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Observed Climate Change over Singapore

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3.1 Introduction

There have been two key reports published recently providing important information on global and regional observed climate changes. First, the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) notes that many of the changes observed in the climate are unprecedented in thousands of years 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).

Secondly, the World Meteorological Organization (WMO) published its annual state of the global climate report based on a network of observing systems spread across the world which are maintained by various organisations, with the National Meteorological and Hydrological Services playing a key role in this effort. Some of the highlight statements from the WMO Report for the year 2022 are:

- The global mean temperature in 2022 was 1.15 [1.02–1.28] °C above the 1850–1900 average. The years 2015 to 2022 were the eight warmest in the 173-year instrumental record. The year 2022 was the fifth or sixth warmest year on record, despite ongoing La Niña conditions.

- The year 2022 marked the third consecutive year of La Niña conditions, an episode which has only occurred three times in the past 50 years.

- Despite continuing La Niña conditions, 58% of the ocean surface experienced at least one marine heatwave during 2022.

- Global mean sea level continued to rise in 2022, reaching a new record high for the satellite altimeter record (1993–2022). The rate of global mean sea level rise has doubled between the first decade of the satellite record (1993–2002, 2.27 mm per year) and the last (2013–2022, 4.62 mm per year).

Most relevant for Singapore, the Meteorological Service Singapore (MSS) publishes its Annual Climate Assessment Report (ACAR) each year on 23rd March, celebrated as the World Meteorological Day, which is an annual assessment of Singapore's climate. Some of the highlight statements from the latest ACAR (ACAR 2022) for the year 2022 are:

- 2022 was Singapore's sixth wettest year since 1980 with an average annual total rainfall of 3012 mm. This is nearly 19% higher than the long-term 1991 – 2020 average. Rainfall for most months was above average, with October 2022 recording the highest October total rainfall in the last four decades.

- Despite the high rainfall, Singapore's annual mean temperature in 2022 was the tenth highest since temperature records began in 1929, tied with five other years.

3.1.1 Climate Monitoring over Singapore

MSS has a network of meteorological observing stations, which includes manned as well as automated stations that provide real-time observations across Singapore (Figure 3.1). 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.

The manned observation station at Changi is MSS's designated climate station (see Figure 3.2). 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. 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).

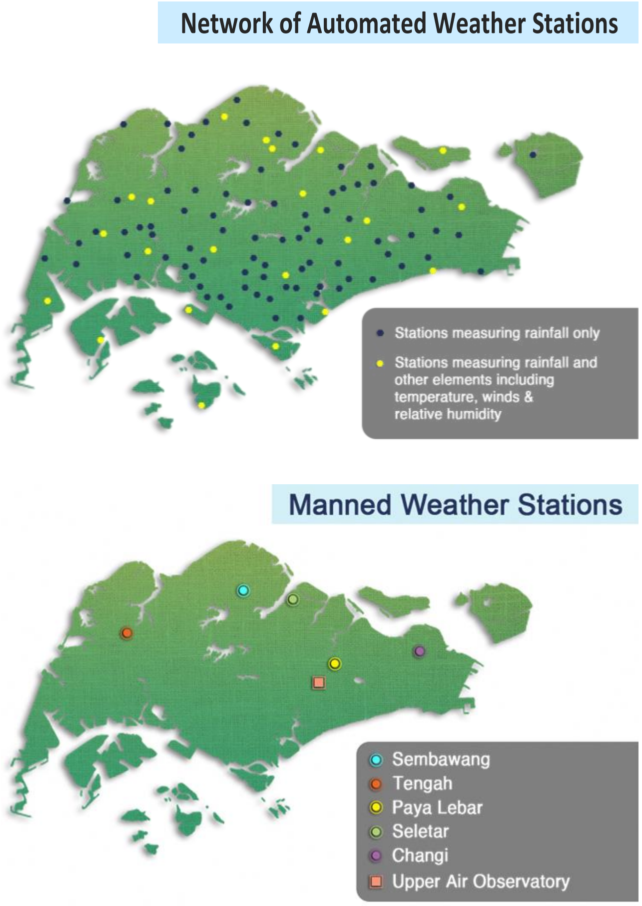

Figure 3.1: Network of automated weather stations (top), and manned weather stations (bottom).

Figure 3.2: Changi climate station.

Figure 3.3: Upper Air Observatory

The installation of the automatic weather station network since 2009 greatly expanded the coverage of weather observations across Singapore. Prior to this, there were around 40 manual rainfall stations and just a few temperature stations in Singapore. For the purpose of analysing long-term climate trends and establishing climatological averages, only stations with continuous long-term (at least 30 years) records can be used.

Singapore is located deep within the tropics, where wind and atmospheric conditions evolve rapidly. The twice-daily soundings provide the main source of complete upper-air information to support operations. In addition to operational purposes, 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 3.3).

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

In addition to the atmospheric monitoring, Singapore also monitors its sea levels using tide gauges. To the best of our current knowledge, Singapore has 19 tide gauges owned and maintained by the Maritime & Port Authority of Singapore (MPA; see Figure 3.4).

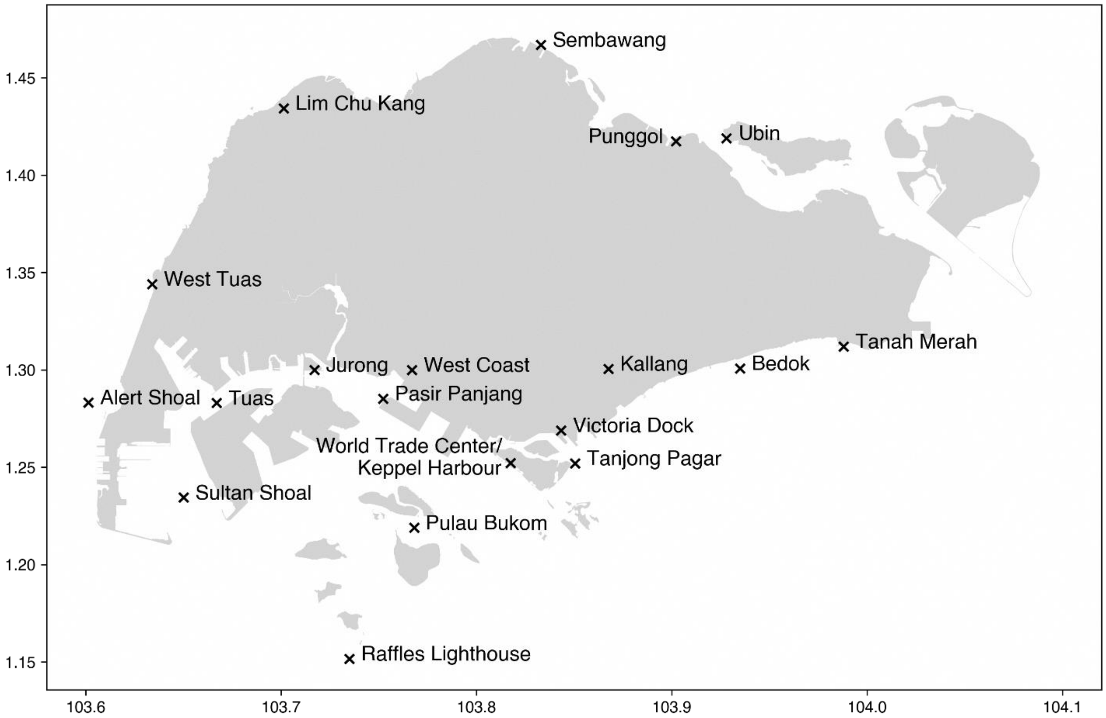

Figure 3.4: Location of the 19 tide gauges around Singapore. Tide-gauge at offshore island, Horsburgh Lighthouse, not shown here.

3.1.2 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 also for validating how well the 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, whether they be short to medium-range weather forecasts, sub-seasonal to seasonal predictions or climate change projections.

3.1.3 General Climate of Singapore and their Drivers

Singapore has a tropical climate, which is warm and humid, with an abundant total annual rainfall of approximately 2490 mm (Hassim & Timbal, 2019). Generally, the eastern parts of Singapore receive less rainfall compared to other parts of the island. The climatological annual mean rainfall is shown in Figure 3.5 below. The winds are generally light but with a diurnal variation due to land and sea breezes.

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.

Singapore’s climate is traditionally classified into four periods according to 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 Dec-Jan and a dry phase during Feb-Mar, 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 usually light and variable in direction.

