surface temperature of the Earth measured from three main sources: satellites, monthly readings from a network of over 3,000 surface temperature observation stations and sea surface temperature measurements taken mainly from the fleet of merchant ships, naval ships and data buoys.

Global climate model (GCM) A global climate model (GCM) is a complex computer-based representation of the Earth's climate system. It incorporates mathematical equations to simulate and predict the behaviour of various components of the climate system, including the atmosphere, oceans, land surface, and sea ice. GCMs are used to study and understand past climate patterns, as well as to project and predict future climate changes. They consider factors such as greenhouse gas concentrations, solar radiation, atmospheric circulation patterns, and interactions between different components of the climate system. GCMs help scientists make predictions about how the Earth's climate might respond to different scenarios, such as changes in greenhouse gas emissions or land use patterns.

Global dimming An observed widespread reduction in sunlight at the surface of the Earth, which varies significantly between regions. The most likely cause of global dimming is an interaction between sunlight and microscopic aerosol particles from human activities. In some regions, such as Europe, global dimming no longer occurs, thanks to clean air regulations.

Global energy budget The global energy budget refers to the balance between the incoming and outgoing energy on Earth. It represents the distribution and flow of energy throughout the Earth's atmosphere, oceans, land, and ice. The incoming energy is primarily in the form of solar radiation, while the outgoing energy is in the form of reflected sunlight, emitted infrared radiation, and heat transfer. The global energy budget plays a crucial role in understanding Earth's climate system and its changes over time.

Global warming Global warming refers to the long-term increase in Earth's average surface temperature due to human activities, primarily the emission of greenhouse gases, such as carbon dioxide, into the atmosphere. Global warming leads to various adverse effects, including climate change, rising sea levels, more frequent and severe extreme weather events, and disruptions to ecosystems.

Global-mean sea-level rise Global-mean sea-level rise for the global mean of relative sea-level change, due to the change in the volume of the ocean.

Global-mean thermosteric sea-level change Global-mean sea-level change due to thermal expansion

Gravitational, Earth's Rotational, viscoelastic solid-Earth Deformational (GRD) effects Changes in gravitation and rotation alter the geopotential field and hence the geoid, while deformation of the solid Earth changes the sea floor topography through vertical land movement.

Greenhouse effect The insulating effect of certain gases in the atmosphere, which allow solar radiation to warm the earth and then prevent some of the heat from escaping. See also Natural greenhouse effect.

Greenhouse gases (GHGs) Natural and industrial gases that trap heat from the Earth and warm the surface. The Kyoto Protocol restricts emissions of six greenhouse gases: natural (carbon dioxide, nitrous oxide, and methane) and industrial (perfluorocarbons, hydrofluorocarbons, and sulphur hexafluoride).

Grid (grid points) Discrete model "cells" which represent computational units of a climate model. The simplest model grids typically divide the globe (or model domain) into constant angular grid spacing (i.e., a latitude / longitude grid). A climate model's horizontal resolution is often expressed as the size of a single grid cell (e.g., 1° x 1° grid or 10 km by 10 km grid).

H

Hadley Cell/Circulation A direct, thermally driven circulation in the atmosphere consisting of poleward flow in the upper troposphere, descending air into the subtropical high-pressure cells, return flow as part of the trade winds near the surface, and with rising air near the equator in the so-called Inter-Tropical Convergence zone.

Halosteric sea-level change Steric sea-level change due to changes in salinity in the ocean.

High emissions scenario This scenario assumes that greenhouse gas concentrations will continue to increase at approximately the same rate as they are increasing today. Under this scenario, the planet's radiative forcing will have increased by 8.5 W/m^2 by the year 2100, relative to 1750 (and continues to rise well after 2100). In the scientific literature, this scenario is referred to as "RCP8.5". Of the four greenhouse gas pathways (RCP8.5, RCP6.0, RCP4.5, RCP2.6) used by the IPCC for its 5th Assessment Report, this pathway results in the most severe global warming and climate change.

Hockey stick The name given to a graph published in 1998 plotting the average temperature in the Northern hemisphere over the last 1,000 years. The line remains roughly flat until the last 100 years, when it bends sharply upwards. The graph has been cited as evidence to support the idea that global warming is a man-made phenomenon, but some scientists have challenged the data and methodology used to estimate historical temperatures. (It is also known as MBH98 after its creators, Michael E. Mann, Raymond S. Bradley and Malcolm K. Hughes.)

