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Executive Summary

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1.1 Background to Singapore's Third National Climate Change Study

The challenge of climate change presents an existential threat to both humanity and the Earth's ecosystems, underscoring the need for a strategic understanding and a proactive response to mitigate its associated risks. Small island nations like Singapore, confronted with increasing evidence of climate change impacts, urgently need reliable and actionable information to effectively prepare for and adapt to the multifaceted risks associated with this global challenge.

Every 6-7 years, the Intergovernmental Panel on Climate Change (IPCC) issues Assessment Reports that provide current insights into the scientific, technical, and socio-economic aspects of climate change. The latest IPCC assessment cycle, featuring reports on the Physical Science Basis, Impacts, Adaptation and Vulnerability, and Mitigation of Climate Change, along with a Synthesis Report and a Climate Change Atlas, contributes valuable information on a global scale. However, these reports, primarily based on global climate models, lack the granularity needed for regional and local assessments and adaptation planning.

Building on the foundation of Singapore's Second National Climate Change Study (V2), the Third National Climate Change Study (V3) addresses this gap by providing high-resolution climate change projections for Singapore and the broader Southeast Asian region. By dynamically downscaling global climate model simulations, the study offers a new dataset crucial for informed adaptation planning, enhancing Singapore's resilience to the adverse effects of climate change.

Led by the National Environment Agency (NEA), and with the Meteorological Service Singapore's Centre for Climate Research Singapore (CCRS) at the forefront of developing high-resolution downscaled climate projections, V3 contributes to Singapore's national endeavors by enhancing understanding of climate change effects and aiding in the formulation of comprehensive, long-term plans for national resilience.

The V3 study comprises a Stakeholder Report and an accompanying Technical Report. The Stakeholder Report provides a succinct overview of V3's key findings, tailored for diverse audiences. This includes Singaporean Government agencies and Southeast Asian counterparts involved in downstream impact studies, policy development, and adaptation planning. It is also designed for researchers in local Institutes of Higher Learning and beyond, along with the general public interested in climate change and sustainability. For a comprehensive understanding, the Technical Report delves into V3's methodology, global and regional projections derived from Global Climate Models (GCMs), the evaluation and sub-selection of GCMs, the setup of the SINGV-RCM, assessment of downscaled simulations, bias adjustment, regional climate change projections, and sea level projections over Singapore and the broader region. Please see Chapter 2 Introduction for more details.

Moreover, to enhance the interpretation and comprehension of the V3 study, individuals can explore specific data visualizations from V3 at https://www.mss-int.sg/V3-climate-projections.

1.2 Recent Climate Trends in Singapore

The global mean temperature for 2022 exceeded the 1850–1900 average by 1.15°C. In Singapore, the average daily mean temperature has shown a steady increase, rising at a rate of 0.24°C per decade over the past four decades since 1984. This temperature rise persists despite substantial year-to-year variability, influenced by large-scale climate drivers like the El Niño-Southern Oscillation (ENSO). El Niño events generally lead to higher annual mean temperatures across Singapore, while La Niña events tend to moderate them. The natural modulations contribute to varying warming rates across decades, e.g., an increase of 0.52°C per decade between 1984 and 1993, contrasting with an increase of 0.07°C per decade between 2013 and 2022. Alongside the mean temperature increase, observations in

Singapore also indicate an upward trend in daily minimum and maximum temperatures.

In terms of rainfall trends, Singapore's annual rainfall has experienced a slight upward trend of 83mm per decade from 1980 to 2022. However, this trend is overshadowed by significant year-to-year variations. It's essential to emphasize that the ENSO has a significant influence on Singapore's rainfall patterns, causing increased rainfall during La Niña years and reduced rainfall during El Niño years. Singapore is known for its humid tropical rainforest climate. Between 1985 and 2020, there has been a slight decline in the annual mean near-surface relative humidity in Singapore.

