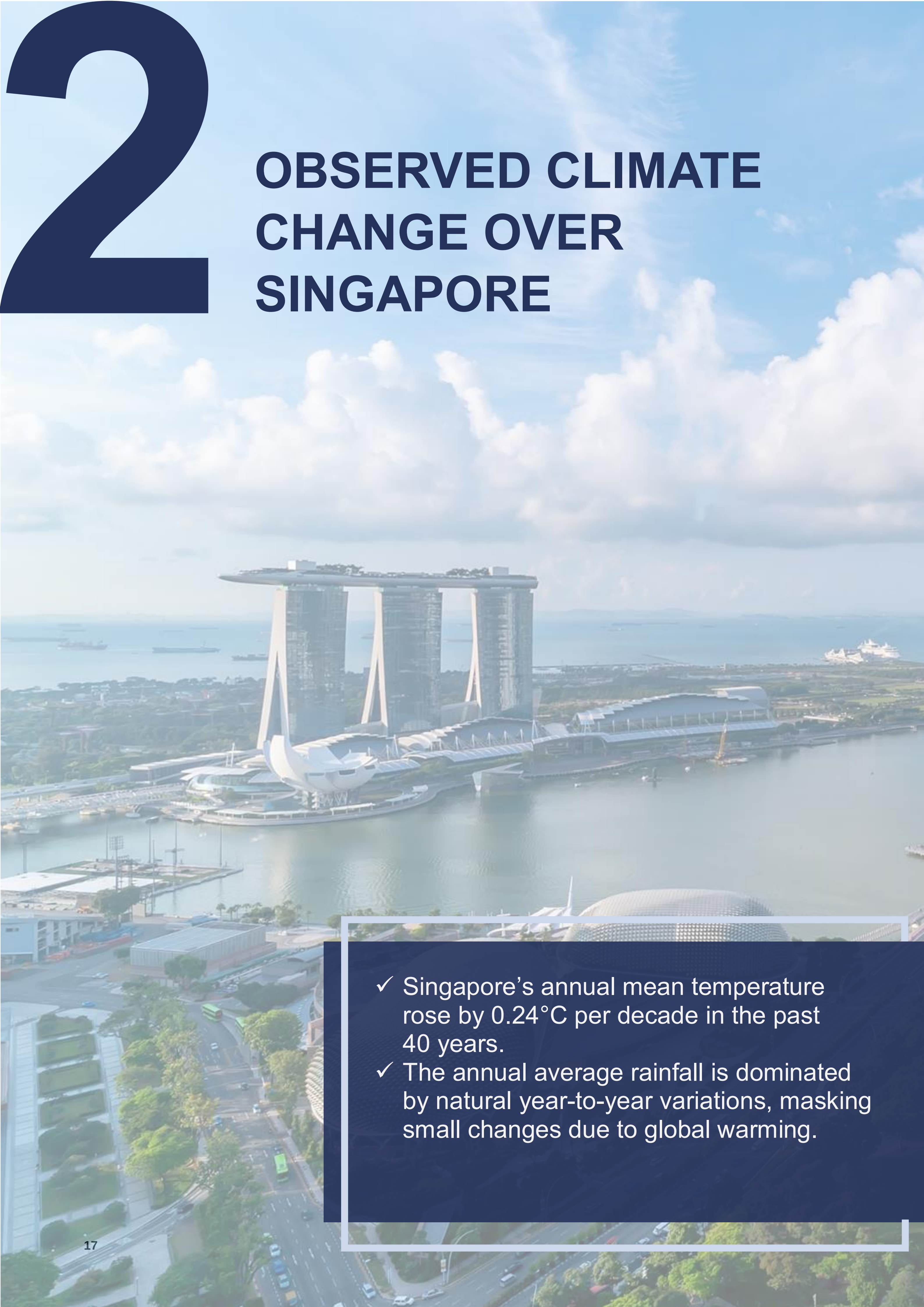


2 OBSERVED CLIMATE CHANGE OVER SINGAPORE

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

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

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

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

2.1 General climate of Singapore and its drivers

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

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

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

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

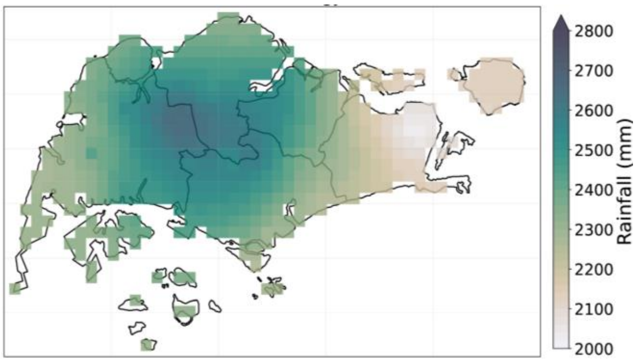


Figure 2.1: Annual rainfall for the 30-year (1991–2020) climatological period based on 28 rainfall stations across Singapore.

