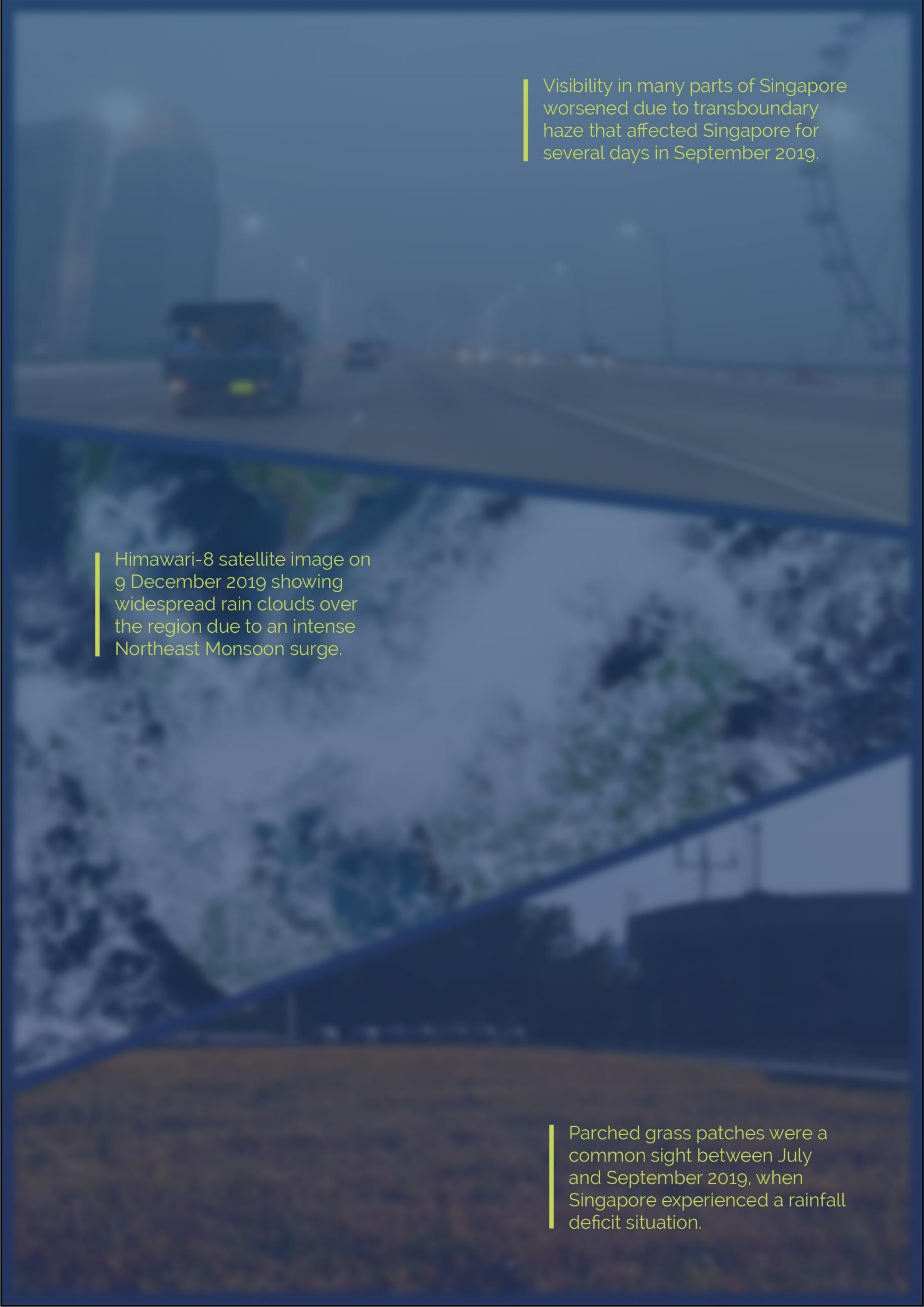
2019

ANNUAL CLIMATE ASSESSMENT

SINGAPORE

Meteorological Service Singapore
Centre for Climate Research Singapore



Visibility in many parts of Singapore worsened due to transboundary haze that affected Singapore for several days in September 2019.

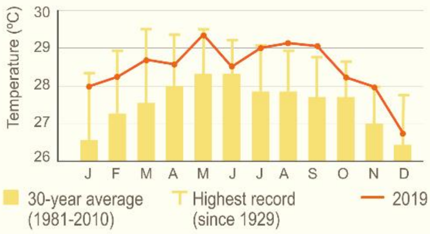
Himawari-8 satellite image on 9 December 2019 showing widespread rain clouds over the region due to an intense Northeast Monsoon surge.

Parched grass patches were a common sight between July and September 2019, when Singapore experienced a rainfall deficit situation.

Singapore's Climate in 2019

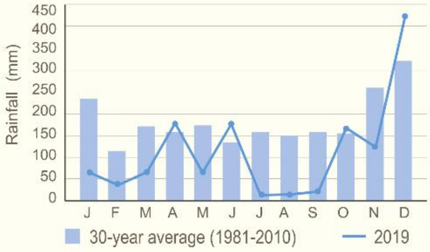
Annual Mean Temperature

Annual mean temperature was 28.4°C, 0.9°C higher than the 1981-2010 long-term average, and equalled the warmest year record of 28.4°C set only recently in 2016.



Monthly Mean Temperatures

Above-average temperatures were recorded in all months. Aug and Sep broke the record for warmest Aug and Sep respectively. Nov also tied the record for warmest Nov.



Monthly Total Rainfall

The third driest year ever recorded since 1869. At the Changi Climate Station, the rainfall recorded was 1368 mm, which was about 37% below the 1981-2010 long-term average.

NOTABLE WEATHER EVENTS IN 2019

Haze

For several days in September, Singapore's air quality was adversely affected by transboundary haze from Sumatra and Kalimantan. The 24-hour PSI peaked at 154 on 19 September, the highest for the year.

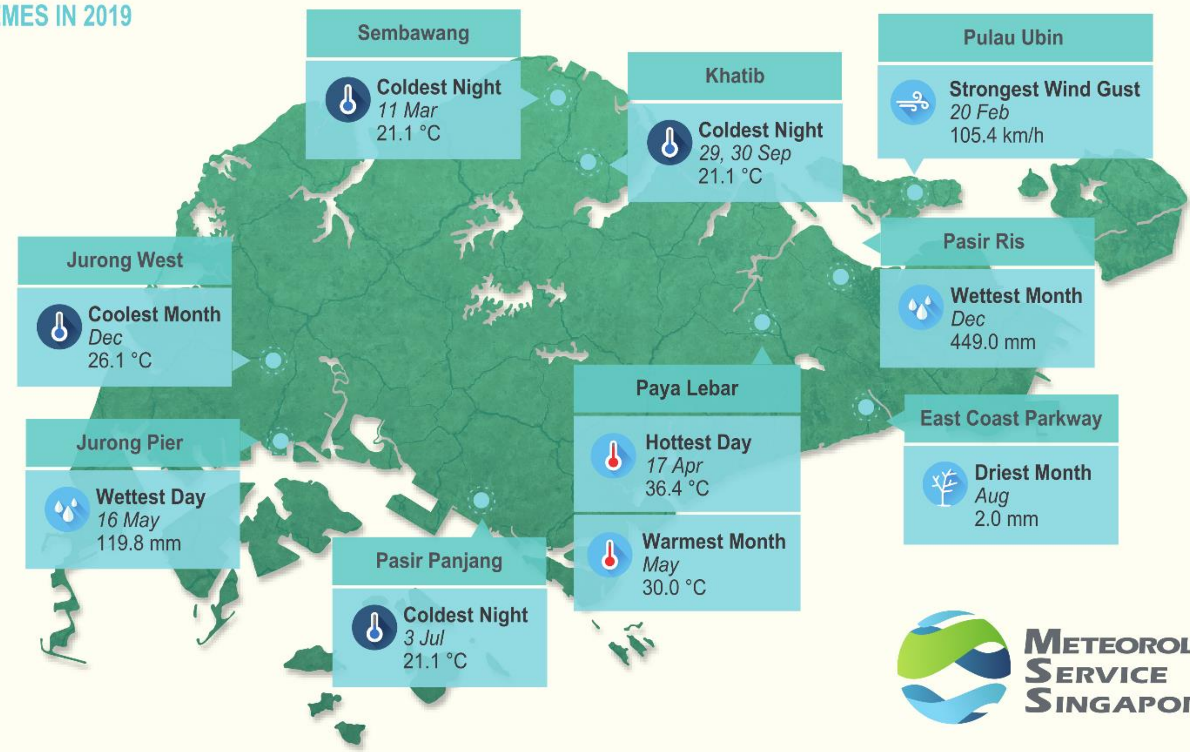
First recorded landspout in Singapore

On 27 September, the first recorded landspout in Singapore generated localised strong winds at Gul Way that ripped off the roof of a factory building.

Longest Northeast Monsoon surge in past 10 years

Lasting about seven days, the monsoon surge brought cool, windy and rainy conditions to Singapore in December. Widespread rain fell continuously for a few days.

EXTREMES IN 2019



Meteorological Service Singapore

Singapore Climate in 2019

The year 2019 continued the warm trend seen in Singapore over the past decades. Since February 2018, Singapore's monthly mean temperatures were above the respective monthly average for 23 consecutive months. The annual mean temperature in 2019 was 28.4°C. This was 0.9°C higher than the 1981-2010 long-term average, and equalled the previous warmest year record of 28.4°C set in 2016.
Four of the past five years are among the top 10 warmest years on record with respect to annual mean temperature, since temperature records began in 1929. Following closely behind the 2019 and 2016 joint warmest years are 2015, 1998 and 1997 as the joint third warmest years (28.3°C). The mean temperature for the last 10 years from 2010 to 2019 was 27.94°C, surpassing the previous warmest decade (27.89°C from 2009 to 2018).
Above-average temperatures were recorded in all months of 2019, with August (29.1°C) and September (29.0°C) breaking the record for the warmest August and September respectively (Figure 1). The previous records were 28.9°C (August 2016) and 28.8°C (September 1997). November 2019 (28.0°C) also tied the record for warmest November.

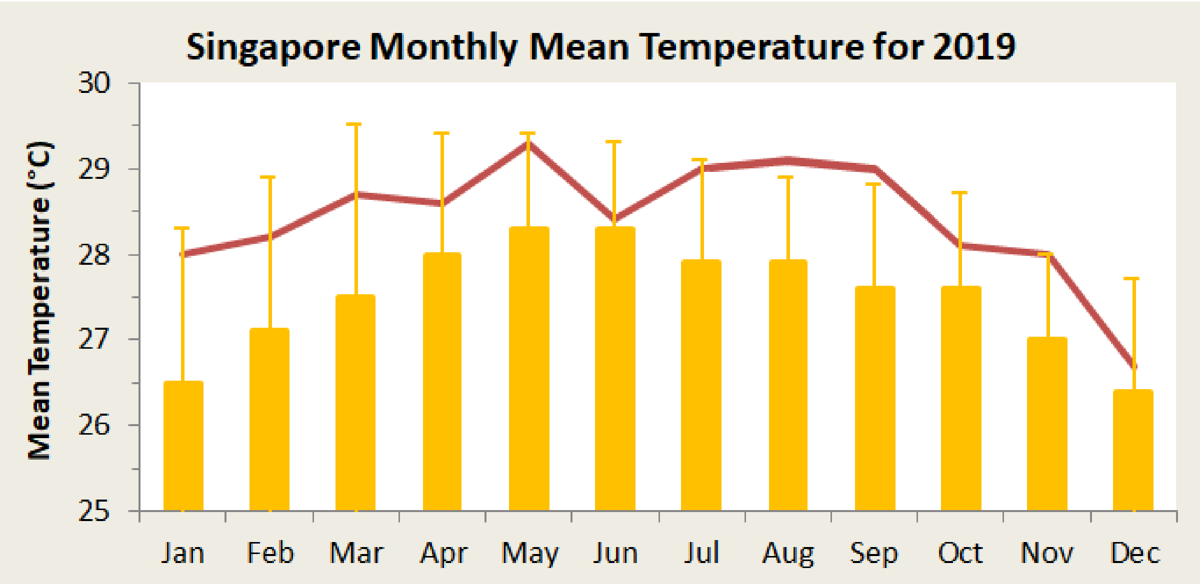


Figure 1: Singapore monthly mean temperature for 30 year average from Changi climate station (yellow bars, 1981 – 2010) compared to 2019 (solid red line). Also shown are the monthly record values for the historical period prior to 2019 as dashed 'whiskers'. Monthly records were equalled in 2019 for November and broken for August and September.