Situated between two monsoon systems, Singapore experiences the Southwest Monsoon from June to September and the Northeast Monsoon from November to early March. The average wind speeds are generally mild over Singapore, with even lighter and variable winds during the inter-monsoon period. The annual mean wind speed exhibits inter-annual and multi-decadal variability. In recent decades, observations suggest a potential increasing trend, which could be part of the multi-decadal variability.

Please see Chapter 3 Observed Climate Change for more details.

1.3 Methodology to Produce Climate Change Projections for Singapore and Southeast Asia

The initial stage in crafting high-resolution climate change projections for Singapore involved the assessment and sub-selection of 49 global climate models employed in the IPCC AR6 for dynamical downscaling. This evaluation adhered to established practices within the international scientific community engaged in dynamical downscaling, led by the World Climate Research Programme (WCRP) Coordinated Regional Downscaling Experiment (CORDEX) community. A thorough examination of key climate variables, including temperature, rainfall, winds, relative humidity, and sea level pressure, was conducted. Relevant climate drivers for the Maritime Continent (MC), such as monsoons, El-Nino Southern Oscillation (ENSO) and its teleconnections, Indian Ocean Dipole (IOD), Northeast Monsoon surges, and Madden-Julian Oscillation (MJO), were also considered. This rigorous evaluation aimed to identify and flag any models deemed implausible for climate change projections in the region.

The sub-selection process extends beyond global model evaluation. Additional dimensions for sub-selection encompass (i) availability of relevant 6-hourly data to drive the regional climate model, (ii) coverage of a broad spectrum of model families, (iii) inclusion of a diverse range of climate sensitivities, and (iv) representation of a comprehensive range of future outcomes from the global models. Please see Chapter 5 GCM Evaluation and Sub-selection for more details.

The regional climate model chosen for dynamical downscaling was the SINGapore Variable resolution model (SINGV), re-configured from a numerical weather prediction model to operate in a climate mode. This conversion exemplifies a seamless modeling framework, allowing the same system to be employed for both numerical weather prediction (hours to days) and climate change projections (decades). To ensure successful configuration as a regional climate model, the SINGV model underwent customization for climate mode through multiple sensitivity studies at different resolutions and domain sizes over the MC. For further details, please refer to Chapter 6 SINGV-RCM.

V3 downscaling simulations include one historical simulation driven by the latest ERA5 reanalysis and multiple simulations driven by sub-selected CMIP6 GCMs. In total, V3 carried out dynamical downscaling from 6 GCMs for the historical period (1955-2014) and the future (2015-2099) under 3 IPCC AR6 global warming scenarios (Shared Socioeconomic Pathway 1-2.6, SSP2-4.5, and SSP5-8.5) at 8km horizontal resolution over the Southeast Asia (SEA) domain. Additional high-resolution simulations at 2km horizontal resolution were carried out over the western MC domain, which encompassed the period of 1995-2014 and the same 3 SSP scenarios, utilizing 5 GCMs for two 20-year time slices in the future (2040-2059 and 2080-2099).

Our investigation has demonstrated that high-resolution regional climate model (RCM) downscaling simulations, conducted at both 8km and 2km resolutions, contribute value across various aspects when compared to coarse resolution Global Climate Models (GCMs). The SINGV-RCM downscaling consistently aligns with the parent driving model, faithfully tracking the long-term trends and variability of the parent model. Notably, the downscaled simulations accurately replicate crucial meteorological parameters, including precipitation, temperature, relative humidity, and wind speed, across different time scales from diurnal to seasonal and their annual cycles.

The variables simulated by the SINGV-RCM exhibit strong agreement with high-resolution regional observations, such as ground-based stations and satellite merged products. This alignment underscores the RCM's skill in representing historical climate conditions. Additionally, the RCM demonstrates abilities in capturing regional climate drivers, such as remote ENSO-teleconnection, and processes like cold surges specific to this region.

For thorough evaluation, the RCM simulations over Singapore are analyzed at each land grid using high-resolution observations. Notably, the 2km resolution simulations show improvements over the 8km resolution simulations and provide a more detailed representation of the climate within the island nation. Further details are available in Chapter 7 Evaluation of Dynamically Downscaled Simulations.