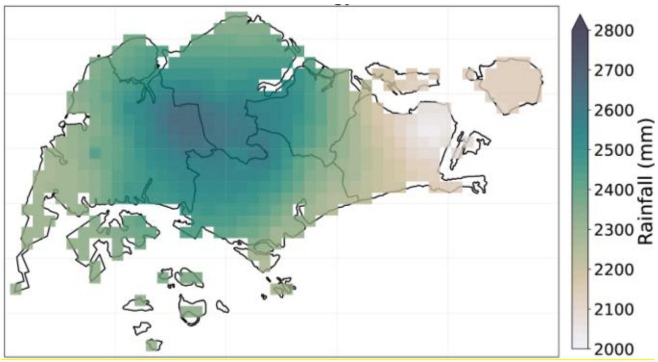

Figure 3.5: Annual rainfall for the 30-year (1991-2020) climatological period based on 28 rainfall stations across Singapore.

The major weather and climate features 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 El-Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and the Madden-Julian Oscillation (MJO), to smaller scale features such as Sumatra squalls, the Borneo Vortex and remote influences from tropical cyclones (see Figure 3.6).

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

Understanding the large- and small-scale features that influence climate variability across the Maritime Continent 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 and supports resilient development in vulnerable local communities. The provision of reliable scientific information for decision-making enables more effective adaptation planning: an essential requirement for securing sustainable development in the region.

The **El Niño – Southern Oscillation (ENSO)** is the major influence on climate variability in the western tropical Pacific and Maritime Continent. 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 Maritime Continent into the Pacific Ocean bringing monsoonal rains. It migrates every year southward across the equator and back again, affecting most countries across the Maritime Continent including Singapore. There are interannual 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).

The **Indian Ocean Dipole (IOD):** Indian Ocean sea surface temperatures impact rainfall and temperature patterns across the Maritime Continent. 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.

The **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 to 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 Maritime Continent. 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.

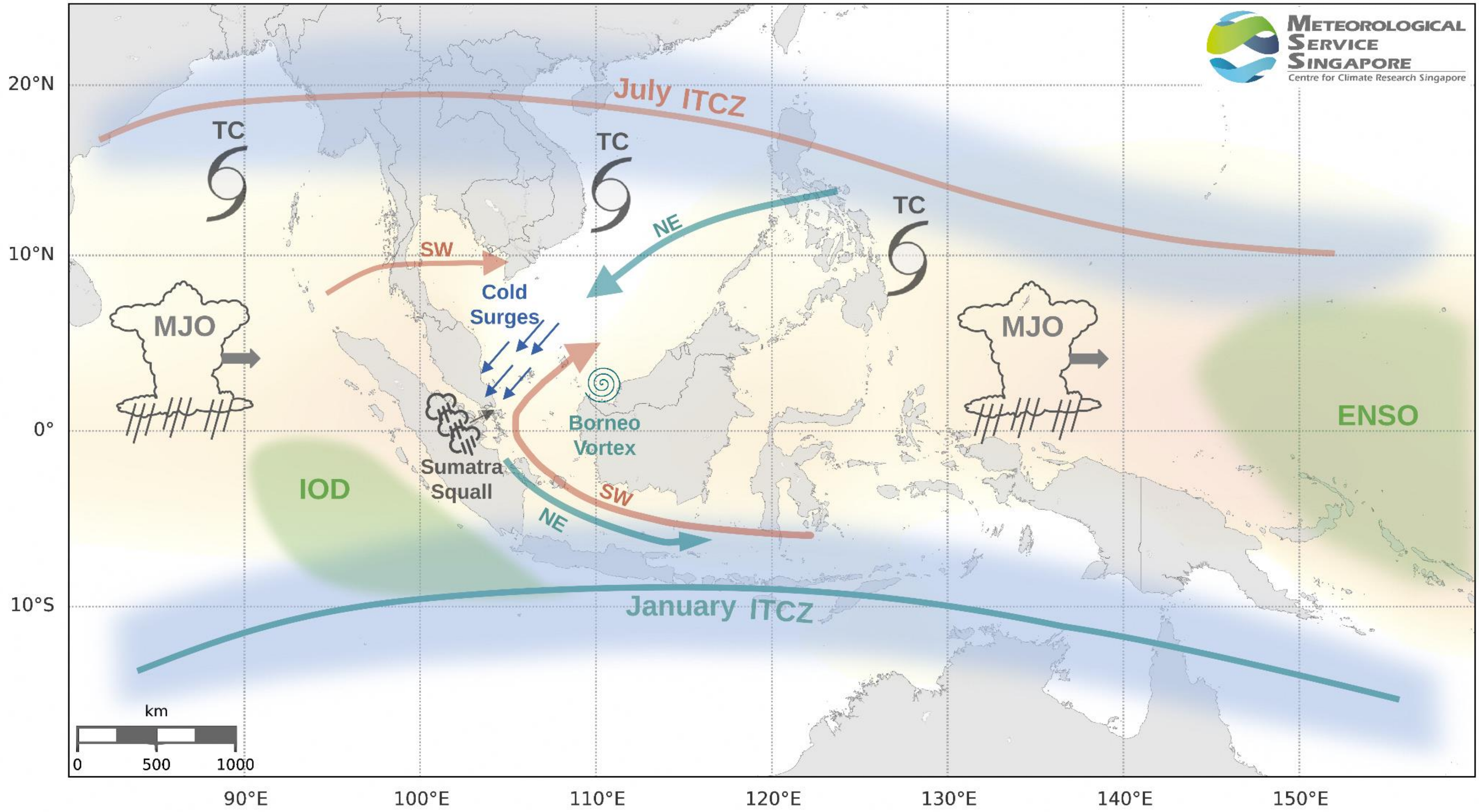

Figure 3.6: Climate drivers influencing weather and climate for the region around Singapore. Included are the average position of the Intertropical Convergence Zone (ITCZ) in blue indicating the furthest northward and southward extent of the seasonal migration of the regional monsoon system. The green 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.

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 to 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 Maritime Continent (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 Maritime Continent (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) usually 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 degrees latitude (north), 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.

3.2 Observed changes in temperature

Historical archives from the National Library of Singapore indicate that observations of monthly temperature and rainy days in Singapore were taken from as far back as 1820 during British colonial times by various individuals, the earliest of which was by Singapore's first Resident, William Farquhar. However, routine measurements for rainfall only began from 1869 when the practice was formally institutionalised by the Medical Department of the Straits Settlements, first in places such as the Convict Jail Hospital in Bras Basah, the Convict Prison in Outram and later at Kandang Kerbau Hospital (Table 3.1).

The location of the officially designated climate station has varied over time following the formation of the Malayan Meteorological Service – the predecessor to the Meteorological Service Singapore – in 1929, beginning with Mount Faber in the south of Singapore (Figure 3.7). Measurements ceased between 1941 to 1947 due to World War II; during this period, the climate station was located at the Botanic Gardens. The climate station was then located at Kallang Airport and then at Paya Lebar Airport before its current site at Changi in the east of Singapore, where it has been since July 1981.

The official climate station record for monthly mean temperature dates back to January 1929 from Mount Faber (Figure 3.8). However, monthly mean temperature observations from Changi climate station (derived from daily mean values) were only used in the official climate station record from 1984 onwards. Prior to that, between 1981 to 1984, the monthly mean observations from Paya Lebar were still used.

As the site of the climate station has changed over time, we consider the period 1984 – present from Changi to constitute the longest and most homogeneous climate station record for monthly mean temperature. Another weather observation station that has long-term daily temperature records going back to 1972 is Tengah, situated in the west of Singapore (Fig. 3.7). The western location of Tengah and its long time series allows us to compare how temperatures across the island have evolved over time during the common overlapping 1984 – 2018 period between the two stations.

Table 3.1: Locations of the Climate Station in Singapore and their period of active service. Reproduced from www.weather.gov.sg/learn_climate. Only records from Mount Faber, Kallang, Paya Lebar and Changi constitute the official climate station record for monthly mean temperature.