I

IDF curves Intensity-Duration-Frequency curves relate short-duration rainfall intensity with its frequency of occurrence and are often used for flood forecasting and urban drainage design.

Index (climate index) Term used to refer to properties of the climate that are not measured in the field or calculated by climate models but rather that are calculated or derived from climate variables such as temperature and precipitation. Examples include the number of growing degree-days, freeze-thaw cycles, and the drought code index. (see variable)

Indian Ocean Dipole (IOD) Large-scale mode of interannual variability of sea surface temperature in the Indian Ocean. This pattern manifests through a zonal gradient of tropical sea surface temperature, which in its positive phase in September to November shows cooling off Sumatra and warming off Somalia in the west, combined with anomalous easterlies along the equator.

Inter-decadal Pacific Oscillation A fluctuation in the sea surface temperature (SST) and mean sea level pressure (MSLP) of both the north and south Pacific Ocean with a cycle of 15-30 years. Unlike ENSO, the IPO may not be a single physical 'mode' of variability but be the result of a few processes with different origins. A related phenomenon, the Pacific Decadal Oscillation (PDO), is also an oscillation of SST that primarily affects the northern Pacific.

Inverse barometer effects on sea-level change Sea-level change due to atmospheric pressure variations.

IPCC The Intergovernmental Panel on Climate Change is a scientific body established by the United Nations Environment Programme and the World Meteorological Organization. It reviews and assesses the most recent scientific, technical, and socio-economic work relevant to climate change, but does not carry out its own research. The IPCC was honoured with the 2007 Nobel Peace Prize.

J

Jet stream A narrow and fast-moving westerly air current that circles the globe near the top of the troposphere. The jet streams are related to the global Hadley circulation.

K

L

Low emissions scenario This scenario assumes that greenhouse gas emissions will continue to increase until mid-century and then decline significantly. The IPCC refers to this scenario as a "peak and decline" scenario that increased the planet's radiative forcing to 2.6W/m2 by year 2100, relative to 1750.In the scientific literature, this scenario is referred to as "RCP2.6". Of the four greenhouse gas pathways (RCP8.5, RCP6.0, RCP4.5, RCP2.6) used by the IPCC for its 5th Assessment Report, this RCP results in the lowest level of global warming and climate change. This scenario is the only one that can ensure the success of the Paris Agreement.

LULUCF This refers to Land Use, Land-Use Change, and Forestry. Activities in LULUCF provide a method of offsetting emissions, either by increasing the removal of greenhouse gases from the atmosphere (i.e., by planting trees or managing forests), or by reducing emissions (i.e. by curbing deforestation and the associated burning of wood).

M

Madden Julian Oscillation (MJO) The largest single component of tropical atmospheric intra-seasonal variability (periods from 30 to 90 days). The MJO propagates eastwards at around 5 m/s in the form of a large-scale coupling between atmospheric circulation and deep convection. As it progresses, it is associated with large regions of both enhanced and suppressed rainfall, mainly over the Indian and western Pacific Oceans.

Manometric sea level Change in the time-mean local mass of the ocean per unit area, assuming the density does not change

Mean sea level The time-mean of the sea surface.

Methane Methane is the second most important man-made greenhouse gas. Sources include both the natural world (wetlands, termites, wildfires) and human activity (agriculture, waste dumps, leaks from coal mining).

Mitigation Action that will reduce man-made climate change. This includes action to reduce greenhouse gas emissions or absorb greenhouse gases in the atmosphere.

Moderate emissions scenario This scenario assumes that greenhouse gas emissions will continue to increase (but more slowly than they are today) until mid-century and then stabilise until the end of the century. However, carbon dioxide concentrations will still end up being much higher than they are today. The IPCC describes this scenario as a "stabilisation pathway" that increases the planet's radiative forcing by 4.5 W/m2 by the year 2100, relative to 1750. In the scientific literature, this scenario is referred to as "RCP4.5". Of the four greenhouse gas pathways (RCP8.5, RCP6.0, RCP4.5, RCP2.6) used by the IPCC for its 5th Assessment Report, this RCP results in the second-lowest level of global warming and climate change.

