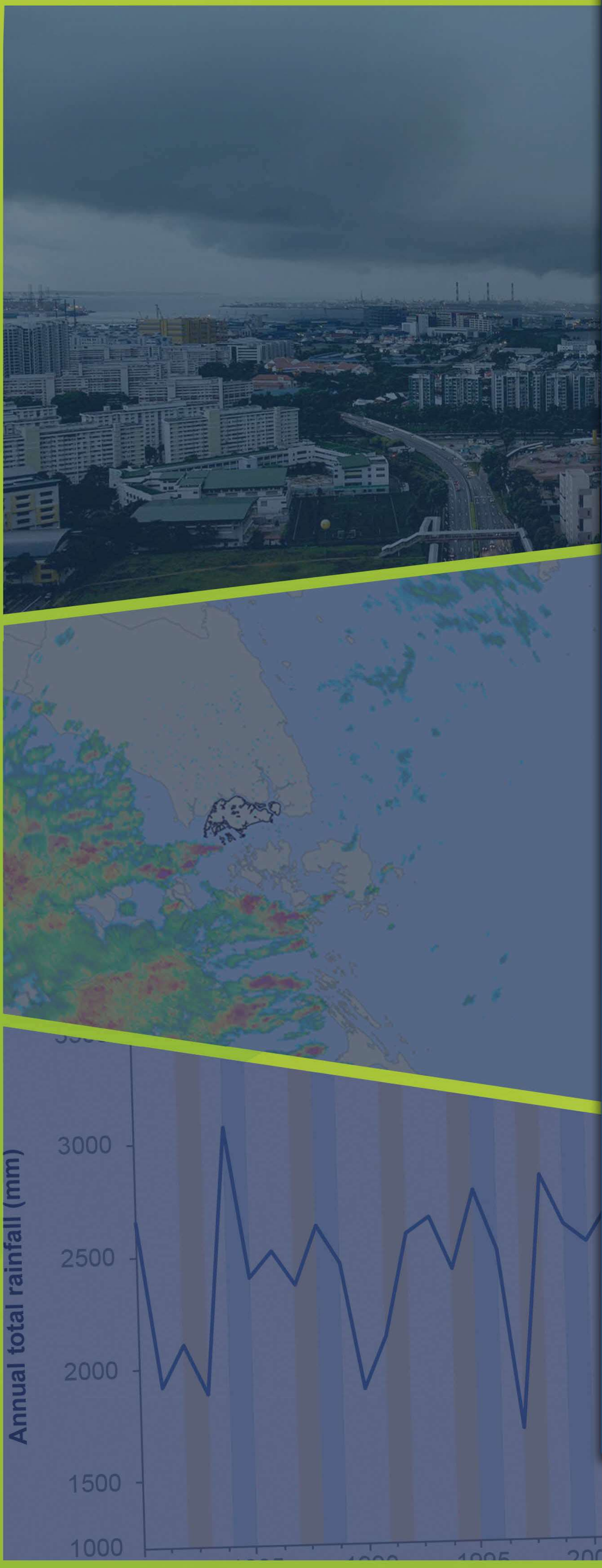
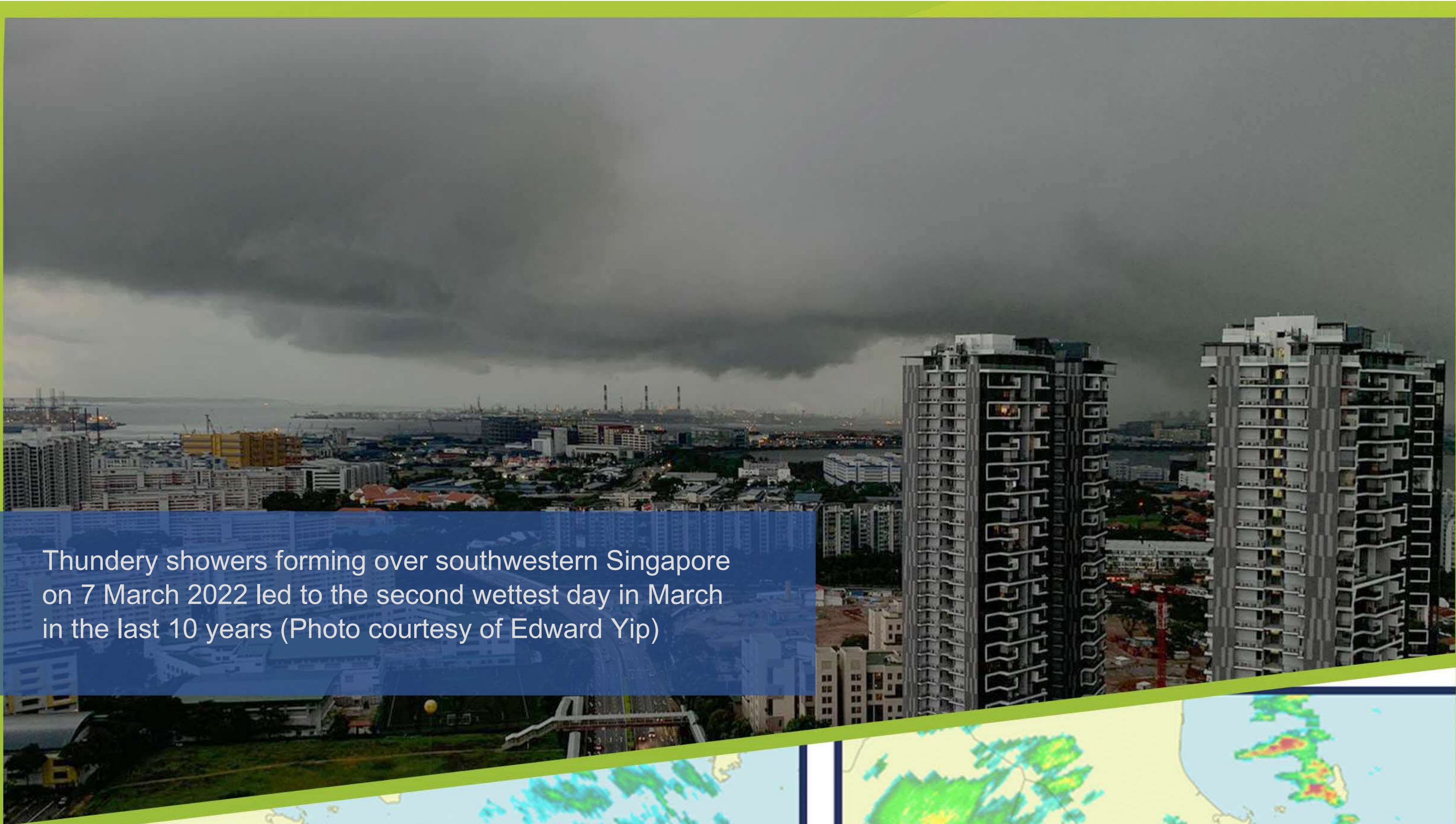


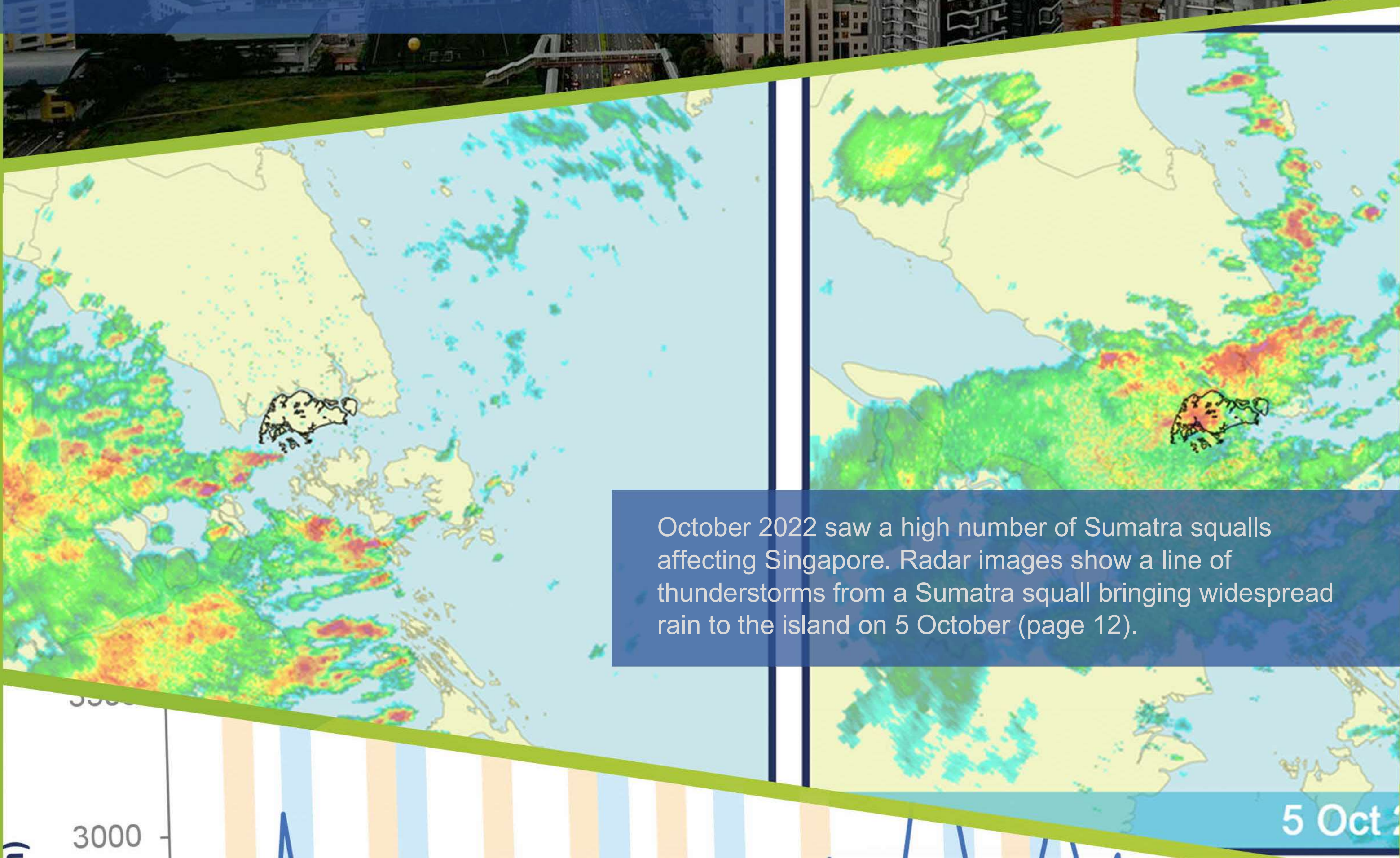
2022 ANNUAL CLIMATE ASSESSMENT

SINGAPORE

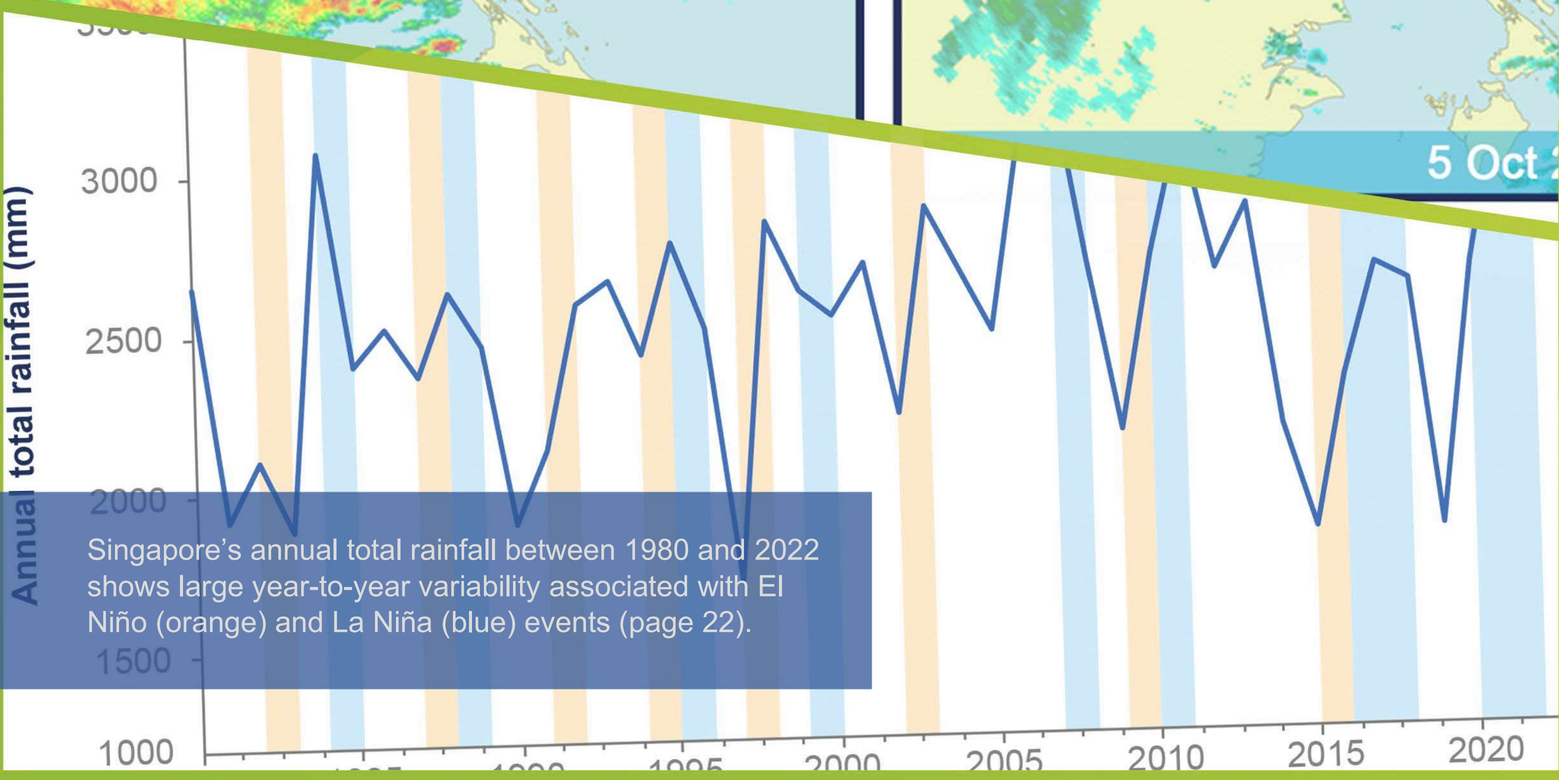
Meteorological Service Singapore



Thundery showers forming over southwestern Singapore on 7 March 2022 led to the second wettest day in March in the last 10 years (Photo courtesy of Edward Yip)



