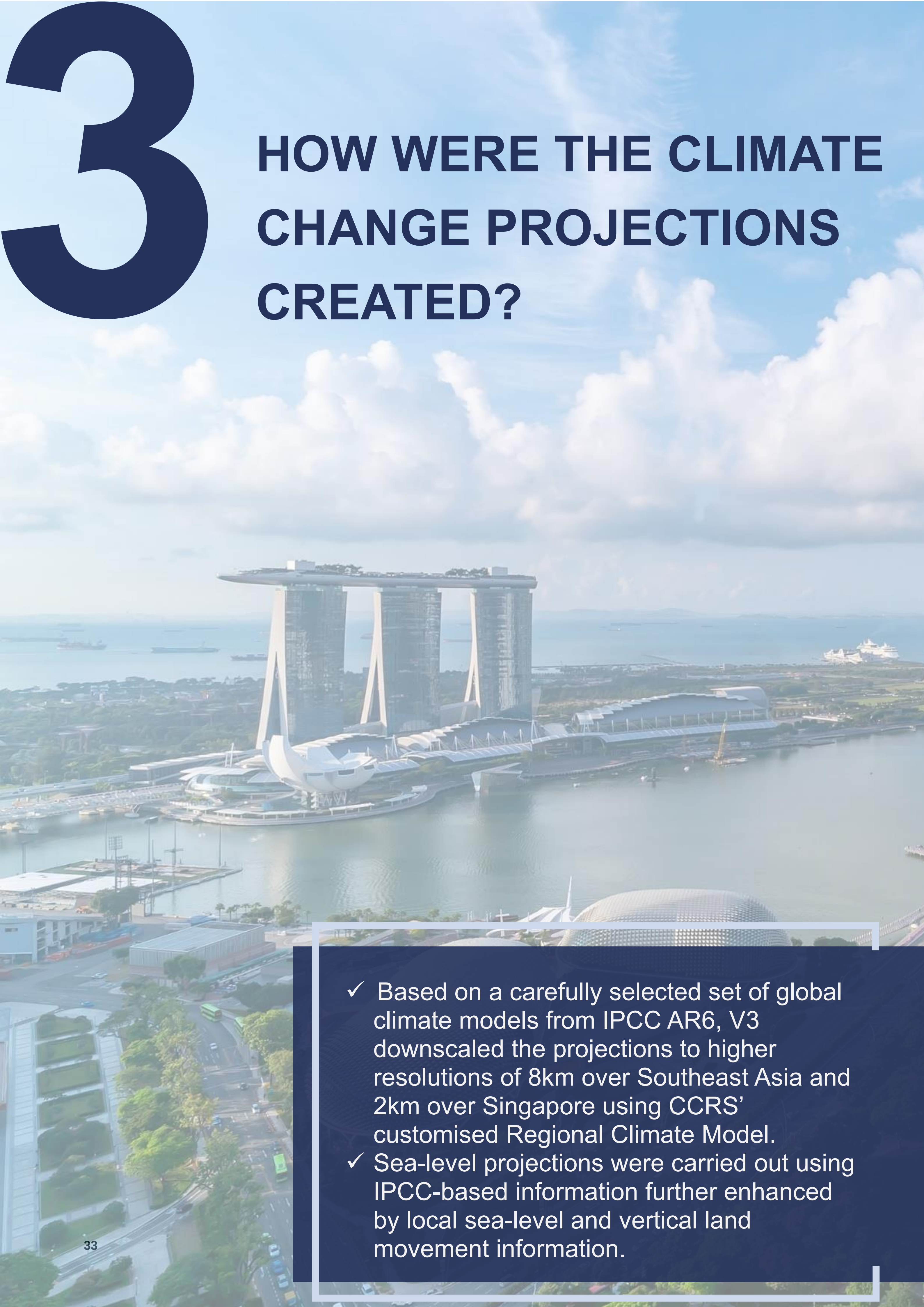
3 HOW WERE THE CLIMATE CHANGE PROJECTIONS CREATED?