	Period of Service	Location of Climate Station
1	Jan 1860 - Dec 1874	Convict Prison (Outram)
2	Jan 1875 - Dec 1928	Kandang Kerbau Hospital
3	Jan 1929 - May 1934	Mount Faber
4	Jun 1934 - Dec 1941	Kallang
5	Jan 1942 - Dec 1947	Botanical Gardens
6	Jan 1948 - Aug 1955	Kallang
7	Sep 1955 - Dec 1983	Paya Lebar
8	Jan 1984 - present	Changi

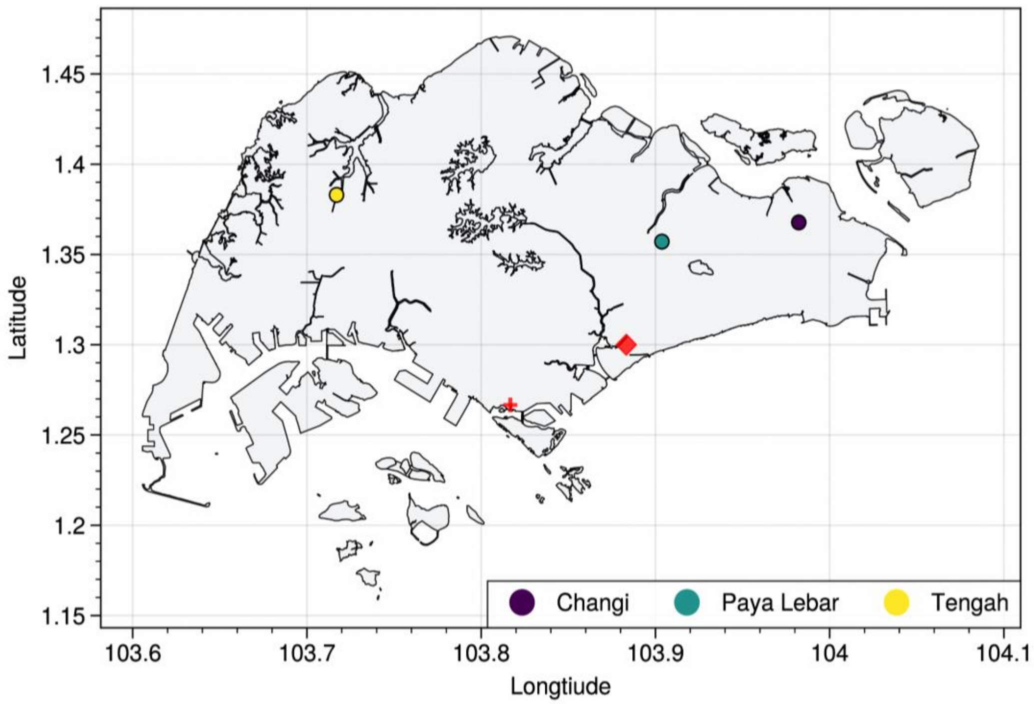

Figure 3.7: Location of Changi Climate Station and the manned stations at Tengah and Paya Lebar (previous climate station from 1955-1984) with long-term observations going back prior 1980. The location of the early climate stations of Singapore (Mt

Faber, 1929-1934) and Kallang Airport (1935-1941, 1948-1955) whose temperature observations are included in the long-term climate station record, are marked by the red cross and red diamond, respectively.

3.2.1 Mean Temperature

Over the last 39 years since 1984, the average daily mean temperature has been steadily rising at the climate station, as seen in Figure 3.8. This rise in temperature is evident even with the large year-to-year variability due to the influence of large-scale climate drivers such as the El Niño-Southern Oscillation (ENSO). El Niño events tend to increase annual mean temperatures across Singapore, while La Niña events tend to moderate them.

Over the 1984 to 2022 period, the long-term warming rate across the two stations are very comparable: the mean temperature at the climate station has increased at a rate of 0.24°C per decade, while Tengah has warmed at a slightly higher rate of 0.26°C per decade. The slightly higher rate is likely due to the rapid rise in annual mean temperature in the last decade (from 2010). Both Tengah and Changi exhibit a warming rate that is slightly higher than the global mean temperature (derived from the Berkeley Earth dataset), which shows a warming trend of 0.21°C per decade over the 1984 to 2022 period.

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 corresponding values for global trends are 0.17°C and 0.22°C per decade respectively. 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 on top of 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.

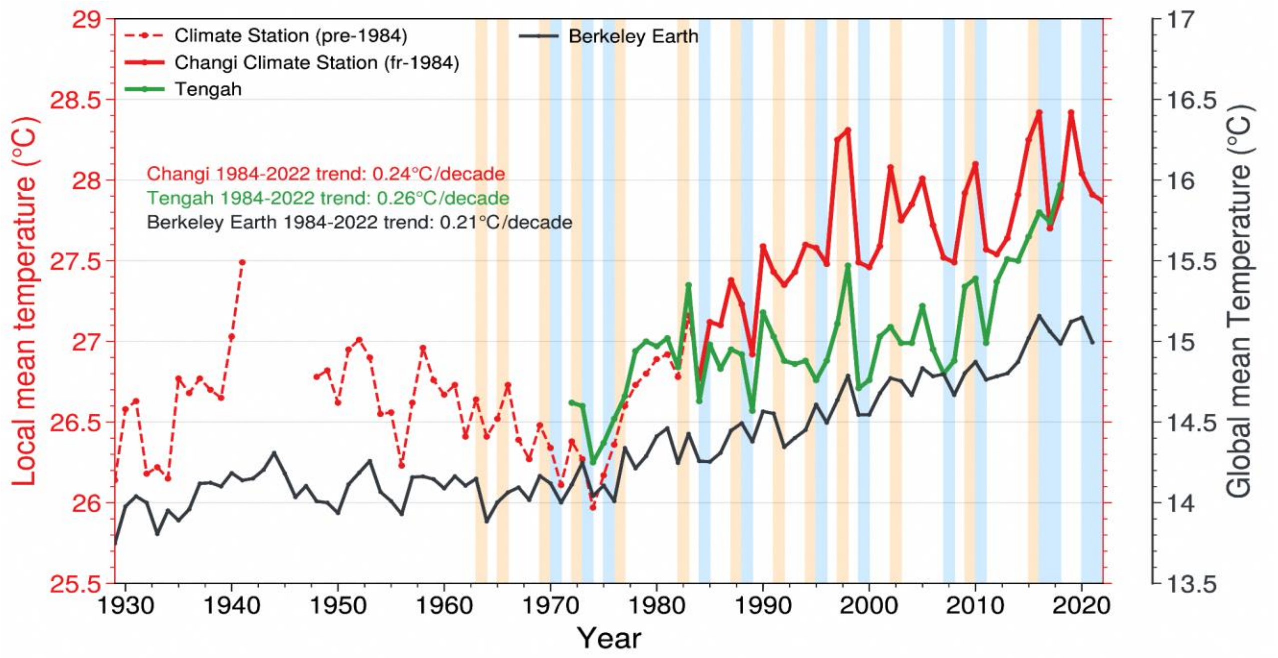

Figure 3.8: Time series of the local annual mean temperature from the climate station (dotted and solid red lines, for pre-1984 and from 1984, respectively) and Tengah (green). Also shown is the global mean temperature time series plotted on the right secondary axis for comparison. The orange and blue shades denote El Niño and La Niña years from 1980, respectively.

Table 3.2: Decade-by-decade trend analysis for the Climate Station vs. the Berkeley Earth global mean (land+ocean) dataset for 1984-2022.

	Decade-by-decade trends (°C per decade)	
	Station Data (Singapore Climate Station)	Gridded Data Berkeley Earth (land+ocean)
1984-1993	0.52	0.24
1993-2002	0.17	0.31
2003-2012	-0.23	0.07
2013-2022	0.07	0.27

3.2.2 Daily Minimum and Maximum Temperatures

Figure 3.9 compares the mean daily minimum temperature anomalies between the Tengah station, the Changi climate station and the global average air temperature over land. The Tengah station is situated close to the Tengah River, surrounded by the more forested areas of western Singapore, while the Changi station is sited near the more developed residential parts in eastern Singapore and close to the airport's runway. Over the last 50 years (1973 – 2022), the night-time minimum temperatures at Changi have warmed more rapidly (0.21°C/decade, Figure 3.9a) than the location's daytime maximum temperatures, which show no significant trend (0.06°C/decade, Figure 3.9b). In contrast, both the night-time low and daytime high temperatures at Tengah are rising almost in tandem (at 0.14°C/decade and 0.13°C/decade, respectively; both trends are statistically significant at the 5% level). In fact, the minimum temperatures at Changi are warming 1.5 times faster than those at Tengah, and comparable to the global land average (0.24°C/decade).

A consequence of Changi warming much faster during the night than it does during the day is that we see a significant reduction in its diurnal temperature range (DTR) (Figure 3.9c). In contrast, the DTR at Tengah exhibits a negligible trend since both daytime maximum and night-time minimum temperatures show similar warming rates there.

