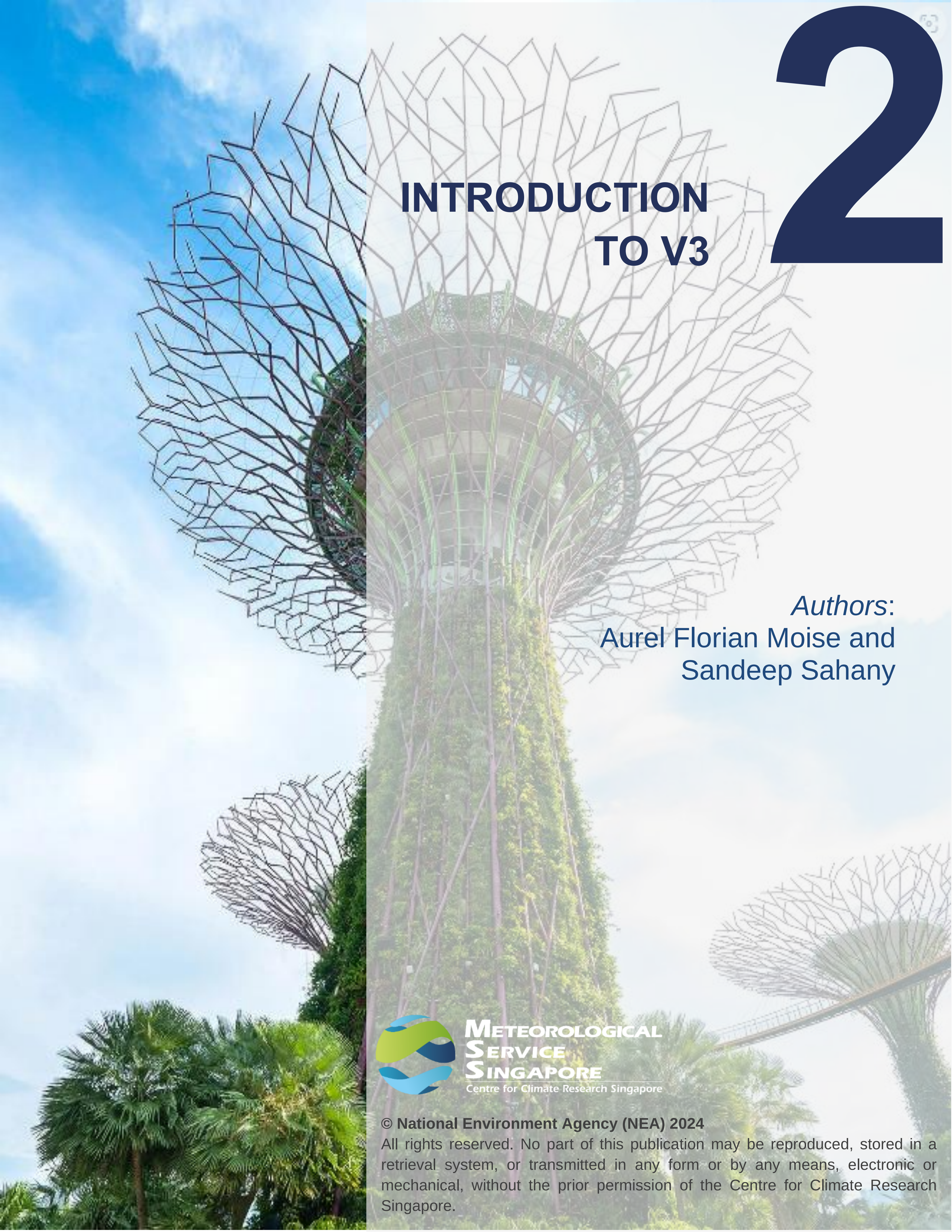

2

INTRODUCTION TO V3

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2.1 Climate Change Governance in Singapore

