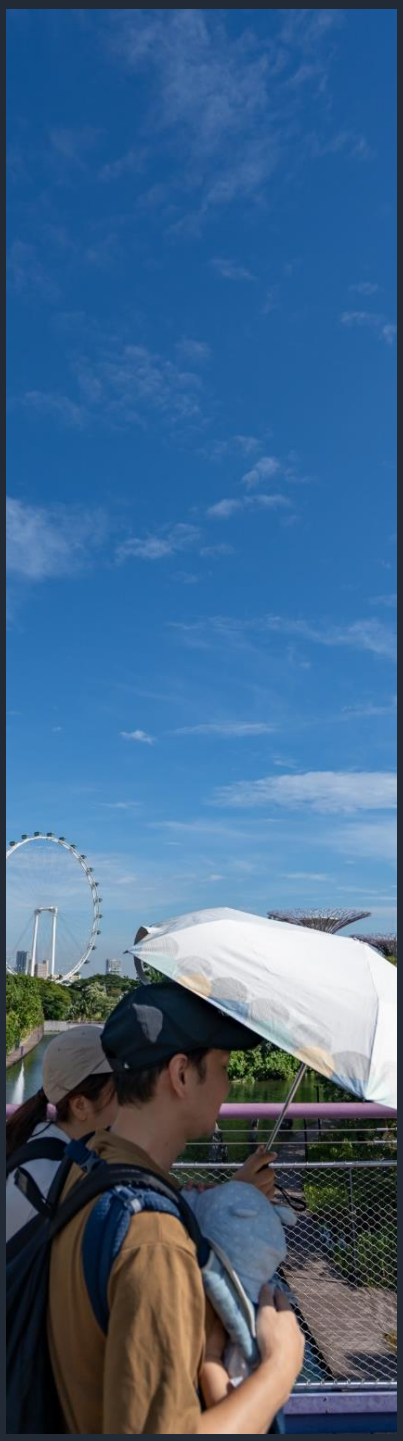


METEOROLOGICAL SERVICE SINGAPORE

2023

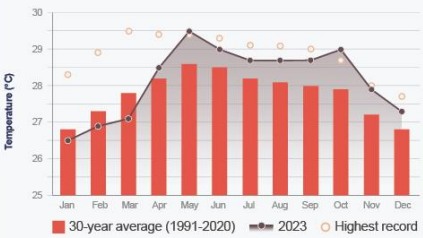
ANNUAL CLIMATE ASSESSMENT SINGAPORE

Singapore's Climate in 2023

Decadal mean temperature

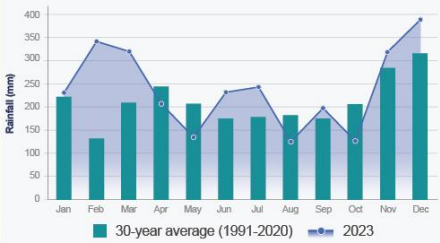
Last 10 years from 2014 to 2023 was Singapore's warmest decade on record, with decadal mean temperature of 28.06°C.

Monthly mean temperature



2023 was the 4th warmest year on record. After a cool start, monthly temperatures from April onwards were above average.

Monthly total rainfall



2023 was the seventh wettest year since 1980, with an average annual rainfall about 13% higher than the long-term average.

NOTABLE WEATHER EVENTS IN 2023

Unusually late surge

A monsoon surge from late February to early March brought heavy rain and cooler weather, along with the wettest February day on record.

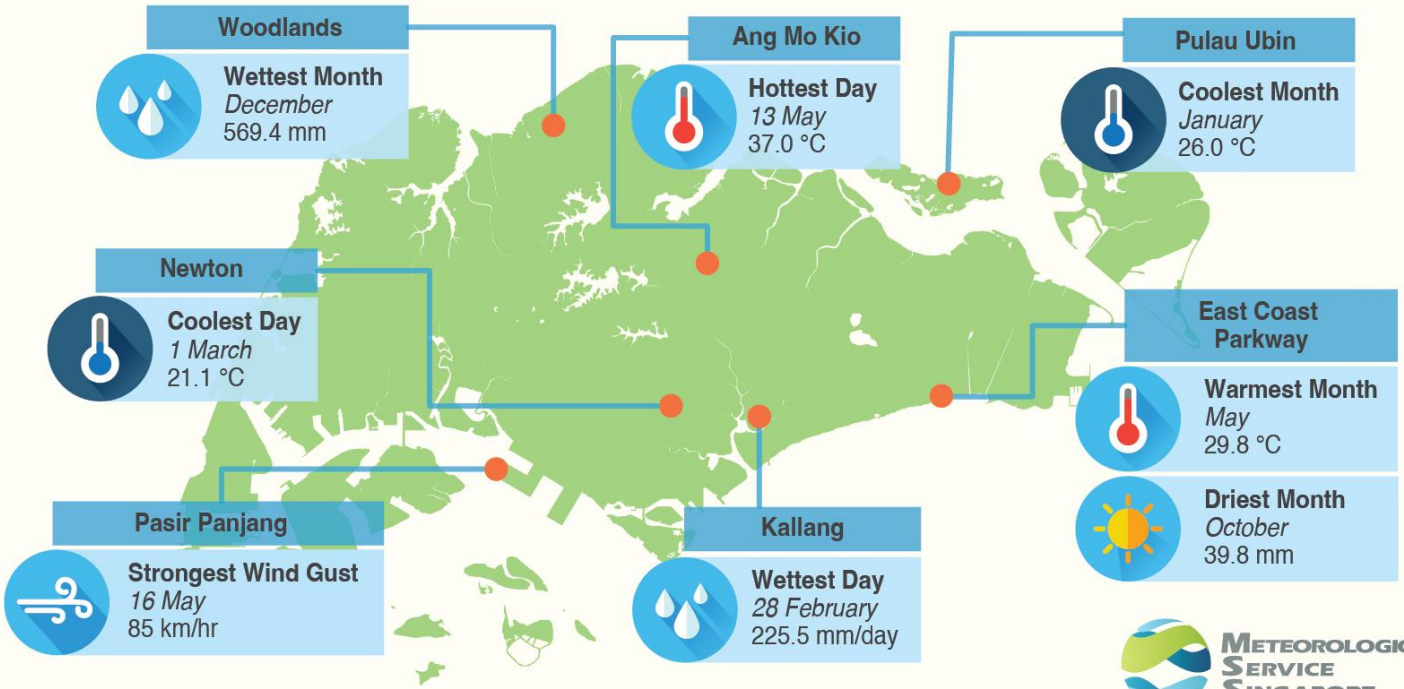
Scorching May

May 2023 was the warmest May on record, including a high of 37°C on 13 May that ties with the highest temperature recorded in Singapore.

Smoke haze

Prevailing winds in the region brought smoke haze to Singapore on 7 – 8 October, leading to a deterioration in air quality.

EXTREMES IN 2023



METEOROLOGICAL SERVICE SINGAPORE

Overview of Singapore's Climate in 2023

2023 was the fourth warmest year on record for Singapore, tied with 1997 and 2015. At the Changi climate station, the last 9 months of the year saw above-average temperatures, with record-breaking temperatures in May and October. A wet start to 2023 contributed to Singapore's rainfall being the seventh highest since 1980[1]. February and March were exceptionally wet. However, there were four months with below-average rainfall, including in October when Singapore briefly experienced transboundary haze. The year's weather was influenced by prevailing La Niña conditions that weakened in early 2023 followed by El Niño conditions in the second half of the year.

This report covers Singapore's weather and climate in 2023, along with a closer look at how climate drivers modulated the climate. There is also a special focus section on Heat Stress. Reference is made to Singapore's Third National Climate Change Study (V3). The study, released in January 2024, provides the world's highest resolution climate projections for Singapore and the surrounding region based on the IPCC Sixth Assessment Report (AR6).

Contents

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

Large-scale Climate Variability in 2023

Climate drivers, such as the El Niño–Southern Oscillation (ENSO), are sources of year-to-year variability for Singapore's climate as well as the global climate.

In 2023, the two key climate drivers were ENSO and the Indian Ocean Dipole (IOD). The transition from La Niña, through ENSO neutral to El Niño contributed to the shift from cooler start of the year to a warmer second half of the year. Further information on ENSO, IOD and the Madden–Julian Oscillation (MJO) and how these drivers modulated Singapore's climate in 2023 is described below. A brief description of the key climate drivers affecting weather and climate in the region can also be found on Page 30.

The El Niño–Southern Oscillation (ENSO) Overview

The La Niña event that developed in 2021 finally ended in the first quarter of 2023 (Figure 1). La Niña refers 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. The Nino3.4 index shown in Figure 1 is a common index used to monitor La Niña (and El Niño) events, with sustained values below -0.65°C indicating La Niña conditions. For Singapore, La Niña events typically bring more rainfall, particularly during the Southwest Monsoon season (June to September), and to a lesser extent the end of the Northeast Monsoon season (February) and into the first inter-monsoon period (March to May). La Niña events also tend to moderate Singapore's temperature, with less frequent above-average temperatures.

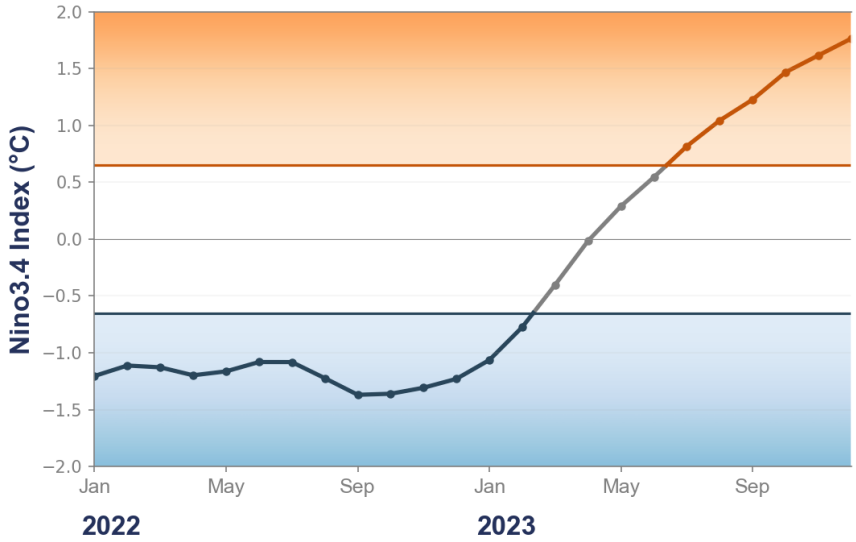


Figure 1: Nino3.4 index from January 2022 to December 2023. The index measures the average sea surface temperature anomaly in the central-eastern equatorial Pacific Ocean (termed the 'Nino3.4 region'), averaged over three months. The anomaly is relative to 1976-2014, with the tropical long-term warming trend removed[2]. The prolonged period of La Niña conditions ended in early 2023, and after four months of ENSO neutral conditions, transitioned to El Niño conditions for the second half of 2023.

[2] Further information available at www.weather.gov.sg/climate-el-la/

The El Niño event dominated the climate of the tropical Pacific Ocean for most of the second half of 2023. El Niño events refer to the ENSO phase where sea surface temperatures are warmer than average over the central and eastern tropical Pacific Ocean, typically resulting in reduced rainfall over the western Pacific. In 2023, sea surface temperatures across much of the tropical Pacific Ocean were warmer than average from April onwards, however, it was not until July 2023 that the sea surface temperatures in Nino3.4 region (black box, Figure 2) were significantly warmer than in the western tropical Pacific Ocean, as found during an El Niño event. The Nino3.4 index also exceeded the 0.65°C threshold from July, indicating El Niño conditions (Figure 1).

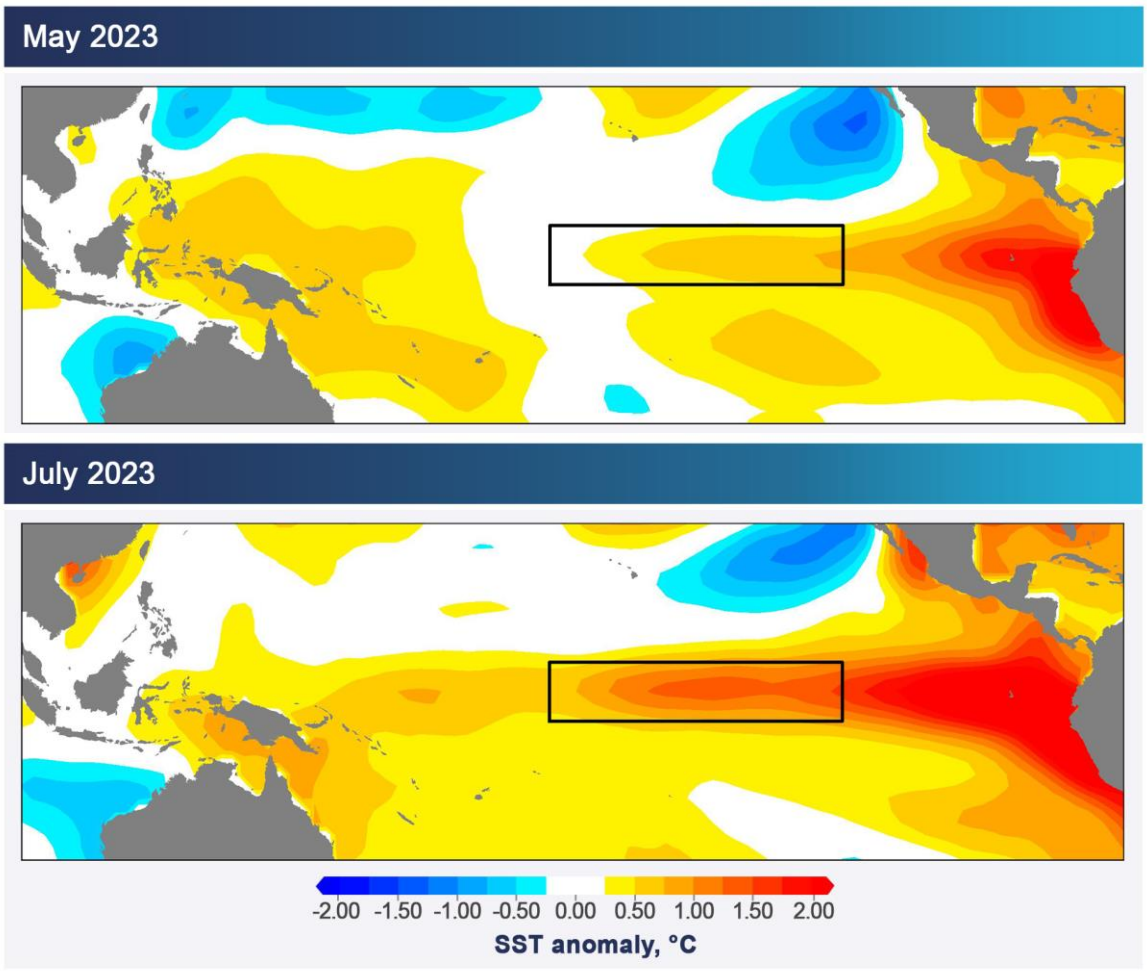


Figure 2: Monthly average sea surface temperatures for the Pacific Ocean for May and July 2023 (Data: NOAA Extended Reconstructed Sea Surface Temperature, Version 5). The black box indicates the region used to calculate the Nino3.4 index, shown in Figure 1. The sea surface temperatures are relative to the 1991-2020 average (without removing the long-term warming trend), with red colours indicating warmer than average temperatures and blue colder than average. In May, the SSTs were warmer in the western Pacific compared to the central Pacific (not indicative of El Niño conditions). However, in July, the SSTs had warmed in the central and eastern Pacific and more indicative of El Niño conditions.