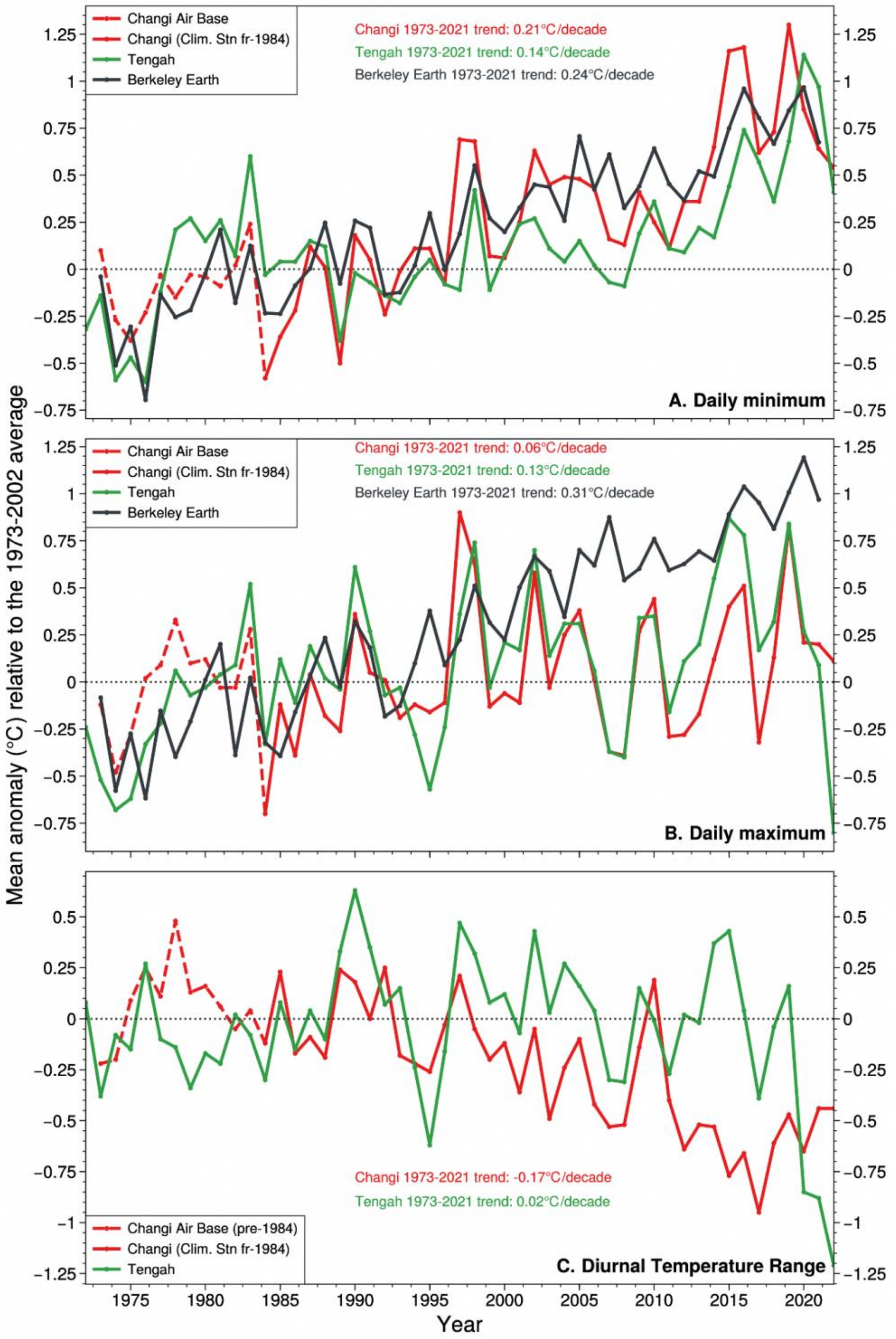

Figure 3.9: As in Fig. 2.1 but for annual average anomaly of (a) daily minimum and (b) daily maximum compared to the corresponding Berkeley Earth Surface Temperature dataset for global land only (black solid line). The diurnal temperature range is shown in (c). The anomalies are calculated relative to the 1981-2010 climatology. Also shown are respective trends (dotted lines) for the 1970-2022 period (greyed background).

3.2.3 Warm Days

Since the mid-1970s, there has been an overall increase in the number of warm days (days when the daily maximum temperature exceeds 34℃), as can be seen in Figure 3.10. An upward trend was observed in some weather stations. For instance, the number of warm days recorded at Tengah and Seletar stations increased to 1.3 and 0.8 days per year between 1972 and 2022, respectively. High temperature characteristics vary spatially across the island, with Changi station experiencing fewer warm days than the other two stations. The fewer warm days could be due to the sea breeze effect. As Changi is located near the coast, where cooler air from the sea replaces the warm air on the island, this can reduce the high afternoon temperatures and relieve the heat. However, it is worth noting that the frequency of warm days exceeding 20 days per year in Changi has increased.

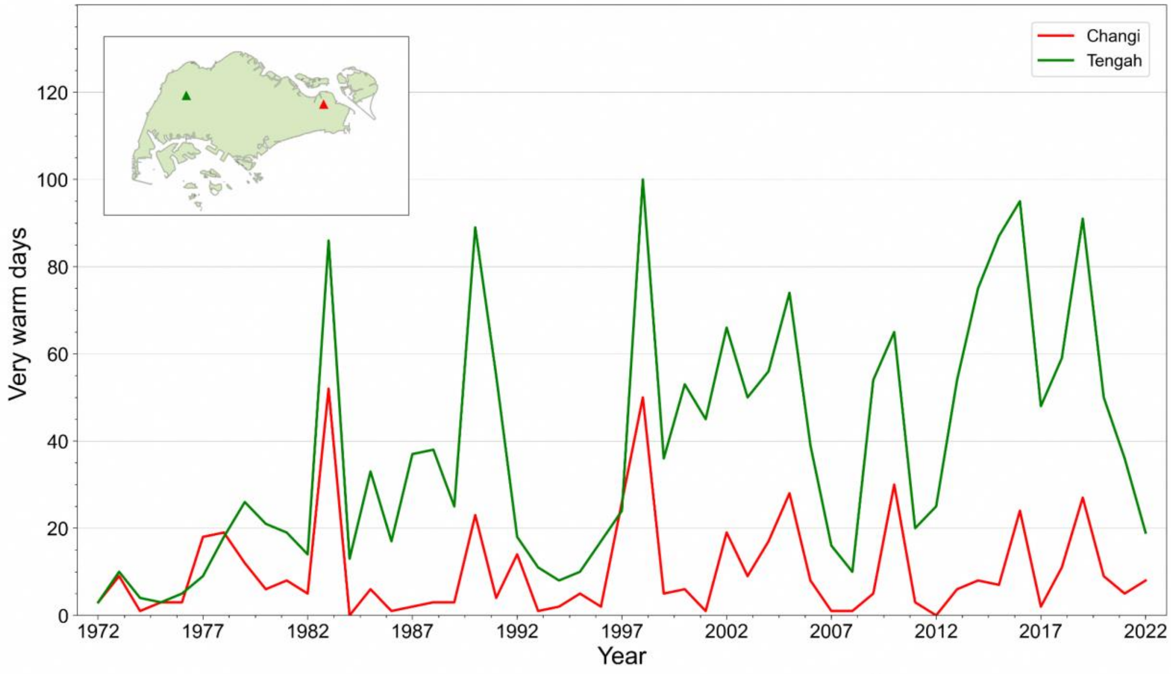

Figure 3.10: The number of warm days, counted as days with maximum daily temperature above 34℃ for Changi (red) and Tengah (green) weather stations from 1972 - 2022.

3.3 Observed change in heat stress

According to the IPCC AR6 WG-II report, heat stress is a range of conditions when the body absorbs excess heat during overexposure to high air or water temperatures or thermal radiation. Heat stress in humans is exacerbated by a detrimental combination of ambient heat, high humidity and low wind speed, causing the regulation of body temperature to fail. Although heat stress can be measured by empirical measures such as wet-bulb globe temperature (WBGT) and apparent temperature that are functions of temperature, humidity, wind and sunlight, we use the wet-bulb temperature (WBT) as a simple and powerful indicator of heat stress.