One more thing worth highlighting here is the HPC aspect of the V3 study. Approximately 2000 model years of dynamical downscaling simulations at 8 km resolution, covering nearly the entire Southeast Asia (SEA), and ~750 model years at 2 km resolution focusing on the western Maritime Continent, were conducted for both current and future climates as part of V3. Due to computing resource constraints and V3 timelines, the simulations were distributed across three High-Performance Computing (HPC) systems on two continents: NSCC Koppen and A2A in Singapore, and NCI Gadi in Australia. Throughout the simulation period, computing and storage requirements fluctuated, reaching peak computing levels exceeding ~35 million core-hours per month and storage capacities reaching ~12 PB. Furthermore, approximately 4 PB of data was efficiently transferred from Australia to Singapore at peak speeds of ~1 Gbps, facilitated by NSCC and SingAREN. The HPC journey for V3 simulations was both challenging and adventurous, demanding significant efforts from CCRS and dedicated time for resource and simulation management. Through collaborative teamwork within MSS/CCRS and support from NSCC, NCI, and SingAREN, coupled with the diligent efforts of the V3 team at CCRS, challenges were successfully navigated, and the desired outcomes were achieved, meeting the V3 delivery timelines. More details are available in Chapter 13 High Performance Computing Aspects.

1.4 CMIP6-informed Global to Regional Climate Projections

CMIP6 models (utilized in the IPCC AR6), offer a comprehensive understanding of climate change at both global and regional scales. In contrast to their CMIP5 counterparts, CMIP6 models boast higher spatial resolution, enhanced model physics through improved parameterization schemes, and an increased incorporation of earth system models featuring carbon cycle and biogeochemistry components. Additionally, CMIP6 models introduce a socioeconomic storyline (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) in conjunction with radiative forcing levels, as opposed to the CMIP5 models' Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0, and 8.5. This inclusion enriches future warming scenarios. Consequently, the utilization of CMIP6 models enhances confidence in projecting future climate variables and processes compared to the earlier CMIP5 models.

The projected global mean surface air temperature is expected to rise by 0.4 to 1.0°C relative to the period 1995-2014 across most scenarios in the near term (2021-2040). Additionally, during the same period, land surface temperatures are anticipated to increase by at least 1.0°C more than ocean temperatures. In the near term, land precipitation is projected to increase under both low emission (-0.2 to 4.7%) and high emission (0.9 to 12.9%) scenarios, with certain regional uncertainties stemming from internal variability, model uncertainty, and aerosol emission uncertainties.

Besides mean state variables, tropical climate drivers are also expected to undergo warming-induced changes. Global monsoon precipitation is anticipated to increase, despite a reduction in circulation strength both in the mid and end century. The El Niño-Southern Oscillation (ENSO) response to warming remains uncertain across different scenarios, but a robust signal of ENSO-induced precipitation variability is evident over the tropical Pacific. Although the frequency of strong positive Indian Ocean Dipole (IOD) events is expected to rise, the IOD response remains uncertain due to the lack of strong evidence and dependence on mean state biases in the model. In a future warmer climate, the Madden-Julian Oscillation (MJO) is projected to intensify, accompanied by an increased magnitude of associated precipitation.

For the Southeast Asia (SEA) region, CMIP6 Global Climate Models (GCMs) indicate a temperature increase slightly below the global average. Daily mean surface temperatures are projected to rise over both land and oceans, with a more pronounced land-sea temperature contrast in high Equilibrium Climate Sensitivity (ECS) models at annual and seasonal time scales. During the hot summer periods in March to May (MAM) and June to August (JJA) seasons over the northern parts of SEA, temperatures are expected to increase by up to 5°C or more. Mean annual rainfall projections indicate increased values over most land regions of SEA, with higher increases over northern SEA, Borneo, and New Guinea. Under the high warming scenario (SSP5-8.5), there is a strong ENSO-rainfall signal over the MC in JJA with strong drier conditions during El Niño and strong wetter conditions during La Niña.