From July 2023, the Nino3.4 index continued to rise until the end of the year (Figure 1). The highest value of 1.67°C (November 2023 – January 2024 average) was much lower than the

previous strong El Niño where the index reached 2.43°C (November 2015 – January 2016 average) and indicates that this El Niño event is of moderate to strong strength[3].

El Niño events typically bring drier-than-usual conditions to Singapore, particularly during the Southwest Monsoon season (June to September). However, in 2023, Singapore's Southwest Monsoon season was slightly wetter than average. Besides the slightly later start to the El Niño event, wetter conditions may also have been associated with warmer sea surface temperatures in the western Pacific, possible remnants of the earlier prolonged La Niña. While it is common for La Niña events to follow El Niño events, it is much less common for El Niño events to form less than half a year after a La Niña event — the previous occurrence of the latter was in 1976[2]. In July 2023, sea surface temperatures in the western tropical Pacific Ocean were still warmer than average (Figure 2). Considering the atmospheric indicators of El Niño events, while there was an increase in cloudiness and decrease in the trade wind speed over parts of the central and eastern tropical Pacific in July (indicative of an El Niño) these changes became more pronounced from mid-September. While no two El Niño events are the same, the warmer SSTs in the western Pacific and more pronounced atmospheric response from September in 2023 may have contributed to the atypical rainfall response in the Southwest Monsoon season in some parts of the region.

For temperature and El Niño events, warmer-than-usual temperatures for Singapore are common, although the warmest temperatures tend to be when the El Niño event decays in the following year (around March–May).

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 first half of 2023, the IOD index was neutral, fluctuating around zero (Figure 3). There were signs of a positive IOD event developing in July, with the positive IOD event established by August 2023. The positive IOD Index was strongest between September and November 2023, and started showing signs of weakening from December. The positive IOD event ended in January–February 2024. The positive IOD index reached 1.92°C at the weekly timescale, indicating a strong positive IOD event, although not as strong as in 2019 (when the weekly index reached 2.15°C).

Positive IOD events tend to bring drier conditions to Singapore, as well as warmer temperatures. Positive IOD events also tend to occur when the ENSO state is either neutral (as in 2019) or when an El Niño event is present (as in 2023). However, while El Niño events can extend well into the following year after they form, positive IOD events end usually with or before the arrival of the rainy monsoon season in the southern hemisphere. This arrival is

[3] The timing and strength of ENSO events based on the Nino3.4 index can differ between centres, due to the data used, as well as how the index is calculated (such as whether the background warming trend is removed and the climatology period).

usually around December, although it can be delayed when there is a strong positive IOD, such as in 2019.

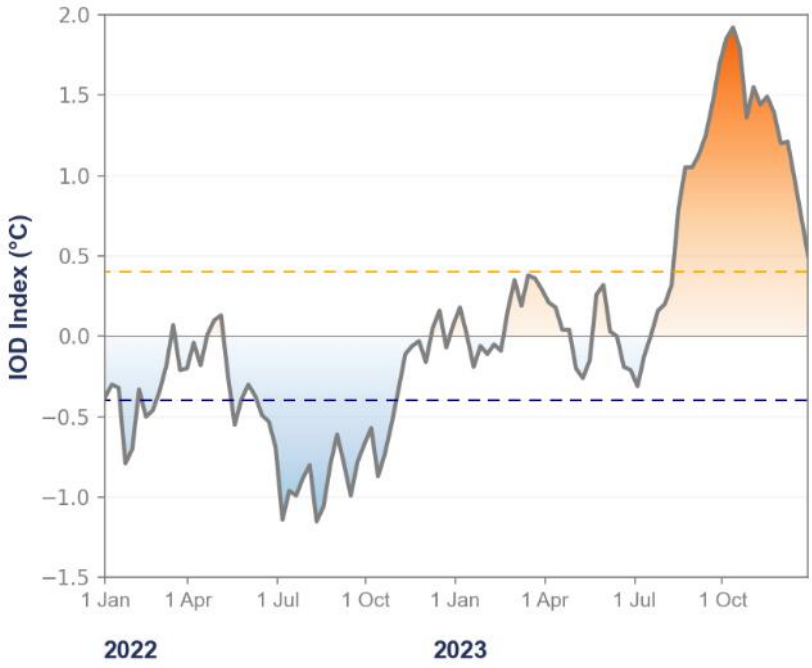


Figure 3: The Indian Ocean Dipole (IOD) Index[4] shows positive values from around August 2023 onwards. Sustained positive values indicate a positive IOD event, while sustained negative values indicate a negative IOD event (as can be seen in the second half of 2022).

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 clouds and 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 of enhanced/or suppressed convective activity and the associated rainfall. While the MJO is not always present, when it is active, it can provide predictability for rainfall in the coming weeks, as well as modulate Singapore's rainfall. Here we review two MJO events that likely impacted Singapore's rainfall in January–February and March 2023 (Figure 4).

Both January and February 2023 were wetter than average, likely with some contribution from the MJO. In the end of January, an MJO signal emerged over the eastern Indian Ocean (Phase 3) and remained active there for more than 10 days (Figure 4, top left). This event likely brought higher amounts of rainfall to Singapore, turning January from a drier than average month until the 19th day of the month to a wetter than average month. This MJO signal continued to be active in Phase 3 during the first week of February 2023, and continued propagating eastwards through the Maritime Continent in Phase 4 and 5. This also contributed to the wetter than average February in the first part of the month.

In the first week of March 2023, the MJO was present over the Western Pacific (Phase 7), and then propagated eastwards through the Western Hemisphere (Phases 8 and 1) during

[4] Data source: Bureau of Meteorology, Australia

the second and third weeks of the month, with an amplitude that was one of the strongest to ever been recorded during Phase 8 (based on the RMM index shown on the diagram in Figure 4, top right). Phase 7, and to some extent Phase 8, normally bring drier than average conditions to the western Maritime Continent, including Singapore. However, overall, in March 2023, Singapore experienced wetter than average conditions, with a major contribution by a wet monsoon surge that occurred during the end of February and early March. Without considering the first 4 days of the month, which were predominantly affected by the surge, March 2023 was drier than average, with the strong MJO signal in Phases 7 and 8 possibly contributing to the reduced rainfall during the rest of the month.

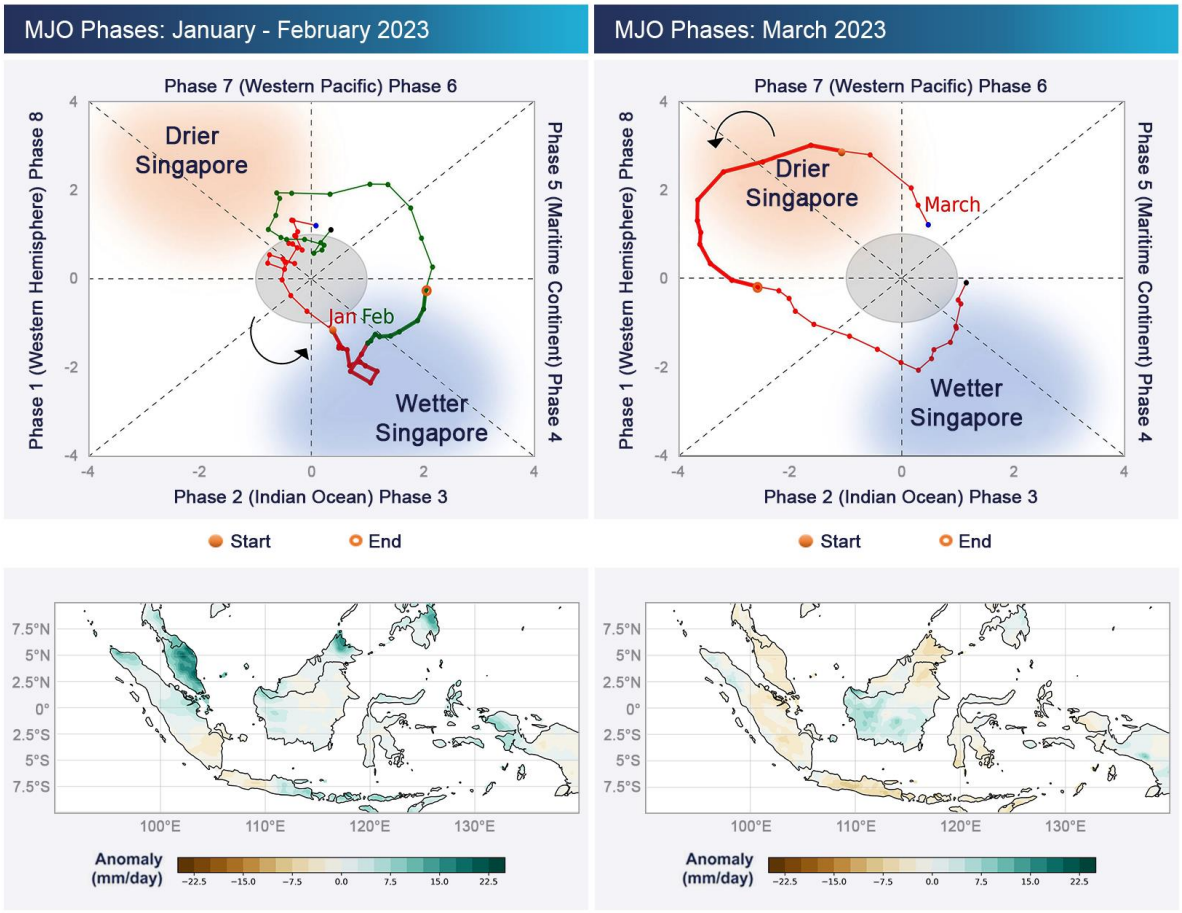


Figure 4: Top: RMM diagram for January–February 2023 (left) and March 2023 (right). Thick lines indicate the periods 20 January–9 February and 5–15 March, respectively. Blue and orange shading indicate phases that typically bring wetter and drier conditions to Singapore, respectively. Bottom: Rainfall anomalies for 20 January–9 February 2023 (left) show wetter than usual conditions around Singapore (green colours) and for 5–15 March 2023 (right) show drier than usual conditions (brown colours[5].

The two examples presented here demonstrate the role the MJO plays in modulating weekly rainfall over the Maritime Continent, with a focus on Singapore. Other impactful large-scale climate drivers, such as ENSO and IOD, also play a major role in the region's rainfall patterns, with their imprint more discernible on the monthly and seasonal timescales. More information on Singapore's rainfall in 2023 can be found under the Rainfall Section (Page 14).

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

Temperature

Global Temperature

In 2023, significant parts of the world recorded above-average temperatures (Figure 5), with the global average temperature for 2023 the warmest year on record[6]. Along with the long-term warming trend, the shift from La Niña to El Niño conditions likely contributed to the warmer temperatures in 2023, including record monthly global ocean near-surface temperatures from April onwards. Furthermore, the past nine years, 2015 to 2023, are the nine warmest years on record.