The release of the IPCC 6th Assessment Report in 2021/22 provided further strong evidence on the state of the science around climate change, from basic science, impacts, adaptation to mitigation (IPCC 2021, 2022a, 2022b). While there is a strong focus on the global picture, many of the conclusions can be translated directly to the various regions. The United Nations Director General Antonio Guterres spoke about 'Code Red for humanity' following the release of the first AR6 report in 2021 and some examples of these conclusions also relevant for our region are:

Recent changes in the climate are widespread, rapid, and intensifying, and unprecedented in thousands of years. Unless there are immediate, rapid, and large-scale reductions in greenhouse gas emissions, limiting warming to 1.5°C will be beyond reach.

It is indisputable that human activities are causing climate change, making extreme climate events, including heat waves, heavy rainfall, and droughts, more frequent and severe.

Climate change is already affecting every region on Earth, in multiple ways. The changes we experience will increase with further warming. There's no going back from some changes in the climate system…

At the release of the second AR6 report on Impacts, Vulnerability and Adaptation in 2022, Hoesung Lee, Chair of the IPCC, concluded "*The report is a dire warning about the consequences of inaction. It shows that climate change is a grave & mounting threat to our wellbeing and to a healthy planet*."

Global warming has caused dangerous and widespread disruption in nature and climate change is affecting the lives of billions of people despite efforts to adapt (IPCC, 2022a). Also, impacts are magnified in cities where more than half of the world's population lives. Climate risks are now regarded as higher even at lower temperatures – and likely to happen sooner & with greater intensity. One of the key conclusions of the WG-II report from AR6 is: "The Science is clear. We have a rapidly narrowing window of opportunity to secure a sustainable & liveable future." (IPCC WG-II Press Release (2022): Press release | Climate Change 2022: Impacts, Adaptation and Vulnerability (ipcc.ch)).

While climate resilience development is already challenging at current global warming levels, Singapore has been committed to enhancing its resilience through multiple pathways. The Energy & Climate Policy Division (ECPD) under the Ministry of Sustainability and the Environment, Government of Singapore, oversees issues such as energy efficiency, renewable energy, climate science and adaptation. Some key aspects of Singapore's plans for climate resilience include (1) enhancement of knowledge and expertise on climate change, (2) coastal protection, (3) water resource management, and (4) drainage and flood prevention.

In addition to building climate resilience through active adaptation planning and implementation, Singapore also has strong climate change mitigation ambitions. Singapore has committed to achieve net zero emissions by 2050 by continuing to find innovative ways to accelerate the low-carbon transition for industry, economy and society through four key thrusts:

1. Catalysing business transformation;
2. Investing in low-carbon technologies;
3. Pursuing effective international cooperation; and
4. Adopting low-carbon practices

The Singapore Green Plan 2030 is a whole-of-nation movement to advance Singapore's national agenda on sustainable development. It charts ambitious and concrete targets over the next 10 years, strengthening Singapore's commitments under the UN's 2030 Sustainable Development Agenda and Paris Agreement, and positioning it to achieve its long-term net zero emissions aspiration by 2050.

Figure 2.1 shows the committees and working groups addressing Singapore's climate change related issues. The Inter-Ministerial Committee on

Climate Change (IMCCC) enhances whole – of – government coordination on climate change policies to ensure that Singapore is prepared for the impacts of climate change. Established in 2007, IMCCC is chaired by Mr Teo Chee Hean, Senior Minister and Coordinating Minister for National Security. The IMCCC is supported by an Executive Committee (Exco) comprising the permanent secretaries of the respective Ministries. The IMCCC Exco oversees the work of the Long-Term Emissions and Mitigation Working Group (LWG), Resilience Working Group (RWG), Sustainability Working Group (SWG), Green Economy Working Group (GEWG) and Communications and Engagement Working Group (CEWG).