October 2022 saw a high number of Sumatra squalls affecting Singapore. Radar images show a line of thunderstorms from a Sumatra squall bringing widespread rain to the island on 5 October (page 12).



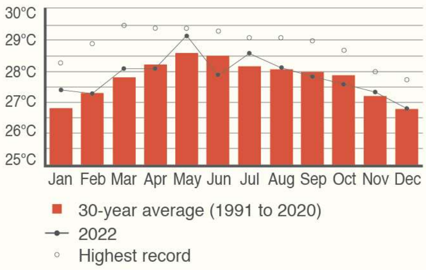
Singapore's annual total rainfall between 1980 and 2022 shows large year-to-year variability associated with El Niño (orange) and La Niña (blue) events (page 22).

Singapore's Climate in 2022

Decadal mean temperature

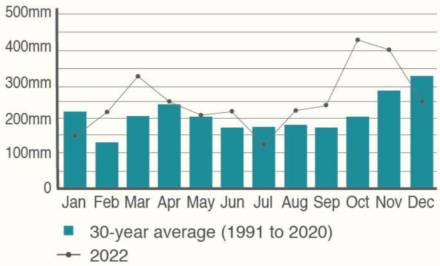
Last 10 years from 2013 to 2022 was Singapore's warmest decade on record, with decadal mean temperature of 28.01°C.

Monthly mean temperature



2022 was the 10th warmest year on record. January and May temperatures were notably above their respective long-term average.

Monthly total rainfall



2022 was the 6th wettest year since 1980. Average annual rainfall was 18.8% above the long-term average.

NOTABLE WEATHER EVENTS IN 2022

Wet March

March 2022 was the wettest March in almost 15 years. Heavy rain in Jurong West on 7 March made it the 2nd wettest March day in the last 10 years.

Scorching May

May 2022 was the 5th warmest since records started in 1929. Temperature at Admiralty reached 36.7°C on 13 May 2022, the warmest May day on record.

Squally October

October 2022 was the wettest October in the last 40 years. A high number of Sumatra squalls passed over Singapore during the month.

WEATHER EXTREMES IN 2022

Meteorological Service Singapore

Overview of Singapore's Climate in 2022

2022 was Singapore's sixth wettest year since 1980 with an average annual total rainfall of 3012 mm[1]. 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. The higher-than-average total rainfall in 2022 was partly influenced by prevailing La Niña conditions along with a negative Indian Ocean Dipole. 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.

This report covers Singapore's weather and climate in 2022, along with a closer look at how climate drivers modulated Singapore's climate. There is also a special section on how the climate this year compares to long-term observations, including a look into how the Urban Heat Island effect is reflected in MSS' long-term temperature records.

Contents

[1] Singapore average rainfall is calculated based on 32 stations across the island with continuous rainfall records since 1980.

Singapore's Weather and Climate in 2022

Temperature

At the Changi climate station, mean temperature for the last 10 years from 2013 to 2022 reached a new high of 28.01°C, 0.04°C above the previous record of 27.97°C for the decade from 2012 to 2021. The annual mean temperature in 2022 was 27.9°C, 0.1°C above the long-term[2] average of 27.8°C. Similar to 2021, 2022 was the tenth warmest year since temperature records began in 1929 (tied with 2021, 2018, 2014, 2009 and 2004). Islandwide, the year's highest temperature of 36.8°C at Admiralty on 1 April was the second highest recorded temperature for Singapore, after the record high of 37.0°C at Tengah in April 1983.

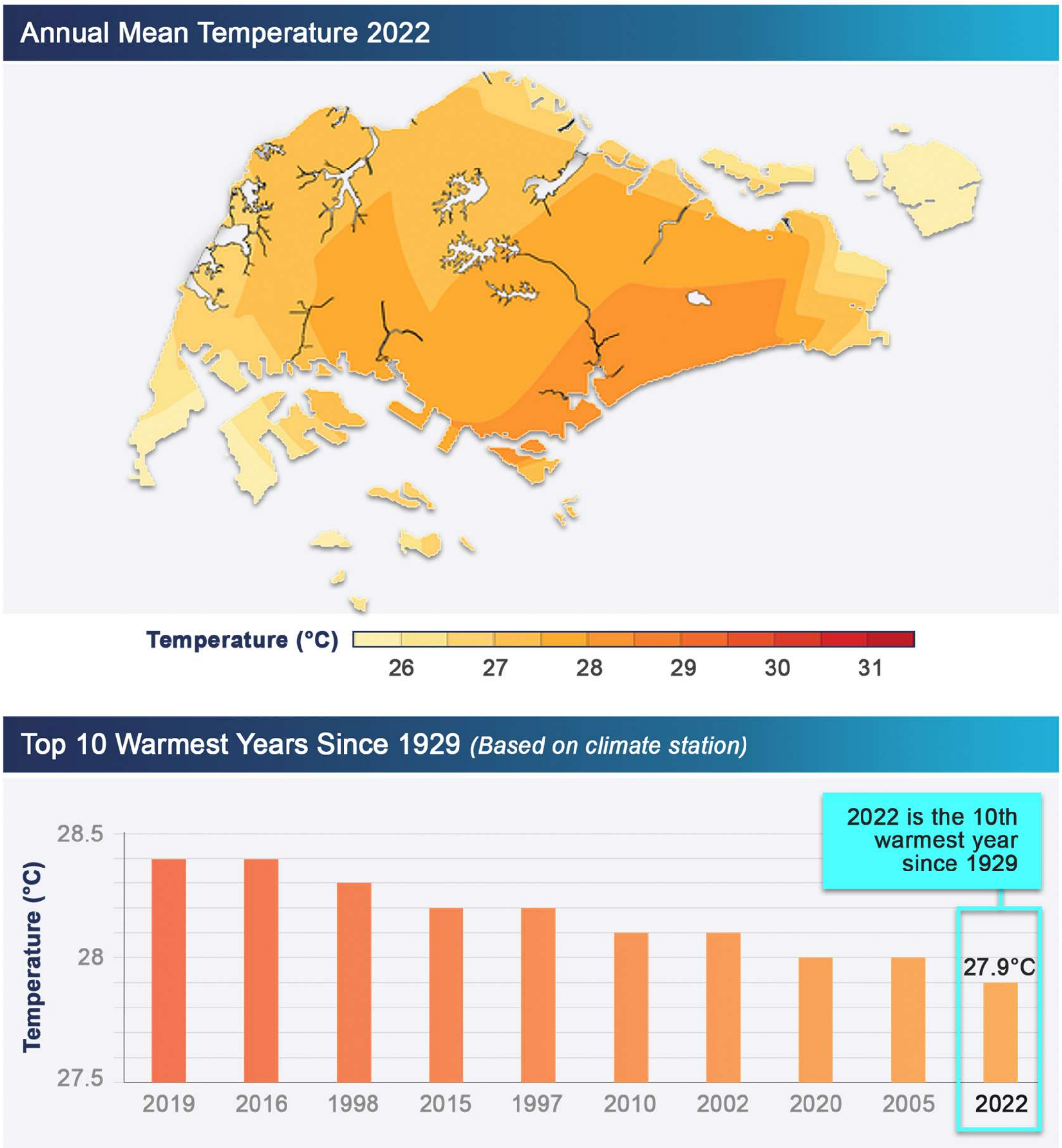


Figure 1: Annual mean temperature across Singapore in 2022 (top) and the top 10 warmest years on record (based on the Changi climate station).

[2] This refers to the most recent 30-year reference period from 1991 to 2020.

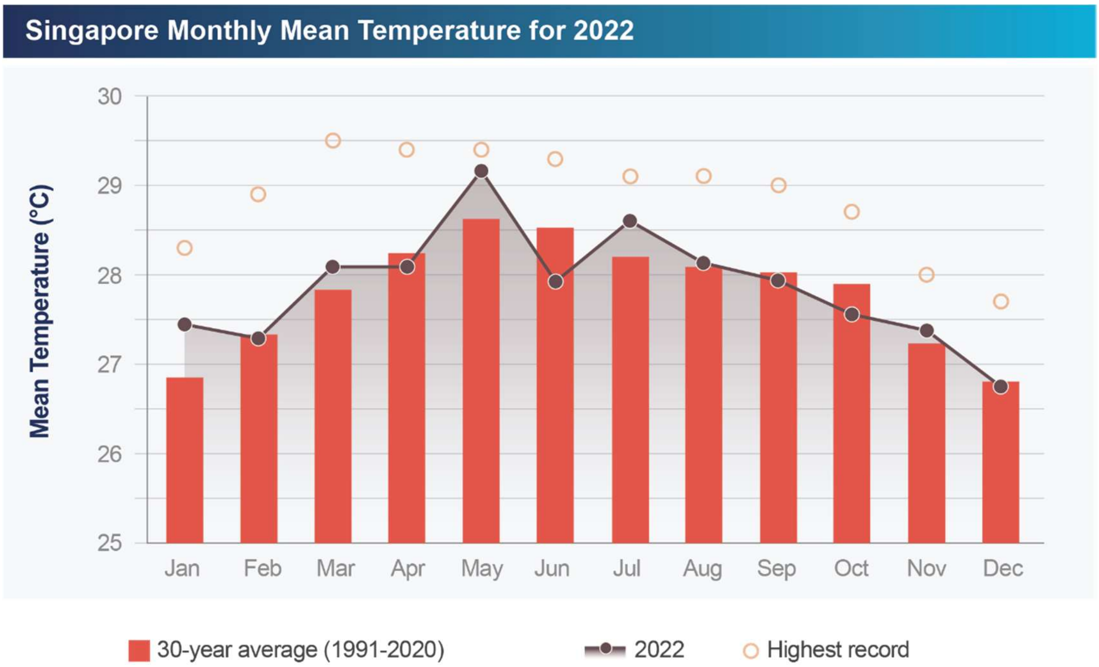


Figure 2: Changi climate station monthly mean temperature for 2022 (solid line), long-term average (bars, 1991 – 2020) and the corresponding historical extremes (circle).

In 2022, monthly mean temperatures at the Changi climate station were mainly near or above the long-term average (Figure 2). In particular, January (27.4°C) and May (29.2°C) were both 0.6°C warmer than their respective long-term monthly mean temperatures and ranked the sixth and fifth warmest of the respective months since temperature records began in 1929. The notably warmer-than-average conditions were associated with well below-average rainfall in these months (see Figure 3 on the next page).

June and October were 0.6°C and 0.3°C cooler than their respective long-term monthly mean temperatures, making them the coolest June and October in the past 10 years.

Rainfall

2022 was a wet year and ranked as the sixth wettest in the past 40 years (Figure 3). The annual total rainfall was above average across most of Singapore (Figure 4), with an average[3] annual total rainfall of 3012.0 mm, 18.5% above the long-term annual total of 2534.3 mm. The Changi climate station recorded 2207.8 mm of rainfall for the year, which is 4.5% above its long-term annual average of 2113.3 mm. The station also observed a total of 210 raindays[4] in 2022, the third highest number of annual raindays on record after the record high of 222 set in 1973 and 1927.