Other than the high temperatures, 2019 was also particularly dry. The 2019 annual total rainfall was below average over most of the islandwide rainfall stations. At the Changi climate station (Figure 2), the rainfall recorded was 1368 mm, which was 37% below the 1981-2010 long-term average. This is the third driest year behind 1997 (1119 mm) and 2015 (1267 mm) since rainfall records began in 1869.

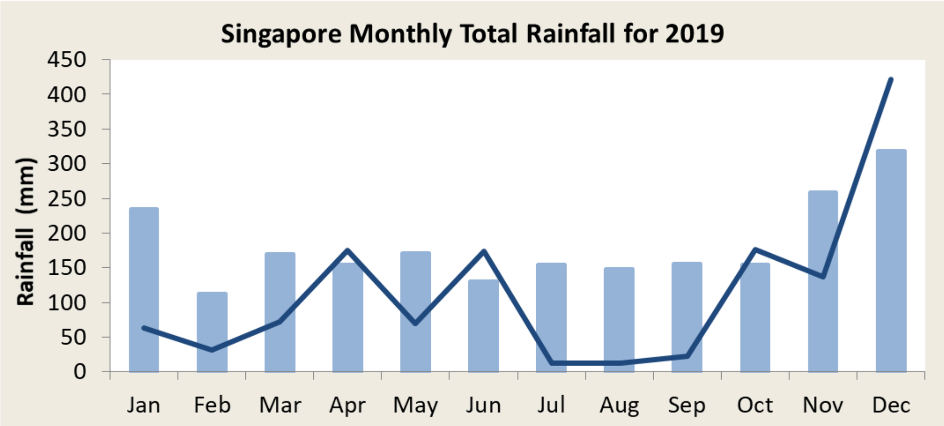


Figure 2: Singapore monthly total rainfall for 30-year average from Changi climate station (blue bars, 1981 – 2010) compared to 2019 (solid blue line). The annual total rainfall of 1368 mm for 2019 was 37% below the long-term annual average.

During the year, the driest periods were from January to March and July to September where rainfall was significantly below normal. For the period from July to September, Singapore entered a rainfall deficit situation[1] where monthly rainfall of more than 40% below normal was recorded in each of these three months (Figure 3).

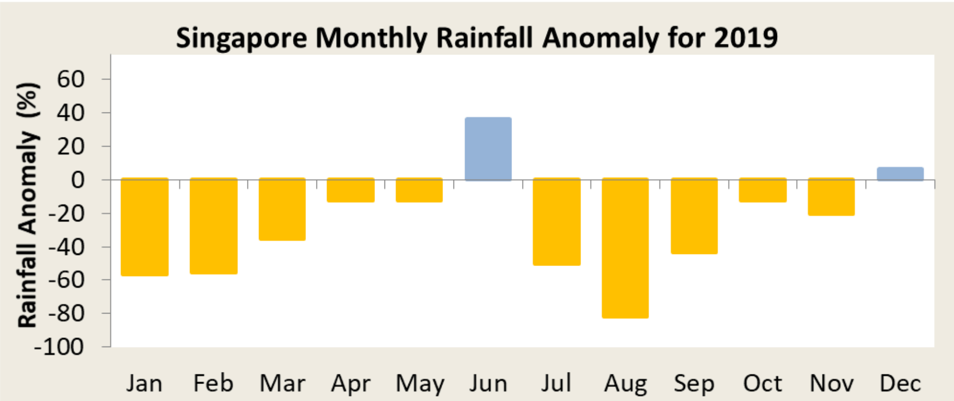


Figure 3: Singapore monthly rainfall anomaly for 2019 averaged over 28 stations islandwide. There were significant below-normal periods early in the year and for the July – September period.

During this period, Singapore experienced a dry spell[2] from 31 July to 16 August 2019.
Overall, 2019 was a neutral year for the El Niño Southern Oscillation (ENSO). At the start of the year, El Niño *conditions* were weak and the effect on global temperature from the end of 2018 to the start of 2019 was not warm or extensive enough in time and space to be attributed to a full-fledged El Niño *event*.
The year however saw the development of one of the strongest, positive Indian Ocean Dipole (IOD) events since the 1960s. A positive IOD typically contributes to drier, and consequently warmer, conditions over Singapore and the nearby region during the Southwest Monsoon season (June – September). Thus, the development of this IOD event since the middle of 2019 contributed significantly to the below-average rainfall and higher temperatures observed, especially during the third quarter.

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[1] A rainfall deficit situation refers to a period of at least three consecutive months with monthly rainfall more than 40% below the climatological rainfall, averaged over rainfall stations with long-term records across the island

[2] A dry spell is defined as a period of at least 15 consecutive days with daily total rainfall of less than 1mm, averaged over rainfall stations with long-term records across the island.

Notable Weather Events in 2019

Transboundary haze occurrence in September

On several days in September 2019, Singapore was affected by transboundary haze from land and forest fires in Sumatra and Kalimantan. The haze caused the 24-hr Pollutant Standards Index (PSI) to deteriorate to within the high end of the Moderate and Unhealthy ranges.

Figure 4: Haze shrouding Singapore's skyline on the morning of 22 September 2019 (Source: Meteorological Service Singapore)

The escalation of fires in the surrounding region can be attributed to significantly drier-than-normal conditions over southern Southeast Asia during the Southwest Monsoon season (June-September). The persistent dry conditions were due to a prevailing Indian Ocean Dipole event that contributed to suppressed rain cloud formation, and to the intrusion of a dry air mass from high-pressure systems over the Australian continent. Smoke haze from persistent land and forest fires in Sumatra and Kalimantan was blown by the prevailing winds and affected many parts of the region including Singapore.

On 14 September, the 24-hr PSI entered the *Unhealthy* range for the first time in 2019 when prevailing southerly winds brought dense haze from southern Sumatra to Singapore (Figure 5;top). The 24-hr PSI remained in the *Unhealthy* range on most days until 23 September. Between 21 and 23 September, a shift in the direction of the prevailing winds brought haze from fires in western Kalimantan to Singapore (Figure 5; bottom). At the peak of the haze episode, the 24-hr PSI reached a high of 154 in southern Singapore on 19 September.

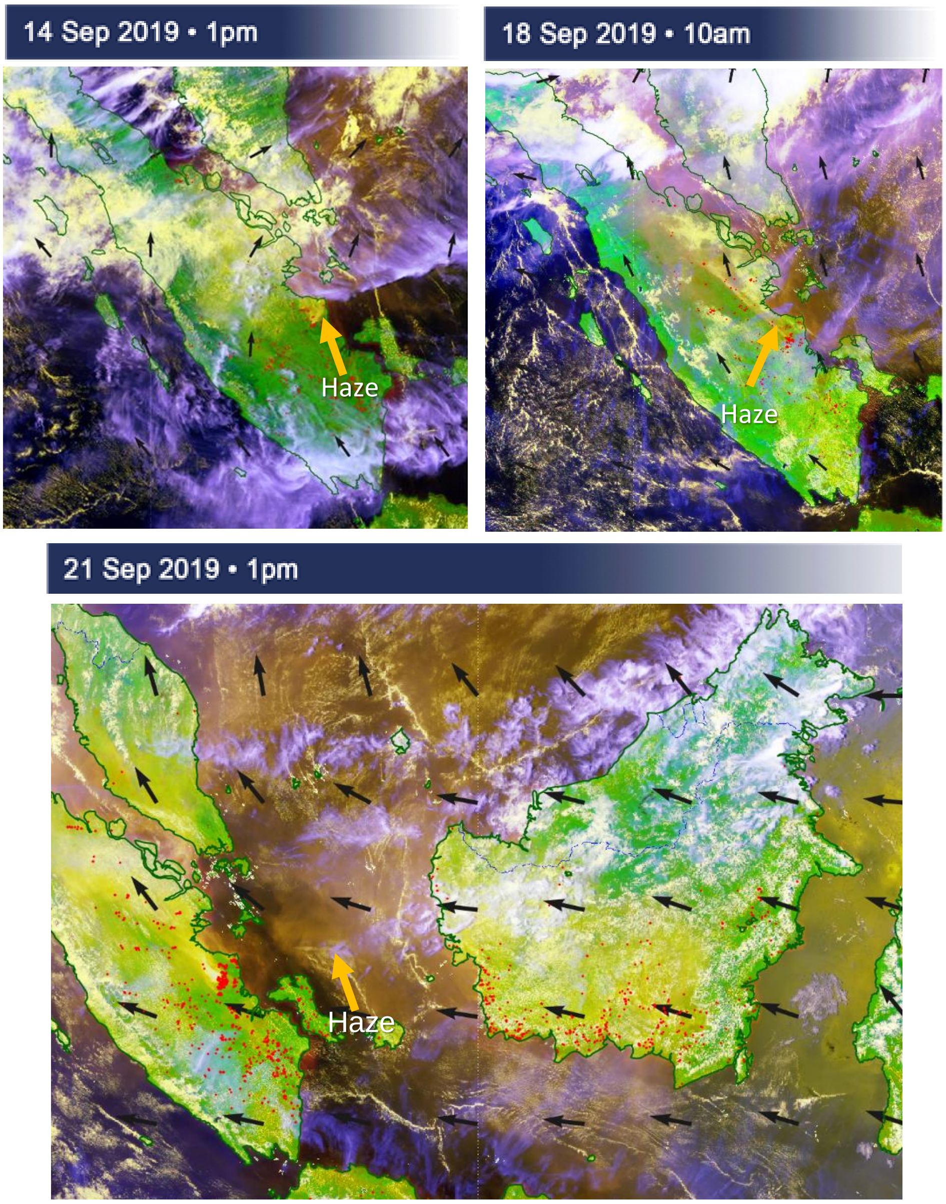


Figure 5: Himawari-8 satellite images showing smoke haze emanating from fire hotspots (red dots) in Sumatra (top) and Kalimantan (bottom) blowing toward Singapore by the prevailing winds (depicted by arrows).

First recorded landspout in Singapore

On 27 September 2019, a landspout was sighted for several minutes at Gul Way in southwestern Singapore. A landspout is a rotating column of air over land that stretches vertically to a developing towering cumulus or cumulonimbus cloud over it.

On that morning, the presence of moist air from the surrounding sea areas and localised convergence of winds over the southern and western coasts of Singapore were conducive for the development of intense thunderstorm clouds over the southwestern part of Singapore (Figure 6 and Figure 7). The intense thunderstorm cloud that developed over Tuas in the morning generated a rotating column of winds over Gul Way. The strong winds ripped off parts of the roof of a factory building (Figure 8).

This was the first recorded occurrence of a landspout in Singapore.