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

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

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

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

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

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

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

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

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

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

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

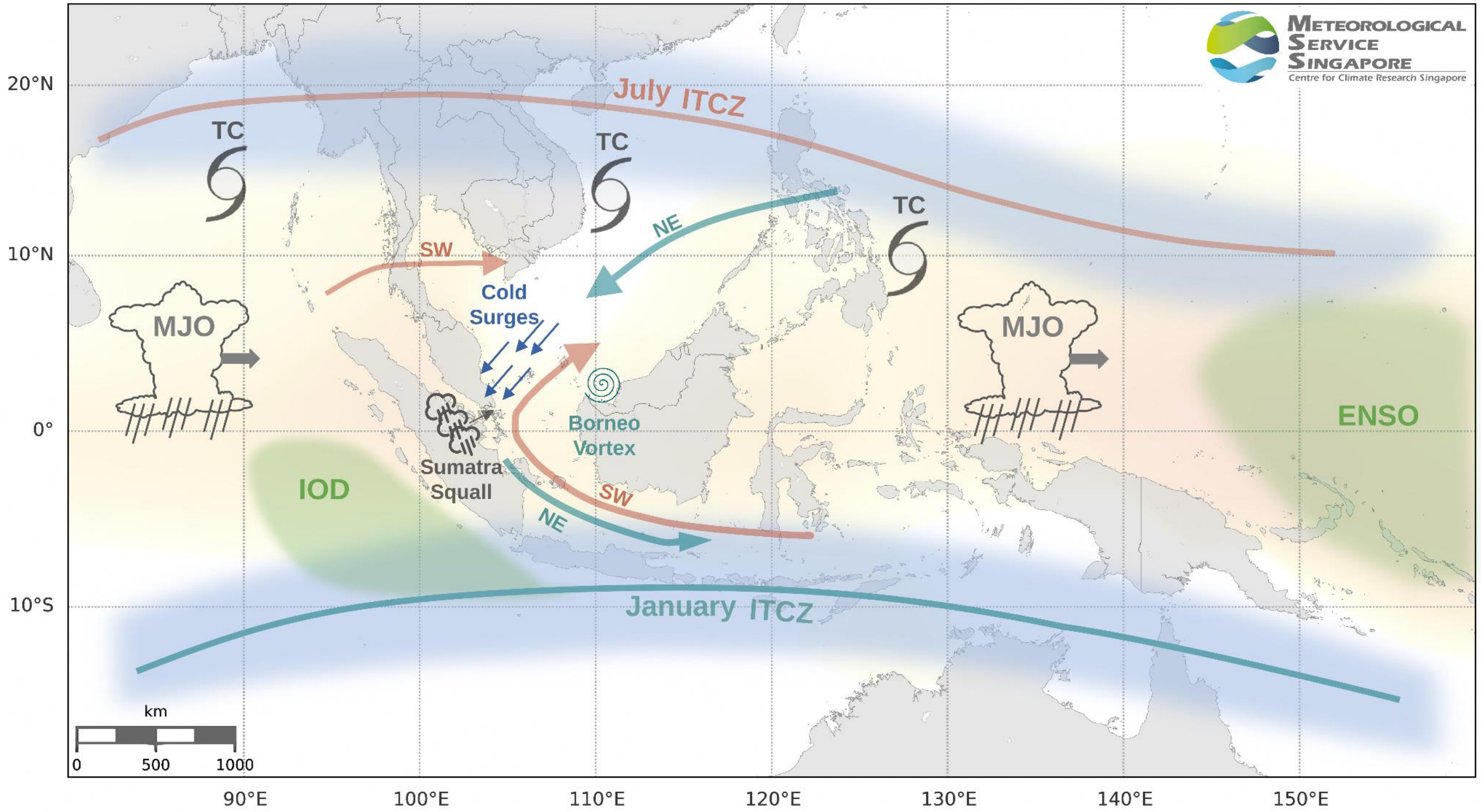
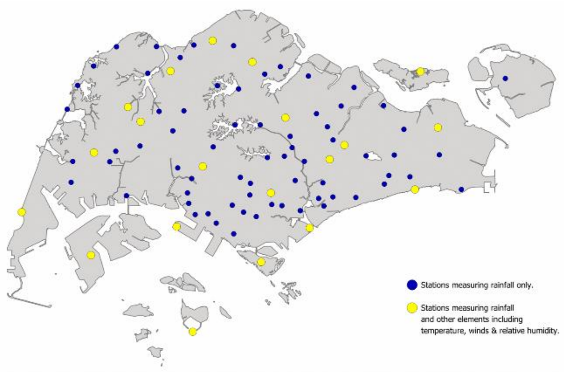


Figure 2.2: Climate drivers influencing weather and climate for the region around Singapore. Included are the average position of the Intertropical Convergence Zone (ITCZ) in blue indicating the furthest northward and southward extent of the seasonal migration of the regional monsoon system. The green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

2.2 Climate monitoring over Singapore

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



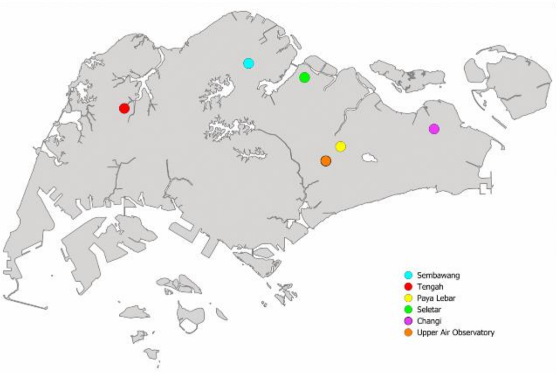


Figure 2.3: Network of automated weather stations (top), and manned weather stations (bottom).