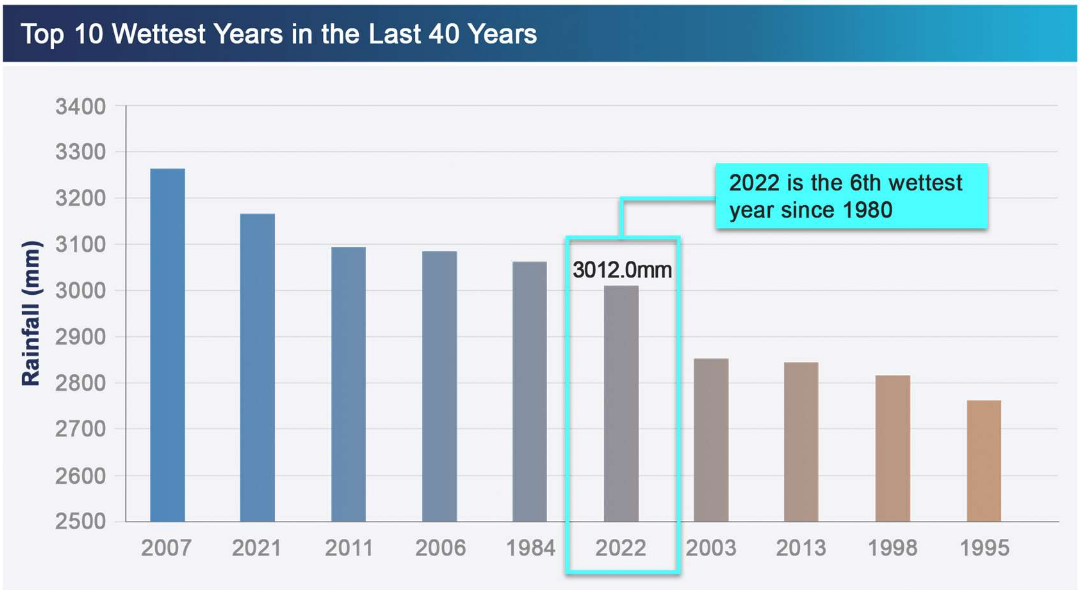


Figure 3: The top 10 wettest years in the last 40 years based on the Singapore average.

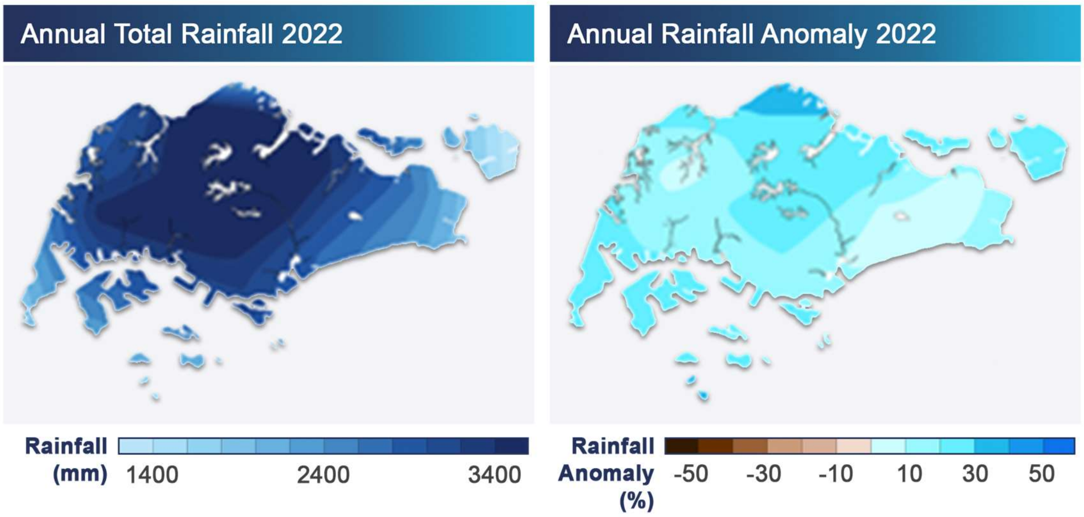


Figure 4: Annual total rainfall distribution across Singapore in 2022 (left), and annual rainfall anomalies (in percentage term) across Singapore in 2022 (right).

[3] Across the 32 stations with continuous rainfall records from 1980.
[4] A rainday is defined as a day with 0.2 mm rainfall recorded at a rainfall station.

Considering the individual months, February and October had the highest wet anomalies, with rainfall above average across the entire country (Figure 5). March, June, September and November recorded above-average rainfall across most of Singapore, with only small areas receiving below-average rainfall. April, May and August recorded a mix of below- and above-average rainfall, although overall were wetter than average. While 2022 was a wet year overall, the first and last months of the year were markedly drier than average, along with July.

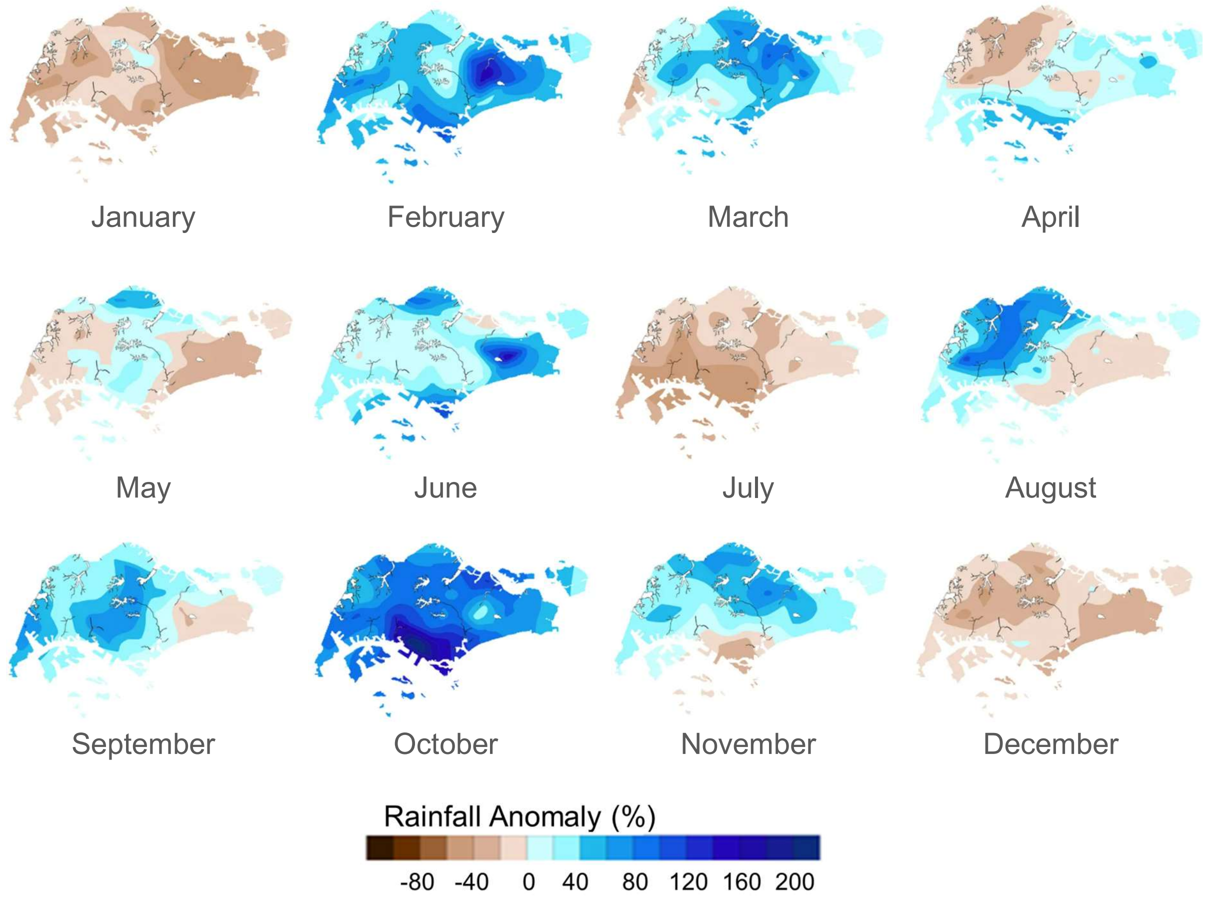


Figure 5: Monthly rainfall anomalies (in percentage term) across Singapore in 2022 (relative to the climatological period 1991 – 2020 for the particular month).

Based on the islandwide average, above-average monthly total rainfall was recorded in nine months of 2022. Six of these months were among the top 10 wettest for their respective months since 1980 (Figure 6). The year's wettest month was October, with total rainfall of 412.0 mm which is about twice the month's long-term average. It is not common for the year's wettest month to fall in October, with the previous occurrence in 1985. October 2022's rainfall of 412.0 mm exceeds the previous October high of 389.3 mm in 2011, making October 2022 the wettest October in the last four decades.

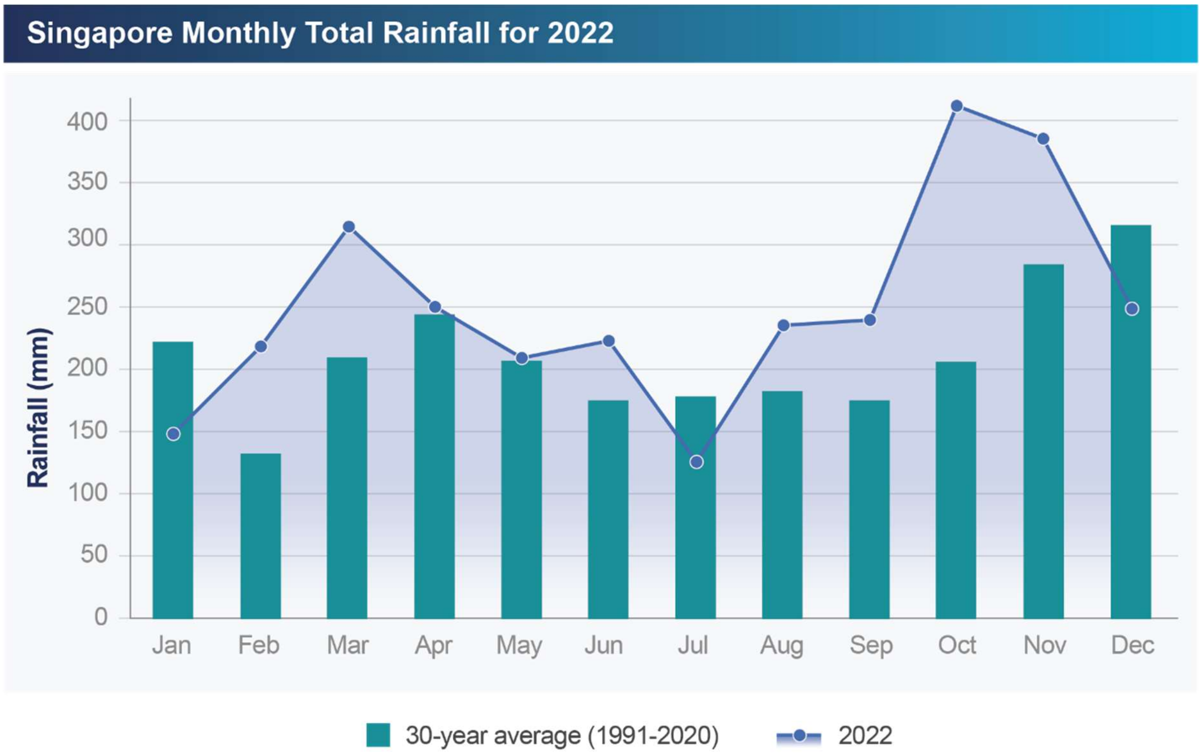


Figure 6: Singapore average monthly total rainfall for 2022 (solid line) and long-term average (bars, 1991 – 2020). The average annual total rainfall of 3012.0 mm for 2022 is 18.8% above the long-term annual average of 2534.3 mm.