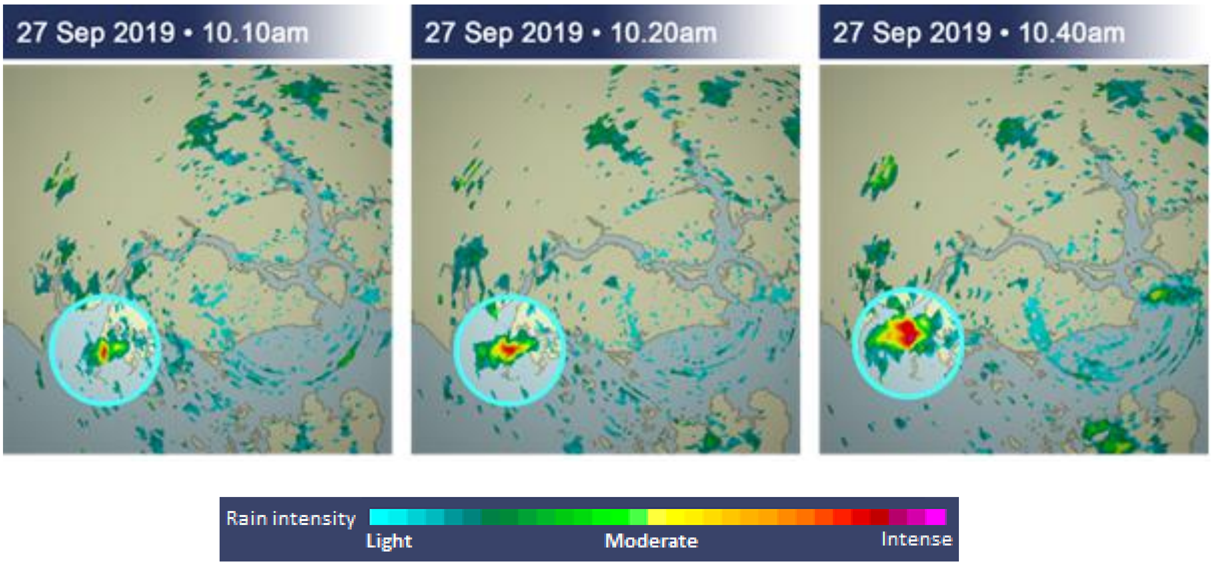


Figure 6: Time series of weather radar images showing the development of an intense thunderstorm over the Tuas area on 27 September 2019.

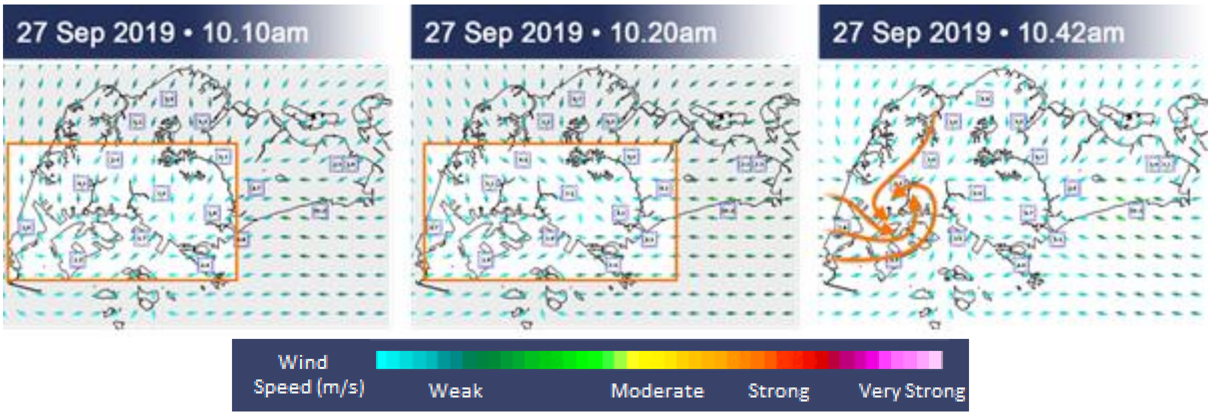


Figure 7: Time series of surface winds (depicted by arrows) on the morning of 27 September 2019. The red box (left and middle) shows the area with localised wind convergence. Streamlines of surface winds (right) shows the rotating wind flow over the area feeding into the intense thunderstorm.

Figure 8: A landspout ripped off parts of a factory building's roof at Gul Way in the Tuas area (Source: STOMP)

Longest Northeast Monsoon surge in past 10 years

In the first two weeks of December 2019, Singapore experienced an extended period of cool, cloudy and windy conditions. Between 9 and 15 December, periods of rain and showers fell over many parts of the island and were heavy on some occasions. In particular, widespread rain fell continuously over the 13 December weekend before dissipating on the evening of 15 December (Figure 9).

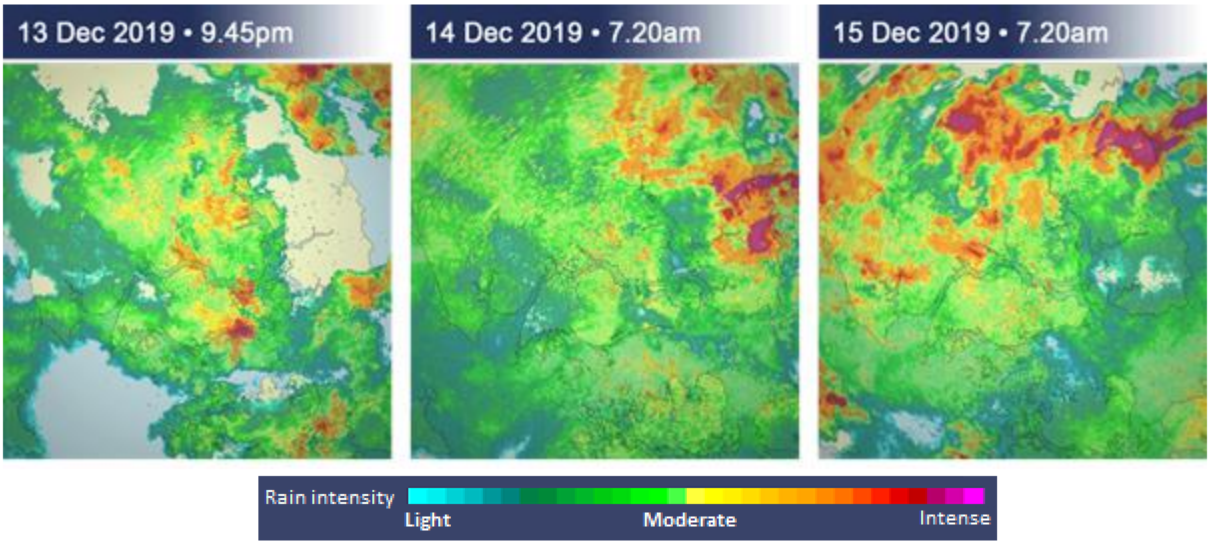


Figure 9: Time series of weather radar images shows widespread continuous rain over Singapore from 13 to 15 December 2019 due to a Northeast Monsoon surge.

The windy and rainy weather was due to a Northeast Monsoon surge[3] that prevailed over the equatorial South China Sea region (Figure 10). Lasting about seven days, it was the longest Northeast Monsoon surge episode affecting Singapore in the past 10 years. Cool conditions prevailed with the daily maximum temperature ranging between 26.5°C and 29.9°C on almost all days, and the lowest daily minimum temperature during the period was 22.0°C on 11 December. The highest daily total rainfall recorded was 100.4 mm on 9 December 2019 at Pulau Ubin.

[3] A monsoon surge refers to the strengthening of northeasterly winds blowing from a strong high-pressure system over the northern Asian continent toward the South China Sea, bringing periods of prolonged widespread rain and windy conditions to the surrounding region including Singapore and Peninsular Malaysia.

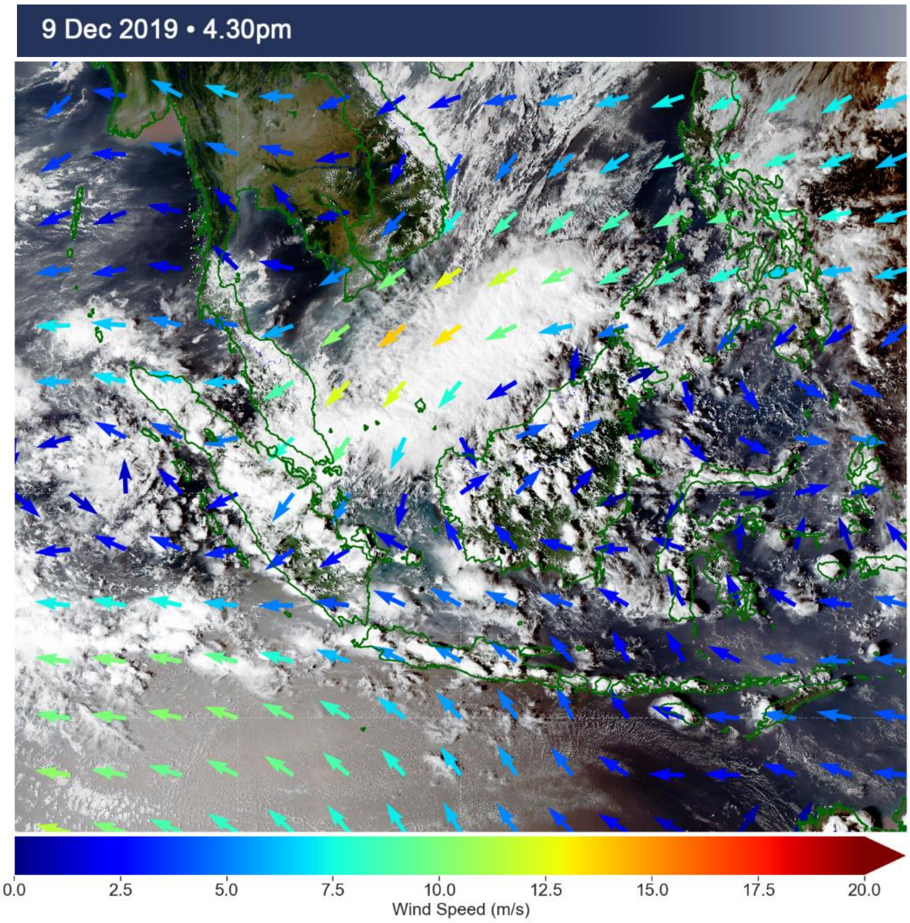


Figure 10: Himawari-8 satellite image showing cloudiness over the southern South China Sea region on 9 December 2019. Prevailing strong winds due to the monsoon surge are depicted by arrows.

Large-scale Climate Variability in 2019

The El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) was in neutral conditions overall in 2019. The Nino3.4 index momentarily breached the El Nino threshold in March 2019. Otherwise, the sea surface temperature over the Nino3.4 region remained largely neutral. As the warm sea surface temperature over the tropical Pacific Ocean did not sustain long enough at El Nino levels, the atmosphere did not show any responses long, or strong enough to merit an El Nino event. It was the Indian Ocean that was relatively more active and impactful to the Southeast Asia region in this year.