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

Figure 2.4: Changi climate station.

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

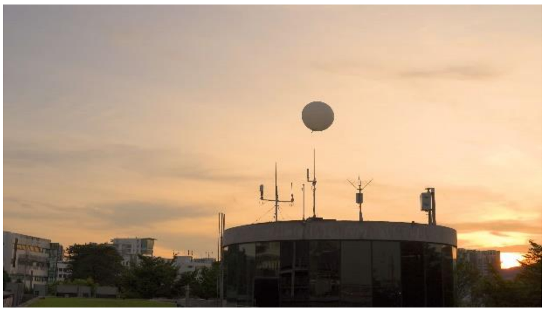


Figure 2.5: Upper Air Observatory.

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

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

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

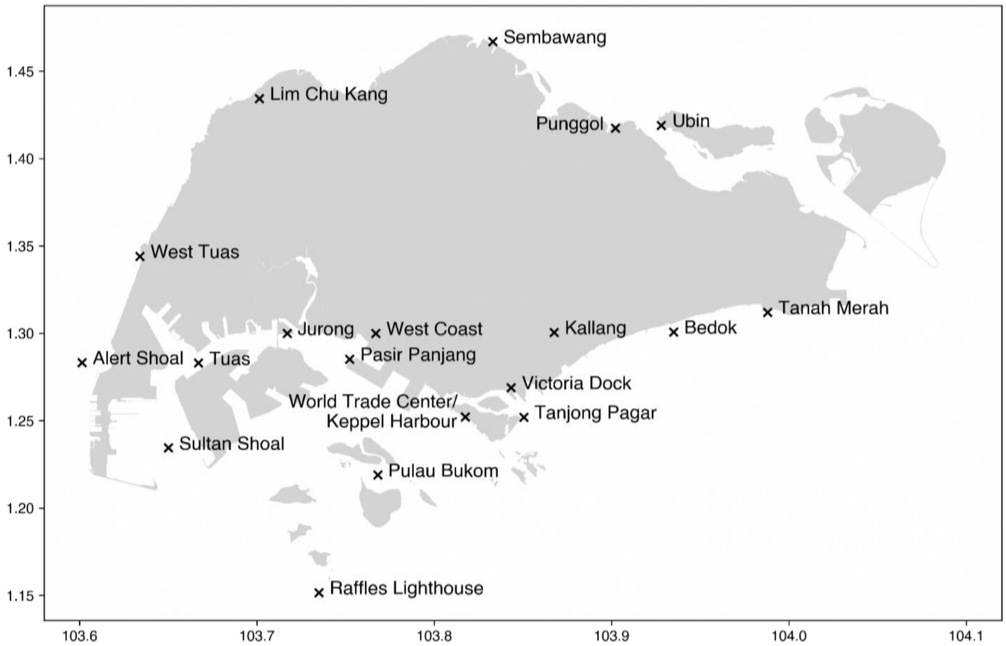


Figure 2.6: Location of the 19 tide gauges around Singapore. The offshore tide-gauge at Horsburgh Lighthouse is not shown.