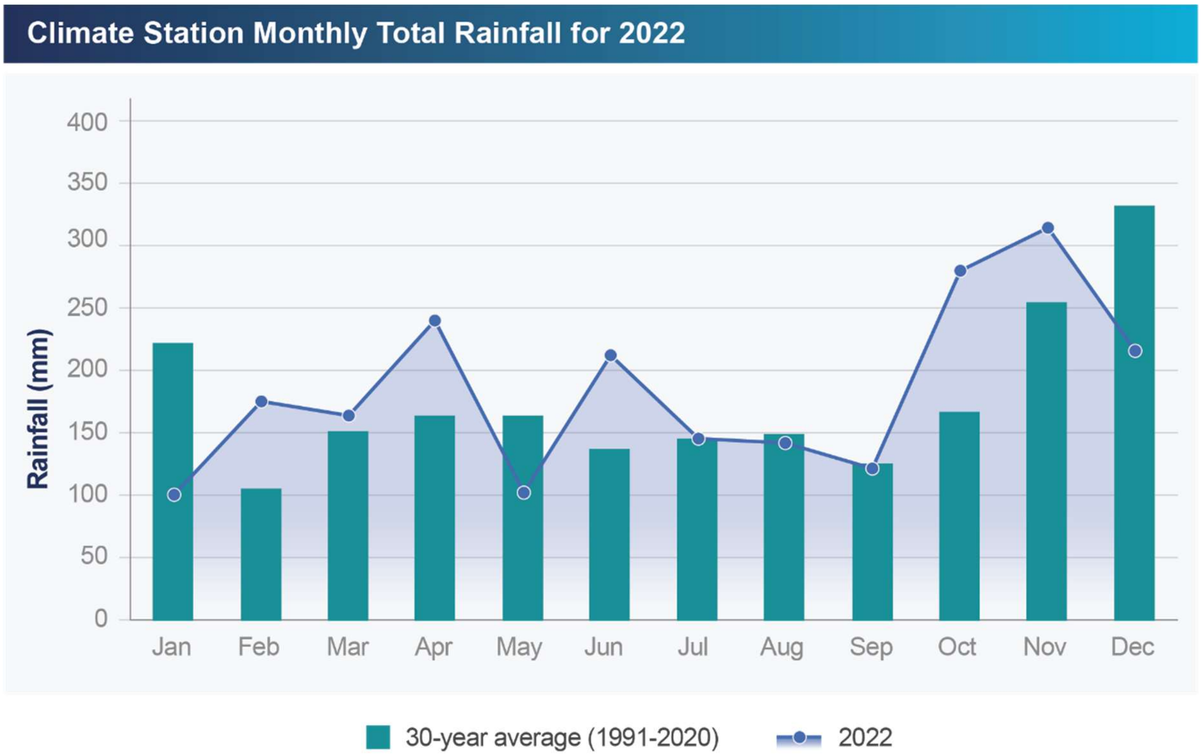


Figure 7: Changi monthly total rainfall for 2022 (solid line) and long-term average (bars, 1991 – 2020). The annual total rainfall of 2207.8 mm for 2022 is 4.5% above the long-term annual average of 2113.3 mm.

Weather Extremes in 2022 at the Climate Station

	Climate Station Records	
	2022	Historical Extremes*
Hottest Day ***(°C)***	35.4 29 May	**36.0** 26 Mar 1998
Coolest Day ***(°C)***	22.2 20 Jul	**19.4** 30 – 31 Jan 1934
Warmest Month ***(°C)***	29.2 May	**29.5** Mar 1998
Coolest Month ***(°C)***	26.8 Dec	**24.2** Jan 1934
Wettest Day ***(mm)***	59.4 3 Jun	**512.4** 2 Dec 1978
Wettest Month ***(mm)***	313.8 Nov	**818.6** Jan 1893
Driest Month ***(mm)***	99.8 Jan	**0.2** Feb 2014
Strongest Wind Gust ***(km/h)***	57.4 17 Apr	**90.7** 29 Nov 2010

**Rainfall records since 1869; temperature records since 1929; wind records since 1984*

Table 1: Temperature, rainfall and wind extremes recorded at the climate station in 2022 and the corresponding historical extremes.

Notable Weather Events in 2022

Wettest March In Almost 15 Years

March 2022 was the wettest March since 2009 and among the wettest months of 2022, with most parts of the island receiving above-average rainfall. The wet weather in March 2022 was mainly triggered by strong solar heating of land areas coupled with convergence of winds over the island (Figure 8).

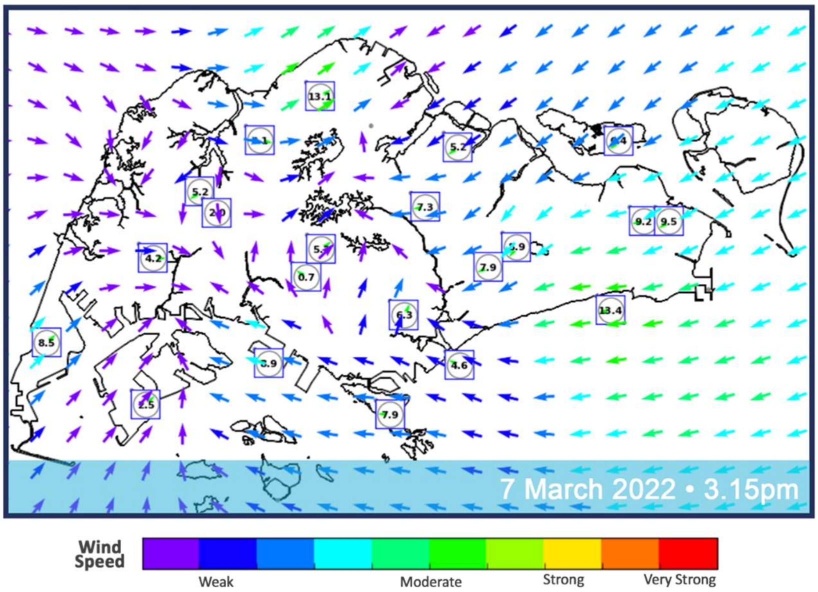


Figure 8: Convergence of surface winds over Singapore on 7 March 2022 led to the formation of thunderstorms.

On 7 March, heavy thundery showers fell in the late afternoon and evening, particularly over southern and western Singapore (Figure 9) where flash floods were reported in some areas including Jurong West. With a highest daily total rainfall of 134.2 mm recorded at Jurong West, this was the second wettest March day in the last 10 years.

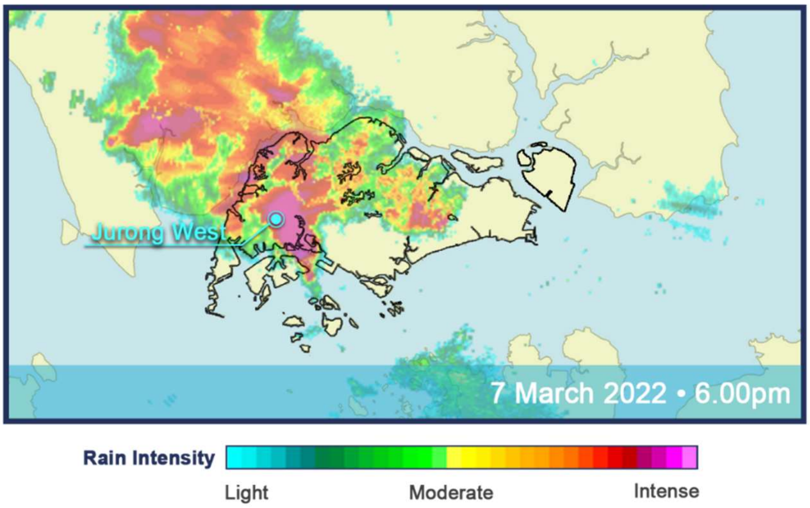


Figure 9. Weather radar image at 6pm on 7 March 2022 showing the formation of heavy thunderstorms over western Singapore.

Scorching May Broke Temperature Records

May is statistically Singapore's warmest month of the year, and May 2022 was no exception. While Singapore's average rainfall for the month was near the long-term average, there were 11 days with little or no rain. In the second half of the month, the presence of dry air over equatorial Southeast Asia (Figure 10) coincided with the dry phase of the Madden-Julian Oscillation, which resulted in very warm weather over Singapore. Daily maximum temperatures exceeded 34.0°C on 22 days in May, and of these, the temperatures exceeded 35.0°C on 13 days.

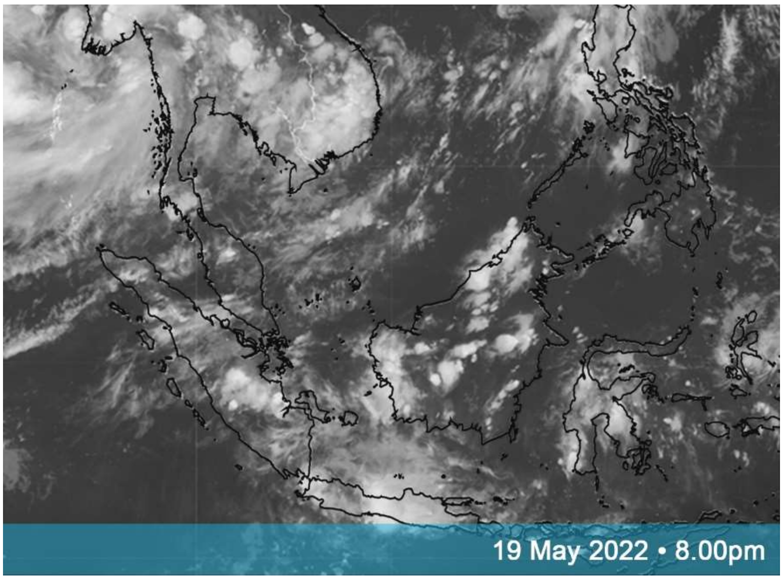


Figure 10: Satellite imagery on 19 May 2022 showing drier weather and clear skies over Singapore and its vicinity.

The dry and warm weather led to new temperature records for May. On 13 May, the highest daily maximum temperature of 36.7°C was recorded at Admiralty, the warmest day in May on record and surpassing the previous high of 36.5°C on 16 May 2010 and 3 May 2016. The highest daily minimum temperature of 29.5°C was recorded at East Coast Park on 18 May, 0.1°C above the previous high on 10 May 2016 and 9 May 2018. On 29 May, the Changi climate station recorded a maximum temperature of 35.4°C, tying the record on 1 May 2005 for the warmest day in May at the climate station.

Wettest October in Four Decades

October 2022 was exceptionally wet, with a high number (11) of Sumatra squalls affecting Singapore. There were several tropical cyclones that formed in the South China Sea and western Pacific Ocean during the month. The large-scale convergence of winds in the region associated with these tropical cyclones is conducive to the formation of Sumatra squalls, which often bring widespread showers and gusty winds to Singapore in the predawn hours and morning. For one such occurrence on 5 October (Figure 11), daily total rainfall of 138.1 mm was recorded at Pasir Panjang, the highest for the month.

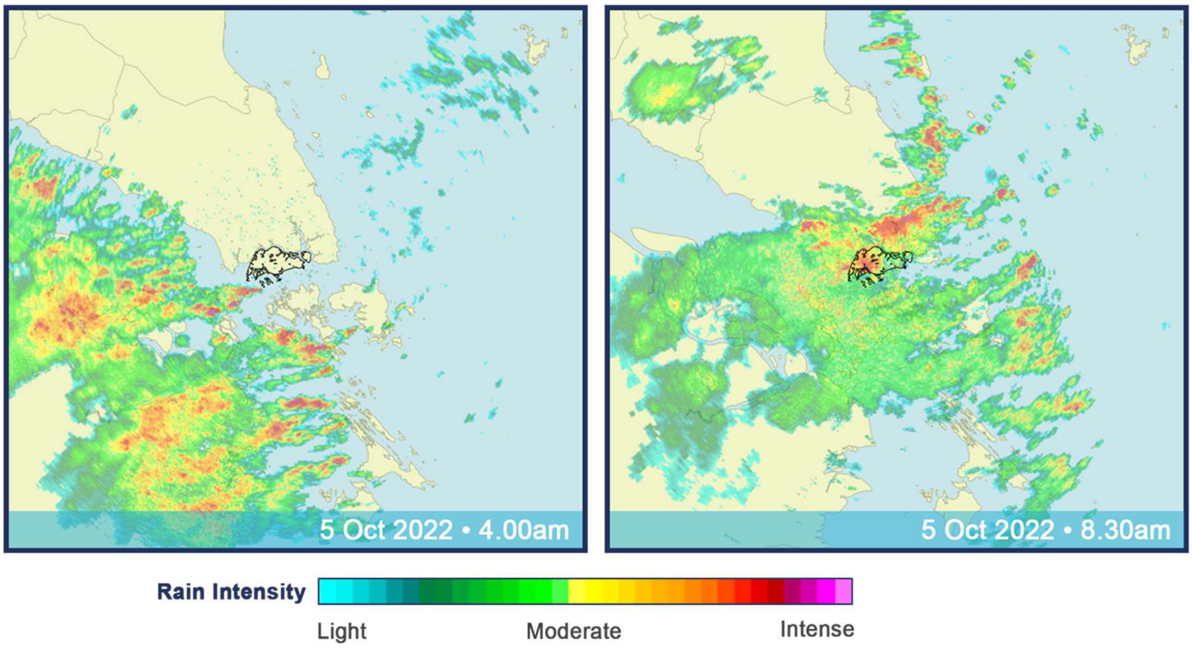


Figure 11: Weather radar images showing an organised line of thunderstorms from a Sumatra squall moving eastward toward Singapore (left) and bringing widespread thundery showers to the island (right) on 5 October 2022.