In Figure 3.11, we show the annual mean of the daily maximum WBT from Changi and Tengah weather stations for the period 1985-2020. It can be seen from the figure that there is no monotonic trend in WBT in either of the stations. There is a strong year-to-year variability associated with

ENSO. During the last decade, while Changi has shown a decreasing trend, Tengah has shown an increasing trend in WBT, which highlights the spatial differences in trends within Singapore.

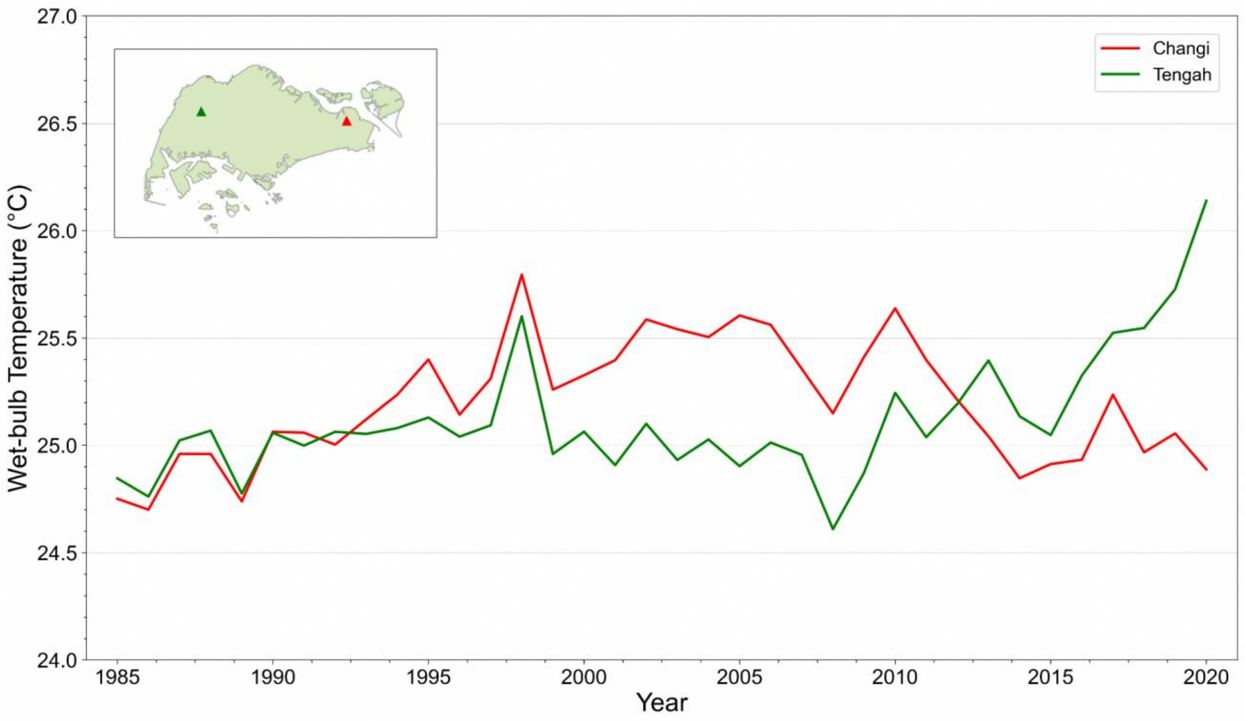

Figure 3.11: Mean wet-bulb temperature at Changi (red) and Tengah (green) weather stations from 1985-2020.

3.4 Observed change in rainfall

3.4.1 Annual Rainfall

The annual total rainfall for Singapore has a gradually increasing trend of 83 mm per decade from 1980 to 2022. However, this trend is not statistically significant (see Figure 3.12). Instead, years that experienced predominantly La Niña conditions (e.g. 2022, 2021, 2011) tend to be wetter, while years when El Niño conditions developed (e.g. 1982, 1997, 2015) tend to be drier. In addition, the first half of the 1980 – 2022 period saw more El Niño events (5 events between 1980 and 2000) compared to the second half (3 events between 2002 and 2022) and fewer La Niña events (4 events compared to 7 events). Future changes in the frequency and intensity of ENSO events will likely impact Singapore’s rainfall.

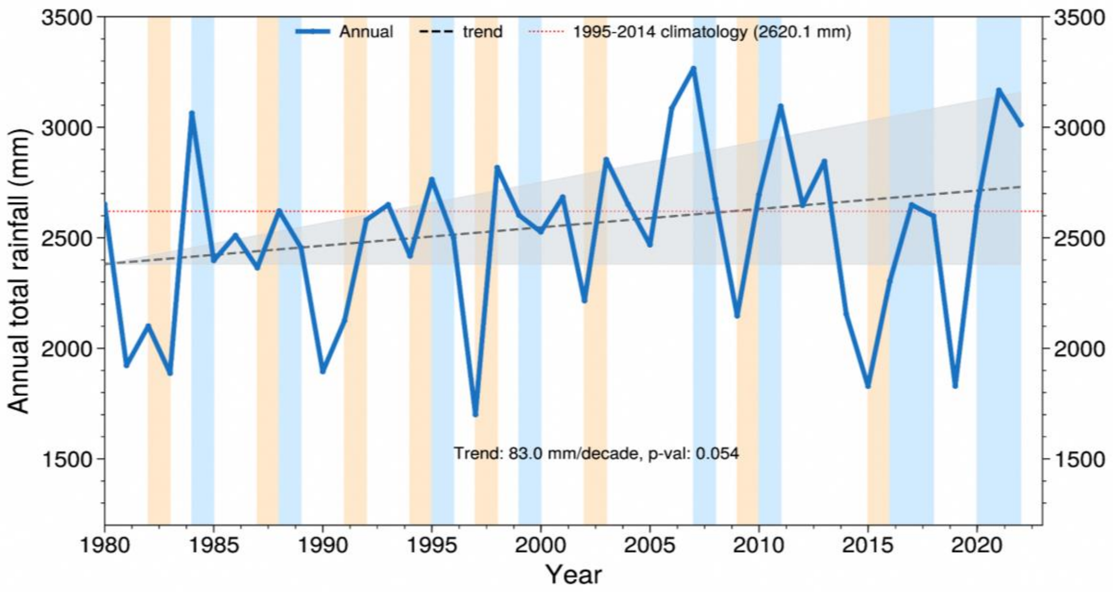

Figure 3.12: Time series of the annual total rainfall (solid blue)averaged over 32 stations with long-term records. The 1995-2014 climatology (2620.1 mm) is shown by the horizontal red dotted line. The black dashed line depicts the upward linear trend (83 mm/decade), computed using the robust non-parametric Theil-Sen slope estimator. Grey-shaded areas represent the 95% confidence interval of the estimated slope.

3.4.2 Monthly and seasonal rainfall

For monthly rainfall (Figure 3.13), statistically significant upward trends at the 5% level are seen only for June (18.4 mm/decade) and April (14.6mm/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, the driest month of the year climatologically, is showing the strongest drying (-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).