2.3 Importance of high-quality observations

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

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

2.4 How has the temperature changed?

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

2.4.1 Daily mean temperature

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

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

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

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

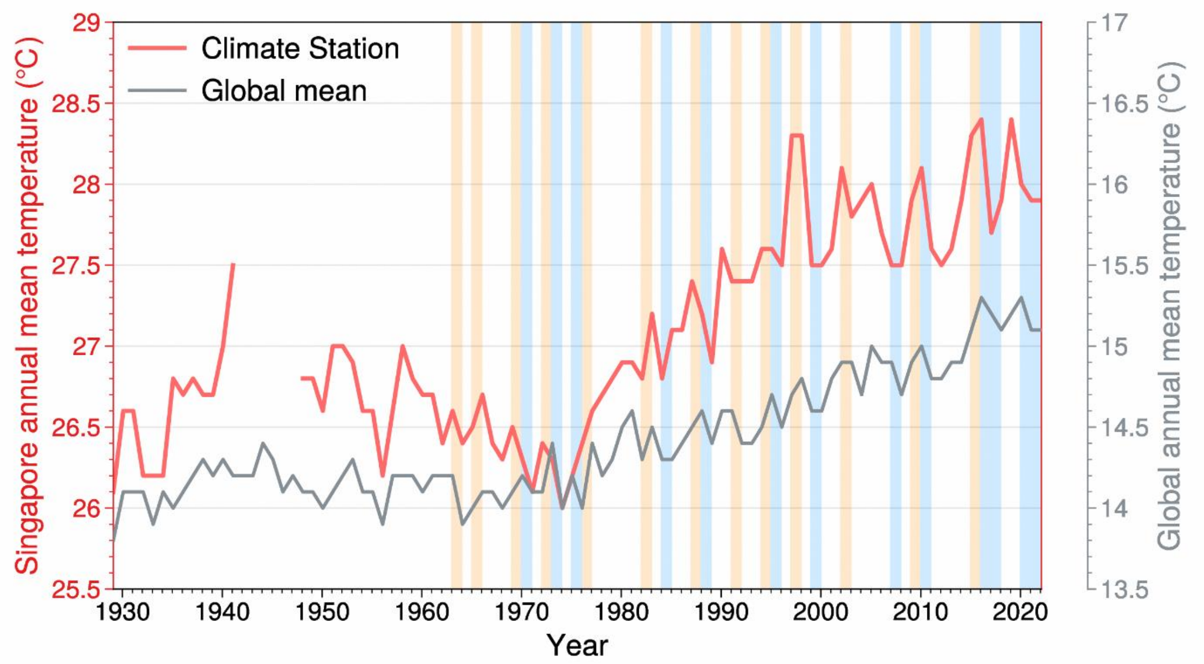


Figure 2.7: Annual mean temperature from 1929-2022 at Singapore's climate station, compared with the global annual mean temperature from the high-resolution (0.25° ✕ 0.25°) Berkeley Earth dataset. The orange and blue bars denote El Niño and La Niña years from 1963, respectively.

2.4.2 Daily Minimum and Maximum Temperatures

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

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

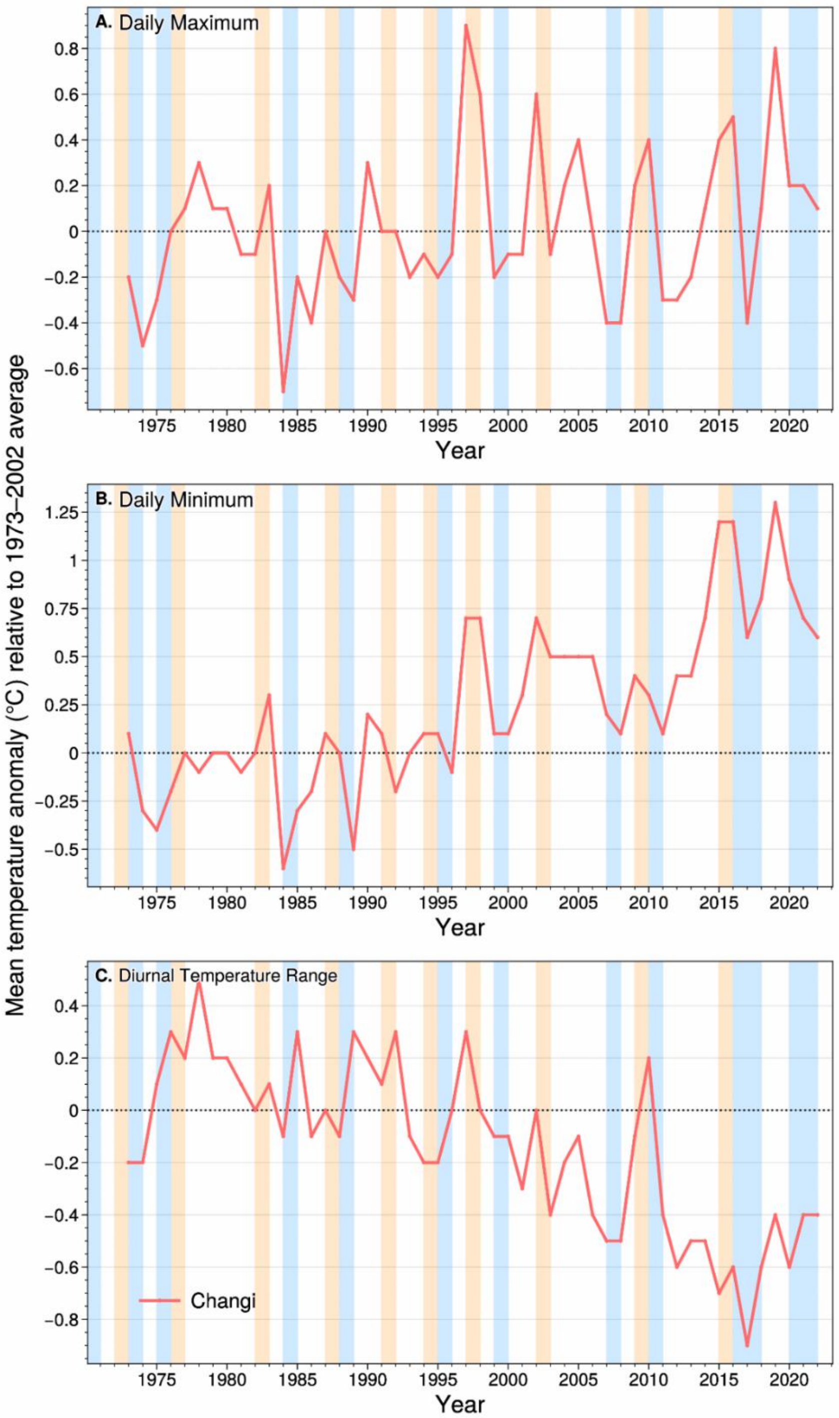


Figure 2.8: The annual average anomaly of (a) daily maximum and (b) daily minimum temperature at Changi. The diurnal temperature range is shown in (c). The anomalies are calculated relative to the 1973–2002 period average. The orange and blue shades denote El Niño and La Niña years, respectively.