- ✓ 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.

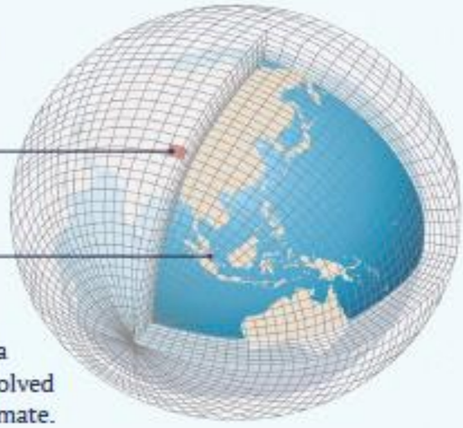
For V3, projections of atmospheric variables (temperature, rainfall, winds, humidity, etc.) were carried out using dynamical downscaling, whereas the sea-level projections were carried out using CMIP6 GCM-based data further enhanced by local sea-level and vertical land movement information.

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

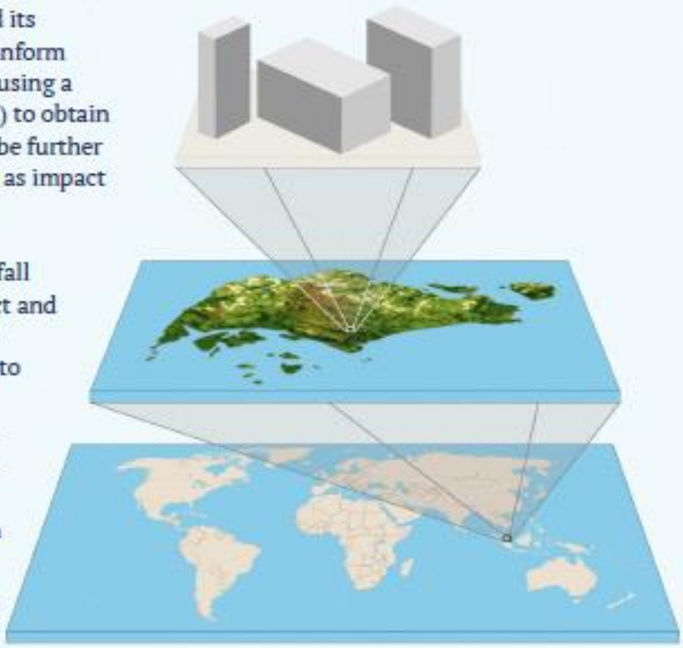
- Developed by leading climate research centres around the world, global climate models (GCMs) consist of computer code that solves mathematical equations used to represent the physical processes in Earth's climate system.
- Generally, the latest GCMs have a resolution of 75–250 km, which means that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



- 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.

