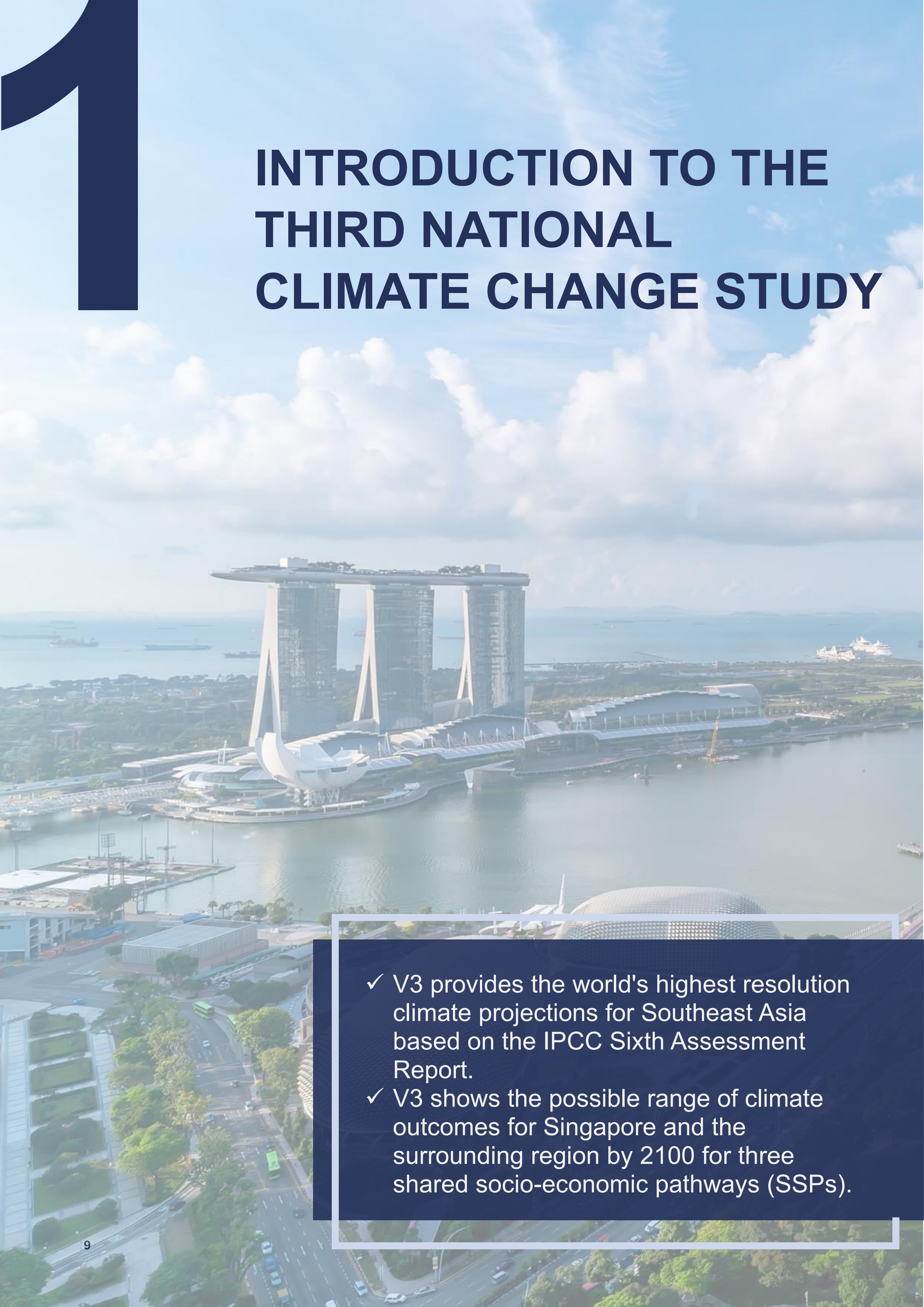

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INTRODUCTION TO THE THIRD NATIONAL CLIMATE CHANGE STUDY

- ✓ 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.

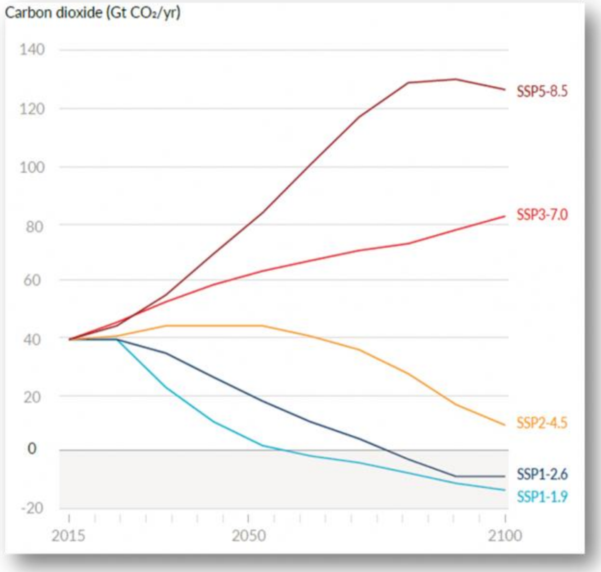

Figure 1.1: Carbon dioxide emissions in Giga-tonnes/per year for the five SSPs. (IPCC AR6)

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.