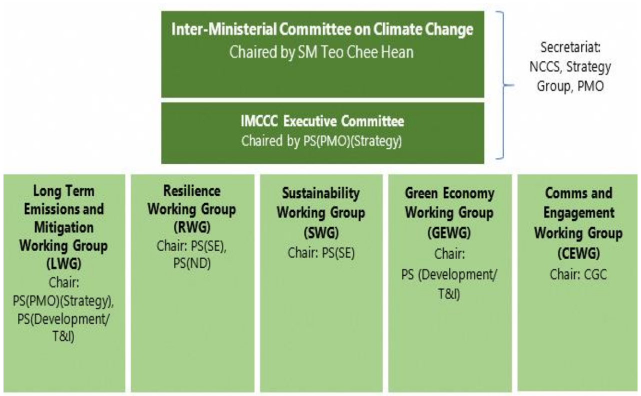

Figure 2.1: Climate Change Governance in Singapore (from NCCS, 2023).

Singapore's National Climate Change Secretariat (NCCS) was established on 1 July 2010 under the Prime Minister's Office (PMO) to develop and implement Singapore's domestic and international policies and strategies to tackle climate change. NCCS is part of the Strategy Group, which supports the Prime Minister and his Cabinet to establish priorities and strengthen strategic alignment across the Government. The inclusion of NCCS enhances strategy-making and planning on vital issues that span multiple Government ministries and agencies.

NCCS' areas of responsibility are to:

- facilitate efforts to mitigate carbon emissions in all sectors;
- help Singapore adapt to the effects of climate change;
- harness economic and green growth opportunities arising from climate change;
- encourage public awareness and promote action on climate change;

The Resilience Working Group (RWG) studies Singapore's vulnerability to the effects of climate change and develops long-term plans that ensure the nation's resilience to future environmental changes. The Long-Term Emissions and Mitigation Working Group (LWG) develops plans to reduce Singapore's long-term emissions. LWG examines mitigation options, and identifies the capabilities, infrastructure and policies needed for long-term emissions reduction. The Sustainability Working Group (SWG) develops the national sustainability agenda to strengthen Singapore's resource resilience and addresses emerging and cross-cutting issues on sustainability. The Green Economy Working Group (GEWG) coordinates and enables the growth of Singapore's green economy, to seize new economic opportunities in sustainability and create good jobs for Singaporeans. Communications and Engagement Working Group (CEWG) establishes communications priorities, to achieve greater whole-of-government coordination in climate change communications and engagement efforts, and to build consensus on Singapore's climate change plans and targets.

The Centre for Climate Research Singapore (CCRS) was launched in 2013 as a government research center to help address some of the key questions for the Singapore Government on tropical weather and climate variability and change and their impacts to Singapore's adaptation and policy planning. In 2018, CCRS was tasked to coordinate the National Sea Level Program to address key gaps in sea- level science. At the same time, initial plans were drafted for the Third National Climate Change Study (V3). Since the delivery of the results from the Second National Climate Change Study (V2) in 2015, the Singapore government has been relying on CCRS to continue to deliver important information on future climate change topics as they are relevant for Singapore and the wider Southeast Asia (SEA) region. In July 2022, the Climate Impact Science Research (CISR) Programme was launched to better understand the long-term impact of climate change on Singapore. The S$23.5 million CISR Programme, managed by CCRS, will focus 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.

2.2 Introduction to the V3 study

V3 is Singapore's Third National Climate Change Study and builds on Singapore's Second National Climate Change Study (V2, Marzin et al. 2015). Although V2 was commissioned by Singapore's National Environment Agency (NEA) to the Met Office Hadley Centre in the UK, the involvement of CCRS scientists in the co-production of V2 significantly helped in taking the leap forward to V3 which is produced entirely in-house by CCRS. Various experiences ranging from stakeholder engagement, model sub-selection, conducting dynamical downscaling simulations, analysis of past, present and future climate, bias adjustment, writing of the V2 Stakeholder and Technical reports, and data dissemination, provided the necessary exposure and confidence to CCRS scientists to be able to make V3 an in-house production.