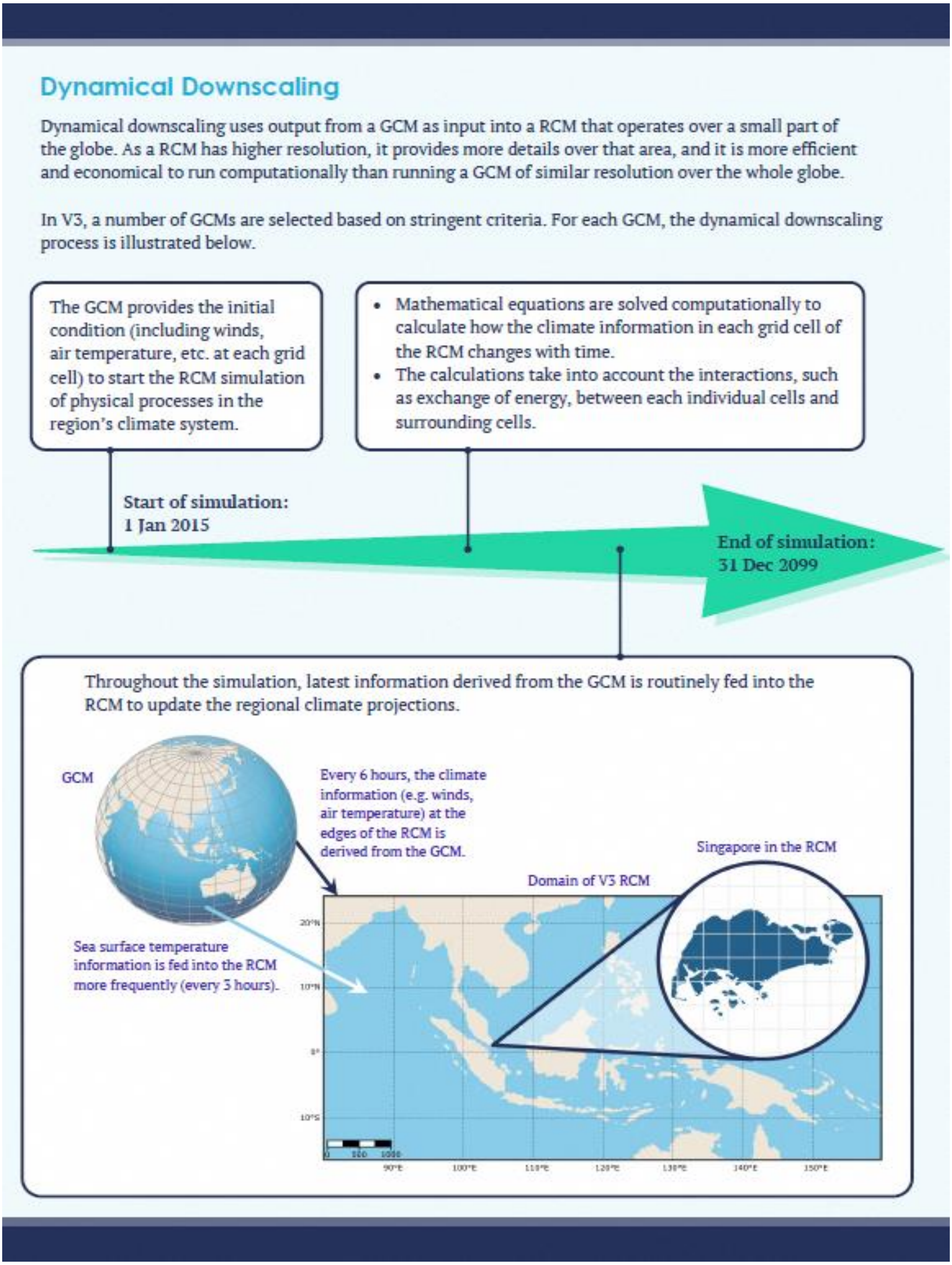