2.4.3 Warm Days

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

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

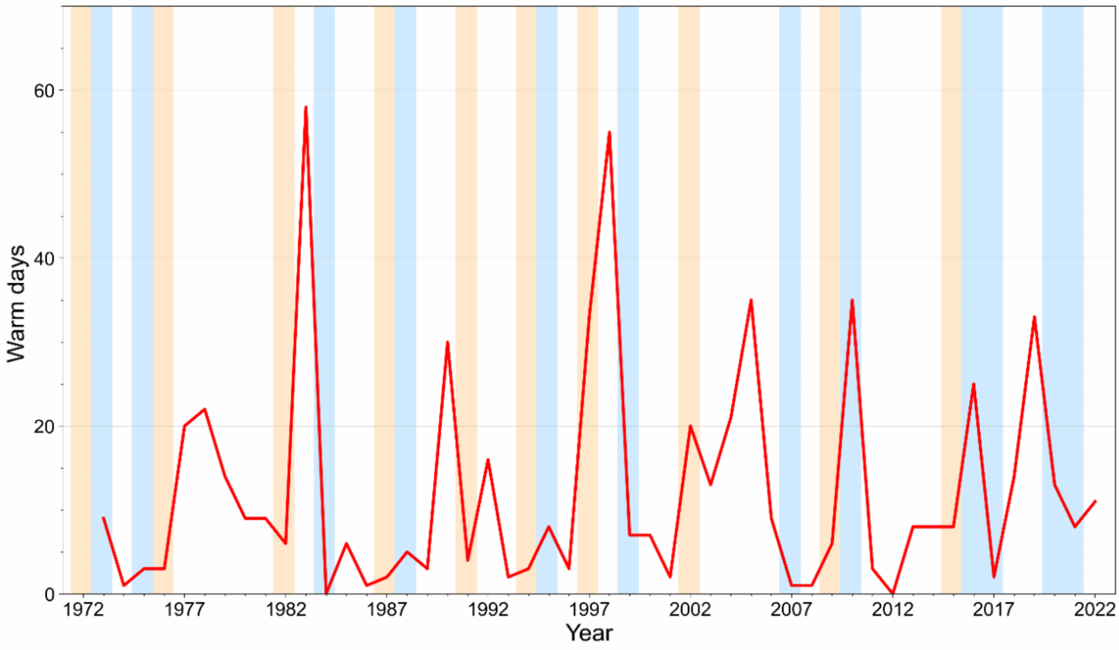


Figure 2.9: The number of warm days per year at the Changi station from 1973 to 2022.

2.5 How has rainfall changed?

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

2.5.1 Annual rainfall

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

2.5.2 Monthly and seasonal rainfall

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

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

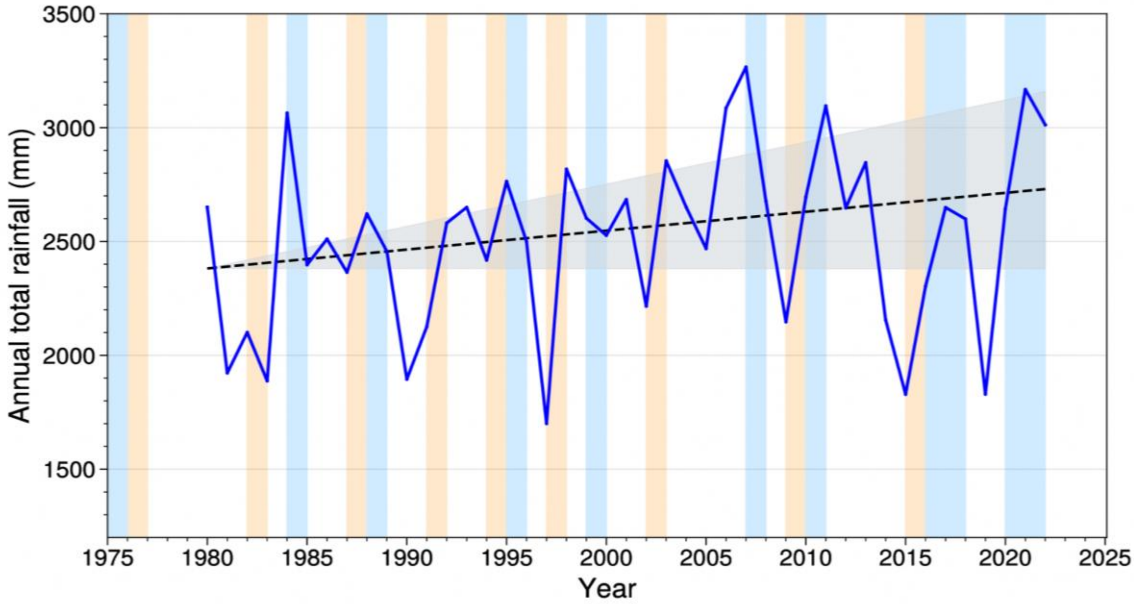


Figure 2.10: Annual total rainfall (solid blue) averaged over 32 stations with continuous records for at least 30 years. The black dashed line depicts an upward but not statistically significant trend (83 mm/decade). The grey shaded area represents the 95% confidence interval of the estimated trend.