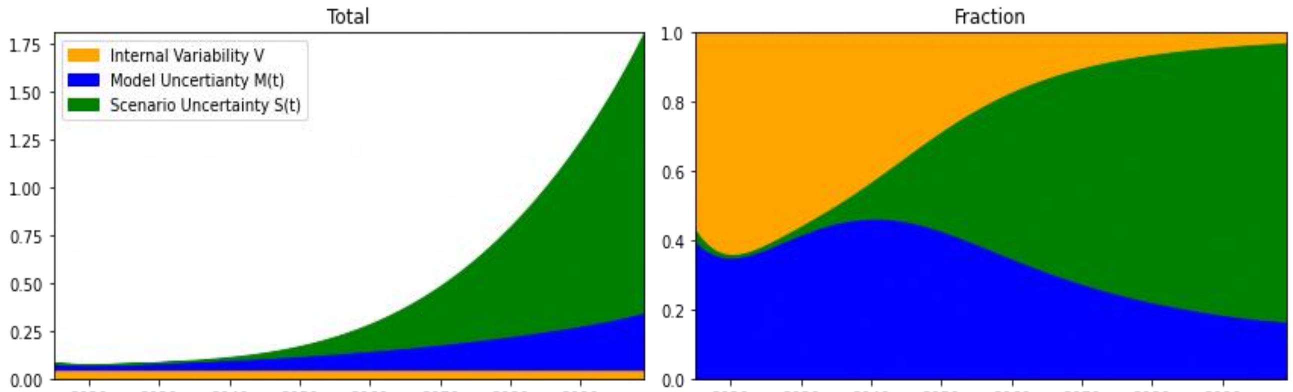

Figure 1.2: Total and fractional variance of surface air temperature over the V3 8 km domain using data from CMIP6 GCMs.

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.

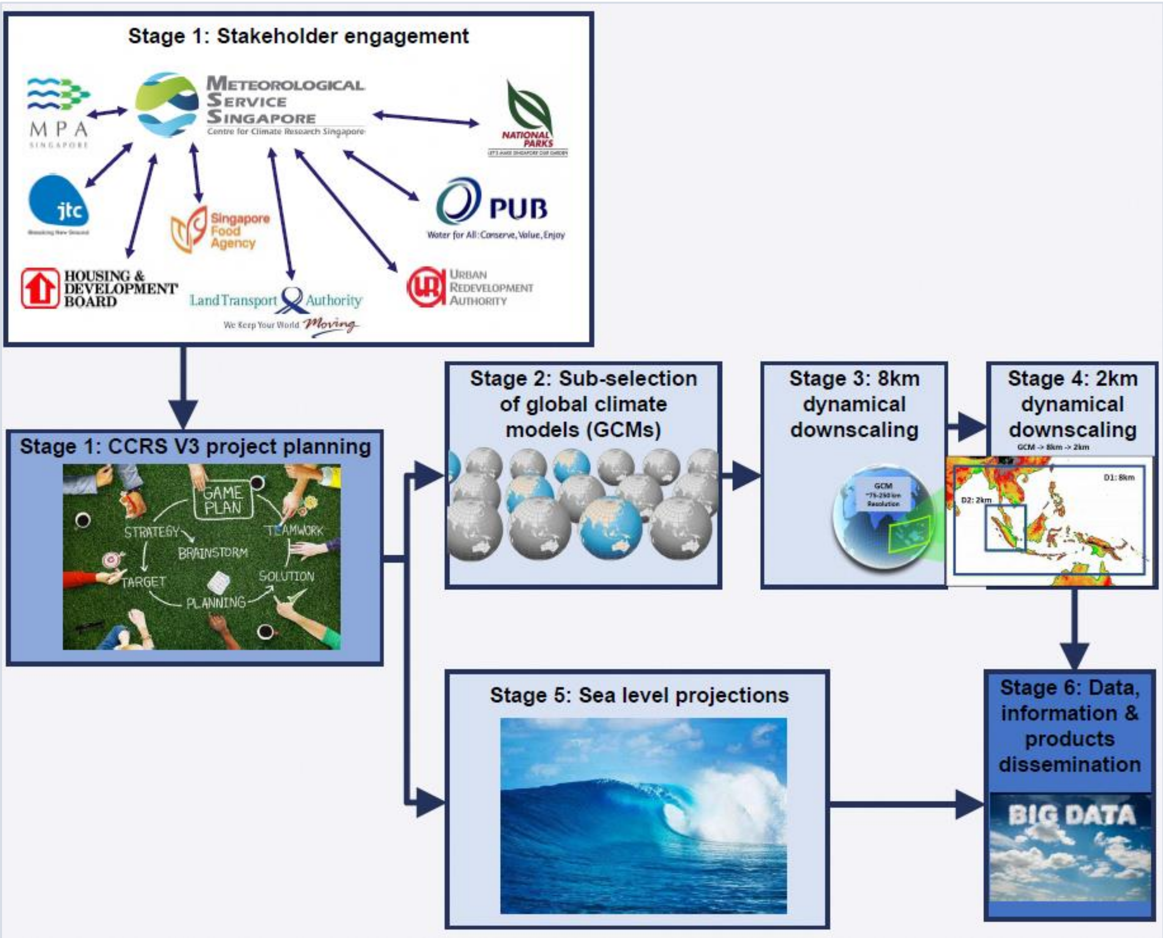

Figure 1.3: V3 Project flow chart.

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).