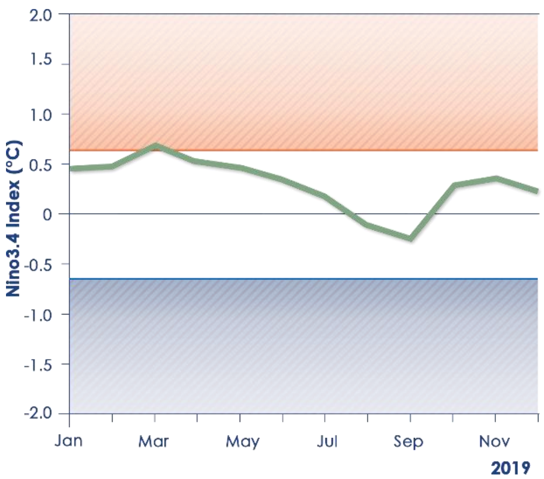


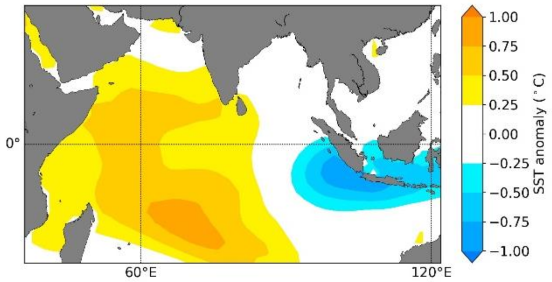
Figure 11: Nino3.4 index from January to December 2019. During this time, the Nino3.4 reached El Nino thresholds only in March 2019.

The Indian Ocean Dipole (IOD)

Southeast Asia sits between the Pacific and Indian Oceans. Like the El Niño-Southern Oscillation in the Pacific, the Indian Ocean also displays year-to-year variability. One of the main modes of variability monitored and studied is the Indian Ocean Dipole (IOD).The IOD refers to variations in sea surface temperature anomalies between the western and eastern Indian Ocean (see insert for more information on IOD characteristics). This section reviews what happened in the Indian Ocean in 2019, reviews the characteristics of IOD as well as answers to questions regarding the 2019 positive IOD event.

Overview of 2019

In contrast to the inactive ENSO, 2019 was a fairly active year for the Indian Ocean. While the ocean started from a neutral state, from May 2019 onwards there were warm anomalies in the western Indian Ocean and negative anomalies in the eastern Indian Ocean (Figure 12). The anomalies around Sumatra and Java were on average more than 1°C below average. The positive anomalies in the western Indian Ocean, while not as strong as the negative anomalies, were more widespread. This gave rise to a positive IOD index (Dipole Model Index, DMI) which peaked in October 2019 (Figure 13). Effectively, it was considered one of the strongest IOD events since 2001 based on the Australian Bureau of Meteorology's (BoM's) assessment. Notably, most models from various international climate centres predicted, from as early as December 2018, a positive IOD development. Given the strength of the IOD, it had significant impact on rainfall and temperature patterns over Singapore and the wider Southeast Asia region.



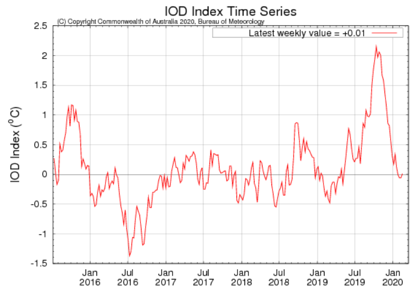
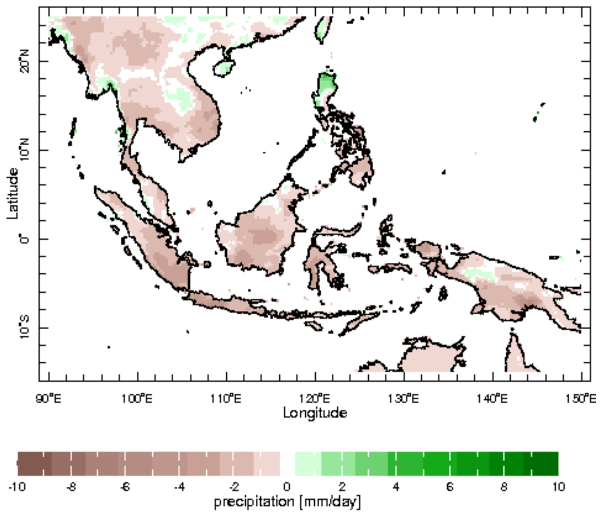


Figure 12: Average Sea Surface Temperature anomalies during the 2019 positive IOD event (May - December 2019). The background warming trend has been removed.

Figure 13: The Indian Ocean Dipole (IOD) index shows that positive IOD values peaked strongly in October 2019. [Credit: Bureau of Meteorology, Australia](#).

2019 IOD's impact on rainfall and temperature

The rainfall patterns showed drier conditions across Southeast Asia from May to December 2019 as expected during positive IOD conditions (Figure 14). In particular, the southern parts of the region (e.g. Sumatra, Java, and Kalimantan) were most affected by the positive IOD. The temperature over the region was also warmer broadly corresponding to the drier conditions over land. This is evident in the surface temperature ERA5 reanalysis dataset (Figure 15). Thus, the positive IOD contributed additional warming to a region already experiencing the effects of long-term global warming trend. Significantly, the drier and warmer conditions contributed to occurrences of transboundary haze which peaked over many parts of southern Southeast Asia in September 2019.



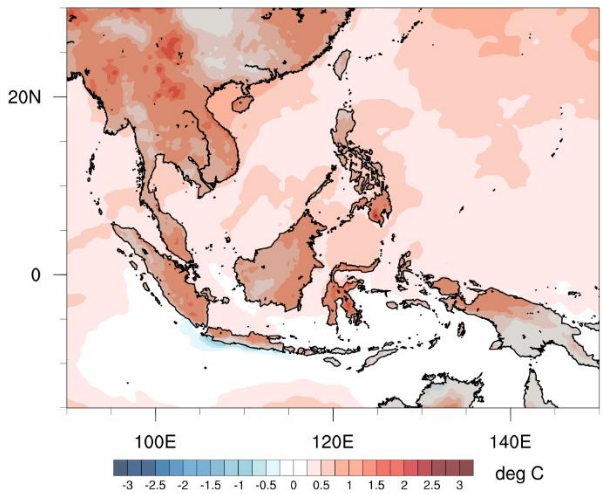


Figure 14: May-December 2019 average daily rainfall anomaly (in mm) against 1981-2010 climatology from CHIRPS dataset. Brown (green) shades show regions of drier (wetter) conditions. [Credit: IRI Data Library](#).

Figure 15: May-December 2019 average surface temperature anomalies (˚C) against 1981-2010 climatology show warmer conditions (red shades) for most parts over land. Data: ERA5

Characteristics of the Indian Ocean Dipole

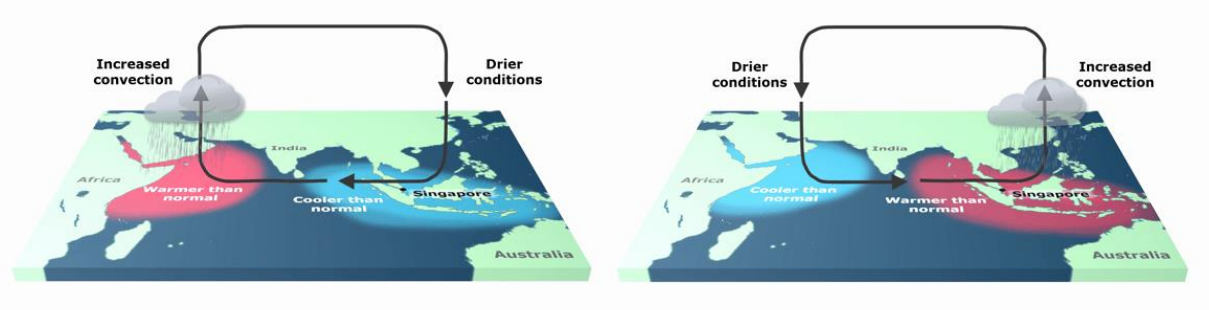


Figure 16: Description of positive (left) and negative (right) IOD events, showing the general sea surface temperature, wind and rainfall conditions.

The Indian Ocean Dipole refers to a broad pattern of temperature differences in the western and eastern Indian Ocean. Normally, or under IOD neutral conditions, sea surface temperatures are warmer in the eastern Indian Ocean compared to the western Indian Ocean, contributed in part by the warm water following through Indonesia from the western Pacific Ocean. As a result, the air above the eastern Indian Ocean and Maritime Continent region rises and then descends over the western half of the Indian Ocean with westerly winds blowing along the equator. During positive IOD events, however, there is a cooling of the sea surface temperatures in the eastern Indian Ocean (blue in Figure 16; left) and warming of the sea surface temperatures in the west. This dipole pattern leads to a weakening of the equatorial westerly anomalies, more rainfall over the western Indian Ocean, and less rainfall over parts of the Maritime Continent. During a negative IOD event (Figure 16; right), the dipole is reversed, with warmer-than-average sea surface temperatures in the eastern Indian Ocean and more rainfall over parts of the Maritime Continent.

IOD events normally start in May or June, lasting until around November with the start of the Northeast Monsoon. However, in some cases, such as the 2019 event, IOD events can last as long as to the start of following year's January. The IOD cycles are irregular, ranging from 1 to 13 years apart in the extreme cases. On average, however, positive and negative IOD events occur every five years. Often positive IOD events coincide with El Niño events (e.g. 1982, 1997, and 2015), but they can also occur without an El Niño event (e.g. 2012 and 2019). Similarly, negative IOD events often coincide with La Niña events (e.g. 1998, 2010 and 2016), but also occur alone (e.g. 1981, 1996 and 2014).

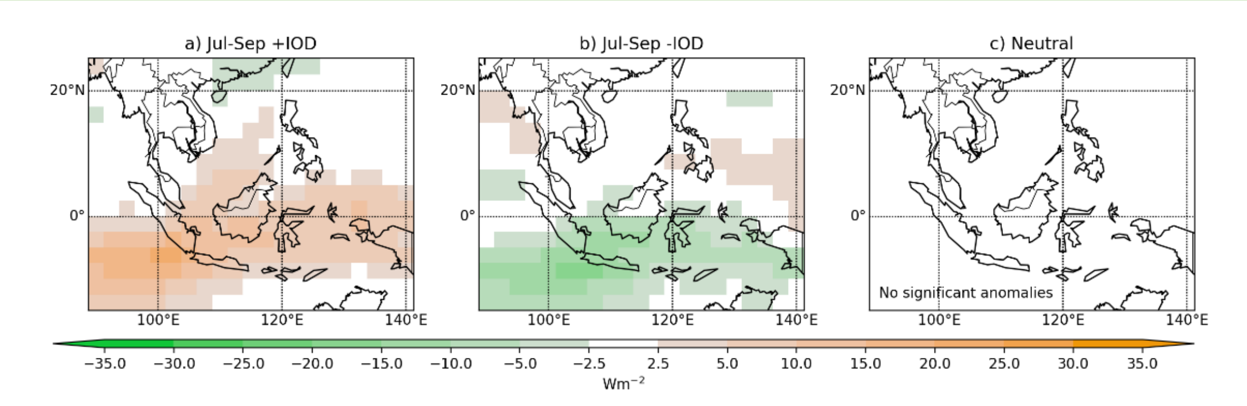


Figure 17: Impact of IOD events on Southeast Asia based on outgoing longwave radiation for past positive IOD events (a) for past negative IOD events (b) and all other years with no IOD (c) for the months July-September between 1960 and 2019.

The typical impact of positive and negative IOD events for Southeast Asia can be found by looking at the long-wave radiation anomalies in Figure 17. Here, orange colour denotes more outgoing longwave radiation (OLR) and hence fewer clouds and associated large-scale precipitation, while green denotes less outgoing longwave radiation (more clouds, and large-scale precipitation). During the July to September period, much of the southern part of Southeast Asia has fewer clouds (and consequently rainfall) than average during positive IOD events (Figure 17; left) and more clouds during negative IOD events (Figure 17; centre). This pattern aligns with the schematic in Figure 16. Looking at the July-September period when there are no IOD events, there are no noticeable anomalies, as other features such as ENSO, MJO, and other sources of variability are averaged out.