Stakeholder engagement has been an important part of the V3 production process, through two annual workshops conducted by CCRS' Climate Science Research Programme Office (CSRPO) in November 2020 and January 2022, and various ad-hoc engagements throughout the year. CCRS has also been working closely with stakeholders through working groups and task forces (e.g. with the Public Utilities Board and the Singapore Food Agency) that were established to deliver science that is readily usable by our stakeholders.

The use of SINGV-RCM (adapted version of the SINGV NWP model operationally used by CCRS/MSS) for the production of V3 has been an important outcome of the SINGV project (Huang *et al*., 2019) named after the five-year collaborative project between the UKMO and MSS to develop a convective-scale NWP system for Singapore based on the UKV model of the UK Met Office.

At the time V3 was planned, Singapore was yet to have a supercomputer to match the computing and storage needs of V3 simulations. Based on stakeholder needs, Singapore's National Supercomputing Centre (NSCC) was in the process of upgrading their HPC ASPIRE-1 to ASPIRE-2A (A2A) which is around 10 times more powerful than its predecessor. This upgrade was able to match the needs of V3 and finally a large fraction of the downscaling was conducted on A2A, and the simulations were able to be completed for timely delivery.

V3 aimed at building the next generation of climate projections for a climate-resilient Singapore. Singapore recognises the need to meet the challenges posed by climate change with actions based on robust science. To further advance our understanding of tropical climate variability and change and its implications for Singapore and the Southeast Asia region, CCRS is carrying out V3 to produce high-resolution future climate projections under various global warming scenarios that are actionable and of use to policymakers.

The **key deliverables** of V3 include past and future high-resolution climate data over Singapore and SEA region, the V3 Stakeholder Report, this Technical Report, communication and outreach materials such as infographics and videos, the V3 Data Sharing and Visualisation Portal, and peer-reviewed scientific publications. The outputs of V3 will not only form the basis of various impact assessment and adaptation studies for various Singapore Government Stakeholder agencies, but they will also underpin key areas of research supported by the Climate Science Research Programme Office (CSRPO) at CCRS, such as sea- level change, water resources, human health, energy, biodiversity, and food security. Details on the workflow of V3 are discussed in Section 2.4.

2.3 Building on Current and Past Science Excellence

The planning and design of V3 very much leveraged from lessons learned in the past, especially the previous V2 project, delivered in

2015 (Marzin et al. 2015). V2 consisted of two phases. The objective of the first phase was to produce high -resolution climate change projections relevant to Singapore, and that of the second phase was to carry out vulnerability assessment to various sectors by using the high-resolution climate change projections from Phase one of the study. Phase one of the V2 study was commissioned by Singapore's National Environment Agency (NEA) and was undertaken by the Met Office Hadley Centre in the UK jointly with scientists from CCRS and included important contributions from the National Oceanography Centre, Liverpool (NOC), and the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the sea level projections. The previous generation Global Climate Models (GCMs) used for IPCC AR5 were used for V2 (from the 5th phase of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project, or CMIP5 GCMs), whereas V3 uses the latest and most advanced GCMs that underpin the latest IPCC AR6 reports. These new GCMs (from the 6th phase of CMIP, or CMIP6 GCMs) have been assessed to provide more accurate simulations of the global climate. Key improvements in V3 over V2 are summarized in Table 2.1 below.

Table 2.1: Key improvements in V3 over V2

	V2 (2015)	V3 (2023)
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]

2.4 Stages of V3

The V3 study consisted of various stages with well-defined objectives and deliverables attached to each of them, as shown in Figure 2.2. Each of the stages and the key components of work for each of them have been described in detail in the following paragraphs.