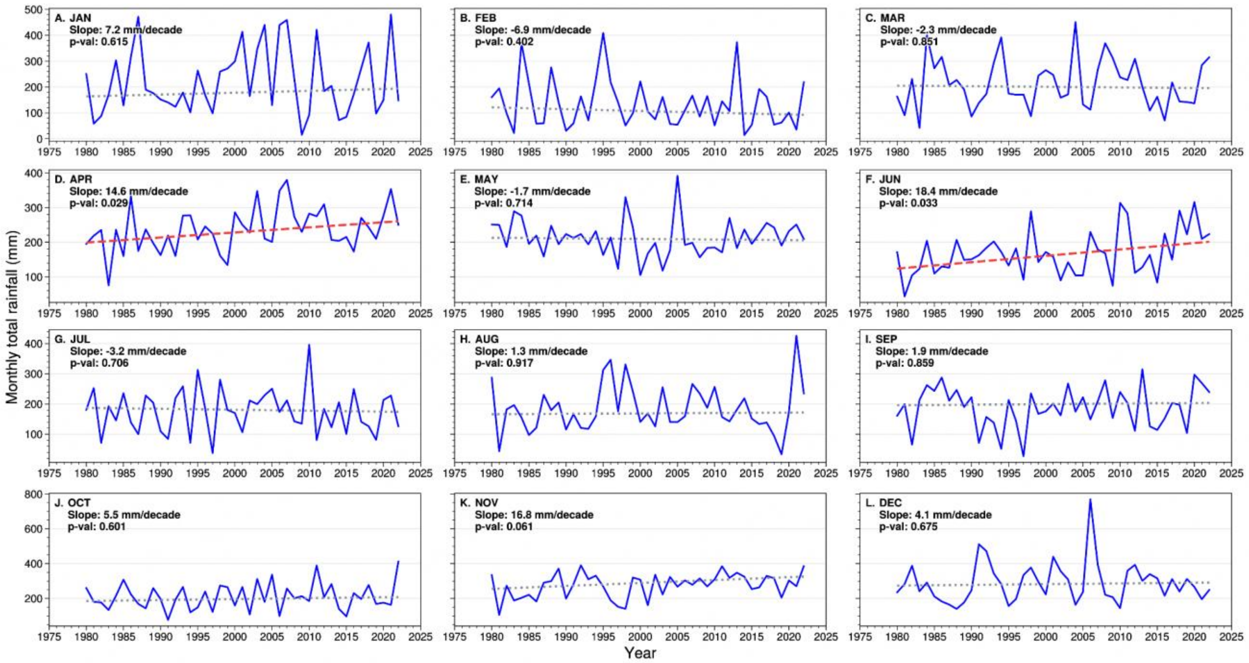

Figure 3.13: Time series of monthly total rainfall averaged from the 32-station record. The red dashed line depicts the individual slope of the trend for each month. Linear trend values, along with the respective *p*-values are shown for reference. All trends are computed using the Mann-Kendall test and the Theil-Sen slope estimator.

Among the four seasons, the second intermonsoon period (Oct-Nov) shows the highest rate of rainfall increase since 1980 at 24.6 mm/decade (95% significance level), followed by southwest monsoon season (JJAS) at 17.0 mm/decade as can be seen in Figure. 3.14. The wet phase of the northeast monsoon season (Dec-Jan) shows an increasing trend of 18.6 mm/decade (90% significance level), and the dry phase of the northeast monsoon (Feb-Mar) shows an decreasing trend at -7.8 mm/decade (90% significance level).

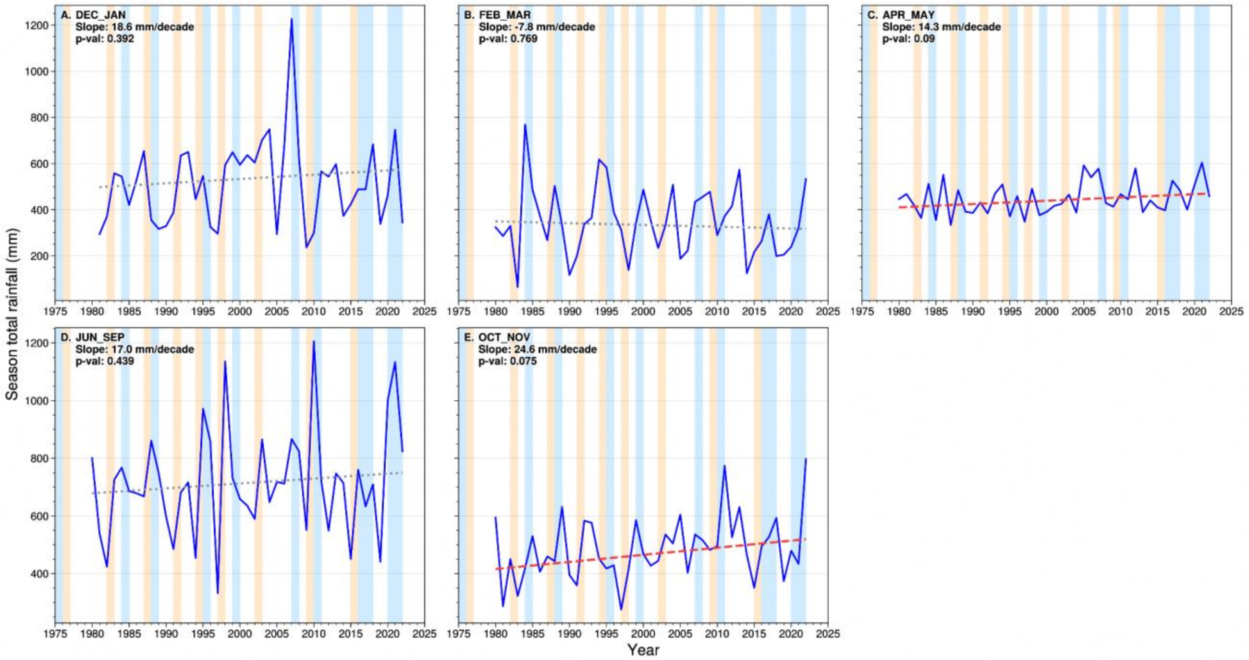

Figure 3.14: Time series of seasonal total rainfall averaged from the 32-station record. The red dashed line depicts the individual slope of the trend for each season. Linear trend values, along with the respective *p*-values are shown for reference. All trends are computed using the Mann-Kendall test and the Theil-Sen slope estimator.

3.4.3 Rainfall Extremes

Singapore’s rainfall climate is largely dominated by convective rainfall. This type of rainfall 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 3.15 presents the annual maximum rainfall intensity at 15 min (RX15min), 30 min (RX30min) and 60 min (RX60min) durations. Overall, no trends have been 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 rainfall depicting only a tiny increase of 0.8 mm/decade. RX60min shows no trend at all (0 mm/decade). There is also little correlation with the ENSO phase on yearly time scales. However, RX60min exhibits 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 of long-term climate drivers in the Pacific, such as the Inter-decadal Pacific Oscillation (IPO) and warrants further investigation.

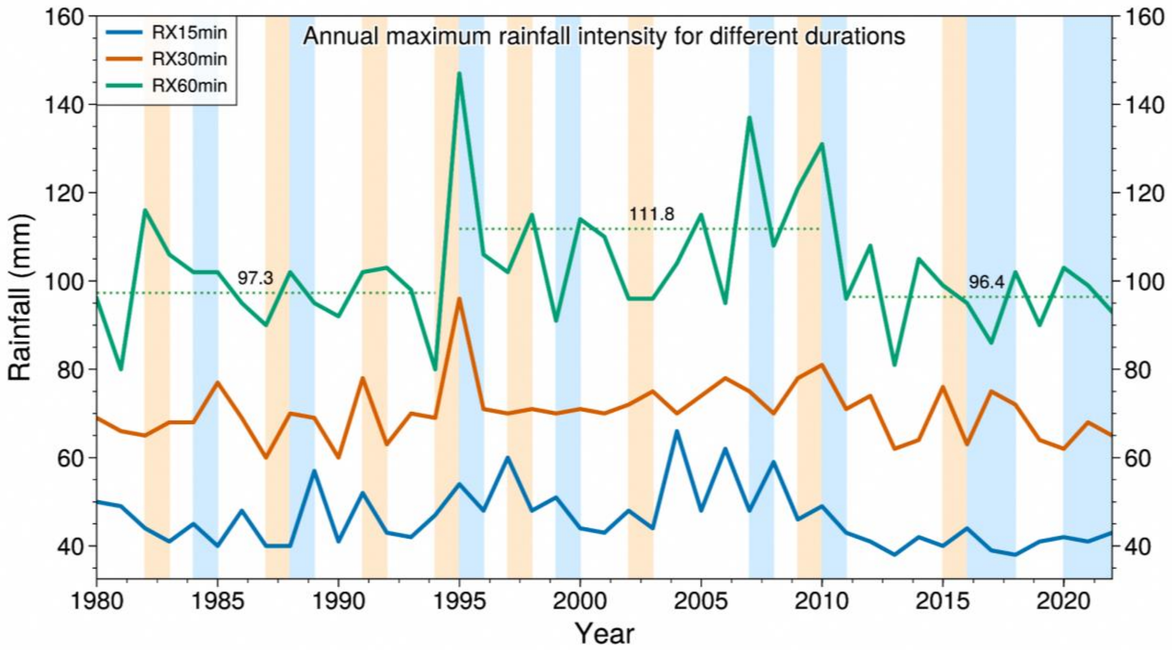

Figure 3.15: Time series of the annual maximum rainfall intensity at 15 min (RX15min, blue), 30 min (RX30min, orange) and 60 min (RX60min, green) durations, computed from a set of 23 stations with long-term observations going back to 1980. Numbers above the green dotted lines denote the RX60min averages 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.

3.5 Observed change in relative humidity

The annual mean near-surface relative humidity (RH) from Changi and Tengah stations for 1985-2020 are shown in Figure 3.16. The figure shows that while there was no discernible trend in RH during 1985-2010, there has been a decreasing trend during the last decade. The observed decreasing trend in RH might look counter-intuitive given the increase in temperature and the expected increase in moisture along with increased temperatures due to more evaporation. Still, the fact is that while the actual moisture content of the air may be increasing, the rate of increase in temperature is higher than that of moisture thus leading to a negative change in RH.