One of the key metrics for monitoring the Indian Ocean Dipole is the Dipole Mode Index (DMI) (Saji, Goswami, Vinayachandran, & Yamagata, 1999). The DMI calculates the difference between the sea surface temperature anomalies in the western tropical Indian Ocean (blue box; Figure 18) and the sea surface temperature anomalies in the southeastern tropical Indian Ocean (red, dotted box; Figure 18). When the western box is warmer-than-average and the southeastern box is colder-than-average, this results in a positive DMI value. Sustained positive values indicate a positive IOD event, while sustained negative DMI values indicate a negative IOD event.

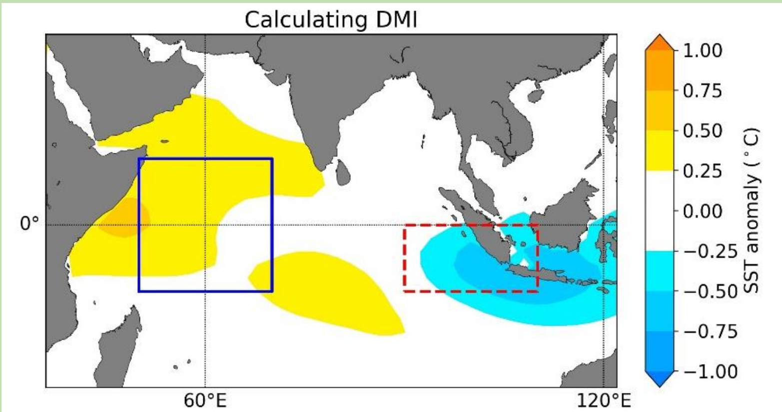


Figure 18: Outline of regions used to calculate the Dipole Mode Index (DMI). The average SST anomalies for between July and September during positive IOD events (1960-2019) is also shown.

Was 2019 similar to other years with strong positive IOD events?

The 2019 was the strongest positive IOD event since the 1997 event. Figure 19 compares the SST anomalies and OLR anomalies for the July-September period for 2019, 1997, as well as 1994 (another strong positive IOD event). From these plots the strong dipole is clearest for the 2019 case. The 1994 event had similar or stronger negative anomalies in the southeastern Indian Ocean, whereas the western Indian Ocean was closer to neutral. The dipole is visible in the 1997 case, although it is not as strong as in 2019. The 1997 event, however, peaked later in the year.

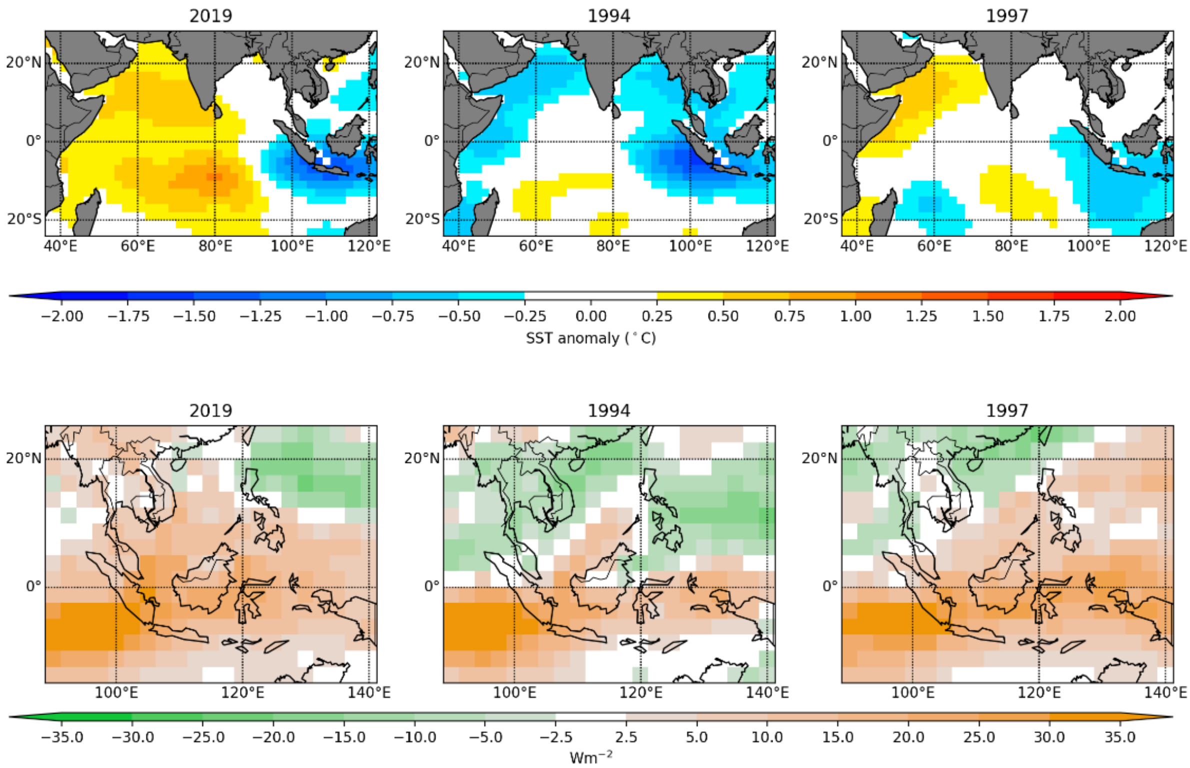


Figure 19: SST anomalies (top) and OLR anomalies (bottom) for the three events. The anomalies are averaged over the July to September period. Background warming has been removed from the SSTs.

The OLR anomalies for the three events are very similar for the southern half of Southeast Asia, all with fewer clouds than normal for the time of year, and hence drier. However, there is less consistency for the northern half of the region, with more clouds for much of Mainland Southeast Asia for July-September in 1994 and 1997, but drier for this region in 2019. One possible explanation is that both 1994 and 1997 were years with El Niño events, and hence could have affected the rainfall over the north differently.

Did the ENSO state influence the 2019 positive IOD event?

Figure 20 compares SST and OLR anomalies in 2019 with previous positive IOD events when an El Niño occurred, and those without one. Note that there were four cases between 1960 and 2018 where an IOD event occurred with no overlapping El Niño event, while there were six that overlapped with an El Niño event. Based on the SSTs, the 2019 looks stronger than average, which cannot be attributed to the absence of an El Niño event. However, when looking at the OLR anomalies, the 2019 event more closely resembled the positive IOD events without an El Niño: drier conditions over Mainland Southeast Asia, and more clouds are observed over the northern Philippines. A similar result is also found for the region around Singapore.

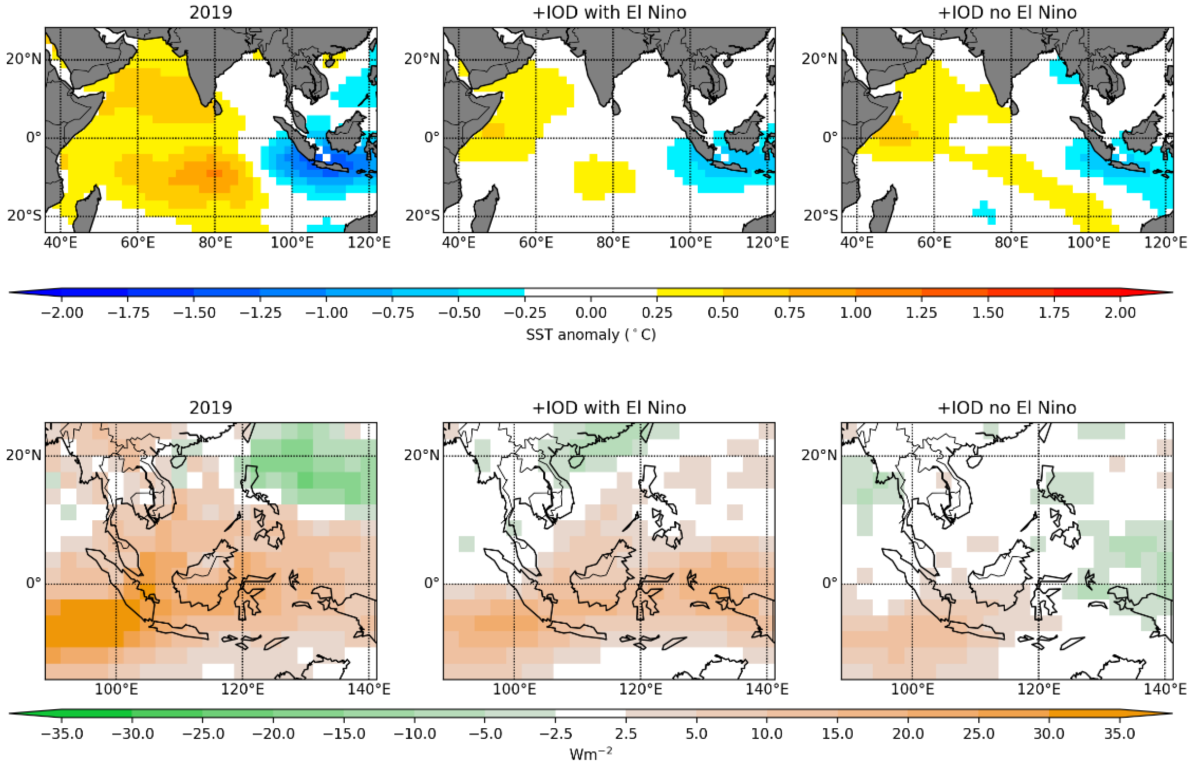


Figure 20: SST (top) and OLR (bottom) anomalies for July-September. The left column is the same as in Figure 19, while the centre column is a composite of all postive IOD events that overlapped with El Niño events, and the right column is for positve IOD events without an El Niño occuring (not including 2019).

Looking at all combinations of ENSO and IOD events between 1960 and 2019 (Table1), positive IOD events only coincide with El Niño or ENSO neutral events, while negative IOD events only coincide with La Niña or ENSO neutral events. So far, no positive IOD events have overlapped with La Niña events between July to September. Hence, while IOD and ENSO events may be monitored separately, there is a relationship between these two modes of climate variability.

	+IOD	Neutral	-IOD
El Nino	6	9	
Neutral	5	19	6
La Nina		10	5

Table 1 The number of times combinations of IOD and ENSO events occurred between 1960 and 2019[4] for the July – September period.

The Centre for Climate Research Singapore will continue to research how the Indian Ocean impacts Singapore and the surrounding region's climate, including developing new products to help inform the Singapore public and other stakeholders. There is still much to learn about the year-to-year variability in the Indian Ocean.

[4] IOD events are based on the BoM inventory, while the ENSO event are classified firstly based on the MSS criteria and then if the event covers at least one month in the July – September period for the year of interest.

The Madden-Julian Oscillation (MJO)

The first half of 2019 saw an active MJO for two periods. Usually, whenever an MJO is active in Phases 2-4, it tends to promote convection (more rainfall) over the Maritime Continent, but in Phases 6-8 it tends to suppress convection (less rainfall) (refer to [ACAR 2018] for details on MJO behaviour). In the first quarter of 2019, the MJO emerged in the first two weeks of the new year in the suppressed convective Phases 6-8 and then weakened momentarily. It then re-emerged in the last week of January 2019 circumnavigating the globe fully through the Maritime Continent (Phases 4-5) and back by the second week of March. In between, as it propagated, it grew in strength over the Indian Ocean (Phases 2-3) between the last week of February and first week of March (Figure 21, left).