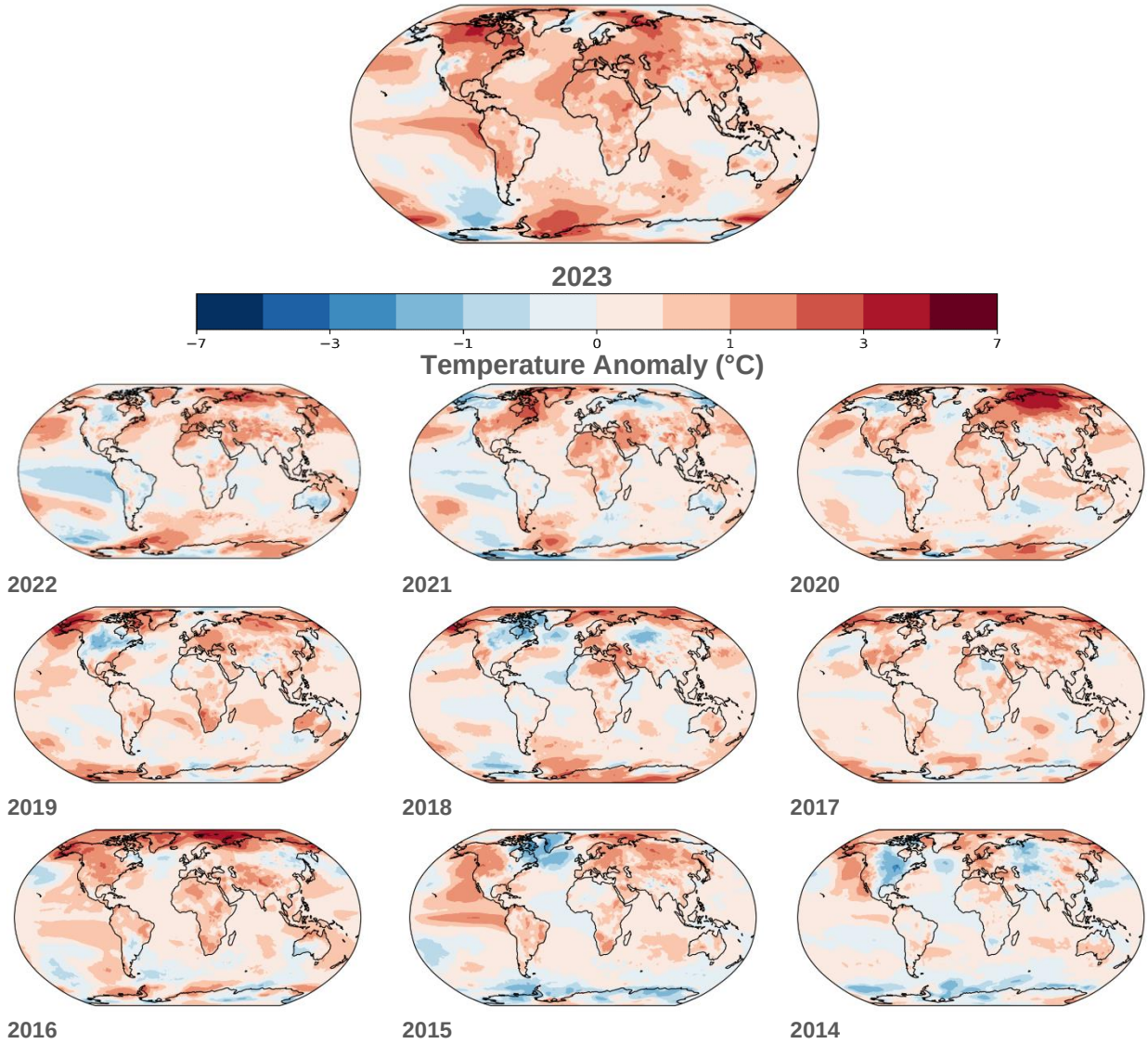


Figure 5: Global annual surface air temperature anomaly for 2023. Subsequent figures show the anomalies for the past 10 years. Anomalies are relative to the 1991 – 2020 climatology [7].

[6] WMO State of the Global Climate Report 2023, 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.

[7] Data source: ERA5

Singapore's Temperature in 2023

At the Changi climate station, the annual mean temperature in 2023 was 28.2°C, 0.4°C above the long-term[8] average and the fourth warmest on record since 1929, tied with 2015 and 1997 (Figure 6). The year also saw high daily maximum and minimum temperatures - the annual mean daily maximum and minimum temperatures of 31.9°C and 25.7°C were ranked sixth (tied with 2005, 2010, and 2015) and fourth highest on record respectively.

The mean temperature for the last decade from 2014 to 2023 reached a new high of 28.06°C, 0.05°C above the previous record for the decade from 2013 to 2022. This is the third consecutive year that Singapore's decadal mean temperature record was broken, with 5 of the top 10 warmest years occurring in the last decade.

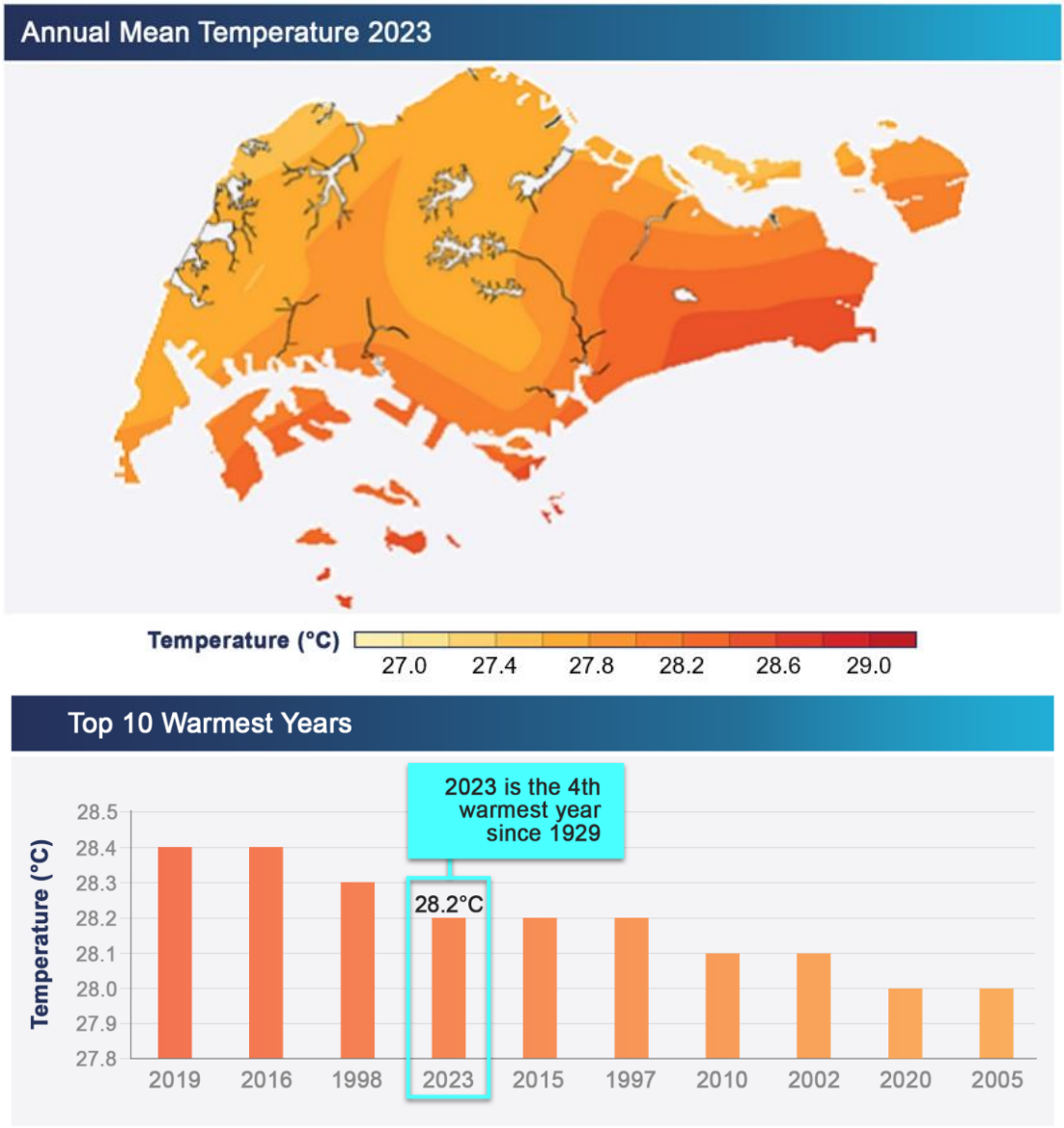


Figure 6: Annual mean temperature across Singapore in 2023 (top) and the top 10 warmest years on record (based on the Changi climate station).

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

Singapore experienced a cool start to 2023 (Figure 7). Below average monthly temperatures were recorded at the Changi climate station from January to March. In particular, March (27.1°C) was 0.7°C below the month's long-term mean and was the coolest March in the last 10 years. The La Niña conditions present at the start of the year likely contributed to the cooler temperatures, along with the wetter conditions. For March, stronger northeasterly winds likely also contributed to the cooler temperatures.

From April, Singapore experienced warmer-than-average weather (Figures 7–9). The year's warmest month was May with mean temperature of 29.5°C, 0.9°C above the long-term May average (more information on May is included in the notable event below). October was also exceptionally warm. The month's mean temperature of 29.0°C was above the long-term average by a wide margin of 1.1°C, surpassing the previous warmest October on record in 2002 by 0.3°C. Other record-matching and record-breaking high temperatures during the year are listed in Table 4 (for the climate station) and Table 5 (for all stations).

The shift to generally warmer than usual conditions from April onwards was likely associated with the end of the La Niña event and the development of the El Niño event in 2023, although the conditions for any particular month depend also on other factors such as cloud cover, rainfall, wind, and other climate drivers.

Notable event: Scorching May with New Record High Temperatures

May is typically one of Singapore's warmest months, and May 2023 was particularly warm, breaking numerous temperature records. With the light low-level winds, typical of inter-monsoon conditions, prevailing over Singapore and the surrounding region, maximum temperatures rose above 34°C on most days at various locations in Singapore. There were nine days in May registering temperatures of 35°C or more. Most of these days occurred in the first half of the month.

Conditions were especially warm in the second week of May when light winds and clear sky conditions resulted in high temperatures across many parts of Singapore. On 13 May 2023, several locations recorded temperatures exceeding 36°C, with the highest temperature of 37.0°C measured at Ang Mo Kio. This temperature reading ties with the record for highest daily maximum temperature in Singapore (previously recorded at Tengah on 17 April 1983) since temperature records started in 1929. It also surpasses the previous warmest temperature for May of 36.7°C, set exactly one year earlier on 13 May 2022 at Admiralty.

Warm night-time temperatures were also experienced during the second half of the month when the temperatures stayed above 29.0°C on some days. On 25 May 2023, the daily minimum temperature recorded at the East Coast Parkway station was 29.7°C, the highest recorded for the month of May. The previous record was 29.5°C, registered at the same station on 18 May 2022. At the Changi climate station, the monthly mean daily minimum temperature for May was 26.7°C, surpassing the previous record in May 2019, 2016 and 2003 by 0.2°C. Overall, the mean temperature of 29.5°C for May 2023 also broke the previous record of 29.4°C set in May 1998.

Besides the long-term warming trend, the MJO and warm sea surface temperatures also made warm temperatures more likely in May 2023. From the second week of May, the dry phase of the MJO influenced Singapore, increasing the chance of dry weather. Sea surface

temperatures across much of the tropics were also warmer than average, including over the South China Sea.

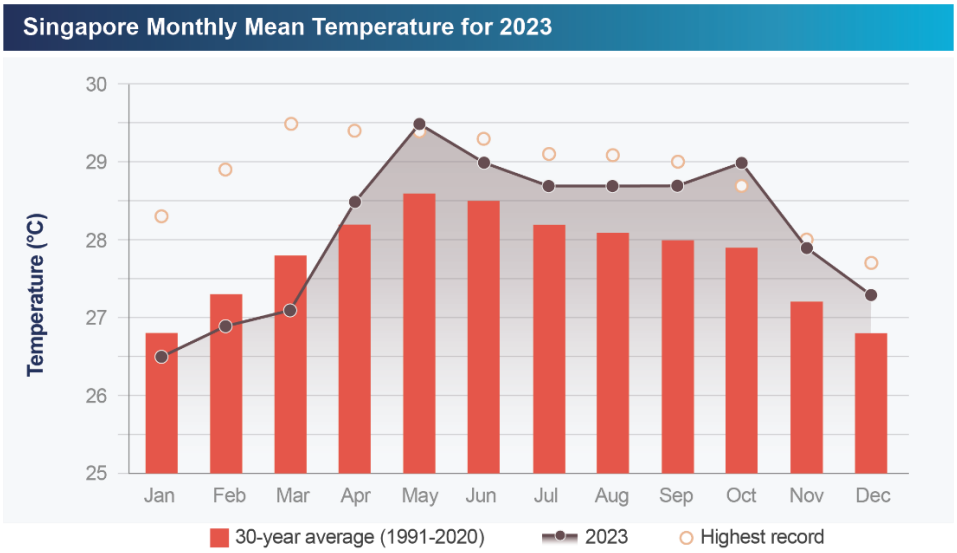


Figure 7: Climate station monthly mean temperature for 2023 (solid line), long-term average (bars, 1991– 2020) and the corresponding historical extremes (circle).

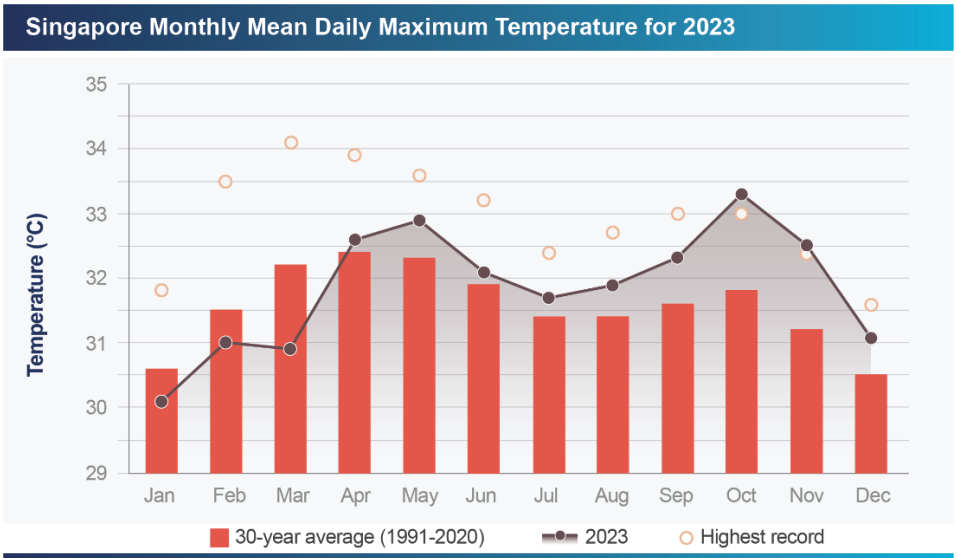


Figure 8: Climate station monthly mean daily maximum temperature for 2023 (solid line), long-term average (bars, 1991– 2020) and the corresponding historical extremes (circle).