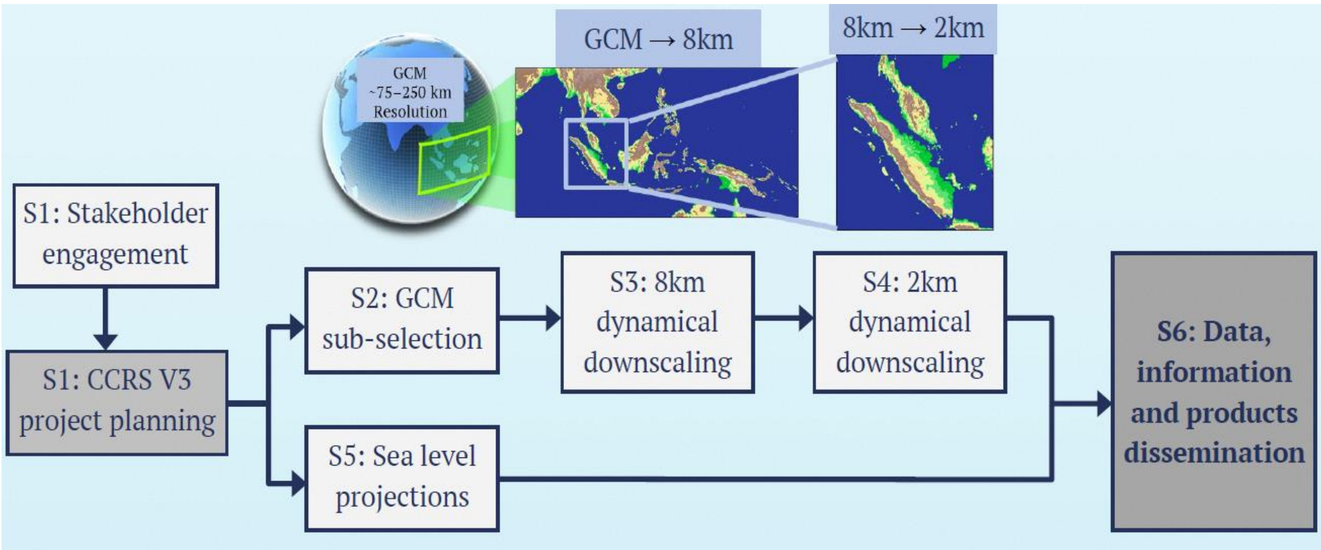

Figure 2.2: V3 Project flow chart.

The first stage of the study consisted of two parts, while one part focused on the stakeholder engagement with various Singapore Government agencies which are a part of the RWG and will be either directly or indirectly using the data and products coming out of V3, the other focused on planning the study and incorporating the stakeholder inputs into the plans. CSRPO organized the first V3 Stakeholder Engagement Workshop in November 2020, which was attended by around 100 participants from 20 Singapore Government agencies. Inputs provided by the agencies at the workshop were incorporated into the overall planning of V3. For example, some climate variables such as incoming solar radiation at the surface which were initially not a part of the V3 data sharing plan were later included based on stakeholder request.

The second stage of the study focused on sub-selecting the tentative list of CMIP6 GCMs that were to be dynamically downscaled to 8km and 2km resolutions for the historical period (1955-2014) and future (2015-2099) for the 3 global warming scenarios used in IPCC AR6, namely, SSP1-2.6 (low challenges to mitigation and adaptation), SSP2-4.5 (medium challenges to mitigation and adaptation), and SSP5-8.5 (high challenges to mitigation, low challenges to adaptation). In order to carry out sub-selection we followed standard practices suggested by the Coordinated Regional Climate Downscaling Experiment (CORDEX; e.g. Gutowski et al. 2016) of the World Climate Research Program. Thus, the sub-selected GCMs should: (1) span the range of GCM projections of temperature and precipitation over SEA, (2) perform satisfactorily in the historical climate, (3) span the range of model diversity in terms of genealogy (e.g. Knutti et al. 2013), and (4) have 6-hourly lateral boundary conditions (LBCs) available to drive the regional climate model. In addition to the aforementioned criteria, we also make use of expert judgment to discard models that are unable to simulate important aspects of regional climate over Southeast Asia (SEA). Based on the above criteria, we finalized the following CMIP6 GCMs for downscaling: **ACCESS-CM2** (Australia), **EC-Earth3** (Europe), **MIROC6** (Japan), **MPI-ESM1-2-HR** (Germany), **NorESM2-MM** (Norway), and **UKESM1-0-LL** (UK).