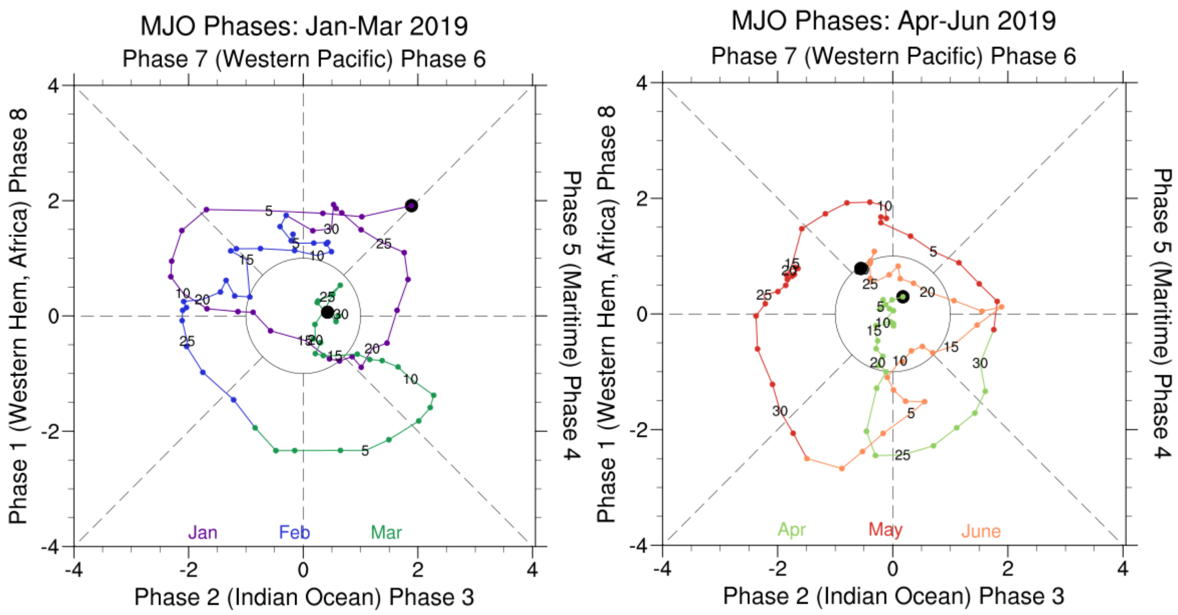


Figure 21: MJO phases from January to March (left) and April to June (right) 2019. The MJO was active during this period and was strong from late February to early March 2019 and from late April to early June 2019. Data: BoM, Australia.

In the second quarter of 2019, the MJO began propagating strongly again starting from the last week of April 2019 in Phase 2 (Figure 21; right). It continued propagating eastward, reaching Phase 2 again in early June 2019. The MJO's propagation through the Maritime Continent, as expected, affected rainfall patterns and intensity. For example, in the second quarter of 2019, the MJO brought enhanced rainfall to parts of the region: Phases 2-4 in late April (Figure 22; left) and Phases 2-3 in June 2019 (Figure 22; right).

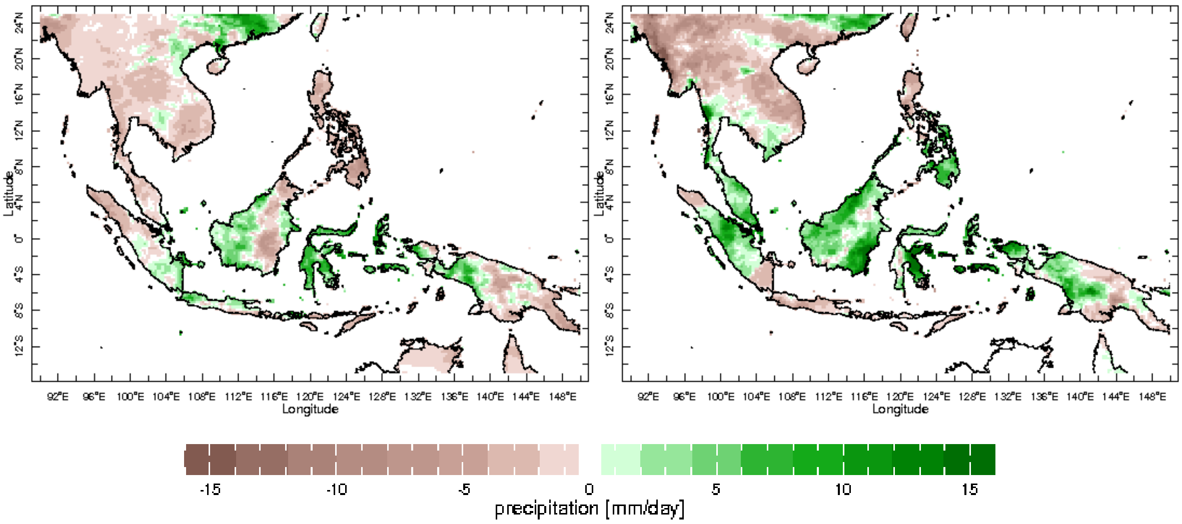


Figure 22: Regional rainfall anomaly patterns (mm/day) during the passage of MJO from 20 to 30 April 2019 when the MJO was in Phases 2-3 (left) and 1 to 10 June 2019 in Phases 2-3 (right). [Credit: IRI Map Room](#).

In the second half of 2019, the MJO was less active. It only propagated with significant strength in November, when the MJO emerged in Phase 5 and then faded into Phase 8 (Figure 23). Even though the MJO is expected to induce drier conditions over the region in these suppressed phases, the rainfall anomalies during this period (1-20 November 2019) more closely resembled the seasonal anomalies caused by an IOD event (Figure 14) instead of the typical rainfall response for an MJO in these phases during November. It is likely that the occurrence of this strong IOD event had suppressed the MJO's influence in the second half of the year.

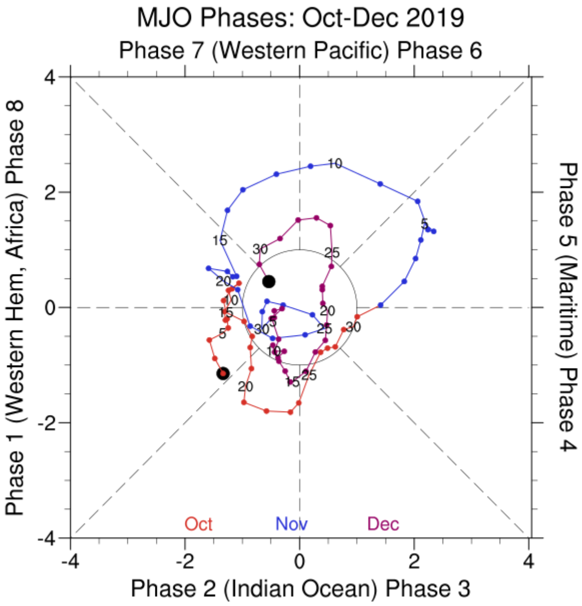


Figure 23: MJO phases from October to December 2019. The MJO was only active during November. [Data: BoM, Australia](#).

Temperature in 2019

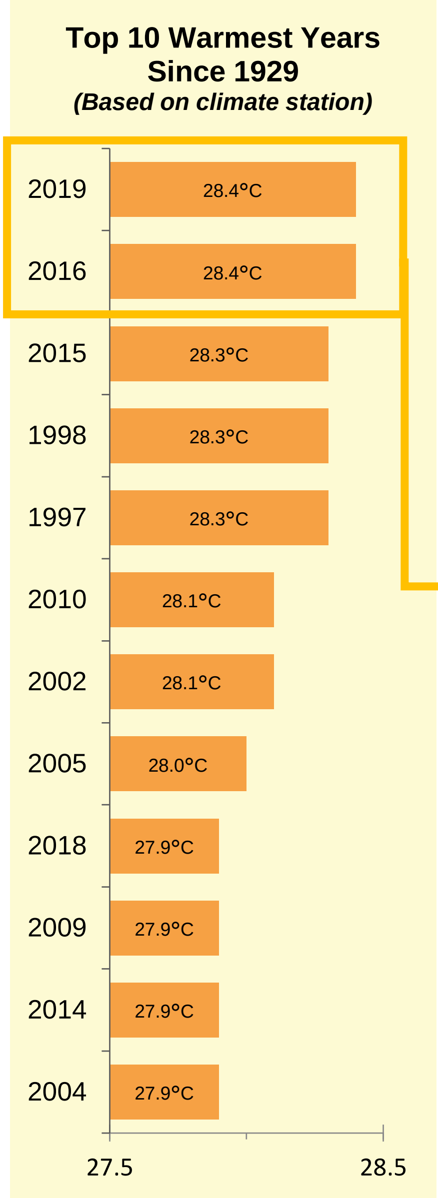


Figure 24: Annual mean temperature across Singapore in 2019.

2019 is the joint warmest year ever recorded in Singapore since 1929.

2019 was the joint warmest year in Singapore. This is on par with 2016, with an annual mean temperature of 28.4°C, 0.9°C higher than the 1981-2010 long-term average. Four out of the last five years are amongst the top 10 warmest years in Singapore based on temperature records in Singapore since 1929. Following closely behind the 2019 and 2016 joint warmest years are 2015, 1998 and 1997 as the joint third warmest years (28.3°C). The mean temperatures for the last 10 years (2010 to 2019 at 27.94°C) and the last five years (2015-2019 at 28.1°C) were the highest on record.

Globally, most parts of the world recorded above average temperatures (Figure 25) and the global average temperature for 2019 was about 0.5°C above the 1981-2010 long-term average and 1.1°C[5] above the pre-industrial baseline (1850-1900). This is the 2nd warmest year on record globally; and the past 5 years (2015-2019) and past ten years (2010-2019) were the highest on record. Since 1980s, each decade has been warmer than the previous one, highlighting the on-going global warming.

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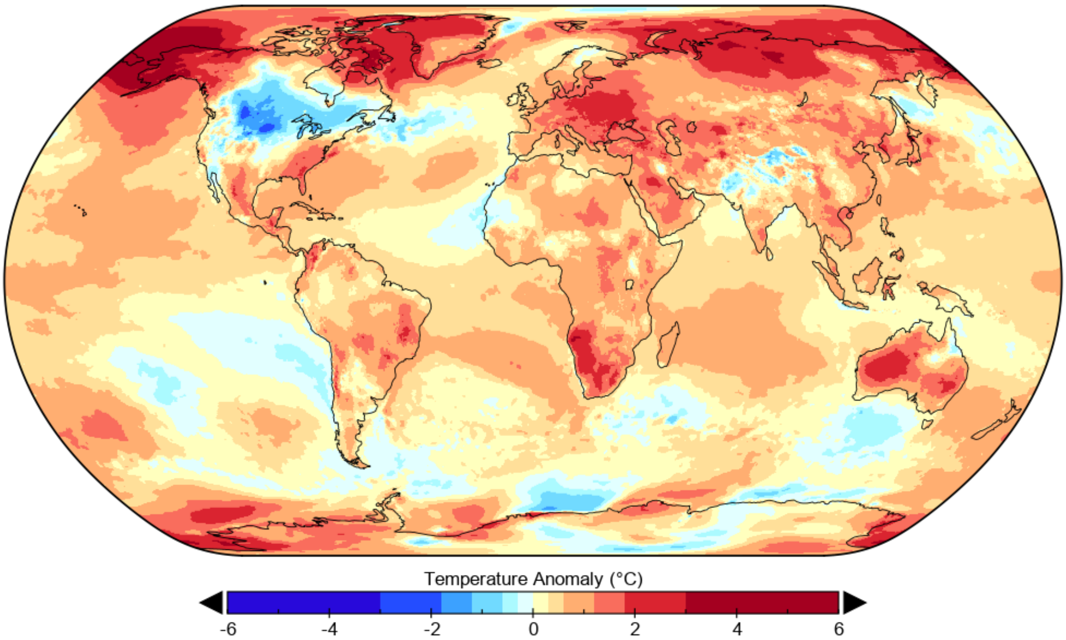
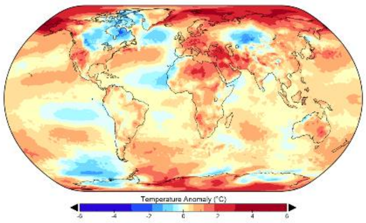
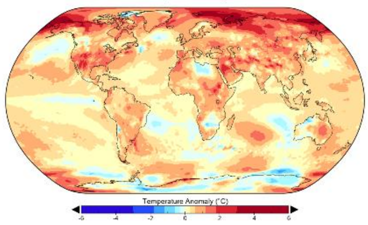
[5] Based on five independently maintained global temperature datasets: HadCRUT.4.6 produced by the UK Met Office in collaboration with the Climatic Research Unit at the University of East Anglia, UK; NOAA Global Temp produced by National Oceanic and Atmospheric Administration, National Centers for Environmental Information, USA; GISTEMP produced by the National Aeronautics and Space Administration Goddard Institute for Space Studies, USA; JRA-55 produced by the Japan Meteorological Agency, Japan; and ERA-Interim produced by the European Centre for Medium-range Weather Forecasts, UK.