The frequency of Northeast monsoon surges is anticipated to increase to 19% (from the current 18%), resulting in heightened rainfall over Borneo, Sulawesi, south Sumatra, New Guinea, and east of the Philippines. Conversely, there is a projection of reduced rainfall around the Maluku islands. The combined impacts of climate change, land subsidence, and regional human activities contribute to a higher level of confidence in the escalation of floods and prolonged inundation across the Mekong Delta region.

In summary, the CMIP6 future projections indicate increased global and regional surface air temperatures, enhanced global precipitation (regional differences; wet gets wetter, dry gets drier), increased monsoon land precipitation, and enhanced ENSO-rainfall teleconnections. In addition to the mean changes, extremes in temperature and rainfall are projected to increase, especially under SSP5-8.5 over many parts of the globe, including SEA. Please see Chapter 4 From Global to Regional Projections – insights from CMIP6 for more details.

1.5 Regional Climate Change Projections for Southeast Asia

In the V3 study, we utilized SINGV-RCM driven by selected CMIP6 GCMs to assess climate changes across Southeast Asia, examining key variables such as temperature, rainfall, and large-scale drivers crucial to the region.

In terms of rainfall, projections indicate an increase in annual-mean domain-average rainfall over Southeast Asia towards the end of the 21st century. The multi-model mean projects a higher end-century change compared to mid-century changes for each scenario, but the inter-model spread is notable. Such slight increase in the annual mean rises from spatially complex changes across individual seasons. For instance, substantial rainfall increases occur in the northern Maritime Continent throughout all seasons, while western and central equatorial Maritime Continent experiences drying, particularly during dry months (JJA). Extreme rainfall events, measured by maximum 1-day rainfall (RX1day) and (RX5day), are expected to rise across most Southeast Asian land regions during all seasons.

As for temperature, the multi-model mean indicates projected temperature increases of 3.3°C over the Southeast Asian domain by the end of the century under the high emission scenario. Land areas in Southeast Asia are expected to experience even higher warming, reaching 4°C by the century's end, consistent with the understanding that land regions warm more than ocean regions. Changes in annual maximum (tasmax) and annual minimum near-surface air temperatures are qualitatively similar to those in annual mean temperature. Temperature extremes, represented by changes in the seasonal maximum of daily maximum temperatures (TXx), show consistent warming trends over the Southeast Asian domain, with larger increases over land areas, exceeding 6oC in parts of Indochina during JJA and SON. The seasonal minimum of daily minimum temperatures (TNn) also increases across much of the domain.

Regarding relative humidity (hurs), seasonal mean near-surface relative humidity changes are generally small or negative over land (ranging from 0 to -1.9%), while increases are observed over oceans. The largest decreases are evident in JJA, particularly over Indochina, Borneo, and New Guinea. This reduction in land relative humidity aligns with existing studies and is accompanied by enhanced land warming.

Examining regional climate drivers, a weakening of the monsoonal flow with anomalous easterlies over the Indian Ocean is observed. Notably, JJA experiences a strengthening of the monsoon flow over Indochina. Changes in the northeast monsoon surge align with the parent GCMs in terms of increased frequency and anomalous easterlies over Indochina and west of Sumatra, as well as anomalous westerlies north of New Guinea. Note that, the magnitude of rainfall changes in the downscaled simulations are enhanced relative to the parent GCMs, with slight differences in the spatial distribution of rainfall.

CMIP6 GCMs indicate that the negative ENSO teleconnection over Southeast Asia (SEA) is expected to expand geographically and intensify with warming. Specifically, SEA is projected to experience heightened aridity during El Niño events, leading to prolonged drying and drought conditions. Conversely, La Niña events are anticipated to bring increased precipitation, resulting in more heightened flood risks. The zonal dipole pattern of the ENSO teleconnection across the Indo-Pacific Ocean is projected to shift eastward. These anticipated changes align consistently between RCMs and their parent GCMs, and the downscaled models offer additional fine-scale spatial details. These climate driver projections carry significant implications for water resource management and agriculture in the region. The potential for prolonged droughts during El Niño events and intensified flooding during La Niña events underscores the importance of adapting water resource strategies and agricultural practices to effectively respond to these anticipated shifts in climate patterns.