Overall, all parts of Singapore received well above-average rainfall (Figure 5), with the Kent Ridge station reporting more than three times its long-term average. Singapore's average rainfall for the month was 412.0 mm, making October 2022 the wettest October in the past four decades (Figure 12). At the Changi climate station, there were 27 raindays, which exceeded the previous record of 23 for the month of October.

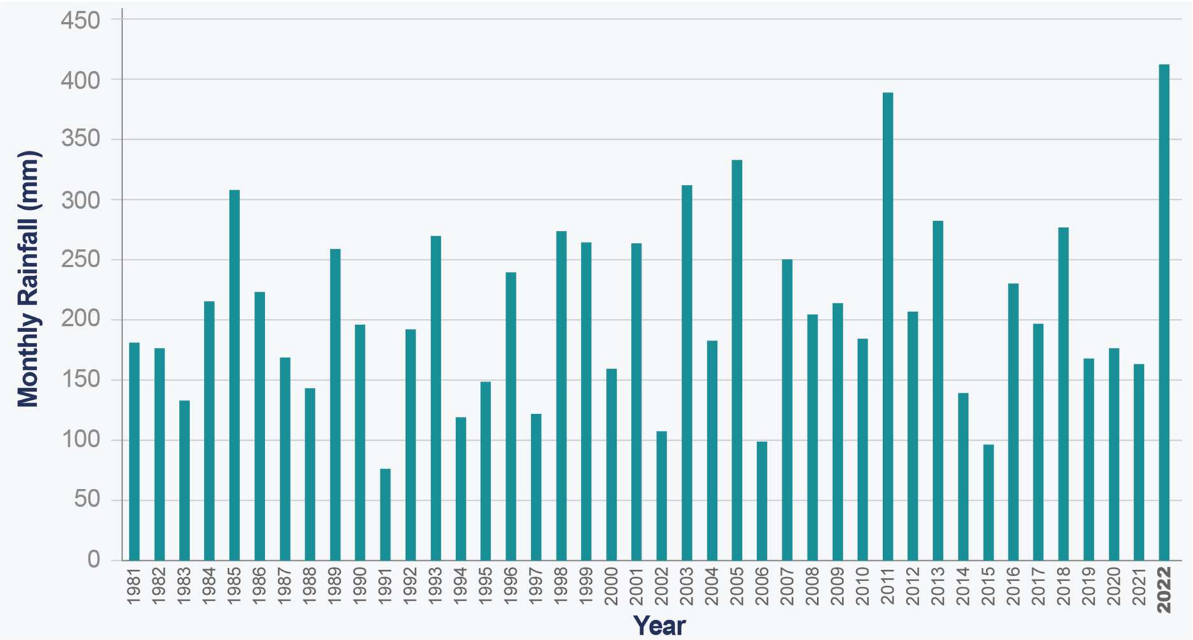


Figure 12: Singapore average rainfall for October between 1981 and 2022, with the highest value recorded in 2022.

Large-scale Climate Variability in 2022

In 2022, the two key climate drivers at the annual scale were the El Niño – Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). The conditions in both Pacific and Indian Oceans increased the chance of wetter conditions for Singapore—contributing to the higher-than-average rainfall in 2022. Further information on ENSO, IOD and the Madden-Julian Oscillation (MJO) and how these drivers modulated Singapore's climate in 2022 is described below.

The El Niño – Southern Oscillation (ENSO) Overview

The key driver from the tropical Pacific Ocean in 2022 was ENSO, with the La Niña event that developed in 2021 persisting throughout 2022. La Niña events refer to the ENSO phase where sea surface temperatures are cooler than average over the central and eastern tropical Pacific Ocean, typically resulting in enhanced rainfall over the western Pacific. For Singapore, La Niña events typically bring more rainfall, particularly during the Southwest Monsoon season (June to September). In 2022, Singapore recorded 824.1 mm of rainfall during the Southwest Monsoon season, about 15% above the long-term average.

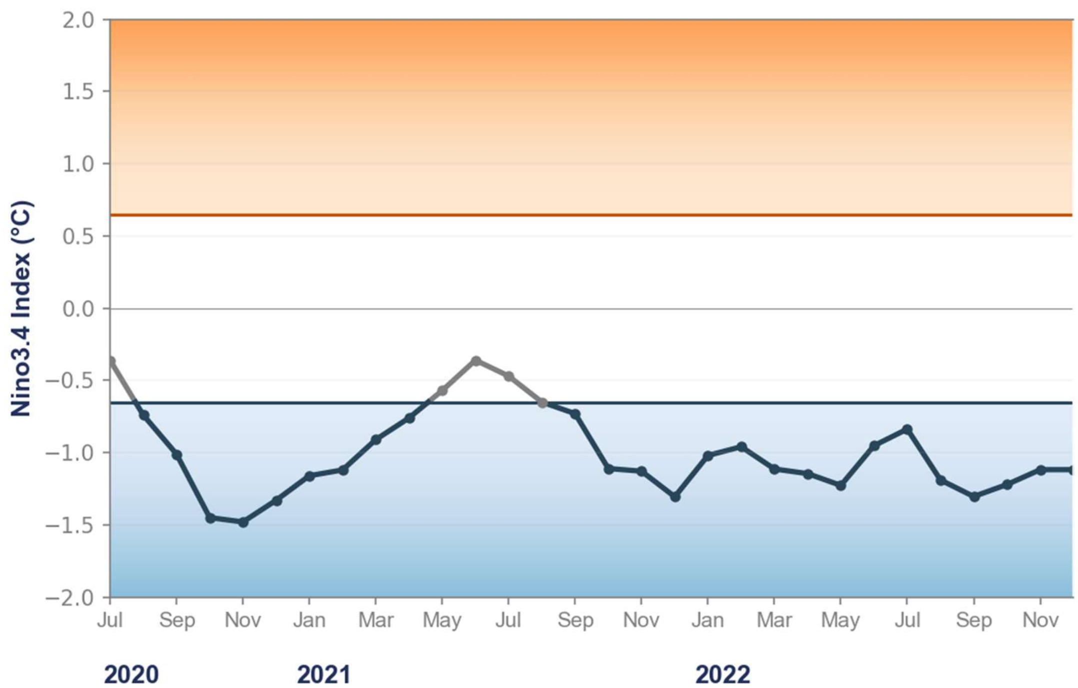


Figure 13: Nino3.4 index from July 2020 to December 2022. The index measures the average sea surface temperature anomaly in the central-eastern equatorial Pacific Ocean (termed the 'Nino3.4 region'). This index indicates two periods of La Niña conditions—one was between August 2020 and April 2021, and the other is from August/September 2021 onwards.

The year 2022 marked the third year in a row where La Niña conditions were present. La Niña conditions developed in the third quarter of 2020, reaching moderate strength by the end of the year. This La Niña event then weakened in 2021, returning to ENSO neutral conditions in the second quarter of 2021. After a brief period of ENSO neutral conditions, La Niña conditions developed again by the end of the third quarter in 2021. These La Niña conditions persisted throughout 2022, although weakened temporarily towards the middle of 2022. While back-to-back La Niña events (or two La Niña events separated by less than a year) are not uncommon, it is unusual to see three consecutive years with La Niña conditions.

When was the previous triple year La Niña?

Based on MSS' criteria, this is the first triple year La Niña since at least the 1960s[5]. However, there are some differences between international centres, as slight differences in how La Niña events are monitored mean that some earlier La Niña-like events may be classified as La Niña events. For example, some centres regard 1998 – 2001 as a previous triple year La Niña.

La Niña events are seasonal events that are marked by changes in both the atmosphere and ocean. Typical indicators include cooler-than-average sea surface temperatures in the central and eastern Pacific, and increased cloudiness in the western Pacific. However, how cool the sea surface temperatures need to be (for the region, MSS uses a threshold of −0.65°C for an index termed 'Nino3.4'), and for how long (MSS requires a minimum of five consecutive months) differ slightly across centres.

An example of a close case for a triple year La Niña is the 1998 – 2000 event. After the strong El Niño event in 1997 – 1998, La Niña conditions developed in the third quarter of 1998. This La Niña event persisted to June 2000, marking two years of continuous La Niña conditions. However, by the middle of 2000, the cool sea surface temperatures in the central Pacific began to warm and indicated weak or borderline La Niña conditions. Based on MSS' criteria, after returning to ENSO neutral in July 2000, the sea surface temperatures only satisfied the criteria for La Niña conditions again between October 2000 and January 2001, not long enough to be declared a La Niña event. However, some centres that use a threshold of −0.50°C for the Nino3.4 index consider 2000/2001 a third ENSO year with La Niña conditions. Looking at the impact on Singapore for this La Niña-like event in the second half of 2000, Singapore typically experiences above-average rainfall during the Southwest Monsoon season, and Singapore's rainfall during the Southwest Monsoon season in 2000 was just below average.

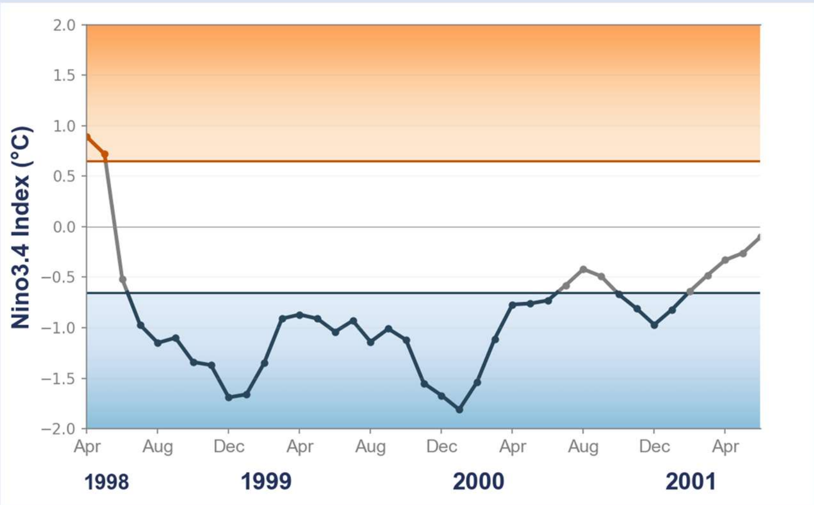


Figure 14: Nino3.4 index from April 1998 to June 2001. The index an extended period of La Niña conditions between July 1998 and June 2000. While the index dipped briefly into La Niña territory between October 2000 and January 2001, it was not long enough to qualify as a La Niña event based on MSS' criteria.

While there may be some disagreement about when the previous triple year La Niña occurred, given the strength of the La Niña conditions over the past three years, centres agree on the current triple year La Niña, and that this is the first triple year La Niña in the 21st century.

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5 MSS' record of ENSO events extends back to the 1960s. While ENSO events have occurred earlier, measurements used to assess these events are less robust. Furthermore, ENSO events typically form in the middle of the year and decay in the following year (termed 'ENSO' year). Therefore, triple year La Niña refers to three ENSO years in a row with La Niña conditions.

The Indian Ocean Dipole (IOD) Overview

The IOD refers to a broad pattern of temperature differences in the western and eastern Indian Ocean. Sustained warmer anomalies in the western tropical Indian Ocean and cooler anomalies in the eastern tropical Indian Ocean indicate a positive IOD event and cooler anomalies in the west and warmer anomalies in the east indicate a negative IOD event. This difference in sea surface temperature is measured by the IOD Index.

In the beginning of 2022, the IOD Index showed negative values but fluctuated around neutral between March and April. There were signs of a negative IOD event developing from May, with the negative IOD event established by June 2022. The negative IOD Index was strongest between July and August 2022, with fluctuations during September, and started showing signs of weakening from October. By December 2022, the IOD Index was close to zero, indicating a return to neutral conditions.

Both negative IOD and La Niña conditions were present during the Southwest Monsoon seasons in 2021 and 2022, though there were differences in the timing of the IOD events in 2021 and 2022. Negative IOD events and La Niña events both tend to bring wetter-than-usual conditions to Singapore and the surrounding region, including during the Southwest Monsoon season.