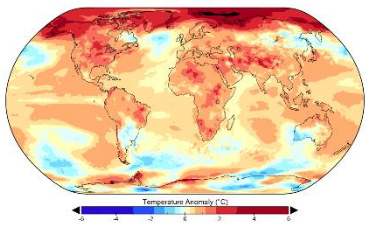
2019



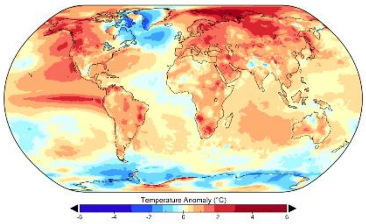
2018



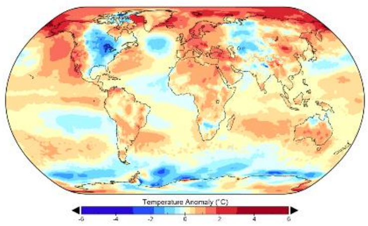
2017



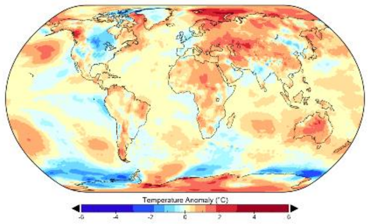
2016



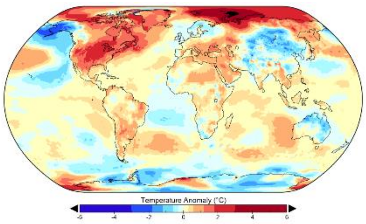
2015



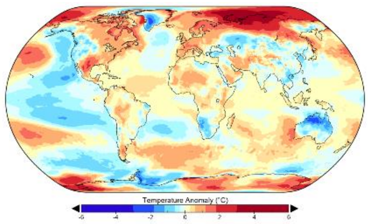
2014



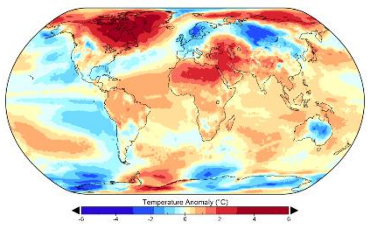
2013



2012



2011



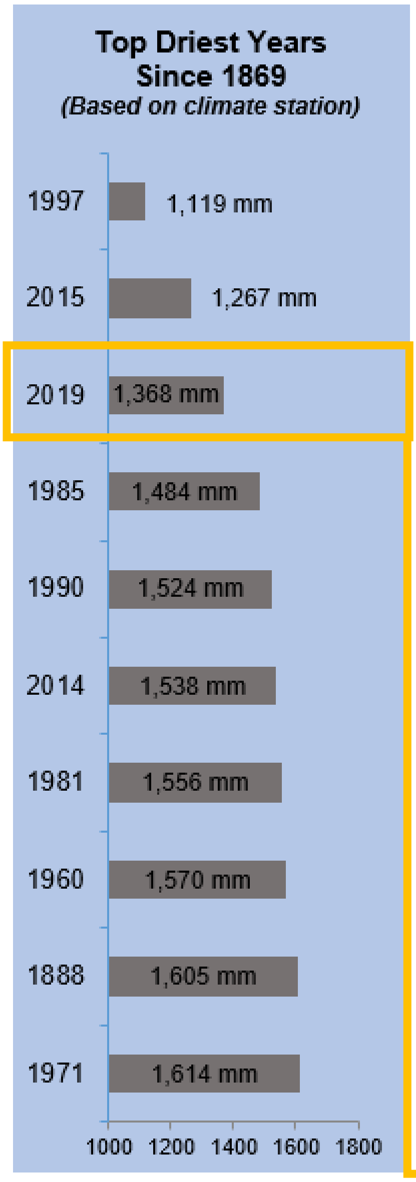
2010

Figure 25: Global annual surface air temperature anomaly (relative to the average from 1981-2010) for the past 10 years. Globally, the last decade (2010-2019) is the warmest decade on record. Since the 1980s, each decade has been warmer than the previous one.
(Data source: ERA5 Credit: ECMWF, Copernicus Climate Change Service)

Rainfall in 2019

2019 was a particularly dry year. The annual total rainfall was below average over most of the island-wide rainfall stations. At the Changi climate station, the rainfall recorded was 1368 mm, which was 37% below the 1981-2010 long-term average and is the third driest year.

Below normal rainfall was experienced for most months of 2019, especially from January to March and July to September. For the period from July to September, Singapore entered a rainfall deficit situation[6] where monthly rainfall of more than 40% below normal was recorded in each of these three months. During this period, Singapore also experienced a dry spell[7] from 31 July to 16 August 2019.



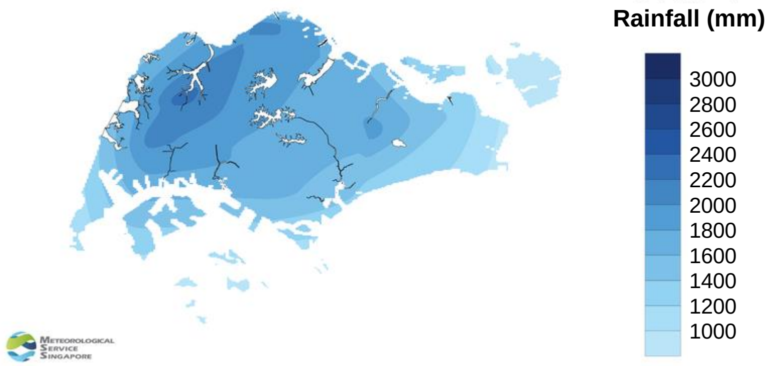


Figure 26: Annual total rainfall distribution across Singapore in 2019.

Figure 27: Annual rainfall anomalies (in percentage term) across Singapore (relative to the 1981-2010 average) in 2019.

In 2019, the climate station recorded its 3rd lowest annual total rainfall on record. Overall rainfall over the whole island was also below normal.

6 A rainfall deficit situation refers to a period of at least three consecutive months with monthly rainfall more than 40% below the climatological rainfall, averaged over rainfall stations with long term records across the island

7 A dry spell is defined as a period of at least 15 consecutive days with daily total rainfall of less than 1mm, averaged over rainfall stations with long-term records across the island.

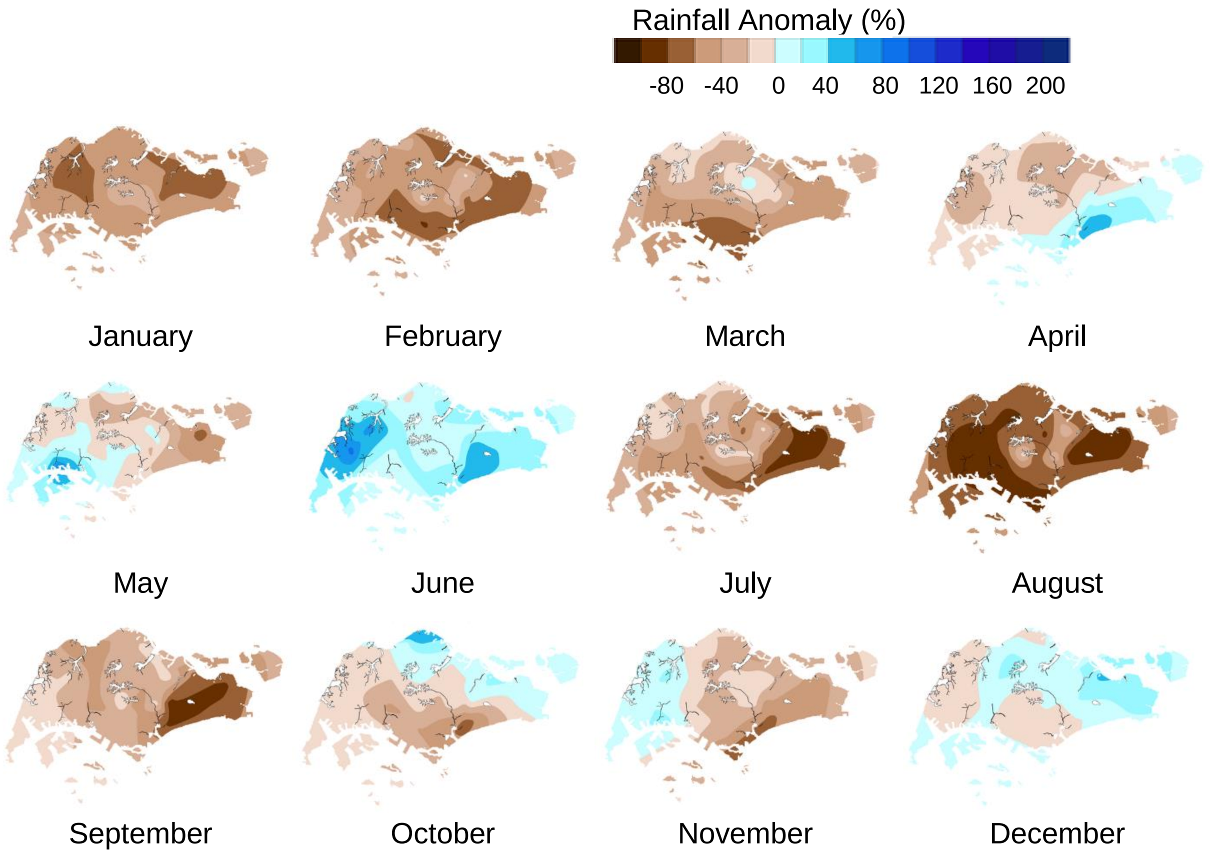


Figure 28: Monthly rainfall anomalies (in percentage term) across Singapore in 2019 (relative to the 1981-2010 average for the particular month).

Sea Level Rise

Recent trends in sea level in Singapore

Global warming has led to several consequences, in particular the increase of the Earth's mean surface temperature and of ocean heat content, the melting of sea ice and glaciers, and the loss of ice mass from the Greenland and Antarctica ice sheets. Warming oceans cause sea level to rise. Similarly, melting of glaciers, Greenland and Antarctica ice sheets ultimately reach the ocean thus further increasing sea level. Thus, in addition to extreme events such as heat waves, floods, droughts, cyclones etc., sea level rise is one of the most severe impacts of climate change posing a major threat especially to highly populated low-lying coastal regions and island nations of the world.