Monsoon A monsoon is a tropical and subtropical seasonal reversal in both the surface winds and associated rainfall, caused by differential heating between a continental-scale land mass and the adjacent ocean. Monsoon rains occur mainly over land in summer.

MSS Meteorological Service Singapore

N

Natural greenhouse effect The natural level of greenhouse gases in our atmosphere, which keeps the planet about 30C warmer than it would otherwise be - essential for life as we know it. Water vapour is the most important component of the natural greenhouse effect.

Natural variability Variability that describes short-term changes in that take place over months, seasons and years. It is due to natural variations in external forces such as changes in the sun's radiation or volcanoes, as well variations in internal processes, such as those related to the interactions of the oceans and the atmosphere, that occur for example in the Pacific Ocean during an El Niño event.

NCCS National Climate Change Secretariat

NEA National Environment Agency

O

Ocean acidification The ocean absorbs approximately one-fourth of man-made CO2 from the atmosphere, which helps to reduce adverse climate change effects. However, when the CO2 dissolves in seawater, carbonic acid is formed. Carbon emissions in the industrial era have already lowered the pH of seawater by 0.1. Ocean acidification can decrease the ability of marine organisms to build their shells and skeletal structures and kill off coral reefs, with serious effects for people who rely on them as fishing grounds.

Ocean dynamic sea-level change The local height of the sea surface above the geoid, with the inverse barometer correction applied

P

Percentile A percentile is a value on a scale of one hundred that indicates the percentage of the dataset values that is equal to, or below it. The percentile is often used to estimate the extremes of a distribution. For example, the 90th (or 10th) percentile may be used to refer to the threshold for the upper (or lower) extremes.

ppm (350/450) An abbreviation for parts per million, usually used as short for ppmv (parts per million by volume). The Intergovernmental Panel on Climate Change (IPCC) suggested in 2007 that the world should aim to stabilise greenhouse gas levels at 450 ppm CO_2 equivalent to avert dangerous climate change. Some scientists, and many of the countries most vulnerable to climate change, argue that the safe upper limit is 350ppm. Current levels of CO_2 only are about 420ppm.

PRCPTOT Annual total precipitation from wet days (wet day defined as any day with daily precipitation >= 1mm).

Pre-industrial levels of carbon dioxide The levels of carbon dioxide in the atmosphere prior to the start of the Industrial Revolution. These levels are estimated to be about 280 parts per million (by volume). The current level is around 420ppm.

Projection (climate projection) Projections represent the future portion of climate model simulations that take into account an emissions scenario. Consequently, a projection is based on assumptions such as those concerning future socioeconomic and technological developments that may or may not be realised and thus are subject to uncertainty.

Q

R

Radiative forcing Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W/m^2) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or the output of the Sun.

Range The term range is used to represent the spectrum of output data from an ensemble of simulations or scenarios.

RCP2.6 See low emissions scenario.

RCP4.5 See moderate emissions scenario.

RCP8.5 See high emissions scenario.

Reference period In practice, it often refers to a period of time from the recent past used in the production of climate scenarios. Future period values produced by climate models are compared with those from this period to evaluate changes. The WMO recommends 30-year intervals as reference periods, such as 1971-2000; however there are exceptions. For example, the current reference period used by the IPCC is 1985-2005. A synonymous term is baseline period. Accordingly, the terms 'reference scenario' or 'baseline scenario' are used to refer to climate scenarios for a reference period.

Regional climate model (RCM) Just like a GCM, the regional climate model is a mathematical representation of the climate system, based on equations describing the physical processes governing the climate. RCMs have a finer resolution than GCMs and therefore contain a better representation of topography and can include processes and features, such as lakes, which are too small to resolve in GCMs. As a consequence they are more expensive to run and typically operate as 'limited domain' models, meaning that they cover only a portion of the globe.

Relative sea-level change The change in local mean sea level relative to the local solid surface, i.e., the sea floor. This includes effects of vertical land movement.

Renewable energy Renewable energy is energy created from sources that can be replenished in a short period of time. The five renewable sources used most often are: biomass (such as wood and biogas), the movement of water, geothermal (heat from within the earth), wind, and solar.