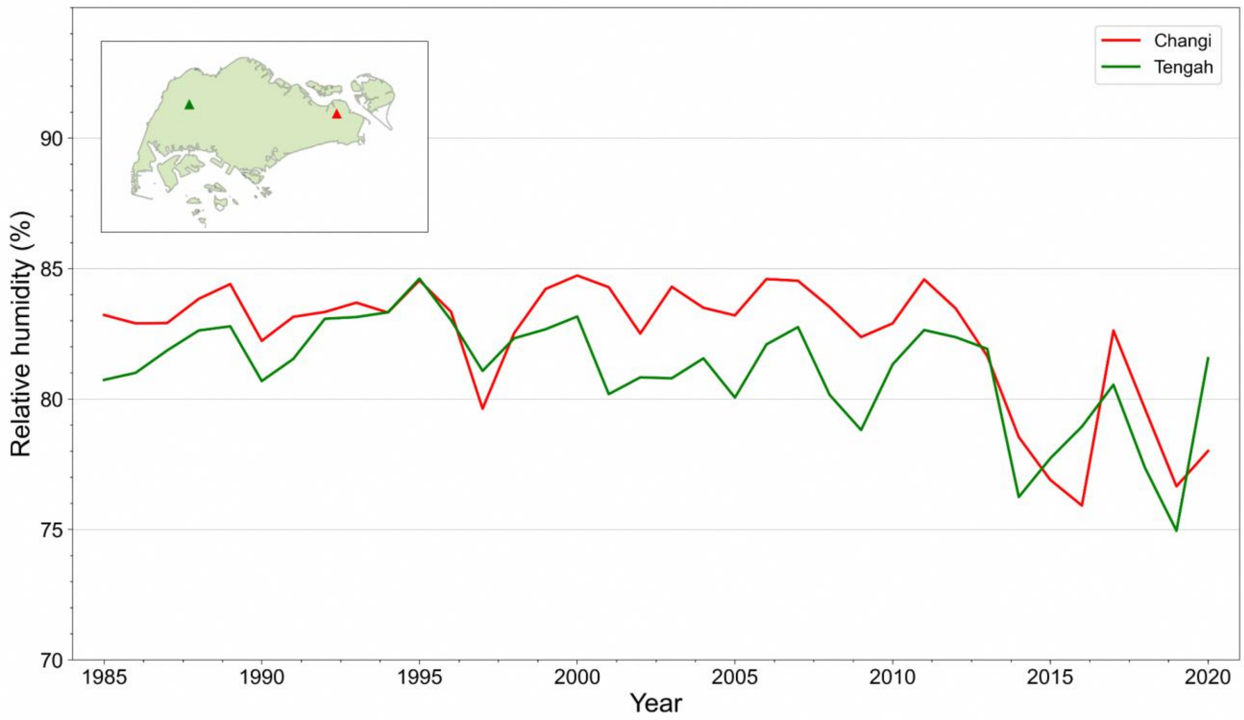

Figure 3.16: Mean relative humidity at Changi (red) and Tengah (green) weather stations from 1985-2020

3.6 Observed change in surface winds

While Singapore does experience a general shift 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 two stations (Changi and Tengah) shows inter-annual variability as well as multi-decadal variability (Fig. 3.17). 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 the late 1990s and early 2000, and a reversal after that.

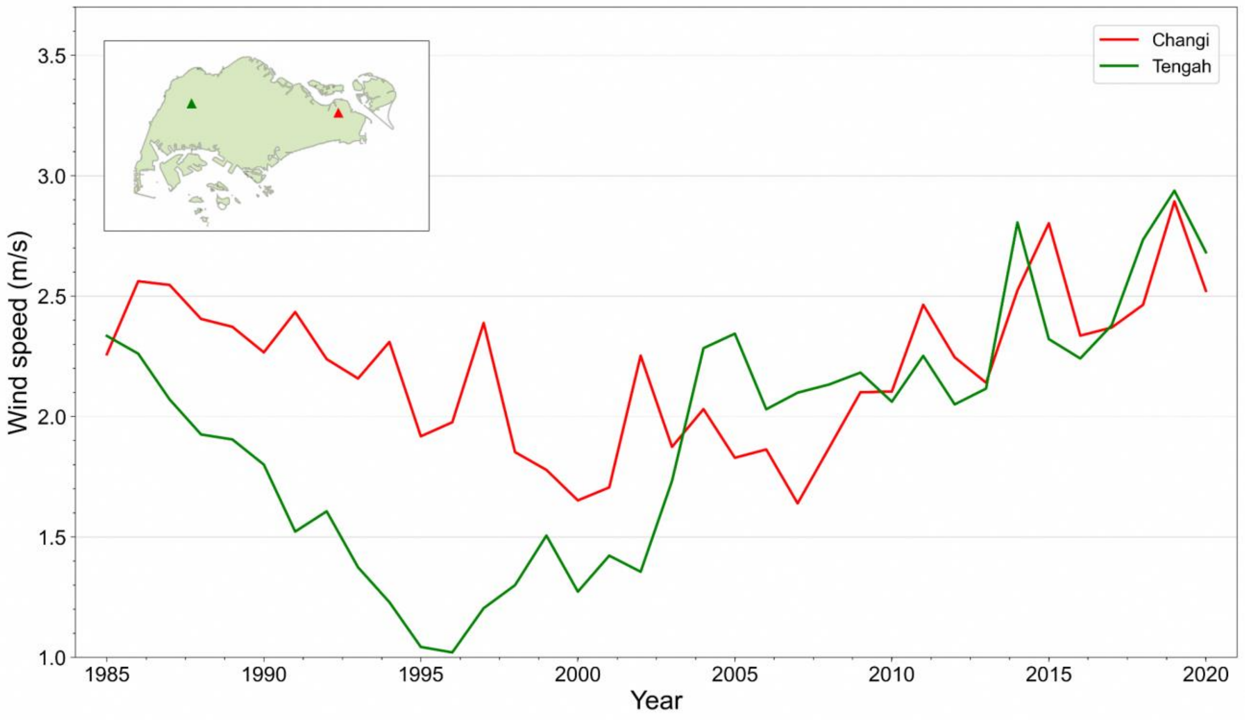

Figure 3.17: Mean wind speed at Changi (red) and Tengah (green) weather stations from 1985-2020

3.7 Observed change in northeast monsoon surges

Our work on northeast monsoon surges predominantly builds on the prior work done at CCRS (Lim et al., 2017), which focuses on the links between the northeast monsoon surge and Southeast Asia rainfall and as such is highly relevant for our region. Their study notes that monsoon surges contribute up to 40% of the total NDJF rainfall and that monsoon surges can increase rainfall to more than 50% above the mean in the checkmark-shaped region that includes Singapore, and potentially even more when combined with MJO events (as shown in their Figure 7a-c).

Little prior work has been done on quantifying changes in northeast monsoon surges over Southeast Asia. To understand observed changes, we examined studies using other definitions relevant to northeast monsoon surges. One caveat is that surges in the high latitudes may not affect our region. In the classification by Abdillah et al. (2020), only 39% of cold air outbreaks from the high latitudes impact the South China Sea. Nevertheless, as a proxy, we note that Juneng and Tanjang (2010) analysed trends in cold surge winds from 1962–2007, as measured by the DJF seasonal 950 hPa wind averaged over 110-117.5E and 12.5-15N, and found that the easterly component had strengthened significantly, but with no significant changes in the northerly component. However, this does not directly indicate the frequency of strong winds, which is used in the definition of a northeast monsoon surge over this region (e.g. Lim et al., 2017). Ting et al. 2009 conducted a study with station data from Mainland China from 1960-2008 and found a long-term decreasing trend (-0.2 times/decade) in cold surges over northeast China. There are signs that this decreasing trend extends slightly south of 30°N, but it is weak at best. Recently, using a cold surge definition using winds over the South China Sea (925 hPa meridional winds averaged over 110–117.5°E along 15°N) and sea level pressure anomalies over East Asia (15–45°N, 100–120°E), Pang et al. (2023) find an increase in surge days in 2005-2020 relative to 1989-2004.