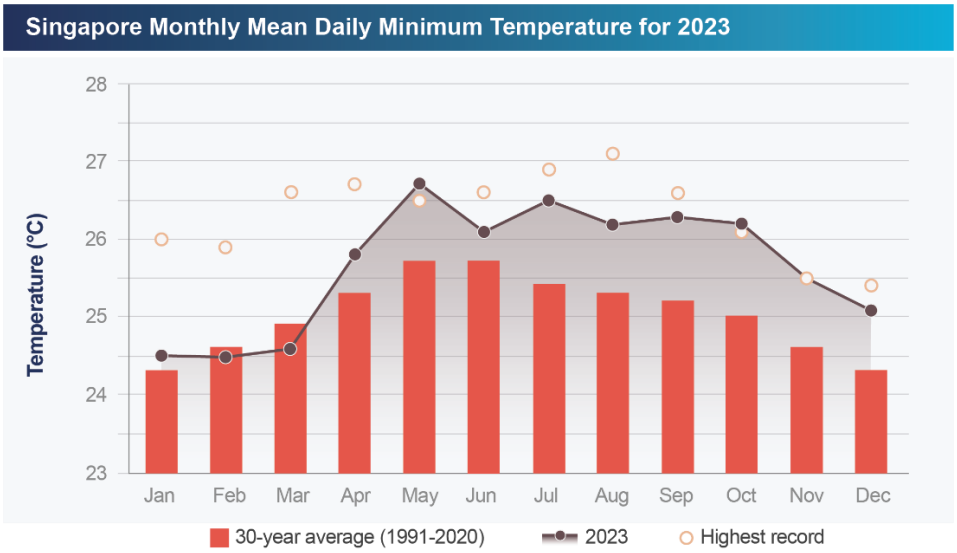


Figure 9: Climate station monthly mean daily minimum temperature for 2023 (solid line), long-term average (bars, 1991– 2020) and the corresponding historical extremes (circle).

Singapore's Long-term Temperature Trends: Historical

Annual temperatures at the Changi climate station have risen between 0.10°C and 0.30°C per decade between 1984 and 2023 (for the maximum and minimum temperatures respectively, Figure 10). On top of this, periods with El Niño (orange shades) tend to amplify the warmer temperatures, while periods with La Niña (blue shades) tend to moderate the warmer temperatures. Temperatures in 2023 continue this pattern — 2023 was warmer than the previous three years (associated with only La Niña conditions), but not as warm as 2016, which was associated with the strong El Niño in 2015/2016, and 2019, which was associated with the strong positive Indian Ocean Dipole in 2019. Singapore's temperature observations highlight the importance of the long-term warming trend, as well as year-to-year variability associated with climate drivers.

Singapore's Long-term Temperature Trends: Future

Future projections from V3 highlight that by mid-century, Singapore's 2023 annual average temperature will already be considered cooler than average. Projected changes in the annual average daily mean and maximum temperatures, during mid- and end-century under the three Shared Socioeconomic Pathway (SSP) scenarios used in AR6 are shown in Table 1. The three SSPs used in V3 are SSP1-2.6, SSP2-4.5, and SSP5-8.5, referred to as the low, medium, and high emissions scenarios, respectively in this report. The table shows that by the end of century:

- Annual average daily mean temperature is projected to increase to between 28.5°C to up to 32.9°C.
- Annual average daily maximum temperature is projected to increase to between 31.9°C to up to 36.7°C.

Table 1: Projected annual average daily mean and maximum temperatures for Singapore, during mid- and end-century under the three SSP scenarios. The number outside the brackets is the mean of five downscaled models and the numbers inside the bracket are the minimum and maximum values.

Scenario	Air Temperature (°C)			
	Annual Average Daily Mean		Annual Average Daily Maximum	
Future	Mid-Century	End-Century	Mid-Century	End-Century
Low	28.9 (28.5 to 29.2)	29.0 (28.5 to 29.5)	32.4 (32.0 to 32.8)	32.5 (31.9 to 33.1)
Medium	29.1 (28.7 to 29.6)	29.9 (29.3 to 30.7)	32.6 (32.2 to 33.2)	33.5 (32.8 to 34.4)
High	29.5 (28.8 to 30.1)	31.7 (30.7 to 32.9)	33.0 (32.3 to 33.6)	35.4 (34.3 to 36.7)

The temperature projections in Table 1 represent the average over a 20-year period to reflect the long-term temperature trends. Mid-century refers to the average over 2040-2059, while end-century refers to the average over 2080-2099. Within these 20 years, some years will likely be even warmer, while others are slightly cooler, depending on other climate drivers such as ENSO and IOD.

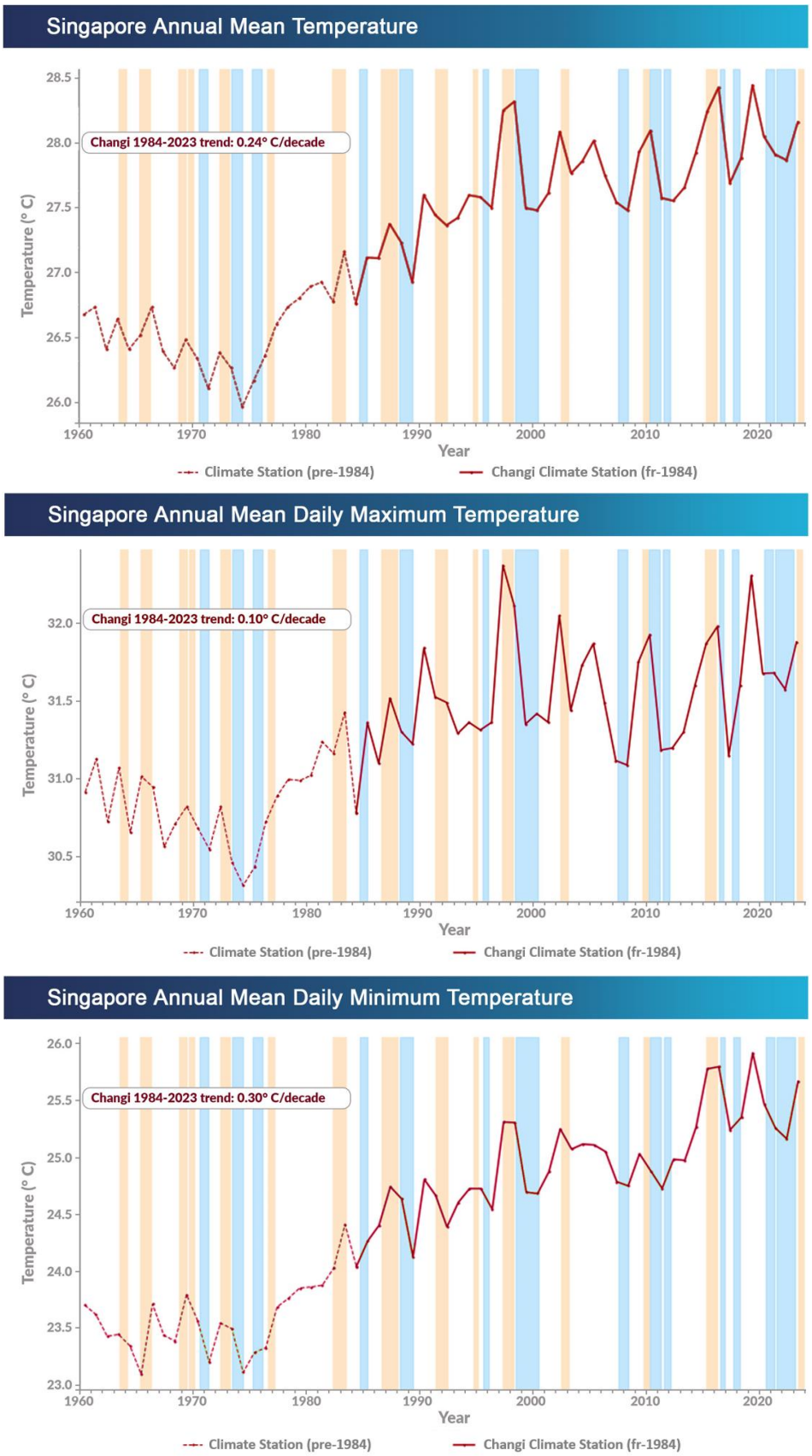


Figure 10: Annual mean temperatures since 1960 (based on the climate station). El Niño and La Niña years from 1961 onwards are highlighted in light orange and blue bars, respectively.

Rainfall

Singapore's Rainfall in 2023

Singapore's annual total rainfall averaged across the islandwide stations[9] (2866.1 mm) was 13.1% above the long-term average of 2534.3 mm, making 2023 Singapore's seventh wettest year since 1980 (Figure 11). West and central Singapore experienced the highest rainfall totals (Figure 12 left), although most of Singapore experienced more rainfall than usual (Figure 12 right). The Changi climate station recorded 2411.2 mm of rainfall in 2023, 14.1% above its long-term average of 2113.3 mm.

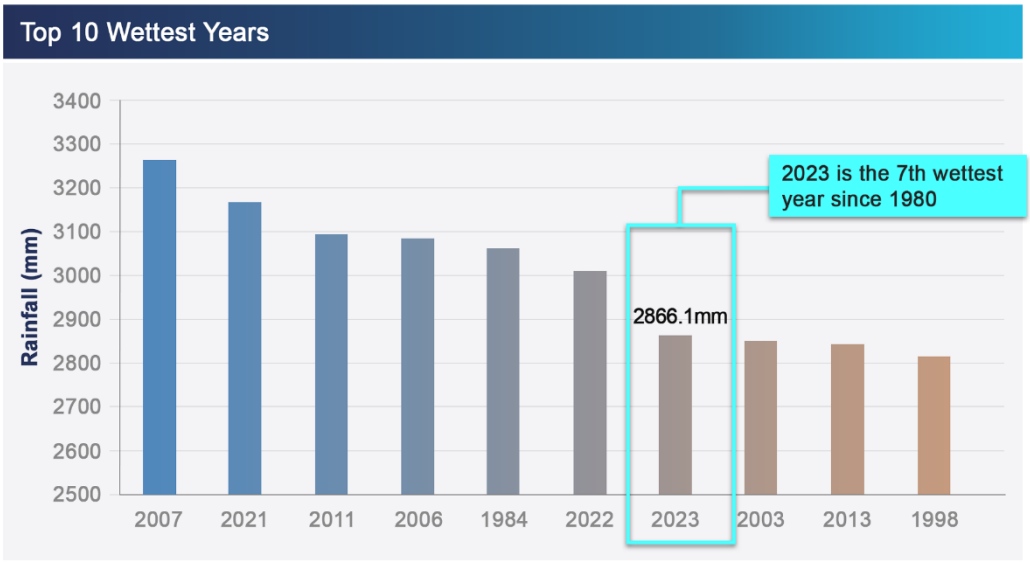


Figure 11: The top 10 wettest years in the last 40 years based on the Singapore average.

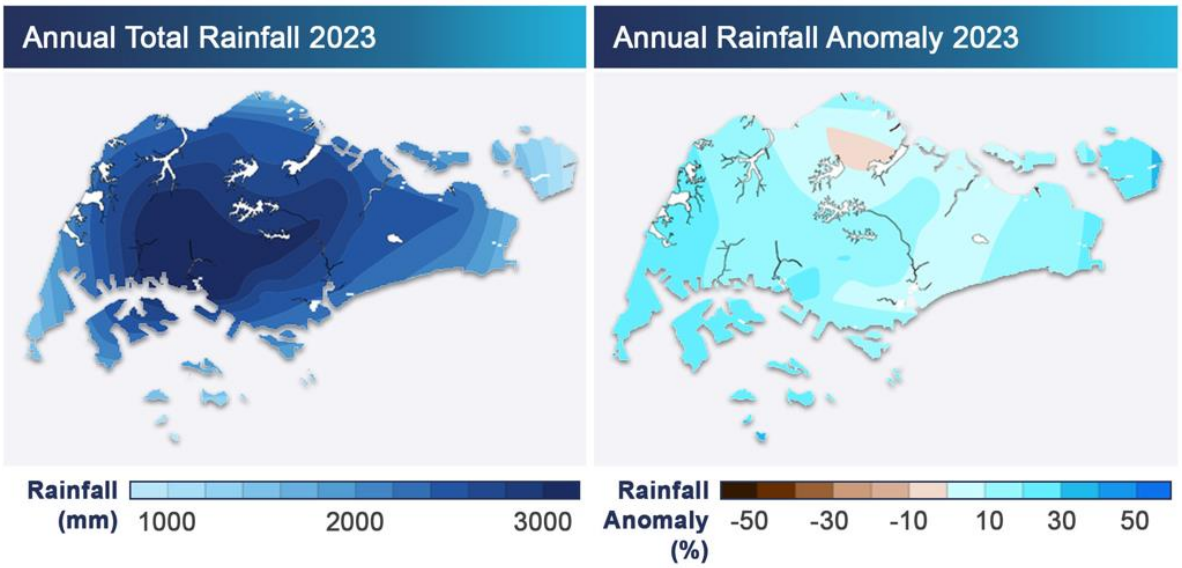


Figure 12: Annual total rainfall distribution across Singapore in 2023 (left), and annual rainfall anomalies (in percentage term) across Singapore in 2023 (right).

[9] The 32 stations with continuous rainfall records starting from 1980.

February's islandwide average rainfall (342.0 mm) was more than twice the month's long-term average of 132.1 mm (Figure 13). Similarly, at the Changi climate station, February's rainfall was about three times the monthly long-term average (Figure 14). This makes February the fourth wettest February since 1980, both islandwide and at the climate station, with both the MJO during the first half of the month and the wet monsoon surge late in the month contributing to the wetter than average conditions. The exceptionally wet weather extended into March, with islandwide average rainfall 52.7% above the long-term monthly average, ranking it the fifth wettest March since 1980.