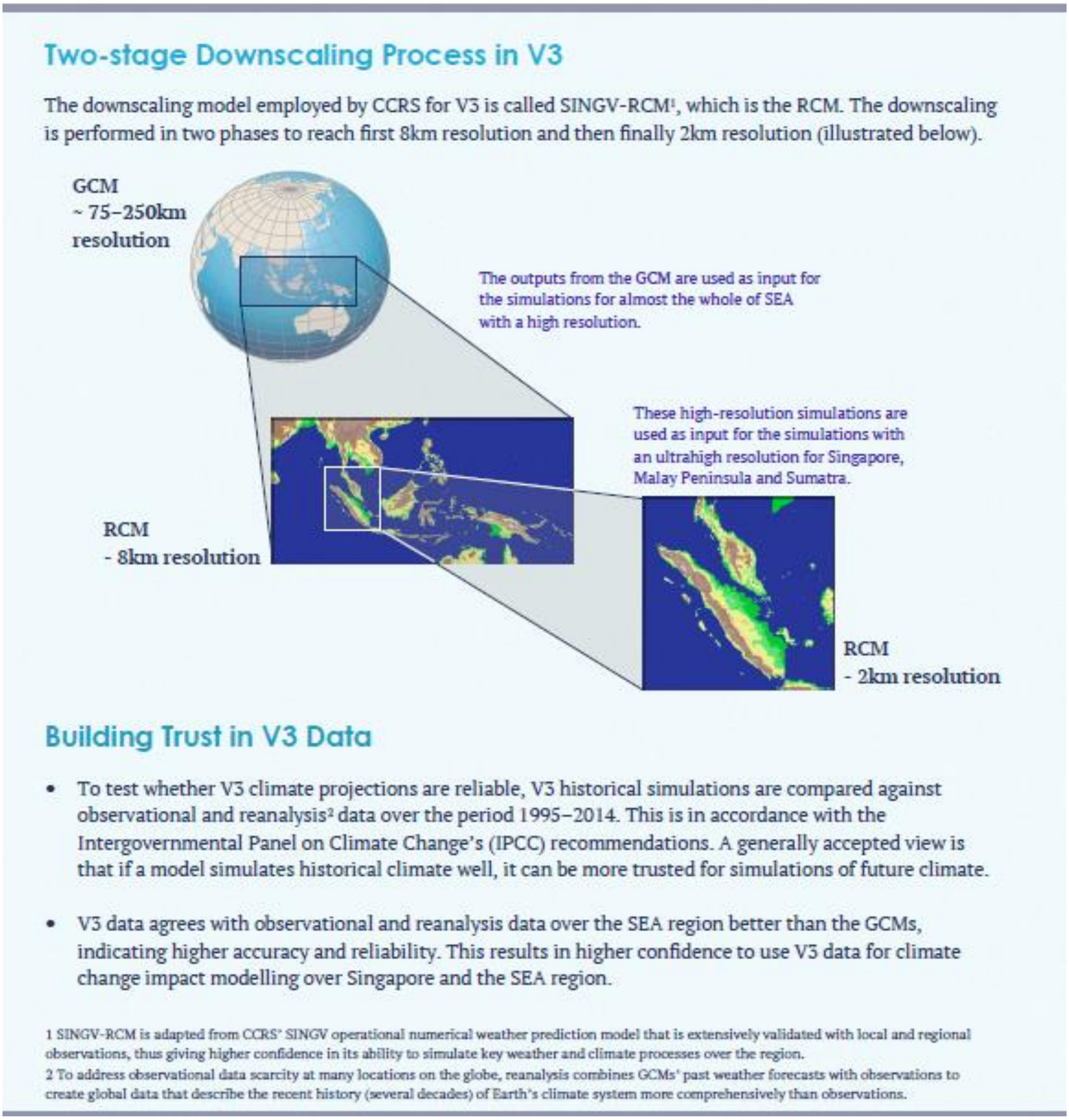