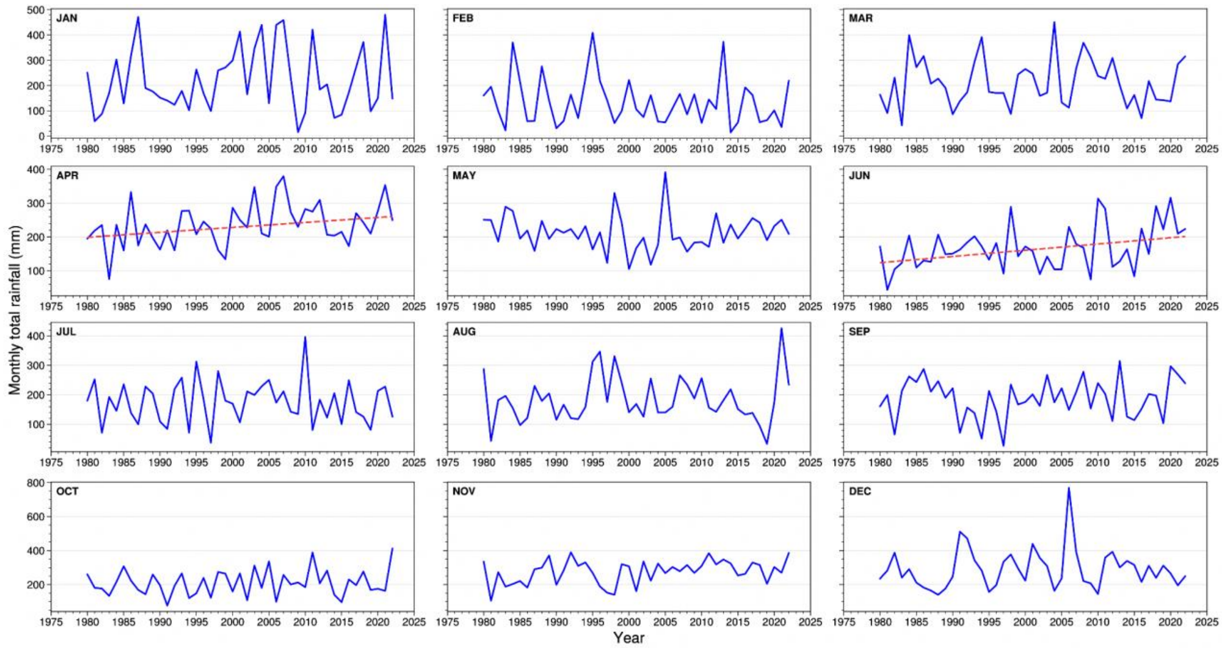


Figure 2.11: Monthly total rainfall averaged from 32 stations with continuous records for at least 30 years. The red dashed line for April (APR) and June (JUN) indicates statistically significant trends at the 5% level.

2.5.3 Rainfall extremes

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

Figure 2.12 shows the annual maximum rainfall intensity at 15 min (RX15min), 30 min (RX30min) and 60 min (RX60min) durations. Overall, no trends are detected over the last 43 years in the extreme rain rates across the three time windows, with RX15min showing a small insignificant decrease of −1.0 mm/decade and

RX30min showing only a tiny increase of 0.8 mm/decade. RX60min shows no trend at all (0 mm/decade). There also appears to be little correlation with the ENSO phase on yearly time scales. However, RX60min seems to exhibit variability on inter-decadal timescales as shown by the period averages, i.e., 97.3 mm between 1980 and 1994, 111.8 mm between 1995 and 2010, and 96.4 mm between 2011 and 2022. The multi-decadal variability in RX60min suggests the possible influence from long-term climate drivers in the Pacific such as the Inter-decadal Pacific Oscillation (IPO) and warrants further investigation.