The third and fourth stages of the study focused on dynamically downscaling the coarse resolution GCM data (~100km grid spacing) to 8km and 2km resolutions, respectively. 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. 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 over small features (e.g. buildings, hills) 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 dynamical downscaling design for V3 is shown in Figure 2.3 below.

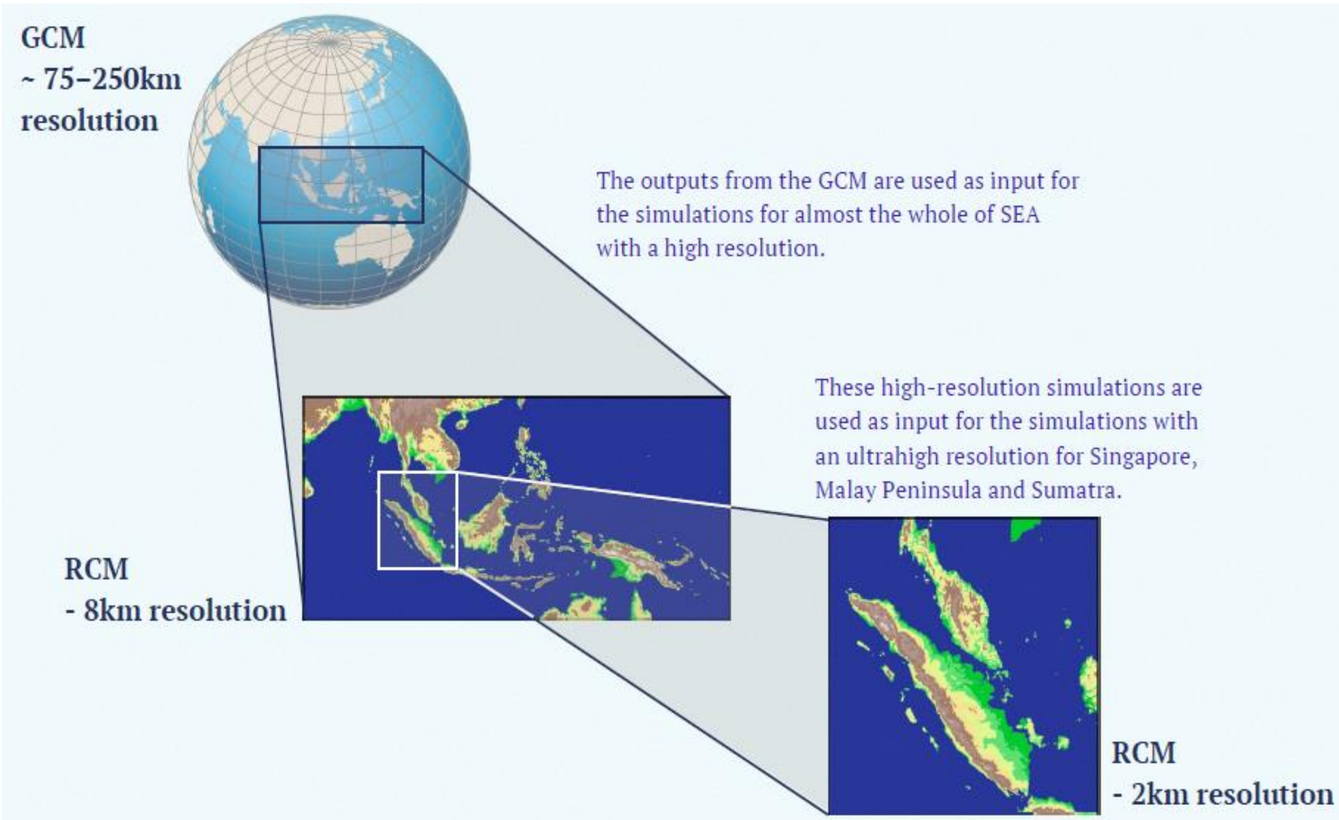

Figure 2.3: The dynamical downscaling design for V3.