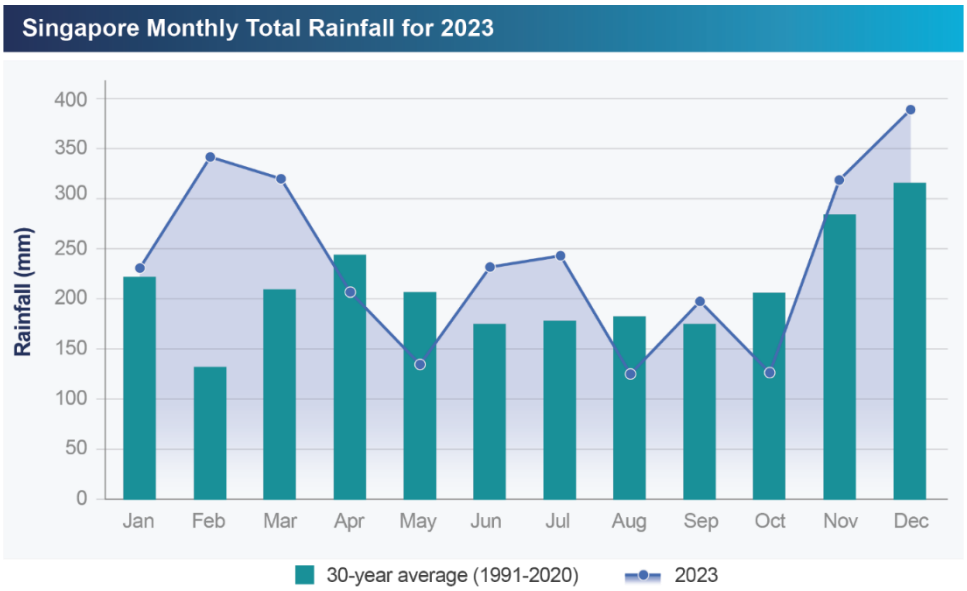


Figure 13: Singapore average monthly total rainfall for 2023 (solid line) and long-term average (bars, 1991 – 2020).

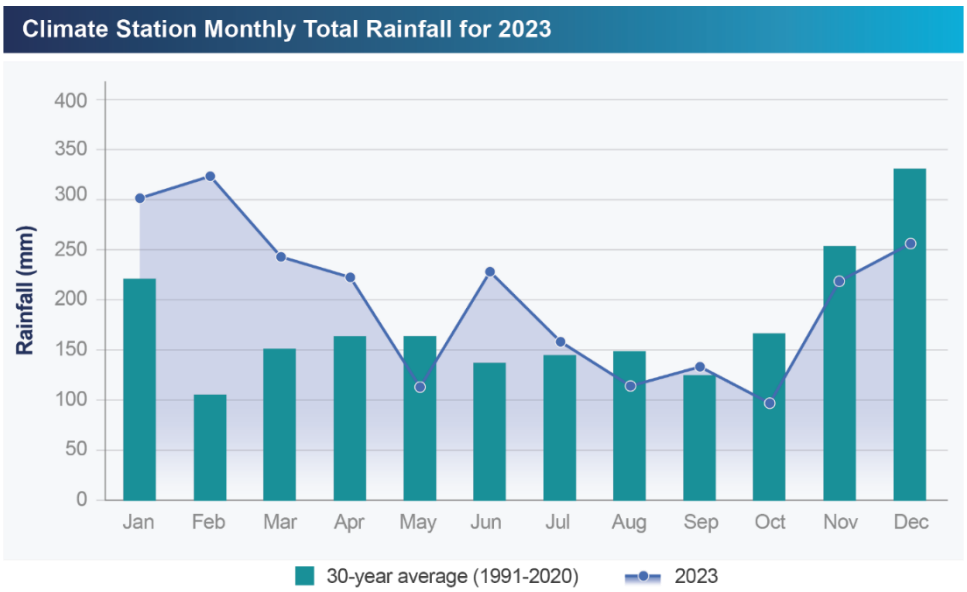


Figure 14: Climate station monthly total rainfall for 2023 (solid line) and long-term average (bars, 1991 – 2020).

Although 2023 was generally wet, there were drier than normal months in April, May, August, and October (Figure 15). These months also turned out to be the top 10 driest for their respective months since 1980.

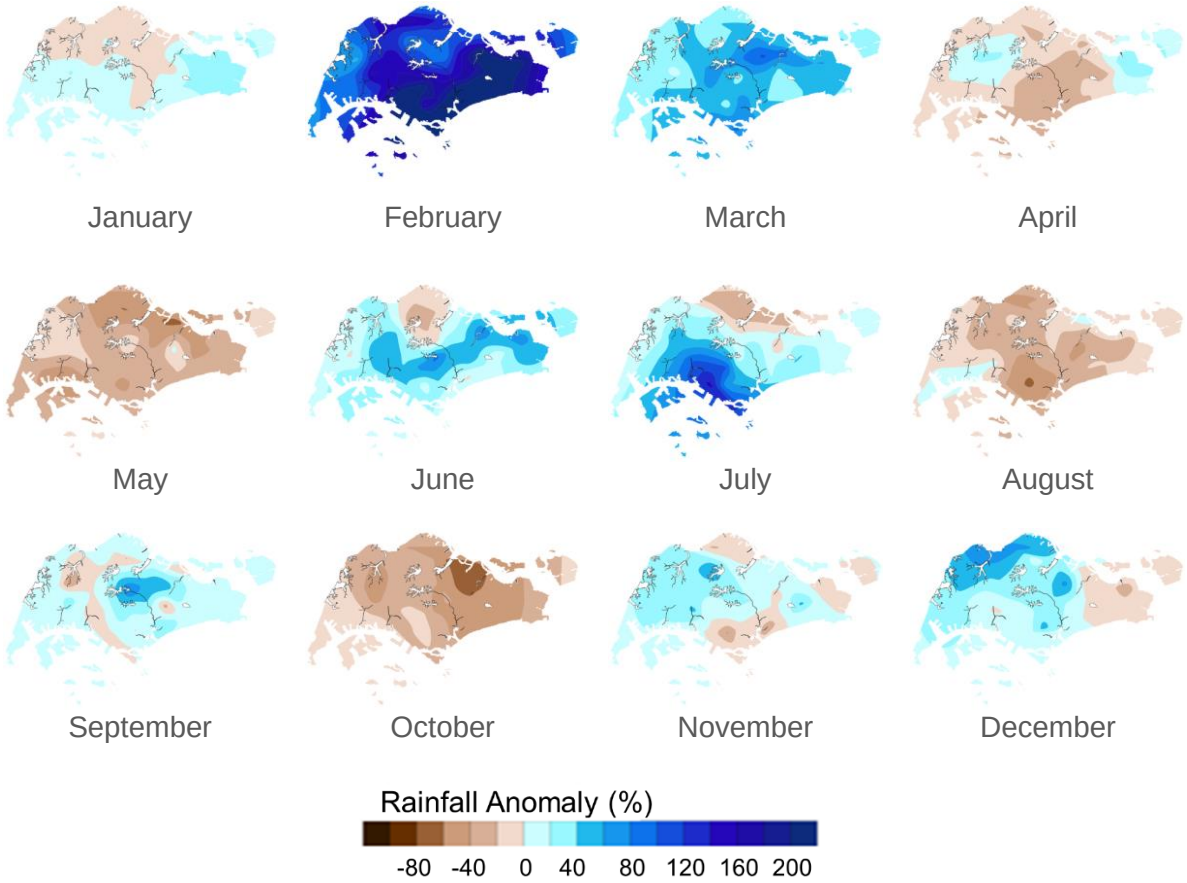


Figure 15: Monthly rainfall anomalies (in percentage term) across Singapore in 2023 (relative to the climatological period 1991 – 2020 for the particular month).

As with temperature, climate drivers also influenced Singapore's rainfall in 2023. The changes arising from El Niño and La Niña events are most noticeable when looking over several months. However, for a particular month, rainfall will also be affected by the presence of other shorter-lived drivers like the MJO, or day-to-day variations in the weather.

The wet start to the year was only partly associated with the La Niña event. When La Niña events are present, January–March period tends to be wetter than average (from past observations, on average about 20% wetter than the long-term average rainfall). However, the three wettest January–March periods since 1980, 1984, 2004, and 2007, all occurred under ENSO neutral conditions (i.e. no La Niña nor El Niño present). As 2023 was the fourth wettest January – March period based on the Singapore average rainfall, this is the wettest start to the year when a La Niña event was present (Figure 16).

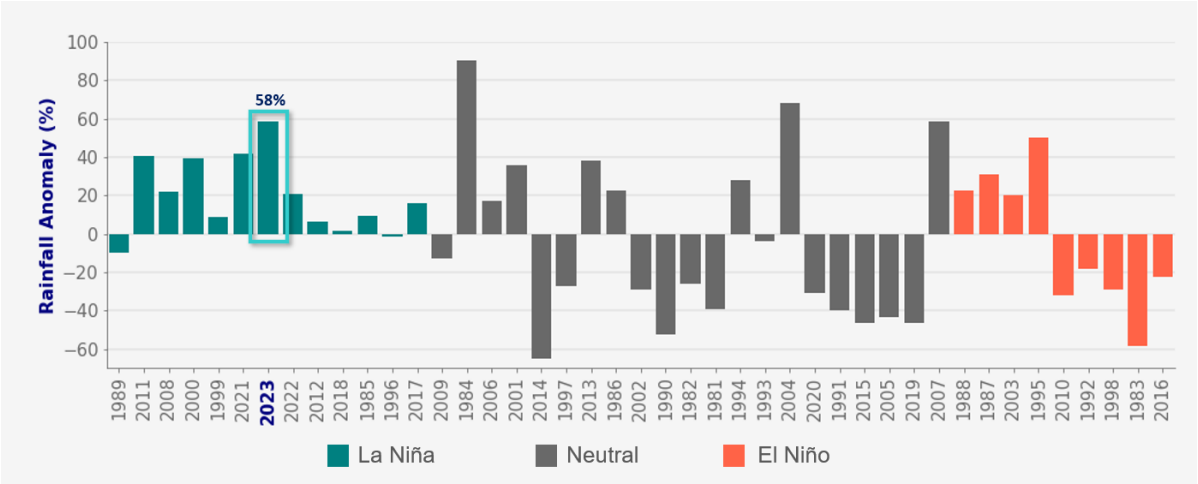


Figure 16: Singapore's average rainfall during January–March for the period 1981–2023 compared to climatology, ordered from strongest La Niña to strongest El Niño.

For the second half of 2023, El Niño conditions were present. While El Niño events typically bring drier conditions, particularly during the Southwest Monsoon season (June – September), in 2023 the Southwest Monsoon was slightly wetter than average. While this may be in part due to the slightly later start of the El Niño event[10], it may also be associated with the persistent warmer sea surface temperatures in the western Pacific Ocean (see Page 5 for more information). For individual months, the MJO might also play a role in modulating the rainfall patterns, such as in September with MJO activity over the Indian Ocean potentially bringing more rainfall to Singapore in the first half of the month.

Notable event: Rare late wet monsoon surges

A wet monsoon surge occurred in late February and early March 2023, an uncommon occurrence as such surges are seldom observed during the end phase of the Northeast Monsoon. On 28 February 2023, the strengthening of the high-pressure system over the northern Asian continent brought a surge of strong north-easterly winds over the South China Sea. This monsoon surge brought widespread continuous moderate to heavy thundery showers over Singapore and the surrounding region with all stations across the island recording more than 100mm of rainfall. The rain was heaviest over the eastern and southern parts of Singapore with the highest daily total rainfall of 225.5mm recorded at Kallang. This was the highest daily total rainfall ever recorded in February, exceeding the previous record of 159.3mm on 4 February 1995.

This same monsoon surge continued into 1 March 2023. The highest daily total rainfall for March 2023, 104.4mm, was recorded at the Seng Kang area that day. On 3–4 March 2023, another monsoon surge brought widespread moderate to heavy rain over Singapore and the surrounding region.

[10] Over half of the El Niño events in the past 40 years have started one or two months earlier than in 2023.

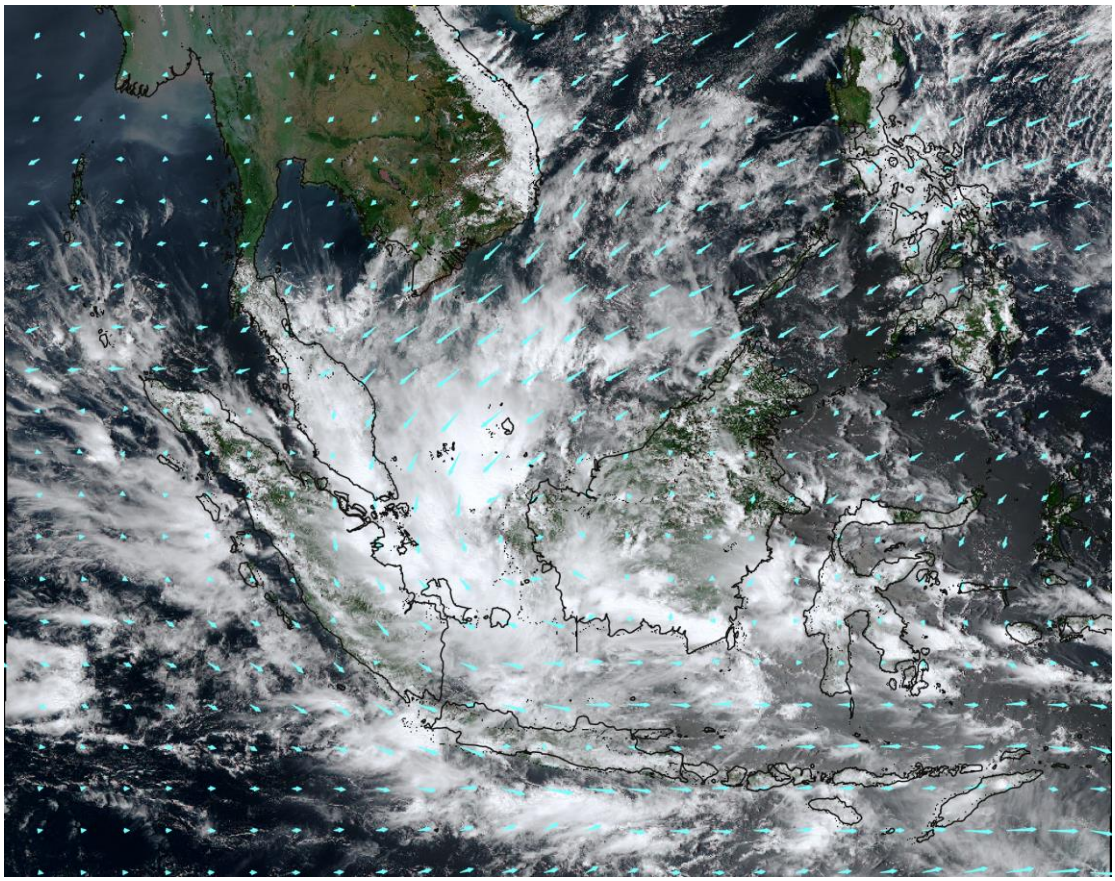


Figure 17: Satellite image on 28 Feb 2023 at 2.00pm showing extensive rainclouds and strong winds (depicted by arrows) from a Northeast Monsoon surge that brought wet weather to Singapore and its surrounding region.