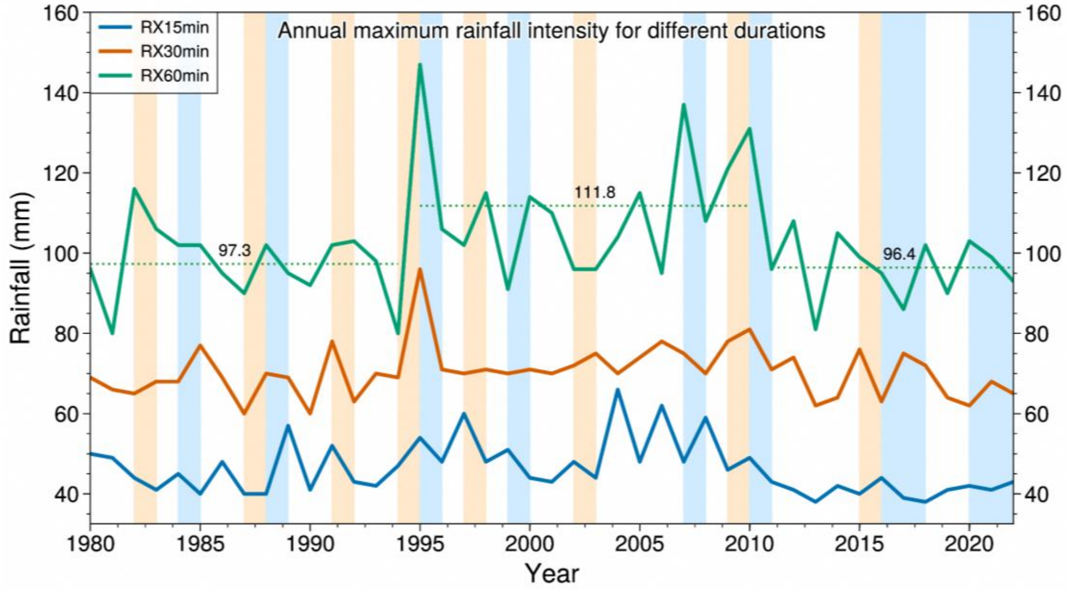


Figure 2.12: Annual maximum rainfall intensity at 15 min (RX15min, blue), 30 min (RX30min, orange) and 60 min (RX60min, green) durations, computed from a set of 23 stations with long-term observations going back to 1980. Numbers above the green dotted lines denote the RX60min averages for the corresponding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

2.6 How has relative humidity changed?

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

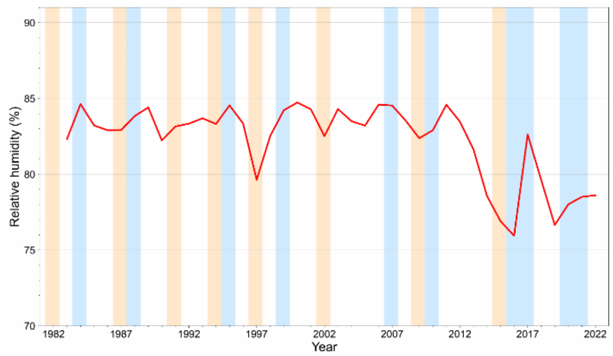


Figure 2.13: Annual mean relative humidity at Changi.