The third stage of the study focused on dynamically downscaling ERA5 and the 6 sub-selected GCMs for the historical and future from their native global model resolution (in the range of 75km to 250km) to 8 km horizontal resolution over the SEA domain (shown in Figure 2.3) using the Singapore Variable Resolution - Regional Climate Model (SINGV-RCM).

SINGV-RCM is an adapted version of SINGV, which is the operational numerical weather prediction model used at CCRS and has undergone comprehensive evaluation over Singapore and SEA, and hence provides us confidence for it to be used for long-term climate change projections. For details of the model and configuration please see Chapter 6.

Major sub-components of stage three included (i) development of SINGV-RCM from SINGV which was done on the CCRS HPC system Athena, (ii) porting and testing of SINGV-RCM on the National Supercomputing Centre (NSCC) HPC system (Koppen), (iii) creation of the ancillary fields such as Land Use and Land Cover (LULC), topography, etc., (iv) downloading hundreds of Terabytes (TBs) of 6-hourly GCM forcing data from the Earth System Grid Federation (ESGF) to Koppen, (v) downloading similar big data files from the European Reanalysis Project 5 (ERA5) from the Copernicus Data Server (vi) generating the lateral boundary conditions and the sea surface temperature, and finally (vii) running the model that also includes troubleshooting and regular housekeeping. The simulation details are shown in Table 2.2.

Table 2.2: 8 km Dynamical Downscaling Simulations

	Length of **8km** simulations/scenarios
ERA5	1 x 36 years (1979-2014)
CMIP6 GCMs for **historical**	6 x 60 years (1955-2014)
CMIP6 GCMs for **future**	6 x 85 years (2015-2099)
Number of future scenarios	3 (SSP1-2.6, SSP2-4.5, SSP5-8.5)
Total number of years	~2000

Table 2.3: 2 km Dynamical Downscaling Simulations

	Length of **2km** simulations/scenarios
ERA5	1 x 20yrs (1995-2014)
CMIP6 GCMs for **historical**	5 x 20yrs (1995-2014)
CMIP6 GCMs for **future**	5 x 40yrs (2040-2059; 2080-2099)
Number of future scenarios	3 (SSP1-2.6, SSP2-4.5, SSP5-8.5)
Total number of years	~750

The fourth stage of the study focused on further downscaling of five out of six GCMs from 8km to 2km resolution over the western Maritime Continent domain covering Singapore, Peninsular Malaysia and parts of Indonesia (shown in Figure 12.3). The simulation details are shown in Table 2.3. Although the 8 km simulations were carried out for longer time periods (60 years for the historical and 85 years for the future), the 2km simulations, being significantly more computationally expensive were run for 20-year time slices for the historical (1995-2014), mid-century (2040-2059) and end-century (2080-2099).

The fifth stage of the study focused on observed sea-level rise and sea-level projections and was carried out in parallel while the dynamical downscaling of atmospheric climate variables was ongoing. The sea-level projections for Singapore did not involve regional ocean downscaling but were mainly derived through synthesizing available sea-level projections from the Framework for Assessing Changes to Sea-level (FACTS; Kopp et al, 2023), which also served as the basis for the IPCC AR6 sea-level projections. The site-specific (at tide-gauge locations) projections from FACTS were evaluated and assessed in Singapore's context by comparing projections with historical sea-level rise estimated at Singapore's tide-gauge stations. For instance, by correcting the tide-gauge datum shift and updating the local VLM (Vertical Land Movements) at tide-gauge stations, V3 provides an updated set of relative sea-level rise projections for Singapore. The report also provides an overview of the sea-level drivers, observed sea-level rise in the Southeast Asian region over the last three decades and a detailed discussion on the local VLM in Singapore (Chapter 12).