These monsoon surges also brought cool weather to Singapore in the first week of March 2023, with three days where the highest daily maximum temperature was below 28°C. On 3 and 4 March 2023, the highest daily maximum temperature was a cool 26.1°C at East Coast Parkway. The temperature at Newton dipped to 21.1°C during the monsoon surge on 1 March 2023, and was the lowest temperature recorded in 2023.

Notable event: Hazy Conditions in October

In 2023, the dry season for the southern part of Southeast Asia lasted from end-May till mid-November. This dry season was much longer than in the previous three years: 6 months in 2023, compared to between 3 to 3.5 months for 2020–2022. The difference in dry season length is likely associated with the transition from La Niña conditions during the previous three years to El Niño conditions for much of the 2023 season.

At the start of the 2023 dry season, there was an escalation in hotspot and smoke haze activities first in Kalimantan and then also in Sumatra towards September and October 2023. In particular, clusters of hotspots and moderate to dense smoke plumes were detected in south Sumatra and in parts of central Sumatra on many days in end September and October.

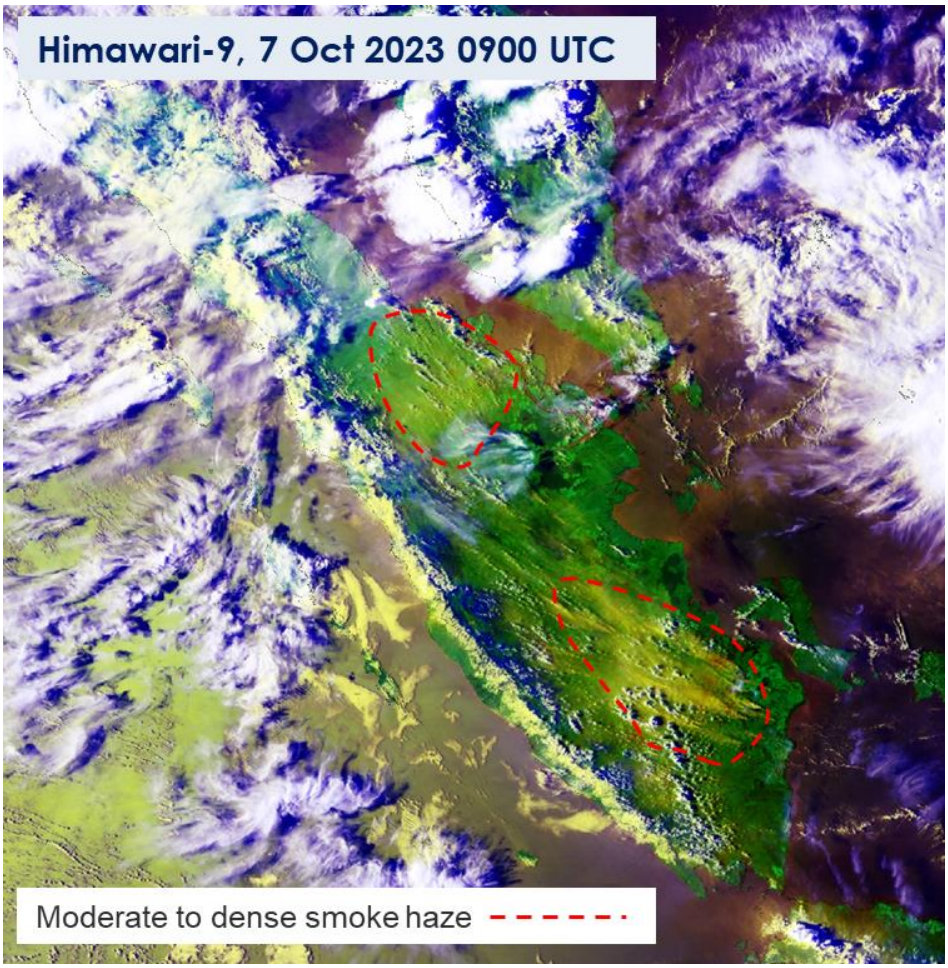


Figure 18: Himawari-9 satellite imagery on 7 October 2023 at 5.00pm showing moderate to dense smoke haze and smoke plumes over central and southern Sumatra.

Figure 19: Marina Bay Sands is obscured in smoke haze on 7 October 2023 (photo by Jass Fong).

A shift in the prevailing winds on 7–8 October 2023 blew lighter smoke haze from forest fires over Singapore. This resulted in hazy conditions with the air quality deteriorating into the Unhealthy range over parts of the island. The highest 24-hour PSI of 123 was recorded in the eastern part of Singapore between 8 and 9 pm on 7 October 2023. This is the highest 24-hour PSI value due to smoke haze since September 2019 when a strong positive IOD was present. The haze situation subsequently gradually improved with increased showers and favourable winds over Singapore and the surrounding region.

Singapore's Long-term Rainfall Trend: Historical

Singapore's annual rainfall is highly variable, characteristic of rainfall in the tropics (Figure 20). For the most recent period from 1980 to 2023, the annual total rainfall for Singapore increased on average 86.4 mm per decade. Notably, 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. 2015, 1997, 1982) tend to be drier. In 2023, La Niña conditions were present followed by El Niño conditions developing (which is unusual), but the particularly wet start to 2023 contributed to Singapore's rainfall to be the seventh highest since 1980.

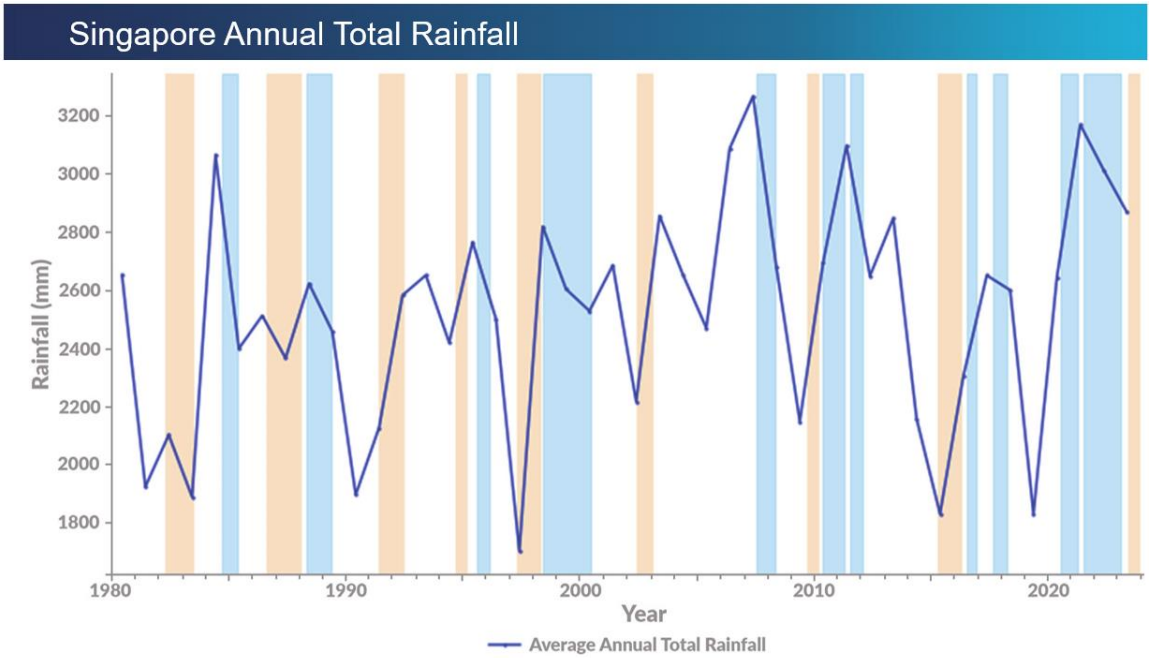


Figure 20: Average annual total rainfall since 1980 (across the islandwide stations). El Niño and La Niña years are highlighted in light orange and blue bars, respectively.

The wet months (December–January[11]) and the dry months (June–September), also show increasing, but not significant, trends in rainfall (Figure 21 and Figure 22, respectively). For the wet months, the total rainfall has been increasing at a rate of 24.1 mm per decade from 1980 to 2023. For most years, the rainfall for the wet months is between 300 mm and 700 mm.

[11] Consecutive December and January, e.g. 2023 refers to December 2023 and January 2024

However, in 2006, 1227.9 mm was recorded over the two months, with the next highest was 795.4 mm for December 2023 and January 2024.

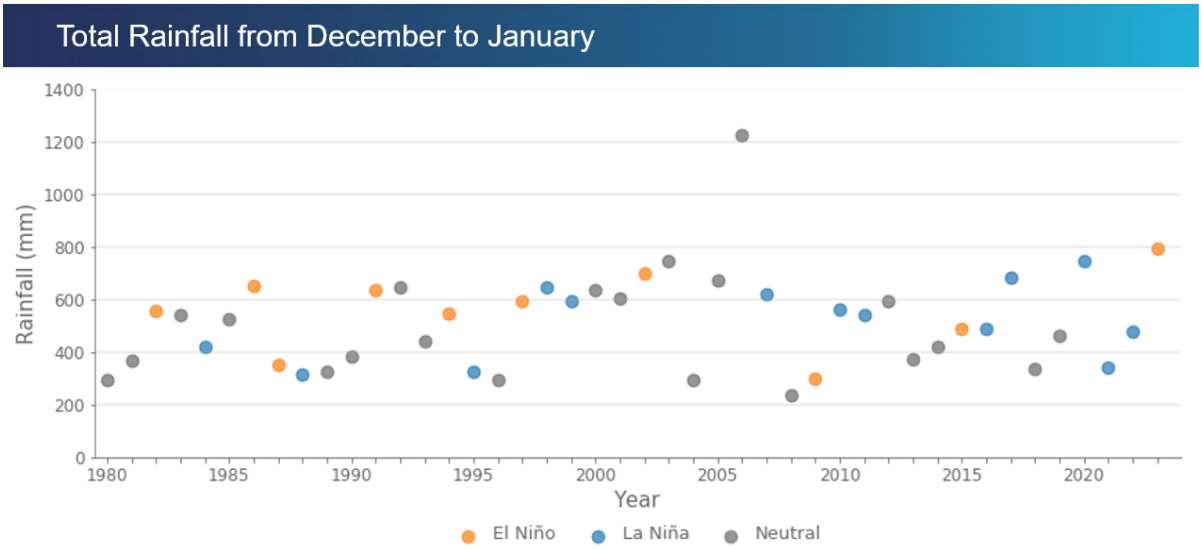


Figure 21: Rainfall over the wet season (December – January) since 1980 (across the islandwide stations). While rainfall has increased over the years, there is no noticeable difference when there is an El Niño event (orange) or La Niña event (blue).

For the dry months (the Southwest Monsoon season), the total rainfall rate of increase from 1980 to 2023 was 22.1 mm per decade, but the trend is not statistically significant. Part of this increase is likely associated with the frequency of El Niño and La Niña events. During La Niña events, rainfall during this season is usually higher than during El Niño events, and there have been more La Niña events in the past 10 years, compared to during the 1980s (5 versus 2), while the opposite for El Niño events (2 versus 3).

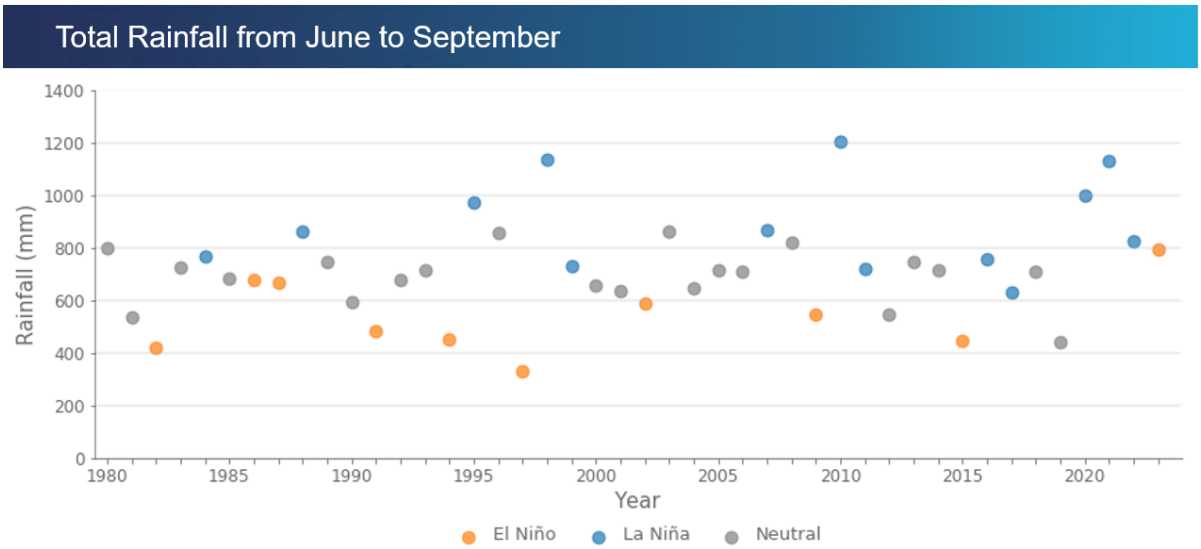


Figure 22: Rainfall over the dry season (June – September) since 1980 (across the islandwide stations). Seasons that coincide with El Niño events (orange) tend to be drier, while those that coincide with La Niña events (blue) tend to be wetter.