It is important to emphasize the added value of future projections derived from high-resolution RCMs compared to coarse-resolution driving GCMs. Note that GCMs often exhibit smoothed spatial changes due to their coarse resolutions. In contrast, high-resolution (8km) RCMs consistently reproduce large-scale changes similar to driving GCMs but offer a more detailed representation of high rainfall variability in the high mountain areas of Java and Papua New Guinea. These enhancements are crucial for advancing regional climate impact studies, and further details can be found in Chapter 8 Regional Climate Change Projections.

1.6 High-resolution Climate Change Projections for Singapore

Our high-resolution regional climate model (RCM) simulations, conducted at resolutions of 8km and 2km, have demonstrated excellent performance over the Maritime Continent. However, these high-resolution RCMs exhibit minor model biases when compared to local observations specifically within Singapore. To ensure that we provide appropriate simulation data for local climate change impact studies, we have conducted bias adjustments for key climate variables. By applying bias adjustments to these selected variables, we aligned the RCM simulations more closely with the observed local climate conditions in Singapore. The bias adjustments conducted in our study have demonstrated very good performance to remove the model biases in the historical period. We consider bias adjustment to be a crucial step in the post-processing of regional downscaling simulations, as it significantly improves the realism and accuracy of the RCM outputs. The successful implementation of bias adjustments enhances our confidence in the climate projections and their suitability for assessing and addressing the impacts of climate change in Singapore. For further details, please refer to Chapter 9 Bias adjustments.

Singapore is projected to experience varying levels of temperature increase under low to high emission scenarios. V3 projections show that the daily mean temperatures over Singapore could increase by 0.6°C - 5.0°C by the end of the century and the daily maximum temperature could increase by 0.5°C - 5.3°C. Notably, the estimated upper limits of potential temperature increase in V3 are higher than V2. Furthermore, the daily mean Wet Bulb Globe Temperature (WBGT) - a key indicator for assessing heat stress - is expected to increase by 0.5°C - 4.3°C. The daily maximum WBGT could increase by 0.5°C - 4.0°C. This shift implies an increase in the frequency of days experiencing high heat stress, with an estimated 54 to 326 days featuring WBGT exceeding 33°C for an hour or more during daylight hours.

Singapore rainfall undergoes a transition from wet to dry across Monsoon seasons. The rainy months are from November to January, which marks the wet phase of the Northeast Monsoon season. On the contrary, Singapore is relatively dry in the months of June – August, which is the dry phase of the Southwest Monsoon. V3 study projects diverging changes in Singapore rainfall across different seasons. An intensification of precipitation is anticipated during the traditionally wet months (i.e., “wet gets wetter”) with an increase in mean rainfall of up to 58%. Conversely, the dry months may experience a potential rainfall decrease of up to 42% (i.e., “dry gets drier”).

The projections also indicate a heightened likelihood of extreme rainfall events throughout all seasons and scenarios, potentially escalating by as much as 92% during April and May. Additionally, the frequency of dry periods is expected to rise, occurring approximately every ten months, and extending for a maximum duration of around 3 weeks.

According to V3 projections, the near-surface wind speed over Singapore has the potential to increase by up to 20% during the Northeast (Dec-Mar) and Southwest monsoon (Jun-Sep) seasons. Additionally, in the intermonsoon months of April and May, under the high emissions scenario, there could be an increase of up to 11% by the end of the century.

For further details, please refer to Chapter 10 Singapore Climate Change Projections.

1.7 Past and Future Sea Level Change in Singapore and Southeast Asia

In conjunction with the downscaling simulations, another aspect of the V3 study centers on observed changes and projections of mean sea level around Singapore and the region. Sea level projections in V3 are derived from the state-of-the-art IPCC AR6 projections. For Singapore, V3 employed the IPCC AR6 methodology to generate relative mean sea level projections using corrected tide-gauge data to produce the most updated vertical land movement projections.