Representative Concentration Pathways (RCPs) Representative Concentration Pathways follow a set of greenhouse gas, air pollution (e.g., aerosols) and land-use scenarios that are consistent with certain socio-economic assumptions of how the future may evolve over time. The well mixed concentrations of greenhouse gases and aerosols in the atmosphere are affected by emissions as well as absorption through land and ocean sinks. There are four Representative Concentration Pathways (RCPs) that represent the range of plausible futures from the published literature.

Resolution In climate models, this term refers to the physical distance (kilometres or degrees) between each point on the grid used to compute the equations. Temporal resolution refers to the time step or time elapsed between each model computation of the equations. See Grid.

Return period An estimate of the average time interval between occurrences of an event (e.g. flood or extreme rainfall) of a defined size or intensity.

Risk The potential for consequences where something of value is at stake and where the outcome is uncertain. Risk is often represented as a probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur.

Risk management The plans, actions, or policies implemented to reduce the likelihood and/or consequences of risks or to respond to consequences.

Risk assessment The qualitative and/or quantitative scientific estimation of risks.

RWG Resilience Working Group

S

Sea level anomaly (SLA) Deviations of sea surface height from a mean level (i.e., variations from mean sea level).

Shared Socioeconomic Pathways (SSPs) A set of scenarios used to describe a range of possible trajectories for crucial factors like future economic development, population growth, technological advancement, energy use and greenhouse gas emissions. These scenarios allow researchers and policymakers to understand and compare how different social, economic and environmental choices may lead to very different greenhouse gas emissions and thus global warming levels along with their potential impacts. Collectively, they span the range of plausible climate futures. In V3, future climate projections are made under SSP1-2.6 (Sustainability: Taking the Green Road), SSP2-4.5 ('Middle of the Road') and SSP5-8.5 (Fossil-Fuel Development: Taking the Highway) scenarios.

Simulation (Climate simulation) Climate simulations represent the outcome of running a climate model for a certain period of time. The time span of a simulation can range from a few years to thousands of years and will iteratively be computed at intervals of a few minutes. They are run for both the past and the future.

SINGV-RCM Singapore Variable Resolution-Regional Climate Model

SSP Shared Socioeconomic Pathway

Statistical downscaling This type of downscaling relies on the use of statistical relationship that relate large scale climate features, named predictors, to local climate variables (predictants).

Steric sea-level change Composed of thermosteric and halosteric sea-level change.

Sterodynamic sea-level change Composed of ocean dynamic sea level and global-mean thermosteric sea-level

T

Thermosteric sea-level change Steric sea-level change due to changes in ocean temperature.

Tipping point A tipping point is a threshold for change, which, when reached, results in a process that is difficult to reverse. Scientists say it is urgent that policy makers halve global carbon dioxide emissions over the next 50 years or risk triggering changes that could be irreversible.

U

Uncertainty A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts).

UNFCCC The United Nations Framework Convention on Climate Change is one of a series of international agreements on global environmental issues adopted at the 1992 Earth Summit in Rio de Janeiro. The UNFCCC aims to prevent "dangerous" human interference with the climate system. It entered into force on 21 March 1994 and has been ratified by 192 countries.

V

V2 Singapore's Second National Climate Change Study

V3 Singapore's Third National Climate Change Study

Variable The term climate variable is used to refer to a variable that can be measured directly in the field (at meteorological stations for example) or that is calculated by climate models. (See Index).

Vertical land movement (VLM) The change in the height of the sea floor or the land surface.

Vulnerability The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change. It is a function of the character, magnitude and rate of change to which a system is exposed and the sensitivity and adaptive capacity of that system.

W

Walker Circulation An east-west circulation of the atmosphere above the tropical Pacific, with air rising above warmer ocean regions (normally in the west), and descending over the cooler ocean areas (normally in the east). Its strength fluctuates with that of the Southern Oscillation.

Weather The state of the atmosphere with regard to temperature, cloudiness, rainfall, wind and other meteorological conditions. It is not the same as climate which is the average weather over a much longer period.

X

Y

Z

METEOROLOGICAL SERVICE SINGAPORE
Centre for Climate Research Singapore

About the Centre for Climate Research Singapore (CCRS)

A research centre and part of the Meteorological Service Singapore (MSS). It was officially launched in March 2013, with the vision to be a world leading centre in tropical climate and weather research focusing on the Southeast Asia region.

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