2.7 How have winds changed?

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

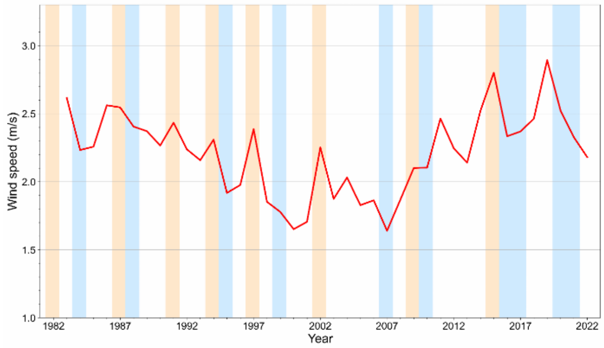


Figure 2.14: Annual mean 10-m wind speed at Changi

2.8 How has the sea level changed?

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

2.8.1 Why is sea level changing?

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

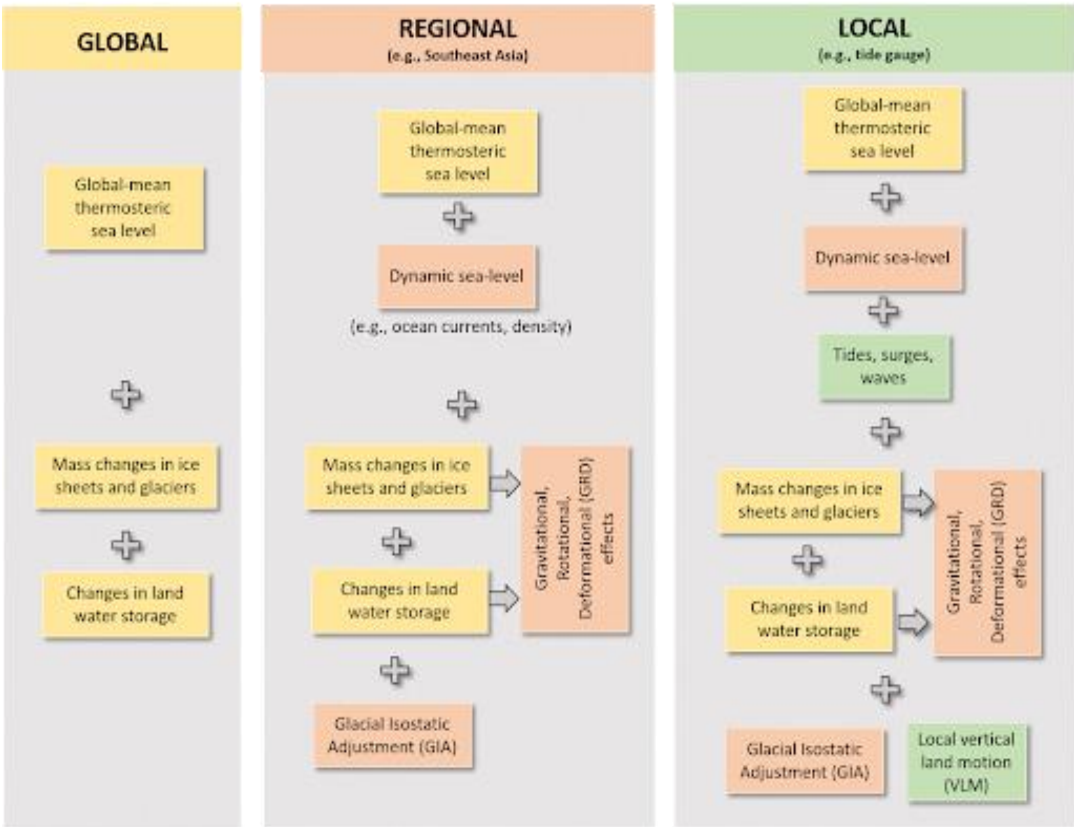


Figure 2.15: Schematic of different geophysical processes contributing to global, regional, and local sea-level change. Note, the color-coding reflects the spatial scales on which the different processes operate, as per the column titles and that these are treated additively as one progresses to smaller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

Global processes

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

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

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

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

Regional and local processes

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

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

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

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

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

2.8.2 Sea-level rise in the Southeast Asian Seas

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

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

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

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

2.8.3 Sea-level rise around Singapore

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

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

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

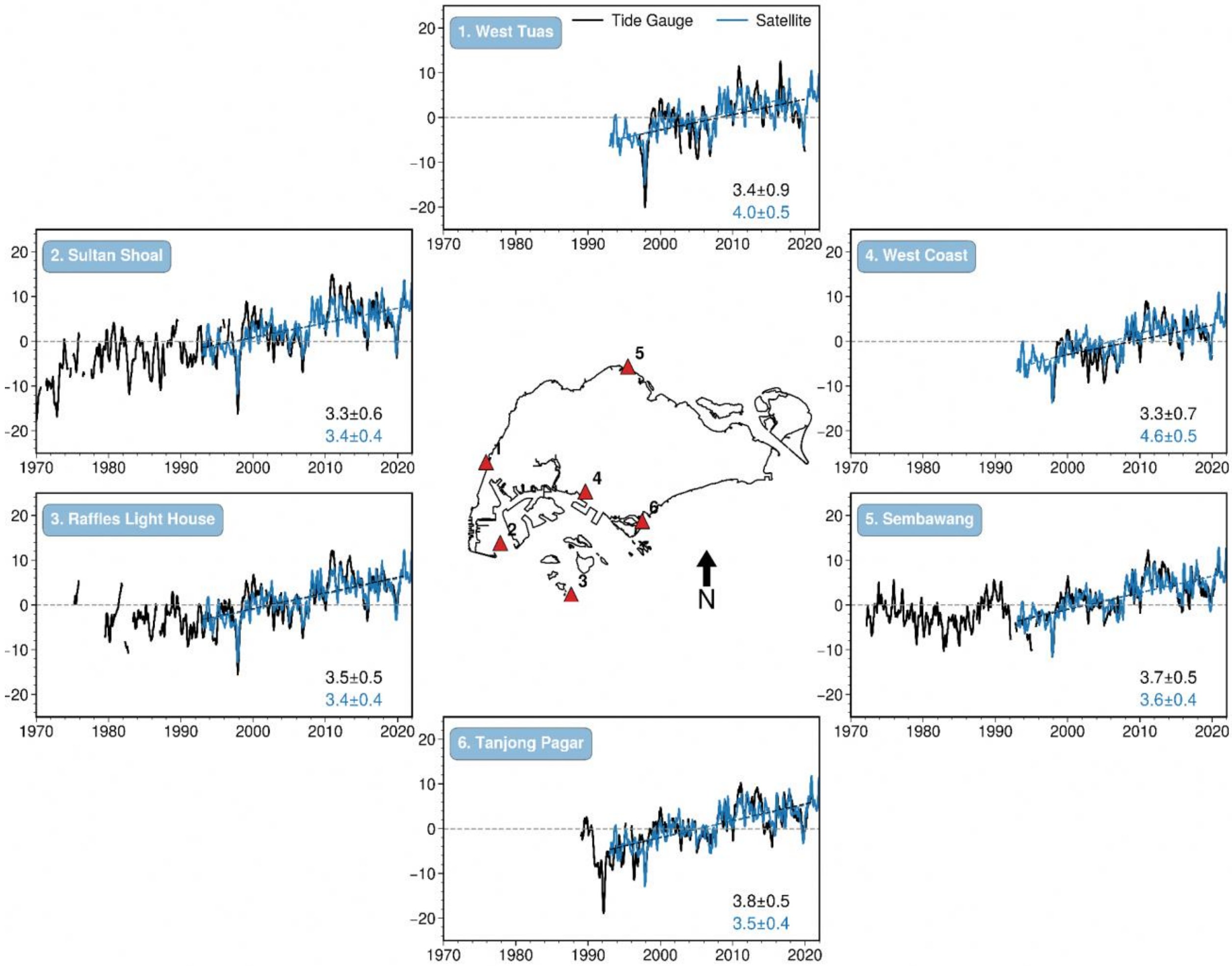


Figure 2.16: Time series of monthly sea-level anomalies (with respect to mean seasonal cycle, unit is in cm) from Singapore's six tide gauges (black curves). The locations of the tide-gauge stations are shown in the map. Sea-level anomalies from satellite altimetry (blue curve, averaged over 1 degree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