Singapore's Long-term Rainfall Trend: Future

The last three years (2021, 2022, and 2023) have been wetter than average, however, this is not necessarily representative of a long-term trend. Projected end-century changes in average annual and seasonal rainfall totals for all SSPs are shown in Table 2. The table shows that the expected end-century changes in average annual rainfall totals are dependent on the emissions scenario used. For the medium and high emissions scenarios, the projected changes could either be negative or positive.

For average seasonal rainfall totals, by end-century, the wet months of December-January are expected to get wetter by up to 58% (under the low emissions scenario), and the dry months of June-through-September are expected to get drier by up to 42% (under the high emissions scenario). While December-January shows an increasing, but not statistically significant, trend in observed rainfall, so far the dry months overall have not been getting drier, which may be due to the influence of other climate drivers.

Table 2: Projected percentage changes in the average annual and seasonal total rainfall during the end-century under the three SSP scenarios compared to 1995-2014 average.

Months	End-Century Rainfall Change (%)		
	Low	Medium	High
Annual	11 (0 to 24)	5 (−6 to 12)	0 (−12 to 17)
DJ[12] (wet)	20 (−12 to 58)	6 (−9 to 28)	2 (−20 to 44)
FM	13 (−2 to 49)	−7 (−39 to 48)	−18 (−43 to 30)
AM	13 (−5 to 23)	10 (−15 to 33)	18 (−6 to 52)
JJAS (dry)	5 (−10 to 17)	0 (−17 to 22)	−14 (−42 to 6)
ON	8 (−4 to 24)	14 (−2 to 31)	14 (−8 to 41)

The values in Table 2 are for 20-year averages. In the future, while there will be considerable year-to-year rainfall variability from ENSO and other climate drivers, V3 projections show that on top of this, there is the potential for the wet periods to become even wetter, and dry periods to become even drier. In the future, the islandwide average seasonal total rainfall during dry season of June–August could fall significantly below the historical low of 305.4 mm (recorded in 1997, based on the 32 islandwide stations average), on average, almost every three years by the end of the century. For the wet season of November-through-January, the corresponding seasonal total rainfall is projected to exceed the historical high of 1531.5 mm (recorded in 2006, based on the 32 islandwide stations average) occasionally.

[12] The months are referenced by their first letter (e.g., DJ refers to December - January)

Weather Extremes and Records in 2023

Table 3: Temperature, rainfall and wind extremes recorded at the climate station in 2023 and the corresponding historical extremes.

	Climate Station Records	
	2023	**Historical Extremes***
Hottest Day *(°C)*	35.0 13 May	**36.0** 26 Mar 1998
Coolest Day *(°C)*	21.7 15 Feb	**19.4** 30 – 31 Jan 1934
Warmest Month *(°C)*	29.5 May	**29.5** Mar 1998
Coolest Month *(°C)*	26.5 Jan	**24.2** Jan 1934
Wettest Day *(mm)*	154.8 28 Feb	**512.4** 2 Dec 1978
Wettest Month *(mm)*	324.4 Feb	**818.6** Jan 1893
Driest Month *(mm)*	96.6 Oct	**0.2** Feb 2014
Strongest Wind Gust *(km/h)*	59.3 19 Aug	**90.7** 29 Nov 2010

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

Table 4: Summary of record-matching and record-breaking (in bold) temperatures at the climate station in 2023.

Record Temperatures for Climate Station			
Climate Extreme	**Date**	**Previous Record (Year)**	**New Record**
Monthly Mean Temperature for May	May 2023	29.4°C (1998)	**29.5°C**
Monthly Mean Daily Minimum Temperature for May	May 2023	26.5°C (2016)	**26.7°C**
Highest Daily Minimum Temperature for August	10 Aug 2023	28.2°C (2020)	28.2°C
Highest Daily Minimum Temperature for September	4 Sep 2023	27.9°C (2015)	27.9°C
Monthly Mean Temperature for October	Oct 2023	28.7°C (2002)	**29.0°C**
Monthly Mean Daily Maximum Temperature for October	Oct 2023	33.0°C (2002)	**33.3°C**
Monthly Mean Daily Minimum Temperature for October	Oct 2023	26.1°C (2015)	**26.2°C**
Highest Daily Maximum Temperature for October	17 Oct 2023	34.6°C (2002, 2016, 2017 and 2022)	34.6°C
Monthly Mean Daily Maximum Temperature for November	Nov 2023	32.4°C (2019)	**32.5°C**
Monthly Mean Daily Minimum Temperature for November	Nov 2023	25.5°C (2015)	25.5°C
Highest Daily Maximum Temperature for November	11 Nov 2023	34.4°C (2019)	**34.6°C**

Table 5: Summary of record-matching and record-breaking (in bold) temperatures at all stations in 2023.

Record Temperatures for All Stations				
Climate Extreme	**Location**	**Date**	**Previous Record (Location, Year)**	**New Record**
Highest Daily Maximum Temperature for May	Ang Mo Kio	13 May 2023	36.7°C (Admiralty, 2022)	**37.0°C**
Highest Daily Minimum Temperature for May	East Coast Parkway	25 May 2023	29.5°C (East Coast Parkway, 2022)	**29.7°C**
Highest Daily Minimum Temperature for September	East Coast Parkway	3 Sept 2023	28.9°C (Tengah, 2022)	28.9°C
Monthly Mean Temperature for October	Tai Seng	Oct 2023	29.4°C (Marina Barrage, 2015)	29.4°C
Highest Daily Maximum Temperature for October	Admiralty	9 Oct 2023	35.7°C (Tengah, 2001; Clementi, 2019)	**36.3°C**
Highest Daily Minimum Temperature for October	East Coast Parkway	16 Oct 2023	29.0°C (Pasir Panjang, 2021)	**29.4°C**
Highest Daily Maximum Temperature for November	Newton	3 Nov 2023	35.8°C (Admiralty, 2019)	35.8°C

Heat Stress in Singapore

Hot ambient conditions can elevate the risk of heat-related illness, mortality and morbidity, whilst reducing physical work capacity with consequences for productivity. The human body responds to heat stress by redistributing blood flow towards the skin to improve heat transfer to the environment, and secreting sweat for evaporative cooling. The restricted evaporation under warmer and more humid environment may lead to heat accumulation in the body and result in heat stress that can cause heat-related illnesses.

The wet bulb globe temperature (WBGT) was developed for identifying environmental conditions experiencing heat stress and for implementing protective controls to prevent heat-related injuries. It was originally invented and used by U.S. Army in the 1950s, and over the years, WBGT has become a widely used index of heat stress by the military, sports, occupational and public health sectors in many countries to implement protective measures to prevent heat-related illness. The outdoor WBGT (in the sun) is the weighted sum of the natural wet bulb temperature *Tw*, the globe temperature *Tg*, and the dry bulb ambient temperature *Ta*, written as following:

$$WBGT = 0.7Tw + 0.2Tg + 0.1Ta$$

where *Tg* measures the combined effect of radiant heat, air temperature, and wind speed; and *Tw* accounts for the cooling effect by low humidity and by wind.

In July 2023, Singapore launched the new Heat Stress Advisory to help the general public plan their prolonged, outdoor activities. Using observed WBGT as a heat stress indicator, the heat stress is categorized into high (WBGT >= 33 °C), moderate (31 °C <= WBGT < 33 °C) and low (WBGT < 31 °C) levels, respectively. The behaviour responses were advised corresponding to different category of heat stress, for example to minimize outdoor activities, stay under shade, take longer breaks, drink more fluids, and avoid multiple layers of clothing etc. under the high heat stress condition.

The Heat Stress Advisory can be accessed via the myENV app and MSS website (www.weather.gov.sg). Real-time WBGT readings collected by automatic weather stations across Singapore are reported as an average value over the past 15 minutes.

Heat Stress in 2023

In 2023, Singapore experienced 37 days of high heat stress[13]. A day of high heat stress is defined when any hourly-average WBGT at a station is equal to or greater than 33°C. Most of these days occurred in April, May, June, and October (Figure 23), which is similar to past observations from 2018 to 2022. The highest hourly-average WBGT in 2023 was 33.7°C, recorded at Woodlands Stadium on 15 May.

The highest 15-min average WBGT in 2023 was 34.8°C, recorded at Bishan Stadium on 24 October. Figure 24 shows the typical daily variation of hourly maximum 15-min average WBGT at Bishan Stadium throughout the year. WBGT is usually above 29ºC from about 10am

[13] Heat stress levels are based on Wet-Bulb Globe Temperature (WBGT). More information is available at: http://www.weather.gov.sg/learn-heat-stress/.

to 4pm and can increase to above 30ºC from about 12pm to 2pm. WBGT also tends to be higher during the warmer months of April and May.

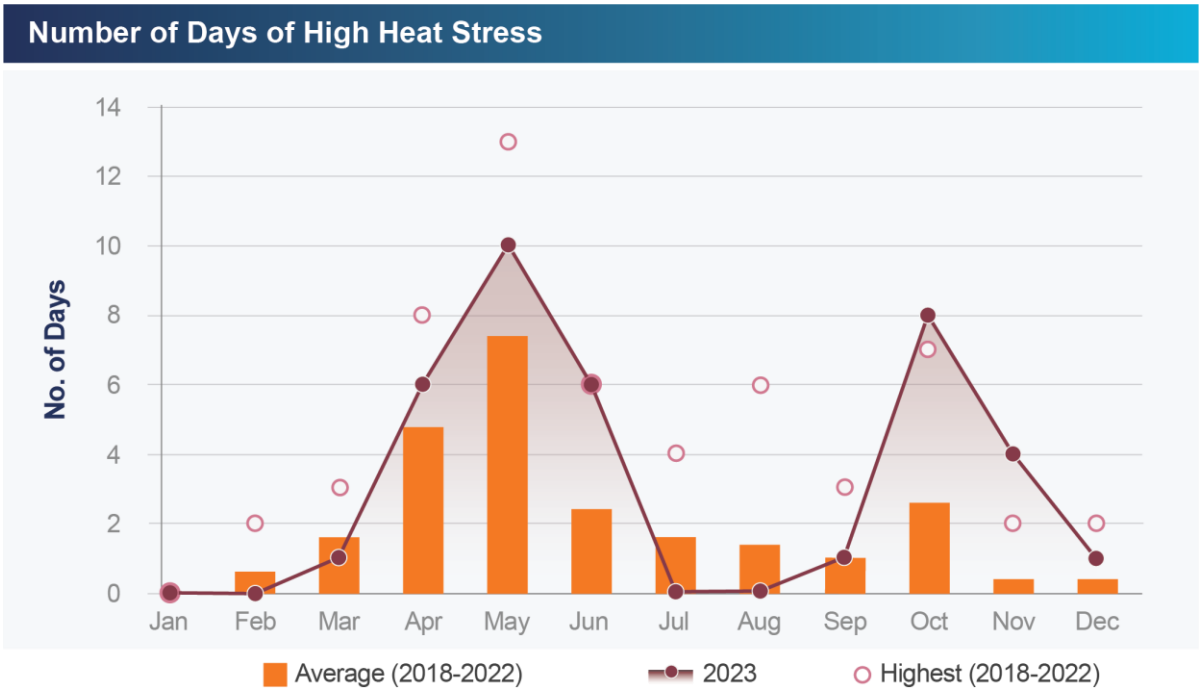


Figure 23: Monthly number of days of high heat stress in 2023 (solid line), monthly average from 2018 to 2022 (bars) and highest monthly number from 2018 to 2022 (circle).

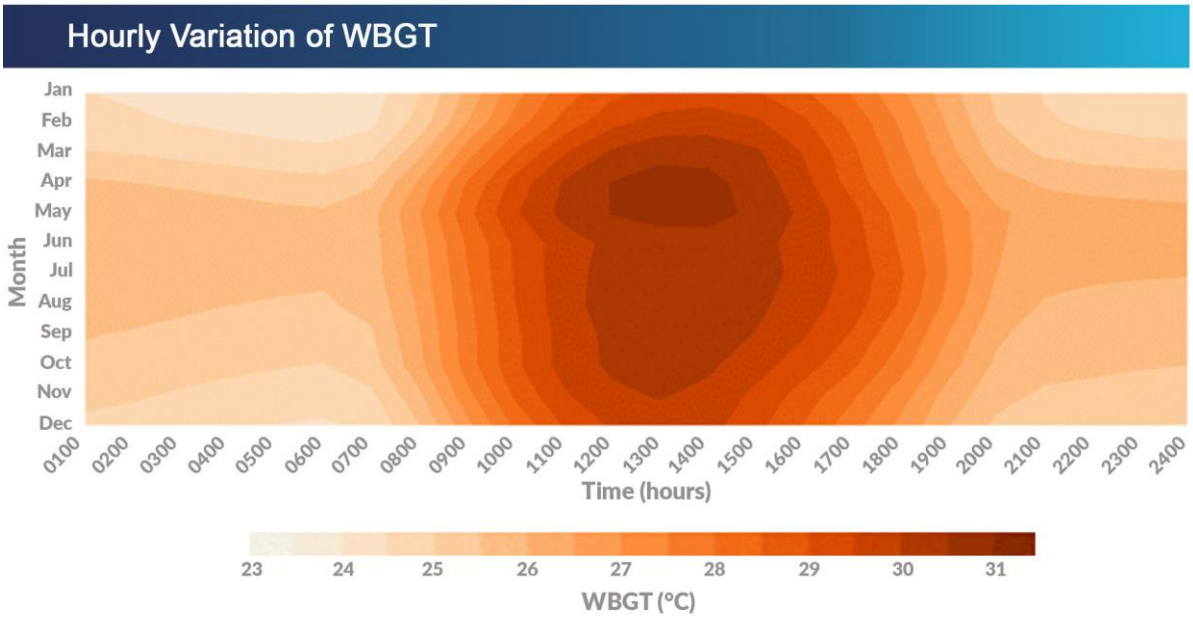


Figure 24: Variation of hourly maximum 15-min average WBGT across the year at Bishan Stadium (based on data from 2018 to 2023).