Figure 3.2: The 'Climate Change – From Global to Local' brochure introduces the concept of dynamical downscaling, using the V3 project as an example to illustrate the concept.



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 (^{o} 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).

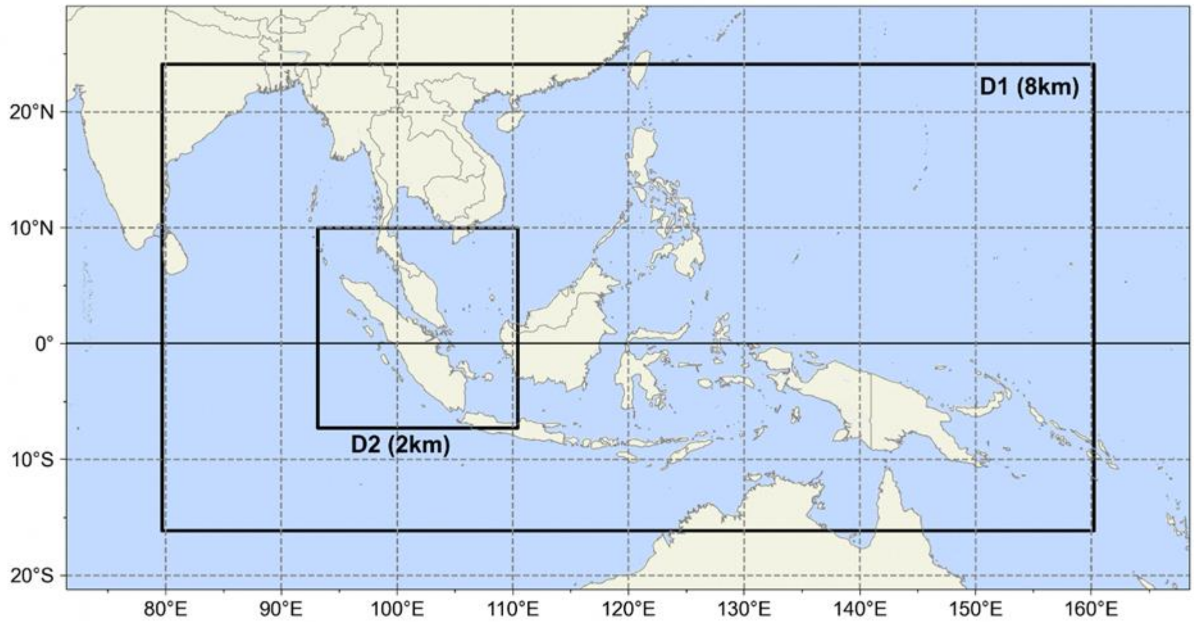


Figure 3.4: Downscaling domains for V3. D1 (16.16 S–24.08 N; 79.68 E–160.248 E) is the 8km domain, and D2 (7.29 S–9.972 N; 93.16 E–110.422 E) is the 2km domain (in solid line).

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.

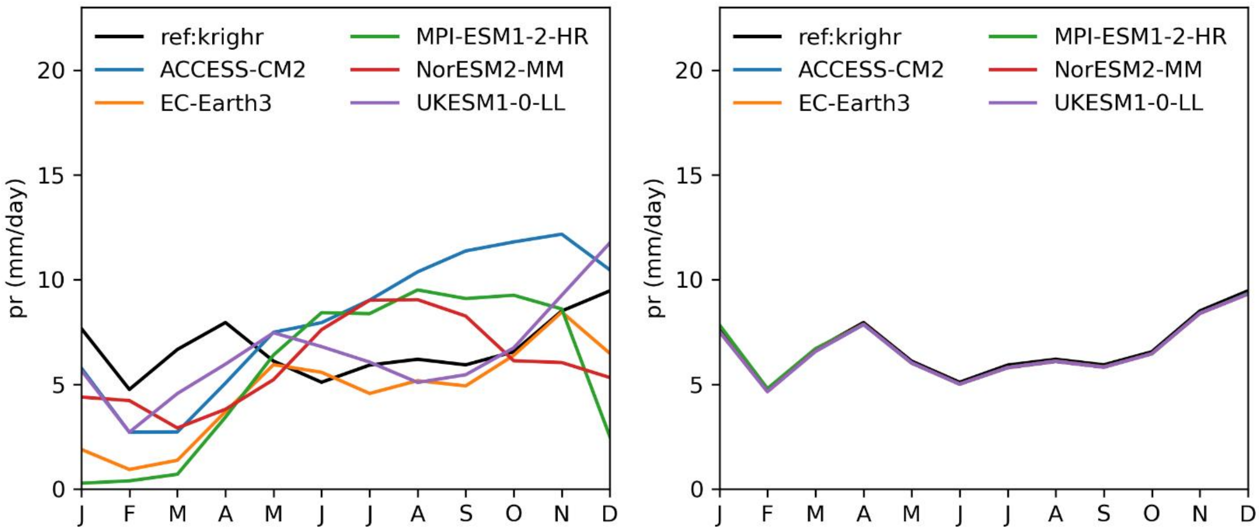


Figure 3.5: Singapore domain-averaged rainfall (pr) in the historical period (1995-2014) at 2km resolution. Non-bias-adjusted and bias-adjusted simulations are compared with observed reference (gridded station rainfall) in the left and right panels, respectively.

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.