Figure 3.18 shows the number of surge days in each season using a definition of cold surges relevant to the Maritime Continent (Table 3.3) over 64 years (NDJF seasons starting 1959-2022) using ERA5 winds and sea level pressure. We do not find any significant (e.g. 90% significance level) trend in the frequency of surge days, showing the large role of interannual variability. There is also no significant difference (e.g. 90% significance level) in the number of surge days in El Nino or La Nina years as compared to neutral years.

Table 3.3: Criteria used for defining cold surges (Lim et al., 2017).

Variable	Criteria	Domain
Mean 850 hPa wind over the domain	Calm or easterly Northerly Wind speed at least 0.75 standard deviations above the long-term NDJF mean	5-10°N, 107-115°E
Max sea level pressure over the domain	At least 1020 hPa.	18-22°N, 105-122°E

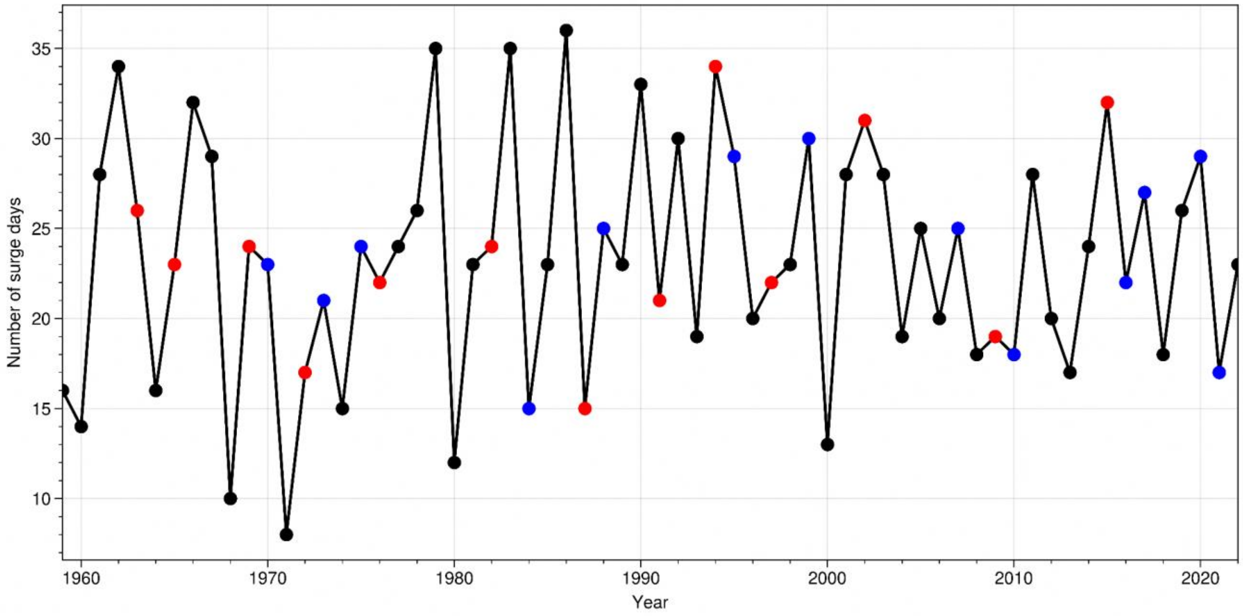

Figure 3.18: Number of surge days in each NDJF season for 1959-2022, using ERA5 winds and sea level pressure. The year shown marks the beginning of the season (e.g. 2022 for the 2022-2023 season). El Niño, ENSO-neutral, and La Nina years are indicated with the red, black and blue dots, respectively.

3.8 Observed change in sea level

In this report, all material on ocean and sea level science is covered in Chapter 12 - Past and Future Sea-level Change.

3.9 Summary

The current chapter discusses the observed climate change information across Singapore using different observational datasets such as automated weather stations, manned weather stations, and tide gauges. Singapore's climate varies across four different periods: Northeast monsoon (December to March), first intermonsoon (April to May), southwest monsoon (June to September), and second intermonsoon (October to November). Different climate drivers at various spatial and temporal scales influence the Singapore weather and climate features. These drivers include seasonal migration of the Intertropical Convergence Zone, ENSO, IOD, MJO, northeast monsoon surges, Sumatra Squalls, Borneo vortex, and remote influences from Tropical cyclones.

Since 1984, the observed daily mean temperatures show an increasing trend with a large interannual variability. At two distinct stations (Changi climate station and Tengah), the warming rate between 1984 and 2022 was 0.24°C and 0.26°C per decade, respectively (Table 3.4). In contrast to the increasing decadal rate of global temperatures, the Singapore temperatures indicate a decreasing rate from 0.52°C/decade (1984-1993) to 0.07°C/decade (2013-2022). At the two weather stations, the daily minimum temperatures show a statistically significant trend of 0.21°C per decade and 0.14°C per decade. Additionally, daily maximum temperatures are increasing at 0.06°C/decade (insignificant) and 0.13°C/decade (95% significant). There has been an increase in the frequency of extremely warm days, with a difference in the number of warm days between Singapore's coastal and inland regions of Singapore (Table 3.4). Despite the WBT's significant year-to-year variability, neither of the two weather stations exhibits a monotonic pattern in time. One station exhibits an increasing trend, while the other exhibits a declining tendency in the WBT.

Table 3.4: Trends in observed Mean and Extreme Temperatures for two Singapore stations.

Weather station	Mean temperature trend [°C/decade]	Daily maximum temperature trend [°C/decade]	Daily minimum temperature trend [°C/decade]	Warm days trend [days/year]	WBT trend
Changi (Coastal)	0.24	0.06	0.21	0.8	Decreasing
Tengah (Inland)	0.26	0.13	0.14	1.3	Increasing

The total annual rainfall over Singapore shows an increasing trend of 83 mm per decade from 1980 to 2022 (Table 3.5). The rainfall over Singapore is strongly modulated by ENSO, with La Niña years experiencing increased rainfall and El Niño years having decreased rainfall. There are also monthly and seasonal variations in total rainfalls across Singapore. The months of June and April show statistically significant increasing trends of rainfall at 18.4 mm/decade and 14.6 mm/decade, respectively; November shows an increase of 16.8 mm/decade (not significant), whereas some months (July, March, and May) show a decreasing trend (not significant).

Although insignificant, the total seasonal rainfalls show an increasing trend across Singapore (Table 3.5). The SON season has the highest rate of rainfall increases since 1980 at 9.5 mm/decade, followed by MAM and JJA at 6.8 mm/decade, and the DJF shows the least amount of rainfall increases by 2.4mm/decade. Rainfall extremes measured using annual maximum intensity at 15 min, 30 min, and 60 min durations show no significant trend (Table 3.5). However, the RX60min shows strong inter-decadal variability with rainfall averages of 97.3 mm between 1980 and 1994, 111.8 mm between 1995 and 2010, and 96.4 mm between 2011 and 2022.

Table 3.5: Trends in Observed Mean annual, monthly, seasonal, and extreme Rainfall, indicating 95% (*) and 90% ($^+$) significance level respectively.

Mean ANNUAL rainfall trend (mm/decade)	Mean MONTHLY rainfall trend (mm/decade)	Mean SEASONAL Rainfall trend (mm/decade)	EXTREME rainfall trend (RX15min, RX30min, RX60min)

83	+4.1 (Dec) +7.2 (Jan) -6.9 (Feb) -2.3 (Mar) +14.6 (Apr)* -1.7 (May) +18.4 (June)* -3.2 (July) +1.3 (Aug) +1.9 (Sep) +5.9 (Oct) +16.8 (Nov)$^+$	+18.6 (DJ) -7.8 (FM)$^+$ +14.3 (AM) +17.0 (JJAS)$^+$ +24.6 (ON)*	No significant trend

The annual mean near-surface relative humidity (RH) decreases at the two weather stations across Singapore for the period 1985-2020.

The annual mean surface wind speed appears to have an increasing trend in the last couple of decades. However, it is also possible that it is just the multi-decadal variability that we see in the time series from the two stations, with decrease in the first part of the times series followed by an increase. There is no apparent trend in the number of northeast monsoon surge days that has a large interannual variability.

Overall, we observe an increase in mean surface temperatures, daily minimum temperatures, daily maximum temperatures, annual mean rainfall totals, and seasonal rainfall across Singapore. There are spatial variations in the changes of daily minimum temperatures, daily maximum temperatures, and WBT. Additionally, there is a strong relationship between ENSO and Singapore's rainfall. There is a decreasing trend of the mean surface relative humidity and no significant trend in the number of surge days.

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