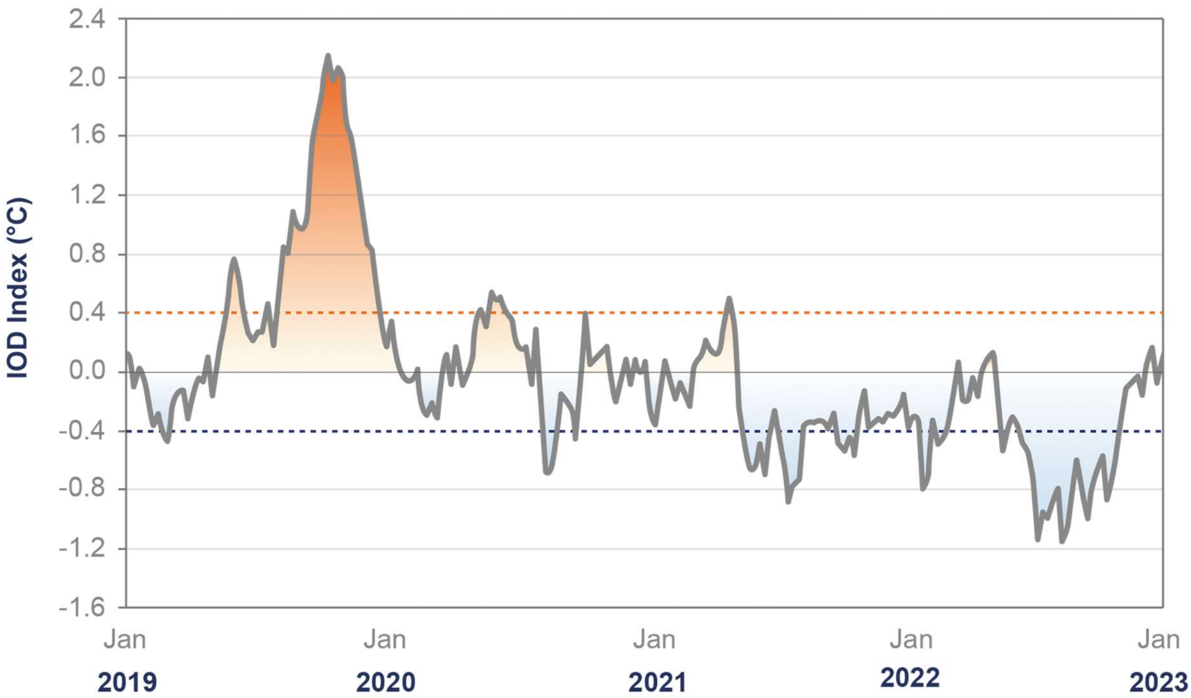

Figure 15: The Indian Ocean Dipole (IOD) Index[6] shows negative values from around May 2022 onwards. Sustained positive values indicate a positive IOD event, while sustained negative values indicate a negative IOD event.

The Madden-Julian Oscillation (MJO) Overview

At the subseasonal timescale, the MJO is an important driver for climate variability in Singapore. The MJO is characterised by a pulse of cloud or rain that moves eastward around the equator, with a typical cycle lasting between 30 to 60 days. The MJO's path along the equatorial region is divided into sub-geographical locations, or phases, marked by the location

[6] Data source: Bureau of Meteorology, Australia

of enhanced or suppressed convective activity and associated rainfall. While the MJO is not always present, when it does occur, it can provide predictability for rainfall in the coming weeks, as well as modulate Singapore's rainfall. Here we review how the MJO modulated the notable weather events in March and May 2022.

In March 2022, MJO activity likely contributed to the above-average rainfall during the month. In the second week of March, an MJO signal developed over the Western Hemisphere (Phase 1). This signal then propagated eastwards over the Indian Ocean (Phase 2 to Phase 3) before weakening in the last week of March (Figure 16 upper left). Phases 2 and 3 typically bring more rainfall to the western Maritime Continent[7], including Singapore, at this time of year, and rainfall was above average for much of this region in March 2022, particularly around the middle of March (Figure 16 lower left).

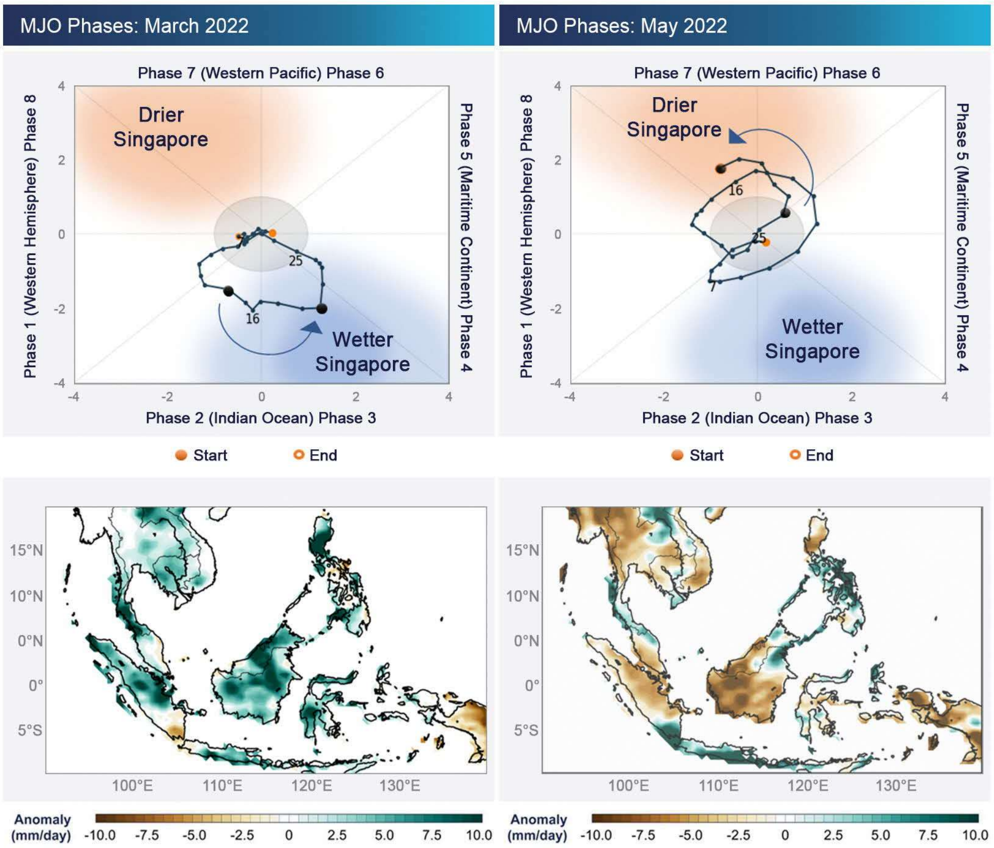

Figure 16: Upper: MJO Phases for March 2022 (left) and May 2022 (right). Blue and orange shading indicate phases that typically bring wetter and drier conditions to Singapore, respectively. Lower: Weekly rainfall anomalies for 14 – 20 March 2022 (left) and 26 – 31 May 2022 (right)[8], with green colours indicating wetter-than-usual conditions and brown colours indicating drier-than-usual conditions.

In May 2022, two periods of MJO signal in the Western Pacific in the middle and towards the end of the month may have contributed to the drier conditions, and therefore also the warmer temperatures experience in Singapore. In May, when an MJO is present over the Western Pacific (Phases 6 and 7), Singapore typically experiences less rainfall than average. Two

[7] The Maritime Continent covers the maritime portion of Southeast Asia, including Indonesia, Malaysia, Philippines, and Singapore.

[8] Data sources: CHIRPS (rainfall), Bureau of Meteorology, Australia (RMM values)

MJO signals passed through these phases in May 2022: the first between 13 and 17 May, and a second slower signal between 27 and 31 May (based on the index in Figure 16 upper right). Particularly during the last week of May 2022, drier conditions were present over much of the western Maritime Continent (Figure 16 lower right). However, for May overall, it would be difficult to discern any impact of MJO on rainfall, given that there was a near-complete circumnavigation of the globe by a fast-moving MJO signal in May 2022.

For the third notable month for Singapore 2022, the wettest October in the last four decades, it is unlikely that an MJO signal contributed to the higher-than-average rainfall. There appeared to be an MJO signal over the Western Pacific (Phases 6 and 7) in the second half of October 2022, although there was little of the usual MJO eastward propagation (not shown). Typically in October, the presence of MJO in over the Western Pacific brings drier-than-average conditions for western parts of Southeast Asia, including Singapore, although in October 2022, only western parts of Mainland Southeast Asia experienced the typical drier MJO conditions. However, La Niña conditions and a negative Indian Ocean Dipole also were present in October 2022.

These two examples, March and May 2022, highlight how MJO signals help to modulate rainfall for Singapore and the surrounding region. The MJO is only one potential climate driver for Singapore's climate—there are also other climate drivers (such as ENSO, IOD and monsoon seasons), as well as interactions between these drivers and other phenomena that all help modulate Singapore's climate.

Singapore's Climate in 2022 Compared to Long-term Observations

This Annual Climate Assessment Report for 2022 takes a closer look at Singapore's long-term observations, in preparation for the release of Singapore's Third National Climate Change Study later in 2023. Accurate measurements, along with information about the location of where the measurements are taken, are key to unlocking how Singapore's climate has been changing.

Temperature

Singapore's climate station record for temperature stretches back to 1929 (Figure 17). The location of the climate station has changed over time; it has been at its current location at Changi Airport since 1984. Therefore, the most reliable long-term records for assessing impact of climate change, urbanisation and other factors on the climate station are for the 1984 – 2022 period, due to earlier changes in the climate station location affecting the measurements.

Over the last 39 years, the daily mean temperatures have been steadily rising at the climate station. This rise in temperature is clear even with large year-to-year variability due to the influence of climate drivers such as El Niño – Southern Oscillation (ENSO). El Nino events tend to increase annual mean temperatures across Singapore, while La Nina events tend to moderate them. This includes in 2022, when the annual mean temperature was cooler than earlier years that corresponded to El Niño or positive Indian Ocean Dipole events (including 2019, 2016, 2015 and 1998), but still overall the tenth warmest year on record. Over the period 1984 – 2022, the climate station has warmed on average 0.24°C per decade.

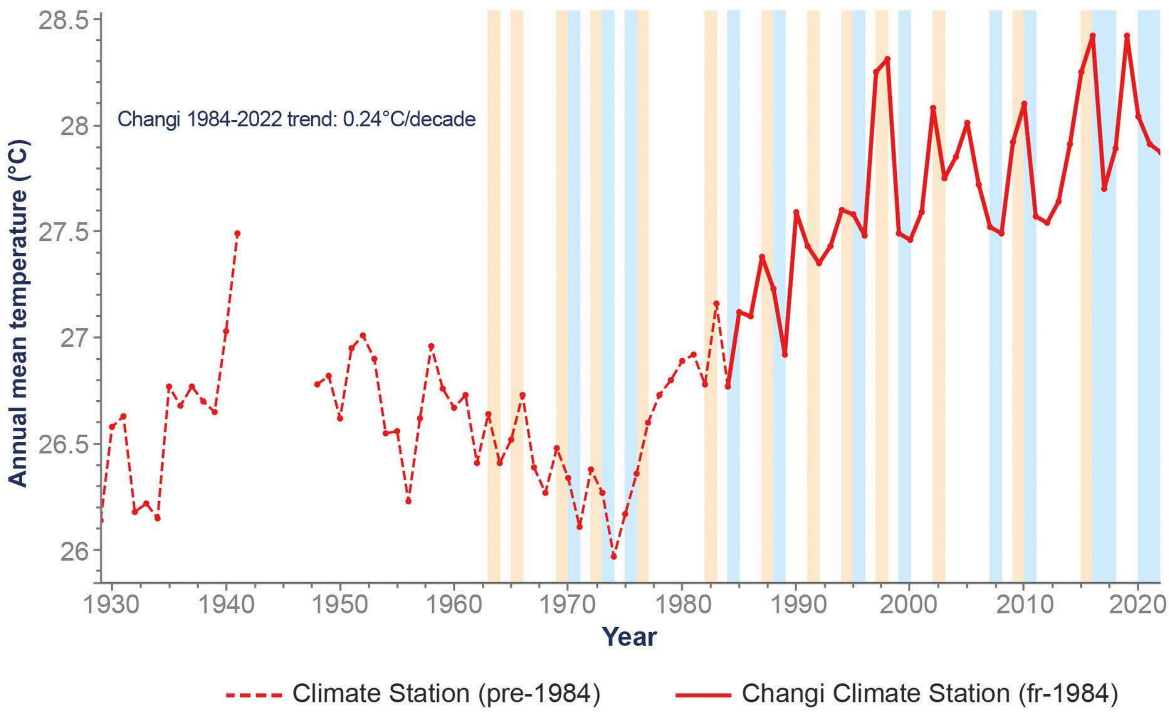

Figure 17: Annual mean temperature at the climate station. The break in the record between 1942 to 1947 was due to the Second World War. El Niño and La Niña years from 1961 onwards are highlighted in light orange and blue bars, respectively.

Not only have the annual mean temperatures been rising, but also the number of very warm days (days when the daily maximum temperature exceeds 34°C). Since the mid-1970s, there has been an overall increase in the number of very warm days, with an upward trend observed in some weather stations. For instance, the number of very warm days between 1972 and 2022 recorded at the Tengah and Seletar stations increased by 13 and 8 days per decade, respectively. The characteristics of high temperature vary spatially across the island, with Changi station experiencing fewer very warm days than the other two stations. The fewer very 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 in the island, this can reduce the high afternoon temperatures and provide relief from the heat. However, it is worth noting that the frequency of very warm days exceeding 20 days per year in Changi has slightly increased.