The sixth and final stage of the study focused on data processing, analysis, report writing, manuscript writing for scientific journals, design, content creation and testing of the V3-DSVP web portal, and production of communication materials in the form of brochures and videos. Almost 10 PetaBytes (PBs) of data was processed from raw model outputs to standardized datasets that are compliant with CMIP and CORDEX standards.

Beyond undertaking the downscaling simulations, some of the key post-downscaling Milestones of the V3 Study include:

Data processing: The processing of the data was carried out using an in-house climate toolbox that was developed for this purpose. One of the major steps in data processing was the bias adjustment of the downscaled data over Singapore, using an advanced method from the ISIMIP3. As a part of bias adjustment, an in-house daily gridded rainfall dataset over Singapore was developed from rain gauge observations by using the kriging method at 2km and 8km resolutions.

Analysis: Analysis of the results comprised of both historical evaluation and future climate change projections of dynamically downscaled data at 8 km and 2 km resolutions for key climate variables (rainfall, temperature, winds, and humidity), and climate drivers (monsoon, ENSO teleconnections, cold surges, and weather regimes). The sea level analysis presented findings on observed and projected sea-level change in Singapore and its surrounding regions.

Report writing: Two V3 reports were written - Report for Stakeholders and the Technical Report. The Stakeholder Report provides key messages of the V3 study and is designed for the Stakeholder agencies, policymakers, and the public, whereas the Technical Report spanning 14 chapters is designed to provide more technical details and would be useful for agencies interested in more in-depth information, researchers from Singapore Institutes of Higher Learning (IHLs), and regional as well as international researchers.

Journal Manuscripts: While the primary objective of V3 is to produce high-resolution climate change projections over Singapore and SEA to assist vulnerability assessment and adaptation planning, it also aims to improve our understanding of the drivers of climate variability and change over the region. New scientific insights developed from the analysis of high-resolution downscaled model outputs will be reported in peer-reviewed scientific journals as our contribution to the scientific literature on climate variability and change over the region.

V3-DSVP: In order to share data, figures, reports, and various communication materials with Stakeholder agencies, researchers and the public, we will be making all this available through a data sharing and visualization portal (DSVP). There will be an interim portal which will be used to share everything mentioned above other than data that will be launched together with the V3 public release, whereas, the final portal will be more advanced and will have the capability to host data as well as have interactive data analytics capability for advanced users that will be tentatively operational in late 2024. The design document along with all the contents of the two web portals have been developed in-house at CCRS, whereas the software development of the portal is outsourced.

Communication materials: Brochures, videos and infographics to communicate various aspects of V3 are developed by CCRS and the MSS Business and Strategy Division. Topics for the brochures and videos include: (1) introduction to V3, (2) dynamical downscaling, (3) sea level projections, (4) climate extremes, (5) using climate change projections in risk assessments, (6) probabilistic climate change projections, (7) weather and climate drivers of Singapore, and (8) application-ready datasets.

2.5 Outline of the V3 Technical Report

The V3 Technical Report is an in-depth description of all the components of the V3 project, as well as highlighting the key results from our analysis. The report consists of 14 chapters; the initial chapters will provide details on historically observed changes in Singapore's climate and the process going from global climate change analysis (as in the recent IPCC AR6 report) to a regional and then local approach applied in V3.

Following on, an evaluation and analysis of the regional and local downscaling is presented. This includes chapters on both bias correction and uncertainty assessment.

As a separate chapter, emphasizing the importance but also the fact that the methodology is different, we present the new sea level projections for Singapore based on IPCC AR6 methodology.

Finally, we give an overview of two important project efforts crucial for the success overall: first, the extensive work on HPC to undertake dynamical downscaling and second, the science communication effort to disseminate the information locally and regionally.

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