The annual average daily mean WBGT and daily maximum WBGT in 2023 were 26.6ºC and 30.4ºC respectively (Figure 25), which were the same as their respective averages from 2018–2022.

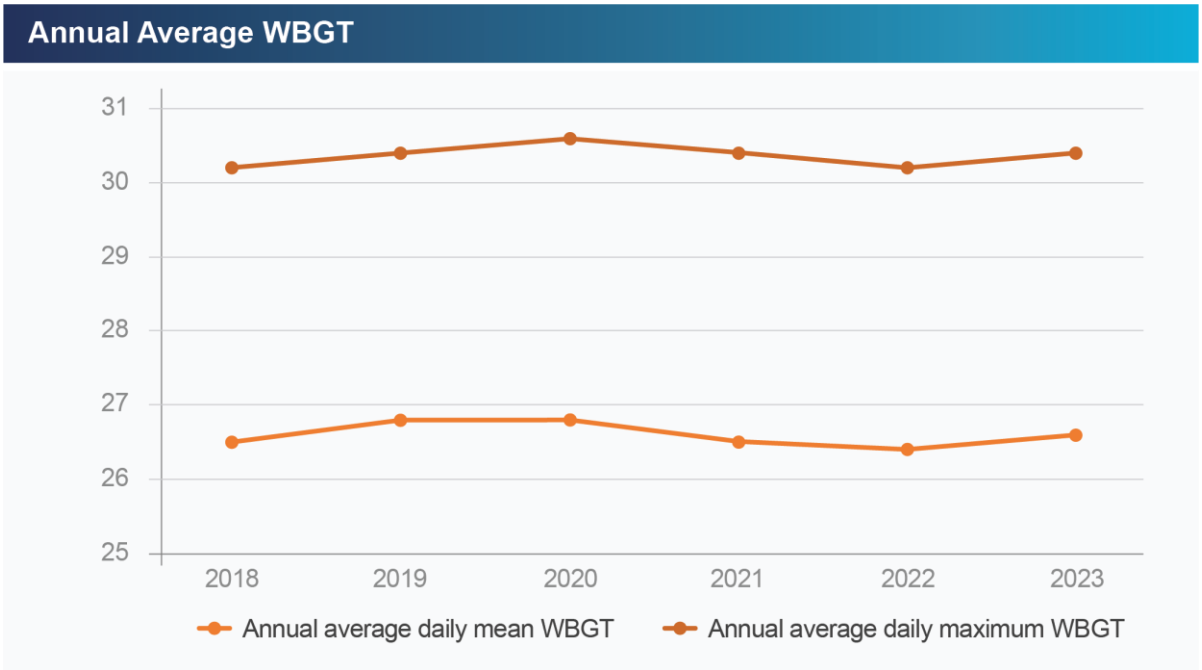


Figure 25: Annual average WBGT based on available data from 9 WBGT stations islandwide from 2018 to 2023.

Future projections of Heat Stress

From V3, the frequency of high heat stress days is projected to rise significantly. By mid-century, the estimated number of high heat stress days are 75 days (ranging from 53 to 112), 87 days (ranging from 61 to 131), and 113 days (ranging from 86 to 155) under low, moderate and high emissions scenarios, respectively (Table 6). Under the high emissions scenario, this is an average increase of around two to four times the number of high heat stress days experienced in 2023. The frequency of high heat stress days will escalate even further by the end-century, reaching an estimated 207 to 326 days on average under the high emissions scenario.

Table 6: Projected high heat stress days in mid- and end-century under the three scenarios.

Scenario	Number of high heat stress days	
Future	Mid-Century	End-Century
Low	75 (53 to 112)	81 (54 to 135)
Medium	87 (61 to 131)	142 (107 to 205)
High	113 (86 to 155)	270 (207 to 326)

CCRS' high-resolution regional climate model SINGV-RCM enables the investigation of spatial patterns in projected climate variables at the urban scale. Figure 26 shows the spatial variation of ensemble mean change in maximum WBGT under the high emissions scenario by end-century. Among the seasons, the projected change of maximum WBGT is notably higher in the Southwest Monsoon season (June–September) with an increase of 3.5–3.8 °C across the island. The projected increase surpasses that of the two inter-monsoon periods in April–May (2.9–3.5 °C) and October–November (3.2–3.6 °C), as well as in the Northeast Monsoon season (2.8–3.3 °C).

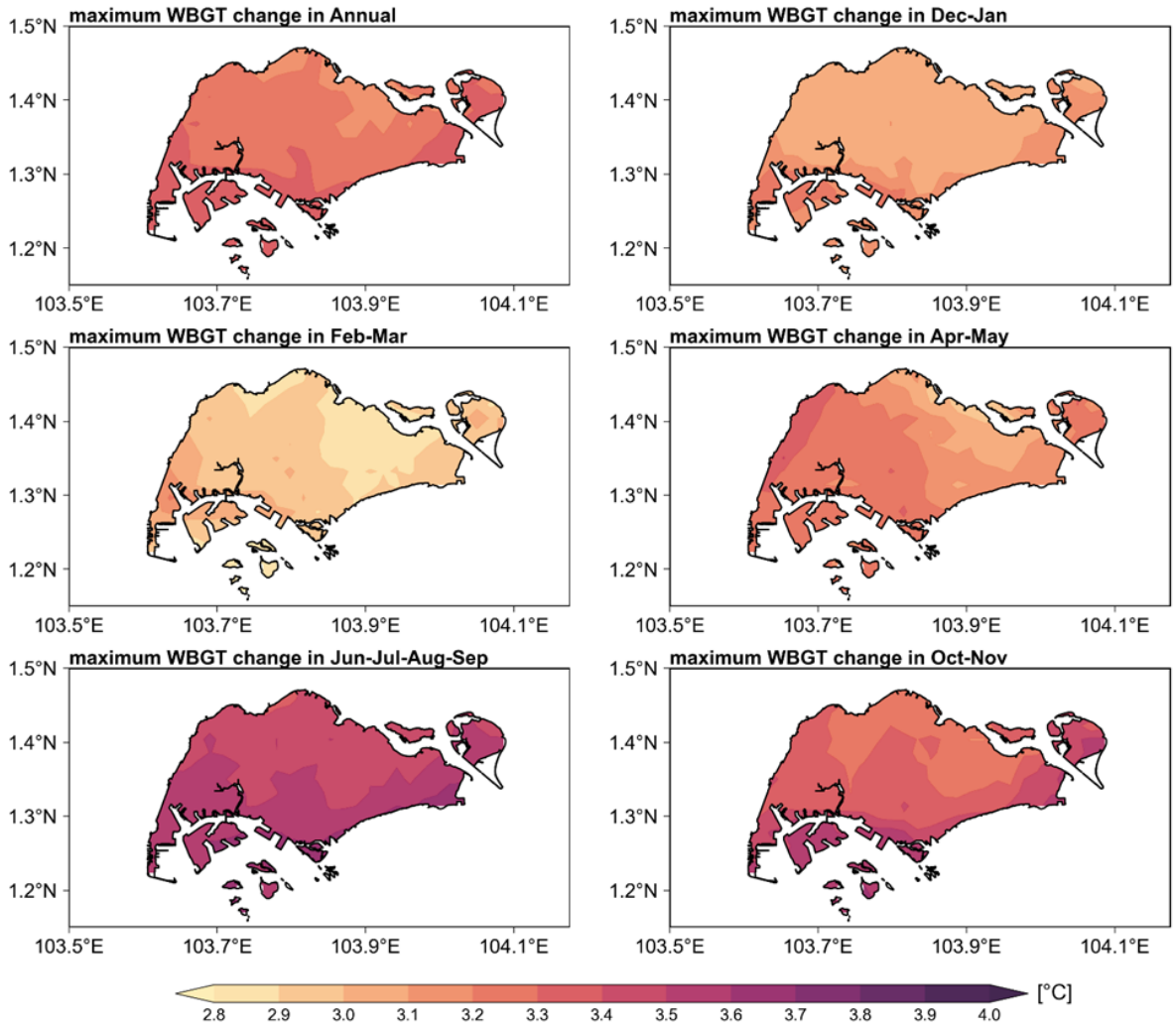


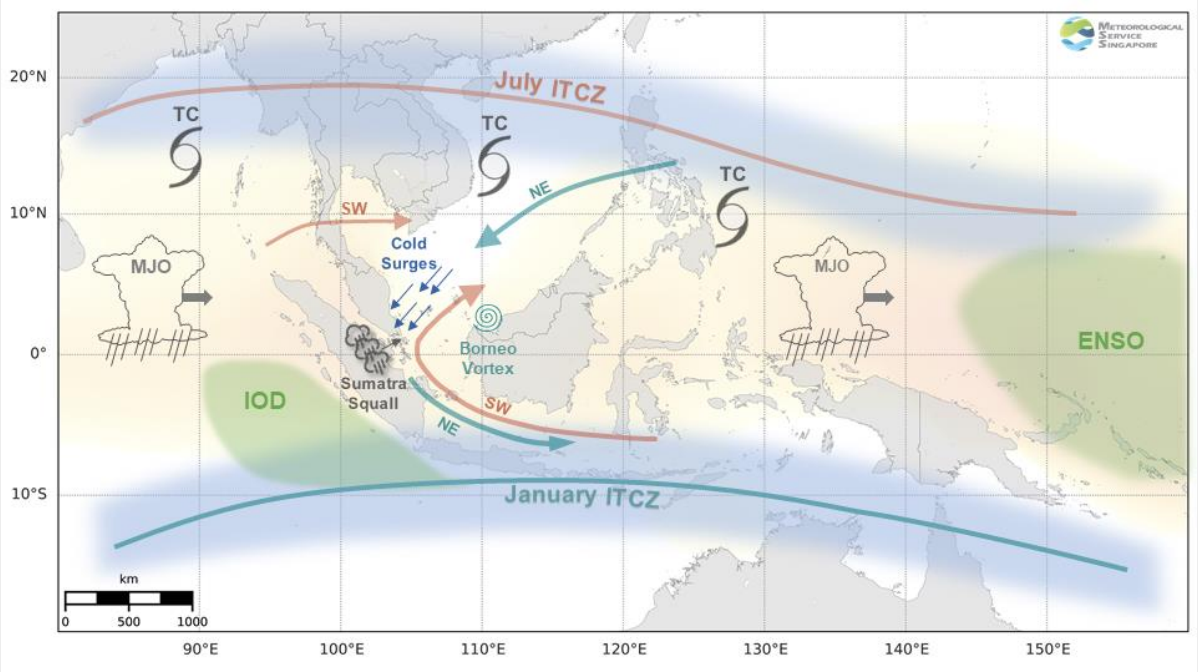
Figure 26: Projected spatial variation of ensemble mean changes in daily maximum WBGT annually, and for each of the seasons during the end-century under high emissions scenario (SSP5-8.5).

Spatially, the projected change of maximum WBGT exhibits an increasing gradient from the northeast to the southwest during the dry phase of Northeast Monsoon season (February–March) and inter-monsoon season (April–May), whilst it increases from north towards south during Southwest Monsoon, wet phase of the Northeast Monsoon (January–February) and inter-monsoon (October–November) seasons. This spatial pattern is different from that of surface air temperature (not shown), which has the highest projected increase in the

northwest of the island. This difference in spatial pattern in the future between surface air temperature and WBGT can be attributed to sustained relative humidity levels along the coast in the south, compared to mean relative humidity across Singapore decreasing by up to 2% in the future. This sustained level of relative humidity along the coast in the future offsets the slight increase in wind speed, thereby limiting evaporating cooling from high temperature.

Against the backdrop of global warming, heat stress is becoming an increasingly important topic around the world, including in Singapore. With current temperature extremes estimated to become more of the norm later this century, high heat stress occurrence is no exception.

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.

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)

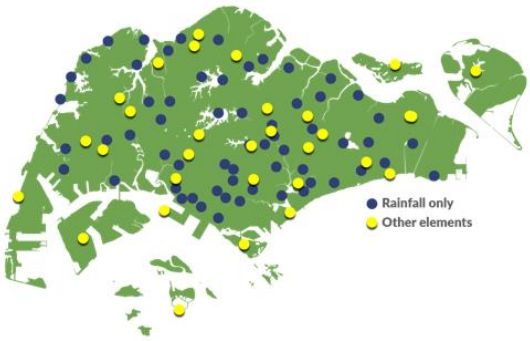
The three main rain-bearing weather systems that affect Singapore are the localised convective showers/thunderstorms, Sumatra squalls and Northeast Monsoon surges. The convective showers/thunderstorms occur throughout the year while Sumatra squalls commonly occur between April and November. The monsoon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

Network of Automated Weather Stations



Manned Weather Stations

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. Almost all the automatic weather stations measure rainfall and more than one-fifth of them measure other meteorological elements such as temperature, relative humidity, pressure, and wind. This observation network serves as the main source of climate data for this report.


The Changi Climate Station

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.


Upper Air Observatory

Further Information
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