Relative mean sea level has been rising at a rate of 3.6 mm/yr off Singapore (average rate across four tide-gauges with rate varies between 3.27 - 3.77 mm/yr) for the 1993 - 2021 period. The contemporary mass redistribution between the oceans and the land, which refers to ocean’s exchange of water between ice sheets, glaciers, and other terrestrial water storages, is the main driver of observed sea-level rise around Singapore during the last three decades (~70% of the total rise). On the other hand, the ocean internal mass redistribution dominates the sterodynamic sea-level rise (~23% of the total rise) with a very weak contribution from local steric changes. These findings hence indicate that nearly 90% of the observed sea-level rise off Singapore is “mass-driven” and highlights the importance of having a bottom pressure recorder in the shelf region of Singapore to assist future studies and monitoring of mean sea-level rise.

By the year 2100, Singapore is expected to undergo a relative mean sea level rise of 0.45 ± 0.03 m under the SSP1-2.6 scenario, 0.57 ± 0.04 m under SSP2-4.5, and 0.79 ± 0.04 m under

SSP5-8.5. These are median values across six locations in Singapore. In the high emission scenario (SSP5-8.5), particularly at Sultan Shoal, Singapore may face a relative sea-level rise of up to 1.15m by 2100.

Looking further into the future, by the year 2150, the projected rise in relative sea level is estimated at 0.72 ± 0.05 m under SSP1-2.6, 0.95 ± 0.06 m under SSP2-4.5, and 1.37 ± 0.06 m under SSP5-8.5. These represent the average estimates of median values at six different locations in Singapore. In particular, at Sultan Shoal, the relative sea level could likely reach up to 2.12 m under SSP5-8.5 by 2150. Additional information is available in Chapter 12 Sea Level Projections.

1.8 Science Communications on Climate Changes and Uncertainty

Projecting future climate changes for Singapore presents a unique set of challenges. Located in between two significantly larger regions where opposing trends in rainfall are projected for most seasons, Singapore faces the intricate and seasonally variable influences of regional climate drivers within the Southeast Asia (SEA) region. The city-state's small size further complicates the task of predicting changes in rainfall, adding to the complexity.

Recognizing the inherent uncertainties in climate projections, the V3 study endeavors to offer valuable insights to users relying on bias-adjusted projections for Singapore, emphasizing the reliability and robustness of the projections. Through our analysis, we observe an escalation in scenario uncertainty over time, particularly from mid-century to end-century. Additionally, this uncertainty is contingent on the chosen climate model. For instance, in a specific model, the scenario uncertainty in precipitation change over Singapore can be as high as 25% during the end-century, and similarly the scenario uncertainty in temperature projections during the end-century can be as high as 3.5°C.

Model uncertainty follows a similar trajectory, amplifying over time and exhibiting greater variability in the end-century compared to the mid-century. Model uncertainty is highest for the SSP5-8.5 scenario. For Singapore during the end-century, the model uncertainty in projected precipitation change under SSP5-8.5 could be as high as 30%, and that for projected temperature change could be as high as 2.2°C. Dynamical downscaling also introduces uncertainty, influencing the sign of precipitation change for individual models and contributing to temperature variations within approximately 2°C. More discussions are available in Chapter 11 Uncertainty Quantification.

Despite these multiple sources of uncertainty, our confidence is anchored in projections that demonstrate robustness across varying time periods, scenarios, and models employed in the analysis. Greater assurance is also placed in projections that align consistently between regional and global climate models, especially when supported by theoretical understanding.

In the utilization of V3 results, opting for the mean or median of the multi-model ensemble can provide an indicative measure of change. However, for decision-making that prioritizes robustness, it is advisable to consider the complete multi-model range of the variables of interest. This comprehensive approach ensures a more nuanced and thorough understanding of the potential climate shifts in Singapore's future. Additional information on science communication can be found in Chapter 14 V3 Comms.