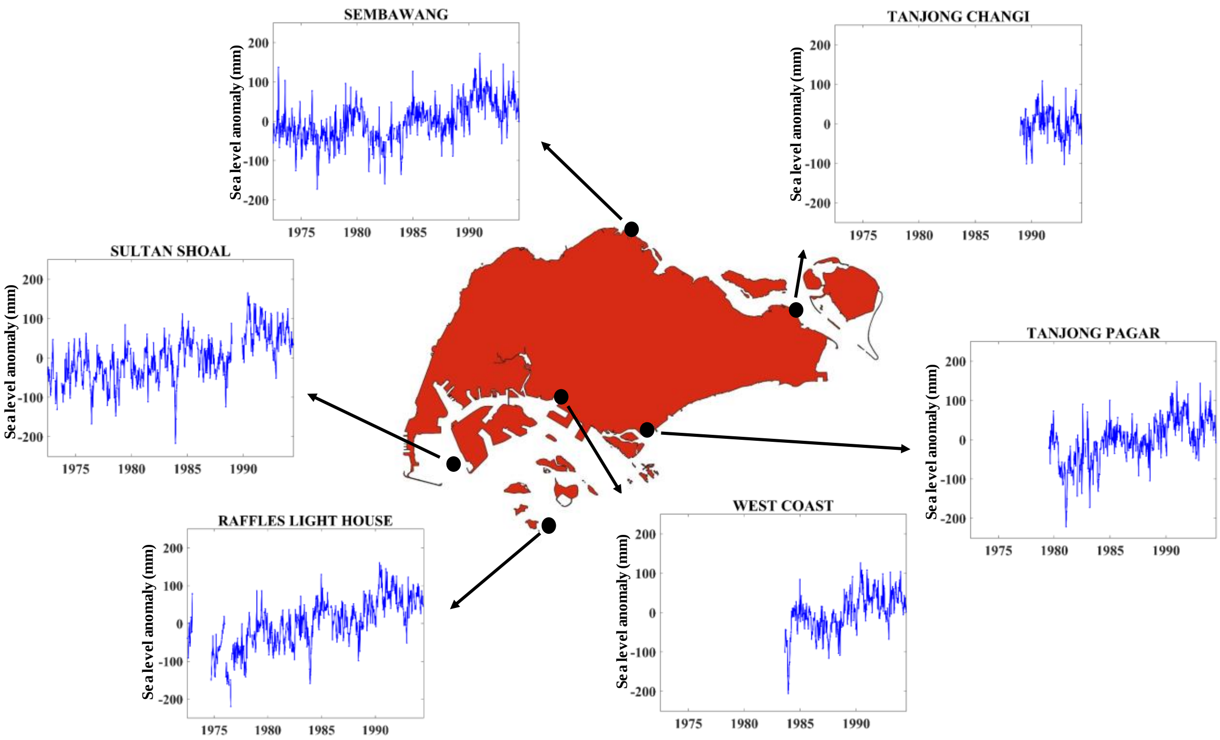


Figure 29: Sea level evolution time series at six tide gauge locations in Singapore (Source: Permanent Service of Mean Sea Level database) relative to baseline over the entire period of available data.

Direct observations from in situ tide gauges available since the mid-to-late 19th century show that on average, the 20th century global sea level has been rising at a rate of 1.2 to 1.9 mm/yr[1]. Since 1993, which marks the beginning of high precision altimetry records[2], the global average sea level has risen at a rate of about 3.24mm/yr and has reached its highest level of about 90mm above the 1993's level in 2019.

Sea level rise is not uniform and varies regionally and at different time scales. In fact, in a number of regions, sea level trends deviate significantly from the global mean[3].

Singapore, a low lying densely populated island state, is highly vulnerable to sea level rise in a warming climate. Figure 29 displays the sea level evolution observed by a subset of the 13 tide gauge records in Singapore[4]. Since the 1970s, Sembawang, Sultan Shoal and Raffles Light House show sea level rise rates of 2.12 ±0.15 mm/yr, 2.78 ± 0.16 mm/yr and 3.55 ± 0.17mm/yr respectively, leading to an average sea level in Singapore today of 140 mm above pre-1970 levels.

Sea level variability in Singapore

Assessing sea level rise over longer time scales requires an understanding of the naturally occurring variations in sea level which is superimposed onto the long term trend.

In terms of variability, local sea level is influenced by both high and low frequency variability occurring at different time scales (from hourly to decadal). For example, the time series in Figure 29 also display the monthly variability of local sea level.

Various climate processes can contribute to sea level variability occurring at these different time scales. For example, at seasonal time scale, northeast (southwest) monsoons can induce up to 0.20m sea level increase (decrease) in southern South China Sea region[5]. On inter-annual timescale, sea level is influenced by the El Nino-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD). While at decadal to inter-decadal timescales, the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation (PDO/IPO) can induce significant sea level variability over the tropical west Pacific Ocean/ Southeast Asia regions[6].

Sea level variability in Singapore on interannual time scales is strongly influenced by the natural climate modes of both ocean basins, Pacific and Indian Ocean. Figure 30 displays this interannual sea level variability observed at the Raffles Light House tide gauge together with the common indices of ocean variability: the Indian Ocean Dipole index and the ENSO index. The sea level variability from the tide gauge shows significant correlation to both ENSO and IOD, but the contribution from either ocean basin may differ for each year.

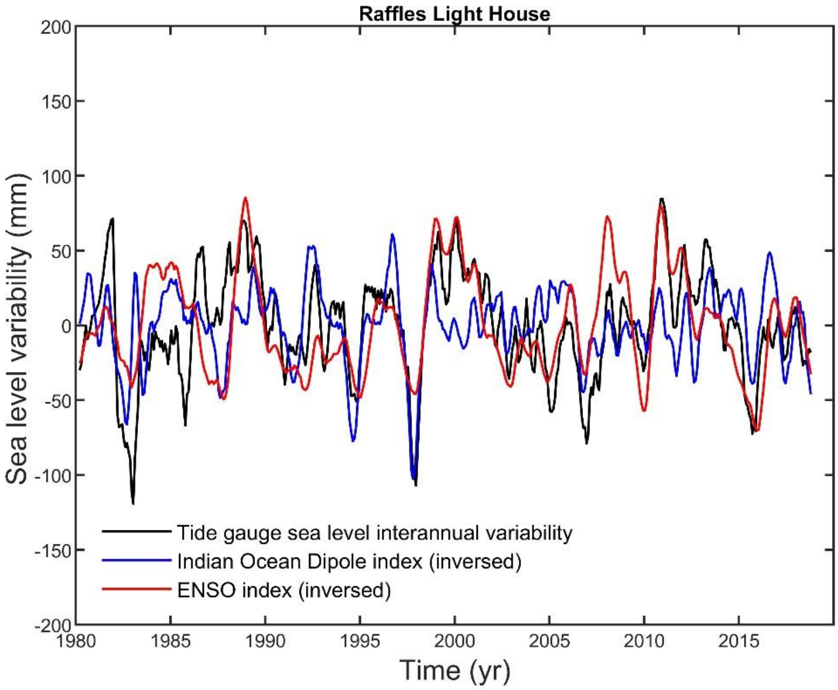


Figure 30: Comparison of Raffles Light House sea level inter-annual variability (in black) with Indian Ocean (Indian Ocean Dipole, in blue) and Tropical Pacific variability (ENSO, in red) indices.

References

[1] *Dangendorf, S., Marcos, M., Wöppelmann, G., Conrad, C. P., Frederikse, T., and Riva, R. (2017). "Reassessment of 20th Century global mean sea level rise," in Proceedings of the National Academy of Sciences, Vol. 114, 5946–5951. doi: 10.1073/pnas.1616007114.*

[2] *WMO Provisional Statement on the State of the Global Climate in 2019: https://library.wmo.int/doc_num.php?explnum_id=10108*

[3] *Cazenave, A., Palanisamy, H., and Ablain, M. (2018). Contemporary sea level changes from satellite altimetry: what have we learned? What are the new challenges? Adv. Space Res. 62, 1639–1653. doi: 10.1016/j.asr.2018.07.017.*

[4] *Data obtained from the Permanent Service of Mean Sea Level (PSMSL) database, provided by the Singapore Maritime Port Authority (MPA).*

[5] *Tkalich P, Vethamony P, Babu MT, Malanotte-Rizzoli P (2012) Storm surges in the Singapore Strait due to winds in the South China Sea. Nat Hazards 66(3):1345–1362.*

[6] *Han, W., Stammer, D., Thompson, P. et al. Surv Geophys (2019) 40: 1493. https://doi.org/10.1007/s10712-019-09562-8*

General Climate of Singapore

Singapore has a tropical climate which is warm and humid, with abundant annual rainfall of about 2,200 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 the 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.

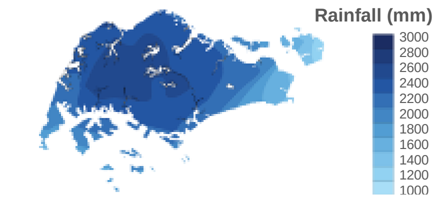
Singapore's climate is traditionally classified into four periods according to the average prevailing wind direction:

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).



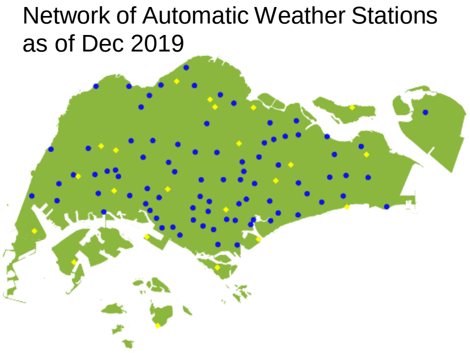
Average Annual Rainfall (1981-2010)
(based on 28 rainfall stations)

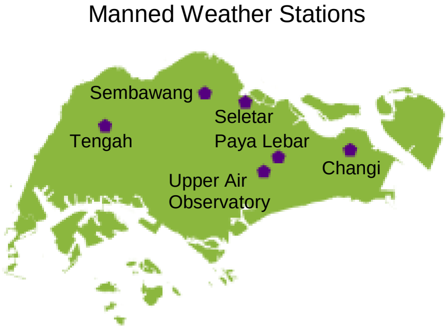
The transitions between the monsoon seasons occur gradually, generally over a period of two months (the inter-monsoon periods). The winds during the inter-monsoon periods are usually light and tend to vary in direction. The three main rain-bearing weather systems that affect Singapore are the Northeast Monsoon surges, "Sumatra" squalls and convective showers/thunderstorms. Convective showers/thunderstorms occur throughout the year. "Sumatra" squalls commonly occur during the Southwest Monsoon and inter-monsoon periods, while 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 thunderstorm line that develops over Sumatra or the Straits of Malacca, often overnight, and then 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 wind gusts with speeds up to 80 km/h (22 m/s) which are strong enough to 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 heartland of Asia including Siberia, experiences very low, cold temperatures. From time to time, this cold air rushes out of Central Asia leading to an abrupt increase in northeasterly winds over the South China Sea blowing towards the warm tropics. The sea warms and moistens the overlaying air and the wind eventually converges to bring about widespread rain in the tropical regions. December and January are usually the wettest months of the year in Singapore and a few 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.





Legend
Stations measuring rainfall only
Stations measuring rainfall and other elements including temperature, winds & relative humidity

About the Meteorological Service Singapore (MSS)

The MSS is Singapore's national authority on weather and climate. It is a division 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 our designated climate station. The climate station, first located at Outram in 1869, has undergone a number of relocations over the years due to changes in local land use, before shifting 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. This limits the number of stations available for such purpose to 28 stations for rainfall and three stations for temperature.

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
Meteorological Service Singapore : www.weather.gov.sg
Centre for Climate Research Singapore : ccrs.weather.gov.sg
Email enquiries : NEA_MSS_Engage@nea.gov.sg