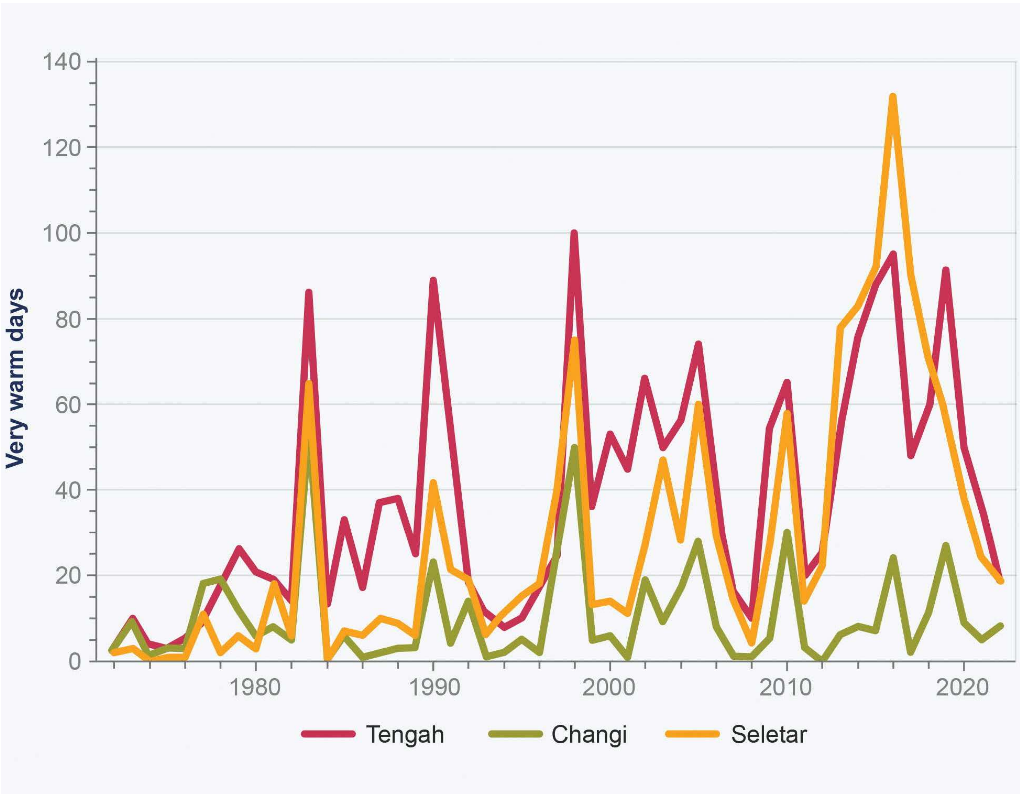

Figure 18: The number of very warm days where the daily maximum temperature was above 34°C for weather stations at Changi, Seletar and Tengah with long-term records (1972 – 2022).

The number of very warm days also increases during El Niño events. El Niño events usually straddle two years – typically forming around the middle of the year and ending in the following Northern Hemisphere spring. The annual number of warm days in Singapore typically peaks in the year after an El Niño event forms, as seen in 1983, 1998 and 2016. These three years correspond to the second half of the three strongest El Niño events in the last 40 years: 1982/1983, 1997/1998, and 2015/2016.

Is there evidence of the Urban Heat Island Effect in the long-term records?

The UHI effect refers to the phenomenon whereby towns and city areas experience much higher air 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. This UHI effect is on top of long-term warming trends due to climate change.

Figure 19 compares the mean daily minimum temperature anomalies between the Tengah station and the Changi station. Tengah station is close to the Tengah River, surrounded by some forested areas, while Changi station is sited near the more developed residential areas and close to Changi Airport's runway. In this analysis, the locations of the stations at Tengah and Changi are considered representative of a rural and semi-urban area, respectively.

Over the last 50 years (1973 – 2022), the night-time minimum temperatures at Changi have warmed more rapidly (0.20°C/decade) than at Tengah (0.14°C/decade), and comparable to the global land average (0.24°C/decade[9]). The upward trends in temperature can be attributed to a combination of factors including global warming. The difference in upward trends between these two stations suggests evidence of urbanisation (the UHI effect) contributing to Singapore's overall long-term temperature trend.

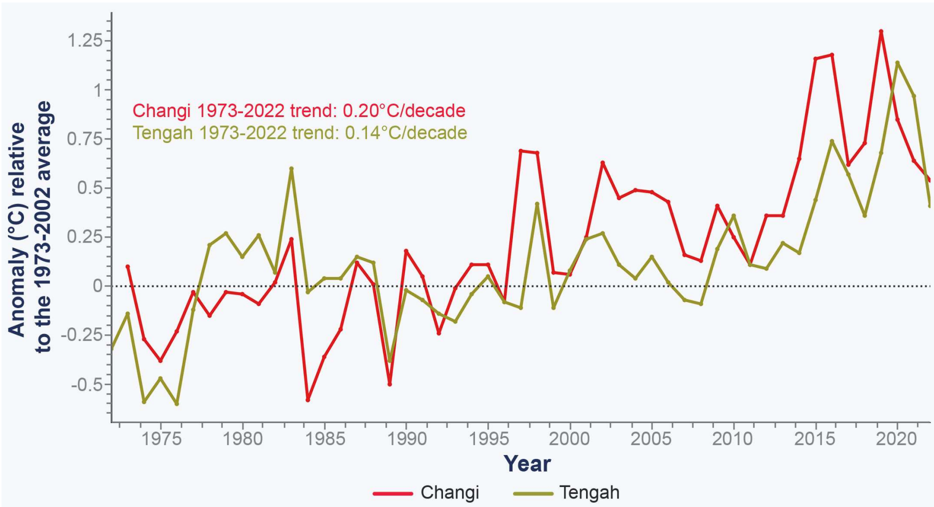

Figure 19: Annual anomalies of daily minimum temperature at Changi (red) and Tengah (green) stations from 1973 to 2022. Between 1973 and 1981, the temperature observations at Changi station were taken at the former Changi Air Base, and thereafter at its current site at Changi Airport. The 1973 – 2002 long-term mean daily minimum temperature of Tengah and Changi are 23.5°C and 24.6°C, respectively.

The UHI effect varies across different parts of Singapore. While Changi station is considered here as a semi-urban station, it is not representative of all urban environments in Singapore. Similarly, Tengah as a rural station is not representative of all rural environments. The extent of the UHI effect depends on various factors, such as the type of urban environment (e.g., low-rise residential compared to high-rise commercial), as well as the degree of human activity (e.g., high energy consumption in industrial areas). There are also local meteorological factors, such as the strength of the sea and land breezes. Nonetheless, the noticeable difference between Changi's and Tengah's long-term temperature records highlights the UHI contribution to Singapore's long-term warming trend.

[9] Global trend calculated over the period 1973 – 2021.

Global Temperature

As mentioned in the previous section, the global average temperature has also been increasing over time. In 2022, significant parts of the world recorded above-average temperatures (Figure 20). It is expected that the global average temperature for 2022 will be either the fifth or sixth warmest year on record[10]. As with Singapore, the continued La Niña conditions have had a cooling effect on the global temperature, although this does not reverse the long-term warming trend. Globally, 2022 is expected to be warmer than in 2011 (after the previous major La Niña event in 2010/2011), and slightly warmer than 2021. Furthermore, it is likely that the past eight years, 2015 to 2022, will be the eight warmest years on record.

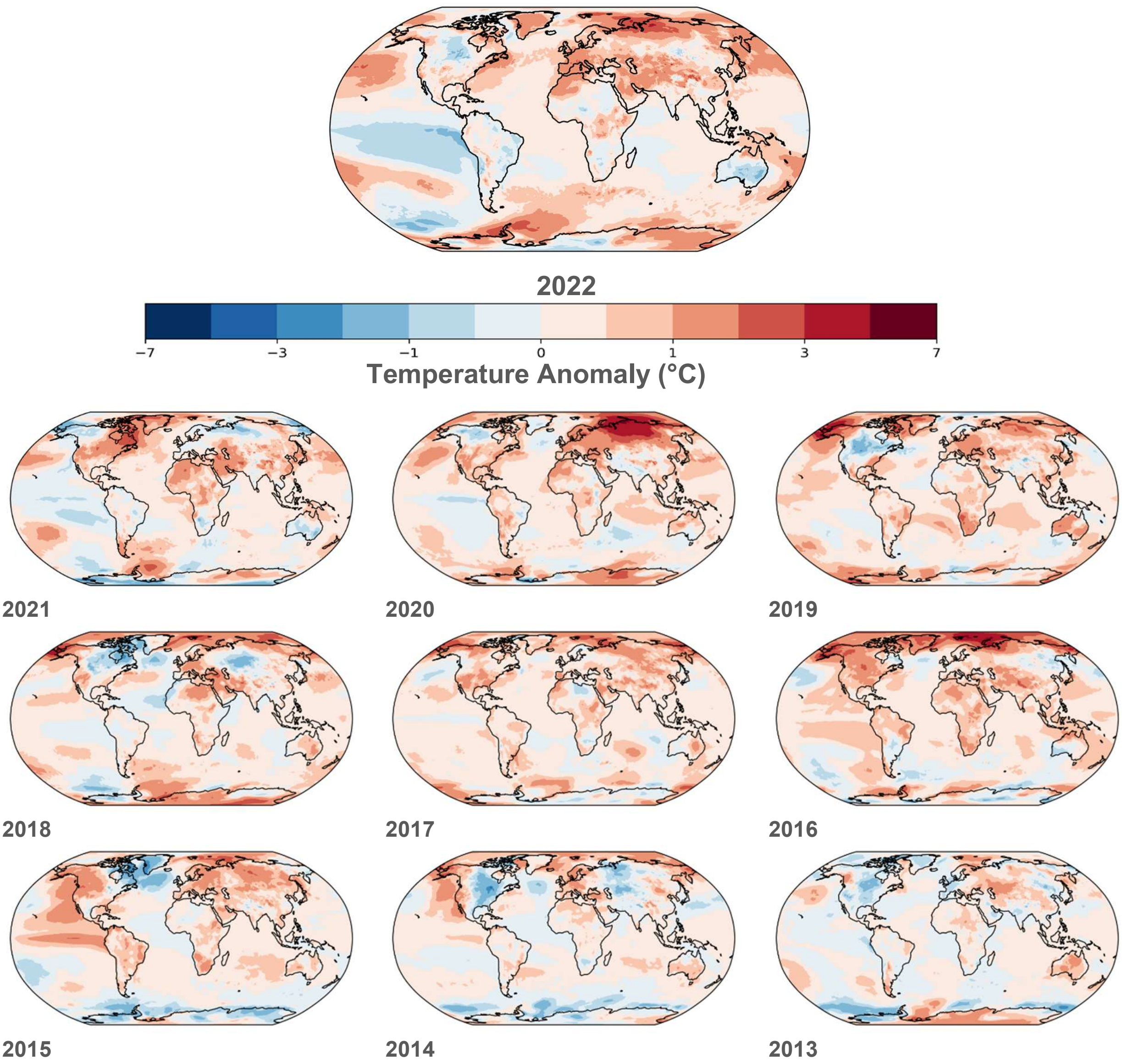

Figure 20: Global annual surface air temperature anomaly for 2022. Subsequent figures show the anomalies for the past 10 years. Anomalies are relative to the 1991 – 2020 climatology[11].

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[10] Based on the WMO State of Global Climate 2022 provisional report, which references several independently maintained global temperature datasets: HadCRUT5 by the UK Met Office in collaboration with the Climatic Research Unit at the University of East Anglia, UK; NOAA Global Temp by National Oceanic and Atmospheric Administration, National Centers for Environmental Information, USA; GISTEMP by the National Aeronautics and Space Administration Goddard Institute for Space Studies, USA; JRA-55 by the Japan Meteorological Agency, Japan; ERA5 by European Centre for Medium-Range Weather Forecasts; and Berkley Earth.

[11] Data source: ERA5

Rainfall

Above-average rainfall in both 2022 and 2021 raises the question as to whether this increase is representative of a long-term trend. While the annual total rainfall for Singapore has a gradual increasing trend of 78 mm per decade from 1980 to 2022, this trend is not statistically significant. Rather, 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.

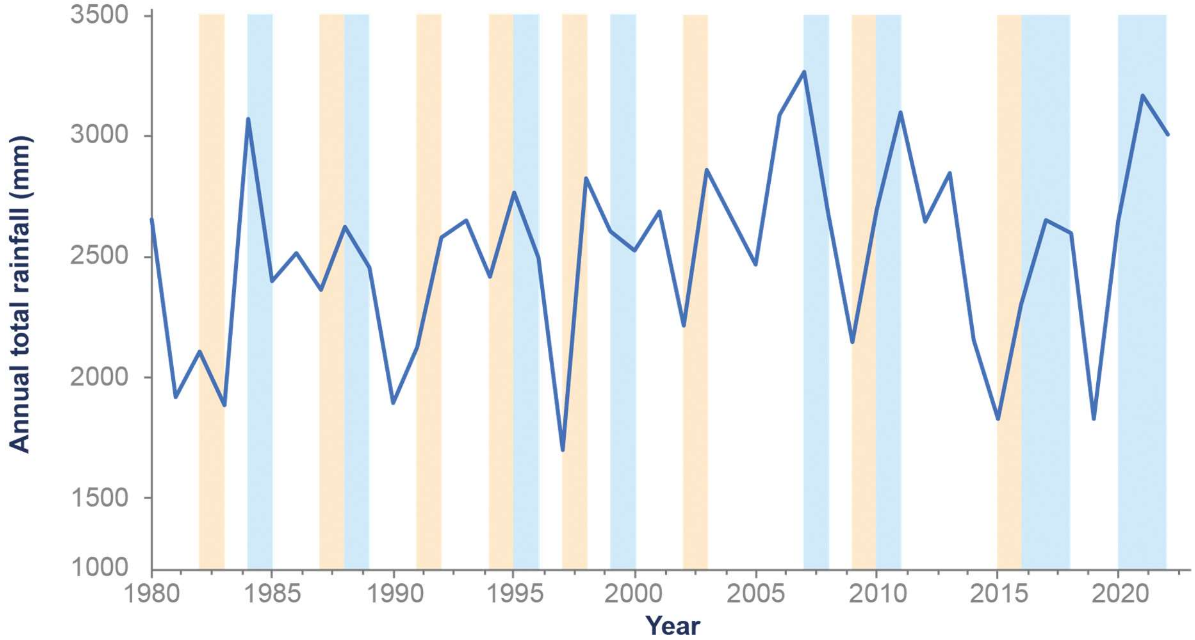


Figure 21. Singapore average annual total rainfall between 1980 and 2022 (solid blue). El Niño and La Niña years are highlighted in light orange and blue bars, respectively.

Rainfall in the tropics is highly variable. When considering extreme rainfall in Singapore, no significant trend has been observed in the maximum sub-daily rainfall intensity over the past 43 years (Figure 22). Based on continuous long-term observations[12], the maximum 60-minute rainfall intensity ranged from 80 to 147 mm from 1980 to 2022. Meanwhile, maximum 30-minute rainfall intensity ranged from 60 to 96 mm. In 2022, while Singapore's annual rainfall was above average, this was not the case for the extreme rainfall.

While there is no significant trend over the past 43 years in the maximum rainfall intensity, there has been considerable year-to-year and longer-term variability. For example, between 1995 and 2010, the average annual maximum rainfall intensity was higher than the preceding 1980 – 1994 period, and subsequent 2011 – 2022 period. The high variability in rainfall intensity comes from a combination of factors including natural climate variability, climate change, and local effects such as urbanisation.

[12] This is based on the 23 weather stations that have the most complete continuous record since 1980.

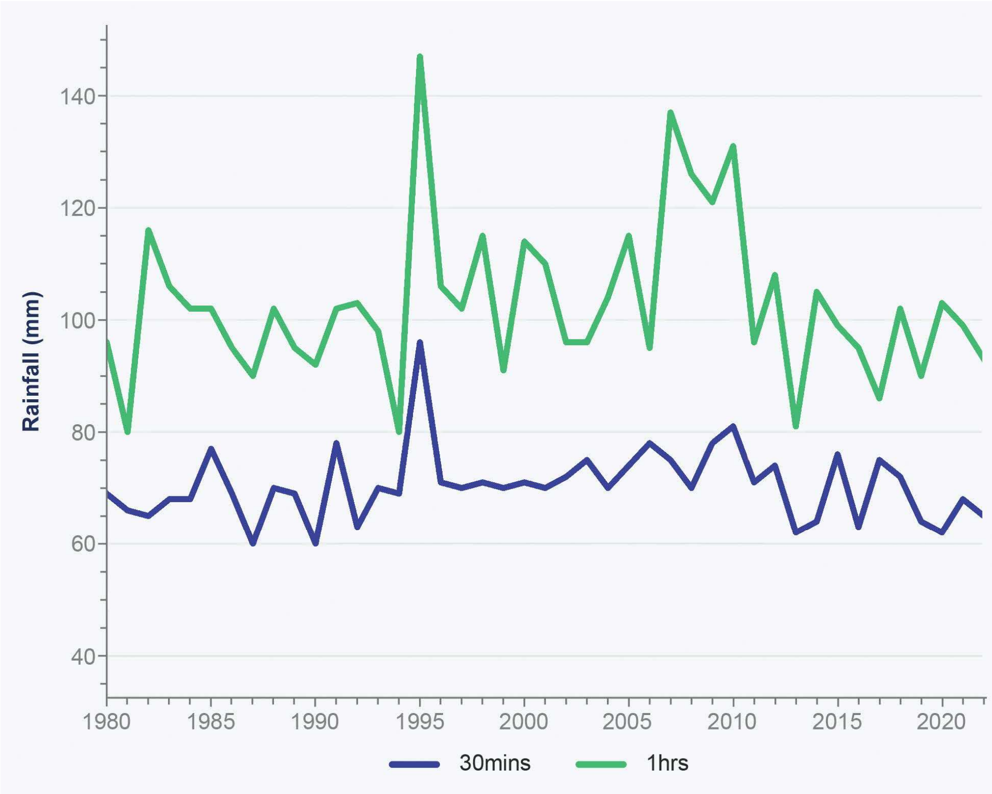


Figure 22. The maximum rainfall intensity for 30-min (blue) and 60-min (green) across 23 weather stations with continuous long-term observations from 1980 – 2022.

General Climate of Singapore

Singapore has a tropical climate which is warm and humid, with abundant total annual rainfall of approximately 2200 mm. Generally, the eastern parts of Singapore receive less rainfall compared to other parts of the island. 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:

a) Northeast Monsoon (December to early March).
b) Inter-monsoon (Late March to May).
c) Southwest Monsoon (June to September).
d) Inter-monsoon (October to November). 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.

Average Annual Rainfall (1991–2020)
(based on 32 rainfall stations)

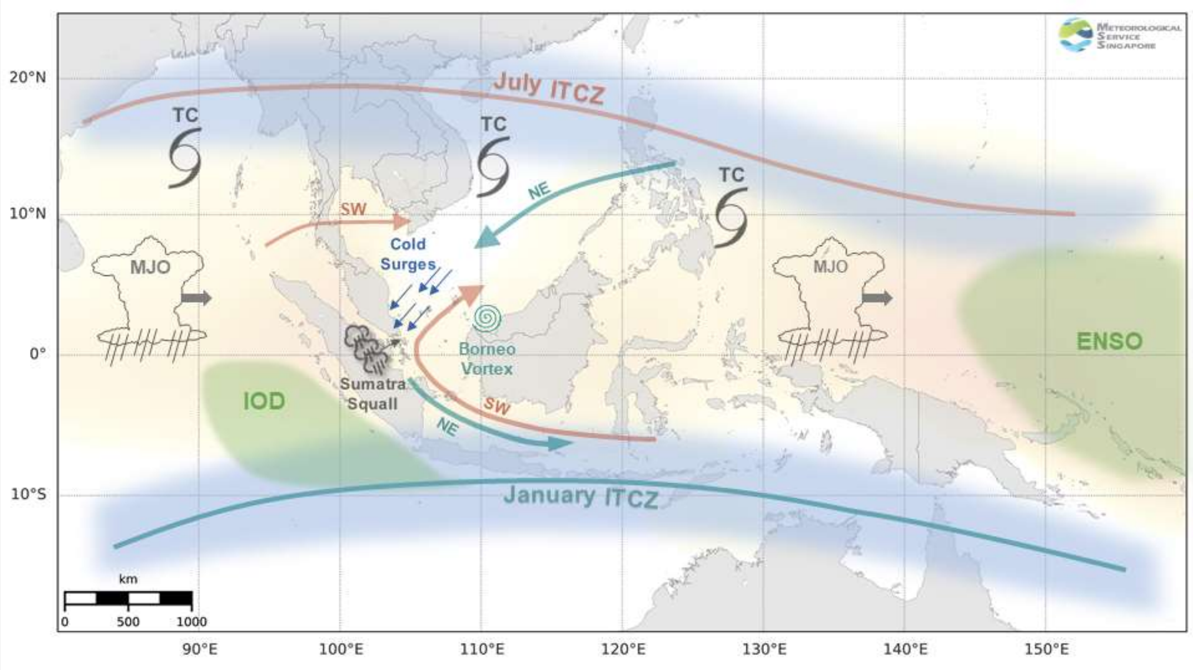
The three main rain-bearing weather systems that affect Singapore are the localised convective showers/thunderstorms, Sumatra squalls and Northeast Monsoon surges. The convective showers/thunderstorms occur throughout the year while Sumatra squalls commonly occur between April and November. The monsoon surges occur during the Northeast Monsoon season.

Sea Breeze Induced Thunderstorms: Sea breezes are winds formed as a result of temperature differences between the land and the adjoining sea. The sea breeze, carrying a large amount of moisture from the sea, blows inland during the day where the moist air mixes with the rising warm land air and, under unstable conditions, form rain clouds in the afternoon. During the Inter-monsoon periods, when winds are light, sea breezes are more common.

Sumatra Squalls: A Sumatra squall is an organised line of thunderstorm that develops over Sumatra or the Strait of Malacca, often overnight, and moves eastward to affect Peninsular Malaysia and Singapore. In a typical event, the squall line can bring about one to two hours of thundery showers. Often this happens in the predawn or morning hours. Some Sumatra squalls are also accompanied by strong wind gusts with speeds up to 80 km/h (22 m/s) which can uproot trees.

Northeast Monsoon Surges: A Northeast Monsoon surge is a surge of cold air from Central Asia. 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 northeasterly winds over the South China Sea blowing toward the warm tropics. The sea warms and moistens the overlaying 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.

Key Climate Drivers Affecting Weather and Climate



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.

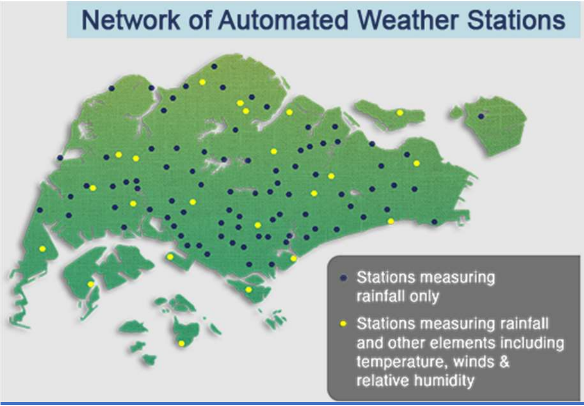
The **Intertropical Convergence Zone (ITCZ)** is a persistent east-west band of converging low-level winds, cloudiness, and rainfall stretching across the Maritime Continent into the Pacific Ocean bringing monsoonal rains. It migrates every year southward across the equator and back again, affecting most countries across the Maritime Continent.

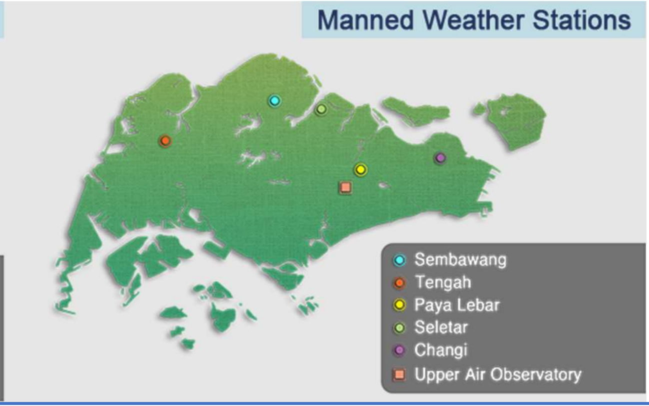
Indian Ocean sea surface temperatures impact rainfall and temperature patterns across the Maritime Continent. Warmer than average sea surface temperatures can provide more moisture for weather systems crossing the region. Sustained changes in the difference between sea surface temperatures of the tropical 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)** can be characterized as an eastward moving "pulse" of cloud and rainfall near the equator that typically takes around 30 to 60 days to circle the globe when present. 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.

A **Borneo Vortex** typically appears off the northwestern 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.





About the Meteorological Service Singapore (MSS)

The MSS is Singapore's national authority on weather and climate. It is a pillar under the National Environment Agency (NEA).

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 of them measure other meteorological elements including temperature, relative humidity, pressure, and wind. This observation network serves as the main source of climate data for this report.

The manned observation station at Changi is MSS's designated climate station. 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).

The installation of the automatic weather station network from 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 would also be useful for monitoring of long-term upper air conditions in the equatorial tropics, as the records extend back many decades to the 1950s.

Further Information
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